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Extended essay cover

✓

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Candidate session number			
Candidate name			
School name			
Examination session (May or November)	MAY	Year	2015

Diploma Programme subject in which this extended essay is registered: PHYSICS

(For an extended essay in the area of languages, state the language and whether it is group 1 or group 2.)

Title of the extended essay: The Temperature of Cr O2 in Relation to its Magnetic Susceptibility

Candidate's declaration

This declaration must be signed by the candidate; otherwise a mark of zero will be issued.

The extended essay I am submitting is my own work (apart from guidance allowed by the International Baccalaureate).

I have acknowledged each use of the words, graphics or ideas of another person, whether written, oral or visual.

I am aware that the word limit for all extended essays is 4000 words and that examiners are not required to read beyond this limit.

This is the final version of my extended essay.

Candidate's signature: ____

Date: Feb 5th 2015

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The supervisor must complete this report, sign the declaration and then give the final version of the extended essay, with this cover attached, to the Diploma Programme coordinator.

Name of supervisor (CAPITAL letters) ______________________________

Please comment, as appropriate, on the candidate's performance, the context in which the candidate undertook the research for the extended essay, any difficulties encountered and how these were overcome (see page 13 of the extended essay guide). The concluding interview (viva voce) may provide useful information. These comments can help the examiner award a level for criterion K (holistic judgment). Do not comment on any adverse personal circumstances that may have affected the candidate. If the amount of time spent with the candidate was zero, you must explain this, in particular how it was then possible to authenticate the essay as the candidate's own work. You may attach an additional sheet if there is insufficient space here.

I suggested to at the start of the essay that magnetism was a fairly difficult subject for an EE, as it is difficult to measure using the tools we have at school. He proceded anyhow, and worked out an interesting process for measur static friction as a means for measuring low magn forces. While I question some of his method others were quite resourceful. ✓

This declaration must be signed by the supervisor; otherwise a mark of zero will be issued.

I have read the final version of the extended essay that will be submitted to the examiner.

To the best of my knowledge, the extended essay is the authentic work of the candidate.

As per the section entitled "Responsibilities of the Supervisor" in the EE guide, the recommended number of hours spent with candidates is between 3 and 5 hours. Schools will be contacted when the number of hours is left blank, or where O hours are stated and there lacks an explanation. Schools will also be contacted in the event that number of hours spent is significantly excessive compared to the recommendation.

I spent $\boxed{3 ✓}$ hours with the candidate discussing the progress of the extended essay.

Supervisor's signature: _ Date: Feb 9/2015

Assessment form (for examiner use only)

Candidate session number		

Criteria	Achievement level: Examiner 1	maximum	Examiner 2	maximum	Examiner 3
A research question	2	2		2	
B introduction	0	2		2	
C investigation	2	4		4	
D knowledge and understanding	1	4		4	
E reasoned argument	2	4		4	
F analysis and evaluation	1	4		4	
G use of subject language	1	4		4	
H conclusion	2	2		2	
I formal presentation	2	4		4	
J abstract	2	2		2	
K holistic judgment	2	4		4	
Total out of 36	17				

Name of examiner 1: ______________________ Examiner number: ____________
(CAPITAL letters)

Name of examiner 2: ______________________ Examiner number: ____________
(CAPITAL letters)

Name of examiner 3: ______________________ Examiner number: ____________
(CAPITAL letters)

IB Assessment Centre use only: B:

IB Assessment Centre use only: A:

The Temperature of CrO2 in Relation to its Magnetic Susceptibility

(CrO_2)

Subject: Physics
Word count: 3330

Abstract

The effect of temperature on the magnetic susceptibility of CrO_2 was investigated using water to heat the chromium (IV) oxide, which was then brought increasingly closer to neodymium magnets until the force of static friction was overcome and the metal was pulled towards the magnets. The force of static friction needed to pull the CrO_2 was then calculated, and upon analyzing the videos of the CrO_2 being attracted to the magnet, the minimum distance required to overcome the force of static friction was calculated. This value was set equal to the force of the magnetic field being exerted on the CrO_2 at a point, which was used to calculate its magnetic field strength. Using this value, its magnetic susceptibility was calculated and graphed. Upon graphing the relationship between magnetic susceptibility and temperature, it was found that the uncertainties in the experiment were much too large to come to a reasonable conclusion, indicating that there were many sources or error.

3rd element :

2/2

159 words

Table of Contents

Contents

Introduction

There have been many physicists such as Neils Bohr and Michael Faraday who have made extremely influential discoveries in the field of electromagnetism. I have chosen to further explore a concept that Madame Curie has discovered, Curie temperature.

elaborate

Since the magnetic susceptibility of a substance can be used as an indicator of Curie point, the relationship between magnetic susceptibility and temperature of CrO_2 was explored. This mainly focused on the curie temperature of a ferro/paramagnetic material, and the effect that temperature has on the ordering of the spins of the electrons in an atom. Since CrO_2 is used in cassette tapes, it can be used to determine the ideal temperature at which to imprint tapes; since it needs to be done when it is magnetic properties are extremely minimal so that recording quality can be optimized. Chromium (IV) oxide was chosen as a metal because of its fairly low curie temperature (386 K)[1]. In order to investigate this relationship, CrO_2 was heated by placing it in a test tube, and heating the test tube with a hot plate while it was in water. This ensured that the plastic from the tape on the CrO_2 did not melt.

not for intro

The aim of this experiment is to determine a relationship between the magnetic susceptibility of CrO_2 and its temperature. This could be applied to the use of cassettes in industry, as it could determine whether or not they are more effective at a certain temperature, since chromium (IV) oxide is used to coat the tapes.

Research Question

2/2 ✓ How does the temperature of chromium (IV) oxide affect its magnetic susceptibility?

Key Terms

? **Magnetic susceptibility**: The quantitative measure of the extent to which a material may be magnetized in relation to a given applied magnetic field[2]. not an operational defn

Curie point/temperature: temperature at which certain magnetic materials undergo a sharp change in their magnetic properties[3].

Ferromagnetic: physical phenomenon in which certain electrically uncharged materials strongly attract others[4].

intro: physics principles involved very limited, almost none;

0/2

✓ [1] Guinier & Jullien, pg. 155

[2] http://www.britannica.com/EBchecked/topic/357313/magnetic-susceptibility

[3] http://www.britannica.com/EBchecked/topic/146902/Curie-point

✓ [4] http://www.britannica.com/EBchecked/topic/205135/ferromagnetism

Theory

Chromium (IV) oxide, having 3 unpaired electrons and an electron configuration of [Ar] 3d3 can be classified as ferromagnetic. Under the presence of a magnetic field, the unpaired electrons align, causing the material to exhibit properties of magnetism.

D elaborate μeff

If the substance follows the Curie law, then the effective magnetic moment (μeff) can be estimated as: G

$$\mu_{eff} = \sqrt{n(n+2)}\mu_B \quad (1)$$

G

In this equation, n is the number of unpaired electrons and μB is a constant known as a Bohr magneton5, defined as: G

G ?

$$\mu_B = \frac{e\hbar}{2m_e} \quad (2)$$

ħ ? ?

G

Where e is the elementary charge, ħ is the reduced Planck constant, me is the electron rest mass and c is the speed of light.

M_e ...

c? where is it?

Substituting n=3 into (1);

$$\mu_{eff} = \sqrt{3(3+2)}\frac{(1.602*10^{-19})(6.636*10^{-34})}{2(9.109*10^{-31})(2\pi)} = 3.597*10^{-23}\ \mathrm{J\,T^{-1}} \quad (3)$$

m_e

use power of ten G

This value, found in terms of one atom, was then multiplied by the mass of the CrO2, measured to be (0.00130±0.00001) kg, divided by its molar mass, which gives the number of particles in the sample used. The uncertainty was calculated by dividing the relative uncertainty by the molar mass of CrO2, and then multiplying it for the value of the effective magnetic moment:

show it

$$\mu_{eff} = 3.597*10^{-23} * \frac{0.00130 \pm 0.00001}{\underset{Cr}{51.9961} + \underset{O_2}{15.9999*2}}$$

$$\mu_{eff} = 5.57 * 10^{-28} \quad (4)$$

unit ? G

The uncertainty was found to be << 1%, which is negligible.

D must explain clearly what each M and H represents;

Using the formula;

$$X_v = MH; \quad (5)$$

? $(\chi_m = M/H)$ see eqn 7

Where X_v is the magnetic susceptibility, M is the magnetization, and H is the magnetic field[6]. units ?

(3) was substituted into (4) to result in the equation:

define terms

---

[5] Hoppe

[6] Kittel, p. 304

see eqn 5...

$$X_v = \frac{5.57 * 10^{-28}}{H} \quad (6)$$

— μeff ?

Since[7]

$$X_v = \frac{M}{H} = \frac{C}{T} \quad (7)$$

? ? G

complex derivation seriously lacks explanation, definitions ...

This leads to a theoretical correlation between magnetic susceptibility (X_v) and the magnetic field (H)[8]

$$X_v = \frac{5.57 * 10^{-28}}{H} \quad (8)$$

— μeff

D

To measure the magnetic field, and thus calculate the magnetic susceptibility, a simplified model will be used, reduced the equation to far fewer variables.

between? G D

The force of attraction (in newtons) can be expressed by:

$$\text{max static } F = \frac{\mu\, m_1 m_2}{4\pi r^2} \quad (9)$$

T/A

Where μ is the permeability of the intervening medium measured in Tesla meter per ampere, m is the magnitude of the magnetic poles measured in Ampere-meters and r is the distance between the two magnets in meters[9].

m1 & m2 A m

To determine the force at a point, only one m needs to be used, and r becomes the distance from the magnet. m is also referred to as magnetic field strength, and will be referred to as such, using the symbol H.

F/m

To determine the magnetic force, the other variables need to be known. The distance between the objects can be measured, the permeability of the intervening medium can be approximated to the magnetic permeability of free space, which has a value of $\mu 0 = 4\pi \times 10^{-7}\ H \cdot m^{-1}$. To determine the force, one can calculate the force needed to overcome the force of static friction, as that is the point at which the magnetic force starts to pull the object. The equation can be written as:

just for air μ0 G

= minimum force (magnetic) required ..

$$F_{max} = \mu_s N \quad (10)$$

?

Where F_{max} is the maximum force of static friction, μ_s is the coefficient of static friction (which is different for every surface), and N is the normal force[10].

surfaces

Setting (8) equal to (9):

μ0?

$$\frac{\mu H}{4\pi r^2} = \mu_s N \quad (11)$$

how H related to (m1 m2) in eqn 9?

I

derivation very unclear incomplete poor

D

[7] Levy, pg. 201-202

[8] Guinier & Jullien, pg. 155

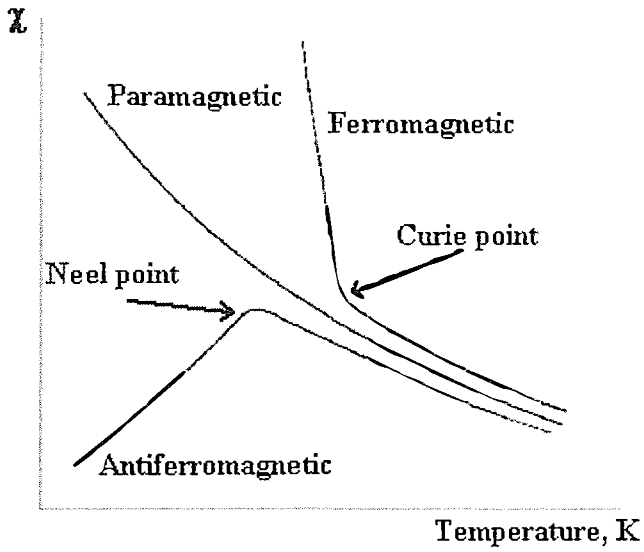
[9] http://geophysics.ou.edu/solid_earth/notes/mag_basic/mag_basic.html

[10] Bhavikatti & Rajashekarappa, pg 112

It is stated that the graphs of magnetic susceptibility, X, and temperature, K, can be shown to have the correlation as follows[11]:

Figure 1: Magnetic Susceptibility vs. Temperature of a Paramagnetic, Ferromagnetic and Antiferromagnetic Substance

general, not specific, no values on axis



which curve of interest? explain

Procedure

set-up diagram required

The chromium (IV) oxide was carefully inserted into a tape cube. When only the tape was weighed, it was found that its mass was negligible. The chromium (IV) oxide was then inserted inside the tape. Tape was used so that there was the lowest force of friction between the chromium (IV) oxide and the table, so that a more accurate value could be measured. The chromium (IV) oxide was then inserted into a glass test tube, which was placed in a water-filled beaker, which was heated. A retort stand was used to hold a device which served as a video camera, which was used to record the experiment so that the results could be more accurate. A ruler was placed under the retort stand, and neodymium magnets were placed at the 0 point of the ruler. After the water was boiling, the metal was removed using tongs, and while the temperature was being recorded with a Vernier surface temperature probe, it was slowly brought closer to the neodymium magnets until the force of attraction overcame the force of static friction. This was repeated at room temperature, as well as after it had been in the freezer for several minutes.

details camera

friction between which surfaces?

why repeat for temps

To calculate the static force of friction a 1 kg mass was placed on top of a wooden block with the tape underneath it. Using a Vernier dual-range force sensor, the force needed to move the block was measured and recorded. This was repeated six times.

minimum

procedure unclear

[11] Lancashire

Data Collection / Analysis

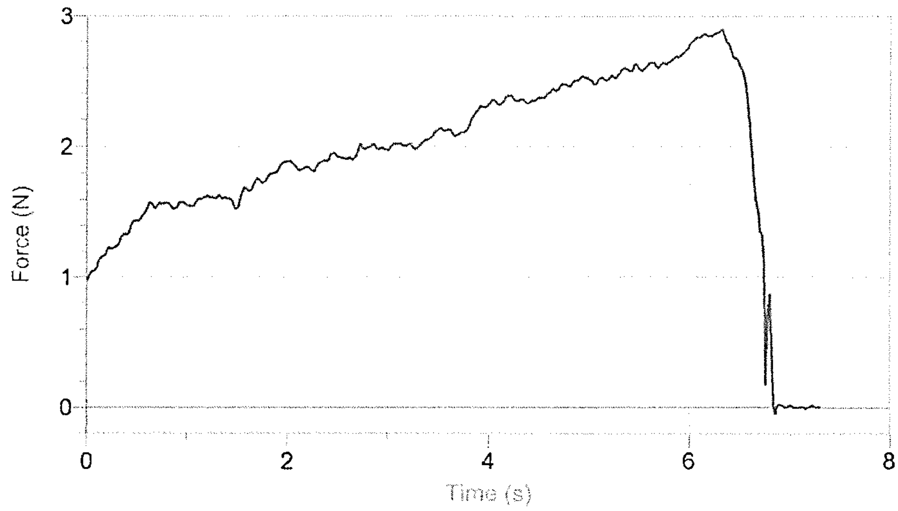
How data was obtained

Before any calculations were made, the force of static friction between the tape and the table was calculated. Using the graph, the exact value of the peak was determined. The following is an example of one the graph for trial 7. The peak is clearly defined, and it is the value for the force of static friction:

details about force sensor

Explain what is done

Figure 2: Force (N) Exerted on a Wooden Block vs. Time (s)



The data were then put into a table.

Table 1: Peak Force Exerted on a Wooden Block

	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7
Peak force (±0.01 N)	3.16	4.13	3.16	3.23	3.15	3.02	2.89

G

Mass of block: Mass: (1.0972 ± 0.0001) kg

how? ± on an average value.

The average of the trials was then taken:

$$\frac{3.16 + 4.13 + 3.16 + 3.23 + 3.15 + 3.02 + 2.89}{7} = (3.25 \pm 0.01)\,N$$

F G

see p.8.

The uncertainty was calculated by dividing the range of the data by 2:

$$= \frac{4.13 - 2.89}{2}$$

$= 0.62$

? see p.8..

(this maximize the uncertainty, not taking advantage of multiple trials assuming a normal distribution

?

$$4.13 - 2.892 = 0.62\ N$$

2

Since this value is greater than 0.01, this value was used as the uncertainty.

why 3.25 ± ...

Using the equation $F_{static} = \mu_s N$, where is μ_s the coefficient of static friction, and N is the force, the coefficient of static friction was calculated by having N = mg:

f: friction force

$\mu_s = \frac{f}{N}$ no units

$$3.25 \pm 0.62 = \mu_s 1.0972 \pm 0.0001 * 9.81$$
$$\mu_s = 0.302\ N\ kg^{-1}m^{-2}$$

not correct way to write an equation

The uncertainty was calculated by adding the relative uncertainties together, which was then multiplied by the value of the force:

$$\left(\frac{0.62}{3.25} + \frac{0.00001}{0.10972}\right) * 0.302 = 0.057\ N$$

8

The force needed to move the chromium (IV) oxide was then calculated by multiplying the normal force by the coefficient of friction. Since the mass of the chromium (IV) oxide was measured to be 0.00130±0.00001kg:

μ_s mg

$$F = 0.302 \pm 0.057 * 0.00130 \pm 0.00001 * 9.81$$
$$F = 0.00385\ N$$

The uncertainty was then calculated by adding the relative uncertainties, and then multiplied by the value of the force to get the absolute uncertainty:

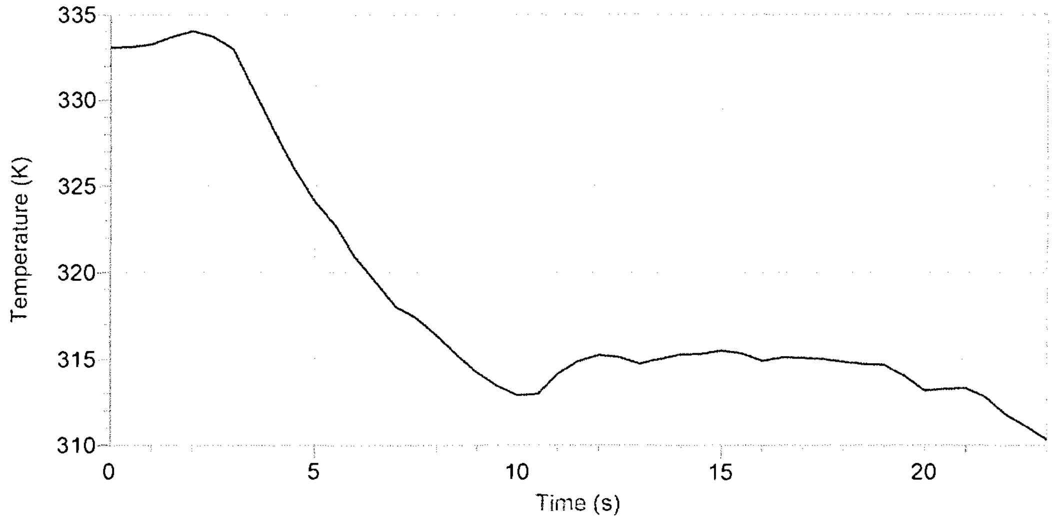
$$\frac{0.057}{0.302} + \frac{0.00001}{0.00130} * 0.00385 = 7.5 * 10^{-4}$$

0.00075 no F = ...

As the temperature probe gave a graph of the temperature over time, the temperature during the procedure needed to be determined. To do this, the average of the most consistent line was taken by adding all of the values together and dividing it by the number of values.

Criterion for this? justification?

Figure 3: Sample for Run 17: Temperature (K) of chromium (IV) Oxide vs. Time (T)



Most consistent line?

E

G

G Part

Sample calculation for run 17:

$$\frac{314.88 + 315.25 + 315.12 + 314.72 + 315.04 + 315.30 + 315.33 + 315.52 + 315.36 + 314.91 + 315.12 + 315.09 + 315.01 + 314.85 + 314.72 + 314.67}{15} = 315.06$$ K ?

The standard deviation was then found by finding the difference of each value from the average, squaring each individual value, then adding up each number, and dividing by the number of numbers and the square root of this value is the standard deviation.

The standard deviation value for run 17 was found to be 0.25 K.

σ is not an uncertainty

The vernier website states that its accuracy is "±0.2°C at 0°C, ±0.5°C at 100°C"[12], so the uncertainty is linear, going from 0.2 to 0.5. The slope was determined using the change in y divided by the change in x.

of ?

Sample:

$$slope = \frac{0.5 - 0.2}{100 - 0} = 0.003$$

The slope was then put into an equation in the form y=mx+b, and the b was determined by substituting (0,0.2) into the equation.

equation of what exactly?

Sample:

$$\begin{aligned} \Delta T \qquad\quad & \qquad T \\ 0.2 &= 0.003(0) + b \\ b &= 0.2 \end{aligned}$$

Therefore the equation for the uncertainty is ΔT=0.003(T-273.15)+0.2, where T is in temperature in Kelvin. The two were calculated for each trial and the larger uncertainty was used.

[12] http://www.vernier.com/products/sensors/temperature-sensors/sts-bta/

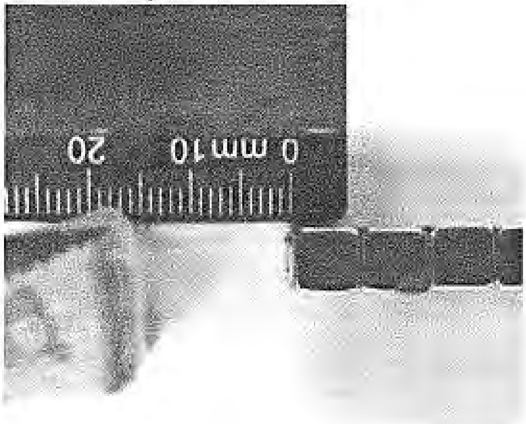
Sample calculation for run 17:

$$\Delta T = 0.003(3.14.71 - 272.15) + 0.2$$
$$\Delta T = 0.33\,K$$

To get the value for the distance, the videos were analyzed, and a still frame was taken at the exact moment before the tape starts to get attracted to the magnet. Then, using photo-editing software, the still frame was analyzed, and the exact pixel distance was found, causing the uncertainty of the measurement to be half the relative distance of one pixel, which is 0.08 mm. A sample picture is shown below: ?

Figure 4: Still Frame From Trial 17 of Experiment Setup Depicting Ruler, Neodymium Magnets, and CrO_2

– how distance measured on video ?
– distance = ?
± ?



~15 mm

?

?

sample shown we ... ?

See Appendix(1) for the raw data table of distance needed to overcome static friction.

After the distances were determined, as explained in the theory section, the formula (11) is used. Since μ can be assumed to simply be the permeability of free space, the values can be substituted and solved for H. Below is a sample calculation for trial 17:

σ ± not to be included in equation

trial 17

$$\frac{\mu H}{4\pi r^2} = \mu_s N$$

$$0.00385 \pm 7.5 * 10^{-4} = \frac{4\pi * 10^{-7}\,H}{4\pi(0.0111 \pm 0.0008)}$$

Solving for H;

in m → but r^2 appears in equation

$$H = 4.74\,A\,m^{-1}$$

F

The uncertainty was then calculated by adding the relative uncertainties. and then multiplying this value by the value of H:

actually calculations with r^2 were done to get this value .. square missing

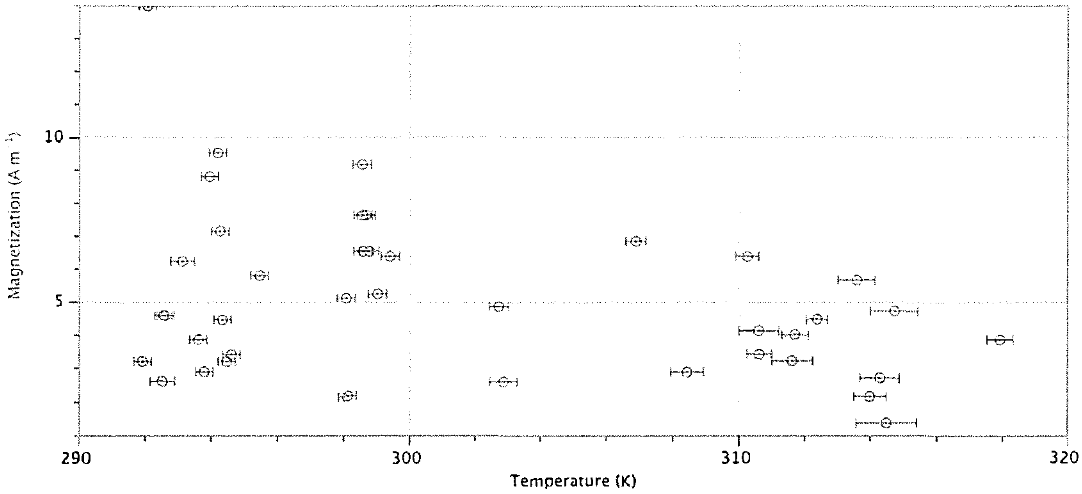
precision error

Sample calculation for trial 17:

$$\Delta H = (\frac{7.5 * 10^{-4}}{0.00385} + \frac{0.0008}{0.0111}) * 4.74 = 1.26\,A\,m^{-1}$$

This was calculated for every value, and then graphed:

Figure 5: Magnetization of CrO_2 vs. Temperature



too small
I
2
0

The uncertainty for H is too small to be seen.

Using the data from the theory section, the magnetization was divided by the value of the magnetic field. The relative uncertainty of the magnetization is the same as the relative uncertainty of volume, and this was added to the relative uncertainty of the magnetic field, and then multiplied by the value of magnetic susceptibility at that point.

Sample calculation of magnetic susceptibility for trial 17:

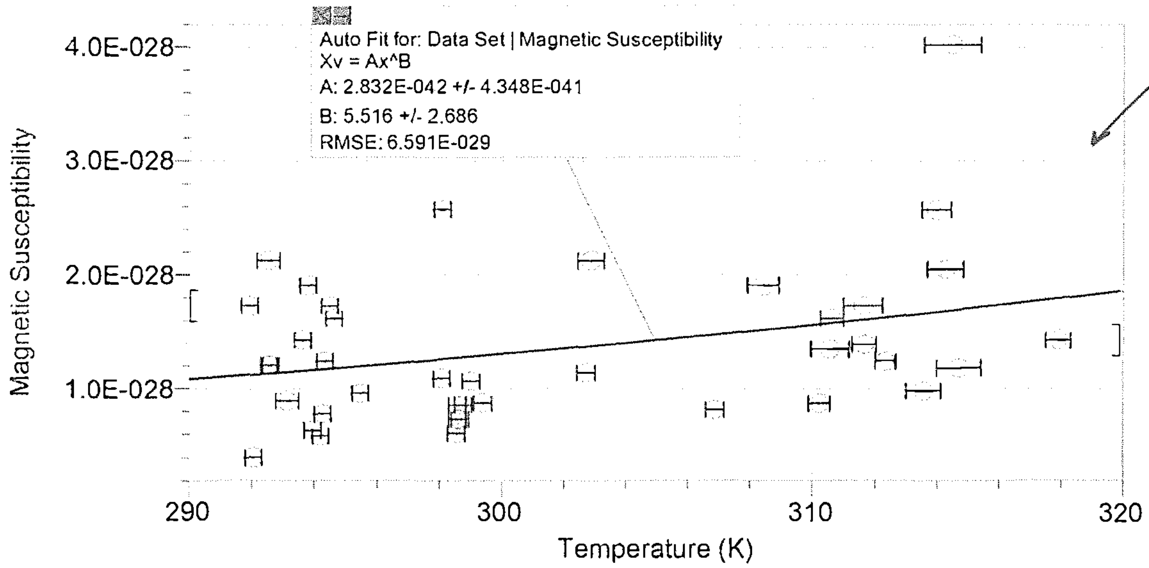
$$X_v = \frac{5.57 * 10^{-28}}{4.74}$$
$$X_v = 1.18 * 10^{-28}$$

Sample calculation of uncertainty for trial 17:

$$\left(\frac{7.5 * 10^{-4}}{0.00385} + \frac{0.0008}{0.0111}\right) * 1.18 * 10^{-28} = 3.15 * 10^{-29}$$

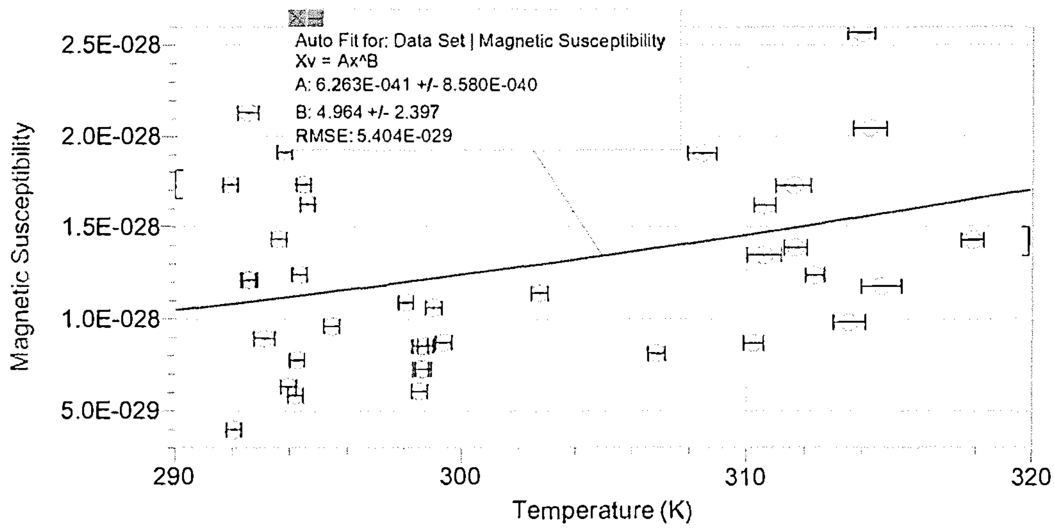
The data were then graphed:

Figure 6: Magnetic Susceptibility of CrO_2 vs. Temperature



This graph, shown without uncertainties of magnetic susceptibility, shows an upward trend of magnetic susceptibility as temperature increases, which contradicts with the theory. The outlier was then removed:

Figure 7: Magnetic Susceptibility of CrO_2 vs. Temperature



Although it did cause the slope to fall more within the range of the data, the data corresponding to point that are very close to each other has an extremely wide range on the axis of magnetic susceptibility. The range of temperature is also extremely small (26 K), which greatly no why work with such a small range of temperatures to start with...?

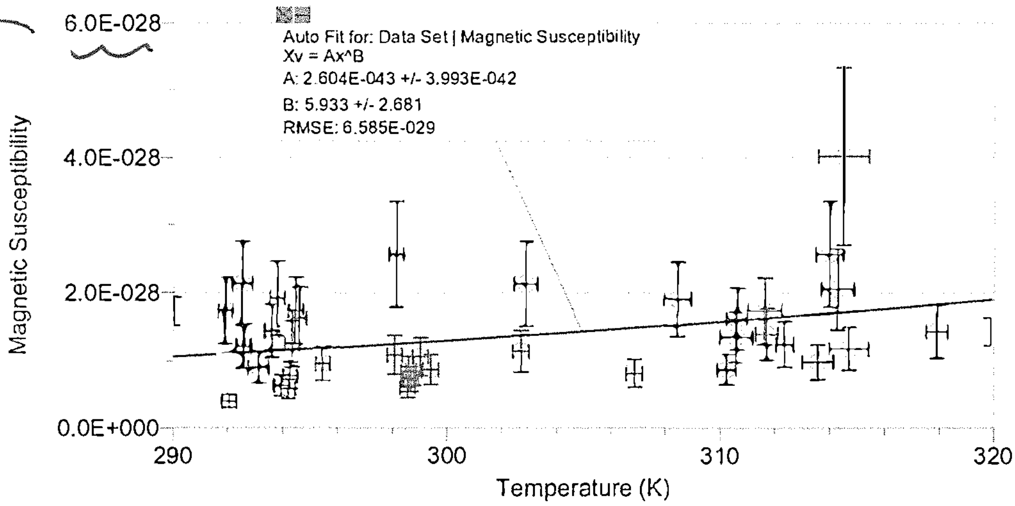
decreases the validity of this experiment. The reason that there are two clusters is that the chromium (IV) oxide was heated using boiling water, so the temperature normalized at around the same point, causing many values at very similar temperatures. The same process occurred when cooling the CrO_2, leading to a cluster of values at the lower end of the end as well.

The following is the same graph with the uncertainties of magnetic susceptibility included:

Figure 8: Magnetic Susceptibility of CrO_2 vs. Temperature

not proper

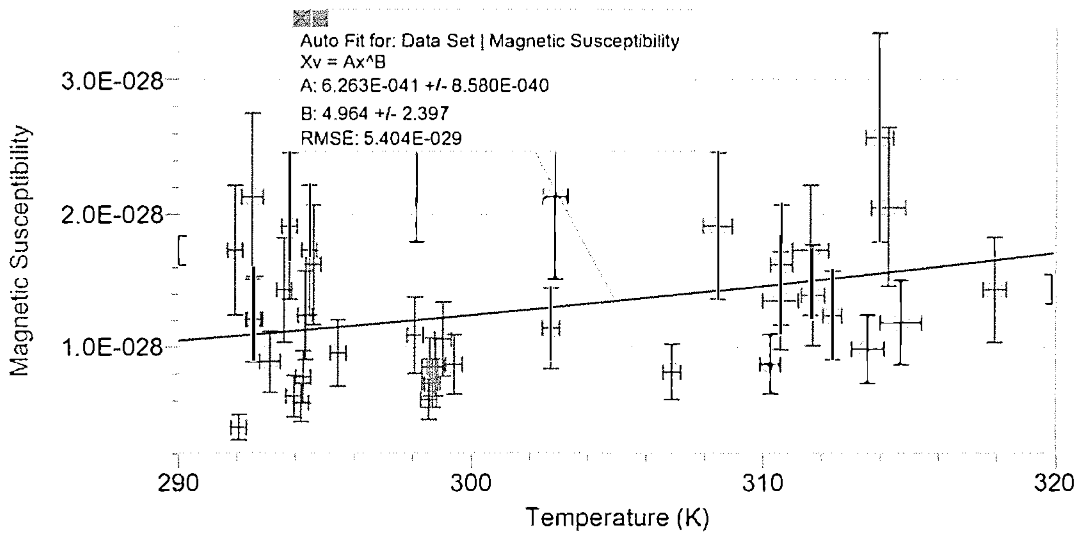
too small



With the included uncertainties, a more positive trend can be seen. However, its validity is put into question by the extremely large uncertainties.

Shown without the outlier: ?

Figure 9: Magnetic Susceptibility of CrO_2 vs. Temperature



(small)

The uncertainty of magnetic susceptibility is far too large to provide any sort of insight as to whether or not this relation is valid. This is explored further in the conclusion section.

Conclusion

The research question "How does the temperature of chromium (IV) oxide affect its magnetic susceptibility?" was analyzed. The temperature of chromium (IV) oxide was measured while it was being slowly pushed towards a magnet. After performing 40 trials with a variety of temperatures, the magnetic susceptibility of the chromium (IV) oxide was graphed versus temperature, providing a graph with error bars that are far too big to provide any useful information.

According to the theoretical model, the graph should look as follows:

Figure 1: Magnetic Susceptibility vs. Temperature of a Paramagnetic, Ferromagnetic and Antiferromagnetic Substance[13]

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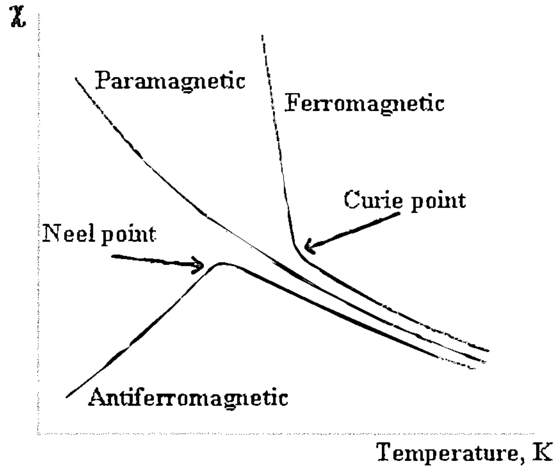
[13] Lancashire

Which one?



no values for CrO2

no procedural flow

It should be an asymptotic graph with a distinct change of slope. Since the data did not go above the curie point of CrO_2, it should be a curve with a negative slope. However, since the range of temperatures is so low, it is likely that there was not nearly enough data acquired. The range of data in temperature is extremely low, indicating that a higher sample size should have been used. The values of magnetic susceptibility for very similar temperatures are also extremely different, indicating. As well as that, the uncertainties are extremely large, causing any line of best fit to hardly be valid at all.

Sources of Error

It is evident that there were some major sources of error in this experiment which caused the data to not follow the theoretical model.

- **Temperature was sometimes difficult to determine because it varied wildly** ⇒ ±?

  There was some error associated with the way that the average temperature was determined. Since some of the graphs for the temperature were not consistent, it meant that the difference in temperature varied significantly, also meaning that the temperature was not as accurate as it could have been. This was likely a small source of the random error, and could have been reduced by using a different sensor, as explained further on.

?

(procedure not followed clearly described initially)

- **Difficult to always keep sensor on tape**

  Another source of random error related to the way that the temperature was determined is that it was at times very difficult to keep the temperature sensor touching the tape, since it needed to be pushed very gently, which made it hard to accurately measure the temperature since the sensor needed to be firmly pressed against the object. This could have caused some of the graphs' temperatures to vary, as explained previously. This could be reduced by using a contact sensor inside which the metal can be placed, causing the temperature to be constantly recorded.

- **The distance may not have been entirely accurate** but ± given --

  The distance recorded to be the distance that overcame the force of static friction may not have been the exact distance, as even the camera is not fast enough to catch minute differences in the position, as some camera stills were too blurry to determine the exact distance, a clearer one was used. Even very small differences in distance could have dramatically changed the distance. This was

no ⇒ ±( )?

likely a source of random error that was quite large, and could have accounted for the large discrepancy in the data. It could be reduced by using a slow motion camera, which would be able to record more frames per second, and thus be able to show more clearly the exact moment that the force of static friction is overcome.

- **Declined rapidly when not heated/cooled**

Another significant source of error is the rapid decline (or increase) in temperature when it is removed from the apparatus. It is likely that chromium (IV) oxide has a low specific heat capacity, so the substance rapidly undergoes changes in temperature. This causes the data points to be very concentrated near room temperature, and very spread out between 300k and 290k. As such, the range in temperature is only 26K, so that is another very large source of systemic error, as it causes the sample size to be very small, restricting the validity of the data. This could be reduced by performing the experiment in an environment that consistently provides (or takes away) energy, allowing it to stay at a consistent temperature.

any value?

- **Premise of experiment is wrong (temp of tape does not equal temp of metal)**

The premise that the experiment takes for measuring the temperature may also be wrong. It is assumed that the temperature of the tape is the exact same as the temperature of the chromium (IV) oxide inside of it. Although much of the energy may be transferred, it is possible that not all of it is, meaning that the values used for the temperature of the metal may be wrong. Although this does not change any of the random error, it does impact the systematic error of the experiment. This could be reduced by using a temperature sensor that is in direct contact with the metal, as it would yield results that are more accurate.

- **Pushing tape may cause wrong distance**

The tape was pushed using the temperature sensor, as this was thought to give the best reading. However, it was found that in several trials, the act of pushing the metal caused it to be attracted to the magnet prematurely, and although these trials were redone, the error was still present. This could be reduced by utilizing a machine that would be able to push the chromium (IV) oxide in small increments, making the measurement of the distance more exact.

- **Assumes that entire area of tape is on the ground**

It was assumed in the model and calculations that the entirety of the tape was on the ground, although practically this is likely to not be true. This systematic source of error likely made the data lower than what it should have been. This could be reduced by using a larger area of tape, causing the area not touching the ground to be more and more negligible. However, this means that it would also require an electromagnet, as the force required to move it would be quite large.

why?

- **Assumes that chromium (IV) oxide is covering the entire volume of the tape**

The model used assumes that the chromium (IV) oxide is covering the entire volume of the tape. In reality, the chromium (IV) oxide was not the entirety the volume; there was inevitably some air in it. This systemic source of error probably negatively skewed the data. This could be reduced by using heat shrink wrap, which would be wrapped around the chromium (IV) oxide, and then heated, causing negligible air presence in the plastic.

Unfortunately, because of the multiple large sources of error, and the significant uncertainties, this experiment did not support or refute the hypothesis. However, if redone, it should be done on a much larger scale, using an electromagnet, since many of the sources of error can be greatly reduced by having a larger-scale experiment, since the uncertainties would be much lower, and many of the other assumptions would be more valid.

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of all of these sources of errors, which source(s) is / are significant ?

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not part of essay

Appendix

1. **Raw data table of temperature and distance**

Trial	Temp (K)	Distance ± 0.0008 m
1	306.88	0.01335
2	314.28	0.0084
3	317.92	0.01005
4	312.37	0.0108
5	298.12	0.0075
6	298.08	0.01155
7	298.59	0.0141
8	299.03	0.0117
9	299.41	0.0129
10	310.25	0.0129
11	310.62	0.00945
12	313.98	0.0075
13	313.58	0.01215
14	311.7	0.0102
15	302.87	0.00825
16	302.72	0.01125
17	314.71	0.0111
18	314.48	0.006
19	310.6	0.01035
20	308.44	0.0087
21	311.62	0.00915
22	298.56	0.01545
23	298.59	0.01305
24	298.68	0.0141
25	298.78	0.01305
26	294.61	0.00945
27	295.46	0.0123
28	292.61	0.01095
29	293.95	0.01515
30	293.61	0.01005

F

in m ⇒ 11.1mm see fig. 4 ∴ 0.215 mm

Trial	Temp (K)	Distance ± 0.0008 m
31	293.79	0.0087
32	294.47	0.00915
33	294.34	0.0108
34	294.2	0.01575
35	292.52	0.00825
36	291.92	0.00915
37	292.55	0.01095
38	292.07	0.01905
39	294.27	0.01365
40	293.13	0.01275

√

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