

1.0) Title:

The effect of changing the splitting between the d orbitals of an octahedral complex ion on the magnetic flux density of the complex ion

1.1) Introduction

Of the entire IB Chemistry portion, I have found ligands to be one of the most interesting parts. They seem to have so many different properties that were not explored in great depth in the portion. As a part of my Internal assessment, I decided to develop my understanding of ligands. Due to the abundance of properties ligands possessed, I was confident that I would be able to observe a trend and learn something new about how they function.

Hence, I explored various concepts about ligands like their colors, bonding or structure, and arrived at my favourite property, their paramagnetic and diamagnetic properties. Magnetism has always been an area of interest to me, who as a child found myself at my father's magnet factories playing with magnets- it was obvious that I explore this for my Internal Assessment.

2.0) Exploration

2.1) Background Information:

2.1.1) Aim

The aim of the investigation was to determine how changing the splitting of the d orbitals of different octahedral complex ions changed the magnetic flux density.

2.1.2) Concepts

The investigation links well to the IB chemistry portion, where ligands are explored and their paramagnetic and diamagnetic properties are described in terms of how many electron pairs they form in their orbitals. As someone who enjoys chemistry and will probably pursue it at a higher level, and someone who enjoys the concept of magnetism, the exploration of magnetic flux density in liquid ligands would definitely not only enrich my understanding of the topic, but also have considerable applications where liquids may be necessary for magnetic induction, if solids are not viable in the particular situation.

It is known that electrons fill in orbitals based on 2 rules- The Pauli exclusion principle, which states that electrons of opposite spins pair in up degenerate orbitals, and Hund's rule, which states that electrons first singly fill in degenerate orbitals before pairing up. These 2 rules are followed to minimize inter-electron repulsion and hence maximize the stability of an element.

It is also defined, that when electrons pair up, their element attains diamagnetic properties, which means that field lines diverge away from the element, and that when electrons remain single in an orbital, they attain paramagnetic properties, which means that converge magnetic field lines.

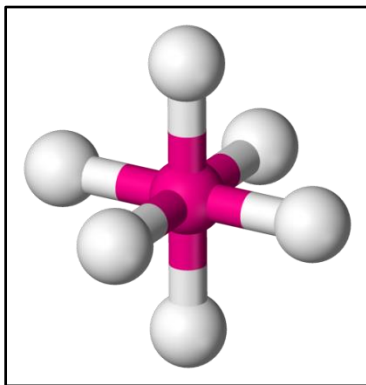


Figure 1: Showing the molecular geometry of an octahedral complex; the complexes considered during the investigation. These positions are taken up by ligands to minimize repulsions and thus maximize stability.

Another concept essential to the understanding of the investigation is the splitting of the d orbitals in complex ions. When a central metal ion is approached by ligands (for the purpose of this investigation- 6 ligands), the ligands take up positions around the ion so as to maximize the stability of the complex by minimizing repulsions (an octahedral setup- for this investigation).

The ligands interact with the d orbitals which are aligned along the axis which the ligands approach, and hence cause these orbitals to obtain a higher amount of energy. As a result of this interaction, the 5 degenerate orbitals no longer possess the same energy, in that 2 of them possess a higher energy than the other 3. Hence, there is an energy gap, between the 3 d orbitals of lower energy and the 2 d orbitals of higher energy. The orbitals of higher energy are called the e_g orbitals and the ones of lower energy are called the t_{2g} orbitals.

Different ligands cause different amounts of splitting in the d orbitals, given by a spectrochemical series.¹

This leads to electrons being distributed in either high spin formations, where electrons exist without pairs, in single orbitals as they have enough energy to overcome the energy difference between orbitals and ascend to the e_g , or low spin formations, where more electrons are paired up in the t_{2g} orbitals as a result of not being possessing enough energy to cross the energy gap and ascend to the higher orbitals. High spin formations are hence, more paramagnetic, while low spin formations are more diamagnetic. Hence, one can determine how paramagnetic or diamagnetic a ligand will be, using an equation from statistical thermodynamics.²

(Equation 1)

$$\ln\left(\frac{N_1}{N_0}\right) = -\frac{\Delta E}{kT}$$

Where N_1 are the number of molecules at a higher energy state, N_0 are the number of molecules at a lower energy state, ΔE is the splitting between the d orbitals of the ligand, k is a constant and T is temperature (which is also constant for the investigation).³

This equation allows one to predict how many paramagnetic and how many diamagnetic complexes will form in a certain number of moles of a complex ion.

To allow for a continuous independent variable, one can consider the ΔE . This is obtained from the maximum wavelength absorbance of the complex ion through the following equation.

(Equation 2)

$$\Delta E = \frac{hc}{\lambda}$$

Where h is Planck's constant, c is the speed of light and λ is the maximum wavelength absorbance of a complex ion.

Spectrochemical Series

$I^- < Br^- < S^{2-} < SCN^- < Cl^- < N_3^-$, $F^- < urea$, $OH^- < ox$, $O^{2-} < H_2O < NCS^- < py$, $NH_3 < en < bpy$, $phen < NO_2^- < CH_3^-$, $C_6H_5^- < CN^- < CO$.

Figure 2: Showing the spectrochemical series, in increasing order of splitting of d orbitals.

¹ Spectrochemical Series. Digital image. N.p., n.d. Web.

<https://www.google.com/url?sa=i&url=https%3A%2F%2Fbrainly.in%2Fquestion%2F2682794&psig=AOvVaw1knKVzs_NKnCaa5oGrA1RW&ust=157168305175000&source=images&cd=vfe&ved=0CAIQjRxxqFwoTCOComeG9q-UCFQAAAAAdAAAAABAE>.

² Magnetic Field Lines: Paramagnetism and Diamagnetism. Digital image. N.p., n.d. Web.

<https://www.google.com/url?sa=i&url=https%3A%2F%2Fbrainly.in%2Fquestion%2F7915922&psig=AOvVaw04NWqX3bp74SWMK90k_yQ2&ust=1571683208842000&source=images&cd=vfe&ved=0CAIQjRxxqFwoTICRkqy-q-UCFQAAAAAdAAAAABAE>.

³ Octahedral Geometry. Digital image. N.p., n.d. Web.

<https://www.google.com/url?sa=i&url=https%3A%2F%2Fen.wikipedia.org%2Fwiki%2FOctahedral_molecular_geometry&psig=AOvVaw1KTx0rOhjbVX01MoI29d4k&ust=1571682685159000&source=images&cd=vfe&ved=0CAIQjRxxqFwoTCJDztkK8q-UCFQAAAAAdAAAAABAE>.

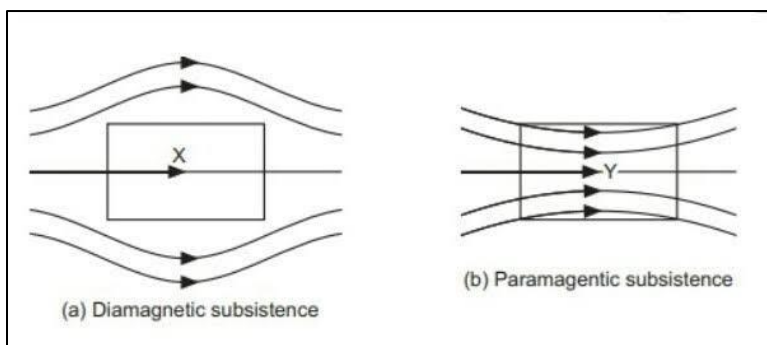


Figure 3: Showing how magnetic field line converge in paramagnetic substances, leading to a higher magnetic flux density, and diverge in the case of diamagnetic substances, leading to a lower magnetic flux density.

A copper wire was wrapped 4000 times around a test tube and oscillated at a constant rate in a magnetic field created by 2 rare earth magnets. The ligand was placed in the test tube and its voltage noted.

2.2) Research Question:

How does changing the splitting of the d orbitals of an octahedral complex (Joules), derived from the maximum wavelength absorbance of the complex (nm), affect the magnetic flux density of the complex (Wb/m^2), derived from the voltage induced (V) as the complex is oscillated in a magnetic field by a stall torque motor.

2.3) Hypothesis:

As the splitting of the d orbitals increases, it is apparent that not as many molecules will be able to transition to the higher d orbitals, and hence, will fill up the lower orbital positions, forming more diamagnetic complexes.

For the purpose of this investigation, Cobalt is considered. Cobalt has 7 electrons to distribute in its d orbitals, and hence, can form 2 different arrangements, based on whether electrons have enough energy to transition to the e_g orbitals.

Hence, using equation 1, one can predict that as the splitting increases, the number of molecules at a higher energy decreases exponentially, and hence, the paramagnetic ability of the ligand decreases exponentially, as shown in the equation below.

(Equation 4)

$$N_1 = N_0 e^{-\frac{\Delta E}{kT}}$$

Hence, as splitting increases, complex ions tend to diverge magnetic field lines (they become more paramagnetic) and hence have a lower magnetic flux density. (Magnetic flux density is defined as the number of field lines per unit area, and hence, if the field lines were made to converge, as a paramagnetic substance does, the magnetic flux density would be higher than if they diverged out of the substance, like in the case of a more diamagnetic configuration.)

Hence, one can predict an exponential relationship between the splitting of the d orbitals and the magnetic flux density.

2.4) Variables:

2.4.1) Independent Variable:

The extent of splitting of d orbitals of complex ions in an octahedral formation.

Range:

This variable will be measured through the maximum wavelength absorbance, and derived using Equation 2.

$$\Delta E = \frac{hc}{\lambda}$$

This variable was chosen as it provided a good indication of how ligands vary, and provided a good range to plot a graph on. The splitting between the d orbitals was an essential part of the investigation and most of any complex ions properties revolve around it. Hence, it was chosen as an Independent variable.

As magnetic flux was being considered as a Dependent variable, it was obvious to choose this Independent variable as the hypothesis suggests that the magnetic properties, like most, depend on the splitting of the d orbitals.

The range was rather large, and hence would provide a well analysable graph and would show the presence of a trend well. It also considered multiple partial substitutions (referenced in the material section), which allowed one to understand how the partial substitution affected the properties of ligands.

2.4.2) Dependent Variable:

Measured: The voltage induced by the solenoid in which the ligand was placed and oscillated in a magnetic field.

Derived: The magnetic flux density of the ligand in a 30ml standard test tube.

This variable was derived using Equation 3.

(Equation 5)

$$B = \frac{V}{\omega NA}$$

A ligand was put into a standard test tube (surface area πcm^2), and wrapped 4000 times with a copper wire. Then, this was oscillated in a magnetic field, using a stall torque motor working at 500 RPM, and the voltage induced was noted. Then, the magnetic flux density was calculated.

There are not many ways to measure the magnetic flux density of a liquid, and this technique allowed one to do so fairly easily. This technique also kept all variables constant, except the identity of the ligand, which helps one attribute any change in the measured dependent variable and hence the derived dependent variable to a change in the Independent variable.

2.4.3) Control Variable:

1. The area of the test tube in which the ligands were oscillated- During the investigation, the test tube was oscillated in a constant magnetic field to induce a current. The induced voltage would vary directly with the area of the coil, and hence, must be kept constant. This can be done by using test tubes of the same diameter in which ligands are tested.

The Dependent variable, magnetic flux density, is measured using the formula for induced voltage.

(Equation 3)

$$V = \omega N B A \sin(\theta)$$

Where V is the Voltage, ω is the frequency of rotation of the solenoid in the magnetic field, N is the number of turns in the coil, B is the magnetic flux density. ($\sin(\theta)$ is kept at 1 for the investigation. [$\theta = 90^\circ$])

2.2.3) Design

Different ligands were prepared for the investigation, each with different splitting energies, as this provided a large range or independent variables to develop a well analyzable trend with. The splitting energies of the ligands were obtained from the maximum wavelength absorbance from online databases, and the voltage values, which were used to obtain the magnetic flux density, were obtained through magnetic induction of currents in solenoids.

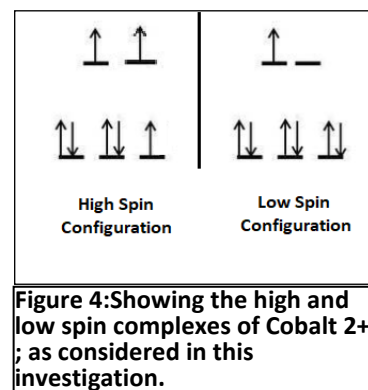


Figure 4: Showing the high and low spin complexes of Cobalt 2+ ; as considered in this investigation.

- The number of coils on the test tube solenoid- the more turns on a solenoid which the ligand was placed in, the more voltage would be induced, and hence, it would be necessary to control the number of turns in the solenoid (controlled at 4000 turns), to hence make voltage changes attributed to the change in ligand more valid.
- The speed at which the test tube was oscillated in a magnetic field- the faster the solenoid, the more voltage would be induced, as the voltage induced is given by the rate of change of magnetic flux- and moving the complex ions into a region of magnetic field lines faster corresponds to a greater rate, hence a greater voltage induced. This is known as Faraday's second law. Hence, it was necessary to control the speed at which the complex ion was oscillated in the test tube. This was done using a stall torque motor kept constant at 500 rotations per minute.
- The strength of a magnetic field in which the test tube was oscillated- the strength of the magnetic field lines affected how much the magnetic flux density can be, as a stronger field would allow for a higher density of field lines and a higher magnetic flux density. Hence, it would be necessary to use the same magnets in each trial.
- The temperature of the room- If the electrons in the room were supplied with more energy, they would be more likely to transition to the e_g orbitals and hence, make the ligand in question more paramagnetic. Hence, it would be essential to control the amount of energy being supplied to the ligand in the form of heat by keeping the room at a fairly constant temperature (room temperature), for the duration of the experiment.
- The number of ligands- It was essential to control to only octahedral complexes, as complexes with different numbers of ligands would cause different splitting of d orbitals, and hence, make the splitting an invalid independent variable.
- The angle at which the complex ions were oscillated in the magnetic field- It was essential to control this, as if not controlled, only a component of the area vector would cause magnetic induction, as magnetic field lines would pass through at an angle, and only a component of their magnetic force would induce a current. Hence, it was essential to control the angle at 90° , done using a ring which limited the complex ions orientation to said angle.
- The orientation of the set-up. It was noticed in the pilot experiment, that the orientation of the set-up led to differing readings, as the rare earth magnets would concentrate the magnetic field, leading to a higher magnetic flux density, if kept in the orientation of the magnetic field. In the experiment, the motor had to be kept at a height, and was kept on a table that was bolted to the ground, hence, the orientation of the set-up was kept constant. If the experiment was conducted at a different orientation, one would observe different results, as a different component of the magnetic field would be concentrated by the magnets.

2.5) Materials:

2.5.1) Chemicals

Table 1: Table showing the chemicals used during the investigation.

Sr No.	Chemical	Concentration
1	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$	1M
2	HCl	1M
3	H_2O_2	1M
4	NH_4Cl	1M
5	En	1M
6	$\text{K}_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$	1M
7	NH_3	1M
8	NaNO_2	1M
9	Distilled Water	-

The chemicals above were used to prepare the following ligands using the following reactions.

Table 2: Showing the complex ions prepared, with reactions as to how they were prepared during the Investigation. These complex ions' differing energies of splitting of d- orbitals were used as independent variables for the investigation.

Sr. No.	Complex Ion Identity	Reaction	Chemicals used (from list above)
1	$[\text{Co}(\text{H}_2\text{O})_6]^{2+}$	$\text{CoCl}_2 + 6\text{H}_2\text{O} \rightarrow \text{Co}(\text{H}_2\text{O})_6\text{Cl}_2$	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ H_2O
2	$[\text{Co}(\text{H}_2\text{O})_4(\text{NH}_3)_2]^{2+}$	$\text{Co}(\text{H}_2\text{O})_6\text{Cl}_2 + 2\text{NH}_3 \rightarrow [\text{Co}(\text{H}_2\text{O})_4(\text{NH}_3)_2]^{2+} + 2\text{NH}_4^+$	NH_3
3	$[\text{Co}(\text{H}_2\text{O})_2(\text{NH}_3)_4]^{2+}$	$\text{Co}(\text{H}_2\text{O})_6\text{Cl}_2 + 4\text{NH}_3 \rightarrow [\text{Co}(\text{H}_2\text{O})_2(\text{NH}_3)_4]\text{Cl}_2 + 2\text{H}_2\text{O}$	
4	$[\text{Co}(\text{NH}_3)_6]^{2+}$	$[\text{Co}(\text{H}_2\text{O})_4(\text{NH}_3)_2]\text{Cl}_2 + 6\text{NH}_3 \rightarrow [\text{Co}(\text{NH}_3)_6]\text{Cl}_2 + 4\text{H}_2\text{O} + 2\text{NH}_3$	
5	$[\text{Co}(\text{NH}_3)_5(\text{OH})]^+$	$2\text{CoCl}_2 \cdot 6\text{H}_2\text{O} + 10\text{NH}_3 + 2\text{HCl} + \text{H}_2\text{O}_2 \rightarrow 2[\text{Co}(\text{NH}_3)_5(\text{OH})]\text{Cl} + 12\text{H}_2\text{O}$	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ HCl H_2O_2
6	$[\text{Co}(\text{NH}_3)_5(\text{Cl})]^+$	$2\text{Co}(\text{H}_2\text{O})_6\text{Cl}_2 + 2\text{NH}_4\text{Cl} + 8\text{NH}_3 + \text{H}_2\text{O}_2 + 3\text{H}_2\text{O} \rightarrow$	NH_4Cl

⁴ Abbas, Nada K., Habeeb, Majeed Ali, Algidsawi, and Alaa J. Kadham. "Preparation of Chloro Penta Amine Cobalt(III) Chloride and Study of Its Influence on the Structural and Some Optical Properties of Polyvinyl Acetate." *International Journal of Polymer Science*. Hindawi, 15 Feb. 2015. Web. 20 Oct. 2019. <<https://www.hindawi.com/journals/ijps/2015/926789/>>.

⁵ "Chemistry 111 Laboratory: Synthesis of a Coordination Compound." N.p., n.d. Web. <<https://www.maclester.edu/~kuwata/Classes/2004-05/chem%20111/111%20experiment%206%20-%20co%20synthesis.pdf>>.

⁶ $\text{Co}(\text{H}_2\text{O})_6^{2+}/\text{CoCl}_4^{2-}$ Equilibrium Demonstration Sheet. N.p., n.d. Web. 20 Oct. 2019. <<https://chemed.chem.purdue.edu/genchem/demosheets/12.10.html>>.

⁷ Cobalt Transition Metal Chemistry Cobalt(II) Co^{2+} Complex Ions Stabilised Ligand Substitution Cobalt(III) Co^{3+} Complexes Redox Chemical Reactions +2 +3 Principal Oxidation States GCE AS A2 IB A Level Inorganic Chemistry Revision Notes. N.p., n.d. Web. 20 Oct. 2019. <<http://www.docbrown.info/page07/transition07Co.htm>>.

⁸ OpenStax. Chemistry. N.p., n.d. Web. 20 Oct. 2019. <<https://opentextbc.ca/chemistry/chapter/19-2-coordination-chemistry-of-transition-metals/>>.

⁹ Palad, Charisse. "Synthesis, Spectroscopic, Electronic, and Magnetic Properties of Some 3D Metal Complexes." *Academia.edu*. N.p., n.d. Web. 20 Oct. 2019. <https://www.academia.edu/9554388/Synthesis_Spectroscopic_Electronic_and_Magnetic_Properties_of_Some_3D_Metal_Complexes>.

¹⁰ "R/chemistry - Complex Preparation: $\text{K}_3[\text{Co}(\text{C}_2\text{O}_4)_3]$." *Reddit*. N.p., n.d. Web. 20 Oct. 2019. <https://www.reddit.com/r/chemistry/comments/1wqfxy/complex_preparation_k3coc2o43/>.

¹¹ "Reactions of Some Transition Metal Ions." N.p., n.d. Web. <http://www.knockhardy.org.uk/sci_htm_files/15tmet2.pdf>.

¹² Schlessinger, Gert G., Doyle Britton, Thornton Rhodes, and Elizabeth Ng. "Chloropentaamminecobalt(III) Chloride." *Wiley Online Library*. John Wiley & Sons, Ltd, 05 Jan. 2007. Web. 20 Oct. 2019. <<https://onlinelibrary.wiley.com/doi/abs/10.1002/9780470132401.ch43>>.

¹³ "Synthesis of a Cobalt Complex." N.p., n.d. Web. <http://www.uvm.edu/~cclandry/chem36/Laboratory_files/lab%206.pdf>.

¹⁴ "Tris(ethylenediamine)cobalt(III) Chloride ($[\text{Co}(\text{en})_3]\text{Cl}_3$) and." *Studylib.net*. N.p., n.d. Web. 20 Oct. 2019. <<https://studylib.net/doc/8121154/tris-ethylenediamine-cobalt-iii-chloride--co-en-3-cl3--and>>.

¹⁵ University of Engineering and Technology. "Synthesis of Chloropentaamminecobalt(III) Chloride." *LinkedIn SlideShare*. N.p., 17 May 2018. Web. 20 Oct. 2019. <<https://www.slideshare.net/saimkhalid04/synthesis-of-chloropentaamminecobaltiii-chloride>>.

		$2[\text{Co}(\text{NH}_3)_5(\text{Cl})]\text{Cl} + 0.5\text{O}_2$	
7	$[\text{Co}(\text{NH}_3)_5(\text{NO}_2)]^+$	$[\text{Co}(\text{NH}_3)_5\text{Cl}]_2\text{Cl} + \text{NaNO}_2 \rightarrow [\text{Co}(\text{NH}_3)_5(\text{NO}_2)]\text{Cl}_2 + \text{Cl}^-$	NaNO_2
8	$[\text{Co}(\text{en})_3]^{2+}$	$\text{CoCl}_2 \cdot \text{H}_2\text{O} + 3\text{en} \cdot 2\text{HCl} \rightarrow [\text{Co}(\text{en})_3]\text{Cl}_2 + 6\text{H}_2\text{O} + 6\text{HCl}$	$3\text{en} \cdot 2\text{HCl}$
9	$[\text{Co}(\text{C}_2\text{O}_4)_3]^{4-}$	$\text{CoCl}_2 + 3\text{K}_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O} \rightarrow [\text{Co}(\text{C}_2\text{O}_4)_3]\text{K}_2 + 2\text{Cl}^-$	$\text{K}_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$

Molar ratios of each of the reactants were added to form exactly 30ml of each complex ions.

2.5.2) Apparatus

Table 3: Showing the apparatus used during the procedure.

Sr No.	Apparatus	Capacity	Least Count	Uncertainty	Used For
1	Stall Torque Motor	-	1 RPM	± 1 RPM	To oscillate the test tube solenoids in the magnetic field
2	Measuring Cylinder	50ml	1 ml	± 0.5 ml	To measure volumes of substances in the formation of complex ions
3	Measuring Cylinder	10ml	0.1 ml	± 0.05 ml	To measure smaller volumes of substances in the formation of complex ions
4	Pipette	10ml	0.1 ml	± 0.05 ml	To measure very small volumes of substances in the formation of complex ions.
5	Syringe Pump	-	-	-	To aid the use of the pipette
6	Funnel	-	-	-	To allow one to make measurements in volumetric flasks and measuring cylinders without spilling
7	Test Tube	30ml	-	-	To store the complex ions as they are oscillated in a magnetic field.
8	Copper Wire	-	-	-	To wrap around the test tube in which the ligand is placed in, and hence act as a solenoid for inducing voltage through electromagnetic induction.
9	Volumetric Flask	100ml	-	-	To measure volumes of materials used to prepare complex ions.
10	Voltmeter	-	1mV	± 1 mV	To measure the induced voltage (DV) when the ligands are oscillated in a magnetic field.
11	Weighing balance	-	0.001g	± 0.001 g	To weigh substances accurately and hence prepare complex ions.
12	Magnetic Stirrer	-	-	-	To dissolve substances in solutions in the preparation of the materials and complex ions.

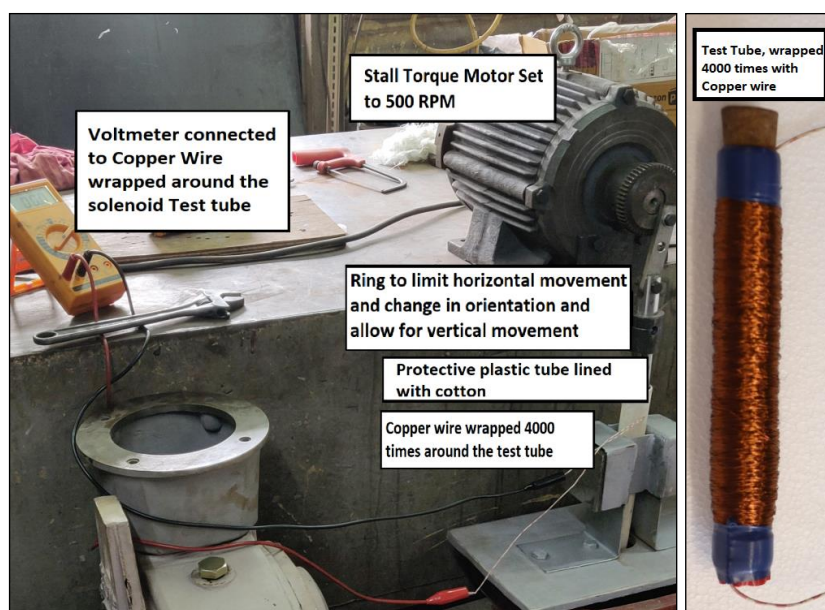
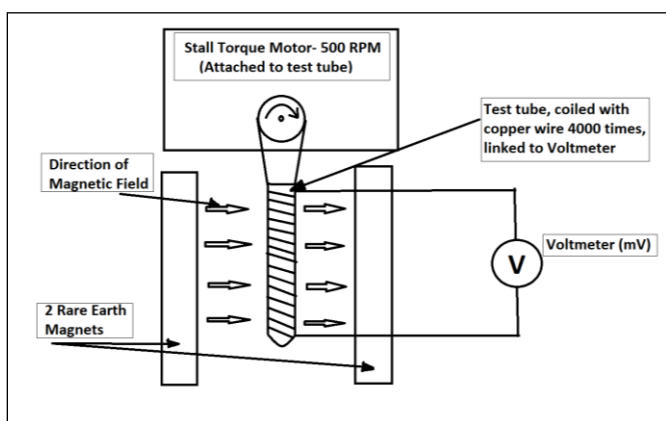


Figure 5: Showing a diagram of the set-up for the experiment.

Figure 6: Showing the set-up of the experiment. The diagram on the left shows the full set-up and the diagram on the right shows a close up of the solenoid test tube.

2.6) Ethical, Safety or Environmental Issues:

Table 4: Showing the ethical, safety or environmental issues, their solutions and emergency aid related to the procedure.

Sr No.	Issue	Prevention	Emergency Aid
1	$\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ and NH_4Cl are hazardous when inhaled, touched or ingested.	Only use $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$ or NH_4Cl after washing hands, wearing safety equipment (lab coat, gloves and lab glasses), to protect skin. Wash hands thoroughly after use. Do not ingest.	In case of Inhalation: Remove victim to fresh air Eye Contact: Rinse with water; do not apply neutralizing agents. Skin Contact: Rinse with water, soap may be used. Ingestion: Rinse mouth with water, drink water
2	HCl , $\text{K}_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ and H_2O_2 are corrosive and harmful if	Only use HCl , H_2O_2 or $\text{K}_2\text{C}_2\text{O}_4 \cdot 2\text{H}_2\text{O}$ after washing hands, wearing safety equipment (lab coat, gloves and lab glasses), to protect skin. Wash hands thoroughly after use. Do not ingest. Use in a fume cabinet to prevent fumes from	In case of Inhalation: Remove victim to fresh air Eye Contact: Flush eyes with gentle but large stream of water for 15 minutes. Skin Contact: Flush affected area with water for

	inhaled, touched or ingested.	escaping. Keep away from flammable materials or sparks.	15 minutes. Ingestion: Do not induce vomiting. Get a medical professional.
3	HCl, NaNO ₂ , and H ₂ O ₂ are dangerous to aquatic organisms if disposed improperly.	Dispose with lots of water (dilution).	Neutralize the HCl in water bodies using a strong base to prevent the acidity from killing aquatic organisms.
4	Complex ions are dangerous to aquatic life.	Dispose with lots of water (dilution).	
5	En is hazardous, flammable and causes burns to exposed skin. It should not be inhaled.	Only use in a fume cabinet to prevent fumes from escaping. Keep away from flammable materials, and avoid ingestion.	If exposed to Take off all exposed lab coat and rinse areas exposed. Move to fresh air. Eye exposure: Rinse cautiously for several minutes.
6	NaNO ₂ is unsafe for contact with skin, eyes or ingestion.	Do not come into contact with the substance. Only use after washing hands, wearing safety equipment (lab coat, gloves and lab glasses), to protect skin. Wash hands thoroughly after use. Do not ingest.	In case of Inhalation: Move to fresh air. Eye contact: Rinse thoroughly for 15 minutes. Skin Contact: Wash off with soap and water. Ingestion: Rinse mouth with water.
7	NH ₃ is dangerous to human exposure. Do not ingest or inhale.	Only use in a fume cabinet. Do not come into contact with the substance. Only use after washing hands, wearing safety equipment (lab coat, gloves and lab glasses), to protect skin. Wash hands thoroughly after use. Do not ingest.	In case of Eye Exposure: Remove contact lenses, if any, and wash with water for 15 minutes. Skin Contact: Use an emergency shower. Inhalation: For small concentrations, no treatment, but if the concentration is large, carry victim to uncontaminated atmosphere. Ingestion: Drink lots of water.
8	Magnets being used are extremely strong and dangerous.	Keep clear of magnets, fix them to beams that prevent their movement. Do not wear any magnetic materials when conducting the experiment. Operate all materials from a safe distance from the magnets. Keep all hard drives at least 2 meters outside the magnetic field to avoid the loss of data.	In case one has been injured by the magnets, remove hand and wash with water for 15 minutes. Do not attempt to separate them without professional help.

2.7) Method:

The procedure was simple to conduct, and allowed for many control variables. Online data was used to establish a fairly large range of independent variables and the complex ions were inputted into a solenoid and oscillated in a magnetic field to observe the amount of voltage induced in the solenoid. This range would allow for a analyzable graph and for one to draw valid conclusions.

While one can possibly use colorimeter, it was discovered in the trial run, that most tested ions had precipitates and hence this method was eliminated, leaving only online data bases as a method to obtain the maximum wavelength absorbance from where one can derive the amount of splitting between the d orbitals of the ion.

Magnetic flux density is a hard concept to measure with simple apparatus, and this method allowed to do so easily. It allowed for one to conduct multiple trials fast and obtain data to plot a graph with a continuous dependent variable and hence, draw valid conclusions.

Conduct a trial run: It is imperative to conduct a trial run, as it informs the experimenter if there are any flaws in the methodology and how to rectify these flaws before beginning the experiment. It is also necessary to check if the experiment actually works and make sure all reactants are not contaminated before beginning the experiment.

In the trial run, the following points were noted:

1. The magnetic field had to be created by 2 magnets, in a linear set up, as a hexagonal setup caused magnetic field lines to short, hence making it impossible to oscillate the test tube in the magnetic field.

2. Spectrophotometry could not be used to determine the maximum wavelength absorbance, as most ligands had a precipitate, which prevented one from using a colorimeter to obtain this data. Hence, one had to resort to online data bases to collect the same.

Independent Variable Data: The independent variable data, the energy of splitting between the d orbitals of the complex ion, was derived from the max wavelength absorbance, as this was an indication of how much energy would be required to allow for an electron to cross the energy gap into the e_g orbitals.

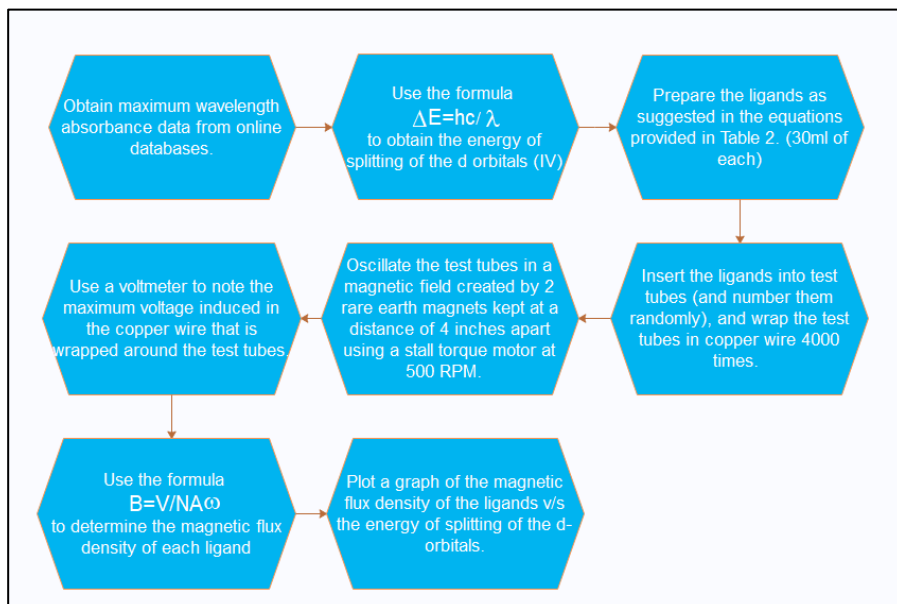


Figure 7: Showing a flowchart of the procedure followed during the investigation.

1. The maximum wavelength absorbance data was obtained from online data bases.
2. Using equation 2, the maximum wavelength absorbance was used to calculate the energy of splitting of the d orbitals of each complex ion. This was the independent variable of the investigation.

$$\Delta E = \frac{hc}{\lambda}$$

Dependent Variable Data: A simple method to measure magnetic flux density was used. This was derived from the dependent variable, voltage, measured using electromagnetic induction.

1. 30ml of the relevant ligands were prepared using the equations in the section on materials.
2. Each 30ml standard test tube was wrapped 4000 times with a copper wire, and placed in a magnetic field. Each test tube had the same area of cross section. The constant amount of wrapping and area of cross section (πcm^2) and constant RPM (500), allowed one to attribute any changes in the magnetic flux density to the voltage that would be measured. This is shown in equation 5.
3. The stall torque motor was attached to the test tube and hence, the test tubes were oscillated in the constant magnetic field created by 2 rare earth magnets at a constant velocity. It was discussed in the control variable section, that a variable magnetic field or a variable oscillation velocity would affect the dependent and so the derived dependent variable, and hence, the values had to be kept constant so as to ensure the validity of the relationships drawn between the dependent and the independent variables.
4. The voltmeter was set to read the maximum voltage during oscillations, which occurred at times of greatest acceleration, which were the when the test tube was at its highest and lowest point in the magnetic field.
5. The motor was then switched of, the voltmeter reset, and hence, 5 readings were taken for each complex ion to ensure consistent readings.
6. The magnetic flux density was then calculated using Equation 5.¹⁶

$$B = \frac{V}{\omega NA}$$

3.0) Analysis

3.1) Raw Data:

Table 5: Showing the qualitative observations and their explanations in the preparation of ligands and their oscillation in a magnetic field.

Sr No.	Qualitative Observations for the preparation of the complex ions and the oscillation of said complex ions in a magnetic field using a motor.	
	Qualitative Observation	Explanation for the Qualitative Observation
1	For all the complex ions with the NH ₃ ligand, a light blue precipitate was observed.	The NH ₃ ion forms a blue precipitate, which settles at the bottom of the flask.
2	For the reaction for the preparation of [Co(NH ₃) ₅ (Cl)] ⁺ , effervescence was observed.	This was the evolution of Oxygen from the flask. As a colorless gas, it was observed in the form of effervescence.
3	As complex ions with greater splitting of their D-orbitals were prepared, the colours observed became higher in wavelength.	As the transmitted colors became higher in wavelength, and lower in frequency and energy, the absorbed light, which were the complimentary colors became higher in frequency and energy. This was the case as higher amounts of energy was required for electrons to transition to the e _g orbitals.
4	The reactions for the preparation of Co(NH ₃) ₅ (NO ₂) ⁺ , [Co(en) ₃] ²⁺ , and [Co(C ₂ O ₄) ₃] ⁴⁻ made the flask cold.	The reaction was endothermic in nature and hence as it proceeded, it drew heat from the environment to occur.

Raw data was collected for 2 sets of complex ions.

In the first set, successive substitutions of the [Co(H₂O)₆]²⁺ Complex ion with NH₃ ligands were considered.

Table 6: Showing the raw data table for the first data set, in which the mentioned ligands were oscillated in a magnetic field, while wrapped with a copper wire- their voltage values were then noted

Sr. No.	Ligand Identity	Max Wavelength Absorbance	V ₁	V ₂	V ₃	V ₄	V ₅	Voltage Measured	Uncertainty in Voltage
		λ /nm	± 0.1 /mV	± 0.1 /mV	± 0.1 /mV	± 0.1 /mV	± 0.1 /mV	V /mV	
1	[Co(H ₂ O) ₆] ²⁺	606	174.3	172.6	173.5	172.8	179.4	174.5	1.5
2	[Co(H ₂ O) ₄ (NH ₃) ₂] ²⁺	493	58.5	56.1	56.9	59.5	57.9	57.8	0.8
3	[Co(H ₂ O) ₂ (NH ₃) ₄] ²⁺	490	45.6	45.9	44.3	49.2	42.3	45.5	1.5
4	[Co(H ₂ O) ₂ (NH ₃) ₅] ²⁺	487	41.5	40.5	44.6	43.7	44.5	42.9	0.9
5	[Co(NH ₃) ₆] ²⁺	474	36.5	39.7	38.7	36.0	35.0	37.2	1.1

In the second set, the ligands [Co(NH₃)₅(___)] were considered, to see how single ligand substitutions would affect the magnetic flux density.

Table 7: Showing the raw data table for the second data set, in which the mentioned ligands were oscillated in a magnetic field, while wrapped with a copper wire- their voltage values were then noted.

Sr. No.	Ligand Identity	Max Wavelength Absorbance	V ₁	V ₂	V ₃	V ₄	V ₅	Voltage Measured	Uncertainty in Voltage
		λ /nm	± 0.1 /mV	± 0.1 /mV	± 0.1 /mV	± 0.1 /mV	± 0.1 /mV	V /mV	
1	[Co(NH ₃) ₅ (Cl)] ⁺	530	85.1	86.9	87.1	84.1	88.3	86.3	0.9

2	$[\text{Co}(\text{NH}_3)_5(\text{OH})]^+$	502	68.5	66.4	69.8	64.0	67.9	67.3	1.3
3	$[\text{Co}(\text{NH}_3)_5(\text{H}_2\text{O})]^{2+}$	487	41.5	40.5	44.6	43.7	44.5	43.0	0.9
4	$[\text{Co}(\text{NH}_3)_6]^{2+}$	474	36.5	39.7	38.7	36.0	35.0	37.2	1.1
5	$[\text{Co}(\text{NH}_3)_5(\text{NO}_2)]^+$	455	30.1	31.6	32.7	30.0	35.6	32.0	1.3

The 2 data sets were then combined to observe one large data set with all the data.

Table 8: Showing the raw data table for the combined data set, in which the mentioned ligands were oscillated in a magnetic field, while wrapped with a copper wire- their voltage values were then noted. ^{[17],[18],[19],[20],[21],[22],[23],[24]}

Sr. No.	Ligand Identity	Max wavelength $\lambda / \text{nm} \pm 1 / \text{nm}$	V_1 $\pm 0.1 / \text{mV}$	V_2 $\pm 0.1 / \text{mV}$	V_3 $\pm 0.1 / \text{mV}$	V_4 $\pm 0.1 / \text{mV}$	V_5 $\pm 0.1 / \text{mV}$	Voltage Measured V / mV	Uncertainty in Voltage
1	$[\text{Co}(\text{H}_2\text{O})_6]^{2+}$	606	174.3	172.6	173.5	172.8	179.4	174.5	1.5
2	$[\text{Co}(\text{NH}_3)_5(\text{Cl})]^+$	530	85.1	86.9	87.1	84.1	88.3	86.3	0.9
3	$[\text{Co}(\text{NH}_3)_5(\text{OH})]^+$	502	68.5	66.4	69.8	64.0	67.9	67.3	1.3
4	$[\text{Co}(\text{H}_2\text{O})_4(\text{NH}_3)_2]^{2+}$	493	58.5	56.1	56.9	59.5	57.9	57.8	0.8
5	$[\text{Co}(\text{H}_2\text{O})_2(\text{NH}_3)_4]^{2+}$	490	45.6	45.9	44.3	49.2	42.3	45.5	1.5
6	$[\text{Co}(\text{H}_2\text{O})_2(\text{NH}_3)_5]^{2+}$	487	41.5	40.5	44.6	43.7	44.5	43.0	0.9
7	$[\text{Co}(\text{NH}_3)_6]^{2+}$	474	36.5	39.7	38.7	36.0	35.0	37.2	1.1
8	$[\text{Co}(\text{NH}_3)_5(\text{NO}_2)]^+$	455	30.1	31.6	32.7	30.0	35.6	32.0	1.3
9	$[\text{Co}(\text{en})_3]^{2+}$	416	25.1	26.1	28.9	27.6	29.0	27.3	0.9
10	$[\text{Co}(\text{C}_2\text{O}_4)_3]^{4-}$	375	22.1	26.5	21.9	23.6	26.0	24.0	1.0

3.2) Data Processing:

Independent Variable:

1. The maximum wavelength value was calculated in meters using $\frac{\lambda(\text{nm})}{10^9}$

2. This value was inputted into the formula $\Delta E = \frac{hc}{\lambda}$ to calculate the associated energy difference between the d orbitals of the complex ion.

Sample:

The following sample calculation was conducted on the first trial for $[\text{Co}(\text{H}_2\text{O})_6]^{2+}$

1. The wavelength value obtained was- 606nm or $606 \times 10^{-9} \text{m}$

2. Hence, the associated splitting of the d orbitals in this complex was given by- $(6.63 \times 10^{-34} \times 3 \times 10^8) \div (606 \times 10^{-9}) = 3.28 \times 10^{-19} \text{J}$

Dependent Variable:

1. The voltage value was inputted into the equation $B = \frac{V}{\omega NA}$, where N was 4000, with a human counting uncertainty of ± 10 turns, and A was calculated using the formula πr^2 , where r was the radius of the test tube, measured to be 1 cm, $\pm 0.05 \text{cm}$.

Hence, the absolute uncertainty of the area of the coil was given by adding the absolute uncertainties of the radius twice and dividing by the area, to give $0.1/\pi$. ω was measured to be 500 rotations per minute, or $500 \times 2\pi$ radians per minute, which translates to $(500 \times 2\pi) \div 60 = 52$ radians per second. The associated uncertainty, was calculated using the relative uncertainty of the RPM, $\pm 10 \text{RPM}$, divided by the RPM, and multiplied by the ω value. This gives 52 ± 1 Radians per second. The absolute uncertainty of the Voltage was obtained using the formula $\frac{\text{maximum Voltage} - \text{minimum Voltage}}{2\sqrt{N}}$, where N was the number of trials conducted- (5).

2. The absolute uncertainties of all the values, were divided by the values ω , V, N and A, to form the relative uncertainties. These relative uncertainties were then added to form the relative uncertainty of B, the magnetic flux density. Then, the relative uncertainty was multiplied by the value of B for a certain λ to obtain the absolute uncertainty associated with a certain B value.

Sample:

The following sample calculation was conducted on the first trial for $[\text{Co}(\text{H}_2\text{O})_6]^{2+}$

1. The voltage values obtained were given by 174.3, 172.6, 173.5, 172.8, and 179.4 milliVolts. This averages out to $\frac{174.3+172.6+173.5+172.8+179.4}{5} = 174.5 \text{ mV}$ (174.5×10^{-3} Volts). The absolute uncertainty is given by the formula

$\frac{\text{maximum Voltage} - \text{minimum Voltage}}{2\sqrt{N}}$, which gives $\frac{179.4-172.6}{2\sqrt{5}} = \pm 1.5 \text{mV}$. This was used to calculate the uncertainty in B.

¹⁷ "Absorption Spectra- Empirical Aspects." N.p., n.d. Web. <<http://milne.ruc.dk/kemikurser/InorgChem/Noter/Notes%202017%20moodle/Absorption%20spectra.pdf>>.

¹⁸ Alom, Robeul. "Inorganic Chemistry Practical." *LinkedIn SlideShare*. N.p., 23 July 2015. Web. 20 Oct. 2019. <<https://www.slideshare.net/RobeulAlom/inorganic-chemistry-practical-50865319>>.

¹⁹ "Behavior of Co 2+ Cations in the Aqueous and Alcoholic Solution of CoCl₂ · 6H₂O." N.p., n.d. Web. <https://www.researchgate.net/figure/Spectrum-of-absorption-of-the-complexes-CoH2O6-2-and-CoH2O4-2-in-the-spectral_fig1_274237740>.

²⁰ "Color of Transition Metal Complexes." N.p., n.d. Web. <http://home.iitk.ac.in/~madhav/CHM102/Notes_on_Color_of_Inorganic_Complexes.pdf>.

²¹ "Colors of Transition Metal Complexes." N.p., n.d. Web. <http://web.iitd.ac.in/~sdeep/Elias_Inorg_lec_4.pdf>.

²² Libretexts. "Colors of Coordination Complexes." *Chemistry LibreTexts*. Libretexts, 05 June 2019. Web. 20 Oct. 2019.

<[https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Supplemental_Modules_\(Inorganic_Chemistry\)/Crystal_Field_Theory/Colors_of_Coordination_Complexes](https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Supplemental_Modules_(Inorganic_Chemistry)/Crystal_Field_Theory/Colors_of_Coordination_Complexes)>.

²³ Ling, Tan Ling, Musa Ahmad, and Lee Yook Heng. "UV-vis Spectrophotometric and Artificial Neural Network for Estimation of Ammonia in Aqueous Environment Using Cobalt(II) Ions." *Analytical Methods*. The Royal Society of Chemistry, n.d. Web. 20 Oct. 2019.

<<https://pubs.rsc.org/is/content/articlelanding/2013/ay/c3ay40887f/unauth#divAbstract>>.

²⁴ *Matter & Motion - Winter 2001*. N.p., n.d. Web. 20 Oct. 2019. <<http://archives.evergreen.edu/webpages/curricular/2000-2001/MANDM2000/Handouts/Labs/Chemistry/lab2wx.htm>>.

2. The formula $B = \frac{V}{NA}$, gives $B = \frac{174.5 \times 10^{-3}}{4000 \times \pi \times 52}$, which gives $B = 0.002671 \text{ Wb/m}^2$. The relative uncertainty is given by the sums of the relative uncertainties of Voltage, Area and Number of coils. This gives $\frac{1.5}{174.5} + \frac{10}{4000} + \frac{0.1}{\pi} + \frac{1}{52} = 0.000166$. Multiplying this by the value of the magnetic flux density, gives $0.139 \times 0.0429 = \pm 0.006 \text{ V/m}^2$, as the absolute uncertainty of the magnetic flux density. This uncertainty was used to plot as error bars on graphs.

3.3) Processed Data:

Table 9: Shows the processed data for the first data set, where the derived independent and dependent variables were noted, using the procedure mentioned above.

Sr. No.	Ligand Identity	Energy of splitting of d orbitals	Magnetic Flux Density	Uncertainty in Magnetic Flux Density
		$\Delta E / \text{J}$	B / Wbm^{-2}	
1	$[\text{Co}(\text{H}_2\text{O})_6]^{2+}$	3.28E-19	0.002671	0.000166
2	$[\text{Co}(\text{H}_2\text{O})_4(\text{NH}_3)_2]^{2+}$	4.03E-19	0.000884	0.000059
3	$[\text{Co}(\text{H}_2\text{O})_2(\text{NH}_3)_4]^{2+}$	4.06E-19	0.000696	0.000061
4	$[\text{Co}(\text{H}_2\text{O})_2(\text{NH}_3)_5]^{2+}$	4.08E-19	0.000657	0.000049
5	$[\text{Co}(\text{NH}_3)_6]^{2+}$	4.20E-19	0.000569	0.000047

Table 10: Shows the processed data for the second data set, where the derived independent and dependent variables were noted, using the procedure mentioned above.

Sr. No.	Ligand Identity	Energy of splitting of d orbitals	Magnetic Flux Density	Uncertainty in Magnetic Flux Density
		$\Delta E / \text{J}$	B / Wbm^{-2}	
1	$[\text{Co}(\text{NH}_3)_5(\text{Cl})]^+$	3.75E-19	0.00132	0.00009
2	$[\text{Co}(\text{NH}_3)_5(\text{OH})]^+$	3.96E-19	0.00103	0.00008
3	$[\text{Co}(\text{NH}_3)_5(\text{H}_2\text{O})]^{2+}$	4.08E-19	0.00066	0.00005
4	$[\text{Co}(\text{NH}_3)_6]^{2+}$	4.20E-19	0.00057	0.00005
5	$[\text{Co}(\text{NH}_3)_5(\text{NO}_2)]^+$	4.37E-19	0.00049	0.00005

Table 11: Shows the processed data for the combined data set, where the derived independent and dependent variables were noted, using the procedure mentioned above.

Sr. No.	Ligand Identity	Energy of splitting of d orbitals	Magnetic Flux Density	Uncertainty in Magnetic Flux Density
		$\Delta E / \text{J}$	B / Wbm^{-2}	
1	$[\text{Co}(\text{H}_2\text{O})_6]^{2+}$	3.28E-19	0.002671	0.000166
2	$[\text{Co}(\text{NH}_3)_5(\text{Cl})]^+$	3.75E-19	0.001321	0.000085
3	$[\text{Co}(\text{NH}_3)_5(\text{OH})]^+$	3.96E-19	0.001030	0.000075
4	$[\text{Co}(\text{H}_2\text{O})_4(\text{NH}_3)_2]^{2+}$	4.03E-19	0.000884	0.000059
5	$[\text{Co}(\text{H}_2\text{O})_2(\text{NH}_3)_4]^{2+}$	4.06E-19	0.000696	0.000061
6	$[\text{Co}(\text{H}_2\text{O})_2(\text{NH}_3)_5]^{2+}$	4.08E-19	0.000657	0.000049
7	$[\text{Co}(\text{NH}_3)_6]^{2+}$	4.20E-19	0.000569	0.000047
8	$[\text{Co}(\text{NH}_3)_5(\text{NO}_2)]^+$	4.37E-19	0.000490	0.000045
9	$[\text{Co}(\text{en})_3]^{2+}$	4.78E-19	0.000418	0.000036
10	$[\text{Co}(\text{C}_2\text{O}_4)_3]^{4-}$	5.30E-19	0.000368	0.000035

*NOTE: As all Magnetic flux values cannot maintain the least count of the voltage (as they would all read 0), they have been kept to the same number of significant digits instead. (3 significant digits)

3.4) Graphs:

Graph Chosen- Scatter Plot.

During the experiment, the Independent and Dependent variables were collected to plot. A scatter plot was chosen as it allows for a line of best fit and hence for the analysis of a trend. One can analyse the slope and hence determine the reason for the outcome of the experiment.

On plotting the data for Data Set 1:

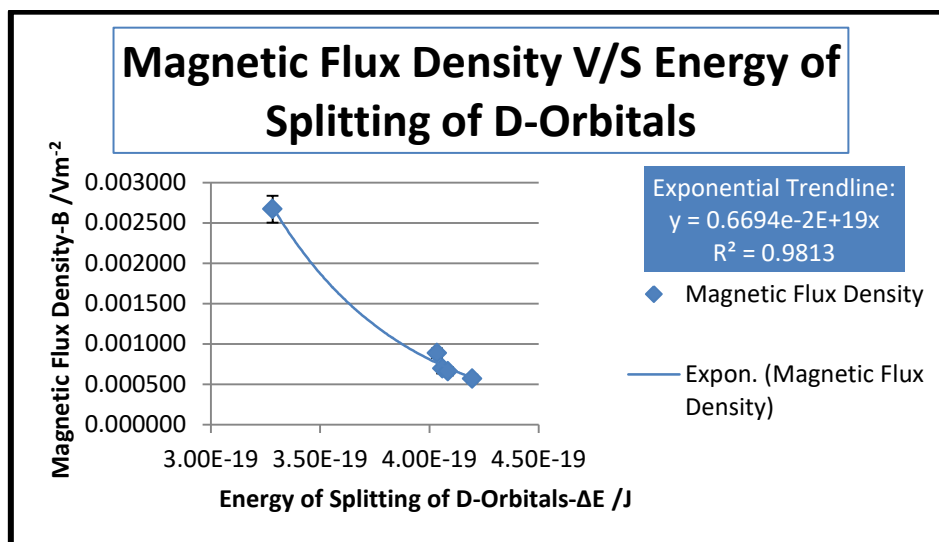


Figure 8: Showing the plotted magnetic flux density values for Data Set 1, plotted against the energy of splitting of the d orbitals of the complex ions in data set 1.

One can observe an exponential trend in the magnetic flux density with varying the energy difference between the e_g and t_{2g} orbitals of a complex ion, while keeping the area of cross section, number of coils in the coil, speed of rotation and strength of magnetic field constant. The trend was expected and predicted by the hypothesis.

As suggested in the hypothesis section, as one increases the splitting between the d orbitals, the number of paramagnetic configurations decreases exponentially (Equation 4), and since paramagnetic configurations cause magnetic field line convergence and so increase the magnetic flux density, the exponentially decreasing number of paramagnetic configurations would cause an exponentially decreasing magnetic flux density trend. Hence, an exponential decay relationship was predicted and chosen. It also indicated the highest R^2 value.

The previous figure was linearized, (in Figure 9) by taking the natural logarithm of the Magnetic flux density, to give a linear graph. This adds to the credibility of the previous graph, showing by this graph's high R^2 value that it is in fact exponential, as that is the only case in which a linear trend can be obtained by taking the natural logarithm of the y variable.

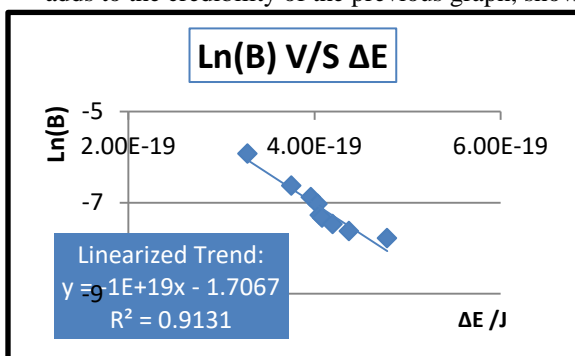


Figure 9: Showing the linearized version of Figure 8. The natural Logarithm of the magnetic flux density is plotted against the energy of splitting of d-orbitals of complex ions of data set 1.

In relation to the data set 1, as successive substitutions of NH_3 occurred (NH_3 , according to the spectrochemical series, is a ligand that causes more splitting than H_2O), the energy difference between the d orbitals increased, and hence the voltage decreased.

Error bars are extremely small and show that random errors have not had a significantly added to the uncertainties. There are also no major outliers, indicated by the fact that all data points are fairly close to the line of best fit. There is, however, the potential for significant systematic errors in the experiment, which would shift the graph vertically, altering the constant before e.

One should note, however, that because one data point is further from the rest, the R^2 value is deceptively high. Further data points make the scale larger and hence make it easier to fit trends by developing a regression line, and hence, easier to develop an equation.

On plotting the data for Data Set 2:

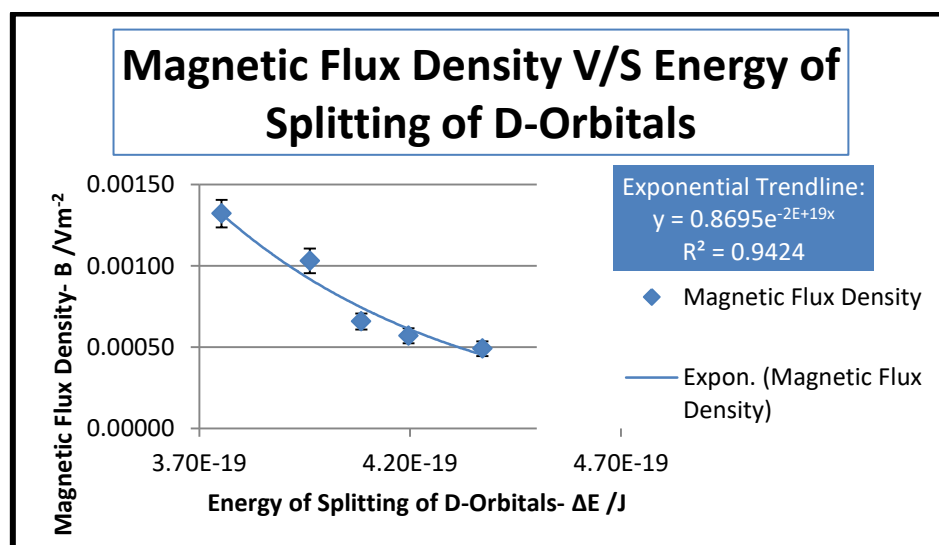


Figure 10: Showing the plotted magnetic flux density values for Data Set 2, plotted against the energy of splitting of the d orbitals of the complex ions in data set 2.

One can observe an exponential trend in the magnetic flux density with varying the energy difference between the e_g and t_{2g} orbitals of a complex ion, while keeping the area of cross section, number of coils in the coil, speed of rotation and strength of magnetic field constant. The trend was expected and predicted by the hypothesis.

As suggested in the hypothesis section, as one increases the splitting between the d orbitals, the number of paramagnetic configurations decreases exponentially (Equation 4), and since paramagnetic configurations cause magnetic field line convergence and so increase the magnetic flux density, the exponentially decreasing number of paramagnetic configurations would cause an exponentially decreasing magnetic flux density trend. Hence, an exponential decay relationship was predicted and chosen. It also indicated the highest R^2 value.

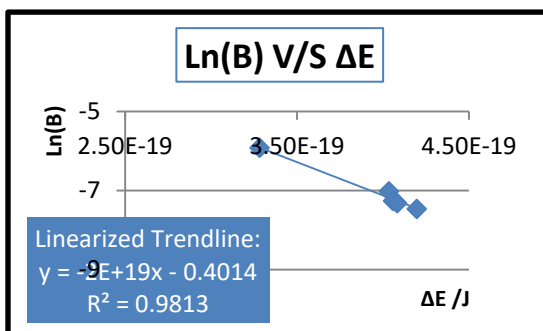


Figure 11: Showing the linearized version of Figure 10. The natural Logarithm of the magnetic flux density is plotted against the energy of splitting of d-orbitals of complex ions of data set 2.

The previous figure was linearized, (in Figure 11) by taking the natural logarithm of the Magnetic flux density, to give a linear graph. This adds to the credibility of the previous graph, showing by this graph's high R^2 value that it is in fact exponential, as that is the only case in which a linear trend can be obtained by taking the natural logarithm of the y variable.

In relation to data set 2, of the 6 ligands, 5 were kept constant at NH_3 , and one was replaced. Hence, any changes to the energy between the e_g and t_{2g} are only because of the one changing ligand. One can also notice, that as the splitting increased, as a result of the changing ligand, the magnetic flux density exponentially decreased, as predicted.

Error bars are extremely small and show that random errors have not had a significantly added to the uncertainties. There are also no major outliers, indicated by the fact that all data points are fairly close to the line of best fit. There is, however, the potential for significant systematic errors in the experiment, which would shift the graph vertically, altering the constant before e.

On plotting the data for the combined data set:

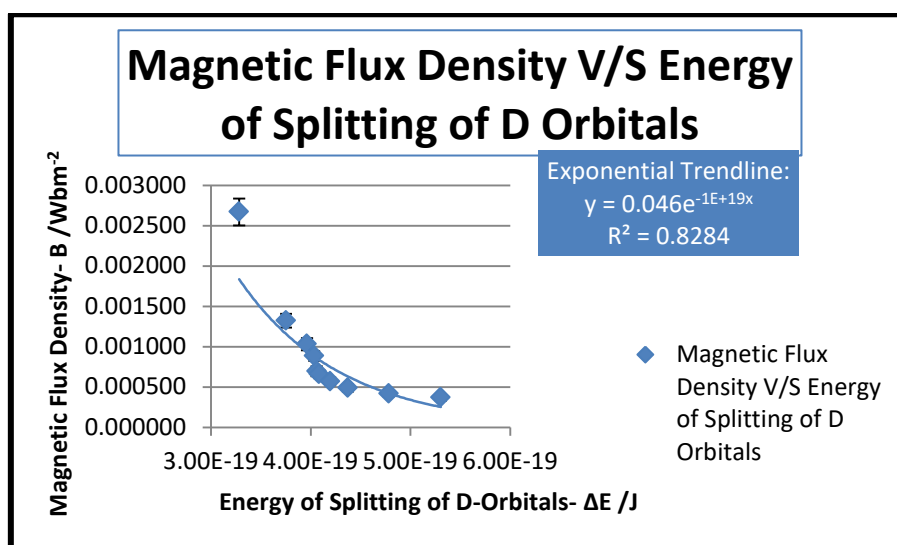


Figure 12: Showing the plotted magnetic flux density values for the Combined Data Set, plotted against the energy of splitting of the d orbitals of the complex ions in combined data set.

One can observe how, when all data points are plotted together, they fit an exponential decay relationship, as predicted.

As suggested in the hypothesis section, as one increases the splitting between the d orbitals, the number of paramagnetic configurations decreases exponentially (Equation 4), and since paramagnetic configurations cause magnetic field line convergence and so increase the magnetic flux density, the exponentially decreasing number of paramagnetic configurations would cause an exponentially decreasing magnetic flux density trend. Hence, an exponential decay relationship was predicted and chosen. It also indicated the highest R^2 value.

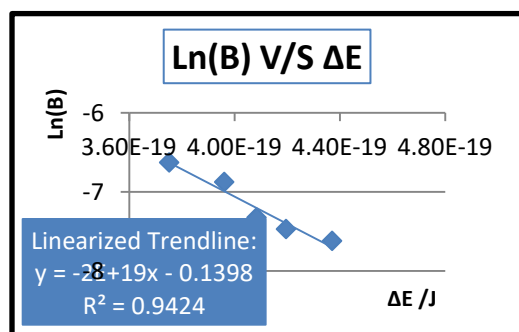


Figure 13: Showing the linearized version of Figure 12. The natural Logarithm of the magnetic flux density is plotted against the energy of splitting of d-orbitals of complex ions of the combined data set.

The previous figure was linearized, (in Figure 13) by taking the natural logarithm of the Magnetic flux density, to give a linear graph. This adds to the credibility of the previous graph, showing by this graph's high R^2 value that it is in fact exponential, as that is the only case in which a linear trend can be obtained by taking the natural logarithm of the y variable.

The first data point seems to be an outlier, in that it is far from the line of best fit. The probable reason for this is that the reaction for the preparation of this ligand was not very entropically favourable in terms of taking in more molecules on the reagents side and leaving with fewer. [Refer to reactions in materials section] Hence, it is possible that the equilibrium position lay towards the reagents side, leading to a partial substitution reaction where a Cl^- ligand (From the $\text{Co}(\text{H}_2\text{O})_6\text{Cl}_2$) took the place of an H_2O ligand. As the Cl^- ligand causes less splitting, it would be easier for electrons to make the transition to the e_g orbitals and hence form more paramagnetic configurations, which would lead to an increased measured voltage and so an increased measured magnetic flux density.

Errors affecting readings: One can definitely conclude that the trend is what was expected, by the high R^2 value. From this, one can also conclude that the data is fairly accurate, and that errors in experimentation were fairly small. Uncertainties in the data

were not too large, and have not caused overly large error bars. The small error bars are also an indication of the small effect of random errors on the experiment. These small error bars do not leave much room for the trend and hence, do not add much ambiguity to the result of the experiment.

The controls kept experimental results fairly precise by eliminating random errors, and hence attributing changes in the dependent variable to the independent variable only. Keeping an octahedral formation, constant magnetic field, oscillation velocity, number of coils and area of coils were all essential to this, as if not kept constant, would cause doubt in the attribution of differing magnetic flux density to a changing d orbital energy gap.

Since the Independent variable data was obtained from online sources, despite their credibility, one cannot discount the fact that the data may have been obtained under slightly different conditions and hence, caused a different maximum wavelength absorbance value. This is a possible source of error in all graphs, and hence would cause some amount of error in the readings. However, it is apparent by the high R^2 value that this has not been the case, as the trend is as expected.

While results were precise and accurate, one cannot ignore the potential presence of systematic errors. If any variable, like voltage, had been miscounted, due to an issue in the measurement device calibration, this would have occurred for all data points, shifting the graph vertically, hence, not changing the nature of the trend, rather the maximum value. Hence, even in case of a systematic error, one could still deduce that the prediction made by the hypothesis was fairly accurate.

4.0) Evaluation

4.1) Conclusion:

Aim: The investigation aimed to determine a relationship between the magnetic flux density of complex ions of octahedral complexes and the splitting between their d orbitals.

Answer to Research Question: The data allowed one to plot a graph of Energy of splitting of D orbitals V/S the magnetic flux density, and obtain an exponential relationship, which was in agreement with the hypothesis.

The relationship observed was probably exponential, as suggested by said hypothesis and the high R^2 values of 0.82, 0.94 and 0.98.

Data: Plotting the graph required one derive the energy of splitting between e_g and t_{2g} using the maximum wavelength absorbance from online databases and the magnetic flux density from measured voltage values.

The data was fairly accurate as uncertainties were minimal and error bars were small enough to not have a significant impact on the nature of the graph. Since the Independent variable data was obtained from online sources, despite their credibility, one cannot discount the fact that the data may have been obtained under slightly different conditions and hence, caused a different maximum wavelength absorbance value. This is a possible source of error in all graphs, and hence would cause some amount of error in the readings. However, it is apparent by the high R^2 value that this has not been the case, as the trend is as expected.

Link to Hypothesis: Considering Cobalt's 2 main energy states, where one has 2 electrons, each in 1 e_g orbital and the other, with only 1 electron ascended, we can see that the first configuration is more paramagnetic, as there are more electrons without pairs.

As predicted by the hypothesis and equation 4, as the energy difference between the levels increases, the number of complex ions with cobalt's electrons in the more paramagnetic configuration decreases exponentially. Hence, the complex's ability to induce voltage decreases exponentially.

It hence follows, from the linear relationship between induced voltage and magnetic flux density, given that area of the coil, number of coils and rate of rotation are kept constant, that the magnetic flux density also decreases exponentially.

This agrees with the theory, which states that paramagnetic substances cause field lines to converge (higher magnetic flux density, causing more voltage induced), and diamagnetic substances cause field lines to diverge (lower magnetic flux density causing less voltage induced).

4.2) Strengths of the Investigation:

1. Variables that could affect results were well controlled in the procedure- The procedure had multiple well controlled variables, which helped attribute any changes in the dependent variable to the independent variable. The speed of rotation (ω) was kept constant, along with the number of coils (N) and the area of the coils (A). These insured that the dependent variable (Voltage), could be the only factor which changed the calculated derived dependent variable (Magnetic Flux density) through linear equation 5. In addition to this, the temperature of the experiment, which could affect the equation, in theory, was not changed. This ensured the reliability of the results by making the experiment more standardisable.

2. Equipment showed small least counts- Equipment like measuring cylinders were chosen with the smallest available uncertainty, so as to reduce the uncertainty and limit the range of potential values for the activation energy of the reaction. Due to the small least counts in the volume of the measured substances, our errors propagated resulted in small error bars and narrowed the range of final values quite a bit. This helped establish the precision of our readings.

3. A large range of Independent variables were considered- The large amount of data points provided a graph with a large range, which allowed for more conclusive observations in to be drawn. The obtained graph was most certainly exponential and hence, allowed for one to confirm the hypothesis.

4. Multiple trials (5) were considered for each independent variable- which allowed for one to control for random errors. This aided the precision of the data, as a random error, averaged out over a larger number of trials, causes less deviation from the group of data. This also aided the reliability of the experiment as random errors (which has been accounted for using multiple trials) would deviate from expected results if the experiment was conducted again.

5. 2 data sets were used, which both showcased different aspects of the concept- The first data set involved successively substituting H_2O ligands with NH_3 ligands, which developed understanding on how successive partial substitution causes a different in the magnetic flux density.

The second data set involved keeping 5 NH_3 ligands and switching out the 6th for different ones, which developed understanding on how a single ligand can change the magnetic flux density.

These combined to form one larger data set, with a larger range of independent variables, which could also be analyzed for a general trend, that confirms the hypothesis. The larger data set also extended to bidentate ligands, which showed to be a part of the same trend, hence developing understanding beyond the tested monodentate ligands.

6. A hypothesis was formulated and followed through- A hypothesis was formed only after the experiment, to prevent confirmation bias in the readings. This adds to the credibility of results as the experimenter was unaware of the nature of the trend being expected and hence, would be immune to confirmation bias in altering results.

The clear hypothesis was also backed by an equation and had an established reason behind the nature of the curve, as discussed in the hypothesis section. Since the hypothesis equation is an integral part of statistical thermodynamics, it holds credibility. The experimental trend agreeing with the trend predicted because of the equation allows the experimental trend to borrow some credibility from the theoretical equation.

7. Single Blind set-up-When conducting the experiment, the ligands were randomly placed in numbered test tubes and their voltages taken as they were oscillated in the magnetic field. The experimenter hence, was unaware of which ligands were being oscillated, preventing confirmation bias. This adds to the credibility of the experiment and hence establishes the results.

4.3) Errors of the Investigation (With Suggested Improvements):

4.3.1) Systematic Errors

1. The RPM of the motor was not calibrated using a standard scale- This could not have been done as there was no standard scale present to use. Hence, it is possible, that the reading (taken off the motor's display), could have an inherent systematic error. If the RPM values were measured as lower of higher as they were, the error would appear in all readings, in the form of the constant ω (the rate of rotation of the complex ions in the magnetic field), which determined the dependent variable. A higher RPM would correspond to a higher ω value. This error can only be eliminated by using a standard RPM measurement on another device to calibrate the motor. Unfortunately, this was not available to the researcher. Hence, the reliability of the results was adversely impacted- if the experiment was redone, and found that the RPM was calibrated differently, one would obtain different results.

2. For safety reasons, the ligands were placed in a protective plastic tube, coated with cotton on the inside- This was done as vibrations could have caused the test tube to shatter if it hit any part of the set-up. The plastic tubing and cotton could have significantly reduced the magnetic field density in the area of the ligand (as it is not a magnetic material), hence reducing voltage values and so magnetic flux density values. The glass of the test tube would have the same effect. This would have been the same for all readings as the same plastic tube, test tube and cotton was used, and hence, is a systematic error in the readings. As this was done for safety, removing this protective layer would be dangerous. If one removes this layer, to eliminate the error, they run the risk of breaking the test tube and spilling the ligands. To eliminate this error, one must take an additional precaution to prevent the same, like layering the floor with a soft material to prevent the test tube from breaking in case of it hitting the bottom. This however, was not done, for lack of resources. To remove the test tube would be impossible, as the ligands are a liquid and hence must be held in a container; hence, avoiding this component of the systematic error is impossible. Hence, the reliability of the experiment was crippled- as one is not measuring the magnetic flux density of only the complex ions, but also the test tube, plastic coating and cotton. If the experiment was redone with different coating or cotton, the results would vary.

3. It was noticed in the pilot experiment, that the orientation of the set-up led to differing readings, as the rare earth magnets would concentrate the magnetic field, leading to a higher magnetic flux density, if kept in the orientation of the magnetic field. In the experiment, the motor had to be kept at a height, and was kept on a table that was bolted to the ground, hence, the orientation of the set-up was kept constant. If the experiment was conducted at a different orientation, one would observe different results, as a different component of the magnetic field would be concentrated by the magnets. Hence, the reliability of the experiment is affected. This could have been improved by setting up the experiment in the direction of the magnetic field of the earth using a compass, and hence always obtaining the maximum possible magnetic flux density, as the magnetic field of the earth, acting in the direction of the magnets would be concentrated the most if the magnetic field lines of the earth and the magnets were in the same direction.

4.3.2) Random Errors

1. During the experiment, it is virtually impossible to keep the RPM of the motor from fluctuating a little bit (± 10 RPM). -This could have lead to readings that varied slightly from reality. Hence, the precision of the data could be adversely impacted, as a larger uncertainty in the RPM readings would lead to a less clustered data group. Unfortunately, all motors RPMs fluctuate, and, while considering a better motor could have reduced this random error, eliminating it is extremely hard. Hence, 5 trials were considered per reading to counter the effects of such random errors, under the assumption that they average out to the real values of the data (that the random errors cancel out).

2. The temperature during the experiment could have varied- As seen in Equation 4, the higher the temperature of the experiment, the more energy is available for the electrons to ascend to the e_g orbitals, and hence, more paramagnetic configurations of the complex ions occur. Hence, the magnetic flux density increases. While temperature was controlled by conducting the experiment in the same location, it is hard to control for temperature, as there was no air conditioner, and the experiment was conducted in open air. Hence, the temperature could have varied. Conducting this in an air conditioned room would have allowed to control this variable better, and hence reduce the uncertainty in the data, hence improving the precision of the data.

3. The angle at which the complex ions were inserted could have varied. To keep this constant, a ring was used, through which the complex ion was suspended, but this could not be kept too tight, as one had to allow the complex ions to oscillate. Hence, the angle, while controlled, could have varied slightly. This would have caused a smaller component of the magnetic field to act in the area of the coil, and could have reduced the induced voltage values (and so magnetic flux density) values. Hence, the reported values could have been lowered by a random error. A better way to counter this error, is to tighten the ring which confines the test tube to solely vertical oscillation, and oil it well from the inside, hence allowing it to move smoothly, while maintaining an angle of 90° , of the magnetic field lines to the area vector (which lies perpendicular to the plane of the area {top of test tube}, as given by Equation 5).

4.4) Weaknesses of the investigation (With Suggested Improvements):

1. As there is no online data available at the same conditions for the same complexes, there is no literature value to compare to. This is problematic, as one is unsure of whether one's data is in the correct range or not. While the trend is what was predicted, the actual values make it hard to hypothesize the presence of systematic errors and how much they effected the readings. This also questions the credibility of the experiment, as its data is not backed by numerical values, only a theoretical equation. There is no percentage error, which makes it hard to judge how much the errors and assumptions have affected the readings. To partially counter this, one can consider the magnetic flux density of other ligands, to make sure that the range is approximately the same, so establishing that the errors, while present, have not drastically changed results.

2. The maximum voltage setting on the voltmeter used measures the voltage at very small time intervals. Then, the maximum voltage is noted. However, if the maximum voltage really occurred between these time intervals, it would never be measured by the voltmeter, and hence, not be reported in the data. Reporting a lower voltage value, would in lead to a lower value for the magnetic flux density, as defined by the linear relationship between voltage and magnetic flux, as given by Equation 4. Hence, this random error would cause imprecision in the data and affect its validity. One can assume that taking multiple values for the readings would average out this random error, and hence, one can use this technique to combat it.

3. The assumptions of the experiment may not have been accurately justified, and hence, may have added to the errors. Hence, they must be evaluated, as done below. These will be addressed briefly, as they have already been discussed in the previous section on errors of the investigation.

a. Temperature- While the temperature was assumed to be constant, there is no saying that it was, as the experiment was not conducted in a temperature controlled room. Hence, it could be possible, as discussed in the random errors section, that variation in temperature caused more or less energy to be supplied to the complex ions. The higher the temperature of the experiment, the more energy is available for the electrons to ascend to the e_g orbitals, and hence, more paramagnetic configurations of the complex ions occur. Hence, the magnetic flux density increases. Hence, this assumption is not valid, but due to the fact that the material was controlled, one can still attribute changes in the dependent variable to the independent variable. This could be improved by conducting the experiment in an air conditioned and temperature controlled room.

b. Angle between magnetic field direction and area vector- was assumed to be a constant 90° , and hence, would not affect readings. This assumption was made as a ring was set to prevent the test tube from changing orientation. That being said, the ring could not have been

made too tight, as there needed to be room for the test tube to oscillate, and therefore, the angle could have varied a little. This could be improved by making the ring tighter but oiling to restrict horizontal movement and changes in the angle but still allow vertical movement.

c. The plastic container, cotton and test tube did not affect magnetic flux density- Which was most probably a false assumption. For safety reasons, the ligands were placed in a protective plastic tube, coated with cotton on the inside- This was done as vibrations could have caused the test tube to shatter if it hit any part of the set-up. The plastic tubing and cotton could have significantly reduced the magnetic field density in the area of the ligand (as it is not a magnetic material), hence reducing voltage values and so magnetic flux density values. This could have been improved partially (as one cannot remove the fact that a container will always be present during measurement and hence affect readings), by layering the floor or any place the test tube may fall instead of the test tube as a safety precaution.

d. The earth's effect on the magnetic field is negligible- During the investigation, the effect of the earth's magnetic field was not considered, and an arbitrary (though constant) orientation was considered. In reality, and as observed during the pilot, the magnets would concentrate the magnetic field lines and hence affect the magnetic flux density. Hence, this assumption is not valid, but due to the fact that the orientation was controlled, one can still attribute changes in the dependent variable to the independent variable. This could have been improved by setting up the experiment in the direction of the magnetic field of the earth using a compass, and hence always obtaining the maximum possible magnetic flux density, as the magnetic field of the earth, acting in the direction of the magnets would be concentrated the most if the magnetic field lines of the earth and the magnets were in the same direction.

4. The independent variable data was obtained from different sources- and so, it is invalid to deduce that the data was all obtained at the same temperature and pressure. These values definitely are known to affect the max wavelength, as given by Wien's law, which states that the temperature and the maximum wavelength absorbance have an inverse relationship. The difference in conditions lays uncertainty in the Independent variable data. If given the proper equipment, one could conduct infrared spectroscopy to determine the energy of the bonds between the central metal ion and the ligands and hence the energy of splitting of the d orbitals. However, this was not available, and hence, secondary data was used. Despite the fact that large amounts of data was obtained from a single source, not all of it was, and hence, the credibility and validity of the investigation is adversely affected.

5. Precipitates, occurred in multiple complex ions, which had the NH_3 ligand. As solids, they would have better magnetic properties than liquids, as solids have magnetic domains which allow them to concentrate a magnetic field efficiently. Hence, the precipitates could have increased the voltage values measured, hence leading to a falsely high magnetic flux density reading. This would also only occur for certain complex ions, which showed precipitates. This would be hard to control for, as using a centrifuge to isolate the precipitate has a tendency to separate the ligands, as observed in the pilot experiment. To control for this, one could use filter paper to remove it from the solution immediately before inserting it into the magnetic field.

4.5) Reliability and Precision:

Reliability- While the trend was exponential, as expected, the experiment is open to systematic errors, and hence, may show different values in an exponential equation if conducted again. Since the temperature was not measured through the experiment, the same experiment conducted again at different temperatures could affect readings significantly. Other random errors, while present, would not affect results too much. Hence, one can deduce that the investigation is fairly reliable.

Precision- As the data was grouped together, as indicated by the small uncertainties, the results were fairly precise (as indicated by small error bars on the graph). This was a result of well controlled variables and hence small random errors. The precision of the experiment, however, does not mean that there are no systematic errors. A systematic error would not change the nature of the trend but still affect the pre-exponential constant.

4.6) Implications:

Understanding how ligands change their paramagnetic properties has interesting applications in transformers. Transformers usually use a soft iron core to concentrate magnetic field lines, a job which can be done by ligands. While soft iron may do this better, ligands have the advantage of being liquids, and hence can be used in situations where it is hard to obtain a solid of a certain shape.

When working with ligands in voltage transformation, one can also use partial substitution reactions to vary the voltage by varying the concentration of magnetic field lines in the conductor. One can add molar ratios of a certain ligand to make the complex ions more paramagnetic and increase the voltage or more diamagnetic to decrease it, and use supplied heat to change the position of equilibrium and have a varying, choosable voltage.

4.7) Extensions:

1. Equation 4 predicts that as the temperature of the complex ions increase, more electrons are able to make the transition to a higher energy state. This relationship would be exponential. It would be fruitful to check this in an investigation. A similar hypothesis can be checked. If the energy supplied to the molecules is larger, more of them would ascend to the e_g orbitals and hence make a more paramagnetic configuration. This would lead to an increased magnetic flux density.

2. A similar investigation can be conducted, except the changing ligands would not be the cause for the change in the difference of energy levels of d orbitals, as they would be kept constant. However, different central metal ions would be used. The energy of splitting of the d orbitals depends on various factors like the charge on the metal ion. If a metal ion has a larger charge, it attracts the ligands donated pairs of electrons more, causing more interaction and repulsion between orbitals and hence causing a larger gap between the e_g and t_{2g} orbitals. This relationship would also be exponential, as the same equation (Equation 4) is relevant, as the only factor being changed is ΔE , like the original experiment, only in a different way.

5.0) Bibliography:

- Abbas, Nada K., Habeeb, Majeed Ali, Algidsawi, and Alaa J. Kadham. "Preparation of Chloro Penta Amine Cobalt(III) Chloride and Study of Its Influence on the Structural and Some Optical Properties of Polyvinyl Acetate." *International Journal of Polymer Science*. Hindawi, 15 Feb. 2015. Web. 20 Oct. 2019. <<https://www.hindawi.com/journals/ijps/2015/926789/>>.
- "Absorption Spectra- Empirical Aspects." N.p., n.d. Web. <<http://milne.ruc.dk/kemikurser/InorgChem/Noter/Notes%202017%20moodle/Absorption%20spectra.pdf>>.
- Alom, Robeul. "Inorganic Chemistry Practical." *LinkedIn SlideShare*. N.p., 23 July 2015. Web. 20 Oct. 2019. <<https://www.slideshare.net/RobeulAlom/inorganic-chemistry-practical-50865319>>.
- "Behavior of Co^{2+} Cations in the Aqueous and Alcoholic Solution of $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$." N.p., n.d. Web. <https://www.researchgate.net/figure/Spectrum-of-absorption-of-the-complexes-CoH2O6-2-and-CoH2O4-2-in-the-spectral_fig1_274237740>.
- "Chemistry 111 Laboratory: Synthesis of a Coordination Compound." N.p., n.d. Web. <<https://www.maclester.edu/~kuwata/Classes/2004-05/chem%20111/111%20experiment%206%20-%20co%20synthesis.pdf>>.
- Co(H₂O)₆²⁺/CoCl₄²⁻ Equilibrium Demonstration Sheet*. N.p., n.d. Web. 20 Oct. 2019. <<https://chemed.chem.purdue.edu/genchem/demosheets/12.10.html>>.
- Cobalt Transition Metal Chemistry Cobalt(II)Co₂⁺ Complex Ions Stabilised Ligand Substitution Cobalt(III)Co₃⁺ Complexes Redox Chemical Reactions +2 +3 Principal Oxidation States GCE AS A2 IB A Level Inorganic Chemistry Revision Notes*. N.p., n.d. Web. 20 Oct. 2019. <<http://www.docbrown.info/page07/transition07Co.htm>>.
- "Color of Transition Metal Complexes." N.p., n.d. Web. <http://home.iitk.ac.in/~madhavr/CHM102/Notes_on_Color_of_Inorganic_Complexes.pdf>.
- "Color of Transition Metal Complexes." N.p., n.d. Web. <http://home.iitk.ac.in/~madhavr/CHM102/Notes_on_Color_of_Inorganic_Complexes.pdf>.
- "Colors of Transition Metal Complexes." N.p., n.d. Web. <http://web.iitd.ac.in/~sdeep/Elias_Inorg_lect_4.pdf>.

- "Edraw Max, All-in-One Diagram Software." *Edraw Max - Excellent Flowchart Software & Diagramming Tool*. N.p., n.d. Web. 20 Oct. 2019. <<https://www.edrawsoft.com/en/edraw-max/>>.
- Libretexts. "Colors of Coordination Complexes." *Chemistry LibreTexts*. Libretexts, 05 June 2019. Web. 20 Oct. 2019. <[https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Supplemental_Modules_\(Inorganic_Chemistry\)/Crystal_Field_Theory/Colors_of_Coordination_Complexes](https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Supplemental_Modules_(Inorganic_Chemistry)/Crystal_Field_Theory/Colors_of_Coordination_Complexes)>.
- Ling, Tan Ling, Musa Ahmad, and Lee Yook Heng. "UV-vis Spectrophotometric and Artificial Neural Network for Estimation of Ammonia in Aqueous Environment Using Cobalt(II) Ions." *Analytical Methods*. The Royal Society of Chemistry, n.d. Web. 20 Oct. 2019. <<https://pubs.rsc.org/is/content/articlelanding/2013/ay/c3ay40887f/unauth#!divAbstract>>.
- Magnetic Field Lines: Paramagnetism and Diamagnetism*. Digital image. N.p., n.d. Web. <https://www.google.com/url?sa=i&url=https%3A%2F%2Fbrainly.in%2Fquestion%2F7915922&psig=AOvVaw04NWqX3bp74SWMK90k_yQ2&ust=1571683208842000&source=images&cd=vfe&ved=0CAIQjRxxqFwoTCICRkqy-q-UCFQAAAAAdAAAAABAE>.
- Matter & Motion - Winter 2001*. N.p., n.d. Web. 20 Oct. 2019. <<http://archives.evergreen.edu/webpages/curricular/2000-2001/MANDM2000/Handouts/Labs/Chemistry/lab2wx.htm>>.
- Octahedral Geometry*. Digital image. N.p., n.d. Web. <https://www.google.com/url?sa=i&url=https%3A%2F%2Fen.wikipedia.org%2Fwiki%2FOctahedral_molecular_geometry&psig=AOvVaw1KTx0rOhjbVX01MoL29d4k&ust=1571682685159000&source=images&cd=vfe&ved=0CAIQjRxxqFwoTCJDztk8q-UCFQAAAAAdAAAAABAE>.
- OpenStax. *Chemistry*. N.p., n.d. Web. 20 Oct. 2019. <<https://opentextbc.ca/chemistry/chapter/19-2-coordination-chemistry-of-transition-metals/>>.
- Palad, Charisse. "Synthesis, Spectroscopic, Electronic, and Magnetic Properties of Some 3D Metal Complexes." *Academia.edu*. N.p., n.d. Web. 20 Oct. 2019. <https://www.academia.edu/9554388/Synthesis_Spectroscopic_Electronic_and_Magnetic_Properties_of_Some_3D_Metal_Complexes>.
- "R/chemistry - Complex Preparation: K₃[Co(C₂O₄)₃]." *Reddit*. N.p., n.d. Web. 20 Oct. 2019. <https://www.reddit.com/r/chemistry/comments/1wqfxy/complex_preparation_k3coc2o43/>.
- "Reactions of Some Transition Metal Ions." N.p., n.d. Web. <http://www.knockhardy.org.uk/sci_htm_files/15tmet2.pdf>.
- Schlessinger, Gert G., Doyle Britton, Thornton Rhodes, and Elizabeth Ng. "Chloropentaamminecobalt(III) Chloride." *Wiley Online Library*. John Wiley & Sons, Ltd, 05 Jan. 2007. Web. 20 Oct. 2019. <<https://onlinelibrary.wiley.com/doi/abs/10.1002/9780470132401.ch43>>.
- Spectrochemical Series*. Digital image. N.p., n.d. Web. <https://www.google.com/url?sa=i&url=https%3A%2F%2Fbrainly.in%2Fquestion%2F2682794&psig=AOvVaw1knKVzs_NKnCaa5oGrA1RW&ust=157168305175000&source=images&cd=vfe&ved=0CAIQjRxxqFwoTCOComeG9q-UCFQAAAAAdAAAAABAE>.
- "Synthesis of a Cobalt Complex." N.p., n.d. Web. <http://www.uvm.edu/~cclandry/chem36/Laboratory_files/lab%206.pdf>.
- "Tris(ethylenediamine)cobalt(III) Chloride ([Co(en)₃]Cl₃) and." *Studylib.net*. N.p., n.d. Web. 20 Oct. 2019. <<https://studylib.net/doc/8121154/tris-ethylenediamine-cobalt-iii-chloride---co-en-3-cl3--and>>.
- University of Engineering and Technology. "Synthesis of Chloropentaamminecobalt(iii) Chloride." *LinkedIn SlideShare*. N.p., 17 May 2018. Web. 20 Oct. 2019. <<https://www.slideshare.net/saimkhalid04/synthesis-of-chloropentaamminecobaltiii-chloride>>.