Zeeman Effect

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Submitted: April 7 2024

Abstract

This report entails the scientific discovery known as Zeeman Effect. By subjecting a cadmium lamp to magnetic fields of varying strengths, distinct spectral line patterns were recorded and analyzed. The Bohr Magneton was experimentally determined to be $1.6610^{-23} \pm 3.54910^{-25}$ J/T and the charge-to-mass ratio of electrons was calculated to be $3.13210^{11} \pm 6.69610^{9}$ C/kg. These values deviate from the expected values, attributed to measurement uncertainties in magnetic field strength and spectral analysis. The observed Zeeman Effect validates the interaction between atomic energy levels and external magnetic fields, proving foundational principles in quantum mechanics.

1 Introduction

The Zeeman Effect is a fundamental principle in quantum mechanics, revealing the splitting of atomic spectral lines when atoms encounter external magnetic fields. This report will investigate the Zeeman Effect by observing a cadmium lamp at different alignments with varying magnetic field strength. When increasing the magnetic field, the electron level's momentum lines become more visible, demonstrating their quantization. This investigation aims to use these quantum principles to measure the known Bohr Magneton as well as the electron charge-to-mass ratio.

2 Background Information

In 1896, the Dutch physicist Peter Zeeman observed the splitting on energy levels of sodium atoms in a magnetic field. This behavior became known as the Zeeman Effect. This phenomenon was later explained by another Dutch physicist, Antoon Lorentz, giving them the second Nobel Prize in physics for their combined efforts.

In the absence of an external magnetic field, the spectral lines of an electron show a single line, per energy level. When an external magnetic field is applied, these lines split into separate components. This occurs due to the interaction between the magnetic moment associated with the electron's spin and orbital angular movement. Depending on the orientation of the electron's magnetic field moment relative to the applied field, the energy levels of the electron will demonstrate different shifts. The Zeeman Effect has been instrumental in the study of atomic properties, the development of quantum physics, and the overall behavior of atoms.

3 Theory

The energy levels of electron in atoms are effected three integer indices: n, l, and m. The first is the principle quantum number (n), which comes from the Bohr quantization conditions and is proportional to the Bohr radius of the electron's orbit. This integer can range from 1 to infinity. The orbital angular quantum number (l), lies between 0 and n-1, while the magnetic quantum number (m) ranges between -l and +l. The magnetic moment can be calculated using $\mu = -\mu_B L$ and the energy from the magnetic field is given by: $E = -\mu \cdot B$. Using this relation, the change of energy between levels is as follows: $\Delta E = \mu_B B$

The largest contribution to the energy splitting of electron states comes from the fine-structure splitting. The magnitude of the electron magnetic moment is calculated as follows:

$$\mu_B = e\hbar/2m_e \approx 5.79 * 10^{-11} MeV/T \tag{1}$$

The energy of μ_B can also be converted to unites of frequency from the emitted light, $14.0GHz/T$. For the normal Zeeman effect, a red filter is used to filter photons at $\lambda_o = 643.847nm$, specifically transition between the 5d and 5p levels. The resulting change in energy between photons, and its relation to the Zeeman magnetic energy is:

$$\Delta E = \mu_B B = \frac{hc}{2\mu t}(\frac{\delta}{\Delta}) \tag{2}$$

Using this equation, the Bohr magneton can be calculated. In terms of Joules, rather than eV, this value theoretically comes out to $\mu_B = 9.273 * 10^{-24} J/T$.

4 Experimental Procedure

A magnetic power supply is set next to a cadmium lamp on a rotating table with an optical bench including a CCD camera, lens +50mm, analyzer, waveplate bracket, green filter bracket, lens +300mm, Fabry-Perot interferometer with red filter holder, and lens +50mm. Pictures of the Zeeman Effect were taken, through a computer from the interferometer, at different magnetic field strengths. The magnetic field was increased through the control of current going through the electromagnet (large inductors). These images were then analyzed using LoggerPro's photo analysis function. The areal ratio was measured through the measurement comparison of the multiple rings, thus not needing a specific scale. There is no measured uncertainty for the diameter measurement and the current applied to get the magnetic field was also estimated.

5 Results

The following images show the Zeeman Effect for both the longitudinal and transversal alignment, with graphs accompanied showcasing the relationship between the magnetic field and areal ratio.

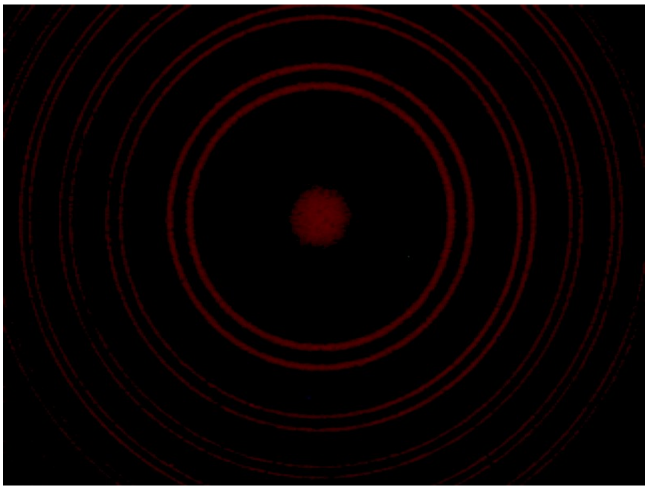


Figure 1A: Low Resolution Longitudinal Unpolarized: The above image shows the longitudinal alignment of the magnetic field when applying around a 4 Amp current to create a magnetic field of about 420 mT. This image shows a lower resolution image of the longitudinal alignment, hence the lighter magnitude shown through the light intensity. This image shows around 3 rings, relating to 3 energy levels, with clear splitting of the angular momentum of those levels. A red filter was placed as well as a lens +50 mm, the analyzer, waveplate bracket, green filter bracket, and lens +300mm. These optical components were adjusted between each experiment to obtain a clearer image. For the longitudinal alignment only the σ can be obtain, giving an electronic transition when $\Delta M_l = \pm 1$.

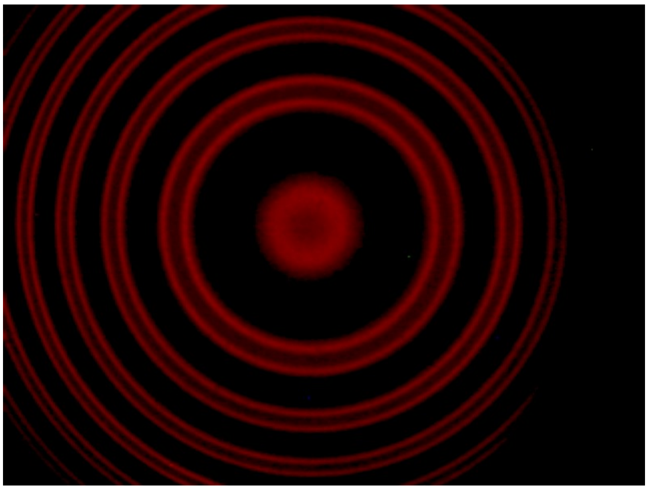
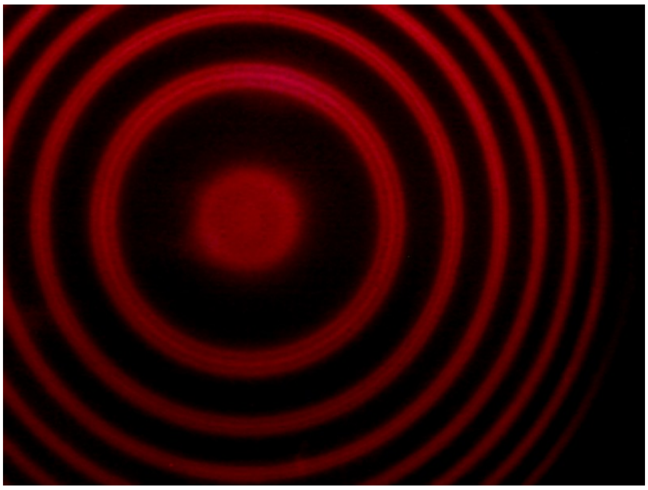


Figure 1B: High-Resolution Longitudinal Unpolarized: This image is a higher resolution image of the longitudinal alignment. This image also shows when a 4 Amp current was applied to the electromagnet creating a 420 mT magnetic field. This experiment has same process for data acquisition and set up as the low resolution alignment. The electronic transitions also occurred when $\Delta M_l = \pm 1$.



Figured 1D: Unpolarized Angle of the Transverse Alignment: The above image shows the transverse alignment of light. For this experiment, the polarizer was remove, giving three distinct rings, two being the σ and one the center one being π alignment. These rings correspond to the transition states for when $\Delta M_l = \pm 1$ and when $\Delta M_l = 0$.

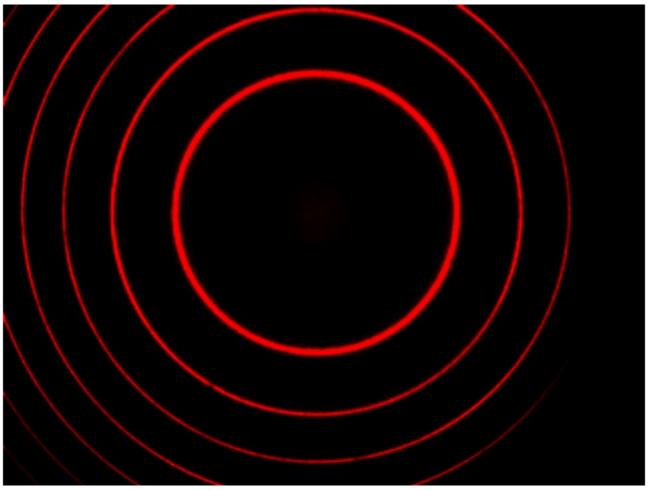


Figure 1C: Transverse σ polarized: This photo shows the transverse alignment but when polarized, showing only the π ring. When an increasing magnetic field is applied, the ring do not change, since $\Delta M_l = 0$. When the π ring is polarized, only the σ show, which is how it was polarized for the graph below.

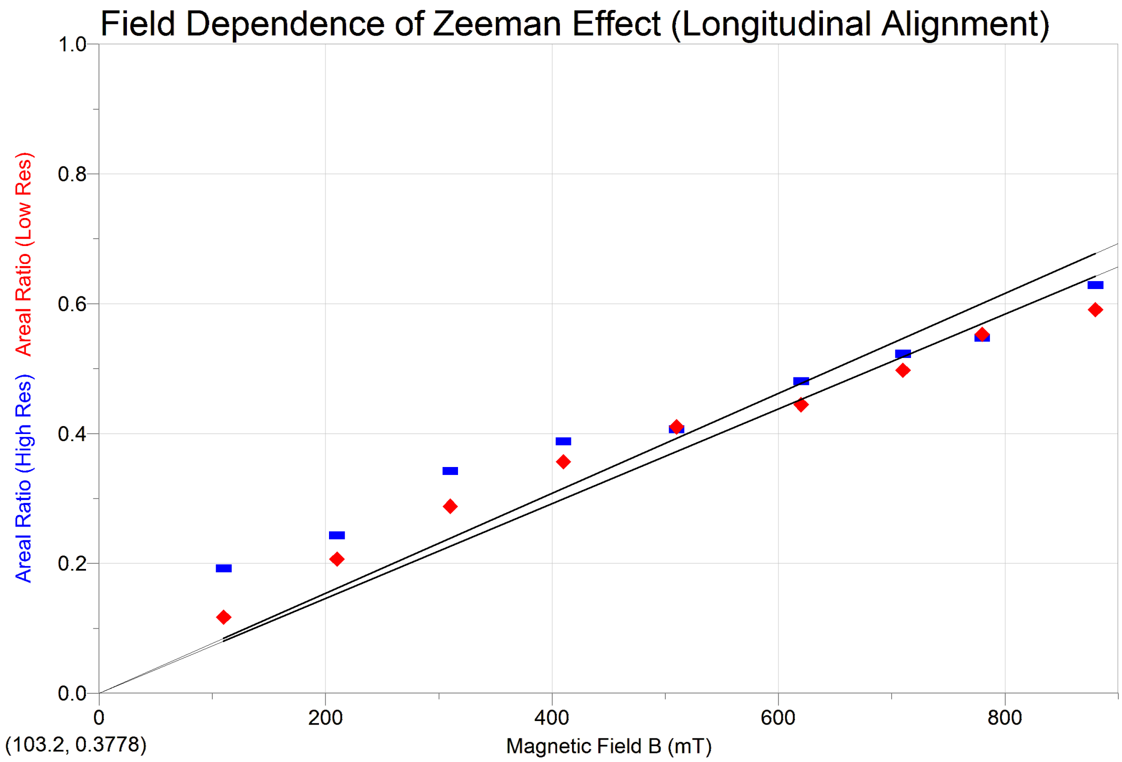


Figure 2: Field Dependence of Zeeman Effect, Longitudinal Alignment: This plot corresponds to the low and high resolution configuration of the Zeeman Effect when aligned longitudinally. Some error is shown because the relationship should have a 0 intercept. This is because since no magnetic field is applied, the three separate lines measured are aligned. A linear regression is used to establish a relationship between the areal ratios and the applied magnetic field. The slope of the low-resolution was measured to be $7.298 * 10^{-4} \pm 2.663 * 10^{-5}$ 1/mT. The slope of the high-resolution image was measured to be $7.697 * 10^{-4} \pm 4.202 * 10^{-5}$ 1/mT.

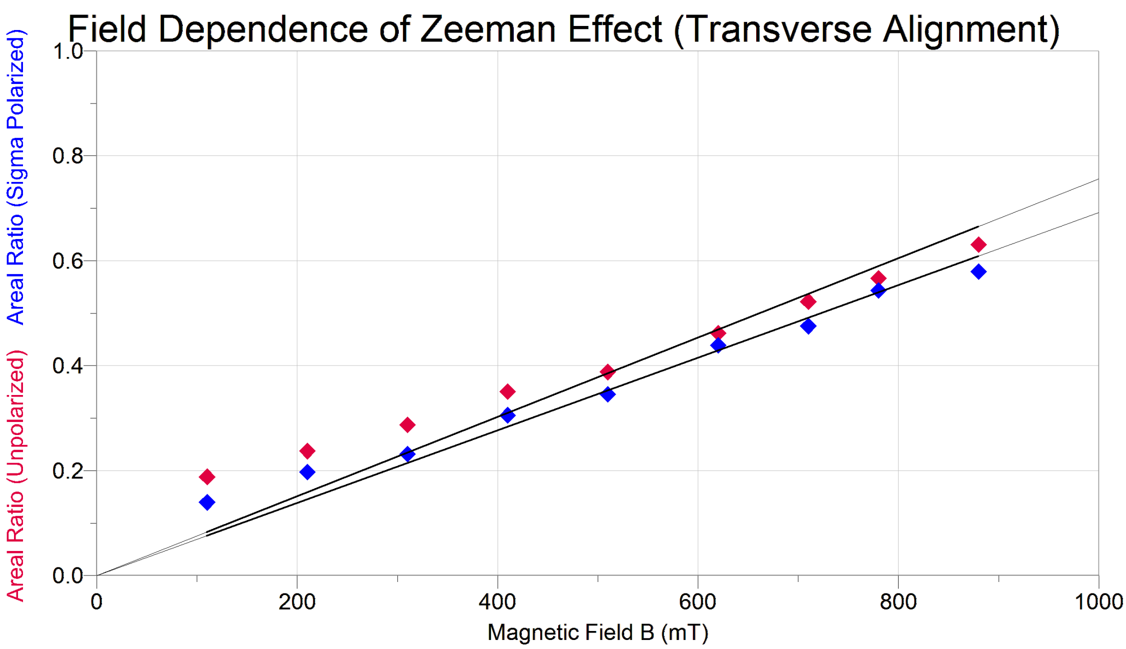


Figure 3: Field Dependence of Zeeman Effect, Transverse Alignment: This graph demonstrate the relationship between the transversal alignment of the magnetic atom with respect to the magnetic field, and the areal ratio. The red points represent the areal ratio with no polarization, while the blue points represent it with a polarization. The slopes will be shown in the table below.

Data Set	Slope
Longitudinal (Low-Res)	$7.298 * 10^{-4} \pm 2.663 * 10^{-5} \frac{1}{mT}$
Longitudinal (High-Res)	$7.697 * 10^{-4} \pm 4.202 * 10^{-5} \frac{1}{mT}$
Transverse (Non-Polarized)	$7.559 * 10^{-4} \pm 3.217 * 10^{-5} \frac{1}{mT}$
Transverse (σ Polarized)	$6.6919 * 10^{-4} \pm 1.965 * 10^{-5} \frac{1}{mT}$
Average	$7.3115 * 10^{-4} \pm 1.56 * 10^{-5} \frac{1}{mT}$

Averaging slopes for each linear regression, the Bohr Magneton(μ_B) can be calculated using equation (2), by rearranging the equation, with $\frac{\delta}{B\Delta}$ being the slope, giving: $\mu_B = 1.66 * 10^{-23} \pm 3.549 * 10^{-25}$ J/T. The charge-to-mass ratio can also be calculated by rearranging equation (1) as follows: $\frac{e}{m_e} = \frac{2\mu_B}{\hbar} = 3.132*10^{11} \pm 6.696*10^{9}$ C/kg.

6 Discussion

By analyzing the Fabry-Perot ring patterns, the Bohr Magneton was measured to have an experimental value of $1.66*10^{-23} \pm 3.549*10^{-25}$ J/T, which is slightly deviated from the theoretical value of $9.273*10^{-24}$ J/T. Using this value, the charge-to-mass-ratio was calculated to be $3.132 * 10^{11} \pm 6.696 * 10^{9}$ C/kg, which has a theoretical value of $-1.7588 * 10^{11}$ C/kg. The analysis, which includes measuring the distance between rings, was done using LoggerPro's photo analysis, which provides the uncertainty measured in the Bohr Magneton value. The magnetic field was not directly measured, but instead the current was, also leading to uncertainty. Overall, the Zeeman Effect was observed and the analysis resulted in proper measurement of the electron's charge-to-mass ratio, validating that electron's have energy levels, which can be effected by an external magnetic field.

7 Conclusion

This report demonstrates the Zeeman Effect through experimental analysis of the Fabry-Perot ring patterns emitted by a cadmium lamp subjected to varying magnetic field strengths. It was found that as the magnetic field increased, the different spectral lines, relating to the spin and angular moment of the electrons, become more distinct. The Bohr Magneton was found to be $1.66 * 10^{-23} \pm 3.549 * 10^{-25}$ J/T, while the charge-to-mass-ratio was calculated to be $3.132 * 10^{11} \pm 6.696 * 10^{9}$ C/kg, showing slight deviations from the theoretical expectations, due to measurement uncertainties. These observations confirmed the quantization of atoms, specifically orbital angular momentum and spin as well the distinct energy levels of an electron orbiting around its nucleus, highlighting the significance of the Zeeman Effect in modern day science.

8 Reference

[1] Adrian C. Melissinos. Experiments in modern physics. *New York, Academic Press,* ,1966