Zeeman Effect

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Abstract

Observation of the Zeeman Effect, i.e. the splitting of energy levels for certain electron transitions in the presence of a magnetic field, from a tube of mercury gas. Using a Fabry-Perot etalon, we projected an image of our split energy levels onto a CCD camera, where we measured the distances between the split interference rings. Using this, we calculated the value of the Bohr magneton - with both the parallel and perpendicularly polarized light - to be respectively 8.37×10^{-24} J T$^{-1} \pm 0.02$ and 8.68×10^{-24} J T$^{-1} \pm$ 0.02.

Introduction

Quantum mechanics seems like a field still waiting for its application, an area where physicists play with theory and hypothesis. However, the role of quantum mechanics in our everyday life is quintessential, ranging from technologies such as the GPS to medical MRI devices, and further developments such as quantum computers making headlines. These technologies find their origins in the early

20th century, with Nobel prizes being awarded to physicists such as Lorentz and Zeeman for their work in discovering the Zeeman effect [1]. This seemingly obscure work is no doubt critical for its modern applications, and our lab's goal is to measure the Zeeman effect and confirm the theories behind it.

In this report, we will first describe the Zeeman effect, which will lead us into the optical apparatus setup used to photograph the Zeeman effect, as well as the software used to measure it. We then proceed with the calibration of the system to verify its accuracy. In a second part, we present the data we recorded with a magnetic field applied to our excited gas to measure the spectral line splitting. Finally, we calculate the value of an important constant in the theory behind the Zeeman effect: the Bohr magneton.

1 Experiment setup and procedures

1.1 The Zeeman Effect

When a pair excited electrons transition from one energy level to the next, the wavelength emitted is a function of the quantum numbers of the electron pair (total spin, total orbital angular momentum, total angular momentum). In this experiment, we are interested in the specific transition where:

- The total spin quantum number (S) of the pair is unchanged.
- The orbital angular momentum quantum number (L) of the pair increases by one unit.
- The total angular momentum quantum number (J) of the pair increases by one unit.

If the total angular momentum quantum number of the two electrons in a state is $J = 1$, then there are three sub-levels, $m_J = -1, 0, 1$ corresponding to different z-components of angular momentum.

Spectral lines from electrons experiencing a transition with the above quantum numbers have an interesting property: the three sub-levels will have slightly different energies in a magnetic field. The shift in the energy levels of an atomic state is proportional to the z-component angular momentum quantum number, m_J. Furthermore, the light emitted from the excited species is polarised:

- Light emitted from the three possible $\Delta m_J = 0$ transitions will be polarized parallel to the magnetic field direction; these are called π (for parallel) transitions.
- Light emitted from the three possible $\Delta m_J = -1$ or three possible $\Delta m_J = +1$ transitions will be polarized perpendicular to the magnetic field direction; these are called σ transitions.

The shift in the energy levels of an atomic state is proportional to the z-component angular momentum quantum number, m_j. The shift (in cgs units) is given by $\delta E = g\mu_0 B m_J$ [3], which simplifies to this equation in our case:

$$\Delta E = \frac{3}{2}\mu_B \cdot B \tag{1}$$

- $g = \frac{3}{2}$ is the Lande g-factor calculated by $g = \frac{J(J+1)+S(S+1)-L(L+1)}{2J(J+1)}$
- μ_0 is the Bohr magneton
- B is the magnetic field in Gauss

In this experiment, we are concerned with the transition of mercury electrons that satisfy our above conditions. We found that mercury has a $7s$ electron decaying into a $6p$ state whose transition has the above properties.

1.2 Optical Setup

To view the spectral lines, we used an optical system 1 4 to view an interference pattern from a Fabry-Perot etalon. The etalon serves to magnify the shifts made through the magnetic field to the wavelengths emitted at around $\lambda = 546.07\,\text{nm}$. The etalon creates interference rings according to the following formula from our manual:

$$\theta_p^2 = \frac{\lambda_0}{t} p \tag{2}$$

- θ_p^2 the angular distance corresponding to ring p
- λ_0 the incident light wavelength
- t the distance separating the etalon's two plates

These wavelengths are isolated through the interference filter.

We excite a mercury lamp with a 40 V voltage source, which is clamped to a strong electromagnet which is connected to a power supply 3. The electromagnet produces a magnetic field, which is approximately uniform across the Cd lamp, and whose force is measured through a hall probe placed perpendicular and touching the lamp.

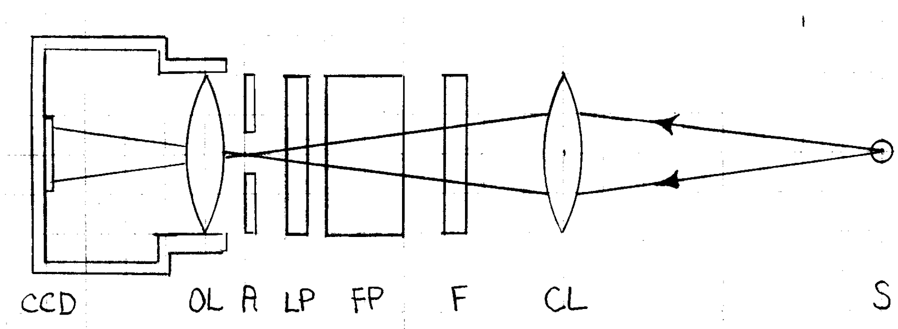

Figure 1: Schematic of optical layout. S=Source, CL=Condenser Lens, F=Interference Filter, FP=Fabry-Perot Interferometer, LP=Linear Polarizer, A=Aperture, OL=Camera Objective Lens, CCD=Charge Coupled Device

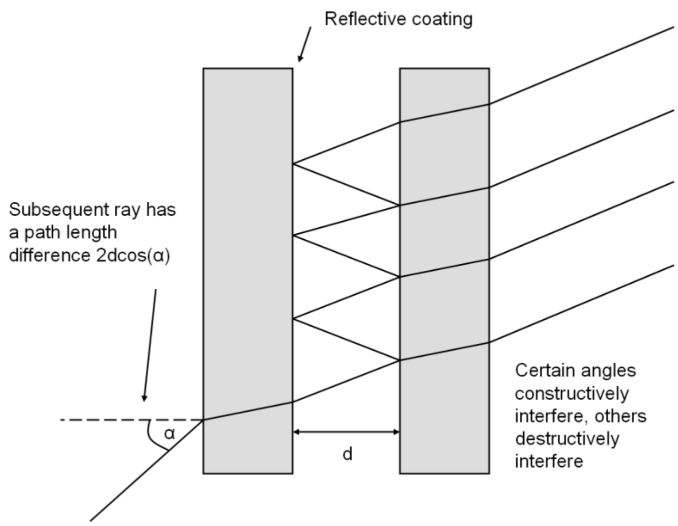

Figure 2: : The Fabry-Perot etalon is responsible for producing the ring-like interference pattern from the Hg spectrum

2 Data discussion and analysis

The Zeeman effect can be used to calculate the value of μ_B, the Bohr Magneton. This constant linearly relates the change in energy levels to the strength of the magnetic field.

2.1 Calibration

We first proceed with calibrating our system by verifying eq. (2). For this, a CCD was used, which measured the positions of the rings from the interference pattern as a 1-D series of intensity peaks. Since the CCD image size is in pixels, rather than the angular distance that we want, we convert knowing that $\alpha = \arctan(\frac{x}{d})$ with α our angle, $x = 9\,\mu\text{m}$ is our pixel length and $d = 150\,\text{mm}$ is our focal length.

We estimated ourselves to have an error of ± 2 pixels when looking at peak pixel intensities on the image, i.e. our angular distances have an error of

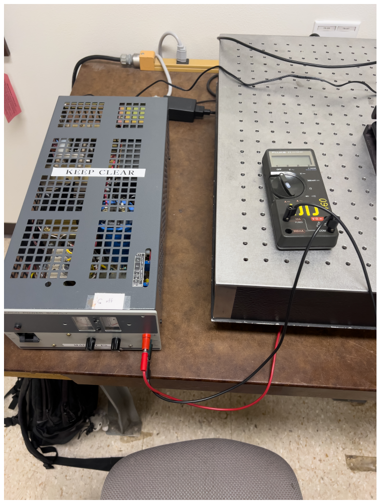

Figure 3: Magnet Power Supply

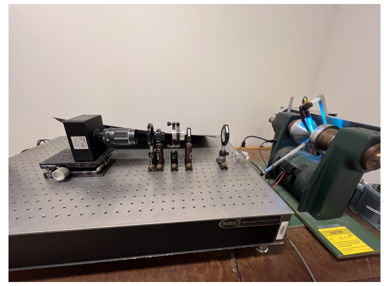

Figure 4: Optical Setup

$\pm 0.000\,12\,\mathrm{rad}$

Plotting these intensities in figure 5 and applying a linear fit gives us a slope of $8.88 \times 10^{-5} \pm 0.2$, which is a slight overestimate (105%) of the theoretical $\frac{\lambda}{t} = 8.40 \times 10^{-5}$.

With this confirming the accuracy of our system, we proceed to measuring the value of the Bohr magneton.

2.2 π Lines

Setting our polarizer to only observe perpendicularly polarized light, we proceed to calculate the Bohr magneton for 5 different magnetic field values ranging from $0.6724\,\mathrm{T} \pm 0.0001$ to $1.0765\,\mathrm{T} \pm 0.0001$. The interference pattern for π lines in fig. 6 can be used to find the angular distances to the different rings, which are related to the geometric properties of the Fabry-Perot etalon and the energy of the transition by the following equation found in Welch's study [2]:

$$\Delta E \approx \frac{-\alpha \Delta\alpha}{n^2} E \tag{3}$$

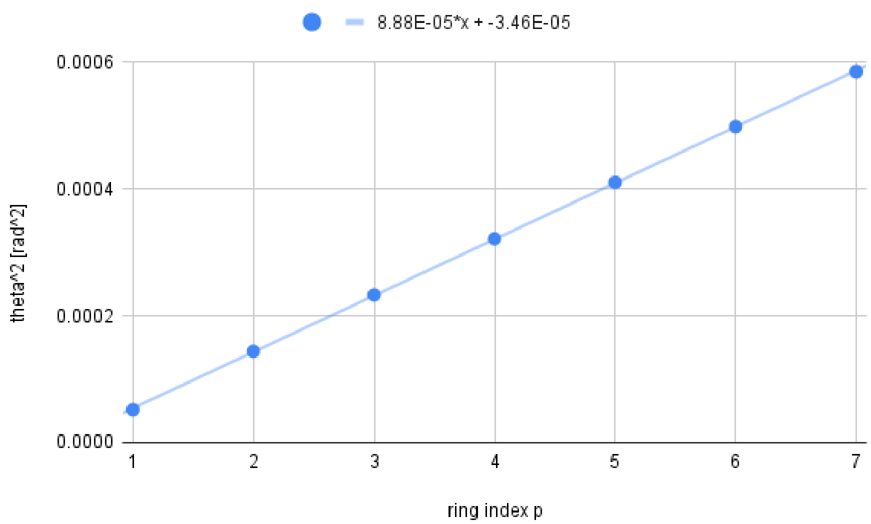

Figure 5: A plot of θ_p^2 versus p, for $\lambda = 546.074\,\text{nm}$, $t = 6.499\,\text{mm}$

Where ΔE is the energy of the transition, α is the distance to the π ring with $B = 0$ from the center, $\Delta\alpha$ is the distance to the σ lines, E is the energy of the original transition and n is the refractive index of the lens. This is illustrated in fig. 7.

We calculate this transition energy for the 3 sets of rings nearest the center, measuring their shift on the left and right sides of the ring. We then used 1 to find the Bohr magneton to be $8.37 \times 10^{-24}\,\text{J}\,\text{T}^{-1} \pm 0.02$ which is a slight underestimate (9.71%) to the accepted literature value of $9.27 \times 10^{-24}\,\text{J}\,\text{T}^{-1}$.

2.3 σ Lines

We repeat the experiment, this time setting our polarizer to only observe parallelly polarized light. We proceed to calculate the Bohr magneton for 5 different magnetic field values ranging from $0.0376\,\text{T} \pm 0.0001$ to $0.3809\,\text{T} \pm 0.0001$. We used a weaker magnetic field since the rings appeared for smaller B values.

The interference pattern for σ lines can also be used to find the angular

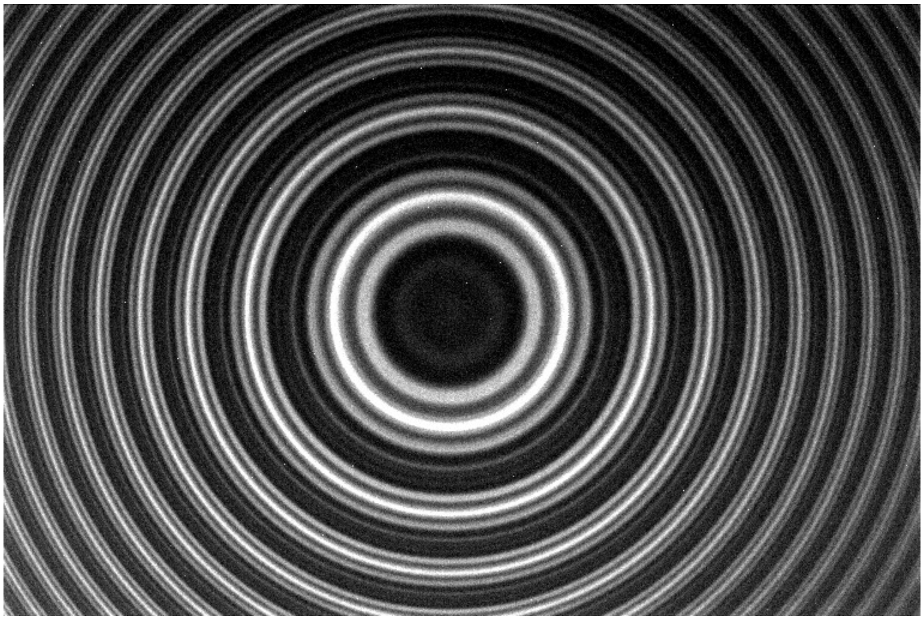

Figure 6: Zeeman Effect with π lines

distances to the different rings, but we use a more appropriate equation found in our manual for these σ line interference patterns [3]:

$$(\theta_p^{(a)})^2 - (\theta_p^{(b)})^2 = 2\frac{\Delta E}{\bar{E}} \tag{4}$$

With $\bar{E} = hc/\lambda$

We calculate this angular separation for the 3 sets of rings nearest the center, measuring their shift on the left and right sides of the ring. We then used 1 to find the Bohr magneton to be $8.68 \times 10^{-24}\,\mathrm{J\,T^{-1}} \pm 0.02$ which is a slight underestimate (6.36%) to the accepted literature value of $9.27 \times 10^{-24}\,\mathrm{J\,T^{-1}}$.

Conclusion

While our data falls within close proximity of the accepted value, it is worthwhile to comment on factors which could have influenced the underestimation we made

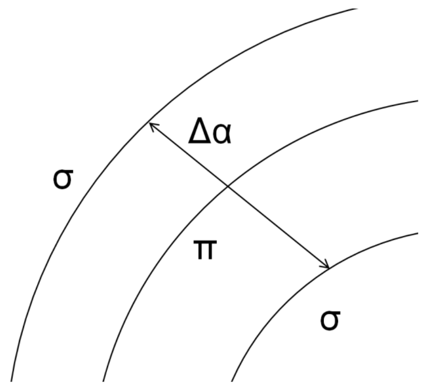

Figure 7: Calculation of $\Delta\alpha$ from the position of the rings. The π line is at position α from the center, and the σ lines are separated by an angular distance $\Delta\alpha$

both for π and σ lines:

- The angular distance relation makes certain assumptions about the geometry of the setup - namely, the light sensor in the CCD is exactly perpendicular to the direction of the incident light, and the sensor inside the CCD is at exactly the focal point of the lens opposite. In reality, neither of these things were precisely true, which resulted in the angles towards one end of the light sensor being a slight overestimate, and angles on the other side being a slight underestimate. This effect could actually be observed on the intensity spectrum, as one side of the CCD was measuring higher intensities than the other.

- A small systematic error was made while measuring the intensity of our electromagnetic field, as we did not place the hall probe directly in the place of our lamp, where the magnetic field is approximately uniform. Measuring it instead touching the lamp introduced a systematic underestimation of the strength of the magnetic field.

References

[1] Pieter Zeeman. The effect of magnetisation on the nature of light emitted by a substance. Nature, 55(1424):347–347, 1897.

[2] Robert Welch. Calculation of the Bohr Magneton Using the Zeeman Effect. `https://robwel.ch/wp-content/uploads/2016/12/Zeeman.pdf`

[3] U.C. Santa Cruz Advanced Physics Laboratory Manual