

Observing the Zeeman Effect in Mercury

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The Zeeman effect describes the splitting of atomic energy levels in the presence of an external magnetic field due to the interaction between the field and the magnetic dipole moments associated with electron orbital and spin angular momentum. In this experiment, the anomalous Zeeman effect was investigated for several emission lines of mercury using a Fabry Perot etalon, polarization optics, and CCD imaging. Emission lines at 404.66 nm (violet), 546.07 nm (green), and the yellow doublet near 578 nm were analyzed by comparing interference fringe patterns with and without an applied magnetic field. Measured wavelength shifts were converted into energy shifts, allowing the determination of Landé g factors for each transition. The g factors were found to be $g = 1.48 \pm 0.16$ for the violet line, $g = 1.38 \pm 0.14$ for the green line, and $g = 1.32 \pm 0.21$ for the yellow doublet. These values confirm anomalous Zeeman behavior and are generally consistent with theoretical expectations based on angular momentum coupling, with larger discrepancies attributed to experimental limitations for the yellow doublet. Using the measured energy shifts and applied magnetic field strength, the electron charge to mass ratio was determined to be $\frac{e}{m_e} = 1.758 \times 10^{11}$ C/kg, in agreement with the theoretical value. This experiment successfully verified the Zeeman effect in mercury emission lines and provided quantitative measurements of Landé g factors, demonstrating the role of angular momentum coupling and polarization in atomic spectroscopy.

I. INTRODUCTION

The Zeeman effect describes the splitting of atomic energy levels when an external magnetic field is applied. This splitting arises from the interaction between the magnetic field and the magnetic dipole moment associated with the orbital and spin angular momenta of electrons. The introduction of orbital and spin angular momentum in electrons allows for more possible energy states. The Zeeman effect was first observed by Pieter Zeeman in 1896 building off the work and hypotheses made by Michael Faraday three decades prior. The observation of the Zeeman effect has led to the basis of modern technologies and research. Processes like MRI's are possible due to the Zeeman effect, while the effect has also been useful for studying magnetic fields in astrophysics. Studying energy shifts in incoming light has allowed astrophysicists to observe the magnetic field strength of stellar objects.

$$\Delta E = \mu_B g m_J B \quad (1)$$

The possible shifts in energy formed by the Zeeman effect are quantified by equation (1) where B is the magnitude of magnetic field applied, μ_0 is the Bohr magneton, m_J is the magnetic sublevel, and g is the Landé g factor specific to the energy level. Δm_J was thought to only be ± 1 or 0. This

simple three line pattern was termed the “normal” Zeeman effect, though real atoms more commonly exhibit “anomalous” behavior featuring more than three components. For a “normal” Zeeman effect, the g factor was typically observed to be close to 1, but in anomalous behavior different results were found.

In this experiment we observed the Zeeman effect for anomalous behavior in order to determine a g factor. We also used the measured splittings and the known structure of the Zeeman effect to calculate the electron charge to mass ratio, a quantity that is well known and central to the development of modern atomic physics. Different Zeeman components produce characteristic polarization states, π components are linearly polarized and σ components are circularly polarized. The experiment uses a quarter-wave plate and linear polarizer to distinguish these transitions. Observations are made both parallel and perpendicular to the magnetic field to isolate the polarization dependence and confirm theoretical selection rules. Overall, this laboratory provides a comprehensive exploration of atomic structure, angular momentum coupling, polarization, and interferometric measurement techniques. By combining high resolution spectroscopy with quantitative image analysis, the Zeeman effect becomes a powerful tool for measuring fundamental constants and

testing the predictions of quantum mechanics.

II. APPARATUS AND METHODS

The light source being used in this experiment is a mercury lamp. Mercury light consists of 4 different wavelengths: green (546.07 nm), violet (404.66 nm), and the yellow doublet (576.96 nm and 579.01 nm). The mercury light source is located in an electromagnet that is practically a solenoid with n turns per unit distance. Using the equation for a magnetic field in a solenoid, equation (2), and plugging in 2.4 amps for our current we can determine the magnitude of the magnetic field applied to our mercury lamp.

$$B = \mu_0 n I \quad (2)$$

A lens placed between the lamp and a slit focuses the emitted light into the telescope, ensuring sufficient intensity and spatial coherence for interferometric observation. On the far side of the electromagnet, a mirror redirected light emitted parallel to the magnetic field toward the optical system, allowing selection between polarizations parallel and perpendicular to the field direction. Adding a quarter wave plate and a linear polarizer after the lens allows us to examine the π and σ components of the Zeeman effect. By rotating the linear polarizer, specific polarization states were selectively transmitted, allowing individual Zeeman transitions to be isolated from the overlapping fringe patterns. The wavelengths are individually observed through the use of an adjustable prism. The prism allows for specific wavelengths to be focused onto our CCD camera. The camera is connected to a computer which allows us to take pictures of the incoming light.

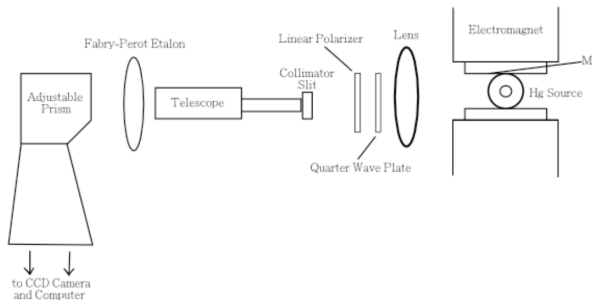


FIG. 1: Diagram of the Setup of our Isolated Tube filled with Gas Medium.

The most significant tool in our setup is the Fabry Perot Etalon located in between the telescope and the prism. The etalon consisted of two parallel, partially reflective plates separated by a fixed distance of $d = 5.047$ mm. Incoming light interferes with its reflections causing constructive interference when equation (3) is true. Our CCD camera observes this interference pattern which also allows us to detect shifts in wavelengths. Images taken showed the interference pattern which through some python code we can convert to gray scale and analyze distances between peaks. Comparing images with and without the B-field allowed us to determine the wavelength shift in equation (4) with a correction R being made due to the conversion between pixels in the CCD to nanometers.

$$2d \cos \theta = m \lambda \quad (3)$$

$$\Delta \lambda = R \frac{\lambda^2}{2d} \quad (4)$$

$$\Delta E = \frac{hc}{\lambda^2} \Delta \lambda \quad (5)$$

$$g = \frac{\Delta E}{\mu_B B} \quad (6)$$

Reworking equation (1), we can determine the g factor for a transition given the approximate energy shift given by equation (5). For theoretical approximations of g we will use equation (7) which depends on the transition level J as well as spin state S and angular momentum state L . To determine the electron charge to mass ratio we relate the experimentally determined energy shifts to the applied magnetic field in equation (8). This allows us to experimentally determine the electron charge to mass ratio from our measured data. Comparing this value to the accepted value provides a consistency check on both our measurements and the assumptions made in our analysis.

$$g_j = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \quad (7)$$

$$\frac{e}{m_e} = \frac{4\pi c}{Bg} \frac{\Delta \lambda}{\lambda^2} \quad (8)$$

III. RESULTS AND DISCUSSION

The Zeeman splitting of the mercury emission lines was successfully observed using a Fabry Perot interferometer and CCD imaging. Clear splitting of the interference fringes was detected when a magnetic field was applied, and the magnitude of the splitting increased linearly with the applied field strength.

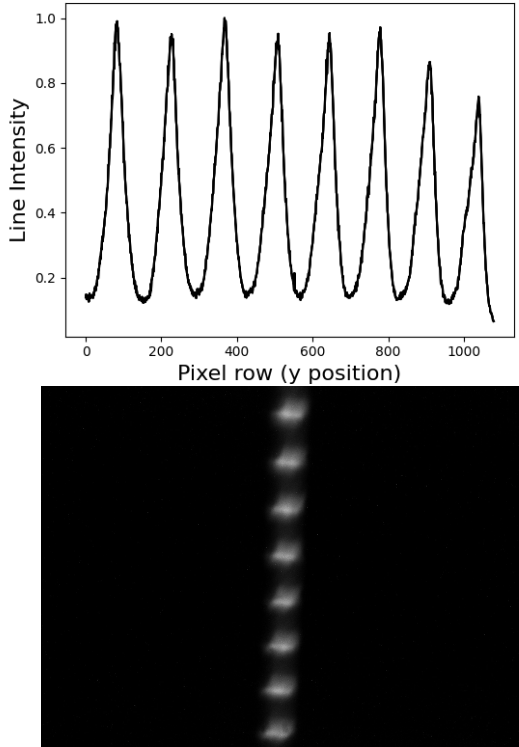


FIG. 2: Intensity Plot (Top) Taken from Image of Mercury Violet Right Line without Magnetic Field (Bottom).

The intensity plots above are taken from the corresponding image of the mercury violet line. The top plots are of the mercury violet without a magnetic field while the bottom ones are when the magnetic field was added. As expected, when a magnetic field was applied we observed splitting in the fringes for mercury violet. Using python code to measure the fringe displacements, wavelength shifts were calculated and converted to energy shifts for each transition. The g factor calculated for mercury violet was $g = 1.48 \pm 0.16$. The classical Zeeman effect produces a g factor of 1, therefore our result presents further evidence that the Zeeman effect for mercury violet is anomalous. For the 3P_0 to 3P_1 transition, equation (7) gives

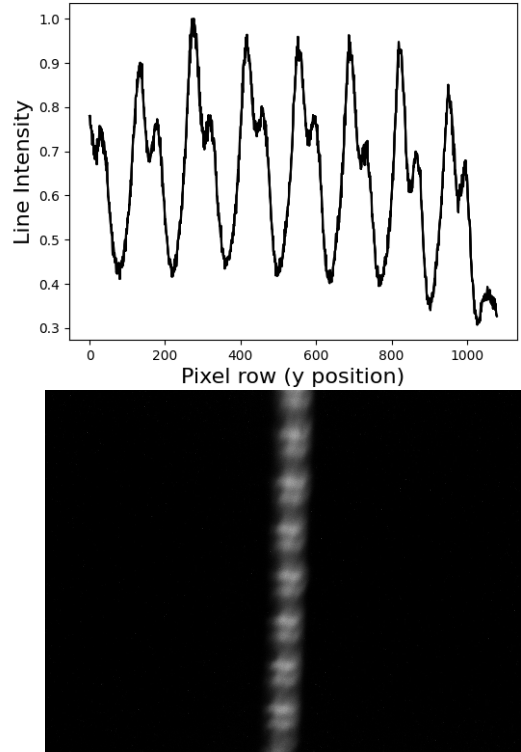


FIG. 3: Intensity Plot (Top) Taken from Image of Mercury Violet Right Line with Magnetic Field (Bottom).

us a theoretical g factor of 1.5. This is well within the range of our calculated g factor and is likely the transition that occurs for mercury violet.

This process was repeated for mercury green and the yellow doublet. In the figures below are the intensity plots of mercury with and without a magnetic field present along with the corresponding images the plots were taken from. Our calculated g factor was $g = 1.38 \pm 0.14$. Once again this provides further evidence that the Zeeman effect's behavior is anomalous for mercury green. The theoretical transition for mercury green is the 3P_2 to 3P_1 transition, or the upper 3P_1 transition. This should also give us a theoretical value of $g = 1.5$. Although our value was further from the expected value then in the case of the mercury violet, it was still within the range of our calculated error. The uncertainties for our g factors differ slightly for each line. Differences in the intensities of the light detected by our CCD can cause anything from saturation to noise and irregular pixels. In our green intensity plot there is a slight amount of saturation occurring for some of the peaks. This causes the exact position of the peak to be slightly obscured

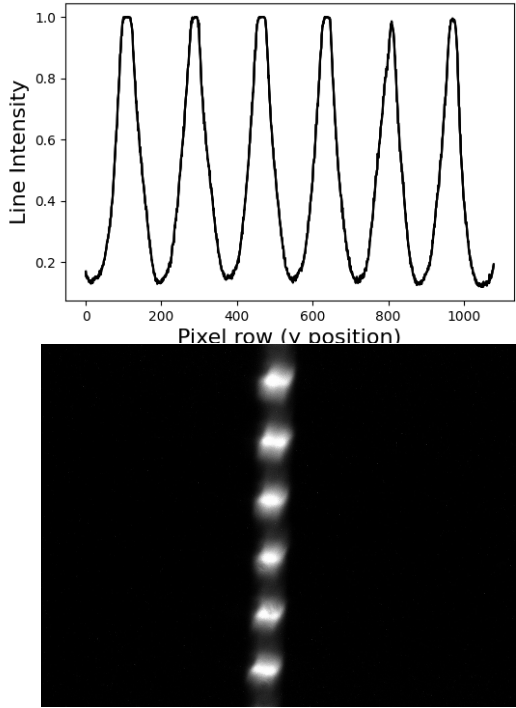


FIG. 4: Intensity Plot (Top) Taken from Image of Mercury Green Right Line without Magnetic Field (Bottom).

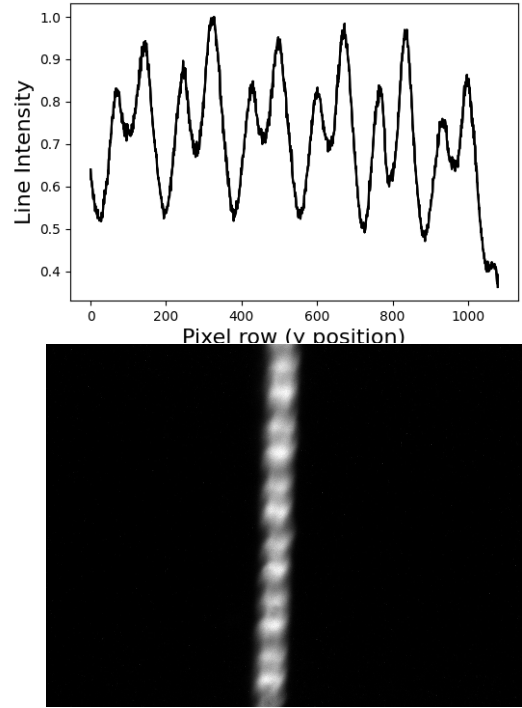


FIG. 5: Intensity Plot (Top) Taken from Image of Mercury Green Right Line with Magnetic Field (Bottom).

which can affect our measurements for the shift in these peaks. Mercury violet does not appear to saturate, but another factor that affects our measurements for wavelength shift in all lines is the resolution of the pixels. Each pixel represents roughly a couple of nanometers in length which does produce small uncertainties in our wavelength shift measurements. To negate noise as much as possible, our intensity plots took an average of several columns of the image given. This allowed us to plot a much smoother intensity plot while also quantifying uncertainties for peak positions.

For our mercury yellow doublet measurements, we determined the wavelength shift for both lines, due to both of their lines being so close together and of the same wavelength we calculated the practically the same g factor for both lines. The g factor determined for the mercury yellow line was $g = 1.32 \pm 0.21$. The reason for the much higher uncertainty is due to a much noisier image than the violet and green lines. The noise in an image was a factor of how naturally bright the light appeared in our CCD. This is due to dimmer light requiring the gain of the CCD to be increased so that our code could plot the intensities properly. A

downside to increasing the gain is that it also will amplify the noise and any irregular pixels. Violet light appeared the brightest and therefore the gain was not set as high giving us less noise. Green was similar if not slightly brighter causing saturation. Yellow was the dimmest which required us to increase the gain the most. As a consequence, there were more hot pixels present giving us false peaks. Our averages mitigated this but it slightly affected our data as shown through our uncertainty calculated. For mercury yellow under the Zeeman effect, the transition that occurs was likely the 1P_1 to 1S_0 transition. This simpler transition gives us a g factor of $g = 1$. Our experimental value for g is higher and out of range compared to the theoretical value. While our methods for calculated error focus mostly on errors within the CCD camera, there were several other factors that were included in our error analysis.

The difference between the g factors in each line can be attributed to the distinct electronic configurations involved in each transition. The violet line originates from a transition involving a $J = 0$ upper state, which restricts the number of allowed Zeeman components and alters the rela-

tive weighting of the magnetic sublevels. In contrast, the green line involves higher total angular momentum states, leading to a greater number of Zeeman split components and more complex overlap in the observed interference patterns. This increased complexity likely contributed to a smaller effective measured g factor for the green line. The Zeeman-split interference fringes consisted of overlapping Gaussian profiles rather than distinct, well-separated peaks, making precise identification of fringe centers difficult. This effect was particularly pronounced for the green line, which exhibited more overlapping transitions, increasing systematic uncertainty and likely contributing to the lower measured g factor. Additional sources of uncertainty include magnetic field non-uniformity within the electromagnet. The electromagnet was simplified to be a solenoid with N amount of turns. While mostly accurate it does not describe the exact configuration of our electromagnet which could give us different values for B .

To determine the electron charge to mass ratio we used our calculated energy shifts and g factors giving us the value of 1.758×10^{11} C/kg. This ended up being the value calculated for each of the spectral lines. The expected value is 1.760×10^{11} C/kg which agrees with our calculated value with the slight difference likely coming from a rounding error more so than an experimental error. With this we can further confirm that potential sources of error such as the Fabry Perot calibration and inconsistent Zeeman splittings were not likely sources of error for our experiment.

IV. CONCLUSION

The Zeeman effect was successfully observed for multiple mercury emission lines using a Fabry Perot interferometer and CCD based image analysis. When a magnetic field was applied, clear splitting of the interference fringes was observed for the mercury violet, green, and yellow lines. The magnitude of the splitting increased with the applied magnetic field, which is consistent with the expected behavior of the Zeeman effect in the weak field regime. By measuring the fringe displacements and converting them into wavelength and energy shifts, Landé g factors were determined for each transition.

The calculated g factor for mercury violet was $g = 1.48 \pm 0.16$, which agrees well with the theoretical value of $g = 1.5$. The mercury green line produced a g factor of $g = 1.38 \pm 0.14$, which is slightly lower than the expected value but still within experimental uncertainty. The mercury yellow doublet yielded a g factor of $g = 1.32 \pm 0.21$, which deviates from the theoretical value of $g = 1.0$. This discrepancy is likely due to increased noise in the CCD images, overlapping transitions, and the relatively low intensity of the yellow emission lines, all of which made accurate peak identification more difficult. Using the measured wavelength shifts and g factors, the electron charge to mass ratio was calculated to be 1.758×10^{11} C/kg. This value is very close to the accepted value and suggests that systematic errors in the Fabry Perot calibration and Zeeman splitting were small. Overall, this experiment provided a direct demonstration of the anomalous Zeeman effect and showed how interferometric techniques can be used to probe atomic energy structure and extract fundamental physical quantities.

[1] Department of Applied and Engineering Physics, Cornell University. *S-6 Zeeman Effect*. Confluence, April 18, 2025.

[2] MIT Department of Physics. *The Zeeman Effect and Hyperfine Structure in Mercury*. (MIT, Cambridge, MA, 2013).