Zeeman Effect

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Abstract

A SPEX 1000M spectrometer was used along with a Hamamatsu R928P side-window photomultiplier photon detector in order to observe the optical Zeeman effect on sample tubes of neon and mercury in the presence of a magnetic field generated via a high voltage supply. The data was recorded and analyzed with Spectramax data software on a local PC and a digital spreadsheet program. The Lande g-factors were calculated from data and compared to theoretical values. The results agree with what was expected through theory, though some issues arose with controlling the magnetic field for the neon sample as well as general issues with apparatus resolution.

1 Introduction

In atomic physics the energy levels of an atom are defined by discrete energies and are noted by quantum numbers $n = 1, 2, 3, ...$ We now that these levels (or states) can be degenerate according to multiple bound states which include other quantum numbers, namely those for orbital angular momentum (L), spin angular momentum (S), total angular momentum (J), and the z-component of the total angular momentum, (m_j). The energies of these states can be seen by the emission of a photon when an electron returns to its ground state from an excited state. In the presence of a magnetic field, these otherwise energy-equivalent degenerate states will split their energies according to the m_j quantum number. This spectral splitting is known as the *Zeeman effect*. The shift in energy for an electron with magnetic moment μ is given by,

$$\Delta E = -\mu B \tag{1}$$

1.1 "Normal" Zeeman Effect

When an electron in a singlet state has spin angular momentum $\mathbf{S} = 0$, it's total angular momentum $\mathbf{J}$ is equal to its orbital angular momentum, $\mathbf{L}$. Therefore, with the quantization of $\mathbf{J}$, $m_j = \pm\ell, 0$, we can see that the singlet state splits into a triplet with three evenly-spaced energies [1],

$$\Delta E = -m_j \mu B \tag{2}$$

1.2 "Anomalous" Zeeman Effect

When the electron has spin angular momentum $\mathbf{S} \neq 0$, a different energy splitting is seen. This splitting is now given by,

$$\Delta E = -m_j g_L \mu_B B \tag{3}$$

Where μ_B is the Bohr magneton and g_L is the *Lande g-factor*,

$$g_L = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)} \tag{4}$$

where it can be seen that this "anomalous" Zeeman effect is actually the real energy shift, it just so happens that the "normal" Zeeman effect occurs when $\mathbf{S} = 0$, and therefore $\mathbf{J} = \mathbf{L}$, resulting in $g_L = 1$[1].

The energy of the released photon is given by

$$E_\gamma = g_{\mathit{eff}} \mu_B B \tag{5}$$

$$g_{\mathit{eff}} = g'_L m'_j - g_L m_j \tag{6}$$

Where g_{eff} is the effective Lande g-factor and (g'_l, m'_j) and (g_L, m_j) correspond to the final and initial states respectively.

The transition from one m_j state to another results in a polarization of the emitted spectrum, with a $\Delta m_j = \pm 1$ resulting in a σ-polarization, which is circularly polarized when viewed from a perspective parallel to the magnetic field and linearly polarized perpendicular to the field when viewed at a perpendicular view to the field. The $\Delta m_j = 0$ shift corresponds to π-polarization, which is linearly polarized parallel to the applied magnetic field. The shift in photon energy will shift the spectral lines according to [2],

$$\Delta \lambda = g_{\mathit{eff}} \left(\frac{\mu_B \lambda^2}{hc} \right) B \tag{7}$$

2 Apparatus & Procedure

2.1 Apparatus

The apparatus for this lab consisted of Hg, Ne, and H samples contained in glass discharge tubes and placed between the poles of an iron core electromagnet. The electromagnet was powered by a Varian 6121 30 amp Variac magnet power supply and the discharge tubes were powered by a separate gas discharge power supply. The spectra of the samples were analyzed with a Spex 1000M 1 meter grating spectrometer connected to a fiber optic feed/collimator with rotatable polarizer which was pointed at the sample at the point of greatest magnetic field. This magnetic field was measured with a RFL Industries model 904 Gaussmeter with Hall probe. The data from the spectrometer was recorded and plotted using SynerJY on a Dell 486 computer.

The spectrometer is a Czerny-Turner scanning spectrometer which contains a holographic diffraction grating to split the incoming light by wavelength. The incident light hits a curved collimating mirror which reflects the rays so they are parallel when they strike the diffraction grating. Specific wavelengths are reflected off the grating towards a curved refocusing mirror so they pass through the exit to the detector. The grating is rotated to change the reflected wavelength so that the range of the spectrum is scanned. The spectrometer contains a thermoelectrically cooled linear diode detector array which can simultaneously observe a range of wavelengths in the spectrum for quicker data collection. However there is also a mirror that can instead reflect the light to a Hamamatsu R928P side-window photomultiplier photon detector with high voltage supply and preamplifier-amplifier. This detector can very precisely measure a single wavelength and also more effectively filter out the background.

2.2 Method

The first part of the experimental procedure was to establish a hysteresis curve for the electromagnet. However this step was skipped in favor of simply measuring the current and corresponding magnetic fields during each step of the spectrum measurements.

The first sample was Hg (mercury). Its spectrum was first recorded at the 404.7 nm line with a step size of 0.0001 nm and an integration time of 0.1 seconds and with the magnet off. The spectra for both the σ and π polarizations were recorded though they should be identical without the magnetic field. Next the magnet was turned on and the power supply was set to a current of 10 amperes and the spectra was recorded for both the σ and π polarizations. The same measurements were repeated for the 435.8 and 546.1 nm Hg lines though these were done at a measured magnetic field of 1.5 Tesla.

The mercury was then swapped out for a neon sample. The rheostat was adjusted to attemp to stop the sample from flickering but the best position was just to set the rheostat to the largest resistance. However the sample still flickered for almost all non-negligible magnetic fields and it was not possible to achieve stability at 5 amps. This caused the splittings to not be visible in the recorded data. This is discussed in the analysis section below. The Ne spectrum was measured for the 585.3 nm line without a magnetic field and also with a field at both σ and π polarization. Again it was difficult to get the neon stable for all but the smallest magnetic fields so it was not possible to record the spectra for very different values of field strength.

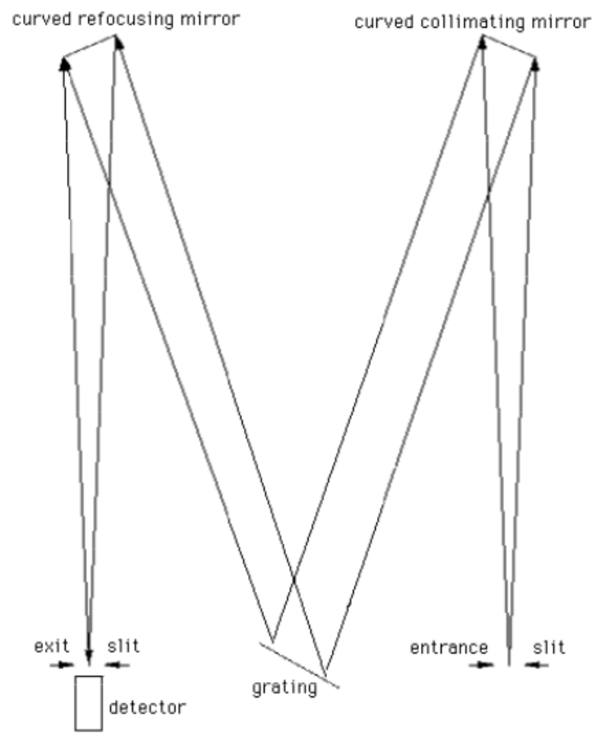

Figure 1: Diagram of the spectrometer mirrors, diffraction grating, and detector layout.

3 Analysis

The g_{eff} where we have multiple measurings of $\Delta\lambda$ and their corresponding magnetic fields is calculated by

$$g_{eff} = \frac{s}{2 \times 4.668 \times 10^{-8} \lambda^2} \tag{8}$$

where s is the slope of the splitting vs. magnetic field. The factor of 2 in the denominator is included as we are including both sides from the center in the $\Delta\lambda$.

3.1 Hg 404.7 nm

The theoretical g_{eff} for the Hg 404.7 nm line (σ) is ± 2. This compares well with our experimental value of $g_{eff} = 2.16(0.12)$ from Fig. 2, but it is higher than theory.

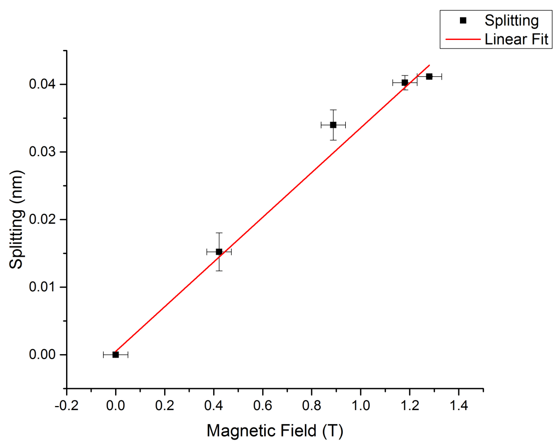

Figure 2: Zeeman splitting vs the magnetic field of the Hg $7s6s^3S_1$ to $6p6s^3P_0$ (404.7 nm) line with σ polarization.

3.2 Hg 435.8 nm

The g_{eff} from a single measurement is calculated by

$$g_{eff} = \frac{\Delta\lambda}{2 \times 4.558 \times 10^{-8} \lambda^2 B} \tag{9}$$

where $\Delta\lambda$ is the splitting and B is the magnetic field. The result from Fig. 3 is $g_{eff} = 1.70(0.023)$. The two possible theoretical values for g_{eff} are $\pm\frac{3}{2}$ and ± 2, so the experimental value is similar to experiment. We only see 2 peaks, presumably because the difference between the two theoretical g_{eff}'s is not significant enough to show up in Fig. 3 given the resolution.

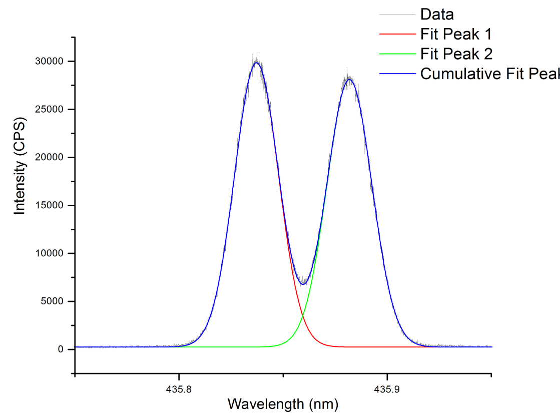

Figure 3: Zeeman splitting of the Hg $7s6s^3S_1$ to $6p6s^3P_1$ (435.8 nm) line, with σ polarization.

The Hg $7s6s^3S_1$ to $6p6s^3P_1$ transition for π polarization as shown in Fig. 4 appears as a single peak. However, by fixing the FWHM, 2 individual peaks appear. The FWHM was taken from the same setup without any magnetic field. This result from Fig. 4 gives $g_{eff} = 0.47(0.023)$. This is between possible values for g_{eff} of the π lines, which is $g_{eff} = 0, \pm\frac{1}{2}$. It was more difficult to extract the g_{eff} because the $g_{eff} = 0$ exists, making it appear that there is no Zeeman splitting upon a first look.

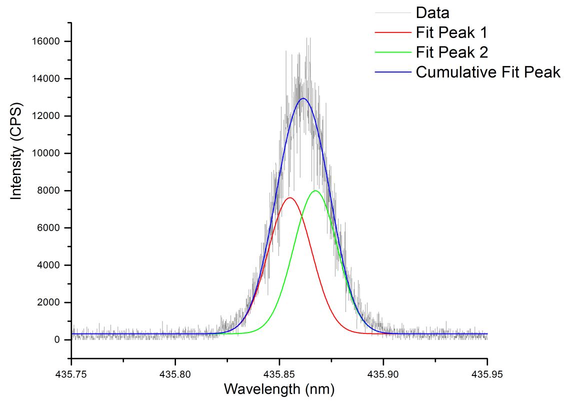

Figure 4: Zeeman splitting of the Hg $7s6s^3S_1$ to $6p6s^3P_1$ (435.8 nm) line, with π polarization. The FWHM was measured from another run with no splitting and fixed in order to extract 2 separate peaks.

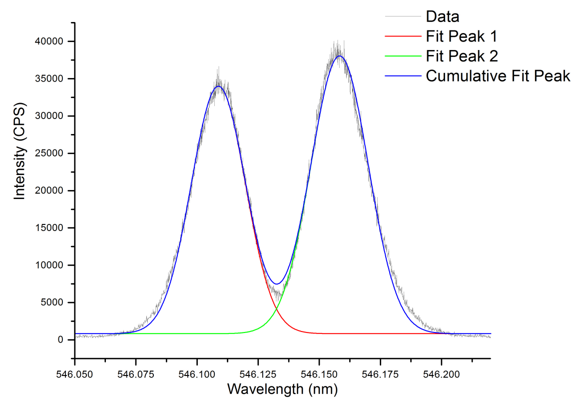

Figure 5: Zeeman splitting of the Hg $7s6s^3S_1$ to $6p6s^3P_2$ (546.1 nm) line, with σ polarization.

3.3 Hg 546.1 nm

The Hg $7s6s^3S_1$ to $6p6s^3P_2$ transition for σ polarization has 2 distinct peaks as shown in Fig. 5. The result ends up being $g_{eff} = 1.20(0.02)$ determined from Fig. 5. However, this is below all theoretical $g_{eff} = \pm\frac{3}{2}, \pm 2, \pm\frac{5}{2}$.

The Hg $7s6s^3S_1$ to $6p6s^3P_2$ transition with π polarization makes it difficult to discern multiple peaks. We can fix the FWHM, but the fit still shows 2 peaks with noticeably different intensities. The g_{eff} from Fig. 6 ends up being $g_{eff} = 0.32(0.01)$. Theoretically $g_{eff} = \frac{1}{2}$, which is around the same area but not close under the apparent error. Because the 2 peaks are so close together, it may cause us to have a lower g_{eff} because it is more difficult to see the difference in the two peaks. Qualitatively upon first inspection of Fig. 6, one would assume that there is a single peak. To get better results, we could try a setup with better resolution or increase the magnetic field.

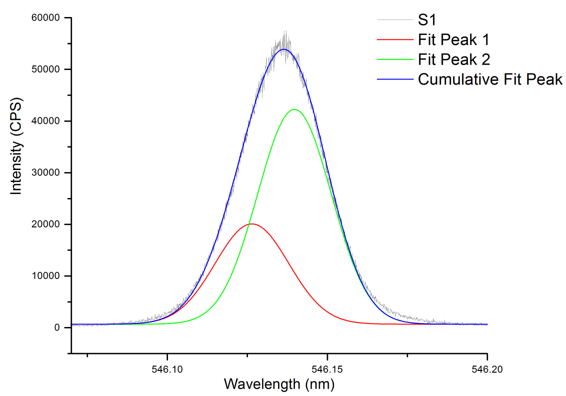

Figure 6: Zeeman splitting of the Hg $7s6s^3S_1$ to $6p6s^3P_2$ (546.1 nm) line, with π polarization. The FWHM was fixed again to extract the 2 different peaks.

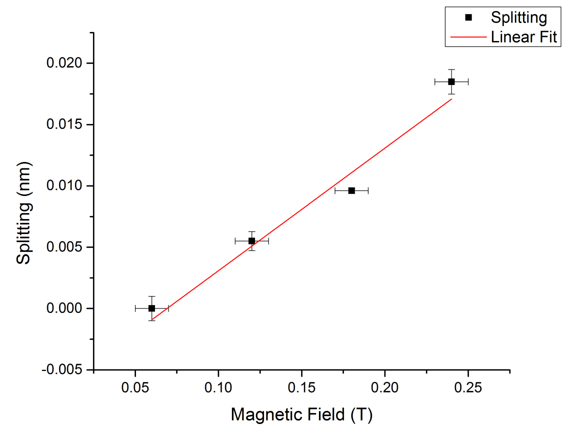

Figure 7: Zeeman splitting vs the magnetic field for the Ne 585.3 nm line with σ polarization.

3.4 Ne 585.3 nm

As in the Hg $7s6s^3S_1$ to $6p6s^3P_0$ transition, we measured the splitting and magnetic field for Ne 585.3 nm at multiple points in order to more accurately determine g_{eff} from multiple measurements. The current to produce the magnetic field can only go up to 2 Amps, and even this caused the Neon tube to flicker. The data at 2 Amps ($B = 0.45$ T) still had noticeable drops even with a long integration time (2 seconds). To adjust for this the maximum from every 5 measurements for just that run was taken in order to rid the data of places with 0 or little CPS, where it should be much higher. This could skew our results towards the peak, and also decreases our accuracy. The result from the linear fit in Fig. 7 gives $g_{eff} = 3.13(0.33)$.

We also took data for the Neon 585.3 nm transition with π polarization, but it was unusable for finding any Zeeman splitting. Even with a low magnetic field of 2 amps, the Neon was not stable and we were unable to fit any peaks with the data.

4 Conclusion

We have observed effective Zeeman splitting and measured g_{eff} for 3 different levels in Hg and one level in Ne, for both σ and π polarizations. In mercury, the Zeeman splitting for σ polarizations is clearly apparent. However, we do not see details in the peaks when there are multiple theoretical values of g_{eff}. With π polarization, it was difficult to calculate any sort of Zeeman splitting. There are a few things that could be done to improve resolution to better show the details in the splitting. The Doppler broadening is

$$\Delta\lambda_{\mathrm{FWHM}} = \lambda_0 \sqrt{\frac{8kT\ln(2)}{mc^2}} \tag{10}$$

where m is the mass of the emitting ion. The temperature could be reduced in the interaction by a cooling chamber. In addition, the detector has a significant broadening, and the resolution could be improved by using a better detector. Any increase in magnetic field will also increase the Zeeman splitting, and also effectively increase our resolution when looking for Zeeman splitting. This would have been especially useful for the Neon lines, if it was kept stable and still produced good data. We also could have completed linear fits and made measurements as the magnetic field went up. The Zeeman splitting based on the slope is much more accurate than a single or even few measurements at a single measurement.

Nevertheless, the Zeeman effect is proof of multiple quantum states that are degenerate under no magnetic field. We have measured several g_{eff} and found some good results.

References

[1] Griffiths, D: Introduction to Quantum Mechanics, 2nd ed., Prentice Hall, 2005

[2] Rutgers University: The Zeeman Effect, physics.rutgers.edu/ugrad/389/Zeeman.pdf Web, 2014

[3] Melissinos, A: Experiments in Modern Physics, 2nd ed., Academic Press, 2003