Zeeman Effect

PHYS3117 Experimental Physics

Student Notes

1 Experimental Aim

To understand the atomic physics involved in the Zeeman effect and to measure the Zeeman splitting of the red cadmium spectral line as a function of applied magnetic field. Hence, to determine the value of the Bohr magneton.

1.1 Learning Outcomes

- Understand the effect of a magnetic field on magntic dipole moments and hence that atom's energy levels.
- Understand the operating principles of a Fabry-Perot interferometer.
- Determine the value of the Bohr magneton.
- Understand the polarisation of the components of the split spectral line.

2 Introduction

In 1896 Pieter Zeeman (Netherlands) discovered that the yellow spectral lines (D lines) emitted by a sodium flame were considerably broadened when the flame was placed in a magnetic field. His observations were explained by H.A. Lorentz and they were jointly awarded the Nobel prize for physics in 1902. What is now known as the Zeeman effect is a consequence of the fact that electrons in atomic shells possess angular momentum (both orbital and spin) and therefore magnetic dipole moments, which can interact with externally imposed magnetic fields, according to the rules of quantum mechanics, giving splittings of the atomic electronic energy levels. If a sufficiently high resolution spectrometer is used to observe the optical transitions between excited electron levels these splittings then manifest themselves as slight shifts in the emitted wavelengths. The present experiment employs a Fabry-Perot étalon to give sufficiently high resolution to measure these slight shifts in the light emitted from a Cd discharge lamp. The experiment furnishes a very nice illustration of quantum mechanics, as applied to atomic electrons.

3 Prework

The theory is presented in Griffiths Section 6.4 [1]. Of relevance to this experiment is the weak-field Zeeman effect, rather than the strong-field case.

When an atom is placed in a uniform external magnetic field **B**, the energy levels - and hence the spectral lines - are shifted. The perturbation is

$$\hat{H}_z = -\boldsymbol{\mu} \cdot \mathbf{B} \tag{1}$$

where $\boldsymbol{\mu}$ is the magnetic dipole moment of the atom. The dipole moment is due to both the orbital angular momentum and spin of the valence electrons. It can be expressed

$$\boldsymbol{\mu} = g\mu_B \mathbf{J} \tag{2}$$

where $\mathbf{J}$ is the total angular momentum, $\mu_B = e\hbar/2m_e$ is the Bohr magneton (SI units), and g is a dimensionless parameter known as the Landé g-factor. g is different for different levels and atoms.

Let's consider the effect of the perturbation $\hat{H}_z$ on an atom with quantum numbers $|nLS\,Jm\rangle$. Here m is the quantum number associated with eigenvalues of the z-component of the total angular momentum:

$$\hat{J}_z \Psi = m\Psi \tag{3}$$

If we take the direction of the applied field as the z-direction, $\mathbf{B} = B\hat{z}$, then the external perturbation causes a shift in the level energy of

$$\begin{aligned}
\Delta E &= \langle\Psi|\hat{H}_z|\Psi\rangle = \langle nLS\,Jm|\hat{H}_z|nLS\,Jm\rangle && (4)\\
&= \langle nLS\,Jm| - g\mu_B \hat{J}_z \mathbf{B}|nLS\,Jm\rangle && (5)\\
&= -g\mu_B \mathbf{B}\langle nLS\,Jm|\hat{J}_z|nLS\,Jm\rangle && (6)\\
&= -g\mu_B \mathbf{B} m && (7)
\end{aligned}$$

The transition of interest to us in this experiment is the 643.8 nm (red) transition from

$$5d^1D_2 \to 5p^1P_1^o$$

in Cd I (neutral cadmium).The notation used here is referred to as the 'Term Symbol', converting this transition into the notation we have been using gives:

$$|n = 5, L = 2, S = 0, J = 2, m\rangle \to |n = 5, L = 1, S = 0, J = 1, m'\rangle$$

The upper level ${}^1D_2$ has magnetic sublevels with $m = -2, -1, 0, 1, 2$.

Question 1: What is the relationship between the orbital quantum number L and the available magnetic sublevels m and hence which values of m' are available to the lower level ${}^1P_1^o$?

Question 2: Draw a graph showing the splitting of energy levels (y-axis) by an applied magnetic field B (x-axis) for the two levels of interest. Remember that both levels have $g = 1$.

Question 3: Using your graph, explain why are there only 3 different red wavelengths emitted when a magnetic field is applied to Cd?

Hint: Look up the quantum mechanical selection rules for allowed electromagnetic transitions (this is an electric dipole transition).

Question 4: Calculate the energy level splitting of the ${}^1D_2$ and ${}^1P_1^o$ levels in a 1 T magnetic field, and hence find the shift in wavelengths of the transition components. Remember that both of these levels in Cd have $g = 1$.

4 Experimental Apparatus

In this experiment, a Cd discharge lamp is placed between the poles of an electromagnet and the resultant spectral line splittings are resolved, by means of a Fabry-Perot étalon and measured, as a function of applied magnetic field, by using a CCD camera and a frame grabber to capture the images of the spectral lines. A schematic diagram of the experimental set-up is given in Figure 1.

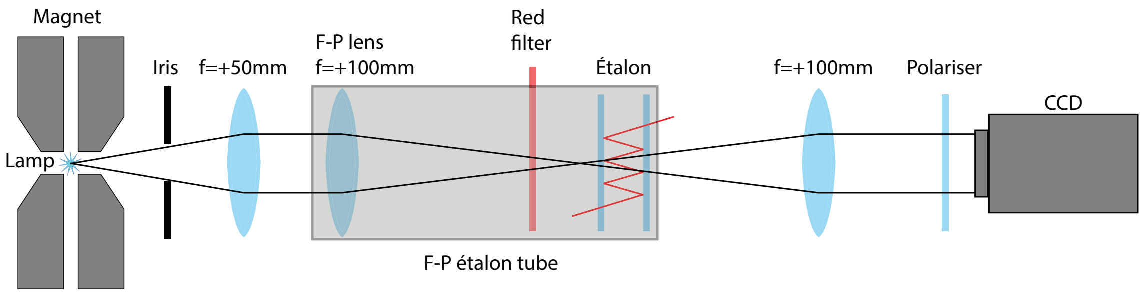

Figure 1: Schematic diagram of Zeeman effect apparatus, this beam path is idealised as it assumes the lamp is a point source.

4.1 Discharge Lamp

The cadmium vapour discharge lamp is driven by a 230V (take care!), 1A power supply and takes about 5 minutes to warm up to full intensity. The wavelengths emitted by the lamp are 467.8 nm, 480.0 nm, 508.6 nm and 643.8 nm so that, apart from the red lines studied in this experiment, the lamp emits very intense blue and green light.

4.2 Magnet

The electromagnet consists of two coils mounted on a U-shaped iron core. There are holes between the pole pieces such that, light emitted in the direction of the magnetic field or perpendicular to it may be observed and the magnet is mounted on a rotating table for this purpose. The coils are connected in parallel to the programmable power supply. The current limit should already be set to 6 A. Adjust the current flow using the large knob on the top right.

4.3 Optical System

All the optical components are mounted on an optical bench which has been levelled relative to the magnet. The set-up is shown in Fig. 1. The F-P étalon tube contains an $f = +100$ mm lens at the input end, the étalon at the other end, and a filter holder in between. For viewing the Cd red line a filter with a lower cutoff wavelength of 595 nm is used. The spacing of the étalon is 3.00 mm and it has a resolution of about 3×10^5 (i.e. will resolve wavelength changes of about 3 parts in a million!); it is a very delicate and expensive piece of optical equipment, so please treat it with respect. Read Ref. [3] pp 309 - 315 for a discussion of the Fabry-Perot étalon - you should then (with a bit of thought) be able to explain the function of each of the optical components on the bench.

4.4 CCD camera

A 1.1" format (4096 H ×3000 V pixels) colour CCD camera is used to photograph the images of the rings produced by the F-P étalon, which are then displayed on the PC. This camera is very expensive, there should be no reason to remove the protective filter, and the cover should be replaced when not in use. The camera heats up when powered, so please ensure that it is unplugged from the computer at the end of the lab session.

5 Warnings!

- The discharge lamp power supply generates dangerous voltages. Take appropriate care!
- The discharge lamp and its housing get HOT when operating!
- The discharge lamp is very bright when fully warmed up. Do not look into it for extended periods without the red filter.
- The magnet OVERLOAD PROTECTOR gets HOT when operating!
- Do not leave > 4A flowing through the magnet coils for extended periods as the magnet coils and leads get too warm.
- The Hall probe is fragile and expensive. Take care.
- The CCD Camera very expensive. Take care.

6 Experimental Instructions

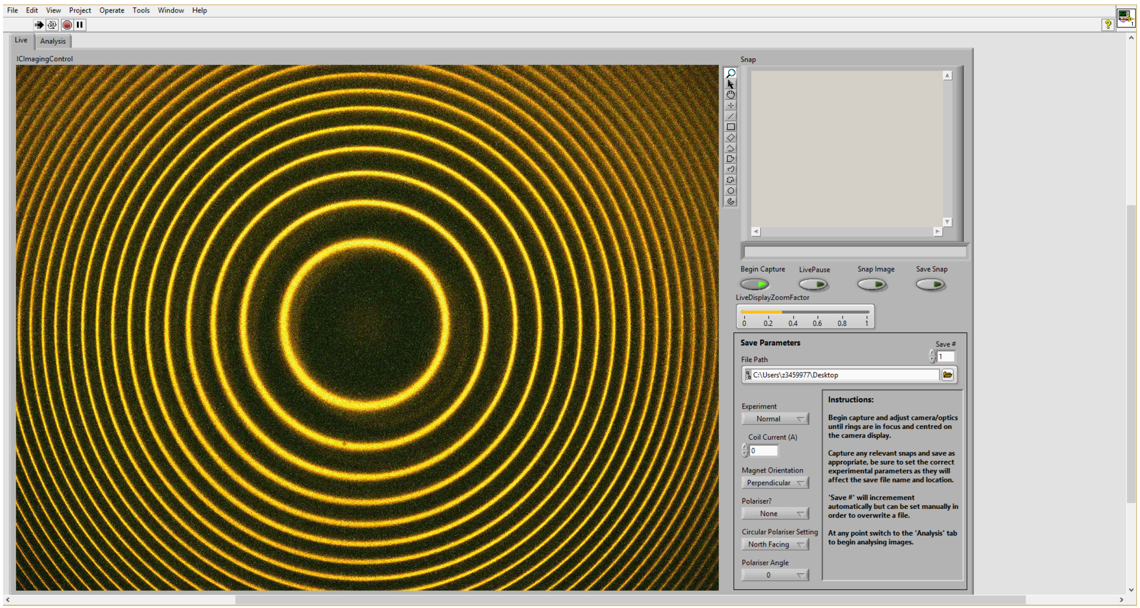

Figure 2: Example of Zeeman Split rings in the LabVIEW capture program.

6.1 Optical Alignment

1. Check that the Cd lamp is positioned centrally between the magnet pole pieces and is covered by the LAMP GUARD (if not, get a demonstrator to help) and switch on the discharge.

2. Remove the iris, both lenses, the polariser and the CCD camera from the optical bench leaving just the étalon (with the filter in) which should be aligned along the bench direction with the filter end furthest from the magnet.

3. Turn the S(outh) pole of the magnet towards the étalon. Slide the étalon to $\sim$ 5 cm from the magnet aperture and check that the back reflection of this lamp's light is centred on the magnet aperture. If not, rotate the magnet until the back reflection is centred.

4. Move the étalon to $\sim$ 15 cm from the pole piece and ensure that the the back reflection remains approximately centred. If not, the mounting stage of the magnet may need to be rotated, this adjustment is not usually necessary, so double check with a demonstrator before you go undoing screws.

5. With your eye about 10 cm behind the filter side of the étalon, observe the rings and adjust the height of the étalon so that the rings are vertically centred in the light spot. Perform minute adjustments in the orientation of the étalon and magnet to give the brightest rings centred on the light spot.

6. Mount the iris about 1 cm from the S pole of the magnet (make sure the magnet is still free to rotate), open the iris and mount the +50 lens ($f = +50$ mm) 5 cm behind the iris and the +100 lens about 2 cm from the filter side of the étalon. Check that all the components are at the same height (if not, see a demonstrator).

7. Mount the CCD camera with its front about 10 cm behind the +100 lens and align it along the bench. Plug the camera into the PC and open the Zeeman Effect Lab-

VIEW program (it should be located on the desktop). Run the program and press begin capture and adjust the camera position to focus and centre the rings on the monitor (dim the table lights). You should see an image similar to that found in Figure 2, do not worry is the coloration of your rings varies from this reference image.

8. To get the best ring definition and focus you may need to decrease the iris size, rotate the magnet slightly, rotate the étalon slightly, dim the room lights etc. If unwanted reflections appear you will need to tilt the appropriate optical component(s) slightly off axis.

6.2 Field Calibration

Perform a field calibration using the Hall probe (remember to take cover off probe and place the flat surface of the probe perpendicular to the field direction). Ensure that you measure the magnetic field as a function of both increasing and decreasing coil current to check for any hysteresis.

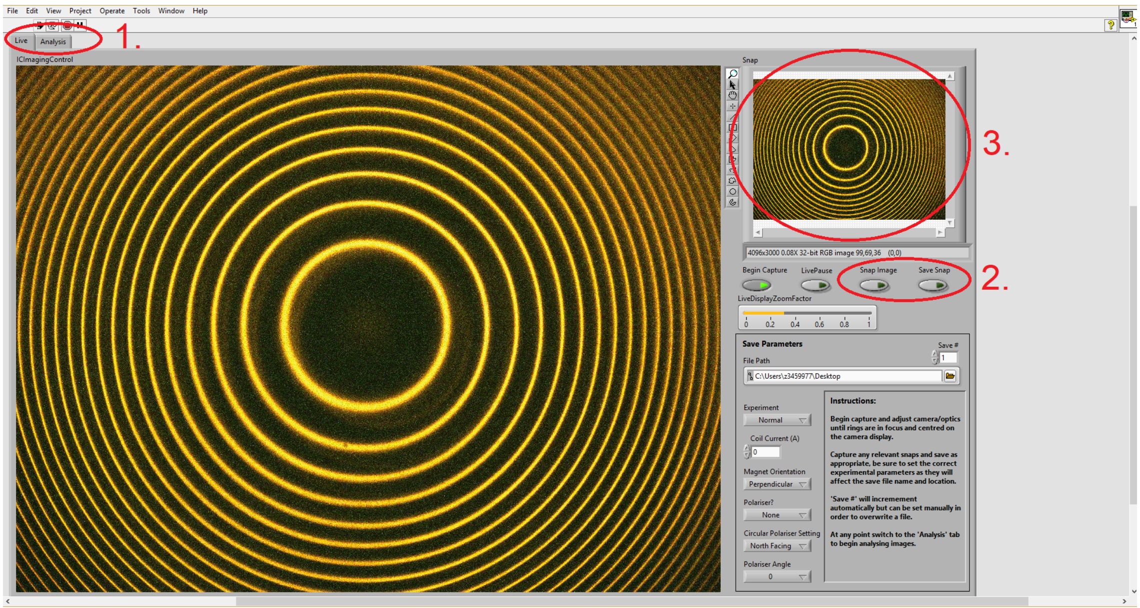

Figure 3: 1. Tab controls, 2. 'Snap Image' and 'Save Snap' buttons, 3. Current snap.

6.3 Zeeman Splitting

The majority of experimental work involves capturing images of interference rings and performing analysis on those images to determine the radii and with of the captured rings. A LabVIEW program has been written to facilitate you with this task, operating instructions are found in the program itself.

1. Begin by capturing and image using the 'Snap Image' and 'Save Snap' buttons, at any time you may switch to the analysis tab. See Figure 3.

2. In the 'Analysis' tab you unwrap the rings from their centre to form a series of parallel lines, then convert these lines to peaks in a linegraph.

3. Getting the best linegraph (sharpest peaks), relies mostly on finding the centre of the ring image accurately, this may take some trial and error. Indications that your centre point needs adjustment may be found in Figure 4, it is clear that the unwrapped image is distorted (the lines are not straight) which results in the extra peaks in the linegraph. Upon adjusting the centre position you should get a linegraph similar to that in Figure 5 where the flat lines in the unwrapped image result in sharp peaks, the distribution of which should follow $n \propto R^2$ where n is the ring order and R is the ring radius.

4. When satisfied with your linegraph you can automatically detect the peak locations using the 'Find Peaks' button. The peaks will be indicated by red dots on the linegraph and their locations are tabulated on the right. Often the peak finder with detect erroneous peaks near the centre of the image, circled in Figure 5, these peaks can simply be ignored or the inner radius can be increased to cut them out as in Figure 6.

6.3.1 Field Strength

With the light emitted parallel to the magnetic field, capture images of the interference rings with currents between 0 and 6 A (1-2 A steps are sufficient) through the magnet coils. REMEMBER: do not leave > 4 A flowing through the coils for extended periods of time. Do not change any of the optics when changing the current, which may take a minute or two to stabilise at each new setting. Make sure that the contrast/definition and centring of the rings on each image is good enough to allow the measurement of the diameters of at least 5 split rings.

Repeat this field strength experiment with the light emitted perpendicular to the magnetic field.

Question 5: Are rings with larger diameters due to lower or higher order interference in the étalon?

Question 6: Does an increase in emitted energy (decrease in wavelength) correspond to a ring with a smaller or larger diameter?

Question 7: Using your measured ring radii fill in the table in the 'Bohr Magneton' tab, the ring order is counted up from the innermost set of split rings and each ring component in the set of 2 or 3 rings (depending on magnet orientation) to determine the energy difference ΔE between the 2 or 3 ring components (parallel/perpendicular field) for each field strength (B) and plot ΔE as a function of B. Determine the value of μ_B from this plot.

6.3.2 Polarisation of Emitted Lines

Using the linear and right-hand circular polariser record Zeeman split rings using the following combinations of field orientation and polarisation state. When using the circular

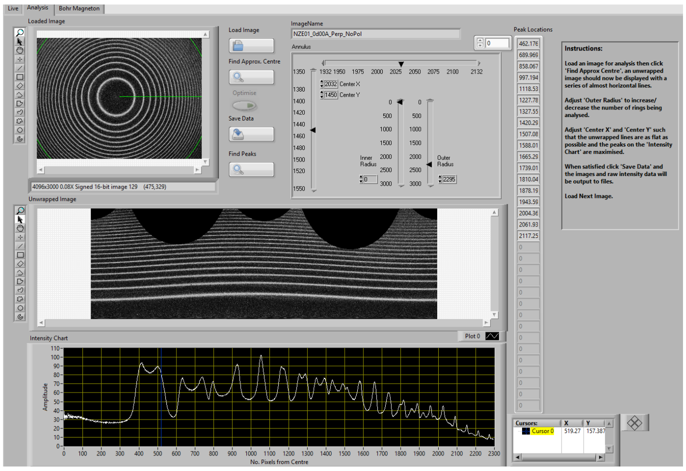

Figure 4: Analysis Tab: In this capture the centre of the annulus is poorly aligned, leading to distortions in the unwrapped image.

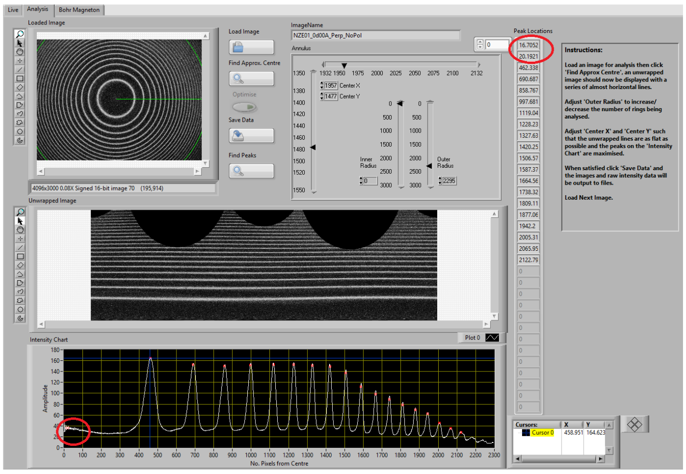

Figure 5: Analysis Tab: The annulus is properly centred and the peaks have been found automatically. Circled in red are erroneous peaks which should not be used for further analysis.

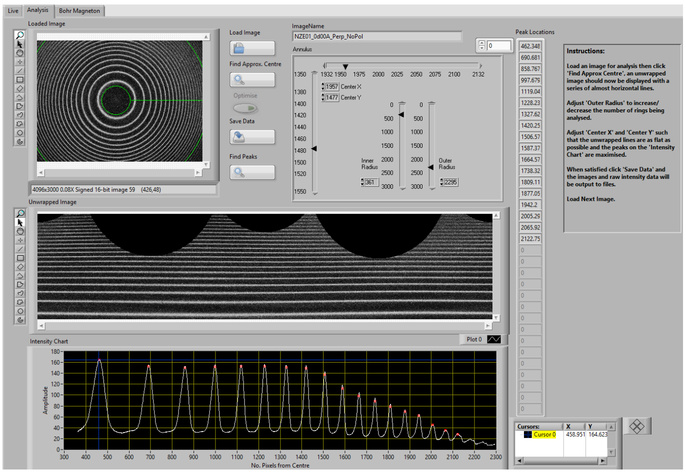

Figure 6: Analysis Tab: The inner radius of the annulus has been increased in order to cut out the erroneous peaks found in Figure 5.

polariser position it between the +100 lens and the camera, with its linear polariser side towards the camera.

Polariser	Polariser Orientation	Field Orientation
None	N/A	Perpendicular
None	N/A	Parallel
Linear	$0°$	Perpendicular
Linear	$90°$	Perpendicular
Linear	$-90°$	Perpendicular
Circular	N/A	Perpendicular
Circular	N/A	Parallel North Facing
Circular	N/A	Parallel South Facing

Other polariser/magnetic field orientation configurations are optional.

Question 8: Using these results, what is the optical polarisation of the three emitted lines?

Question 9: Why do you expect to only see 2 red components with Cd when viewing parallel to the field direction? What is the splitting of these rings in units of μ_B?

Hint: Consult ref. [2] for a classical explanation of polarisation in the Zeeman effect.

References

[1] David J. Griffiths. Introduction to quantum mechanics, 2005.

[2] Francis A. Jenkins and Harvey E. White. Fundamentals of optics, 1976.

[3] Adrian C. Melissinos. Experiments in modern physics, 1966.