Zeeman Effect

Introduction:

The first person to study the effects of magnetic fields on the optical spectra of atoms was Zeeman in 1896. He observed that the transition lines split when the magnetic field is applied.

The "Zeeman effect" is the energy shift of atomic states caused by a magnetic field. This shift is due to the coupling of the either orbital electron magnetic moment or combined orbital and spin electron magnetic moment to the external magnetic field.

If only orbital electron magnetic moment is involved it is known as normal Zeeman effect and if both orbital and spin magnetic moment are involved it is known as Anomalous Zeeman effect.

In this experiment we use Cd lamp. We use red light (643.847 nm) of Cd lamp for Normal Zeeman effect and green light (508.588nm) of Cd lamp for Anomalous Zeeman effect. Further Zeeman splitting can be observed both in transverse and longitudinal external magnetic field.

Objectives:

1. Quantitatively study transverse normal Zeeman effect by observing the splitting of the rings due to magnetic field resolved by Fabry-Perot etalon using a CMOS camera and evaluate the value of Bohr's magneton (μ_B). Observe the polarization of the rings using a polarizer
2. Observe the left circular and right circular polarized lines in anomalous normal Zeeman effect by using quarter wave plate and polarizer.
3. Observe the transverse anomalous Zeeman effect and polarization of the rings using a polarizer.
4. Observe the longitudinal anomalous Zeeman effect and left circular and right circular polarized lines in anomalous normal Zeeman effect by using quarter wave plate and polarizer

(Note. In this manual line and ring are synonymously used for spectral line)

Theory:

In quantum mechanics, a shift in the frequency and wavelength of a spectral line implies a shift in the energy level of one or both of the states involved in the transition. The Zeeman effect that occurs for spectral lines resulting from a transition between *singlet* states is traditionally called the *normal* effect, while that which occurs when the total spin of either the initial or final states, or both, is nonzero is called the *anomalous* effect**.**

The splitting of the Cd-spectral line l = 643.8 nm into three lines, the so-called Lorentz triplets, occurs since the Cd-atom represents a singlet system of total spin S = 0. In the absence of a magnetic field there is only one possible $D \to P$ transition of 643.8 nm, as indicated by Fig. 1. In the presence of a magnetic field the associated energy levels split into 2 L + 1 components. Radiating transitions between these components are possible, provided that the selection rules

$$\Delta M_L = -1, \Delta M_L = 0, \Delta M_L = +1$$

are taken into account. In this case, therefore, there are a total of nine permitted transitions. These nine transitions can be grouped into three groups of three transitions each, where all transitions in a group have the same energy and hence the same wavelength. Therefore, only three lines will be visible.
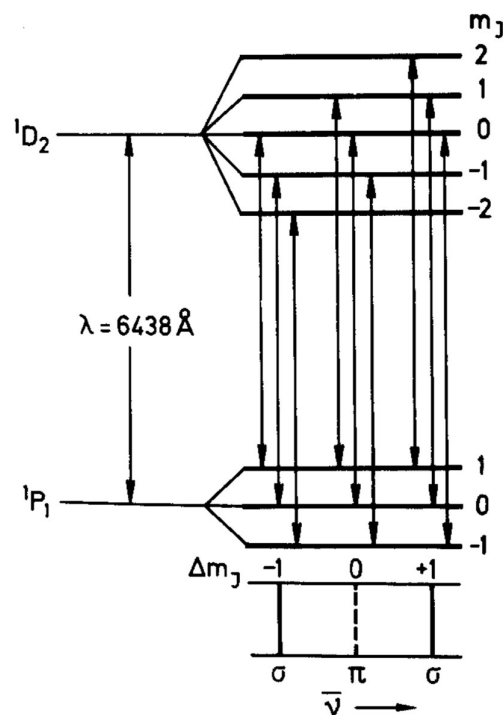
Fig.1: Splitting of lines for Cd spectral line in magnetic field and allowed transitions: Normal Zeeman effect

The first group where $\Delta M_L = -1$ gives a σ-line the light of which is polarized vertically to the magnetic field in the transverse magnetic field. The middle group $\Delta M_L = 0$ gives a π-line. This light is polarized parallel to the direction of the field in the transverse magnetic field. The last group where $\Delta M_L = +1$ gives an σ-line the light of which is again polarized vertically to the magnetic field in the transverse magnetic field. (Fig.2)

In the longitudinal field, we see only sigma lines (Fig.2) which are right circular and left circular polarized (σ^+ and σ^-).
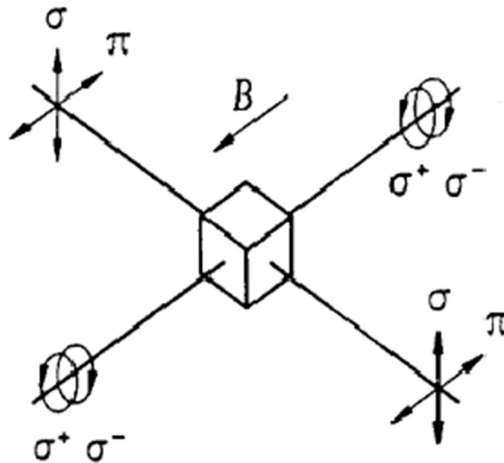
**Fig.2: polarization of lines in transverse and longitudinal magnetic field**

In the normal Zeeman effect with the transition $3\,^1D_2 \rightarrow 2\,^1P_1$ with 643.847 nm the electron spins cancel each other in both the initial and final state (S=0) and the energy of an atomic state in a magnetic field depends only on the magnetic moments of the electron orbit. Term symbol is ($^{2S+1}L_J$)

In the anomalous Zeeman effect with the transition S=1 for both initial and final states of the transition $2\,^3S_1 \rightarrow\,^3P_2$. For this transition green light of Cd at 508.5 nm light is used. Energy diagram splitting of the lines and allowed transitions is given in Fig. 3

There are total nine transitions in presence of magnetic field with three each for the below selection rules.

$$\Delta M_J = -1, \Delta M_J = 0, \Delta M_J = +1$$

This corresponds to total 9 transitions with six sigma lines (vertically polarized) and three pi lines (horizontally polarized in the transverse anomalous Zeeman effect and 6 sigma lines in longitudinal anomalous Zeeman effect with three left circularly polarized and three right circularly polarized.
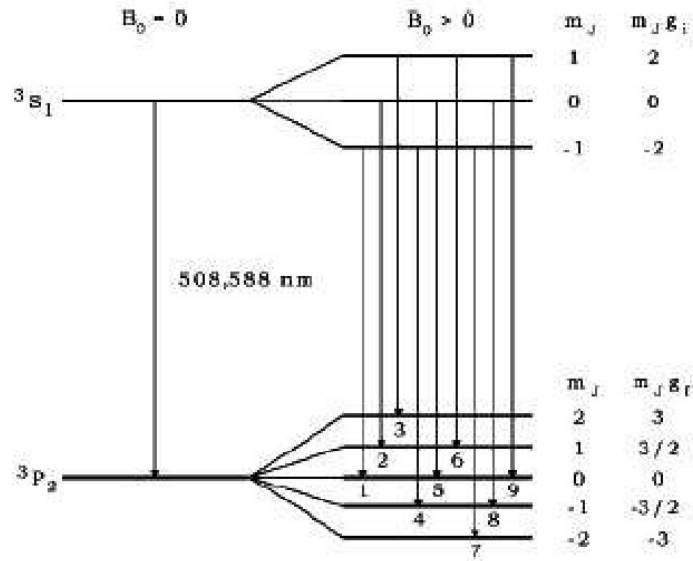
Fig.3: Splitting of lines for Cd spectral line in magnetic field and allowed transitions: anomalous Zeeman effect

So in case of LS-coupling in the anomalous Zeeman effect nine equidistant lines are expected in this transition instead of three without spin magnetism. The polarization of the transitions with in transversal observation is parallel to the magnetic field (here horizontal) and the polarization of the other transitions is perpendicular to the magnetic field.

In the case of Normal Zeeman effect, there are only two σ-lines which are termed as 'a' and 'b'. Separation of them is function of transverse magnetic field (B).

$$\Delta E = \mu_B B \quad \text{---(1)}$$

The difference in wave numbers of one of the lines with respect to central line of the same order is Δk/2. For this case

$$\Delta E = hc \frac{\Delta k}{2} \quad \text{--(2)}$$

Combing above two equations,

$$\mu_B = hc \frac{\Delta k}{2B} \quad \text{---(3)}$$

For the σ-lines of the transversal Zeeman effect, amount of splitting increases with increasing magnetic field strength. For a quantitative measurement of this splitting in terms of number of wavelengths, The Fabry-Perot étalon has a resolution of approximately 400000 is used in this experiment. That means that a wavelength change of less than 0.002 nm can still be detected. The étalon consists of a quartz glass plate of 3 mm thickness coated on both sides with a partially reflecting layer (90

% reflection, 10 % transmission). Refractive index of quartz at 509 nm is 1.4519 and at 644 n is 1.4560.

$$\Delta k = \frac{1}{2\mu t}\left(\frac{\delta}{\Delta}\right) \text{ ---(4)}$$

Where 'δ' is difference of squares of radii of different lines of same order of interference and 'Δ' is the difference of squares of radii of different order. For complete derivation of the above equations refer to the references.
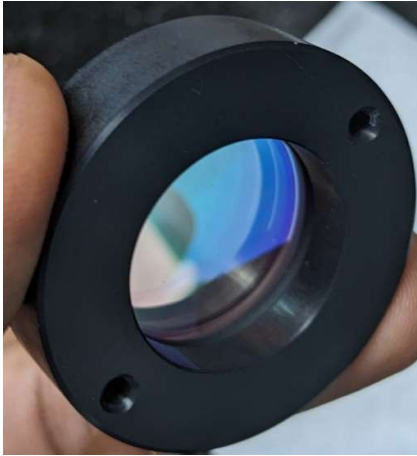
Fig 4. Fabry-perot etalon

Experimental arrangement:

Experimental setup consists of Cd lamp with power supply, permanent magnet on rotating table, two 50 mm convex lenses, 300 mm convex lens, Etalon arrangement with holder for red filter and attached to 100 mm lens in a tube, CMOS camera with 8 mm lens attached to it and connected to computer, green filter, polarizer and quarter wave plate. Complete picture is given in the following figure.

Fig.5: complete experimental setup

In the above arrangement first 50 mm lens is to focus light on the lens attached to tube with Fabry-perot etalon. Light coming out of Etalon is focused with 300 mm lens and brought to camera by 50 mm lens. Polarizer and quarter wave plate can be placed in between the 300 mm lens and 50 mm lens whenever required.

Procedure:

1. Switch on the Cd lamp and wait for warm up. Identify all the optical components given to you.
2. There two main parts of the experiment. Normal Zeeman effect and Anomalous Zeeman effect. In each part there are two subparts: magnetic field in transverse direction and magnetic field in longitudinal direction.
3. Get familiarized with software which captures images from CMOScamera. Use only 'Red gain' in the Software for Normal Zeeman effect and 'green' for Anomalous Zeeman.
4. Align the lamp, first 50 mm lens and Fabry-perot tube and observe the ring pattern coming out from etalon with a naked eye.
5. Now place the 300 mm lens and 50 mm lens along with camera and align the entire setup, adjust the camera settings and observe the rings of first three orders in normal Zeeman effect in the transverse field. An example picture is given in the figure 6. (some part of the third order and may be second order is not captured as the CMOS sensor in the camera is rectangular)
6. See that CMOS camera is equally illuminated to get the ring pattern at the center of the screen.
7. Sometimes you may observe the pattern as Fig. 7. In Figure 7, first ring is filled with light, try to trouble shoot by adjusting the light using given aperture by decreasing the light and/or slightly moving the Cd lamp, finally locate the ring.
8. Sometimes you may observe the pattern as in Fig.8. Ignore the center spot and it does not correspond to interference.
9. Observe that splitting is function of magnetic field by varying the distance between pole pieces.
10. After confirming the ring pattern of Normal Zeeman effect with the ring pattern up to 3 orders, take pictures using the software for each magnetic field and save them. You need to use the saved files for estimating the radius. (here the size of the ring (magnification) is not important as the calculation involves only relative dimensions)
11. Place the polarizer and notice that middle line of each order is horizontally polarized and outer lines (rings) are vertically polarized. Identify σ and π lines.
12. Use the camera software and record pictures for first three orders (for each order record three rings) for each magnetic field. Magnetic field versus pole separation data is provided to you in the figure 10.
13. Tabulate the square of ring radius readings (to get the radius, measure diameter using the software and divide by 2) and calculate wave number using equation (4) that is equation $\Delta k = \frac{1}{2\mu t}\left(\frac{\delta}{\Delta}\right)$

Table1. Components of each order rings are designated as 'a, b and c'.

Here the outer 'a' and 'c' are σ lines and the middle 'b' is π line

	1st order	2nd order	3rd order
a	$R_{1,a}{}^2$	$R_{2,a}{}^2$	$R_{3,a}{}^2$
b	$R_{1,b}{}^2$	$R_{2,b}{}^2$	$R_{2,b}{}^2$
c	$R_{1,c}{}^2$	$R_{3,c}{}^2$	$R_{3,c}{}^2$

$$\delta = \frac{1}{6}\left(\delta_{1,ab} + \delta_{1,bc} + \delta_{2,ab} + \delta_{2,bc} + \delta_{3,ab} + \delta_{3,bc}\right) \text{ Where } \delta_{n,xy} = \left(R_{n,y}^2 - R_{n,x}^2\right)$$

$$\Delta = \frac{1}{6}\left(\Delta_1^a + \Delta_1^b + \Delta_1^c + \Delta_2^a + \Delta_2^b + \Delta_2^c\right) \quad \text{Where, } \Delta_n^x = \left(R_{n+1,x}^2 - R_{n,x}^2\right)$$

'δ' is difference of squares of radii of different lines of same order, calculate it for both the components of 'σ' line and take average. 'Δ' is the difference of squares of radii of different order. You may avoid some of them if they are deviated from other values.

14. Use equation 3 to calculate Bohr magnetron(μ_B) by plotting necessary graph.
15. Record a picture in longitudinal normal Zeeman effect after rotating the magnetic field and realigning the optics. In this case identify the left circularly and right circularly polarized light using quarter wave plate and polarizer. (quarter wave plate converts linearly polarized light to circularly polarized light and here we use the inverse effect)
16. Bring back the magnet to transverse field, Remove Red filter and attach the green filter to one of the lens holder.
17. Align the optics and observe 8 rings for each order (due to the insufficient resolution of Fabry perot etalon, instead of 9 rings, we see only 8 or sometimes 7 rings.)
18. Identify the σ and π lines and record pictures for the same. Does the σ lines are separated by π lines like in the normal Zeeman effect? They won't.
19. Rotate the magnetic field and identify the lines left circularly polarized and right circularly polarized σ lines in longitudinal anomalous Zeeman effect, record pictures for the cases. Verify that all σ lines are bunched together unlike in normal Zeeman effect in which they are separated by π line.
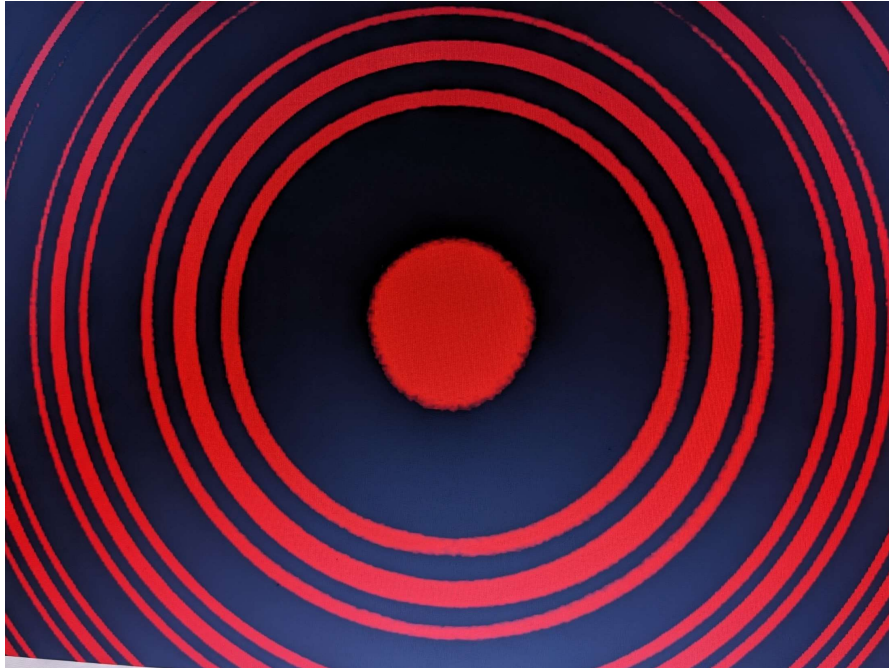
Fig.6 Pattern recorded with lab setup for Normal Zeeman effect after alignment
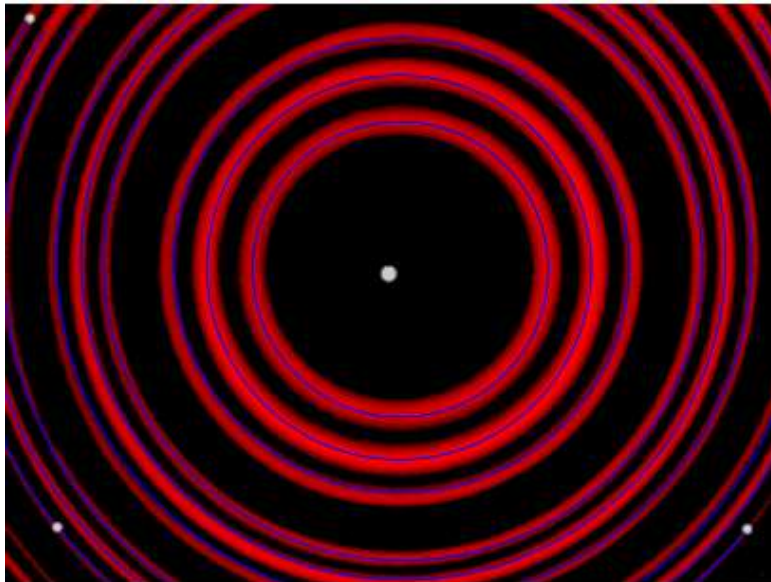

Fig.7. In this case first ring is filled with light instead of ring. Adjust the intensity or use the aperture and locate the ring diameter
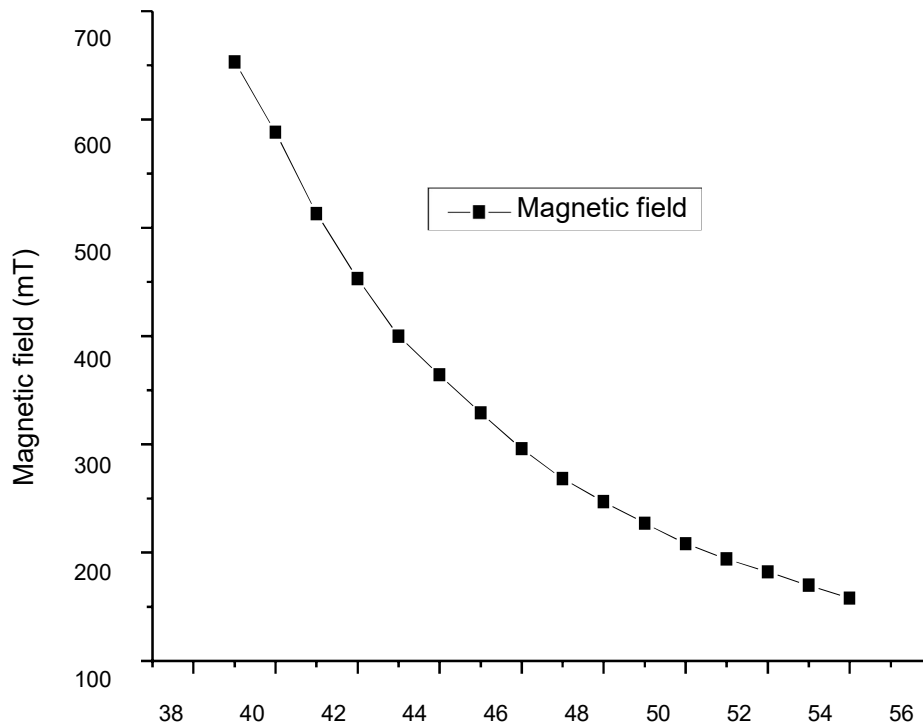
Fig.8. In this case there is a bright spot in the center. It does not correspond to first order. Ignore this and take readings of diameter of rings.

Fig.9 Rings radius determination with the software (in the calculation we use the relative radii and calibration is not necessary)

Fig.10. pole piece separation gap(mm)

Precautions:

1. Don't touch the lenses and filters in your finger. The single finger print will make the things dirty and the interference fringes will be distorted.

2. Handle the filters carefully. Take the Technician help to change them.

3. While setting the optical path don't look to the Cd-lamp in naked eye for long time. It has a bad effect on the eye.

References:

1. For derivation of the formulas, Refer Phywe manual
   https://www.nikhef.nl/~h73/kn1c/praktikum/phywe/LEP/Experim/5_1_10.pdf

2. Chapter 6, Experiments in Modern Physics, Adrian C. Melissinos and Jim Napolitano, Academic Press.