Zeeman Effect

Physics Lab (Optics and spectroscopy)

INDEX

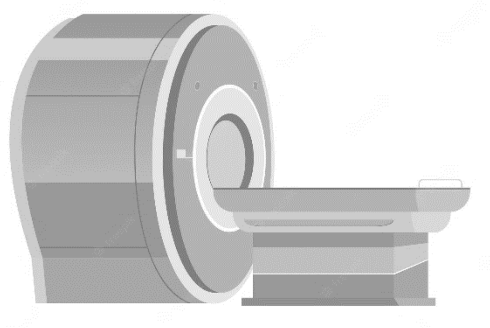
SYMBOLS and CONSTANTS

$\hbar$ = Reduced Plank's constant	μ = Magnetic moment
λ = Wavelength	μ_B = Bohr magneton
m_e= Mass of electron	$\boldsymbol{S}$ = Spin angular momentum
f = Frequency	$\boldsymbol{L}$ = Orbital angular momentum
F = Focal length	$\boldsymbol{J}$ = Total angular momentum
g = Lande Factor	

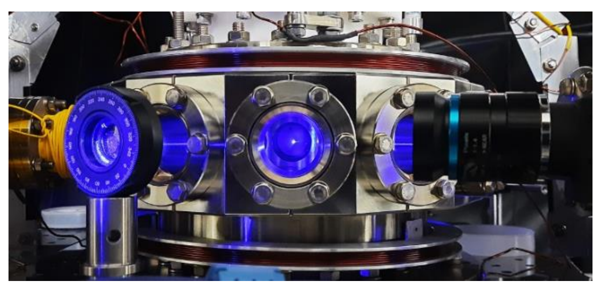
ABSTRACT

The discovery of the atom has motivated scientists to explore the atom in greater depths. For hundreds of years, many scientists did extensive theoretical and experiment study to compile a comprehensive knowledge of atom. This knowledge led to the development of numerous technologies and applications that we use today. There are thousands of scientists still working to reveal the deeper secrets of atom and its constituent particles.

In this experiment, we will revise one of many events in the process of atomic study. Pieter Zeeman discovered in 1896 that the atom's energy levels split into multiple levels [1] when subjected to external magnetic field. This effect, named after P. Zeeman, played an important role in the development of quantum theory. Addition to this basic science, some noted examples of the applications, which use Zeeman effect, are MRI (Magnetic Resonance Image), MRS (Magnetic Resonance Spectroscopy), atomic clocks, astronomy, material science and more.



In MRI, the magnetic field is applied with superconducting magnets and energy splitting of water molecules is used to images deep tissues of body.



Scientists in IISER Pune [2] are building India's firsts atomic clock which offers the most accurate measure of time till now.

We will also explore the Zeeman effect experimentally and try to verify the underlying quantum theory. In addition, we will investigate the interferometer which is crucial in measuring this Zeeman effect.

THEORY

This manual does not provide a comprehensive information; therefore, students are encouraged to consult an atomic physics book [3-5] to thoroughly understand the Zeeman effect. However, we will go through this effect briefly. We know from the initial Bohr atomic model that electrons can orbit around nucleus within specific orbits which allows a quantized angular moment ($|\vec{L}|$) of electron as integer multiple of $\hbar$. The occupation of electrons(s) in these orbits decides the energy of atoms. When electron(s) jumps from one orbit to another, energy of atom changes accordingly. One of the methods by which these quantized change in energy is released/absorbed is exchange of photons. By analysing the emission from atom (the energy and polarization of photons), we can infer the energy levels and their respective momentum. The calculations of energy levels of hydrogen atom are given in above references [3-5]. There, we will find that emission of hydrogen atom is categorized in different series depending upon the initial and final energy level of atom. There is another experiment in this lab on one such series[a]. Since energy levels are sharp, their difference also generates photons of precise energy[b]. These photon energies project as sharp line on the photographic plate of a spectrograph. Spectrograph was the instrument used to measure spectrum of a light source. Remember prism spectrometer experiment in undergraduate lab where emission from mercury lamp was refraction into

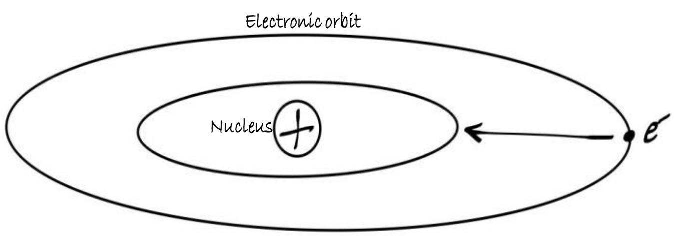


Fig. 1: Bohr's atomic model

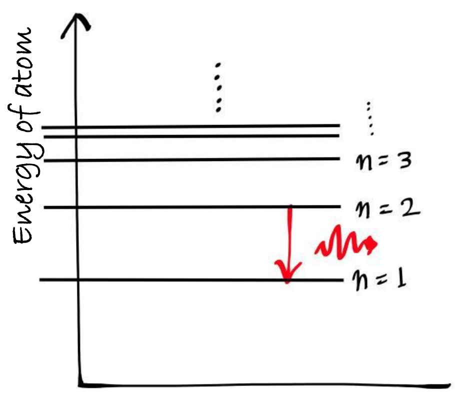


Fig. 2: Energy levels of atoms

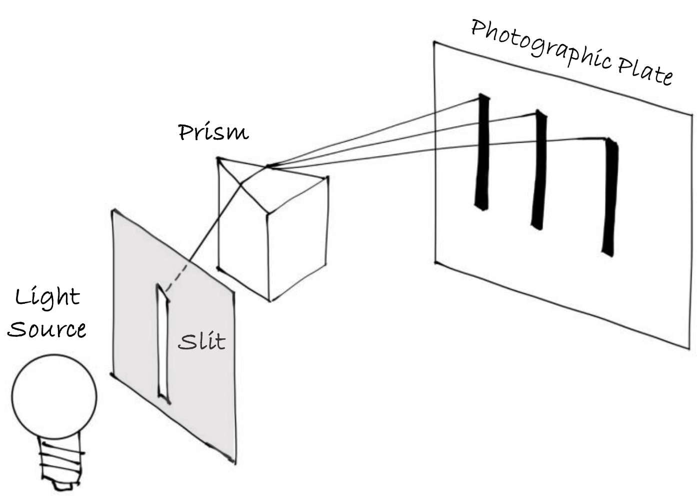


Fig. 3: Spectrometer and generation of emission lines

multiple bands/lines of color on screen. Similarly, spectrograph also projected the light of different energy (wavelength) on a photographic plate in the form of a band. Therefore, emission from atoms sometimes called ‘**emission lines**’. Do not confuse these lines with atomic energy level. Emission lines do not represent atomic levels, it only represents atomic transitions. Zeeman effect is observed as the appearance of additional emission lines when an external magnetic field is applied. When this effect was first observed, the concept of electron spin was not known and quantum mechanics was beginning to develop. Then, HA Lorentz explained this effect partially with semiclassical theory where he adopted the Bohr model of atom and electrons were considered rotating in fixed orbits around nucleus. This rotation of charged particle generated a magnetic moment which got affected by external magnetic field. Please see the appendix 1 for Lorentz’s explanation for Zeeman effect. Although this theory explained Zeeman effect in some of the atoms like He, Zn, Ca, Hg etc. up to some extent. But it could not explain the splitting of emission lines in Na, Cr etc. In these atoms, splitting of emission line omitted the original line. That is why it was anomalous Zeeman effect. Later, when it was discovered through experiments like Stern-Garlach that electron possess an intrinsic angular momentum referred as spin[c]. Also, the Schrodinger’s quantum mechanical theory was successfully able to explain the hydrogen emission lines. Still, the hydrogen fine structure was unexplained. Then, the theory of relativity was incorporated and interaction (coupling) of spin and orbital angular momentum was included in quantum mechanical treatment. These three concepts are the foundation of the atomic theory which explained the normal as well anomalous Zeeman effect adequately.

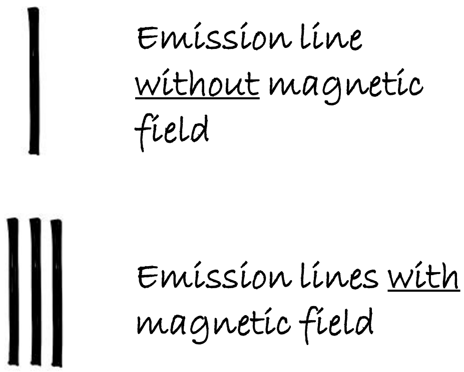


Fig. 4: Emission lines splitting in Normal Zeeman effect

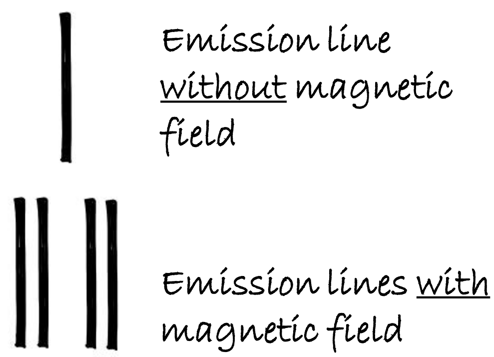


Fig. 5: Emission lines splitting in Anomalous Zeeman effect

After the historical note, we will understand a bit of mathematical concepts. In Lorentz’s explanation, the magnetic moment of electron is related to orbital angular momentum by

$$\overrightarrow{\mu_L} = \left(\frac{e\hbar}{2m_e}\right)\frac{\vec{\boldsymbol{L}}}{\hbar}$$

The subscript L is to denote the orbital angular momentum. The constant $\frac{e\hbar}{2m_e}$ is called Bohr magneton (μ_B). Similarly, spin angular momentum is related to magnetic moment as,

$$\vec{\boldsymbol{u}}_S = g_S\mu_B\frac{\vec{\boldsymbol{S}}}{\hbar}$$

where a new term g_S got introduced and it is called Lande factor. It came out to be ≈ 2 for relation between $\vec{\boldsymbol{u}}_S$ and $\vec{\boldsymbol{S}}$. This unexplained factor of 2 was later incorporated in the explanation of Pauli and Dirac. The coupling of orbital and spin angular momentum (LS coupling) generated a new quantum number called total angular momentum ($\vec{\boldsymbol{J}}$) which is similarly related to total magnetic moment,

$$\vec{\boldsymbol{u}}_J = g_J\frac{\mu_B}{h}\vec{\boldsymbol{J}}$$

where $\vec{\boldsymbol{J}} = \vec{\boldsymbol{L}} + \vec{\boldsymbol{S}}$ and, the expression of new Lande factor g_J is

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

The calculation can be consulted in reference [3,4].

We can again apply the same principal as used by Lorentz that when magnetic field is applied, the magnetic moment ($\overrightarrow{\mu_J}$ in this case) will interact with external magnetic field and raise the potential energy by $\Delta E = \overrightarrow{\mu_J}.\vec{B}$. In quantum mechanical treatment, this ΔE is taken as perturbation to the atomic Hamiltonian. And we know that $\vec{\boldsymbol{J}}$ has quantized projection, hence $\Delta E = \vec{\mu}_J.\vec{B} = m_J|\mu_J||B|$ where m_J can have discrete values from $+J$ to $-J$.

We have estimated the deviation in atomic level when applied external magnetic field. Now let us move to the calculation part. The electronic configuration of an atom reveals the quantity and quantum numbers of electrons in partially filled subshells which gives the idea about total $\vec{\boldsymbol{J}}$, $\vec{\boldsymbol{S}}$ and $\vec{\boldsymbol{L}}$.

The Lande factor g_J can be calculated for the atomic level and energy variation can be calculated as

$$\boxed{\Delta E_J = g_J \vec{\mu}_B . \vec{B} \text{ or } \Delta E_J = g_J m_J \mu_B B \qquad (2)}$$

where m_J is projection of $\vec{\mu}_B$ on $\vec{B}$.

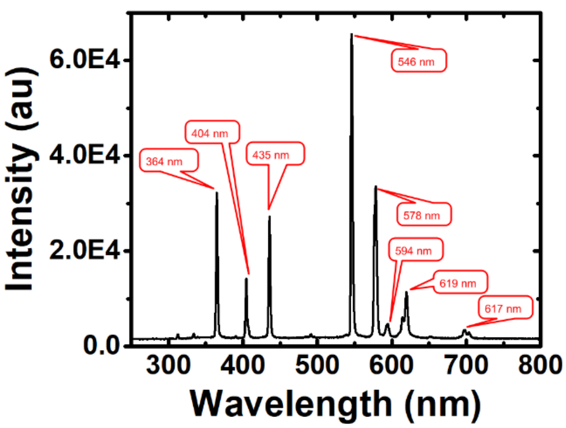


Fig. 6: Emission spectrum of mercury

We will take the example of mercury atom which is used in this experiment. The spectrum of mercury atom is given in figure 6. There are multiple emission lines from 364 nm to 617 nm. Each peak shows the transition of atom from higher energy level to lower energy level. In Zeeman effect, these lines split into multiple lines[d] when applied with magnetic field and this splitting depends upon the deviation of the energy levels. In figure 7, the horizontal lines are atomic energy level and vertical lines are transitions.

We select the emission line near 546 nm for the experiment. The energy levels before and after splitting are shown in figure 7, and electronic configuration of outer subshells and term symbol are also given. **Please see appendix 4 to know about term symbols.**

Exercise 1 (compulsory): Calculate the value of g_J for $6s7s\ ^3S_1$ and $6s7p\ ^3P_2$?

After application of magnetic field ($\vec{B}$), the splitting of energy occurs as shown in equation (2). If energy level 6s7s $^3\mathbf{S}_1$ is called E_H (Energy higher) and 6s7p $^3\mathbf{P}_2$ is called E_L (Energy lower), then transition between E_H to E_L emits photon of wavelength 546.1 nm. Whereas after splitting, emission energy should depend upon initial and final state. There are 9 transition shown as downward arrows in figure 7. These transitions

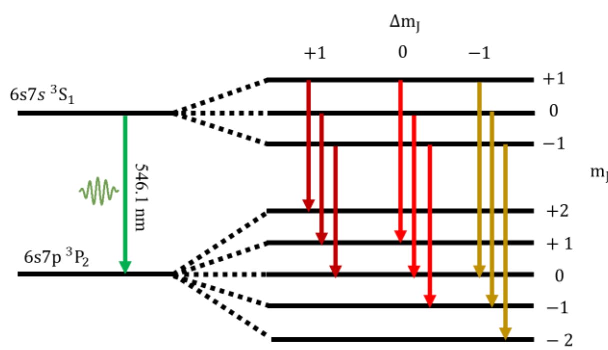


Fig 7. Transition of mercury atom resulting in 546.1 nm.

and polarization of light emitted from these transitions depend upon the selection rule. Please refer [3-5] to understand the selection rules. The selection rule and polarization are given below. We will only calculate transition energy for $\Delta m_J = 0$ lines.

The Energy of photon going from $^3S_1$ $m_J = +1$ to $^3P_2$ $m_J = +1$

$$\boxed{(E_H + \Delta E_H) - (E_L + \Delta E_L) \qquad (3)}$$

putting ΔE from equation 2 and putting values of m_J

$$(E_H - E_L) + \Delta E_H - \Delta E_L = (E_H - E_L) + g_{JH}(+1)\mu_B B - g_{JL}(+1)\mu_B B$$

Similarly, for $^3S_1$ $m_J = -1$ to $^3P_2$ $m_J = -1$

$$(E_H - E_L) + g_{JH}(-1)\mu_B B - g_{JL}(-1)\mu_B B$$

The energy difference between two transitions,

$$\mu_B B(2g_{JH} - 2g_{JL}) = 2\mu_B B(g_{JH} - g_{JL}) \qquad (4)$$

If the value of energy difference of two transition and g_J for both atomic levels and magnetic field are known, the value of Bohr magneton can be calculated. In the experiment, we will use the same approach and find the Bohr magneton value for verification of above quantum theory.

Exercise 2: Calculate the energy of photons emitted by $\Delta m_J = +1$ lines and compare it with $\Delta m_J = -1$ lines by using the theoretical value of μ_B.

Selection rule and polarization

Selection rules are criteria which decide the allowed transitions between two energy levels. TO understand more about these rule's derivation, please read Fermi's golden rule [3-5]. The selection rules are summarized in figure 7. When $\Delta m_J = 0, \pm 1$ the transitions are allowed. The value of Δm_J and direction of emission decides the polarization. The emission from $\Delta m_J = 0, \pm 1$ in perpendicular direction of magnetic field are plane polarized. The plane of polarization is different for 0 and $\pm$ 1. The emission from $\Delta m_J = \pm 1$ will emit circularly polarized light perpendicular in the direction of magnetic field.

Two modes of observation: a) Traverse 2 Longitudinal

Traverse mode is when observation is done perpendicular to magnetic field.

Longitudinal mode is when observation is done parallel to magnetic field.

Both modes are done in this experiment.

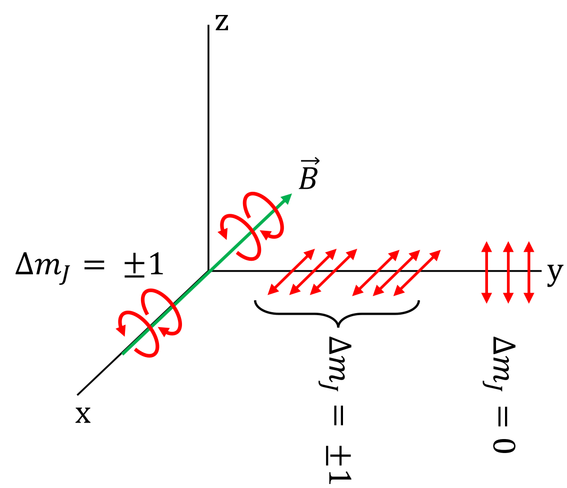


Fig 8. Emission direction of different atomic transition. 9 transition emits a plane polarized light in the direction perpendicular to magnetic field and 6 transition emits circularly polarized light parallel to magnetic field.

EXPERIMENT

Bohr magneton (μ_B) can be estimated by Zeeman splitting as show in THEORY section. We will test this theory by calculating μ_B and compare it with correct value. We require the following components for the experiment. The emission from mercury atom, magnetic field (B) and precise spectral measurement of split in emission lines.

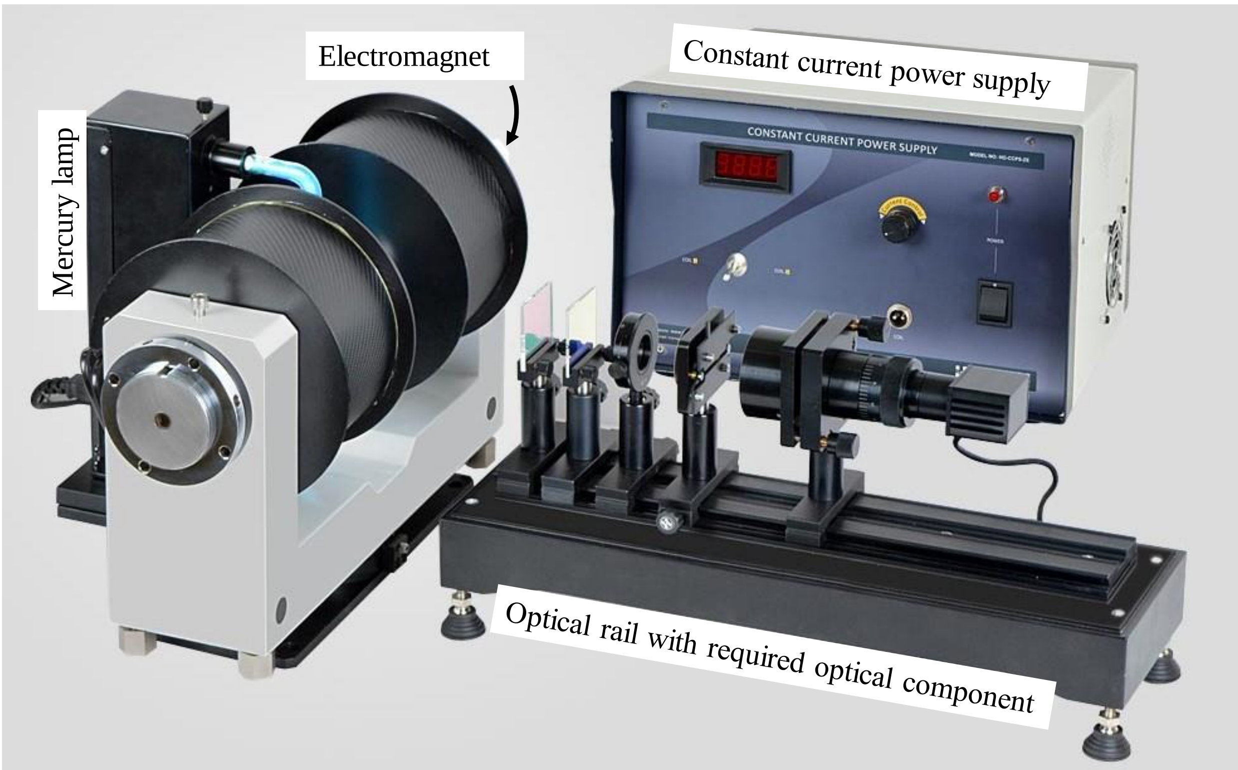


Fig. 9: The setup to observe Zeeman splitting.

The detailed list of individual components is given below

1. Mercury lamp (*for emission*)
2. Electromagnet and it's constant current power supply (*for magnetic field*)
3. Optical components on rail (*for spectral measurement*)
    a. IR Filter
    b. Green Filter
    c. Polarizer + Slit
    d. Fabry-Perot etalon + focusing lens + CCD camera

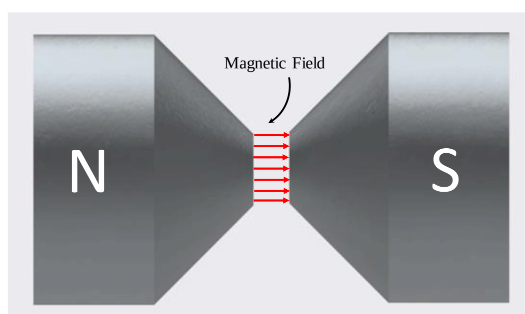


Fig. 10: Magnetic field generated between two poles of electromagnet

The electromagnet generates magnetic field when current is applied. The value of current is known from the power supply but the magnetic field is to be determined. The calibration of magnetic field is given in Appendix 6.

Experiment 1: Finding the spacing between the reflecting plates Fabry-Perot interferometer

The mercury emission spectrum (without any magnetic field) is given in figure 6. There are multiple significant emission peaks from 364 nm-578 nm. We isolate one specific line in the emission and observe the splitting under the magnetic field. If more than one line is selected, the emission will overlap on the CCD camera and it will be difficult to isolate the splitting of a particular emission line.

Therefore, we select emission line around 546.1 nm and use two optical filters to isolate this line. Optical filter allows (or blocks) the transmission of a particular range of wavelengths. Figure 13 shows the placement of different optical component including filters on optical rail. The first filter is IR (infrared) filter which blocks the IR emission from 750-1150 nm and allows the transmission of 425-675 nm.

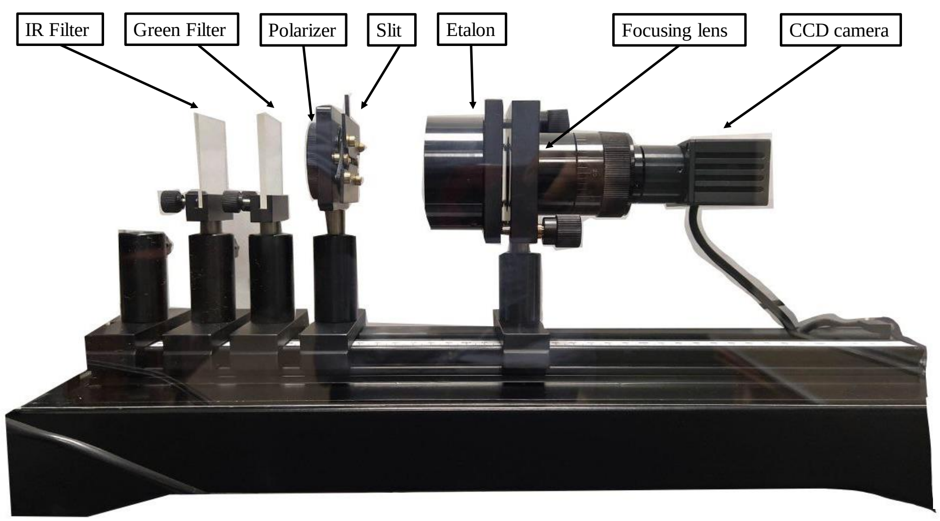


Fig. 13: Optical component placed on optical rail to collect and process one emission line from mercury lamp.

Green filter is placed after IR filter, which allows the emission of green line (around 546.1 nm). The green line is isolated with these filters. {See appendix 4 for the transmission curve of green filter.} We have calibrated the magnetic field (B) and isolated one emission line so far in the experiment. Next thing is to measure the splitting energy of the emission line. The spectrometer/monochromators[f] are used to measure the wavelength/energy of emitted light. We can estimate the energy splitting as $\Delta E = h\Delta\nu = \frac{hc\Delta\lambda}{\lambda^2}$ from the wavelength measurement. However, a large and sophisticated spectrometer is required to achieve the resolution needed for this experiment. The splitting of energy due to Zeeman under 10^4 Gauss magnetic field is 10^5 times smaller than the wavelength (546.1 nm in our case). Also, we are interested in difference of wavelength than the value of wavelength itself. Therefore, Fabry-Perot interferometer is used which can measure small variation of wavelength. It is two parallel plates of partially reflecting mirror. The space between two plates works as delay between rays which undergo the interference process. The condition of interference is used to estimate wavelength difference. Please see appendix A2 to know brief working of Fabry-Perot interferometer. The spacing between the reflecting plates is

$$d = \frac{\lambda F^2}{(\chi_{n-1}^2 - \chi_n^2)}$$

STEPS TO FOLLOW

See the working of camera in Appendix 3

Step 1: Turn on the mercury lamp.

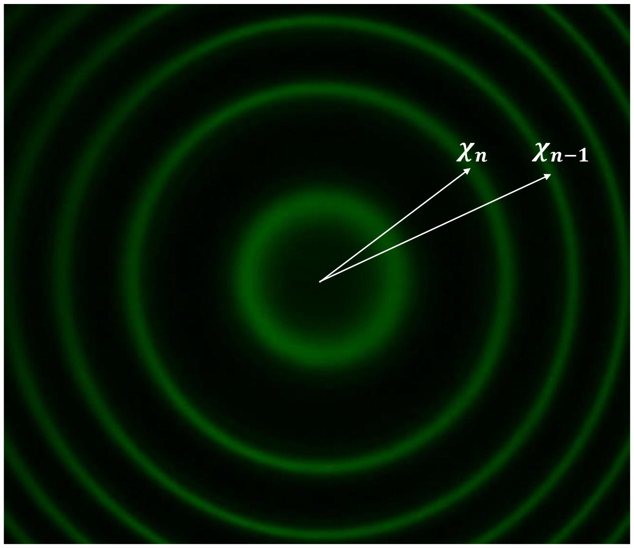


Fig. 14: Constructive interference from etalon resulting in concentric rings.

Step 2: Plug the camera USB into computor. Open the '**Camera application**' from the desktop. **Select resolution** to 800x600x24 while tuning the etalon. If the rings are too dark, increase the exposure time from Display control on camera application. In case, rings are too dark, slightly open the slit.

Step 3: Use the kinematic mounts of Fabry-Perot to adjust the rings at the center of screen and focus it with focus ring.

Step 4: Once the rings are adjusted, click the puase button and change the resolution to 1280x960x24.

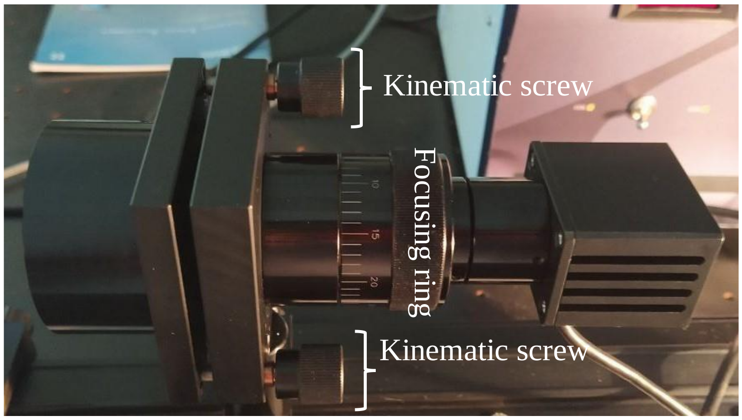


Fig. 15: Kinematic screw to move circular rings on camera to move vertically and horizontally. The focusing ring is to focus rings on camera.

Step 5: Capture the image and save it in the desktop folder with folder name as your roll number and file name as 0A_Tran.

Follow the table II for analysis.

Observation table II					
S No	Radius (pixel)	Radius (μm)			d
1	$\chi_n=$	$\chi_n=$	$\chi_n^2=$	$\chi_n^2 - \chi_{n-1}^2=$	
2	$\chi_{n-1}=$	$\chi_{n-1}=$	$\chi_{n-1}^2=$	$\chi_{n-1}^2 - \chi_{n-2}^2=$	
3	$\chi_{n-2}=$	$\chi_{n-2}=$	$\chi_{n-2}^2=$	$\chi_{n-2}^2 - \chi_{n-3}^2=$	
4	$\chi_{n-3}=$	$\chi_{n-3}=$	$\chi_{n-3}^2=$	-------------	--------
				Average d	

Experiment 2: Observation of Zeeman splitting and calculation of Bohr magneton in Traverse mode

After applying magnetic field, three sets of emission marked as $\Delta m_J = 0, +1, -1$ (see figure 8) are expected. These nine emission lines will make closed spaced concentric circles on screen. Therefore, only $\Delta m_J = 0$ is selected using a polarizer. Once the polarizer is aligned in the direction of polarization plane of $\Delta m_J = 0$ lines. Three concentric rings should appear (see figure 16). To measure the splitting, we should again use the equation (A2.a) in appendix 2, for any ring χ_n after splitting. Say outer ring has radius χ_{n+} and inner ring has radius χ_{n-},

$$2d.cos(\theta_{n+}) = n\lambda_+$$

$$2d.\left(1 - \frac{\chi_{n+}^2}{2F^2}\right) = n\lambda_+ \tag{4(a)}$$

and

$$2d.\left(1 - \frac{\chi_{n-}^2}{2F^2}\right) = n\lambda_- \tag{4(b)}$$

Notice here wavelength of outer and inner ring is different. After (a)-(b)

$$\left[2d.\left(1 - \frac{\chi_{n-}^2}{2F^2}\right)\right] - \left[2d.\left(1 - \frac{\chi_{n+}^2}{2F^2}\right)\right] = n\lambda_- - n\lambda_+$$

$$\frac{d}{F^2}(\chi_{n+}^2 - \chi_{n-}^2) = n\,(\lambda_- - \lambda_+)$$

The value of $n \approx N$ since value of n is very large.

Q: Find the difference between values of μ_B with N, $N-1$ $N-2$ as value of n.

$$\frac{d}{F^2}(\chi_{n+}^2 - \chi_{n-}^2) = \frac{2d}{\lambda}(\lambda_- - \lambda_+)$$

The difference of wavelength can be converted to difference of energy (which is required in this experiment)

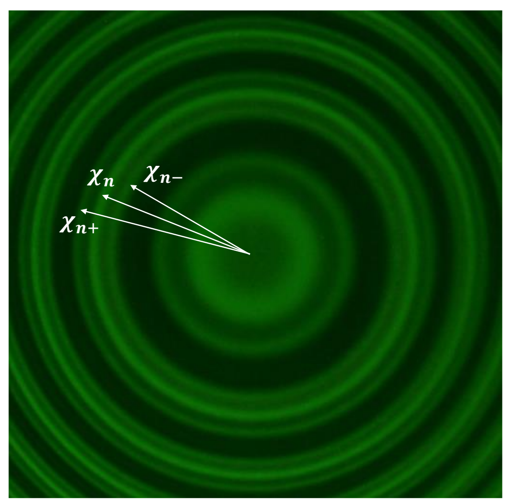


Fig. 16: Splitting of energy lines resulting in three concentric circles.

$$\Delta E = h\nu_+ - h\nu_- = hc\left(\frac{1}{\lambda_+} - \frac{1}{\lambda_-}\right) = hc\frac{\lambda_- - \lambda_+}{\lambda_+\lambda_-} = \ hc\frac{\lambda_- - \lambda_+}{\lambda^2}$$

here $\lambda_+\lambda_- \approx \lambda^2$. Finally, we compare this energy difference which is expected experimentally to the theoretical value (see equation (4)) and see if these values match.

$$\Delta E = \frac{hc(\chi_{n+}^2 - \ \chi_{n-}^2)}{2\lambda F^2} = 2\vec{\mu}_B.\vec{B}(g_{JH} + g_{JL})$$

Hence,

$$\overrightarrow{|\mu_B|} = \frac{hc(\chi_{n+}^2 - \ \chi_{n-}^2)}{4(g_{JH} - g_{JL})\lambda F^2|\vec{B}|}$$

<u>STEPS TO FOLLOW</u>

Step 1: Go to the setup 1.

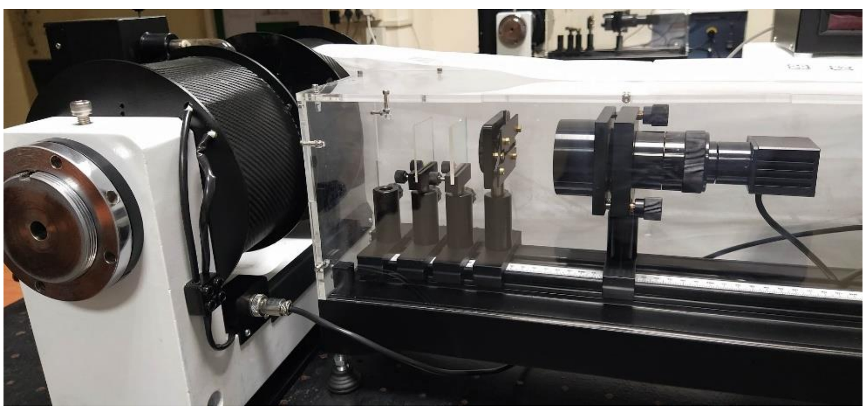


Fig. 17: Setup 1. Traverse mode.

Step 2: Turn on the magnetic field and set the current at 3 A and notice the splitting of radii into multiple lines. Rotate the polarizer until three sharp lines appear as shown in figure 16. This is the direct evidence of quantization of magnetic moment of atom. Capture the image in resolution 1280x960x24. Save as file name 3A_Tran.

Step 3: Capture the image for current value of ~2.75 A and ~2.50 A.

Observation Table III								
S No	χ_+(pixel)	χ_+ (μm)	χ_+^2 (μm^2)	χ_- (pixel)	χ_- (μm)	χ_-^2 (μm^2)	$\chi_+^2 - \chi_-^2$ (μm^2)	μ_B (Joule/Gauss)
1	$\chi_{n+}=$	$\chi_{n+}=$	$\chi_{n+}^2=$	$\chi_{n-}=$	$\chi_{n-}=$	$\chi_{n-}^2=$		
2	$\chi_{(n-1)+}=$	$\chi_{(n-1)+}=$	$\chi_{(n-1)+}^2=$	$\chi_{(n-1)-}=$	$\chi_{(n-1)-}=$	$\chi_{(n-1)-}^2=$		
3	$\chi_{(n-2)+}=$	$\chi_{(n-2)+}=$	$\chi_{(n-2)+}^2=$	$\chi_{(n-2)-}=$	$\chi_{(n-2)-}=$	$\chi_{(n-2)-}^2=$		
4	$\chi_{(n-3)+}=$	$\chi_{(n-3)+}=$	$\chi_{(n-3)+}^2=$	$\chi_{(n-3)-}=$	$\chi_{(n-3)-}=$	$\chi_{(n-3)-}^2=$		
Information: Outer radius is χ_+ and inner radius is χ_-.								

Follow the observation table III and find the value of $|\vec{\mu}_B|$

Warning! - Do not keep the high current more than 2 minutes

Experiment 3: Observation of Zeeman splitting in Longitudinal mode

In longitudinal mode, after applying magnetic field, 6 sets of emission marked as $\Delta m_J = +1, -1$ as shown in figure 7. The energy for different transition can be calculated from equation 2 and 3 if the value of g_J and m_J are known. Here we will only observe the longitudinal Zeeman effect.

<u>STEPS TO FOLLOW</u>

Step 1: Go to the setup 2.

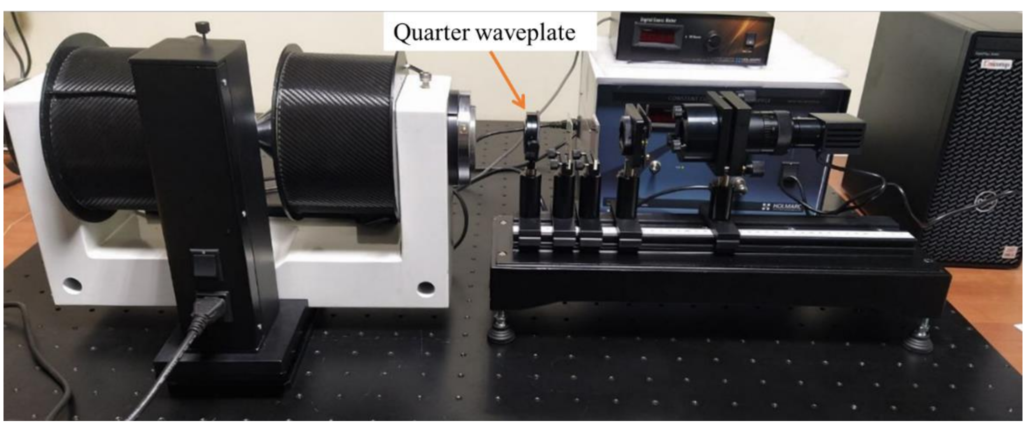


Fig. 18: Setup 2. Longitudinal mode.

Step 2: Turn on the mercury lamp and observe the rings on screen. Do not turn the magnetic field on. Take a picture without putting quarter waveplate. Save it as 0A_Lon (resolution 1280x960x24)

Step 3: Turn on the magnetic field by keeping current at 0.75 A. See the splitting in circular fringes. Take the picture and save it as 0.75A_log_NoQWP.

Step 4: Place the quarter waveplate and rotate it to see that one of the split fringes appears at one angle while other ring appears at another angle. Save the images at both angles with angle in the name. 0.75A_log_QWP_220 and 0.75A_log_QWP_xyz.

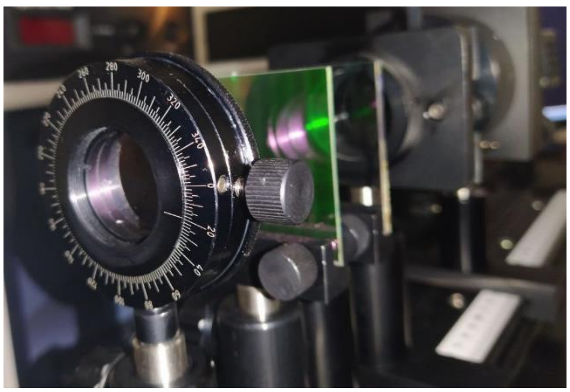
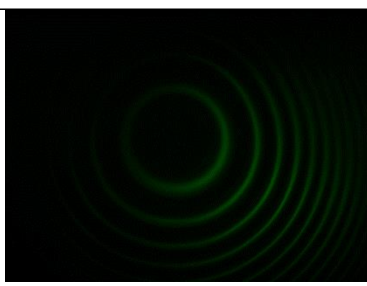
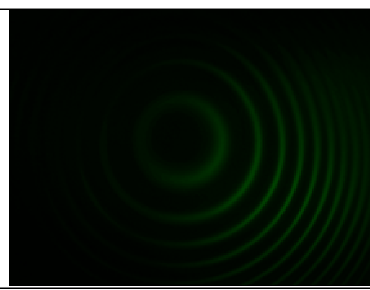
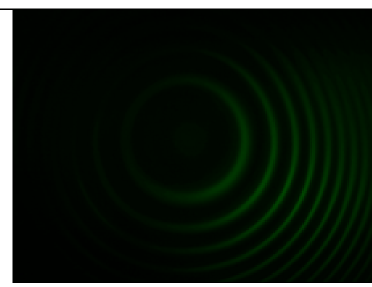
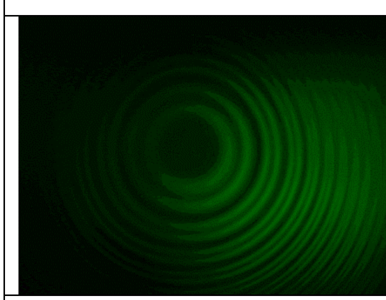


Fig. 19: Quater wave plate and angle markings

		
Fringes at zero magnetic field	Fringe at one angle where one circular polarization is visible	Fringe at angle where other circular polarization is visible
	The image can be edited to enhance the contrast in image capture software Or after the image is taken.	
Fringes at 0.75A with no quarter waveplate		

ERROR ANALYSIS

The error in $\vec{\mu}_B$ requires error in $\chi_{n+}, \chi_{n-}, \lambda, F, B$ and their respective propagation because $\vec{\mu}_B$ depends upon all these quantities as

$$|\overrightarrow{\mu_B}| = \frac{hc(\chi_{n+}^2 - \chi_{n-}^2)}{4(g_{JH} - g_{JL})\lambda F^2 |\vec{B}|}$$

The complete error analysis is beyond the scope of this lab given the limited time. However, the percentage error can be calculated as

$$\%\, Error = \frac{|Theoretical\ value - Calculated\ value|}{Theoretial\ \ value}$$

Please consult a book on error analysis [7] to understand the basics.

REFERENCES

[1] Zeeman, P. (1896). On the influence of magnetism on the nature of the light emitted by a substance. Royal Academy of Sciences in Amsterdam (in Dutch). 5: 181–184 and 242–248

[2] Umakant Rapol's Lab (http://sites.iiserpune.ac.in/~umakant.rapol/research/)

[3] Demtröder, Wolfgang. "Atoms, Molecules and Photons: An Introduction to Atomic-, Molecular- and Quantum Physics." Springer Science & Business Media, 2010

[4] Fox, Mark. "Atomic and Molecular Physics: An Introduction." Oxford University Press, 2018

[5] Haken, H. and Wolf, H.C. "The Physics of Atoms and Quanta: Introduction to Experiments and Theory." Springer-Verlag, 2005

[2] Source for semiclassical theory

[3] Mark Fox atomic theory

[4] Area Vector

[5] The comprehensive details are available at

[6] The information of angular momentum are stored in this symbol

[7] Taylor, J.R. An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurement

[a] Balmer series

[b] Despite energy levels being sharp, there is broadening i.e spectrum has spread over a range of wavelength. This is due to various factors like Lifetime broadening, Doppler broadening, Collision (Pressure) broadening etc. Please read: Fox Mark, Quantum Optics: An Introduction. (Oxford University Press, 2006) Chapter 4.

[c] The atomic theory borrowed ideas from solar system hence the intrinsic angular momentum of electron was called spin like spinning of planets on an axis. However, there is no such evidence for any fundamental particle to rotate around any axis.

[d] The number of peaks after splitting depends upon the initial and final energy level of atom.

[e] The minimum reading of **gauss meter** is 1x10 Gauss i.e. one order higher than the earth's magnetic field (<1 Gauss). therefore, earth's magnetic field cannot be picked with this device.

[f] One monochromator is used in Balmer series experiment.