T. Y. B. Sc. Physics (PH-354) Paper-IV

Atomic and Molecular Physics (CBCS Pattern)

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Chapter 4

Zeeman Effect

Introduction

The effect magnetic field on the spectrum was first discovered by Zeeman in 1836 and is called Zeeman Effect. It was observed that, a single spectral line splits up into three components, one has large frequency and other has lower frequency than original line. The third line has the frequency of original line.

When a sodium flame is kept between the poles of powerful electromagnet, two lines of principal doublet are broadened. According to Lorentz's theory, when light source is placed in magnetic field, the motion of the electron is changed. i. e. electrons will either speed up or slow down by certain amount which depends on magnetic field (H), mass (m), charge on electron (e) and velocity (v). If υ_0 the orbital frequency of electron without field, frequency in presence of field is given as $\upsilon_0 + \Delta\upsilon$

Where, $\Delta\upsilon = \frac{eH}{4\pi MC}$

Zeeman Effect-

Zeeman Effect is a magneto-optical phenomenon in which spectral lines are affected by an applied magnetic field and split up into several components. The simple splitting known as normal Zeeman Effect is obtained with strong magnetic field. Normal Zeeman effect consists of a triplet in a transverse view (perpendicular to magnetic field) and doublet in longitudinal direction (parallel to magnetic field). And more complex lines are observed in anomalous Zeeman Effect in weak magnetic field.

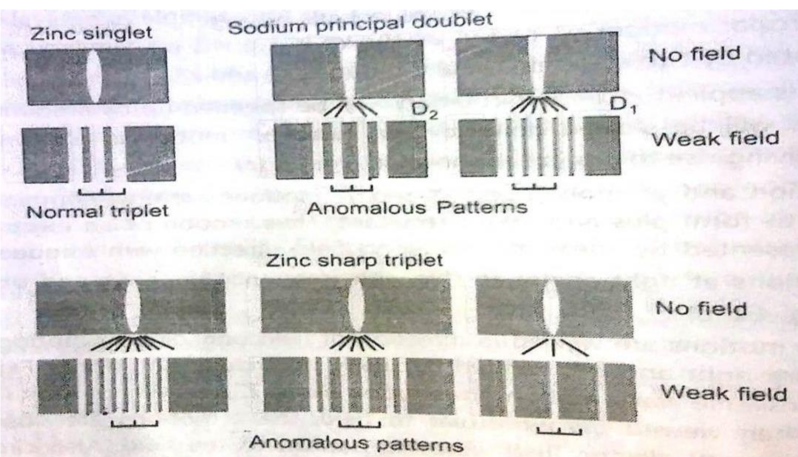


Fig. 4.2 : Normal and anomalous Zeeman effect (viewed perpendicular to the magnetic field)

Experimental arrangement-

Experimental set up consist of an electromagnet MM produce strong magnetic field having conical pole PP. Source L (Sodium vapour lamp) emitting spectral lines is kept between pole pieces. High resolving power instrument such as Lummer Gerke plate with constant deviation spectrometer S is used to observe spectral lines. To obtain a photograph, a camera is used in place of eyepiece of spectrometer.

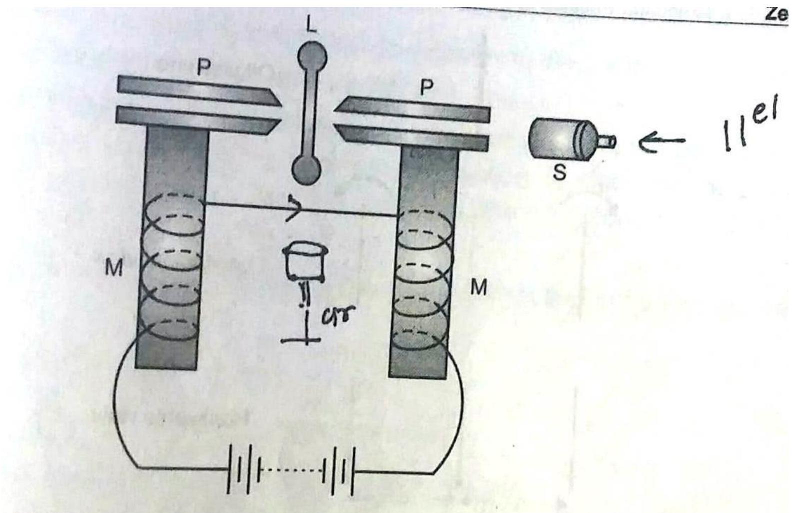
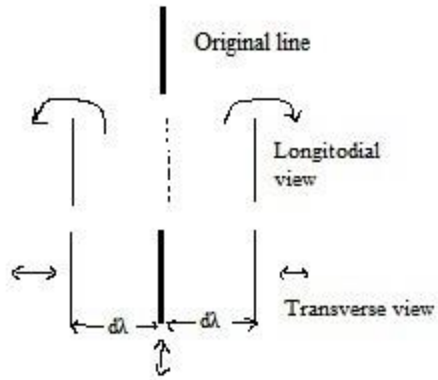


Fig. 4.3 : Experimental set up of normal Zeeman effect

When electromagnetic field is applied, spectral lines are observed in parallel view through the holes drilled to pole pieces and found to split up into two (doublet) lines of different frequency. And these lines are disappearing by removing electromagnetic field. In EM field these lines are found to be symmetrically situated about the position of parent line so that Zeeman shift (change in wavelength dλ) is same in both side. These two lines are found to be circularly polarized in opposite directions as shown by arrows.

When observed in perpendicular to the direction of magnetic field the line becomes triplet, the central line has same wavelength as original line and other two lines occupying same position as doublet in previous case. All these three lines are plane polarized, but vibrations of central line are parallel to magnetic field and other lines are perpendicular to the EM field. These lines can be photographed using camera in place of eyepiece of spectrometer and obtained Zeeman shift dλ.

In short Zeeman Effect is splitting of a single spectral line into two or more lines of different frequencies observed when radiation (such as light) originates in a magnetic field. There are two types of Zeeman Effect, Normal Zeeman Effect and Anomalous Zeeman Effect.



1. **Normal Zeeman Effect-** The splitting of spectral lines into three components in a magnetic field when viewed in a direction perpendicular to the magnetic field is called Normal Zeeman Effect. Normal Zeeman Effect is obtained from Ca, Cu, Zn, Cd sources of elements.
2. **Anomalous Zeeman Effect-** When a single spectral line is split up into four or more lines when observed in a direction perpendicular that of magnetic field is called Anomalous Zeeman Effect. This effect is observed in a weak magnetic field and obtained from elements like Na, Cr, etc.

Classical theory of Normal Zeeman Effect-

We know that, the splitting of spectral lines into three components in a magnetic field when observed in perpendicular direction to the magnetic field is called Normal Zeeman Effect. Consider electron revolving in a circular orbit, the centripetal force acting on it is given by

$$F = \frac{m\,v^2}{r}$$

Where v = velocity of electron, r = radius of orbit

But, v = rω $= \frac{2\pi}{T}$r = $2\pi r\boldsymbol{\upsilon}$

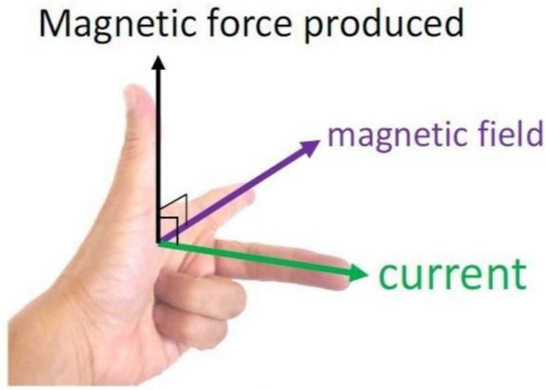
Now put value of v =$2\pi r\boldsymbol{\upsilon}$ in above equation,

$F = \frac{m}{r} 4\pi^2 r^2 \upsilon^2$

F = $4\pi^2 m r \upsilon^2$

If magnetic field is applied in direction perpendicular to the plane of orbit, the additional force = Hev

= He 2 $\pi r\boldsymbol{\upsilon}$ acts on electron.



Fleming's Left Hand Rule

According to Fleming left hand rule,

The direction of this force will be towards or away from the centre, so the motion of electron is clockwise or anticlockwise. If additional force is towards centre of the atom, the orbit contract and frequency of the rotation increases. If additional force is away from the centre of the atom, the orbit expands and frequency of the rotation decreases, then net force is,

$$F \pm He2\pi r\upsilon = 4\pi^2 mr\upsilon_l^2$$

where υ_l = Frequency of orbit

Substituting in equation (4.2) from equation (4.3), we g

$$4\pi^2 mr\left(\upsilon_l^2 - \upsilon^2\right) = \pm He2\pi r\upsilon$$

$$\upsilon_l^2 - \upsilon^2 = \pm \frac{He\upsilon}{2\pi m}$$

$$(\upsilon_l + \upsilon)(\upsilon_l - \upsilon) = \pm \frac{He\upsilon}{2\pi m}$$

But $\upsilon_l \approx \upsilon$, $\upsilon_l + \upsilon = 2\upsilon$ and $\upsilon_l - \upsilon = d\upsilon$

$$d\upsilon \cdot 2\upsilon = \pm \frac{He\upsilon}{2\pi m}$$

$$d\upsilon = \pm \frac{He}{4\pi m}$$

$$\upsilon = \frac{c}{\lambda}$$

$$d\upsilon = -\frac{c}{\lambda^2} d\lambda$$

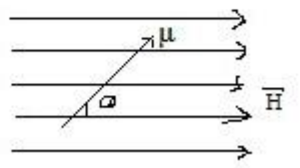
$$d\lambda = \pm \frac{\lambda^2}{c} \frac{He}{4\pi m}$$

λ = Wavelength of original line. $d\lambda$= Change in wavelength or Zeeman shift.

Quantum theory of Normal Zeeman Effect-

Atom in a magnetic field:

When atom is placed in a magnetic field H, a magnetic dipole moment μ exists. This magnetic dipole moment has potential energy dE, it depends upon magnitude and orientation of this momentum with respect to field.



Magnetic dipole moment μ at an angle θ relative to magnetic field H.

A torque τ acting on a magnetic dipole moment in H is given by,

$\tau = \mu H \sin\theta$

Where θ is angle between μ and H

When μ dipole moment is parallel or antiparallel to the field H then τ is zero and P.E. is zero. Any other orientation of μ the external work must be done to rotate the dipole from 90^o to the angle θ

$$\boldsymbol{dE = \int_{90}^{\theta} \tau d\theta}$$

$$dE = \mu H \int_{90}^{\theta} \sin\theta \; d\theta$$

$dE = -\mu H\cos\theta$

When $\tilde{\mu}$ points in the same direction of H, then θ=0 and cosθ

dE =-μH minimum value.

In magnetic moment of a current loop of area A and current I .Then $\vec{\mu} = I\vec{A}$

An electron revolving around nucleus of mass m, radius r with velocity v has angular momentum L= mv r Where v=rw w = 2πn i. e. V = 2πnr and L= $2\pi mnr^2$

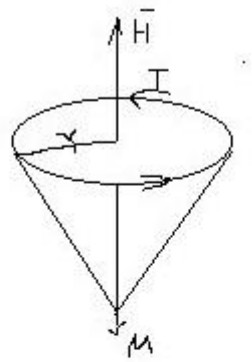
μ is magnetic momentum of electron due to orbital motion of electron. L is angular momentum.

$\mu = -\frac{e}{2m}L$

We know that,

$dE = -\mu H\cos\theta$

Put value of μ in above equation,



$dE = \frac{e}{2m} L$ Hcosθ --------------1.

But, **$L = \sqrt{l(l+1)}.\frac{h}{2\pi}$** ℓ is orbital quantum number, h is plank constant and

$\cos\theta = \frac{L_Z}{L} = \frac{M_l}{\sqrt{l(l+1)}}$

L_Z is in the direction of magnetic field vector H and m_ℓ is magnetic quantum number has value,

$m_\ell = (2\ell + 1)$

Values are from -ℓ to +ℓ through 0. Then put values of L and cosθ in equation 1.

$$dE = m\ell(\frac{eh}{4\pi m})H$$

The quantity $\frac{eh}{4\pi m}$ is called Bohr magneton and has value 9.27×10^{-24}Joule /tesla. It is a unit of magnetic momentum.

Suppose, electron goes from initial higher energy level to lower energy level E_{oi} to E_{of} respectively when no field is applied. Then frequency is,

$$\upsilon_0 = \frac{E_{OI} - E_{Of}}{h}$$

When magnetic field, H is applied the energy of initial and final state is given by,

$$E_i = E_{OI} + m_{li}(\frac{eh}{4\pi m})H$$

$$E_f = E_{of} + m_{lf}(\frac{eh}{4\pi m})H$$

The frequency of emitted photon is given by,

$\upsilon = \frac{E_i - E_f}{h} = \frac{E_{Oi} - E_{OJ}}{h} + (m_{li} - m_{lj})\left(\frac{e}{4\pi m}\right)H$

$\upsilon = \upsilon_0 + \Delta m\ell\,(\frac{e}{4\pi m})H$

Selection rule for $\Delta m\ell$ = +1, 0, -1.

$\upsilon_1 = \upsilon_0 + (\frac{e}{4\pi m})H = \upsilon_0 + \Delta\upsilon$

$\upsilon = \upsilon_0$

$\upsilon = \upsilon_0 - (\frac{e}{4\pi m})H = \upsilon_0 - \Delta\upsilon$

Where, $\Delta\upsilon = (\frac{e}{4\pi m})H$ Bohr magneton

But, $C = \upsilon\lambda$

$\upsilon = \frac{c}{\lambda}$

$d\upsilon = -c\frac{d\lambda}{\lambda^2}$

$d\lambda = -\frac{\lambda^2}{c}d\upsilon$ Shift in wavelength is,

$d\lambda = \pm\frac{\lambda^2}{c}\left(\frac{e}{4\pi m}\right)H$

Normal Zeeman Effect for single valence electron system-

The effect of magnetic field on the spectrum of an atom was studied by Zeeman in 1896, When a sodium source is kept in between the pole pieces of a strong magnetic field, a spectral line splits up into three components one having larger frequency and other having lower frequency than frequency of original line and third line has equal to frequency of original line. Such splitting effect is called normal Zeeman Effect.

Here electron has orbital and spin motion, but due strong magnetic field ℓ-s coupling gets broken and splitting is due to $\vec{\ell}$ only. So we neglects the spin of electron, then angular momentum posses by electron is given as,

$$p_l = l\frac{h}{2\pi}$$

And orbital magnetic moment is,

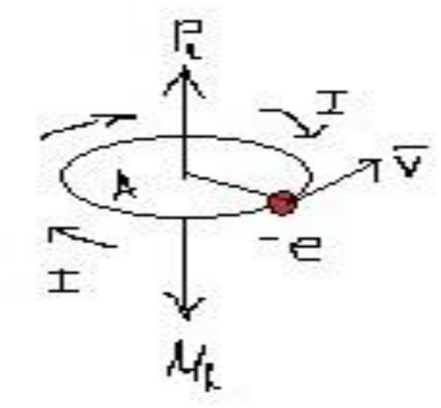
$$\mu_\ell = e\frac{lh}{4\pi m} = \frac{e}{2m}p_l$$

Now, in presence of external magnetic field, $\vec{\ell}$ possesses around the field direction. Such precession is called Larmour precession.

$\omega\ell = H\frac{\mu_\ell}{p_\ell} = \frac{e}{2m}H$

Here μ_ℓ and P_ℓ i.e. orbital magnetic moment and orbital angular moment is antiparalllel.

Here H is magnetic field and $\frac{\mu_\ell}{p_\ell}$ ratio is called as gyro magnetic ratio.

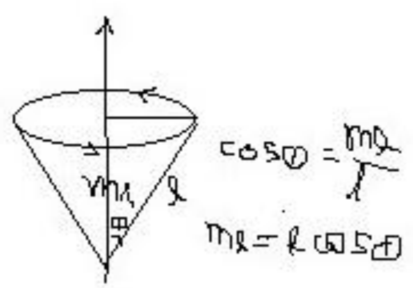


The electron gains an additional energy due to this precession,

ΔE= ω_ℓ X Projection of angular momentum on field direction.

ΔE = $\frac{e}{2\pi}H.$ P_ℓ Cosθ   but $P_\ell = \ell\frac{h}{2\pi}$

ΔE = $\frac{e}{2m}H.\ \frac{h}{2\pi}$ ℓCosθ



ΔE = $\frac{e}{2m}H.\ \frac{h}{2\pi}$ m_ℓ where m_ℓ is ℓCosθ   and values are (2ℓ+1) i.e. mℓ has value -ℓ, o, +ℓ.

If E_{1H} and E_{2H} are energies of two levels in presence of magnetic field and if E_1 and E_2 are energies in absence of magnetic field having values of mℓ,

$$E_{iH} = E_I + m_{li}(\frac{eh}{4\pi m})H$$

$$E_{2H} = E_2 + m_{l2}(\frac{eh}{4\pi m})H$$

Hence, radiations will be emitted in presence of magnetic field,

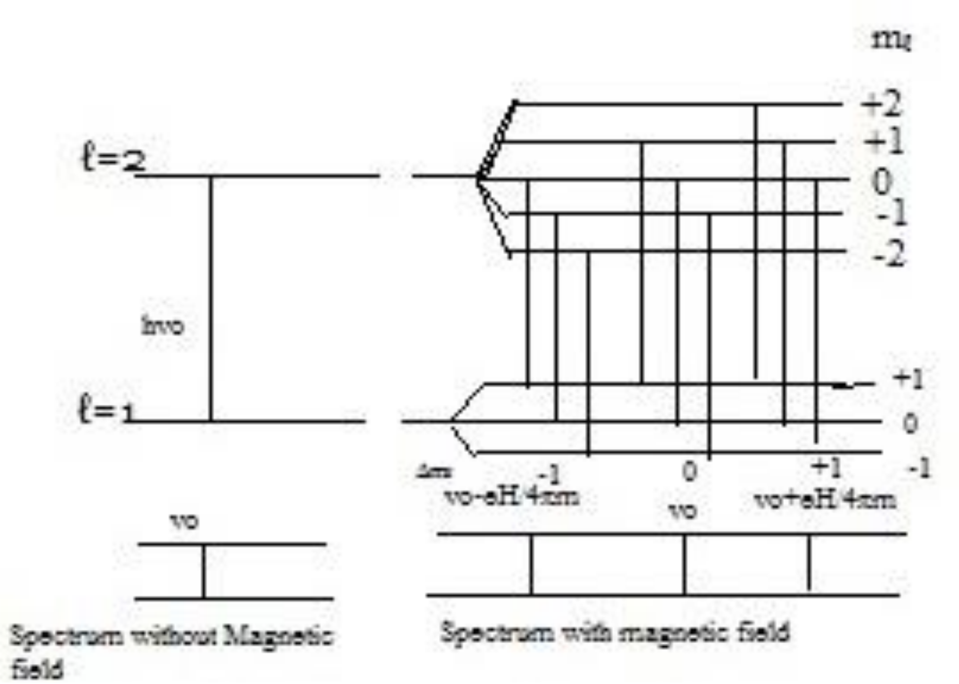
$$E_{iH} - E_{2H} = E_I - E_2 + \left(\frac{eh}{4\pi m}\right)H(m_{li} - m_{l2})$$

hυ = $h\upsilon_0 + \left(\frac{eh}{4\pi m}\right)H\ \Delta m_\ell$

$\upsilon = \upsilon_0 + \left(\frac{e}{4\pi m}\right) H\ \Delta m_\ell$, where υ_0 is the frequency of a line in absence magnetic field. The splitting is observed on the basis of selection rule, $\Delta m_\ell = 0$ or ± 1.

1. If $\Delta m_\ell = 0$ then $\upsilon_1 = \upsilon_0$
2. If $\Delta m_\ell = +1$ then $\upsilon_2 = \upsilon_0 + \left(\frac{e}{4\pi m}\right) H$
3. If $\Delta m_\ell = -1$ then $\upsilon_3 = \upsilon_0 - \left(\frac{e}{4\pi m}\right) H$

When atom is placed in a magnetic field, their energies slightly more or less than the energy of original line, thus splitting of spectral line takes place. The spacing of spectral lines will depends on magnitude of the field as shown in normal Zeeman Effect.



In the diagram, three transitions in a bracket represent due to the value of $\Delta m\ell$, and energy changes, hence a single spectral line split up unto three lines.

Stark Effect

The action electric field on the spectrum of hydrogen atom was discovered by stark in 1913, he was observed the splitting of Balmer lines. This phenomenon is exhibited by the spectra of all elements and is called as stark effect. The stark effect is the splitting of spectrum line into sevsral components by the application of an electric field.

Applications of Zeeman Effect

1. The zeman Effect is very useful in NMR Spectroscopy, electron spin resonance ESR, magnetic resonance imaging MRI and Mossbauer spectroscopy.
2. It may also be utilized to improve accuracy in atomic absorption spectroscopy.
3. It also used to determine the energy levels in atoms and identify them in terms of angular moments.
4. It also provides an effective means of studying atomic nuclei.
5. It is used in LASER cooling and in Astrophysics, Zeeman Effect to produce magneto-grams showing the variations of magnetic field on the Sun. It also used to study magnetic field in the diffuse and dense interstellar medium.