CHAPTER 7
ZEEMAN EFFECT

A. Introduction

Gambar 7.1. Pieter Zeeman

What happens if atom is placed in magnetic field? In external magnetic field $\vec{B}$, magnetic dipole has potential energy of V_m which its value depend on magnetic dipole $\vec{\mu}$ and orientation of magnetic dipole from external magnetic field as shown in Figure 7.1 as follow:

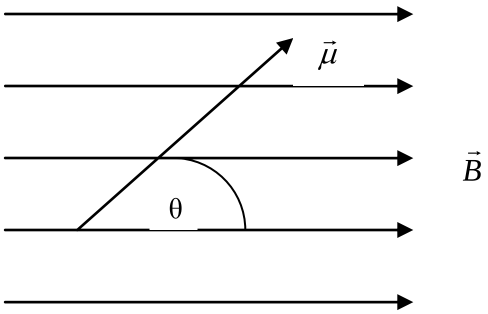


Figure 7.1. Magnetic dipole moment $\vec{\mu}$ has an angle of θ from magnetic field $\vec{B}$

Torque which exerts in magnetic dipole moment in external magnetic field $\vec{B}$ is:

$$\vec{\tau} = \vec{\mu} x \vec{B} = \mu B \sin\theta \tag{7.1}$$

This torque will be maximum if the magnetic dipole moment is perpendicular from the direction of magnetic field, and will be zero if it is parallel or anti parallel from the direction of magnetic field.

B. Magnetic Potential Energy

To determine value of potential energy V_m it must be determined the reference configuration (example: it is taken V_m=0 for $\theta = 90^o$, in this case $\vec{\mu}$ is perpendicular from $\vec{B}$. Potential energy in other orientation of $\vec{\mu}$ equal to external work which has to be done for rotate dipole moment $\vec{\mu}$ from $\theta = 90^o$ to the angle of θ :

$$V_m = \int_{90^o}^{\theta} \tau d\theta = \mu B \int_{90^o}^{\theta} \sin\theta \; d\theta = -\mu B \cos\theta \qquad (7.2)$$

If $\vec{\mu}$ is in parallel direction with $\vec{B}$ so $V_m = -\mu B$, it is a minimum energy. It is a consequence from the fact that magnetic dipole moment tend to make a parallel direction with external magnetic field.

C. Magnetic Moment of Current Loop

Because of magnetic motion of orbital electron in hydrogen atom depends on angular momentum $\vec{L}$, and the direction of $\vec{L}$ from magnetic field, it gives a contribution in total energy of atom if atom is placed in external magnetic field. Magnetic moment of *current loop* is:

$$\mu = I \; A \qquad (7.3)$$

where I is electrical current, and A is the area surrounded by the current loop. Electron has rotation frequency of in circular orbit of r proportional with current of -e υ (because charge of electron is –e), and its magnetic dipole moment is:

$$\mu = -e\upsilon\pi r^2 \qquad (7.4)$$

Linear speed of electron is, so the value of orbital momentum of electron is:

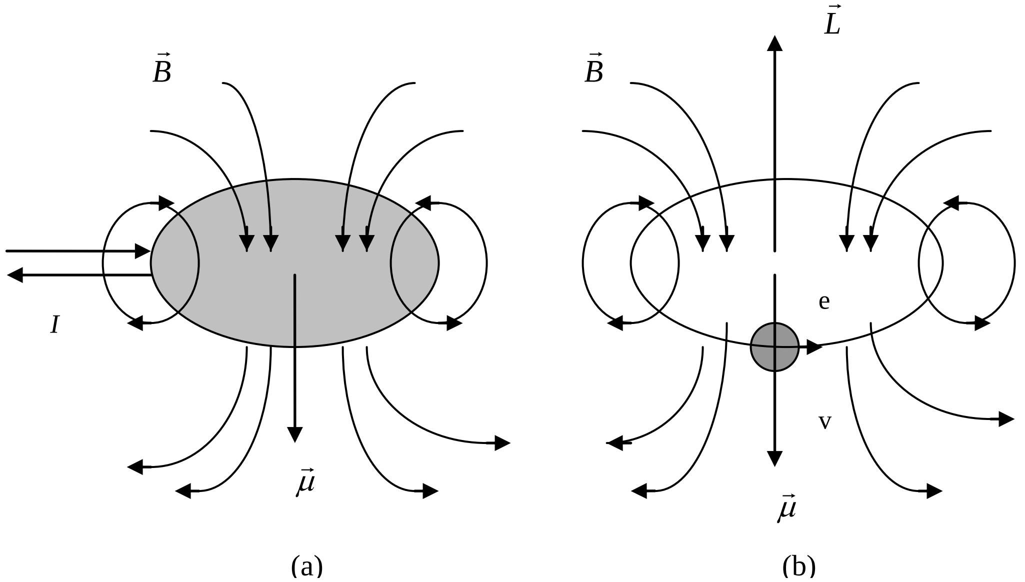
$$L = mvr = m(2\pi\upsilon \; r)r = 2\pi m\upsilon \; r^2 \qquad (7.5)$$

By comparing equation of magnetic dipole moment (7.4) with equation of angular momentum (7.5) it is obtained magnetic dipole momen of orbital electron:

$$\vec{\mu} = -\frac{e}{2m_e}\vec{L} \tag{7.6}$$

Ratio $-\frac{e}{2m_e}$ which only depend on charge and mass of electron is called *rasio giromagnetik*. The minus sign (-) show that the direction of magnetic dipole moment of orbital electron $\vec{\mu}$ in opposite direction with the direction of angular momentum $\vec{L}$. The formulae of magnetic dipole moment of orbital electron in equation (7.6) is obtained classically, and the fact that quantum mechanics gives the sma result. It means that magnetic potential energy of atom which placed in external magnetic field is:

$$V_m = \left(\frac{e}{2m_e}\right)LB \ \cos\theta \tag{7.7}$$



(a) (b)

Gambar 7.1. Momen Magnetik Pada Simpal Arus dan Elektron Orbital

Selanjutnya berpijak pada Gambar 7.2 berikut dapat dilihat bahwa sudut antara $\vec{L}$ dan z hanya boleh memiliki harga tertentu yang memenuhi hubungan:

$$\cos\ \theta = \frac{m_l}{\sqrt{l(l+1)}} \tag{7.8}$$

The value of angular momentum which permitted is:

$$L = \hbar\sqrt{l(l+1)}$$

Substitute equation (7.8) in equation (7.7) is resulted magnetic energy of atom which placed in external magnetic field:

$$V_m = m_l\left(\frac{e\hbar}{2m_e}\right)B = m_l\mu_B B \qquad (7.9)$$

where $\mu_B = \left(\frac{e\hbar}{2m_e}\right) = 9{,}27.10^{-24}\ J/T$ which is called as Bohr magneton.

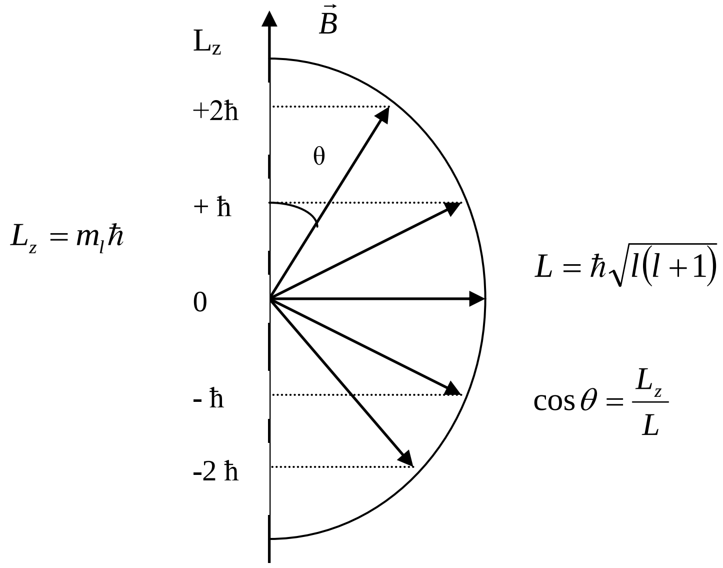


Figure 7.2. Determination the angle of θ

So in external magnetic field, a certain energy states of atom depend on magnetic quantum number of m_l and principal quantum number of n. State with principal quantum number n will be splitted in several substates if atom is placed in external magnetic field and its energy undergoes shift to be lower or higher compared without magnetic field. That phenomenon cause the splitting of single line spectral (singlet) to be triple line spectral (triplet) if atom placed in external magnetic field. The distance among the lines spectral depend on the intensity of magnetic field $\vec{B}$.

D. Zeeman Effect

The phenomenon of the splitting of line spectral which caused by atom placed in external magnetic field is called Zeeman effect. This term is taken from the name of physicist of Zeeman who observed this phenomenon in 1896. Zeeman Effect is a clear proven of space quantification.

Because m_l can have value of (2l+1), from +l pass through 0 until –l, so the state with orbital quantum number of l is splitted to be (2l+1) sub states which have difference energy of $\mu_B B$ if atom placed in external magnetic field. Nevertheless, because of the difference of m_l is limited at $\Delta m_l = 0, \ \pm 1$, so we can hope spectral lines which resulted by transition between two states with different l is only splitted to be three component. Normal Zeeman effect consist of spectral lines with frequency of υ_o to be three component of frequency:

$$\upsilon_1 = \upsilon_o - \frac{\mu_B B}{\hbar} = \upsilon_o - \frac{eB}{4\pi m} \tag{7.10}$$

$$\upsilon_2 = \upsilon_o \tag{7.11}$$

$$\upsilon_1 = \upsilon_o + \frac{\mu_B B}{\hbar} = \upsilon_o + \frac{eB}{4\pi m} \tag{7.12}$$

In Figure 7.3 is presented single line is splitted to be three lines in Zeeman effect.

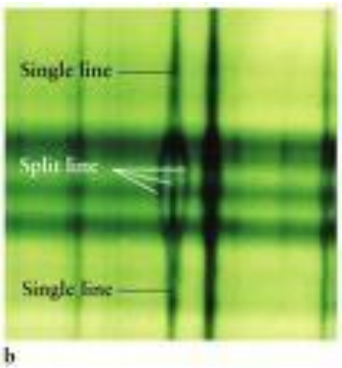


Figure 7.3. Zeeman Effect

Furthermore in Figure 7.4 is presented normal Zeeman effect for state l = 1 and l = 2.

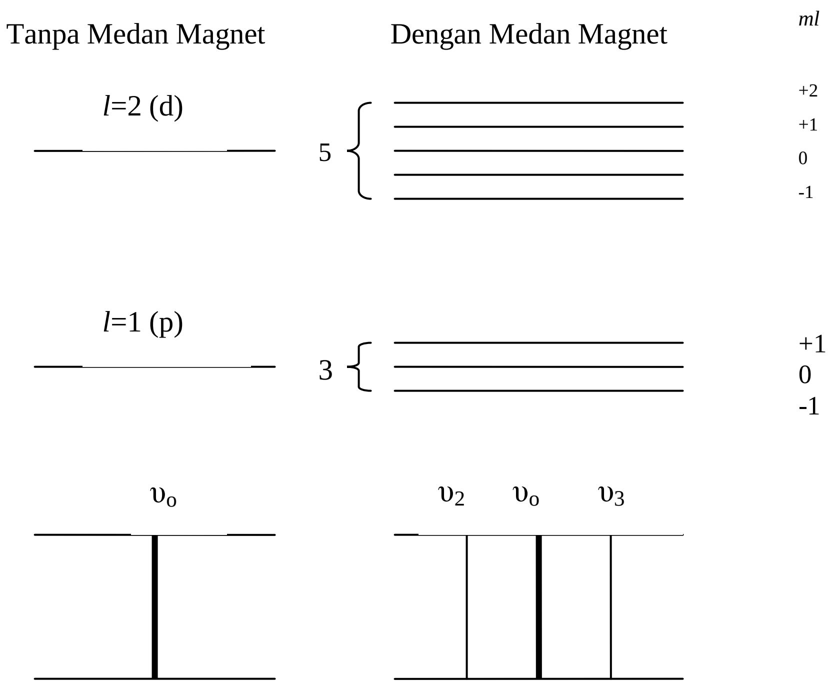


Figure 7.4. Normal Zeeman Effect

E. Reference

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