**NATIONAL UNIVERSITY OF SCIENCE AND TECHNOLOGY**

**FACULTY OF SCIENCE AND TECHNOLOGY EDUCATION**

**DEPARTMENT OF SCIENCE, MATHEMATICS AND TECHNOLOGY EDUCATION**

**MASTER OF SCIENCE EDUCATION IN PHYSICS**

**ATOMIC AND OPTICAL PHYSICS (PST 6174)**

**Main Examination Paper**

**November 2024**

**This Examination Paper consists of 5 printed pages**

| | |
|---|---|
| Time allowed | : 3 hours |
| Total Marks | : 100 |
| Special requirements | : None |
| Internal Examiner | : Mr J. Hlongwane |
| External Examiner | : Dr Zezekwa |

**INSTRUCTIONS**

1. Answer **any four** questions (each question carries 25 marks).
2. Show all your working steps clearly in any calculation.
3. Start the answer for any question on a new page.

**MARK ALLOCATION**

| QUESTION | MARKS |
|---|---|
| 1. | 25 |
| 2. | 25 |
| 3. | 25 |
| 4. | 25 |
| 5. | 25 |
| **TOTAL (Four questions)** | 100 |

**Physical constants**

| | |
|---|---|
| Rest mass of an electron | $m = 9.1x10^{-31}kg$<br>$m_e = 0.000549u$ |
| Atomic mass unit | $u = 1.66x10^{-27}kg$<br>$u = 931.48MeV$ |
| Speed of light | $c = 2.998x10^{8}ms^{-1}$ |
| Mass of hydrogen atom | $m_H = 1.007825u$ |
| Mass of neutron | $m_n = 1.008665u$ |
| Mass of Helium atom $^{4}_{2}He$ | $m_{He} = 4.002604u$ |
| Mass of Deuterium $^{2}_{1}H$ | $m_D = 2.01419u$ |
| Charge of electron | $e = 1.60217657x10^{-19}C$ |
| Boltzmann constant | |
| Planck's constant | $h = 6.62606957x10^{-34}Js$<br>$\hbar = \frac{h}{2\pi}$ |
| Rydberg constant | $R_\infty = 1.097373156854X10^{7}m^{-1}$ |
| Bohr radius | $a_0 = 5.291772109x10^{-11}m$ |
| Bohr magneton | $\mu_B = 9.2740097 \times 10^{-24}J/T$ |
| Nuclear magneton | $\mu_N = 5.0507835 \times 10^{-27}J/T$ |
| Permittivity of free space | $\varepsilon_0 = 8.85x10^{-12}Fm^{-1}$ |
| Permeability of free space | $\mu_0 = 4\pi \times 10^{-7}Hm^{-1}$ |

**Spherical Harmonics**

$$Y_{lm}(\theta,\varphi) = (-1)^m \sqrt{\frac{2l+(l-m)!}{4\pi(l+m)!}} P_l^m(\cos\theta) e^{im\varphi} \qquad u = \cos\theta$$

$$P_l^m(u) = (-1)^{l+1} \frac{(l+1)!}{(l-m)!} \frac{(1-u^2)^{-m/2}}{2^l l\ !} \left(\frac{d}{du}\right)^{l-m} (1-u^2)^l \qquad u = \cos\theta$$

**The first few spherical harmonics, $Y_l^m(\theta,\varphi)$**

$$Y_0^0(\theta,\varphi) = \sqrt{\frac{1}{4\pi}}$$

$$Y_1^0(\theta,\varphi) = \sqrt{\frac{3}{4\pi}}\cos\theta$$

$$Y_2^{\pm 1}(\theta,\varphi) = \mp\sqrt{\frac{15}{8\pi}}\,\sin\theta\cos\theta\,e^{\pm i\varphi}$$

$$Y_2^{\pm 2}(\theta,\varphi) = \sqrt{\frac{15}{32\pi}}\,sin^2\theta e^{\pm 2i\varphi}$$

1. a. Discuss how you would apply the knowledge of Atomic, molecular and optical (A.M.O) Physics to design a production plant to sustainably benefit from a renewable energy source of your choice. [10]

   b. With the aid diagrams explain the normal and anomalous Zeeman Effects to show the behaviour of atoms in external magnetic fields. [10]

   c. Briefly outline what Rydberg atoms are. [5]

2. a. Discuss five major shortfalls of the Bohr atomic model that led to the Quantum atomic model. [10]

   b. By applying your knowledge of the photoelectric effect and that of the Compton effect outline how electromagnetic radiation interacts with physical matter. [10]

   c. Given that $= \sqrt{l(l+1)}\hbar$ , where all symbols have their usual meanings in Physics, compute all the possible values of L for the hydrogen atom's p and d orbitals. [5]

3. a. The direction of an electron in orbit around the nucleus is quantised. Refer to the precession diagram in Fig 3.1 to explain this. [3]

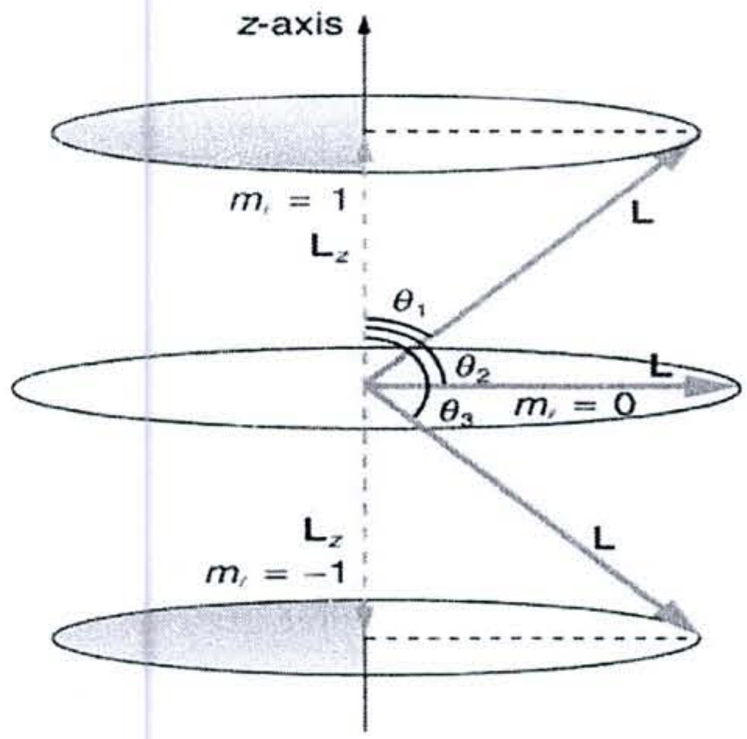


Fig 3.1

   b. Given that $L_z = m_l\hbar$. Determine all possible values of Lz for an electron in the p-orbital. [4]

   c. Calculate the magnitudes of the angles $\theta_1, \theta_2, \theta_3$ that L makes with the z-axis for l=1. [5]

   d. Discuss how an optical phenomenon like X-ray diffraction can be used to study the structure of atoms. [10]

   e. Explain the Lamb shift for the hydrogen atom. [3]

4. a. A particle with momentum p , position vector $\hat{r} = (x, y, z)$ and classical angular momentum $\widehat{L} = \hat{r}\,X\,\hat{p}$. Use vector algebra to find the x, y and z components of $\widehat{L}$. [10]

Hence or otherwise derive the corresponding expressions for the Quantum mechanical angular momentum components in units of $\hbar$, clearly stating the appropriate operators and mathematical method used.

b. Prove that in the units of $\hbar$, The components $L_x \; and \; L_z$ do not commute. [7]

c. Outline, giving two examples of applications how laser cooling can be achieved. [8]

5. a. One of the properties of laser light is that it is coherent. State and explain three major characteristics of coherent light sources. [6]

b. Explain the significance of studying the spherical harmonics in the understanding of atomic structure. [4]

c. A certain orbital electron is depicted by the wave-function [15]

$$\psi(\theta, \varphi) = 3 \sin\theta \cos\theta e^{i\varphi} - 2(1 - cos^2\theta)e^{2i\varphi}$$

Write $\psi(\theta, \varphi)$ in terms of the spherical harmonics.

**END OF EXAMINATION**