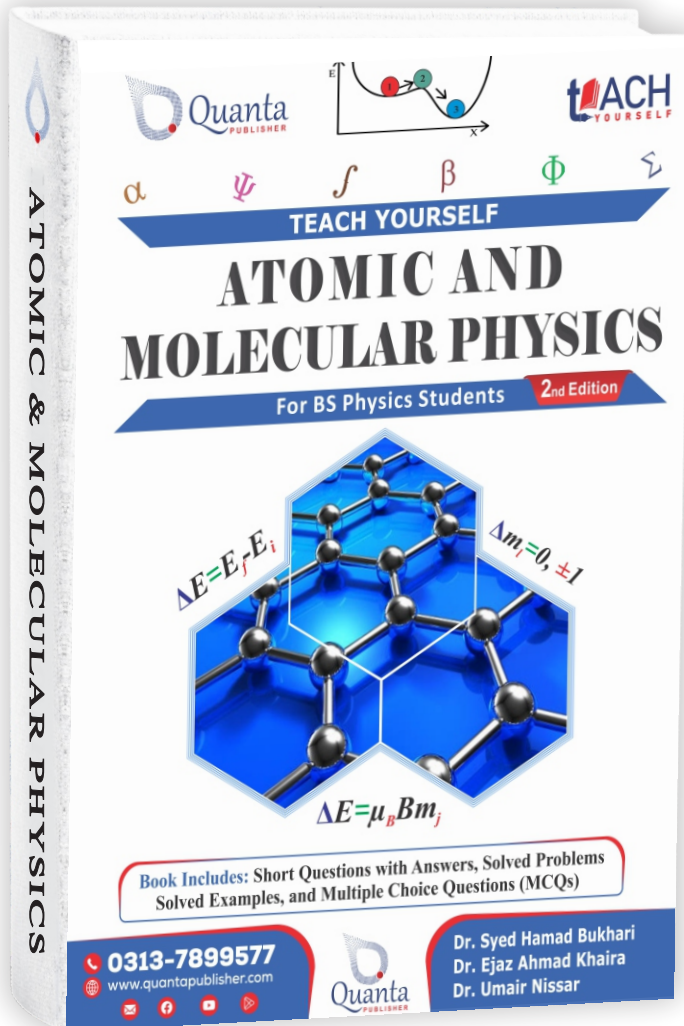




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# ATOMIC & MOLECULAR PHYSICS

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2nd Edition

For **BS Physics** Students of all Pakistani Universities/Colleges

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**Quanta** Publisher, Raza Abad, Shah Shamas, Multan. 03137899577

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## Chapter 1

# Structure of Atoms

**A**TOMS are defined as **the basic building blocks of matter**. An atom itself is made up of three tiny kinds of particles called subatomic particles: electrons, protons, and neutrons. The protons and the neutrons make up the center of the atom called the nucleus and the electrons moves around the nucleus in a small cloud. It was common perception that electrons revolve around the nucleus like planets do around the sun. But, classical electromagnetic theory rejected the possibility of stable electron orbit. To resolve this paradox, Neil Bohr applied quantum theory to understand atomic structure in 1913, and developed a model which is still a convenient mental picture of an atom. In this chapter, the main concern will be on Thomson model, Rutherford model, alpha particle scattering, electron orbits, atomic spectra of hydrogen, correspondence principle and Bohr atomic model. In addition, nuclear model and reduced mass, Sommerfeld model, Frank-Hertz experiment and approximation methods are discussed.

### 1.1 Thomson Model

**Question** On the basis of which known properties, Thomson proposed his model? Discuss its postulates and limitations.

The description of Thomson's atomic model is one amongst various scientific models about the structure of atom. It was proposed by J. J. Thomson in the year 1904 just after the discovery of electron. However, at that time the atomic nucleus was yet to be discovered. So, he proposed a model on the basis of known properties available at that time. The known properties are:

- Atoms are neutrally charged.
- Negatively charged particles called electrons are present in an atom (see Fig.(1.1)).

#### Postulates

- According to the postulates of Thomson's atomic model, an atom resembles a sphere of positive charge with electrons (negatively charged particles) present inside the sphere.
- The positive and negative charge is equal in magnitude and therefore an atom has no charge as a whole and is electrically neutral.

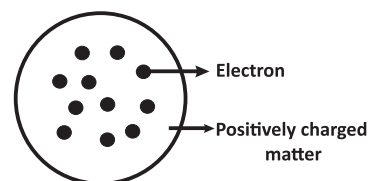


Fig. 1.1. The schematic picture of an atom.

## Chapter 2

# One Electron System

**T**HIS chapter is a profound exploration of essential quantum principles. Commencing with an extensive review of the Schrödinger equation for the hydrogen atom, it systematically covers Fermi's golden rule, quantum numbers, atoms in a radiation field, radiative transitions, and selection rules. The discussion extends to the refined realm of X-ray spectra, shedding light on magnetic moments and the intrinsic importance of the Bohr magneton. This comprehensive journey offers a thorough understanding of the distinctive characteristics and intricate behaviors inherent in single-electron systems, providing a foundational arm of quantum phenomena within this delicate and critical domain of physics.

### 2.1 Review of Schrödinger Equation for Hydrogen Atom

**Question** Discuss the review of Schrödinger equation for hydrogen atom. Explain its classical and quantum treatment also write the solution of the radial equation for the hydrogen atom.

The hydrogen atom consists of an electron and a proton (inside the nucleus). For simplicity, we will ignore their spins. The electron is at a distance  $\vec{r}$  from proton. Considering, the mass of electron and proton are  $m_1$  and  $m_2$  having  $\vec{r}_1$  and  $\vec{r}_2$  as the position vectors of electron and proton, respectively. The Coulomb's interaction between electron and proton is:

$$V(\vec{r}) = -\frac{1}{4\pi\epsilon_0} \frac{e \cdot e}{r}$$

In CGS system, we write 1 for  $\frac{1}{4\pi\epsilon_0}$ , we get

$$V(\vec{r}) = -\frac{e^2}{r} \quad (2.1)$$

Now, the Hamiltonian for hydrogen atom can be written as:

$$\hat{H} = -\frac{\hbar^2}{2m_1} \nabla_1^2 - \frac{\hbar^2}{2m_2} \nabla_2^2 + V(\vec{r}) = -\frac{\hbar^2}{2m_1} \left( \frac{\partial^2}{\partial x_1^2} + \frac{\partial^2}{\partial y_1^2} + \frac{\partial^2}{\partial z_1^2} \right) - \frac{\hbar^2}{2m_2} \left( \frac{\partial^2}{\partial x_2^2} + \frac{\partial^2}{\partial y_2^2} + \frac{\partial^2}{\partial z_2^2} \right) + V(\vec{r})$$

Moreover, the Schrödinger wave equation for two particle can be written as:

$$\hat{H}\psi(\vec{r}_1, \vec{r}_2) = E\psi(\vec{r}_1, \vec{r}_2) \quad (2.2)$$

## Chapter 3

# Many Body System

**E**MBARKING on the exploration of many-body systems, this journey reveals the tricky dance of interacting entities across physics. From the foundational Pauli exclusion principle to electronic configurations and the Stern-Gerlach experiment, each step resolves quantum mysteries. Central field approximations and advanced methodologies like the Hartree-Fock method illuminate multi-electron system dynamics. Spin-orbit coupling, LS coupling, and JJ coupling enrich atomic and molecular physics through angular momentum interplay. Specifically, the helium atom, from its ground state to electronic transitions, takes the spotlight. The exploration extends to the hyperfine structure, resolving interactions between electron and nuclear spins, contributing to the varieties of modern physics.

### 3.1 Pauli Exclusion Principle

**Question** State and explain the Pauli exclusion principle.

#### Statement

It states that no two electrons in an atom can have the same set of four quantum numbers  $n, \ell, m_\ell$  and  $m_s$ . This means that the two electrons that fill any particular orbital must have opposite spins. Orbitals are filled in order of increasing energy, with no more than two electrons per orbital which must have opposite spins.

#### Explanation

The concept of electron spin is based on the fact that electrons behave like tiny magnets. An electron spins about its axis much like a toy top. The revolving electrical charge generates a magnetic field. The electron can spin in two directions, either **clockwise** or **counter-clockwise**. Using the left hand rule for magnetic fields, the clockwise spinning electrons generate a north pole on top and a south pole on the bottom. The counter-clockwise spinning electrons generate a north pole on the bottom and a south pole on the top. In 1925, an Austrian Physicist, Wolfgang Pauli, expressed the importance of electron's spin in determining electronic configurations. **What happens if an orbital contains one electron?** Then its magnetic field is not cancelled out and it can be attracted to other outside magnetic fields. Atoms having at least one unpaired electron are **paramagnetic** and can be attracted to magnetic fields. Atoms with no unpaired electrons are said to be **diamagnetic** and are not seen to be magnetic.

## Chapter 4

# Interaction with Field

**E**XPLORING into the profound interplay between matter and electromagnetic fields, this exploration unveils absorbing phenomena such as the Zeeman effect. In the realm of atomic spectra, the normal and anomalous Zeeman effects complicated reveal the influence of magnetic fields on spectral lines. Shifting focus to electric fields, the Stark effect introduces a dynamic interplay, causing line splitting and shifting. Transitioning to longer wavelengths, the Paschen-Back effect further enriches our understanding of spectral phenomena in external fields. Together, these phenomena weave a narrative of the tricky dance between matter and the universal forces that shape its behavior in the realm of quantum physics.

### 4.1 Zeeman Effect

**Question** Define and explain the Zeeman effect.

Zeeman effect, in physics and astronomy, **the splitting of a spectral line into two or more components of slightly different frequency, when the light source is placed in a magnetic field.** It was first observed in 1896 by the Dutch physicist Pieter Zeeman as a broadening of the yellow D-lines of sodium in a flame held between strong magnetic poles. Later the broadening was found to be a distinct splitting of spectral lines into as many as 15 components. Zeeman's discovery earned him the 1902 Nobel prize for Physics, which he shared with a former teacher, Hendrik Antoon Lorentz, another Dutch physicist. Lorentz, who had earlier developed a theory concerning the effect of magnetism on light, hypothesized that the oscillations of electrons inside an atom produce light and that a magnetic field would affect the oscillations and thereby the frequency of the light emitted. This theory was confirmed by Zeeman's research and later modified by quantum mechanics, according to which spectral lines of light are emitted when electrons change from one discrete energy level to another. Each of the levels, characterized by an **angular momentum (quantity related to mass and spin)**, is split in a magnetic field into sub-states of equal energy. These sub-states of energy are revealed by the resulting patterns of spectral line components. The Zeeman effect has helped physicists to determine the energy levels in atoms and identify them in terms of angular momentum. It also provides an effective means of studying atomic nuclei and such phenomena as electron paramagnetic resonance. In astronomy, the Zeeman effect is used in measuring the magnetic field of the sun and of other stars.



# Chapter 5

## Molecules

**I**N the complex world of molecules, diverse bonding forces shape their properties. From ionic bonds, where electrons transfer between atoms, to covalent bonds, marked by electron sharing, and the refined world of polar and hydrogen bonding, molecular interactions govern substance characteristics. The fundamental  $H_2$  molecule, a cornerstone of diatomic systems, introduces us to rotational, vibrational, and electronic spectra. The Born-Oppenheimer approximation simplifies molecular dynamics, while polyatomic molecules broaden our understanding. The vector atom model and the LCAO approximation examine into molecular structures, and the Raman effect, explored classically and quantum mechanically, reveals the molecular harmony of interactions.

### 5.1 Chemical Bond and Molecular Formation

**Question** What is chemical bonding? How molecules are formed by chemical bonding? What are the types of chemical bonds?

Chemical bonding refers to the formation of a chemical bond between two or more atoms, molecules, or ions to give rise to a chemical compound. These chemical bonds are what keep the atoms together in the resulting compound. **The attractive force which holds various constituents (atom, ions, etc.) together and stabilizes them by the overall loss of energy is known as chemical bonding.** Therefore, it can be understood that chemical compounds are depending on the strength of the chemical bonds between its constituents; the stronger the bonding between the constituents, the more stable the resulting compound would be. The opposite also holds true; if the chemical bonding between the constituents is weak, the resulting compound would lack stability and would easily undergo another reaction to give a more stable chemical compound (containing stronger bonds). **To find stability**, the atoms try to lose their energy. Whenever matter interacts with another form of matter, a force is exerted on one by the other. When the **forces are attractive in nature**, then **energy decreases**. When the **forces are repulsive in nature**, then **energy increases**.

#### Types of Chemical Bonds

When substances participate in chemical bonding and yield compounds, the stability of the resulting compound can be estimated by the type of chemical bonds it contains. The type of chemical bonds formed vary in strength and properties. There are 4 primary types of chemical

## Chapter 6

# LASER

**E**MBARKING on the fascinating realm of lasers, this chapter resolve the foundational principles underlying these transformative devices. Beginning with the profound exploration of black body radiations, Wein's, Rayleigh-Jean's, and Max Planck's contributions set the stage for understanding the interplay of energy and matter. Exploring into the quantum realm, the chapter navigates through absorption, spontaneous emission, and the groundbreaking concept of stimulated emission, epitomized by Einstein coefficients. Discovering the unique characteristics of lasers, we delve into pumping schemes that energize these systems. Further, the narrative unfolds with a comprehensive exploration of laser types, including the iconic ruby laser, He-Ne laser, CO<sub>2</sub> laser, and Nd:YAG laser. Throughout, we examine diverse laser applications, illuminating the multiple ways in which these devices have revolutionized science, technology, and everyday life.

### 6.1 Black Body Radiation

**Question** Define and explain the black body radiation. Discuss the energy distribution spectrum and formulae for black body radiation. Also, describe the quantum theory and Max. Planck's formula for radiation and its assumptions.

**An object that absorbs all radiation falling on it, at all wavelengths, is called a black body.** When a black body is at a uniform temperature, its emission has a characteristic frequency distribution that depends on the temperature. This emission is called black body radiation. An ideal black body does not exist but a good approximation to a black body is a heat resisting material containing a cavity with a small hole called cavity radiator. It consists of hollow cavity having small opening at one end. Its inner walls are made rough and coated with lamp black or some good absorber. If any radiation is allowed to enter the cavity through the hole, it suffers reflection for a number of times inside the cavity and finally it is totally absorbed in it. The body tries to bring itself in thermal equilibrium with surrounding by emitting these radiations. These radiations are called black body radiations temperature radiations or cavity radiations and such body is called black body. **Black body is an object that is a perfect emitter and a perfect absorber of radiation.** The difference between the normal hot body and perfect black body is that energy emitted by the normal hot body depends on the temperature as well as nature of the body, where as the black body radiation are called temperature radiation because the

dergoing inelastic collision. Another sharp drop in plate current occurs which arises from excitation of the same energy level in other atom by the electrons. Fig.(1.22), shows series of critical potentials for a given atomic vapor is obtained. Thus, higher potentials result from two or more inelastic collisions and multiple of lowest one. To check whether the critical potentials are due to atomic energy levels, Franck and Hertz observed emission spectra of various vapor during electron bombardment. For example, in case of mercury, minimum electron energy of 4.9 eV was required to excite the 253.6 nm spectral line. Theoretically, photon of wavelength 253.6 nm has energy:

$$E = h\nu = \frac{hc}{\lambda} \quad \left( \because \nu = \frac{c}{\lambda} \right)$$

$$E = \frac{6.63 \times 10^{-34} \times 10^8}{253.6 \times 10^{-9}} = 7.84 \times 10^{-17} \text{ J} = 4.9 \text{ eV} \quad \left( \because 1 \text{ J} = 6.25 \times 10^{18} \text{ eV} \right)$$

Thus theoretical results agree with experiments observations as shown in Fig.(1.22).

### Results

The process of energy absorption from electron collisions is clearly visible in Fig.(1.22). When the accelerated electrons excite the electrons in mercury to upper states, they de-excite in such a way to produce a visible glow in the gas region in which the excitation is taking place. This confirms the concept of **quantization of energy levels** according to Bohr's model of an atom.

**Example 1.10.1** In the Frank-Hertz experiment, a beam of electrons is accelerated through a potential difference and collides with mercury atoms. Calculate the energy of the incident electrons when they produce their first excitation of mercury atoms at a potential difference of 4.9 V.

**Solution:** In the Frank-Hertz experiment, the incident electrons gain energy from the applied voltage, and they collide with mercury atoms. The minimum energy required to excite a mercury atom is the ionization energy or the energy difference between the ground state and the first excited state. The energy of an electron can be calculated using the formula:

$$E = eV = (1.602 \times 10^{-19} \text{ C})(4.9 \text{ V}) = 4.9 \times 1.602 \times 10^{-19} \text{ CV} = 4.9 \times 1.602 \times 10^{-19} \text{ J} = 4.9 \text{ eV}$$

This energy corresponds to the minimum energy required to excite mercury atoms in the Frank-Hertz experiment.

## 1.11 Approximation Methods

**Question** Explain the approximation methods in detail.

In an atom with many electrons, the potential in which an electron moves is far more complicated than the simple central Coulomb potential that the electron experiences in a hydrogen atom. This is because apart from the strong central Coulomb potential created by the positively charged nucleus of charge  $+Ze$ . The electron also has the pairwise electrostatic repulsive potentials caused by the other electrons. This repulsive potential is non-central. If this later part is neglected, the problem becomes much simpler and tractable. Consider, for example, two electrons atom with a nucleus of charge  $+2e$ . The total energy of the system is, under the as-

## 1.12 Short Questions with Answers

### 1.1 Could you provide a succinct explanation of Rutherford's atomic model?

**Answer:** Rutherford's model envisions an atom with a small, dense, positively charged nucleus at its center, housing most of the mass and positive charge. Negatively charged electrons orbit the nucleus in empty space. The gold nucleus, for instance, has a radius less than  $3 \times 10^{-14}$  m, significantly smaller than the overall atomic radius.

$$R = \frac{2z e^2}{4\pi\epsilon_0 K.E_{\text{initial}}}$$

### 1.2 In Bohr's model the electron is in constant motion. How can such electron have a negative amount of energy?

**Answer:** In Bohr's model, the hydrogen atom's total energy is negative, signifying electron-nucleus binding. With positive energy ( $E > 0$ ), an electron can't sustain a closed orbit. In the ground state, the electron has negative energy due to the attractive force with the nucleus, confining it to a stable, low-energy orbit. Absorbing energy allows transitions to higher, less negative energy levels.

$$E = -\frac{e^2}{8\pi\epsilon_0 r}$$

### 1.3 Could you elucidate the concept of space quantization?

**Answer:** In quantum mechanics, space quantization dictates that certain physical properties, such as angular momentum and magnetic moment, can only exist in discrete levels, not a continuous spectrum. This fundamental principle shapes the behavior of subatomic particles, playing a pivotal role in comprehending the dynamics of atoms and other quantum systems.

### 1.4 If Bohr's theory and wave mechanics predict the same result for energies, then which is the best?

**Answer:** Although, Bohr's theory and wave mechanics yield similar results for hydrogen atom energies, the latter's greater complexity is essential. Wave mechanics provides a comprehensive description of particles at atomic and subatomic levels, extending beyond hydrogen. It explains phenomena like wave-particle duality, interference, and tunneling, crucial for modern physics, chemistry, and technology.

### 1.5 Write the limitations of Thomson model of an atom.

**Answer:** Limitations of Thomson's atomic model are:

- Thomson's atomic model failed to explain how the positive charge holds on the electrons inside the atom.
- It also failed to explain an atom's stability.
- The theory did not mention anything about the nucleus of an atom.
- It was unable to explain the scattering experiment of Rutherford.

### 1.6 Why current drops abruptly in Franck and Hertz experiment?

**Answer:** Franck Hertz's experiment reveals current drops due to inelastic collisions between accelerated electrons and gas atoms. At specific voltages, electron energy matches the gas atom excitation threshold. In these collisions, electrons lose energy, slowing down and causing a current reduction. This supports quantum mechanics by demonstrating quantized energy levels in atoms.

### 1.7 What is Sommerfeld model of an atom.

**Answer:** The Sommerfeld model extended Bohr's atomic model by using elliptical orbits and introducing the azimuthal quantum number, providing a more accurate representation of complex atom's behavior and offering

## 1.13 Solved Problems

**Problem 1.1.** Calculate the linear velocity of an electron in the first, second and third orbit of hydrogen atom.

### Solution

Given that:  $e = 1.6 \times 10^{-19} \text{ C}$ ,  $\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2\text{N}^{-1}\text{m}^{-2}$ ,  $h = 6.63 \times 10^{-34} \text{ Js}$ ,  $Z = 1$ ,  $v_1 = ?$   $v_2 = ?$   $v_3 = ?$

The velocity of an electron in  $n$ th orbit is given by:

$$v_n = \frac{e^2 Z}{2\epsilon_0 n h}$$

For first orbit, we have  $n = 1$ ,  $Z = 1$ :

$$v_1 = \frac{(1.6 \times 10^{-19})^2 \times 1}{2 \times 8.85 \times 10^{-12} \times 1 \times 6.63 \times 10^{-34}} = 2.17 \times 10^{-2} \times 10^{-38} \times 10^{46} = 2.17 \times 10^6 \text{ ms}^{-1}$$

For second orbit,  $n = 2$ :

$$v_2 = \frac{(1.6 \times 10^{-19})^2 \times 1}{2 \times 8.85 \times 10^{-12} \times 2 \times 6.63 \times 10^{-34}} = 1.08 \times 10^{-2} \times 10^{-38} \times 10^{46} = 1.08 \times 10^6 \text{ ms}^{-1}$$

For third orbit,  $n = 3$ :

$$v_3 = \frac{(1.6 \times 10^{-19})^2 \times 1}{2 \times 8.85 \times 10^{-12} \times 3 \times 6.63 \times 10^{-34}} = 0.72 \times 10^{-2} \times 10^{-38} \times 10^{46} = 0.72 \times 10^6 \text{ ms}^{-1}$$

**Problem 1.2.** Calculate the frequency of revolution of an electron in first and second orbit of hydrogen atom.

### Solution

Given that:  $m = 9.1 \times 10^{-31} \text{ kg}$ ,  $e = 1.6 \times 10^{-19} \text{ C}$ ,  $\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^{-2}\text{N}^{-1}\text{m}^{-2}$

$h = 6.63 \times 10^{-34} \text{ Js}$ ,  $Z = 1$ ,  $f_1 = ?$ ,  $f_2 = ?$

The frequency of revolution of an electron in the  $n$ th orbit is given by:

$$f_n = \frac{m e^4 Z^2}{4\pi \epsilon_0^2 h^3 n^3}$$

For first orbit,  $n = 1$ :

$$f_1 = \frac{9.1 \times 10^{-31} \times (1.6 \times 10^{-19})^4 (1)^2}{4 \times 3.14 \times (8.85 \times 10^{-12})^2 \times (6.63 \times 10^{-34})^3 (1)^3} = \frac{59.6377 \times 10^{-107}}{2.8817 \times 10^5 \times 10^{-126}}$$

$$f_1 = 2.06 \times 10^{-4} \times 10^{14} = 2.06 \times 10^{10} \text{ rev. s}^{-1}$$

For second orbit,  $n = 2$ :

$$f_2 = \frac{9.1 \times 10^{-31} \times (1.6 \times 10^{-19})^4 (1)^2}{4 \times 3.14 \times (8.85 \times 10^{-12})^2 \times (6.63 \times 10^{-34})^3 (2)^3} = \frac{59.6377 \times 10^{-107}}{2.8817 \times 10^5 \times 10^{-126}} \frac{1}{8}$$

$$f_2 = \frac{2.06}{8} \times 10^{-4} \times 10^{14} = 0.257 \times 10^{10} \text{ rev. s}^{-1}$$

**Problem 1.3.** An electron collides with a hydrogen atom in its ground state and excites into state of  $n = 2$ . How much energy was given to hydrogen atom in this inelastic collision?

### Solution

Here,  $n_i = 1$ ,  $n_f = 2$ ,  $E_1 = -13.6 \text{ eV}$ ,  $\Delta E = ?$

Energy change of a hydrogen atom that goes from its initial state of quantum number  $n_i$  to final state of quantum number  $n_f$  is:

$$\Delta E = E_f - E_i = \frac{E_1}{n_f^2} - \frac{E_1}{n_i^2} = -13.6 \left( \frac{1}{2^2} - \frac{1}{1^2} \right) = -13.6 \left( \frac{1}{4} - 1 \right) = 10.2 \text{ eV}$$

## 1.14 Multiple Choice Questions (MCQs)

- Which model of the atom introduced the concept of discrete electron orbits?  
 (a) Rutherford model      (b) Thomson model      (c) **Bohr atomic model**      (d) Sommerfeld model
- What did the Thomson model propose about the structure of the atom?  
 (a) The atom is mostly empty space      (b) The atom has a dense, positively charged nucleus  
 (c) Electrons are arranged in discrete orbits      (d) **Electrons are uniformly distributed**
- What did Rutherford's alpha particle scattering experiment reveal about the atom?  
 (a) **Atoms have a dense, positively charged nucleus**  
 (b) Electrons are arranged in concentric orbits around the nucleus  
 (c) Atoms are mostly empty space  
 (d) Electrons are evenly distributed throughout the atom
- What did Rutherford's alpha particle scattering experiment reveal about the atom's structure?  
 (a) Mostly empty      (b) **Dense nucleus**      (c) Uniform distribution      (d) Positive charge
- Which particles were used in Rutherford's scattering experiment?  
 (a) Electrons      (b) Protons      (c) **Alpha**      (d) Neutrons
- According to Rutherford's model, where are electrons located?  
 (a) Nucleus      (b) Protons      (c) **Orbits**      (d) Alpha particles
- How did Rutherford describe the motion of electrons in his model?  
 (a) Fixed      (b) **Random**      (c) Circular      (d) Eccentric
- What did Rutherford's experiment disprove about Thomson's model?  
 (a) **Uniform distribution**      (b) Positive nucleus      (c) Stable orbits      (d) Negative charge
- What interaction caused the deflection of alpha particles in Rutherford's experiment?  
 (a) **Electrostatic**      (b) Magnetic      (c) Gravitational      (d) Nuclear
- What did Rutherford conclude about the atom's structure based on his experiment?  
 (a) **Mostly empty**      (b) Uniformly dense      (c) Electron cloud      (d) Solid nucleus
- What is the significance of Bohr's atomic model?  
 (a) Introduced quantum mechanics      (b) **Described atomic structure**  
 (c) Explained chemical bonding      (d) Discovered the electron
- According to Bohr's model, which orbits are stable?  
 (a) Any orbit      (b) **Inner orbits**      (c) Outer orbits      (d) Random orbits
- What determines the energy of an electron in Bohr's model?  
 (a) Velocity      (b) Radius      (c) Quantum number      (d) **Principal quantum number**
- How did Bohr's model explain atomic spectra?  
 (a) Continuous      (b) **Discrete**      (c) Variable      (d) Infrared
- What does the principal quantum number signify in Bohr's model?  
 (a) **Energy level**      (b) Orbital shape      (c) Spin direction      (d) Electron density
- What happens when an electron transitions to a lower energy level in Bohr's model?  
 (a) Absorbs energy      (b) **Emits energy**      (c) Stays unchanged      (d) Increases speed
- What is the formula for calculating the energy of an electron in Bohr's model?  
 (a)  $E = mv$       (b)  $E = mc^2$       (c)  $E = -13.6/n^2 \text{ eV}$       (d)  $E = Fd$

Course outline of various universities are given below. The page numbers of topics are mentioned to follow your respective university outline.

### Government College University, Faisalabad (GCUF)

**Course Title:** Modern Physics-II                      **Course Code:** PHY-404                      **Semester-IV**

Review of Bohr's theory (P#15), Sommerfeld model (P#20), Frank-Hertz Experiment (P#23), Stern-Gerlach Experiment (P#66), Quantum numbers (P#42), Radiative transition (P#48), Selection rules (P#49), Zeeman Effect (P#90) (normal (P#91) and anomalous Zeeman Effect (P#93), The Stark Effect (P#95), Pauli exclusion principle (P#63), Spin orbit coupling (P#75), LS coupling (P#76), JJ coupling (P#77), X-ray spectra (P#51), Molecular spectra, Ionic and covalent bonding (P#111), Diatomic molecular-rotational (P#116), Vibrational and electronic spectra (P#118), Polyatomic molecules (P#123), Black body radiation (P#139), Einstein co-efficient (A and B coefficients) (P#144) and stimulated emission (P#144), Pumping schemes (P#148), Characteristics of laser (P#146), Different types of lasers (P#149), Laser applications (P#161), The fine structure of hydrogen, Helium (P#78), The ground state of helium (P#79), Excited states of helium (P#80), Transitions in helium (P#81).

### Ghazi University, D. G. Khan

**Course Title:** Atomic and Molecular Physics                      **Course Code:** PHY-607                      **Semester-VII**

**Structure of Atoms:** Review of Bohr's theory (P#15), Sommerfeld model (P#20), Frank Hertz experiment (P#23) and approximation methods (P#24).

**One Electron System:** Review of Schrodinger equation for hydrogen atom (P#35), Fermi Golden rule (P#39), Quantum numbers (P#42), Atoms in radiation field (P#44), Radiative transitions (P#48), Einstein coefficients (P#144), Selection rules (P#49), Normal Zeeman effect (P#92), Stark effect (P#95), Hyperfine structure (P#77).

**Many body Systems:** Pauli exclusion principle (P#63), Periodic system of the elements (P#64), Stern Gerlach experiment (P#66), Spin orbit coupling (P#75), Central field approximation (P#69), Hartree Fock methods and self-consistent field (P#71), Thomas Fermi potential (P#72), LS coupling (P#76), jj coupling (P#77) and other type of coupling, X-ray spectra (P#51).

**Interaction with field:** Many electron atoms in an electromagnetic field (P#44), Anomalous Zeeman effect (P#93), Paschen back effect (P#96), Stark effect (P#95).

**Molecules:** Ionic and covalent bonding (P#111), Diatomic molecules-rotational (P#116), Vibrational, and electronic spectra (P#118); Born Oppenheimer approximation (P#121), Transition probabilities of diatomic molecules (P#81), electron spin and Hund's cases (P#127), Polyatomic molecules (brief introduction) (P#123), Raman effect (P#97), Hydrogen Molecular ion (LCAO approximation) (P#129), Hydrogen molecule (Heitler London and molecular orbital theories).

### University of Education, Lahore

**Course Title:** Atomic and Molecular Physics      **Course Code:** PHYS-4113      **Semester-VII**

**Structure of Atoms:** Review of Bohr's theory (P#15), Sommerfeld Model (P#20), Frank Hertz Experiment (P#23), Approximation Method (P#24).

**One Electron System:** Review of Schrodinger equation for Hydrogen atom (P#35), Fermi Golden rule (P#39), Quantum Numbers (P#42), Atoms in Radiation Field (P#44), Radiative transitions (P#48), Einstein coefficients (P#144), Selection rule (P#49), Normal Zeeman effect (P#92), Stark effect (P#95), Hyperfine structure (P#77).

**Many Body Systems:** Pauli exclusion principle (P#63), Periodic system of the elements (P#64), Stern Gerlach experiment (P#66), Spin orbit coupling (P#75), Central Field approximation (P#69), Hartree-Fock Method and self-consistent field (P#71), Thomas Fermi potential (P#72), LS coupling (P#76), JJ coupling and other types of coupling (P#77), X-Ray Spectra (P#51).

**Molecules:** Ionic and covalent bonding (P#111), Diatomic Molecules rotational (P#116), Vibrational and electronic spectra (P#118), Born Oppenheimer approximation (P#121), Transition probabilities of diatomic molecules (P#81), Electron spin and Hund's cases (P#127), Raman effect (P#97), LCAO approximation (P#129).

### Higher Education Commission (HEC)

**Course Title:** Atomic and Molecular Physics      **Course Code:** Phys-433      **Semester-VII**

**One Electron Atoms:** Review of Bohr Model of Hydrogen Atom (P#15), Reduced Mass (P#19), Atomic Units and Wavenumbers, Energy Levels and Spectra (P#10), Schrodinger Equation for One-Electron Atoms (P#35), Quantum Angular Momentum and Spherical Harmonics, Electron Spin (P#127), Spin-Orbit interaction (P#75). Levels and Spectroscopic Notation, Lamb Shift, Hyperfine Structure (P#77) and Isotopic Shifts. Rydberg Atoms.

**Interaction of One-Electron Atoms with Electromagnetic Radiation:** Radiative Transition Rates (P#48), Dipole Approximation, Einstein Coefficients (P#144), Selection Rules (P#50), Dipole Allowed and Forbidden Transitions (P#49). Metastable Levels, Line Intensities and Lifetimes of Excited States, Shape and Width of Spectral Lines, Scattering of Radiation by Atomic Systems (P#4), Zeeman Effect (P#90), Linear and Quadratic Stark Effect (P#95).

**Many-Electron Atoms:** Schrodinger Equation for Two-Electron Atoms, Para and Ortho States (P#81), Pauli's Principle and Periodic Table (P#63), Coupling of Angular Momenta, L-S (P#76) and J-J Coupling (P#77). Ground State and Excited States of many electrons system (P#80).

**Molecular Structure and Spectra:** Structure of Molecules (P#106), Covalent and Ionic Bonds (P#111), Electronic Structure of Diatomic Molecules (P#116), Rotation and Vibration of Diatomic Molecules (P#118), Born-Oppenheimer Approximation (P#121). Electronic Spectra (P#114), Transition Probabilities (P#81) and Selection Rules (P#49), Frank-Condon Principle (P#120), H<sub>2</sub><sup>+</sup> and H<sub>2</sub> (P#114). Effects of Symmetry and Exchange. Bonding and Anti-bonding Orbitals. Electronic Spin and Hund's Cases (P#127)

**Nuclear Motion:** Rotation and Vibrational Spectra (Rigid Rotation, Harmonic Vibrations). Selection Rules. Spectra of Triatomic and Polyatomic Molecules, Raman Spectroscopy (P#97), Mossbauer Spectroscopy.





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