Quantum Mechanics

First Lecture

Physical Foundations of Quantum Mechanics

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1. What is quantum mechanics or what is the concept of quantum mechanics?

It is a field of physics that deals with the study of microscopic systems and found the failure of classical mechanics to solve some problems such as the generation of the electron-positron pair, or the Compton phenomenon.

- Physics, which is often called at the present time ***classical physics***, included, until 1909, three main topics:
  - ✓ ***Classical mechanics*** is the study of the motion of virtual bodies. treats phenomena that can be seen with the naked eye (***Macroscopic System***)
  - ✓ ***Thermodynamics*** is concerned with the study of thermal interactions between objects and their surroundings.
  - ✓ ***Electromagnetic theory*** is concerned with the study of electric and magnetic fields and the relationship between them and between charges and current.
- ***Quantum mechanics*** deals with phenomena that cannot be seen with the naked eye (***Microscopic System***). It studies of matter and radiation at an atomic level, i. e. study the theory of atomic and nuclear system.

2. Why the needful of Quantum Mechanics?

The needful of quantum mechanics come from the failure of classical physics to explain several physical phenomena Such as Black Body Radiation, Stability of atoms, Photoelectric effect, Compton effect.

- ***Quantum mechanics is necessary*** because it deals with phenomena that classical mechanics has been unable to explain, including:
  1. ***Stability of Atoms.***
  2. ***Photoelectric Effect.***
  3. ***Compton Effect.***
  4. ***Generation of The Minimum X-Ray Wave Length.***
  5. ***Pair Production (Electron-Positron pair).***

1. Stability of Atoms.

Classical mechanics ***failed*** to explain the stability of the atom, while quantum mechanics ***succeeded*** in explaining it.

- ***How did classical mechanics explain the concept of stability of the atom?***

The electron in the atom revolves around the nucleus, therefore it changing the direction of it movement continuously, and so it is an accelerating body. According to the classical electromagnetic theory(any electric charge moving at an acceleration emits electromagnetic radiationand) therefore the revolving electron around the nucleus inside atom must lose part of its energy during the rotation, meaning that it loses its energy continuously. Therefore, it must end in a spiral motion, approaching the nucleus.

- ***Why does classical mechanics fail to explain the stability of the atom?***

Under natural conditions, the atom represents a stable structure that does not emit radiation.

- ***How did quantum mechanics explain the concept of stability of the atom?***

According to Bohr's model:

1. The electron can orbit in distinct and stable orbits if its angular momentum is equal to the product of an integer multiplied by a constant quantity.

Angular Momentum (L) is equal to:

$$L = n\hbar = p\,r$$

$\hbar = 1.05 \times 10^{-34}$?

2. An electron can move from one orbit to another if there is a change in energy (ΔE) due to the absorption or emission of radiation so that the *frequency of the radiation is*

$$\upsilon = \frac{\Delta E}{h}$$

- Bohr assumed that the electron revolves on a circular path, the nucleus in the center and radius (r) and angular velocity (ω)

$$L = n\hbar$$

$$pr = n\hbar$$

$$mvr = n\hbar$$

$$m\omega rr = n\hbar \quad \Rightarrow \quad m\omega r^2 = n\hbar \qquad \ldots\ldots\ldots \quad (1)$$

Where n is positive integer number (n = 1,2, 3, …….)

- The electrostatic attraction force between the electron and the nucleus

$$F = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r^2} = m\,\omega^2\,r \qquad \ldots\ldots\ldots \quad (2)$$

- From equations (1) and (2) found the radius and angular velocity for n orbitals (r_n)

$$r_n = \frac{4\pi\,\varepsilon_\circ\hbar^2}{me^2}n^2 \qquad \omega_n = \frac{me^4}{16\pi^2\,\varepsilon_\circ^2\hbar^3}\frac{1}{n^3} \qquad \ldots\ldots\ldots(3)$$

- This means that there is a wide range of stable orbitals characterized by values of n.
- Each electron in the stable orbital has an energy equal to the sum of the ***kinetic*** and ***potential*** energies
- ***Potential energy*** **(*V*)** is equal to:

$$V = -\frac{me^4}{16\pi^2\,\varepsilon_\circ^2\hbar^2}\frac{1}{n^2} \qquad \ldots\ldots\ldots(4)$$

- ***Kinetic energy*** (***T***) is equal to: $T = 1\backslash 2\ mv^2 = 1\backslash 2\ m\omega^2 r^2$

$$\therefore T = \frac{me^4}{32\pi^2\,\varepsilon_\circ^2\hbar^2}\frac{1}{n^2} \qquad \ldots\ldots\ldots(5)$$

- ✓ Total energy E_n equal to:

$$E_n = T + V = -\frac{me^4}{32\pi^2\ \varepsilon_\circ^2\ \hbar^2}\ \frac{1}{n^2} \qquad \text{.........(6)}$$

- ✓ When the electron transfer from the orbital n = n_1 to the orbital n = n_2, it loses its energy and the ***lost energy*** can be calculated from the equation:

$$\Delta E_{12} = \frac{me^4}{32\pi^2\ \varepsilon_\circ^2\ \hbar^2}\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)$$

- ✓ The ***radiation frequency*** corresponding to the transition of the electron from the orbital n_1 to orbital n_2

$$\upsilon = \frac{\Delta E_{12}}{h} = -\frac{me^4}{8\ \varepsilon_\circ^2\ \hbar^3}\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right) \qquad \text{..........(7)}$$

- ✓ The ***wave number*** is given by the relationship:

$$\bar{\upsilon} = \frac{\upsilon}{c} = \frac{1}{\lambda}$$

$$\bar{\upsilon} = \frac{me^4}{8\ \varepsilon_\circ^2\ c\hbar^3}\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right)$$

$$\therefore \qquad \bar{\upsilon} = R\left(\frac{1}{n_2^2} - \frac{1}{n_1^2}\right) \qquad \text{............(8)}$$

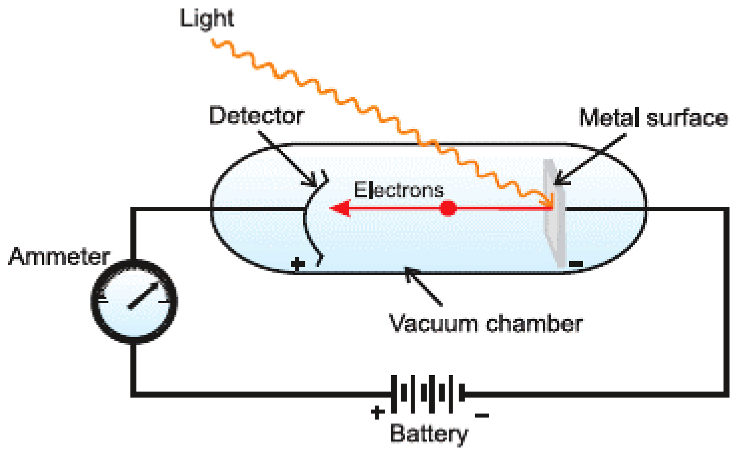
- ✓ Where R is Rydberg constant is equal to:

$$R = \frac{me^4}{8\ \varepsilon_\circ^2\ c\hbar^3}$$

- ✓ Equation (8) is the main measure of the success of Bohr's theory.

2. Photoelectric Effect.

- It is the phenomenon of the emission of electrons from the surface of a metal as a result of its illumination by electromagnetic radiation of an effective frequency



- According to the quantum theory, radiation consists of tiny particles called photons, and the energy of one photon is:

$$E = h\upsilon = \hbar\omega$$

- The emission of an electron occurs as a result of an electron colliding with a photon and it absorbs its energy completely, and this energy is represented in two processes:

  1. ***The energy required to remove an electron from a metal is ω_0***

  2. ***Kinetic energy 1\2 mv^2***

  3. ***Einstein's equation***

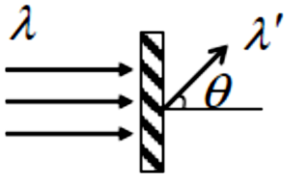
$$h\upsilon = \omega_\circ + \tfrac{1}{2} m v^2$$

- ***What is the condition for electron emission in the photoelectric effect?***

  An electron is emitted only if the energy it has absorbed is more than ω_0 This happens when the frequency of the photon is greater than the threshold frequency $\upsilon >> \upsilon_\circ$ Each photon emits an electron with kinetic energy $K.E = h\upsilon - \omega_\circ = h(\upsilon - \upsilon_\circ)$ $\omega_0 = h\upsilon_0$

3. Compton Effect.

- When a beam of X-rays falls on a metal plate, part of the rays will be scattered, and these scattered rays are subject to a change in wavelength

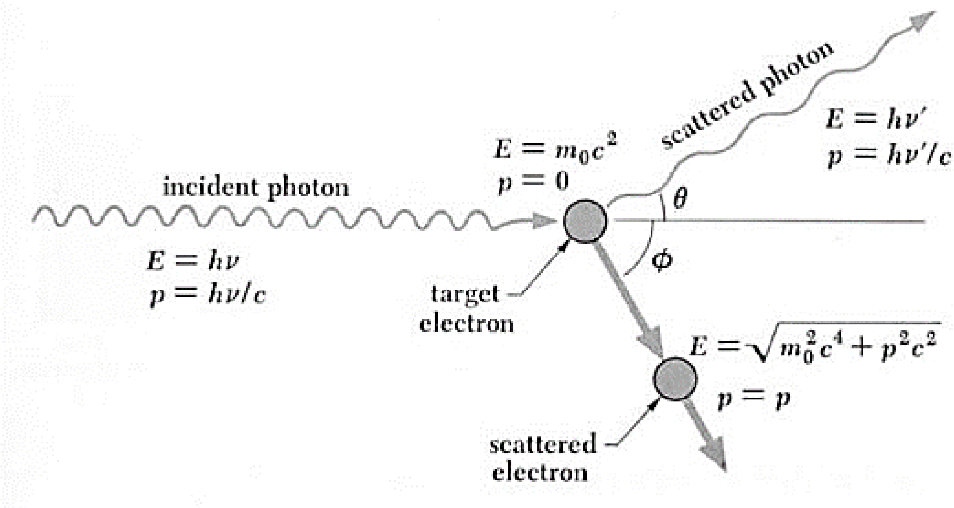


$$\lambda' - \lambda = \frac{h}{mc}(1 - \cos\theta)$$

- The classical theory fails to explain the above equation, while Compton scattering supports the quantum theory.
- ***Compton scattering assumed that radiation is a particles have quantum energy hυ, it can interact with the matter without absorption.***
- From the equivalence of momentum and energy, photon has energy ***hυ*** equivalent momentum $\frac{hc}{\lambda}$

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

- From the law of conservation of energy and momentum, the Compton scattering equation can be derived



$$\Delta\lambda = \lambda' - \lambda = \frac{h}{mc}(1 - \cos\theta)$$ ***Compton scattering equation***

4. Generation of The Minimum X-Ray Wave Length.

- It is known that the high-energy electrons in the X-ray tube can generate X-ray photons with a specific maximum energy.
- This phenomenon that can only be explained on the basis that electromagnetic radiation behaves as a photon.

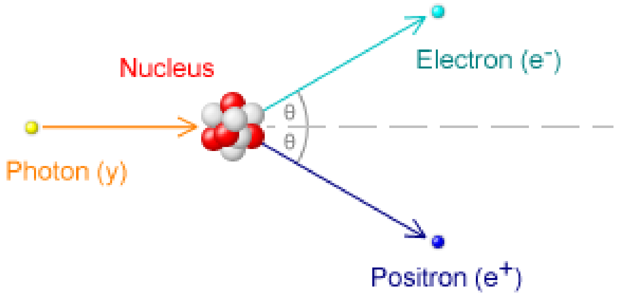
$$\lambda_{min} = \frac{12396}{V} \ \mathring{A}$$

5. Pair Production (Electron-Positron pair).

- Electron-positron pair (e^-, e^+) generation in air when ***the energy of X-rays exceeds twice the rest energy of the electron and positron.***

$$h\upsilon >> 2m_{\circ}c^2$$

- Where $2m_0 c^2 = 1.02$ MeV.



- *Pair Annihilation* the inverse phenomenon of electron-positron pair formation, it done by the formation of two photons the energy of each one is ***hυ*** after the pair's annihilation.