

17. Atoms, Molecules and Nuclei

Rutherford's model of atom:

- Most of the mass of the atom and all its positive charge are concentrated in a tiny nucleus, and the electrons revolve around this nucleus.
- **Limitations**
 - It predicts that atoms are unstable because the accelerated electrons revolving around the nucleus must spiral into the nucleus. This contradicts the stability of matter.
 - It could not explain the characteristic line spectra of atoms of different elements.
- Total energy of electron in hydrogen atom

$$E = k + U = \frac{e^2}{8\pi\epsilon_0 r} - \frac{e^2}{4\pi\epsilon_0 r}$$

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

Origin of Spectral Lines:

- The atomic hydrogen emits a line spectrum consisting of various series. The frequency of any line in a series can be expressed as a difference of two terms:

$$\bar{\nu} = R \left[\frac{1}{1^2} - \frac{1}{n^2} \right]; n = 2, 3, 4, \dots$$

- Lyman series:

$$\bar{\nu} = R \left[\frac{1}{2^2} - \frac{1}{n^2} \right]; n = 3, 4, 5, \dots$$

- Balmer series:

$$\bar{\nu} = R \left[\frac{1}{3^2} - \frac{1}{n^2} \right]; n = 4, 5, 6, \dots$$

- Paschen series:

$$\bar{\nu} = R \left[\frac{1}{4^2} - \frac{1}{n^2} \right]; n = 5, 6, 7, \dots$$

- Bracket series:

$$\bar{\nu} = R \left[\frac{1}{5^2} - \frac{1}{n^2} \right]; n = 6, 7, 8, \dots$$

- Pfund series:

Bohr model of hydrogen atom

- In a hydrogen atom, electrons can revolve only in certain discrete, non-radiating orbits—called stationary orbits—for which the total angular momentum of the revolving electrons is an integral multiple of $\frac{h}{2\pi}$ i.e.,



$$mvr = \frac{nh}{2\pi}$$

Where, n is any positive integer, 1, 2, 3 ...

- The emission/absorption of energy occurs only when an electron jumps from one of its specified non-radiating orbit to another.

$$h\nu = E_2 - E_1$$

Where,

$E_1 \rightarrow$ Total energy of the electron in an inner stationary orbit

$E_2 \rightarrow$ Total energy of the electron in the outer stationary orbit

$\nu \rightarrow$ Frequency of radiation emitted

- When an electron in a hydrogen atom jumps from the higher energy level to the lower energy level, the difference of energies of the two energy levels is emitted as a radiation of a particular wavelength.

The different spectral series are as follows:

- Lyman series

$$\frac{1}{\lambda} = R_H \left(\frac{1}{1^2} - \frac{1}{n_i^2} \right)$$

$$n_i = 2, 3, 4 \dots$$

It lies in ultraviolet region.

- Balmer series

$$\frac{1}{\lambda} = R_H \left(\frac{1}{2^2} - \frac{1}{n_i^2} \right)$$

$$n_i = 3, 4, 5 \dots$$

It lies in the visible region.

- Paschen series

$$\frac{1}{\lambda} = R_H \left(\frac{1}{3^2} - \frac{1}{n_i^2} \right)$$

$$n_i = 4, 5, 6 \dots$$

It lies in the infra-red region.

- Brackett series

$$\frac{1}{\lambda} = R_H \left(\frac{1}{4^2} - \frac{1}{n_i^2} \right)$$

$$n_i = 5, 6, 7 \dots$$

It lies in the infra-red region.

- P fund series

$$\frac{1}{\lambda} = R_H \left(\frac{1}{5^2} - \frac{1}{n_i^2} \right)$$

$$n_i = 6, 7, 8 \dots$$

It lies in the far infra-red region.

The X rays are of two types:

- Characteristic X-rays: The intensity of these X-rays is very high at certain sharply defined frequencies.
- Continuous X-rays: At all the wavelengths other than those corresponding to K_α and K_β , the intensity of these X-rays varies gradually.
- The unit in which atomic and nuclear masses are measured is called atomic mass unit (amu).
- One amu is defined as $1/12^{\text{th}}$ of the mass of an atom of ${}_6\text{C}^{12}$ isotope.

$$\text{i.e., } 1 \text{ amu} = 1.66 \times 10^{-27} \text{ kg}$$

- Atomic masses can be measured using a mass spectrometer.
- The different types of atoms of the same element which exhibit similar chemical properties, but have different masses are called isotopes.
- Isotopes are the atoms of an elements whose nuclei have the same number of protons, but have different number of neutrons.
- Isobars are the nuclei with the same mass number (A), but with different atomic numbers.
- Isotones are the atoms of different elements with the same atomic weight, but with different atomic numbers.

Nucleus

- The nucleus has the positive charge possessed by the protons. For an element of atomic number Z, the total charge on an atomic electron is $(-Ze)$, while the charge of the nucleus is $(+Ze)$.
- The composition of a nucleus is described using the followings terms and symbols:

$$Z = \text{atomic number} = \text{number of protons}$$

$$N = \text{neutron number} = \text{number of neutrons}$$



$A = \text{mass number} = Z + N = \text{total number of protons and neutrons}$

Nuclear Size:

- $R = R_0 A^{\frac{1}{3}}$

Where,

$R \rightarrow$ Radius of the nucleus

$R_0 \rightarrow$ Empirical constant, whose value is found to be $1.2 \times 10^{-15} \text{ m}$

$A \rightarrow$ Mass number

Nuclear Binding Energy:

- The nuclear mass M is always less than the total mass $\sum m$ of its constituents. The difference between the mass of a nucleus and its constituents is called the mass defect.

$$\Delta M = [Zm_p + (A - Z)m_n] - M$$

- Using Einstein's mass-energy relation, we express this mass difference in terms of energy as $\Delta E_b = \Delta Mc^2$
- The energy E_b represents the binding energy of the nucleus. In the mass number range $A = 30$ to 170, the binding energy per nucleon is nearly constant, about 8 MeV/nucleon.

- Law of radioactive decay:**

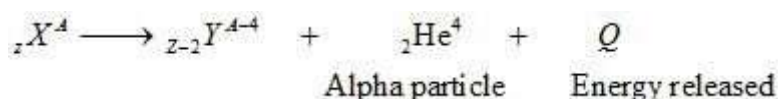
$$N(t) = N(0)e^{-\lambda t}$$

Where, λ is the decay constant or disintegration constant

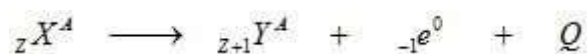
- The half life $T_{1/2}$ of a radionuclide is the time in which N has been reduced to one-half of its initial value. The mean life τ is the time at which N has been reduced to e^{-1} of its initial value.

$$T_{1/2} = \frac{\ln 2}{\lambda} = \tau \ln 2$$

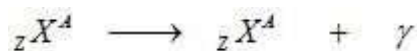
- Alpha decay:** The phenomenon of emission of an α particle from a radioactive nucleus



- **Beta Decay:** The phenomenon of emission of an electron from a radioactive nucleus



- **Gamma Decay:** The phenomenon of emission of a gamma ray photon from a radioactive nucleus



- Einstein's mass-energy relation and is given as $\Delta E = \Delta M c^2$
- **Nuclear Fission:** A reaction in which a heavy nucleus breaks into two small nuclei with the liberation of energy is known as nuclear fission.
 - Example: ${}_0^1 n + {}_{92}^{235} \text{U} \rightarrow {}_{92}^{236} \text{U} \rightarrow {}_{56}^{144} \text{Ba} + {}_{36}^{89} \text{Kr} + 3{}_0^1 n$
- A continuous nuclear fission reaction is called a **chain reaction**.
- When the fission neutrons are built up to a level and the number of fission producing neutrons is kept constant, then it is known as **controlled chain reaction**.
- **Nuclear reactors** work on the principle of controlled chain reaction.
- **Critical Size:** The minimum size of fissionable material required to sustain a nuclear fission chain reaction.
- **Nuclear Fusion:** A reaction in which two light nuclei combine to form a heavy nuclei with the liberation of energy is known as nuclear fusion.
 - Example: ${}_1^2 \text{H} + {}_1^2 \text{H} \rightarrow {}_1^3 \text{H} + \text{Energy}$
- The energy produced per unit mass in nuclear fusion is higher than that of nuclear fission.

Radiation Hazards

- Radiations are dangerous to both human health and the environment
- Gamma radiations and X rays are highly penetrative and cause serious to the DNA and may lead to cancer, genetic defects and birth defects.
- UV rays cause skin burns, premature cataract and skin cancer

Dual nature of matter

- Matter possesses dual nature: particle-like as well as wave-like nature.
- **de Broglie's Hypothesis**
 - A moving particle sometimes acts as a wave and sometimes as a particle; or a wave is associated with a moving material particle which controls the particle in every respect.
 - The wave associated with the moving particle is called matter wave.



- de Broglie wavelength is given by

$$\lambda = \frac{h}{mv}$$
 where m = mass of particle; v = velocity of the particle and h = planck's constant.
- According to de Broglie, wavelength of an electron in terms of voltage is given by

$$\lambda = \frac{12.27}{\sqrt{V}}$$
 where V is voltage in volt and λ is wavelength in Angstrom.

Davisson and Germer Experiment

- It confirmed wave nature of the matter that was given in De-Broglie's hypothesis.
- In the experiment
 - The electrons from an electron gun were made to strike the Nickel crystal
 - Scattering of electrons was observed.
 - The intensity of the electrons in the given direction was measured.
 - Graph was plotted between intensity and the angle of reflection.
 - Maximum intensity was observed at $\theta = 50^\circ$ the energy of the electron beam being 54 eV with a voltage of 54 V.