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 nucelus 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

$$E = k + U = \frac{e^2}{8\pi\varepsilon_0 r} - \frac{e^2}{4\pi\varepsilon_0 r}$$

$$\boxed{E = -\frac{e^2}{8\pi\varepsilon_0 r}}$$

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:
- Lyman series: $\bar{\nu} = R\left[\frac{1}{1^2} - \frac{1}{n^2}\right]; n = 2, 3, 4, \ldots$
- Balmer series: $\bar{\nu} = R\left[\frac{1}{2^2} - \frac{1}{n^2}\right]; n = 3, 4, 5, \ldots$
- Paschen series: $\bar{\nu} = R\left[\frac{1}{3^2} - \frac{1}{n^2}\right]; n = 4, 5, 6, \ldots$
- Bracket series: $\bar{\nu} = R\left[\frac{1}{4^2} - \frac{1}{n^2}\right]; n = 5, 6, 7, \ldots$
- Pfund series: $\bar{\nu} = R\left[\frac{1}{5^2} - \frac{1}{n^2}\right]; n = 6, 7, 8, \ldots$

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

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

$n_i = 2, 3, 4 \ldots$

It lies in ultraviolet region.

- Balmer series

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

$n_i = 3, 4, 5 \ldots$

It lies in the visible region.

- Paschen series

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

$n_i = 4, 5, 6 \ldots$

It lies in the infra-red region.

- Brackett series

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

$n_i = 5, 6, 7 \ldots$

It lies in the infra-red region.

- P fund series

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

$n_i = 6, 7, 8 \ldots$

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 $K_{\beta,}$ 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 1/12th of the mass of an atom of ${}_6C^{12}$ isotope.

  i.e., 1 amu = 1.66×10-27 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 = atomic number = number of protons

  N = neutron number = number of neutrons

A = mass number = $Z + N$ = 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 1.2×10^{-15} 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.

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

- Using Einstein's mass–energy relation, we express this mass difference in terms of energy as $\Delta E_b = \Delta M c^2$
- The energy ΔE_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

$$ {}_Z X^A \longrightarrow {}_{Z-2}Y^{A-4} + \underset{\text{Alpha particle}}{{}_2\text{He}^4} + \underset{\text{Energy released}}{Q}$$

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

$$_{Z}X^{A} \longrightarrow {}_{Z+1}Y^{A} + {}_{-1}e^{0} + Q$$

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

$$_{Z}X^{A} \longrightarrow {}_{Z}X^{A} + \gamma$$

- Einstein's mass-energy relation and is given as $\Delta E = \Delta Mc^2$
- **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: ${}_0^1n + {}_{92}^{235}U \rightarrow {}_{92}^{236}U \rightarrow {}_{56}^{144}Ba + {}_{36}^{89}Kr + 3{}_0^1n$
- 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 nulei with the liberation of energy is known as nuclear fusion.
    - Example: ${}_1^2H + {}_1^2H \rightarrow {}_1^3H + Energy$
- The energy produced per unit mass in nuclear fusion is higher that 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 equals fraction numerator h over denominator m v end fraction, 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 space equals space fraction numerator 12.27 over denominator square root of V end fraction A degree.

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 $\theta = 50^{o}$ the energy of the electron beam being 54 eV with a voltage of 54 V.