Atoms and Nuclei

I. Atoms

1. Alpha-Particle Scattering and Rutherford's Model

- **Geiger-Marsden Experiment:** Alpha particles (He^{2+}) were directed at a thin gold foil. Most passed through, but some were deflected at large angles, and a few $(1$ in $8000)$ even bounced back.

- **Rutherford's Conclusions:**
  - Most of the atom is **empty space**.
  - The entire positive charge and most of the mass are concentrated in a tiny region called the **nucleus**.
  - Electrons revolve around the nucleus in orbits, similar to planets around the sun.

- **Impact Parameter (b):** The perpendicular distance of the initial velocity vector of the alpha particle from the centre of the nucleus.

- **Distance of Closest Approach (r_0):** The distance where the entire kinetic energy of the alpha particle is converted into electrostatic potential energy. $r_0 = \frac{1}{4\pi\epsilon_0}\frac{2Ze^2}{K}$

2. Bohr Model of the Hydrogen Atom

Bohr combined classical mechanics with early quantum concepts through three postulates:

- **Postulate 1:** Electrons exist in stable, non-radiating "stationary states".

- **Postulate 2 (Quantisation of Angular Momentum):** An electron can revolve only in orbits where its orbital angular momentum (L) is an integral multiple of $h/2\pi$. $L = mvr = \frac{nh}{2\pi}$ where $n = 1, 2, 3 \dots$ is the Principal Quantum Number.

- **Postulate 3:** Energy is emitted or absorbed only when an electron jumps from one stationary orbit to another. $h\nu = E_i - E_f$

3. Expressions for Radius, Velocity, and Energy

For an electron of mass m and charge e in the n^{th} orbit of an atom with atomic number Z:

- **Radius (r_n):** $r_n = \frac{n^2h^2\epsilon_0}{\pi m Z e^2}$ For Hydrogen ($Z = 1, n = 1$), the Bohr radius is $a_0 \approx 0.53\ \#$.

- **Velocity (v_n):** $v_n = \frac{Ze^2}{2\epsilon_0 nh}$

- **Energy (E_n):** The total energy is the sum of Kinetic and Potential energies. $E_n = -\frac{mZ^2e^4}{8\epsilon_0^2n^2h^2} = -13.6\frac{Z^2}{n^2}\ \mathrm{eV}$ The negative sign indicates that the electron is **bound** to the nucleus.

4. Hydrogen Line Spectra

When an electron transitions from a higher orbit (n_2) to a lower orbit (n_1), the wavelength (λ) of the emitted photon is given by the Rydberg formula: $\frac{1}{\lambda} = RZ^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$ where R is the Rydberg constant ($\approx 1.097 \times 10^7\ \mathrm{m}^{-1}$).

- **Lyman Series:** $n_1 = 1$ (Ultraviolet region).
- **Balmer Series:** $n_1 = 2$ (Visible region).
- **Paschen Series:** $n_1 = 3$ (Infrared region).

II. Nuclei

1. Composition and Size of Nucleus

- **Composition:** A nucleus consists of **protons** and **neutrons** (collectively called **nucleons**).
- **Atomic Number (Z):** Number of protons.
- **Mass Number (A):** Total number of protons and neutrons ($A = Z + N$).
- **Nuclear Size:** The volume of the nucleus is proportional to the mass number A. The radius R is: $R = R_0 A^{1/3}$ where $R_0 \approx 1.2 \times 10^{-15}\ \text{m}$.
- **Nuclear Density:** It is constant for all nuclei, approximately $2.3 \times 10^{17}\ \text{kg m}^{-3}$.

2. Classification of Nuclei

- **Isotopes:** Same Z, different A (e.g., ${}^1_1H, {}^2_1H, {}^3_1H$).
- **Isobars:** Same A, different Z (e.g., ${}^{40}_{18}Ar, {}^{40}_{20}Ca$).
- **Isotones:** Same number of neutrons ($N = A - Z$).

3. Nuclear Force

The force that holds nucleons together despite the strong electrostatic repulsion between protons.

- It is the **strongest force** in nature but has a very **short range** ($\approx 2 - 3\ \text{fm}$).
- It is **charge-independent** (the force between $p - p$, $n - n$, and $p - n$ is the same).
- It is non-central and saturated.

4. Mass-Energy Relation and Mass Defect

- **Einstein's Relation:** Mass and energy are interconvertible. $E = mc^2$
- **Mass Defect (Δm):** The difference between the sum of the masses of individual nucleons and the actual mass (M) of the nucleus. $\Delta m = [Zm_p + (A - Z)m_n] - M$

- **Binding Energy (E_b):** The energy equivalent of the mass defect; it is the energy required to break a nucleus into its constituent nucleons. $E_b = \Delta mc^2$

5. Binding Energy per Nucleon (E_{bn}) $E_{bn} = E_b/A$ is a measure of **nuclear stability**.

- **Variation with A:**
  - E_{bn} is low for very light $(A < 20)$ and very heavy $(A > 170)$ nuclei.
  - It reaches a maximum of $\approx 8.8 \text{ MeV}$ for ^{56}Fe.
  - Heavy nuclei are less stable due to electrostatic repulsion, leading to **fission**. Light nuclei have low E_{bn}, leading to **fusion**.

6. Nuclear Fission and Fusion

- **Nuclear Fission:** The process in which a heavy nucleus (e.g., U^{235}) splits into two lighter nuclei when bombarded with a neutron, releasing a large amount of energy and more neutrons.

- **Nuclear Fusion:** The process in which two light nuclei combine to form a single heavier nucleus (e.g., hydrogen to helium in stars). This requires extremely high temperatures and pressures to overcome the Coulomb repulsion. It releases more energy per unit mass than fission.