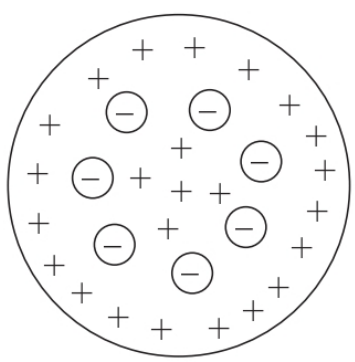
Atomic Physics

Dalton's Atomic Theory

All elements are consists of very small invisible particles, called atoms. Atoms of same elements are exactly same and atoms of different elements are different.

Thomson's Atomic Model

Every atom is uniformly positive charged sphere of radius of the order of 10^{-10} m, in which entire mass is uniformly distributed and negative charged electrons are embedded randomly. The atom as a whole is neutral.



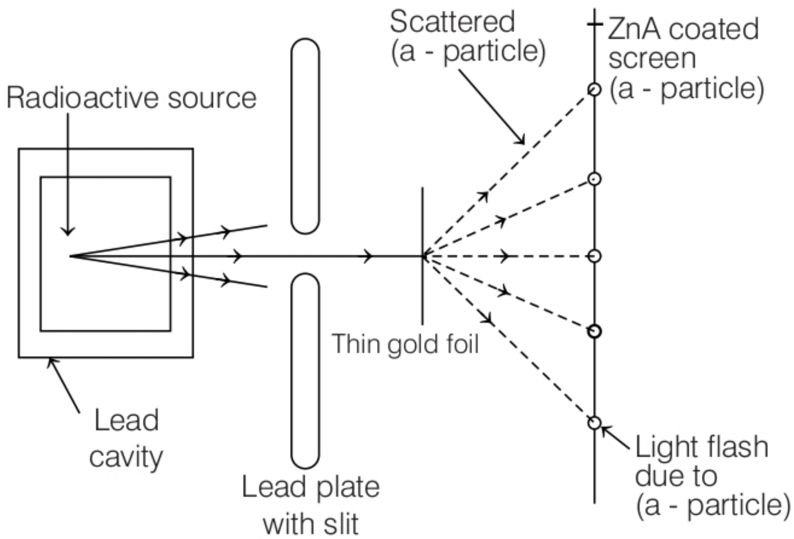
Limitations of Thomson's Atomic Model

(i) It could not explain the origin of spectral series of hydrogen and other atoms.

(ii) It could not explain large angle scattering of α-particle.

Rutherford's Atomic Model

The setup of Rutherford's α-particle scattering experiment is shown in the figure given below



On the basis of this experiment, Rutherford made following observations.

(i) The entire positive charge and almost entire mass of the atom is concentrated at its centre in a very tiny region of the order of 10^{-15} m, called nucleus.

(ii) The negatively charged electrons revolve around the nucleus in different orbits.

(iii) The total positive charge on nucleus is equal to the total negative charge on electron. Therefore, atom is overall neutral.

(iv) The centripetal force required by electron for revolution is provided by the electrostatic force of attraction between the electrons and the nucleus.

Distance of Closest Approach

$$r_0 = \frac{1}{4\pi\varepsilon_0} \cdot \frac{2Ze^2}{E_K}$$

where, E_K = kinetic energy of the α-particle.

Impact Parameter

The perpendicular distance of the velocity vector of α-particle from the central line of the nucleus, when the particle is far away from the nucleus is called impact parameter.

$$\text{Impact parameter, } b = \frac{1}{4\pi\varepsilon_0} \cdot \frac{Ze^2 \cot\left(\frac{\theta}{2}\right)}{E_K}$$

where, Z = atomic number of the nucleus,

E_K = kinetic energy of the α-particle and

θ = angle of scattering.

Rutherford's Scattering Formula

$$N(\theta) = \frac{N_i nt Z^2 e^4}{(8\pi\varepsilon_0)^2 r^2 E^2 \sin^4\left(\frac{\theta}{2}\right)}$$

where, $N(\theta)$ = number of α-particles, N_i = total number of α-particles reaching the screen, n = number of atoms per unit volume in the foil, Z = atomic number, E = kinetic energy of the α-particle and t = foil thickness.

$$\therefore \quad N \propto \frac{1}{\sin^4\left(\frac{\theta}{2}\right)}$$

Limitations of Rutherford 's Atomic Model

(i) **About the Stability of Atom** According to Maxwell's electromagnetic wave theory, electron should emit energy in the form of electromagnetic wave during, its orbital motion. Therefore, radius of orbit of electron will decrease gradually and ultimately it will fall in the nucleus.

(ii) **About the Line Spectrum** Rutherford atomic model cannot explain atomic line spectrum.

Bohr's Atomic Model

Electron can revolve in certain non-radiating orbits called **stationary orbits** for which the angular momentum of electron is an integer multiple of $\left(\frac{h}{2\pi}\right)$.

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

where, $n = 1, 2, 3, \ldots$ called principal quantum number.

The radiation of energy occurs only, when any electron jumps from one permitted orbit to another permitted orbit.

Energy of emitted photon, $h\nu = E_2 - E_1$

where, E_1 and E_2 are energies of electron in orbits.

Radius of orbit of electron is given by

$$r = \frac{n^2h^2}{4\pi^2\, mK\, Ze^2}$$

$$\Rightarrow \qquad r \propto \frac{n^2}{Z}$$

where, $n =$ principal quantum number, $h =$ Planck's constant, $m =$ mass of an electron, $K = \frac{1}{4\pi\varepsilon_0}$, $Z =$ atomic number and $e =$ electronic charge.

The radius of the first orbit ($n = 1$) of H-atom is given as

$$r_1 = \frac{h^2\varepsilon_0}{\pi me^2} = 0.53\ \text{Å}$$

This is called Bohr's radius.

Velocity of electron in any orbit is given by

$$v = \frac{2\pi KZe^2}{nh}$$

$$\Rightarrow \qquad v \propto \frac{Z}{n}$$

Frequency of electron in any orbit is given by

$$\nu = \frac{KZe^2}{nhr} = \frac{4\pi^2Z^2e^4mK^2}{n^3h^3}$$

$$\Rightarrow \qquad \nu \propto \frac{Z^2}{n^3}$$

Kinetic energy of electron in any orbit is given by

$$E_K = \frac{2\pi^2me^4Z^2K^2}{n^2h^2} = \frac{13.6\,Z^2}{n^2}\ \text{eV}$$

Potential energy of electron in any orbit is given by

$$E_P = \frac{-4\pi^2me^4Z^2K^2}{n^2h^2} = -\frac{27.2\,Z^2}{n^2}\ \text{eV}$$

Total energy of electron in any orbit is given by

$$E = \frac{-2\pi^2 me^4 Z^2 k^2}{n^2 h^2} = -\frac{13.6\, Z^2}{n^2} \text{ eV}$$

$$\Rightarrow \qquad E \propto \frac{Z^2}{n^2}$$

Wavelength of radiation emitted in the radiation from orbit n_2 to n_1 is given by

$$\frac{1}{\lambda} = \frac{2\pi^2 m K^2 e^4 Z^2}{ch^3}\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]$$

$$\frac{1}{\lambda} = R\left[\frac{1}{n_1^2} - \frac{1}{n_2^2}\right]$$

where,

$$R = \frac{2\pi^2 m K^2 e^4 Z^2}{ch^3}$$

$$= 1.097 \times 10^7 \text{ m}^{-1}$$

Excitation Energy and Potential

The energy required to take an atom from its lower state to higher state is called excitation energy.

The potential through which an electron should be accelerated to gain higher state is called excitation potential.

Ionisation Energy and Potential

$$E_{\text{ionisation}} = E_\infty - E_n = \frac{13.6 Z^2}{n^2} \text{ eV}$$

$$\text{Ionisation potential} = \frac{E_{\text{ionisation}}}{e} = \frac{13.6 Z^2}{n^2} \text{ V}$$

de-Broglie's Explanations of Bohr's Second Postulate

According to de-Broglie, a stationary orbit is that which contains an integral number of de-Broglie waves associated with the revolving electrons. For electron revolving in nth orbit of radius r_n.

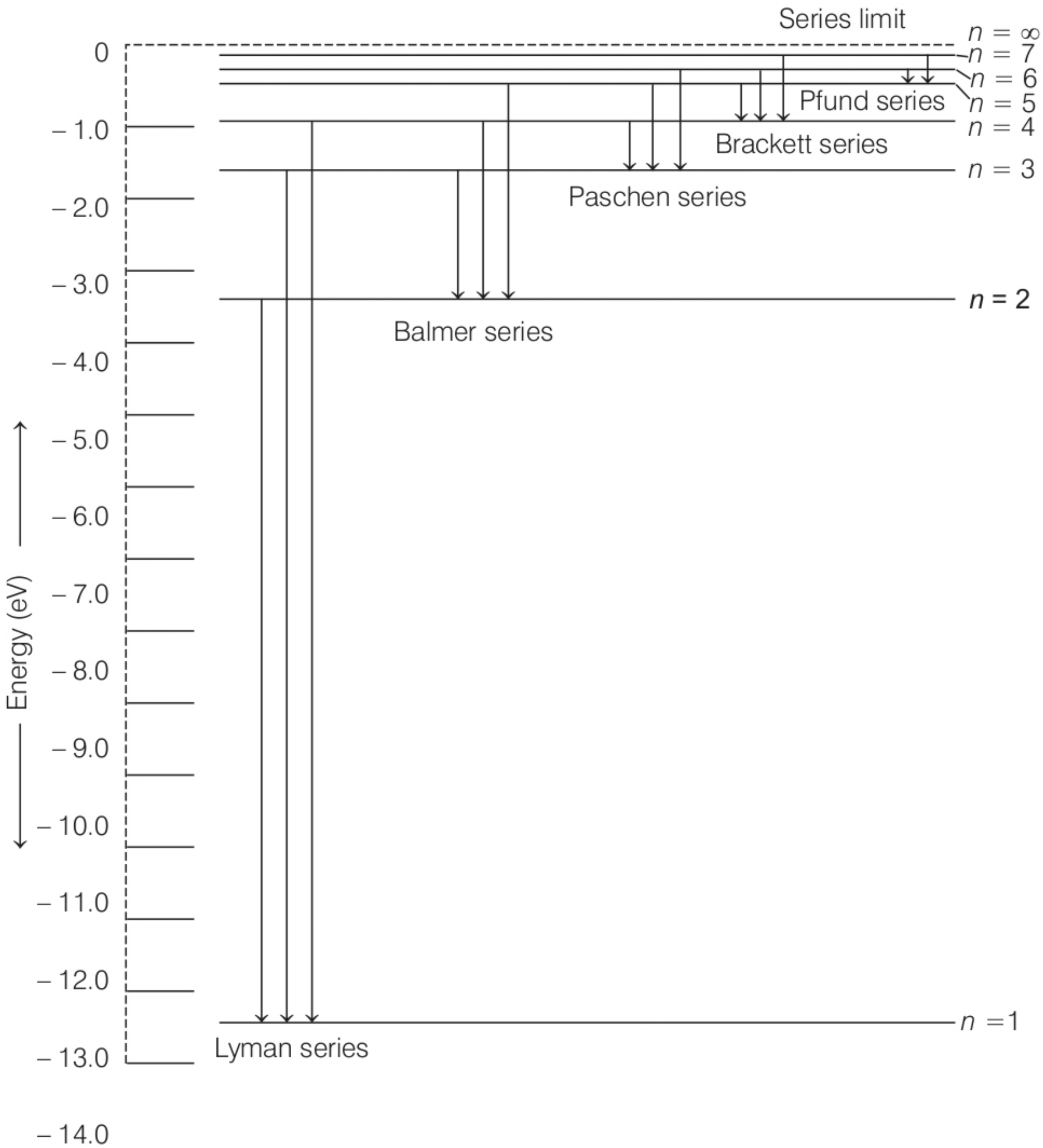
$$2\pi r_n = n\lambda = \frac{nh}{mv_n}$$

or

$$mv_n r_n = \frac{nh}{2\pi}$$

Hydrogen Spectrum Series

Each element emits a spectrum of radiation, which is characteristic of the element itself. The spectrum consists of a set of isolated parallel lines and is called the **line spectrum.**



Hydrogen spectrum contains five series.

(i) **Lyman Series** When electron jumps from $n = 2, 3, 4, \ldots$ orbit to $n = 1$ orbit, then a line of Lyman series is obtained.

This series lies in **ultra violet region**.

(ii) **Balmer Series** When electron jumps from $n = 3, 4, 5, \ldots$ orbit to $n = 2$ orbit, then a line of Balmer series is obtained.

This series lies in **visible region.**

(iii) **Paschen Series** When electron jumps from $n = 4, 5, 6, \ldots$ orbit to $n = 3$ orbit, then a line of Paschen series is obtained.

This series lies in **infrared region.**

(iv) **Brackett Series** When electron jumps from $n = 5, 6, 7, \ldots$ orbit to $n = 4$ orbit, then a line of Brackett series is obtained.

This series lies in **infrared region**.

(v) **Pfund Series** When electron jumps from $n = 6, 7, 8, \ldots$ orbit to $n = 5$ orbit, then a line of Pfund series is obtained.

This series lies in **infrared region.**

Wave Model

It is based on wave mechanics.

Quantum numbers are the numbers required to completely specify the state of the electrons.

In the presence of strong magnetic field, the four quantum numbers are

(i) Principal quantum number (n) can have value 1, 2, ...∞.

(ii) Orbital angular momentum quantum number l can have value $0, 1, 2, \ldots, (n-1)$.

(iii) Magnetic quantum number (m_e) which can have values $-l$ to l.

(iv) Magnetic spin angular momentum quantum number (m_s) which can have only two value $+\frac{1}{2}$.

Nuclear Physics

Nucleus

The entire positive charge and nearly the entire mass of atom is concentrated in a very small space called the nucleus of an atom.

The nucleus consists of protons and neutrons. They are called **nucleons.**

Terms Related to Nucleus

(i) **Atomic Number** The number of protons in the nucleus of an atom of the element is called atomic number (Z) of the element.

(ii) **Mass Number** The total number of protons and neutrons present inside the nucleus of an atom of the element is called mass number (A) of the element.

(iii) **Nuclear Size** The radius of the nucleus $R \propto A^{1/3}$

$$\Rightarrow \qquad R = R_0 A^{1/3}$$

where, $R_0 = 1.1 \times 10^{-15}$ m is an empirical constant.

(iv) **Nuclear Density** Nuclear density is independent of mass number and therefore same for all nuclei.

$$\rho = \frac{\text{mass of nucleus}}{\text{volume of nucleus}} \Rightarrow \rho = \frac{3m}{4\pi R_0^3}$$

where, m = average mass of a nucleon.

(v) **Atomic Mass Unit** It is defined as $\frac{1}{12}$th the mass of carbon-12 atom nucleus.

It is abbreviated as amu and often denoted by u. Thus,

$$1 \text{ amu} = \frac{1.992678 \times 10^{-26}}{12} \text{ kg}$$

$$= 1.6 \times 10^{-27} \text{ kg} = 931 \text{ MeV}$$

Isotopes

The atoms of an element having same atomic number but different mass numbers are called isotopes. *e.g.* $_1H^1$, $_1H^2$, $_1H^3$ are isotopes of hydrogen.

Isobars

The atoms of different elements having same mass numbers but different atomic numbers are called isobars. *e.g.* $_1H^3$, $_2He^3$ and $_{11}Na^{22}$, $_{10}Ne^{22}$ are isobars.

Isotones

The atoms of different elements having different atomic numbers and different mass numbers but having same number of neutrons are called isotones. *e.g.* $_1H^3$, $_2He^4$ and $_6C^{14}$, $_8O^{16}$ are isotones.

Isomers

Atoms having the same mass number and the same atomic number but different radioactive properties are called isomers.

Nuclear Force

The force acting inside the nucleus or acting between nucleons is called nuclear force.

Nuclear forces are the strongest forces in nature.

It is a very short range attractive force.

It is non-central and non-conservative force.

It is independent of charge.

It is 100 times that of electrostatic force and 10^{38} times that of gravitational force.

According to the Yukawa, the nuclear force acts between the nucleons due to continuous exchange of meson particles.

Mass Defect

The difference between the sum of masses of all nucleons (M) and mass of the nucleus (m) is called mass defect.

$$\text{Mass defect } (\Delta m) = M - m = [Zm_p + (A - Z)m_n - m_N]$$

Mass Energy Relation

Einstein showed that mass is another form of energy and can convert mass energy into other forms of energy.

$$\text{Einstein-mass energy, } E = mc^2$$

Nuclear Binding Energy

The minimum energy required to separate the nucleons upto an infinite distance from the nucleus is called nuclear binding energy.

$$\text{Binding energy, } E_b = [Zm_p + (A - Z)\, m_n - m_N]c^2$$

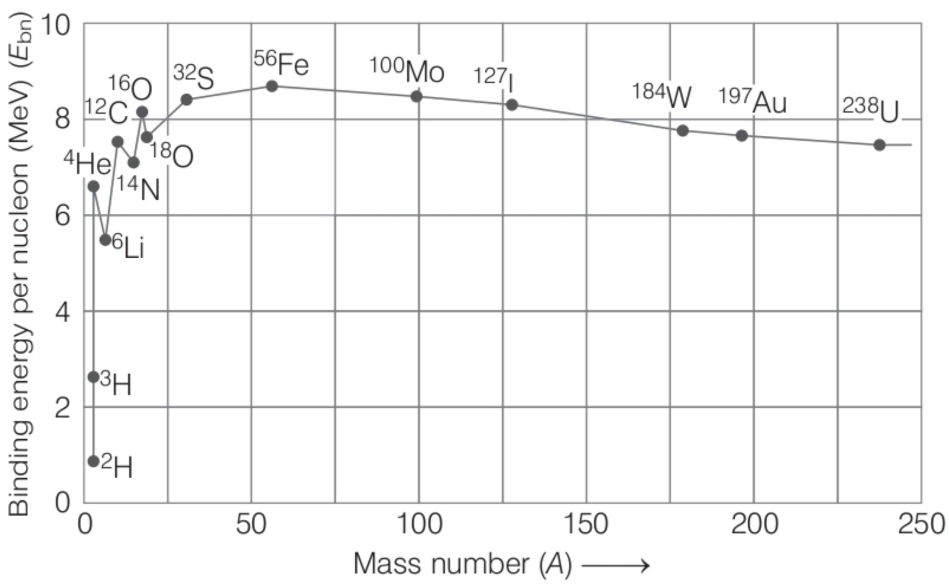
$$\text{Nuclear binding energy per nucleon} = \frac{\text{Nuclear binding energy}}{\text{Total number of nucleons}}$$

Packing Fraction (P)

$$P = \frac{\text{(Exact nuclear mass)} - \text{(Mass number)}}{\text{Mass number}} = \frac{M - A}{M}$$

The larger the value of packing friction, greater is the stability of the nucleus.

Binding Energy Curve



Some features of this curve are given below as

(i) Nuclei having mass number 50 to 80 are most stable.

(ii) Nuclei having mass number more than 80, the average binding energy per nuclei decreases. The nuclei of heavier atoms beyond $_{83}\text{Bi}^{209}$ are radioactive.

(iii) Nuclei having mass number below 20 are comparatively less stable.

(iv) Even-Even nuclei are more stable than their intermediate neighbours.

The nuclei containing even number of protons and even number of neutrons are **most stable**.

The nuclei containing odd number of protons and odd number of neutrons are **most unstable**.

Nuclear Reaction

The process by which the identity of a nucleus is changed when it is bombarded by an energetic particle is called nuclear reaction. Its general expression is

$$\underset{\text{(parent nucleus)}}{X} + \underset{\text{(incident particle)}}{a} \longrightarrow \underset{\text{(compound nucleus)}}{c}$$

$$\longrightarrow \underset{\text{(product nucleus)}}{Y} + \underset{\text{(daughter nucleus)}}{b} + \underset{\text{(energy)}}{Q}$$

Q-Value

It means the difference between the rest mass energy of initial constituents and the rest mass energy of final constituents of a nuclear reaction.

Nuclear Energy

The energy released during nuclear reaction is nuclear energy. Two distinct ways of obtaining energy from nucleus are as

(i) Nuclear fission (ii) Nuclear fusion

Nuclear Fission

The process of the splitting of a heavy nucleus into two or more lighter nuclei is called nuclear fission.

When a slow moving neutron strikes with a uranium nucleus ($_{92}U^{235}$), it splits into $_{56}Ba^{141}$ and $_{36}Kr^{92}$ along with three neutrons and a lot of energy.

$$_{92}U^{235} + {}_0n^1 \longrightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + 3\,{}_0n^1 + \text{energy}$$

Nuclear Chain Reaction

If the particle starting the nuclear fission reaction is produced as a product and further take part in the nuclear fission reaction, then a chain of fission reaction started, which is called nuclear chain reaction.

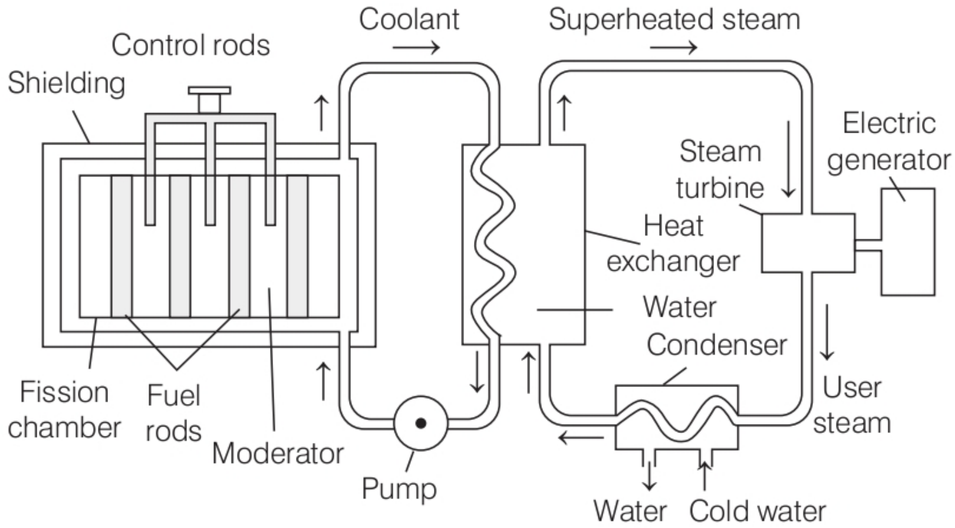
Nuclear chain reaction are of two types

(i) Controlled chain reaction

(ii) Uncontrolled chain reaction

Nuclear Reactor

The main parts of a nuclear reactor are following



(i) **Fuel** Fissionable materials like ${}_{92}U^{235}$, ${}_{92}U^{238}$, ${}_{94}Pu^{239}$ are used as fuel.

(ii) **Moderator** Heavy water, graphite and baryllium oxide are used to slower down fast moving neutrons.

(iii) **Coolant** The cold water, liquid oxygen etc are used to remove heat generated in the fission process.

(iv) **Control rods** Cadmium or boron rods are good absorber of neutrons and therefore used to control the fission reaction.

Note Atom bomb's working is based on uncontrolled chain reaction.

Nuclear Fusion

The process of combining of two lighter nuclei to form one heavy nucleus is called nuclear fusion.

When three deuteron nuclei (${}_1H^2$) are fused, 21.6 MeV is energy released and nucleus of helium (${}_2He^4$) is formed.

$${}_1H^2 + {}_1H^2 + {}_1H^2 \longrightarrow {}_2He^4 + {}_1H^1 + {}_0n^1 + 21.6\text{ MeV}$$

In this process, a large amount of energy is released.

Nuclear fusion takes place at very high temperature approximately about 10^7 K and at very high pressure 10^6 atmosphere. Thus, the energy released during nuclear fusion is known as thermonuclear energy. Hydrogen bomb is based on nuclear fusion.

The source of sun's energy is the nuclear fusion taking place in the interior of sun.

Radioactivity

The phenomenon of spontaneous emission of radiations by nucleus of some elements is called radioactivity.
This phenomenon was discovered by Henry Becquerel in 1896.

Radiations Emitted by a Radioactive Element

Three types of radiations emitted by radioactive elements are
(i) α-rays (ii) β-rays (iii) γ-rays

S.No.	Property	α-particle	β-particle	γ-rays
1.	Nature	Helium nucleus	Fast moving electrons	Electromagnetic waves
2.	Charge	$+2e$	$-e$	zero
3.	Rest mass	6.67×10^{-27} kg	9.1×10^{-31} kg	zero
4.	Speed	1.4×10^{7} to 2.2×10^{7} ms^{-1}	1 to 99% of $c = 3\times10^{8}$ ms^{-1}	$c = 3\times10^{8}$ ms^{-1}
5.	Ionising power	10^4	10^2	1
6.	Penetrating power	1	10^2	10^4

- When an α-particle is emitted by a nucleus its atomic number decreases by 2 and mass number decreases by 4.

$$_Z X^A \xrightarrow{\alpha\text{-particle}} {}_{Z-2}Y^{A-4} + {}_2\text{He}^4$$

- When a β-particle is emitted by a nucleus its atomic number is increases by one and mass number remains unchanged.

$$_Z X^A \xrightarrow{\beta\text{-particle}} {}_{Z+1}Y^{A} + e^- + \bar{\nu}$$

- When a γ-particle is emitted by a nucleus its atomic number and mass number remain unchanged.

Radioactive Decay Law

The rate of disintegration of radioactive nuclei at any instant is directly proportional to the number of radioactive nuclei present in the sample at that instant.

$$\text{Rate of disintegration}\left(-\frac{dN}{dt}\right) \propto N \text{ or } -\frac{dN}{dt} = \lambda N$$

where, λ is the decay constant.

The number of nuclei present undecayed in the sample at any instant $N = N_0 e^{-\lambda t}$.

where, N_0 is number of nuclei at time $t = 0$ and N is number of nuclei at time t.

Half-life of a Radioactive Element

The time in which the half number of nuclei present initially in any sample decays is called half-life (T) of that radioactive element.

Relation between half-life and disintegration constant is given by

$$T_{1/2} = \frac{\log_e 2}{\lambda} = \frac{0.6931}{\lambda}$$

Average Life or Mean Life (τ)

Average life or mean life (τ) of a radioactive element is the ratio of total life time of all the nuclei and total number of nuclei present initially in the sample.

Relation between average life and decay constant, $\tau = \frac{1}{\lambda}$

Relation between half-life and average life, $\tau = 1.44\, T_{1/2}$

The number of nuclei left undecayed after n half-lives is given by

$$N = N_0 \left(\frac{1}{2}\right)^n = N_0 \left(\frac{1}{2}\right)^{\frac{t}{T_{1/2}}}$$

where, $n = \frac{t}{T_{1/2}}$, here t = total time.

Activity of a Radioactive Element

The activity of a radioactive element is equal to its rate of disintegration.

$$\text{Activity, } R = \left(-\frac{dN}{dt}\right)$$

Activity of the sample after time t, $R = R_0 e^{-\lambda t}$

Its SI unit is Becquerel (Bq).

Its other units are Curie and Rutherford.

$$1 \text{ Curie} = 3.7 \times 10^{10} \text{ decay/s}$$

$$1 \text{ Rutherford} = 10^6 \text{ decay/s}$$