Chapter
26

Atomic and Nuclear Physics

Thomson's Atomic Model

J.J. Thomson gave the first idea regarding structure of atom. According to this model.

(1) An atom is a solid sphere in which entire and positive charge and it's mass is uniformly distributed and in which negative charge (*i.e.* electron) are embedded like seeds in watermelon.

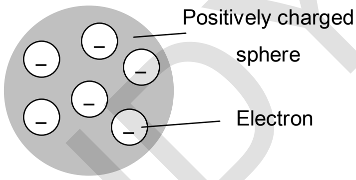


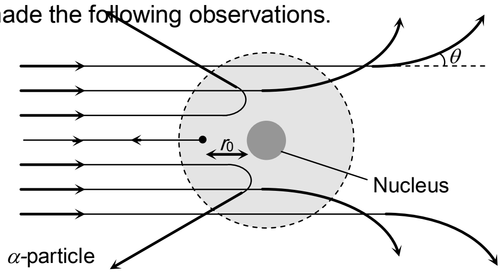
Fig. 26.1

(2) This model explained successfully the phenomenon of thermionic emission, photoelectric emission and ionization.

(3) The model fail to explain the scattering of α- particles and it cannot explain the origin of spectral lines observed in the spectrum of hydrogen and other atoms.

α-Scattering Experiment

'Geiger and Marsden (students of Rutherford) studied the scattering of α-particles by gold foil on the advice of Rutherford and made the following observations.



(1) Most of the α-particles pass through the foil straight away undeflected.

(2) Some of them are deflected through small angles.

(3) A few α-particles (1 in 1000) are deflected through the angle more than 90°.

(4) A few α-particles (very few) returned back *i.e.* deflected by 180°.

(5) Number of scattered particles : $N \propto \dfrac{1}{\sin^4(\theta/2)}$

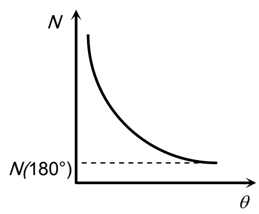


Fig. 26.3

(6) If t is the thickness of the foil and N is the number of α-particles scattered in a particular direction (*i.e.* θ = constant), it was observed that $\frac{N}{t} = \text{constant} \Rightarrow \frac{N_1}{N_2} = \frac{t_1}{t_2}$

(7) **Distance of closest approach** (Nuclear dimension) :

The minimum distance from the nucleus up to which the α-particle approach, is called the distance of closest approach (r_0). At this distance the entire initial kinetic energy has been converted into potential energy so

$$\frac{1}{2}mv^2 = \frac{1}{4\pi\varepsilon_0}.\frac{(Ze)2e}{r_0} \Rightarrow r_0 = \frac{Ze^2}{mv^2\pi\varepsilon_0} = \frac{4kZe^2}{mv^2}$$

(8) **Impact parameter** (b) : The perpendicular distance of the velocity vector ($\vec{v}$) of the α-particle from the centre of the nucleus when it is far away from the nucleus is known as impact parameter. It is given as

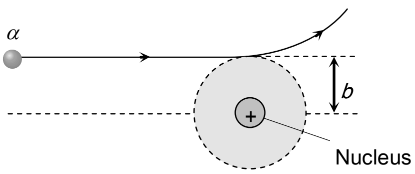


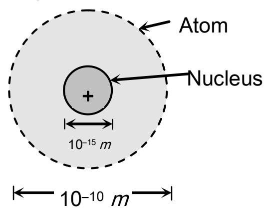
Fig. 26.4

$$b = \frac{Ze^2 \cot(\theta/2)}{4\pi\varepsilon_0\left(\frac{1}{2}mv^2\right)} \Rightarrow b \propto \cot(\theta/2)$$

For large b, α particles will go undeviated and for small b the α-particle will suffer large scattering.

Rutherford's Atomic Model

After α-particles scattering experiment, following conclusions were made by Rutherford as regard as atomic structure :



Size of the nucleus = 1 *Fermi* = 10^{-15} *m*

Size of the atom 1 Å = 10^{-10} *m*

Fig. 26.5

(1) Most of the mass (at least 99.95%) and all of the charge of an atom concentrated in a very small region is called atomic nucleus.

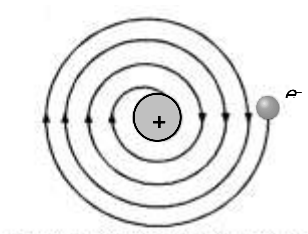
(2) Nucleus is positively charged and it's size is of the order of

10^{-15} *m* ≈ 1 *Fermi*. The nucleus occupies only about 10^{-12} of the total volume of the atom or less.

(3) In an atom there is maximum empty space and the electrons revolve around the nucleus in the same way as the planets revolve around the sun.

Failure of Rutherford's Model

(1) **Stability of atom :** It could not explain stability of atom because according to classical electrodynamics theory an accelerated charged particle should continuously radiate energy. Thus an electron moving in an circular path around the nucleus should ove into smaller and smaller orb us and it should ultimately fall int



Instability of atom

Fig. 26.6

(2) According to this model the spectrum of atom must be continuous where as practically it is a line spectrum.

(3) It did not explain the distribution of electrons outside the nucleus.

Bohr's Atomic Model

Bohr proposed a model for hydrogen atom which is also applicable for some lighter atoms in which a single electron revolves around a stationary nucleus of positive charge Ze (called hydrogen like atom)

Bohr's model is based on the following postulates.

(1) He postulated that an electron in an atom can move around the nucleus in certain circular stable orbits without emitting radiations.

(2) Bohr found that the magnitude of the electron's

Angular momentum is quantized *i.e.* $L = mv_n r_n = n\left(\frac{h}{2\pi}\right)$

where n = 1, 2, 3, ... each value of n corresponds to a permitted value of the orbit radius.

r_n = Radius of n^{th} orbit, v_n = corresponding speed

(3) The radiation of energy occurs only when an electron jumps from one permitted orbit to another.

When electron jumps from higher energy orbit (E_2) to lower energy orbit (E_1) then difference of energies of these orbits *i.e.* $E_2 - E_1$ emits in the form of photon. But if electron goes from E_1 to E_2 it absorbs the same amount of energy.

Draw Backs of Bohr's Atomic Model

(1) It is valid only for one electron atoms, *e.g.* : H, He^+, Li^{+2}, Na^{+1} *etc.*

(2) Orbits were taken as circular but according to Sommerfield these are elliptical.

(3) Intensity of spectral lines could not be explained.

(4) Nucleus was taken as stationary but it also rotates on its own axis.

(5) It could not be explained the minute structure in spectrum line.

(6) This does not explain the Zeeman effect (splitting up of spectral lines in magnetic field) and Stark effect (splitting up in electric field)

(7) This does not explain the doublets in the spectrum of some of the atoms like sodium (5890 Å & 5896 Å)

Bohr's Orbits (for Hydrogen and H_2-like Atoms)

(1) **Radius of orbit :** For an electron around a stationary nucleus the electrostatics force of attraction provides the necessary centripetal force

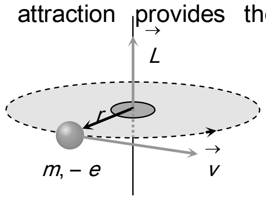


Fig. 26.7

i.e. $\frac{1}{4\pi\varepsilon_0}\frac{(Ze)e}{r^2} = \frac{mv^2}{r}$ .... (i)

also $mvr = \frac{nh}{2\pi}$ ....(ii)

From equation (i) and (ii) radius of n^{th} orbit

$$r_n = \frac{n^2h^2}{4\pi^2 kZme^2} = \frac{n^2h^2\varepsilon_0}{\pi mZe^2} = 0.53\frac{n^2}{Z}\,\text{Å} \qquad \left(k = \frac{1}{4\pi\varepsilon_0}\right)$$

$$\Rightarrow\ r_n \propto \frac{n^2}{Z}$$

(2) **Speed of electron :** From the above relations, speed of electron in n^{th} orbit can be calculated as

$$v_n = \frac{2\pi kZe^2}{nh} = \frac{Ze^2}{2\varepsilon_0 nh} = \left(\frac{c}{137}\right).\frac{Z}{n} = 2.2\times10^6\,\frac{Z}{n}\,m/sec$$

where (c = speed of light 3×10^8 *m/s*)

Table 26.1 : Some other quantities for revolution of electron in n^{th} orbit

Quantity	Formula	Dependency on n and Z
(1) Angular speed	$\omega_n = \frac{v_n}{r_n} = \frac{\pi m z^2 e^4}{2\varepsilon_0^2 n^3 h^3}$	$\omega_n \propto \frac{Z^2}{n^3}$
(2) Frequency	$\nu_n = \frac{\omega_n}{2\pi} = \frac{mz^2e^4}{4\varepsilon_0^2 n^3 h^3}$	$\nu_n \propto \frac{Z^2}{n^3}$
(3) Time period	$T_n = \frac{1}{\nu_n} = \frac{4\varepsilon_0^2 n^3 h^3}{mz^2e^4}$	$T_n \propto \frac{n^3}{Z^2}$
(4) Angular momentum	$L_n = mv_n r_n = n\left(\frac{h}{2\pi}\right)$	$L_n \propto n$
(5) Corresponding current	$i_n = e\nu_n = \frac{mz^2e^5}{4\varepsilon_0^2 n^3 h^3}$	$i_n \propto \frac{Z^2}{n^3}$
(6) Magnetic moment	$M_n = i_n A = i_n(\pi r_n^2)$ (where $\mu_0 = \frac{eh}{4\pi m}$ = Bohr magneton)	$M_n \propto n$
(7) Magnetic field	$B = \frac{\mu_0 i_n}{2r_n} = \frac{\pi m^2 z^3 e^7 \mu_0}{8\varepsilon_0^3 n^5 h^5}$	$B \propto \frac{Z^3}{n^5}$

Energy

(1) **Potential energy :** An electron possesses some potential energy because it is found in the field of nucleus potential energy of electron in n^{th} orbit of radius r_n is given by $U = k.\frac{(Ze)(-e)}{r_n} = -\frac{kZe^2}{r_n}$

(2) **Kinetic energy :** Electron posses kinetic energy because of it's motion. Closer orbits have greater kinetic energy than outer ones.

As we know $\frac{mv^2}{r_n} = \frac{k.(Ze)(e)}{r_n^2}$

$\Rightarrow$ Kinetic energy $K = \frac{kZe^2}{2r_n} = \frac{|U|}{2}$

(3) **Total energy :** Total energy (E) is the sum of potential energy and kinetic energy *i.e.* $E = K + U$

$$\Rightarrow \quad E = -\frac{kZe^2}{2r_n} \text{ also } r_n = \frac{n^2h^2\varepsilon_0}{\pi mze^2}.$$

Hence $E = -\left(\frac{me^4}{8\varepsilon_0^2h^2}\right).\frac{z^2}{n^2} = -\left(\frac{me^4}{8\varepsilon_0^2ch^3}\right)ch\frac{z^2}{n^2}$

$$= -R\,ch\frac{Z^2}{n^2} = -13.6\frac{Z^2}{n^2}eV$$

where $R = \frac{me^4}{8\varepsilon_0^2ch^3}$ = Rydberg's constant = 1.09 × 10^7 *per m*.

(4) **Ionisation energy and potential :** The energy required to ionise an atom is called ionisation energy. It is the energy required to make the electron jump from the present orbit to the infinite orbit.

Hence $E_{ionisation} = E_\infty - E_n = 0 - \left(-13.6\frac{Z^2}{n^2}\right) = +\frac{13.6Z^2}{n^2}eV$

For H_2-atom in the ground state

$$E_{ionisation} = \frac{+13.6(1)^2}{n^2} = 13.6\,eV$$

The potential through which an electron need to be accelerated so that it acquires energy equal to the ionisation energy is called ionisation potential. $V_{ionisation} = \frac{E_{ionisation}}{e}$

(5) **Excitation energy and potential :** When energy is given to an electron from external source, it jumps to higher energy level. This phenomenon is called excitation.

The minimum energy required to excite an atom is called excitation energy of the particular excited state and corresponding potential is called exciting potential.

$$E_{Excitation} = E_{Final} - E_{Initial} \text{ and } V_{Excitation} = \frac{E_{excitation}}{e}$$

(6) **Binding energy (B.E.) :** Binding energy of a system is defined as the energy released when it's constituents are brought from infinity to form the system. It may also be defined as the energy needed to separate it's constituents to large distances. If an electron and a proton are initially at rest and brought from large distances to form a hydrogen atom, 13.6 *eV* energy will be released. The binding energy of a hydrogen atom is therefore 13.6 *eV*.

(7) **Energy level diagram :** The diagrammatic description of the energy of the electron in different orbits around the nucleus is called energy level diagram.

Table 26.2 : Energy level diagram of hydrogen/hydrogen like atom

	Principle quantum number	Orbit	Excited state	Energy for H_2 – atom
	$n = \infty$	Infinite	Infinite	0 *eV*
	$n = 4$	Fourth	Third	– 0.85 *eV*
	$n = 3$	Third	Second	– 1.51 *eV*
	$n = 2$	Second	First	– 3.4 *eV*
	$n = 1$	First	Ground	– 13.6 *eV*

Transition of Electron

When an electron makes transition from higher energy level having energy $E_2(n_2)$ to a lower energy level having energy E_1 (n_1) then a photon of frequency ν is emitted

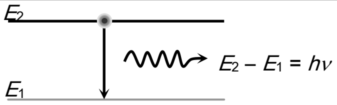


Fig. 26.8

(1) **Energy of emitted radiation**

$$\Delta E = E_2 - E_1 = \frac{-Rch\,Z^2}{n_2^2} - \left(-\frac{Rch\,Z^2}{n_1^2}\right)$$

$$= 13.6 Z^2 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

(2) **Frequency of emitted radiation**

$$\Delta E = h\nu \Rightarrow \nu = \frac{\Delta E}{h} = \frac{E_2 - E_1}{h} = Rc\,Z^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$$

(3) **Wave number/wavelength**

Wave number is the number of waves in unit length $\bar{\nu} = \frac{1}{\lambda} = \frac{\nu}{c} \Rightarrow \frac{1}{\lambda} = RZ^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right) = \frac{13.6 Z^2}{hc}\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$

(4) **Number of spectral lines** : If an electron jumps from higher energy orbit to lower energy orbit it emits raidations with various spectral lines.

If electron falls from orbit n_2 to n_1 then the number of spectral lines emitted is given by

$$N_E = \frac{(n_2 - n_1 + 1)(n_2 - n_1)}{2}$$

If electron falls from n^{th} orbit to ground state (*i.e.* $n_2 = n$ and $n_1 = 1$) then number of spectral lines emitted $\boldsymbol{N_E = \frac{n(n-1)}{2}}$

(5) **Recoiling of an atom** : Due to the transition of electron, photon is emitted and the atom is recoiled

Recoil momentum of atom = momentum of photon $= \frac{h}{\lambda} = hRZ^2\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$

Also recoil energy of atom $= \frac{p^2}{2m} = \frac{h^2}{2m\lambda^2}$ (where m = mass of recoil atom)

Hydrogen Spectrum and Spectral Series

When hydrogen atom is excited, it returns to its normal unexcited (or ground state) state by emitting the energy it had absorbed earlier. This energy is given out by the atom in the form of radiations of different wavelengths as the electron jumps down from a higher to a lower orbit. Transition from different orbits cause different wavelengths, these constitute spectral series which are characteristic of the atom emitting them. When observed through a spectroscope, these radiations are imaged as sharp and straight vertical lines of a single colour.

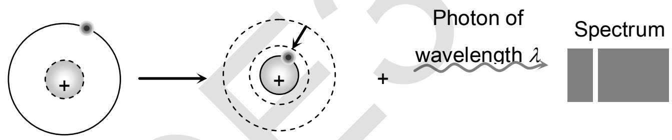


Fig. 26.9 : Emission spectra

The spectral lines arising from the transition of electron forms a spectra series.

(1) Mainly there are five series and each series is named after it's discover as Lymen series, Balmer series, Paschen series, Bracket series and Pfund series.

(2) According to the Bohr's theory the wavelength of the radiations emitted from hydrogen atom is given by

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

where n_2 = outer orbit (electron jumps from this orbit), n_1 = inner orbit (electron falls in this orbit)

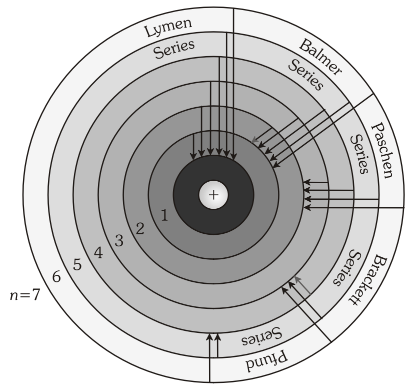


Fig. 26.10

(3) First line of the series is called first member, for this line wavelength is maximum (λ_{max})

For maximum wavelength if $n_1 = n$ then $n_2 = n + 1$

So $\lambda_{max} = \frac{n^2(n+1)^2}{(2n+1)R}$

(4) Last line of the series is called series limit, for this line wavelength is minimum (λ_{min})

For minimum wavelength $n_2 = \infty, n_1 = n$ So $\lambda_{min} = \frac{n^2}{R}$

(5) The ratio of first member and series limit can be calculated as $\frac{\lambda_{max}}{\lambda_{min}} = \frac{(n+1)^2}{(2n+1)}$

Table 26.3 : Different spectral series

Spectral series	Transition	λ_{max}	λ_{min}	$\frac{\lambda_{max}}{\lambda_{min}}$	Region
1. Lymen series	$n_2 = 2, 3, 4 \dots\infty$ $n_1 = 1$	$\frac{4}{3R}$	$\frac{1}{R}$	$\frac{4}{3}$	Ultraviolet region
2.Balmer series	$n_2 = 3, 4, 5 \dots\infty$ $n_1 = 2$	$\frac{36}{5R}$	$\frac{4}{R}$	$\frac{9}{5}$	Visible region
3. Paschen series	$n_2 = 4, 5, 6 \dots\infty$ $n_1 = 3$	$\frac{144}{7R}$	$\frac{9}{R}$	$\frac{16}{7}$	Infrared region
4. Bracket series	$n_2 = 5, 6, 7 \dots \infty$ $n_1 = 4$	$\frac{400}{9R}$	$\frac{16}{R}$	$\frac{25}{9}$	Infrared region
5. Pfund series	$n_2 = 6, 7, 8 \dots \infty$ $n_1 = 5$	$\frac{900}{11R}$	$\frac{25}{R}$	$\frac{36}{11}$	Infrared region

Quantum Numbers

An atom contains large number of shells and subshells. These are distinguished from one another on the basis of their size, shape and orientation (direction) in space. The parameters are expressed in terms of different numbers called quantum number.

Quantum numbers may be defined as a set of four number with the help of which we can get complete information about all the electrons in an atom. It tells us the address of the electron *i.e.* location, energy, the type of orbital occupied and orientation of that orbital.

(1) **Principal Quantum number (*n*) :** This quantum number determines the main energy level or shell in which the electron is present. The average distance of the electron from the nucleus and the energy of the electron depends on it.

$E_n \propto \frac{1}{n^2}$ and $r_n \propto n^2$ (in *H*-atom)

The principal quantum number takes whole number values, $n = 1, 2, 3, 4, \dots \infty$

(2) **Orbital quantum number (*l*) or azimuthal quantum number (*l*) :** This represents the number of subshells present in the main shell. These subsidiary orbits within a shell will be denoted as 1, 2, 3, 4 … or *s*, *p*, *d*, *f* … This tells the shape of the subshells.

The orbital angular momentum of the electron is given as $L = \sqrt{l(l+1)}\frac{h}{2\pi}$ (for a particular value of *n*).

For a given value of *n* the possible values of *l* are $l = 0, 1, 2, \dots$ upto $(n - 1)$

(3) **Magnetic quantum number (m_l) :** An electron due to it's angular motion around the nucleus generates an electric field. This electric field is expected to produce a magnetic field. Under the influence of external magnetic field, the electrons of a subshell can orient themselves in certain preferred regions of space around the nucleus called orbitals.

The magnetic quantum number determines the number of preferred orientations of the electron present in a subshell.

The angular momentum quantum number *m* can assume all integral value between $-l$ to $+l$ including zero. Thus m_l can be $-1, 0, +1$ for $l = 1$. Total values of m_l associated with a particular value of *l* is given by $(2l + 1)$.

(4) **Spin (magnetic) quantum number (m_s) :** An electron in atom not only revolves around the nucleus but also spins about its own axis. Since an electron can spin either in clockwise direction or in anticlockwise direction. Therefore for any particular value of magnetic quantum number, spin quantum number can have two values, *i.e.* $m_s = \frac{1}{2}$ (Spin up) or $m_s = -\frac{1}{2}$ (Spin down)

This quantum number helps to explain the magnetic properties of the substance.

Table 26.4 : Quantum states of the hydrogen atom

n	l	m_l	Spectroscopic notation	Shell
1	0	0	1 *s*	*K*
2	0	0	2 *s*	*L*
2	1	– 1, 0, 1	2 *p*	
3	0	0	3 *s*	
3	1	– 1, 0, 1	3 *p*	*M*
3	2	– 2, – 1, 0, 1, 2	3 *d*	
4	0	0	4 *s*	*N*

Electronic Configurations of Atoms

The distribution of electrons in different orbitals of an atom is called the electronic configuration of the atom. The filling of electrons in orbitals is governed by the following rules.

(1) **Pauli's exclusion principle :** "It states that no two electrons in an atom can have all the four quantum number (n, l, m_l and m_s) the same."

It means each quantum state of an electron must have a different set of quantum numbers n, l, m_l and m_s. This principle sets an upper limit on the number of electrons that can occupy a shell.

$N_{\max}$ in one shell = $2n^2$; Thus $N_{\max}$ in K, L, M, N …. shells are 2, 8, 18, 32,

(2) **Aufbau principle :** Electrons enter the orbitals of lowest energy first.

As a general rule, a new electron enters an empty orbital for which ($n + l$) is minimum. In case the value $(n+l)$ is equal for two orbitals, the one with lower value of n is filled first.

Thus the electrons are filled in subshells in the following order (memorize)

1*s*, 2*s*, 2*p*, 3*s*, 3*p*, 4*s*, 3*d*, 4*p*, 5*s*, 4*d*, 5*p*, 6*s*, 4*f*, 5*d*, 6*p*, 7*s*, 5*f*, 6*d*, 7*p*, ……

(3) **Hund's Rule :** When electrons are added to a subshell where more than one orbital of the same energy is available, their spins remain parallel. They occupy different orbitals until each one of them has at least one electron. Pairing starts only when all orbitals are filled up.

Pairing takes place only after filling 3, 5 and 7 electrons in *p*, *d* and *f* orbitals, respectively.

Nucleus

(1) Rutherford's α-scattering experiment established that the mass of atom is concentrated with small positively charged region at the centre which is called 'nucleus'.

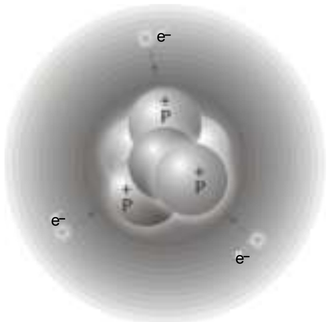


Fig. 26.11

(2) The stability or instability of a particular nucleus is determined by the competition between the attractive nuclear force among the protons and neutrons and the repulsive electrical interactions among the protons. Unstable nuclei *decay*, transforming themselves spontaneously into other structure by a variety of decay processes.

(3) We could not survive without the 3.90×10^{26} *watt* output of one near by fusion reactor, our sun.

(4) Nuclei are made up of proton and neutron. The number of protons in a nucleus (called the atomic number or proton number) is represented by the symbol *Z*. The number of neutrons (neutron number) is represented by *N*. The total number of neutrons and protons in a nucleus is called it's mass number *A* so *A* = *Z* + *N*.

(5) Neutrons and proton, when described collectively are called ***nucleons***. A single nuclear species having specific values of both *Z* and *N* is called a nuclide.

(6) Nuclides are represented as $_ZX^A$; where *X* denotes the chemical symbol of the element.

Neutron

Neutron is a fundamental particle which is essential constituent of all nuclei except that of hydrogen atom. It was discovered by Chadwick. A free neutron outside the nucleus is unstable and decays into proton and electron.

$$_0n^1 \rightarrow \underset{\text{Proton}}{_1H^1} + \underset{\text{Electron}}{_{-1}\beta^0} + \underset{\text{Antinutrino}}{\overline{\nu}}$$

(1) The charge of neutron : It is neutral

(2) The mass of neutron : 1.6750×10^{-27} *kg*

(3) It's spin angular momentum : $\frac{1}{2} \times \left(\frac{h}{2\pi}\right) J - s$

(4) It's magnetic moment : 9.57×10^{-27} *J/Tesla*

(5) It's half life : 12 minutes

(6) Penetration power : High

(7) Types : Neutrons are of two types slow neutron and fast neutron, both are fully capable of penetrating a nucleus and causing artificial disintegration.

Thermal Neutrons

Fast neutrons can be converted into slow neutrons by certain materials called moderator's (Paraffin wax, heavy water, graphite) when fast moving neutrons pass through a moderator, they collide with the molecules of the moderator, as a result of this, the energy of moving neutron decreases while that of the molecules of the moderator increases. After sometime they both attains same energy. The neutrons are then in thermal equilibrium with the molecules of the moderator and are called thermal neutrons.

Energy of thermal neutron is about 0.025 *eV* and speed is about 2.2 *km/s*.

Types of Nuclei

The nuclei have been classified on the basis of the number of protons (atomic number) or the total number of nucleons (mass number) as follows

(1) **Isotopes :** The atoms of element having same atomic number but different mass number are called isotopes. All isotopes have the same chemical properties. The isotopes of some elements are the following

$$_1H^1,\ _1H^2,\ _1H^3 \qquad _8O^{16},\ _8O^{17},\ _8O^{18} \qquad _2He^3,\ _2He^4$$
$$_{17}Cl^{35},\ _{17}Cl^{37} \qquad _{92}U^{235},\ _{92}U^{238}$$

(2) **Isobars :** The nuclei which have the same mass number (*A*) but different atomic number (*Z*) are called isobars. Isobars occupy different positions in periodic table so all isobars have different chemical properties. Some of the examples of isobars are

$$_1H^3 \text{ and } _2He^3, \quad _6C^{14} \text{ and } _7N^{14},\ _8O^{17} \text{ and } _9F^{17}$$

(3) **Isotones :** The nuclei having equal number of neutrons are called isotones. For them both the atomic number (*Z*) and mass number (*A*) are different, but the value of (*A* – *Z*) is same. Some examples are

$$_4Be^9 \text{ and } _5B^{10},\ _6C^{13} \text{ and } _7N^{14},\ _8O^{18} \text{ and } _9F^{19}$$
$$_3Li^7 \text{ and } _4Be^8,\ _1H^3 \text{ and } _2He^4$$

(4) **Mirror nuclei :** Nuclei having the same mass number *A* but with the proton number (*Z*) and neutron number (*A* – *Z*) interchanged (or whose atomic number differ by 1) are called mirror nuclei for example.

$_1H^3$ and $_2He^3$, $_3Li^7$ and $_4Be^7$

Size of Nucleus

(1) **Nuclear radius :** Experimental results indicates that the nuclear radius is proportional to $A^{1/3}$, where A is the mass number of nucleus *i.e.* $R \propto A^{1/3} \Rightarrow R = R_0 A^{1/3}$, where R_0 = 1.2×10^{-15} *m* = 1.2 *fm*.

(2) **Nuclear volume :** The volume of nucleus is given by $V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi R_0^3 A \Rightarrow V \propto A$

(3) **Nuclear density** : Mass per unit volume of a nucleus is called nuclear density.

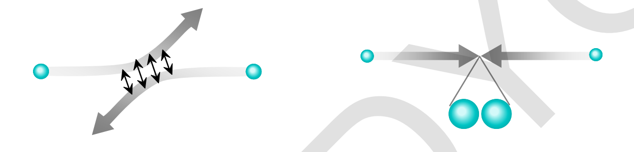
$$\text{Nuclear density}(\rho) = \frac{\text{Mass of nucleus}}{\text{Volume of nucleus}} = \frac{mA}{\frac{4}{3}\pi (R_0 A^{1/3})^3}$$

where m = Average of mass of a nucleon (= mass of proton + mass of neutron = 1.66×10^{-27} *kg*) and mA = Mass of nucleus

$$\Rightarrow \rho = \frac{3m}{4\pi R_0^3} = 2.38 \times 10^{17}\ kg/m^3$$

Nuclear Force

Forces that keep the nucleons bound in the nucleus are called nuclear forces.



(A) At low speeds, electromagnetic repulsion

(B) At high speeds, nuclei come close enough for the strong

Fig. 26.12

(1) Nuclear forces are short range forces. These do not exist at large distances greater than 10^{-15} *m*.

(2) Nuclear forces are the strongest forces in nature.

(3) These are attractive force and causes stability of the nucleus.

(4) These forces are charge independent.

(5) Nuclear forces are non-central force.

(6) **Nuclear forces are exchange forces :** According to scientist Yukawa the nuclear force between the two nucleons is the result of the exchange of particles called mesons between the nucleons.

π - mesons are of three types – Positive π meson (π^+), negative π meson (π^-), neutral π *meson* (π^0)

The force between neutron and proton is due to exchange of charged meson between them *i.e.*

$$p \to \pi^+ + n, \quad n \to p + \pi^-$$

The forces between a pair of neutrons or a pair of protons are the result of the exchange of neutral meson (π^0) between them *i.e.* $p \to p' + \pi^0$ and $n \to n' + \pi^0$

Thus exchange of π meson between nucleons keeps the nucleons bound together. It is responsible for the nuclear forces.

Dog-Bone analogy

The above interactions can be explained with the dog bone analogy according to which we consider the two interacting nucleons to be two dogs having a common bone clenched in between their teeth very firmly. Each one of these dogs wants to take the bone and hence they cannot be separated easily. They seem to be bound to each other with a strong attractive force (which is the bone) thc emselves are strong enemies. The meson pla of the common bone in between two nucleons

Fig. 26.13

Atomic Mass Unit (*amu*)

(1) In nuclear physics, a convenient unit of mass is the unified atomic mass unit abbreviated *u*.

(2) The *amu* is defined as $\frac{1}{12}th$ mass of a $_{B}C^{12}$ at on.

(3) 1 *amu* (or 1 *u*) = 1.6605402 × 10^{-27} *kg* .

(4) **Masses of electron, proton and neutrons :**

Mass of electron (m_e) = 9.1 × 10^{-31} *kg* = 0.0005486 *amu*, Mass of proton (m_p) = 1.6726 × 10^{-27} *kg* = 1.007276 *amu*

Mass of neutron (m_n) = 1.6750 × 10^{-27} *kg* = 1.00865 *amu*, Mass of hydrogen atom ($m_e + m_p$) = 1.6729 × 10^{-27} *kg* = 1.0078 *amu*

(5) The energy associated with a nuclear process is usually large, of the order of *MeV*.

(6) According to Einstein, mass and energy are inter convertible. The Einstein's mass energy relationship is given by $E = mc^2$

If *m* = 1 *amu*, *c* = 3 × 10^8 *m/sec* then *E* = 931 *MeV* *i.e.* 1 *amu* is equivalent to 931 *MeV* or **1 *amu* (or 1 *u*) = 931 *MeV***

(1 *u*) c^2 = 931 *MeV* ⇒ $1u = 931\frac{MeV}{c^2}$ or $c^2 = 931\frac{MeV}{u}$

Table 26.5 : Neutral atomic masses for some light nuclides

Element and isopore	Atomic mass (*u*)
Hydrogen $({}_1^1H)$	1.007825
Deuterium $({}_1^2H)$	2.014102
Tritium $({}_1^3H)$	3.016049
Helium $({}_2^3He)$	3.016029
Helium $({}_2^4He)$	4.002603
Lithium $({}_3^7Li)$	7.016004
Beryllium $({}_4^9Be)$	9.012182
Carbon $({}_6^{12}C)$	12.000000
Nitrogen $({}_7^{14}N)$	14.003074
Oxygen $({}_8^{16}O)$	15.994915

Pair Production and Pair-Annihilation

When an energetic γ-ray photon falls on a heavy substance. It is absorbed by some nucleus of the substance and an electron and a positron are produced. This phenomenon is called pair production and may be represented by the following equation

$$\underset{(\gamma-\text{photon})}{h\nu} = \underset{(\text{Positron})}{{}_{1}\beta^0} + \underset{(\text{Electron})}{{}_{-1}\beta^0}$$

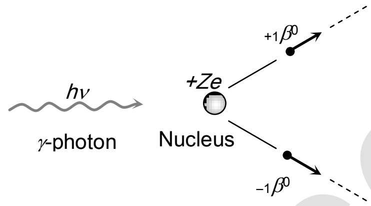


Fig. 26.14

The rest-mass energy of each of positron and electron is

$E_0 = m_0c^2$ = (9.1 × 10^{-31} *kg*) × (3.0 × 10^8 *m/s*)^2

= 8.2 × 10^{-14} *J* = **0.51 *MeV***

Hence, for pair-production it is essential that the energy of γ-photon must be at least 2 × 0.51 = 1.02 *MeV*. If the energy of γ-photon is less than this, it would cause photo-electric effect or Compton effect on striking the matter.

The converse phenomenon pair-annihilation is also possible. Whenever an electron and a positron come very close to each other, they annihilate each other by combining together and two γ-photons (energy) are produced. This phenomenon is called pair annihilation and is represented by the following equation.

$$\underset{(\text{Positron})}{{}_{+1}\beta^0} + \underset{(\text{Electron})}{{}_{-1}\beta^0} = \underset{(\gamma\text{-photon})}{h\nu} + \underset{(\gamma\text{-photon})}{h\nu}$$

Nuclear Stability

Among about 1500 known nuclides, less than 260 are stable. The others are unstable that decay to form other nuclides by emitting α, β-particles and γ - EM waves. (This process is called radioactivity). The stability of nucleus is determined by many factors. Few such factors are given below :

(1) **Neutron-proton ratio** $\left(\frac{N}{Z}\text{Ratio}\right)$: The chemical properties of an atom are governed entirely by the number of protons (*Z*) in the nucleus, the stability of an atom appears to

depend on both the number of protons and the number of neutrons.

(i) For lighter nuclei, the greatest stability is achieved when the number of protons and neutrons are approximately equal ($N \approx Z$) *i.e.* $\frac{N}{Z} = 1$

(ii) Heavy nuclei are stable only when they have more neutrons than protons. Thus heavy nuclei are neutron rich compared to lighter nuclei (for heavy nuclei, more is the number of protons in the nucleus, greater is the electrical repulsive force between them. Therefore more neutrons are added to provide the strong attractive forces necessary to keep the nucleus stable.)

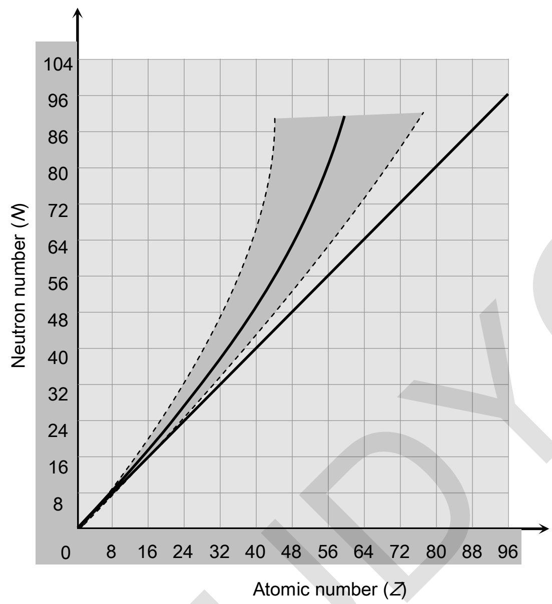


Fig. 26.15

(iii) Figure shows a plot of N verses Z for the stable nuclei. For mass number upto about A = 40. For larger value of Z the nuclear force is unable to hold the nucleus together against the electrical repulsion of the protons unless the number of neutrons exceeds the number of protons. At Bi (Z = 83, A = 209), the neutron excess in $N - Z$ = 43. There are no stable nuclides with $Z > 83$.

(2) **Even or odd numbers of Z or N :** The stability of a nuclide is also determined by the consideration whether it contains an even or odd number of protons and neutrons.

(i) It is found that an even-even nucleus (even Z and even N) is more stable (60% of stable nuclide have even Z and even N).

(ii) An even-odd nucleus (even Z and odd N) or odd-even nuclide (odd Z and even N) is found to be lesser sable while the odd-odd nucleus is found to be less stable.

(iii) Only five stable odd-odd nuclides are known : ${}_1H^2$, ${}_3Li^6$, ${}_5Be^{10}$, ${}_7N^{14}$ and ${}_{75}Ta^{180}$

(3) **Binding energy per nucleon :** The stability of a nucleus is determined by value of it's binding energy per nucleon. In general higher the value of binding energy per nucleon, more stable the nucleus is

Mass Defect and Binding Energy

(1) **Mass defect (Δm) :** It is found that the mass of a nucleus is always less than the sum of masses of it's constituent nucleons in free state. This difference in masses is called mass defect. Hence mass defect

Δm = Sum of masses of nucleons – Mass of nucleus

$$= \{Zm_p + (A-Z)m_n\} - M = \{Zm_p + Zm_e + (A-Z)m_z\} - M'$$

where m_p = Mass of proton, m_n = Mass of each neutron, m_e = Mass of each electron

M = Mass of nucleus, Z = Atomic number, A = Mass number, M' = Mass of atom as a whole.

(2) **Packing fraction :** Mass defect per nucleon is called packing fraction

Packing fraction $(f) = \frac{\Delta m}{A} = \frac{M - A}{A}$ where M = Mass of nucleus, A = Mass number

Packing fraction measures the stability of a nucleus. Smaller the value of packing fraction, larger is the stability of the nucleus.

(i) Packing fraction may be of positive, negative or zero value.

(ii) At A = 16, $f \rightarrow$ Zero

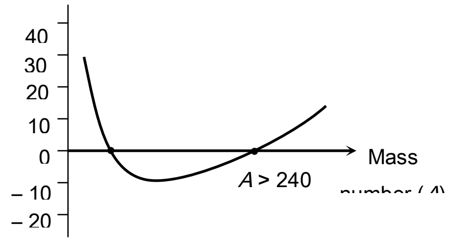


Fig. 26.16

(3) **Binding energy (B.E.) :** The neutrons and protons in a stable nucleus are held together by nuclear forces and energy is needed to pull them infinitely apart (or the same energy is released during the formation of the nucleus). This energy is called the binding energy of the nucleus.

or

The binding energy of a nucleus may be defined as the energy equivalent to the mass defect of the nucleus.

If Δm is mass defect then according to Einstein's mass energy relation

Binding energy = $\Delta m \cdot c^2$ = $[\{m_p Z + m_n(A - Z)\} - M] \cdot c^2$

(This binding energy is expressed in *joule*, because Δm is measured in *kg*)

If Δm is measured in *amu* then binding energy = Δm *amu* = $[\{m_p Z + m_n(A - Z)\} - M]$ *amu* = $\Delta m \times 931$ *MeV*

(4) **Binding energy per nucleon :** The average energy required to release a nucleon from the nucleus is called binding energy per nucleon.

Binding energy per nucleon

$$= \frac{\text{Total binding energy}}{\text{Mass number } (i.e. \text{ total number of nucleons})} = \frac{\Delta m \times 931}{A} \frac{MeV}{Nucleon}$$

Binding energy per nucleon $\propto$ Stability of nucleus

Binding Energy Curve

It is the graph between binding energy per nucleon and total number of nucleons (*i.e.* mass number A)

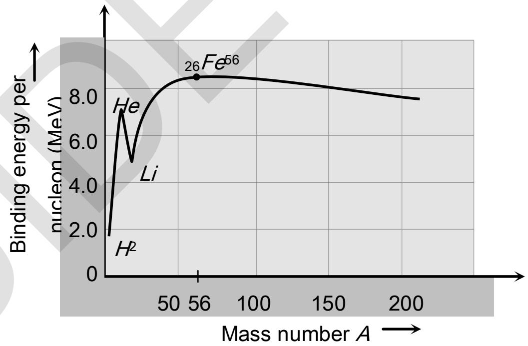


Fig. 26.17

(1) Some nuclei with mass number A < 20 have large binding energy per nucleon than their neighbour nuclei. For example ${}_2He^4, {}_4Be^8, {}_6C^{12}, {}_8O^{16}$ and ${}_{10}Ne^{20}$. These nuclei are more stable than their neighbours.

(2) The binding energy per nucleon is maximum for nuclei of mass number A = 56 $({}_{26}Fe^{56})$. It's value is 8.8 *MeV* per nucleon.

(3) For nuclei having A > 56, binding energy per nucleon gradually decreases for uranium (A = 238), the value of binding energy per nucleon drops to 7.5 *MeV*.

Nuclear Reactions

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

$$\underset{\text{(Parent nucleus)}}{X} + \underset{\text{(Incident particle)}}{a} \longrightarrow$$

$$\underset{\text{(Compound nucleus)}}{C} \longrightarrow \underset{\text{(Compound nucleus)}}{Y} + \underset{\text{(Product particles)}}{b} + \underset{\text{(Energy)}}{Q}$$

Here *X* and *a* are known as reactants and *Y* and *b* are known as products. This reaction is known as (*a*, *b*) reaction and can be represented as *X*(*a*, *b*) *Y*

(1) ***Q* value or energy of nuclear reaction :** The energy absorbed or released during nuclear reaction is known as *Q*-value of nuclear reaction.

Q-value = (Mass of reactants – mass of products)c^2 *Joules*

= (Mass of reactants – mass of products) *amu*

If $Q < 0$, The nuclear reaction is known as endothermic. (The energy is absorbed in the reaction)

If $Q > 0$, The nuclear reaction is known as exothermic (The energy is released in the reaction)

(2) **Law of conservation in nuclear reactions**

(i) Conservation of mass number and charge number : In the following nuclear reaction

$${}_2He^4 + {}_7N^{14} \to {}_8O^{17} + {}_1H^1$$

Mass number (*A*) $\to$ Before the reaction After the reaction

4 +14 = 18 17 + 1 = 18

Charge number (*Z*) $\to$ 2 + 7 = 9 8 + 1 = 9

(ii) Conservation of momentum : Linear momentum/angular momentum of particles before the reaction is equal to the linear/angular momentum of the particles after the reaction. That is $\Sigma p = 0$

(iii) Conservation of energy : Total energy before the reaction is equal to total energy after the reaction. Term *Q* is added to balance the total energy of the reaction.

(3) **Common nuclear reactions :** The nuclear reactions lead to artificial transmutation of nuclei. Rutherford was the first to carry out artificial transmutation of nitrogen to oxygen in the year 1919.

$${}_2He^4 + {}_7N^{14} \to {}_9F^{18} \to {}_8O^{17} + {}_1H^1$$

It is called (α, *p*) reaction. Some other nuclear reactions are given as follows.

(*p*, *n*) reaction $\Rightarrow$ ${}_1H^1 + {}_5B^{11} \to {}_6C^{12} \to {}_6C^{11} + {}_0n^1$

(*p*, α) reaction $\Rightarrow$ ${}_1H^1 + {}_3Li^{11} \to {}_4Be^8 \to {}_2He^4 + {}_2He^4$

(*p*, γ) reaction $\Rightarrow$ ${}_1H^1 + {}_6C^{12} \to {}_7N^{13} \to {}_7N^{13} + \gamma$

(*n*, *p*) reaction $\Rightarrow$ ${}_0n^1 + {}_7N^{14} \to {}_7N^{15} \to {}_6C^{14} + {}_1H^1$

(γ, *n*) reaction $\Rightarrow$ $\gamma + {}_1H^2 \to {}_1H^1 + {}_0n^1$

Nuclear Fission

(1) The process of splitting of a heavy nucleus into two lighter nuclei of comparable masses (after bombardment with a energetic particle) with liberation of energy is called nuclear fission.

(2) The phenomenon of nuclear fission was discovered by scientist Ottohann and F. Strassman and was explained by N. Bohr and J.A. Wheeler on the basis of liquid drop model of nucleus.

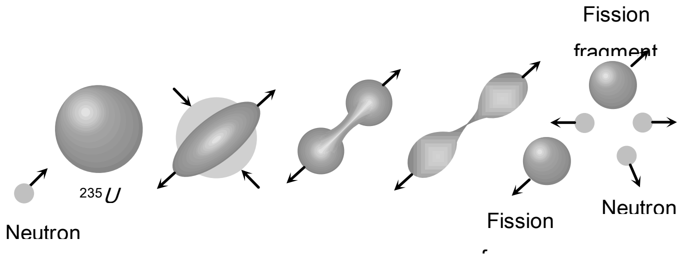


Fig. 26.18

(3) **Fission reaction of U^{235}**

$$_{92}U^{235} + {_0}n^1 \rightarrow \underset{\text{(unstable nucleus)}}{_{92}U^{236}} \rightarrow {_{56}}Ba^{141} + {_{36}}Kr^{92} + 3{_0}n^1 + Q$$

(4) The energy released in U^{235} fission is about 200 *MeV* or 0.8 *MeV* per nucleon.

(5) By fission of $_{92}U^{235}$, on an average 2.5 neutrons are liberated. These neutrons are called fast neutrons and their energy is about 2 *MeV* (for each). These fast neutrons can escape from the reaction so as to proceed the chain reaction they are need to slow down.

(6) Fission of U^{235} occurs by slow neutrons only (of energy about 1*eV*) or even by thermal neutrons (of energy about 0.025 *eV*).

(7) 50 *kg* of U^{235} on fission will release ≈ 4 × 10^{15} *J* of energy. This is equivalence to 20,000 tones of *TNT* explosion. The nuclear bomb dropped at Hiroshima had this much explosion power.

(8) The mass of the compound nucleus must be greater than the sum of masses of fission products.

(9) The $\dfrac{\text{Binding energy}}{\text{A}}$ of compound nucleus must be less than that of the fission products.

(10) It may be pointed out that it is not necessary that in each fission of uranium, the two fragments $_{56}Ba$ and $_{36}Kr$ are formed but they may be any stable isotopes of middle weight atoms.

(11) Same other U^{235} fission reactions are

$$_{92}U^{235} + {_0}n^1 \rightarrow {_{54}}Xe^{140} + {_{38}}Sr^{94} + 2{_0}n^1$$

$$\rightarrow {_{57}}La^{148} + {_{35}}Br^{85} + 3\,{_0}n^1$$

$\rightarrow$ Many more

(12) The neutrons released during the fission process are called prompt neutrons.

(13) Most of energy released appears in the form of kinetic energy of fission fragments.

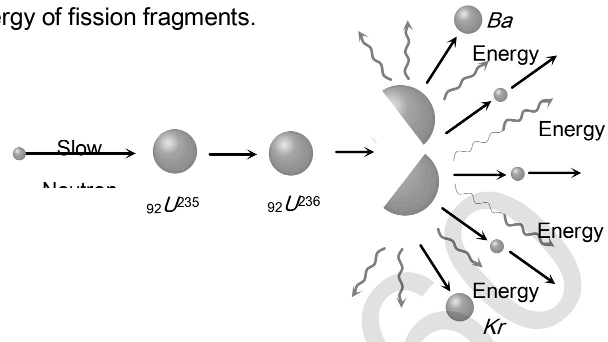


Fig. 26.19

Chain Reaction

In nuclear fission, three neutrons are produced along with the release of large energy. Under favourable conditions, these neutrons can cause further fission of other nuclei, producing large number of neutrons. Thus a chain of nuclear fissions is established which continues until the whole of the uranium is consumed.

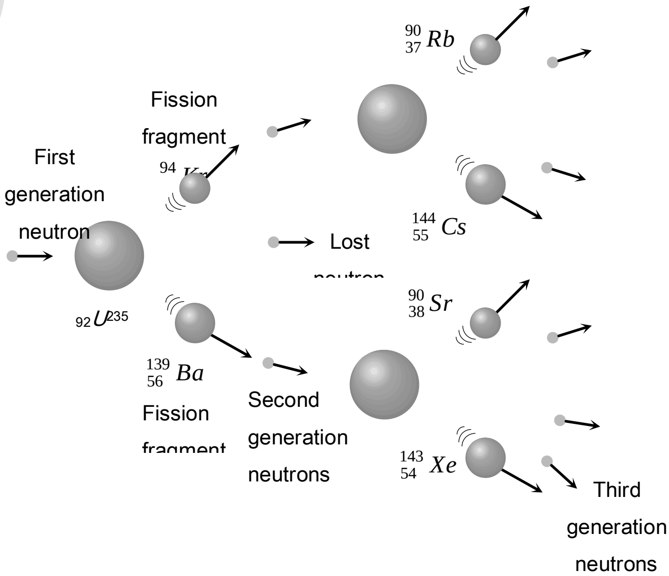


Fig. 26.20

In the chain reaction, the number of nuclei undergoing fission increases very fast. So, the energy produced takes a tremendous magnitude very soon.

Difficulties in Chain Reaction

In chain reaction following difficulties are observed

(1) **Absorption of neutrons by U^{238} :** the major part in natural uranium is the isotope U^{238} (99.3%), the isotope U^{235} is very little (0.7%). It is found that U^{238} is fissionable with fast neutrons, whereas U^{235} is fissionable with slow neutrons. Due to the large percentage of U^{238}, there is more possibility of collision of neutrons with U^{238}. It is found that the neutrons get slowed on coliding with U^{238}, as a result of it further fission of U^{238} is not possible (Because they are slow and they are absorbed by U^{238}). This stops the chain reaction.

Removal : (i) To sustain chain reaction ${}_{92}U^{235}$ is separated from the ordinary uranium. Uranium so obtained $\left({}_{92}U^{235}\right)$ is known as enriched uranium, which is fissionable with the fast and slow neutrons and hence chain reaction can be sustained.

(ii) If neutrons are slowed down by any method to an energy of about 0.3 *eV*, then the probability of their absorption by U^{238} becomes very low, while the probability of their fissioning U^{235} becomes high. This job is done by moderators. Which reduce the speed of neutron rapidly graphite and heavy water are the example of moderators.

(2) **Critical size :** The neutrons emitted during fission are very fast and they travel a large distance before being slowed down. If the size of the fissionable material is small, the neutrons emitted will escape the fissionable material before they are slowed down. Hence chain reaction cannot be sustained.

Removal : The size of the fissionable material should be large than a critical size.

The chain reaction once started will remain steady, accelerate or retard depending upon, a factor called neutron reproduction factor (*k*). It is defined as follows.

$$k = \frac{\text{Rate of production of neutrons}}{\text{Rate of loss of neutrons}}$$

If *k* = 1, the chain reaction will be steady. The size of the fissionable material used is said to be the critical size and it's mass, the critical mass.

If *k* > 1, the chain reaction accelerates, resulting in an explosion. The size of the material in this case is super critical. (Atom bomb)

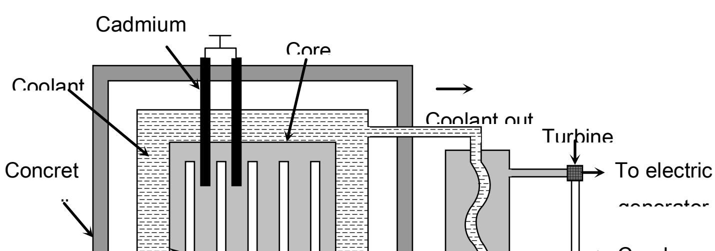
If *k* < 1, the chain reaction gradually comes to a halt. The size of the material used us said to be sub-critical.

Table 26.6 : Types of chain reaction

Controlled chain reaction	Uncontrolled chain reaction
Controlled by artificial method	No control over this type of nuclear reaction
All neurons are absorbed except one	More than one neutron takes part into reaction
It's rate is slow	Fast rate
Reproduction factor *k* = 1	Reproduction factor *k* > 1
Energy liberated in this type of reaction is always less than explosive energy	A large amount of energy is liberated in this type of reaction
Chain reaction is the principle of nuclear reactors	Uncontrolled chain reaction is the principle of atom bomb.

Nuclear Reactor

A nuclear reactor is a device in which nuclear fission can be carried out through a sustained and a controlled chain reaction. It is also called an atomic pile. It is thus a source of controlled energy which is utilised for many useful purposes.



(1) **Fissionable material (Fuel) :** The fissionable material used in the reactor is called the fuel of the reactor. Uranium isotope (U^{235}) Thorium isotope (Th^{232}) and Plutonium isotopes (Pu^{239}, Pu^{240} and Pu^{241}) are the most commonly used fuels in the reactor.

(2) **Moderator :** Moderator is used to slow down the fast moving neutrons. Most commonly used moderators are graphite and heavy water (D_2O).

(3) **Control Material :** Control material is used to control the chain reaction and to maintain a stable rate of reaction. This material controls the number of neutrons available for the fission. For example, cadmium rods are inserted into the core of the reactor because they can absorb the neutrons. The neutrons available for fission are controlled by moving the cadmium rods in or out of the core of the reactor.

(4) **Coolant :** Coolant is a cooling material which removes the heat generated due to fission in the reactor. Commonly used coolants are water, CO_2 nitrogen *etc.*

(5) **Protective shield :** A protective shield in the form a concrete thick wall surrounds the core of the reactor to save the persons working around the reactor from the hazardous radiations.

(6) **Uses of nuclear reactor**

(i) In electric power generation.

(ii) To produce radioactive isotopes for their use in medical science, agriculture and industry.

(iii) In manufacturing of Pu^{239} which is used in atom bomb.

(iv) They are used to produce neutron beam of high intensity which is used in the treatment of cancer and nuclear research.

Nuclear Fusion

(1) In nuclear fusion two or more than two lighter nuclei combine to form a single heavy nucleus. The mass of single nucleus so formed is less than the sum of the masses of parent nuclei. This difference in mass results in the release of tremendous amount of energy

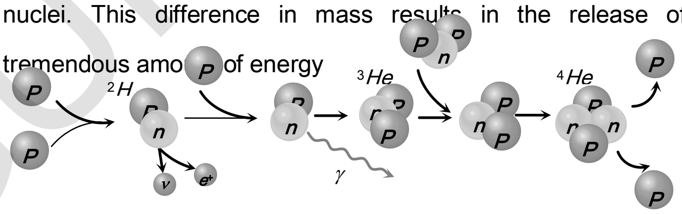


Fig. 26.22

(2) For fusion high pressure ($\approx 10^6$ *atm*) and high temperature (of the order of 10^7 *K* to 10^8 *K*) is required and so the reaction is called thermonuclear reaction.

(3) Here are three examples of energy-liberating fusion reactions, written in terms of the neutral atoms. Together the reactions make up the process called the proton-proton chain.

$$^1_1H + ^1_1H \rightarrow ^2_1H + \beta^+ + \nu_e$$

$$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma$$

$$^3_2He + ^3_2He \rightarrow ^4_2He + ^1_1H + ^1_1H$$

$$4\ _1H^1 \rightarrow _2He^4 + 2\,\beta^+ + 2\gamma + 26.73\,MeV$$

(4) The proton-proton chain takes place in the interior of the sun and other stars. Each gram of the suns mass contains about 4.5×10^{23} protons. If all of these protons were fused into helium, the energy released would be about 130,000 *kWh*. If the sun were to continue to radiate at its present rate, it would take about $75 \times 10^{9}\ years$ to exhaust its supply of protons.

(5) For the same mass of the fuel, the energy released in fusion is much larger than in fission.

(6) **Plasma :** The temperature of the order of 10^8 K required for thermonuclear reactions leads to the complete ionisation of the atom of light elements. The combination of base nuclei and electron cloud is called plasma. The enormous gravitational field of the sun confines the plasma in the interior of the sun.

The main problem to carryout nuclear fusion in the laboratory is to contain the plasma at a temperature of $10^8 K$. No solid container can tolerate this much temperature. If this problem of containing plasma is solved, then the large quantity of deuterium present in sea water would be able to serve as in-exhaustible source of energy.

Table 26.7 : Nuclear bomb (Based on uncontrolled nuclear reactions)

Atom bomb	Hydrogen bomb
Based on fission process it involves the fission of U^{235}	Based on fusion process. Mixture of deutron and tritium is used in it
In this critical size is important	There is no limit to critical size
Explosion is possible at normal temperature and pressure	High temperature and pressure are required
Less energy is released compared to hydrogen bomb	More energy is released as compared to atom bomb so it is more dangerous than atom bomb

Radioactivity

The phenomenon of spontaneous emission of radiatons by heavy elements is called radioactivity. The elements which shows this phenomenon are called radioactive elements.

(1) Radioactivity was discovered by Henery Becquerel in uranium salt in the year 1896.

(2) After the discovery of radioactivity in uranium, Piere Curie and Madame Curie discovered a new radioactive element called radium (which is 10^6 times more radioactive than uranium)

(3) Some examples of radio active substances are : Uranium, Radium, Thorium, Polonium, Neptunium *etc.*

(4) Radioactivity of a sample cannot be controlled by any physical (pressure, temperature, electric or magnetic field) or chemical changes.

(5) All the elements with atomic number (Z) > 82 are naturally radioactive.

(6) The conversion of lighter elements into radioactive elements by the bombardment of fast moving particles is called artificial or induced radioactivity.

(7) Radioactivity is a nuclear event and not atomic. Hence electronic configuration of atom don't have any relationship with radioactivity.

Nuclear Radiations

According to Rutherford's experiment when a sample of radioactive substance is put in a lead box and allow the emission of radiation through a small hole only. When the radiation enters into the external electric field, they splits into three parts (α-rays, β-rays and γ-rays)

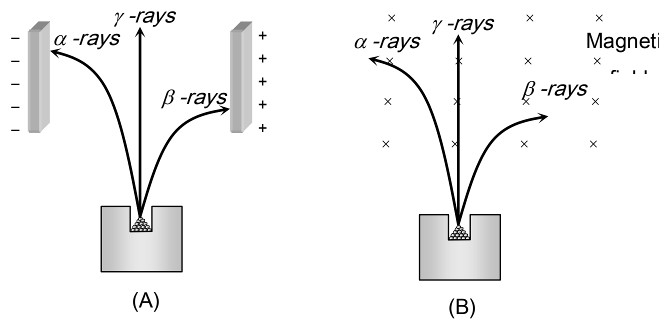


Fig. 26.23

(1) **α-decay** : Nearly 90% of the 2500 known nuclides are radioactive ; they are not stable but decay into other nuclides

(i) When unstable nuclides decay into different nuclides, they usually emit alpha (α) or beta (β) particles.

(ii) Alpha emission occurs principally with nuclei that are too large to be stable. When a nucleus emits an alpha particle, its *N* and *Z* values each decrease by two and *A* decreases by four.

(iii) Alpha decay is possible whenever the mass of the original neutral atom is greater than the sum of the masses of the final neutral atom and the neutral helium- atom.

(2) **β-decay** : There are different simple type of β-decay β^-, β^+ and electron capture.

(i) A beta minus particle (β^-) is an electron. Emission of β^- involves transformation of a neutron into a proton, an electron and a third particle called an antineutrino $(\bar{\nu})$.

(ii) β^- decay usually occurs with nuclides for which the neutron to proton ratio $\left(\frac{N}{Z}ratio\right)$ is too large for stability.

(iii) In β^- decay, *N* decreases by one, *Z* increases by one and *A* doesn't change.

(iv) β^- decay can occur whenever the neutral atomic mass of the original atom is larger than that of the final atom.

(v) Nuclides for which *N*/*Z* is too small for stability can emit a positron, the electron's antiparticle, which is identical to the electron but with positive charge. The basic process called beta plus β^+ decay

$p \to n + \beta^+ + \nu$ (ν = neutrino)

(vi) β^+ decay can occur whenever the neutral atomic mass of the original atom is at least two electron masses larger than that of the final atom

(vii) The mass of ν and $\bar{\nu}$ is zero. The spin of both is $\frac{1}{2}$ in units of $\frac{h}{2\pi}$. The charge on both is zero. The spin of neutrino is antiparallel to it's momentum while that of antineutrino is parallel to it's momentum.

(viii) There are a few nuclides for which β^+ emission is not energetically possible but in which an orbital electron (usually in the *k*-shell) can combine with a proton in the nucleus to form a neutron and a neutrino. The neutron remains in the nucleus and the neutrino is emitted.

$p + \beta^+ \to n + \nu$

(3) **γ-decay** : The energy of internal motion of a nucleus is quantized. A typical nucleus has a set of allowed energy levels, including a *ground state* (state of lowest energy) and several excited states. Because of the great strength of nuclear interactions, excitation energies of nuclei are typically of the order of the order of 1 *MeV*, compared with a few *eV* for atomic energy levels. In ordinary physical and chemical transformations the nucleus always remains in its ground state. When a nucleus is placed in an excited state, either by bombardment with high-energy particles or by a radioactive transformation, it can decay to the ground state by emission of one or more photons called gamma rays or gamma-ray photons, with typical energies of 10 *keV* to 5 *MeV*. This process is called gamma (γ) decay.

All the known conservation laws are obeyed in γ-decay.

The intensity of γ-decay after passing through *x* thickness of a material is given by $I = I_0 e^{-\mu x}$ (μ = absorption co-efficient)

Radioactive Disintegration

(1) **Law of radioactive disintegration :** According to Rutherford and Soddy law for radioactive decay is as follows.

"At any instant the rate of decay of radioactive atoms is proportional to the number of atoms present at that instant" *i.e.*

$-\frac{dN}{dt} \propto N \Rightarrow \frac{dN}{dt} = -\lambda N$. It can be proved that $N = N_0 e^{-\lambda t}$

In terms of mass $M = M_0 e^{-\lambda t}$

where *N* = Number of atoms remains undecayed after time *t*, N_0 = Number of atoms present initially (*i.e.* at *t* = 0), *M* = Mass of radioactive nuclei at time *t*, M_0 = Mass of radioactive nuclei at time *t* = 0, $N_0 - N$ = Number of disintegrated nucleus in time *t*

$\frac{dN}{dt}$ = rate of decay, λ = Decay constant or disintegration constant or radioactivity constant or Rutherford Soddy's constant or the probability of decay per unit time of a nucleus.

Table 26.8 : Properties of α, β and γ-rays

Features	α- particles	β - particles	γ - rays
1. Identity	Helium nucleus or doubly ionised helium atom ($_2He^4$)	Fast moving electron $(-\beta^0 \text{ or } \beta^-)$	Photons (E.M. waves)
2. Charge	+ 2*e*	– *e*	Zero
3. Mass 4 m_p (m_p = mass of proton = 1.87×10^{-27}	4 m_p	m_e	Massless
4. Speed	$\approx 10^7$ *m/s*	1% to 99% of speed of light	Speed of light
5. Range of kinetic energy	4 *MeV* to 9 *MeV*	All possible values between a minimum certain value to 1.2 *MeV*	Between a minimum value to 2.23 *MeV*
6. Penetration power (γ, β, α)	1 (Stopped by a paper)	100 (100 times of α)	10,000 (100 times of β upto 30 *cm* of iron (or *Pb*) sheet
7. Ionisation power ($\alpha > \beta > \gamma$)	10,000	100	1
8. Effect of electric or magnetic field	Deflected	Deflected	Not deflected
9. Energy spectrum	Line and discrete	Continuous	Line and discrete
10. Mutual interaction with matter	Produces heat	Produces heat	Produces, photo-electric effect, Compton effect, pair production
11. Equation of decay	$_ZX^A \xrightarrow{\alpha-decay}$ $_{Z-2}Y^{A-4} + {}_2He^4$ $_ZX^A \xrightarrow{n\alpha} {}_{Z'}Y^{A'}$ $\Rightarrow \boldsymbol{n_\alpha = \frac{A - A'}{4}}$	$_ZX^A \to {}_{Z+1}Y^A + {}_{-1}e^0 + \bar{\nu}$ $_ZX^A \xrightarrow{n_\beta} {}_{Z'}X^A$ $\Rightarrow \boldsymbol{n_\beta = (2n_\alpha - Z + Z')}$	$_ZX^A \to {}_ZX^a + \gamma$

(2) **Activity :** It is defined as the rate of disintegration (or count rate) of the substance (or the number of atoms of any material decaying per second) *i.e.*

$$A = -\frac{dN}{dt} = \lambda N = \lambda N_0 e^{-\lambda t} = A_0 e^{-\lambda t}$$

where A_0 = Activity of $t = 0$, A = Activity after time t

Units of activity (Radioactivity)

It's units are *Becqueral* (*Bq*), Curie (*Ci*) and Rutherford (*Rd*)

1 *Becquerel* = 1 *disintegration*/*sec*,

1 *Rutherford* = 10^6 *dis/sec*, 1 *Curie* = 3.7×10^{11} *dis/sec*

(3) **Half life ($T_{1/2}$)** : Time interval in which the mass of a radioactive substance or the number of it's atom reduces to half of it's initial value is called the half life of the substance.

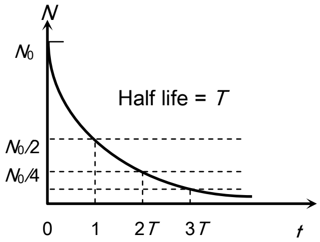


Fig. 26.24

i.e. if $N = \frac{N_0}{2}$

then $t = T_{1/2}$

Hence from $N = N_0 e^{-\lambda t}$

$$\frac{N_0}{2} = N_0 e^{-\lambda (T_{1/2})} \Rightarrow T_{1/2} = \frac{\log_e 2}{\lambda} = \frac{0.693}{\lambda}$$

Table 26.9 : Fraction of active/decayed atom at different time

Time (*t*)	Remaining fraction of active atoms (N/N_0) probability of survival	Fraction of atoms decayed $(N_0 - N)/N_0$ probability of decay
$t = 0$	1 (100%)	0
$t = T_{1/2}$	$\frac{1}{2}$ (50%)	$\frac{1}{2}$ (50%)
$t = 2(T_{1/2})$	$\frac{1}{4}$ (25%)	$\frac{3}{4}$ (75%)
$t = 3(T_{1/2})$	$\frac{1}{8}$ (12.5%)	$\frac{7}{8}$ (87.5%)
$t = 10\ (T_{1/2})$	$\left(\frac{1}{2}\right)^{10} \approx 0.1\%$	$\approx 99.9\%$
$t = n\ (N_{1/2})$	$\left(\frac{1}{2}\right)^{n}$	$\left\{1 - \left(\frac{1}{2}\right)^{n}\right\}$

(4) **Mean (or average) life (τ) :** The time for which a radioactive material remains active is defined as mean (average) life of that material.

(i) or it is defined as the sum of lives of all atoms divided by the total number of atoms

i.e. $\tau = \frac{\text{Sum of the lives of all the atoms}}{\text{Total number of atoms}} = \frac{1}{\lambda}$

(ii) From $N = N_0 e^{-\lambda t} \Rightarrow \frac{\ln \frac{N}{N_0}}{t} = -\lambda$ slope of the line shown in the graph *i.e.* the magnitude of inverse of slope of $\ln \frac{N}{N_0}$ *vs* t curve is known as mean life (τ).

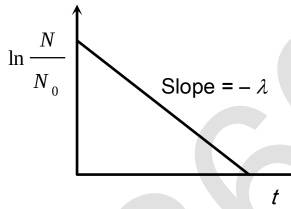


Fig. 26.25

(iii) From $N = N_0 e^{-\lambda t}$, if $t = \frac{1}{\lambda} = \tau$

$\Rightarrow N = N_0 e^{-1} = N_0 \left(\frac{1}{e}\right) = 0.37 N_0 = 37\%$ of N_0.

i.e. mean life is the time interval in which number of undecayed atoms (N) becomes $\frac{1}{e}$ times or 0.37 times or 37% of original number of atoms. or

It is the time in which number of decayed atoms ($N_0 - N$) becomes $\left(1 - \frac{1}{e}\right)$ times or 0.63 times or 63% of original number of atoms.

(iv) From $T_{1/2} = \frac{0.693}{\lambda} \Rightarrow \frac{1}{\lambda} = \tau = \frac{1}{0.693} . (t_{1/2}) = 1.44 (T_{1/2})$

i.e. mean life is about 44% more than that of half life. Which gives us $\tau > T_{(1/2)}$

Radioactive Series

(1) If the isotope that results from a radioactive decay is itself radioactive then it will also decay and so on.

(2) The sequence of decays is known as radioactive decay series. Most of the radio-nuclides found in nature are members of four radioactive series. These are as follows

Table 26.10 : Four radioactive series

Mass number	Series (Nature)	Parent	Stable end product	Integer *n*
$4n$	Thorium (natural)	${}_{90}Th^{232}$	${}_{82}Pb^{208}$	52
$4n + 1$	Neptunium	${}_{93}Np^{237}$	${}_{83}Bi^{209}$	52

	(Artificial)			
$4n + 2$	Uranium (Natural)	$_{92}U^{238}$	$_{82}Pb^{206}$	51
$4n + 3$	Actinium (Natural)	$_{89}Ac^{227}$	$_{82}Pb^{207}$	51

(3) The $4n + 1$ series starts from $_{94}Pu^{241}$ but commonly known as neptunium series because neptunium is the longest lived member of the series.

(4) The $4n + 3$ series actually starts from $_{92}U^{235}$.

Successive Disintegration and Radioactive Equilibrium

Suppose a radioactive element *A* disintegrates to form another radioactive element *B* which intern disintegrates to still another element *C*; such decays are called successive disintegration.

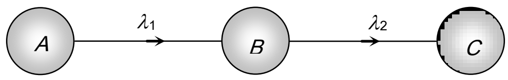


Fig. 26.26

Rate of disintegration of $A = \frac{dN_1}{dt} = -\lambda_1 N_1$ (which is also the rate of formation of *B*)

Rate of disintegration of $B = \frac{dN_2}{dt} = -\lambda_2 N_2$

$\therefore$ Net rate of formation of *B* = Rate of disintegration of *A* – Rate of disintegration of *B*

$$= \lambda_1 N_1 - \lambda_2 N_2$$

Equilibrium

In radioactive equilibrium, the rate of decay of any radioactive product is just equal to it's rate of production from the previous member.

i.e. $\lambda_1 N_1 = \lambda_2 N_2 \Rightarrow \frac{\lambda_1}{\lambda_2} = \frac{N_2}{N_2} = \frac{\tau_2}{\tau_1} = \frac{(T_{1/2})}{(T_{1/2})_1}$

Uses of Radioactive Isotopes

(1) **In medicine**

(i) For testing blood-chromium - 51

(ii) For testing blood circulation - *Na* - 24

(iii) For detecting brain tumor- Radio mercury - 203

(iv) For detecting fault in thyroid gland - Radio iodine - 131

(v) For cancer - cobalt - 60

(vi) For blood - Gold - 189

(vii) For skin diseases - Phospohorous - 31

(2) **In Archaeology**

(i) For determining age of archaeological sample (carbon dating) C^{14}

(ii) For determining age of meteorites - K^{40}

(iii) For determining age of earth-Lead isotopes

(3) **In agriculture**

(i) For protecting potato crop from earthworm- CO^{60}

(ii) For artificial rains - *AgI* (iii) As fertilizers - P^{32}

(4) **As tracers** - (Tracer) : Very small quantity of radioisotopes present in a mixture is known as tracer

(i) Tracer technique is used for studying biochemical reaction in tracer and animals.

(5) **In industries**

(i) For detecting leakage in oil or water pipe lines (ii) For determining the age of planets.

Tips & Tricks

✍ According to Bohr theory the momentum of an e^- revolving in second orbit of H_2 atom will be $\frac{h}{\pi}$

✍ For an electron in the n^{th} orbit of hydrogen atom in Bohr model, circumference of orbit $= n\lambda$; where λ = de-Broglie wavelength.

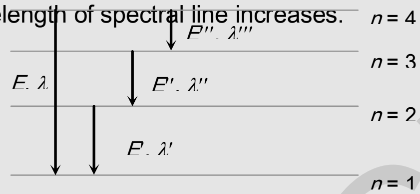
✍ *Rch* = Rydberg's energy $\simeq 2.17\times10^{-18}\,J \simeq 13.6\,eV$.

✍ For hydrogen atom principle quantum number $n=\sqrt{\dfrac{13.6}{(\text{B.E.})}}$.

✍ In an H_2 atom when e^- makes a transition from an excited state to the ground state it's kinetic energy increases while potential and total energy decreases.

✍ The maximum number of electrons in a subshell with orbital quantum number *l* is 2(2*l* + 1).

✍ With the increase in principal quantum number the energy difference between the two successive energy level decreases, while wavelength of spectral line increases.



$E' > E'' > E'''$

$\lambda' < \lambda'' < \lambda'''$

$E = E' + E'' + E'''$

$$\frac{1}{\lambda} = \frac{1}{\lambda'} + \frac{1}{\lambda''} + \frac{1}{\lambda'''}$$

✍ **Rydberg constant is different for different elements**

R(=1.09 × 10^7 m^{-1}) is the value of Rydberg constant when the nucleus is considered to be infinitely massive as compared to the revolving electron. In other words, the nucleus is considered to be stationary.

In case, the nucleus is not infinitely massive or stationary, then the value of Rydberg constant is given as $\boldsymbol{R'} = \dfrac{\boldsymbol{R}}{\boldsymbol{1}+\dfrac{\boldsymbol{m}}{\boldsymbol{M}}}$ where m is the mass of electron and *M* is the mass of nucleus.

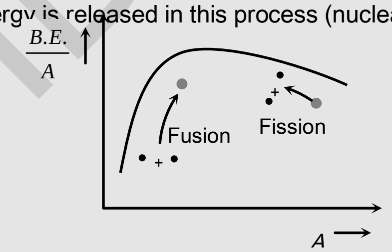
✍ **Atomic spectrum is a line spectrum**

Each atom has it's own characteristic allowed orbits depending upon the electronic configuration. Therefore photons emitted during transition of electrons from one allowed orbit to inner allowed orbit are of some definite energy only. They do not have a continuous graduation of energy. Therefore the spectrum of the emitted light has only some definite lines and therefore atomic spectrum is line spectrum.

✍ Just as dots of light of only three colours combine to form almost every conceivable colour on T.V. screen, only about 100 distinct kinds of atoms combine to form all the materials in the universe.

✍ Density of a nucleus is maximum at it's centre and decreases as we move outwards from the nucleus.

✍ When two very light nuclei combines to form a relatively heavy nucleus, then binding energy per nucleon increases. Thus, energy is released in this process (nuclear fusion).



✍ It may be noted that Plutonium is the best fuel as compared to other fissionable material. It is because fission in Plutonium can be initiated by both slow and fast neutrons. Moreover it can be obtained from U^{238}.

✍ Nuclear reactor is firstly devised by fermi.

✍ Apsara was the first Indian nuclear reactor.

✍ A type of reactor that can produce more fissile fuel than it consumes is the breeder reactor.

✍ To achieve fusion in laboratory a device is used to confine the plasma, called **Tokamak**.

✍ A test tube full of base nuclei will weight heavier than the earth.

✍ The nucleus of hydrogen contains only one proton. Therefore we may say that the proton is the nucleus of hydrogen atom.

✍ If the relative abundance of isotopes in an element has a ratio $n_1 : n_2$ whose atomic masses are m_1 and m_2 then atomic mass of the element is $\boldsymbol{M = \frac{n_1 m_1 + n_2 m_2}{n_1 + n_2}}$

✍ No radioactive substance emits both α and β particles simultaneously. Also γ-rays are emitted after the emission of α or β-particles.

✍ β-particles are not orbital electrons they come from nucleus. The neutron in the nucleus decays into proton and an electron. This electron is emitted out of the nucleus in the form of β-rays.

✍ Activity per *gm* of a substance is known as specific activity. The specific activity of 1 *gm* of radium – 226 is 1 *Curie*.

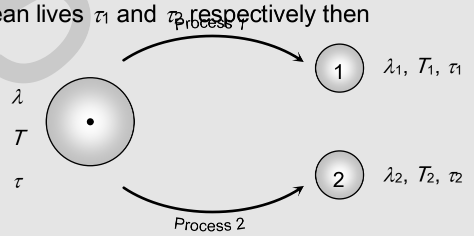
✍ 1 *millicurie* = 37 *Rutherford*

✍ The activity of a radioactive substance decreases as the number of undecayed nuclei decreases with time.

✍ $\text{Activity} \propto \frac{1}{\text{Half life}}$

✍ Half life and mean life of a substance doesn't change with time or with pressure, temperature *etc*.

✍ If a nuclide can decay simultaneously by two different process which have decay constant λ_1 and λ_2, half life T_1 and T_2 and mean lives τ_1 and τ_2 respectively then



$\Rightarrow \lambda = \lambda_1 + \lambda_2$ $\qquad$ $\Rightarrow T = \frac{T_1 T_2}{T_1 + T_2}$

✍ There are at least three varieties of neutranas, each with it's corresponding antineutrino; one is associated with beta decay and the other two are associated with the decay of two unstable particles, the muon and the tau particles.

✍ Are all fusion reaction exoergic ?

Fusion reaction between sufficiently light nuclei are exoergic because the $\frac{B.E.}{A}$ increases. If the nuclei are too massive, however $\frac{B.E.}{A}$ decreases and fusion is endoergic (*i.e.* it takes in energy rather than releasing it)

✍ The Zeeman effect is the spliting of atomic energy levels and the associated spectrum lines when the atoms are placed in a magnetic field. This effect confirms experimentally the quantization of angular momentum.