Nuclear Physics and Radioactivity

The Nucleus

(1) It exists at the centre of an atom, consisting proton (positive charge) and neutron (neutral).

(2) The common name of proton and neutron in the nucleus is Nucleons.

(3) A particular set of nucleons forming an atom is called as Nuclide. It is represented as $_ZX^A$; where X = Chemical symbol for the element of the atom, Z = Atomic number = Number of protons, A = Mass number = Number of nucleons.

(4) **Nuclear force :** Keeps neutrons and protons bound inside the nucleus.

(i) It is suggested by Yukawa.

(ii) Nuclear forces are short range, charge independent, strongest, spin dependent, saturated, non central and exchange forces [exchange of π mesons $(\pi^+, \pi^- \text{ and } \pi^0)$ keeps the two nucleons bound together in the nucleus]

(5) The nucleus is more stable when $n_{\text{proton}} = n_{\text{neutron}}$.

(6) The nuclides having same Z but different A are called as isotopes *e.g.* $_1H^1$, $_1H^2$, $_1H^3$.

(7) The nuclides having same A but different Z are called isobares *e.g.* $_1H^3$, $_2He^3$, and $_3Li^7$, $_4Be^7$ etc.

(8) The nuclide having same number of neutrons $(A - Z)$ are called as isotones *e.g.* $_4Be^9$, $_5B^{10}$ and $_6C^{13}$, $_7N^{14}$ *etc.*

(9) The nuclide having same mass number (A) but whose atomic number (Z) differ by 1 are called mirror isobars *e.g.* $_1H^3$, $_2He^3$ and $_3Li^7$, $_4Be^7$ etc.

(10) **Size of nucleus :**

(i) It's radius $R = R_0 A^{1/3}$; where A = Atomic mass and R_0 = Constant $= 1.2 \times 10^{-15}\, m$.

(ii) It's density is of the order of $10^{17}\, Kg/m^3$. Density is independent of mass number of an atom.

(11) For a nucleus to be stable, the correct relation between neutron number N and proton number Z is $N \geq Z$.

(12) **Atomic mass unit (*amu*) :** $1\, amu = \frac{1}{12}(\text{mass of carbon nucleus}) = 1.67 \times 10^{-27}\, Kg$

(13) **Neutron**

(i) Discovered by Chadwick.

(ii) It has no charge and it's mass is about $1.6748 \times 10^{-27}\, Kg$.

(iii) High penetrating power, low ionising power.

(iv) Inside the nucleus they are stable and outside the nucleus they are unstable and decays as follows.

$$_0n^1 \rightarrow \underset{\text{(proton)}}{_1H^1} + \underset{\text{(electron)}}{_{-1}e^0} + \underset{\text{(Antineutrino)}}{\bar{\nu}}$$

(v) Half life period of a free neutron is about 12 minutes.

(vi) Thermal neutrons are suitable for causing nuclear reaction. They have energy about 0.025 eV and speed is about 2.2 $Km./sec.$

Mass Defect and Binding Energy

(1) **Mass defect (Δm) :** It is observed that the mass of a nucleus is always less than the mass of constituent (free) nucleons. This difference in mass is called mass defect.

i.e. $\Delta m = \{m_p Z + m_n(A - Z)\} - M$.

Note : ❑ Mass defect per nucleon is called packing fraction (f)

$f = \frac{\Delta m}{A}$; where A = Number of nucleons.

(2) **Binding energy ($B.E.$) :** The total energy required to disintegrate the nucleus into it's constituent particles (i.e. nucleus) is called $B.E.$ of the nucleons.

(3) **Mass energy equivalence**

(i) According to Einstein $E = mc^2$; where c = Speed of light $= 3 \times 10^8\ m/s$

(ii) 1gm of matter is equivalent to $9 \times 10^{13}\ J = 2.5 \times 10^7\ Kwh$.

(iii) The amount of energy equivalent to 1 amu is 931 MeV.

(iv) If mass defect Δm is expressed in Kg then $B.E.$ = $\Delta m . c^2\ Joules$

(v) If mass defect Δm is expressed in amu then $B.E. = \Delta m\ \ amu = \Delta m \times 931\ \ MeV$

Example : If a proton and antiproton come closer to each other and annihilate then –

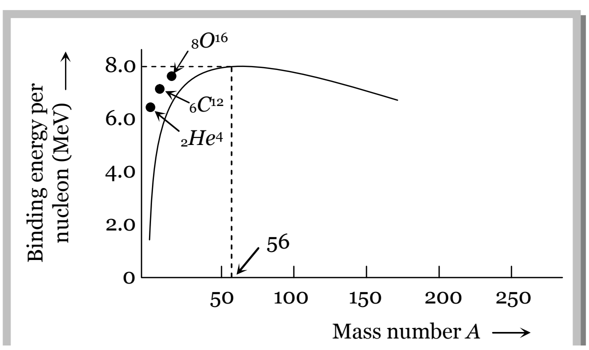
Mass of proton = Mass of antiproton $= 1.67 \times 10^{-27}\ Kg = 1\ amu$. Here mass defect Δm = 2 amu.

So equivalent energy $= 2 \times 931\ MeV = 1862 \times 10^6 \times 1.6 \times 10^{-19} = 2.97 \times 10^{-10}\ J$.

(4) **Binding energy per nucleon**

(i) $B.E.$ per nucleon $= \frac{\Delta m . c^2}{A} Joule / Nucleon$ or $\frac{\Delta m \times 931}{A} MeV / nucleon$

(ii) $B.E.$ curve



(a) B.E. per nucleon is a measure of stability of the nucleus.

(b) The maximum B.E. per nucleon is 8.8 MeV and it is for Fe^{56}.

Nuclear Reactions

(1) The transformation of a nucleus into another isotope by bombarding it with a fast moving particle is called Nuclear reaction.

(2) General expression is as follows.

$$\underset{\text{(parent nucleus)}}{X} + \underset{\text{(Incident particle)}}{a} \rightarrow \underset{\text{(Daughter nucleus)}}{Y} + \underset{\text{(product particle)}}{b} + \underset{\text{(Energy)}}{Q}$$

Symbolical presentation $\rightarrow X(a,b)Y$ *e.g.* In the nuclear reaction $X(n,\alpha)\ {}_3Li^7$ the term X will be ${}_5B^{10}$.

(3) Energy $Q = (\text{mass of reactant} - \text{mass of products})c^2\ Joule$

$Q = (\text{mass of reactant} - \text{mass of products})c^2\ amu$

(4) Laws of nuclear reaction :

(i) Conservation of charge. (ii) Conservation of nucleon number. (iii) Conservation of energy. (iv) Conservation of momentum.

(5) The nuclear reactions are generally named in terms of incident and product particles *e.g.*

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

(p,α) reaction $\Rightarrow {}_1H^1 + {}_3Li^7 \rightarrow {}_4Be^8 \rightarrow {}_2He^4 + {}_2He^4$

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

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

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

Nuclear Fission and Fusion

(1) **Nuclear fission :** It is a process of splitting a heavy nucleus into two lighter nuclei along with the emission of large amount of energy.

(i) Discovered by Otto Hahn and Strassman

(ii) $${}_{92}U^{235} + {}_0n^1 \rightarrow {}_{92}U^{236} \rightarrow {}_{56}Ba^{141} + {}_{36}Kr^{92} + \underset{\text{(prompt neutron)}}{3({}_0n^1)} + Q \qquad \{Q \approx 200\ MeV\}$$

(iii) The average number of neutrons produced in fission of uranium is 2.5.

(iv) In nuclear fission 0.1% of mass is converted into energy.

(v) ${}_{92}U^{238}$ is fissionable only by fast neutrons (1.2 MeV). Whereas ${}_{92}U^{235}$ is fissionable by slow neutron or thermal neutrons.

(vi) For fission $\frac{B.E.}{A}$ for compound nucleus must be less than that of the fission products.

(vii) Easily fissionable element is plutonium $({}_{94}PU^{239})$ which is an artificially formed element.

(viii) Natural uranium contains 0.7% ${}_{92}U^{235}$ and 99.3% of U^{238}

(ix) The energy released in the fission of 1gm U^{235} is $8.2 \times 10^{10}\ J = 2.22 \times 10^4\ Kwh$.

Note : ❑ Principle of atom bomb is uncontrolled fission reaction.

(2) **Nuclear fusion :** It is a process in which lighter nuclei $(A \leq 8)$ combine to form a heavy nucleus with simultaneous release of large amount of energy.

$${}_1H^2 + {}_1H^2 \rightarrow {}_2He^4 + 24\ MeV$$

$${}_1H^3 + {}_1H^2 \rightarrow {}_2He^4 + {}_0n^1 + 17.6\ MeV$$

(i) For fusion very high temperature of the order of $10^7 K$ to $10^8 K$ is required, so the reaction is called thermonuclear reaction.

(ii) Fusion energy is greater than fission energy.

(iii) The source of solar energy or steller energy is nuclear fusion. The sun radiates $3.8 \times 10^{26} J$ of energy in each second.

(iv) The steller energy is explained by proton-proton cycle and carbon-nitrogen cycle.

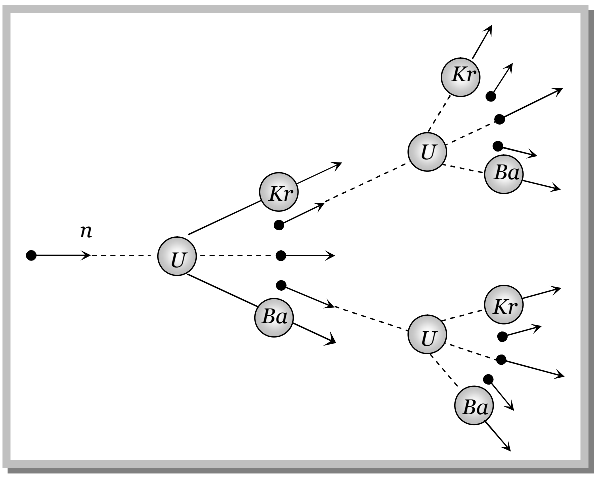
Note : ❑ The principle of hydrogen bomb is uncontrolled fusion reaction.

Chain Reaction and Nuclear Reactor

(1) **Chain reaction**

(i) It is a self propagating process

(ii) To start a chain reaction a minimum mass of the fissile material is required. This mass is called Critical mass or Critical size.



(iii) Types

Uncontrolled chain reaction	Controlled chain reaction
(a) More than one neutron is available for further fission	(a) Only one neutron is available for further fission
(b) This reaction is fast	(b) This reaction is slow
(c) It is the principle of atom bomb	(c) It is the principle of nuclear reactor or thermopile

(2) **Nuclear reactor :** It is a device in which energy is generated by controlled chain reaction of nuclear fission.

(i) Nuclear reactor was first devised by fermi.

(ii) APSARA was the first Indian nuclear reactor.

(iii) Main parts of nuclear reactors are as follows :

Nuclear Reactor				
Fuel	**Moderator**	**Control rods**	**Coolant**	**Protective shield**
${}_{92}U^{235}$, ${}_{92}U^{238}$ ${}_{94}Pu^{239}$, ${}_{90}Th^{232}$, etc.	Graphite, heavy water, beryllium oxide (used to slow down the fast moving neutrons)	*Cd* rods (to control the chain reaction)	Water, CO_2, N_2 *etc.* (to remove the generated heat)	Made of cement and concrete (to save the persons working around the reactor from the hazardous radiations)

Note : ❑ In a Breeder reactor more nuclear fuel would be produced than consumed. In this reactor non fissionable *U*-238 is converted into fissionable *Pu*-239.

❑ Rate of Nuclear fission in Nuclear reactor $= \dfrac{\text{Power of reactor}}{\text{Energy per fission of } U^{235}}$.

Radioactivity

(1) Radioactivity was discovered by Henry Becquerrel in the year 1896.

(2) The phenomenon of spontaneous emission of radiations by heavy elements is called radioactivity.

(3) All the atoms with $Z > 82$ are naturally radioactive.

(4) Rate of disintegration of radioactive element is not affected by the external condition of temperature, pressure electric field and magnetic field.

(5) Radiations emitted by radioactive elements.

(i) **α-particles :** Is a helium atom from which two electrons have been taken away.

$(\alpha - \text{particles} = He^{++} = {}_2He^4)$

$${}_ZX^A \xrightarrow{\alpha} {}_{Z-2}X^{A-4} \text{ also } {}_ZX^A \xrightarrow{n_\alpha} {}_{Z'}X^{A'} \Rightarrow n_\alpha = \frac{A' - A}{4}$$

(ii) **β-particles :** Are fast moving electrons (β particle $= {}_{-1}e^0$)

$${}_ZX^A \xrightarrow{-\beta} {}_{Z+1}X^A \text{ also } {}_ZX^A \xrightarrow{n_\beta} {}_{Z'}X^A \Rightarrow n_\beta = 2n_\alpha - Z + Z'$$

(iii) **γ-rays :** Are neutral and EM radiations.

(6) β-particles comes from within the nuclei. Also β-decay produces isobars.

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

Note : ❑ Radium was isolated by Pierre Curie and Madam Curie.

❑ Increasing order of ionisation. $\alpha > \beta > \gamma$.

Law of Radioactive Disintegration and Other Important Terms

(1) The rate of decay or disintegration of a radioactive substance is directly proportional to the number of atoms remains undecayed.

i.e. $\frac{dN}{dt} \propto N \Rightarrow \frac{dN}{dt} = -\lambda N \Rightarrow N = N_0 e^{-\lambda t}$ where $\lambda =$ Decay constant

Note : ❑ If $t = \frac{1}{\lambda}$ then $N = \frac{1}{e} N_0 = 37\%$ of N_0

(2) **Half life (T) :** The time in which half of the radioactive substance disintegrate is called it's half life.

$$T = \frac{0.693}{\lambda}$$

(i) After n half lives number of undecayed atom $N = N_0 \left(\frac{1}{2}\right)^n$ where $n = \frac{\text{given time}(t)}{\text{half life}(T)}$

(ii) Fraction of undecayed atom $= \left(\frac{N}{N_0}\right) = \left(\frac{1}{2}\right)^{t/T}$. While fraction of decayed atom $= \left(1 - \frac{N}{N_0}\right) = \left\{1 - \left(\frac{1}{2}\right)^{t/T}\right\}$

Note : ❑ 99% of a radioactive element will decay between 6 and 7 half lives.

❑ Half life is measured by Geiger-mullar Counter.

❑ Half life period of *Pb* is ∞.

(3) **Mean life or average life (τ) :** $\tau = \frac{\text{Sum of lives of all atoms}}{\text{Total number of atoms}} = \frac{1}{\lambda}$

In a sample of radioactive substance 63% of the initial number of active nuclei will decay during one mean life. (or 37% remains undecayed).

(4) **Activity (A) :** It is defined as the rate of disintegration of the substance.

$$\text{Activity } A = \left|\frac{dN}{dt}\right| = \lambda N$$

(i) At any instant $A = A_0 e^{-\lambda t}$; where A_0 = Activity at (t = 0)

(ii) Activity $\propto \frac{1}{\text{Half life}}$

(5) **Units of radioactivity (activity) :** 1 Curie $= 3.7 \times 10^{10}$ disintegration/sec, 1 Rutherford $= 10^6$ disintegration/sec, 1 Becquerel $= 1$ disintegration/sec, also 1 milli curie = 37 Rutherford.