Radioactivity

1. Natural Radioactivity

a) The nuclei of certain elements disintegrate spontaneously by emitting alpha (α), beta (β) and gamma (γ) rays. This phenomenon is called natural radioactivity

b) Natural radioactivity is displayed by heavy nuclei, beyond lead in the periodic table. There are also naturally radioactive light nuclei, such as potassium isotope $^{40}_{19}K$, the carbon isotope $^{14}_{6}C$ and the rubidium isotope $^{87}_{37}Rb$.

i) Alpha Radiation

a) When a nucleus disintegrates and radiates α-rays it is said to undergo α-decay.

b) When a nucleus emits an alpha particle its atomic number Z decreases by two units and its mass number A decreases by four units.

c) Both electric charge and nucleon number are conserved in the process of -decay.

d) The general form of -decay can be written as

$$^{A}_{Z}P \rightarrow ^{A-4}_{Z-2}D + ^{4}_{2}He$$

Ex-1: $^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$

e) A beam of -particles can be deflected by an electric field as well as magnetic field.

f) The speed of α-particles is of the order of 10^6 m/s.

g) α-particle produce intense ionization of the medium through which they pass.

g) α-particles can penetrate small distances in matter and can be stopped after travelling a few mm in air. Due to large mass, the penetrating power of α-particles is lower than both β-rays and γ-rays.

i) α- particle produces scintillations when they strike fluorescent materials such as zinc sulphide.

j) α-particles affect photographic plate.

ii) Beta Radiation

a) When a nucleus disintegrates and radiates -rays it is said to undergo β-decay.

b) β - particles are nothing but electrons. Hence when a nucleus emits a β particle, the atomic number of the nucleus increase by one unit, but the mass number does not change.

c) The general form of β-decay can be written as $_Z^AP \rightarrow _{Z+1}^{A}D + _{-1}^{0}e$.

Ex: $_{90}^{234}Th \rightarrow _{91}^{234}Pa + _{-1}^{0}e$

d) β - particles are deflected by electric as well as magnetic fields.

e) The speed of α-particle is of the order of 1/10th of the speed of light.

f) β-particles ionize the medium through which they pass. The ionizing power is 1/100th of α-particles.

g) β-particles penetrate through matter. They travel a few centimeters in air. The penetrating power of β-particles is greater than that of α-rays but less than that of α-rays.

h) β-rays affect photographic plate.

iii) Gamma Radiation

a) When a nucleus disintegrates and releases α-rays it is said to undergo γ-decay.

b) The emission of γ-rays from the nucleus does not alter either atomic number Z or mass number A.

c) The wavelengths of -rays is less than 1A^0.

d) γ-rays are not deflected either by electric or magnetic fields because they do not posses any charge.

e) γ-rays travel with the speed of light.

f) The ionizing power of the -radiations is small when compared to α and β rays.

g) The penetrating power of -rays is the largest when compared to α and β rays.

h) γ-rays also produce scintillations when they strike fluorescent material.

i) γ-rays affect photographic plates more than α and β particles.

2. The radioactive decay law

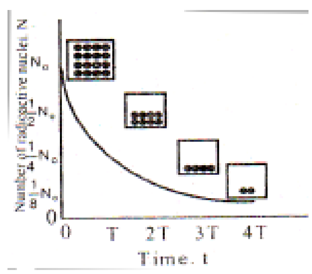
a) The radioactive decay is a random process such that the rate of disintegration is proportional to the number of nuclei (N) available for disintegration.

$$\frac{dN}{dt} \propto N \Rightarrow \frac{dN}{dt} = -\lambda N$$

Where λ is decay constant

On solving N = $N_0 e^{-\lambda t}$

Where N_0 is the initial number of atoms



This shows that the number of atoms of radioactive element decreases exponentially with time.

b) The number of disintegrations per second is called the activity of a radioactive sample.

$$A = \lambda N = \lambda N_0 e^{-lt} = A_0 e^{-\lambda t}$$

c) $A = \lambda N \Rightarrow A = \frac{0.693}{t_{1/2}} N$

$$A = \frac{0.693}{t_{1/2}} \left(\frac{\text{Weight in grams}}{\text{mass number(A)}} \right) 0.693 \times 10^{23}$$

$$\therefore A \propto \frac{N}{t_{1/2}}$$

d) **The unit of activity**

a) Units of activity are Curie and Rutherford.

b) 1 Curie = 3.7×10^{10} disintegrations/sec

c) 1 Rutherford = 10^6 disintegrations/sec

d) 1 Becquerel = 1 disintegration per sec

e) The activity of 1gm of material is defined as specific activity.

f) The decay constant of the end product of a radioactive series is infinity.

e) **Half-life ($t_{1/2}$):** The time taken by the number of atoms to decrease from N_0 to N is

$$t = \frac{1}{\lambda}\log_c \frac{N_0}{N} \Rightarrow t = \frac{2.303}{\lambda}\log_{10}\frac{N_0}{N}$$

The half life ($t_{1/2}$) of radioactive nuclei is the time taken by the radioactive element to disintegrate to half the initial number of atoms.

$$t_{1/2} = \frac{2.303}{\lambda}\log_{10}(2) \Rightarrow t_{1/2}\frac{0.693}{\lambda}$$

After n half lives (i.e. $t = nt_{1/2}$)

$$\frac{N}{N_0} = \left(\frac{1}{2}\right)$$

f) $\left({}^{238}_{92}U\right)$ has a half -life of 4.47×10^9 years and $\left({}^{89}_{36}Kr\right)$ has a half-life of 3.16 minutes.

g) Mean life (τ): - The mean life (or) average life of a radioactive substance is equal to the average time for which the nuclei of atoms of the radioactive substance exist.

h) The mean life of an atom of a radioactive nuclide is equal to the inverse of its decay constant.

$$\tau = \frac{1}{\lambda}$$

$$\rightarrow \tau = 1.44\ t_{1/2}, \rightarrow t_{1/2} = 0.693\tau$$

i) Time required for disintegration of 75% (or) 3/4 of the radioactive element is $2t_{1/2}$.

Similarly

$t_{7/8}$ (or) $t_{87.5\%} = 3\ t_{1/2}$

$t_{15/16}$ (or) $t_{93.75\%} = 4\ t_{1/2}$

$$t_{90\%} = \frac{10}{3} t_{1/2}$$

$$t_{99\%} = \frac{20}{3} t_{1/2}$$

$$t_{99.9\%} = 10 t_{1/2}$$

$$t_{29.3\%} = \frac{1}{2} t_{1/2}$$

3. Mass defect and binding energy of a nucleus

a) The actual mass of a nucleus is always found to be less than the sum of the masses of the nucleons present in it. The mass difference is known as the "mass defect" and is denoted by Δm.

b) $\Delta m = \lfloor Zm_p + (A - Z)m_n \rfloor - M$ Where m_p and m_n are the masses of proton and neutron respectively and M is the actual mass of the nucleus.

c) The mass defect per nucleon of the nucleus is defined as "Packing fraction".

Packing fraction= $\frac{\text{mass defect}}{\text{Mass number}} = \frac{\Delta m}{A}$

d) **Binding Energy:** The energy equivalent of the mass defect is the binding energy of the nucleus. Binding energy is also defined as the minimum energy required to split the nucleus into its constituent nucleons.

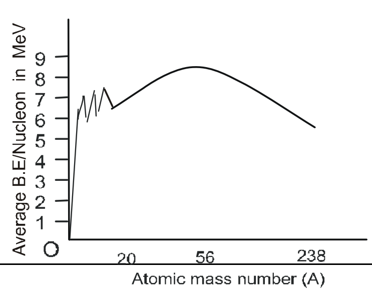
e) The ratio of binding energy of nucleus and the total number of nucleons in the nucleus is called the binding energy per nucleon. It is also called as "binding fraction" or average binding energy or specific binding energy.

Binding fraction= $\frac{\text{Binding energy of the nucleus}}{A}$

4. Binding energy of the nucleus= Δm x 931.5 MeV

The graph of binding energy per nucleon as a function of mass number is shown in the figure.

The conclusions from the binding fraction verses mass number curve are



a) Nuclei of the intermediate mass are most stable,

b) Heavier nuclei and lighter nuclei are less stable,

c) A large amount of energy can be liberated if heavier nuclei can be split into lighter nuclei. (This is what happens when $_{92}U^{235}$ undergoes fission).

d) A large amount of energy can be liberated if lighter nuclei can be made to fuse to form heavier nuclei (this is what happens when hydrogen nuclei combine to form heavier nucleus $_{2}He^{4}$ in nuclear fusion).