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Course Name: Nuclear and Radiation Chemistry

Paper Number – 4104

Section – B

Topic: Interaction of Radiation with matter

Number of Classes: Two (02)

Introduction:

Nuclear Radiation: > ~ 100 eV

Ionization Energy: Usually < 15 eV

Energy involved in chemical bonds: normally 1-5 eV

Therefore, nuclear radiation can cause ionization when it passes through any matter.

Nuclear Radiation: is used to include all elementary particles, both charged and uncharged, having energies in excess of ~ 100 eV.

The passage of such high energy radiation through matter results in the transfer of energy to the atoms and molecules of the absorbed material. This transfer of energy continues until the radiation has reached the same K.E. as that of atoms comprising the material i.e. Until thermal equilibrium is obtained.

This phenomenon has two aspects:

(1) Processes occurring to the nuclear particles themselves as their energies are reduced to the thermal equilibrium value
(2) Processes in the absorbing material due to the effect of the transfer of energy » results in excitation and ionization which cause physical and chemical changes.

(A) Passage of Neutron through matter:

Being uncharged, neutrons face NO Coulomb barrier and can freely penetrate atomic nucleus. The type of interaction depends on the energy of the n_s and the mass of the largest atom. These include scattering (Elastic/Inelastic) and Capture (Radiative/ Non-Radiative).

If non-radiative capture takes place, then a compound nucleus results and that decays further (Fission, Spallation etc.

Radiation Capture Ex. A (n, γ) B type reaction.

(B) Passage / Absorption of protons and other heavier (Example: α) ions:

Generally, α particles emitted by radioactive nucleus have energies between 4-9 MeV. Since α-particles are much heavier than electrons, they are only slightly deflected, when their coulomb fields interact with atoms to form ion-pairs (+ve ion and electrons resulted from ionization). As a result, α-particle travel in a straight line as they pass through matter.

In solid and liquid the total path length for α-particles from radioactive decay is quite short. However, in gases at STP the paths are several cm long. The range in air for α-particle with an initial energy E_α MeV is

$$\hat{R}_{air} = 0.31E_\alpha^{3/2}\ (\text{cm}) \longrightarrow = 0.31(5\ \text{MeV})^{3/2} = \mathbf{3.5\ cm}$$

$$\downarrow$$

$$= 0.31E_\alpha^{3/2} \times \rho_{air} = 0.40\ E_\alpha^{3/2}\ (\text{mg/cm}^2) \qquad \rho_{air} = 1.293\ \text{kg/m}^3)$$

The range in other materials can be approximately given by

$$\hat{R}_{Z} = 0.173\, E_{\alpha}^{3/2}\, A_{Z}^{1/3}\ (\text{mg/cm}^2)$$

Where A_{Z}= Atomic weight of the absorber

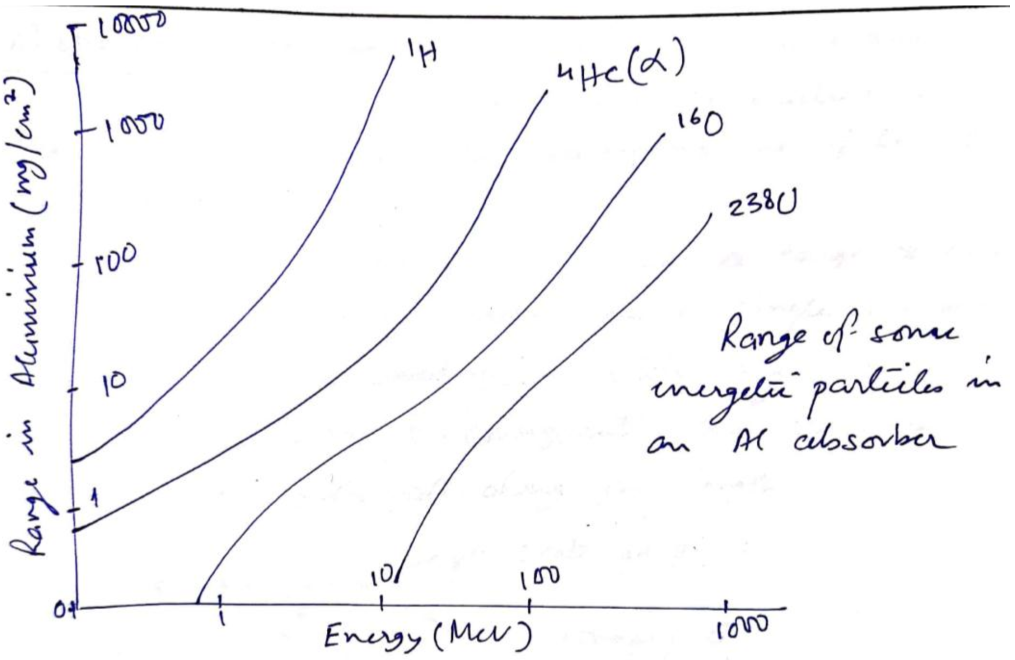
$$\hat{R}_{Z}/\rho_{material} = \text{thickness of the sheet}$$

Ex. $\hat{R}_{Al}$= 6 mg/cm^2 for 5 MeV α

$\rho_{Aluminium}$ = 30.0 mg/cm^3 =30 Kg/m^3

= $6\times10^{-3}/\rho_{Al}$=0.002 cm = 0.002 mm that means α-particle (of 5MeV intensity) can be stopped by thin sheet of 0.002 mm thickness

- α-particle from radioactive decay can be easily stopped even by the thickness of a sheet of paper.



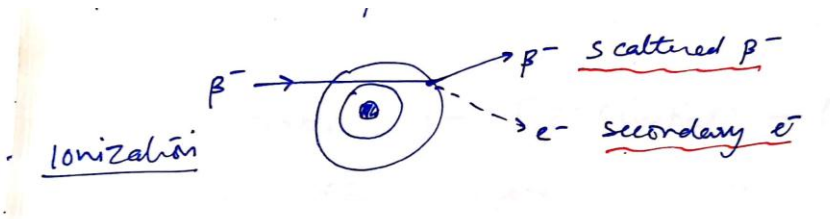
Range of some energetic particle in an Al Absorber

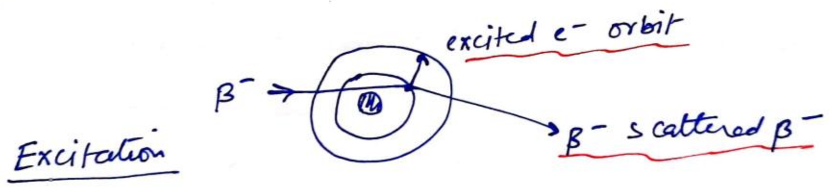
» As the energy of the particles increases, they travel much longer distance or they penetrate harder in/on the absorber.

(C) Passage / Absorption of Electrons

Absorption of high energy electrons occurs through interactions with the orbital electrons and the electromagnetic field at the atom.

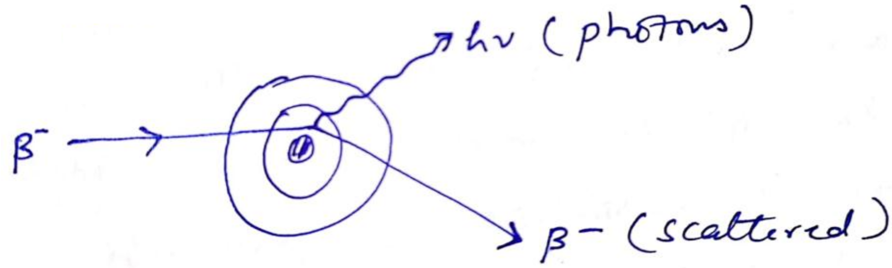
(a) **Ionization:** β-particle can core a large fraction of their energy in a single collision. The β-particles undergo a wide-angle deflection in such collisions and consequently are scattered out of the beam path all along the length.





Approximately half of the total energy of the β- particle is lost by the ionization and half by excitation.

(b) **Bremsstrahlung:** As a β-particle approaches an atomic nucleus, it is attracted by the +ve field of the nucleus and deflected from its path. The deflection results in an acceleration that leads to emission of electromagnetic radiation.



$$E_{\beta-}(\text{Scattered}) = E_{\beta-}(\text{Initial}) - E_{h\nu}$$

This radiation is known as Bremsstrahlung. This loss of energy by radiation increases with the β energy and with the atomic number of the absorbed materials.

- In Al ~ 1% of the energy of a 1 MeV e^- is lost by bremsstrahlung and 99% by ionization, but in Pb the loss by radiation is about 10%. For e^-s of greater than 10MeV energy, bremsstrahlung is the predominant mode of energy loss in Pb.

(c) **Cherenkov radiation:** The velocity of light in matter C depends on the refractive index n_r

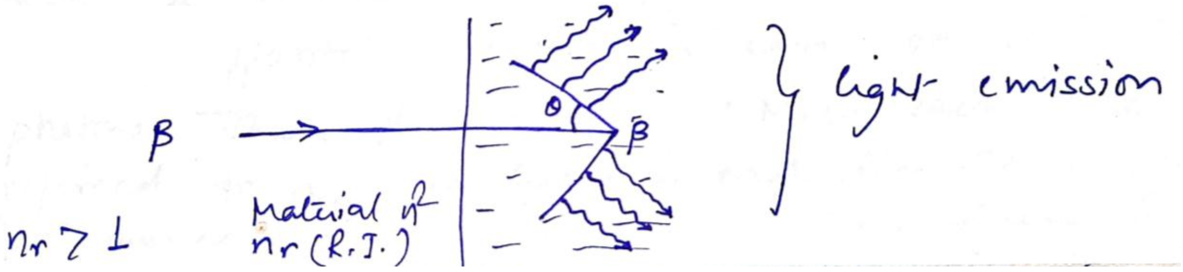
$$C=C_l\times n_r^{-1}$$

In Water n_r= 1.33
In Plexiglass n_r= 1.5

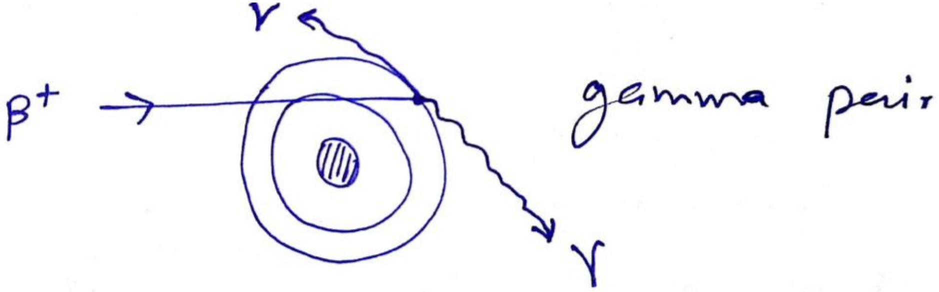
β- particles with energies >0.6 MeV move faster than light in water. When the particle velocity (V_p) > C, electromagnetic radiation is emitted coherently in a cone whose axis is the direction of the moving particle.

$$\sin\theta = C/v_p$$

This radiation can be used for detecting β- particles. Energy loss by Cherenkov radiation is ≤ 0.1% of the energy loss by other processes.



(d) Positron Annihilation:

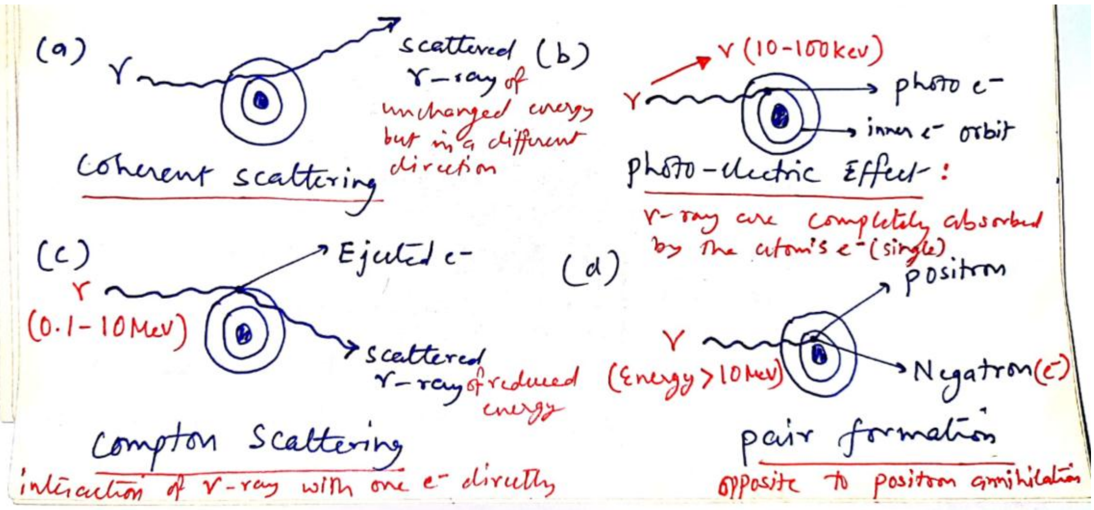


As the K.E. of the positron decreases in the absorber, there is an increase in probability of direct interaction between the positron and an electron (of the absorber) in which both the positron and electron are annihilated. The energy of the two electron masses is converted into electromagnetic radiation.

Since an electron mass is equivalent to 0.51MeV. The total energy of the annihilation process is 1.02MeV. In order to conserve momentum, the photons must be emitted with equal energy and in exactly opposite direction in case of only two photons. These photons of 0.51MeV each are referred to as annihilation radiation. The presence of γ-rays at 1.51MeV in spectrum is strong evidence of positron emission by that nuclei.

(D) Passage / Absorption of γ-radiation:

The absence of charge and rest mass for γ-rays results in little interactions with the absorbing atoms and in long ranges. The number of ion pairs produced in a given path length by γ-rays is only 1-10% of that produced by β-particles of the same energy e.g. a 1MeV. γ-rays produces only about one ion-pair per cm of air. As a consequence of this low specific ionization of γ-rays, the ionization is almost completely secondary in nature resulting from the action of a few high energy primary ion-pair.



Linear Energy Transfer (**LET**): Energy absorbed in matter per unit path length travelled by a charged particle.

$$LET = dE_{abs}/dx$$

Radiation	Energy (MeV)	Range in H_2O /mm	Average LET value in H_2O (KeV/μ)
e^-	1	4.1	0.24
	3	-	0.20
	10	52	0.19
p	1	0.023	43
	3	-	21
	10	1.2	8.3
$^4He_2$ (α)	1	-	190
	3	-	180
	10	0.11	92
Fission fragments	100		3300

For the same energy and the same absorbing material, the LET values increases in order:

Increasing LET ↓

High energy e^-s, γ-rays
β-particles
protons
deuterons
α
fission fragments

Stopping Power**:** The specific energy loss of a particle in matter is called the stopping power S.

$S = dE_{loss} / dn$ (J/m**)**

Relationship between LET & S

$dE_{loss} / dn = dE_{abs} / dn \quad + E_n$ or $E_x = S – LET$

E_n = energy loss by electromagnetic radiation

≡ Bremsstrahlung

Radiation Dose**:**

The absorbed dose (D) is the amount of radiation energy absorbed per unit mass (m):

$D = dE_{abs} /dm$ where $E_{abs} = E_{in} - E_{out}$

The S.I. unit is the Grey (GY).

1 Gy = 1 J/Kg

The dose rate is the absorbed dose per unit time.

Unit = Gy/Sec

The specific γ-ray dose rate, Ḋ, is a practical measure for estimation of the radiation hazard to people from γ emitting radionuclides.

$\dot{D} = A_r^{-2} \Sigma n_i k_i B_i e^{-\mu i x}$

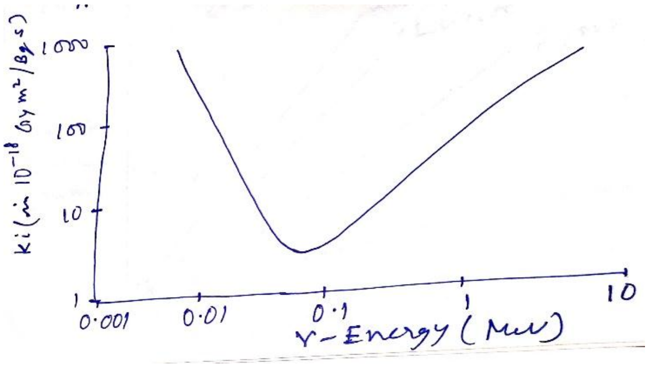
where $A_r^{-2}\,\Sigma n_i\,k_i = \dot{D}_o \Rightarrow$ relative dose rate without any radiation shield,

$\dot{D} \Rightarrow$ ………. With shield

$B_i \Rightarrow$ buildup factor; $e^{-\mu i\,x} \Rightarrow$ alteration factor

$n_i \Rightarrow$ fraction of all delays yielding a γ-ray of energy E_i corresponding to the source constant K_i (γ dose rate constant)

A ⇒ source length (B_q/s)



Radiation Shielding: For charged particles shielding is usually slightly thicker than that required for the maximum range of projectile's in the material.

*****Absorption thickness of 0.2 mm are adequate to completely absorb α-particles. By contrast 15 mm of materials of low Ƶ such as water, plastic, paraffin, etc. are required for the absorption of β-radiation with energies up to 3 MeV. Radiation shielding constructed from material of higher At. No. (Ƶ) require correspondingly thinner thickness**.**