Problem-1 (10 points): a) What are the mechanisms of producing swift beta particles? b) What are the interactions of beta particles with matter?

(Solution)

a) The swift electrons (e^+ or e^-) are produced from the following mechanisms:

- β-decay; e^+ or e^- in continuous energy spectrum
- pair production; e^+ or e^- in continuous energy spectrum
- internal conversion; e^-, mono-energetic orbital electron
- cathode rays, synchrotron, betatron, etc.; e^-, mono-energetic
- Compton scattering; e^-, in continuous energy spectrum
- interaction of heavy ionizing particles with matter; e^-, δ-rays (avalanche of electrons)
- muon decay; $\mu^- \rightarrow e^- + \nu + \underline{\nu}$ (neutrino + antineutrino) τ = 2.15 μsec

  $\mu^+ \rightarrow e^+ + \nu + \underline{\nu}$ ($\pi^+ \rightarrow \mu^+ + \nu$: τ = 0.02 μsec)

  where, τ = mean time = $1/\lambda$.

b) The beta-ray reactions with matter are summarized as follows:

- collision with atomic electrons: ionization, excitation (dominates in few MeV region)
- collision with nucleus: bremsstrahlung (in high energy region, especially in high Z material, ex. E_c of Pb =7.8 MeV)

"Bremsstrahlung" is the radiative loss of energy which appears as the continuous electromagnetic radiation produced by inelastic scattering of beta particle with nuclei. Bremsstrahlung becomes significant with high energy beta particles in high Z materials. In particular, we should be very careful about using most common Pb (lead: Z=82) shield since shielding of high energy beta using lead creates an accompanying problem of secondary radiation of electromagnetic radiation. Extra shielding should be considered for photons due to bremsstrahlung.

- annihilation: positron + negatron.

Problem-2 (30 points): a) Find the photon flux (#/sec.cm^2) at 20 cm away form a point source of 10^{10} photons per second in a vacuum. b) Find the uncollided and flux through a 2 cm Pb shield at 10 cm away from the source. c) Find the observed flux through a 2 cm Pb shield at 10 cm away from the source. The photon source has the energy of 1 MeV energy. Consider the linear attenuation factor of Pb for 1 Mev photon is μ(E=1 Mev) = 1.2 cm^{-1} and the corresponding dose buildup factor $B_r(\mu r=2.4, E=1.2\ \text{MeV})$ for a point source is 3.37.

(Solution)

a) photon flux

Φ(r=20cm)

$= S_o / 4\pi r^2$

$= (10^{10}$ photons/sec$) / 4\pi(20\text{ cm})^2$

= $\underline{1.99\text{x}10^6 \text{ photons/sec.cm}^2}$

b) uncollided flux

Φ_u(t=2 cm; r=10cm)

$= S_o \exp(-\mu t) / 4\pi r^2$

$= (10^{10}$ photons/sec$) \exp(-[(1.2\text{cm}^{-1})(2\text{ cm})] / 4\pi(10\text{ cm})^2$

= $\underline{7.22\text{x}10^5 \text{ photons/sec.cm}^2}$

c) observed flux

Φ(t=1 cm; r=10cm)

$= B_r(\mu t=2.4, E=1 \text{ MeV})\ \Phi_u(t=2 \text{ cm}; r=10\text{cm})$

$= (3.37)(7.22\text{x}10^5)$

= <u>$2.43\text{x}10^6$ photons/sec.cm^2</u>

Problem-3 (20 points): I-131 is produced in a thermal reactor as a fission product in the fuel. a) Write down the I-131 nuclei balance equation in the reactor. b) Considering the thermal power level of 4,000 MWt, find the equilibrium activity of I-131 in the core (Ci) of APR1400. Assume the fission yield of 3%, and neglect the neutron absorption of I-131 in the reactor. The half-life of I-131 is 8 days. Consider 1 fission/sec produces the thermal power of 3×10^{-17} MWt.

(Solution)

a) The rate of change in the number of I-131 nuclei in the core fuel is given by:

$dN/dt = V \gamma \Sigma_f \Phi - \lambda N$

where, N = number of I-131 atoms in the core fuel,

V = reactor core volume, cm^3,

γ = fission yield of I-131,

Σ_f = macroscopic fission X-section of the fuel, cm^{-1},

Φ = average thermal neutron flux, #/sec.cm^2

λ = nuclear transformation constant of I-131, sec^{-1}.

b) In an equilibrium state, dN/dt = 0. In this case, the I-131 activity in the core is:

$A \equiv \lambda N = \gamma V \Sigma_f \Phi = \gamma P$ (power in fissions per second) Bq,

where $P = V \Sigma_f \Phi$ fissions/sec.

If we replace 1 fission/sec with the thermal power of 3×10^{-17} MWt and express the activity in curies, then the I-131 activity becomes:

$A = 9\times10^{5} \gamma P$ (power in MWt) Ci

where, $9\times10^{5} = 1/ (3.1\times10^{10}$ Bq/Ci) (3×10^{-17} MWt per fission/sec).

Therefore, the equilibrium I-131 activity in the core of a 4,000 MWt reactor becomes:

$A = 9 \times 10^{5} \gamma P$

$= (9 \times 10^{5})(0.03)(4000 \text{ MWt})$

$= \underline{1.08 \times 10^{8} \text{ Ci}}$

Problem-4 (20 points): a) Calculate the equilibrium concentration of Rn-222 (Ci/m^3) in a sealed room of 4X10X20m when 1 Ci of Ra-226 is stored. b) Find the ventilation exhaust rate (m^3/hour) in order to keep the concentration of Rn-222 under $4X10^{-6}$ μCi/ml. Half-lives of Ra-226 and Rn-222 are 1,620 years and 3.82 days, respectively.

(Solution)

$$\text{Ra-226} \xrightarrow{\alpha} \text{Rn-222} \xrightarrow{\alpha}$$

$T_{1/2}$ = 1,620y $T_{1/2}$ = 3.82 d

The rate of change in the number of Rn-222 atoms in the room is given by:

$dN_{Rn}/dt = \lambda_{Ra} N_{Ra} - \lambda_{Rn} N_{Rn} - R_f N_{Rn}$

where, N_{Rn} , N_{Ra} = number of Rn and Ra atoms in the room, respectively,

λ_{Ra} , λ_{Rn} = nuclear transformation constants of Ra and Rn, sec^{-1}, respectively,

R_f = room ventilation rate, vol/sec.

a) In a sealed room without ventilation, Rn-222 (radon gas) is in secular equilibrium with Ra-226. If Rn-222 is in secular equilibrium with Ra-226, then

$dN_{Rn}/dt = \lambda_{Ra} N_{Ra} - \lambda_{Rn} N_{Rn} - R_f N_{Rn} = 0$ and $R_f = 0$.

In this case, Rn-222 activity in the room becomes:

$A_{Rn} \equiv \lambda_{Rn} N_{Rn}$

$= \lambda_{Ra} N_{Ra} \equiv A_{Ra} = \quad = 1$ Ci

Hence, the concentration in the room becomes:

$C_{Rn} = (1 \text{ Ci})/(V \text{ m}^3) = 1 \text{ Ci}/(4\text{m}X10\text{m}X20\text{m})$

$=$ <u>$1.25\text{x}10^{-3}$ Ci/cm^3</u>.

b) Let R (= V R_f) be the ventilation exhaust rate (m^3/hour) required to reduce the concentration down to 4X10^{-6} μCi/ml. Then, since the ventilation rate is much bigger than the nuclear transformation constant of Rn-222, the concentration of Rn-222 in the room easily saturates. In this case,

$R_f N_{Rn} = \lambda_{Ra} N_{Ra}$

The ventilation rate becomes:

$R = V R_f = V \lambda_{Ra} N_{Ra} / N_{Rn}$

$= \lambda_{Rn} \{\lambda_{Ra} N_{Ra} / (\lambda_{Rn} N_{Rn} / V)\}$

$= \lambda_{Rn} \{A_{Ra} / C_{Rn}\}$

$= \{0.693/(3.82 \text{ days})(24 \text{ hours/day})\} \{1 \text{ Ci}/ (4X10^{-6} \text{ Ci/m}^3)\}$

$=$ <u>$1.89\text{x}10^3$ m^3/hr</u>.

Problem-5 (20 points): Find the thickness of Al foil to stop Po^{210}-α (E=5.3 MeV). The range of the alpha particle in the STP air is 3.95 meters. Densities of aluminum and air are 2.7 and 1.293×10^{-3} g/cm^3, respectively. Mass numbers of aluminum and air are 27 and 14.5, respectively.

(Solution)

By ***Bragg-Kleeman Rule,*** the ranges of alpha in different absorber media are:

$$\frac{R_1}{R_2} = \frac{\rho_2}{\rho_1}\frac{\sqrt{A_1}}{\sqrt{A_2}}$$

where, ρ = density of absorber medium, g/cm^3, and

A = atomic number.

$\rho_{Al} = 2.7\ g/cm^3$ $\qquad$ $A_{Al} = 27$

$\rho_{air} = 1.293 \times 10^{-3}\ g/cm^3$ $\qquad$ $A_{air} = 14.5$

The range of Po-210-α in the aluminum becomes:

$$R_{Al} = \frac{\rho_2}{\rho_1}\frac{\sqrt{A_1}}{\sqrt{A_2}} R_{air}$$

$$= \frac{1.293x10^{-3}}{2.7}\sqrt{\frac{27}{14.5}}(3.95)$$

= $\underline{2.58 \times 10^{-3}\ m}$