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Fundamentals of Radiation Physics

Scientific MEIR
AFRRI - July 2008
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Objectives

- **Define ionizing radiation**
- **Describe sources of ionizing radiation**
- **Describe interaction of ionizing radiation with matter at microscopic level**
- **Describe interaction of ionizing radiation with matter at macroscopic level**

Categories of Ionizing Radiation

- Directly ionizing
  - Charged particles
  - e^- e^+ p^+ α^{++} π^- heavy nuclei
    - $\alpha^{++} = {}^4He^{+2}$
- Indirectly ionizing
  - Photons
    - $E = h\nu$ (Greek letter nu = frequency)
    - γ rays = photons of nuclear origin
  - Neutrons

Sources of Ionizing Radiation

- Electrically generated
  - Charged particle accelerators
    - Van de Graaff generator, cyclotron linear accelerator, synchrotron, betatron, microtron, rhodotron
- Radionuclides
  - Atom with an unstable nucleus
    - Naturally occurring
    - Man-made (induced)

Basic Nuclear Physics

- Nuclei have different energy states
  - Ground state
  - Metastable or isomeric nuclear states
    - Often > 10^{-12} sec or on the order of hours
  - Excited nuclear states
    - Usually < 10^{-12} sec
- Terminology
  - Isotopes: same Z (atomic number)
  - Isobars: same A (atomic mass)
  - Isotones: same N (number of neutrons)

Nuclear Processes

- β^- decay
  - $n \rightarrow p^+ + e^- +$ antineutrino + KE
- β^-, γ decay
  - $n \rightarrow p^+ + e^- +$ antineutrino + KE
    followed by γ release
- β^+ decay
  - $p^+ \rightarrow n + e^+ +$ neutrino + KE
    followed by e^+/e^- annihilation
- β^+, γ decay
  - $p^+ \rightarrow n + e^+ +$ neutrino + KE
    followed by γ release and e^+/e^- annihilation

More Nuclear Processes

- Electron capture
  - $p^+ + e^- \rightarrow n + \text{neutrino} + KE$

    then characteristic x-rays or Auger electrons
- Electron capture, γ
  - $p^+ + e^- \rightarrow n + \text{neutrino} + KE$

    followed by γ release

    then characteristic x-rays or Auger electrons
- α decay
- α decay, γ

  followed by γ release

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Basic Mathematical Formulation

- $-dN/dt = \lambda N$ (λ = decay constant)
- $N(t)/N_o = e^{-\lambda t}$
- $N(t) = N_o\, e^{-\lambda t}$
- Activity is defined as $-dN/dt$
- $A(t) = A_o\, e^{-\lambda t}$
- $\ln 2 = \lambda T_{½}$ ($T_{½}$ = half life)
- $0.693 = \lambda T_{½}$
- $\lambda = 0.693/\, T_{½}$
- Often useful to use e^{-x} where $x = (0.693/\, T_{½})t$
- For small values of λt: $e^{-\lambda t} \approx 1-\lambda t$
- Average lifetime: $\tau = 1/\lambda = 1.44T_{½}$

International System of Units (SI) and Radionuclide Activity & Decay

- SI unit of activity is becquerrel (Bq)
- 1 Bq = 1 sec^{-1}
- Describes rate of decay as number/sec
- Thus 1 Bq = 1 “disintegration” per sec (dps)
- Another unit of activity is the Curie (non-SI)
- 1 Ci = 3.7×10^{10} sec^{-1} or 3.7×10^{10} Bq
- Therefore 1 Bq = 2.7×10^{-11} Ci

Specific Activity

- Carrier: stable isotopes of same element in the sample are called carriers
- Specific activity defined as:
  radioisotope activity/total mass of element present
- Units of specific activity (non-SI): Ci/g
- m = activity/specific activity
- Highest possible specific activity is referred to as the carrier free specific activity

Production of Radionuclides

- Nuclear reactor
  - Neutron activation
  - Not carrier free; tend to decay by β^- emission
- Particle accelerator
  - Cyclotron often used to add positive charge
  - Carrier free; tend to decay by β^+ emission
- Photonuclear
  - Low yield
  - Not carrier free; tend to decay by β^+ emission

SI Units - Matter - Energy

- Fundamental units of nature (MKS-A)
  length - mass - time - ampere
  meter - kilogram - second - ampere
- Other supplementary units
  temperature (kelvin: K)
  amount of substance (mole: mol)
  luminous intensity (candela: cd)
- All other units are derived
  eg: electrical potential (volt)
  $1\ V = 1\ m^2\ kg\ s^{-3}\ A^{-1}$

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SI Units - Matter - Energy

- Matter: fundamental property in universe
- Energy: fundamental component of nature
- Energy = ability to do work
- Recall: work = force x distance (newton x meter)
- Energy can be expressed in several ways
- SI unit of energy is joule (J)
- $1\ J = 1\ m^2\ kg\ s^{-2}$
- Total energy = kinetic energy + potential energy
- Consider 1 e- accelerated across an electrical potential of 1 volt acquires a KE of 1 eV
- $1\ eV = 1.6022 \times 10^{-19}\ J$

SI Units - Matter - Energy

- Matter represents a form of potential energy
- Mass increases as KE approaches speed of light
- An object at rest has its own rest mass energy

	m_0c^2	m_{e-}
e^-	0.511 MeV	1
μ^-	106 MeV	207
π^-	140 MeV	273
p^+	938.26 MeV	1836
n	939.55 MeV	1839

Fundamental Quantities

- Particle fluence

  $\Phi = dN/da$

- Energy fluence

  $\Psi = dE/da$

- Exposure (roentgen - R)

  $X = dQ/dm$

  where dQ is the sum of the electrical charges of one sign on all the ions produced in air when all the electrons liberated by photons in a volume of air of mass dm are completely stopped in air

  $1\ R = 2.58 \times 10^{-4}\ C/kg$

Principles of Attenuation

- Attenuation = reduction in the number of particles in a radiation beam as it passes through an absorber
- Can occur as a single event or series of events
- Energy loss by an extended series of energy transfer events predominates for charged particle beams
- The concept of range and path length mostly appropriate for charged particle beams
- Energy loss by indirectly ionizing radiation beams can occur in a single event or gradual degradation
- Mean free range & half value thickness of absorber more meaningful for indirectly ionizing radiation

More on Attenuation

- Involves the processes of absorption and scatter
- Based on the concept of a reaction cross section
- Cross section = probability per target per unit area
- Probabilities of independent processes additive
- Attenuation terminology different for charged particle and indirectly ionizing radiation beams
- Charged particle beams scatter elastically
- Energy loss related mostly to inelastic processes
- Linear attenuation coefficient best describes attenuation for indirectly ionizing radiation beams

Energy Loss by Charged Particles

- Predominantly occurs through inelastic collisions with atomic electrons and nuclei
- Involves coulomb force and strong force
- Energy loss per unit length called stopping power
- Depends on particle, its KE, and Z of medium
- KE often symbolized by T
- Stopping power: collisional and radiative

  $dT/dx = dT/dx_C + dT/dx_R$
- Mass stopping power

  $dT/\rho dx = dT/\rho dx_C + dT/\rho dx_R$

Photon Attenuation Processes

- Atomic photoelectric effect

  $_{a}\tau \leftrightarrow Z^4/(h\nu)^3$ x-section/atom for $h\nu \leq 0.1$ MeV
- Compton scattering

  $_{e}\sigma \leftrightarrow Z$ x-sec/electron & $_{a}\sigma = Z\ _{e}\sigma$ x-sec/atom

  Compton effect dependent on atomic e^- density

  Atomic e^- density mostly constant except for H
- Atomic pair production

  $_{a}\kappa \leftrightarrow Z^2$ cross section/atom
- Rayleigh scattering

  $_{a}\sigma_R \leftrightarrow (Z/h\nu)^2$ cross section/atom

Photon Attenuation

- Total linear attenuation coefficient

  $\mu = \tau + \sigma + \kappa + \sigma_R$

- Total mass attenuation coefficient

  $\mu/\rho = \tau/\rho + \sigma/\rho + \kappa/\rho + \sigma_R/\rho$

- Under ideal narrow beam conditions

  $N(x) = N_0 e^{-\mu x}$ (similar to radioactive decay eqn.)

- Under less ideal conditions (broad beam conditions)

  $N(x) = N_0 e^{-\mu' x}$

  where μ' = effective total linear attenuation coefficient

Photon Energy Transfer

- Photons transfer energy by generating secondary charged particles
- Almost all charged secondary particles are e^-
- Total energy transfer coefficient

$$\mu_{tr} = \tau_{tr} + \sigma_{tr} + \kappa_{tr} + (\gamma,p^+)_{tr} + (\gamma,n)_{tr}$$

- Total mass energy transfer coefficient

$$\mu_{tr}/\rho = \tau_{tr}/\rho + \sigma_{tr}/\rho + \kappa_{tr}/\rho + (\gamma,p^+)_{tr}/\rho + (\gamma,n)_{tr}/\rho$$

Photon Energy Absorption

- Mass energy absorption coefficient

  $\mu_{en}/\rho = (\mu_{tr}/\rho)(1 - g)$

  where g = fraction lost to radiative interactions

  g increases gradually with increasing Z or h*v*
- Energy absorbed per unit volume correlates the amount of radiation with the effects of radiation
- Energy deposited per unit length along the track of radiation important and correlates to effects
- Duration of time associated with the delivery of radiation especially important in living systems

(Above subjects covered shortly or in next lecture)

Kerma and Exposure

- Kerma = kinetic energy released in matter (K)
- $K = K_C + K_R$
- Energy required to produce a unit charge in air $(W/e)_{AIR}$ = 33.97 J/C
- Exposure (X) is ionization equivalent of K_C in air
- Equivalence valid only for photon energies < 3 MeV
- $(K_C)_{AIR} = X(W/e)_{AIR}$
- SI units: $X(W/e)_{AIR}$ = (C/kg)(J/C) = J/kg
- Energy per unit mass ↔ J/kg
- Roentgen: 1 R = 2.58 x 10^{-4} C/kg
- 1 C/kg = 3876 R

Kerma and Dose

- $K = K_C + K_R$
- $K = dE_{tr}/dm$
- $K = E_{tr}\Phi(\mu/\rho) = \Psi(\mu_{tr}/\rho)$
- $K_C = \Psi(\mu_{en}/\rho)$
- SI unit of dose (D) is the Gray (Gy)
- 1 Gy = 1 J/kg (1 rad = 1 x 10^{-2} J/kg = 100 cGy)
- $D = K_C$ under conditions of CPE
- Charged particle equilibrium is an important and necessary condition for D at the macrocsopic level

Neutrons

- Characterized by their kinetic energy T
  - Cold neutrons: 5×10^{-5} eV ≤ T < 0.025 eV
  - Thermal neutrons: T = 0.025 eV at 293° K
  - Epithermal neutrons: 0.025 eV ≤ T < 1 eV
  - Slow neutrons: 1 eV ≤ T < 1 keV
  - Intermediate neutrons: 1 keV ≤ T < 0.5 MeV
  - Fast neutrons: 0.5 MeV ≤ T < 10 MeV
  - High energy neutrons: 10 MeV ≤ T
- Neutron beams essentially always occur as mixed photon/neutron beams

Neutrons

- Decay in free space with $T_{½}$ = 10.6 min according to

  $n \rightarrow p^{+} + e^{-}$ + antineutrino
- Reacts with other particles predominantly by the strong nuclear force at a range of 10^{-14} m
- Interactions produce elastic neutrons, γ photons inelastic neutrons, recoil atoms (nuclei), & fragments
- Neutron kerma $K = \Phi F_n$ with F_n = neutron kerma factor
- Neutron dose $D = K = \Phi F_n$ under conditions of CPE
- Dose effect from neutrons enhanced in living systems

Linear Energy Transfer (LET)

- Recall collisional and radiative stopping power

  $dT/dx = dT/dx_C + dT/dx_R$

- LET equates to a restricted collisional stopping power with energy transfers ≤ a specified value of Δ
- $L_\Delta = (-dT/dx)_C$ with $E \leq \Delta$

  250 kV_P x-rays: LET = 2 keV/μm

  ^{60}Co γ rays: LET = 0.3 keV/μm

  6 to 50 MeV e^-: LET ≈ 0.2 keV/μm

  14 MeV n: LET = 12 keV/μm

  > 100 MeV p^+: LET = 0.5 keV/μm → 100 keV/μm

  50 MeV π^-: LET = 0.3 keV/μm → 100 keV/μm

Sievert – SI Unit of Dose Equivalent

- Sievert: H = DQN
- D= absorbed dose (Gy)
- Q = quality factor
- N = product of all other dose-modifying factors
  eg: spatial dose distribution or rate of delivery
- 1 Sv = 1 J/kg (1 rem = 1 x 10^{-2} J/kg = 100 cSv)
  250 kV_P x-rays: Q = 1
  ^{60}Co γ rays: Q = 1
  6 to 50 MeV e^-: Q = 1
  14 MeV n: Q = 10 if ≥ 10 keV & Q = 3 if < 10 keV
  > 100 MeV p^+: Q = 1 to > 10 as a function of keV
  50 MeV π^-: Q = 1 to > 10 as a function of keV

Thank you for your attention

- Questions
- Comments
- Discussion