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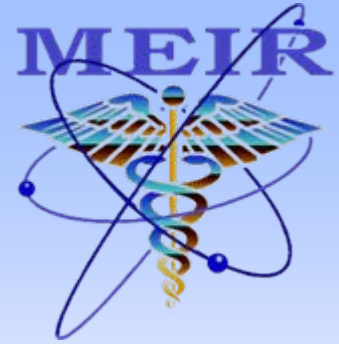
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# Fundamentals of Radiation Physics



## 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
  - $e^-$   $e^+$   $p^+$   $\alpha^{++}$   $\pi^-$  heavy nuclei
    - $\alpha^{++} = {}^4\text{He}^{+2}$
- Indirectly ionizing
  - Photons
    - $E = h\nu$  (Greek letter nu = frequency)
    - $\gamma$  rays = photons of nuclear origin
  - Neutrons



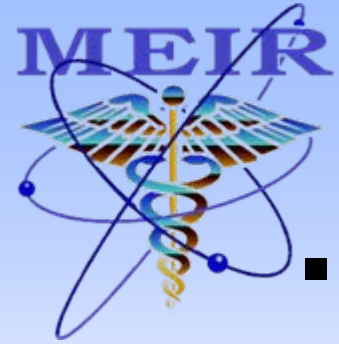
## Sources of Ionizing Radiation

- 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

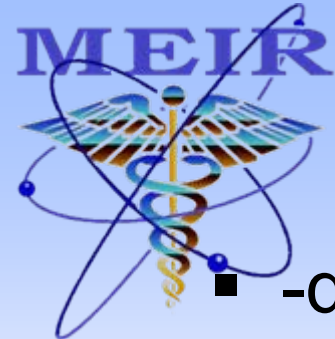
- $\beta^-$  decay
  - $n \rightarrow p^+ + e^- + \text{antineutrino} + \text{KE}$
- $\beta^-, \gamma$  decay
  - $n \rightarrow p^+ + e^- + \text{antineutrino} + \text{KE}$   
followed by  $\gamma$  release
- $\beta^+$  decay
  - $p^+ \rightarrow n + e^+ + \text{neutrino} + \text{KE}$   
followed by  $e^+/e^-$  annihilation
- $\beta^+, \gamma$  decay
  - $p^+ \rightarrow n + e^+ + \text{neutrino} + \text{KE}$   
followed by  $\gamma$  release and  $e^+/e^-$  annihilation





## More Nuclear Processes

- Electron capture
  - $p^+ + e^- \rightarrow n + \text{neutrino} + \text{KE}$   
then characteristic x-rays or Auger electrons
- Electron capture,  $\gamma$ 
  - $p^+ + e^- \rightarrow n + \text{neutrino} + \text{KE}$   
followed by  $\gamma$  release  
then characteristic x-rays or Auger electrons
- $\alpha$  decay
- $\alpha$  decay,  $\gamma$ 
  - followed by  $\gamma$  release



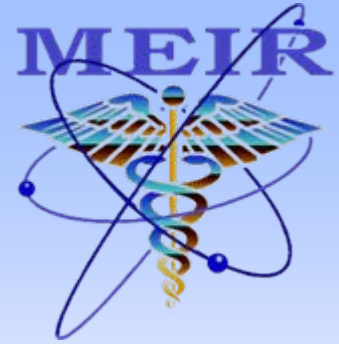
## Basic Mathematical Formulation

- $-dN/dt = \lambda N$  ( $\lambda$  = decay constant)
- $N(t)/N_0 = e^{-\lambda t}$
- $N(t) = N_0 e^{-\lambda t}$
- Activity is defined as  $-dN/dt$
- $A(t) = A_0 e^{-\lambda t}$
- $\ln 2 = \lambda T_{1/2}$  ( $T_{1/2}$  = half life)
- $0.693 = \lambda T_{1/2}$
- $\lambda = 0.693 / T_{1/2}$
- Often useful to use  $e^{-x}$  where  $x = (0.693 / T_{1/2})t$
- For small values of  $\lambda t$ :  $e^{-\lambda t} \approx 1 - \lambda t$
- Average lifetime:  $\tau = 1/\lambda = 1.44 T_{1/2}$



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

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



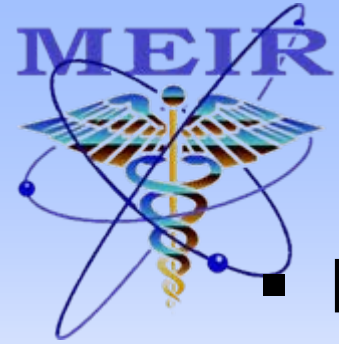
## Specific Activity

- 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
- $m = \text{activity/specific activity}$
- 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  $\beta^-$  emission
- Particle accelerator
  - Cyclotron often used to add positive charge
  - Carrier free; tend to decay by  $\beta^+$  emission
- Photonuclear
  - Low yield
  - Not carrier free; tend to decay by  $\beta^+$  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)  
 $1 \text{ V} = 1 \text{ m}^2 \text{ kg s}^{-3} \text{ A}^{-1}$



## 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)
- $1 \text{ J} = 1 \text{ m}^2 \text{ kg s}^{-2}$
- Total energy = kinetic energy + potential energy
- Consider 1 e- accelerated across an electrical potential of 1 volt acquires a KE of 1 eV
- $1 \text{ eV} = 1.6022 \times 10^{-19} \text{ J}$



## 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

	$m_0 c^2$	$m_{e^-}$
$e^-$	0.511 MeV	1
$\mu^-$	106 MeV	207
$\pi^-$	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

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



## 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
$$dT/pdx = dT/pdx_C + dT/pdx_R$$



## Photon Attenuation Processes

- Atomic photoelectric effect

$${}_a\tau \leftrightarrow Z^4/(h\nu)^3 \text{ x-section/atom for } h\nu \leq 0.1 \text{ MeV}$$

- Compton scattering

$${}_e\sigma \leftrightarrow Z \text{ x-sec/electron} \quad \& \quad {}_a\sigma = Z {}_e\sigma \text{ x-sec/atom}$$

Compton effect dependent on atomic  $e^-$  density

Atomic  $e^-$  density mostly constant except for H

- Atomic pair production

$${}_a\kappa \leftrightarrow Z^2 \text{ cross section/atom}$$

- Rayleigh scattering

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



## 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  $\mu'$  = 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

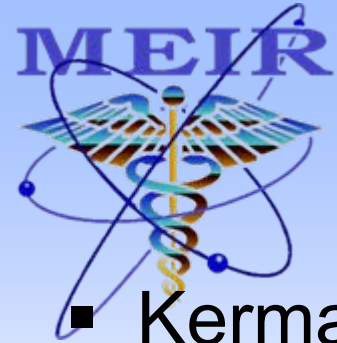
$$\mu_{tr}/\rho = \tau_{tr}/\rho + \sigma_{tr}/\rho + \kappa_{tr}/\rho + (\gamma, p^+)_{tr}/\rho + (\gamma, n)_{tr}/\rho$$



## Photon Energy Absorption

- Mass energy absorption coefficient
$$\mu_{\text{en}}/\rho = (\mu_{\text{tr}}/\rho)(1 - g)$$
where  $g$  = fraction lost to radiative interactions  
 $g$  increases gradually with increasing  $Z$  or  $h\nu$
- 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 relaxed in matter (K)
- $K = K_C + K_R$
- Energy required to produce a unit charge in air  
 $(W/e)_{AIR} = 33.97 \text{ J/C}$
- Exposure (X) is ionization equivalent of  $K_C$  in air
- Equivalence valid only for photon energies  $< 3 \text{ MeV}$
- $(K_C)_{AIR} = X(W/e)_{AIR}$
- SI units:  $X(W/e)_{AIR} = (\text{C/kg})(\text{J/C}) = \text{J/kg}$
- Energy per unit mass  $\leftrightarrow \text{J/kg}$
- Roentgen:  $1 \text{ R} = 2.58 \times 10^{-4} \text{ C/kg}$
- $1 \text{ C/kg} = 3876 \text{ R}$



## 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)
- $1 \text{ Gy} = 1 \text{ J/kg}$     ( $1 \text{ rad} = 1 \times 10^{-2} \text{ J/kg} = 100 \text{ cGy}$ )
- $D = K_C$  under conditions of CPE
- Charged particle equilibrium is an important and necessary condition for D at the macroscopic level



## Neutrons

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



## Neutrons

- Decay in free space with  $T_{1/2} = 10.6$  min according to  
$$n \rightarrow p^+ + e^- + \text{antineutrino}$$
- Reacts with other particles predominantly by the strong nuclear force at a range of  $10^{-14}$  m
- Interactions produce elastic neutrons,  $\gamma$  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  $\leq$  a specified value of  $\Delta$
- $L_\Delta = (-dT/dx)_C$  with  $E \leq \Delta$

250 kV<sub>p</sub> x-rays: LET = 2 keV/ $\mu$ m

$^{60}\text{Co}$   $\gamma$  rays: LET = 0.3 keV/ $\mu$ m

6 to 50 MeV  $e^-$ : LET  $\approx$  0.2 keV/ $\mu$ m

14 MeV  $n$ : LET = 12 keV/ $\mu$ m

$> 100$  MeV  $p^+$ : LET = 0.5 keV/ $\mu$ m  $\rightarrow$  100 keV/ $\mu$ m

50 MeV  $\pi^-$ : LET = 0.3 keV/ $\mu$ m  $\rightarrow$  100 keV/ $\mu$ m



## 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
- $1 \text{ Sv} = 1 \text{ J/kg}$     ( $1 \text{ rem} = 1 \times 10^{-2} \text{ J/kg} = 100 \text{ cSv}$ )
  - 250 kV<sub>P</sub> x-rays:  $Q = 1$
  - $^{60}\text{Co}$   $\gamma$  rays:  $Q = 1$
  - 6 to 50 MeV  $e^-$ :  $Q = 1$
  - 14 MeV  $n$ :  $Q = 10$  if  $\geq 10 \text{ keV}$  &  $Q = 3$  if  $< 10 \text{ keV}$
  - $> 100 \text{ MeV } p^+$ :  $Q = 1$  to  $> 10$  as a function of keV
  - 50 MeV  $\pi^-$ :  $Q = 1$  to  $> 10$  as a function of keV



Thank you for your attention

- Questions
- Comments
- Discussion

