Interactions with Matter

ACADs (08-006) Covered

1.1.4.2 1.1.4.3 3.3.1.4 3.3.3.1 3.3.3.2 3.3.3.3 3.3.3.4 3.3.3.5
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4.11.6

Keywords

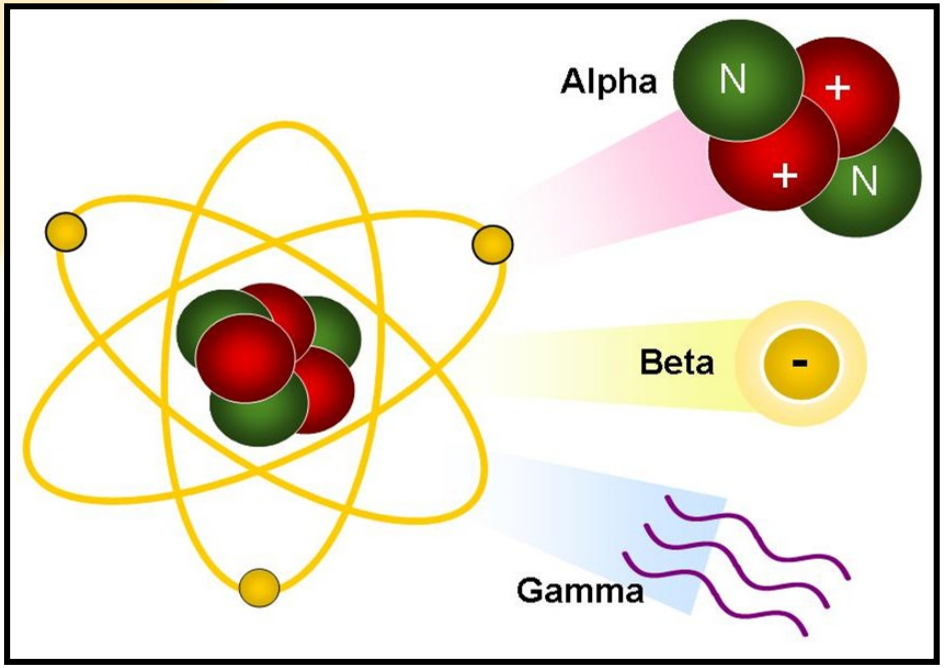
Energy transfer, ionization, excitation, Bremsstrahlung, linear energy transfer, alpha, beta, gamma, range, Compton scattering, indirectly ionizing, pair production, neutron interactions, fission, elastic scattering, inelastic scattering, radiation shielding.

Description

Supporting Material

RCNET
Regional Center for
Nuclear Education & Training

Radiation’s Interaction with Matter



Energy Transfer Mechanisms

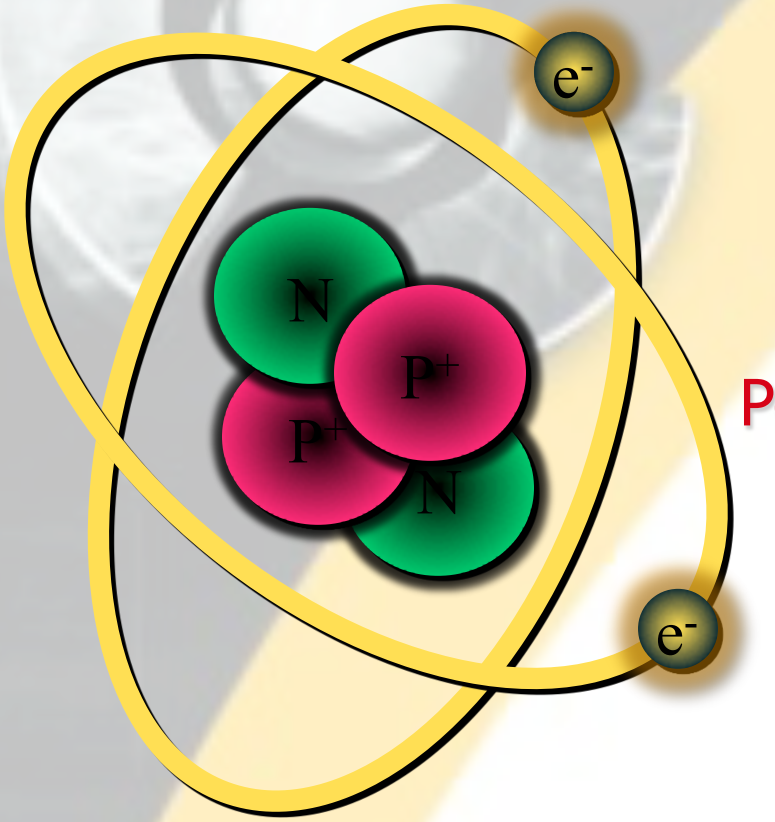
- Introduction
  - All radiation possesses energy
    - Inherent — electromagnetic
    - Kinetic — particulate
  - Interaction results in some or all of the energy being transferred to the surrounding medium
    - Scattering
    - Absorption

Energy Transfer Mechanisms

- Ionization
  - Removing bound electron from an electrically neutral atom or molecule by adding sufficient energy to the electron, allowing it to overcome its BE
  - Atom has net positive charge
  - Creates ion pair consisting of negatively charged electron and positively charged atom or molecule

Energy Transfer Mechanisms

Ionizing Particle



Negative Ion

Positive Ion

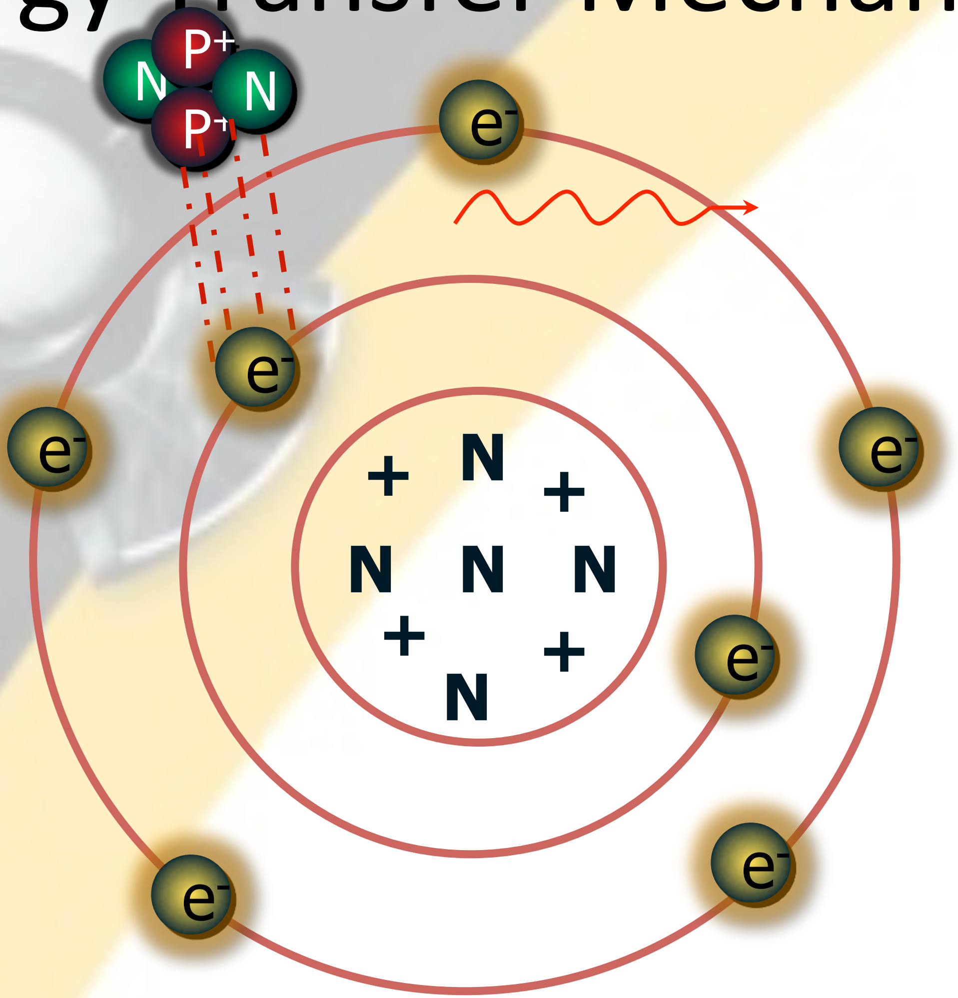
Energy Transfer Mechanisms

- Excitation
  - Process that adds sufficient energy to e^- or molecule such that it occupies a higher energy state than it’s lowest bound energy state
  - Electron remains bound to atom or molecule, but depending on role in bonds of the molecule, molecular break-up may occur
  - No ions produced, atom remains neutral

Energy Transfer Mechanisms

- After excitation, excited atom eventually loses excess energy when e^- in higher energy shell falls into lower energy vacancy
- Excess energy liberated as X-ray, which may escape from the material, but usually undergoes other absorptive processes

Energy Transfer Mechanisms



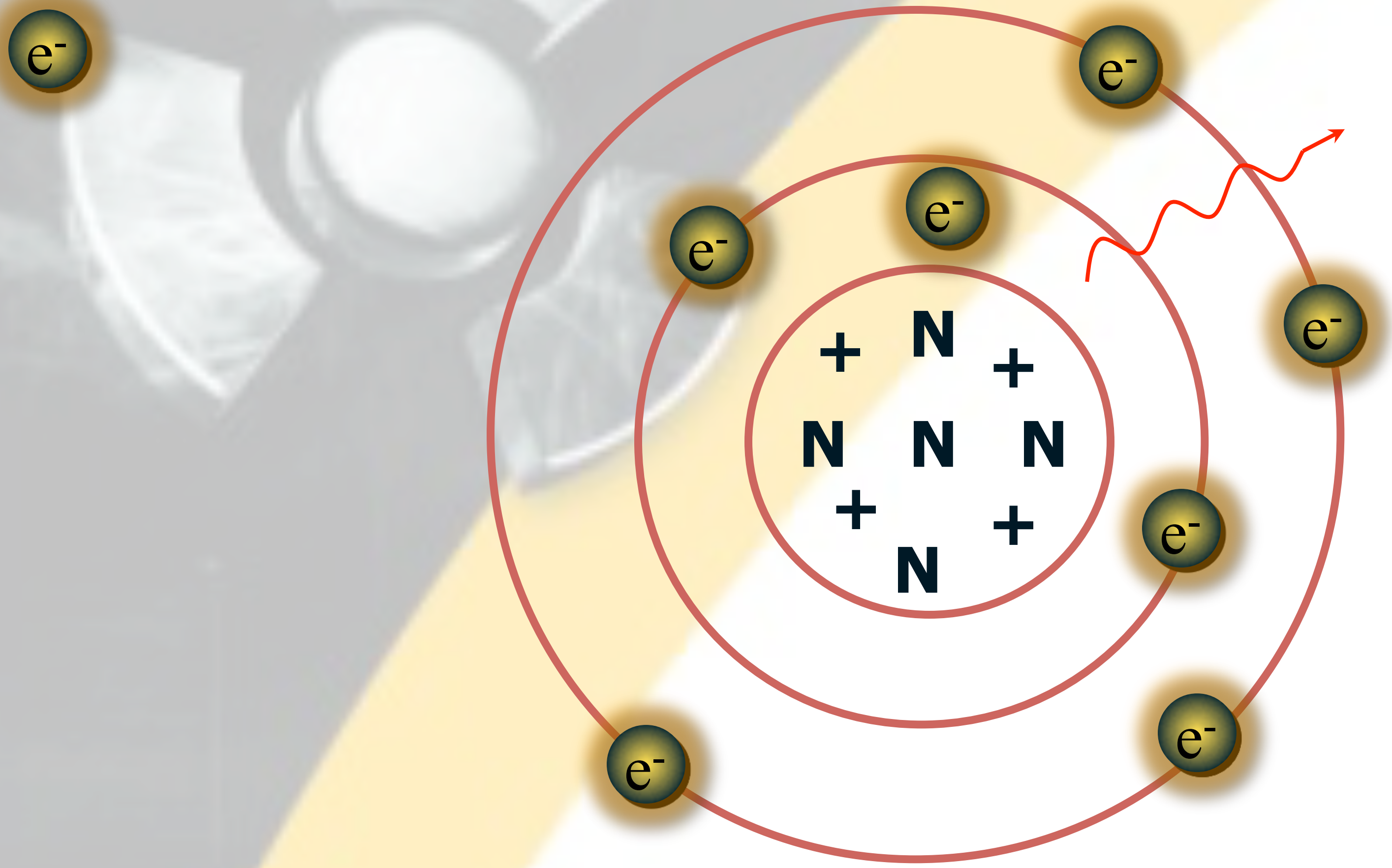
Energy Transfer Mechanisms

- Bremsstrahlung
  - Radiative energy loss of moving charged particle as it interacts with matter through which it is moving
  - Results from interaction of high-speed, charged particle with nucleus of atom via electric force field
  - With negatively charged electron, attractive force slows it down, deflecting from original path

Energy Transfer Mechanisms

- KE particle loses emitted as x-ray
- Production enhanced with high-Z materials (larger coulomb forces) and high-energy e^- (more interactions occur before all energy is lost)

Energy Transfer Mechanisms



Directly Ionizing Radiation

- Charged particles don’t need physical contact with atom to interact
- Coulombic forces will act over a distance to cause ionization and excitation
- Strength of these forces depends on:
  - Particle energy (speed)
  - Particle charge
  - Absorber density and atomic number

Directly Ionizing Radiation

- Coulombic forces significant over distances > atomic dimensions
- For all but very low physical density materials, loss of KE for e$^-$ continuous because of "Coulomb force"
- As charged particle passes through absorber, energy loss can be measured several ways

Directly Ionizing Radiation

- Specific Ionization
  - Number of ion pairs formed per unit path length
  - Often used when energy loss is continuous and constant, such as with α or β- particles
  - Number of pairs produced depends on ionizing particle type and material being ionized
    - α — 80,000 ion pairs per cm travel in air
    - β — 5,000 ion pairs per cm travel in air

Directly Ionizing Radiation

- Linear Energy Transfer
  - Average energy a charged particle deposits in an absorber per unit distance of travel (e.g., keV/cm)
  - Used to determine quality factors for calculating dose equivalence

Directly Ionizing Radiation

- Alpha Interactions
  - Mass approximately 8K times > electron
  - Travels approximately 1/20th speed of light
  - Because of mass, charge, and speed, has high probability of interaction
  - Does not require particles touching—just sufficiently close for Coulombic forces to interact

Directly Ionizing Radiation

- Energy gradually dissipated until α captures two e^- and becomes a He atom
- α from given nuclide emitted with same energy, consequently will have approximately same range in a given material

Directly Ionizing Radiation

- Calculating Range
  - Approximate general formula for range in air in cm

$R_{air} = 0.56E$ for E < 4 MeV

$R_{air} = 2.24E - 2.62$ for 4 < E < 8 MeV

Where: E = Alpha energy

Directly Ionizing Radiation

- In other media, range in media (R_m in mg/cm^2)

$$R_m = 0.56\sqrt[3]{A} \cdot R_{air}$$

Where: A = atomic mass of absorber

Directly Ionizing Radiation

Sample Problem

How far will a 2.75 MeV α travel in air?

$$R_{air} = 0.56E$$

$$R_{air} = (0.56)(2.75)$$

$$R_{air} = 1.54\ cm$$

How far will that same α travel in ${}_{92}^{210}Pb$?

$$R_m = 0.56\sqrt[3]{A} \cdot R_{air}$$

$$R_m = 0.56\sqrt[3]{210} \cdot (1.54)$$

$$R_m = (0.56)(5.944)(1.54)$$

$$R_m = 5.126\ mg/cm^2$$

Directly Ionizing Radiation

Sample Problem

How far will a 950 keV α travel in air?

How far will it travel in ^13↑27↓Al ?

Directly Ionizing Radiation

What is a beta?

An unbound electron with KE. It's rest mass and charge are the same as that of an orbital electron.

Directly Ionizing Radiation

- Beta Interactions
  - Interaction between β- or β+ and an orbital e^- is interaction between 2 charged particles of similar mass
  - βs of either charge lose energy in large number of ionization and/or excitation events, similar to α
  - Due to smaller size/charge, lower probability of interaction in given medium; consequently, range is >> α of comparable energy

Directly Ionizing Radiation

- Because β’s mass is small compared with that of nucleus
    - Large deflections can occur, particularly when low-energy βs scattered by high-Z elements (high positive charge on the nucleus)
    - Consequently, β usually travels tortuous, winding path in an absorbing medium
- β may have Bremsstrahlung interaction resulting in X-rays

Directly Ionizing Radiation

- Calculating Range (mg/cm^2)

$R=412E^{1.265-0.0954\ln E}$ for 0.01 < E < 2.5 MeV

$R=530E-106$ for E > 2.5 MeV

Where: E = Beta energy

Directly Ionizing Radiation

Sample Problem

How far will a ^{90}Sr β^- travel in air?

$$\mathrm{R}=412E^{1.2965-0.0954(\ln E)}$$

$$R=(412)(2.3)^{1.2965-0.0954\,(\ln 2.3\,)}$$

$$R=(412)(2.3)^{1.2965-0.0954\,(0.8329)}$$

$$R=(412)(2.3)^{1.2965-0.07946}$$

$$R=(412)(2.3)^{1.217}$$

$$R=(412)(2.756)$$

$$R=1{,}135\ mg/cm^{2}$$

Directly Ionizing Radiation

Sample Problem

How far will a ^{133}Xe β^- travel in air?

Indirectly Ionizing Radiation

- No charge
- γ and n
- No Coulomb force field
- Must come sufficiently close for physical dimensions to contact particles to interact
- Small probability of interacting with matter

Indirectly Ionizing Radiation

- Don’t continuously lose energy by constantly interacting with absorber
- May move “through” many atoms or molecules before contacting electron or nucleus
- Probability of interaction depends on its energy and absorber’s density and atomic number
- When interactions occur, produces directly ionizing particles that cause secondary ionizations

Indirectly Ionizing Radiation

- Gamma absorption
  - γ and x-rays differ only in origin
  - Name used to indicate different source
    - γs originate in nucleus
    - X-rays are extra-nuclear (electron cloud)
  - Both have 0 rest mass, 0 net electrical charge, and travel at speed of light
  - Both lose energy by interacting with matter via one of three major mechanisms

Indirectly Ionizing Radiation

- Photoelectric Effect
  - All energy is lost – happens or doesn’t
  - Photon imparts all its energy to orbital e^-
  - Because pure energy, photon vanishes
  - Probable only for photon energies < 1 MeV
  - Energy imparted to orbital e^- in form of KE, overcoming attractive force of nucleus, usually causing e^- to leave orbit with great velocity

Indirectly Ionizing Radiation

- High-velocity e^-, called photoelectron
  - Directly ionizing particle
  - Typically has sufficient energy to cause secondary ionizations
- Most photoelectrons inner-shell (K) electrons

Indirectly Ionizing Radiation

- Probability of interaction per gram of absorber (σ)
  - Directly proportional to cube of atomic number (Z)
  - Inversely proportional to cube of photon energy (E)

$\sigma = Z^{3} / E^{3}$

Where: Z = Absorber atomic number

E = Photon energy

Indirectly Ionizing Radiation

– When calculating σ for absorber with >1 element, must use Z_{eff}

$$Z_{eff} = \sqrt[2.94]{a_1 z_1^{2.94} + a_2 z_2^{2.94} \cdots + a_n z_n^{2.94}}$$

- a_1 and a_2 are the fraction of total electrons in the compound
- For water (H_2O) = 10 electrons total
  - H = 2/10 = 0.2
  - O = 8/10 = 0.8

Indirectly Ionizing Radiation

Sample Problem

What is the probability of a 661 keV photon interacting with a water molecule?

$$Z_{eff} = \sqrt[2.94]{a_H z_H^{2.94} + a_O z_O^{2.94}}$$

$$Z_{eff} = \sqrt[2.94]{(0.2)(1)^{2.94} + (0.8)(8)^{2.94}}$$

$$Z_{eff} = \sqrt[2.94]{(0.2)(1) + (0.8)(451.9)}$$

$$Z_{eff} = \sqrt[2.94]{0.2 + 361.6}$$

$$Z_{eff} = \sqrt[2.94]{361.8}$$

$$Z_{eff} = 7.417$$

Indirectly Ionizing Radiation

Sample Problem cont’d

$\sigma = Z_{eff}^{3} / E^{3}$

$\sigma = (7.417)^{3} / (0.661)^{3}$

$\sigma = 408 / 0.2888$

$\sigma = 1413$

Indirectly Ionizing Radiation

Sample Problem

What is the probability of a 2.4 MeV photon interacting with a molecule of BF_3?

Indirectly Ionizing Radiation

Gamma Photon

(< 1 MeV)

Photoelectron

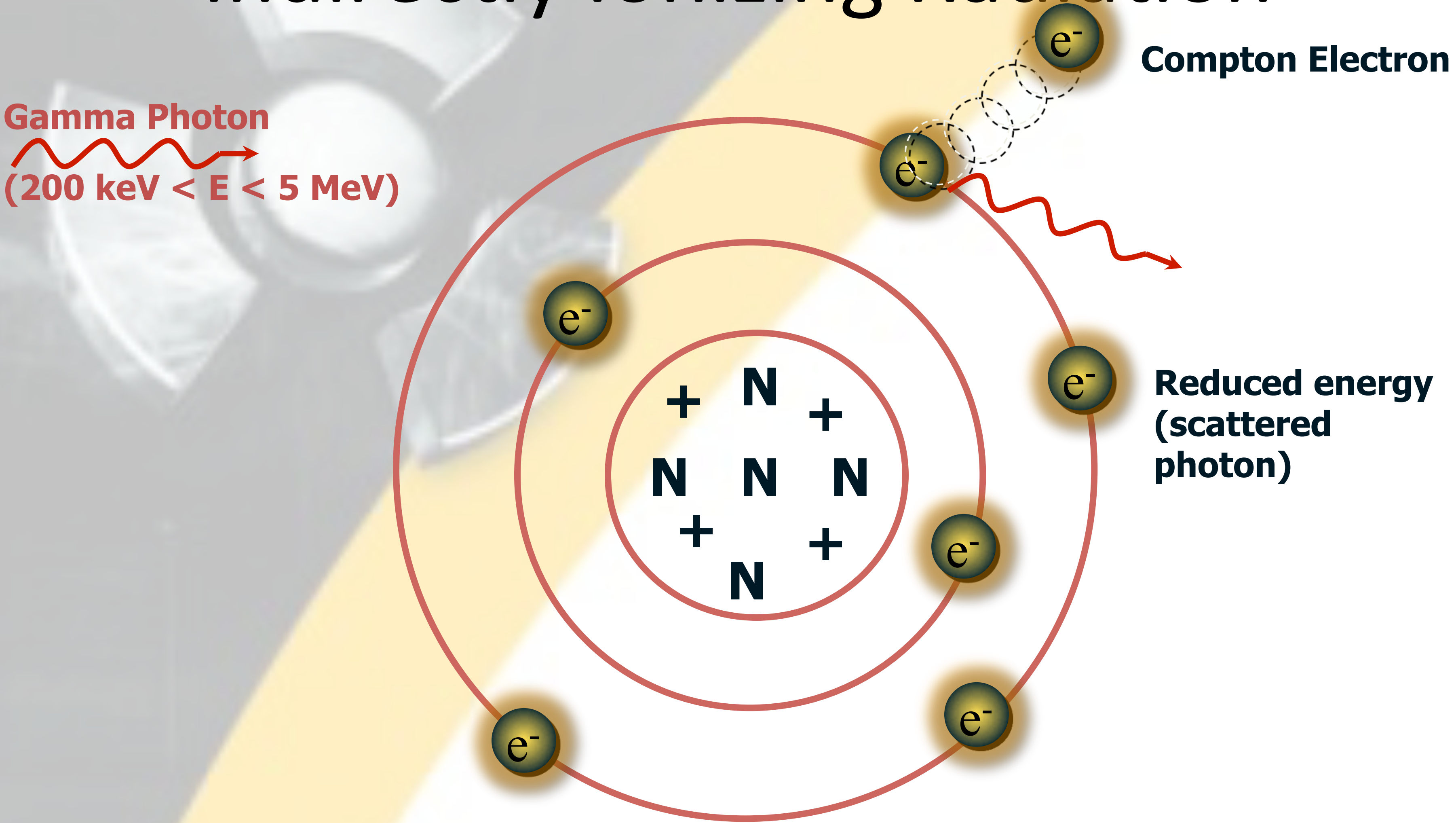
Indirectly Ionizing Radiation

- Compton Scattering
  - Partial energy loss for the incoming photon
  - Dominant interaction for most materials for photon energies 200 keV-5 MeV
  - Photon continues with less energy in different direction to conserve momentum
  - Probability of Compton interaction ↑ with distance from nucleus — most Compton electrons are valence electrons

Indirectly Ionizing Radiation

- Beam of photons may be randomized in direction and energy, so that scattered radiation may appear around corners and behind shields where there is no direct line of sight to the source
- Probability of Compton interaction ↑ with distance from nucleus — most Compton electrons are valence electrons
- Difficult to represent probability mathematically

Indirectly Ionizing Radiation



Gamma Photon

(200 keV < E < 5 MeV)

Compton Electron

Reduced energy (scattered photon)

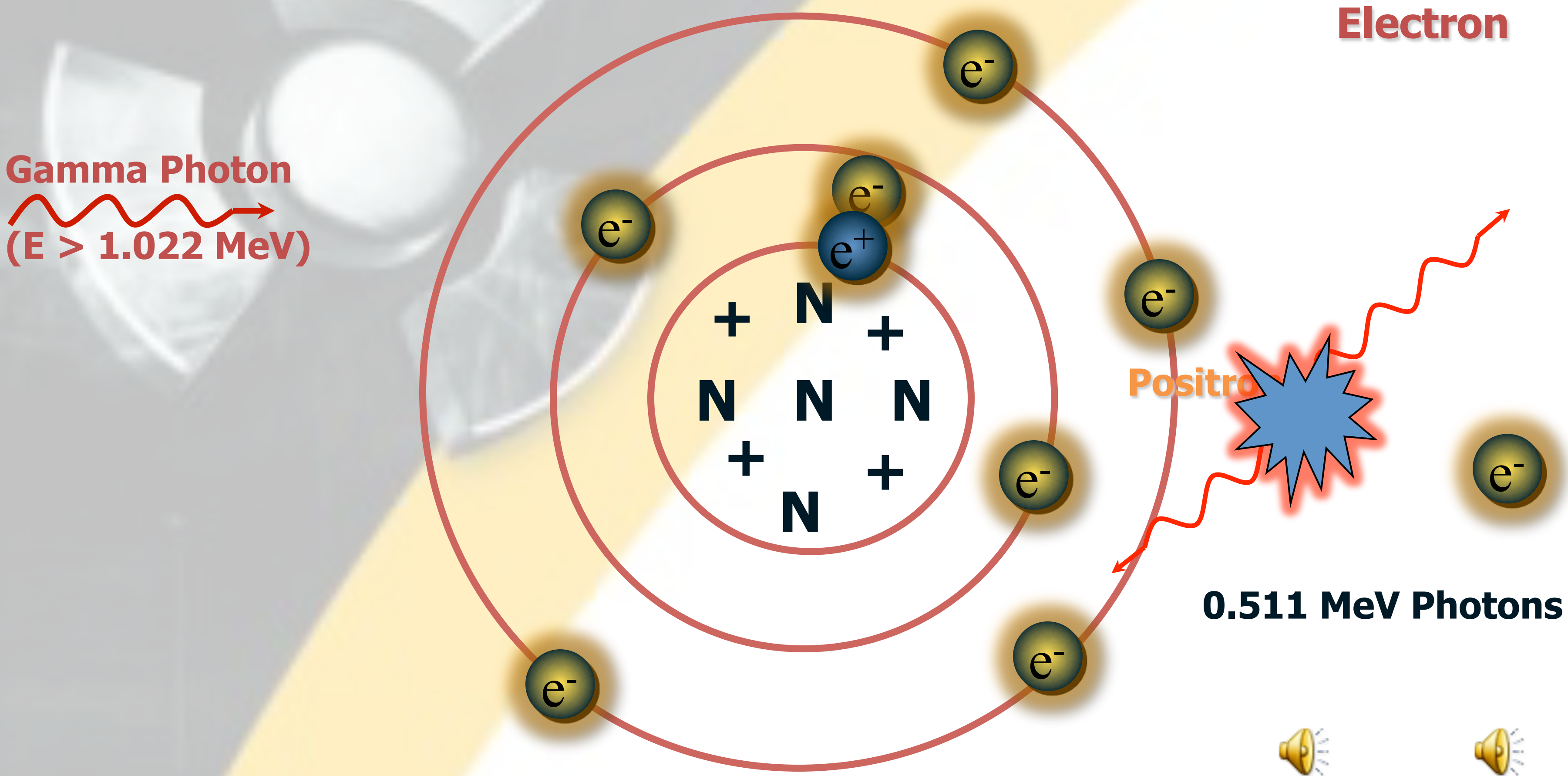
Indirectly Ionizing Radiation

- Pair Production
  - Occurs when all photon energy is converted to mass (occurs only in presence of strong electric field, which can be viewed as catalyst)
  - Strong electric fields found near nucleus and are stronger for high-Z materials
  - γ disappears in vicinity of nucleus and β^-- β^+ pair appears

Indirectly Ionizing Radiation

- Will not occur unless $\gamma \geq 1.022$ MeV
- Any energy > 1.022 MeV shared between the β^--β^+ pair as KE
- Probability < photoelectric and Compton interactions because photon must be close to the nucleus

Indirectly Ionizing Radiation



Electron

Gamma Photon

(E > 1.022 MeV)

Positro

0.511 MeV Photons

Absorption and Attenuation

- To describe energy loss and photon beam intensity penetrating absorber, need to know absorption and attenuation coefficient of absorbing medium.
- Represents probability or cross-section for interaction.
- Represented by μ

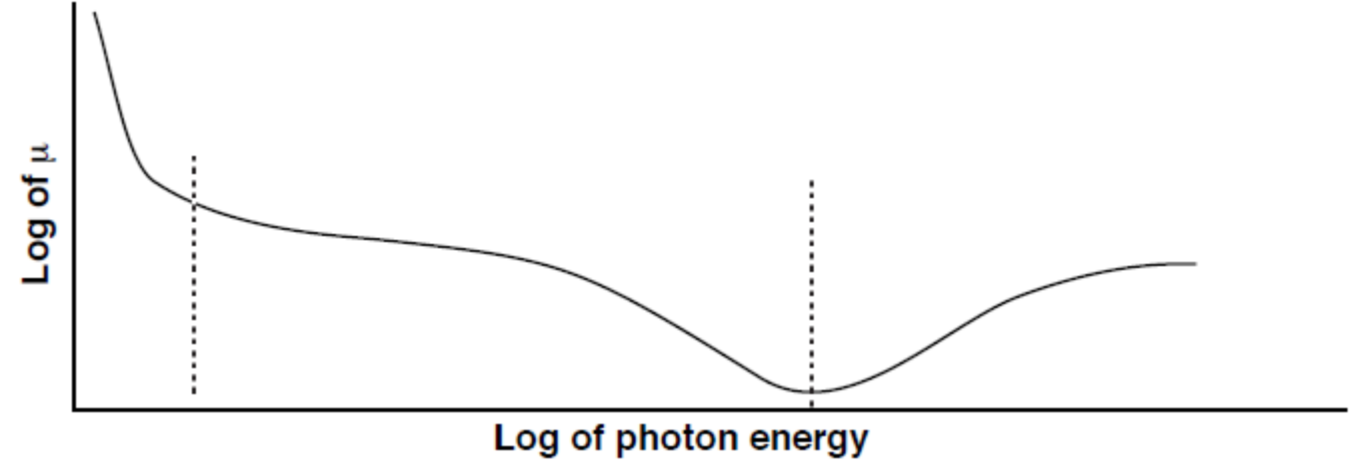
Absorption and Attenuation

$\mu = total\ linear\ attenuation\ coefficient$

$= \mu_{pe} + \mu_{cs} + \mu_{pp}$

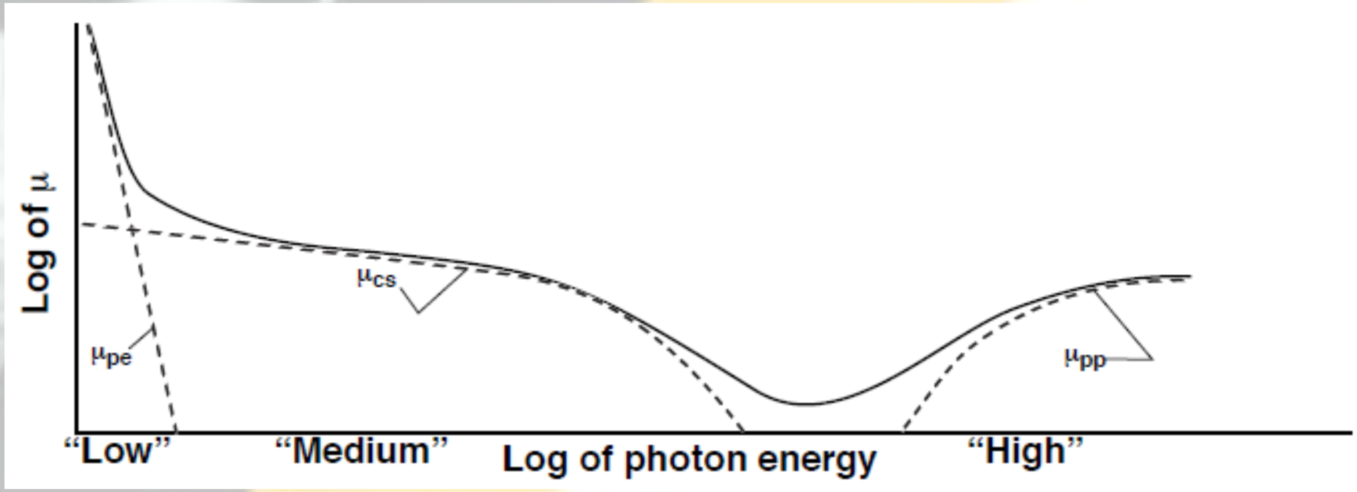
- Represents the sum of the individual probabilities
- Because each reaction is energy dependent, μ is energy dependent too

Absorption and Attenuation



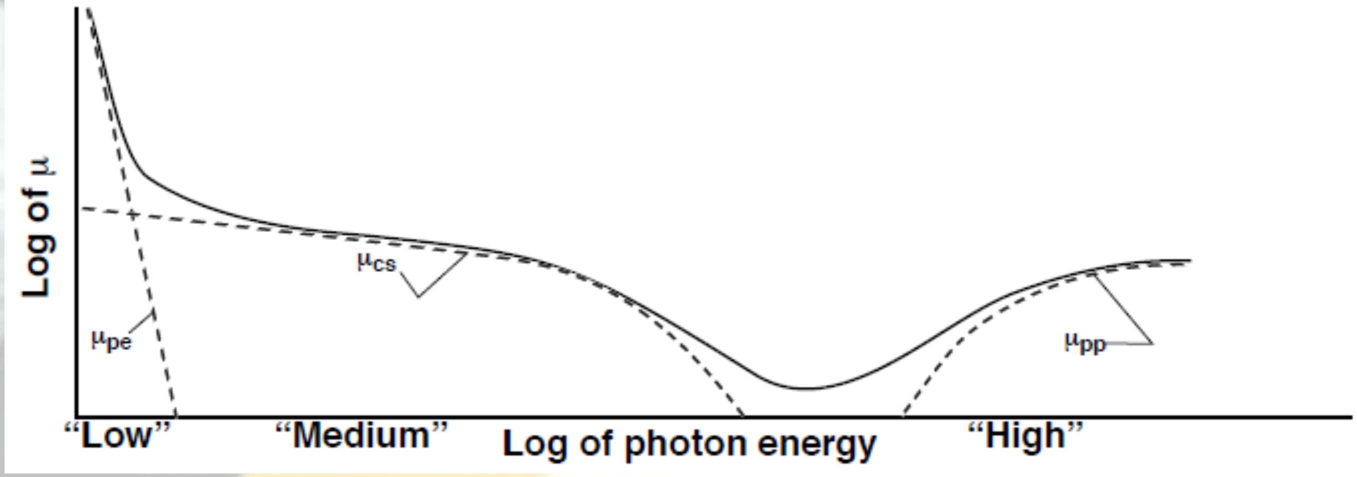
- Curve has three distinct regions
- Curve makes more sense when individual contributions are shown

Absorption and Attenuation



- Dividing line between low and medium occurs at energy where PE and CS are equally likely
  - Intersection of two dashed lines

Absorption and Attenuation



- Energy dependent
  - Tissue — 25 keV
  - Al and Bone — 50 keV
  - Pb — 700 keV

Absorption and Attenuation

- μ = fraction of photons in beam that interact per unit distance of travel
  - If expressed in per cm units (cm^{-1}), then numerically equal to fraction of interactions, by any process, in an absorber of 1 cm thickness
  - μ depends on number of electrons in path, so is proportional to density
  - While the same substance, ice, water, and steam all have different μs at any given energy

Absorption and Attenuation

- To eliminate this annoyance, μ is divided by the absorber density (ρ)
- Gives new coefficient, called the total mass attenuation coefficient (μ/ρ)
- μ/ρ represents the probability of interaction per unit density of material
- Expressed in units of cm^2/gm

Absorption and Attenuation

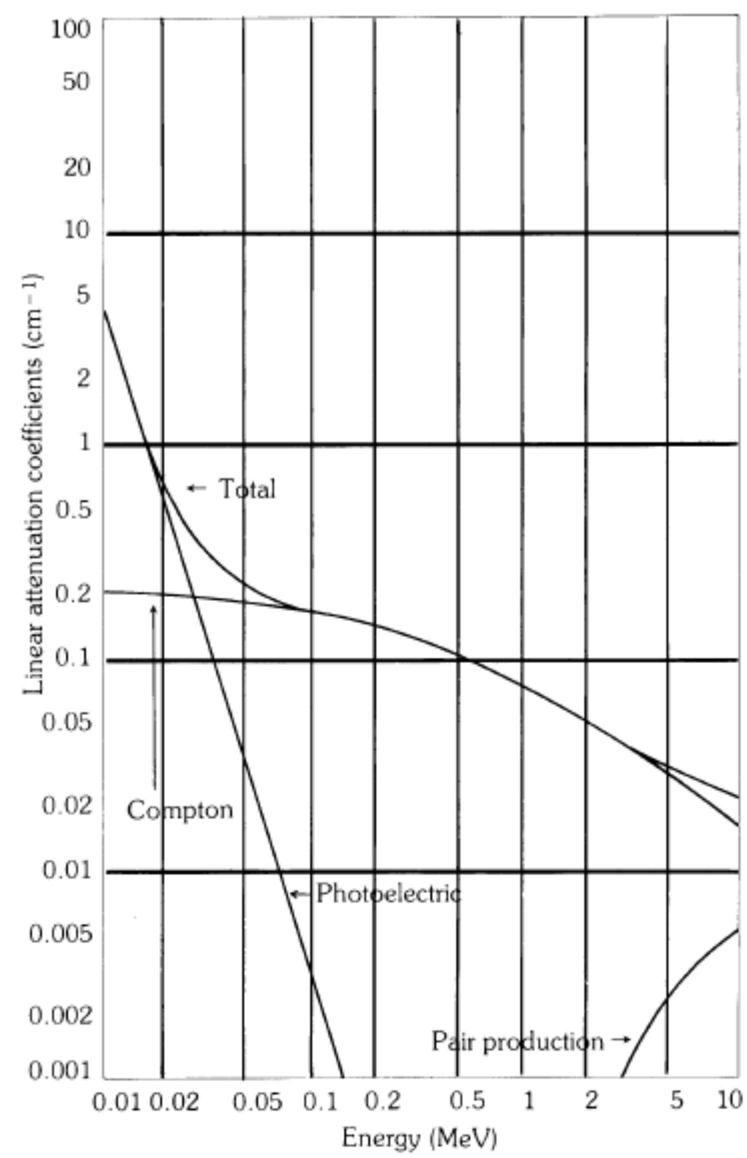
- Theory of photon interactions predicts that attenuation ↓ beam intensity exponentially with distance into the absorber
- Written in equation form as

$$I_x = I_0 e^{-\mu x}$$

- To use this equation, μ/ρ is taken from a plot of μ/ρ vs. energy, such as

Absorption and Attenuation

Linear Attenuation Coefficient of Water



Absorption and Attenuation

Example: 1 MeV γs are emitted by an underwater source. What effect would 2 cm of water have on the intensity of the beam.

$\mu = 0.07/\text{cm}$ for 1 MeV photons

$$I_x = I_0 e^{-\mu x}$$

$$I_x / I_0 = e^{-\mu x}$$

$$I_x / I_0 = e^{-\mu x}$$

$$I_x / I_0 = e^{-(0.07/cm)(2\ cm)}$$

$$I_x / I_0 = e^{-0.14}$$

$$I_x / I_0 = 0.87$$

Indirectly Ionizing Radiation

- Neutron Interactions
  - Free, unbound $_0n^1$ unstable and disintegrate by β^- emission with half-life of ≈ 10.6 minutes
  - Resultant decay product is $_1p^0$, which eventually combines with free e^- to become H atom
  - $_0n^1$ interactions energy dependent, so classified based on KE

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Indirectly Ionizing Radiation

- Most probable velocity of free ${}_0n^1$ in various substances at room temperature ≈ 2.2 kps
- Classification used for ${}_0n^1$ tissue interaction important in radiation dosimetry

Category	**Energy Range**
Thermal	**~ 0.025 eV (< 0.5 eV)**
Intermediate	**0.5 eV–10 keV**
Fast	**10 keV–20 MeV**
Relativistic	**> 20 MeV**

Indirectly Ionizing Radiation

- Classifying according to KE important from two standpoints:
  - Interaction with the nucleus differs with ${}_0n^1$ energy
  - Method of detecting and shielding against various classes are different

Indirectly Ionizing Radiation

- ${}_0n^1$ detection relatively difficult due to:
  - Lack of ionization along their paths
  - Negligible response to externally applied electric, magnetic, or gravitational fields
  - Interact primarily with atomic nuclei, which are extremely small

Indirectly Ionizing Radiation

- Probability of interaction inversely proportional to square root of energy.

$$P_i = 1/\sqrt{E}$$

Indirectly Ionizing Radiation

Example: Determine the chance of a fast neutron interacting as it slows from 1 MeV to 200 keV.

$$\left(\frac{1\ MeV}{}\right)\left(\frac{1E3\ keV}{MeV}\right) = 1E3\ keV$$

$$\frac{2E2\ keV}{1E3\ keV} = 2E-1$$

$$P_i = \frac{1}{\sqrt{E}} = \frac{1}{\sqrt{2E-1}} = \frac{1}{4.47E-1} = 2.24 = 224\%$$

Indirectly Ionizing Radiation

- Slow Neutron Interactions
    - Radiative Capture
        - Radiative capture with γ emission most common for slow $_0n^1$
        - Reaction often results in radioactive nuclei

[redacted]

- Process is called *neutron activation*

Indirectly Ionizing Radiation

- Charged Particle Emission
  - Target atom absorbs a slow $_0n^1$, which ↑ its mass and internal energy
  - Charged particle then emitted to release excess mass and energy
  - Typical examples include (n,p), (n,d), and (n,α). For example

[redacted]

Indirectly Ionizing Radiation

- Fission
  - Typically occurs following slow $_0n^1$ absorption by several of the very heavy elements
  - Nucleus splits into two smaller nuclei, called primary fission products or fission fragments
  - Fission fragments usually undergo radioactive decay to form secondary fission product nuclei
  - There are some 30 different ways fission may take place with the production of about 60 primary fission fragments

Indirectly Ionizing Radiation

- Fast Neutron Interactions
  - Scattering — the term generally used when the original free ${}_0n^1$ continues to be a free ${}_0n^1$ following the interaction
  - The dominant process for fast ${}_0n^1$
  - Probability of interaction inversely proportional to square root of energy.

Indirectly Ionizing Radiation

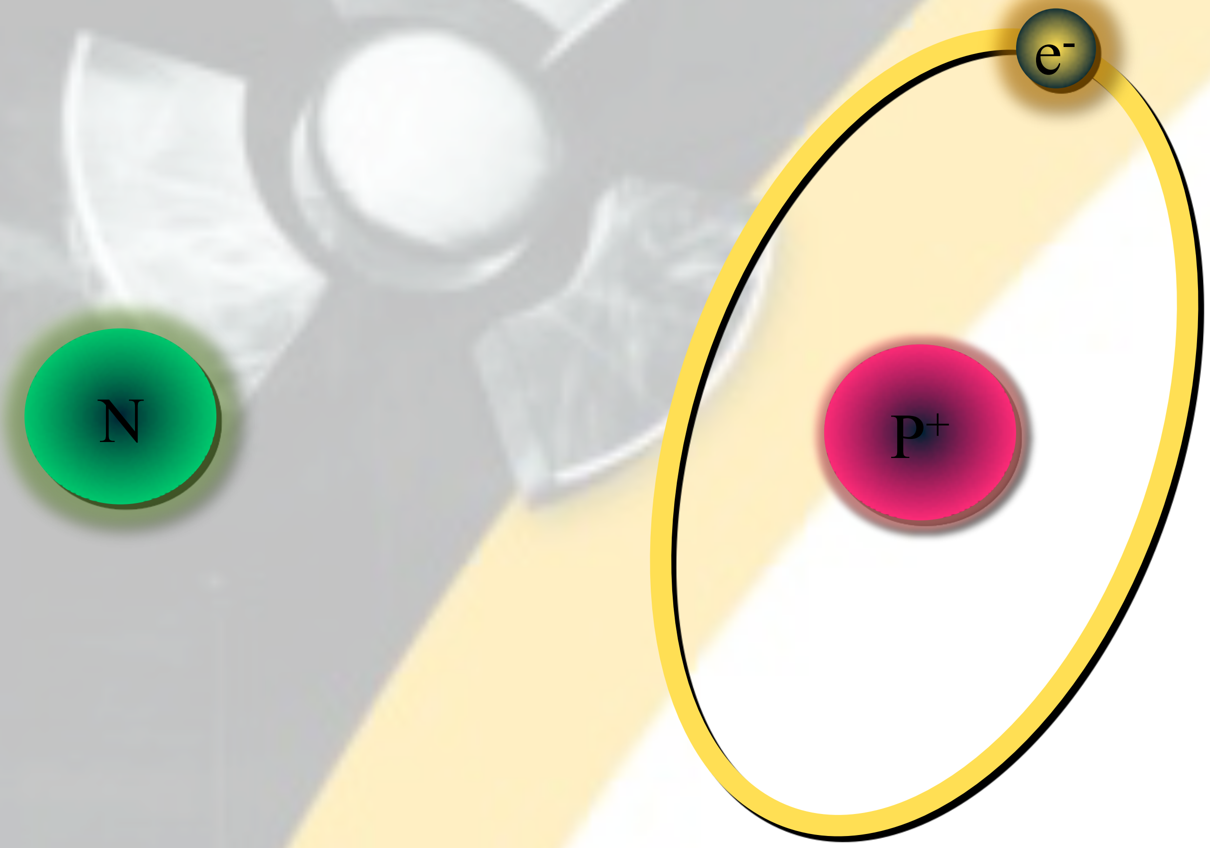
Fast Neutron Interactions

- Scattering — the term generally used when the original free ${}_0n^1$ continues to be a free ${}_0n^1$ following the interaction
- The dominant process for fast ${}_0n^1$
- Probability of interaction inversely proportional to square root of energy.

Indirectly Ionizing Radiation

- Elastic Scattering
  - Typically occurs when neutron strikes nucleus of approx. same mass
  - Depending on size of nucleus, neutron can xfer much of its KE to that nucleus, which recoils off with energy lost by ${}_0n^1$
  - During elastic scattering, no γ emitted by nucleus
  - Recoil nucleus can be knocked away from its electrons and, being (+) charged, can cause ionization and excitation

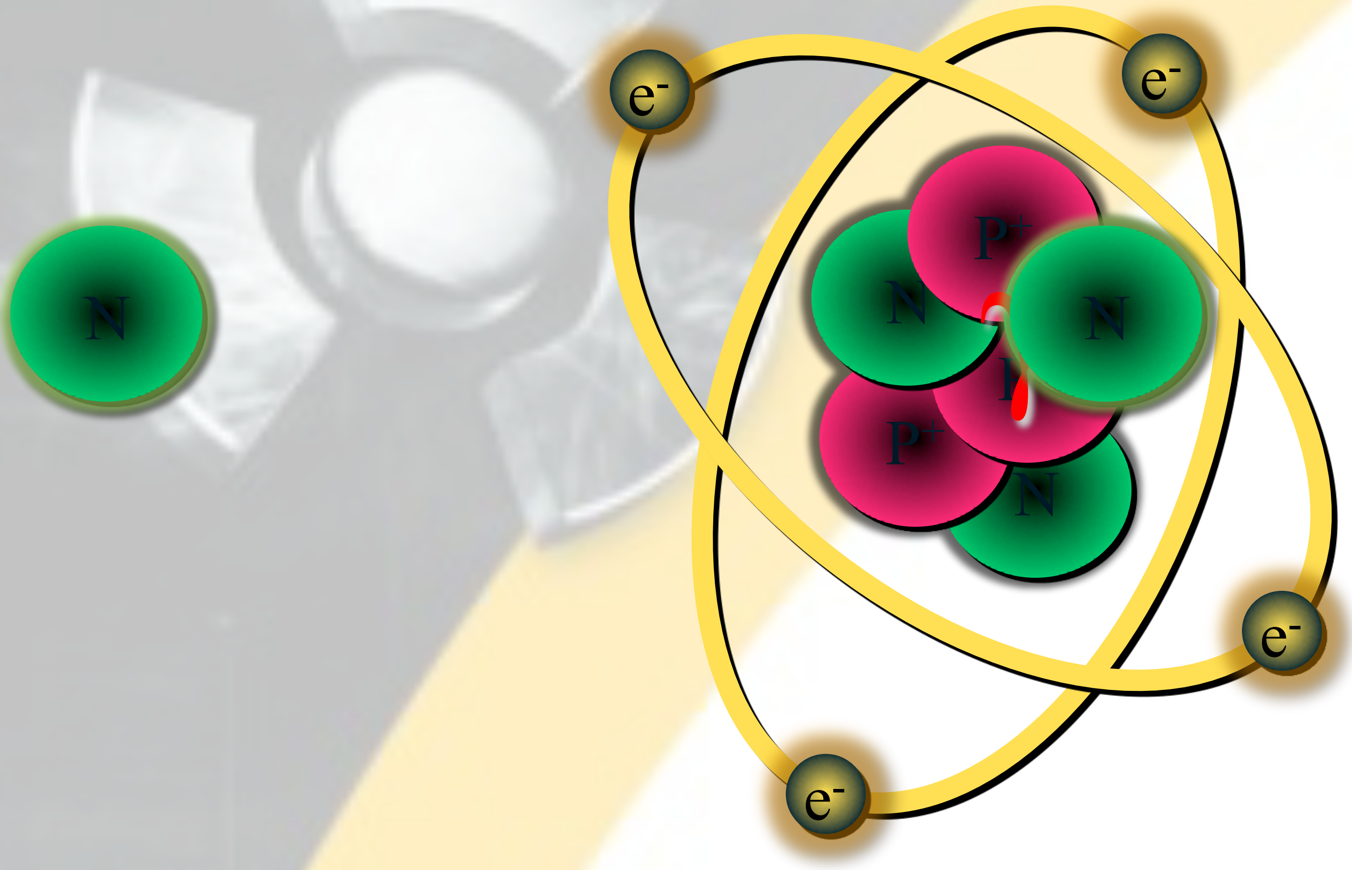
Indirectly Ionizing Radiation



Indirectly Ionizing Radiation

- Inelastic Scattering
  - Occurs when $_0n^1$ strikes large nucleus
    - $_0n^1$ penetrates nucleus for short period of time
    - Xfers energy to nucleon in nucleus
    - Exits with small decrease in energy
  - Nucleus left in excited state, emitting γ radiation, which can cause ionization and/or excitation

Indirectly Ionizing Radiation



Indirectly Ionizing Radiation

- Reactions in Biological Systems
  - Fast $_0n^1$ lose energy in soft tissue largely by repeated scattering interactions with H nuclei
  - Slow $_0n^1$ captured in soft tissue and release energy in one of two principal mechanisms:

(2.2 MeV) and

(0.66 MeV)

Indirectly Ionizing Radiation

- γ and ${}_{1}p^{0}$ energies may be absorbed in tissue and cause damage that can result in harmful effects

Radiation Shielding

- Radiation Shielding
  - Principles applicable to all radiation types, regardless of energy
  - Application varies quantitatively, depending on source type, intensity and energy
    - Directly ionizing particles —reduces personnel exposure to 0
    - Indirectly ionizing — exposure can be minimized consistent with ALARA philosophy

Radiation Shielding

- Shielding Gammas and X-Rays
  - Photons removed from incoming beam on basis of probability of interaction such as photoelectric effect, Compton scattering, or pair production
  - Process called attenuation
  - Intensity is ↓ exponentially with shielding thickness and only approaches 0 for large thicknesses, but never actually = 0

Radiation Shielding

- Important shielding considerations
  - Shielding present does not imply adequate protection
  - Wall or partition not necessarily "safe" shield for individuals on the other side
  - In effect, radiation can be deflected around corners (i.e., can be scattered)

Radiation Shielding

- Shielding Betas
  - Relatively little shielding required to completely absorb βs
  - Absorbing large β intensities results in Bremsstrahlung, particularly in high-Z materials
  - To effectively shield β, use low-Z material (such as plastic) and then to shield Bremsstrahlung X-rays, use suitable material, such as Pb on the downstream side of the plastic

Radiation Shielding

- Shielding Neutrons
  - Most materials will not absorb fast $_0n^1$ —merely scatter them through the material
  - To efficiently shield fast $_0n^1$, must first be slowed down and then exposed to an absorber
    - Greatest energy xfer takes place in collisions between particles of equal mass, hydrogenous materials most effective for thermalizing
    - Water, paraffin, and concrete all rich in hydrogen and excellent neutron shields

Radiation Shielding

- Shielding Alphas
  - Because of relatively large mass and charge, have minimal penetrating power and are easily shielded by thin materials
  - Primarily an external contamination problem — not an external dose problem