Chapter 4

Interactions of Radiation with Matter

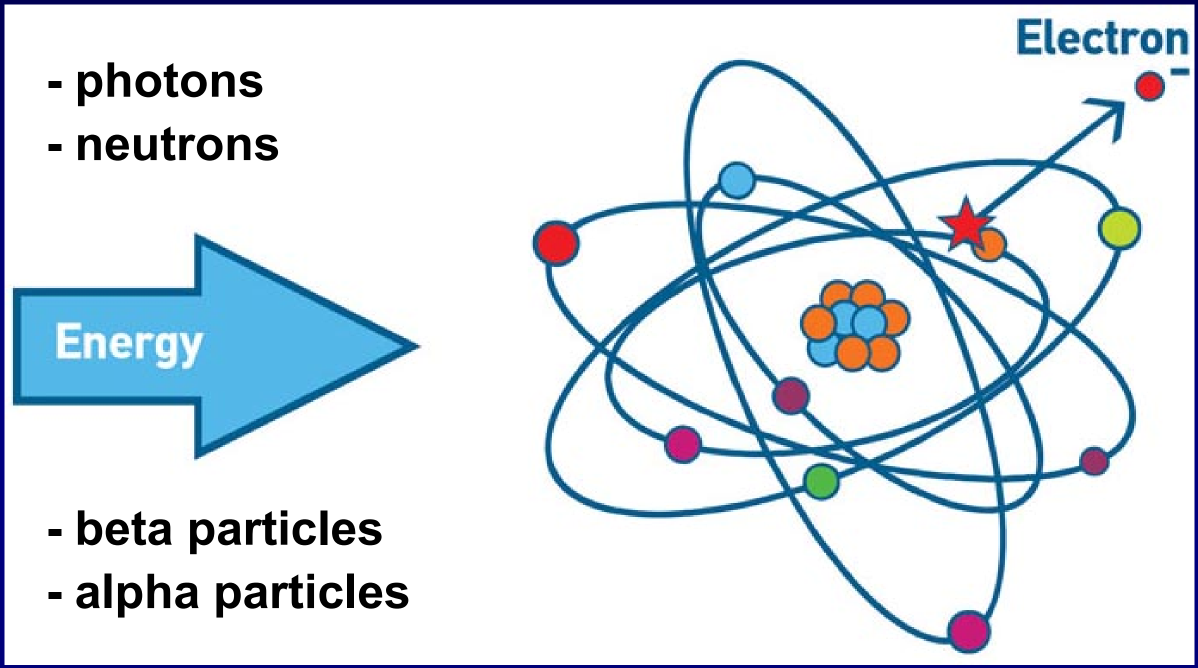
Objectives

- Discuss charged particle interactions in matter
- Discuss bremsstrahlung radiation and how it is produced
- Define the terms monoenergetic and polyenergetic
- State three primary photon interactions with matter

Objectives

- Discuss the concept of range of a charged particle
- Define the term linear energy transfer (LET)
- Explain the concept of density thickness
- Discuss neutron interactions with matter
- Define the terms cross section and barn

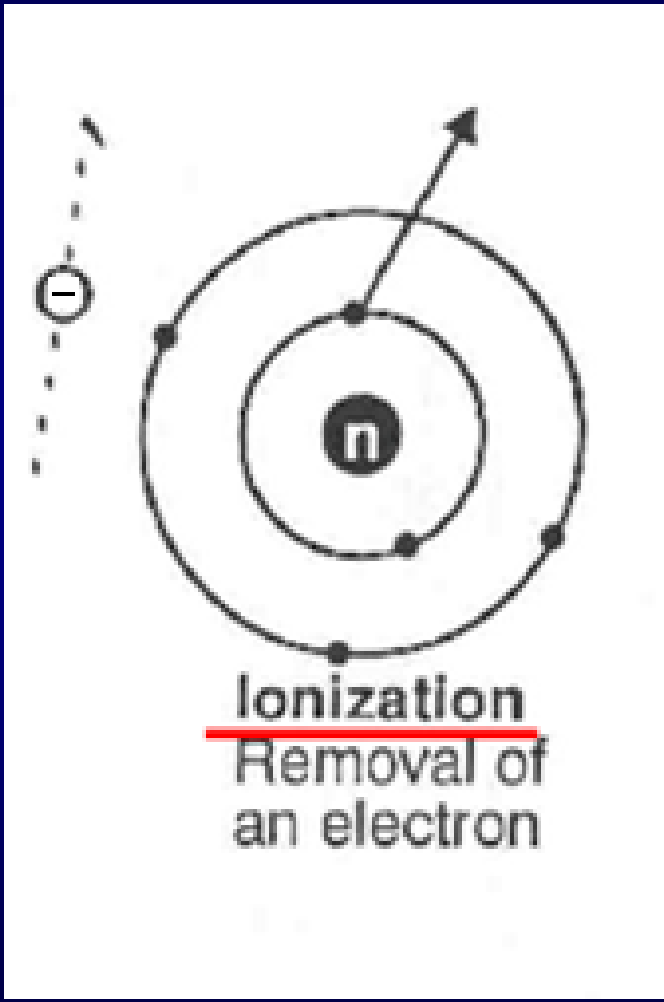
Ionizing Radiation & Radioactivity



- Ionizing radiation, often referred to simply as "radiation," removes orbital electrons from atoms or molecules with which it interacts.
- Atoms that emit ionizing radiation are called radioactive.

Charged Particle Interactions

Charged Particle Interactions



1. Ionization:

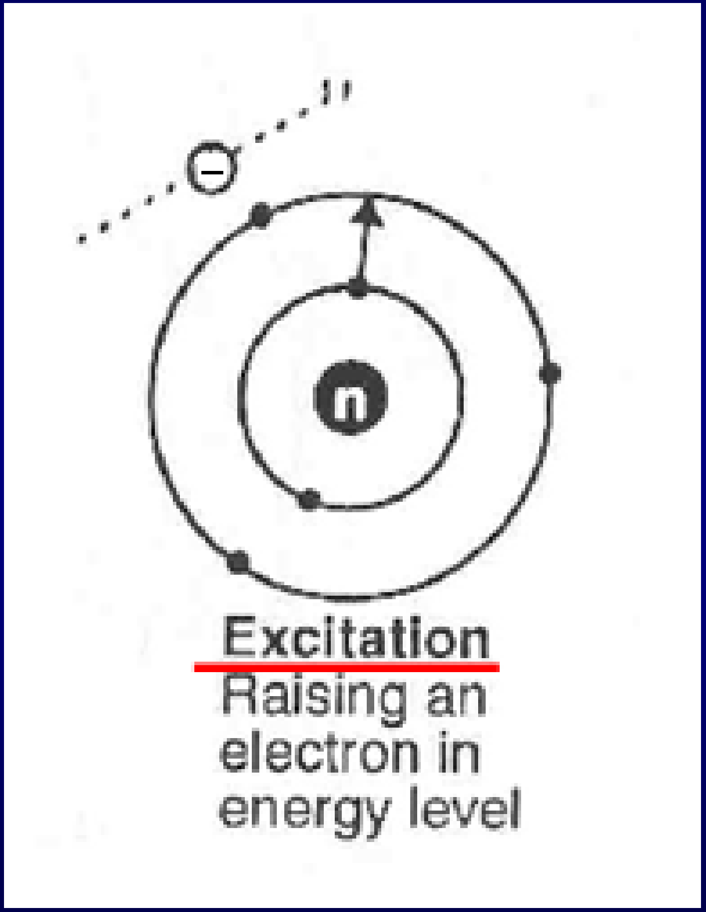
An electron is ejected from an atom by the passage of a charged particle

Charged Particle Interactions

2. Excitation:

An electron is raised to a higher orbit by the passage of a charged particle, leaving the atom in an excited state.

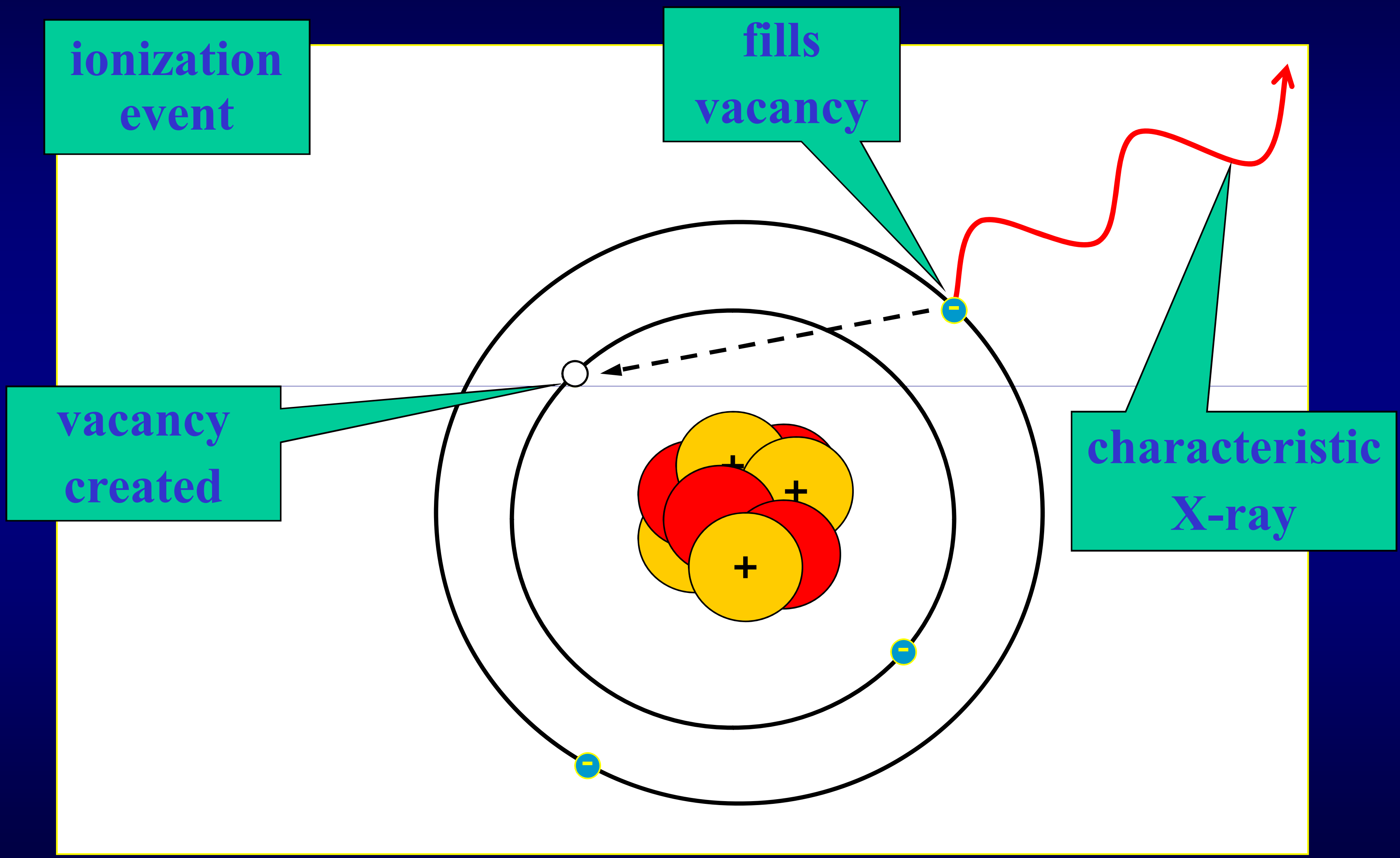
Both ionization and excitation can be accompanied by emission of characteristic X-rays.



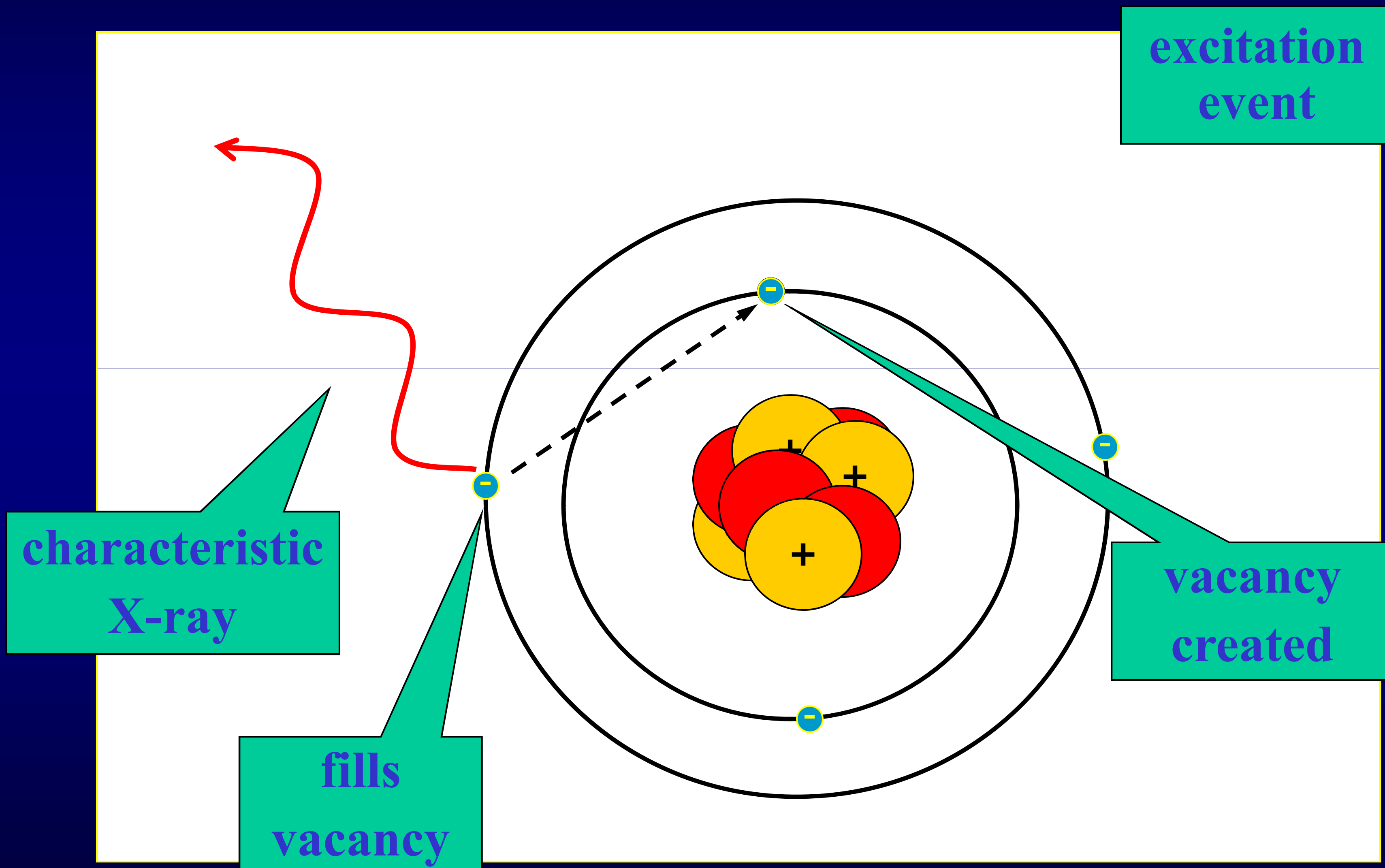
Charged Particle Interactions

The average amount of energy expended per ionization is called the "w" value (average of about 34 eV for betas and 35 eV for alphas).

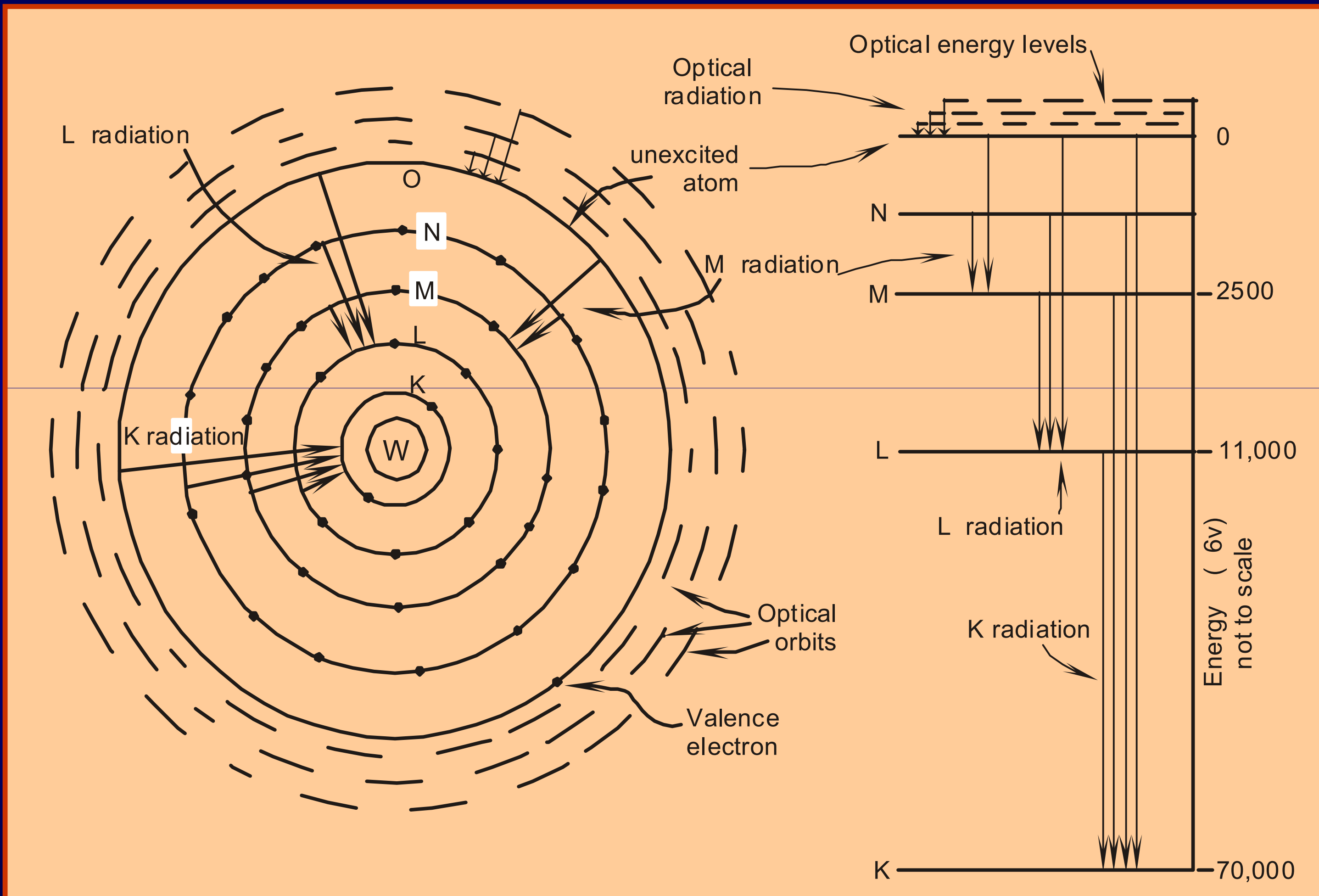
Characteristic X-rays (Ionization)

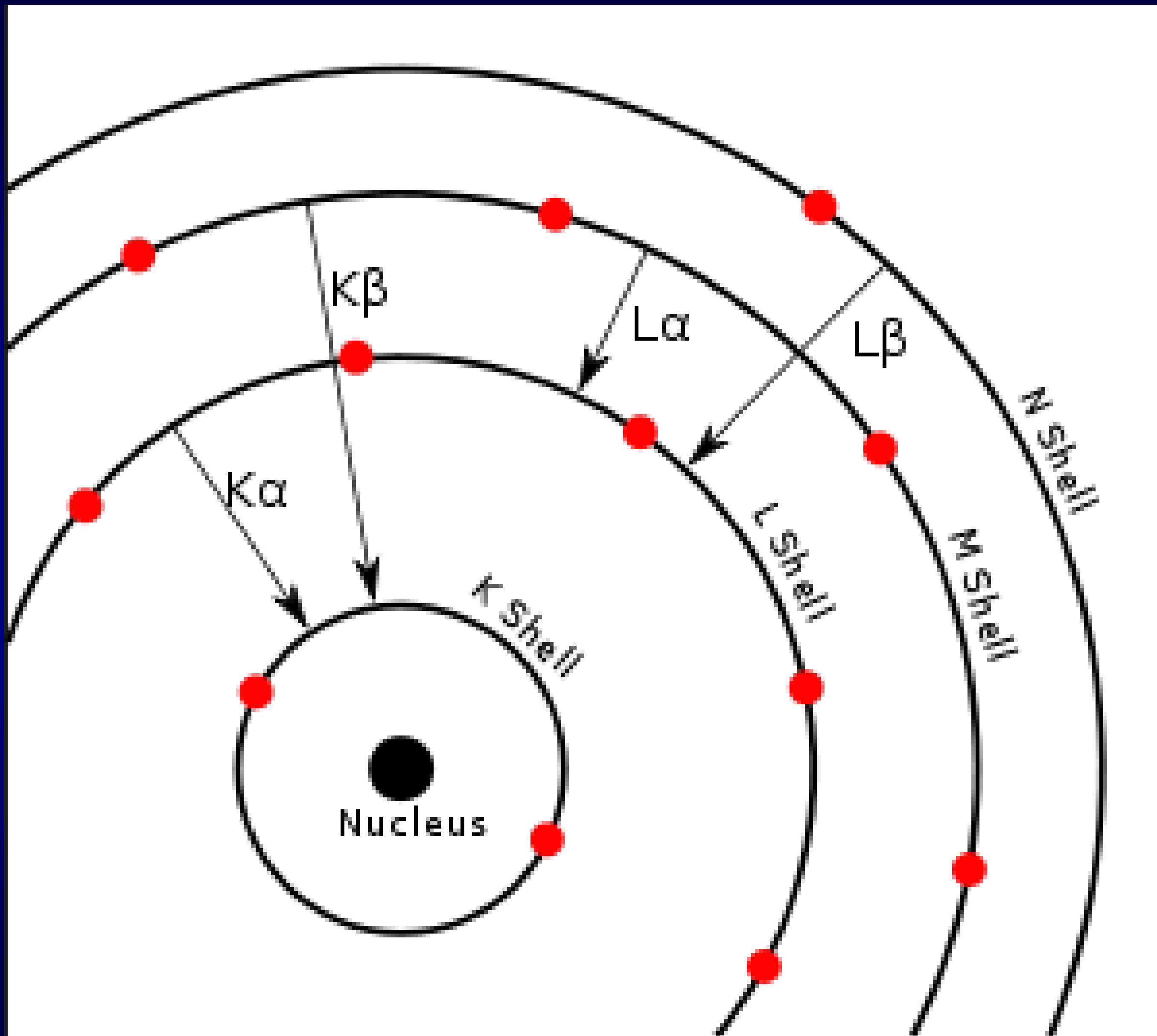


Characteristic X-rays (Excitation)



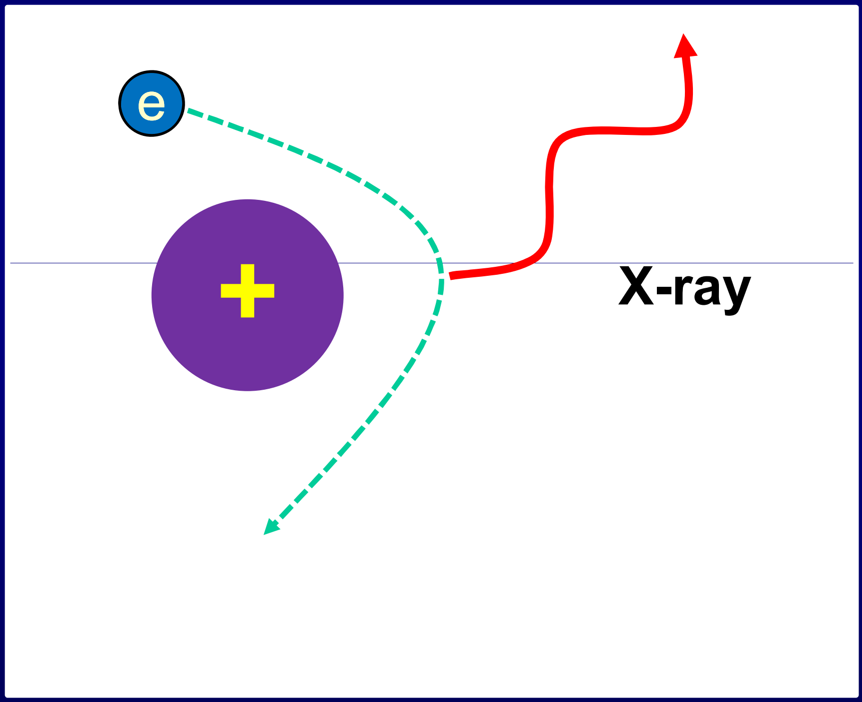
Electron Energy Levels




Kβ
Lα
Lβ
Kα
N Shell
M Shell
L Shell
K Shell
Nucleus

Charged Particle Interactions

- **Bremsstrahlung: "Braking Radiation"**
- **When a charged particle is deflected from its path by a nucleus, an X-ray is emitted**
- **Maximum energy of X-ray is equal to the kinetic energy of the electron**



Beta Shielding

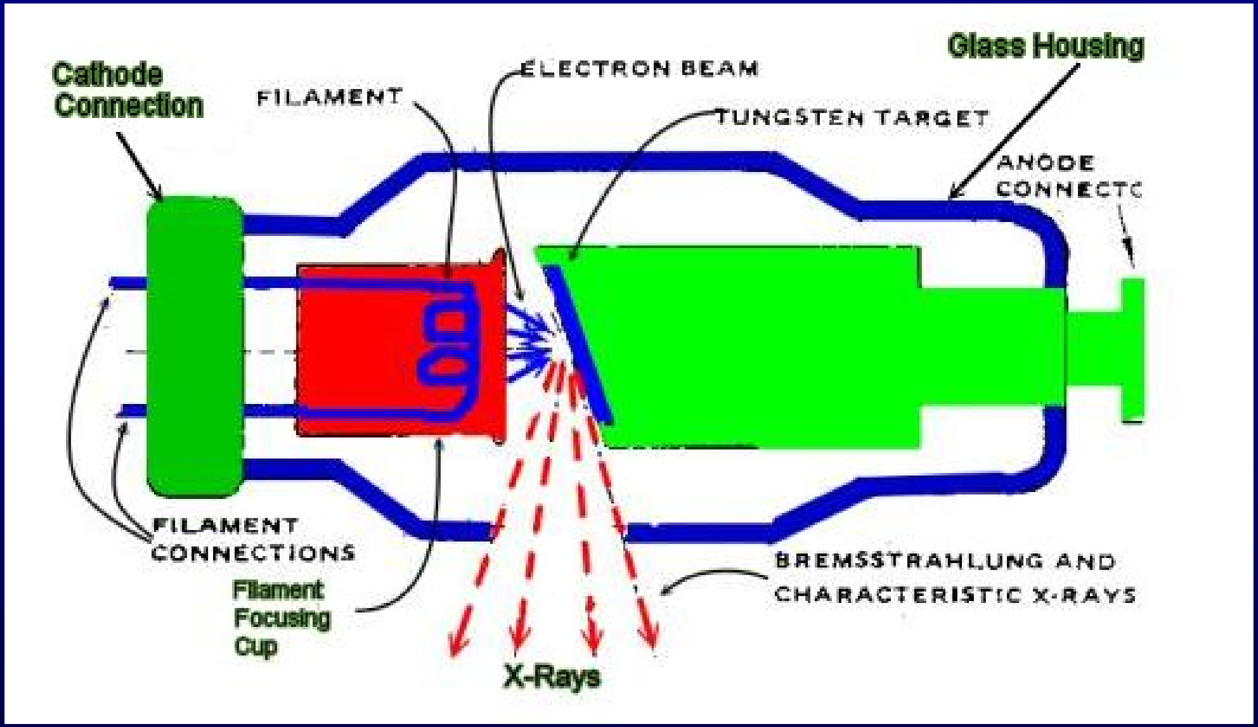
- Shielding energetic beta-emitting isotopes requires consideration of bremsstrahlung production.
- Bremsstrahlung production also depends on the atomic number (Z) of the shielding material. The fraction of beta energy that is converted to photons can be approximated by the following relationship:

$$f = 3.5 \times 10^{-4}\ Z\ E_{max}$$

- Use low-Z materials, e.g., plastic such as Lucite, to shield high-energy beta-emitting isotopes to completely stop the betas and minimize production of bremsstrahlung

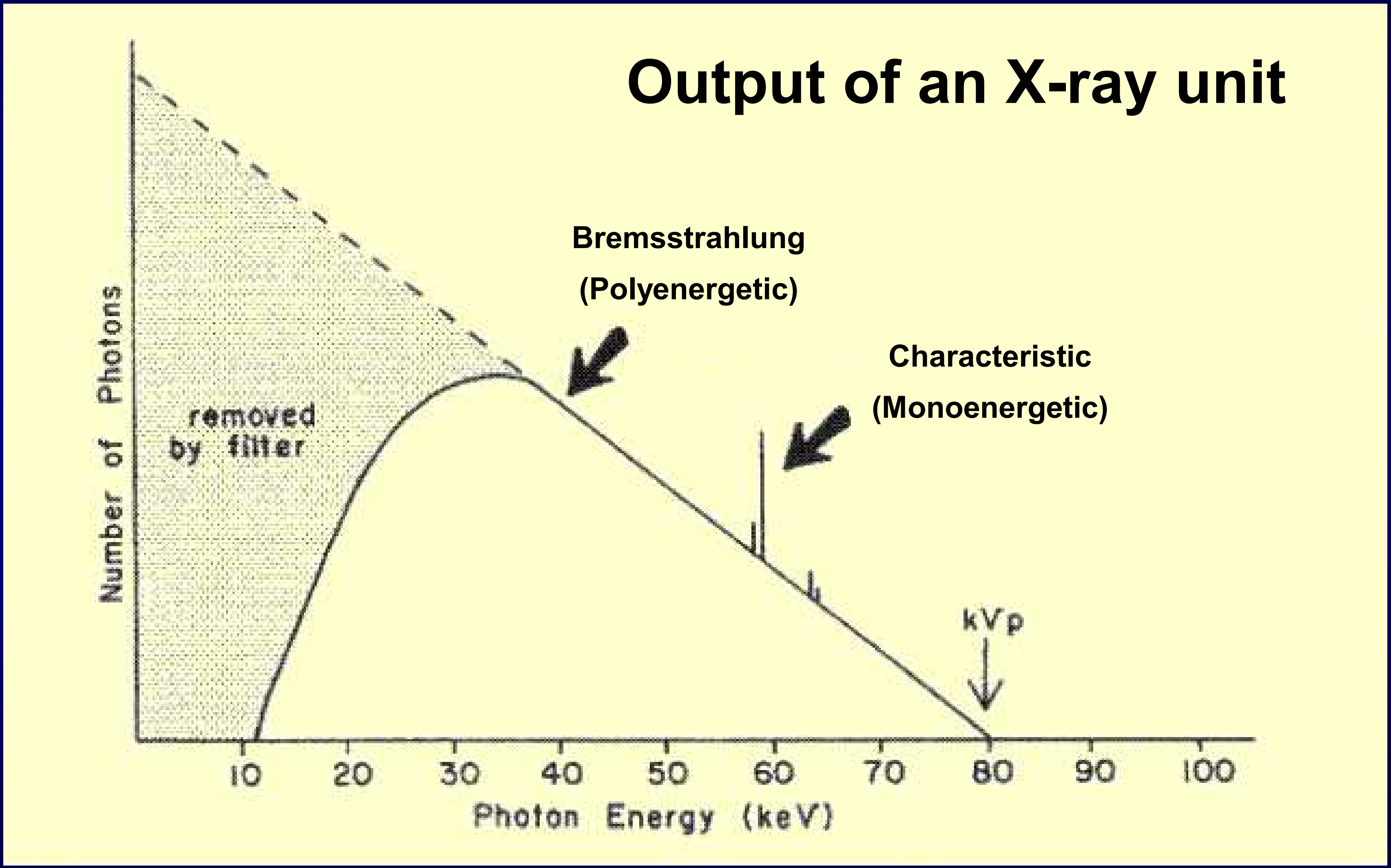
X-ray Production

In an X-ray tube, both bremsstrahlung and characteristic X-rays are produced when accelerated electrons impact a tungsten (or other high Z) target.

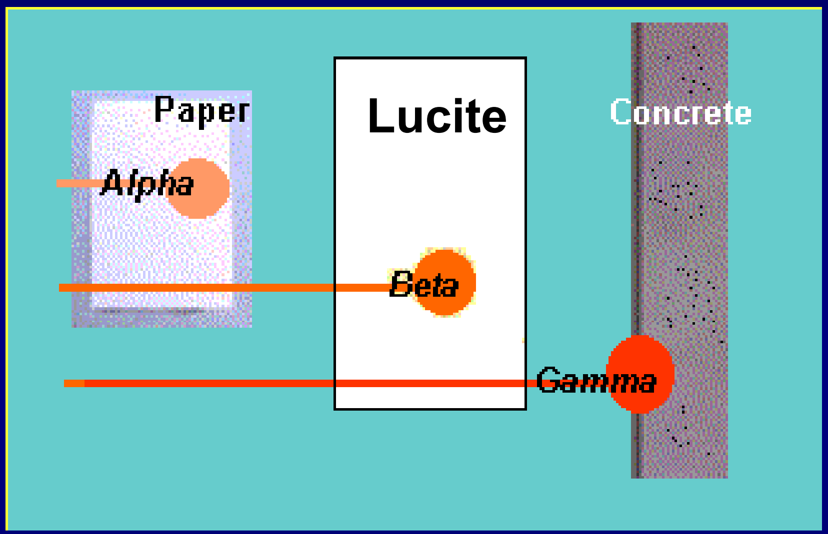


- **X-rays do not make things radioactive.**
- **Once the unit is turned off, it no longer produces radiation.**

Monoenergetic vs. Polyenergetic



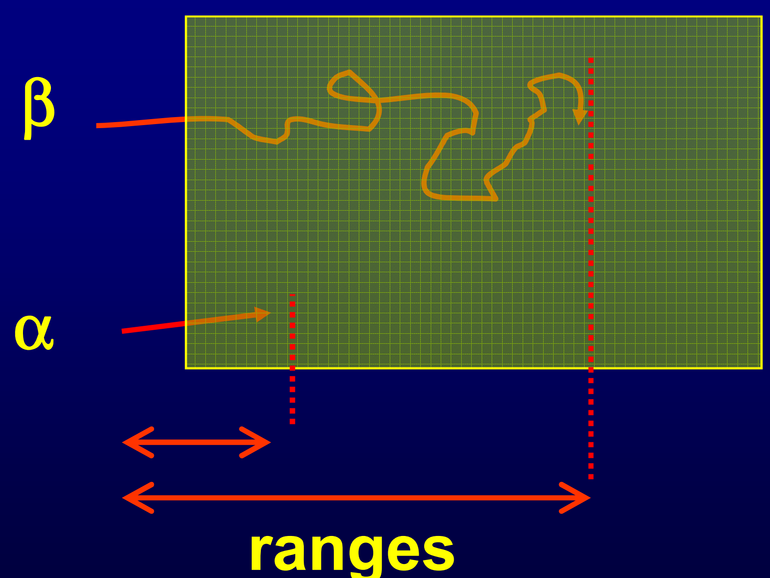
Penetrating Distances/Shielding

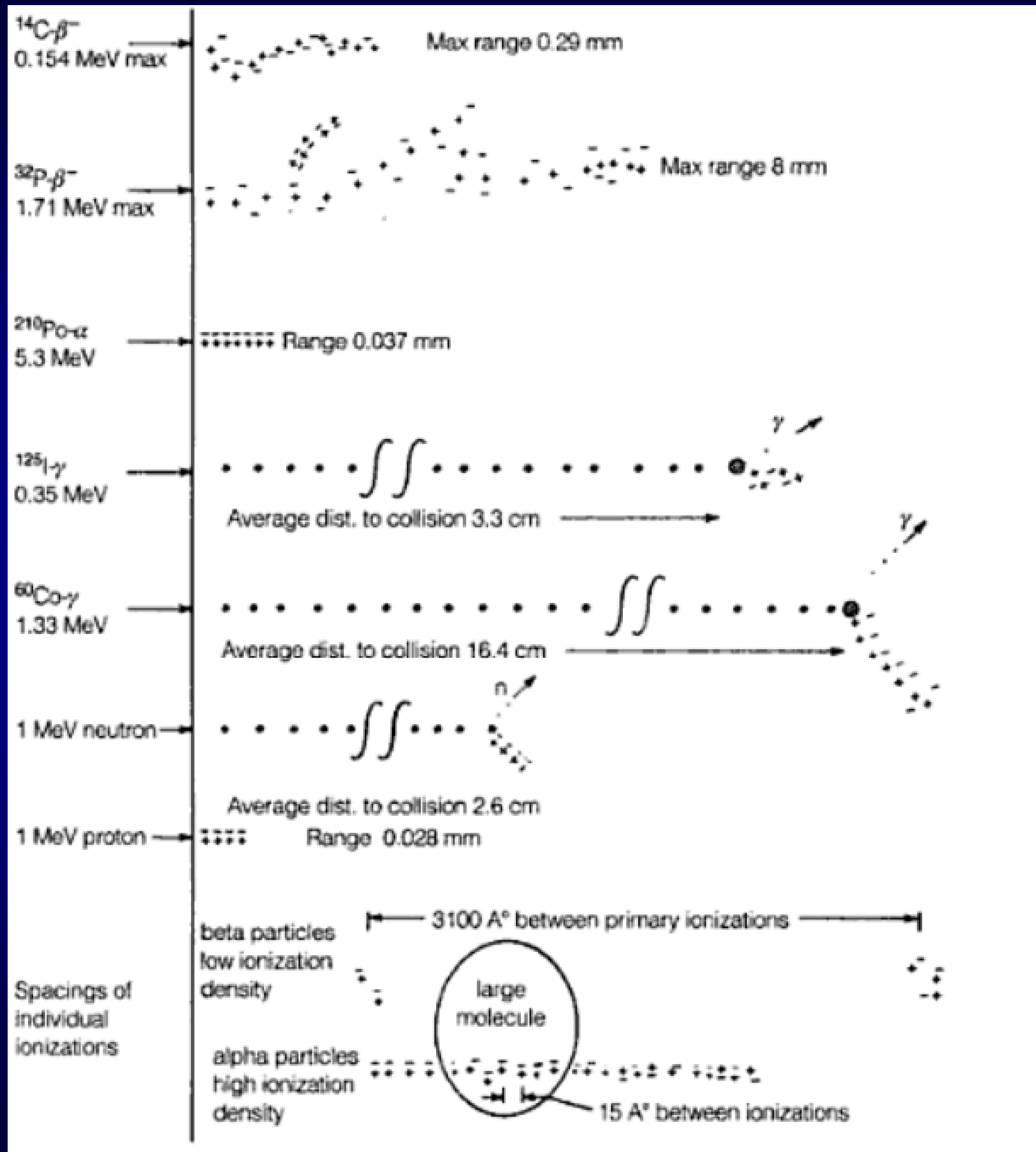


- Alpha particles are easily shielded by the dead layer of skin on your body (internal hazard only)
- Beta particles are typically shielded using plastic or low-Z material (e.g., plastic safety glasses or Lucite shields) because they can penetrate tissue (0.5 cm per MeV)
- Gamma rays and X-rays are more penetrating and require high density or very thick shielding (e.g., depleted uranium, lead, concrete, or water)

Range of A Charged Particle

- Range is the average distance a charged particle travels in a medium before coming to rest.
- The path of a heavy charged particle is almost a straight line, but the path of electrons is not straight.





^{14}C-β^-
0.154 MeV max
Max range 0.29 mm
^{32}P-β^-
1.71 MeV max
Max range 8 mm
^{210}Po-α
5.3 MeV
Range 0.037 mm
^{125}I-γ
0.35 MeV
γ
Average dist. to collision 3.3 cm
^{60}Co-γ
1.33 MeV
γ
Average dist. to collision 16.4 cm
1 MeV neutron
n
Average dist. to collision 2.6 cm
1 MeV proton
Range 0.028 mm
Spacings of individual ionizations
3100 A° between primary ionizations
beta particles low ionization density
large molecule
alpha particles high ionization density
15 A° between ionizations

Density Thickness

- The range of a charged particle depends on the density of electrons within the absorber material.
- Electron density is directly proportional to the product of the absorber density (g/cm^3) and its linear thickness. We call this product the "density-thickness" of a material.
- Units are typically in g/cm^2

$$\text{Density Thickness} = \frac{g}{cm^3} \times cm = \frac{g}{cm^2}$$

Density Thickness

NRC annual occupational dose limits are defined at depths in tissue (and density thicknesses).

- **Whole body – tissue depth of 1 cm (1,000 mg/cm^2)**
- **Lens of the eye – tissue depth of 0.3 cm (300 mg/cm^2)**
- **Skin – tissue depth of 0.007 cm (7 mg/cm^2)**

Charged Particle Energy Transfer

- **Specific ionization** – average number of ion pairs created per unit distance a charged particle travels

  Examples:

Alpha particles in air	20,000 – 60,000 ion pairs/cm
Beta particles in air	100 ion pairs/cm

- **Linear Energy Transfer (LET)** – rate of energy transfer per unit distance along a charged particle's path (MeV/cm)

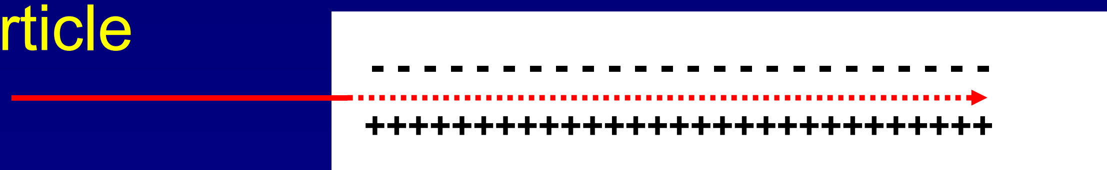
  Examples:

5.3 MeV alpha	47 μm in tissue	474 MeV/cm
1 Mev beta	4300 μm in tissue	1.87 MeV/cm

Specific Ionization and LET

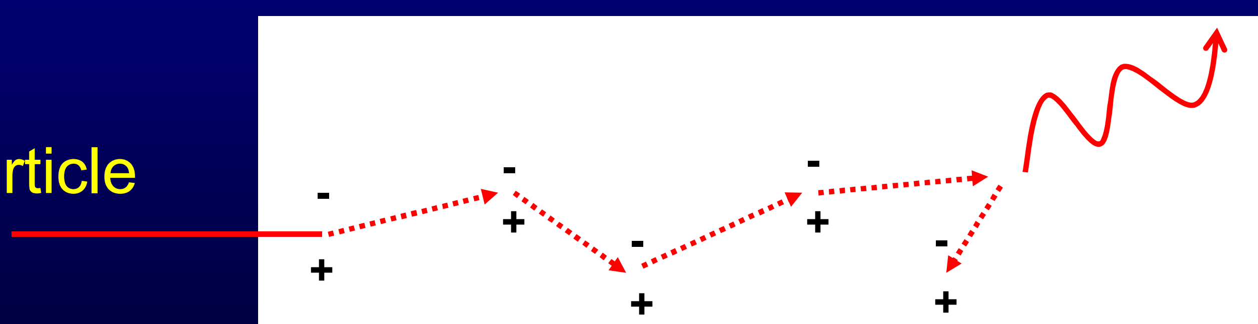
- **Alpha particles have high specific ionization and high LET due to their mass and double positive charge**

α particle



- **Beta particles have low specific ionization and low LET due to their small mass and single negative charge**

β particle



LETs in Water

Table 2.6 Transfer of energy per centimeter in water by energetic charged particles (linear energy transfer).

Particle	Mass[a]	Charge	Energy (MeV)	Speed (cm/sec)	LET (MeV/cm)	Range (microns)
Electron	1	−1	0.01	0.59×10^{10}	23.2	2.5
			0.1	1.64×10^{10}	4.20	140
			1.0	2.82×10^{10}	1.87	4,300
			10.0	3.00×10^{10}	2.00[b]	48,800
			100.0	3.00×10^{10}	2.20[c]	325,000
Proton	1835	+1	1.0	1.4×10^{9}	268	23
			10.0	4.4×10^{9}	47	1,180
			100.0	1.3×10^{10}	7.4	75,700
Alpha	7340	+2	1.0	0.7×10^{9}	1,410[d]	7.2
			5.3[e]	1.6×10^{9}	474	47

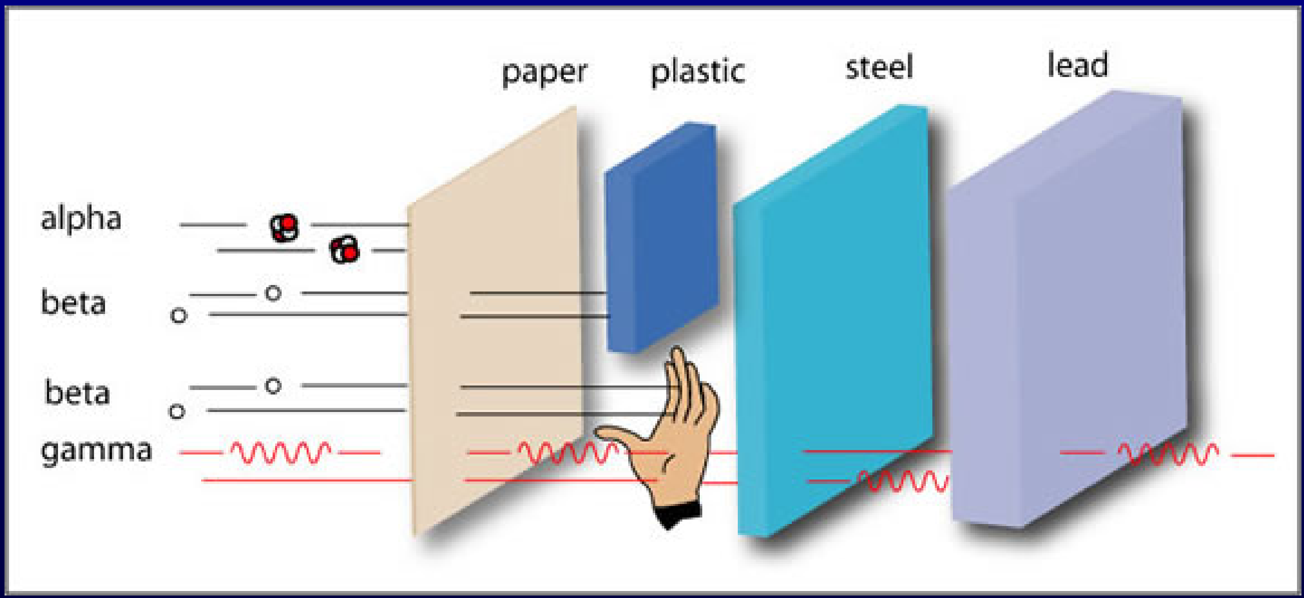
Sources: ICRU, 1970, Report 16 (protons and electrons); Morgan and Turner, 1967, p. 373 (alpha particles); Etherington, 1958, pp. 7–34 (ranges for alpha particles, tissue values used).

Photon Interactions

Photons vs. Charged Particles

- Since photons have no charge, they interact with matter differently than charged particles

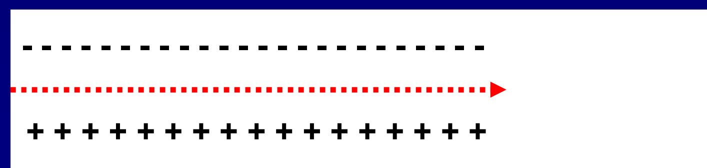
- For photons, we discuss the probability of interaction per unit distance travelled



Photons vs. Charged Particles

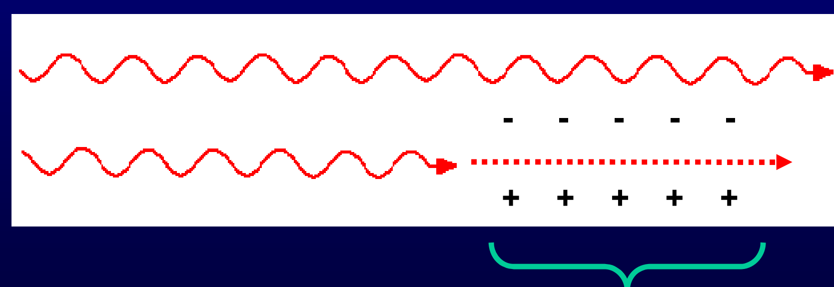
- **Remember, as charged particles penetrate matter, they lose energy continuously along their travel path through the creation of ion pairs**

α or β particle



- **Contrast this with photon interactions, where gamma rays can interact or emerge from a shield with the same energy**

photons



ion pairs caused by secondary electron

Primary Photon Interactions

Photons interact with matter by three primary means:

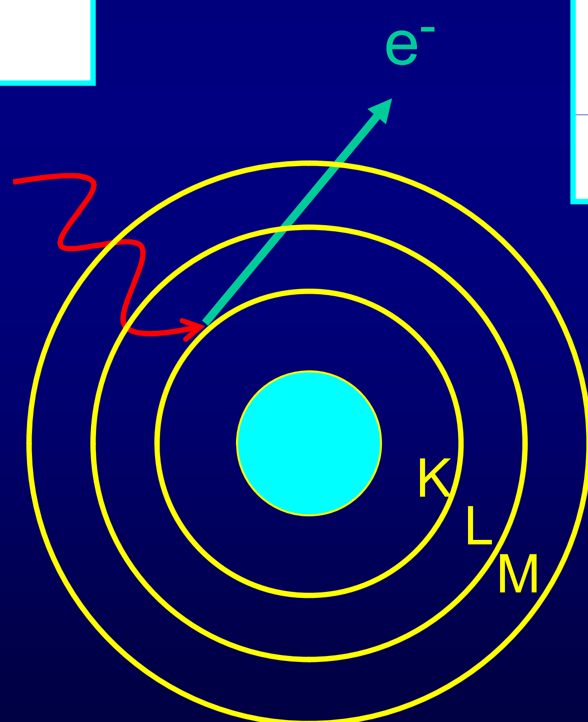
- **Photoelectric Effect**
- **Compton Scattering**
- **Pair Production**

Photoelectric Effect

The photoelectric effect is the predominant interaction mechanism for low energy photons.

1. Incoming photon interacts with an atom as a whole.

2. Photon disappears after giving up all its energy, and an electron (usually from the K-shell) is ejected from the atom.



PEE ≈ Z^4

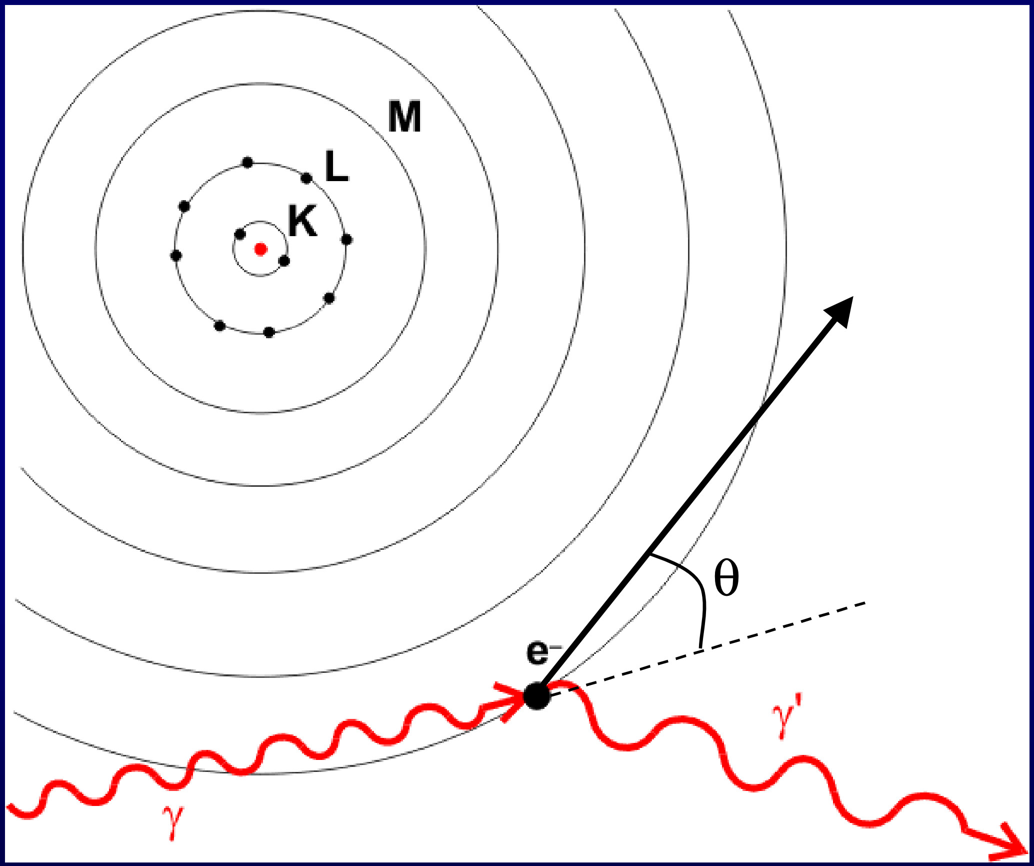
Compton Scattering

Compton scattering is dominant for intermediate photon energies.

Photon (γ) interacts with outer orbital electron.

Photon is scattered after transferring energy to the electron which is ejected from the atom.

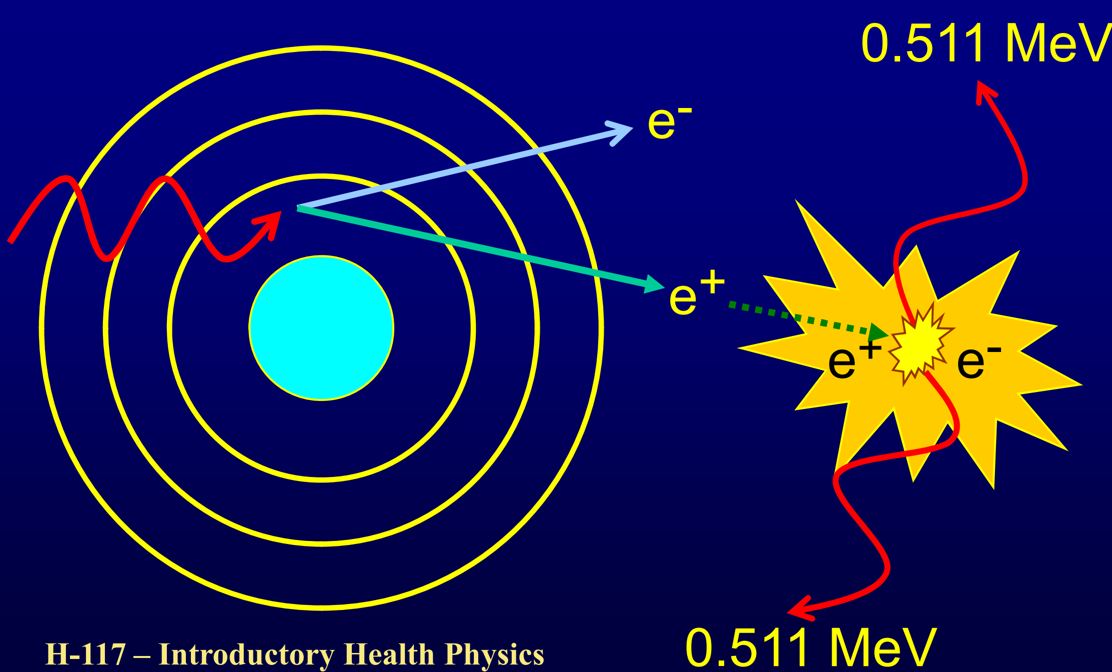
The scattered photon (γ') leaves at a different angle with less energy.



Pair Production

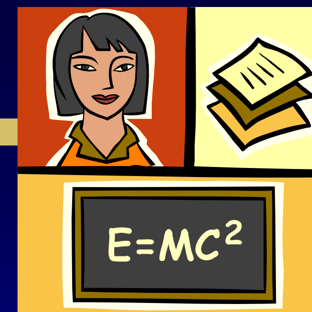
Must occur in the close vicinity of a nucleus. Incoming photon absorbed, and an electron-positron pair appears

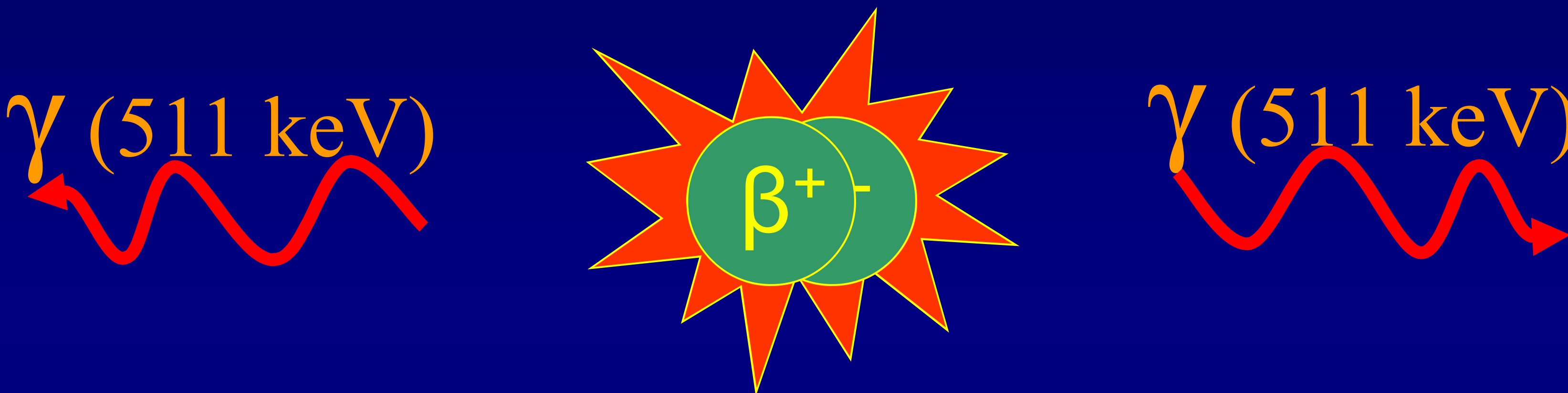
Requires minimum incoming photon energy of 1.022 MeV (0.511 MeV for the electron + 0.511 MeV for the positron)



Positron ultimately combines with a stationary electron. They annihilate to produce two photons, each having 0.511 MeV energy and travelling in opposite directions

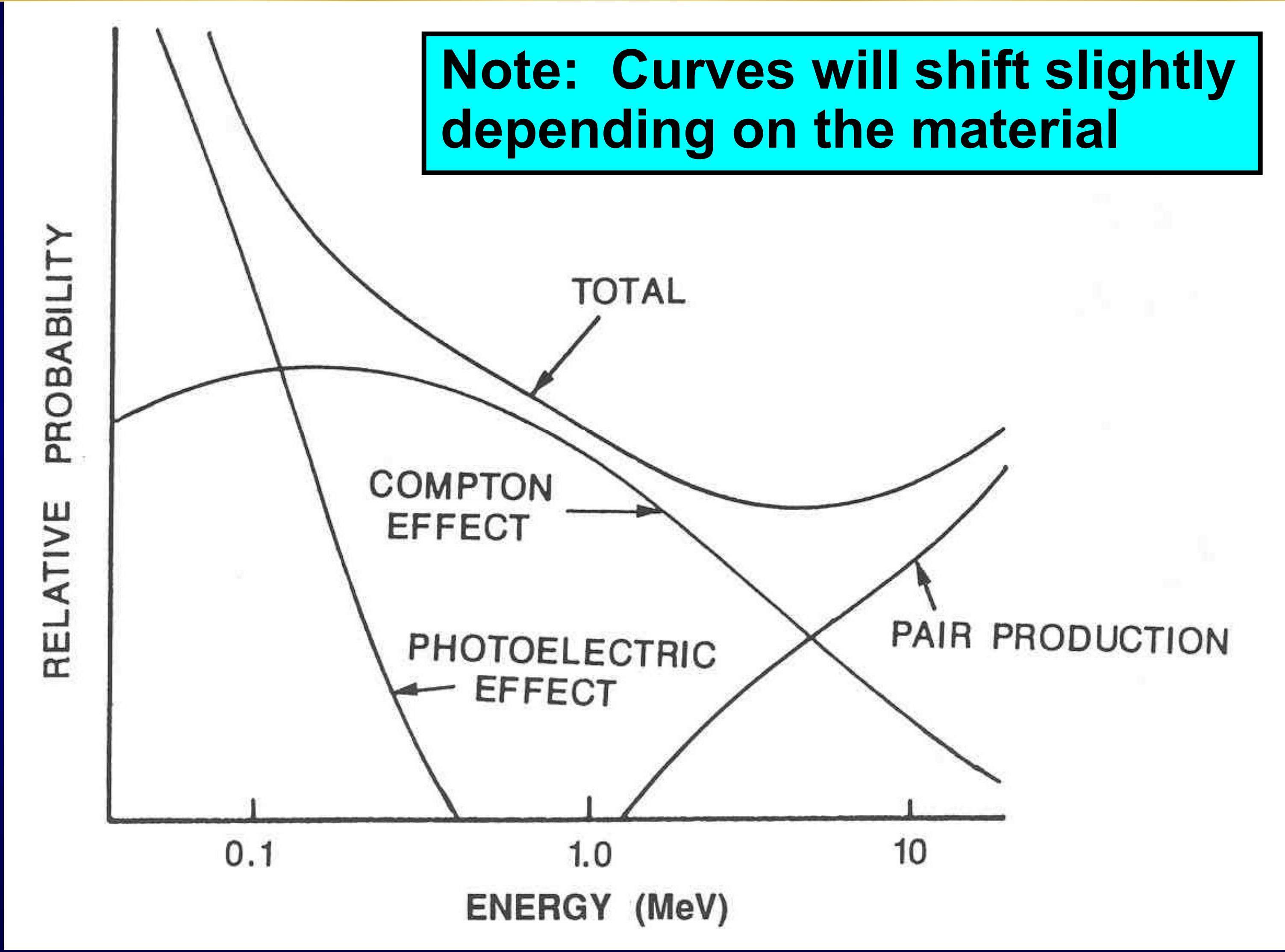
Positron Annihilation



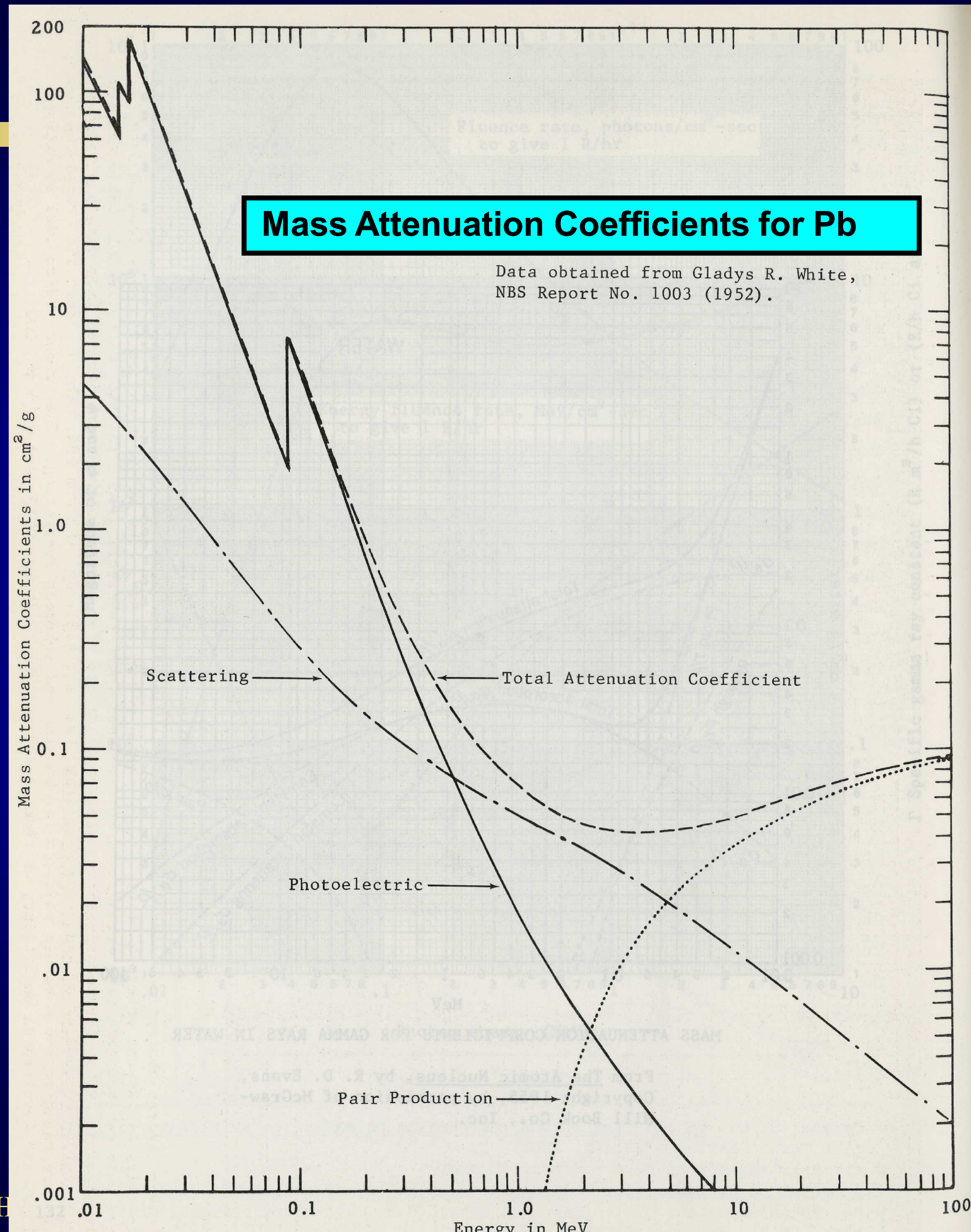


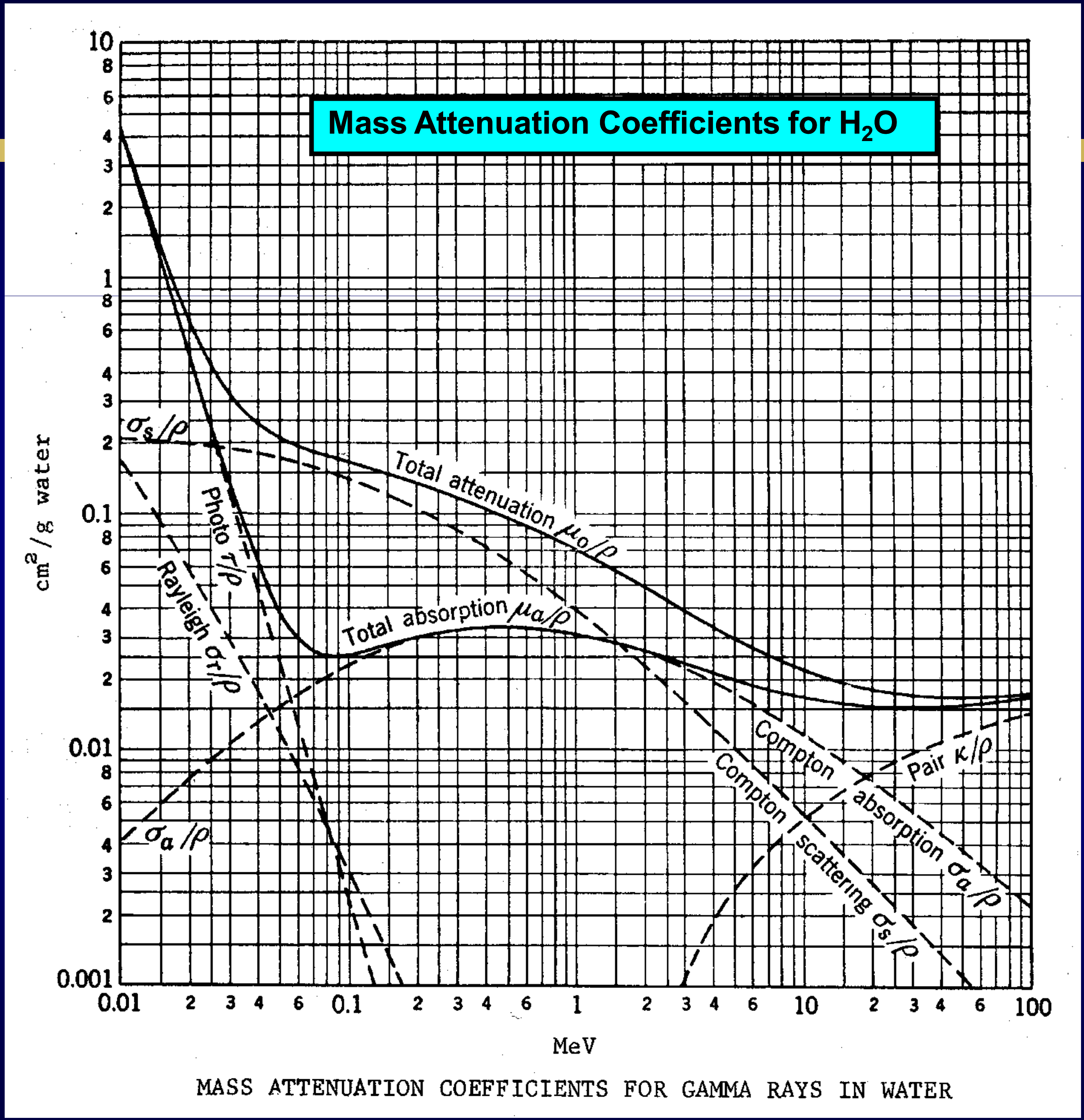
Matter is transformed to pure energy (the rest mass of both the electron and positron are 511 keV, hence the 511 keV gamma rays)

Photon Interactions with Matter



Mass Attenuation Coefficients for Pb





Mass Attenuation Coefficients for H_2O
Total attenuation μ_o/ρ
Total absorption μ_a/ρ
Photo τ/ρ
Rayleigh σ_r/ρ
σ_s/ρ
σ_a/ρ
Compton absorption σ_a/ρ
Compton scattering σ_s/ρ
Pair κ/ρ
cm^2/g water
MeV
MASS ATTENUATION COEFFICIENTS FOR GAMMA RAYS IN WATER

Linear Attenuation Coefficient

- The linear attenuation coefficient (μ) is the total probability that a photon interacts per unit distant traveled in a material (cm^{-1}).
- It is the sum of the probabilities of the different photon interactions occurring:

$$\mu = \mu_{PE} + \mu_{CS} + \mu_{PP}$$

- The contribution of these different interactions depends on the photon's energy and the absorber material.

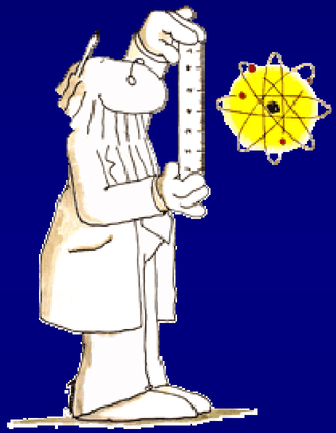
Neutron Interactions

Neutrons

- Neutrons are particulate radiation with no charge.
- Biological effects are strongly energy dependent.
- Neutrons are born fast and lose energy primarily through elastic and inelastic scattering interactions until they reach thermal energies (~0.025 eV).
- Primary neutron absorption interactions are fission and activation.

Neutron Cross Sections

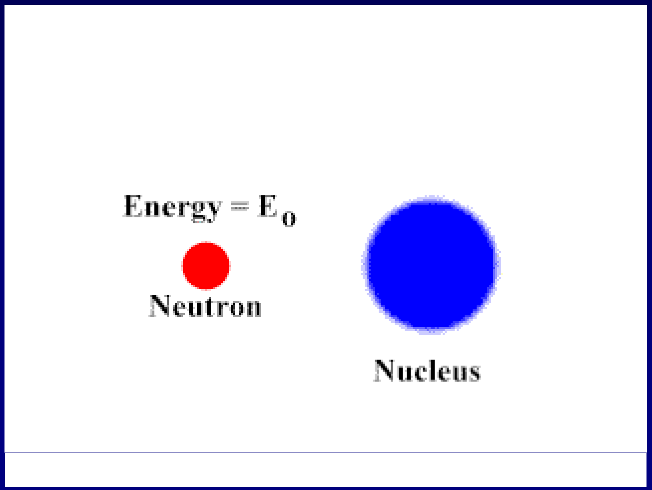
- The probability that neutrons will interact with a nucleus of a given element is called the cross section.
- Unit is the barn, where 1 barn = 10^{-24} cm^2

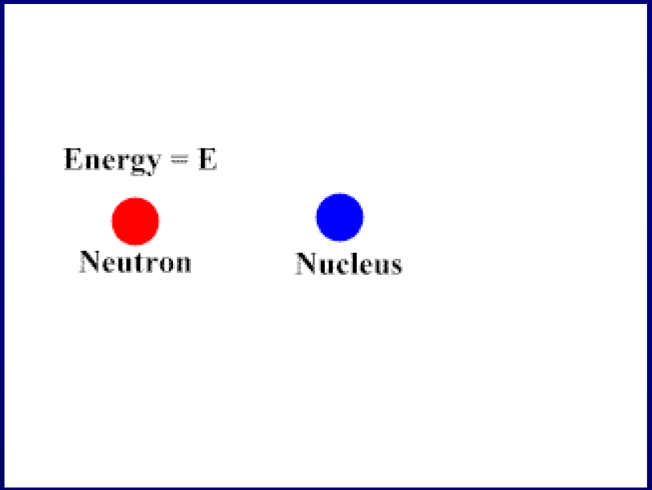


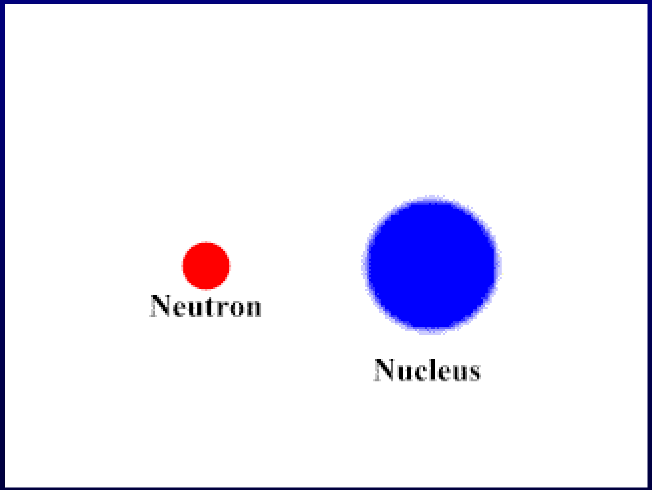
The "size" of the barn depends on the energy (speed) of the neutron. To a fast neutron, the barn appears to be small. To a slower neutron, the barn seems much larger, so an interaction is more likely to occur.

Neutron Interactions

- Water in a reactor slows, or thermalizes, neutrons primarily through elastic collisions with hydrogen nuclei
  - billiard ball-type of interaction
  - up to 100% of the neutron's energy lost in a single collision, although average is ½
  - For U-235, the probability of neutron absorption (cross section) increases as neutrons are slowed
- Inelastic scattering becomes important to slow fast neutrons in high Z materials and >1 MeV neutrons

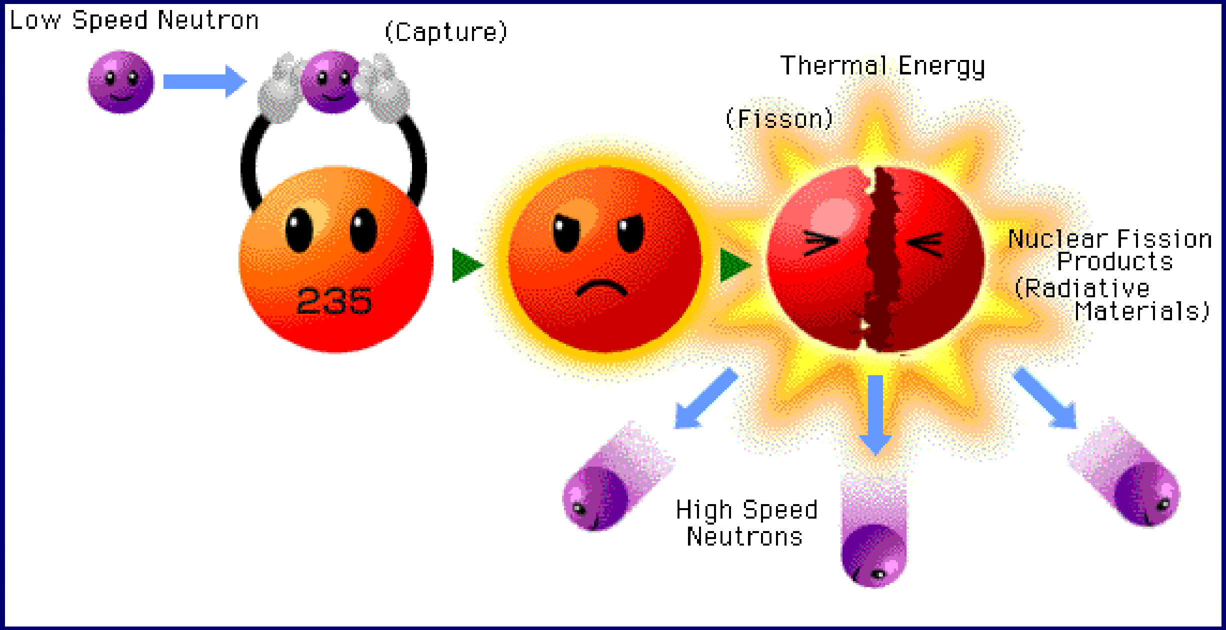

Energy = E_0
Neutron
Nucleus


Energy = E
Neutron
Nucleus


Neutron
Nucleus

Fission

Fission occurs when a neutron interacts with a fissile nucleus (like U-235), causing the nucleus to split into radioactive fission fragments.



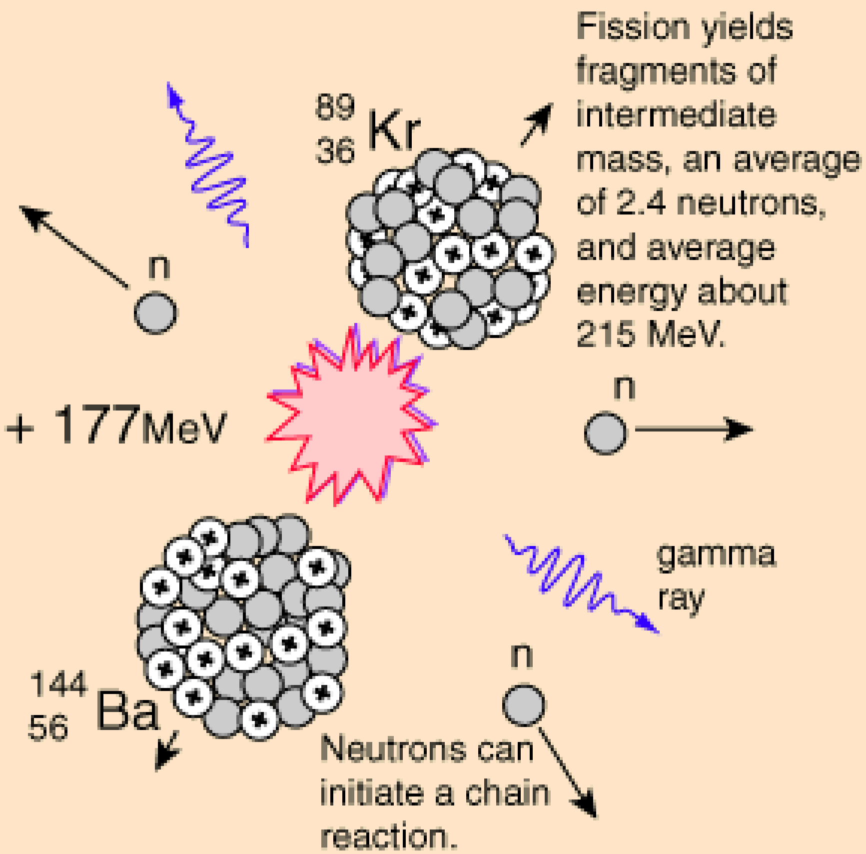
Neutrons are produced which can create more fissions.

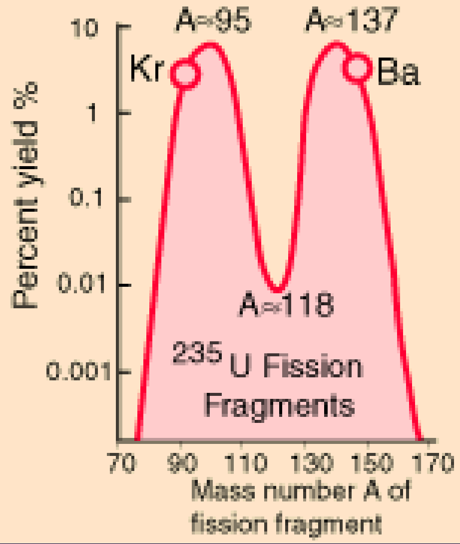
Uranium-235 Fission Example

An example of one of the many reactions in the uranium-235 fission process.

$$n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U$$

$${}^{236}_{92}U \rightarrow {}^{144}_{56}Ba + {}^{89}_{36}Kr + 3n + 177\,\text{MeV}$$



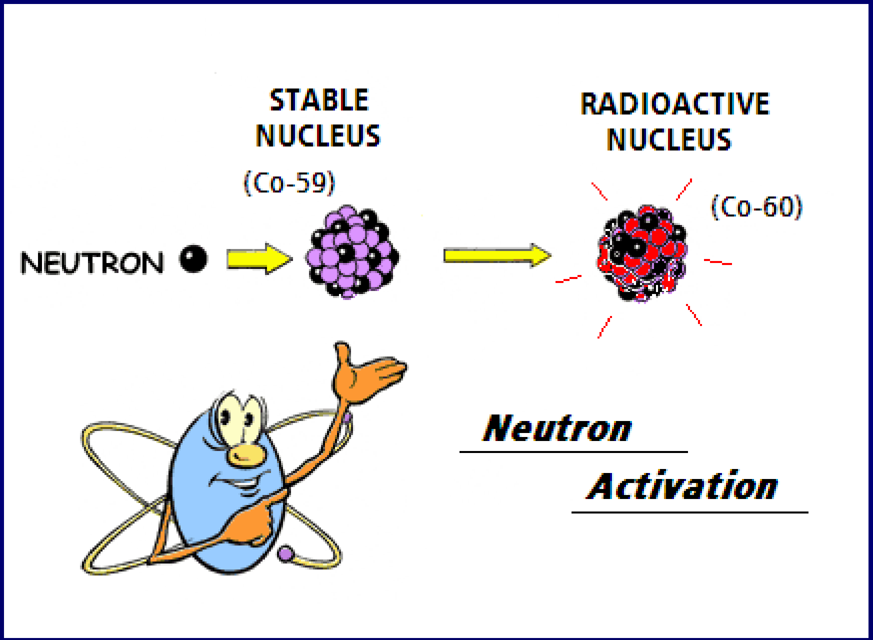


Fission Fragments

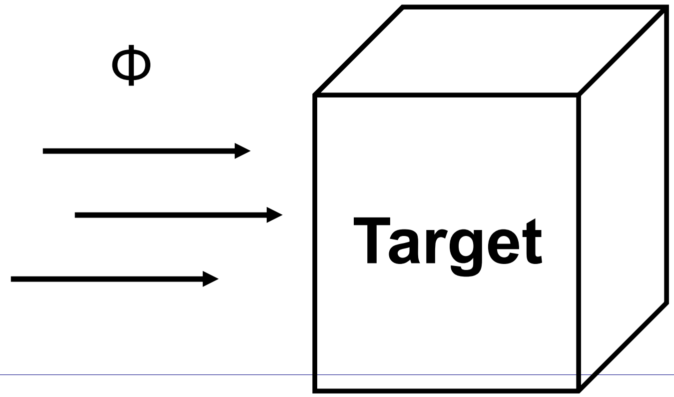
- The vast majority of fission fragments are radioactive isotopes with high specific activities.
- Most fission fragments will be contained within the fuel rods – the high level waste of reactor operations.
- Some fission products decay to other isotopes that are also radioactive.

Neutron Activation

- **Activation** is the process by which a stable nucleus absorbs a neutron and become radioactive.
- Cobalt-60 (Co-60) is the activation product that contributes the most dose to worker at commercial reactors.



Activation from Neutron Bombardment



Φ = neutrons/cm^2-s

σ = cm^2/n-atom

N_0 = target atoms

Activation Rate = $\Phi\sigma N_0$

- ϕ **is the flux, or the number of neutrons incident on a target area per unit time (n/cm^2 · s)**
- **Cross section, σ, is the probability of neutron absorption by a target atom, in units of barns**
- **N_0 is the number of target atoms being irradiated by neutrons**

QUESTIONS?

END OF INTERACTIONS OF RADIATION WITH MATTER

Review Questions

- List three charged particle interaction mechanisms.
- How is bremsstrahlung produced?
- Bremsstrahlung X-rays are ______ - energetic.
- Characteristic X-rays are _______ - energetic.
- What type of charged particle has high LET?

Review Questions

- ________ is the average distance a charged particle travels in a medium before coming to rest.
- How do you calculate density thickness? What are typical units?
- What is the reaction called which results in a non-radioactive atom becoming radioactive?
- What are three types of photon interactions?

Review Questions

- Which type of photon interaction requires a minimum energy of 1.02 MeV?
- In which photon interaction does the photon disappear after interacting with a tightly bound orbital electron?
- Which photon interaction occurs at all energy levels, but is dominant in the intermediate range?
- Which value is typically given - the linear attenuation coefficient or the mass attenuation coefficient?

Review Questions

- What type of material would be good for shielding: beta particles? gamma rays? neutrons?
- Are alpha particles an external hazard to humans? Why?
- What are the dimensions of the unit barn?
- Which type of neutron interaction is utilized in a nuclear power plant?

Review Questions

- Cobalt-60 is an example of an _________ product.
- Cesium-137 is an example of a ________ product.

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