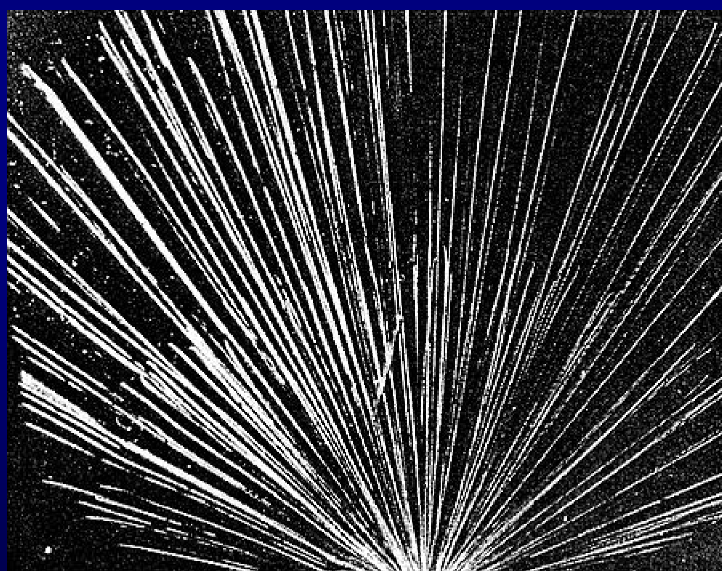
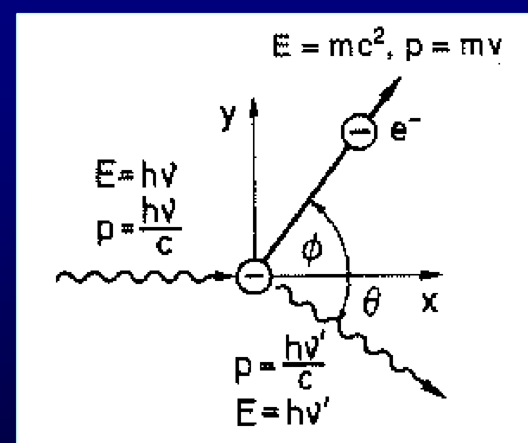
$$E(\tau) = \sum_T w_T \cdot H_T(\tau),$$

Health Physics Fundamentals





Objectives

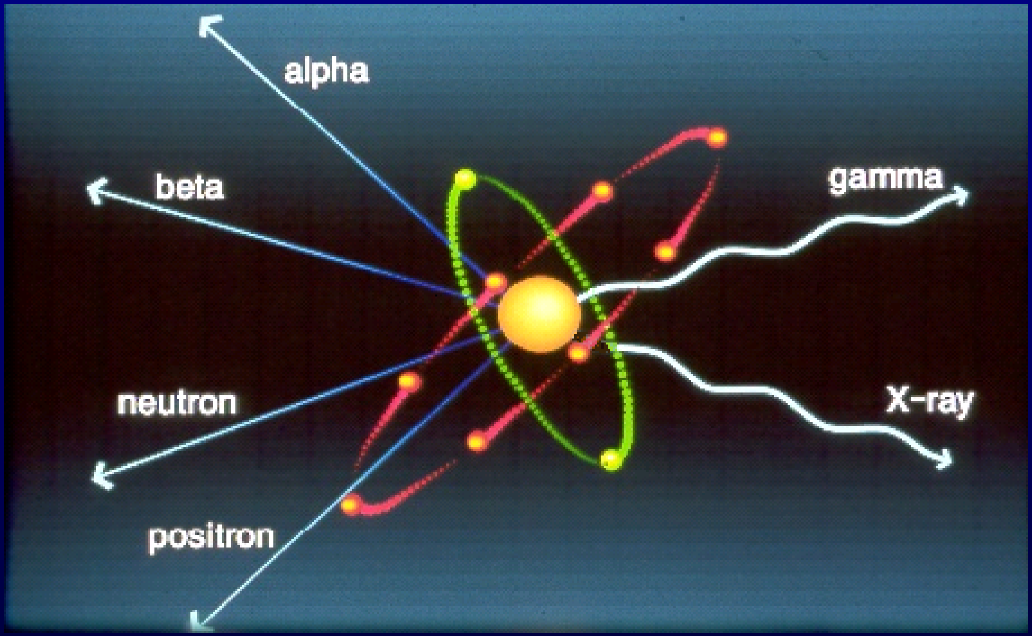
- Review the types of ionizing radiation and modes of decay
- Review charged particle interactions, photon interactions, and neutron interactions with matter
- Review the units for exposure, absorbed dose, and dose equivalent

Objectives

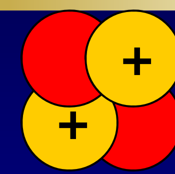
- Describe stochastic and deterministic (non-stochastic) effects of radiation exposure
- Review NRC Dose Limits for the whole body, organs, lens of the eye, skin and extremities
- Review the concept of density thickness and state the tissue-depths for the Deep Dose Equivalent (DDE), Lens Dose Equivalent (LDE), and Shallow Dose Equivalent (SDE)

Types of Ionizing Radiation

- Ionizing radiation can be in the form of particles or electromagnetic waves (photons).
- The particulate forms are alpha, beta, neutrons, and positrons.
- The non-particulate forms are gamma rays and X-rays.



Alpha Radiation (α)



- **Alpha particles consist of two protons and two neutrons.**
- **Heavier atoms such as transuranics emit alpha particles.**
- **Because of their double positive charge and relatively large size, alpha particles have a limited range – no more than a couple of inches in air. They ionize other atoms by removing orbital electrons and can create relatively high numbers of ionizations in a very small volume.**
- **Alpha particles are not a hazard if they are outside of the body (cannot penetrate the skin's dead layer), but can cause a lot of damage if they enter your body.**

$$^{241}_{95}Am \rightarrow \, ^{237}_{93}Np + \, ^{4}_{2}He^{++}$$

Beta Radiation (β^-)

- Beta radiation is also particulate. A beta particle is the same as an electron and has a single negative charge.
- Since they are less massive than alpha particles and have less charge, they travel further in material. The distance depends upon their energy.
- An energetic (~1 MeV) beta particle can travel up to 12 feet in air, and has the ability to penetrate your skin.

Beta Emission

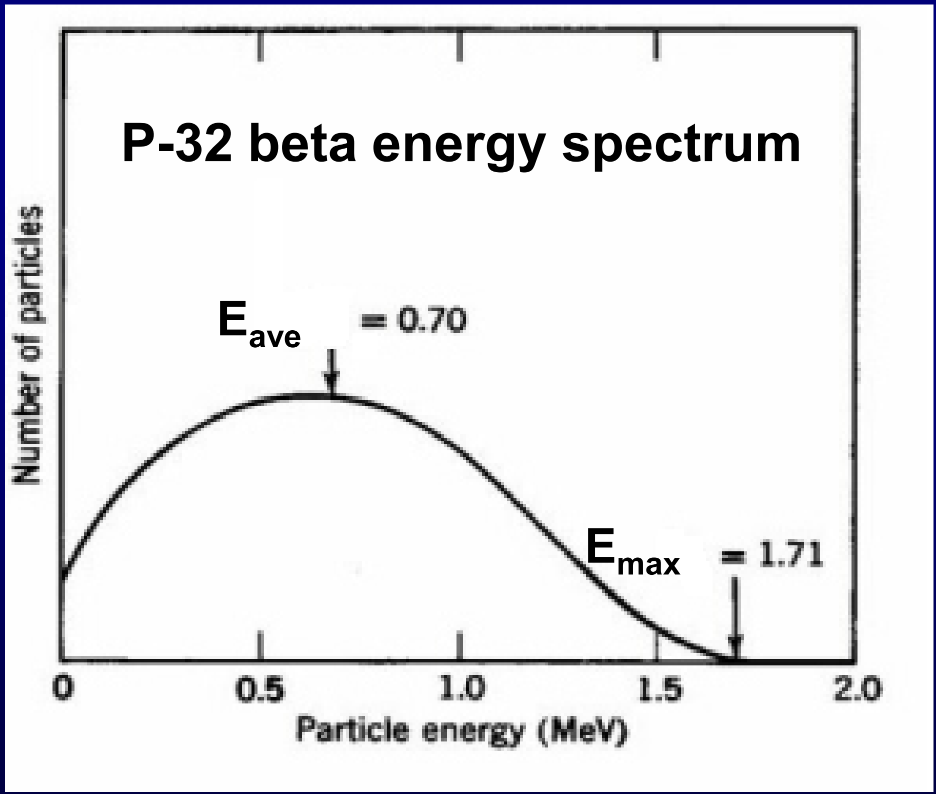
- **Emission of an electron from the *nucleus* of a radioactive atom**
- **Occurs when neutron to proton ratio is too high, i.e., a surplus of neutrons:**

$$n \rightarrow p^+ + \beta^- + \bar{\nu}$$

$$^{3}_{1}H \longrightarrow \, ^{3}_{2}He + e^- + \bar{\nu}$$

Beta Energy Spectrum

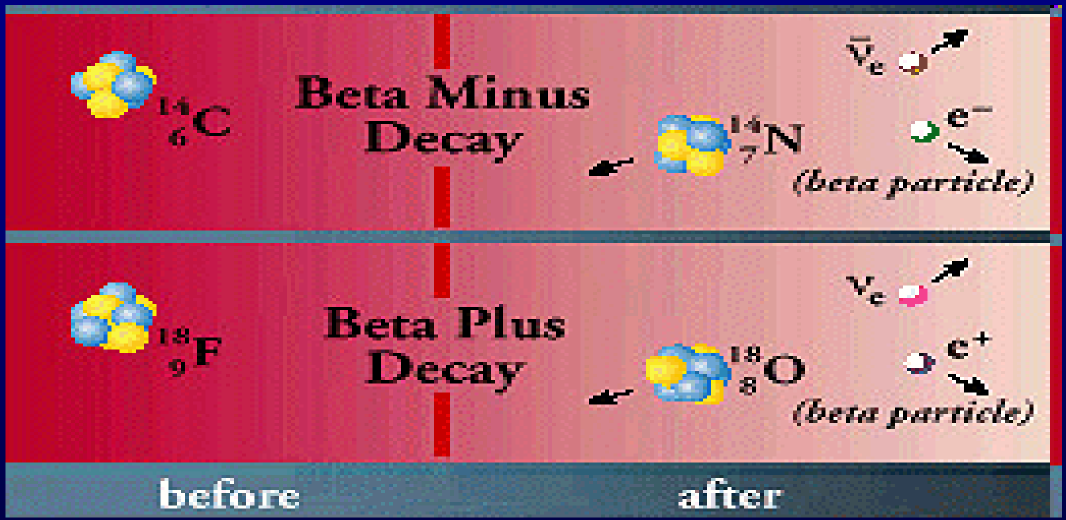
Beta particles are emitted with a spectrum of energies (unlike alpha particles) since their energy is shared with an antineutrino.



Positron (β^{+}) Radiation

- Occurs when the nucleus contains too many protons (neutron to proton ratio is too low)

- Nucleus emits a positron (a beta particle with a positive charge) and a neutrino $p^{+} \rightarrow n + \beta^{+} + \nu$



Orbital Electron Capture

- Nucleus captures an electron which transforms a proton into a neutron and emits a neutrino

$$p + e^- \rightarrow n + \nu$$

- Similar to B+ decay because the atomic number decreases by one unit and the mass number remains the same

$$^{103}_{46}Pd + ^{0}_{-1}e \rightarrow ^{103}_{45}Rh + \nu$$

Gamma Rays

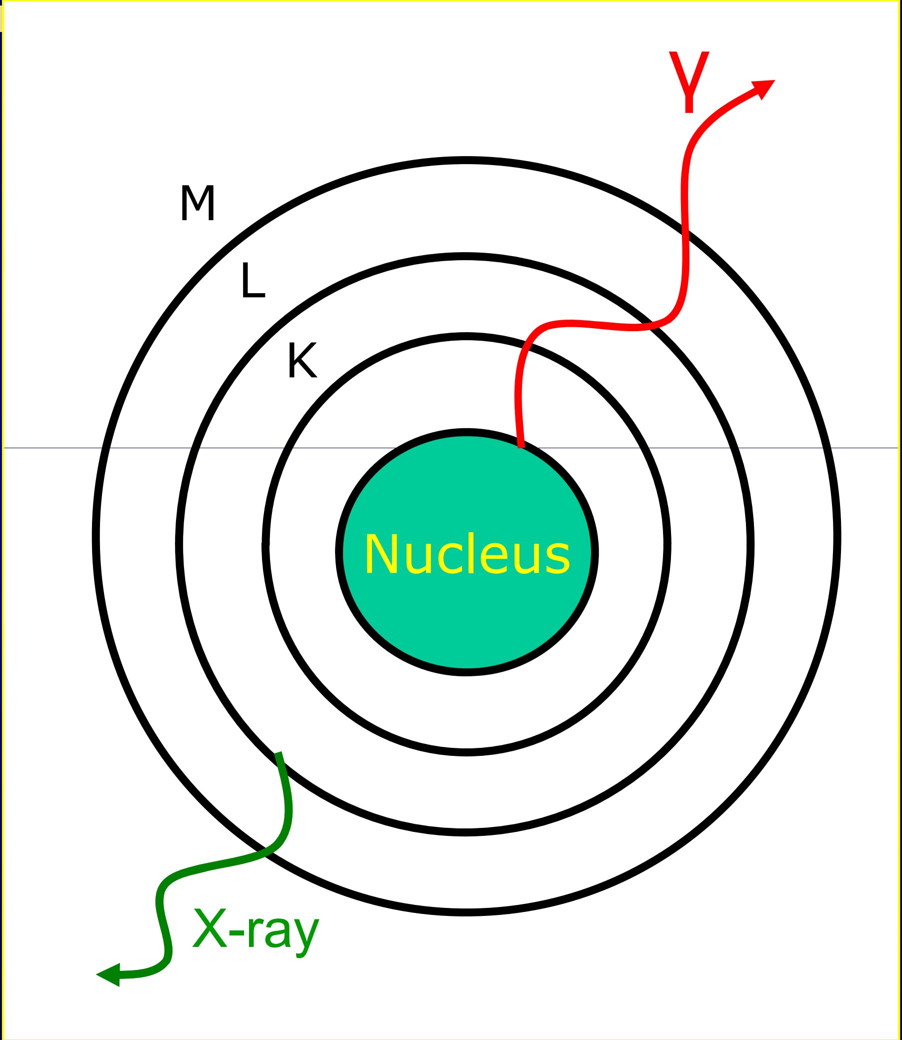
- Gamma rays are non-particulate radiation usually emitted from the nucleus of an atom following radioactive decay to rid the nucleus of excess energy
- Gamma rays are electromagnetic radiation just like visible light and UV rays, but they are more penetrating
- Gamma rays have characteristic energies that can be used to identify the radionuclide, e.g., Cs-137 decay results in the emission of 662 keV gamma rays

Internal Conversion

- Competes with gamma ray emission when there is an excited daughter nucleus
- Energy difference between initial and final states of nucleus is transferred to bound electron which is ejected from the atom
- Emission of internal conversion electrons (ce)

Gamma and X-Ray Emission

- Gamma rays and X-rays have no mass or charge - they are pure energy.
- They differ in that gamma rays originate in the nucleus of a radioactive atom while characteristic X-rays are produced outside of the nucleus.
- The Greek symbol for gamma radiation is γ



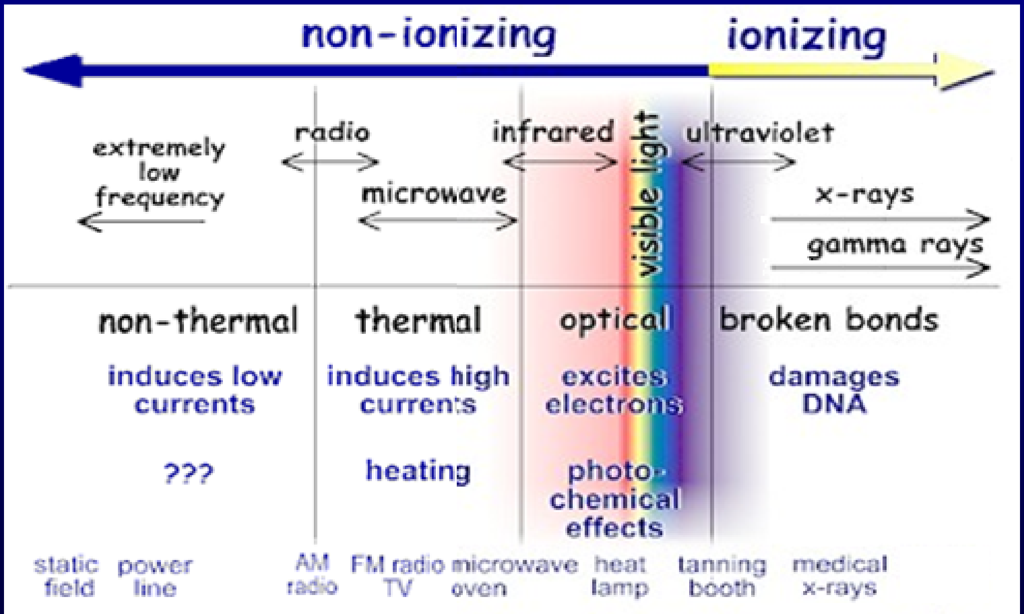
AUGER ELECTRONS

- Competes with X-Rays as a means of carrying off the energy released by filling an inner-shell vacancy with an electron from an outer shell

- Accompanied by ejection of an outer-shell electron from the atom

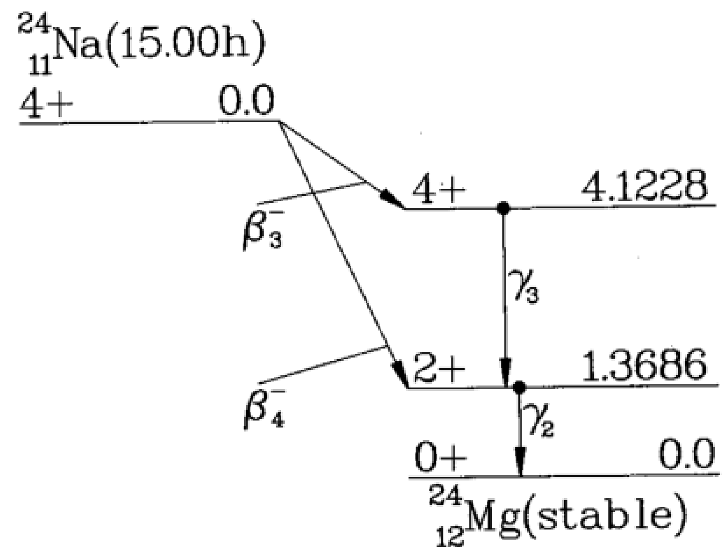
Gamma and X-ray radiation

- Photons (electromagnetic radiation) are grouped by wavelength. The shorter the wavelength, the higher the energy.
- Not all forms of radiation are ionizing.
- No defined energy cut-off between x-rays and gamma rays



Decay scheme example

$^{24}\text{Na} \rightarrow \, ^{24}\text{Mg} + \beta^-$



11-SODIUM-24

HALFLIFE = 15 HOURS 13-OCT-77
DECAY MODE(S): β^-

RADIATION	y(i) (Bq-s)$^{-1}$	E(i) (MeV)	y(i)×E(i)
β 3	9.99E-01	5.537E-01*	5.53E-01
γ 2	1.00E 00	1.369E 00	1.37E 00
γ 3	9.99E-01	2.754E 00	2.75E 00

LISTED X, γ AND γ± RADIATIONS	4.12E 00
OMITTED X, γ AND γ± RADIATIONS**	2.45E-03
LISTED β, ce AND Auger RADIATIONS	5.53E-01
OMITTED β, ce AND Auger RADIATIONS**	1.35E-04
LISTED RADIATIONS	4.67E 00
OMITTED RADIATIONS**	2.59E-03

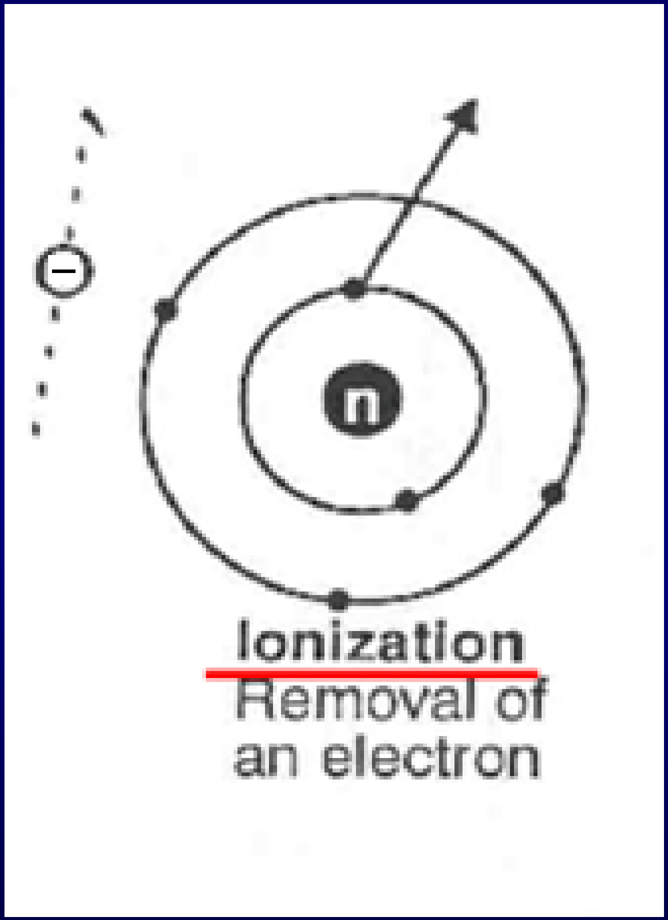
* AVERAGE ENERGY (MeV)
** EACH OMITTED TRANSITION CONTRIBUTES <0.100% TO Σy(i)×E(i) IN ITS CATEGORY.
MAGNESIUM-24 DAUGHTER IS STABLE.

Decay Schemes

- Isotopes 17
- Isotopes 18
- Isotopes 3
- Isotopes 4

Charged Particle Interactions

Charged Particle Interactions



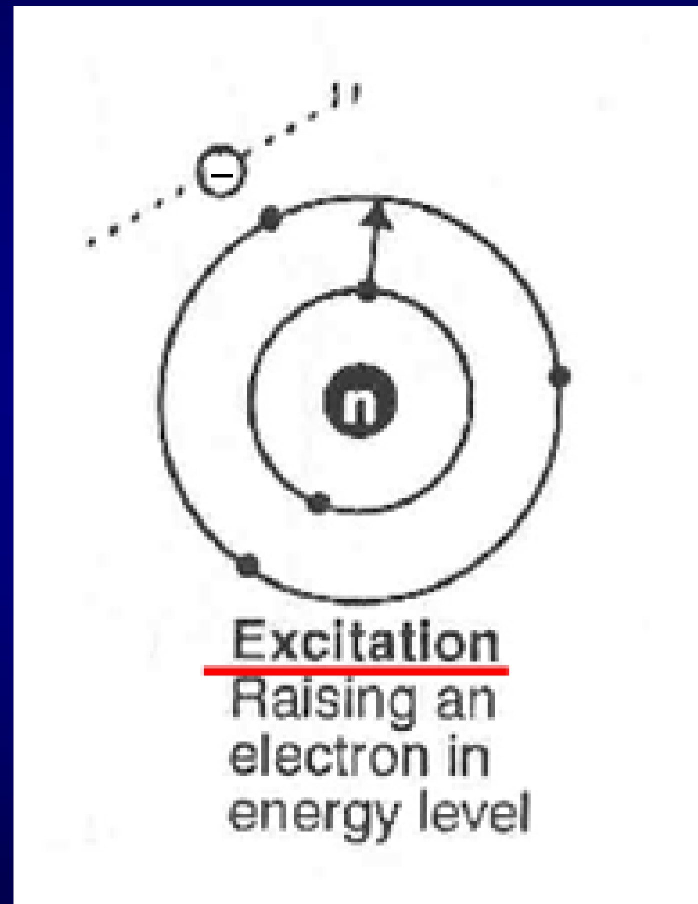
1. Ionization:

An electron is ejected from an atom by the passage of a charged particle - the average amount of energy expended is called the “w” value (about 33 eV).

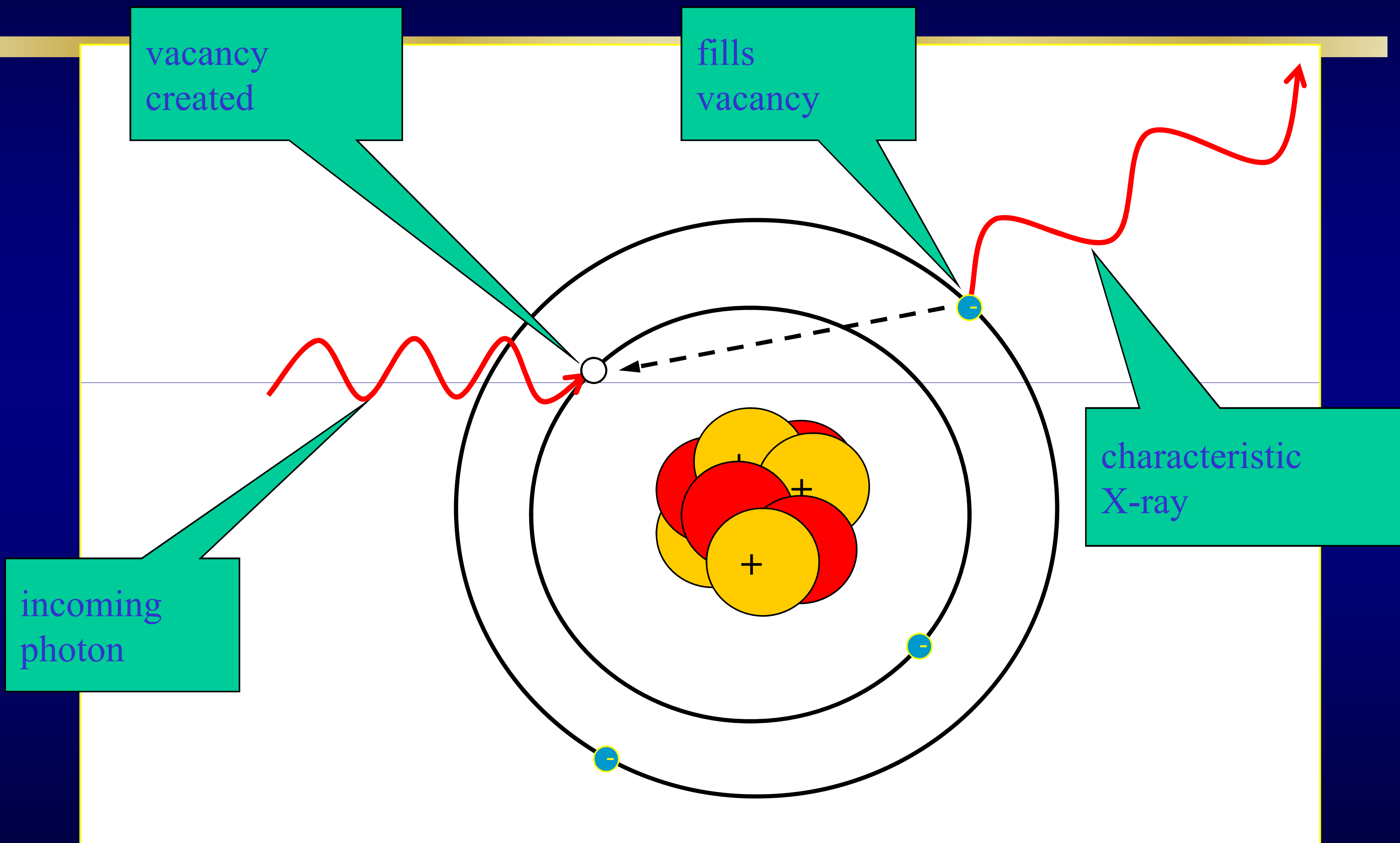
Charged Particle Interactions

2. Excitation:

An electron is raised to a higher orbit by the passage of a charged particle. Both Ionization and Excitation can be accompanied by emission of characteristic X-rays.

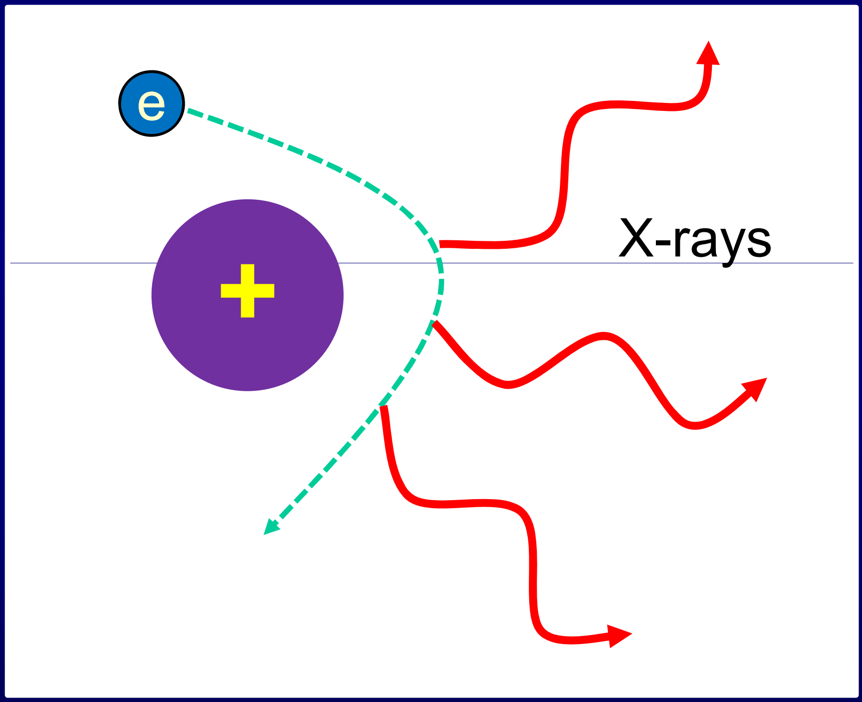


Characteristic X-rays



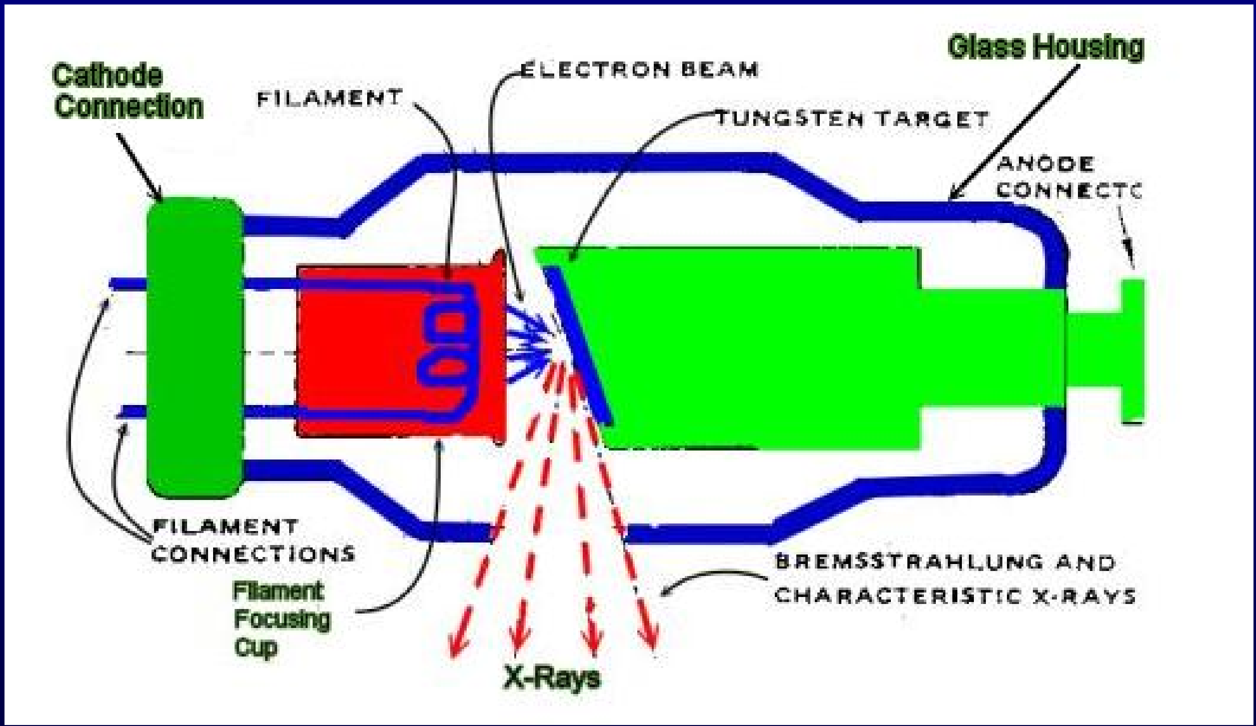
Bremsstrahlung

- "Braking Radiation"
- When a charged particle is deflected from its path, it sheds energy in the form of X-rays
- Maximum energy of X-ray is equal to the kinetic energy of the electron



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.

Bremsstrahlung Calculation

Suppose you want to shield P-32 with lead to make sure that the emitted beta particles are not a hazard to individuals handling the source. Approximately what percent of the energy from each P-32 beta particle will be converted to bremsstrahlung X-rays?

Answer:
Z = 82 (ISOTOPES-50)
E_{max} = 1.71 (if you use MISC-41)

f = 3.5E-4 (Z)(E) = (3.5E-4)(82)(1.71) = 0.05

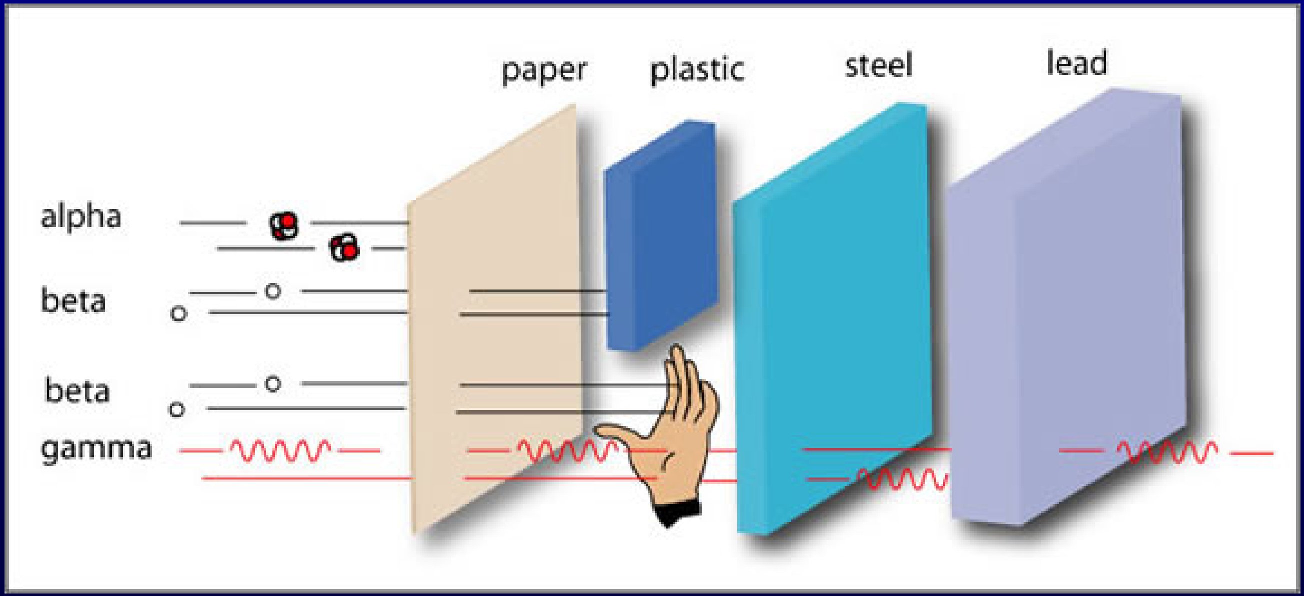
5% of the beta energy is converted to X-rays.

Photon Interactions

Photon Interactions

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

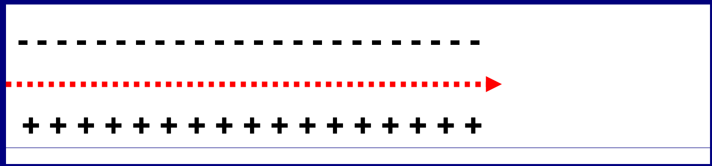
- For photons, we discuss the probability of interaction per unit distance travelled



Photon Interactions (cont)

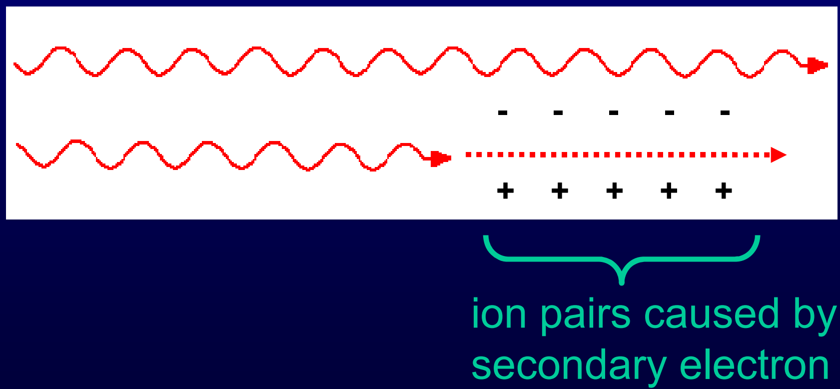
- As charged particles penetrate matter, they lose energy continuously along their travel path through the creation of ion pairs

α or β particle



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

photons



Photon Interactions (cont)

Photons interact with matter by three primary means:

- Photoelectric Effect
- Compton Scattering
- Pair Production

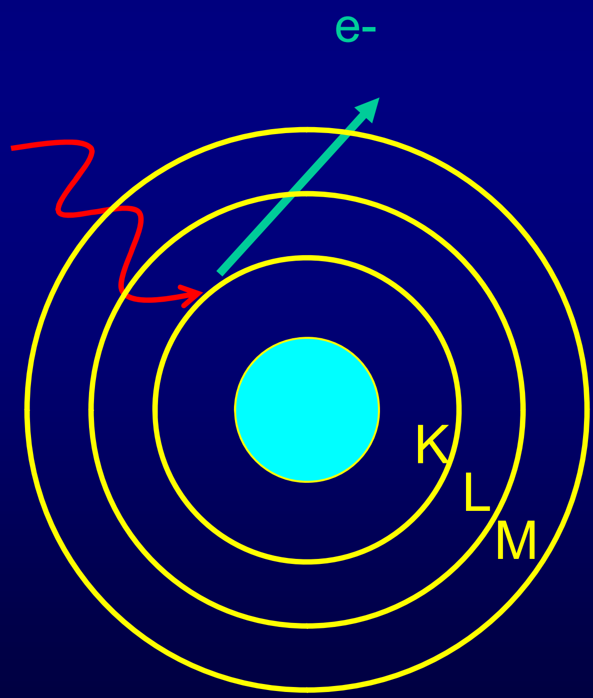
Photoelectric Effect

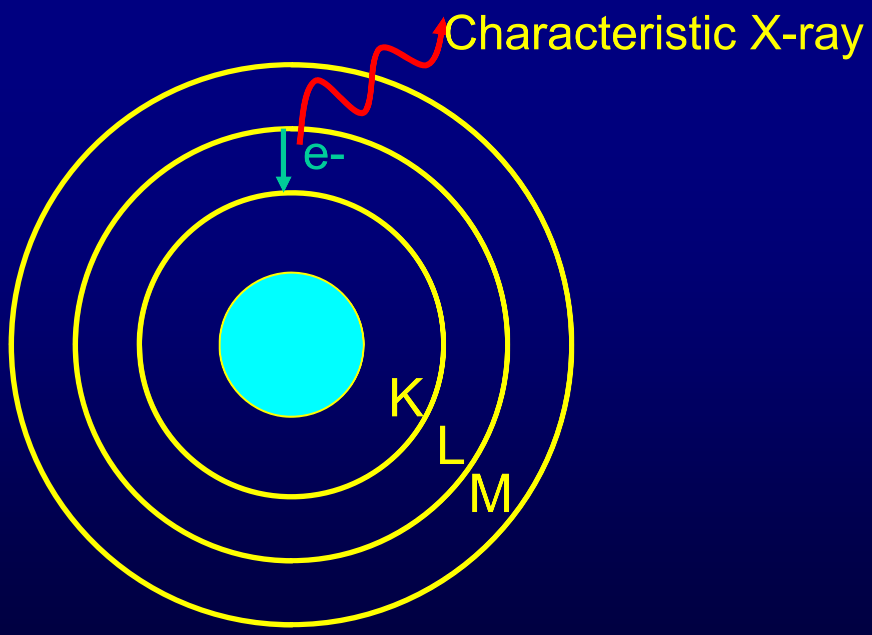
The photoelectric effect is the predominant interaction mechanism for low energy photons.

1. Incoming photon interacts with inner shell orbital electron (usually K shell).

2. Photon disappears after giving up all its energy to the electron that is ejected from the atom.

3. Higher orbital electron drops to the lower orbit that lost its electron. Energy difference between two orbits is released as a characteristic X-ray.





Compton Scattering

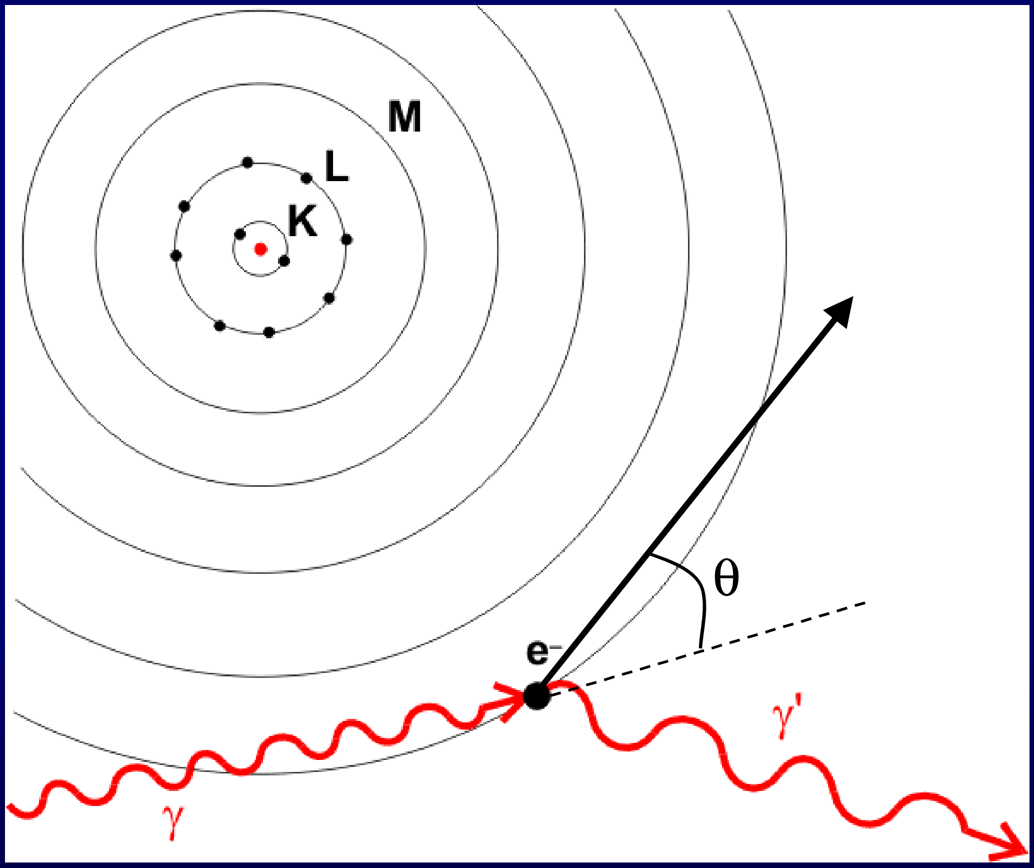
Compton scattering is most important for intermediate photon energies.

Photon (g) interacts with outer orbital electron.

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

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

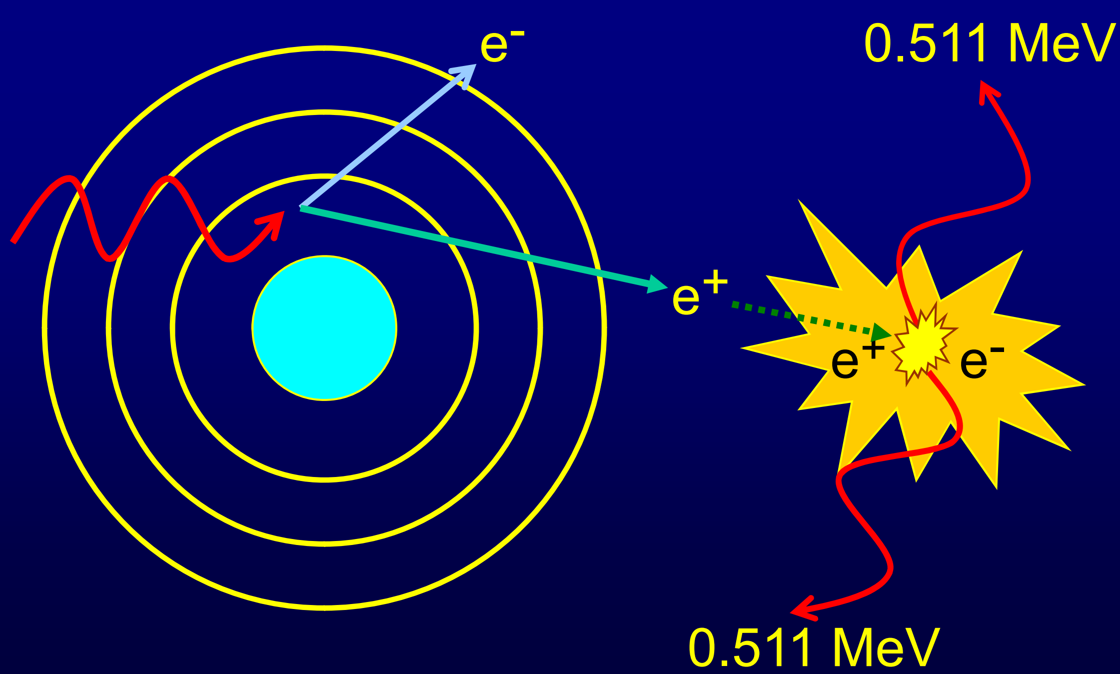
Add proportional density



Pair Production

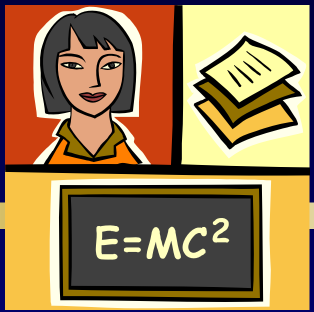
Must occur in the close vicinity of a nucleus. Incoming photon disappears, and an electron/positron pair appears

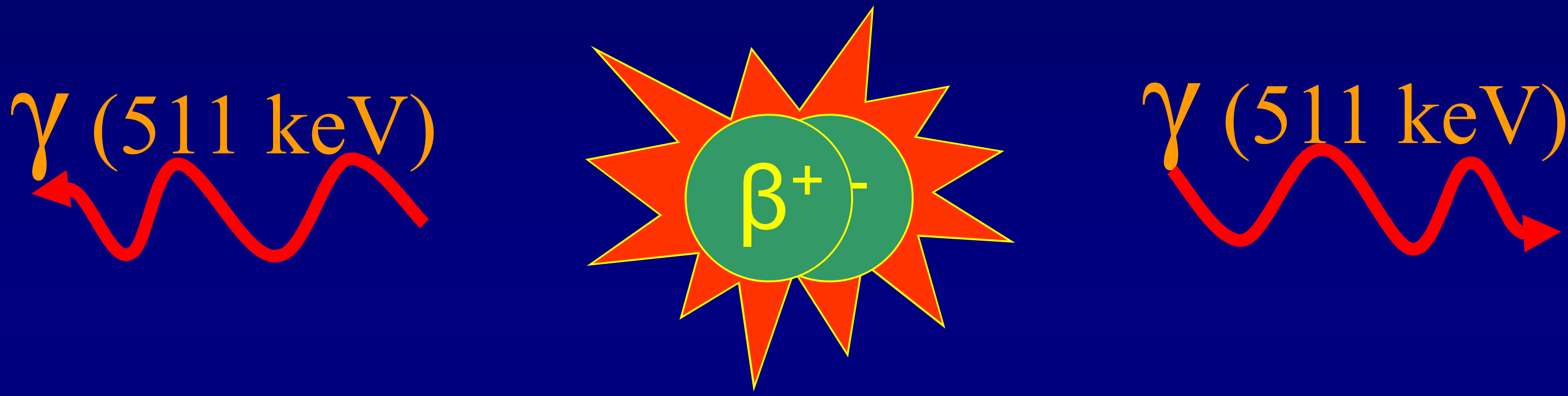
Requires minimum incoming photon energy of 1.022 MeV (0.511 MeV for the electron + 0.511 MeV for the positron)



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

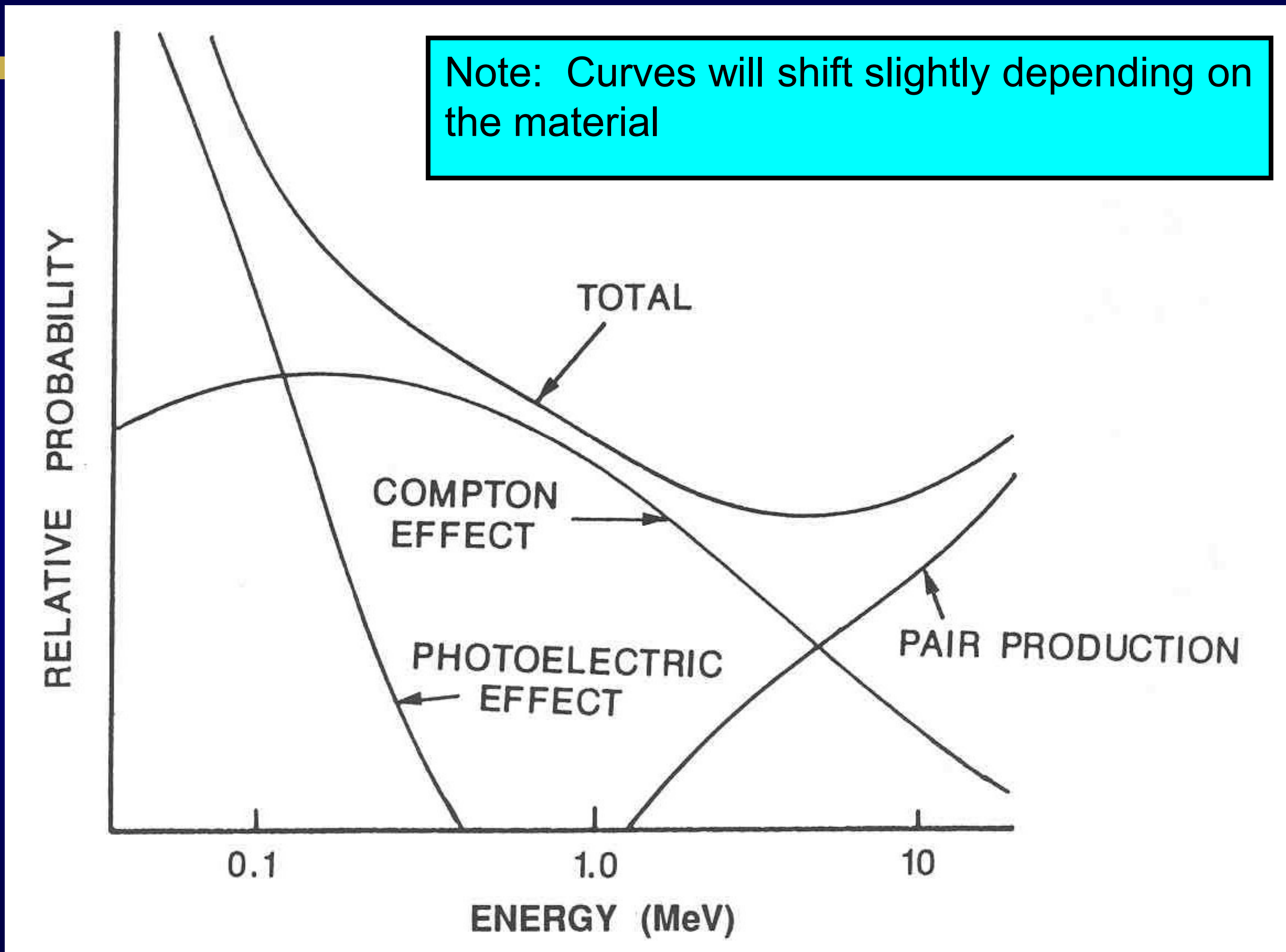
Positron Annihilation





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



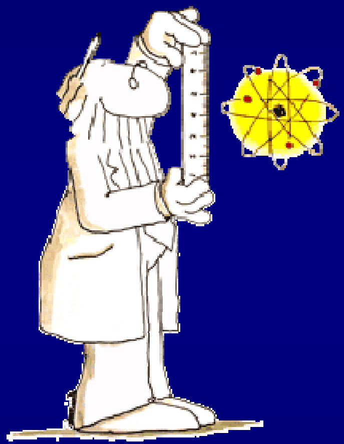
Neutron Interactions

Neutrons

- Neutrons are particulate radiation with no charge.
- Biological effects are strongly energy dependent.
- Vast majority of 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

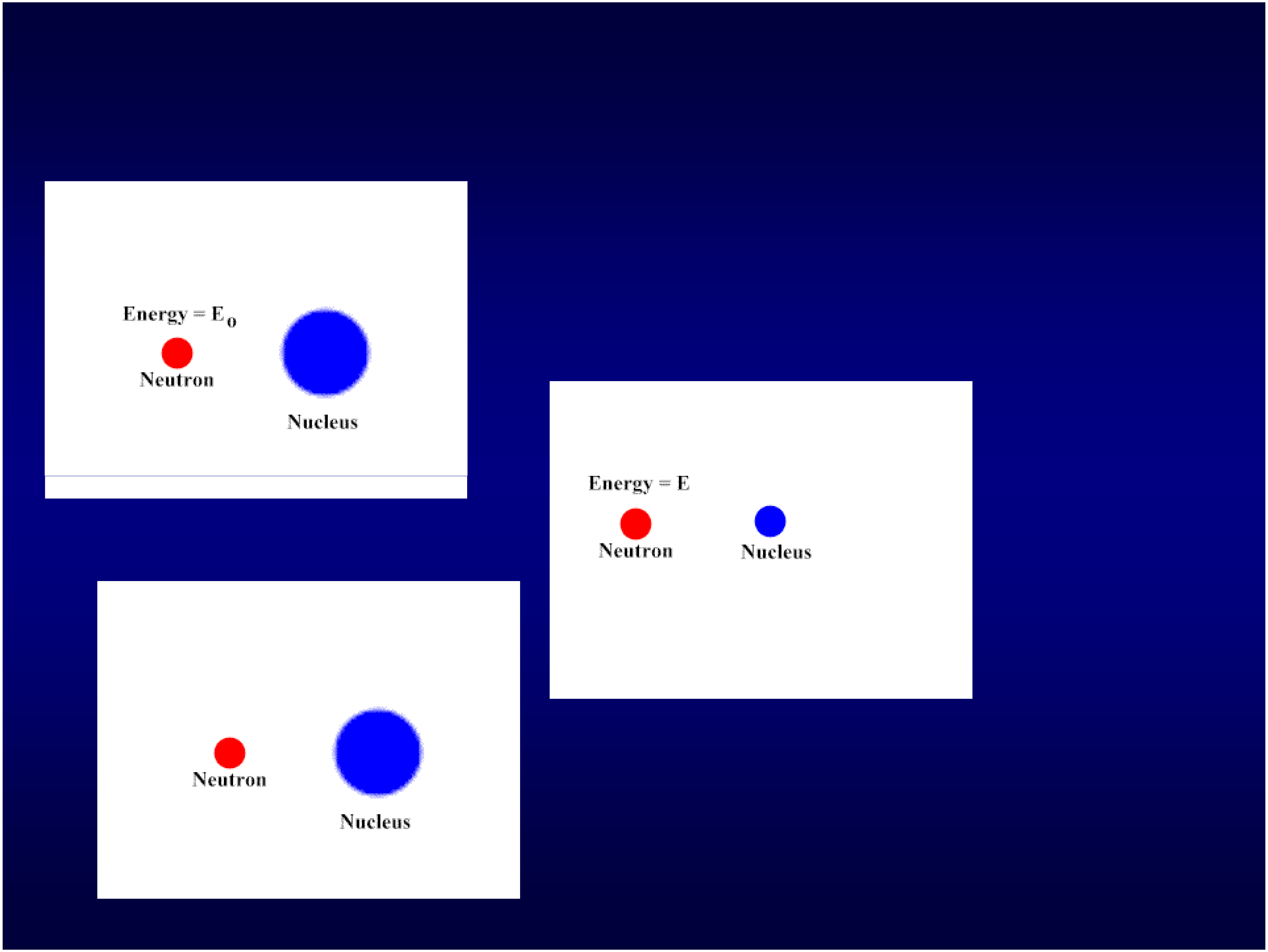
- Probability that neutrons will interact with a material
- Unit is the barn, where 1 barn = 10^{-24} cm^2



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.

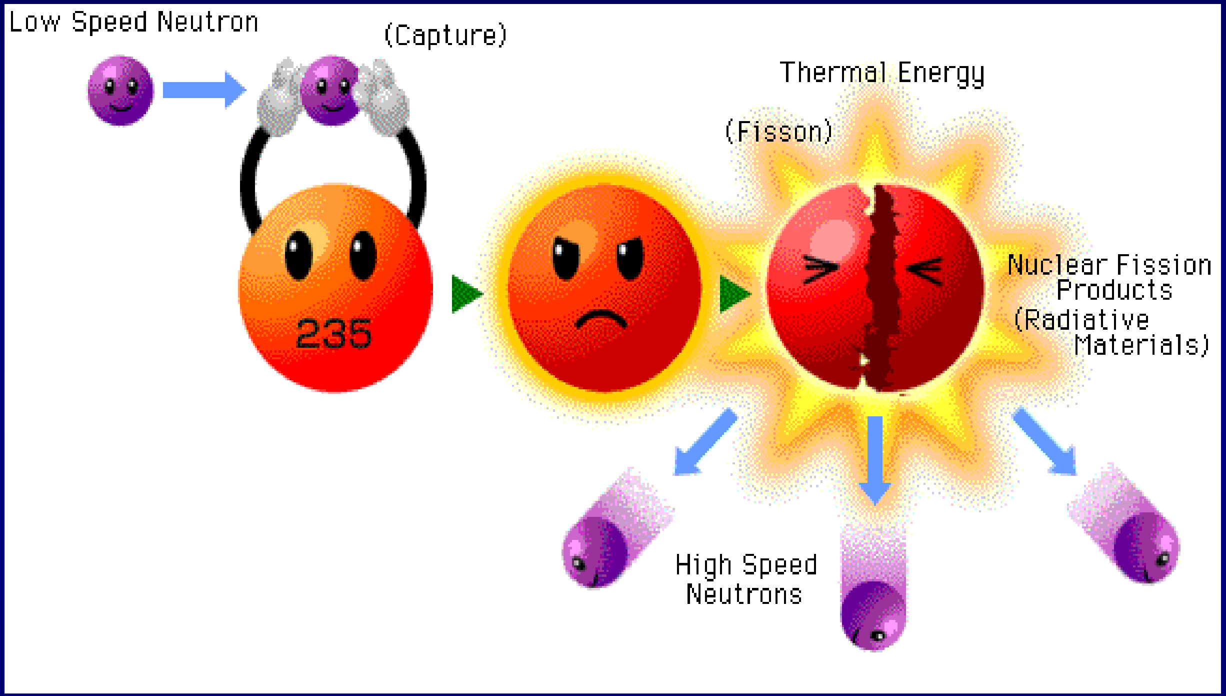
Neutron Interactions

- 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 o
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, with average energy of 0.7 MeV but range from 0 – 19 MeV, are produced which can create more fissions.

Fission Products

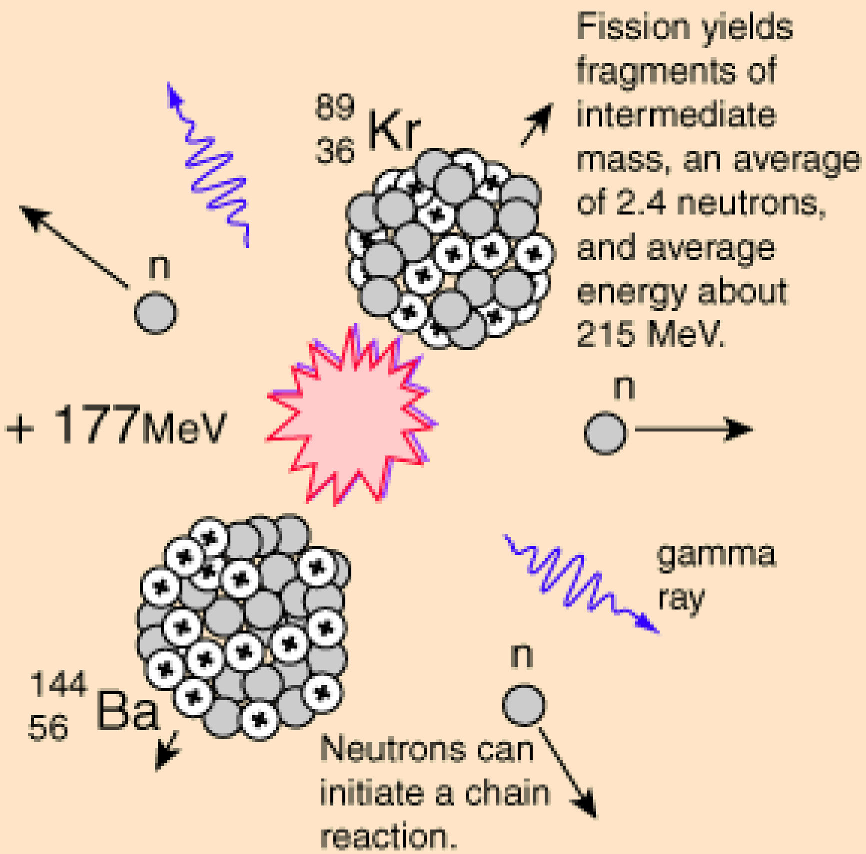
- Fission fragments are highly radioactive isotopes
- Most fission fragments produced in reactor fuel will be contained within the fuel rods (80% of the total energy released from fission is kinetic energy of fragments)
- Some fission products decay to other isotopes that are also radioactive (4-5% of the total energy released from fission is heat from fission product decay)

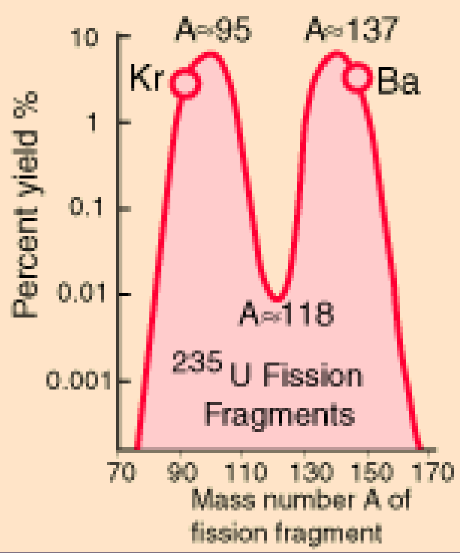
Uranium-235 Fission Example

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

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

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



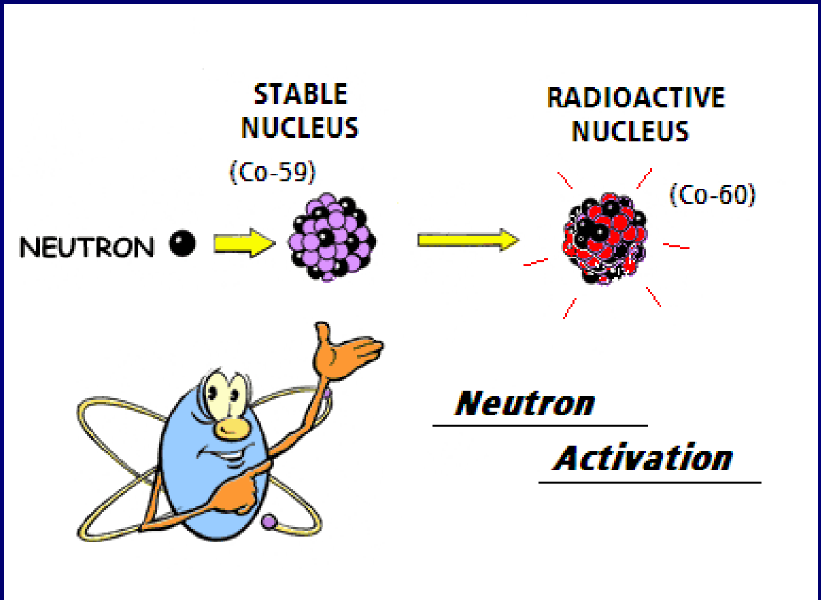


Neutron Activation

Neutrons can interact with atoms that are not radioactive.

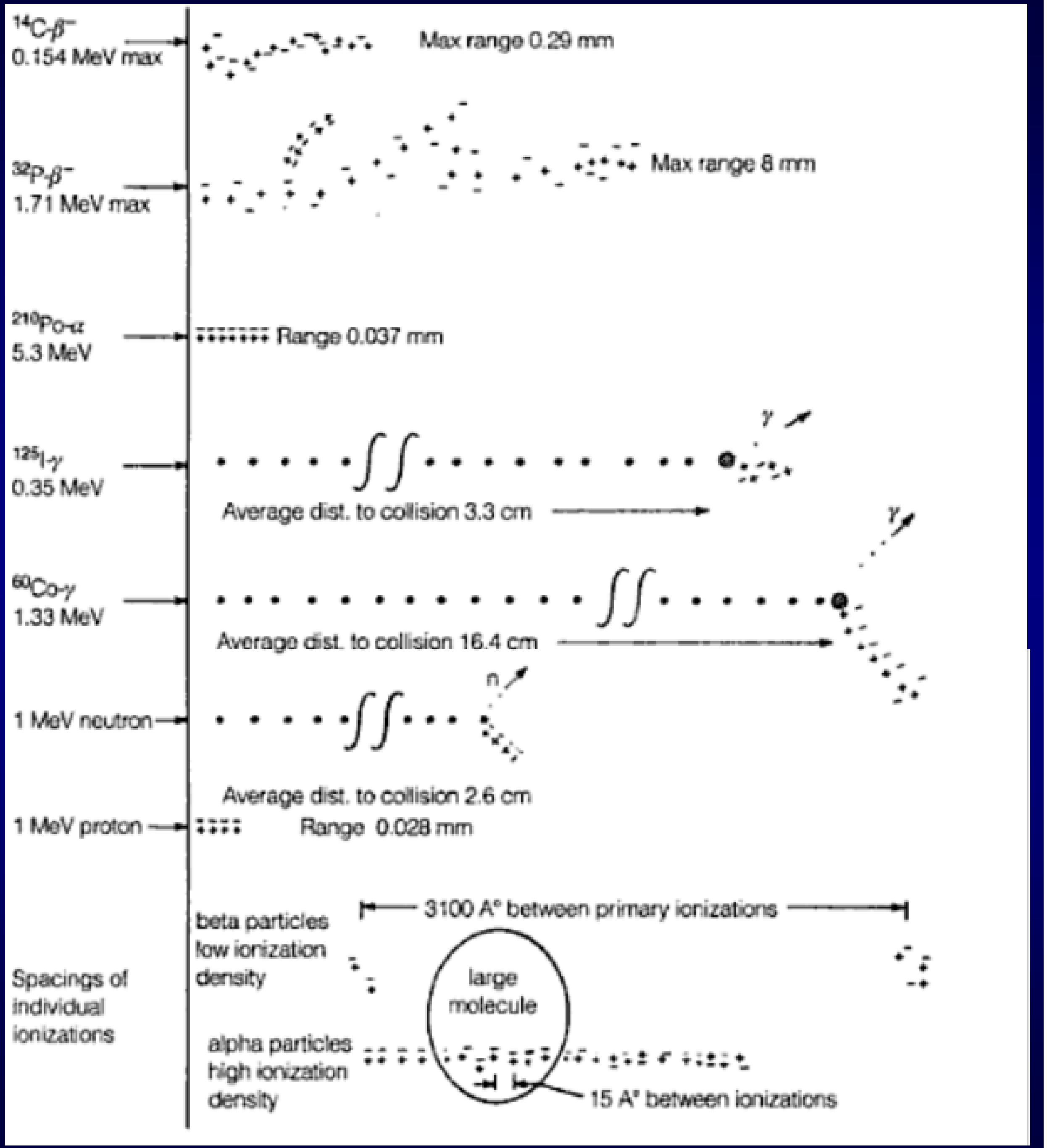
Activation is the term used to describe the process when stable atoms absorb a neutron and become radioactive.

Cobalt-60 (Co-60) is the activation product that contributes the most dose to personnel working in commercial reactors.



Interactions Summary:

Ionization patterns in tissue



END OF DECAY / INTERACTIONS

Radiation Units

Units Matter!

NASA's metric confusion caused Mars orbiter loss

September 30, 1999
Web posted at: 1:46 p.m. EDT (1746 GMT)

(CNN) -- NASA lost a $125 million Mars orbiter because one engineering team used metric units while another used English units for a key spacecraft operation, according to a review finding released Thursday.

Exposure

- Exposure is related to the amount of energy transferred from photons (X-rays and gamma rays) to a given mass of air.
- The unit of exposure is the Roentgen, R.
- 1 R = 2.58E-4 coulombs/kg

  = 87 ergs/g

Use of the Roentgen

- Roentgen is defined only for photon energies up to 3 MeV
- No similar unit in the International System (SI).
- Not used or defined in 10 CFR Part 20
- Not allowed as official record of dose (use rem or sievert)

Absorbed Dose

- Absorbed dose is the energy deposited by radiation in a given mass of any material
- Traditional unit is the rad, which equals 100 ergs/gram
- SI unit is the gray, Gy
- 1 Gy = 100 rad,
- Absorbed dose applies to all ionizing radiations at all energies in all media, including human tissue.

Relationship Between the Roentgen and Rad

- Recall that an exposure of 1 R results in 87 ergs/g in air
- Thus, in air, $1\text{ R} = 87\text{ ergs/g} \times \dfrac{1\text{ rad}}{100\text{ ergs/g}} = 0.87\text{ rad}$
- In human tissue, 1 R results in about 96 ergs/g
- Thus, 1 R = 0.96 rad or …

1 R ≈ 1 rad for human tissue.

Limitations of the Rad

- Does not account for differing biological effectiveness of various types of radiations
- For example, 1 rad of alpha exposure will result in a different biological endpoint than 1 rad of beta exposure
- Since 1 rad from each radiation deposits the same amount of energy in tissue (100 ergs/g), the difference is related to energy distribution in tissue
- Thus, we need another factor that accounts for differing biological effects of the various types of radiation

Quality Factor

- The Quality Factor, Q, is the factor by which absorbed dose is multiplied to account for differing biological effects
- Absorbed Dose x Q = Dose Equivalent
- Note that dose equivalent is only defined for human tissue and only for doses within the range of the occupational limits

Quality Factors (10 CFR 20.1004)

Radiation Type	Quality Factor
beta	1
gamma	1
x-ray	1
neutron	2–11 (depending on energy)
alpha	20

Dose Equivalent

- Traditional unit for dose equivalent is rem
- Since Q = 1 for X-rays, gamma rays and beta particles, 1 rad of these radiations equals 1 rem
- SI unit is sievert, Sv, where 1 Sv = 100 rem
- 50 mSv = <u>5000</u> mrem?

Biological Effects of Ionizing Radiation

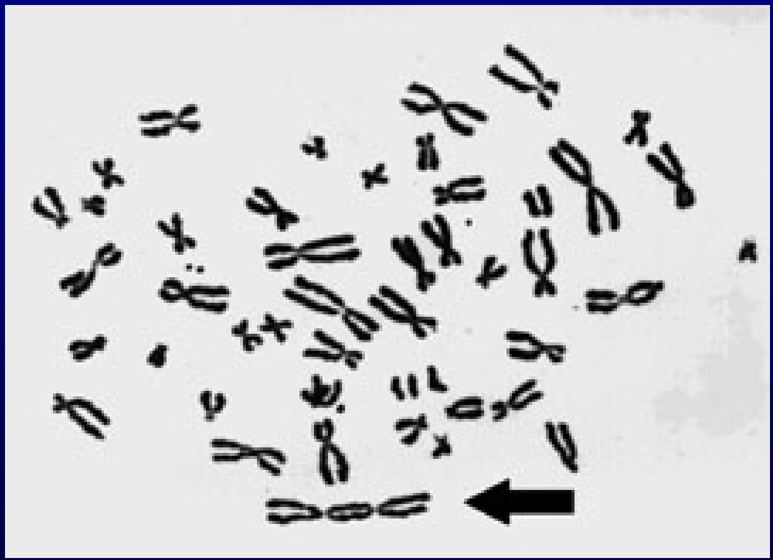
Stochastic Effects

- Stochastic effects are health effects that occur randomly and for which the probability of the effect occurring, rather than its severity, is assumed to be a linear function of dose without a threshold

- Hereditary effects and cancer are examples of stochastic effects

Cancer

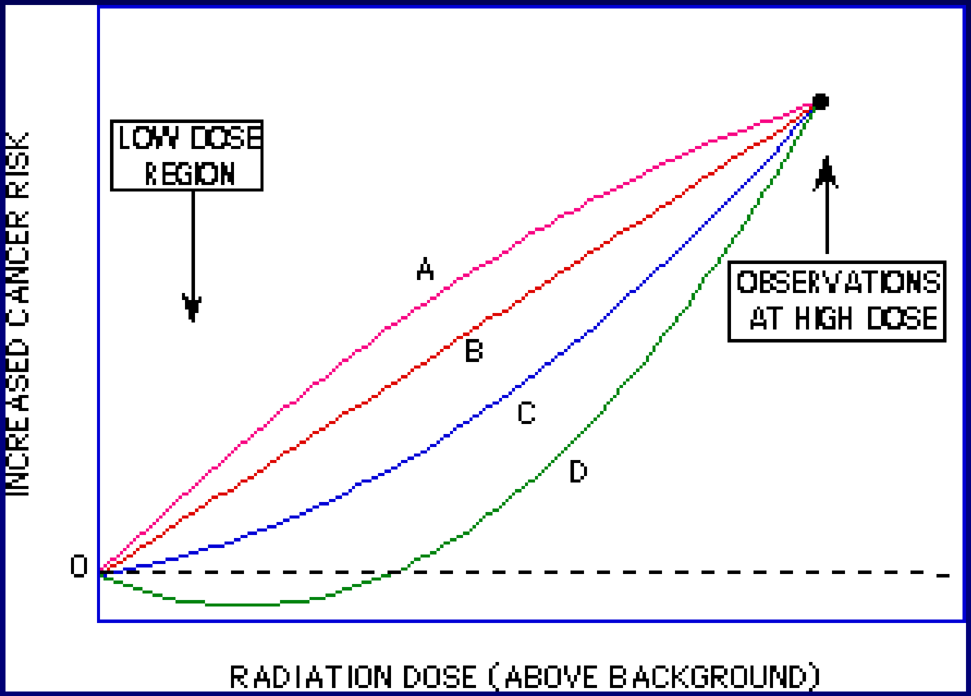
- Most cancers are due to acquired mutations vs. inherited mutations. Acquired mutations are changes to a person's DNA over their lifetime
- Having a mutation does not mean that you will get cancer



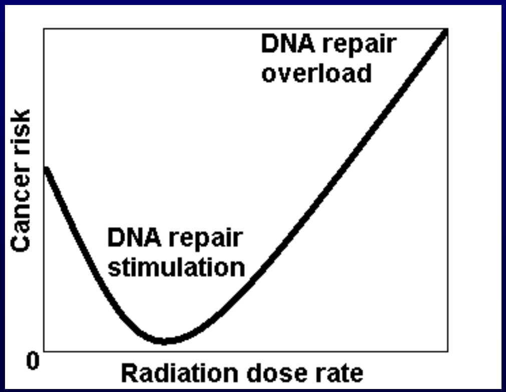
Linear No-Threshold (LNT)

No threshold dose - any dose increases the probability of an effect occurring. "Linear No-Threshold," (LNT)

Any dose is assumed to have a risk (vs. Hormesis theory below)



(Basis for NRC whole body dose limits)



Deterministic Effects

- Deterministic (non-stochastic) effects have a dose threshold, beyond which the severity of the effects increases

- Examples include radiation-induced cataracts and erythema (reddening of the skin)
- Evidence from medical therapy indicates threshold of 2,500 rem over 50 years. Exceptions are: bone marrow, lens of eye, gonads

- ICRP recommended threshold/50 years

Dose Limits

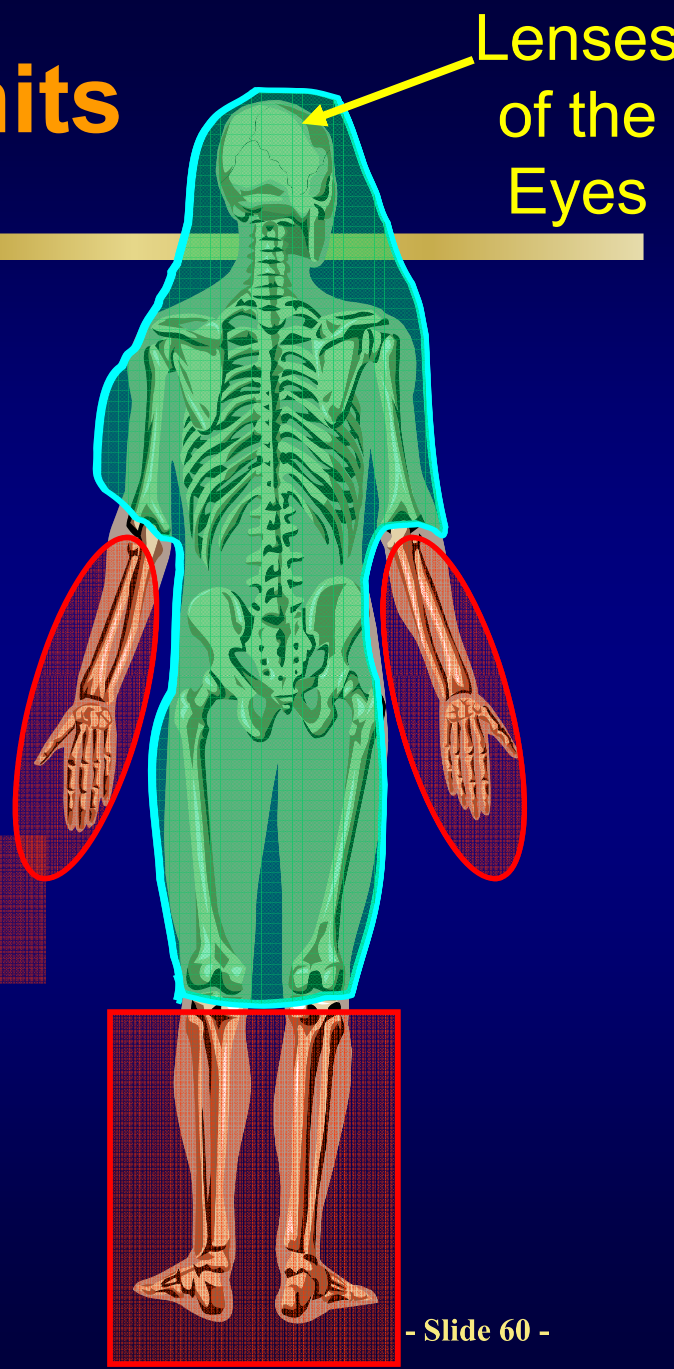
Occupational Dose Limits

Whole Body -
everything except extremities

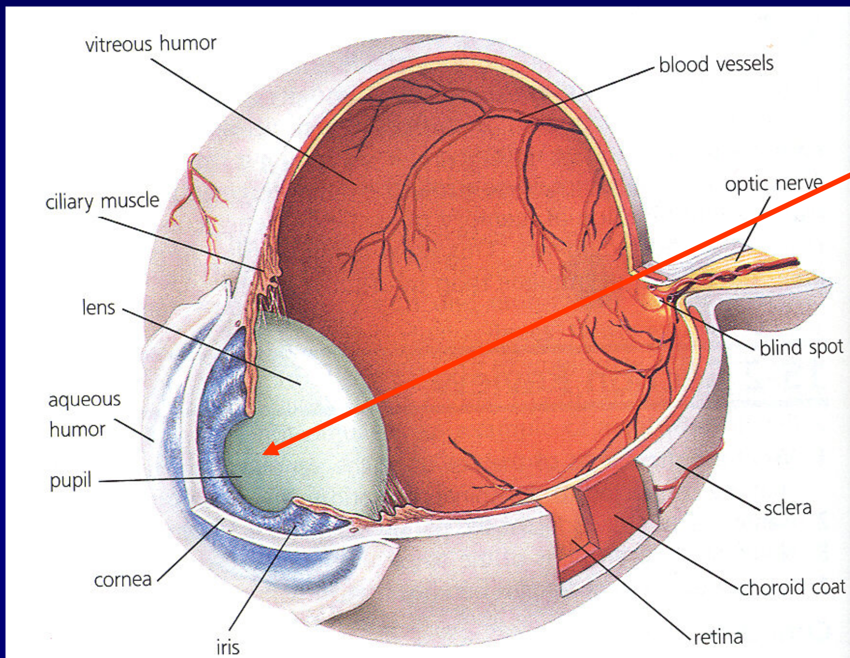
Skin of the Whole Body -
skin covering everything except extremities

Skin of the Extremities -
skin covering extremities

Extremities -
Elbows, and arms below elbows
knees, and legs below knees



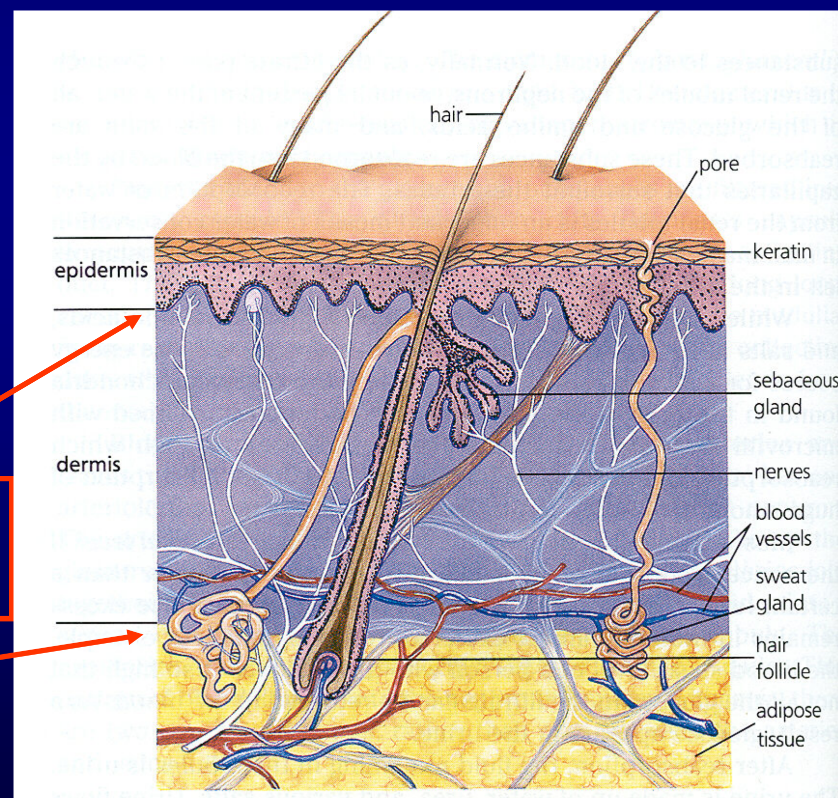
Depths at which External Radiation Dose is Measured



The lens dose equivalent, LDE, is measured at a depth of 0.3 cm

The shallow dose equivalent, SDE, (skin) is measured at a depth of 0.007 cm

The deep dose equivalent, DDE, (whole body) is measured at a depth of 1 cm



Dose Limits - Whole Body

- TEDE = Total Effective Dose Equivalent
- TEDE = 5 rem per year
- TEDE = External (EDE) + Internal (CEDE)

Dose Limits - Whole Body

- External dose = EDE or DDE
  - Deep Dose Equivalent, DDE, is measured
  - Effective Dose Equivalent, EDE, is calculated
- Internal Dose = Committed Effective Dose Equivalent (CEDE)
  - Committed means dose over 50 years assigned to year of intake (CEDE = CDE x W_T)

Weighting Factors (W_T)

- These factors relate the organ exposure to an effective whole body exposure.
- Weighting factors are found in 10 CFR 20.1003

Organ or Tissue	W_T
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder	0.30
Whole Body	1.00

Dose Limits - Organs

- Total Organ Dose Equivalent (TODE) = External + Internal
- TODE = 50 rem per year
- TODE is not defined in 10 CFR 20.1003, but is discussed in 10 CFR 20.1201
- External dose = EDE or DDE
- Internal = Committed Dose Equivalent (CDE)

Other Dose Limits

- Shallow Dose Equivalent (SDE) = 50 rem/year
- SDE is a deterministic limit intended to prevent formation of erythema (i.e. reddening of the skin)
- SDE is measured at a depth of 0.007 cm (7 mg/cm^2).
- Applies to the skin of the whole body SDE_{WB} or the skin of an extremity SDE_{ME}

Other Dose Limits

- Lens Dose Equivalent (LDE) = 15 rem/year,
- LDE is a deterministic limit intended to prevent formation of cataracts within the lens of the eye
- LDE is measured at a depth of 0.3 cm (300 mg/cm^2)

Doses to Minors & DPWs

- Occupational dose limits for minors are 10% of the annual dose limits for adult workers

- The dose limit to an embryo/fetus of a Declared Pregnant Woman (DPW) is 0.5 rem (uniformly distributed during the pregnancy, i.e., 50 mrem/month)

  - NOTE: Monitoring is required if a DPW is likely to receive 100 mrem/yr from external radiation

	Dose Term	Annual Limit	
OCCUPATIONAL	LDE	15 rem	
	SDE_{ME}	50 rem	
	SDE_{WB}	50 rem	
	DDE + CDE = TODE	50 rem	per organ
	EDE + CEDE = TEDE	5 rem	
	Minor	10% of adult limits	
	Dose to E/F of DPW	0.5 rem	Pregnancy
	Public TEDE	0.1 rem = 100 mrem	

Occupational Dose Limits: Stochastic vs. Deterministic

Stochastic Dose Limits:

- 5 rem/yr (TEDE)
- 1/10th adult limits for minors
- 0.5 rem/yr for DPW (pregnancy)

Deterministic Dose Limits:

- 50 rem to an organ in a year (TODE)
- 15 rem to the lens of the eye (LDE)
- 50 rem to the skin of the whole body (SDE_{WB})
- 50 rem to extremities (SDE_{ME})

Planned Special Exposures (PSE)

- Special requirements apply: complete dose history, planned in advance, exceptional case, person informed of expected dose, dose rates in area & risk (RG 8.29), NRC Regional office notified, person told dose.

- Limits are: annual dose up to the annual occupational limits but not to exceed 5 times the annual limit in their lifetime (e.g., 5 rem TEDE, 25 rem lifetime TEDE PSE; 15 rem LDE as PSE, 75 rem lifetime LDE as PSE).

Density Thickness

Dose Limits and Density Thickness

- Dose limits are defined for given depths in tissue
- These depths can be discussed using the concept of "density thickness"
- Density thickness is the product of the density and thickness of the tissue of interest . For human tissue, assume an average density of 1 gram / cm^3 (ρ = 1 g/cm^3).

Density Thickness - SDE

- For skin, the tissue depth (or thickness) for measuring shallow dose equivalent is 0.007 cm, so the corresponding density thickness is:
- $(0.007\ \text{cm})(1\ \text{g/cm}^3) = 0.007\ \text{g/cm}^2$
- $(0.007\ \text{g/cm}^2)(1000\ \text{mg/g}) = 7\ \text{mg/cm}^2$

Density Thickness - DDE

DDE is at a depth of 1 cm in tissue, or a density thickness of 1 cm x 1 g/cm^3 = 1 g/cm^2 = 1,000 mg/cm^2

Density Thickness - LDE

LDE is at a depth of 0.3 cm in tissue, or a density thickness of 0.3 cm x 1 g/cm^3 = 0.3 g/cm^2 = 300 mg/cm^2

Density Thickness

- The density thickness for another material is useful in simulating the density thickness for tissue.

- For example, we could determine the amount of copper needed to simulate the density thickness of tissue to make a dosimeter for measuring DDE:

  For copper, $\rho = 9\ g/cm^3$, so the equivalent thickness of copper is:

  $(\rho_{Cu}) \times (t_{Cu}) = (\rho_{Tissue}) \times (t_{Tissue})$
  $(9\ g/cm^3) \times (t_{Cu}) = (1\ g/cm^3) \times (1\ cm)$, solving for t_{Cu}
  $t_{Cu} = 0.11\ cm$

Problem

What thickness of copper is required to simulate tissue density thickness for SDE and LDE?

END OF
HP FUNDAMENTALS