Principles of Radiation Physics and Dosimetry

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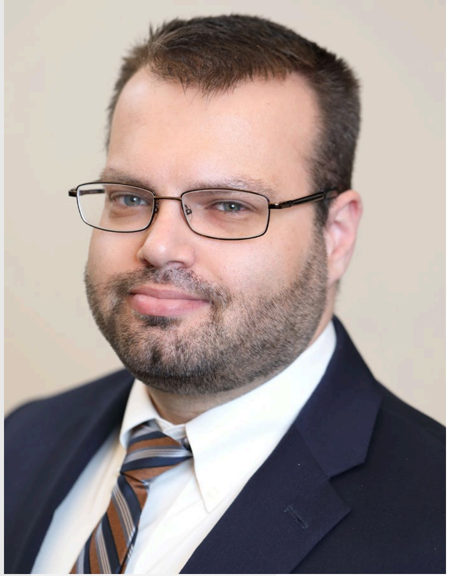


DCEG Radiation Epidemiology and Dosimetry Course 2019

Physics is HARD even for physicists!

“Physics is very muddled again at the moment; it is much too hard for me anyway, and I wish I were a movie comedian or something like that and had never heard anything about physics.”

-Wolfgang Pauli (1900-1958)

Pioneer of Quantum Physics

Learning Objectives

- Difference between ionizing and non-ionizing radiation
- Basic concepts of the nucleus and nuclear particles involved in radioactive decay
- Difference between radioactivity and radiation
- Processes that result in emission of radiation
- How radiation interacts with tissue (because these lead to “dose”)
- Definition of dose quantities and units
- Sources of radiation exposure in everyday life

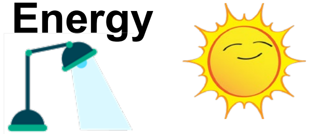
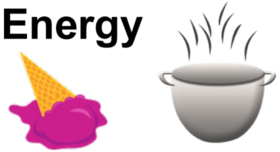
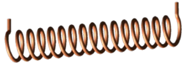
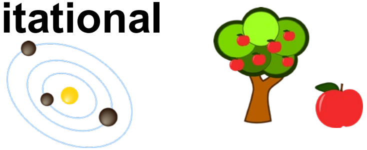
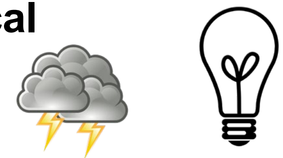
Physics Principles

ENERGY is the fundamental concept in Radiation Dosimetry

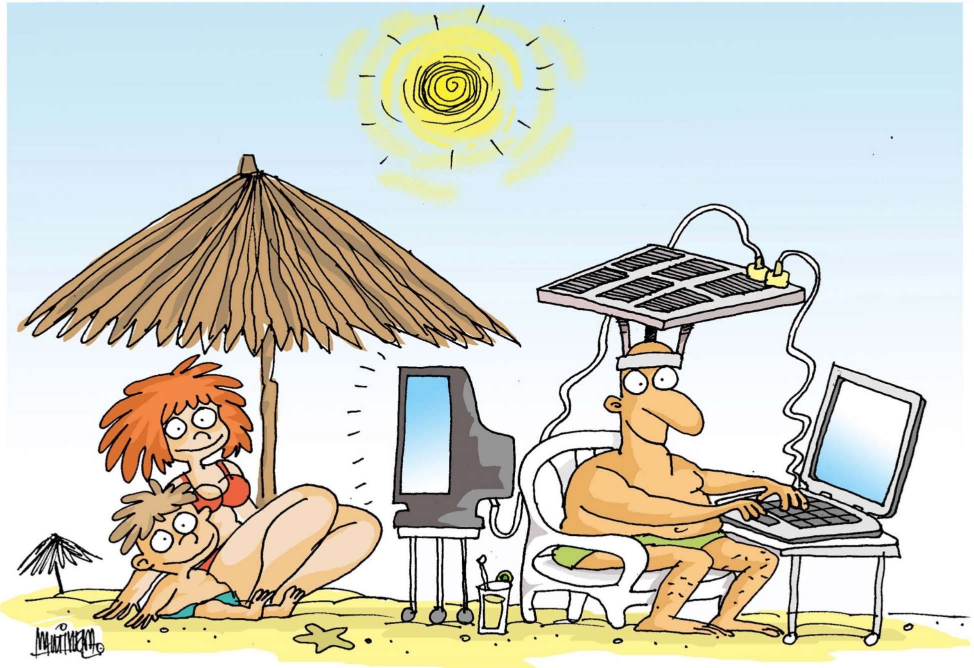
ENERGY is defined as the “capacity to do work”

- **Kinetic energy** – form of energy possessed by virtue of motion
- **Potential energy** – stored energy possessed by virtue of position, internal stresses, electric charge, and other factors
- May exist in various forms
- Measured in units of joules (J) or electron volts (eV)

$$1 \text{ eV} = 1.60218 \times 10^{-19} \text{ J}$$

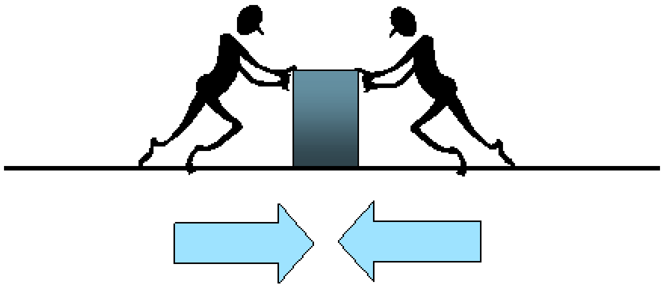
Kinetic Energy	Potential Energy
Radiant Energy 	**Nuclear** 
Thermal Energy 	**Chemical** 
Motion 	**Stored Mechanical** 
Sound 	**Gravitational** 
Electrical 	

Understanding how ENERGY is transferred is necessary for understanding radiation dose



ENERGY is conserved. *It can be neither created or destroyed, only transferred from one system to another or from one form to another.*

ENERGY is transferred by "FORCES"



Only four fundamental **FORCES** are recognized in physics:

(1) Strong,

(2) Electromagnetic,

(3) Weak, and

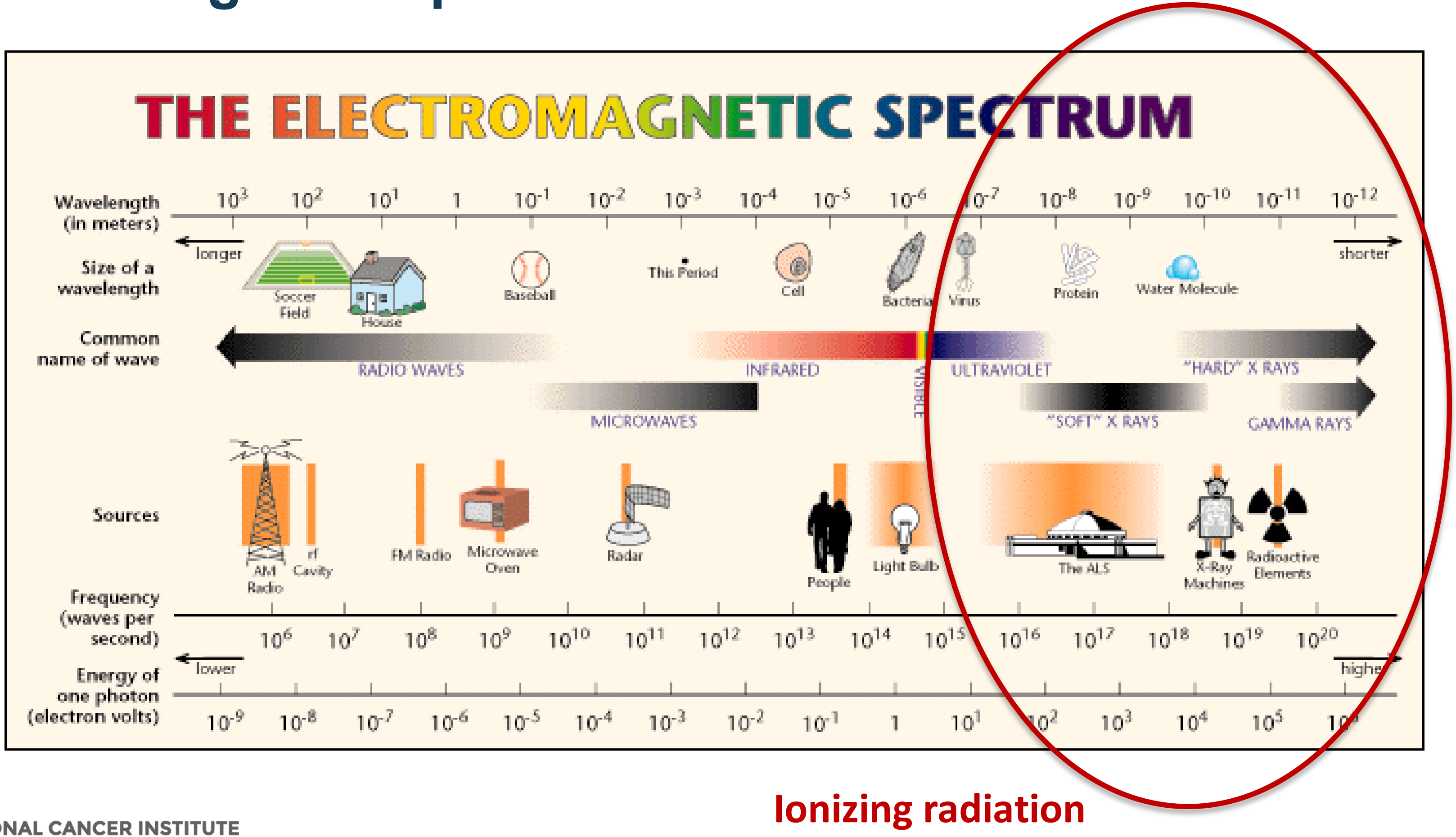
(4) Gravitational (in order of decreasing strength).

These fundamental forces account for why the nuclei of all atoms stay together and also explains radioactive decay.

How are ENERGY and FORCES related to Radiation Epidemiology and Dosimetry?

- **Radiation Dosimetry** refers to the determination of the amount of radiation energy absorbed by ("transferred to") a substance or biological material (human body, tissues, organs)
- **ENERGY** and "how it is transferred" explains radioactivity, and are relevant for understanding where radiation comes from and how it interacts with materials
- **Radiation Epidemiology** helps us understand the health effects associated with a radiation exposure
- Therefore, the principles of radiation **ENERGY** and **FORCES** provide logical links for understanding **Radiation Dosimetry** and **Radiation Epidemiology**

Electromagnetic Spectrum



Ionizing versus Non-ionizing Radiation

Radiation, in our context, is energy in the form of high speed particles or electromagnetic waves.

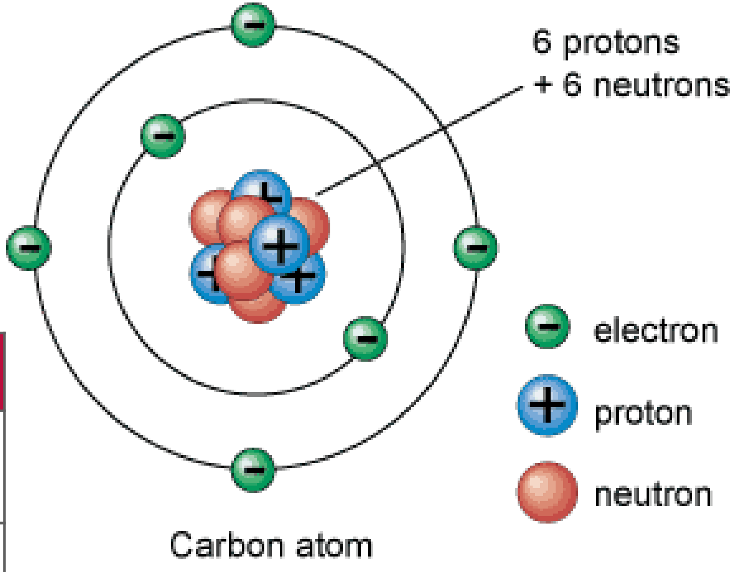
- **Ionizing radiation** has enough energy to remove bound electrons, causing atoms to become charged or "ionized" (E > 10-33 eV)
  - Examples are x-rays, gamma rays, electrons
- **Non-ionizing radiation** does NOT have enough energy to removed bound electrons (E < 10-33 eV)
  - Examples are microwaves, radar, and visible light

The Atom and Radioactive Decay

Bohr Model of the Atom

- Atoms consist of a nucleus surrounded by orbiting electrons (or electron clouds)
- Nucleus contains protons and neutrons

	Electron	Proton	Neutron
Symbol	e-	p	n
Charge	-1	+1	0
Relative mass (amu)	1/1836	1.0073	1.0087

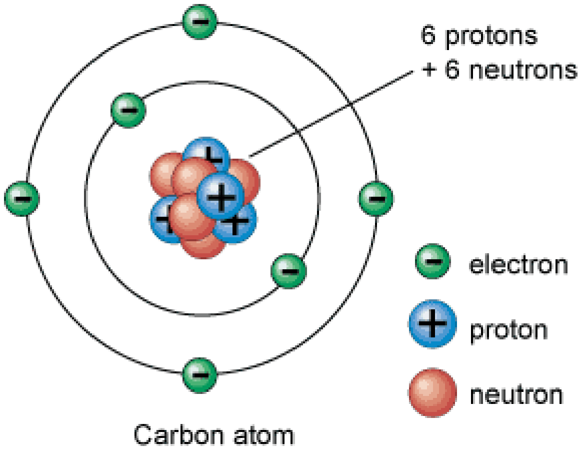


Diameter of nucleus ~10^{-12} cm
Diameter of atom ~10^{-8} cm

Atomic Nomenclature (1)

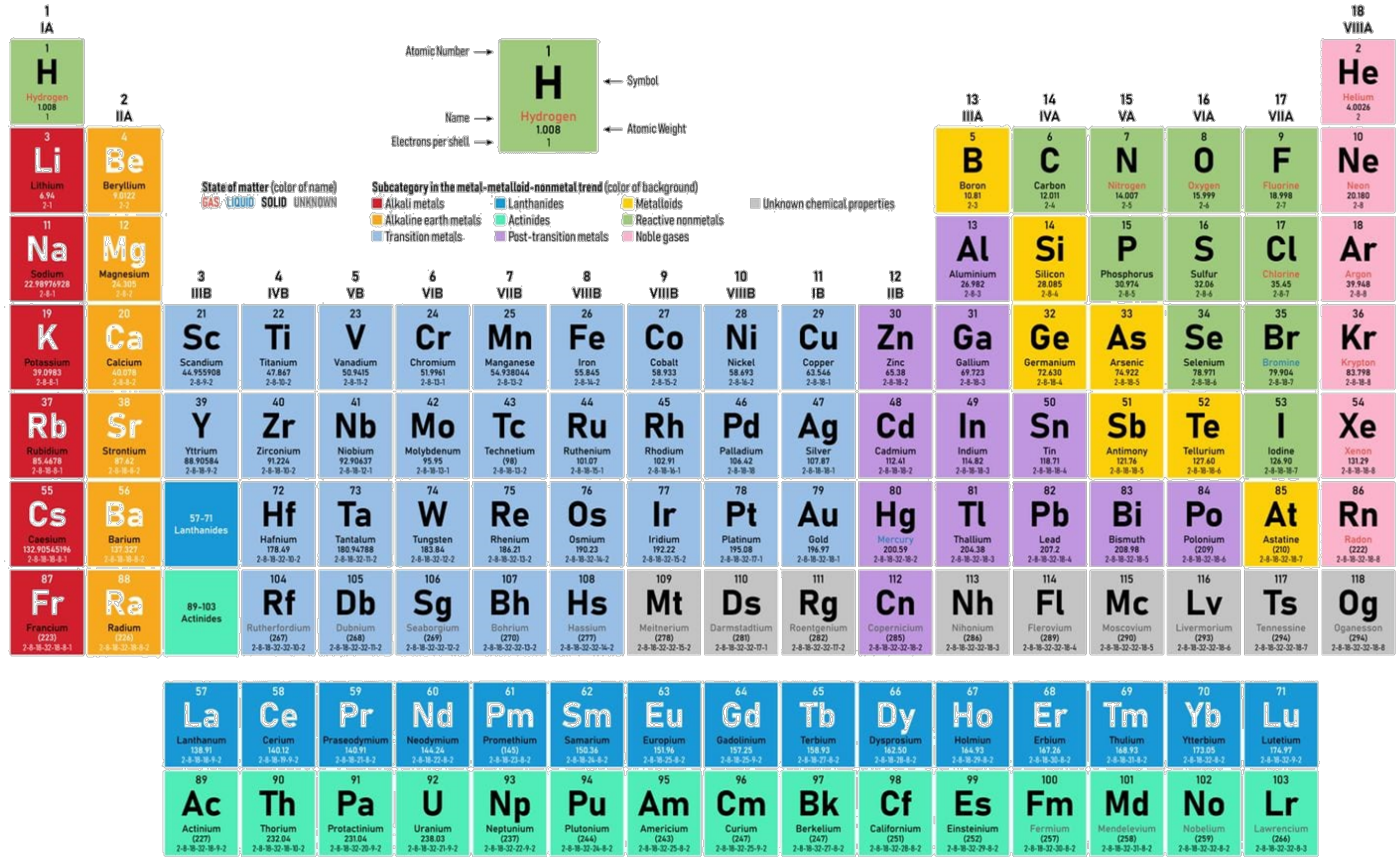
- Atomic symbol X = element symbol
- Atomic number Z = # protons
- Mass number A = # protons + neutrons

$${}^{A}_{Z}X$$



$${}^{12}_{6}C$$ OR **C-12**

Periodic Table of the Elements



Atomic Nomenclature (2)

- Isotopes (same chemical element or Z)

$$^{123}_{53}\mathrm{I}\,,\ ^{124}_{53}\mathrm{I},\ ^{125}_{53}\mathrm{I}\,,\ ^{126}_{53}\mathrm{I},\ ^{127}_{53}\mathrm{I}\,,\ ^{128}_{53}\mathrm{I},\ ^{129}_{53}\mathrm{I}\,,\ ^{130}_{53}\mathrm{I},\ ^{131}_{53}\mathrm{I}\,,\ ^{132}_{53}\mathrm{I}$$

- Isobars (same A)

$$^{131}_{50}\mathrm{Sn}\,,\ ^{131}_{51}\mathrm{Sb},\ ^{131}_{52}\mathrm{Te}\,,\ ^{131}_{53}\mathrm{I},\ ^{131}_{54}\mathrm{Xe}\,,\ ^{131}_{55}\mathrm{Cs}$$

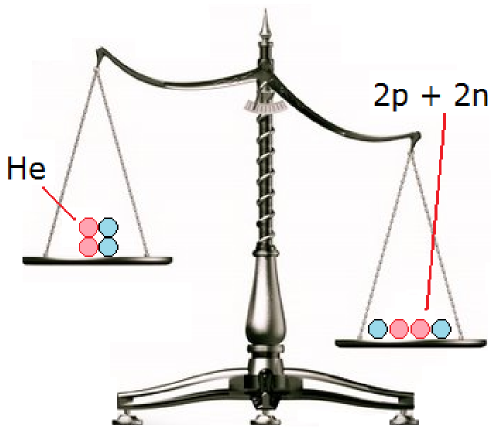
- Isotones (same # neutrons)

$$^{125}_{48}\mathrm{Cd}\,,\ ^{126}_{49}\mathrm{In},\ ^{127}_{50}\mathrm{Sn}\,,\ ^{128}_{51}\mathrm{Sb},\ ^{129}_{52}\mathrm{Te}$$

- Metastable states (excess energy state)

$^{130m}_{53}\mathrm{I}$ (half−life 9 minutes), $^{132m}_{53}\mathrm{I}$ (half−life 1.4 hours)

Mass of an atomic nucleus is always smaller than the sum of rest masses of components



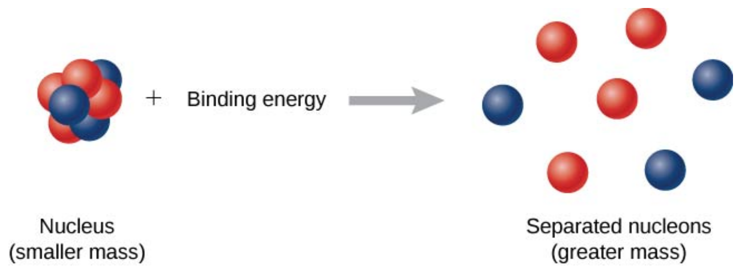
Mass Defect

A helium nucleus has slightly less mass than the total mass of 2 protons and 2 neutrons.

This missing mass is called the mass defect, and the energy equivalent of the mass defect is the binding energy of the helium nucleus.

Binding Energy

$$BE = [Zm_p + (A\text{-}Z)m_n - {}^{A}_{Z}\mathrm{m}\,]\,c^2$$

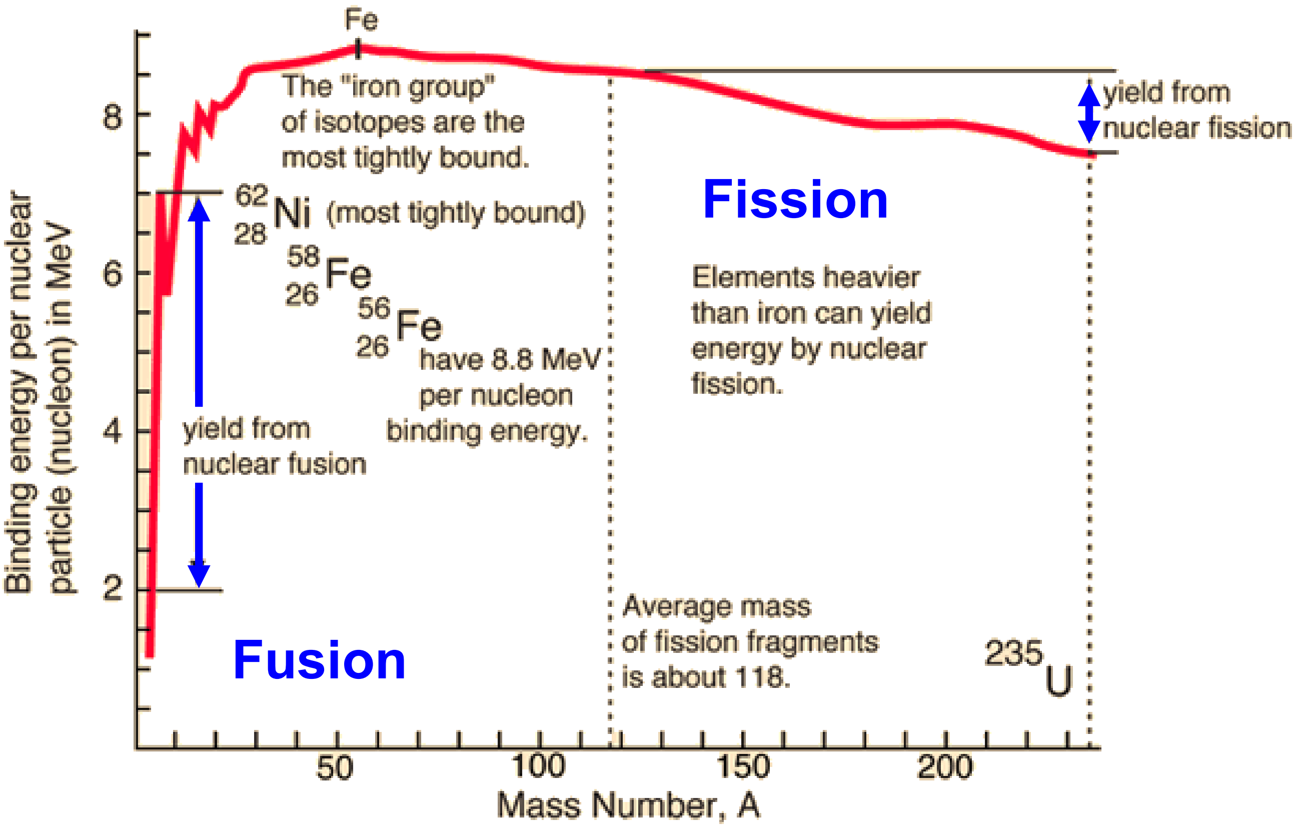


m_{He} m_p m_n

$$4.0016 - 2\times(1.0073) + 2\times(1.0087) = 0.0304\ \text{amu} \times 931.5\ \frac{MeV/c^2}{amu} = 28.3\ \frac{MeV}{c^2}$$

Binding energy explains the source of the energy released during radioactive decay

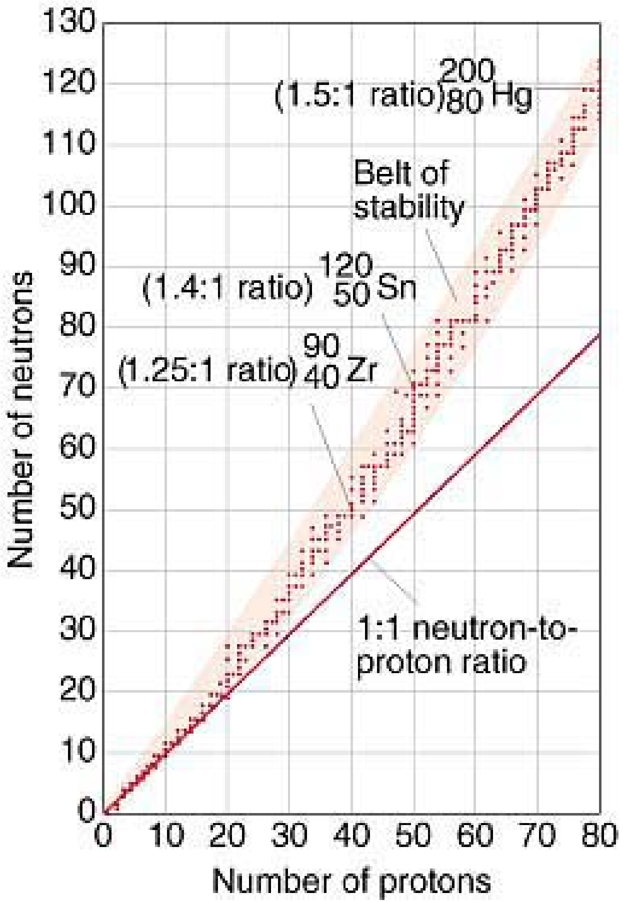
Nuclear Binding Energy Curve



Nuclear Decay

- Transformation of unstable atoms towards more stable conditions is called **nuclear transformation** or **radioactive decay**
- **Nuclear transformation** occurs because of instability in neutron-to-proton ratio or because nucleus in excited state from previous transformation
- **Radioactivity** is property of unstable atoms transforming to more stable configuration, releasing energy in form of photons or charged particles – **radiation**!!!

Plot of p vs n for stable nuclides



"Activity" is the strength of radioactive source

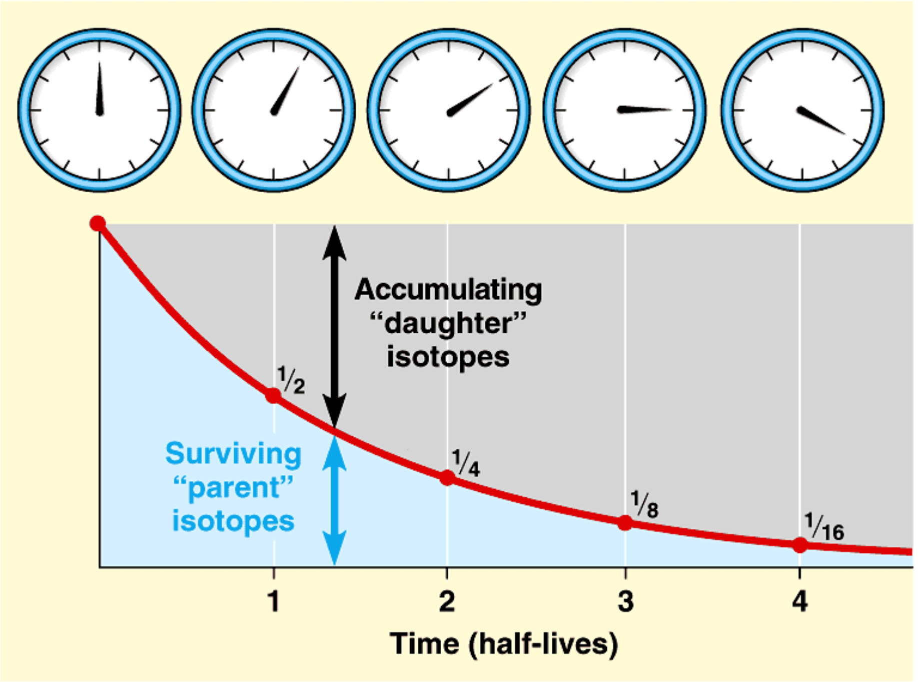
- Unit of radioactivity historically was the **Curie** and was defined to be equal to the disintegration rate of 1 gm of ^{226}Ra or 3.7×10^{10} disintegrations per second (d/s)
- The units of radioactivity in the international system of units is the **Becquerel (Bq) which is equal to 1 d/s**.

1 Bq	**≈ 27 pCi**
1 kBq	**≈ 27 nCi**
1 MBq	**≈ 27 µCi**
1 GBq	**≈ 27 mCi**
1 TBq	**≈ 27 Ci**


Marie Curie

Radionuclide Half-Life

- Half-life is the length of time for **half of the atoms** of a given nuclide to decay
- Half-life determines the rate at which nuclides release radiation (energy)
- The half-life is a unique characteristic of each nuclide and **range from millionths of a second to millions of years**

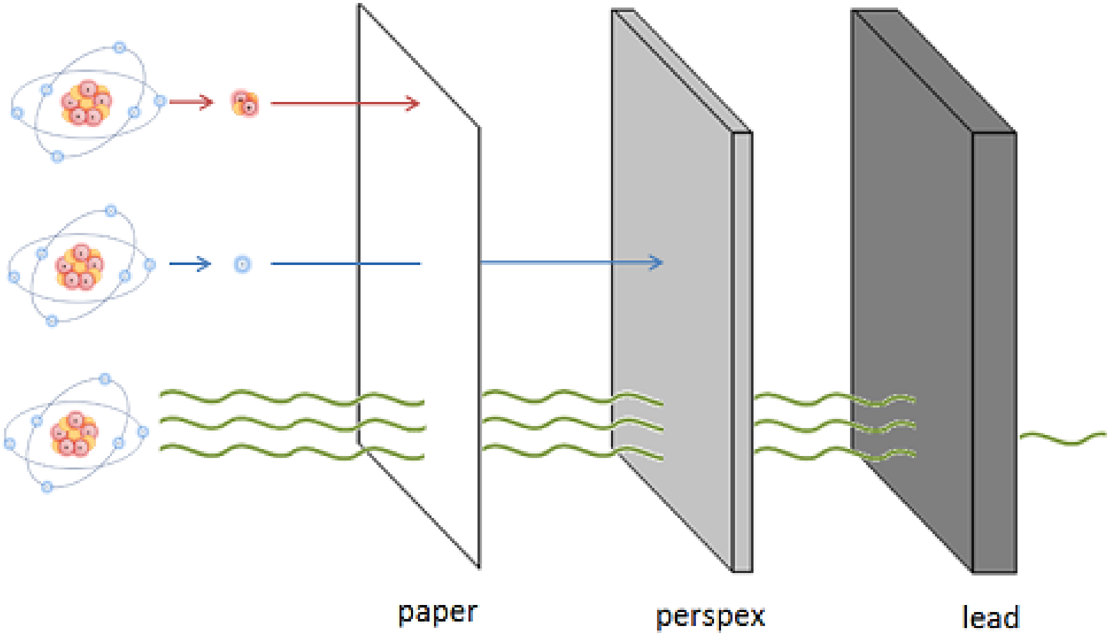


Emitted radiation “transfers” energy, resulting in “dose”

Alpha particles α

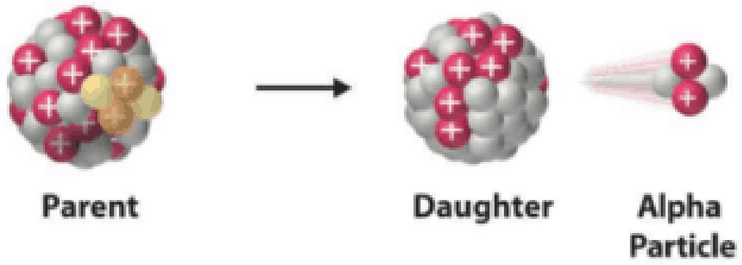
Beta particles β

Gamma rays γ



Alpha Decay (1)

- All elements heavier than lead are unstable; most decay by alpha emission
- Alpha particle consists of 2 protons and 2 neutrons
- Disintegration energy (Q-value) determined by difference in rest masses of the reactants and products
- Typical Q-value is 4 to 6 MeV, with most appearing as kinetic energy of the alpha particle (conservation of momentum)



$$Q = \left[m_{parent} - \left(m_{daughter} + m_{alpha}\right)\right]c^2$$

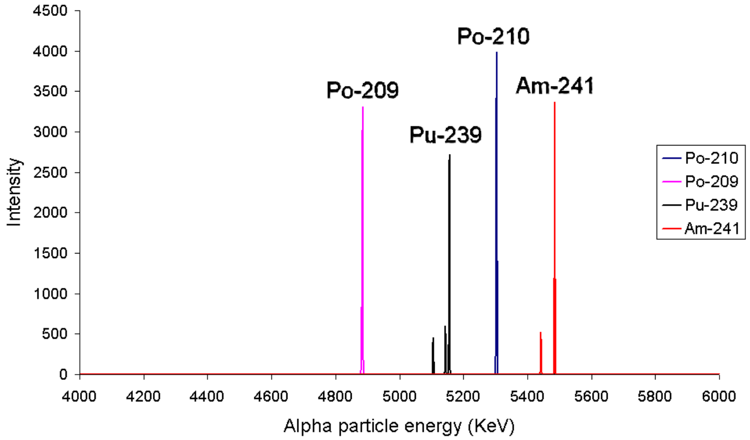
<u>Example:</u>

$$^{226}_{88}Ra \rightarrow \ ^{222}_{86}Ra + \,^{4}_{2}He + 4.78\ MeV$$

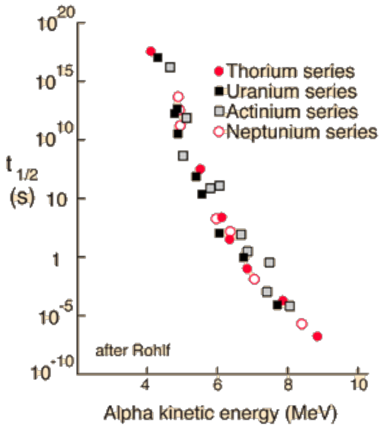
Half-life 1600 years

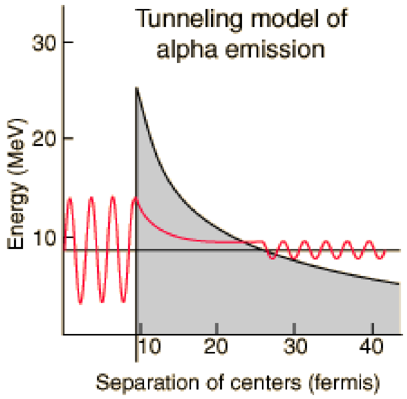
Alpha Decay (2)

Alpha decay is monoenergetic



Alpha decay modeled as quantum tunneling through a Coulomb barrier





Geiger-Nuttal Law

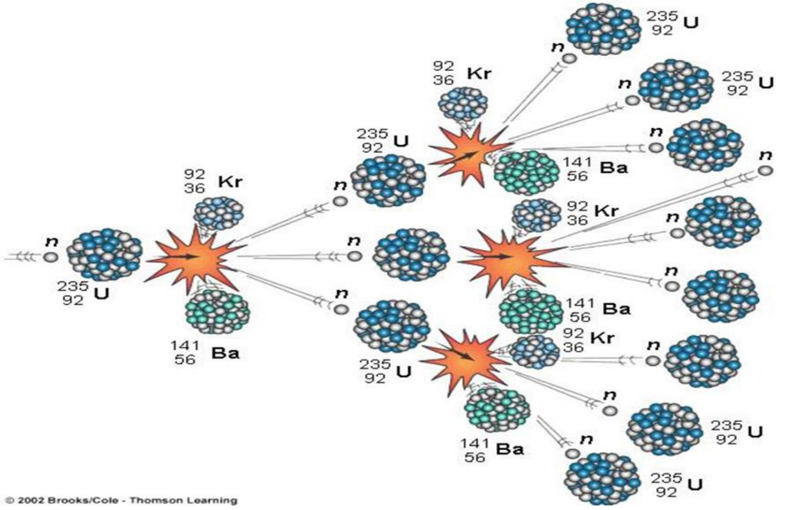
$$\log(t_{1/2}) = A + \frac{B}{\sqrt{Q_\alpha}}$$

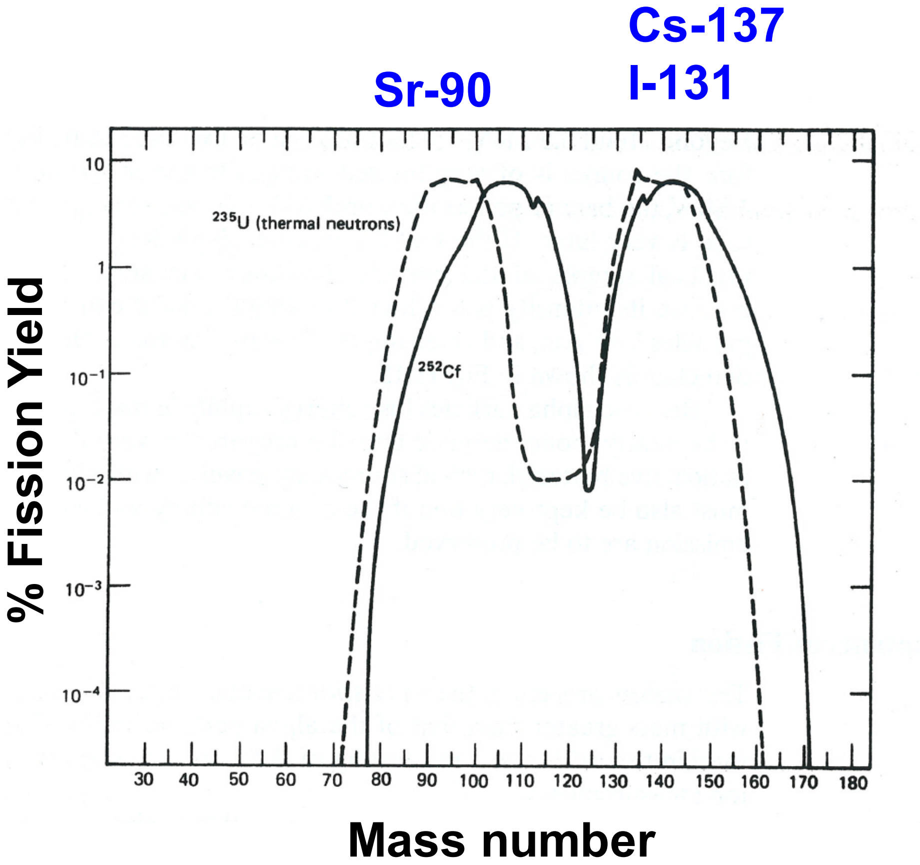
Theory of alpha decay

http://www.physics.usyd.edu.au/teach_res/mp/doc/qp_alpha_decay.pdf

Nuclear Fission

Some heavy nuclei can split into several smaller fragments plus neutrons.





Beta Decay (1)

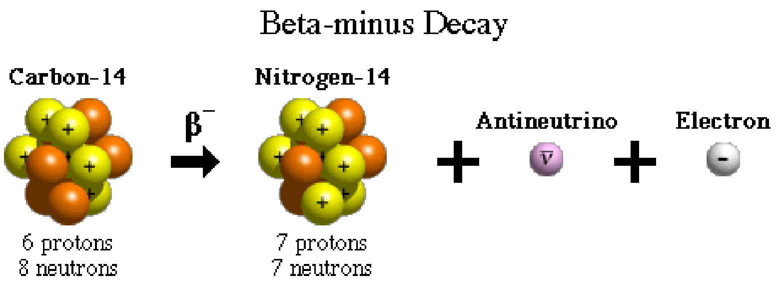
Type of radioactive decay in which an energetic electron or positron is emitted from an atomic nucleus.

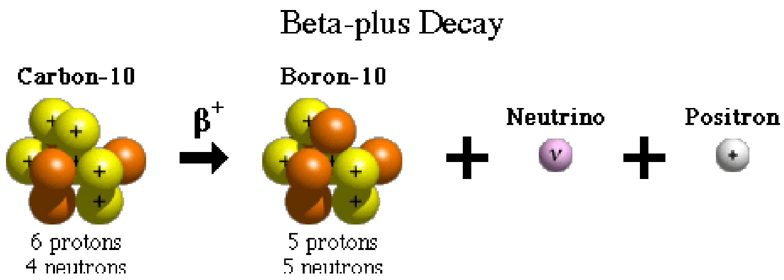
In β decay, there are 3 processes:

$n \rightarrow p + \beta^- + \bar{\nu}$ (**negative β decay**) ← n:p ratio too high

$p \rightarrow n + \beta^+ + \nu$ (**positive β decay**) ← n:p ratio too low

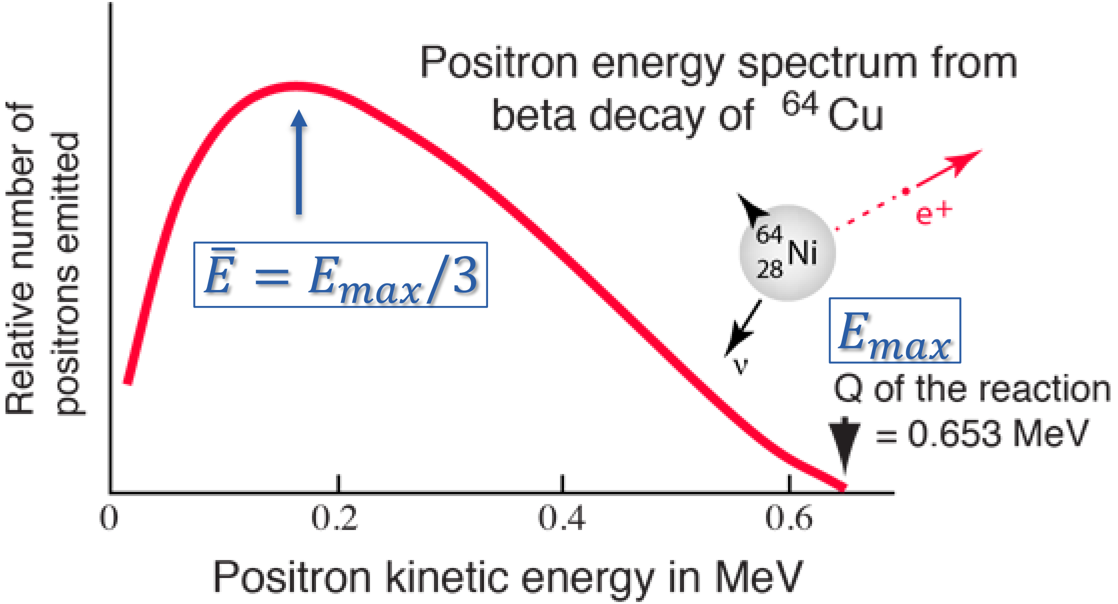
$p + e^- \rightarrow n + \nu$ (**electron capture, not discussed**)





Beta Decay (2)

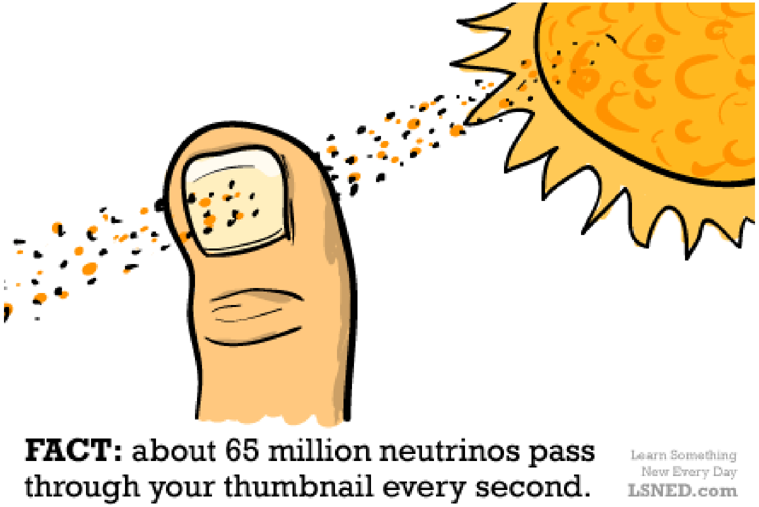
Because the energy of the recoil nucleus is essentially zero, the Q value is shared between the beta particle and the “invisible” neutrino, resulting in an energy spectrum

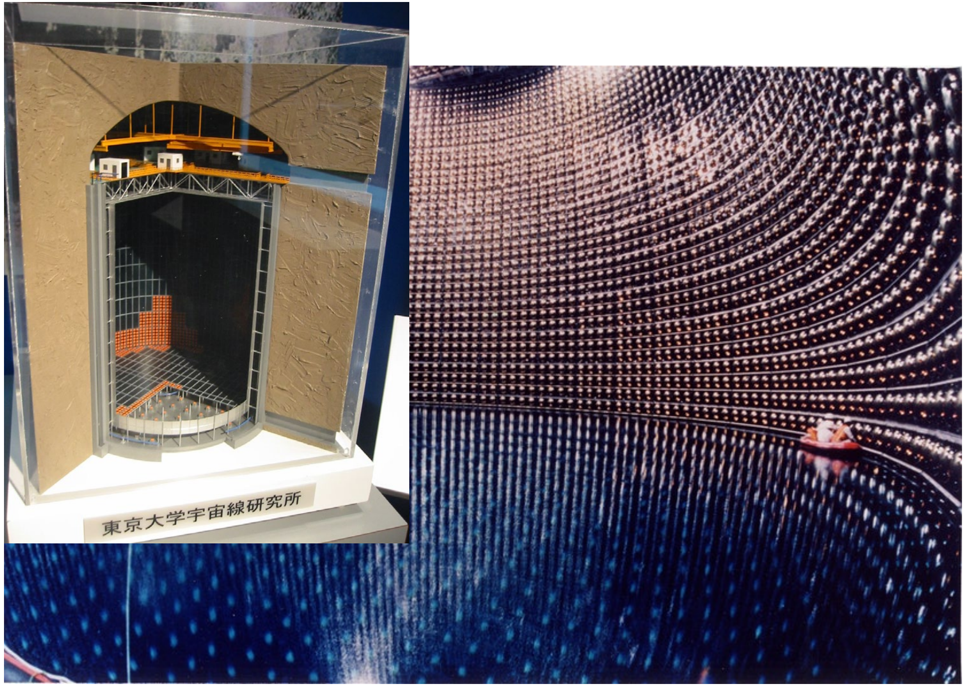


Neutrinos everywhere, but contribute negligible dose

Neutrinos have no charge and tiny, but finite, mass – weakly interacting

$$m_{neutrino} < \frac{m_{electron}}{4 \times 10^6}$$

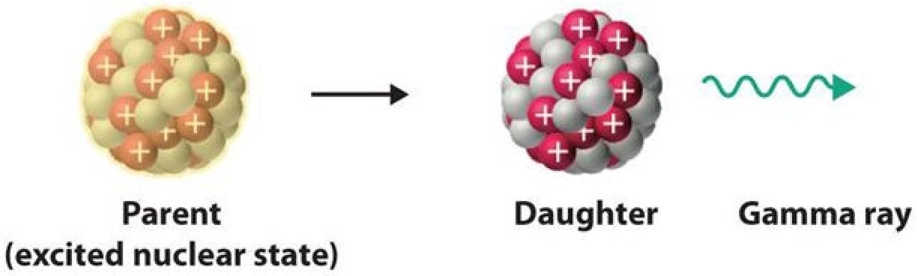




Super-Kamiokande Neutrino Detector (Japan)

Gamma ray Emission

- Nuclei can be left in excited states following radioactive decay
- The nuclei can “settle” by emitting heavy particle or a gamma ray
- Gamma rays have no mass or charge

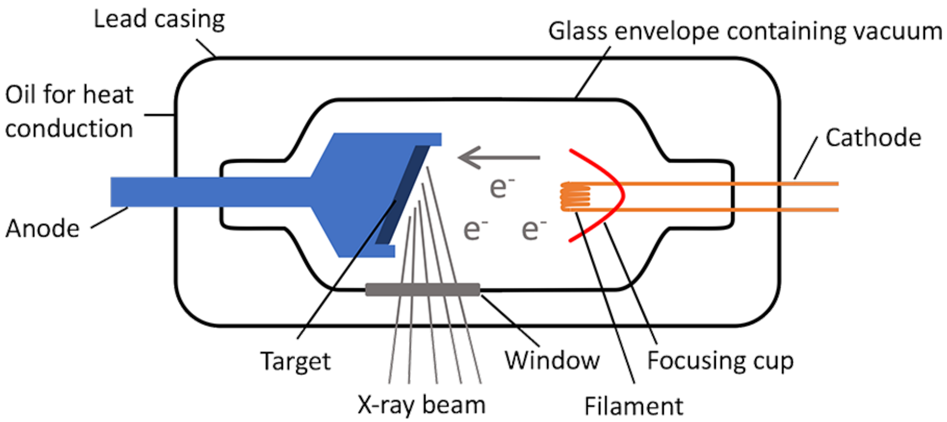


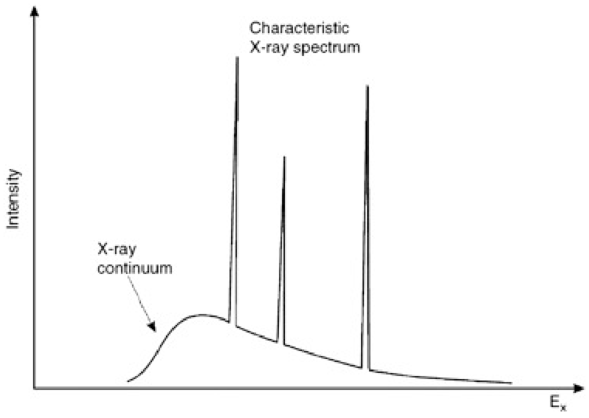
$$^{238}_{92}\mathrm{U} \rightarrow \underset{\substack{\text{excited}\\ \text{nuclear}\\ \text{state}}}{^{234}_{90}\mathrm{Th}^*} + ^{4}_{2}\alpha \xrightarrow{\text{relaxation}} {^{234}_{90}\mathrm{Th}} + ^{0}_{0}\gamma$$

Gamma ray versus X-ray

- Both are **photons** or **electromagnetic radiation**
- Key difference is how they are produced
  - **Gamma ray** – Emitted as part of settling processing of an excited nucleus after it undergoes radioactive decay. Highest energy in the electromagnetic spectrum.
  - **X-rays** – Produced when electrons rearranged within atomic orbitals or when electrons strike a target.

How are medical x-rays produced?



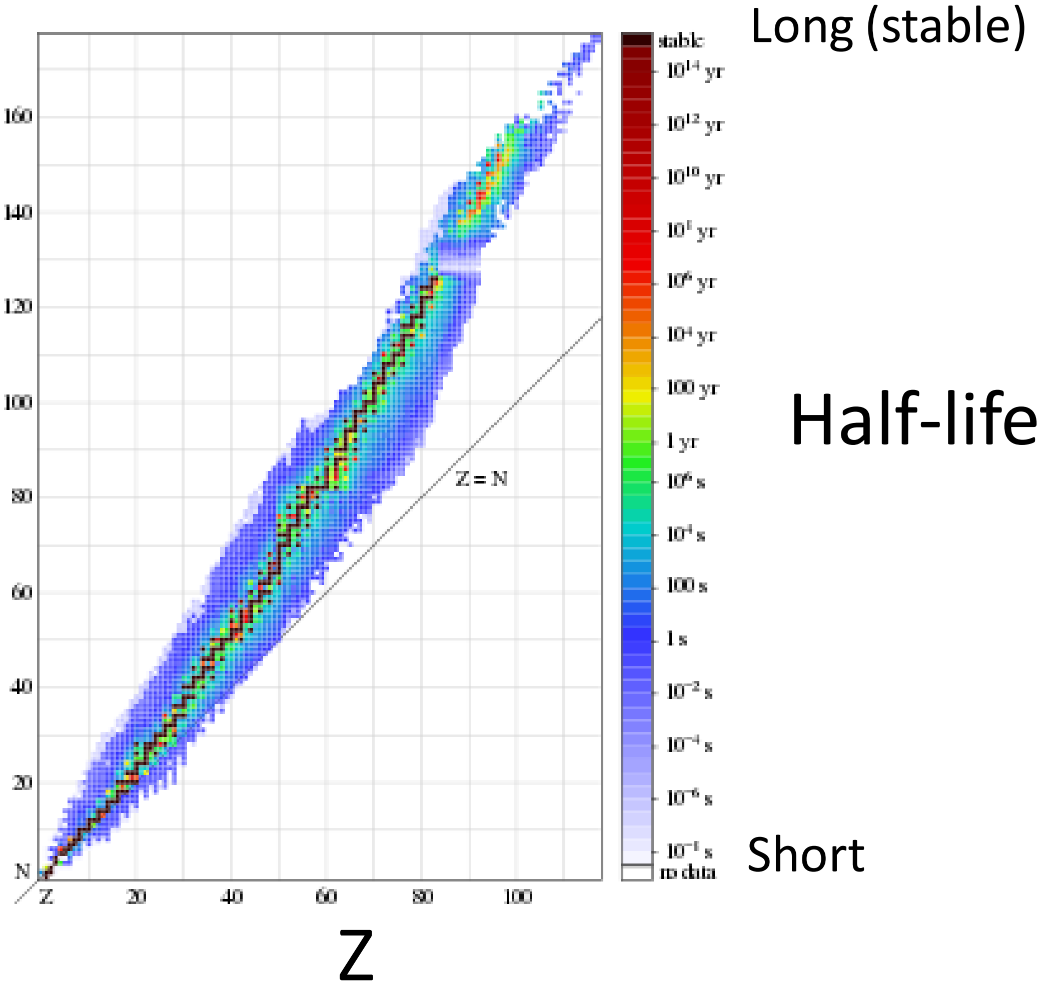


Bremsstrahlung is the mechanism used to generate x-rays for medical use.

Electrons are emitted by a hot filament and drawn to metal target of opposite charge.

When the electrons interact or "brake" inside the target, x-rays are emitted.

Table of Nuclides



LNHB Decay Data

http://www.nucleide.org/DDEP_WG/DDEPdata.htm

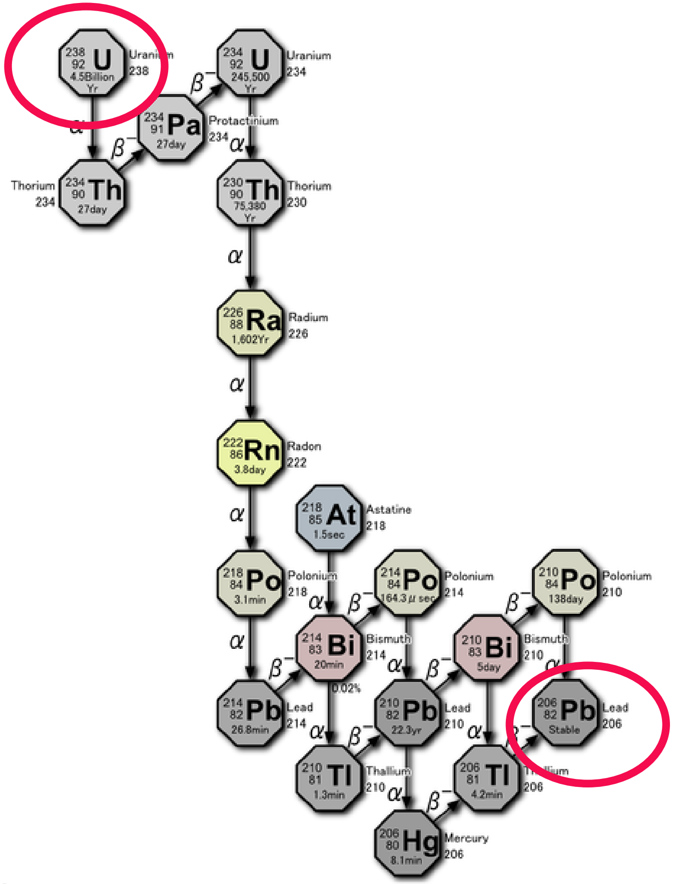
Some Facts About Radionuclides

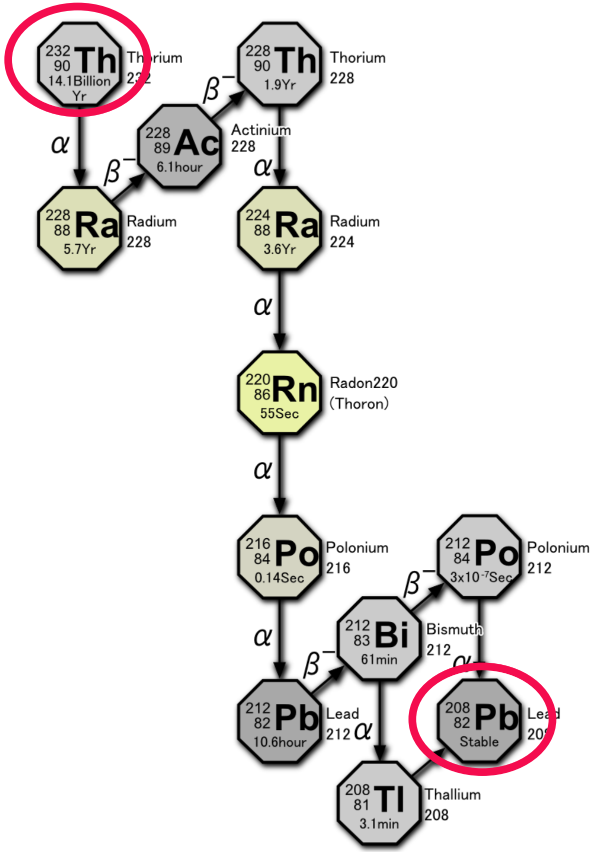
- While there about 113 chemicals, there about 3,100 radionuclides found in nature
- About 25 radionuclides have half-lives sufficiently long to have survived since the formation of earth
- About 35 radionuclides have shorter half-lives but are being continuous produced by the decay of parent nuclides
- About 1,000 radionuclides are artificially produced
  - Those with Z > 92 (uranium) are called **"transuranics"** and are produced by bombarding lighter atoms with neutrons or alpha particles

There are four families of *naturally* occurring radionuclides

- Each family begins with a parent radionuclide that decays through a number of progeny nuclides to a final stable nuclide
- The transition between each successive nuclides occurs by successive alpha and beta decay
- Two series are particularly important to human exposure: **Uranium-238 (^{238}U)** and **Thorium-232 (^{232}Th):**
- **The most important nuclide in terms of public exposure is Radon-222 (^{222}Rn)**

Uranium-238 and Thorium-232 Chains





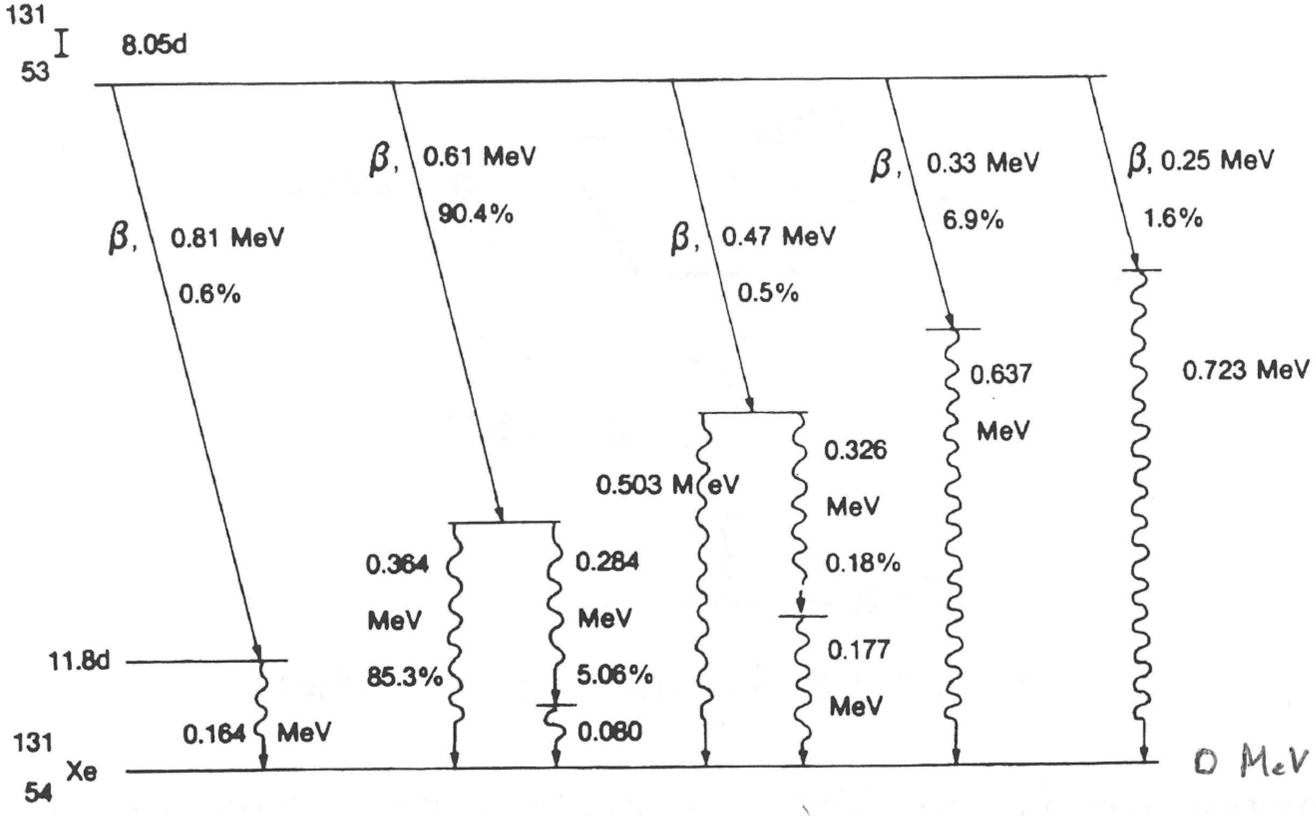
Radionuclides

- Isotopes react the same chemically, but have unique
  - Half-life
  - Type(s) of radiation emitted
  - Energy of emitted radiation
- Some radionuclide have very complex decay patterns

Example Isotopes of Iodine

Isotope	Half Life
I-122	3.6 minutes
I-123	13.2 hours
I-124	4.2 days
I-125	60.1 days
I-126	13.0 days
I-127	Stable
I-128	25.0 minutes
I-129	1.57E7 years
I-130	12.4 hours
I-131	8.0 days
I-132	2.3 hours
I-133	20.8 hours
I-134	52.6 minutes
I-135	6.6 hours
I-136	1.4 minutes

Decay Scheme of I-131



Q1: Which are examples of charged particles?

- A. Beta particles
- B. Gamma rays
- C. Alpha particles
- D. Electrons
- E. Neutrinos

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Q2: Nuclides having the same number of protons, but different number of neutrons are called?

- A. Isobars
- B. Isotopes
- C. Isomeric
- D. Isotones

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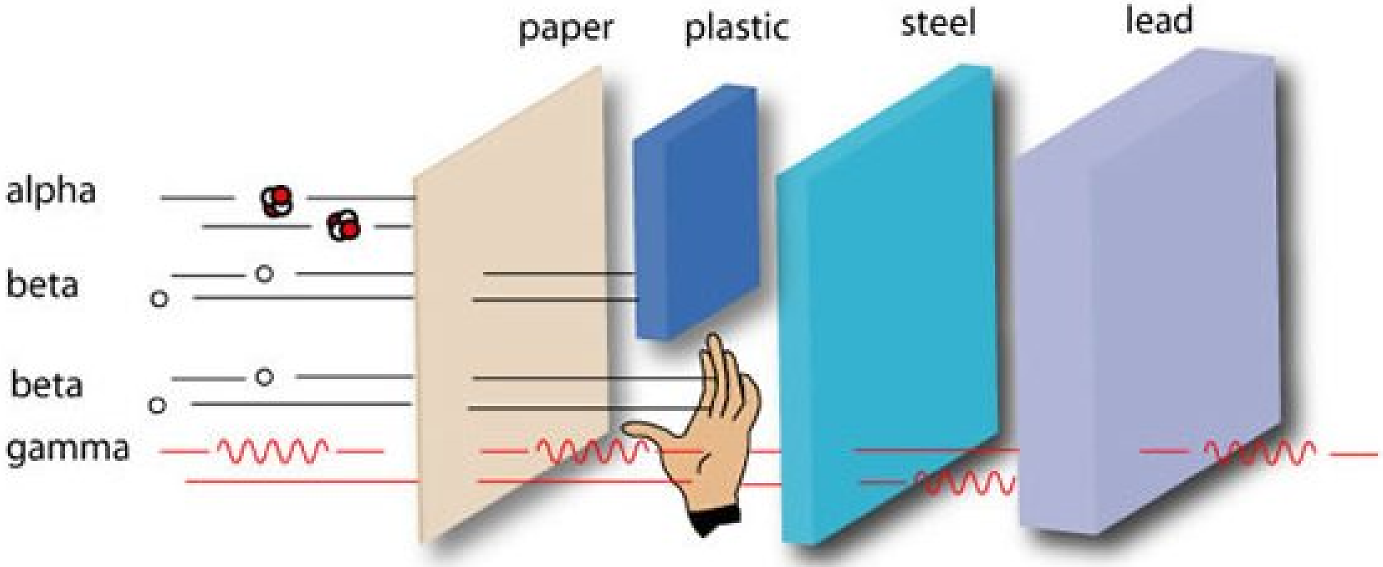
Interaction of Radiation with Matter

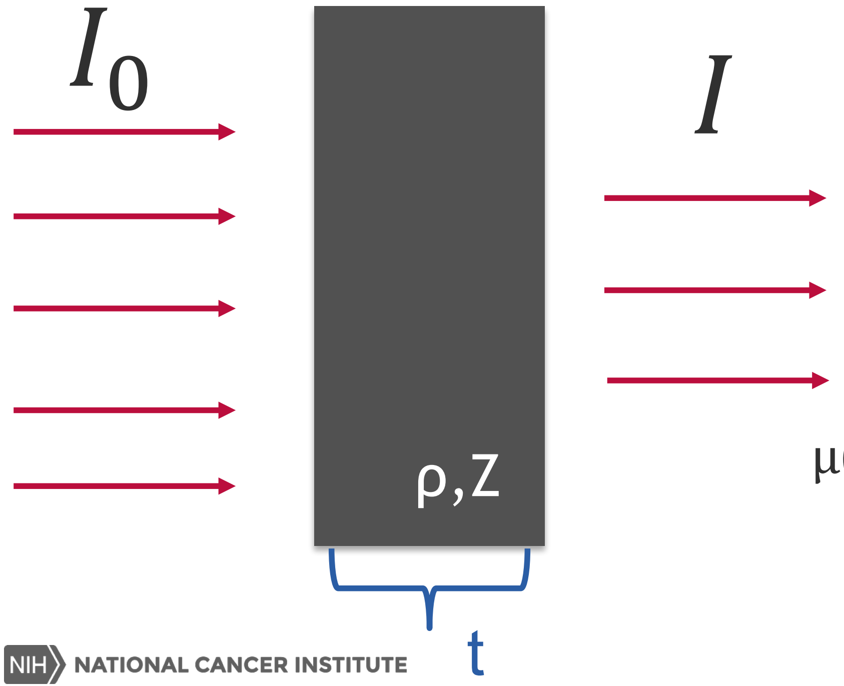
Radiation Interactions Result in Transfer of Energy

Understanding how radiation interacts with matter leads to an understanding of its penetrating power and how to protect against it



Photon Attenuation

Photon beams interact with the matter through which they pass and consequently the beam intensity is attenuated.



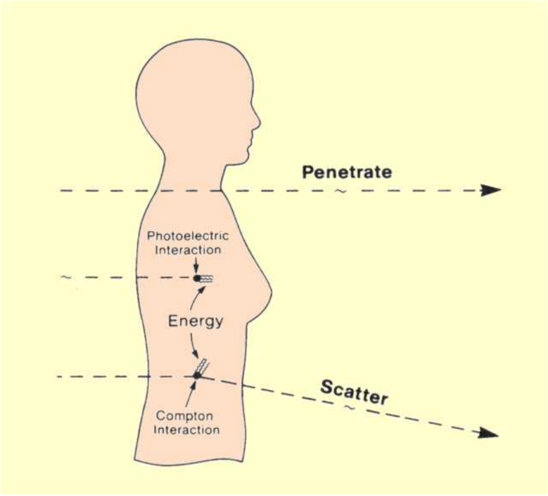
$$I = I_0 e^{-\mu t}$$

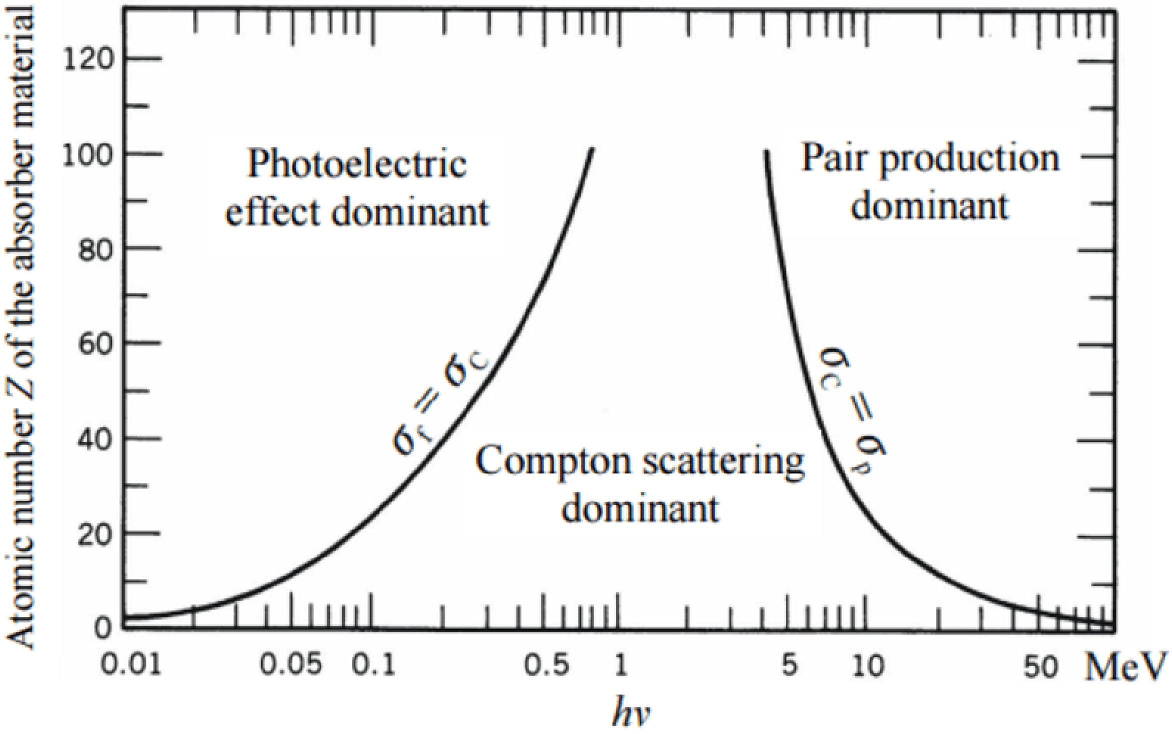
Linear attenuation coefficient

$\mu(\rho, Z) = \tau(\text{photoelectric}) + \sigma(\text{Compton}) + \kappa(\text{pair})$

Three Types of Photon Interactions with Matter

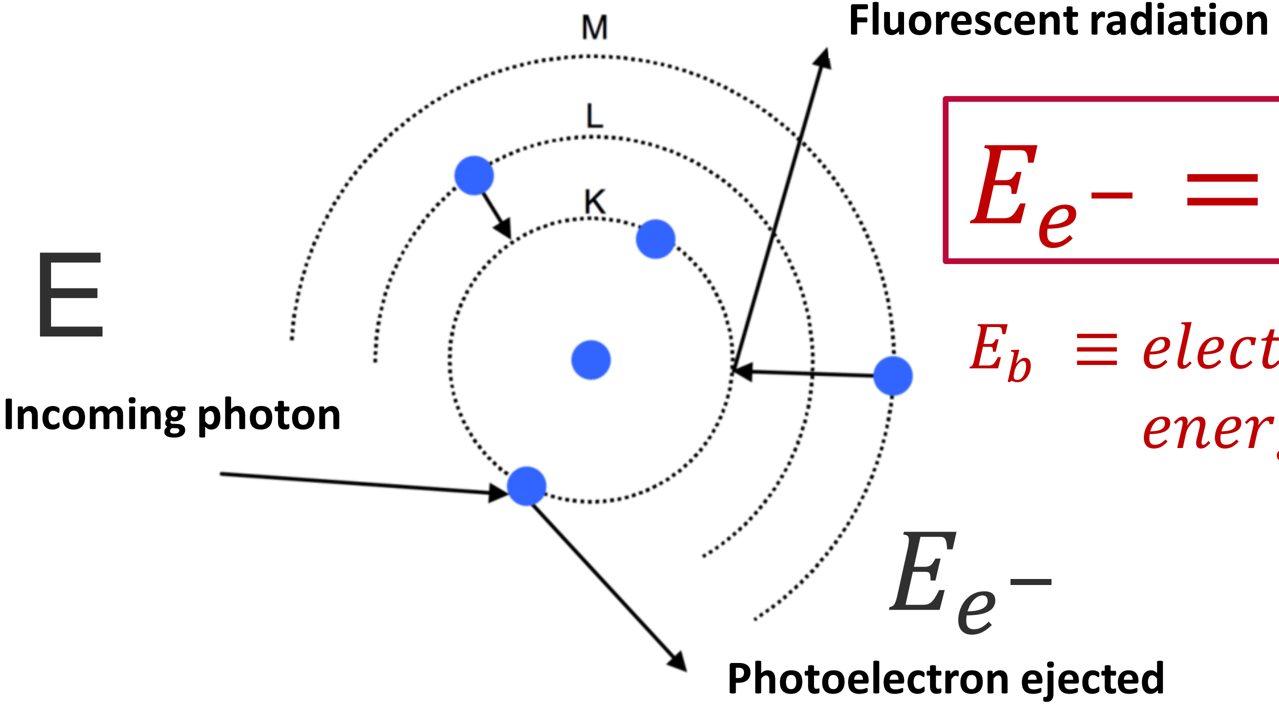
Likelihood of each interaction depends on the energy of the photon and atomic number (Z) of the absorber





Photoelectric Absorption

Interaction of photon with tightly bound electron. This photon is "absorbed" and electron ejected.

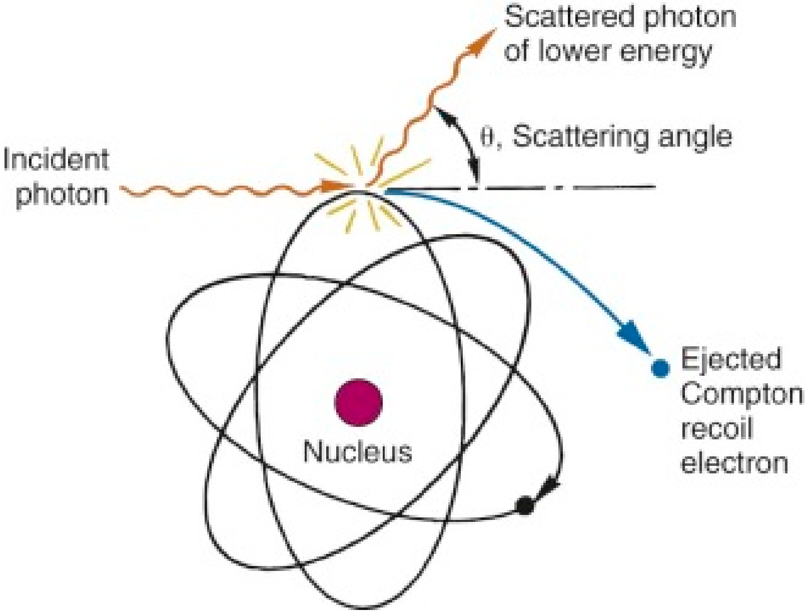


$$\boxed{E_{e^-} = E - E_b}$$

$E_b \equiv electron\ binding\ energy$

Compton Scattering

Interaction of photon with loosely bound electron. The photon scatters with reduced energy and the electron is ejected.



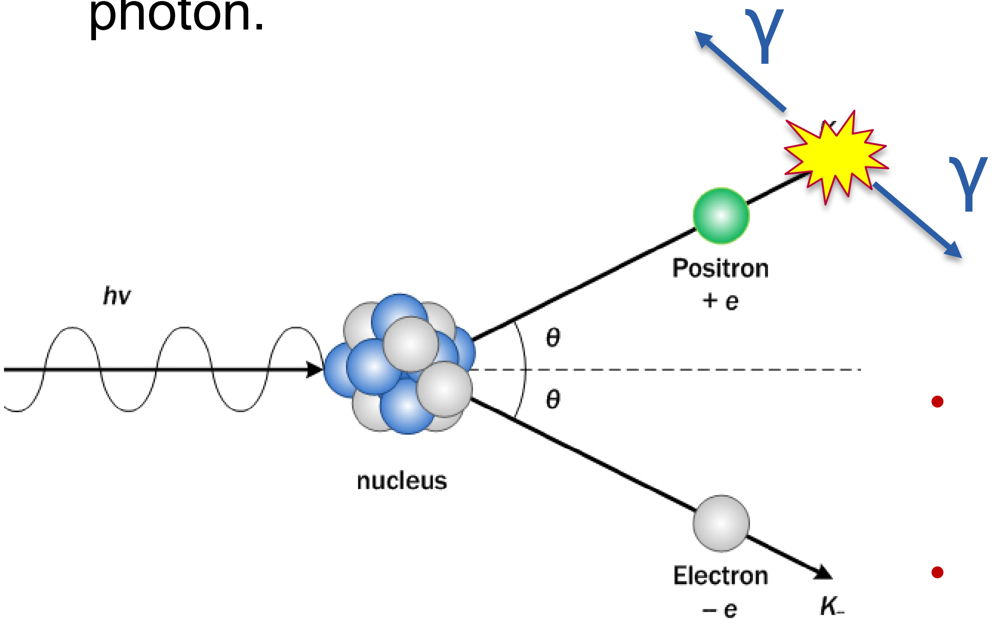
- Wavelength (energy) of the scattered photon depends of the scattering angle:

$$\lambda - \lambda' = \frac{h}{m_e c}(1 - \cos\theta)$$

- Remaining energy transferred to the Compton electron
- Angular distribution predicted by **Klein-Nishina formula**

Pair Production

Incident photon disappears and an electron and positron (positive electron) are created with total energy equal to energy of the incident photon.



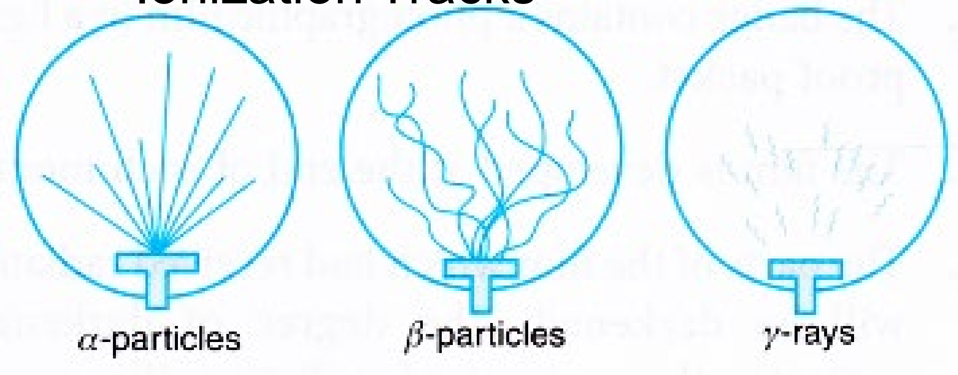
- Energetically allowed only when incident photon energy exceeds twice rest mass of the electron or 1.02 MeV
- Positron annihilates (combines) with an electron resulting in two 511 keV gamma rays

Charged Particle Interactions

- Electrons released by photon interactions and from beta decay will be moving in the tissue with some kinetic energy
- Coulomb interactions with electrons from neighboring atoms gradually slow them down
- Rate of energy loss with distance is proportional to charge of the particle and electron density of the material
- Electrons cause ionization and excitation as they lose their energy in the material --- delivering **"dose"**

Beta versus Alpha Particle Interactions

Ionization Tracks



Beta Particles

Alpha Particles

Alpha particles are relatively heavy (~7300x that of electron) and have 2 units of charge, thus, they have much shorter range because each Coulomb interaction is 2x greater than for electrons

Q3: Which photon interaction dominates at intermediate energies (10 keV to 5 MeV)?

- A. Photoelectric effect
- B. Compton Scattering
- C. Pair Production
- D. Annihilation

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Q4: Which type of radiation poses an internal, but not an external hazard to the body?

- A. Beta particles
- B. Gamma rays
- C. Alpha particles
- D. Electrons
- E. Neutrinos

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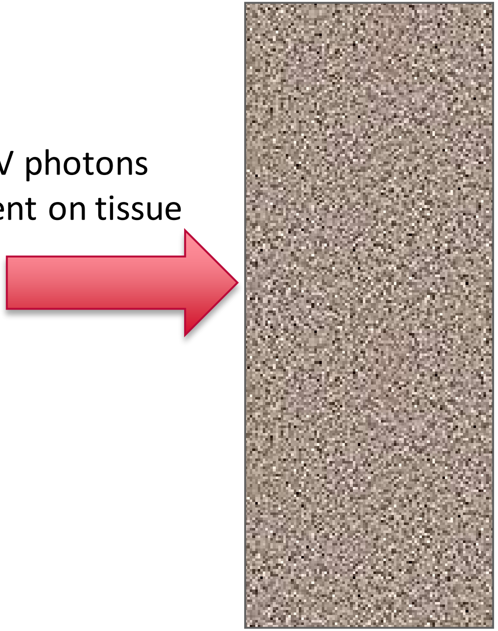
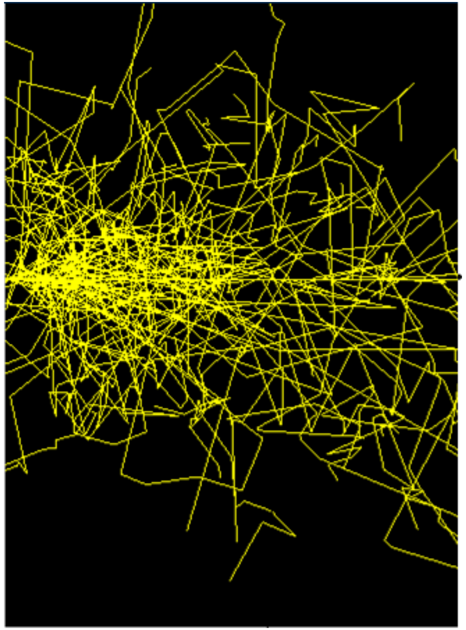
Dosimetry

Radiation Interactions Result in Deposition of Energy

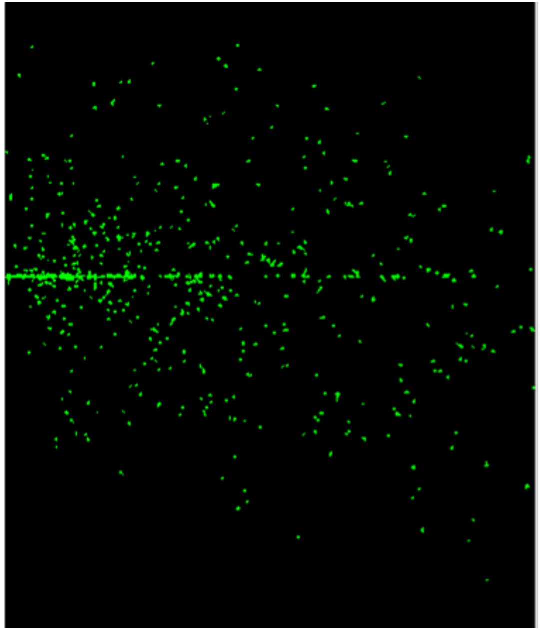
- Radiation interactions result in release of electron or photons
- The energy is not absorbed in a single event, but rather a cascade of events until all energy is absorbed

1 MeV photons incident on tissue



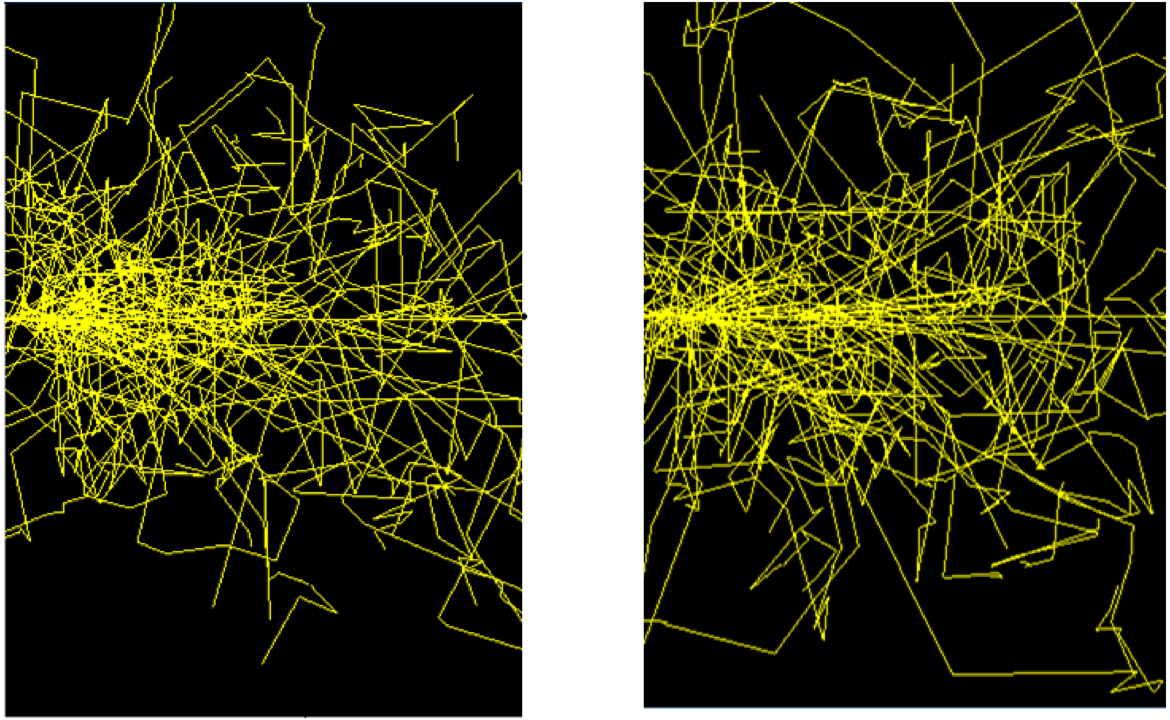


Scattered photons



Points of ionization

Interactions are random on micro-scale, but result in predictable average ionization



1^{st} 100 photons   *Next 100 photons*

Exposure

- Exposure, *X*, is defined as the absolute value of the total charge of one sign produced in air within a small volume of air as a result of ionization of the air

$$X = dq/dm$$

where **dq** is the charge liberated by the photons in the mass **dm** of material

- In SI unit is the C/kg or sometimes Roentgen (R)
- 1 R = 2.58 x 10^-4 C/kg

Kerma

- Kerma or "kinetic energy released per unit mass" characterizes a beam of photons in terms of the energy transferred to any material

$$K = dE_{tr}/dm$$

where $\mathbf{dE_{tr}}$ is the sum of the initial kinetic energies of the charged particles liberated by the photons in the mass **dm** of material

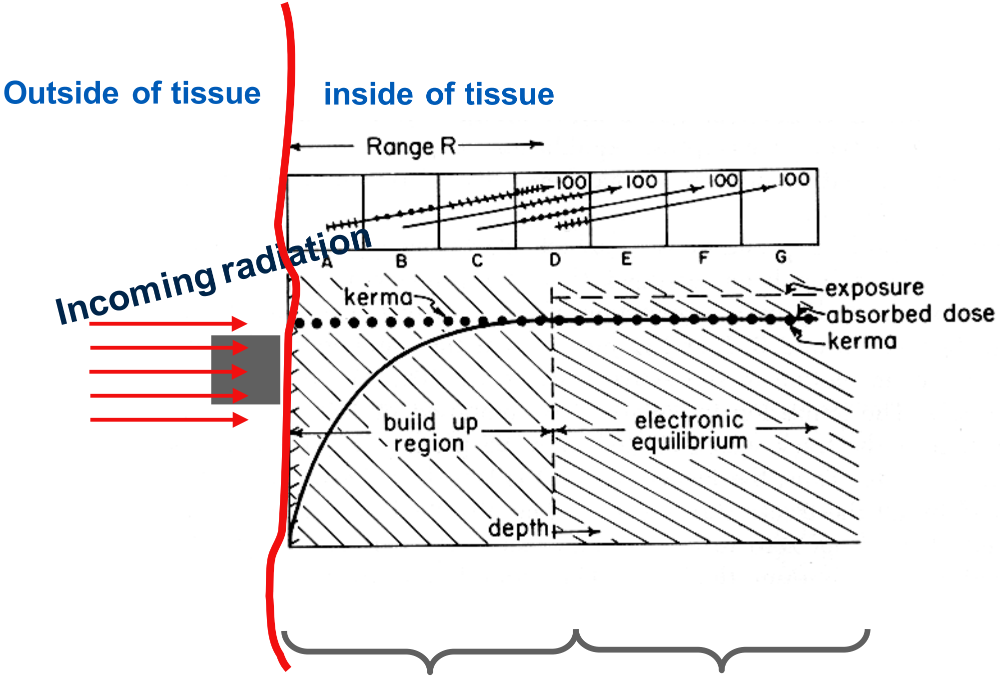
- SI unit is the J/kg which has special name **gray** (Gy)

$$K_{\mathrm{air}} \approx X \cdot (W/\mathrm{e})/(1-\bar{g}).$$

Absorbed Dose

- Radiation damage is approximately proportional to the concentration of absorbed energy in tissue. For this reason, the basic unit of radiation dose is the **absorbed energy per unit mass of tissue**.
- SI unit is the J/kg which has special name **gray** (Gy)
- Conventional units are the rad or erg/g (1 Gy = 100 rad)
- **Organ absorbed dose**, or absorbed dose averaged over an organ, is the dosimetric quantity most relevant for epidemiology

Absorbed Dose versus Kerma



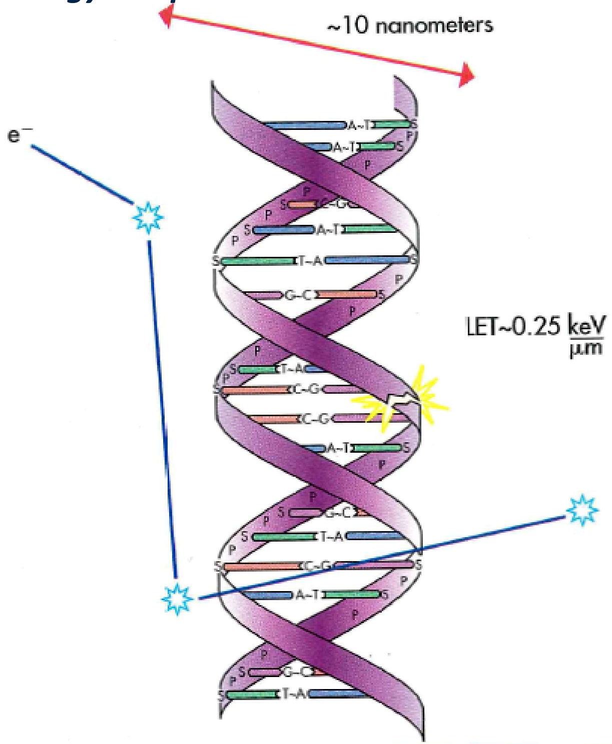
Kerma > dose in this region

Kerma = dose in this region (where number of secondary electrons entering equals those leaving)

Linear Energy Transfer (LET)

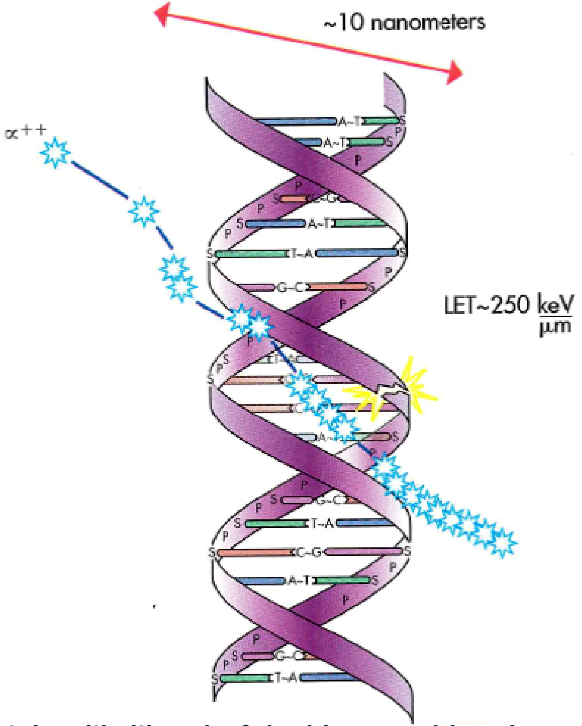
LET captures the concept that the rate of transfer of energy over same path can result in different degree of local damage

Example of "low" LET radiation damage for photons and electrons, ~0.25 keV energy lost per micron



Low likelihood of double strand DNA breakage

Example of "high" LET radiation damage for alpha particles, ~250 keV energy lost per micron



Higher likelihood of double strand breakage

Equivalent Dose

$$H_T = \sum_R w_R D_{T,R}$$

- Weighted sum of absorbed doses for each radiation type
- SI unit is the Sievert (Sv)
  (older unit is the rem, 1 Sv = 100 rem)
- Accounts for differences in LET for different radiation types and has some (but limited value) for radiation epidemiology

Absorbed dose
Energy deposited in a kilogram of a substance by the radiation

↓

Equivalent dose
Absorbed dose weighted for harmful effects of different radiations (radiation weighting factor w_R)

Radiation Weighting Factors

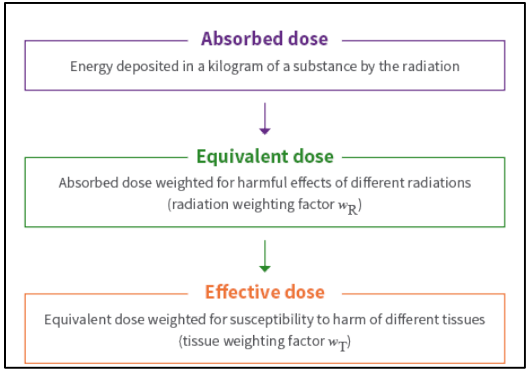
Table 2. Recommended radiation weighting factors.

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons[a] and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (see Fig. 1 and Eq. 4.3)

Effective Dose

$$E = \sum_T w_T H_T$$

- Weighted sum of equivalent doses to various organs
- SI unit is the Sievert (Sv)
  (older unit is the rem, 1 Sv = 100 rem)
- Accounts for differences in tissue sensitivity for radiation protection (regulatory) purposes and has little use in epidemiology



Tissue weighting factors

ORGAN	ICRP 26	ICRP 60	ICRP 103
Bone marrow (red)	0.12	0.12	0.12
Colon	-	0.12	0.12
Lung	0.12	0.12	0.12
Stomach	-	0.12	0.12
Breast	0.15	0.05	0.12
Gonads	0.25	0.20	0.08
Bladder	-	0.05	0.04
Esophagus	-	0.05	0.04
Liver	-	0.05	0.04
Thyroid	0.03	0.05	0.04
Bone Surface	0.03	0.01	0.01
	1977	**1991**	**2007**

Q5: Which are examples of high LET radiation?

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- B. Gamma rays
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- E. Neutrons

Q6: Which dose quantity is used primarily for radiation protection purposes and has little value for radiation epidemiology?

- A. Kerma
- B. Absorbed Dose
- C. Effective Dose
- D. Equivalent Dose

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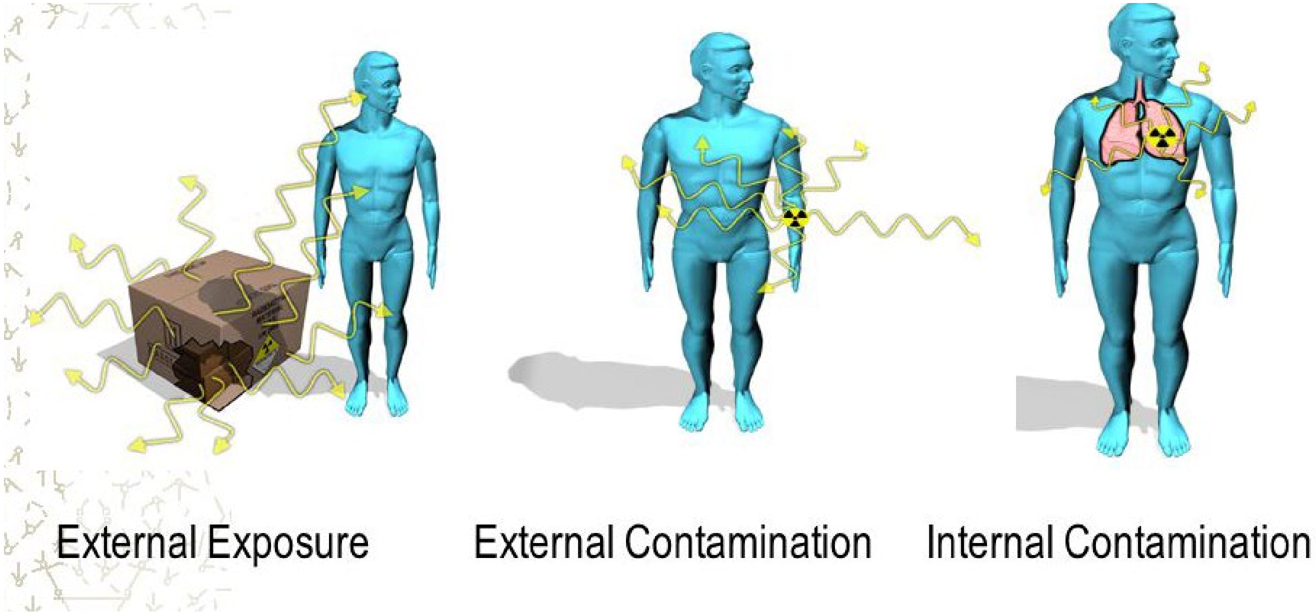
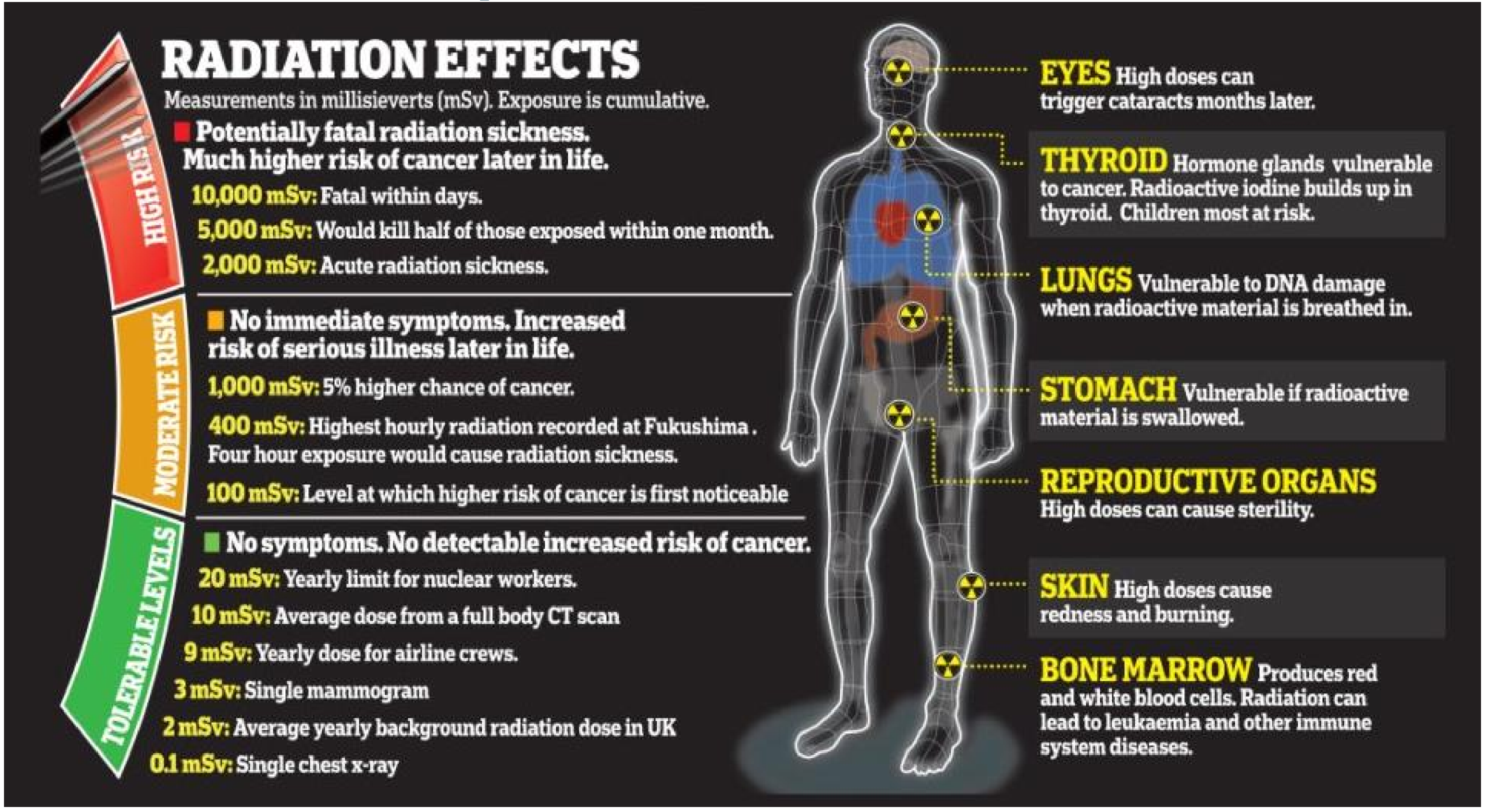
External versus Internal Dosimetry



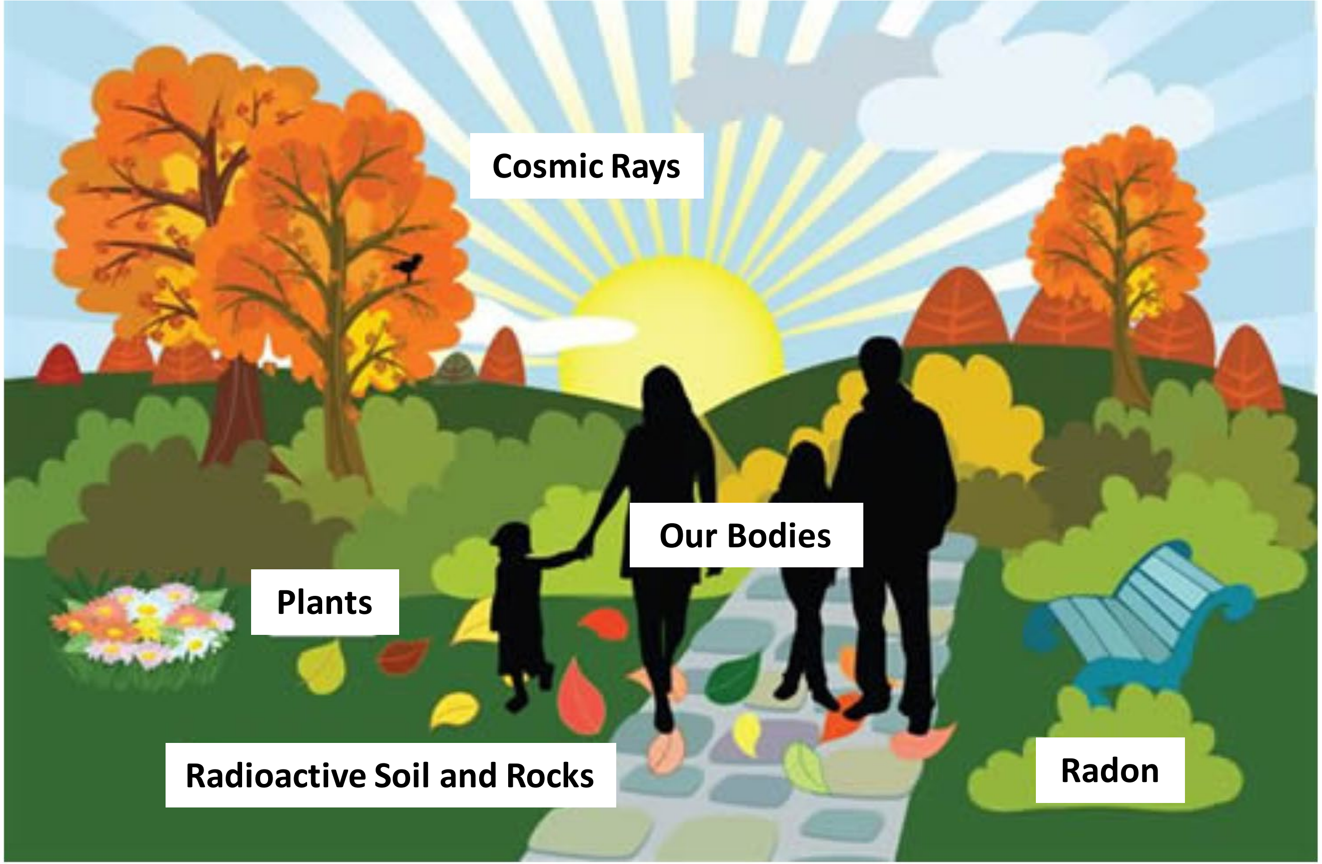
- **Inhalation**
- **Ingestion**
- **Absorption through skin or wounds**

Radiation Effects Depend on How Much Dose Received



This is why dose assessment is important…

Natural Radiation is Everywhere



Radiation Has Important Benefits to Mankind

Where Can I Go For More Information?

- **REB Tools and Resources - Useful Links**

https://dceg.cancer.gov/about/organization/programs-ebp/reb/tools-useful-links

- **Health Physics Society "Ask the Experts"**

https://hps.org/publicinformation/ate/

- **National Nuclear Data Center Chart of Radionuclides**

https://www.nndc.bnl.gov/nudat2/

- **LNHB Decay Data**

http://www.nucleide.org/DDEP_WG/DDEPdata.htm

- **NIST XCOM Photon Cross Sections Tables**

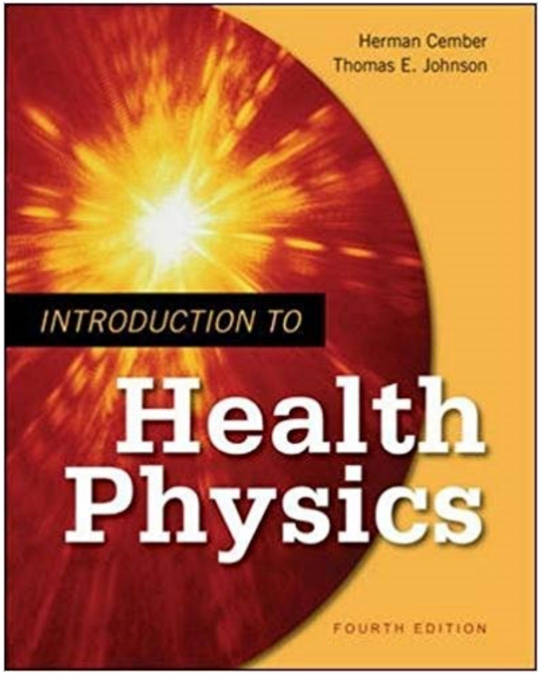
https://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html

- **NIST ESTAR Electron Stopping and Range Tables**

https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html

- **EPA Background Dose Calculator**

https://www.epa.gov/radiation/calculate-your-radiation-dose



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