Part 1: Basic Radiation Physics

Peter Jenkins, MS, CHP

Nuclear Medicine Physics for Technologists

Fall 2008

- Radiation: Energy propagated through space in the form of waves or particles.

- Examples of Radiation:
  - Radiowaves
  - Visible light
  - Heat
  - X-rays

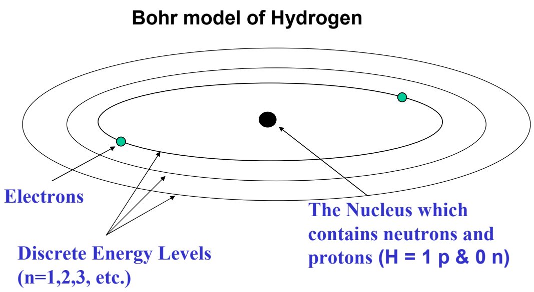
- Radiation may be in the form of either *Particles* or *Waves*
- Depending on the amount of *Energy* transferred, Radiation may be classified as either *Ionizing* or *Non-Ionizing* Radiation
- For our purposes, we will use the term *Radiation* to refer to Ionizing radiation, unless specifically noted

- The structure of the atom is important in understanding the origins and nature of radiation and radioactivity
- Though the existence of the atom has long been speculated, the modern theory of the atom began to develop in the early 1900's
- The Bohr model of the atom is useful in illustrating the processes of nuclear and atomic transformations

- Classical atomic structure suggests that, in general, atoms consist of dense, positively-charged nucleus surrounded by a number of electrons some distance away
- Often referred to as the solar system model
  - First purposed by Rutherford
- Classical theory does not allow such a model
  - Electrons would gradually lose Kinetic Energy until pulled into nucleus

- In 1913, Neils Bohr stated that the classical theory didn't apply to orbiting electrons

- Bohr based his theory on two postulates:
  - electrons can only occupy specific energy levels
  - an atomic electron can only change energy (i.e., give off or absorb) by changing from one level to another

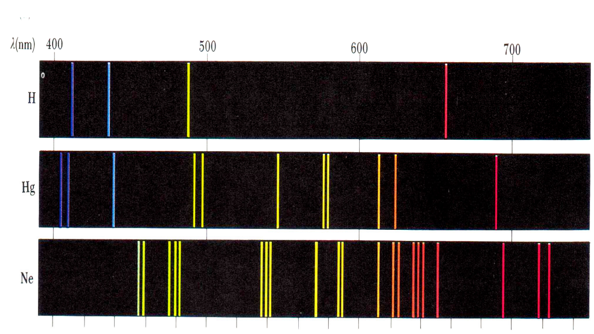


Basic Radiation Physics - Atomic Structure

- Bohr used the data on atomic spectra to support his theory of atomic structure
- Atomic spectra occurs when energy is transferred to an element causing it to radiate certain colors of light
  - (Neon signs (red light), Mercury (blue light), etc)
- Bohr was able to predict the sharp-line spectrum of Hydrogen

Basic Radiation Physics - Atomic Structure

- Bohr was able to demonstrate that orbital electrons posses discrete energy levels, and that when an electron changes from one energy level to another, the transition is accompanied by emission of electromagnetic radiation.



Basic Radiation Physics - Atomic Structure (EM waves)

- What is electromagnetic radiation?
- Visible light, radiowaves, and UV-rays are all forms of radiation propagated as waves
- These are all examples of a more general classification of radiation known as the electromagnetic spectrum
- Electromagnetic (EM) waves transport energy and momentum from one source to a receiver

Basic Radiation Physics - Atomic Structure (EM waves)

- EM waves travel at the speed of light in a vacuum
- Both the wavelength (λ) and frequency (f) are related by: $c = f\lambda$

  where c is the speed of light
- Einstein introduced the idea of *photons,* which he defined as small packets of energy

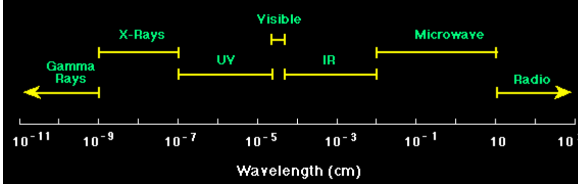
Basic Radiation Physics -
Atomic Structure (EM waves)

- These photons, which travel through space as waves, have energy (E) proportional to their frequency (f):

$$E = hf$$ where h is Planck's constant.

- It can be seen that as the frequency of the EM wave increases, so does the photon's energy
- Also, as frequency increases, wavelength decreases
  - Visible light and gamma rays only differ by their wavelength

- Electromagnetic spectrum



Basic Radiation Physics -
Atomic Structure

- When energy is transferred to an orbital electron which exceeds the energy of the energy level, it will move to a higher energy level. The electron is in an *Excited* state
- If enough energy is transferred so that the electron is completely removed from the influence of the nucleus, the atom is said to be *Ionized*

Basic Radiation Physics -
Atomic Structure

- To move a electron from the ground state to the first excited state in Hydrogen, 10.2 eV would need to be imparted to the electron
- For an electron to move from the first excited state to the ground state, a 10.2 eV photon would be emitted
- E of the photon determines the wavelength, and, thus, the color (in the visible region)

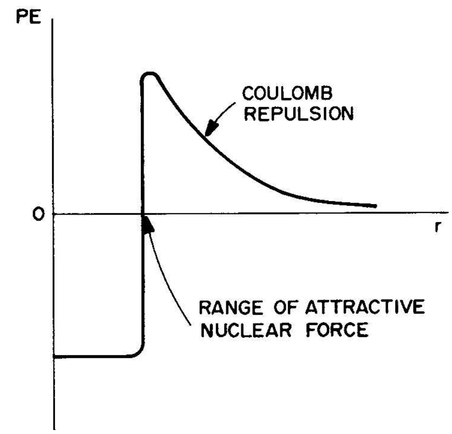
Basic Radiation Physics -
Atomic Structure

- Same process for all orbital electron energy level changes
- Hydrogen emission lines lie in visible and UV regions
- Photons emitted in such a process which posses enough energy to cause ionization are referred to as *x-rays*

Basic Radiation Physics -
Atomic Structure

- Bohr was successful only in developing theory for Hydrogen
- Modern quantum theory is based on electron clouds and wave functions rather than orbits
- Bohr model useful as simple presentation of the idea of discrete energy levels
- The idea of atomic particles possessing only discrete energies applies to nucleons as well as electrons

- Protons and Neutrons bound together inside the nucleus by the nuclear force
- Nuclear force strong enough to overcome the Coulomb repulsion at very close ranges ($\sim 10^{-15}$ m)
- Energy associated with Nuclear reactions on the order of 10^6 eV; about a million times greater than chemical reactions involving orbital electrons



- $E=mc^2$
- 1 AMU = 931.49 MeV
- Example, production of deuterium:

$$ {}_0^1n + {}_1^1H \rightarrow {}_1^2H + {}_0^0\gamma $$

- Energy carried off by photon is 2.2245 MeV

- The energy released was found by comparing the total masses on both sides of the equation

$$ Q = \Delta m_n + \Delta m_{H-1} - \Delta m_{H-2} $$
$$ Q = 8.0714 + 7.2890 - 13.1359 = 2.2245 MeV $$

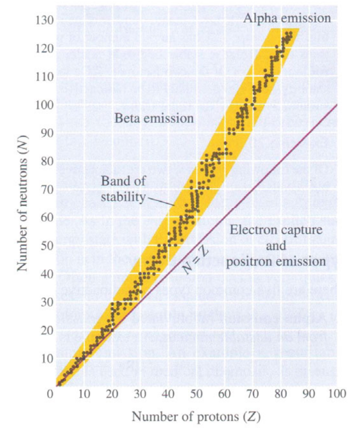
- Δm is the difference of the atomic mass number and the atomic mass in units of MeV (Δ = M-A)

- The energy required to separate nucleons is known as the *binding energy*. The binding energy of the deuteron is 2.2245 MeV.
- This represents the minimum energy required to be imparted to the nucleus in order to separate the nucleons

- The attraction of the nuclear force appears to about the same for all nucleons, whether p-p, n-n, or n-p
- In a nucleus, this force attracts protons to each other at the same time they repel each other through Coulomb repulsion
- Nuclei in which the nuclear force far exceeds the Coulomb repulsion are "stable"

Basic Radiation Physics - Atomic Structure

- There are about 400 stable nuclei
- Light nuclei are most stable when N=Z (same number of protons as neutrons)
- Heavier nuclei are more stable when N>Z
- In order to compensate for the additional repulsion, a greater number of neutrons are needed to stabilize the nucleus
- Nuclides are unstable when Z>83



Basic Radiation Physics - Chart of the Nuclides

- The Periodic Table of the elements organizes the elements into groups based on their physical and chemical properties
- The Chart of the Nuclides was developed to describe the nuclear properties of a specific nuclide
- A *nuclide* is a specific nucleus defined by an atomic number and mass number

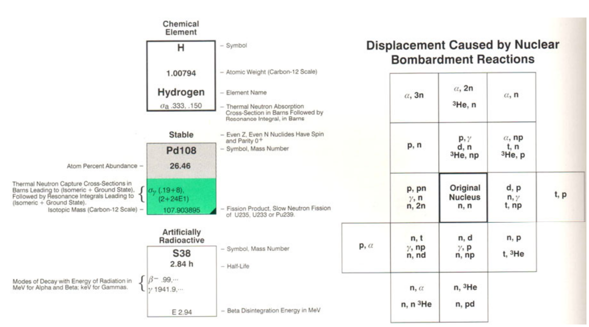
Basic Radiation Physics - Chart of the Nuclides

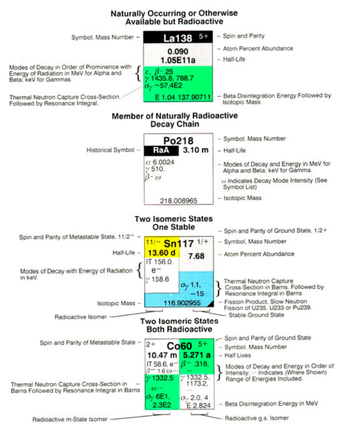
- The *atomic number* of an atom refers to the number of protons contained in the nucleus, and is denoted by Z
- The *mass number* of an atom refers to the total number of protons and neutrons in a nucleus and is denoted by A

$$\begin{matrix} MassNumber \rightarrow \\ AtomicNumber \rightarrow \end{matrix} {}^{238}_{92}U$$

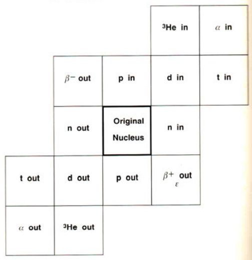
Basic Radiation Physics - Chart of the Nuclides

- The use of the term *radionuclide* simply indicates that the atom is radioactive
- Chart of the Nuclides, lists information related to both stable and radioactive species





Relative Locations of the Products of Various Nuclear Process



Radiation and Decay

- α — alpha particle
- β− — negative electron (beta decay)
- β+ — positron
- γ — gamma ray
- n — neutron
- p — proton
- d — deuteron
- t — triton
- ε — electron capture
- IT — isomeric transition
- D — delayed radiation (see page 6)
- SF — spontaneous fission
- E — disintegration energy
- e− — conversion electron
- β−β− — double beta decay
- C14 — particle emission (C14 nuclei)
- Ne — particle emission (neon nuclei)

Colors Used for Half Lives (Appear in Upper Half of Nuclide Block)

- 1 Day to 10 Days
- 10 Days to 100 Days
- 100 Days to 10 Years
- 10 Years to 5E8 Years
- > 5E8 Years or Stable

Time

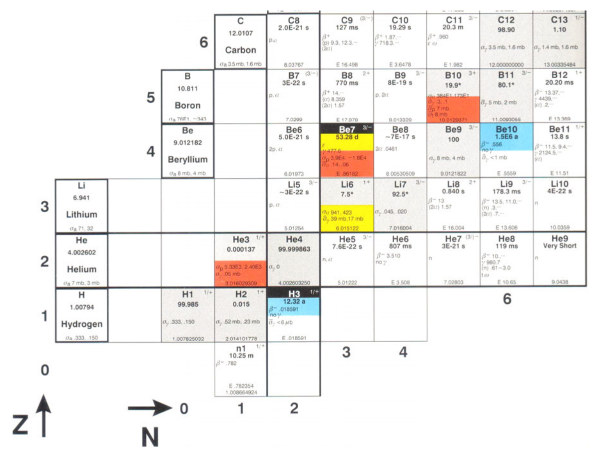
- μs — microseconds (1.0E-6s)
- ms — milliseconds (1.0E-3s)
- s — seconds
- m — minutes
- h — hours
- d — days
- a — years

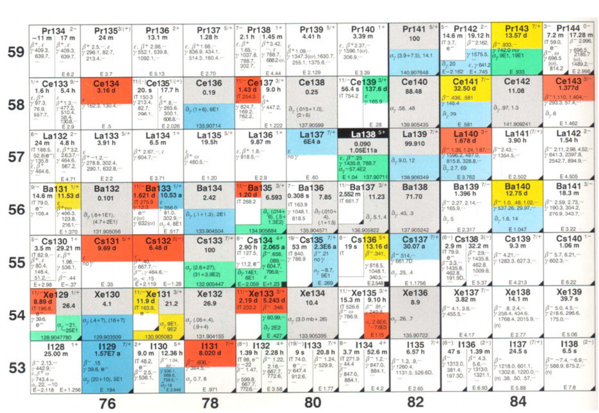
Colors Used for Neutron Absorption Properties (Appear in Lower Half of Nuclide Block)

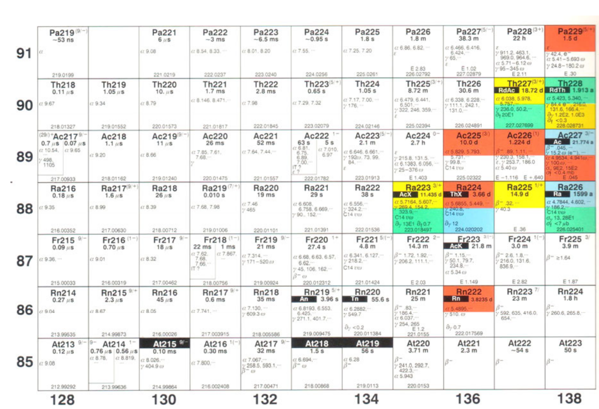
- 10 Barns to 100 Barns
- 100 Barns to 500 Barns
- 500 Barns to 1000 Barns
- > 1000 Barns

Other Symbols

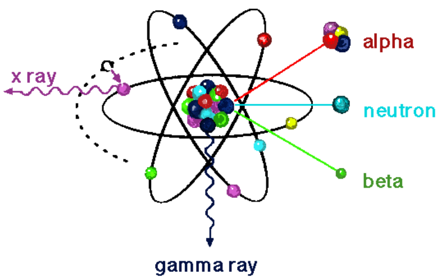
- ω — absolute abundance less than 1%
- υω — absolute abundance less than 1.0E-3%
- υυω — absolute abundance less than 1.0E-6%
- E — indicates exponential format, e.g., 1.06E11a is 1.06 x 10^{11} years
- ↔ — indicates assignment to metastable (m) and ground (g) states inconclusive
- ↕ — indicates assignment of m_2 and m_1 states inconclusive
- χ — unspecified number of particles of a given type emitted, e.g., χp
- ◢ — nuclide formed as a product in fission of







Basic Radiation Physics - Radioactivity



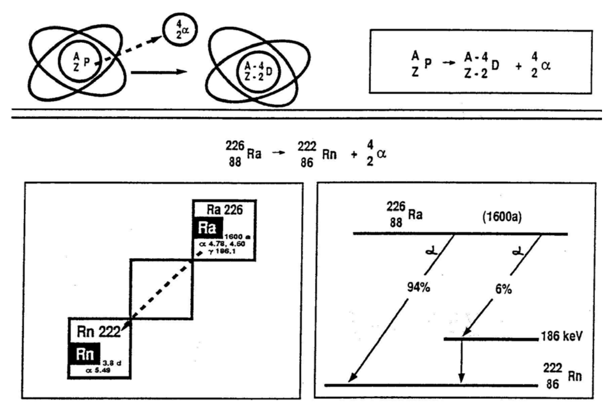
Basic Radiation Physics - Radioactivity

- *Radioactive Decay* is the process why which a nucleus will expel mass or energy in order to become more stable
- Five common types of decay:
  - Alpha Decay
  - Beta Decay
  - Positron Emission
  - Electron Capture
  - Gamma Emission

Basic Radiation Physics - Alpha Decay

- Alpha decay occurs in nuclides where Z > 83
- Occurs when the n-p ration is too low
- During *alpha* decay a particle, identical to the nucleus of a helium atom (both are made up of two neutrons and two protons), is ejected from the nucleus of the atom
- The atomic mass of the new nucleus decreases by 4 (Z decreases by 2)

I. ALPHA DECAY

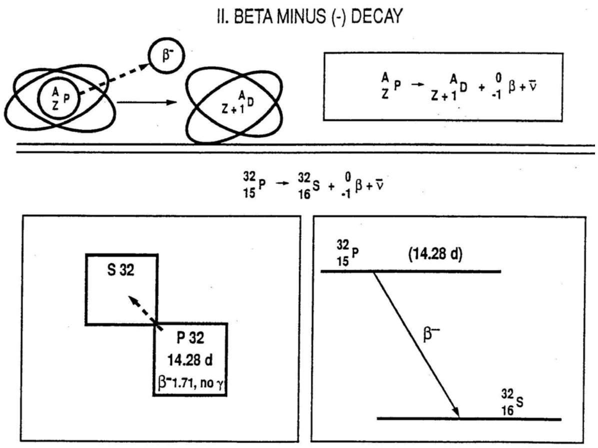


Basic Radiation Physics - Alpha Decay

- Due to its relative high mass, alpha particles travel only short distances but cause many ionizations before stopping
- Alpha particles typically cannot penetrate the dead layer of skin on our bodies and can be stopped by a thin sheet of paper
- Due to this fact, they do not constitute an external radiation hazard

Basic Radiation Physics - Beta Decay

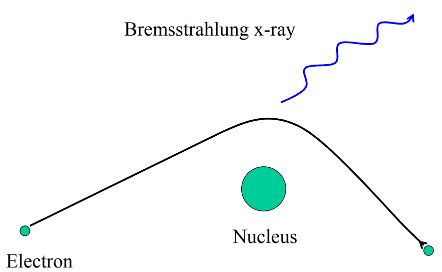
- Depending on the n-p ratio, a nucleus may undergo positron or beta emission
- Negative beta decay usually occurs in nuclei with surplus neutrons
- A neutron is transformed into a proton and a beta particle carries off the excess energy and charge



Basic Radiation Physics - Beta Decay

- Depending on the energy of the beta particle, it may penetrate varying depths in different density materials
- Most beta particles will not penetrate the skin, but higher energy particles may
- Under certain circumstances, beta particles will cause the emission of bremsstrahlung radiation

Peter Jenkins, MS, CHP



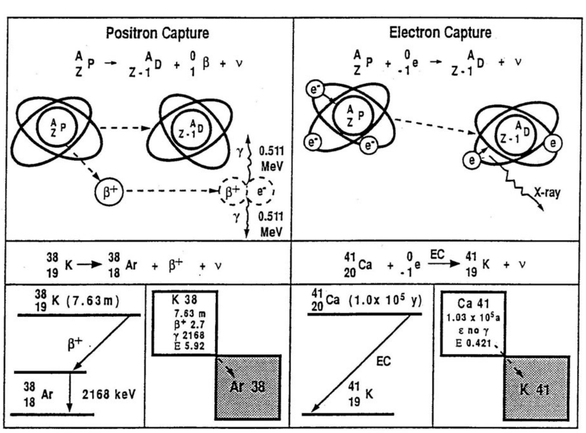
Basic Radiation Physics - Positron Emission/Electron Capture

- Positron emission competes with Electron capture
- A proton is converted into a neutron and the excess charge energy carried off as positron

- or -

- A proton may capture an orbital electron and become a neutron
  - The vacancy will be filled by another orbital electron; the transition will emit an x-ray

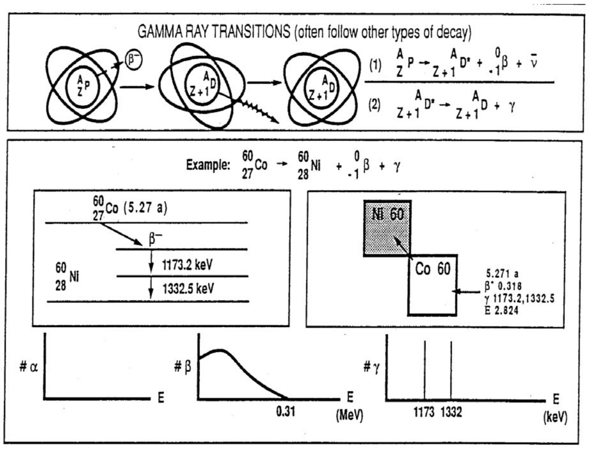
Peter Jenkins, MS, CHP



Basic Radiation Physics - Gamma Emission

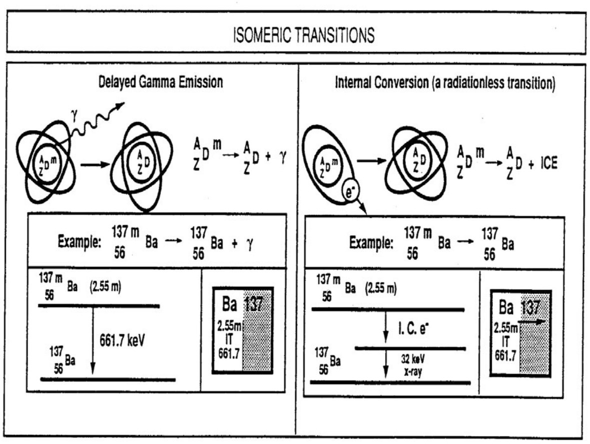
- Following different modes of decay, a gamma photon may be emitted as the nucleus sheds excess energy
- No change in number of protons or neutrons (no move on chart)
- Useful in radionuclide identification

Peter Jenkins, MS, CHP



Basic Radiation Physics - Gamma Emission

- Certain nuclei may possess more than one nuclear state--called *Metastable state*
- Often half-lives vary greatly
  - ^{99}Tc (2.13 x 10^5 years) v. ^{99m}Tc (6.02 hours)
- Nuclides with metastable states are called *isomers*
- Isomeric transition: emission of a gamma ray when change in nuclear state



Type of Decay	Radiation	Equivalent process	Nuclear Change Z	Nuclear Change M	Usual Nuclear Condition
α	^4_2He		-2	-4	Z>83
β^-	$^0_{-1}\beta$	$^1_0n \rightarrow ^1_1p + ^0_{-1}\beta$	+1	0	N/Z too large
β^+	$^0_1\beta$	$^1_1p \rightarrow ^1_0n + ^0_1\beta$	-1	0	N/Z too small
EC	X-rays	$^1_1p + ^0_{-1}\beta \rightarrow ^1_0n$	-1	0	N/Z too small
γ	$^0_0\gamma$		0	0	Excited Nucleus

Basic Radiation Physics - Types of Radiation

- Particles (protons, neutrons, electrons, and atomic nuclei) may obtain enough kinetic energy to travel through matter
- These particles may cause excitation and ionization
- Only those which transfer enough to cause an ionization are classified as ionizing radiation

Peter Jenkins, MS, CHP

Basic Radiation Physics - Radioactivity and Units

- *Radioactivity* is a general term used to describe atoms that release this excess energy in the form of particles or radiation
- Radioactivity, or activity (A), is simply defined as the number of radioactive atoms (N) present times the radionuclide's transformation constant (λ)

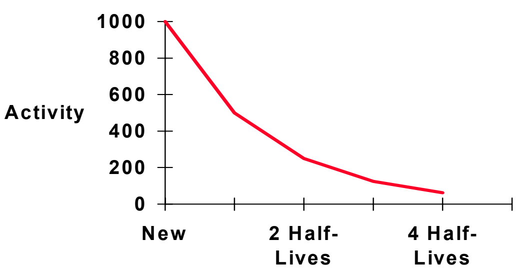
$$A = N\lambda$$

Peter Jenkins, MS, CHP

- The transformation constant is simply a value that represents the average time that elapses between transformations
- Each radionuclide has a unique transformation constant
- No known chemical or physical processes that can alter the transformation constant

- The *half-life* of a material is defined as the amount of time that will have elapsed when one-half of the original atoms remain
- Half-life is calculated using the transformation constant:

$$T_{1/2} = \frac{\ln 2}{\lambda}$$



- The activity of a known radionuclide at any time can be calculated using the following formula:

$$A = A_o e^{-\lambda t}$$

  - where t is the time which elapsed since the initial activity (A_o) was known

- The SI unit of activity is the Becquerel (Bq)
  - The Bq is defined as one transformation per second

$$Bq = \frac{1}{\sec}$$

- The old unit of activity (still used in the U.S.) is the Curie (Ci)
  - One Ci is equal to $3.7\text{x}10^{10}$ transformations per second.

$$1Ci = 3.7x10^{10}\ Bq$$

- *Exposure* refers to the amount of ionization produced in air by x- or gamma rays.
- The unit of exposure is the *roentgen* (R) and is defined as the sum of all charges of one sign produced in air when all the electrons liberated by photons in a mass of air are stopped.

$$1R = 2.58x10^{-4}\ \frac{C}{kg}$$

- *Absorbed Dose* is the primary quantity used to describe energy absorbed per unit mass material from any kind of ionizing radiation in any target
- The unit of absorbed dose (D), or just dose, is the *gray* (Gy). The traditional unit is the *rad* and is defined as 100 erg/g

$$1Gy = \frac{1J}{kg} = \frac{10^7 erg}{10^3 g} = 10^4 \frac{erg}{g} = 100 rad$$

- In order to convert from *exposure* in air to *absorbed dose* in air, one must know the energy needed in order to create an ion pair (W)
  - For air (at STP), W= 34 eV per ion pair (= 34 J/C).
- Absorbed dose in air from 1R exposure can be thus calculated:

$$1R = \frac{2.58x10^{-4} C}{kg} x \frac{34J}{C} = 8.8x10^{-3} \frac{J}{kg} = 0.88 rad$$

- Just as this calculation demonstrates the difference between exposure in air and dose in air, similar calculations can be performed for dose for any material.
- It is very important to not confuse the idea of dose with exposure. Often these terms are used incorrectly and an incorrect idea is relayed.
- Exposure is defined for ionization (*charge*) in air; absorbed dose is defined for *energy* deposited in matter.
- Energy and charge are not the same thing!

- Different types of radiation interact differently with matter
- Different types of radiation cause different types of biological damage
  - *Not all radiation has the same biological effect, even for the same amount of absorbed dose!*
- The quantity of *Dose Equivalent* was introduced to account for the different biological effects

- The unit of *dose equivalence* (H) is the *sievert* (Sv)
  - formerly the *rem* (roentgen equivalent man), still used in the U.S.
- H attempts to account for the different effects of different radiation types by using a radiation quality factor, Q
  - The quality factor is a unique value that relates the radiation's relative biological effectiveness to a value that is multiplied by the absorbed dose

- Dose equivalence is calculated by multiplying the dose by the quality factor for the type of radiation delivering the dose:

$$H = QD$$

- (rem = rad x Q)

Basic Radiation Physics - Interactions with Matter

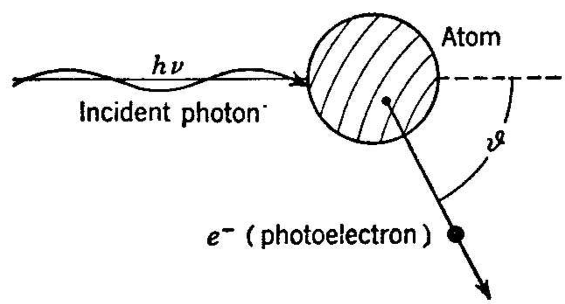
- Charged particles interact constantly as they pass through matter
  – The principle types of charged particle interaction include ionization, excitation, and bremsstrahlung production
- Non-charged particles can interact though scattering reactions (elastic or inelastic), absorption, or spallation
  - will not be discussed here

Basic Radiation Physics - Interactions with Matter

- Photon interact *indirectly* with matter
  - All ionization occurs after the photon has deposited its energy
- Three major ways photons interact and lose their energy are:
  – Photo-Electric Effect
  – Compton Scattering
  – Paired Production

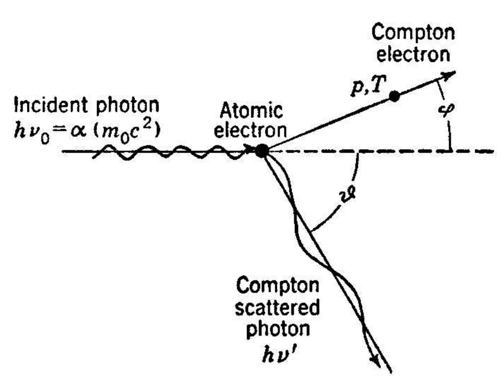
Basic Radiation Physics - Photo-Electric Effect

- The *Photoelectric Effect* is an interaction between a photon and a tightly bound electron whose binding energy is equal to or less than the energy of the photon
- The photon is absorbed by the electron and, as a result of the added energy, is ejected form the atoms with KE equal to the difference between the original gamma ray energy and the electron's BE



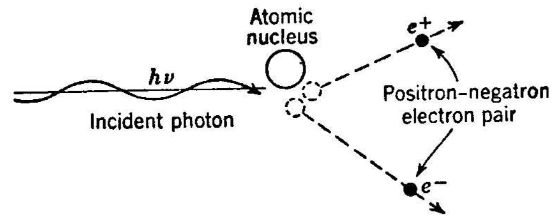
Basic Radiation Physics - Compton Scattering

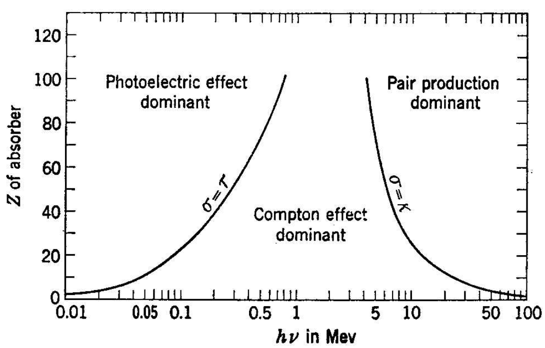
- *Compton Scattering* occurs when a photon interacts with a loosely bound outer-shell electron
- The electron will absorb the photon, but will emit another photon at a lower energy
- The incident photon energy is now shared between the scattered photon and electron



Basic Radiation Physics -
Paired Production

- In order for a *Paired Production* interaction to occur, the photon energy must exceed 1.02 MeV (rest mass of two electrons)
- As the photon approached the nucleus of an atom, it completely disappears
- The energy absorbed is then expressed by the emission of an electron-positron pair.
- Any remaining energy will be distributed between the two particles as kinetic energy.





Basic Radiation Physics -
Sources of Radiation

- Natural and Man-made sources of radiation
- Natural sources divided into different categories:
  - Cosmic
  - Terrestrial