Lecture 11 Nuclear Radiations

ICPY473 Nuclear Physics, MUIC-3-Trimester, 2020-21

Udom Robkob, Physics-MUSC

Monday 7, JUne 2021

Today Topics

- The radiations
- Interaction of photons with matter
- Interaction of charged particles with matter
- Radiations detection and measurement
- Radiations protection

The Radiations

- Nuclear radiations are energetic particles and gamma photon from nuclear processes
- They are classified into
  - photon, i.e., X-rays, γ-ray
  - charged particles, i.e, $\beta^{\pm}$, $p^{\pm}$, α, heavy ions
  - charge neutral particles, i.e., neutron and neutrino
- Three of them, α, β, γ come from decay of radioisotopes, and are common to us
- We will study their interactions with matter, which will lead us to their detection, measurement and protection

Interaction of Photon with Matter

- Photons are quantum of electromagnetic waves, they interaction with mater with electromagnetic force, this results to *ionization* of matter atoms
- The main mechanisms for energy lose are
  - photoelectric effects
  - Compton scattering
  - pair production

Interaction of Photon with Matter

- Photons are quantum of electromagnetic waves, they interaction with mater with electromagnetic force, this results to *ionization* of matter atoms
- The main mechanisms for energy lose are
  - photoelectric effects
  - Compton scattering
  - pair production
- The *cross section* of low energy photon photoelectric interaction with matter atom is

$$\sigma_{ph} = \begin{cases} Z^4/(h\nu)^3, & \text{low energy} \\ Z^5/h\nu, & \text{high energy} \end{cases} \tag{1}$$

- Photoelectric cross section

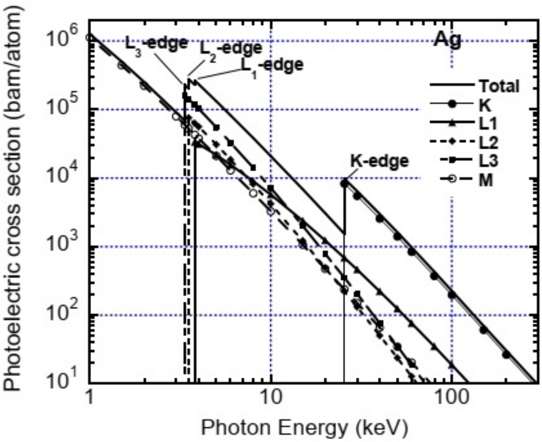


Figure: H. Hirayama, KEK-report, 2000

- The *cross section* of moderate energy photon Compton scattering of atomic electron of matter atom, according to *Klein-Nishina*, is

$$\sigma_{KN} = 2\pi r_0^2 \left\{ \frac{1+k}{k^2} \left[\frac{2(1+k)}{1+2k} - \frac{\ln(1+2k)}{k} \right] + \frac{\ln(1+2k)}{2k} - \frac{1+3k}{(1+2k)^2} \right\} \tag{2}$$

where $r_0 = \frac{e^2}{4\pi\epsilon_0^2 m_e c^2} \simeq 2.818 fm$ is classical electron radius, and $k = \frac{h\nu}{m_e c^2}$ is dimensionless photon kinematic variable.
- Thomson limit, $k \to 0$, of Klein-Nishina formula is

$$\sigma_T = \frac{8\pi}{3} r_0^2 \tag{3}$$

- Compton scattering cross section of photon

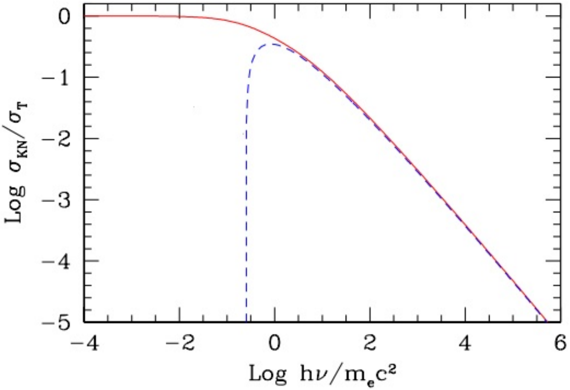


Figure: O. Klein and Y. Nishina, Z. Physik (52), 1929 (853-868).

- The *cross section* of energetic photon pair production, according to Bethe-Heitler formula, is

$$\sigma_{pair}(E_\gamma) = \simeq \alpha Z^2 r_0^2 \ln E_\gamma \tag{4}$$

where α is fine structure constant and Z is nuclear charge of target atom.

- According to the pair production process

$$\gamma + X \to X + 2e^- + Q$$

It appears with threshold energy of pair production as

$$T_{th}^{CM} = 2m_e c^2 \tag{5}$$

$$Q = -2m_e c^2 (-T_{th}^{CM}) \tag{6}$$

$$T_{th}^{LAB} = \frac{2m_e c^2 (m_e c^2 + M_X c^2)}{M_X c^2} \tag{7}$$

- Pair production cross section of photon

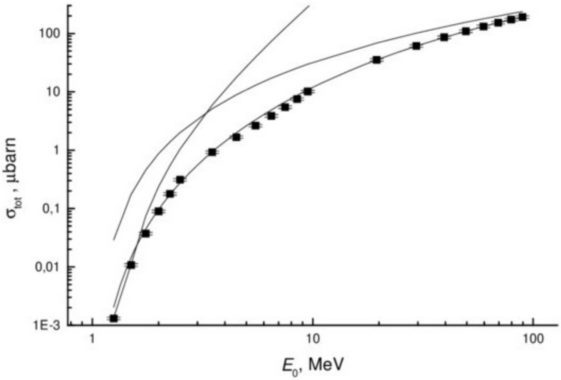


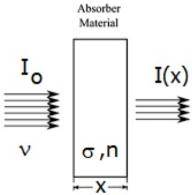
Figure: H. Bethe and W. Heitler (1954).

- Absorption of photon by matter and *linear attenuation coefficient* μ

$$dI(x) \propto -dx \rightarrow dI(x) = -\mu dx \rightarrow I(x) = I(0)e^{-\mu x} \tag{8}$$

$$\mu = n\sigma \quad [m^{-1}] \tag{9}$$

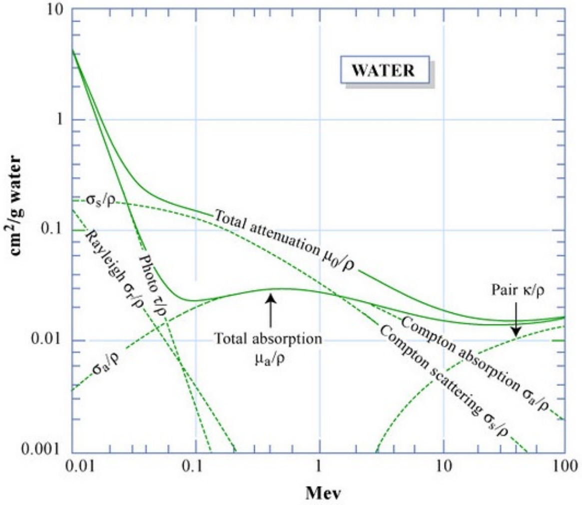
where $n[\#/m^3]$ is number density of target atom and $\sigma[m^2]$ is the cross section of the corresponding interaction.



- Mass attenuation coefficient μ_m is defined with mass density $\rho[gm/cm^3]$ as

$$\mu_m = \left(\frac{\mu}{\rho}\right)\rho \rightarrow [cm^2/gm] \tag{10}$$

- Mass attenuation coefficient of water



- Table of mass attenuation coefficient of some matters

TABLE 24.1

Mass attenuation coefficient as a function of X-ray photon energy in water, air, muscle, bone, and fat. Average densities, atomic numbers and electron number densities are included, with values for air at $p = 1.0$ atm.

Energy (keV)	Water μ/ρ (cm^2/g)	Air μ/ρ (cm^2/g)	Muscle μ/ρ (cm^2/g)	Fat μ/ρ (cm^2/g)	Bone μ/ρ (cm^2/g)
5	42.1	40.3	42.0	24.6	138
10	5.07	4.91	5.15	3.08	19.8
15	1.57	1.52	1.60	1.01	6.19
20	0.761	0.733	0.778	0.533	2.75
30	0.361	0.340	0.365	0.296	0.953
40	0.263	0.243	0.264	0.235	0.509
50	0.224	0.205	0.224	0.210	0.347
80	0.183	0.166	0.182	0.179	0.208
100	0.171	0.154	0.169	0.168	0.180
150	0.151	0.136	0.149	0.150	0.149
200	0.137	0.123	0.136	0.137	0.133
1000	0.071	0.064	0.070	0.071	0.068
5000	0.030	0.028	0.030	0.030	0.030
Density (kg/m^3)	1000	1.20	1040	915	1650
Electron density (e/kg)	3.34×10^{26}	3.01×10^{26}	3.31×10^{26}	3.34×10^{26}	3.19×10^{26}
Atomic number $\langle Z \rangle$	7.5	7.8	7.6	6.5	12.3

- The *halve value thickness* (HVT) $d_{1/2}$ is defined as

$$I(d_{1/2}) = \frac{1}{2} I_0 = I_0 e^{-\mu d_{1/2}} \rightarrow d_{1/2} = \frac{\ln 2}{\mu} \quad [cm] \tag{11}$$

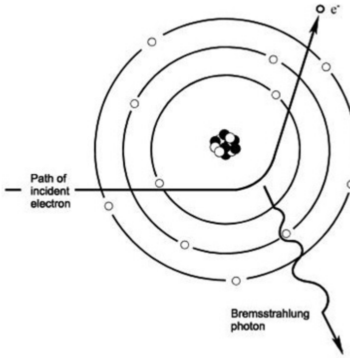
- It seem that HVT is matter dependent.

Absorber	100 keV	200 keV	500 keV
Air	3555	4359	6189
Water	4.15	5.1	7.15
Carbon	2.07	2.53	3.54
Aluminium	1.59	2.14	3.05
Iron	0.26	0.64	1.06
Copper	0.18	0.53	0.95
Lead	0.012	0.068	0.42

- The *halve value layer* (HVL) is then defined by mutiplical with mass density of an absorber
$$HVL = \rho d_{1/2}$$
in unit of $[gm/cm^2]$, and become matter independent and it is characteristic to the photon. It is an amount of matter in gram per square centimeter to reduce photon density by one-half.

Interaction of Charged Particle with Matter

- The interaction is electromagnetic interaction, and results with excitation or ionization of medium atom. They are three types of charged particle energy lost
  - elastic scattering
  - inelastic scattering
  - Bremsstrahlung



- Stopping power $S(E)$ is defined to be the energy lose rate of charged particle inside matter as

$$S(E) = -\frac{dE}{dx} \tag{12}$$

- *Range* R is defined to be the longest of penetration depth of struggling path of the charged particle inside matter.

- By definition

$$R = \int_E^0 (-dE/dx)dE = \int_E^0 S(E)dE \tag{13}$$

- Bethe-Bloch formula

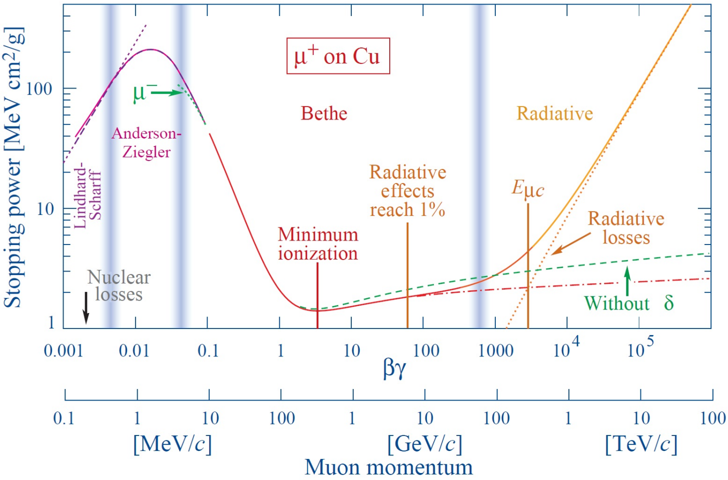
$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2(k_e e^2)^2}{\beta^2} \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I(1-\beta^2)} - \beta^2\right)\right] \tag{14}$$

where

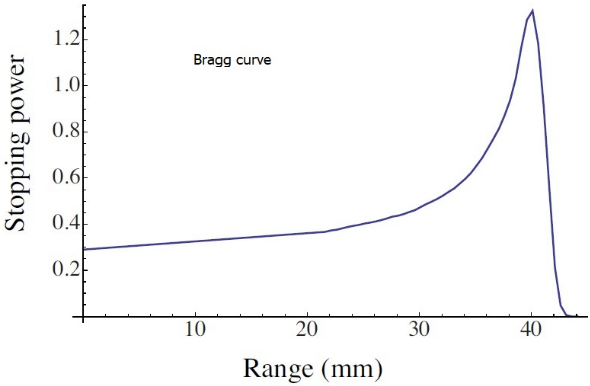
$$n = \frac{N_A \cdot Z \cdot \rho}{A \cdot M}$$

is the electron density of the medium, $\beta = v/c$ is a particle velocity (in unit of light speed) and charged z. I is the ionization energy.

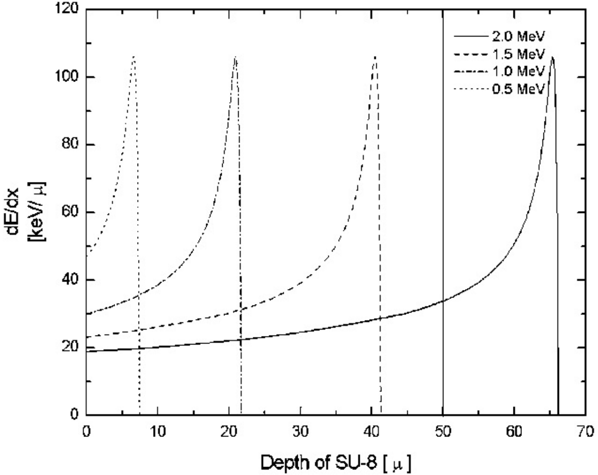
- Bethe-Bloch stopping power



- The range and stopping power are related by Bragg curve

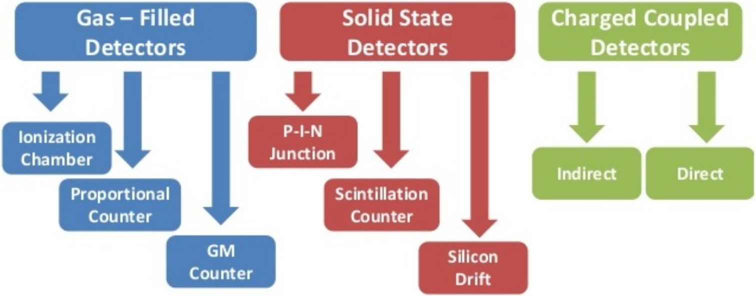


- Bragg curve at various energies

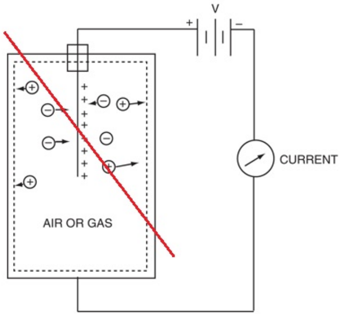


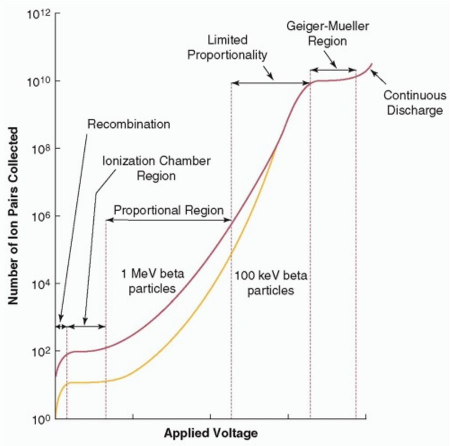
Radiations Detection and Measurement

- Radiation detectors

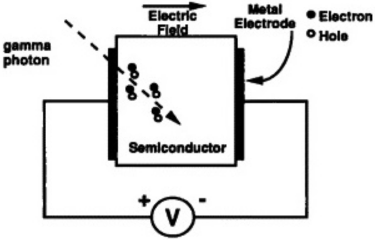


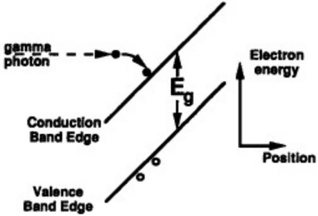
- Gas-filled detectors



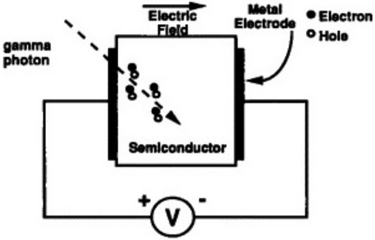


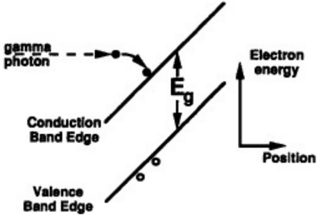
- Solid state detectors



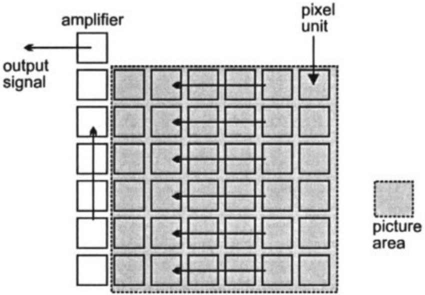


- Solid state detectors





- Charge-coupling (capacitors) detector



- Radiations measurement

Ionizing radiation	Roentgen (R)	Charge/unit mass	$1\ R = 2.58 \times 10^{-4}\ C/kg$
Absorbed dose	Rad Gray (Gy)	$1\ rad = 0.01\ J/kg$ $1\ Gy = 1\ J/kg$	$1\ rad = 0.01\ Gy$ $1\ Gy = 100\ rad$
Equivalent dose/ effective dose	Rem Sievert (Sv)	$Rem = rad \times W$ $Sv = Gy \times W$	$1\ rem = 0.01\ Sv$ $1\ Sv = 100\ rem$

- Radiations measurement

Ionizing radiation	Roentgen (R)	Charge/unit mass	1 R = 2.58×10^{-4} C/kg
Absorbed dose	Rad Gray (Gy)	1 rad = 0.01 J/kg 1 Gy = 1 J/kg	1 rad = 0.01 Gy 1 Gy = 100 rad
Equivalent dose/ effective dose	Rem Sievert (Sv)	Rem = rad $\times$ W Sv = Gy $\times$ W	1 rem = 0.01 Sv 1 Sv = 100 rem

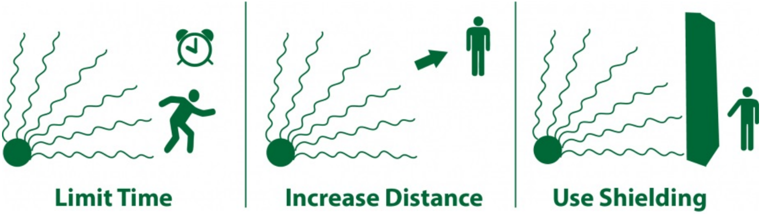
- Weigh factor

Radiation type and energy range	**Radiation weighting factor, wR**
Photons, all energies	1
Electrons and muons, all energies	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy nuclei	20

Radiations Protections

- Follows the rule of three *L*:

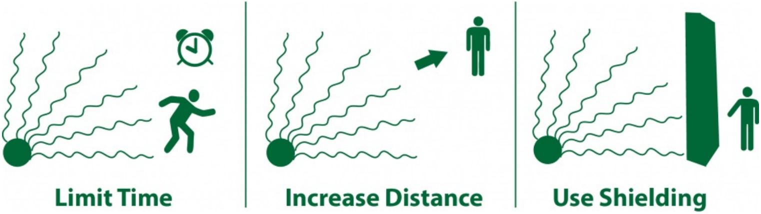
  Long distance, **L**arge shielding, **L**east time



Radiations Protections

- Follows the rule of three L:

Long distance, **L**arge shielding, **L**east time



- Beware of radiations sign