CHAPTER (2)
INTERACTION OF PHOTONS WITH MATTER

Photons are electrically neutral and do not steadily lose energy as they penetrate matter. Instead, they can travel some distance before interacting with an atom. How far a given photon will penetrate is governed statistically by a probability of interaction per unit distance traveled, which depends on the specific medium traversed and on the photon energy. When the photon interacts, it might be absorbed and disappear or it might be scattered, changing its direction of travel, with or without loss of energy.

If all the energy of a bombarding particle or photon is transferred, the radiation will appear to have been stopped within the irradiated matter. Conversely, if the energy is not completely deposited in the matter, the remaining energy will emerge as though the matter were transparent or at least translucent.

Interaction of Photons with Matter

The principal mechanisms of energy deposition by photons in matter are photoelectric absorption, Compton scattering, pair production, and photonuclear reactions.

As photon pass through matter, photons interact with atoms. The type of interaction is a function of the energy of the photons and the atomic number *(Z)* of elements composing the matter.

Types of Photon Interactions in Matter

In the practice of nuclear medicine, where gamma rays with energies between 50keV and550keV are used, ***Compton scattering*** is the dominant type of interaction in materials with lower atomic numbers, such as human tissue ($Z = 7.5$). The ***photoelectric effect*** is the dominant type of interaction in materials with higher atomic numbers, such as lead (Z=82). A third type of interaction of photons with matter, ***pair production***, only occurs with very high photon energies (greater than 1020keV) and is therefore not important in clinical nuclear medicine. Figure (1) depicts the predominant type of interaction for various combinations of incident photons and absorber atomic numbers.

Compton Scattering

In Compton scattering the incident photon transfers part of its energy to an outer shell or (essentially) “free” electron, ejecting it from the atom. Upon ejection this electron is called a **Compton electron**. The photon is scattered Figure (2) at an angle that depends on the amount of energy transferred from the photon to the electron. The scattering angle can range from nearly 0° to 180°.

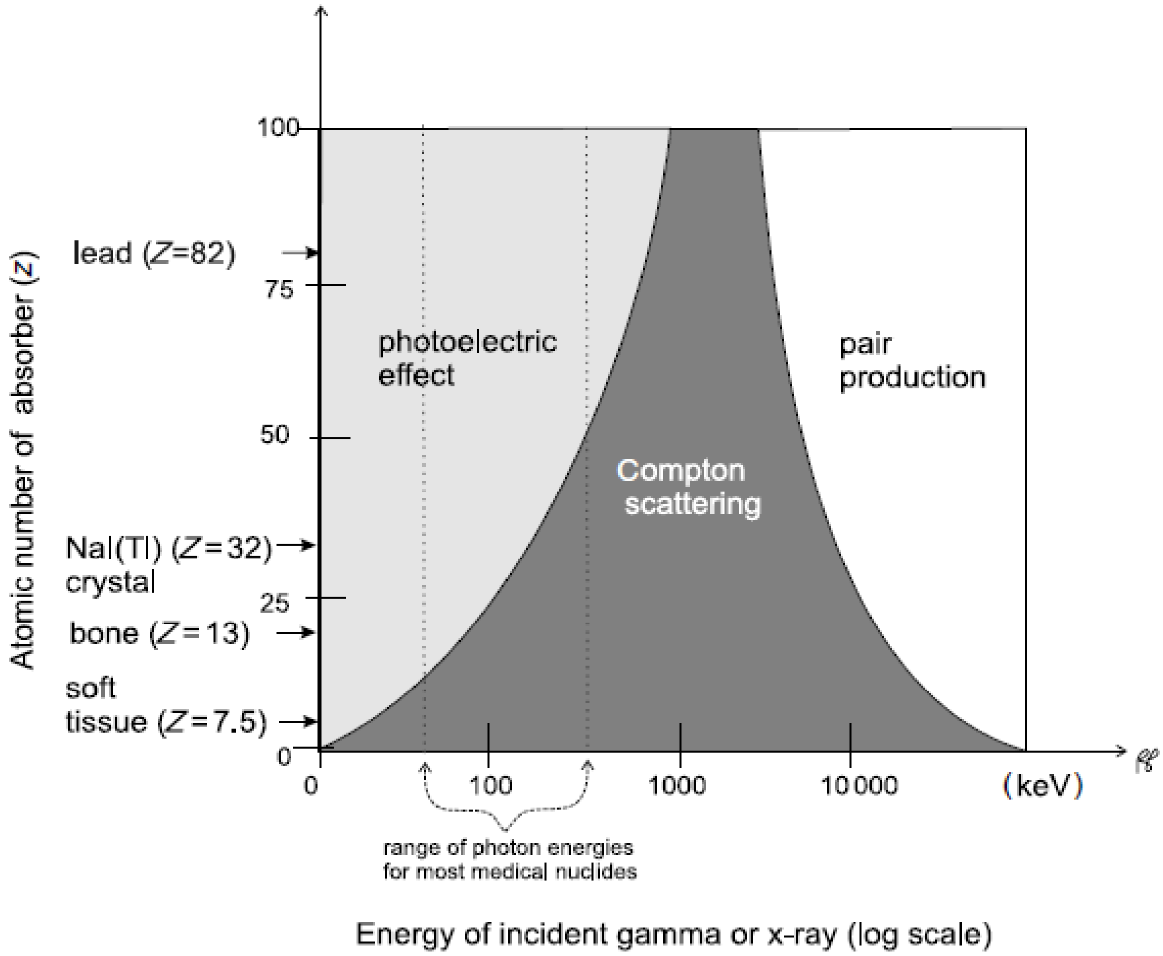

Fig. (1): Predominant type of interaction for various combinations of incident photons and absorber atomic numbers.

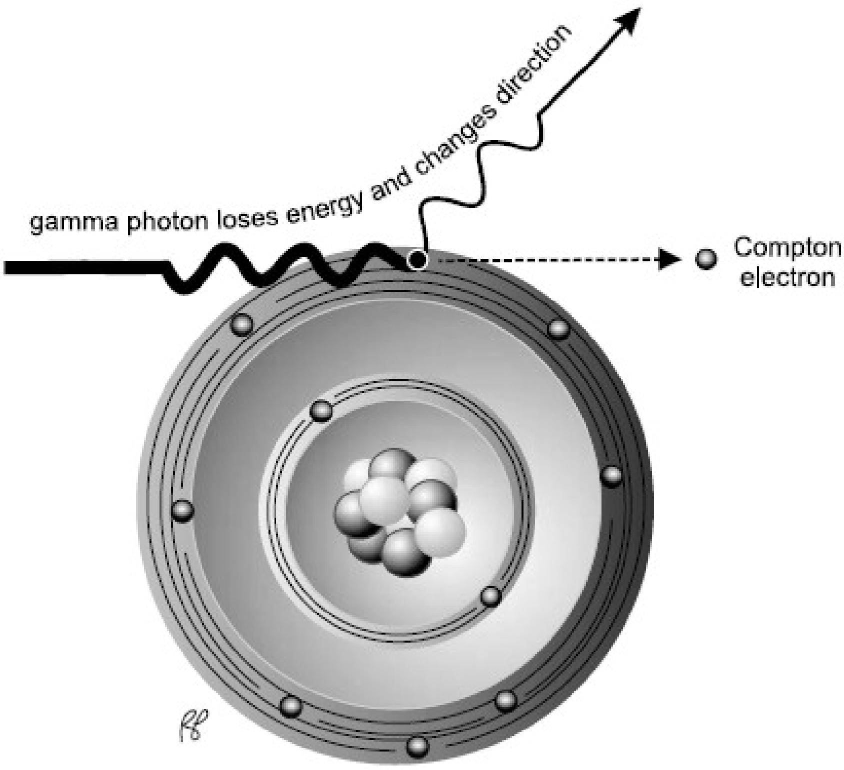

Fig. (2): Compton scattering.

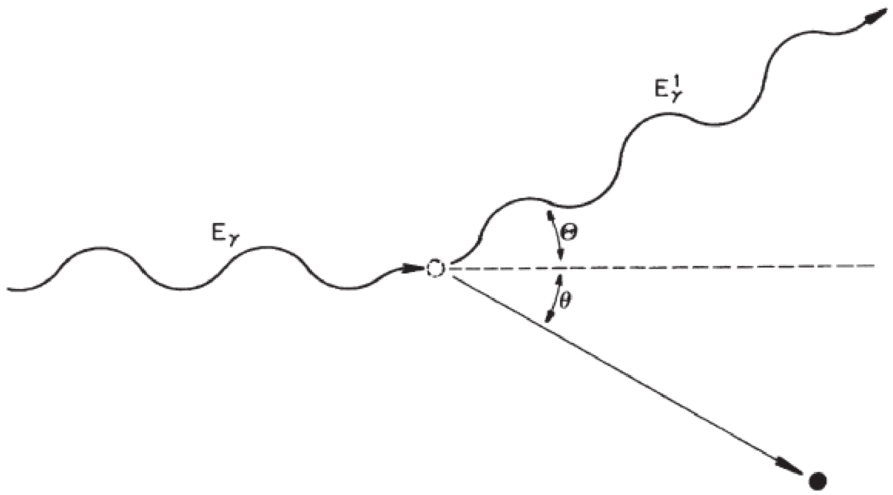

Fig. (3): The Compton effect. An incident photon collides with an atomic electron and imparts energy to it, the photon and electron being deflected at angles Θ and *Θ*, respectively, to the trajectory of the incident photon.

Compton derived the equation, which describes the wavelength shift between the incident and scattered photons and angle of scatter as shown in figure (3), which can be describe by the equation:

$$\lambda' - \lambda = \frac{h}{m_0\, c}(1 - \cos\Theta) \qquad \text{----------} \ (1)$$

Where λ' and λ are the wavelengths of the incident and deflected photons, *h* is Planck's constant (6.626×10^{-34} J.s), m_o is the rest mass of the electron, c is the speed of light, and Θ is the angle of scatter of the photon relative to its original direction of travel.

In Fig. (3), a photon of energy *hν* and momentum *hν/c* (wavy line) is incident on a stationary, free electron. After the collision, the photon is scattered at an angle θ with energy *hν'* and momentum *hν'/c*. The struck electron recoils at an angle ϕ with total energy *E'* and momentum *P'* . Conservation of total energy in the collision requires that:

$h\nu + mc^2 = h\nu' + E'$ ------- (2)

Conservation of the components of momentum in the horizontal and vertical directions gives the two equations:

$h\nu/c = h\nu'/c \cos(\boldsymbol{\theta}) + P' \cos(\phi)$ ----- (3)

and

$h\nu' l c \sin(\boldsymbol{\theta}) = P' \sin(\phi)$ ----- (4)

Eliminating *P*' and ϕ from these three equations and solving for ν' , one finds that:

$h\nu' = h\nu / [1 + (h\nu/mc^2)(1 - \cos(\boldsymbol{\theta}))]$ -------- (5)

With this result, the Compton shift is given by:

$\Delta\lambda = \lambda' - \lambda = c\,[1/\nu' - 1/\nu] = h/mc\,(1 - \cos(\boldsymbol{\theta}))$.

The Compton-scatter photon will always be of longer wavelength (lower energy) than the incident photon, because of energy lost in the collision with the electron.

Example (1): let us calculate the wavelength shift and energy loss by an incident photon of wavelength 0.300 nm that collides with a free electron, and where the photon is scattered at an angle of 70°.

$$\begin{aligned}
\lambda' &= \lambda + \frac{h}{m_0 c}(1 - \cos\Theta) \\
&= 3.0 \times 10^{-10}\ \text{m} + \frac{6.626 \times 10^{-34}\ \text{J s}}{(9.109 \times 10^{-31}\ \text{kg})(2.997 \times 10^{8}\ \text{m s}^{-1})}(1 - \cos 70^\circ) \\
&= 3.0 \times 10^{-10}\,\text{m} + 2.43 \times 10^{-12}\,\text{m}(1 - 0.342) \\
&= 0.3016\,\text{nm}
\end{aligned}$$

A Compton scatter photon is of longer wavelength and lower energy than the incident photon. The energy of the Compton electron, E_e , may be described by:

$$E_e = E_\gamma - E'_\gamma - \phi \quad \text{--------- (6)}$$

where E_γ and E'_γ are the energies of the incident and deflected photons, respectively, and is the binding energy of the electron.

As the binding energy of the atomic electron is relatively small, the energy of the ejected electron is essentially the difference between the incident and deflected photon energies. Substituting the value of E'_γ from:

$$E'_\gamma = \frac{E_\gamma}{1 + (E_\gamma / m\,c^2)(1 - \cos\Theta)} \quad \text{-------- (7)}$$

Ignoring the electron binding energy, the Compton electron energy can be expressed as:

$$E_e = E_\gamma - \frac{E_\gamma}{1 + (E_\gamma / mc^2)(1 - \cos\Theta)}$$

or } -------- (8)

$$= E_\gamma - \frac{E_\gamma}{1 + (E_\gamma / 0.511\ \text{MeV})(1 - \cos\Theta)}$$

H.W: Calculate the energy of a Compton electron, E_e, scattered at 180^o (Compton edge: Cos Θ = -1) and originating from an incident gamma ray photon from ^{137}Cs (E_γ = 0.662MeV).

Photoelectric Effect

A gamma ray of low energy, or one that has lost most of its energy through Compton interactions, may transfer its remaining energy to an orbital (generally inner-shell) electron. This process is called the **photoelectric effect** and the ejected electron is called a **photoelectron,** as shown in Figure (4). This electron leaves the atom with an energy equal to the energy of the incident gamma ray diminished by the binding energy of the electron. An outer-shell electron then fills the inner-shell vacancy and the excess energy is emitted as an x-ray.

$$E_{photoelectron} = E_{photon} - E_{binding} \quad \text{--------} \ (9)$$

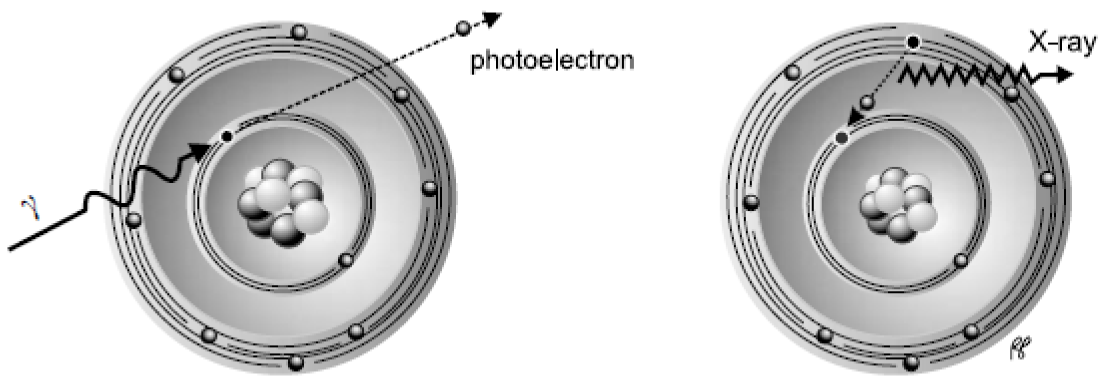

Fig. (4): Photoelectric effect.

In the photoelectric absorption process, a photon undergoes an interaction with an absorber atom in which the **photon completely disappears**.

The photoelectric process is the ***predominant mode of photon interaction*** at :

• Relatively low photon energies.

• High atomic number Z .

Energy–Momentum Requirements for Photon Absorption by an Electron

As with charged particles, when the energy transferred by a photon to an atomic electron is large compared with its binding energy, then, the electron can be treated as initially free and at rest. So that, the conservation of energy and momentum prevents the *absorption* of a photon by an electron under these conditions.

Thus, the binding of an electron and its interaction with the rest of the atom are essential for the photoelectric effect to occur. However, a photon can be *scattered* from a free electron, either with a reduction in its energy (Compton effect, next section) or with no change in energy (Thomson scattering). If an electron, initially free and at rest (rest energy mc^2), absorbs a photon of energy $h\nu$ and momentum $h\nu/c$, then the conservation of energy and momentum requires, respectively, that

$mc^2 + h\nu = \gamma mc^2$ ------ (10)

and

$h\nu/c = \gamma mc\,\beta$ ------- (11)

where $\gamma = (1 - \beta^2)^{-1/2}$ the relativistic factor, $\beta = v/c$ is the ratio of the speed of the electron after absorbing the photon and the speed of light c. Multiplying both
sides of Eq.(11) by c and subtracting from Eq.(10) gives:

$mc^2 = \gamma mc^2(1 - \beta)$ ------- (12)

This equation has only the trivial solution $\beta = 0$ and $\gamma = 1$, which, by Eq.(6), leads to the condition $h\nu = 0$. Which, conclude that the photoelectric effect occurs because the absorbing electron interacts with the nucleus and the other electrons in the atom to conserve the total energy and momentum of all interacting partners.

Pair Production

Pair production, as another mechanism of γ-energy dissipation in matter, results in the creation of nuclear particles from the γ-energy. Photons with energy greater than 1.024 MeV, under the influence of the electromagnetic field of a nucleus, may be converted into electron and positron. The photon, passing near the nucleus of an atom, is subjected to strong field effects from the nucleus and may **disappear as a photon** and **reappear as a positive and negative electron pair**, as shown in figure (5). At least 1.024MeV of photons energy are required for pair production, because the energy equivalent of the rest mass of the electron and positron is 0.511MeV each. Pair production is not very probable, however, until the photon energy exceeds about (2x0.511)MeV. The available kinetic energy to be shared by the electron and the positron is the photon energy minus 1.024MeV, or that energy needed to create the pair, as:

$E_{e+} + E_{e-} = h\gamma - 1.022$ (MeV) -------- (13)

where:
E_{e+} : positron kinetic energy.
E_{e-} : electron kinetic energy.
$h\gamma$: photon energy.

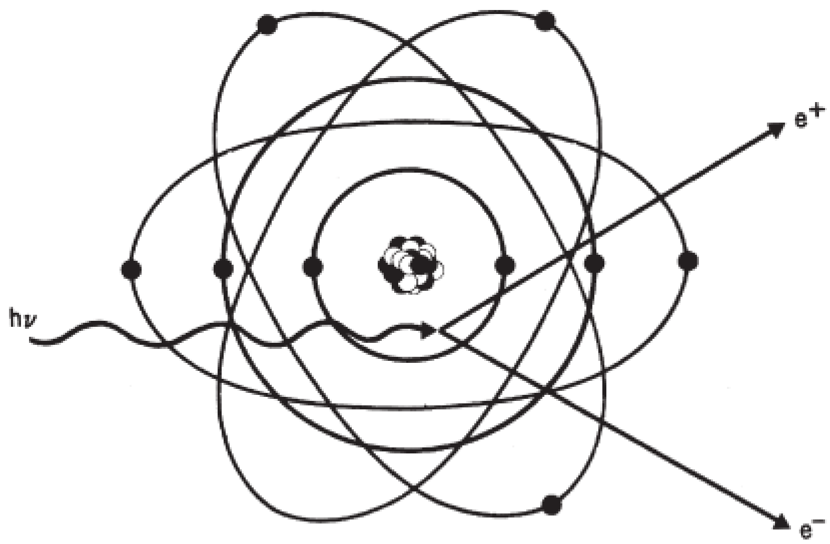

Fig. (5): Pair production. The conversion of a gamma ray photon into a negatron and positron pair.

Consequently, this phenomenon involves the creation of mass from energy. The creation of an electron requires a certain quantum of energy of a gamma-ray photon, which may be calculated according to Einstein's equation for the equivalence of mass and energy, by:

$E = m_e c^2$ --------- (14)

where E is energy, m_e is the electron rest mass, and c is the speed of light in a vacuum. According to Eq. (7) the rest energy of the electron (negatron or positron) is calculated as:

$$E = (9.109 \times 10^{-31}\ \text{kg})(2.997 \times 10^{8}\ \text{m s}^{-1})^2 = 8.182 \times 10^{-14}\ \text{J}$$

Since by definition, $1\,\text{eV} = 1.602 \times 10^{-19}$ J, the electron rest energy in joules is converted to electron volts as

$$8.182 \times 10^{-14}\ \text{J}/1.602 \times 10^{-19}\ \text{J eV}^{-1} = 0.511\ \text{MeV}$$

Thus, the creation of an electron (negatron) requires a minimum energy of 0.511 MeV. The two electrons produced e^- and e^+, are **not scattered orbital electrons**, but they are created, *de novo*, in the energy/mass conversion of the disappearing photon.

The probability of pair production increases with Z of the absorber and with the photon energy hγ.

Attenuation of Photons in Matter

As the result of the interactions between photons and matter, the **intensity** of the **beam** (stream of photons), that is, the number of photons remaining in the beam, decreases as the beam passes through matter as shown in Figure(6). This loss of photons is called **attenuation**; the matter through which the beam passes is referred to as the attenuator.

Specifically, attenuation is the ratio of intensity at the point the beam exits the attenuator, I_{out}, to the intensity it had when it entered, I_{in}. Attenuation is an exponential function of the thickness, *x*, of the attenuator in centimeters. That the function is exponential can be understood to mean that if half of the beam is lost in traversing the first centimeter of material, half of the remainder will be lost traversing the next centimeter, and so on. This resembles the exponential manner in which radioactivity decays with time. Expressed symbolically,

$$I_{out} = I_{in}\, e^{-(\mu x)} \quad \text{-------} \ (15)$$

where μ, the **linear attenuation coefficient**, is a property of the attenuator.

When, as is usually the case, thickness is given in centimeters, the linear attenuation coefficient is expressed as “per centimeter.” As might be expected, the linear attenuation coefficient is greater for dense tissue such as bone than for soft tissue such as fat. In general, the linear attenuation coefficient depends on both the energy of the photons and on the average atomic number *(Z)* and thickness of the attenuator.

A separate term, the **mass attenuation coefficient** (μ/ρ), is the linear attenuation coefficient divided by the density of the attenuator. When the density of a material is given in grams/cm^3 the units of the mass attenuation coefficient are cm^2/gram.

Absorption of radiation describes another aspect of the process of attenuation. Attenuation describes the weakening of the beam as it passes through matter. Absorption describes the transfer of energy from the beam to the matter.

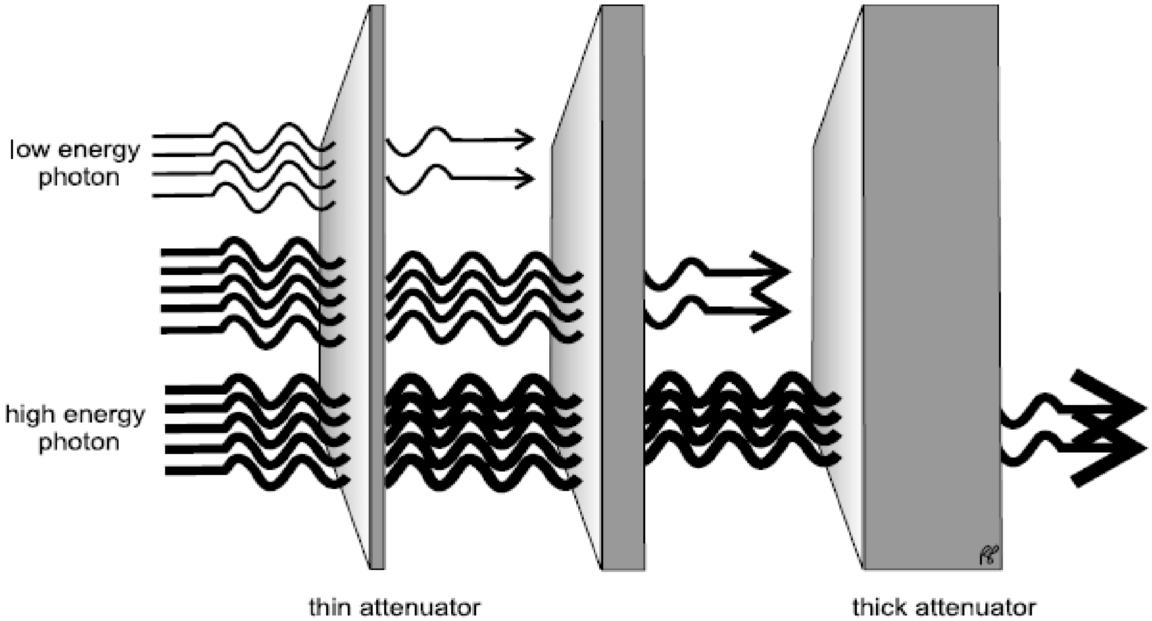

Fig. (6): Attenuation.

Half-Value Layers

A material's effectiveness as a photon attenuator is described by the attenuation coefficient. An alternative descriptor, one that is more easily visualized, is the "half-value layer" (HVL), which is simply the thickness of a slab of the attenuator that will remove exactly one half of the radiation of a beam. A second slab of the same thickness will remove half of the remainder, leaving one quarter of the original beam, and so forth. For a gamma photon of 100keV, the HVL in soft tissue is about 4cm. For any attenuator the **HVL** can be determined experimentally using a photon source and a suitable detector. For calculations involving attenuation of high-intensity radiation beams, an entirely similar concept, the **tenth-value layer** (TVL), is useful. The **TVL** is the thickness of the attenuator that will transmit only one-tenth of the photons in the beam.

The linear attenuation coefficient, μ, introduced above, can be calculated from the HVL as follows:

$\mu = 0.693/\text{HVL}$ --------- (16)

The term **penetrating radiation** may be used to describe x-ray and gamma radiation, as they have the potential to penetrate a considerable thickness of any material. Although we have just described some of the many ways photons interact with matter, the likelihood of any of these interactions occurring over a short distance is small. An individual photon may travel several centimeters or farther into tissue before it interacts. In contrast, charged particles (alpha, beta) undergo many closely spaced interactions. This sharply limits their penetration as shown in Figure (7).

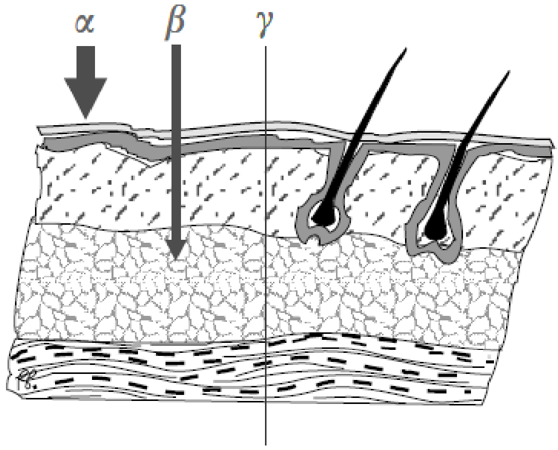

Fig.(7): Penetrating radiation and non-penetrating radiation.

H.W.

1- An old rock of volcanic origin is found and measured to contain 0.1 g of potassium. The rock is then heated and the ^{40}Ar from transformation of ^{40}K is collected and measured by mass spectroscopy to be 1.66×10^{-10} g. What is the age of the rock?