RADIATION PROTECTION NOTE 2:
THE INTERACTION OF IONISING RADIATION WITH MATTER

Alpha, beta, gamma and X radiations are all ionising radiation with the ability to produce ions in living tissue. It is most important to understand the manner in which radiation interacts with matter and transfers its energy. Energy from radiation is transferred to matter in two ways: Ionisation and Excitation. Ionisation is the process of removal of an electron from an atom leaving the atom with a net positive charge. In excitation, the energy of incoming radiation raises an outer electron to a higher energy state from which it returns very rapidly (10^{-8}s) to its original state emitting a photon of light in the process.

The mechanisms involved in the transfer of energy are dependent on the nature of the ionising radiations involved. Alpha and beta radiations are made up of charged particles and these interact with matter via electrostatic forces. Gamma and X radiations are a type of electromagnetic wave and interact with matter via the Compton Effect and the Photoelectric Effect described below.

CHARGED PARTICLES

The charged particles (α and β) interact with matter via electrostatic forces leaving behind an ionised atom or molecule. After each interaction the α or β-particle loses energy and with sufficient interactions will eventually be ‘stopped’.

ALPHA PARTICLES

α particles are relatively large, doubly charged and travel at about 1/20 of the speed of light. Because of its slow speed and high charge the α particle will ionise virtually every molecule it encounters, consequently they lose their energy in a short distance and have a short range.

BETA PARTICLES

β^- and β^+ particles are much lighter than alphas, are singly charged and travel at about the speed of light. Consequently they interact less strongly than alphas and will produce an ion pair once every thousand molecules encountered (air or water).

When β particles pass close to an atom they can lose some of their energy by a radiative process[1] and emit bremsstrahlung radiation (‘breaking radiation’) in the form of X-rays. Most of the β energy is lost by ionisation and only a small amount is lost to bremsstrahlung.

X AND GAMMA RADIATION

The Photoelectric Effect

The photoelectric effect (figure 2.1) is an absorption process and usually occurs for low energy photons (<0.1 MeV) such as X-rays. The energy E_X of the X-ray is transferred (absorbed) to an inner electron, normally a K-shell electron, and this gives the electron sufficient energy to escape from the atom. The atom is left positively charged (ie, an ion) and in an excited state due to the vacancy left in the inner shell. This vacancy is quickly filled by another electron dropping down from a higher shell with the subsequent release of a photon of frequency determined by the two shells involved.

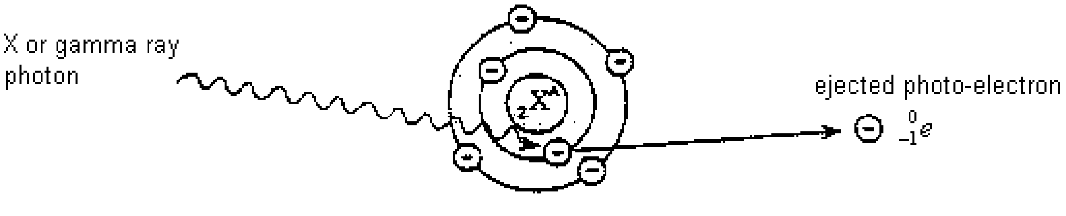

Fig 2.1: The Photoelectric Effect.

The energy of the ejected electron is given by the simple formula; $E_e = E_X - BE$, where:
E_e = energy of ejected electron
E_X = energy of incoming X or γ ray photon
BE = binding energy of ejected electron.
The ejected electron will then travel through the surrounding medium creating ion pairs in the same way as a beta particle of equivalent energy.

The Compton Effect

The Compton Effect (figure 2.2) is essentially an inelastic collision process and generally occurs for high-energy photons (>0.1 MeV) such as gamma rays. An incoming photon of high energy (γ - ray) collides with an electron in the valence band, ejecting the electron from the atom. A photon of lower energy (and hence different frequency) than the original is produced that travels at an angle to the direction of the incident photon, determined by conservation of momentum. The energy of the ejected or Compton electron can be determined by knowledge of the energies of the incoming and scattered photons.

As in the Photoelectric Effect, the ejected electron will then travel through the surrounding medium creating ion pairs in the same way as a beta particle of equivalent energy.

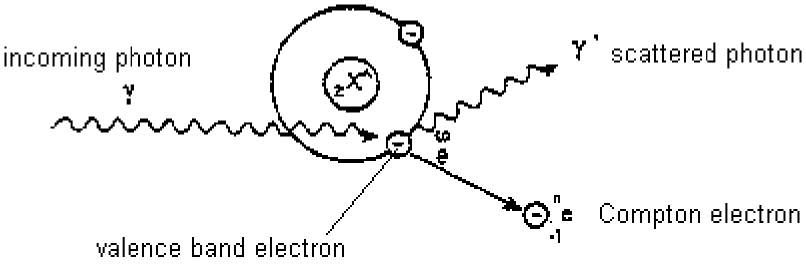

Fig 2.2: The Compton Effect

RANGE

The initial energy of an α or β particle is finite. We find that in traversing matter it continuously loses energy producing ionisations and is finally stopped, thus charged particle radiations have a finite range.

The range of an α or β particle is dependent on the number of atoms the particle encounters when it travels through a medium. The best way to estimate the number of atoms in a medium is using the concept of mass per unit area. If the density of a material is given by ρ gcm^{-3}, then the mass per unit area of a sheet of thickness t is ρt gcm^{-2}.

If we express the range in this form then we find that the formula for the range of α and β particles can be given in terms of the energies of the particles only. Symbolically:

$R_\beta = \frac{E_\beta}{2}\ gcm^{-2}$ (2.1) for β particles of maximum energy E_β (in MeV), and

$R_\alpha = \frac{E_\alpha}{1000}\ gcm^{-2}$ (2.2) for α particles of maximum energy E_α (in MeV).

Example 1

If the maximum energy of a ^{32}P beta particle is 1.7 MeV
a) What is the range of this beta?

If the density of a sheet of perspex is 1.2 gcm^{-3}
b) How far into the perspex would the beta particle penetrate?

Answer 1

a) Using formula 2.1, the range of this beta is $\frac{1.7}{2}$ = 0.85 gcm^{-2}.

b) Given the density of perspex, the penetration distance is simply $\frac{R_\beta}{\rho}$; ie, $\frac{0.85}{1.2} = 0.7cm$

Example 2

How far will 5 MeV alpha particles penetrate in skin, given the density of skin is 1 gcm^{-3}?

Answer 2

Range R_α = $\frac{5}{1000}$ = 5 x 10^{-3} gcm^{-2}, but
Density of skin, ρ = 1 gcm^{-3}

$\therefore$ penetration distance is $\frac{R_\alpha}{\rho}$ = 5 x 10^{-3} cm = 50 μm (the outer dead layer of skin $\geq$ 70 μm)

We can use the concept of range to calculate the thickness of shielding needed to stop any particular beta, in example 1 above the correct shielding for a ^{32}P beta would be ≥ 0.7 cm. However, we have to be careful when choosing the type of shielding to use. If we use a high-density material (eg lead) then we will stop the beta very quickly and this can lead to the emission of bremstraahlung radiation. Use of lower-density materials such as perspex requires greater thickness of absorber but produce much less bremstraahlung.

In example 2 above we see that alphas are easily stopped and will travel only a few cm in air.

X and Gamma Radiation

X and gamma radiation are types of electromagnetic waves and as such are chargeless and virtually massless. The probability of interaction with the orbital electrons of an atom is much smaller than that of alpha and beta radiation. This accounts for the well-known penetrability of X and gamma radiation.

As the probability of interaction with matter is small we find that a given thickness of absorber produces the same fractional reduction in intensity. We say that the incident radiation is attenuated and the degree of attenuation is dependent on the absorber material and the energy of the radiation. For all absorber materials this attenuation is exponential in character and, unlike the charged particle radiations, there is no thickness of material which will completely ‘stop’ X or gamma radiation (Figure 2.3)

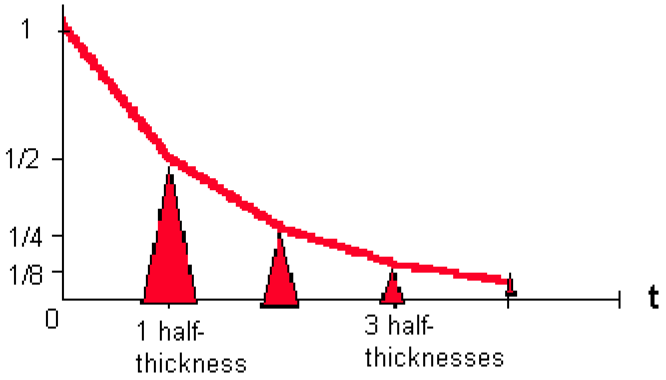

Figure 2.3: Attenuation of X and Gamma Radiation

You can see from figure 2.3 that this is a similar graph as that for half-life. In place of half-life $\tau_{1/2}$ we have half-thickness $t_{1/2}$. Hence, placing three layers of absorber each of thickness $t_{1/2}$ would attenuate a beam by ½ x ½ x ½ = $^1/_8$.

SHIELDING

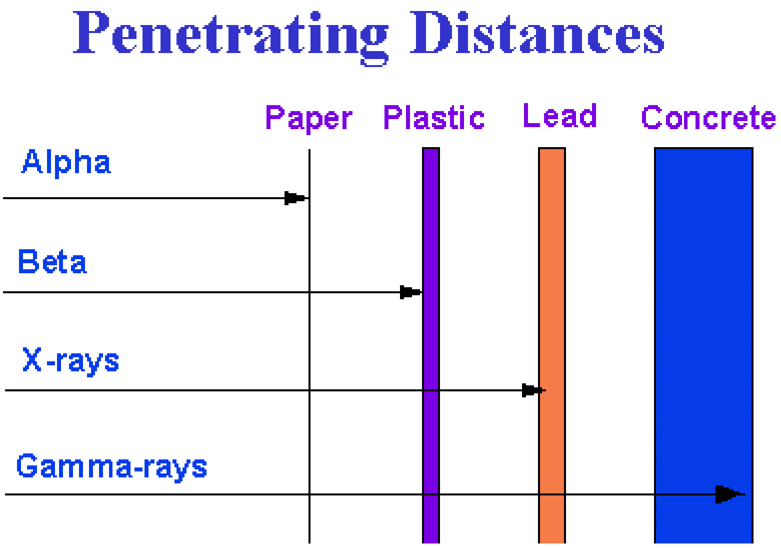

Figure 2.4: Some examples of suitable shielding, alpha and beta radiation can be completely stopped by shielding, X and gamma radiation can only be attenuated

Alpha

Alpha radiation penetrates less than 4 cm in air and will not penetrate the dead outer layer of skin; consequently most materials can be used for shielding.

Beta

Beta radiation can penetrate several metres in air and up to 0.8 cm in tissue: therefore shielding is required. As a result of the possibility of bremstraahlung radiation, it is best to use low-density materials, such as perspex, for shielding.

X Radiation

The energy of an X-ray is generally less than 0.1 MeV, consequently the interaction mechanism is the Photoelectric Effect. It turns out that the Photoelectric Effect is proportional to the fourth power of the atomic number, therefore we need to choose an absorber with a high atomic number – lead (Z = 82) is a good choice and a thickness of about 1 mm should be sufficient.

Gamma Radiation

The interaction mechanism is the Compton Effect. As this depends on the availability of valence electrons, it does not vary greatly with atomic number and subsequently we choose an absorber with a high mass per unit area and, again, lead is a good choice. However, if cost considerations are important, concrete can be used to replace lead but greater thickness will be required.

In all instances where shielding is required, shielding the source of radiation in its immediate vicinity is always the most effective and economical solution.

Notes:

1. *Bremstraahlung* is German for ‘breaking radiation’ and describes an effect whereby an accelerating/decelerating charge (in this case a beta particle) will emit electromagnetic radiation. Only a small fraction of the incident energy is converted into X-rays and this fraction is given approximately by the formula $\frac{E_\beta \ x \ Z}{1000}$; where the beta energy is in MeV and Z refers to the atomic number of the absorber. The resulting bremstraahlung is a continuous spread of energies in the X-rays produced, up to a maximum energy. A fuller explanation of this effect is beyond the scope of this course.