Chapter Four
(Interaction of Radiation with Matter)

Different types of radiation interact with matter in widely different ways. A large, massive, charged alpha particle cannot penetrate a piece of paper and even has a limited range in dry air. A neutrino, at the other extreme, has a low probability of interacting with any matter, even if it passed through the diameter of the earth.

Radiation can be classified into two general groups, charged and uncharged; therefore, it may be expected that interactions with matter fall into two general types. Charged particles directly ionize the media through which they pass, while uncharged particles and photons can cause ionization only indirectly or by secondary radiation.

A moving charged particle has an electrical field surrounding it, which interacts with the atomic structure of the medium through which it is passing. This interaction decelerates the particle and accelerates electrons in the atoms of the medium. The accelerated electrons may acquire enough energy to escape from the parent atom, this process is called ionization. Uncharged moving particles have no electrical field, so they can only lose energy and cause ionization by such means as collisions or scattering. A photon can lose energy by the photoelectric effect, Compton effect, or pair production.

Because ionizing radiation creates ions in pairs, the intensity of ionization or the specific ionization is defined as the number of ion-pairs formed per centimeter of travel in a given material. The amount of ionization produced by a charged particle per unit path length, which is a measure of its ionizing power, is roughly proportional to the particle's mass and the square of its charge as illustrated in the equation below.

$$I = \frac{mz^2}{K.E.}$$

Where: I is the ionizing power, m is the mass of the particle, z is the number of unit charges it carries and K.E. is its kinetic energy

Since m for an alpha particle is about 7300 times as large as m for a beta particle, and z is twice as great, an alpha will produce much more ionization per unit path length than a beta particle of the same energy. This phenomenon occurs because the larger alpha particle moves slower for a given energy and thus acts on a given electron for a longer time.

Alpha Radiation:

Alpha radiation is normally produced from the radioactive decay of heavy nuclides and from certain nuclear reactions. The alpha particle consists of 2 neutrons and 2 protons, so it is essentially the same as the nucleus of a helium atom. Because it has no electrons, the alpha particle has a charge of +2. This positive charge causes the alpha particle to strip electrons from the orbits of the target atoms. As the alpha particle passes through material, it removes electrons from the orbits of atoms it passes near. Energy is required to remove electrons and the energy of the alpha particle is reduced by each reaction. Eventually the particle will expend its kinetic energy, gain 2 electrons in orbit, and become a helium atom. Because of its strong positive charge and large mass, the alpha particle deposits a large amount of energy in a short distance of travel. This rapid, large deposition of energy limits the penetration of alpha particles. The most energetic alpha particles are stopped by a few centimeters of air or a sheet of paper.

Beta-Minus Radiation:

A beta-minus particle is an electron that has been ejected at a high velocity from an unstable nucleus. An electron has a small mass and an electrical charge of -1. Beta particles cause ionization by displacing electrons from atom orbits. The ionization occurs from collisions with orbiting electrons. Each collision removes kinetic energy from the beta particle, causing it to slow down. Eventually the beta particle will be slowed enough to allow it to be captured as an orbiting electron in an atom. Although more penetrating than the alpha, the beta is relatively easy to stop and has a low power of penetration. Even the most energetic beta radiation can be stopped by a few millimeters of metal.

Positron Radiation:

Positively charged electrons are called positrons. Except for the positive charge, they are identical to beta-minus particles and interact with matter in a similar manner. Positrons are very short-lived, however, and quickly are annihilated by interaction with a negatively charged electron, producing two gammas with a combined energy (calculated below) equal to the rest mass of the positive and negative electrons.

$$2 \text{ electrons} \left(\frac{0.000549 \text{ amu}}{\text{electron}}\right)\left(\frac{931.5 \text{ MeV}}{\text{amu}}\right) = 1.02 \text{ MeV}$$

Bremsstrahlung:

Small charged particles such as electrons or positrons may be deflected by nuclei as they pass through matter, which may be due to the positive charge of the atomic nuclei. This type of interaction generates x-radiation known as bremsstrahlung (Fig. below), which in German means "braking radiation."

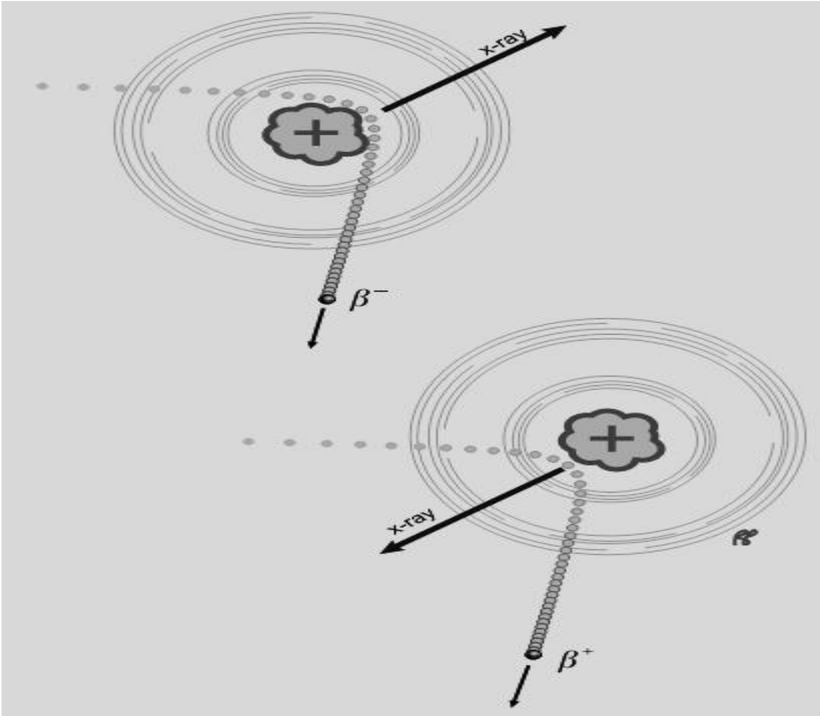

Figure (4-1): Bremsstrahlung. Beta particles (β−) and positrons (β+) that travel near the nucleus will be attracted or repelled by the positive charge of the nucleus, generating x-rays in the process.

Neutron Radiation:

Neutrons have no electrical charge. They have nearly the same mass as a proton (a hydrogen atom nucleus). A neutron has hundreds of times more mass than an electron, but 1/4 the mass of an alpha particle. The source of neutrons is primarily nuclear reactions, such as fission, but they may also be produced from the decay of radioactive nuclides. Because of its lack of charge, the neutron is difficult to stop and has a high penetrating power. Neutrons are attenuated (reduced in energy and numbers) by three major interactions, elastic scatter, inelastic scatter, and absorption. In elastic scatter, a neutron collides with a nucleus and bounces off. This reaction transmits some of the kinetic energy of the neutron to the nucleus of the atom, resulting in the neutron being slowed, and the atom receives some kinetic energy (motion). As the mass of the nucleus approaches the mass of the neutron, this reaction becomes more effective in slowing the neutron. Hydrogenous material attenuates neutrons most effectively. In the inelastic scatter reaction, the same neutron/nucleus collision occurs as in elastic scatter. However, in this reaction, the nucleus receives some internal energy as well as kinetic energy. This slows the neutron, but leaves the nucleus in an excited state. When the nucleus decays to its original energy level, it normally emits a gamma ray. In the absorption reaction, the neutron is actually absorbed into the nucleus of an atom. The neutron is captured, but the atom is left in an excited state. If the nucleus emits one or more gamma rays to reach a stable level, the process is called radiative capture. This reaction occurs at most neutron energy levels, but is more probable at lower energy levels.

Electromagnetic (Gamma) Radiation:

Gamma radiation is electromagnetic radiation. It is commonly referred to as a gamma ray and is very similar to an x-ray. The difference is that gamma rays are emitted from the nucleus of an atom, and x-rays are produced by orbiting electrons. The x-ray is produced when orbiting electrons move to a lower energy orbit or when fast-moving electrons approaching an atom are deflected and decelerated as they react with the atom's electrical field (called Bremsstrahlung).

The gamma ray is produced by the decay of excited nuclei and by nuclear reactions. Because the gamma ray has no mass and no charge, it is difficult to stop and has a very high penetrating power. A small fraction of the original gamma stream will pass through several feet of concrete or several meters of water. There are three methods of attenuating gamma rays. The first method is referred to as the photoelectric effect. When a low energy gamma strikes an atom, the total energy of the gamma is expended in ejecting an electron from orbit (generally inner shell). The result is ionization of the atom and expulsion of a high energy electron. This reaction is most predominant with low energy gammas interacting in materials with high atomic weight and rarely occurs with gammas having energy above 1 MeV. Any gamma energy in excess of the binding energy of the electron is carried off by the electron in the form of kinetic energy.

The second method of attenuation of gammas is called Compton scattering. The gamma interacts with an orbital (outer shell) or free electron; however, in this case, the photon loses only a fraction of its energy. The actual energy loss depending on the scattering angle of the gamma (scattering angle can range from nearly 0^o to 180^o). The gamma continues on at lower energy, and the energy difference is absorbed by the electron. This reaction becomes important for gamma energies of about 0.1 MeV and higher.

In Compton scattering, a photon scatters from an electron, resulting in a scattered electron (Compton electron) and a less energetic photon. If we regard the stuck electron as free and at rest (good approx.), we can use relativistic conservation to find a formula for:

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

At higher energy levels, a third method of attenuation is predominant. This method is pair-production. When a high energy gamma passes close enough to a heavy nucleus, the gamma completely disappears, and an electron and a positron are formed. For this reaction to take place, the original gamma must have at least 1.02MeV energy. Any energy greater than 1.02 MeV becomes kinetic energy shared between the electron and positron. The probability of pair-production increases significantly for higher energy gammas.

If we consider a beam of photons on a slab of thickness x, we have μ as a "total linear attenuation coefficient", where simply $\mu=\tau+\sigma+\kappa$ (for photoelectric absorption, Compton scattering, and pair production losses, respectively). The fractional loss in intensity is:

$dI/I=-\mu dx$ so that $I=I_o e^{-\mu x}$

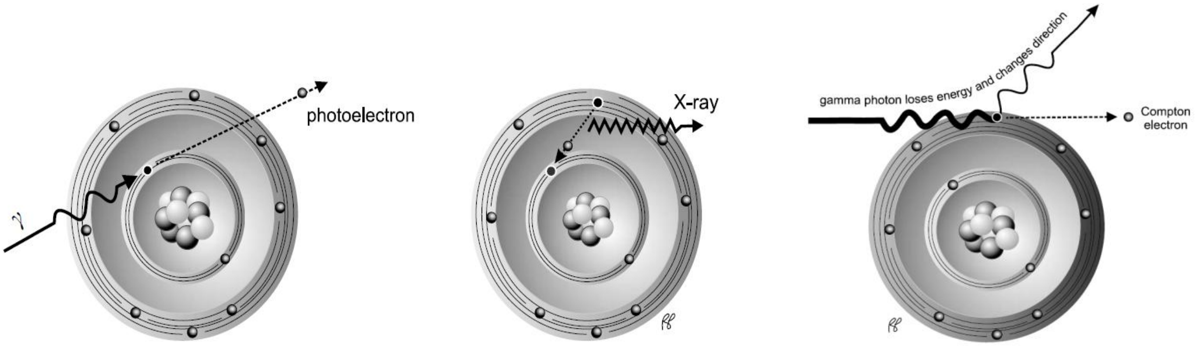

Figure (4-2): (a) Photoelectric effect, (b) Compton scattering.

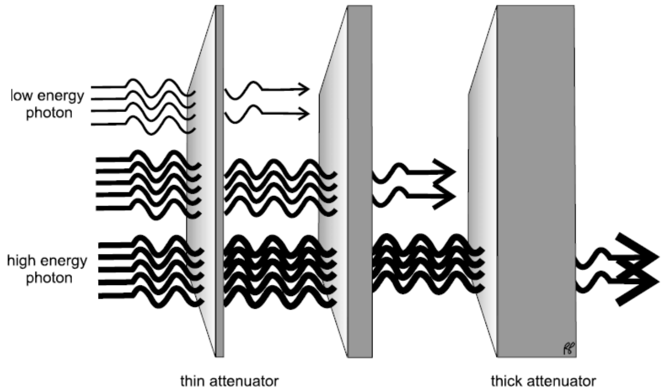

Figure (4-3): Half-value layer.

Shielding

Alpha particles can be shielded by a piece of paper.

Beta particles can be shielded by a thin sheet of metal.

Gamma rays require thicker metal, often of high Z such as lead.

Neutrons moderated (slowed down) by low Z materials, captured by boron, cadmium.