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Basic Modes of Radioactive Decay

Hasna Albandar

Abstract

This basic modes of radioactive decay review “Gamma Rays” reviews some topics related to radiation, its classification and importance. In general, gamma rays interfere with our life, so we need to comprehend radiation as fact around us all the time and all the time. We live in a naturally radioactive world, but to what extent do physicians, nurses, and medical technicians, who may have to deal with urgent cases of a radiation, know about it? This chapter will address what radiation is and what is its role. This chapter will guide us toward the knowledge of ionizing radiation and its certain forms such as alpha particles, beta particles, gamma rays, and X-rays. as well as it will review on radioactive decay (nuclear decay) as well as help us learn about radioactivity and radiation, in addition to the types of decays, which are divided into beta decay, gamma decay, electron capture, positron decay, and alpha decay. This chapter will focus on radioactive decay, the activity and units of radioactive activity, and half-life of it. The last part of this chapter discusses attenuation as the reduction in the intensity of gamma ray or X-ray beam. The most important subtitles that are scattered from attenuation are HVL mean free path, the linear attenuation coefficient, pair production, and photoelectric scattering.

Keywords: activity, alpha particle, beta particle, decay (radioactive), electron capture, electromagnetic radiation, electron, emissions, energy, electron volt (eV), gamma rays, gray (Gy), half-life (radiological), ionizing radiation, isotopes, molecule, nonionizing radiation, nucleus (of an atom), nuclide, photon, positron, positron emission, proton, radiation, radionuclide, X-ray

1. What is radiation?

Radiation is a form of energy that is released as electromagnetic waves or particles, moves through space, and may be able to penetrate or interact with different materials.

Radiation-caused changes in materials depend on the origin, type of radiation, and the deposited energy [1].

1.1 Classification of radiations

Radiation is classified into ionizing and nonionizing radiation. Ionizing radiation is divided into direct ionizing and indirect ionizing (as shown in **Figure 1**).

1.1.1 Ionizing radiation

Ionization radiation refers to the capability of ionizing material either directly or indirectly because of their higher energy such as X-rays, γ -rays, energetic neutrons, electrons, protons, and heavier particles (as shown in **Figure 2**).

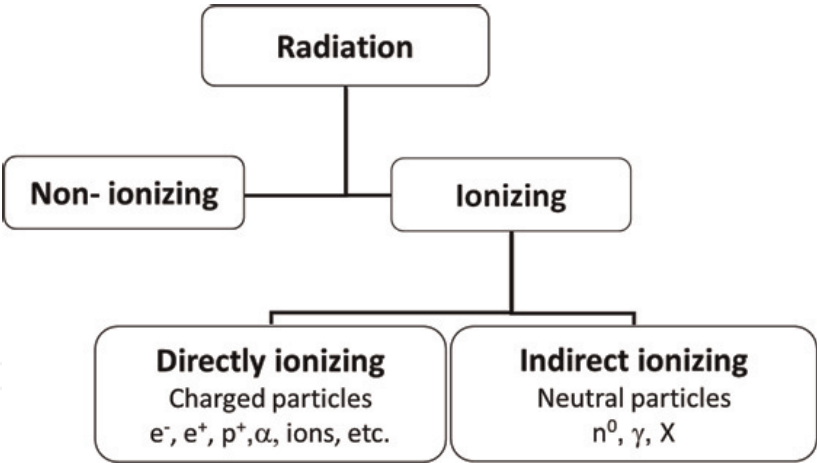


Figure 1.
Classification of radiations.

- If the energy of electromagnetic waves is high, the frequency will be high with short wavelength such as those of gamma rays or heavy particles (beta and alpha).
- Enough high energy to pull electron from orbit [2].

1.1.2 Nonionizing radiation

Nonionizing radiation refers to the inability of ionizing materials because of their lower energy, Such as ultraviolet radiation, visible light, infrared photons, microwaves and radio waves (as shown in **Figure 2**).

- If the energy of electromagnetic waves is low, the frequency will be low with long wavelength such as those of radio waves and microwaves.
- Not enough energy to pull electron from orbit, but the electron can exit [3].

1.2 Classification of ionizing radiation

Ionizing radiation is classified into two types:

- i. Directly ionizing radiation

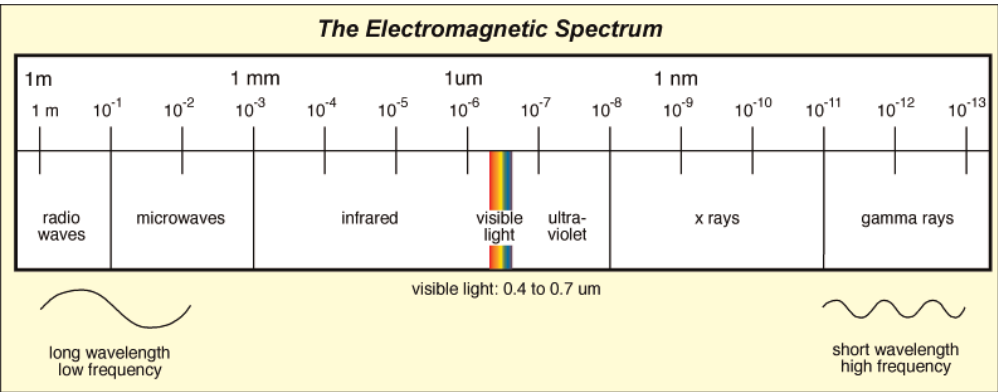


Figure 2.
The schematic representation of the different regions of the electromagnetic spectrum.

- This consists of charged particles, such as electrons, protons, α particles, and heavy ions.
 - Energy can be deposited by directly ionizing radiation in the medium through direct coulomb interaction between the directly ionizing charged particles and orbital electrons of atoms.

ii. Indirectly ionizing radiation

- This consists of neutral particles, photons (X-ray and γ -rays), and neutrons.
 - Energy can be deposited by indirectly ionizing radiation (photons or neutrons) in the medium through two steps:
 1. First step: a charged molecule is transmitted in the medium (photons discharge electrons or positrons; neutrons discharge protons or heavier particles).
 2. The second step: the produced charged particles store vitality to the medium through direct Coulomb interaction with the orbital electrons of the atoms.

1.2.1 Ionizing radiation takes a few forms

Alpha, beta, neutron particles, gamma rays and X-rays are each caused by unstable atoms, either through the overabundance of vitality or mass (or both of them).

To reach a steady state, they must discharge that additional vitality or mass within the frame of radiation.

Alpha particles (α particle): positive charged particles (+2), which are released in the radioactive decay of some nuclei. An alpha is a particle which is emitted from the nucleus of an atom, which consists of (+2) protons and (2) neutrons with mass number (4) (Helium atom). It is strong ionizing with low penetration power and short range.

Beta particles (β^+ or β^-): They are particles with electric charge ((+) or (-)) emitted from the nucleus during radioactive decay. They take the form of either an electron or a positron (a particle with the size and mass of an electron, but with a positive charge).

- Electrons or positrons have small mass and variable energy. Electrons are formed when a neutron transforms into a proton and an electron.

Gamma rays: are different from alpha or beta rays, because they do not contain any particles, as they are used in electromagnetic radiation. Instead, they consist of a photon of energy, which is released from an unstable nucleus of an atom.

Isomeric transition: It occurs when the excited atomic nucleus changes from a higher to a lower state of the energy by emitting gamma ray.

Internal conversion electron: This process occurs when the gamma rays are not released sometimes, so they provide their exceed energy to the electron in the atomic orbit; this process usually happens to the nearest nucleus (as shown in **Figure 3**).

X-rays: They are similar to gamma radiation; the only one primary difference is that they originate from the electron shell. This is generally caused by energy

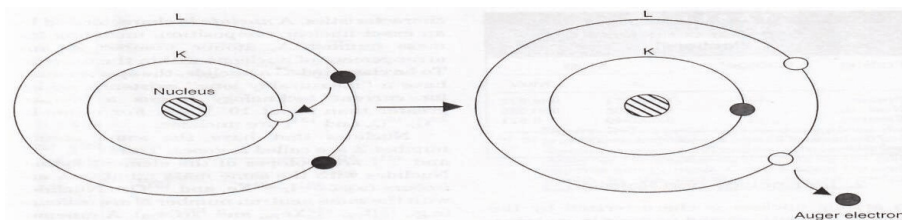


Figure 3.
Emission of an auger electron as an alternative to X-ray emission. No X-ray is emitted.

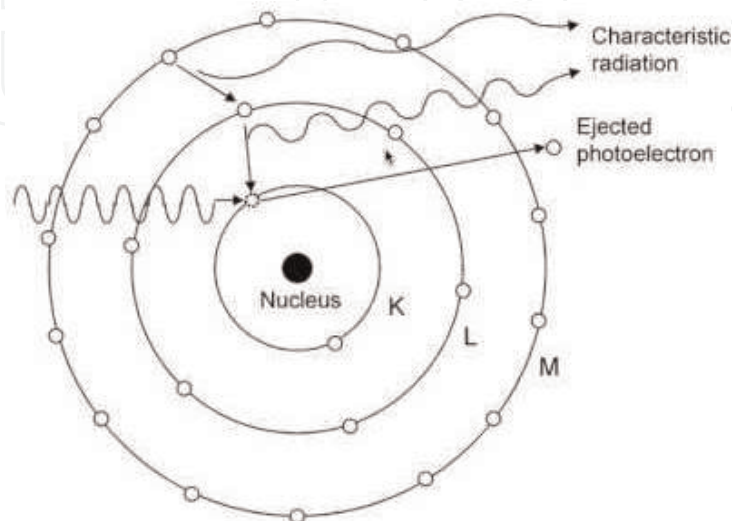


Figure 4.
How the emission of the characteristics of X-ray occurs when the orbital electrons move from an outer shell so as to fill in the inner shell vacancy.

changes in an electron, such as moving from a higher energy level to a lower one. This causes the excess energy to be released. X-rays are called **characteristic X-ray**. It (X-ray) has longer wavelength and possess (usually) lower energy than gamma radiation, as well. The emission of high-energy waves came from the electron of an atom (as shown in **Figure 4**).

A **neutron particle** is an uncharged element particle with a mass that is slightly greater than that of the proton, and it is found in the nucleus. It is usually released because of spontaneous or induced nuclear fission.

2. Radioactive decay (nuclear decay)

Radioactive decay is a process in which an unstable nucleus transforms into a more stable one by releasing particles or photons. In addition, it results in the conversion of mass into energy.

In some decay modes, electron mass is converted into energy as well. The total mass-energy conversion amount is called the transition energy. Most of this energy is imparted as kinetic energy to released particles or is converted to photons with a small portion as kinetic energy.

In a few decay modes, electron mass is changed into vitality as well. The full mass-energy transformation sum is called the transition energy. Most of this energy is imparted as active energy to discharged particles or is changed over to photons with a little portion as kinetic energy [4].

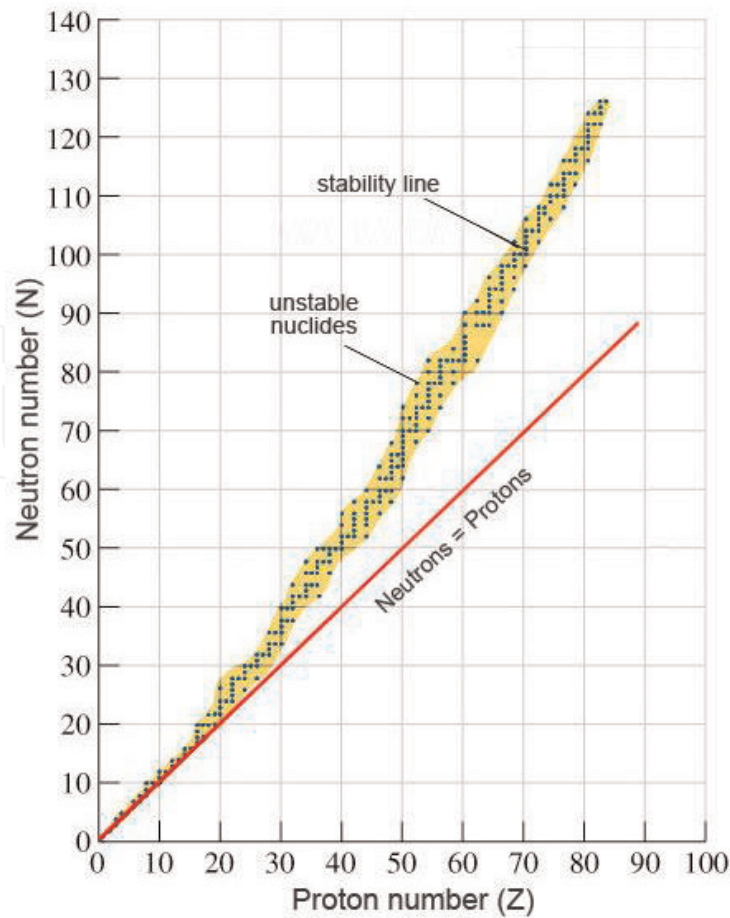


Figure 5.
 For proton numbers (Z) up to 20, $N = Z$ could be a straight line. For all nuclei with $Z > 20$, stable nuclei have less protons than neutrons; the line bends upwards. Unsteady nuclei over the soundness bend are called neutron-rich [1].

The neutron - Proton ratio shows that if the number of protons increase, the number of neutrons must increase even more for stability. This process is shown in **Figure 5**.

2.1 Radioactive decay

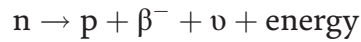
Radioactive decay is the process by which the unstable nucleus tries to change into a more stable form. As, it is the process in which the transformation will take place depending on the composition of the nucleus.

2.2 Types of decays

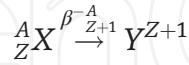
1. Beta decay
2. Gamma decay
3. Electron capture
4. The positron decay
5. Alpha decay

2.2.1 Beta decay

Beta decay or (β^- decay) is a process in which the neutron in the nucleus is essentially transformed into a proton and electron:



Beta decay is also the decay of one of the neutrons to a proton via the weak interaction:



The electron is called β^- particle (ν), meanwhile the neutrino is a particle that has no mass or electrical charge. It does not virtually undergo interactions with matter and therefore is essentially undetectable.

The energy released in β^- decay is shared between β^- particle and neutrino (ν). This sharing of energy is more or less random from one decay to the next. As shown in **Figure 6**, the plot displays the distribution of β^- particle energy. It is also noticed that beta particles are not monoenergetic for a particular radionuclide, but they are released at varying energy levels over a continuous range (spectrum). The average energy of beta emission can be estimated as one-third of the maximum energy of emission: $E_{\text{avg}} = 1/3 E_{\text{max}}$ (as shown in **Figure 6**) [1].

2.2.2 Gamma decay

It is a mechanism for an excited nucleus to release energy. Emanation could be a sort of radioactivity in which a few unsteady nuclear nuclei disseminate excess energy by an unconstrained electromagnetic radiation.

Within the most common form of gamma decay, which is called gamma emission, gamma rays (photons or bundles of electromagnetic vitality, of highly short wavelength) are radiated.

Gamma rays are electromagnetic radiation (high-energy photons) with an extreme frequency and a high energy. They are created by the decay of nuclei as they travel from a high-energy state to a lower state; this process is called “gamma decay.” Most of atomic responses are accompanied by gamma emission.

Gamma decay also includes two other electromagnetic processes: internal conversion and pair production.

Internal conversion (IC) is a process in which the excess energy of the nucleus is directly transferred to one of its own orbital electrons which is ejected instead of the ray. In this case, the ejected electron is called a conversion electron (as shown in **Figure 7**).

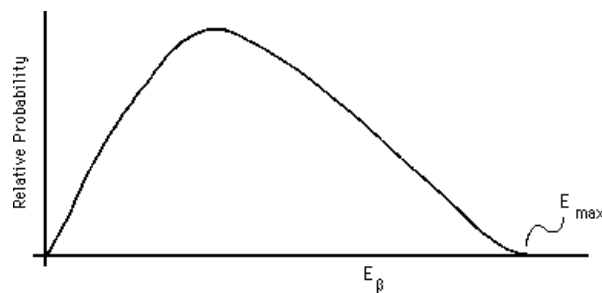


Figure 6.
The distribution or spectrum for β^- particle.

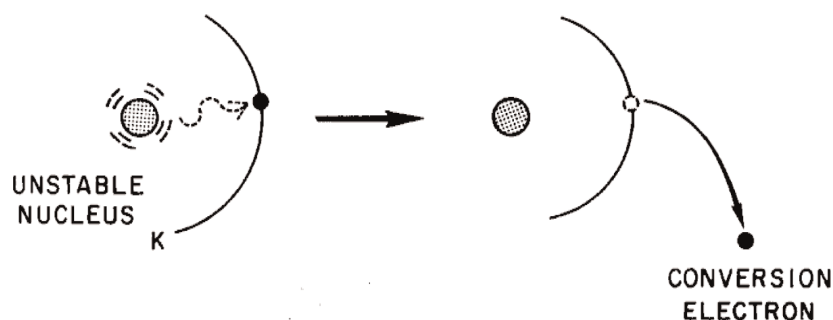


Figure 7. Schematic representation of internal conversion involving a K shell electron. Unstable nucleus transfers its energy to an orbital electron to release a converted electron.

In internal pair production, the excess energy is converted within the electromagnetic field of a nucleus into an electron and a positron that are released together. Internal conversion always accompanies the predominant process of gamma emission.

Internal pair production needs the excess energy of the unstable nucleus to be at least equivalent to the combined masses of an electron and a positron (as shown in **Figure 8**).

2.2.2.1 Isomeric transition conversion

The daughter of radioactive parent may be formed in a long-lived metastable (isomeric state) as opposed to an excited state. The decay of the metastable (isomeric state) by the emission of a γ -ray is called isomeric transition.

Isomeric transition: a nuclear process in which a nucleus has abundant energy following the emanation of an alpha molecule or a beta molecule and in turn discharges energy without a change in its number of protons or neutrons. Isomeric moves can occur through the emission of a gamma ray or through the process called “internal conversion.”

In many nuclides, isomeric transitions produce gamma photons and internal conversion electrons. When an electron is removed from the atom by internal conversion, a vacancy is created. All transitions are usually followed by either gamma or internal conversion electron emission.

The energized atomic state taking after the emission of a beta particle may be nearly steady, and the nucleus may be able to remain in this state for minutes, hours, or even days, sometimes recently discharging a gamma ray.

The isomer (no change of the number of proton or neutron) works as a separate radioactive material, which is decaying exponentially with the emission of a gamma ray only [5].

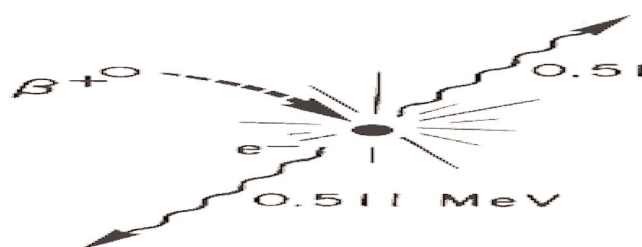


Figure 8. Schematic representation of mutual annihilation reaction between a positron (β^+) and an ordinary electron. A pair of 0.511 MeV annihilation photons is released “back to back” at 180° to each other.

2.2.3 Electron capture

Electron capture decay: it is an inverted β^- decay, whereas an orbital electron is captured by the nucleus and combines with a proton to form a neutron:



In other words, we can say that the electron capture is a process, in which a parent nucleus captures one of its orbital electrons and releases a neutrino. This neutrino is emitted from the nucleus and carries away some of the transitions energy. The remaining energy appears in the form of characteristic X-rays and Auger electrons, which are emitted by daughter product, whereas the resulting orbital electron vacancy is filled (as shown in **Figure 9**).

2.2.4 The positron decay β^+

In case of radioactive decay by positron emission, a proton in the nucleus is transformed into a neutron and a positively charged electron (positron β^+) then a proton ejected from the nucleus. A positron is an antiparticle of an ordinary electron:



After ejection from the nucleus, it loses its kinetic energy in collision with atoms of the surrounding matter and comes to rest; this usually happens within a few millimeters from the site of its origin in body tissue [6].

2.2.5 Alpha decay

Radionuclide that decayed by a particle emission or by nuclear fission has relatively little importance for direct usage as tracers in nuclear medicine.

Both of these decay modes occur primarily among very heavy elements that are of a little interest as physiological tracers [7].

The particles, which are released with kinetic energy, are usually found between 4 and 8 MeV.

Decay by alpha particle emission results in transmission of elements, but it is not isobaric.

Activity: It is the total number of nuclei that are decaying per second. It is the probability that any individual atom will undergo decay during the same period:

$$A = \lambda N \quad (5)$$

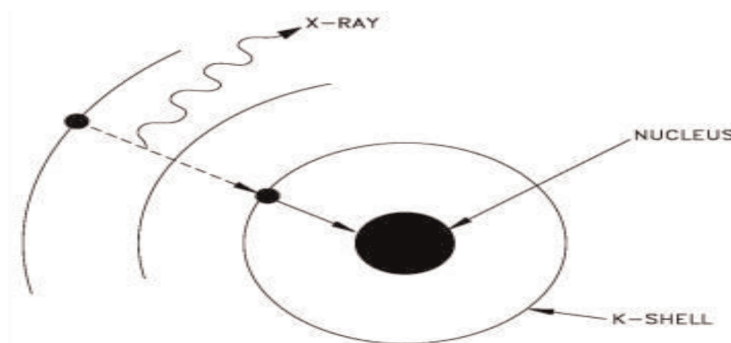


Figure 9.
The nucleus captures one of its orbital electrons and X-ray.

where A = activity; N = the number of decay nuclei in the sample; λ = decay constant.

The decay factor ($e^{-\lambda t}$) is an exponential function of time (t). Exponential decay is characterized by disappearance of a constant function of activity or number of atoms prevented per unit time interval:

$$A = A_0 e^{-\lambda t} \tag{6}$$

where A is the activity of radionuclide at a given time t ; A_0 is the activity of radionuclide at time $t = 0$; decay constant (λ).

The decay constant (λ) is the probability that a nucleus will decay per second, so its unit is (s^{-1}). Activity can be determined by direct measurement.

2.2.6 Units of radioactivity

1. Conversion unit

-Curie, where $1 \text{ Ci} = 3.7 \times 10^{10}$ disintegration per second

2. SI unit

-Becquerel, where $1 \text{ Bq} = 1$ disintegration per second.

$$1 \text{ Ci} = 3.7 \times 10^{10} \text{ dps} = 37 \text{ GBq}.$$

$$1 \text{ mCi} = 3.7 \times 10^7 \text{ dps} = 37 \text{ MBq}.$$

$$1 \mu\text{Ci} = 3.7 \times 10^4 \text{ dps} = 37 \text{ kBq}.$$

Half-life: It is the amount of time taken for the given quantity so as to be decreased to half of its initial value. As shown in **Figure 10**, the term is most commonly used in relation to atoms undergoing radioactive decay, but it can be used to describe other types of decay, whether exponential or not. One of the most well-known applications of half-life is:

$$T_{1/2} = \ln 2 / \lambda \tag{7}$$

where $T_{1/2}$ is the half-life of radionuclides; $\ln 2 = 0.693$ is the base of natural logarithms; λ is decay constant of radionuclides.

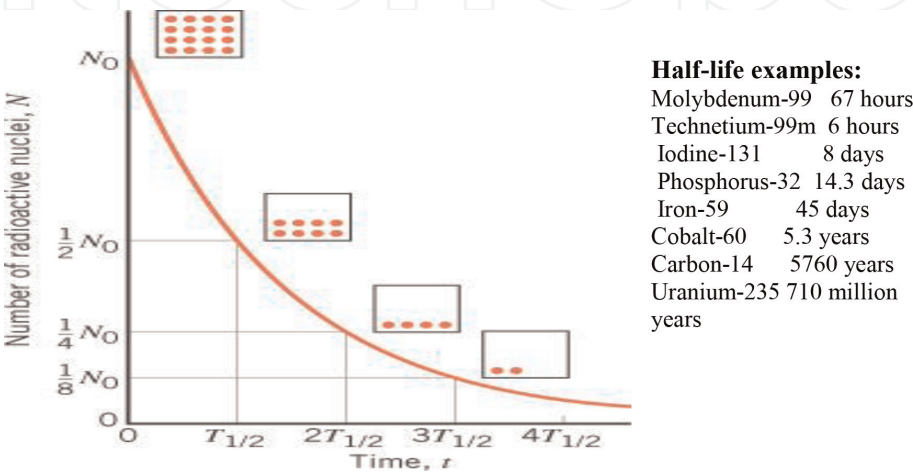


Figure 10.
The time required for it to decay the number of radioactive nuclei to 50% of the (N_0).

3. Attenuation

Attenuation is the reduction in the intensity of gamma ray or X-ray beam, as it traverses matter either by the absorption of photons or by deflection (scattering) of photons from the beam.

Attenuation results from the interaction between penetrating radiation and matter, as it is not a simple process. These interactions include the photoelectric effect, scattering, and pair production [8].

3.1 HVL

Half-value layer (HVL): It is defined as the thickness of material required to reduce intensity of gamma ray or X-ray beam to one-half of its initial value (as shown in **Figure 11**).

3.2 Mean free path

The range of a single photon in matter that cannot be predicted. The distance traveled some time recently interaction can be calculated from direct attenuation coefficient or the HVL of the beam.

Mean free path (MFP) of photon beam is:

$$MFP = \frac{1}{\mu} = \frac{1}{0.693/HVL} = 1.44HVL \quad (8)$$

3.3 Linear attenuation coefficient

The linear attenuation coefficient (μ) can be characterized as the division of a beam of X-rays or gamma rays that's retained or scattered per unit thickness of the absorber.

This esteem accounts for the volume of number of atoms in a cubic cm of material and the probability of a photon of being scattered or absorbed from the nucleus or an electron of one of these atoms.

Linear attenuation coefficient is the sum of individual linear attenuation coefficients for each type of interaction:

$$\mu = \mu_{\text{coherent}} + \mu_{\text{photo}} + \mu_{\text{Compton}} + \mu_{\text{pair}} \quad (9)$$

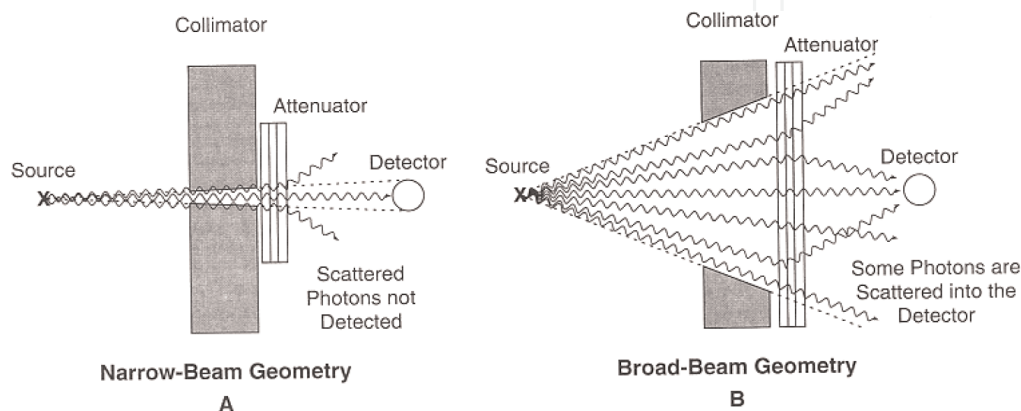


Figure 11. Monoenergetic photons under narrow-beam geometry conditions. The probability of attenuation remains the same for each additional HVL thickness placed in the beam.

In diagnostic energy range, μ decreases with increasing energy except at absorption edges (e.g., K-edge) [9].

3.3.1 Linear attenuation coefficient

- The process of fraction of photons removed from a monoenergetic beam of X-ray or gamma ray per unit thickness of material is called linear attenuation coefficient (μ), and it is typically expressed in cm^{-1} .
- The number of photons removed from the beam traversing a very small thickness μ_x :

$$n = \mu N \Delta x \quad (10)$$

where n = the number removed from beam; N = the number of photons incident on the material; X = the thickness of material.

- For a given thickness of material, the probability of interaction depends on the number of atoms which the X-rays or gamma rays encounter per unit distance.
- The density (μ) of material affects this number.
- -Linear attenuation coefficient is proportional to the density of the material:

$$\mu_{\text{water}} > \mu_{\text{ice}} > \mu_{\text{water vapour}} \quad (11)$$

3.3.2 Mass attenuation coefficient

- For a given thickness, the probability of interaction relies on the number of atoms per volume.
- Dependency can be overcome by normalizing linear attenuation coefficient for thickness of material:

$$\text{mass attenuation coefficient } (\mu/\rho) = \frac{\text{linear attenuation coefficient } (\mu)}{\text{density of material } (\rho)} \quad (12)$$

1. Mass attenuation coefficient ordinarily can be seen in cm^2/g units.

2. Mass attenuation coefficient is autonomous of density.

3. For a given photon energy:

$$\mu_{\text{water}}/\rho_{\text{water}} = \mu_{\text{ice}}/\rho_{\text{ice}} = \mu_{\text{water vapour}}/\rho_{\text{water vapour}} \quad (13)$$

4. In radiology, we usually differentiate between regions of an image that correspond to irradiation of adjacent volumes of tissue.

5. In density, the mass contained within a given volume plays an important role.

$$N = N_0 e^{-\left(\frac{\mu}{\rho}\right) \rho x} \quad (14)$$

The photon interactions are dependent on the atomic properties of a material rather than its density; the attenuation coefficients for isolated processes are often given as mass attenuation coefficients (divided by ρ).

3.3.2.1 Attenuation from coherent scattering

Coherent scattering is vital for low kilo voltage photons as it increases with atomic number.

3.3.2.2 Attenuation from photoelectric effect

The mass photoelectric attenuation coefficient is commensurate to the cube of the atomic number (Z^3) and inversely proportional to the cube of the beam energy (E^3).

3.3.2.3 Attenuation from incoherent scattering

The mass incoherent scattering attenuation coefficient is comparative to most values of Z , but it diminishes gradually with the expanding of beam energy. It is most dependent on the electron density [10].

3.3.2.4 Attenuation from pair production

Pair production happens only with higher beam energies (over 1.02 MeV). The mass attenuation coefficient for pair production is linearly related to the atomic number.

Increasing beam energy also raises the attenuation from pair production in a logarithmic style [11].

The attenuation of gamma radiation can be achieved using a wide range of materials. Understanding the basic principles involved in the physical interactions of gamma radiation with matter that lead to gamma attenuation can help in the choice of shielding for a given application. Utilizing this understanding and considering the physical, chemical, and fiscal constraints of a project will lead to better application of resources to develop the most appropriate type of shielding [1].

3.3.3 The methodology

Experimental and analytical methods are methods that are used to describe actions to be taken so as to investigate this subject in detail and the rationale for the application of specific procedures or techniques used to identify, select, process, and analyze information applied for understanding, thereby allowing the reader to critically evaluate a study's overall validity and reliability. Both of these methods are prime methods of inquiry in science. The key features are controlled over variables' careful measurement and establishing cause and effect relationships. An advantage of both is that the experimental and analytical methods should be objective.

4. Conclusion

Radiation has always been present around us. Life has evolved in a world containing significant levels of ionizing radiation. We are also exposed to fabricated radiation from sources such as medical treatments and activities involving radioactive materials. Since the early twentieth century, radiation's impacts have been

considered in profundity, in both the research facility and among human populaces. Because dangers of radiation on the well-being are known, it must be carefully utilized and entirely controlled. A balance must be struck between radiation's societal benefits and the dangers that radiation postures to individuals, wellbeing, and the environment. It can be confirmed that ionizing radiation has long been vital in medicine and industry.

Modern medicine would be impossible without ionizing radiation. X-ray imaging, computed tomography scans, diagnostic and therapeutic nuclear medicine, the gamma knife, and linear accelerators are a few of the technologies that have revolutionized medical diagnosis and treatment. Radiation's benefits for human wellbeing can be measured in thousands of lives spared and indeed more prominent numbers of people whose quality of life has been made strides each year by these innovations. Indeed in spite of the fact that the utilization of ionizing radiation in medicine offers gigantic benefits, in any case, it moreover postures potential dangers to patients, restorative faculty, and the public. The diagnostic and helpful devices that remedy moreover can cause intestinal wounds and chronic illness such as cancer.


In expansion to the gamma rays, the attenuation of gamma radiation can be accomplished by employing a wide range of materials. Understanding the fundamental standards included within the physical interactions of gamma radiation with matter that lead to gamma radiation can offer assistance within the choice of protecting for a given application. Utilizing this understanding and considering the physical and chemical limits of a project will lead to a better application of resources to develop the most suitable type of shielding.

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