

INTERACTION OF RADIATION WITH MATTER

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9.1. INTRODUCTION

The interaction of radiation with matter is a fundamental concept in both physics and various scientific disciplines, including nuclear physics, medical physics, and radiation protection. When radiation—whether in the form of particles or electromagnetic waves—encounters matter, it can transfer energy to the atoms and molecules within that material. This process can lead to various effects, ranging from the ionization of atoms to the excitation of electrons, and can even cause chemical changes in the substance being irradiated. Understanding these interactions is essential for applications in medical imaging, radiation therapy, nuclear energy, and radiation protection. Radiation interacts with matter in different ways depending on its type and energy. The most common types of radiation include alpha particles, beta particles, gamma rays, X-rays, neutrons, and ultraviolet light. Each type of radiation has distinct properties and interacts with matter differently based on factors such as mass, charge, energy, and wavelength. In the case of ionizing radiation (which includes alpha, beta, gamma, and X-ray radiation), the primary interactions are those that result in the removal of electrons from atoms, creating charged particles called ions. This ionization process can have significant effects on biological tissues and materials, which is why ionizing radiation is closely monitored in medical and environmental settings. For non-ionizing radiation, such as ultraviolet light and microwaves, the interactions are primarily associated with the excitation of electrons rather than their complete removal from atoms ^[1]. There are several key processes through which radiation interacts with matter, including photoelectric absorption, Compton scattering, and pair production for electromagnetic radiation, and elastic scattering and nuclear reactions for particle radiation. The type of interaction depends on the energy of the radiation and the atomic composition of the material. In medical and radiological contexts, understanding the interaction of radiation with biological tissues is crucial for both diagnostic and therapeutic applications. For example, X-rays and gamma rays are widely used in medical imaging and cancer treatments, respectively, while alpha and beta particles are used in targeted therapies. Additionally, the interaction of radiation with matter is essential for designing radiation shielding and protecting individuals from unnecessary exposure ^[2].

This chapter aims to explore the different ways in which radiation interacts with matter, examining the physical principles, the types of interactions, and their relevance to fields such as medicine, radiation safety, and nuclear technology. Understanding these interactions provides a foundation for advancing the safe and effective use of radiation in various scientific and industrial applications. Radiation interacts with matter in fundamental ways that underpin various scientific, technological, and medical applications. These interactions determine how radiation propagates through different materials, its effects on atomic and molecular structures, and its practical uses in fields such as medical imaging, radiation therapy, nuclear energy, materials science, and astrophysics. The interaction of radiation with matter is broadly classified based on the nature of the radiation—ionizing and non-ionizing radiation—each exhibiting distinct mechanisms of interaction. Understanding these interactions is critical for optimizing radiation-based technologies while ensuring safety and effectiveness in their applications ^[3]. Ionizing radiation, which includes alpha (α) particles, beta (β) particles, gamma (γ) rays, X-rays, and neutron

radiation, carries sufficient energy to remove electrons from atoms, leading to ionization. This ability to ionize matter makes ionizing radiation particularly significant in medical applications such as cancer treatment, where it is used to destroy malignant cells. Additionally, ionizing radiation is harnessed in radiation detection, sterilization, and nuclear power generation. However, its ability to alter molecular structures, including DNA, also necessitates careful regulation and protective measures to mitigate harmful biological effects ^[4]. Non-ionizing radiation, which includes radio waves, microwaves, infrared radiation, visible light, and ultraviolet (UV) radiation (with some exceptions), lacks the energy to ionize atoms. Instead, it interacts with matter primarily through excitation, causing atoms and molecules to absorb energy and move to higher energy states without ionization. These interactions are widely exploited in applications such as laser technology, optical communication, and medical treatments like phototherapy. While non-ionizing radiation is generally less hazardous than ionizing radiation, prolonged exposure to certain forms, such as UV radiation, can still cause biological damage, including skin cancer and cataracts ^[5]. The mechanisms of radiation interaction with matter include absorption, scattering, ionization, and transmission, each of which influences the behaviour of radiation as it encounters different materials. Absorption occurs when radiation energy is transferred to matter, often leading to ionization or excitation. The degree of absorption depends on factors such as radiation energy, material composition, and atomic number. For instance, high-energy X-rays and gamma rays are absorbed more effectively by dense materials like lead, which is why lead shielding is commonly used for radiation protection. Scattering occurs when radiation changes direction due to interactions with atoms or molecules. In medical imaging, for example, Compton scattering plays a significant role in the attenuation of gamma radiation, impacting image quality in diagnostic radiology. Ionization is particularly important in biological and technological applications, as it can damage molecular structures, making it useful in cancer treatment while posing risks of radiation-induced mutations. Transmission describes the passage of radiation through a material without significant interaction, a principle utilized in imaging techniques such as X-ray radiography and computed tomography (CT) scans, where different tissues allow varying degrees of radiation transmission to create detailed images of internal structures ^[6].

Several factors influence how radiation interacts with matter, including radiation energy, material density, atomic composition, and thickness. Higher-energy radiation has greater penetration ability, allowing it to travel through materials before being absorbed or scattered. For example, gamma rays and X-rays can pass through soft tissues but are absorbed by bones, enabling their use in diagnostic imaging. Conversely, low-energy radiation, such as alpha particles, interacts strongly with matter and is easily stopped by thin barriers like paper or human skin. The atomic number (Z) of a material also plays a crucial role, as materials with higher atomic numbers, such as lead or tungsten, contain more electrons and stronger electromagnetic fields, making them more effective at absorbing high-energy radiation. Additionally, the density of a material influences radiation interactions, as denser materials contain more atoms per unit volume, increasing the likelihood of absorption and scattering events. The thickness of a material further affects the degree of radiation interaction, as increasing thickness enhances absorption and reduces the intensity of transmitted radiation. These principles are essential in designing effective radiation shielding, ensuring safety in medical, industrial, and nuclear environments ^[7]. The study of radiation interactions with matter has led to numerous innovations and technological advancements. In medical physics, understanding these interactions has enabled the development of advanced imaging techniques such as positron emission tomography (PET), single-photon emission computed tomography (SPECT), and magnetic resonance imaging (MRI), as well as therapeutic applications like radiation therapy for cancer treatment. In radiation safety, knowledge of radiation attenuation and shielding materials has contributed to the protection of workers and the public from harmful radiation exposure. Additionally, in nuclear energy, these principles govern reactor design, radiation shielding, and fuel cycle management. Furthermore, in astrophysics, radiation interactions help scientists study cosmic phenomena, including the effects of cosmic radiation on interstellar matter and planetary atmospheres.

9.2. TYPES OF RADIATION INTERACTIONS

Radiation interacts with matter in several ways, and these interactions are fundamental to radiology, influencing both diagnostic imaging and radiation therapy. The nature of these interactions depends on the energy of the X-ray or gamma-ray photons and the atomic composition of the material they encounter. In radiology, the most

significant interactions include the photoelectric effect, Compton scattering, Rayleigh scattering, pair production, and photodisintegration. Understanding these interactions is essential for optimizing image quality, ensuring radiation safety, and improving therapeutic applications ^[10].

9.2.1. Compton Interaction

Compton interaction, also known as Compton scattering, is a fundamental mechanism by which X-ray and gamma-ray photons interact with matter. It occurs when an incident photon collides with a loosely bound outer-shell electron, transferring part of its energy to the electron. As a result, the electron is ejected from the atom (now called a Compton electron or recoil electron), and the original photon is scattered in a different direction with reduced energy. Compton scattering is the dominant interaction in soft tissues in the diagnostic X-ray energy range (30–150 keV) and is the primary cause of scattered radiation, which degrades image quality in radiology ^[11]. The Compton process follows these steps:

- **Incident Photon Interaction:** A high-energy X-ray photon approaches an atom and interacts with an outer-shell electron. The outer-shell electrons have lower binding energies compared to inner-shell electrons, allowing for easier ejection.
- **Energy Transfer and Electron Ejection:** The photon transfers a portion of its energy to the electron, ejecting it from the atom (this ejected electron is called the Compton electron or recoil electron). The atom is left ionized.
- **Scattered Photon:** The remaining energy of the photon is emitted as a scattered photon, which has lower energy and a longer wavelength than the original photon. The angle at which the photon scatters depends on how much energy is transferred to the Compton electron.
- **Secondary Interactions:** The Compton electron moves through the tissue, causing further ionization before it loses all energy and recombines. The scattered photon may undergo further interactions, including more Compton scattering or photoelectric absorption.

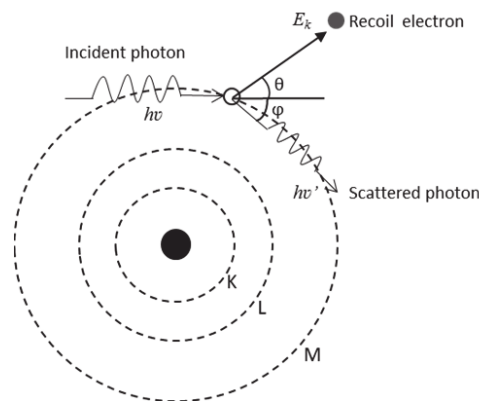


Fig: 9.1. Compton Scattering

Factors Affecting Compton Scattering: Several factors influence the probability and effects of Compton scattering. One key factor is photon energy. Low-energy photons (below 30 keV) are more likely to undergo photoelectric absorption rather than Compton scattering. In the medium to high-energy range (30 keV to 10 MeV), Compton scattering becomes the predominant interaction. However, at very high photon energies (greater than 10 MeV), other interactions, such as pair production and photodisintegration, become more significant. Another important factor is the atomic number (Z) of the material. Unlike the photoelectric effect, which strongly depends on atomic number, Compton scattering is largely independent of Z . Instead, it is more probable in materials with low atomic numbers, such as soft tissues, which have an approximate Z value of 7. Additionally, electron density plays a crucial role in Compton scattering ^[12]. The probability of this interaction occurring is directly proportional to the number of available electrons within a material. Since soft tissue contains a high number of free or loosely bound electrons, Compton scattering is the dominant interaction in human tissues. This characteristic makes it a

significant contributor to image noise in radiology, requiring techniques like anti-scatter grids and beam collimation to minimize its effects.

Significance of Compton Scattering in Radiology: Compton scattering plays a crucial role in radiology, influencing both image quality and radiation exposure. While it is an unavoidable interaction in diagnostic imaging, its effects must be managed to optimize radiographic techniques. One of the most significant impacts of Compton scattering is image degradation due to scattered radiation. When an X-ray photon undergoes Compton interaction, the scattered photons travel in different directions, some reaching the detector at incorrect locations. This unwanted radiation contributes to image fogging, reducing contrast and making it more difficult to distinguish between different tissues. The effect is particularly problematic in soft tissue imaging, such as chest and abdominal X-rays, where contrast differences between tissues are already minimal. In addition to affecting image quality, Compton scattering also contributes to radiation exposure for both patients and radiology staff. Since scattered photons can deflect at various angles, they increase the overall radiation dose received by the patient. More importantly, these scattered photons pose a significant risk to radiographers and medical personnel working near the radiation source. Protective measures, such as lead aprons, shielding barriers, and distance precautions, are essential to minimize occupational exposure ^[13]. In X-ray and CT imaging, Compton scattering is the primary cause of image noise. Scattered photons reaching the detector reduce the clarity of diagnostic images, making pathology detection more challenging. To counteract this effect, anti-scatter grids are commonly used in radiography. These grids selectively absorb scattered photons before they reach the detector, thereby improving image contrast. Additionally, collimation (beam restriction) helps by limiting the X-ray beam to only the area of interest, reducing the volume of tissue exposed to radiation and minimizing scatter production. While Compton scattering is generally undesirable in diagnostic imaging, it has a beneficial role in radiation therapy. In cancer treatment, particularly in megavoltage radiation therapy, Compton scattering contributes to the dose deposition in deeper tissues. This allows high-energy photon beams to deliver therapeutic radiation to tumours located within the body while sparing superficial tissues. The controlled use of Compton scattering in radiation therapy enhances the effectiveness of cancer treatments by ensuring that the prescribed radiation dose reaches the target area ^[14].

9.2.2. Coherent Scattering

Coherent scattering, also known as Rayleigh scattering or classical scattering, is a fundamental interaction between X-ray photons and matter that occurs at low photon energies (typically below 30 keV). Unlike other interactions such as the photoelectric effect and Compton scattering, coherent scattering does not involve ionization or energy loss. Instead, the incident photon interacts with the entire atom, causing it to momentarily become excited before releasing the photon in a different direction but with the same wavelength and energy as the original photon. This scattering is elastic, meaning there is no energy transfer to the atom or its electrons.

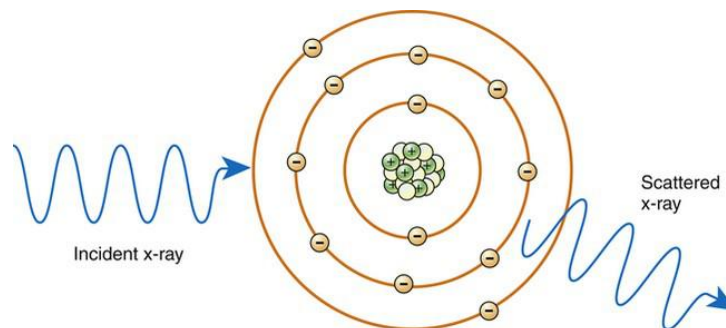


Fig: 9.2. Coherent Scattering

Coherent scattering occurs when an X-ray photon approaches an atom and interacts with its electron cloud rather than with individual electrons. Because the energy of the incoming photon is too low to ionize the atom or eject an electron, the atom absorbs the photon's energy momentarily, enters an excited state, and then almost

immediately re-emits the photon in a different direction. The emitted photon has the same wavelength, frequency, and energy as the incident photon, but its direction is altered slightly due to the scattering process. Since no energy is transferred to the atom, there is no production of secondary electrons or ionization. Mathematically, coherent scattering follows the principle of elastic scattering, where the energy of the scattered photon (E') is equal to the energy of the incident photon (E):

$$E' = E$$

Because the energy of the scattered photon remains unchanged, coherent scattering does not contribute to significant attenuation of the X-ray beam but does lead to small-angle scattering of photons. The angular distribution of scattered photons depends on the wavelength of the X-rays and the size of the atom. Generally, lower-energy photons (longer wavelengths) scatter at larger angles, higher-energy photons (shorter wavelengths) scatter at smaller angles. This means that in diagnostic X-ray imaging, where photon energies typically range from 30 to 150 keV, coherent scattering is relatively infrequent because the probability of this interaction decreases as photon energy increases.

Factors Influencing Coherent Scattering: Several factors determine the likelihood of coherent scattering occurring:

1. **Photon Energy:** Coherent scattering is most significant at low photon energies, typically below 30 keV. As photon energy increases, the probability of coherent scattering decreases sharply. In high-energy X-ray imaging (e.g., CT scans, radiography above 70 keV), coherent scattering is negligible.
2. **Atomic Number (Z) of the Material:** The probability of coherent scattering increases with the atomic number (Z) of the material. This is because higher-Z materials have larger electron clouds, making them more likely to scatter low-energy photons coherently. Coherent scattering is more common in soft tissues (which contain elements like carbon, oxygen, and nitrogen) than in denser materials like bone.
3. **Photon Wavelength:** Longer-wavelength (lower-energy) X-rays have a higher probability of undergoing coherent scattering. Shorter-wavelength (higher-energy) X-rays are less likely to undergo this interaction.
4. **Scattering Angle:** Most coherent scattering occurs at small angles (below 20 degrees) relative to the original photon direction. Since the scattered photon has the same energy as the incident photon and undergoes only minor deviation, it does not contribute significantly to image degradation.

Significance of Coherent Scattering in Radiology: Although coherent scattering is a fundamental interaction, its impact on diagnostic imaging is relatively small compared to photoelectric absorption and Compton scattering. However, in certain imaging techniques where low-energy X-rays are used, coherent scattering plays a more noticeable role.

- **Effect on Image Quality:** Since coherent scattering does not involve energy loss or ionization, it does not directly contribute to radiation dose. However, the small-angle deviation of scattered photons can lead to minor image blurring by introducing additional photons that do not correspond to the original anatomical structures. Unlike Compton scattering, which produces significant image noise due to randomly scattered lower-energy photons, coherent scattering's impact is much smaller and mostly limited to low-energy X-ray techniques.
- **Role in Mammography:** Coherent scattering is more prominent in mammography, where X-ray energies range from 20 to 30 keV to maximize soft tissue contrast. The increased proportion of coherent scattering in mammography slightly affects image sharpness, but its effect is much less than that of Compton scattering.
- **Negligible Contribution in High-Energy Imaging:** In general radiography and CT imaging, where X-ray energies exceed 70 keV, coherent scattering is insignificant because the probability of occurrence is very low at higher photon energies. The dominant interactions in these modalities are Compton scattering and photoelectric absorption, both of which have a much greater effect on image contrast and radiation dose.
- **Minimal Impact on Radiation Dose:** Unlike the photoelectric effect (which leads to complete photon absorption) and Compton scattering (which produces ionizing secondary electrons), coherent scattering does not contribute significantly to radiation exposure. Since the scattered photon retains its original

energy and simply changes direction, it does not deposit additional energy in tissues, making it a non-ionizing interaction.

9.2.3. The photoelectric effect

It is one of the most critical interactions between X-ray or gamma-ray photons and matter, playing a pivotal role in diagnostic radiology, radiation therapy, and radiation detection. This interaction occurs when an incident photon collides with an inner-shell electron of an atom, transferring all of its energy to the electron. As a result, the electron is ejected from the atom, leaving behind a vacancy in the inner shell. This vacancy is unstable, and to restore atomic stability, an electron from a higher energy shell moves down to fill the gap, releasing characteristic X-rays or Auger electrons as a by-product of the energy transition. The photoelectric effect is particularly significant in medical imaging because it contributes to image contrast by allowing X-ray photons to be absorbed differentially by various tissues.

Mechanism of the Photoelectric Effect

Step-1. Photon Interaction with the Atom: In the photoelectric effect, the process begins when an incoming X-ray or gamma photon approaches an atom and interacts specifically with one of the atom's inner-shell electrons. For this interaction to occur, the energy of the photon must be equal to or greater than the binding energy of that electron. If the photon does not possess sufficient energy to overcome this binding energy, the photoelectric effect will not take place. Therefore, the process depends heavily on the photon energy in relation to the electron's shell binding energy.

Step-2. Complete Absorption of Photon Energy: Once the photon encounters a suitable inner-shell electron, it transfers all of its energy to that electron. This complete transfer of energy results in the disappearance of the photon. Because the photon is fully absorbed in this interaction, there is no scattered photon produced. This total energy transfer differentiates the photoelectric effect from scattering processes such as Compton interaction, where the photon only loses part of its energy.

Step-3. Ejection of the Photoelectron: After absorbing the photon's energy, the inner-shell electron gains enough energy to overcome the attractive force that binds it to the nucleus and is ejected from the atom. This ejected electron is called a photoelectron, and it carries the remaining energy as kinetic energy. This can be calculated using the formula: $KE = E_p - E_b$, where KE is the kinetic energy of the emitted electron, E_p is the incoming photon energy, and E_b is the binding energy of the electron. The photoelectron then travels through the surrounding matter causing further ionization events.

Step-4. Creation of a Vacancy in the Inner Shell: The removal of the inner-shell electron results in an empty space or vacancy within that specific shell, which renders the atom unstable. The atom will naturally attempt to regain stability by replacing this missing electron. This vacancy therefore initiates a chain of internal atomic rearrangements that ultimately leads to the emission of secondary radiation.

Step-5. Filling of the Vacancy and Release of Secondary Radiation: To restore stability, an electron from a higher energy shell (such as the L or M shell) drops down to fill the inner-shell vacancy. During this transition, energy is released. This energy may be released in two possible forms. It may be emitted as characteristic X-rays, which have specific and recognizable energies for each element. Alternatively, the released energy may be transferred to another electron, causing that electron to be ejected from the atom, forming what is known as an Auger electron. Characteristic X-rays and Auger electrons therefore represent secondary radiation resulting from the photoelectric interaction.

Step-6. Local Energy Deposition and Ionization: Finally, the emitted photoelectron and any Auger electrons produced in the process travel only short distances within the material and deposit their energy locally. This leads to dense ionization in a small region, which contributes to dose absorption within tissues. In medical imaging, this localized absorption plays a significant role in image contrast and radiation dose. The photoelectric effect is especially important at lower X-ray energies and in materials with high atomic numbers, such as bone, iodine, and barium, which explains why these materials produce strong contrast in diagnostic radiography.

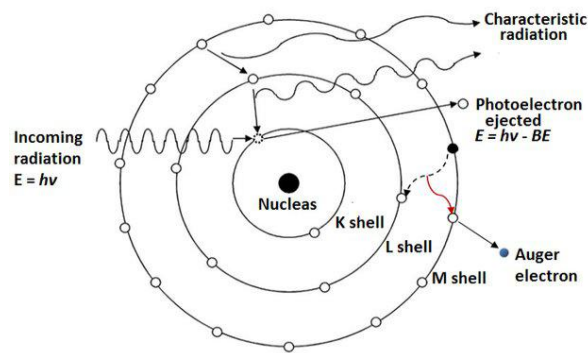


Fig: 9.3. Photoelectric Interaction

Factors Influencing the Photoelectric Effect: The photoelectric effect refers to the interaction in which an incident photon transfers all of its energy to an inner-shell electron of an atom, causing the electron to be ejected. The probability of this effect occurring is influenced by several key factors, most notably the energy of the incident photon, the atomic number of the absorbing material, and to a lesser extent, the density and thickness of the material.

1. **Photon Energy:** The energy of the incoming photon must be greater than or equal to the binding energy of the electron it intends to eject—typically from the K-shell or L-shell of an atom. The photoelectric effect is most probable when the photon energy is just above the binding energy. If the photon energy is too low, it cannot overcome the electron's binding energy, and no ejection occurs. Conversely, if the photon energy is too high, other processes such as Compton scattering become more dominant, reducing the likelihood of photoelectric interaction.
2. **Atomic Number (Z) of the Material:** The probability of the photoelectric effect is strongly dependent on the atomic number of the absorbing material. Specifically, the probability is approximately proportional to Z^3 (Z cubed). This means that materials with higher atomic numbers have a much greater likelihood of undergoing photoelectric absorption. For example, lead ($Z = 82$) is an excellent absorber of X-rays and gamma rays, making it ideal for use in radiation shielding. On the other hand, calcium ($Z = 20$) in bones absorbs more X-rays than soft tissue (which has lower-Z elements like carbon, hydrogen, and oxygen), creating the necessary contrast in medical radiography.
3. **Density and Thickness of the Material:** While not directly influencing the fundamental probability of the photoelectric effect per interaction, the density and thickness of a material affect the overall attenuation of radiation. Denser and thicker materials contain more atoms per unit volume, thus increasing the chances of interactions such as the photoelectric effect occurring as photons pass through.

Significance of Photoelectric Effect: The photoelectric effect plays a fundamental role in medical imaging, particularly in X-ray radiography and computed tomography (CT) scans, by determining how X-rays are absorbed by different tissues. This interaction is essential for generating image contrast, as tissues with varying atomic numbers absorb X-rays at different rates. Bones, which contain calcium ($Z = 20$), have a higher atomic number and absorb more X-rays, resulting in a white appearance on radiographs. In contrast, soft tissues, primarily composed of carbon, hydrogen, and oxygen ($Z = 6, 1, \text{ and } 8$, respectively), absorb fewer X-rays and appear darker on the image. This differential absorption enables radiologists to distinguish bones, organs, and abnormalities effectively. Additionally, the photoelectric effect is crucial in the use of contrast agents to enhance imaging clarity. High-atomic-number substances such as iodine ($Z = 53$) and barium ($Z = 56$) are commonly used in X-ray and CT imaging to improve the visibility of blood vessels, gastrointestinal structures, and tumours. These contrast agents increase photoelectric absorption, leading to a more detailed differentiation between normal and pathological tissues, thereby enhancing diagnostic accuracy. However, a significant consequence of the photoelectric effect is its impact on radiation dose. Since this interaction involves complete absorption of X-ray photons, no scattered radiation reaches the detector, which improves image quality and sharpness. However, this also means that higher doses of radiation are absorbed by the patient, increasing potential risks. Therefore,

radiologists must carefully optimize imaging techniques to achieve the best balance between image clarity and radiation safety, ensuring that diagnostic benefits outweigh radiation exposure risks.

Limitation of photoelectric effect: Despite its crucial role in medical imaging, the photoelectric effect has certain limitations that must be considered. One major limitation is that it becomes less dominant at high photon energies, particularly above 100 keV, where Compton scattering takes over as the primary interaction. This reduces the contribution of the photoelectric effect in high-energy diagnostic imaging and radiation therapy, making it less effective in those applications. Another drawback is its impact on radiation dose. Because the photoelectric effect involves complete absorption of X-ray photons, it significantly increases the radiation dose received by the patient. This necessitates careful dose optimization in diagnostic procedures to ensure patient safety while maintaining image quality. Additionally, the photoelectric effect leads to the production of secondary radiation due to the emission of characteristic X-rays. These emitted X-rays can contribute to additional radiation exposure, which is an important consideration in radiation shielding and safety protocols to minimize unintended exposure to both patients and healthcare workers.

9.2.4. Pair Production

Pair production is a high-energy photon interaction that occurs when an incident photon with energy greater than 1.02 MeV interacts with the nucleus of an atom. Unlike other interactions, such as the photoelectric effect and Compton scattering, where photons are absorbed or scattered by atomic electrons, pair production directly involves the atomic nucleus due to the high energy requirement. This interaction results in the complete disappearance of the photon, with its energy being converted into two subatomic particles:

1. **A positron (e^+)** – A positively charged electron (antimatter particle).
2. **An electron (e^-)** – A negatively charged electron (normal matter particle).

The minimum energy required for this interaction is 1.02 MeV (the combined rest mass energy of an electron and a positron, each having 0.511 MeV), pair production does not occur in conventional diagnostic radiology because X-ray photons used in medical imaging typically have energies in the range of 20–150 keV, which is far below the required threshold. Instead, pair production becomes significant in radiation therapy and nuclear medicine, where high-energy gamma rays or X-ray beams (above 10 MeV) are used for cancer treatment and imaging applications.

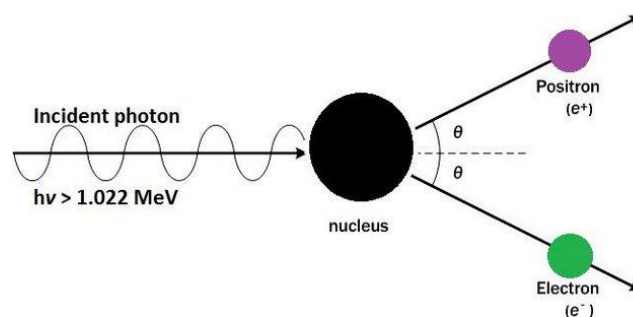


Fig: 9.4. Pair Production

Mechanism of Pair Production

1. **Photon-Nucleus Interaction:** A high-energy photon ($E > 1.02$ MeV) approaches the nucleus of an atom. The nucleus plays a crucial role in conserving momentum and energy during the process.
2. **Photon Disappearance & Energy Conversion:** The incident photon is completely annihilated, and its energy is converted into mass ($E = mc^2$) to form an electron (e^-) and a positron (e^+).
3. **Particle Movement:** The created electron and positron move away from the interaction site, carrying kinetic energy depending on the initial photon energy.

4. **Positron-Electron Annihilation:** Since positrons do not naturally exist in matter, they travel only a short distance before encountering a free electron in the surrounding medium. When a positron collides with an electron, they undergo annihilation, completely converting their mass into two gamma-ray photons (0.511 MeV each). These photons are emitted in opposite directions (180° apart), which is a key principle used in positron emission tomography (PET) imaging.

Significance of Pair Production in Medical Imaging and Radiation Therapy: Pair production is a high-energy interaction between a photon and the electromagnetic field of a nucleus, in which the photon is converted into a particle-antiparticle pair—specifically, an electron and a positron. This phenomenon occurs only when the energy of the incident photon exceeds 1.022 MeV, which is the combined rest mass energy of an electron (0.511 MeV) and a positron (0.511 MeV). While pair production is not commonly involved in routine diagnostic medical imaging due to the relatively lower energy levels used (typically below 150 keV), it becomes highly significant in radiation therapy and certain advanced imaging modalities. In radiation therapy, particularly high-energy photon beam therapy such as linear accelerator (LINAC)–based treatments operating above 10 MeV, pair production contributes significantly to the overall dose deposition within tissues. As photon energies increase, pair production becomes one of the dominant interactions alongside Compton scattering. The resulting electron and positron generated by pair production deposit their kinetic energy locally, contributing to the therapeutic dose aimed at destroying cancer cells. Understanding and accounting for pair production is crucial in the dosimetry and treatment planning process to ensure accurate and effective radiation delivery. In positron emission tomography (PET), pair production is indirectly involved. PET imaging relies on the emission of positrons from radiotracers introduced into the body. When a positron encounters an electron, they annihilate each other, producing two 511 keV gamma photons that are emitted in opposite directions. These photons are then detected to form high-resolution images of physiological processes. While PET does not involve pair production initiated by incoming photons, the principle of electron-positron interaction is central to its functionality.

Factors Affecting Pair Production: Several factors influence the probability of pair production occurring:

1. **Photon Energy:** The minimum threshold for pair production is 1.02 MeV, but higher photon energies increase the likelihood of this interaction. At photon energies above 10 MeV, pair production becomes a dominant interaction.
2. **Atomic Number (Z) of the Material:** The probability of pair production increases with atomic number (**Z**) because heavier elements provide a stronger nuclear field for photon interaction. This is why high-Z materials like lead (Pb) or tungsten (W) are used in radiation therapy equipment and shielding to manage high-energy radiation exposure.
3. **Density of the Medium:** Denser materials contain more atomic nuclei per unit volume, increasing the likelihood of pair production occurring. In medical applications, tissue-equivalent materials are considered when designing PET scanners and radiotherapy devices to optimize dose delivery and imaging accuracy.

9.2.5. Photodisintegration

Photodisintegration is a high-energy nuclear interaction that occurs when an X-ray or gamma-ray photon with an energy greater than 10 MeV is absorbed by an atomic nucleus, causing the nucleus to become unstable and eject a subatomic particle. Unlike other interactions such as the photoelectric effect, Compton scattering, or pair production, which primarily involve the electrons surrounding an atom, photodisintegration directly affects the nucleus itself, making it a nuclear reaction rather than an atomic one.

Mechanism of Photodisintegration

- **Photon Absorption by the Nucleus:** When a high-energy gamma-ray or X-ray photon (>10 MeV) collides with an atomic nucleus, the photon is completely absorbed rather than scattered. The entire energy of the photon is transferred to the nucleus, pushing it into an excited, unstable state.
- **Nuclear Instability and Nucleon Ejection:** The nucleus, now in an excited state, becomes unstable and must release excess energy. To stabilize itself, the nucleus ejects one or more particles, which could be:

- A neutron (n)
 - A proton (p)
 - An alpha particle (α) (helium nucleus)
 - Other nuclear fragments, depending on the photon energy and the target nucleus.
- **Resulting Nuclear Transformation:** The ejection of a nucleon changes the identity of the atom since the number of protons defines the element. This process can lead to the formation of a different isotope or even a completely different element with altered nuclear properties. In some cases, the residual nucleus may undergo further radioactive decay, emitting additional radiation in the form of beta particles, gamma rays, or secondary neutrons.

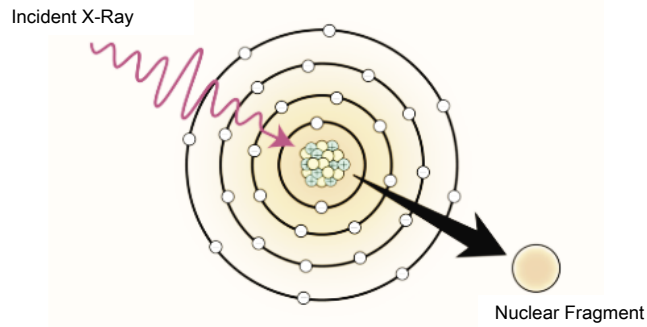


Fig: 9.5. Photodisintegration

Significance of Photodisintegration in Radiology and Radiation Therapy: Photodisintegration is not relevant in diagnostic radiology (such as X-rays, CT scans, or mammography) because the photon energies used in these procedures, typically ranging from 20 keV to 150 keV, are far below the 10 MeV threshold required for photodisintegration to occur. However, this interaction becomes significant in high-energy radiation therapy, particularly in external beam treatments that involve photon energies exceeding 10 MeV. One example is linear accelerator (LINAC)-based therapy, which is commonly used in advanced treatment modalities such as intensity-modulated radiation therapy (IMRT), stereotactic body radiation therapy (SBRT), and proton therapy. Modern LINACs can generate photon beams with energies up to 20 MeV or higher, making photodisintegration a potential concern. At these high energies, the interaction may occur in high-density shielding materials or even within components of the treatment device itself, leading to the emission of secondary radiation. Additionally, high-energy photon beams interacting with human tissue may induce neutron production, particularly when they interact with oxygen or nitrogen nuclei. Although photodisintegration is not a primary mode of energy deposition in tissue, these secondary neutrons can contribute to undesired radiation dose deposition, which can increase the risk of radiation-induced tissue damage or even secondary malignancies.

Neutron Production and Radiation Shielding: A major concern in high-energy radiotherapy facilities is the production of secondary neutrons through photodisintegration. When high-energy photons interact with materials containing hydrogen, oxygen, or heavy metals, free neutrons may be generated. These neutrons can pose a radiation exposure risk to both patients and medical staff, necessitating specialized radiation shielding measures. To minimize exposure, treatment rooms must be equipped with neutron-absorbing materials such as boron, polyethylene, and concrete, which help capture or scatter these secondary neutrons. In proton therapy and heavy-ion therapy, where even higher energy levels are used, photodisintegration and neutron production become critical considerations in designing protective barriers to ensure safety in the treatment environment. **Impact on Medical Equipment and Infrastructure:** Another important consequence of photodisintegration is its impact on medical equipment and radiation shielding materials. In high-energy LINACs, photodisintegration can lead to neutron activation of metallic components such as collimators, filters, and shielding structures. When these machine parts become radioactive, they require careful handling and continuous monitoring to prevent unnecessary exposure to radiation. Additionally, prolonged exposure to high-energy photon beams can cause degradation of shielding

materials, leading to structural and chemical changes over time. As a result, periodic maintenance and material replacement are necessary to ensure continued radiation protection and treatment accuracy.

Table: 9.1. Comparison of different types of Radiation Interactions

Interaction Type	Photon Energy Range	Primary Effect	Significance in Radiology
Photoelectric Effect	20–150 keV	Photon absorption, inner-shell electron ejection	Responsible for contrast in X-ray and CT imaging
Compton Scattering	30 keV – 10 MeV	Outer-shell electron ejection, scattered photon emission	Reduces image quality due to scattered radiation
Rayleigh (Coherent) Scattering	<30 keV	Photon scattering without ionization	Minimal impact, observed in low-energy imaging like mammography
Pair Production	>1.02 MeV	Photon annihilation, creation of electron-positron pair	Important in PET imaging and radiation therapy
Photodisintegration	>10 MeV	Photon absorption by nucleus, nucleon emission	Occurs in high-energy radiation therapy and nuclear physics

9.3. ATTENUATION

Attenuation refers to the reduction in the intensity of the X-ray beam as it passes through matter, and it is a key concept in radiology because it directly influences image contrast and overall image quality in X-ray, CT, and fluoroscopic examinations. When X-rays enter the body, the photons may be absorbed, scattered, or transmitted, and the degree to which the beam is attenuated depends on factors such as the thickness, density, and atomic number of the tissues being imaged. There are two main processes that contribute to attenuation. The first is absorption, which occurs when an X-ray photon transfers all of its energy to an electron, resulting in the ejection of the electron and complete elimination of the photon—this is mainly explained by the photoelectric effect, particularly at lower photon energies. The second is scattering, where the photon interacts with an atom but only loses part of its energy and is deflected in a different direction. In diagnostic radiology, Compton scattering is the most important form of scattering, and although the scattered photons do not contribute to image formation, they increase image noise and reduce image contrast. Thus, attenuation is fundamental for generating diagnostic images, and understanding the balance between absorption and scattering helps in optimizing imaging techniques and minimizing unwanted artefacts.

Factors Affecting Attenuation: Several factors influence the degree of attenuation of X-rays in different tissues:

1. **Atomic Number (Z) of the Tissue:** Tissues with a higher atomic number (Z), such as bones, have a greater tendency to absorb X-rays because their inner-shell electrons are more tightly bound. This results in a higher photoelectric effect and greater attenuation. Tissues with a lower atomic number, such as soft tissues (muscle, fat), have fewer tightly bound electrons, making them less likely to absorb X-rays. These tissues allow more X-rays to pass through, resulting in less attenuation.
2. **Density of the Tissue:** The density of a tissue also plays a critical role in X-ray attenuation. Denser tissues, such as bone, contain more atoms per unit volume and therefore interact more with the X-rays, causing higher attenuation. Less dense tissues, like the lungs, allow more X-rays to pass through with less attenuation.
3. **Thickness of the Tissue:** The thicker the tissue, the greater the attenuation. A thicker body part will have more material for the X-rays to interact with, leading to more absorption and scattering. This is why thicker body parts, such as the chest or abdomen, require higher doses of radiation to produce clear images.
4. **X-ray Energy:** The energy (or photon energy) of the X-rays also impacts attenuation. Higher-energy photons are less likely to be absorbed and are more likely to scatter, leading to reduced contrast in the final image. Lower-energy photons are more likely to be absorbed (via the photoelectric effect), leading to higher contrast images but also potentially higher radiation doses.

Attenuation and Image Formation: In diagnostic radiology, the amount of X-ray attenuation determines the contrast of the final image. The areas of the body that attenuate the most X-rays, such as bones or dense organs, appear lighter (whiter) on the image. In contrast, areas with less attenuation, such as soft tissues and air-filled organs (e.g., lungs), appear darker. This differential attenuation creates the necessary contrast in the image, allowing radiologists to distinguish between different types of tissues. For instance, in a chest X-ray, the lungs, which contain air (and thus attenuate fewer X-rays), appear dark, while the heart and bones (which are denser and absorb more X-rays) appear lighter. In CT imaging, attenuation values are quantified and assigned Hounsfield Units (HU), which allow for the precise measurement of tissue density. The ability to assess varying levels of attenuation in CT scans is particularly useful for identifying abnormalities, such as tumours, fractures, or haemorrhages.

9.3.1. Linear Attenuation

Linear Attenuation refers to the reduction in the intensity of an X-ray beam as it travels through a material, measured per unit distance. It is represented by the symbol μ (mu) and is expressed in units of cm^{-1} . Linear attenuation depends on the thickness of the material, the atomic number (Z), and the energy of the X-ray beam. The relationship between the initial X-ray intensity (I_0) and the transmitted intensity (I) after passing through a material of thickness x can be described by the exponential equation: $I = I_0 e^{-\mu x}$. This means that the intensity of the X-ray beam decreases exponentially as it travels through the material. The linear attenuation coefficient (μ) represents how likely X-ray interactions (absorption or scattering) are to occur per unit length. Higher μ values indicate greater attenuation. In radiology, materials with high atomic numbers such as bone have higher μ values, meaning they absorb more X-rays and appear white on radiographs. In contrast, soft tissues and air have lower μ values, causing less attenuation and appearing darker on X-ray images.

9.3.2. Mass Attenuation

Mass Attenuation refers to the reduction in X-ray beam intensity per unit mass of the material it passes through. It is represented by the symbol μ/ρ (mu over rho), where ρ is the density of the material, and is expressed in units of cm^2/g . Unlike linear attenuation, which is based on the material's thickness, mass attenuation considers the density of the material, making it more useful when comparing materials with different densities. The mass attenuation coefficient is mathematically related to the linear attenuation coefficient by the formula: $\mu/\rho = \mu \div \text{density of the material}$. Mass attenuation is commonly used to compare tissues or materials that may have similar atomic composition but vary in density. For example, muscle and fat contain similar elements, but their densities are different. By using mass attenuation values, it becomes easier to compare how well each tissue attenuates X-rays per unit mass rather than per unit thickness.

Relationship Between Linear and Mass Attenuation: Both linear and mass attenuation coefficients describe the extent to which a material can attenuate X-rays, but they do so from different perspectives:

- Linear attenuation is dependent on the thickness and atomic number of the material, with denser and higher atomic number materials leading to greater attenuation.
- Mass attenuation normalizes this effect by considering the density of the material, which allows for easier comparison across different materials and tissue types of varying densities.

In practical applications, mass attenuation is often more useful when comparing the X-ray attenuation properties of biological tissues, such as fat, muscle, bone, or lungs, because these tissues vary in density but are made up of similar atomic components. For example, while both bone and muscle contain carbon, oxygen, and hydrogen, bone is much denser and thus will have a higher mass attenuation coefficient.

Clinical Significance of Attenuation: Understanding linear and mass attenuation is fundamental to the practice of radiology because it directly influences the quality and diagnostic value of the images produced. For example:

- In X-ray imaging and CT scans, attenuation is used to differentiate between different types of tissue. Bone, which has a high atomic number and density, attenuates X-rays much more than soft tissues like

- muscles or fat, resulting in a high contrast image.
- In CT imaging, the mass attenuation coefficient is particularly important for creating detailed cross-sectional images of the body, allowing radiologists to visualize internal structures and abnormalities. The varying levels of attenuation enable the differentiation of tissues with varying densities (e.g., tumours, fractures, organs).
 - In radiation therapy, attenuation is also considered when planning treatments. For example, understanding how X-rays or particles will attenuate through different tissues allows clinicians to adjust the dosage and intensity of radiation to target a tumour while minimizing damage to surrounding healthy tissue.

9.4. LET AND RBE

Linear Energy Transfer (LET) and Relative Biological Effectiveness (RBE) are critical concepts in radiobiology and radiation therapy, helping to understand how different types of radiation interact with biological tissues and their potential effects on human cells. Both of these concepts are used to evaluate the effectiveness of radiation in causing biological damage, which is essential for assessing patient safety in medical imaging and radiation therapy.

9.4.1. Linear Energy Transfer (LET)

Linear Energy Transfer (LET) refers to the amount of energy deposited by ionizing radiation per unit length of tissue as the radiation passes through it. In simple terms, it is a measure of how much energy a particle transfers to the medium (usually biological tissue) over a given distance. LET is typically expressed in units of keV/μm (kiloelectron volts per micrometer). The type of radiation significantly influences its LET value; for instance, alpha particles have a high LET, while gamma rays and X-rays have low LET. Radiations with high LET (such as alpha particles, protons, and heavy ions) deposit more energy in a smaller volume of tissue, which results in more localized damage to the DNA and other cellular structures. This leads to greater biological damage per unit of radiation dose, often causing double-strand breaks in DNA, which are difficult for the cell to repair. High-LET radiation is generally more effective at inducing cell death and mutations compared to low-LET radiation. On the other hand, low LET radiation, such as gamma rays and X-rays, spreads its energy over a larger area, resulting in less concentrated damage. While this form of radiation is more likely to induce single-strand breaks in DNA or cause indirect damage via the production of free radicals, it is generally less effective at directly killing cells compared to high-LET radiation. The biological effects of low-LET radiation are often a result of the cumulative damage to the DNA over time or the indirect effects caused by the radiation's interaction with water molecules in cells. Understanding LET is crucial in the context of radiation therapy and radiation protection because it helps determine how much biological damage will result from a given dose of radiation. High-LET radiations, while effective in therapy for their ability to kill tumour cells, also pose a higher risk of damage to surrounding healthy tissues. This balance between effectiveness and side effects is a critical consideration in treatment planning.

9.4.2. Relative Biological Effectiveness (RBE)

Relative Biological Effectiveness (RBE) is a measure of the biological effectiveness of different types of ionizing radiation in producing a specific biological effect, such as cell death or DNA damage, compared to a standard radiation, usually X-rays or gamma rays. RBE is expressed as the ratio of the dose of standard radiation required to produce a specific biological effect to the dose of the radiation in question that produces the same effect. Mathematically, RBE is defined as:

$$RBE = D_{\text{standard}} / D_{\text{test}}$$

Where:

D_{standard} is the dose of standard radiation (typically X-rays or gamma rays) required to achieve a given biological effect. D_{test} is the dose of the test radiation (such as alpha particles, neutrons, etc.) required to achieve the same biological effect.

RBE varies depending on several factors, including the type of radiation, the energy of the radiation, the biological endpoint being measured (e.g., cell death, mutation, or DNA damage), and the tissue type involved. For example, alpha particles have a much higher RBE than X-rays, meaning that the same amount of biological damage is achieved with a lower dose of alpha radiation. This is primarily due to the higher LET of alpha particles, which leads to more localized energy deposition and a greater probability of damaging critical cellular structures. The concept of RBE is crucial in radiation therapy for cancer treatment. Certain high-LET radiation, such as protons or carbon ions, have a higher RBE than conventional X-ray or gamma radiation, which means they can be more effective in killing cancer cells, particularly those that are difficult to treat with traditional X-rays. However, the higher RBE of these radiations can also increase the potential for damage to surrounding healthy tissues. Thus, RBE helps radiation oncologists choose the appropriate radiation modality and dosage to maximize tumour control while minimizing harm to normal tissue.

Relationship Between LET and RBE: The relationship between LET and RBE is complex. Generally, as the LET of a radiation increases, its RBE also increases, but only up to a certain point. For low-LET radiations like X-rays, the RBE is usually around 1, as they are used as the standard for comparison. As the LET increases (as with alpha particles or heavy ions), the RBE increases as well, because high-LET radiation causes more severe and localized damage. However, after reaching a certain LET value (typically between 100 and 200 keV/ μm), the RBE begins to plateau or even decrease. This plateau occurs because at very high LET values, the radiation causes such extensive damage that the additional energy deposition does not lead to proportionally greater biological effects. In these cases, the damage is often so severe that it overwhelms the cellular repair mechanisms.

In clinical radiology and radiation therapy, understanding both LET and RBE is essential for optimizing patient treatment plans. High LET radiations are increasingly used in particle beam therapy, such as proton therapy and heavy ion therapy, because of their ability to deliver more localized energy to tumours, minimizing damage to surrounding tissues and maximizing the tumour-killing effect. Conversely, low LET radiation, while effective, requires careful management to avoid excessive side effects. By evaluating LET and RBE, medical professionals can tailor treatments to the specific characteristics of the tumour and the surrounding tissues, ensuring that patients receive the most effective radiation treatment with the least risk of adverse effects.

9.4.3. Dose-Effect Relationship in Radiology

The dose-effect relationship refers to the correlation between the amount of radiation (dose) administered to a biological system and the resulting biological effects. This concept is central to understanding how radiation interacts with living tissues and is crucial for optimizing medical imaging techniques, radiation therapy, and ensuring patient safety in diagnostic radiology. Radiation dose is typically quantified in units of Gray (Gy), which represents the energy deposited per unit mass of tissue. The biological effect of radiation depends not only on the dose but also on factors such as the type of radiation, the tissue or organ being irradiated, and the duration of exposure. There are two main types of dose-effect relationships:

- 1. Linear Dose-Effect Relationship:** In this case, biological effects increase in direct proportion to the radiation dose. A constant increase in radiation dose results in a proportional increase in biological damage. This relationship is typically observed in low doses, where the radiation damage is less likely to be repaired and is generally used for cancer therapy. The linear no-threshold (LNT) model assumes that any radiation dose, no matter how small, can cause harm to tissues and may increase the risk of cancer or genetic mutations.
- 2. Non-Linear Dose-Effect Relationship:** In a non-linear relationship, the biological effect does not increase proportionally with the dose. The damage caused by low doses may be minimal, and higher doses may result in less than a proportional increase in biological damage. This kind of relationship is commonly seen with high doses of radiation or when the body's repair mechanisms can mitigate the effects of low radiation doses. Radiation hormesis (the hypothesis that small doses of radiation may be beneficial) falls into this category, although it remains a debated topic in radiation biology.

Factors Influencing the Dose-Effect Relationship: Several factors affect the dose-effect relationship, including:

1. **Radiation Type:** Different types of radiation (e.g., alpha particles, beta particles, gamma rays, X-rays) interact with tissues in different ways. High-LET (Linear Energy Transfer) radiation, such as alpha particles or neutrons, tends to cause more severe damage with lower doses due to its dense energy deposition. In contrast, low-LET radiation, like gamma rays or X-rays, requires higher doses to produce similar biological effects.
2. **Tissue Sensitivity:** The biological effect of a given dose of radiation depends on the type of tissue exposed. Tissues with rapidly dividing cells, such as bone marrow, gastrointestinal lining, and skin, are generally more sensitive to radiation than more differentiated tissues, such as muscle and bone. The relative biological effectiveness (RBE) of radiation varies depending on the tissue, as well as the type and energy of the radiation.
3. **Dose Rate:** The rate at which radiation is delivered also plays a significant role in the dose-effect relationship. Fractionated doses (delivered in smaller, spaced-out amounts) are typically less damaging than a single, large dose of radiation, as the body has time to repair some of the damage between exposures. This principle is used in radiation therapy to minimize harm to healthy tissues while still targeting tumours effectively.
4. **Time Factor:** The timing of radiation exposure can influence the biological response. For instance, acute radiation exposure can cause immediate tissue damage, while chronic exposure to lower doses can lead to long-term effects, such as radiation-induced cancer or genetic mutations, which may not become apparent until years later.

Clinical Implications of Dose-Effect Relationship

1. **Radiation Protection:** Understanding the dose-effect relationship is essential in radiation protection to minimize the risk of deterministic and stochastic effects in patients, healthcare workers, and the general public. In diagnostic radiology, efforts to reduce the radiation dose (e.g., using the ALARA principle—As Low As Reasonably Achievable) are crucial for minimizing unnecessary radiation exposure.
2. **Radiation Therapy:** In radiation therapy, understanding the dose-effect relationship is key to effectively treating tumours while minimizing harm to healthy tissues. By carefully calculating the radiation dose and using techniques such as fractionation, doctors can maximize tumour cell death while minimizing the risk to normal cells. Additionally, understanding the relationship helps oncologists select the right type of radiation, considering factors like LET and RBE, to optimize treatment efficacy.
3. **Imaging Techniques:** For diagnostic imaging procedures (X-ray, CT scans), the goal is to obtain high-quality images with the lowest possible radiation dose. Understanding how radiation dose affects image quality and biological effects helps radiologists and medical physicists optimize imaging protocols to balance diagnostic needs with patient safety.

9.4.4. Energy Deposition

Energy deposition in radiation refers to the transfer of energy from ionizing radiation to matter, such as biological tissues. This process is central to understanding the effects of radiation in medical applications, including radiology, radiation therapy, and diagnostic imaging. The primary mechanisms of energy deposition include ionization and excitation, both of which lead to changes in the material, particularly in biological systems. Ionization occurs when an incident radiation particle, such as an X-ray photon or charged particle, transfers energy to an atom or molecule, causing the ejection of an electron and creating ions. Ionization can be direct or indirect. In direct ionization, charged particles like alpha or beta particles directly interact with atoms, causing the ejection of electrons. In indirect ionization, uncharged radiation, such as X-rays or gamma rays, interacts with atoms and produces secondary electrons that then cause ionization in surrounding molecules. These secondary electrons often play a significant role in the damage caused by radiation, especially in biological tissues where water is a predominant component. Another important energy deposition mechanism is excitation, where radiation imparts energy to an atom or molecule, raising it to a higher energy state without removing an electron. The energy is typically released when the atom or molecule returns to its original state, either through light emission (fluorescence) or heat. While excitation does not create ions, it still contributes to molecular damage, especially in the context of biological cells. Additionally, Bremsstrahlung (or braking radiation) occurs when charged

particles like beta particles or electrons are decelerated by the electric fields of atoms, leading to the emission of energy in the form of X-ray photons. This phenomenon is important in radiation therapy, where high-energy radiation is used for cancer treatment. Another energy deposition mechanism is radiative recombination, which occurs when an ejected electron from ionization recombines with a positive ion, releasing energy in the form of X-ray photons. The Auger effect also plays a role, where the energy from an inner-shell ionization event is transferred to an electron from a higher energy level, causing the ejection of a secondary electron. This secondary electron can interact with surrounding atoms, contributing to further ionization and energy deposition.

In biological tissues, which are primarily composed of water, ionizing radiation typically interacts with water molecules, leading to indirect damage. This interaction generates free radicals, such as hydroxyl and hydrogen radicals, which can cause damage to DNA and other critical cellular components. While radiation can also directly damage DNA through ionization, indirect damage is more common. Free radicals can cause single-strand or double-strand DNA breaks, leading to mutations or cell death. Direct DNA damage occurs when the radiation directly interacts with the DNA molecule itself, which can result in cell death or mutations, both of which are key contributors to radiation-induced health effects like cancer. The type of radiation influences the way energy is deposited. Alpha particles, for example, have high Linear Energy Transfer (LET), meaning they deposit large amounts of energy over short distances and cause dense ionization. This makes them highly damaging, especially when internalized, such as from inhaling alpha-emitting particles. Beta particles have lower LET than alpha particles but still contribute to ionization and energy deposition in tissues. Gamma rays and X-rays, on the other hand, are low LET radiation, which interact less densely with matter but have greater penetrating power, allowing them to deposit energy deeper within the body. These types of radiation typically cause indirect damage by ionizing water molecules and producing free radicals, which can lead to DNA damage.

9.5. HVL AND TVL

The Half-Value Layer (HVL) and Tenth-Value Layer (TVL) are important concepts used to describe the attenuation of radiation as it passes through a material. These terms are crucial in the fields of radiation protection, radiology, and nuclear physics, as they help determine how effective a material is at shielding against various types of radiation, such as X-rays, gamma rays, or beta particles. The Half-Value Layer (HVL) refers to the thickness of a material required to reduce the intensity of incident radiation by half. Essentially, when a beam of radiation passes through a material, it interacts with the atoms in the material, and some of the radiation energy is absorbed or scattered. The HVL is the point at which the radiation intensity is reduced to 50% of its initial value. This value is dependent on the type of radiation and the properties of the material it is passing through. The denser or attenuative the material, the thinner the layer needed to reduce the radiation by half. For example, lead is commonly used as a radiation shield because it has a relatively low HVL for X-rays and gamma rays, meaning a small thickness of lead is needed to significantly reduce radiation exposure.

The Tenth-Value Layer (TVL) is similar to the HVL, but it represents the thickness of a material needed to reduce the radiation intensity to one-tenth (10%) of its original value. In other words, the TVL is a measure of how effective a material is at reducing radiation over a larger scale. It provides a more significant reduction in radiation intensity compared to the HVL. The TVL is particularly useful when considering materials for more extensive shielding, such as in nuclear reactors or high-radiation environments. Like the HVL, the TVL depends on the material's attenuation properties and the type of radiation. Both HVL and TVL are derived from the exponential attenuation law, which describes how the intensity of radiation decreases as it passes through a material. According to this law, the attenuation of radiation is exponential, meaning the more material the radiation passes through, the more rapidly its intensity decreases.

End of Chapter

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