

# FUNDAMENTALS OF RADIATION PHYSICS

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## 6.1. OVERVIEW OF RADIATION PHYSICS

**R**adiation physics is the study of the behaviour and properties of radiation, including the interaction of radiation with matter. It encompasses a wide range of phenomena, from the natural radiation emitted by cosmic sources and the Earth, to the man-made radiation used in medical imaging, nuclear energy, and industrial applications. Radiation can be broadly classified into two categories: ionizing radiation and non-ionizing radiation. Ionizing radiation, which includes alpha particles, beta particles, gamma rays, and X-rays, has enough energy to remove electrons from atoms, potentially causing damage to living tissues and altering molecular structures. Non-ionizing radiation, such as radio waves, microwaves, infrared, visible light, and ultraviolet radiation, does not carry sufficient energy to ionize atoms but can still affect matter in various ways, such as heating or causing molecular vibrations. Radiation physics also delves into the processes of absorption, scattering, and transmission of radiation through different materials, which is essential for understanding radiation shielding, dose calculations, and medical treatment planning, particularly in radiotherapy. The study of radiation also includes the measurement and detection of radiation, using tools like Geiger counters, scintillation detectors, and dosimeters. In medical applications, radiation physics plays a critical role in fields such as radiology, nuclear medicine, and radiation therapy, where controlled exposure to radiation is used for diagnostic imaging and treating cancer. Furthermore, radiation protection is an integral part of the discipline, ensuring that radiation exposure to individuals and the environment remains within safe limits. As our understanding of radiation physics advances, it continues to drive technological innovations while also raising important concerns about safety and health risks, particularly in relation to radiation exposure from medical treatments, industrial activities, and environmental sources.

### Historical Development of Radiation Physics

The history of radiation physics can be traced back to the late 19th century when ground-breaking discoveries laid the foundation for understanding the nature and behaviour of radiation. The field began to take shape with the discovery of X-rays by Wilhelm Conrad Roentgen in 1895. Roentgen's accidental discovery, while experimenting with cathode rays, revealed a form of invisible radiation that could pass through various materials, creating images on photographic plates. This discovery revolutionized medical diagnostics and earned Roentgen the first Nobel Prize in Physics in 1901. In the same era, the study of radioactivity began with the work of Henri Becquerel. In 1896, Becquerel discovered that uranium salts emitted rays capable of exposing photographic plates, a phenomenon he called "spontaneous radiation." This was followed by the pioneering research of Marie and Pierre Curie, who investigated the properties of radioactive materials, leading to the discovery of new elements like polonium and radium. The Curie's work contributed significantly to the understanding of ionizing radiation, a key concept in radiation physics. Marie Curie's discovery of radium in 1898 further opened doors to research in both medical and industrial applications of radiation.

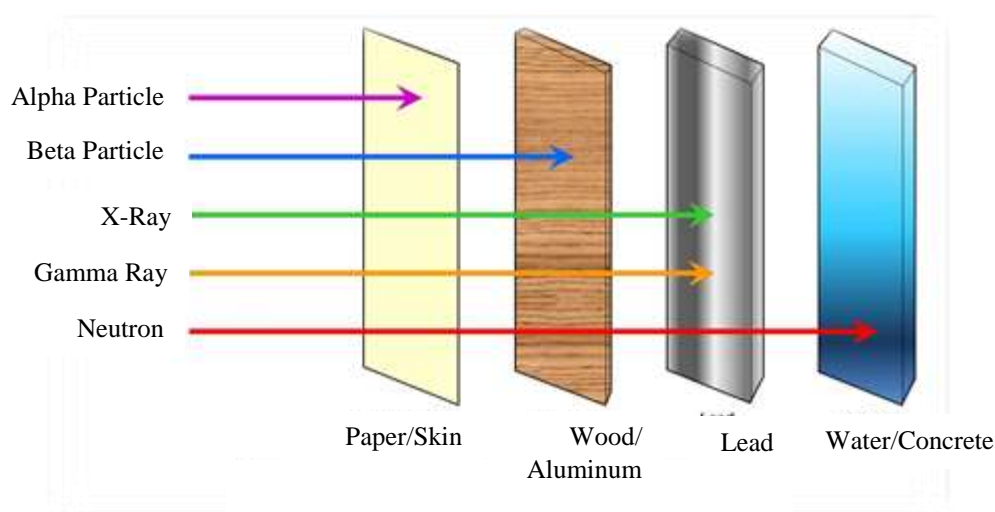
By the early 20th century, the understanding of radiation expanded as scientists like Ernest Rutherford and J.J. Thomson advanced the theory of atomic structure. Rutherford's gold foil experiment in 1909 led to the discovery of the atomic nucleus, providing essential insight into how alpha particles (helium nuclei) interact with matter. His work on the behaviour of radioactive decay also laid the groundwork for later developments in nuclear physics and radiation safety. During this period, Rutherford and others were instrumental in understanding the different types of radioactive emissions, including alpha, beta, and gamma radiation. The subsequent decades saw the rise of quantum mechanics and its application to radiation. The early 20th century was marked by Max Planck's introduction of the quantum theory, followed by Albert Einstein's explanation of the photoelectric effect, which connected light to

particle-like behaviour and established the wave-particle duality of radiation. These developments influenced how radiation was understood, not just as a wave, but as discrete particles or quanta of energy. In the mid-20th century, the advent of nuclear energy and the use of radiation in medical applications marked significant milestones. The development of the atomic bomb during World War II brought with it the need for a better understanding of nuclear reactions and radiation safety, particularly after the bombings of Hiroshima and Nagasaki. This led to the establishment of international radiation safety standards and regulations. The peaceful use of nuclear energy for power generation began in the 1950s, with the first nuclear power plant being commissioned in 1954 in Obninsk, Soviet Union.

Simultaneously, radiation therapy began to gain widespread use in medicine, with X-rays and gamma rays being used to treat cancer patients. The application of radiation in diagnostic imaging also expanded with the invention of technologies like CT (computed tomography) scans and nuclear medicine, which began to play crucial roles in modern medical diagnostics. In the latter half of the 20th century, as technology advanced, radiation physics continued to evolve. The development of particle accelerators allowed for more detailed studies of atomic and subatomic particles. These accelerators were key to research in high-energy physics, particularly the discovery of new particles and forces. At the same time, advancements in radiation detection and radiation protection became more sophisticated, reducing risks to both patients and healthcare professionals. The 21st century has seen continued progress in radiation therapy, especially with the advent of proton therapy and stereotactic radiosurgery, which offer more precise ways to treat cancer with minimal damage to surrounding healthy tissues. New techniques for radiation shielding and radiation monitoring have been developed to ensure safety in industries dealing with nuclear materials, space exploration, and medical radiation applications. Today, radiation physics is a crucial part of numerous scientific fields, from medical imaging and cancer treatment to energy production and environmental monitoring. The study of radiation and its interactions with matter continues to drive innovations in medicine, technology, and industrial applications, making it an essential component of modern science and healthcare.

### Basic Concept of Radiation

Radiation refers to the emission and propagation of energy through space or matter in the form of electromagnetic waves or subatomic particles. This energy can travel in the form of electromagnetic radiation (such as light, radio waves, X-rays, and gamma rays) or as particulate radiation (such as alpha particles, beta particles, and neutrons). The term "radiation" is commonly used to describe various forms of energy transfer, whether in the form of heat, light, or nuclear particles. Radiation occurs naturally in the environment, but it can also be generated artificially for various technological and medical applications. The fundamental concept of radiation is rooted in energy transfer. Radiation involves the release of energy from a source, which then travels outward through space or matter until it is absorbed or interacts with another object. In the case of electromagnetic radiation, this energy is carried by oscillating electric and magnetic fields that travel at the speed of light. The energy of electromagnetic radiation is quantified by its frequency and wavelength—higher frequencies correspond to higher energy levels, while shorter wavelengths typically have higher energy content.



**Fig: 6.1. Type of radiation and what they can penetrate**

## 6.2. CLASSIFICATION OF RADIATION

Radiation is classified based on energy, ionization ability, and source of origin. It is broadly categorized into ionizing and non-ionizing radiation. Ionizing radiation, including X-rays, gamma rays, alpha, beta, and neutron radiation, has high energy capable of removing electrons from atoms, leading to ionization and potential biological damage. It is widely utilized in medical imaging, cancer treatment, and nuclear applications. In contrast, non-ionizing radiation, such as radio waves, microwaves, infrared, and visible light, has lower energy and cannot ionize atoms but can cause heating effects. This type is commonly employed in communication, medical therapy, and industrial processes.

Additionally, radiation is classified into particulate radiation and electromagnetic (EM) radiation, depending on the nature of the emitted particles or energy. Particulate radiation consists of subatomic particles like alpha particles, beta particles, neutrons, and protons, which have mass and charge and interact strongly with matter. Electromagnetic radiation, on the other hand, consists of massless energy waves, including radio waves, visible light, X-rays, and gamma rays, which propagate through space as oscillating electric and magnetic fields. These two forms of radiation exhibit distinct properties, effects on matter, and biological interactions, making them essential in various scientific, medical, and industrial applications.

### Particulate Radiation

Particulate radiation consists of subatomic particles that carry mass, energy, and momentum, differentiating it from electromagnetic radiation, which has no mass. These particles include alpha particles, beta particles, neutrons, and protons, each with distinct properties and levels of ionization. Alpha particles, composed of two protons and two neutrons, are highly ionizing but have low penetration, being stopped by paper or a few centimeters of air. Beta particles, which are high-energy electrons or positrons, have greater penetration power than alpha particles but cause moderate ionization. Neutrons, being electrically neutral, have deep penetration and are commonly used in nuclear reactors, radiation shielding, and therapy. Protons, positively charged subatomic particles, are used in proton therapy to target cancerous cells with high precision. Particulate radiation is primarily produced from radioactive decay, nuclear reactions, and particle accelerators. Due to its strong ionizing potential, it can cause DNA damage, mutations, and cellular destruction, making it hazardous to living tissues. However, these same properties make it beneficial in cancer treatments, industrial sterilization, and nuclear energy production. Effective shielding is crucial in radiation protection, with materials like lead, concrete, or water used depending on the type of particle and its energy level. Alpha particles require minimal shielding, while beta particles need plastic or aluminium, and neutron radiation is best absorbed by materials rich in hydrogen, such as water or polyethylene. Understanding particulate radiation is essential in nuclear medicine, radiation safety, and advanced scientific research.

- **Alpha ( $\alpha$ ) Particles:** Alpha particles ( $\alpha$ -particles) are a type of particulate radiation composed of two protons and two neutrons, making them essentially helium nuclei ( ${}^4_2\text{He}$ ). These particles are positively charged and emitted during the radioactive decay of heavy, unstable atomic nuclei such as uranium-238, radium-226, and polonium-210. Alpha radiation is one of the most ionizing forms of radiation but has low penetration power due to its relatively large mass and charge. Because of their strong ionizing ability, alpha particles can cause significant damage to biological tissues if inhaled, ingested, or introduced into the body through an open wound. However, externally, alpha radiation poses little risk as it cannot penetrate human skin or even a sheet of paper. In air, alpha particles travel only a few centimetres before losing their energy and becoming harmless helium atoms by capturing two electrons. Alpha particles interact with matter primarily through Coulombic forces, causing intense ionization along their short path. This high ionization density leads to DNA damage, increasing the risk of mutations and cancer if alpha-emitting materials enter the body. Because of this, strict safety measures are required when handling alpha-emitting substances, particularly in nuclear facilities, radiopharmaceuticals, and radiation laboratories. Despite their potential hazards, alpha particles have practical applications. They are used in smoke detectors, radioisotope thermoelectric generators (RTGs) for space missions, and cancer treatment through targeted alpha therapy (TAT). Understanding alpha radiation's properties, risks, and applications is essential in fields like nuclear physics, medicine, and radiation protection. Alpha particles are produced during the process of alpha decay, which is a type of radioactive decay observed in heavy elements. This occurs when an unstable nucleus emits an alpha particle in order to become more stable. The most common elements that undergo alpha decay include:
  - i. **Uranium:** Uranium-238 and Uranium-235 are well-known alpha emitters. They undergo alpha decay to produce thorium and radium isotopes.

- ii. Radium: Radium-226 is a significant alpha emitter. It was once widely used in luminous paints but has since been phased out due to its radioactive properties.
- iii. Thorium: Thorium-232 is another radioactive element that undergoes alpha decay.
- iv. Polonium: Polonium-210 is a highly radioactive alpha emitter that has been used in various applications, including in the investigation of nuclear weapons and as a component in some types of ionization chambers.
- v. Radon: Radon-222, a decay product of radium-226, is a colourless, odourless, and tasteless gas that is released naturally from the decay of uranium in rocks and soil. It is considered a significant source of alpha radiation in certain environments.

### Alpha Particles and Biological Effects

Although alpha particles have low penetration power, they can still cause significant damage if they are able to enter the body. Inhalation, ingestion, or open wounds can all allow alpha-emitting materials to enter the body, where they can interact with living tissues and cause significant harm. The biological effects of alpha radiation depend on the amount of radiation exposure and the specific part of the body that is affected. Some of the effects include:

- i. **DNA Damage:** Alpha particles have the ability to ionize molecules within cells, especially DNA. This can lead to mutations, breaks in the DNA strands, and other forms of genetic damage. These mutations can result in uncontrolled cell growth, which is the hallmark of cancer.
- ii. **Cancer Risks:** Because of the high ionization potential of alpha particles, they can cause severe damage to tissues, particularly in sensitive organs like the lungs and bones. Prolonged exposure to alpha-emitting materials, such as radon gas in poorly ventilated areas, increases the risk of lung cancer. Radon is the second leading cause of lung cancer after smoking.
- iii. **Radiation Sickness:** Although the skin and outer layers of the body provide some protection from alpha particles, exposure to alpha-emitting substances inside the body can lead to radiation sickness. Symptoms of radiation sickness include nausea, vomiting, hair loss, and in extreme cases, organ failure.

### Shielding Against Alpha Particles

Due to their low penetration ability, alpha particles are easily shielded against. The simplest materials can prevent alpha particles from reaching the body or penetrating further into materials. Common shielding materials include:

- i. **Paper:** A sheet of paper is sufficient to stop most alpha particles. This is why alpha particles pose little risk when they are outside the body and are not inhaled or ingested.
  - ii. **Skin:** The outer layers of human skin provide an effective barrier against alpha particles. However, if alpha-emitting materials are inhaled, ingested, or enter the body through wounds, they can pose significant health risks.
  - iii. **Clothing:** While alpha particles are unable to penetrate most clothing, protective clothing can be used to minimize exposure in workplaces where alpha-emitting materials are handled, such as laboratories or industrial environments.
- **Beta ( $\beta$ ) Particles:** Beta particles ( $\beta$ -particles) are a type of particulate radiation consisting of high-energy, fast-moving electrons or positrons emitted from the nucleus of an unstable atom during beta decay. Unlike alpha particles, which are heavy and carry a double positive charge, beta particles are significantly lighter and travel at much higher speeds. Because of their smaller mass and greater velocity, beta particles can penetrate deeper into materials compared to alpha particles, though they are still less penetrating than gamma radiation. Beta radiation occurs in two forms: beta-minus ( $\beta^-$ ) decay and beta-plus ( $\beta^+$ ) decay. In beta-minus decay, a neutron inside the nucleus transforms into a proton, emitting a beta-minus particle (which is an electron) and an antineutrino. This increases the atomic number of the element by one, converting it into a different element. An example of this is Carbon-14 decaying into Nitrogen-14. In beta-plus decay, also known as positron emission, a proton inside the nucleus converts into a neutron, releasing a positron (a positively charged electron) and a neutrino. This decreases the atomic number by one, changing the element. An example is Fluorine-18 decaying into Oxygen-18.

Beta particles have distinct properties that determine their behaviour and applications. They are negatively charged ( $\beta^-$ ) or positively charged ( $\beta^+$ ) and have a very small mass, equivalent to that of an electron. Their penetration ability is greater than that of alpha particles; they can travel several meters in air and pass through materials like paper and skin, but they are stopped by plastic, glass, or thin sheets of aluminum. Beta particles move at very high speeds, sometimes approaching the speed of light. Their ionization power is lower than that of alpha particles, meaning they do not cause as much direct damage to atoms and molecules. However, they can still interact with biological tissues and cause harmful effects, especially at high energy levels. Exposure to beta radiation poses potential health risks, particularly if beta-emitting substances are inhaled, ingested, or absorbed through the skin. Direct exposure can cause skin burns and DNA damage, which may lead to mutations and cancer. In cases of high radiation doses, radiation sickness may occur. Since beta particles have more penetration power than alpha particles, proper shielding is essential to prevent excessive exposure. Materials like plastic, glass, or aluminum are commonly used as protective barriers. Lead is not preferred because when beta particles strike lead, they produce secondary X-rays (bremsstrahlung radiation), which can be harmful. Despite these risks, beta radiation has significant scientific, medical, and industrial applications. In medicine, beta radiation is widely used in radiation therapy for treating cancer, with isotopes like phosphorus-32 and strontium-90 targeting and destroying cancer cells. In industry, beta radiation is used for thickness measurement of materials such as plastic films, paper, and metal sheets. In scientific research, beta-emitting isotopes serve as tracers in biological and chemical studies, helping scientists track chemical reactions in living organisms.

- **Neutrons:** Neutrons are subatomic particles found in the nucleus of atoms alongside protons. Unlike protons, neutrons have no electric charge, making them neutral particles. They have a mass nearly equal to that of a proton and play a crucial role in atomic stability and nuclear reactions. Neutrons are significant in radiation studies because they have high penetration power and can induce nuclear reactions in certain materials. One of the key properties of neutrons is their ability to penetrate deep into materials. Since they have no charge, they are not repelled by the electric fields of atoms, allowing them to travel through matter with minimal interaction. This makes neutron radiation particularly dangerous as it can pass through materials like metals, concrete, and the human body, potentially causing significant biological damage. Based on energy levels, neutrons are classified into thermal neutrons (low-energy), epithermal neutrons (intermediate-energy), and fast neutrons (high-energy). Thermal neutrons have low energy and move slowly, while fast neutrons have higher energy and are more likely to induce nuclear reactions. Neutrons are produced from various natural and artificial sources. In nuclear fission reactions, such as those occurring in nuclear reactors and atomic bombs, heavy atomic nuclei split, releasing neutrons. Nuclear fusion, which occurs in stars like the Sun, also generates neutrons. Additionally, cosmic rays interacting with Earth's atmosphere produce secondary neutrons, contributing to background radiation. Neutrons can also be produced artificially in particle accelerators, where high-energy protons collide with heavy elements, and through spontaneous fission of certain radioactive elements like uranium-238.

Despite being neutral, neutrons can cause biological damage when they interact with human tissues. They do not directly ionize atoms, but they transfer energy to atomic nuclei, which then create secondary ionization effects. This can damage DNA and cellular structures, increasing the risk of mutations and cancer. High doses of neutron radiation can also lead to radiation sickness, with symptoms such as nausea, fatigue, and immune system failure. Since neutrons can penetrate deep into the body, they are more harmful than alpha or beta particles, which are stopped by the skin. Due to their high penetration ability, specialized shielding materials are required to protect against neutron radiation. Hydrogen-rich materials like water, polyethylene, and paraffin are effective, as hydrogen atoms can slow down neutrons through collisions. Boron and boron-containing compounds are also used, as boron-10 effectively absorbs neutrons. Concrete and lead can provide additional shielding, especially when combined with hydrogen-rich materials. Despite their dangers, neutrons have many important applications. In nuclear reactors, they are essential for sustaining chain reactions that generate electricity. Neutron activation analysis (NAA) is a technique used in material testing, helping scientists identify element compositions. In medical therapy, neutron radiation is sometimes used to treat cancer, especially in cases resistant to conventional radiation. Neutron-based imaging, such as neutron radiography, is valuable in industrial testing, allowing for non-destructive examination of materials.

- **Protons:** Proton radiation is a type of particulate radiation consisting of high-energy protons, which are positively charged subatomic particles. Protons, found in the nucleus of atoms, have a charge of +1 and a mass of approximately 1 atomic mass unit (amu). Compared to other forms of radiation, protons interact strongly with matter due to their charge and mass, making them significant in various applications, including medicine, research, and space exploration. Protons possess unique properties that define their behaviour and interactions with matter. Since they carry a positive charge, they interact with electrons in atoms, causing ionization and excitation of molecules. Their penetration power is higher than that of alpha particles but lower than beta particles and gamma rays. The distance protons can travel depends on their energy level—high-energy protons can pass through several centimetres of material before stopping. A key characteristic of protons is the Bragg peak, where they release the maximum amount of energy at a specific point, making them useful in medical applications like cancer treatment. Proton radiation can be generated from both natural and artificial sources. One major source is cosmic rays, which continuously bombard Earth with high-energy protons from space. These protons can interact with the atmosphere, producing secondary radiation such as neutrons and gamma rays, and pose radiation risks to astronauts and high-altitude pilots. Another source is particle accelerators, where protons are accelerated to high speeds for scientific research and medical treatments like proton therapy. Additionally, proton radiation is produced in nuclear reactions, such as fission and fusion, where protons may be emitted from certain radioactive materials during decay processes.

When protons travel through matter, they ionize atoms along their path, gradually losing energy until they come to a stop. Unlike uncharged radiation such as neutrons or gamma rays, protons interact more directly with electrons in materials, leading to localized energy deposition. This property makes proton radiation highly useful in medical treatments, particularly in cases where precise targeting of radiation is required. Proton radiation has significant biological effects when it interacts with living tissues. As protons pass through cells, they ionize molecules, breaking chemical bonds and causing cellular damage. High-energy protons can damage DNA, leading to mutations and an increased risk of cancer. However, due to the Bragg peak effect, protons release most of their energy at a specific depth, allowing for precise targeting of tumours while minimizing damage to surrounding healthy tissue. This makes proton therapy a preferred treatment option for cancers located near sensitive organs like the brain and spine. In addition to medical applications, proton radiation poses challenges in space exploration. Astronauts exposed to high-energy protons from cosmic rays and solar flares face increased risks of radiation sickness and long-term health effects, including cancer. To mitigate these risks, effective shielding materials such as plastic, water, and concrete are used to protect against proton exposure. Low-energy protons can be stopped by thin shielding materials, but high-energy protons require denser materials like lead or concrete. Beyond its biological impact, proton radiation has a wide range of applications. In the medical field, proton therapy is a cutting-edge treatment for cancer, providing precise radiation delivery with minimal damage to healthy tissues. In scientific research, protons are used in particle physics experiments, such as those conducted at the Large Hadron Collider (LHC), where they help scientists study fundamental particles and forces. In space exploration, researchers study cosmic protons to develop better radiation shielding for astronauts and spacecraft.

**NOTE:** Heavy ions are atoms of elements with a higher atomic number than hydrogen. These ions are typically emitted in high-energy processes, such as nuclear reactions or cosmic ray interactions. Heavy ions carry significant amounts of energy and are highly ionizing, meaning they can cause considerable damage to biological tissues. Heavy ion radiation is also used in certain types of cancer therapy, particularly for tumours that are difficult to treat with conventional methods.

### Classification Based on Ionizing Ability

- **Ionizing Radiation:** Ionizing radiation is a high-energy form of radiation capable of removing electrons from atoms, leading to ionization. This process can cause chemical changes in matter, affecting both biological tissues and materials. Ionizing radiation is categorized into electromagnetic radiation (X-rays and gamma rays) and particulate radiation (alpha particles, beta particles, neutrons, and protons). X-rays and gamma rays are forms of electromagnetic radiation with no mass or charge, but they have high penetrating power. X-rays are widely used in medical imaging, while gamma rays, emitted from radioactive materials, are used in cancer treatment and nuclear applications. Alpha particles, consisting of two protons and two neutrons, are highly ionizing but have low penetration, stopping in air or thin materials like paper. Beta particles are high-energy electrons or positrons that penetrate deeper than alpha particles but cause less

ionization. Neutrons, being neutral, penetrate deeply into matter and are used in nuclear reactors and radiation therapy. Ionizing radiation is beneficial in medicine, industry, and research, but it poses serious health risks. Exposure can cause DNA damage, mutations, and cellular destruction, leading to conditions like radiation sickness, cancer, and genetic mutations. Protection against ionizing radiation includes using shielding materials (lead, concrete, or water), maintaining safe exposure limits, and employing proper safety protocols. Despite its risks, ionizing radiation plays a crucial role in diagnostics, treatment, sterilization, and energy production, making it an essential aspect of modern science and technology.

- **Non-Ionizing Radiation:** Non-ionizing radiation is a type of radiation that does not have enough energy to remove electrons from atoms but can excite molecules and cause heating effects. It consists of low-energy electromagnetic waves, including radio waves, microwaves, infrared radiation, visible light, and low-energy ultraviolet (UV) radiation. Unlike ionizing radiation, which can cause severe biological damage, non-ionizing radiation is generally considered safer, though prolonged exposure to certain forms can still have harmful effects. Radio waves and microwaves are widely used in communication technologies, such as radio broadcasting, mobile phones, and satellite communication. Microwaves are also utilized in cooking appliances and medical treatments like diathermy therapy. Infrared radiation, which is felt as heat, is used in thermal imaging, remote controls, and industrial heating applications. Visible light, the only part of the electromagnetic spectrum detectable by the human eye, is essential for vision, photography, and various optical technologies. Although non-ionizing radiation does not cause ionization, excessive exposure to some types can still pose health risks. Prolonged exposure to ultraviolet (UV) radiation from the sun can cause skin damage, premature aging, and increase the risk of skin cancer. High-intensity microwaves and infrared radiation can cause thermal burns, while excessive exposure to artificial light sources may lead to eye strain and sleep disturbances. Despite these risks, non-ionizing radiation plays a crucial role in medicine, industry, and daily life, offering numerous technological and scientific benefits while generally posing lower health risks compared to ionizing radiation.

### Classification Based on Source of Origin

Another way to classify radiation is by its source of origin, either natural or artificial. Natural radiation occurs in the environment and comes from naturally occurring sources such as cosmic rays from space, terrestrial radiation from radioactive materials in the Earth's crust, and radon gas released from rocks and soil. Internal radiation, such as that from isotopes like potassium-40 and carbon-14 within the human body, also contributes to background radiation. The levels of natural radiation can vary based on factors like geographic location, altitude, and soil composition. Artificial radiation, by contrast, is produced through human activities and technologies. It is typically controlled and used for specific purposes. Examples of artificial radiation sources include medical applications like X-rays and radiation therapy, nuclear power plants producing fission products, industrial applications such as radiography and nuclear medicine, and consumer products like smoke detectors that contain americium-241. While artificial radiation exposure can be minimized through regulation and safety measures, it remains a significant concern in settings where exposure is common.

### Classification Based on Energy Levels

Radiation can also be classified according to its energy level, which determines its ability to penetrate materials and its potential biological effects. High-energy radiation has enough energy to penetrate deeply into materials, including biological tissues, and is typically ionizing. It poses significant biological risks due to its ability to cause deep cellular damage. Examples of high-energy radiation include gamma rays ( $\gamma$ ), X-rays, and high-energy neutrons. These types of radiation are used in medical imaging and treatments, as well as in nuclear reactors, but they require protective shielding to prevent harm. Low-energy radiation, on the other hand, is less penetrating and generally non-ionizing. It interacts more with the surface of materials and is less likely to cause deep biological damage. Examples of low-energy radiation include radio waves, microwaves, and infrared (IR) radiation. These forms of radiation are commonly used in communication, heating, and light-based applications, and they pose less of a risk to human health.

### Electromagnetic Radiation

Electromagnetic radiation consists of energy waves that travel through space at the speed of light ( $3.00 \times 10^8$  m/s) without requiring a medium. It encompasses a broad spectrum of waves, including radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays, each differing in wavelength, frequency, and energy.

Electromagnetic waves are produced by accelerating charged particles and propagate as perpendicular oscillating electric and magnetic fields. Unlike particulate radiation, electromagnetic radiation has no mass or charge and can travel vast distances through vacuum or matter. The energy of electromagnetic radiation determines its interaction with matter. Lower-energy waves, such as radio waves and visible light, are widely used in communication, broadcasting, heating, and optical technologies. Higher-energy waves, including ultraviolet rays, X-rays, and gamma rays, are ionizing, meaning they can remove electrons from atoms, leading to molecular changes and potential biological damage. This property makes them valuable in medical imaging, radiation therapy, and industrial sterilization. When electromagnetic waves interact with matter, they can be absorbed, reflected, refracted, or transmitted, depending on the material's properties. For example, radio waves pass through the atmosphere for long-distance communication, while X-rays are absorbed by dense tissues, making them useful in medical diagnostics. Gamma rays, the highest-energy form of electromagnetic radiation, are extensively used in nuclear medicine and radiation therapy. Understanding electromagnetic radiation is crucial in fields like physics, engineering, healthcare, and telecommunications, as it plays a fundamental role in modern technology and scientific advancements.

- **Radio Waves:** Radio-waves are a type of electromagnetic radiation with wavelengths longer than those of infrared light, typically ranging from a few millimeters to thousands of kilometers. They are part of the electromagnetic spectrum and are characterized by their ability to travel long distances and penetrate through various materials, making them ideal for communication purposes. Radiowaves are produced by the movement of charged particles, like electrons, and can be generated by natural sources such as lightning or by artificial sources like radio transmitters. These waves carry information through the modulation of their frequency, amplitude, or phase, a process that is fundamental to technologies such as radio broadcasting, television, and wireless communication systems like cell phones and Wi-Fi. Due to their relatively low energy, radiowaves are generally not harmful to human health. In addition to communication, radiowaves also play a significant role in radar systems, astronomy, and remote sensing, where they help in the detection of objects and the study of distant celestial bodies. The ability of radiowaves to cover vast distances and pass through the atmosphere without significant attenuation makes them indispensable in modern communication infrastructure.
- **Microwaves:** Microwaves are a type of electromagnetic radiation with wavelengths ranging from one millimeter to one meter, lying between infrared radiation and radio waves in the electromagnetic spectrum. They have higher frequencies than radio waves but lower frequencies than infrared radiation, typically ranging from 300 MHz to 300 GHz. Due to their ability to penetrate through various materials, microwaves are widely used in communication systems, including satellite communication, radar, and wireless networks like Wi-Fi and Bluetooth. One of the most common uses of microwaves is in microwave ovens, where they are absorbed by water, fats, and sugars in food, causing these molecules to vibrate and generate heat, thus cooking the food quickly and efficiently. Microwaves are also utilized in radar systems for detecting objects and measuring distances, as they can bounce off objects and return to the source, providing valuable information about the object's location and speed. In addition, microwaves are used in weather forecasting, astronomy, and remote sensing, where they help analyze atmospheric conditions or observe distant celestial bodies. While microwaves have numerous practical applications, they can also pose health risks if exposure is excessive. However, the levels of microwave radiation typically encountered in everyday life, such as from microwave ovens or communication devices, are generally considered safe. Shielding is often employed to contain microwave radiation in devices like ovens, ensuring that users are not exposed to harmful levels.
- **Infrared (IR) Radiation:** Infrared (IR) radiation is a type of electromagnetic radiation that lies between microwaves and visible light in the electromagnetic spectrum. It has longer wavelengths than visible light, typically ranging from 700 nanometers (nm) to 1 millimeter (mm), corresponding to frequencies between 430 terahertz (THz) and 300 gigahertz (GHz). Infrared radiation is closely associated with heat, as it is emitted by objects as thermal energy. Based on wavelength, IR radiation is categorized into three regions: near-infrared (NIR), mid-infrared (MIR), and far-infrared (FIR). The near-infrared region (700 nm to 1,500 nm) is closest to visible light and is widely used in optical fiber communication and remote sensing. Mid-infrared radiation (1,500 nm to 5,000 nm) is essential for thermal imaging, spectroscopy, and chemical analysis, as many molecular vibrations occur in this range. Far-infrared radiation (5,000 nm to 1 mm) is associated with lower-energy radiation and is commonly used for heating applications. Infrared radiation has unique properties that make it valuable in various applications. It is invisible to the human eye but can be felt as heat. All objects with a temperature above absolute zero emit infrared radiation, with the intensity and



wavelength depending on their temperature. IR radiation can transfer heat without requiring a medium, making it the primary means by which the Sun's heat reaches Earth through space. Different materials absorb and emit infrared radiation at varying efficiencies. Darker objects absorb and emit more IR radiation compared to lighter-colored surfaces. Specific molecular structures also absorb infrared radiation at particular wavelengths, a property that is crucial in spectroscopy.

One of the most significant applications of infrared radiation is thermal imaging. Infrared cameras detect heat emitted by objects, enabling applications in medical diagnostics, search and rescue operations, and building inspections. In medical diagnostics, thermal imaging is used to detect fever, inflammation, and circulation disorders. In search and rescue missions, infrared cameras help locate people in darkness or through smoke. Engineers and inspectors use thermal imaging to identify heat leaks and insulation failures in buildings. Infrared radiation is also extensively used in remote sensing and satellite imaging. Earth observation satellites monitor temperature changes, detect wildfires, and track weather patterns using IR sensors. This technology is also useful for studying greenhouse gases like carbon dioxide and water vapour in the atmosphere. In communications, infrared radiation plays a vital role in short-range wireless communication, such as remote controls, wireless mice, and infrared sensors. It is also employed in optical fibre communication, particularly in the near-infrared spectrum, for fast data transmission over long distances. Another common use of infrared radiation is heating. Infrared heaters emit IR radiation that directly warms objects and people, making it an energy-efficient heating method. In astronomy, infrared telescopes are used to observe celestial objects that emit most of their energy in the infrared spectrum. Many astronomical bodies, such as stars, nebulae, and galaxies, are obscured in visible light but can be studied through their infrared emissions. Infrared spectroscopy is another critical application, allowing scientists to identify substances and analyse their chemical composition based on how molecules absorb infrared radiation.

Infrared radiation also has medical applications. Infrared therapy is used for pain relief, muscle relaxation, and improving blood circulation. Additionally, pulse oximeters, which measure blood oxygen levels, utilize infrared sensors for non-invasive diagnostics. Although infrared radiation is generally non-ionizing and not harmful, prolonged exposure to intense IR radiation can cause skin burns and eye damage. Protective measures, such as eyewear and specialized clothing, are necessary when working with high-intensity infrared sources. Infrared radiation plays a crucial role in Earth's energy balance. The Earth absorbs sunlight and re-emits it as infrared radiation, which is then absorbed and re-radiated by greenhouse gases. This natural greenhouse effect helps regulate the planet's temperature but can be intensified by human activities, leading to climate change.

- **Visible Light:** Visible light is a small but vital portion of the electromagnetic spectrum, consisting of electromagnetic radiation with wavelengths between approximately 400 and 700 nano-meters. It is the only part of the spectrum that can be detected by the human eye, enabling us to see and interpret the world around us. Within this range, different wavelengths correspond to different colours, with violet light having the shortest wavelength (around 400 nm) and red light having the longest (around 700 nm). The visible spectrum is often described by the acronym ROYGBIV, which stands for the colours of the rainbow—red, orange, yellow, green, blue, indigo, and violet—each of which corresponds to a specific range of wavelengths. Visible light plays an essential role in many natural and technological processes. For example, it is crucial for photosynthesis, the process by which plants use sunlight to produce food and oxygen, supporting life on Earth. In addition to its biological importance, visible light is fundamental for human vision. Photoreceptor cells in the retina, known as rods and cones, respond to different wavelengths of light, allowing us to perceive colours, shapes, and depth. Beyond vision, visible light is used in a wide range of technologies, such as optical devices like microscopes, telescopes, cameras, and fiber optics, all of which rely on the manipulation and detection of visible light. Additionally, visible light is essential in communication technologies like laser pointers, optical communication systems, and display screens. Moreover, visible light's ability to travel through space and Earth's atmosphere without being significantly absorbed or scattered makes it ideal for a range of uses in science, such as astronomy, where it is used to observe distant stars and galaxies. Overall, visible light not only enables us to perceive the world around us but also supports critical life processes and facilitates various technologies across many fields.

- **Ultraviolet (UV) Radiation:** Ultraviolet (UV) rays are a form of electromagnetic radiation with wavelengths shorter than visible light but longer than X-rays, ranging from about 10 to 400 nanometers. These rays are invisible to the human eye, but they have a significant impact on both the environment and human health due to their high energy. UV radiation is divided into three types based on wavelength: UV-A, UV-B, and UV-C. UV-A rays, with wavelengths between 320 and 400 nm, are the least energetic and make up about 95% of the UV radiation reaching Earth. They are responsible for skin aging and tanning and can penetrate deeper into the skin layers. UV-B rays, which have wavelengths between 280 and 320 nm, are more energetic and are the primary cause of sunburn. They can damage the DNA in skin cells, increasing the risk of skin cancer. UV-C rays, with wavelengths between 100 and 280 nm, are the most dangerous type of UV radiation, but they are almost entirely absorbed by the Earth's ozone layer and do not reach the surface. Despite their potential for harm, UV rays also have beneficial effects. For example, exposure to UV-B rays helps the body produce vitamin D, which is essential for bone health and immune function. UV radiation is also used in various practical applications, including sterilization, water purification, and medical treatments. UV-C rays are commonly used to disinfect surfaces, air, and water because they can kill bacteria, viruses, and other microorganisms by damaging their DNA. However, overexposure to UV rays, especially UV-B and UV-C, can cause severe health problems. These include premature aging of the skin, increased risk of skin cancer, and eye damage such as cataracts. Due to these risks, it is important to protect the skin and eyes from excessive UV exposure by using sunscreen, wearing protective clothing, and avoiding prolonged sun exposure, particularly during peak UV radiation hours. Despite the dangers, UV radiation remains an important tool in medicine, industry, and environmental monitoring, requiring careful management and protection to mitigate its harmful effects.
- **X-rays:** X-rays are a form of electromagnetic radiation that have wavelengths shorter than ultraviolet light but longer than gamma rays, typically in the range of 0.01 to 10 nanometers. First discovered by German physicist Wilhelm Conrad Roentgen in 1895, X-rays have become an essential tool in a wide variety of scientific, medical, and industrial applications due to their ability to penetrate various materials and provide insights into the internal structures of objects, including the human body. X-rays belong to the electromagnetic spectrum, which includes radio waves, microwaves, infrared radiation, visible light, ultraviolet rays, X-rays, and gamma rays. All these types of radiation travel at the speed of light and are fundamentally different in terms of their wavelengths and frequencies. X-rays are characterized by very short wavelengths and high energy, meaning they have higher frequencies and higher photon energies compared to visible light and ultraviolet radiation. The energy of X-rays typically ranges from approximately 100 eV (electron volts) to 100,000 eV, much higher than visible light (which is measured in eV). This high energy enables X-rays to ionize atoms, which can lead to chemical reactions and damage to biological tissues at high doses. Their ability to penetrate materials makes them unique among forms of radiation, and this property is exploited in many practical applications.
- **Gamma Ray:** Gamma rays are a form of electromagnetic radiation with the highest energy and shortest wavelengths in the electromagnetic spectrum, typically less than 0.01 nanometers. They have frequencies above 10 exahertz (EHz) and are produced by nuclear reactions, radioactive decay, and high-energy astrophysical processes. Unlike other forms of electromagnetic radiation, gamma rays are highly penetrating and can pass through most materials, making them both useful and hazardous. Their ionizing nature allows them to interact with matter by stripping electrons from atoms, leading to various applications in medicine, industry, and scientific research. One of the primary sources of gamma radiation is radioactive decay, where unstable atomic nuclei release excess energy in the form of gamma photons. This process commonly occurs in isotopes such as cobalt-60, cesium-137, and radium-226. Gamma rays are also emitted during nuclear fission and fusion reactions, making them a significant aspect of nuclear energy production and nuclear weapons. In astrophysics, gamma rays are produced by extreme cosmic events such as supernovae, neutron star collisions, and black hole activity. These high-energy phenomena are studied using gamma-ray telescopes, which provide insights into the most energetic and distant objects in the universe. Due to their high energy and penetration ability, gamma rays interact with matter through three primary processes: photoelectric absorption, Compton scattering, and pair production. In the photoelectric effect, a gamma photon transfers all its energy to an electron, ejecting it from an atom. In Compton scattering, a gamma photon collides with an electron, transferring some of its energy and changing direction. Pair production occurs when a high-energy gamma photon creates an electron-positron pair upon interacting with a strong electromagnetic field near an atomic nucleus. These interactions make gamma rays useful for imaging and

treatment in medicine, while also posing potential health hazards. One of the most significant applications of gamma radiation is in medical imaging and cancer treatment. In diagnostic imaging, gamma rays are used in nuclear medicine techniques such as positron emission tomography (PET) and single-photon emission computed tomography (SPECT), where radioactive tracers emit gamma photons that are detected to create detailed images of internal organs. In cancer therapy, gamma rays from sources like cobalt-60 are used in radiation therapy to target and destroy cancerous cells while minimizing damage to surrounding healthy tissue. The precise control of gamma radiation allows for effective tumour treatment, particularly in cases where surgery is not an option.

Beyond medicine, gamma radiation has industrial and scientific applications. It is used in non-destructive testing to inspect welds and structural integrity in materials. Gamma-ray sterilization is employed to eliminate bacteria and pathogens in medical equipment, food, and pharmaceuticals. In space exploration, gamma-ray spectrometers are used to analyze the composition of planetary surfaces. However, gamma radiation exposure poses health risks, as prolonged exposure can cause DNA damage, mutations, and radiation sickness. To mitigate these risks, shielding materials such as lead, concrete, and dense metals are used to absorb or block gamma rays.

### 6.3. X-RAYS

X-rays are a type of electromagnetic radiation that falls within the high-energy region of the electromagnetic spectrum. Their wavelengths range from approximately 0.01 to 10 nanometers (nm), positioning them between ultraviolet (UV) light and gamma rays. The discovery of X-rays by Wilhelm Conrad Roentgen in 1895 marked a major breakthrough in science and medicine. Roentgen found that these rays could penetrate solid objects and produce images of internal structures, leading to their rapid adoption in medical diagnostics and various other fields. X-rays are widely used today for imaging, security screening, and industrial inspections due to their ability to pass through most substances while being absorbed by denser materials like bone and metal. X-rays exhibit several fundamental properties that distinguish them from other types of radiation.

1. **Short Wavelength:** X-rays have wavelengths ranging from 0.01 to 10 nanometers, which are shorter than ultraviolet (UV) light but longer than gamma rays. This short wavelength is crucial because it allows X-rays to have high energy and the ability to penetrate most substances.
2. **High Energy:** X-rays carry significantly higher energy compared to visible light and ultraviolet radiation. The energy of X-ray photons typically ranges from 100 eV to 100,000 eV. This high energy is what allows them to ionize atoms, making them capable of causing chemical changes and biological effects, such as DNA damage, at high doses.
3. **Penetrating Power:** One of the defining characteristics of X-rays is their ability to pass through many materials, including human tissues, metals, and concrete, depending on the energy and thickness of the material. This property is what makes X-rays so useful for imaging internal structures in the body (like bones and organs) and inspecting the integrity of materials in non-destructive testing.
4. **Ionizing Radiation:** X-rays are a form of ionizing radiation, meaning they have enough energy to remove electrons from atoms or molecules, creating charged particles (ions). This ability to ionize matter is useful for medical imaging and therapy but also means that prolonged or excessive exposure to X-rays can be harmful to living tissues, potentially causing cellular damage and increasing the risk of cancer.
5. **Transparency to Air:** X-rays are not absorbed significantly by air, which allows them to travel through the atmosphere and reach objects or people that they need to image or analyze. This feature is particularly useful for non-destructive testing and in applications such as airport security, where X-rays are used to scan luggage.
6. **Dual Nature (Wave and Particle):** Like all forms of electromagnetic radiation, X-rays exhibit both wave-like and particle-like properties. As waves, X-rays have characteristics such as frequency and wavelength, which determine their energy. As particles (photons), X-rays can interact with matter, transferring energy to atoms and molecules, which is essential in processes like ionization and X-ray imaging.
7. **Contrast in Imaging:** X-rays have the ability to provide contrast between different materials, which is why they are widely used in medical imaging. Dense materials, such as bones, absorb more X-rays and appear white on an X-ray image, while less dense materials, such as soft tissues, allow more X-rays to pass through and appear darker.

8. **Production via High-Energy Electrons:** X-rays are typically produced in X-ray tubes, where high-energy electrons collide with a target material (often tungsten or molybdenum). When these electrons strike the target, they generate X-ray radiation through either characteristic or bremsstrahlung radiation mechanisms.
9. **Energy Spectrum:** X-rays do not consist of a single energy level but rather a spectrum of energies. In particular, the spectrum of X-rays includes both discrete characteristic X-rays (produced by specific atomic transitions) and a continuous range of energies from bremsstrahlung radiation. This wide range of energies allows X-rays to be tailored for different types of imaging and materials analysis.
10. **Uses in Non-Destructive Testing (NDT):** X-rays are widely used in industrial applications for non-destructive testing (NDT), where they help inspect the internal structures of objects such as pipelines, machinery, or aircraft components without damaging them. X-rays can reveal internal flaws like cracks, voids, or inclusions that are invisible to the naked eye, ensuring the safety and integrity of critical infrastructure.
11. **Medical Applications:** X-rays are most famously used in medical imaging techniques such as X-ray radiography, computed tomography (CT) scans, mammography, and fluoroscopy. These applications allow healthcare professionals to visualize bones, organs, and soft tissues inside the body for diagnostic purposes, from detecting fractures and infections to identifying tumors.
12. **Safety Considerations:** While highly useful, X-rays pose potential health risks due to their ionizing nature. Overexposure to X-rays can lead to radiation damage to cells and tissues, potentially causing radiation burns, cancer, or genetic mutations. Because of these risks, medical and industrial applications of X-rays are carefully regulated, and safety measures such as lead shielding, minimizing exposure time, and using the lowest possible doses are employed.
13. **Invisible to the Human Eye:** X-rays are not visible to the human eye, as their wavelengths are much shorter than visible light. To detect X-rays, special sensors or films are used, which convert the X-ray photons into an image or a signal that can be observed.
14. **Interaction with Matter:** When X-rays interact with matter, they can undergo several different processes: absorption, scattering, and transmission. The degree to which X-rays are absorbed by a material depends on factors like the atomic number ( $Z$ ) of the material, the density of the material, and the energy of the X-rays. High- $Z$  materials (like lead) absorb more X-rays, making them effective for shielding.

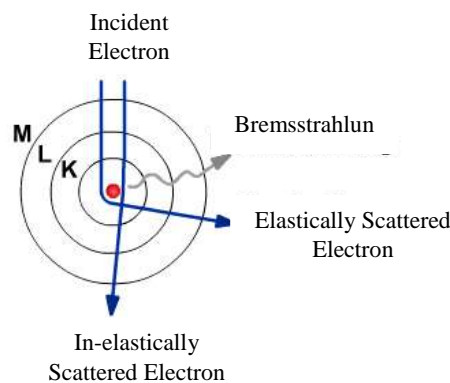
**Table: 6.1. Summary of X-ray properties**

Property	Description
Electromagnetic Waves	X-rays are a form of electromagnetic radiation with wavelengths shorter than visible light but longer than gamma rays.
High Energy and Penetration	X-rays have high energy, allowing them to penetrate most materials, including soft tissues, while being absorbed by denser materials like bones and metals.
Short Wavelength	X-rays have wavelengths ranging from 0.01 to 10 nanometers, making them highly effective for imaging and material inspection.
Ionizing Radiation	X-rays have enough energy to ionize atoms, meaning they can remove tightly bound electrons, which can lead to potential biological effects.
Travel in Straight Lines	X-rays propagate in straight lines unless deflected or scattered by objects they encounter.
Cannot Be Deflected by Electric or Magnetic Fields	Unlike charged particles, X-rays are neutral and are not influenced by electric or magnetic fields.
Fluorescence Induction	X-rays can cause certain materials to fluoresce, which is used in X-ray imaging screens and detection systems.
Photoelectric Effect	X-rays can eject electrons from atoms (photoelectric effect), which is utilized in X-ray detectors and imaging technologies.
Scattering (Compton Effect)	When X-rays interact with matter, they can scatter, altering their energy and direction, which is important in medical and industrial applications.
Absorption Depends on Material Density	Dense materials (e.g., bones, metals) absorb more X-rays, appearing white on X-ray images, while less dense materials (e.g., soft tissues) absorb fewer X-rays, appearing darker.

## Production of X-Ray

X-ray production is a complex physical process that occurs when high-energy electrons interact with matter, typically within an X-ray tube. The process involves the conversion of kinetic energy from electrons into electromagnetic radiation (X-rays) through two primary mechanisms: characteristic radiation and bremsstrahlung radiation. Below, we will provide a detailed scientific explanation of each mechanism, the conditions under which X-rays are produced, and the setup commonly used for X-ray generation. There are two primary processes by which X-rays are produced in an X-ray tube: characteristic radiation and bremsstrahlung radiation. These processes occur when high-energy electrons collide with the atoms of the target material, leading to the emission of X-ray photons.

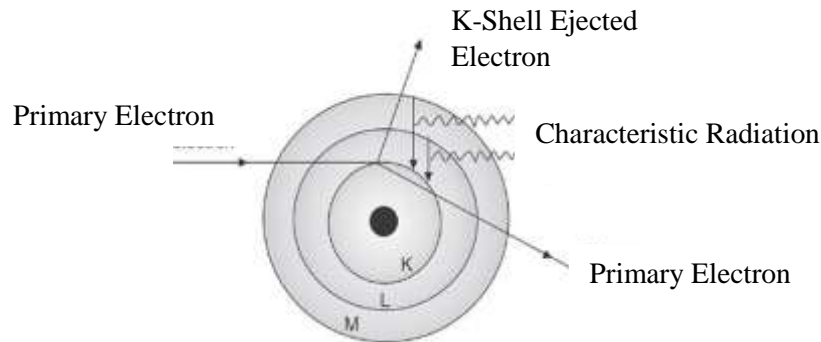
- Bremsstrahlung Radiation (Braking Radiation):** Bremsstrahlung radiation, also known as braking radiation, is a type of X-ray production that occurs when high-energy charged particles, typically electrons, are rapidly decelerated or deflected upon interacting with the nucleus of an atom. This process takes place in an X-ray tube, where a stream of fast-moving electrons is directed toward a high atomic number target, such as tungsten (W) or molybdenum (Mo). When these high-speed electrons approach the positively charged nucleus of a target atom, they experience an attractive force due to the Coulomb interaction. As a result, the electrons undergo a sudden deceleration or change in direction, leading to the loss of kinetic energy. The lost energy is emitted in the form of continuous X-ray photons, which form the Bremsstrahlung spectrum of X-rays.



**Fig: 6.2. Bremsstrahlung Radiation (Braking Radiation)**

The energy of the emitted X-ray photon depends on the degree of deceleration; if the electron undergoes a significant energy loss, a high-energy X-ray photon is produced, whereas smaller energy losses result in lower-energy X-rays. Since the degree of deceleration varies randomly for different electrons, Bremsstrahlung radiation produces a continuous spectrum of X-rays rather than discrete wavelengths. This characteristic distinguishes it from characteristic X-ray radiation, which arises from electronic transitions within atoms. The maximum energy of Bremsstrahlung X-rays is determined by the accelerating voltage applied across the X-ray tube, and the intensity of radiation increases with the atomic number of the target material. Bremsstrahlung radiation is the dominant mechanism of X-ray production in diagnostic radiology, industrial imaging, and radiation therapy. Its ability to generate a broad spectrum of X-ray energies makes it particularly useful for medical imaging and material analysis, where different tissue densities or material compositions can be distinguished based on their interaction with X-rays. Additionally, this type of radiation plays a crucial role in astrophysical processes, such as in high-energy cosmic events where charged particles interact with strong electromagnetic fields.

- Characteristic Radiation:** Characteristic radiation is a type of X-ray production that occurs when an incoming high-energy electron ejects an inner-shell electron from an atom, creating a vacancy. This vacancy makes the atom unstable, prompting an electron from a higher energy level (such as the L or M shell) to



**Fig: 6.3. Characteristic Radiation**

transition into the lower-energy vacant shell (typically the K or L shell). During this transition, the excess energy is released in the form of an X-ray photon with a specific wavelength and frequency, characteristic of the element in which the process occurs. The energy of the emitted characteristic X-ray is equal to the difference in energy levels between the two shells involved in the transition.

Since each element has unique energy levels for its electrons, the emitted X-ray photons have well-defined energies, forming a discrete spectrum rather than a continuous one. This is why this type of radiation is called characteristic radiation, as it is unique to each element and can be used for material identification in techniques like X-ray fluorescence (XRF) spectroscopy. Characteristic radiation is especially significant in medical imaging and industrial applications, where specific X-ray wavelengths are needed for better contrast and resolution. It is also widely used in analytical chemistry, crystallography, and elemental analysis. The intensity and presence of characteristic radiation depend on the atomic number of the target material and the energy of the incident electrons in an X-ray tube. When the accelerating voltage is sufficiently high, characteristic radiation is observed alongside Bremsstrahlung radiation, contributing to the overall X-ray spectrum.

### Types of X-Rays

X-rays can be classified into two primary types based on their energy levels and applications: soft X-rays and hard X-rays. Each type serves different purposes due to their varying energy and wavelength characteristics, which affect their penetration abilities and how they interact with matter. Soft X-rays are characterized by relatively low energy and longer wavelengths, typically ranging from about 0.1 to 10 nanometers. Because of their low energy, soft X-rays are less penetrating compared to their harder counterparts. This means they are typically absorbed by the outer layers of matter, such as the air and the skin's surface. Due to their limited penetration power, soft X-rays are not commonly used for imaging internal structures in humans or animals. However, they are extremely useful in scientific fields like material science and biological studies. In material science, soft X-rays are employed to examine thin films, coatings, and molecular structures with high precision. Their ability to interact with delicate materials without causing significant penetration damage makes them ideal for surface-level analysis. Similarly, in biological research, soft X-rays can be used for imaging microscopic samples or studying cellular structures, providing detailed insights into the composition of biological materials without deep tissue penetration. They are also used in certain types of spectroscopy, such as X-ray absorption spectroscopy, to understand material properties at the atomic level.

On the other hand, hard X-rays have much higher energy and shorter wavelengths, typically ranging from 0.01 to 0.1 nanometers. This increased energy allows hard X-rays to penetrate much more effectively through dense materials like bone, metal, and even some forms of concrete, making them far more versatile for a range of applications that require deep tissue or material penetration. Hard X-rays are commonly used in medical imaging techniques, such as X-ray radiography, computed tomography (CT) scans, and fluoroscopy. In medical imaging, their ability to pass through the body and produce detailed images of internal structures—like bones, organs, and tissues—has revolutionized diagnostics. For example, X-ray radiography is widely used to detect fractures, lung conditions, and dental issues, while CT scans offer detailed cross-sectional images of the body, aiding in the diagnosis of complex internal conditions such as tumors, vascular diseases, or injuries. Fluoroscopy, which utilizes continuous X-ray imaging, provides real-time video images for procedures like catheter insertions or gastrointestinal studies.

In addition to medical applications, hard X-rays are also used extensively in industrial applications. One of the primary uses is in non-destructive testing (NDT), where hard X-rays are employed to inspect the internal structure of materials and products without causing any damage. For instance, in industries like aerospace, automotive, and manufacturing, X-ray technology can be used to detect structural defects in metals, welds, and components, such as cracks or voids. This is crucial for ensuring the safety and reliability of critical components in high-risk industries. The ability of hard X-rays to pass through thick materials and reveal internal flaws makes them an indispensable tool in quality control and maintenance.

### X-Rays in Medical Applications

The most widely known application of X-rays is in the medical field, where they are used for diagnostic imaging. X-ray technology has revolutionized medicine by providing a non-invasive way to look inside the human body and diagnose a range of medical conditions, from fractures to tumours.

1. **Radiography:** The most common medical application of X-rays is in the form of traditional X-ray radiography. During an X-ray examination, a controlled burst of X-rays is directed at the patient, and the X-rays pass through the body, being absorbed at different rates by various tissues. Dense tissues like bones absorb more X-rays and appear white on the X-ray image, while softer tissues like muscles and organs allow more X-rays to pass through and appear darker. Radiography is commonly used to detect broken bones, joint issues, infections, and certain types of cancer, such as lung or breast cancer.
2. **Computed Tomography (CT) Scans:** A CT scan, also known as a CAT scan, is an advanced form of X-ray imaging that provides detailed cross-sectional images of the body. In a CT scan, X-ray beams are rotated around the body, and a computer processes the information to create highly detailed images of soft tissues, bones, and blood vessels. CT scans are frequently used for detecting internal injuries, tumors, and abnormalities in organs such as the brain, liver, and lungs.
3. **Fluoroscopy:** Fluoroscopy is a technique that allows continuous X-ray imaging, providing real-time video of internal organs and structures. It is commonly used in procedures like barium X-rays, where a patient ingests a contrast material (such as barium sulfate) to highlight the gastrointestinal tract, or during catheter-based procedures like angioplasty.
4. **Mammography:** Mammography uses X-rays specifically for imaging the breast tissue to detect signs of breast cancer. The breast is compressed between two plates, and X-rays are passed through the tissue to create detailed images of the breast. Mammography is a vital screening tool for early detection of breast cancer, often leading to improved outcomes due to early intervention.
5. **Dental X-Rays:** Dentists use X-rays to examine the teeth, jawbone, and surrounding tissues for conditions such as cavities, tooth infections, and bone loss. Dental X-rays can help detect problems that are not visible during a regular dental exam, including cavities between teeth and issues below the gumline.
6. **DEXA Scans (Dual-Energy X-ray Absorptiometry):** DEXA scans measure bone mineral density to assess the risk of osteoporosis and fractures. By using two different X-ray energy levels, DEXA provides precise evaluations of bone health, helping doctors diagnose and monitor conditions related to bone loss.

**Table: 6.2. Applications of X-rays in medicine**

Application	Description	Common Uses
Radiography	Traditional X-ray imaging where X-rays pass through the body, creating images based on tissue density differences.	Detection of fractures, joint problems, lung infections, and certain cancers (e.g., lung, breast).
Computed Tomography (CT) Scans	Advanced imaging technique that rotates X-ray beams around the body to create detailed cross-sectional images.	Diagnosis of internal injuries, tumours, brain abnormalities, organ conditions (e.g., liver, lungs).
Fluoroscopy	Real-time X-ray imaging that captures moving structures inside the body.	Used in barium studies for gastrointestinal exams, catheter-based procedures like angioplasty.
Mammography	X-ray imaging of breast tissue for early detection of abnormalities and cancer.	Screening and diagnosis of breast cancer.

Dental X-Rays	X-ray imaging of teeth, gums, and jawbone to detect oral health issues.	Identification of cavities, infections, bone loss, and impacted teeth.
DEXA (Dual-Energy X-ray Absorptiometry)	Measures bone mineral density using two different X-ray energy levels.	Diagnosis and monitoring of osteoporosis and bone health assessment.

### X-Rays in Industrial Applications

Beyond the medical field, X-ray technology is indispensable in various industrial sectors, offering a non-invasive means of inspecting materials, ensuring product quality, and enhancing security measures. One of its most significant uses is in non-destructive testing (NDT), where X-rays help examine the internal structure of objects without causing damage. This capability makes X-rays an essential tool in industries such as aerospace, manufacturing, electronics, and security. X-ray inspection of materials and structures is a critical application in industries that require high safety and quality standards. In aerospace, automotive, and manufacturing sectors, X-ray imaging is used to detect hidden defects, cracks, and inconsistencies in materials. For example, in aircraft manufacturing, X-ray radiography is employed to inspect welds and metal components, ensuring structural integrity and compliance with safety regulations. Similarly, in the automotive industry, X-rays help detect imperfections in engine components, castings, and welded joints, preventing failures that could lead to costly or dangerous malfunctions.

In quality control, X-ray inspection plays a vital role, particularly in the electronics industry. Printed circuit boards (PCBs), essential components of modern electronic devices, require precise manufacturing to function correctly. X-ray imaging allows manufacturers to identify defects such as soldering irregularities, internal fractures, and missing connections, which might not be visible through standard inspection methods. By utilizing X-ray technology, manufacturers can maintain high production standards while minimizing material waste and product recalls. Another crucial industrial use of X-rays is in security screening, where they are used to inspect luggage, cargo, and packages for concealed threats. At airports, X-ray scanners provide security personnel with real-time images of baggage contents, enabling them to detect prohibited items such as weapons, explosives, and contraband. X-ray security systems are also deployed in government buildings, transportation hubs, and border checkpoints to enhance public safety. Additionally, in customs and logistics, X-ray imaging helps inspect shipments for smuggled goods or hazardous materials without the need for manual unpacking, streamlining security protocols and efficiency.

X-ray technology continues to evolve, expanding its role in industrial applications. With advancements in digital imaging and artificial intelligence, X-ray systems are becoming more efficient, providing higher-resolution images and automated defect detection. As industries increasingly rely on precision, safety, and security, X-ray inspection remains a fundamental tool in ensuring product quality, regulatory compliance, and public safety.

## 6.4. GAMMA RAYS: OVERVIEW

Gamma rays are the highest-energy form of electromagnetic radiation, possessing extremely short wavelengths (typically less than 0.01 nanometers) and high frequencies. Unlike visible light or radio waves, gamma rays have the ability to penetrate most materials, making them one of the most powerful and energetic waves in the electromagnetic spectrum. Due to their ionizing nature, gamma rays can interact with matter by knocking electrons out of atoms, leading to potential biological effects such as cell damage or DNA mutations. However, this same property makes gamma rays highly useful in various scientific, medical, and industrial applications. Gamma rays are produced through nuclear reactions, radioactive decay, and high-energy astronomical events. In nuclear decay, unstable atomic nuclei release gamma radiation to achieve a more stable state, often following alpha or beta decay. For example, isotopes like cobalt-60 and cesium-137 emit gamma rays as they undergo radioactive decay. In addition to terrestrial sources, gamma rays are also generated in cosmic events such as supernova explosions, neutron star collisions, and black hole activity. These high-energy emissions from space are studied using specialized telescopes, such as the Fermi Gamma-ray Space Telescope, which helps scientists explore the most energetic phenomena in the universe.

### Properties of Gamma Rays

Gamma rays are high-energy electromagnetic waves that occupy the shortest wavelength and highest frequency range in the electromagnetic spectrum. They exhibit unique characteristics that differentiate them from other forms of



radiation, such as X-rays and ultraviolet rays. Due to their extreme energy levels, gamma rays can penetrate most materials, ionize atoms, and cause significant interactions with matter. These properties make them both highly useful and potentially hazardous.

- **Electromagnetic Radiation with High Energy:** Gamma rays belong to the electromagnetic spectrum but have significantly higher energy than visible light, X-rays, and ultraviolet rays. Their photon energy typically exceeds 100 keV (kiloelectron volts), making them capable of penetrating dense materials.
- **Short Wavelength and High Frequency:** Gamma rays have wavelengths shorter than 0.01 nanometers (nm) and frequencies above  $10^{19}$  Hz. Their short wavelength allows them to pass through materials that would absorb or scatter lower-energy radiation.
- **Ionizing Nature:** Due to their high energy, gamma rays can ionize atoms by knocking electrons out of their orbit. This ionization process can lead to biological effects, such as DNA damage in living organisms, making gamma rays useful in cancer treatment but hazardous in uncontrolled exposure.
- **Produced by Nuclear Reactions:** Unlike X-rays, which are generated by electronic transitions, gamma rays originate from the nucleus of an atom. They are commonly emitted during radioactive decay, nuclear fission, fusion reactions, and particle interactions in space.
- **Penetrating Power:** Gamma rays can travel through most substances, including human tissues, metals, and concrete. However, their penetration ability depends on the density and atomic number of the material. Lead, thick concrete, and water are commonly used as shielding materials to block gamma radiation.
- **Unaffected by Electric and Magnetic Fields:** Gamma rays are uncharged and do not contain mass, which means they are not influenced by electric or magnetic fields. This property distinguishes them from alpha and beta particles, which are charged and can be deflected.
- **Interaction with Matter (Compton Scattering & Pair Production):** Gamma rays interact with matter primarily through Compton scattering, where a gamma photon transfers some of its energy to an electron, and pair production, where a high-energy gamma photon transforms into an electron-positron pair when interacting with a strong electric field near an atomic nucleus.
- **Travel at the Speed of Light:** Like all electromagnetic waves, gamma rays travel at the speed of light (299,792,458 m/s in a vacuum). This allows them to be used for fast and precise applications in medical imaging and astrophysics.
- **Fluorescence and Photographic Effects:** Gamma rays can excite certain materials, causing them to emit fluorescence or be recorded on photographic film. This property is utilized in gamma-ray spectroscopy, imaging techniques, and radiation detection.

**Table: 6.3. Properties of Gamma Rays**

Property	Description
Electromagnetic Nature	Gamma rays are high-energy electromagnetic waves with no mass or charge.
High Energy	Energy levels exceed 100 keV, making them the most energetic waves in the electromagnetic spectrum.
Short Wavelength & High Frequency	Wavelengths are shorter than 0.01 nm, with frequencies above $10^{19}$ Hz.
Ionizing Ability	Gamma rays ionize atoms by removing electrons, which can damage living tissues but is useful in radiation therapy.
Origin from Atomic Nuclei	Emitted from nuclear reactions, radioactive decay, and high-energy cosmic events.
Strong Penetration Power	Can pass through most materials; shielding requires dense substances like lead or thick concrete.
Unaffected by Electric & Magnetic Fields	Neutral radiation, unlike charged particles such as alpha and beta rays.
Interaction with Matter	Interacts through Compton scattering, pair production, and the photoelectric effect.
Speed of Travel	Moves at the speed of light (299,792,458 m/s in a vacuum).

Fluorescence & Photographic Effects	Can excite certain materials to emit fluorescence and be captured on photographic film.
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### Applications of Gamma Rays

Gamma rays have a wide range of applications across various fields, including medicine, industry, and scientific research:

- **Medical Applications:** Gamma rays are extensively used in medicine, particularly in cancer treatment. A technique known as radiotherapy or gamma knife surgery employs precisely targeted gamma radiation to destroy cancerous cells while minimizing damage to surrounding healthy tissue. Additionally, gamma rays are used in sterilization to eliminate bacteria and pathogens from medical equipment, ensuring a contamination-free environment.
- **Industrial Applications:** In industry, gamma rays are used for non-destructive testing (NDT) to inspect the integrity of metal structures, welds, and pipelines. Gamma radiography enables engineers to detect hidden defects and structural weaknesses without dismantling the material. Furthermore, gamma rays are used for food irradiation, a process that eliminates harmful microorganisms from food products, extending shelf life and ensuring food safety.
- **Scientific Research and Space Exploration:** Gamma-ray spectroscopy is used in nuclear physics and astrophysics to study the composition of materials and cosmic phenomena. Gamma-ray bursts (GRBs), the most energetic explosions in the universe, provide valuable insights into the formation and evolution of celestial bodies. Space agencies use gamma-ray detectors on satellites to monitor solar flares, cosmic radiation, and the effects of high-energy particles on Earth's atmosphere.

### Dangers and Safety Precautions

While gamma rays have valuable applications, their high energy and ionizing properties make them potentially hazardous to living organisms. Prolonged or excessive exposure to gamma radiation can lead to radiation sickness, genetic mutations, and an increased risk of cancer. To mitigate these risks, strict safety protocols are followed in environments where gamma radiation is used. Shielding materials like lead, concrete, or dense water barriers are employed to protect workers and researchers from excessive exposure. Personal protective equipment (PPE), radiation detectors, and controlled exposure times are also crucial in minimizing health risks associated with gamma rays.

### Production of Gamma Rays

Gamma rays are produced through various high-energy processes that involve nuclear reactions, radioactive decay, and interactions between particles. Unlike X-rays, which are generated by electron transitions in atoms, gamma rays originate from the nucleus of an atom or high-energy astrophysical phenomena. These rays are among the most energetic forms of electromagnetic radiation and can be created in both natural and artificial environments.

- i. **Radioactive Decay (Gamma Decay):** One of the primary sources of gamma rays is radioactive decay, specifically gamma decay. When an unstable atomic nucleus undergoes decay, it often emits alpha ( $\alpha$ ) or beta ( $\beta$ ) particles to achieve a more stable state. However, after such emissions, the daughter nucleus may still be in an excited energy state. To transition to a lower and more stable energy level, the nucleus releases excess energy in the form of gamma radiation. For example, cobalt-60 ( $\text{Co-60}$ ) is a radioactive isotope commonly used in medical and industrial applications. It undergoes beta decay to form an excited nickel-60 ( $\text{Ni-60}$ ) nucleus, which then emits gamma rays to stabilize itself. Similarly, uranium-238, cesium-137, and radium-226 are other radioactive isotopes that naturally emit gamma radiation as they decay. Gamma decay does not change the atomic number or mass number of the element, as it only involves the release of energy rather than particles. This distinguishes it from alpha and beta decay, which result in the transformation of one element into another.
- ii. **Nuclear Reactions (Fission & Fusion):** Gamma rays are also produced during nuclear fission and nuclear fusion reactions.

- **Nuclear Fission:** In a nuclear fission reaction, a heavy atomic nucleus (such as uranium-235 or plutonium-239) splits into smaller fragments when bombarded with a neutron. This process releases a large amount of energy, including gamma radiation, alongside additional neutrons. Fission-based nuclear power plants and atomic bombs generate gamma rays as a by-product of their reactions.
  - **Nuclear Fusion:** In contrast, nuclear fusion occurs when two light atomic nuclei (such as hydrogen isotopes, deuterium, and tritium) combine to form a heavier nucleus, releasing immense energy. This process powers the Sun and other stars, where gamma rays are continuously generated due to fusion reactions. The Sun's core produces high-energy gamma photons, which then undergo multiple interactions, gradually losing energy before being emitted as visible light and other forms of radiation.
- iii. **Particle-Antiparticle Annihilation:** Gamma rays can also be produced when a particle and its corresponding antiparticle collide and annihilate each other. One of the most well-known examples is electron-positron annihilation. When an electron ( $e^-$ ) meets a positron ( $e^+$ ), the two particles annihilate, converting their mass into pure energy in the form of two gamma photons. These photons typically have an energy of 511 keV (kiloelectron volts) each. This process is fundamental in positron emission tomography (PET) scans, a medical imaging technique that relies on positron annihilation to produce gamma rays for diagnostic purposes.
- iv. **Cosmic and Astrophysical Events:** High-energy cosmic events are another natural source of gamma rays. These phenomena occur in space and are among the most energetic processes known in the universe.
- **Gamma-Ray Bursts (GRBs):** These are the most powerful explosions detected in the universe, emitting massive amounts of gamma radiation. They are believed to result from the collapse of massive stars into black holes or neutron star collisions.
  - **Supernova Explosions:** When a massive star reaches the end of its life cycle, it explodes as a supernova, releasing a burst of gamma radiation along with other forms of energy.
  - **Black Holes and Neutron Stars:** Highly energetic processes occurring near black holes and neutron stars generate intense gamma rays due to extreme gravitational and magnetic fields accelerating particles to near-light speeds.
  - **Solar Flares:** The Sun occasionally emits gamma rays during solar flares, which result from intense magnetic activity on its surface. These flares release high-energy radiation, including X-rays and gamma rays, which can affect space weather and communication systems on Earth.
- v. **Artificial Production of Gamma Rays:** Gamma rays can also be generated artificially through laboratory processes and controlled experiments:
- **Particle Accelerators:** High-energy particle accelerators, such as the Large Hadron Collider (LHC), produce gamma radiation when particles collide at extremely high speeds. These collisions mimic the conditions of the early universe and provide insights into fundamental physics.
  - **Gamma-Ray Sources in Medical and Industrial Applications:** Gamma radiation is intentionally produced using isotopes such as **cobalt-60** and **cesium-137** for medical treatments (radiotherapy) and industrial inspections (non-destructive testing). These sources emit controlled gamma rays for specific applications, such as killing cancer cells or inspecting materials for hidden defects.

## 6.5. SIMILARITIES AND DIFFERENCES BETWEEN X-RAYS AND GAMMA RAYS

X-rays and gamma rays are both high-energy electromagnetic waves that share several fundamental characteristics, but they also have distinct differences in their origins, energy levels, and applications. Understanding their similarities and dissimilarities is crucial in fields like medicine, industry, and nuclear physics.

### Similarities Between X-Rays and Gamma Rays

1. **Electromagnetic Radiation:** Both X-rays and gamma rays belong to the electromagnetic spectrum and travel in the form of electromagnetic waves at the speed of light (299,792,458 m/s in a vacuum). They have no mass or charge, which allows them to propagate freely through space.
2. **High Energy and Short Wavelengths:** Both X-rays and gamma rays have high frequencies (above  $10^{16}$  Hz) and short wavelengths (less than 10 nanometers), making them highly penetrating forms of radiation. Their small wavelength allows them to interact with atomic and subatomic particles.

3. **Ionizing Radiation:** Both X-rays and gamma rays are ionizing radiation, meaning they have enough energy to knock electrons out of atoms, leading to ionization. This property makes them useful in applications such as medical imaging, radiotherapy, and material testing, but it also means they can be hazardous to living tissue in high doses.
4. **Interaction with Matter:** Both types of radiation interact with matter through photoelectric absorption, Compton scattering, and pair production. These interactions determine their effectiveness in applications such as imaging, material analysis, and cancer treatment.
5. **Used in Medical and Industrial Applications:** Both X-rays and gamma rays are widely used in medicine, particularly for diagnostic imaging and cancer treatment (radiotherapy). In industry, they are used for non-destructive testing (NDT), security screening, and sterilization of equipment.

### Differences Between X-Rays and Gamma Rays

1. **Origin:** X-rays originate from electron interactions outside the atomic nucleus. They are produced when high-energy electrons strike a metal target (as in X-ray tubes) or when electrons undergo energy transitions in atoms. Gamma rays, on the other hand, originate from nuclear reactions, radioactive decay, nuclear fission, fusion, and astrophysical events like supernovae.
2. **Energy and Wavelength:** Gamma rays typically have higher energy (above 100 keV) and shorter wavelengths (less than 0.01 nm) compared to X-rays. X-rays usually have lower energy (ranging from a few eV to 100 keV) and slightly longer wavelengths (ranging from 0.01 to 10 nm).
3. **Production Methods:** X-rays are produced artificially in X-ray tubes and particle accelerators by accelerating electrons and striking them against a target material. Gamma rays are naturally emitted from radioactive isotopes, nuclear reactions, and cosmic events, though they can also be artificially generated in nuclear reactors and high-energy physics experiments.
4. **Penetrating Power:** Gamma rays have greater penetration power than X-rays because of their higher energy. They can pass through several centimeters of lead or meters of concrete. X-rays, while still highly penetrating, are generally stopped by thinner layers of lead or denser materials than gamma rays require.
5. **Medical Applications:** X-rays are primarily used for diagnostic imaging (e.g., radiography, CT scans, mammography, and dental X-rays). Gamma rays are mainly used for therapeutic applications (e.g., radiotherapy for cancer treatment) and medical sterilization.
6. **Effect on Living Tissues:** Gamma rays pose a higher biological risk than X-rays due to their stronger ionizing power. They can cause DNA mutations and radiation sickness if exposure is excessive. X-rays also pose risks, but they are generally considered safer when used at controlled low doses in medical imaging.
7. **Shielding Requirements:** Gamma rays require thicker and denser shielding materials, such as several centimeters of lead or thick concrete walls, to block their penetration. X-rays can be blocked with thinner lead sheets or specialized protective barriers used in medical X-ray rooms.

**Table: 6.4. Similarities and Differences Between X-Rays and Gamma Rays**

Feature	X-Rays	Gamma Rays
Type of Radiation	Electromagnetic waves	Electromagnetic waves
Speed	Travel at the speed of light ( <b>299,792,458 m/s</b> )	Travel at the speed of light ( <b>299,792,458 m/s</b> )
Energy Range	Lower energy (a few eV to 100 keV)	Higher energy (above 100 keV)
Wavelength	0.01 nm to 10 nm	Less than 0.01 nm
Frequency	Above $10^{16}$ Hz	Above $10^{19}$ Hz
Origin	Produced by electron interactions outside the nucleus (X-ray tubes, electron transitions)	Emitted from nuclear reactions (radioactive decay, nuclear fission, cosmic events)
Production	Artificially generated using X-ray tubes and particle accelerators	Naturally emitted from radioactive isotopes, nuclear reactions, and cosmic events
Penetrating Power	High but less than gamma rays; stopped by thin lead sheets or protective barriers	Extremely high; requires thick lead or concrete shielding
Interaction with Matter	Absorption, Compton scattering, pair production	Absorption, Compton scattering, pair production

Ionization Ability	Ionizes atoms, but with less energy than gamma rays	Stronger ionization effects, can cause severe biological damage
Medical Applications	Diagnostic imaging (radiography, CT scans, mammography, dental X-rays)	Cancer treatment (radiotherapy), sterilization of medical equipment
Industrial Applications	Non-destructive testing, baggage screening, crystallography	Non-destructive testing, food irradiation, nuclear reactors
Effect on Living Tissue	Can cause DNA damage, but lower risk with controlled doses	Higher risk of radiation sickness, DNA mutations, and cancer
Shielding Requirement	Lead sheets, protective walls	Thick lead, concrete, or water shielding

## 6.6. SOURCES OF RADIATION: A COMPREHENSIVE ANALYSIS

Radiation is energy that travels through space and matter in the form of waves or particles. It is categorized primarily into two broad types: ionizing radiation and non-ionizing radiation. Ionizing radiation is powerful enough to remove electrons from atoms, potentially damaging or altering biological tissues and DNA. Non-ionizing radiation, on the other hand, includes radiation types like visible light, microwaves, and radio waves that do not have sufficient energy to cause ionization. The sources of radiation can be categorized into natural and human-made (artificial) sources. Both types of radiation play crucial roles in modern life, but they can also pose risks to human health and the environment if not properly managed.

### Natural Sources of Radiation

Natural sources of radiation are present all around us and are responsible for the background radiation that humans are constantly exposed to. These sources stem from the environment, including cosmic rays from space, naturally occurring radioactive materials in the Earth's crust, and radiation from naturally occurring gases such as radon.

- I. **Cosmic Radiation:** Cosmic radiation consists of high-energy particles that come from outer space. These particles primarily consist of protons, with a smaller percentage being heavier nuclei like helium and ions. When these high-energy cosmic rays enter the Earth's atmosphere, they collide with atoms, producing secondary radiation, such as gamma rays and neutrons. These cosmic rays come from various sources, including the Sun and distant galaxies. The intensity of cosmic radiation increases with altitude and latitude. For instance, people living at higher altitudes (e.g., mountain regions) and frequent flyers are exposed to higher cosmic radiation levels than people living at sea level. Astronauts in space are also at risk of significant radiation exposure. Scientists are keenly studying cosmic radiation, as it can be dangerous to astronauts on long-term missions, such as future trips to Mars. NASA's Radiation Assessment Detector (RAD) on the Mars Curiosity rover has been monitoring radiation on the planet's surface to ensure safe space exploration.

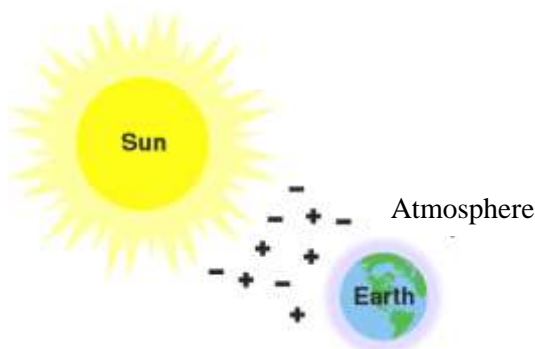


Fig: 6.4. Cosmic Radiation

- II. **Terrestrial Radiation:** Terrestrial radiation refers to the natural background radiation that originates from radioactive materials present in the Earth's crust. These materials include naturally occurring radionuclides such as uranium-238, thorium-232, potassium-40, and their decay products. Radioactive material is found

throughout nature—in the soil, water, and vegetation. Low levels of uranium, thorium, and their decay products are distributed widely across the environment. Some of these radioactive substances enter the human body through ingestion of food and water, while others, like radon gas, are inhaled from the air. As these elements undergo radioactive decay, they emit ionizing radiation, including alpha, beta, and gamma radiation, which contributes to the background radiation exposure experienced by living organisms.

The intensity of terrestrial radiation varies depending on geographical location and the natural composition of the soil and rocks in that area. Regions with higher concentrations of uranium and thorium in the ground tend to have elevated levels of radiation. For example, areas rich in granite or shale often exhibit higher radiation levels due to their content of radioactive elements. Human activities, such as mining or the use of phosphate-based fertilizers, can also increase the concentration of these radionuclides in the environment. The major isotopes of concern in terrestrial radiation include uranium and its decay products—most notably thorium, radium, and radon. Although terrestrial radiation is a constant presence in our environment, it typically poses minimal health risks under normal circumstances. However, monitoring and understanding exposure levels is important, especially in areas with naturally high background radiation or where occupational exposure may occur.

**Naturally Occurring Radioactive Materials (NORM):** NORM refers to materials in the environment that contain radioactive isotopes naturally present in Earth's crust. These materials include coal, phosphate rock, and even certain building materials like granite. Though these materials are relatively low in radioactivity, they still contribute to the overall background radiation levels. People who work in industries that involve mining, coal burning, or the processing of materials like phosphate may have higher exposures to NORM. For instance, workers in the phosphate fertilizer industry are exposed to higher levels of radium and uranium, which are found in phosphate rock.

**III. Endogenous Radiation:** Endogenous radiation refers to the natural ionizing radiation that originates from within the human body, primarily due to the presence of naturally occurring radioactive isotopes incorporated into biological tissues. These radionuclides are part of the body's normal biochemical composition and metabolic processes, and they emit radiation internally throughout a person's lifetime. The primary contributors to endogenous radiation are potassium-40 (K-40) and carbon-14 (C-14). Potassium-40 is a naturally occurring isotope of potassium, which is an essential element required for nerve function, muscle contraction, and cellular activity. Since potassium is distributed throughout the body—especially in muscle tissue—K-40 continuously emits beta particles and gamma rays, contributing significantly to the internal background radiation dose. Carbon-14, on the other hand, is a radioactive isotope of carbon produced in the atmosphere through interactions between cosmic rays and nitrogen. This isotope is absorbed by plants through photosynthesis and enters the human body through the food chain. Once incorporated into proteins, fats, carbohydrates, and nucleic acids, carbon-14 emits low-energy beta radiation and becomes a source of internal exposure. While the radiation dose from C-14 is relatively low, it is persistent and contributes to the overall radiation burden over time.

The average adult human body contains approximately 4,000–5,000 Bq of potassium-40 and around 3,000 Bq of carbon-14, depending on body composition and diet. Together, these isotopes account for a measurable fraction of the annual natural radiation dose, typically around 0.3 mSv from internal sources. Endogenous radiation is considered a normal and unavoidable part of human biology and is not usually associated with health risks under typical environmental and physiological conditions. However, understanding it is important in fields like radiobiology, internal dosimetry, and radiation protection, particularly when assessing additional radiation exposure from medical, occupational, or environmental sources.

**IV. Radiation Source from Vegetation:** Vegetation, like all living organisms, contains trace amounts of naturally occurring radioactive materials absorbed from its surrounding environment. This includes radionuclides present in the soil, water, and air. One of the most significant contributors to radiation from vegetation is potassium-40 (K-40), a naturally occurring isotope of potassium. Potassium is an essential nutrient for plant growth and is found in all living cells, so K-40 is inherently present in all types of plants and plant-based foods. Since potassium-40 undergoes radioactive decay, it emits beta and gamma radiation, contributing to the low levels of radiation exposure experienced through dietary intake. In addition to potassium-40, plants can also absorb trace amounts of other radionuclides from the soil, such as uranium-238, thorium-232, and their decay products including radium-226. The extent to which these radionuclides

are taken up by vegetation depends on various environmental factors, including the concentration of radioactive elements in the soil, the type of plant species, soil chemistry, pH, moisture content, and the presence of organic matter. For instance, plants grown in soils that are naturally rich in uranium or thorium—such as those in granite-rich or volcanic regions—may contain slightly elevated levels of these radioactive substances. Another important radionuclide associated with vegetation is radon-222, a decay product of uranium-238. Although radon itself is a gas and not taken up by plants, it can deposit its solid decay products (such as lead-210 and polonium-210) on plant surfaces through atmospheric deposition. These particles can then be ingested when leafy vegetables are consumed without thorough washing, adding another minor pathway for radiation exposure from vegetation.

Table: 6.5. Radiation in Fruits and Vegetables

Radioactive Isotope	Type of Radiation	Natural/Man-made	How It Enters Plants	Examples of Foods Affected	Approx. Radiation Level	Health Risk
Potassium-40 (K-40)	Beta & Gamma	Natural	Absorbed from soil and water as potassium	Bananas, avocados, potatoes, spinach, beans	~0.1 µSv per banana (banana equivalent dose)	Very low; essential for human body
Radium-226	Alpha & Gamma	Natural	Taken up from soil, especially in certain rock-rich areas	Carrots, beets, radishes, turnips	Extremely low (~0.001–0.01 Bq/kg)	Negligible at dietary levels
Uranium-238	Alpha	Natural	Trace amounts in mineral-rich soils	Leafy greens, root crops (in rare cases)	Trace levels, often < 0.001 Bq/kg	Extremely low; usually filtered out
Cesium-137 (Cs-137)	Beta & Gamma	Man-made (fallout)	Fallout from nuclear accidents, absorbed like potassium	Contaminated zone crops (e.g., near Chernobyl, Fukushima)	Can range from 1–1000+ Bq/kg (in contaminated areas)	Harmful only if exposed long-term in large amounts
Strontium-90 (Sr-90)	Beta	Man-made (fallout)	Mimics calcium, enters through root absorption	Dairy (via feed), leafy greens	Rare outside of fallout areas	Can accumulate in bones, long-term risk if contaminated
Carbon-14 (C-14)	Beta	Natural	Taken up during photosynthesis	All plant-based foods	Very low and stable naturally	No risk at normal levels

Human exposure to radiation from vegetation occurs primarily through the consumption of plant-based foods—such as fruits, vegetables, grains, and even tea or medicinal herbs. Livestock that feed on contaminated plants can also become indirect sources of radiation through meat or dairy products. However, the levels of radiation from these sources are generally very low and are considered part of the normal background radiation that humans have always been exposed to. Despite this constant presence, radiation from vegetation typically poses minimal health risk under normal environmental conditions. Regulatory agencies and environmental monitoring programs often test food and agricultural products to ensure that levels of naturally occurring radionuclides remain well below safety thresholds. However, in specific cases—such as near uranium mines, phosphate-rich agricultural regions, or areas impacted by nuclear accidents—closer monitoring is necessary to assess potential risks from elevated environmental radioactivity entering the food chain.

Table: 6.6. Potassium-40 Content in Food

Food	Becquerel (Bq) per 500 grams
Red meat	56 Bq
Carrot	63 Bq

White potato	63 Bq
Banana	65 Bq
Lima bean	86 Bq
Brazil nut	103 Bq

### Human-Made (Artificial) Sources of Radiation

Human-made sources of radiation have become integral to modern technology and medicine. Radiation plays a key role in diagnostics, treatment, and industrial applications, but improper use or uncontrolled exposure can lead to adverse health effects. Below are some of the most significant human-made sources of radiation.

- I. **Medical Radiation:** Medical radiation is one of the most significant sources of man-made radiation exposure in modern society. It refers to the use of ionizing radiation in various medical procedures for the purposes of diagnosis, treatment, and research. This form of radiation is intentionally applied in controlled doses and environments to benefit human health, particularly in the detection and management of diseases. The most common source of medical radiation is diagnostic imaging, which includes procedures such as X-rays, computed tomography (CT) scans, mammography, and fluoroscopy. Among these, CT scans contribute the highest radiation dose due to the detailed and multiple cross-sectional images they produce. Dental X-rays and chest X-rays contribute much lower doses but are still considered part of cumulative medical exposure. Another major contributor is nuclear medicine, where radioactive isotopes (radiopharmaceuticals) are administered to the patient either orally or through injection. These isotopes emit gamma rays or other forms of ionizing radiation, which are detected using specialized imaging equipment like PET (Positron Emission Tomography) or SPECT (Single Photon Emission Computed Tomography) scanners. Common radiopharmaceuticals include technetium-99m, iodine-131, and fluorine-18. Radiation therapy is another significant application, especially in the treatment of cancer. In this context, high doses of ionizing radiation are used to destroy cancerous cells while minimizing damage to surrounding healthy tissue. Techniques such as external beam radiation, brachytherapy, and stereotactic radiosurgery are common in modern oncology.

While medical radiation offers immense benefits for diagnosis and treatment, it also poses potential risks if not properly managed. Repeated or high-dose exposure can increase the long-term risk of developing cancer or other health complications. To ensure safety, medical professionals adhere to the principles of ALARA (As Low As Reasonably Achievable), which aim to minimize patient and healthcare worker exposure without compromising diagnostic or therapeutic effectiveness.

- II. **Industrial Radiation:** In industrial settings, radiation is commonly produced or harnessed through various controlled sources for specific applications. These sources may be either naturally occurring radioactive materials (NORM) or artificial (man-made) radioactive isotopes, depending on the intended use. Industrial sources of radiation are used under strict safety regulations to ensure controlled exposure and effective outcomes. One of the most common sources is radioisotopes, which are unstable atoms that emit radiation as they decay. Industrial processes frequently utilize isotopes such as Cobalt-60, Cesium-137, and Iridium-192. For instance, Cobalt-60 is widely used in radiation sterilization and food irradiation due to its high-energy gamma radiation, which is effective in destroying bacteria and pathogens. Iridium-192, on the other hand, is often used in non-destructive testing (NDT) for inspecting metal welds, pipelines, and structural components in industries like aerospace, construction, and oil and gas. Another key industrial source is the X-ray tube, a machine-based device that generates X-rays when high-speed electrons collide with a metal target. Unlike radioisotopes, X-ray tubes do not involve radioactive material and can be turned on or off as needed, offering more control. These are commonly used in industrial radiography, cargo scanning, and material analysis.

Additionally, particle accelerators are used in some advanced industrial applications to generate high-energy radiation, especially for treating materials or altering their properties, such as in polymer cross-linking or semiconductor manufacturing. These machines accelerate charged particles, such as electrons or protons, to high speeds and direct them onto a target, producing controlled radiation for specific tasks.



- III. **Consumer Products:** Radiation is not limited to industrial or medical applications—it can also be found in a variety of everyday consumer products, often in very small and safe amounts. These products may contain naturally occurring radioactive materials (NORM) or use radiation for a specific functional purpose. Importantly, the levels of radiation in such products are strictly regulated and pose no significant health risk to consumers when used properly. One of the most well-known examples is the smoke detector. Many smoke detectors contain a small amount of Americium-241, a man-made radioactive isotope that emits alpha particles. It helps detect smoke particles by ionizing the air inside the device, triggering an alarm when smoke interrupts the ion flow. The amount of radiation is extremely low and safely enclosed within the device, making it harmless under normal use.

Some ceramics, glassware, and antique items may also contain trace amounts of radioactive materials. For example, older uranium glass (also called Vaseline glass) glows under ultraviolet light due to uranium content, while certain ceramic glazes made in the past used thorium or uranium compounds for coloration. Though these items may emit low levels of radiation, they are not considered hazardous unless broken or ingested. Luminous watches, dials, and instruments, especially vintage models, may use radioactive materials such as radium-226 or tritium to glow in the dark. Modern versions typically use safer alternatives like phosphorescent paint or tritium gas tubes, which are sealed and pose minimal risk. Other consumer products that may contain small amounts of radiation include fertilizers (due to naturally occurring potassium and phosphate minerals), granite countertops (which may emit small amounts of radon gas), and lantern mantles (especially older ones that used thorium).

While these items do emit radiation, the exposure levels are extremely low and generally fall within safe background radiation levels. Regulatory bodies such as the U.S. Nuclear Regulatory Commission (NRC) and International Atomic Energy Agency (IAEA) enforce strict guidelines to ensure that radiation in consumer products remains at harmless levels.

## 6.7. SITUATIONS OF RADIATION EXPOSURE

Radiation exposure can occur in a variety of contexts, each with distinct characteristics and implications for health and safety. The primary categories of radiation exposure are planned, unplanned, and accidental exposure. Each of these situations carries different levels of risk, regulations, and safety measures.

- **Planned radiation exposure:** It refers to situations where exposure to radiation is intentional, controlled, and typically associated with beneficial purposes. This type of exposure is carefully managed and monitored to ensure that the benefits outweigh any potential risks. Common examples of planned radiation exposure occur in medical, industrial, and research applications. In the medical field, diagnostic imaging procedures such as X-rays, CT scans, and MRI scans involve controlled doses of radiation to assist in diagnosing various health conditions. Radiation therapy, another planned exposure, uses high-energy radiation to treat cancer, targeting malignant cells while minimizing damage to surrounding healthy tissue. Similarly, nuclear medicine, which includes procedures like PET and SPECT scans, uses radioactive isotopes to diagnose and treat diseases, with the exposure carefully calculated based on the patient's specific needs. Planned radiation exposure is also prevalent in industrial and research settings. In the nuclear industry, workers in nuclear power plants, research reactors, and laboratories are exposed to controlled radiation as part of their daily work. Similarly, in industries such as manufacturing, non-destructive testing using radiation (X-rays and gamma rays) is used to inspect materials without damaging them. In scientific research, radiation is used to study a variety of phenomena, from biological processes to material science experiments. In all these contexts, radiation exposure is carefully regulated by national and international bodies, such as the International Commission on Radiological Protection (ICRP), to ensure that workers and the public remain safe. To minimize the risks associated with planned radiation exposure, strict safety protocols are in place. Regular monitoring of radiation doses through dosimeters, proper shielding such as lead aprons or walls, and comprehensive training in radiation safety all play a crucial role in protecting individuals. Additionally, the ALARA (As Low As Reasonably Achievable) principle is followed to minimize exposure to radiation, ensuring that levels stay as low as possible while still achieving the intended benefits.

- **Unplanned radiation exposure:** It refers to situations where individuals are exposed to radiation unexpectedly, often due to equipment malfunction, human error, or other unforeseen circumstances. While this exposure is not part of a deliberate activity, it can still lead to significant health risks depending on the level and duration of exposure. Unplanned radiation exposure can occur in many contexts. For instance, a malfunction in industrial radiography equipment or a failure of radiation-producing machines in nuclear facilities can result in workers being exposed to higher-than-expected levels of radiation. In medical settings, unplanned exposure may occur if there is an error in radiation treatment, such as an overdose during radiation therapy, or if medical imaging equipment malfunctions. Unplanned exposure is also a concern for workers in nuclear facilities and those involved in the transportation and handling of radioactive materials. Accidental releases or mishandling of radioactive substances can lead to unintended radiation exposure, not only to workers but also to the public in some cases. Although unplanned exposure is often unpredictable, there are safety protocols in place to reduce the likelihood of such incidents. Regular equipment maintenance, strict operational checks, and real-time radiation monitoring systems are essential in preventing unplanned exposure. When unplanned radiation exposure does occur, emergency response plans, including decontamination procedures and medical treatment, are immediately enacted to minimize health risks.

The most concerning form of radiation exposure is accidental radiation exposure, which involves unexpected and typically high levels of radiation reaching individuals. These exposures usually occur as a result of significant accidents, such as nuclear plant meltdowns, radiation leaks, or the release of radioactive materials during accidents or attacks. Notable examples include the **Chernobyl disaster** in 1986 and the **Fukushima Daiichi nuclear disaster** in 2011. These nuclear accidents resulted in massive releases of radioactive materials into the environment, exposing large populations to dangerous levels of radiation. The health consequences of such accidents are severe and long-lasting, with increased rates of cancer, particularly thyroid cancer, and other radiation-induced diseases observed in affected populations. Emergency responders and workers involved in dealing with the aftermath of these accidents are also at high risk.

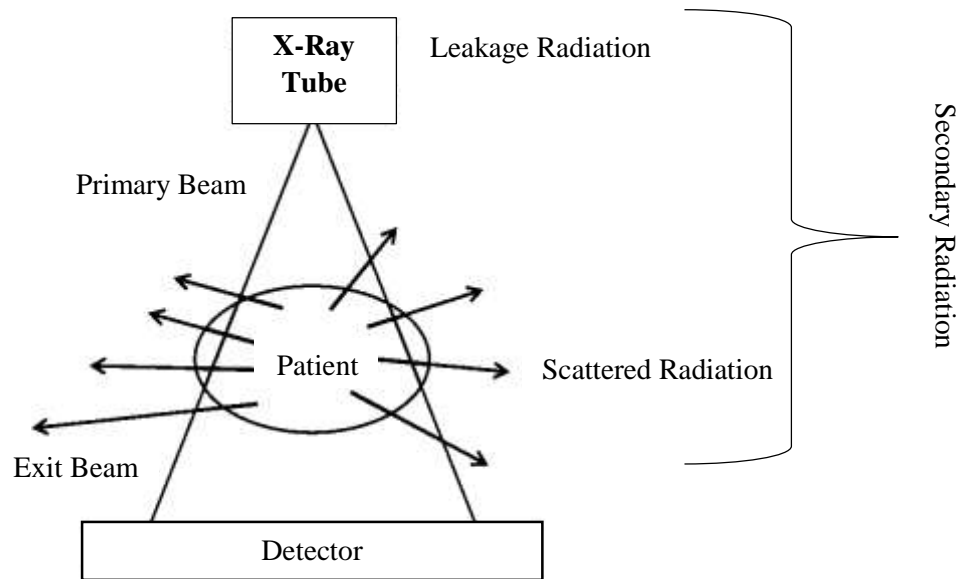
In medical settings, accidental radiation exposure can occur when radiation treatment equipment malfunctions or radioactive materials are mishandled. Such exposures can lead to significant harm, requiring immediate decontamination and medical intervention. Another example of accidental exposure is the leakage of radioactive materials from improperly stored waste sites or during the transport of radioactive substances. If these materials leak into the environment, they can contaminate the air, water, and food supply, affecting surrounding communities. Accidental radiation exposure presents the highest risk, and responding to such events requires coordinated efforts at both the national and international levels. Immediate measures include evacuating affected areas, decontaminating individuals, and providing medical treatment to mitigate the effects of exposure. In the aftermath of major radiation accidents, long-term health monitoring is essential to track the development of radiation-related diseases. This includes monitoring cancer rates and other health conditions that may arise years or even decades after the exposure.

## 6.8. TYPES OF RADIATION AND ITS EXPOSURE IN DIAGNOSTIC RADIOLOGY

Radiation plays a crucial role in diagnostic radiology, enabling healthcare professionals to visualize the internal structures of the human body for medical diagnosis and treatment. The radiation used in medical imaging is classified into primary radiation and secondary radiation, each with specific characteristics and implications for patient care and radiation safety. Additionally, radiation exposure is categorized into personnel exposure, medical exposure, and public exposure, which helps in understanding how radiation affects different groups of individuals. Proper radiation protection measures are essential to minimize unnecessary exposure while ensuring effective diagnostic imaging. Radiation in diagnostic radiology is broadly classified into primary radiation and secondary radiation. Primary radiation is the direct X-ray beam used for imaging, while secondary radiation consists of scattered and leaked radiation that may contribute to unintended exposure.

- **Primary radiation:** It is the initial beam of X-rays produced by an X-ray tube and directed toward the patient's body. This radiation is highly controlled and plays a fundamental role in forming diagnostic images. When the primary X-ray beam passes through the body, different tissues absorb the radiation at varying levels. Dense structures such as bones absorb more X-rays and appear white on the radiograph, while softer tissues absorb less radiation and appear in varying shades of gray. The ability of primary radiation to create detailed images of internal structures makes it indispensable in diagnostic radiology. It is used in various

imaging techniques, including X-rays, computed tomography (CT) scans, fluoroscopy, and mammography. Since primary radiation is essential for medical imaging, safety measures are in place to regulate its use and minimize unnecessary exposure.

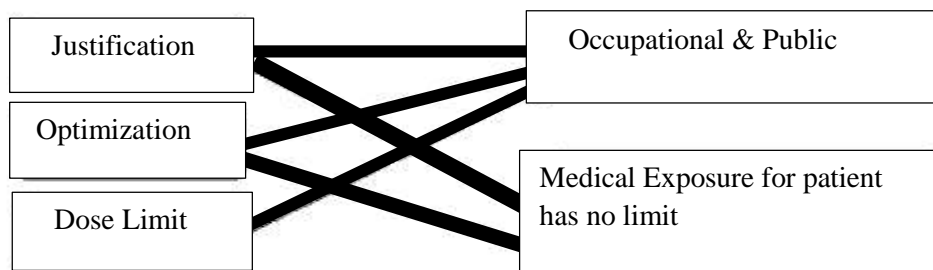


**Fig: 6.5. Types of x-ray in Radiology**

- Secondary radiation:** It refers to radiation that is produced when primary X-rays interact with matter. This type of radiation includes scatter radiation and leakage radiation. Scatter radiation occurs when X-rays are deflected after striking the patient's body or another surface, causing the radiation to spread in multiple directions. This scattered radiation can expose radiologic technologists and other healthcare workers to unintended radiation doses. Leakage radiation, meanwhile, originates from the X-ray machine itself. While modern X-ray equipment is designed to minimize leakage, small amounts of radiation may still escape from the machine's protective housing. Since secondary radiation can contribute to unnecessary radiation exposure, protective measures such as lead aprons, thyroid shields, lead-lined walls, and proper positioning of the X-ray machine are implemented to reduce risks.

### Types of Radiation Exposure in Diagnostic Radiology

Radiation exposure in diagnostic radiology is classified into personnel exposure, medical exposure, and public exposure, each affecting different groups of individuals. Understanding these categories helps ensure that radiation safety protocols are properly followed to protect healthcare workers, patients, and the general public.



- Personnel exposure,** also known as occupational exposure, refers to the radiation exposure received by healthcare professionals who work with X-ray equipment, including radiologists, radiologic technologists, nurses, and other medical staff. Since these individuals are regularly exposed to ionizing radiation, strict radiation protection measures are essential. Personnel exposure primarily occurs due to scatter radiation from the patient during imaging procedures or leakage radiation from the X-ray machine. Those who work in fluoroscopy, interventional radiology, and nuclear medicine are at a higher risk due to prolonged exposure

to radiation-emitting devices. To minimize occupational exposure, healthcare workers must follow protective measures, such as wearing lead aprons, lead gloves, thyroid shields, and radiation dosimeters to monitor their exposure levels. Additionally, radiology rooms are equipped with lead-lined walls, protective barriers, and shielding devices to reduce exposure. The International Commission on Radiological Protection (ICRP) has established an annual dose limit of 20 millisieverts (mSv) for radiation workers, averaged over a five-year period. Within this timeframe, a maximum of 50 mSv may be received in any single year, provided the total dose does not exceed 100 mSv over five years. This means that if a worker receives the full 50 mSv in one year, their exposure over the remaining four years must not exceed 50 mSv, ensuring their overall dose stays within the recommended safe limit.

- **Medical exposure** refers to radiation exposure received by patients undergoing diagnostic or therapeutic radiology procedures. Unlike occupational exposure, medical exposure is intentional and justified, as the benefits of accurate diagnosis and treatment outweigh the potential risks. Various imaging modalities contribute to medical exposure, including X-ray radiography, CT scans, fluoroscopy, mammography, nuclear medicine (PET and SPECT scans), and radiation therapy for cancer treatment. The level of exposure varies depending on factors such as the type of imaging test, the part of the body being examined, and the patient's age and sensitivity to radiation. For example, a chest X-ray typically delivers a low radiation dose (0.1 mSv), while an abdominal CT scan may expose the patient to a higher dose (10 mSv or more). To minimize medical exposure, radiologists follow the ALARA ("As Low As Reasonably Achievable") principle, ensuring that the lowest possible dose is used while still obtaining high-quality diagnostic images. Alternative imaging techniques, such as MRI and ultrasound, which do not use ionizing radiation, are preferred when appropriate to reduce unnecessary exposure.
- **Public exposure** refers to radiation exposure received by individuals who are not directly involved in medical imaging procedures, such as hospital visitors, administrative staff, and the general public. While public exposure is significantly lower than occupational or medical exposure, it must still be managed to ensure radiation safety. The primary sources of public exposure include scatter radiation from radiology rooms, exposure from medical waste containing radioactive materials, and accidental exposure from improperly stored radiopharmaceuticals used in nuclear medicine. To minimize public exposure, healthcare facilities implement strict safety protocols, such as restricting access to radiology departments, ensuring proper disposal of radioactive materials, and designing radiology rooms with adequate shielding. The recommended dose limit for public exposure is 1 mSv per year, significantly lower than the limits for occupational exposure.

End of Chapter

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