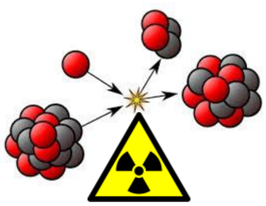
People's Democratic Republic of Algeria

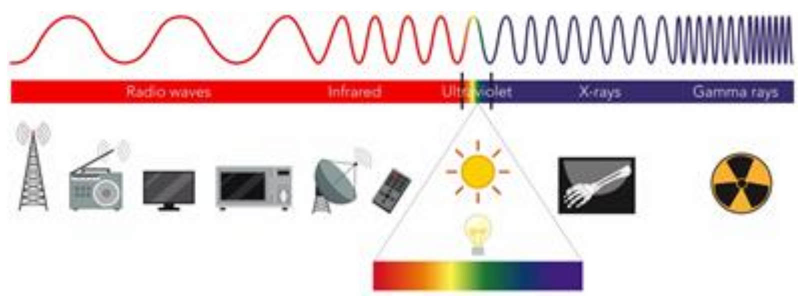
University of Tiaret

Veterinary Sciences Institute

Department of Biomedicine

Biophysics of Radiation





Prepared by: **Dr. BEZZERROUK Mohamed Amine**

mabezzerrouk@univ-tiaret.dz

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Preface

Electromagnetic radiation plays a crucial role in various scientific fields, including veterinary sciences. From diagnostic imaging to radiation therapy, an understanding of the fundamental principles of electromagnetic waves, X-rays, and radioactivity is essential for students pursuing a career in veterinary medicine.

This work is prepared for First-year veterinary students, providing a clear and concise introduction to these important topics. It is divided into three chapters:

- Chapter 1: Electromagnetic Radiation – This chapter introduces the concept of electromagnetic waves, their properties, and their interaction with matter.
- Chapter 2: X-Rays – Focuses on the principles of X-ray production, their medical applications, and safety measures to minimize exposure risks.
- Chapter 3: Radioactivity – Explores the nature of radioactive decay, its biological effects.

The content is presented in a student-friendly manner, with simple explanations, equations, images and real-images examples to facilitate understanding. By the end of this book, students will gain a solid grasp of the fundamental concepts necessary for further studies in veterinary radiology and related disciplines.

Mohamed Amine BEZZERROUK
Veterinary sciences institute
Ibn Khaldoun University of Tiaret

Content

General Introduction

Introduction

Radiation is a fundamental phenomenon that plays a crucial role in nature and various technological applications. It encompasses a broad range of energies, from low-energy radio waves to high-energy gamma rays, and interacts with matter in diverse ways. In the field of biophysics, the study of radiation is essential for understanding its effects on biological systems, as well as its applications in medicine, industry, and scientific research.

This manuscript is structured into three key chapters, each focusing on a specific aspect of radiation and its relevance in biophysics:

Chapter 1: Electromagnetic Radiation

Electromagnetic (EM) radiation consists of waves of electric and magnetic fields that propagate through space. This chapter provides a detailed exploration of the electromagnetic spectrum, ranging from radio waves to gamma rays, and discusses the fundamental properties of electromagnetic waves, such as wavelength, frequency, and energy.

Chapter 2: X-Rays

X-rays are a form of high-energy electromagnetic radiation with significant applications in medical diagnostics and treatment. This chapter explores the physics behind X-ray production, their interaction with tissues, and their use in radiology and radiotherapy.

Chapter 3: Radioactivity

Radioactivity is a natural and artificial process involving the spontaneous decay of unstable atomic nuclei, leading to the emission of ionizing radiation. This chapter provides an in-depth study of radioactive decay, the types of radiation emitted (alpha, beta, and gamma rays), and their biological implications.

Chapter 1: Electromagnetic Radiation

1.1 Definition

Radiation consists of fluxes of particles of different nature and energy. Radiation is classified according to its nature and its effect on biological matter.

We distinguish: 1- According to nature:

- Electromagnetic radiation (E.M.R)
- Particulate radiation (P.R)

2- According to the effect on biological matter:

- Ionizing radiation
- Non-ionizing radiation

1.2 Electromagnetic Radiation and Photon

Electromagnetic radiation is a double vibration of the electric field E and the magnetic field B, which propagates in space. The vibration of these two fields occurs in two perpendicular planes.

Electromagnetic radiation is characterized by its:

- Energy (Joules) or (eV)
- Frequency ν (Hz)
- Wavelength λ (m)
- Period T (s)

All these physical quantities are related by the equations:

$$E=h\,\nu$$

$$\nu = c/\lambda$$

$$T = 1/\nu$$

Where:

c is the speed of light in a vacuum ($c = 3.0 \times 10^8$ m/s).

h is the Planck's constant ($h = 6{,}62.10^{-34}$ j.s)

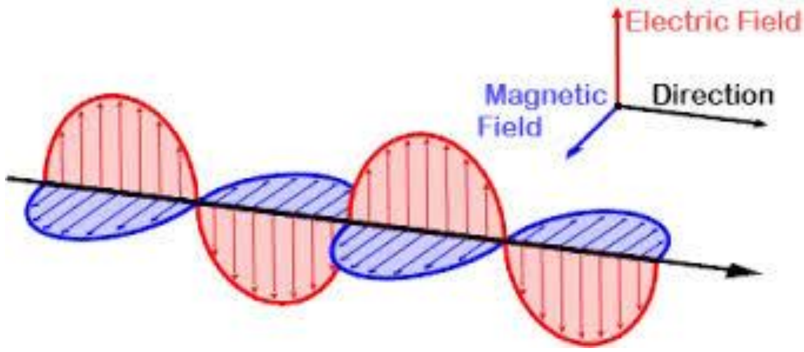


Figure 1.1 Electromagnetic Radiation

1.3 Electromagnetic Radiation

The behavior of electromagnetic radiation can sometimes be described as a wave and sometimes as massless corpuscles called photons. This is the wave-particle duality principle. The wave aspect dominates at low energy (radio waves, TV signals, etc.), while the particle aspect dominates at high energy (Compton effect, pair production, etc.). For intermediate energies, both behaviors coexist (photoelectric effect, interference, etc.).

The energy exchanges carried by electromagnetic radiation, occurring between the Sun and the Earth-ocean-atmosphere system, do not take place continuously but in discrete packets, transported by massless elementary particles called photons.

Each photon carries a quantum of energy proportional to the frequency of the electromagnetic wave.

In 1905, Einstein used Planck's quanta to establish the photon energy equation as a function of wave frequency: $E = h\nu = hc / \lambda$

In these energy domains, the electron volt (eV) is a more appropriate unit:

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$$

There are some practical formulas for quick energy calculations:

$$E(eV) = 1240 / \lambda(nm)$$

$$E(eV) = 12400 / \lambda(Å)$$

1.4 Particulate Radiation

Particulate radiation is characterized by:

- The mass of the particle
- The charge of the particle
- The velocity of the particle

In the classical (non-relativistic) case, meaning for low velocities compared to the speed of light, the kinetic energy of the particle is given by:

$$E_c = 1/2\ m_0 v^2$$

Where m_0 is the rest mass of the particle and v is its velocity.

In the relativistic case, meaning for velocities close to the speed of light, we have:

$$m = m_0 / \sqrt{(1 - v^2/c^2)}$$

$$E = E_c + m_0c^2 = mc^2$$

Where **m** is the relativistic mass and **E** is the total energy of the particle.

Taking the example of an electron, we can calculate its kinetic energy and relativistic mass for different velocities:

Table 1.1: Electron's Kinetic energy, relativistic mass for different velocities

v	**m**	**E_c**
0.416c	$1.01m_0$	0.051 MeV
0.866c	$2m_0$	0.511 MeV

0.942c	$3m_0$	1.022 MeV
0.996c	$11m_0$	5.110 MeV

Particulate radiation can also be described by wave behavior, meaning as a wave. A particle with relativistic mass m and velocity v is associated with a wavelength λ, called the De Broglie wavelength, given by:

$$\lambda = h / mv$$

1.5 Detailed Electromagnetic Classification

The electromagnetic spectrum consists of all types of electromagnetic radiation, arranged by wavelength and frequency. Here's a detailed in this table:

Table 1.2: Electromagnetic radiation's quantities

Type	**Wavelength**	**Frequency**	**Energy**	**Sources & Uses**
Radio Waves	>1 mm (mm to km)	< 300 GHz	< 1 meV	AM/FM radio, TV signals, Wi-Fi, cell phones
Microwaves	1mm – 1cm	300GHz – 30GHz	1 meV – 1 meV	Microwave ovens, radar, satellite communication
Infrared (IR)	700nm – 1mm	430THz – 300GHz	1.24 meV – 1.7 eV	Remote controls, night vision, heat sensing
Visible Light	400nm - 700nm	750THz – 430THz	1.7 eV – 3.1 eV	Human vision, photography, optical communication
Ultraviolet (UV)	10nm – 400nm	30PHz – 750THz	3.1 eV – 124 eV	Sunlight, sterilization, black lights
X-rays	0.01nm – 10nm	30EHz – 30PHz	124 eV – 120 keV	Medical imaging, security scans
Gamma Rays	< 0.01 nm	> 30 EHz	> 120 keV	Nuclear reactions, cancer treatment, cosmic rays

A note on units:

1 angstrom (Å) = 10^{-10} meters

1 nanometer (nm) = 10^{-9} meters

1 micrometer (μm) or micron = 10^{-6} meters

1 millimeter (mm) = 10^{-3} meters

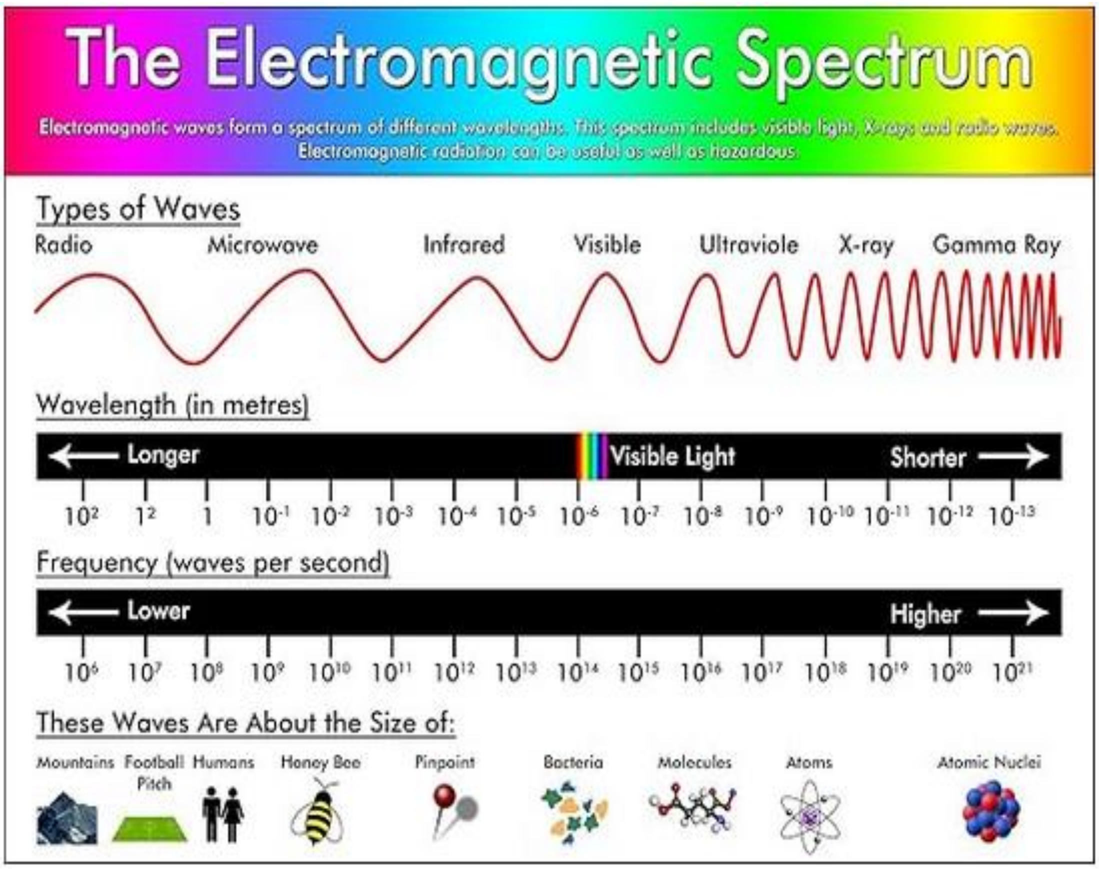


Figure 1.2 Electromagnetic Spectrum

* Key Facts:

- Shorter Wavelength = Higher Frequency = More Energy

- Longer Wavelength = Lower Frequency = Less Energy

* Visible Light Spectrum Colors:

Table 1.3: Color's Wavelength values

Color	λ(nm)	
Violet	400	Highest Energy
Blue	450	
Green	500	
Yellow	570	
Orange	600	
Red	700	Lowest Energy

1.6 Wave-Particle Duality

Light can be considered as a flow of photons or as the propagation of an electromagnetic wave. Light is a special form of energy. It sometimes manifests as a wave (wave aspect) and sometimes as a flow of elementary particles called quanta or photons (particle aspect). This is known as the wave-particle duality principle.

In 1922, Louis de Broglie partially solved the problem of wave and particle duality in electromagnetic waves by associating them with mass. This allowed the application of Einstein's equation:

$$E = mc^2$$

De Broglie established a relation for any material particle in motion, which possesses a wave aspect. This means that a wavelength λ can be associated with it, depending on its momentum:

$$E = h\nu = hc/\lambda = mc^2$$

$$\lambda = h/P \text{ or } \lambda = h/mv$$

1.7 Medical Applications of Electromagnetic Radiation

- Radio Waves: Used in MRI (Magnetic Resonance Imaging) to create detailed images of organs and tissues.
- Microwaves: Used in diathermy to generate deep tissue heating for therapeutic treatment.

- Infrared (IR): Infrared therapy helps in muscle relaxation and improving blood circulation.
- Visible Light: Used in phototherapy for newborn jaundice and seasonal affective disorder (SAD).
- Ultraviolet (UV): UV radiation is used in sterilization of medical equipment and phototherapy for skin conditions like psoriasis.
- X-rays: Used for diagnostic imaging in radiography, detecting fractures, and dental examinations.
- Gamma (γ): Applied in cancer treatment through radiotherapy, sterilization of medical instruments, and imaging techniques like PET scans.

1.8 Gamma Radiation (γ)

Gamma rays were discovered in 1900 by Paul Villard, a French chemist. They have the shortest wavelength (10^{-14} m to 10^{-12} m) and are highly energetic, penetrating matter easily and being dangerous to living cells.

Gamma radiation consists of photons, just like visible light or X-rays. Its energy is given by:

$$E_\gamma = h\nu = hc/\lambda$$

1.9 Mechanism of Gamma Radiation Production

a) Thermal Radiation

Only an extremely hot medium ($T = 10^8$ K) is capable of producing gamma radiation. Such environments are extremely rare, and this process is not fundamental for gamma radiation production.

b) Bremsstrahlung Radiation (Braking Radiation)

An electron passing near a charged particle is subjected to its Coulomb field. The deceleration of the electron is accompanied by an energy loss in the form of gamma radiation, especially when the electron is moving at relativistic speeds.

c) Nuclear De-excitation

Gamma emission generally accompanies radioactive transformations. When a nucleus is in an excited state, it returns to a stable state (spontaneous de-excitation) by emitting a gamma photon whose energy corresponds to the difference between the initial and final energy levels.

The energy levels are quantized, meaning the gamma photon emission spectrum is discontinuous. Gamma disintegration is usually instantaneous and closely follows the emission of alpha or beta particles.

Chapter 2: X-Ray

2.1 Definition

X-rays were discovered in 1895 by Wilhelm Conrad Röntgen and have since become essential in various fields, particularly medicine. X-rays have the ability to penetrate soft tissues while being absorbed by denser materials like bones, making them useful for imaging.

X-rays are electromagnetic radiation (photons), similar to radio waves, visible light, or infrared waves. Their wavelengths range approximately between 0.001 nanometers and 10 nanometers (10^{-12} m to 10^{-8} m), corresponding to frequencies from 3×10^{16} Hz to 3×10^{20} Hz. The energy of these photons varies from a few hundred electron volts (eV) to about one mega-electron volt (MeV). X-rays are ionizing radiation used in medicine (medical imaging, etc.) and industry (crystallography).

The purpose of this document is to explore the production of X-rays, their fundamental principles, and their diverse applications, particularly in medical imaging and treatment.

2.2 History and Discovery

Wilhelm Röntgen discovered X-rays while experimenting with cathode rays in a dark room. He noticed that a fluorescent screen in the room began to glow despite being covered by opaque materials. Further investigation led to the realization that an unknown type of radiation was responsible, which he called "X-rays" to signify their unknown nature.

Shortly after their discovery, X-rays were quickly adopted in medicine. The first medical X-ray image, taken by Röntgen, was of his wife's hand. By the early 1900s, hospitals around the world had begun using X-rays for diagnostic purposes.

2.3 Discovery of Diffraction

Studies of x-rays revealed that they could be polarized, but could not be refracted, leading to controversy over whether x-rays were particles or waves. It was understood that if they were waves, the wavelength must be extremely small (10-10 meters or less). Max von Laue theorized that if x-rays could also be diffracted if the slits were small enough. Since it was understood that molecular spacings in crystalline materials were on the order of a tenth of a nanometer, he devised an experiment in which x-rays were allowed into a lead box

containing a crystal, with sensitive film behind the crystal. When the films were developed there was a large central point from the incident x-rays, but also many smaller points in a regular pattern. These could only be due to the diffraction of the incident beam and the interference of many beams. By using a crystal as a diffraction grating, von Laue had proved the x-rays were not particles, but waves of light with very small wavelengths. He published his results in 1912.

Lawrence Bragg and his father W.H. Bragg used von Laue's discovery and, for monochromatic radiation, were able to show that diffraction could be treated geometrically like reflection, and derived Bragg's law, which allows diffraction to be treated in simple mathematical terms. The Bragg equation provides a simplified framework for diffraction that works for basic calculations:

$$n\lambda = 2d \sin\theta$$

where:

n is an integer

λ is the wavelength of the X-radiation

d is the interplanar spacing in the crystalline material and

θ is the diffraction angle

The wavelengths of X-radiation commonly used for x-ray diffraction lie between 0.7 and 2.3 Å. This is very close to the interplanar spacings of most crystalline materials. The more penetrating radiation used for medical x-rays has a smaller wavelength

2.4 Generation of X-rays

X-rays are short-wavelength, high-energy electromagnetic radiation, having the properties of both waves and particles. They can be described in terms of both photon energy (E) or wavelength, λ (lamda the distance between peaks) and frequency ν (nu the number of peaks passing a point in a unit of time). The relationships between these quantities are expressed in the following equations:

$$\nu = c/\lambda$$

$$E = h\nu$$

Where: E is the energy of the electron flux in KeV

h is Planck's constant (4.135×10^{-15} eV.s)

c is the speed of light (3×10^{18} Å/s)

λ is the wavelength in Å

Substituting the first equation in the second yields:

$$E = hc/\lambda$$

which describes the energy of X-rays in terms of their wavelength. Substituting the values of the constants above in the equation yields the following relationship:

$$E(eV) \simeq 12400/\lambda(Å)$$

Immediately apparent from this equation is that there is an inverse relationship between the energy and wavelength of X-rays.

2.5 Fundamental Principles of X-Ray Production

X-rays are produced when high-energy electrons interact with a target material, usually a metal. There are two main mechanisms through which X-rays are generated:

1- Bremsstrahlung (Braking Radiation):

When high-energy electrons are decelerated upon striking a metal target, they lose kinetic energy, which is emitted as X-ray photons.

2- Characteristic Radiation:

When electrons from the cathode collide with inner-shell electrons of the target material, they create vacancies. These vacancies are filled by electrons from higher energy levels, releasing X-rays with specific wavelengths.

2.6 X-Ray Production

X-rays are produced using specialized equipment such as X-ray tubes and synchrotrons. The most commonly used X-ray source is the X-ray tube, which consists of the following components:

- Cathode: A heated filament that emits electrons when heated.
- Anode: A tungsten or molybdenum target that produces X-rays when struck by high-energy electrons.
- High-Voltage Power Supply: Accelerates electrons from the cathode to the anode.
- Vacuum Chamber: Prevents electron scattering and enhances efficiency.

X-rays are created when electrons are fired at a high-accelerating voltage into a target element or alloy. Most elements, from atomic numbers 20 to 84, are, in principle, capable of generating X-rays. However, for practical reasons, a more limited set of materials is typically used to produce X-rays for today's applications and Tungsten (Wolfram) is one of the most common. X-ray generation is achieved in two ways from the incoming accelerated electrons.

Firstly, they can interact with a bound electron of the target material and cause its ejection from the inner shell of the atom. Outer shell electrons then relax into this vacant energy level and release the energy difference as X-rays. These are known as the characteristic, or shell, X-rays and have specific wavelengths depending on the target material used. Characteristic X-rays were discovered by Charles Glover Barkla in 1909 and he won the Nobel Prize in Physics for his discovery in 1917.

Secondly, accelerated electrons can pass close to the much more massive nuclei of the target material. This interaction causes the electrons to slow and the reduction in energy through this slowing is given out as X-rays. These are known as the bremsstrahlung X-rays, or 'braking radiation' X-rays, from the German. Bremsstrahlung X-rays have a wide range of X-ray wavelengths, up to that created from the maximum accelerating voltage applied, owing to the variability in the braking interaction of the electrons with the nuclei.

❖ The Coolidge tube:

The Coolidge tube allowed for improved X-ray quality and quantity for medical and other applications. The advances within the Coolidge tube meant that it operated at a much better level of vacuum and used a heated tungsten filament as the electron source. The improved vacuum ensured little, if any, remaining residual gas stayed within the vacuum enclosure and thereby prevented any X-ray production from its discharge at the expense of X-ray production at the target. By heating the cathode filament, the tube is able to emit electrons much more efficiently and the hotter the filament gets then the greater the emission of electrons. With more electrons available then more can strike the target and so provide a much brighter (more intense) X-ray source. Additionally, Coolidge tubes were much more stable and reliable compared to what went before. They also gave the user independent control over the achievable X-ray energy and the source intensity through, respectively, the setting of the applied accelerating voltage (kV) and the current (mA) or power (W)) through the filament.

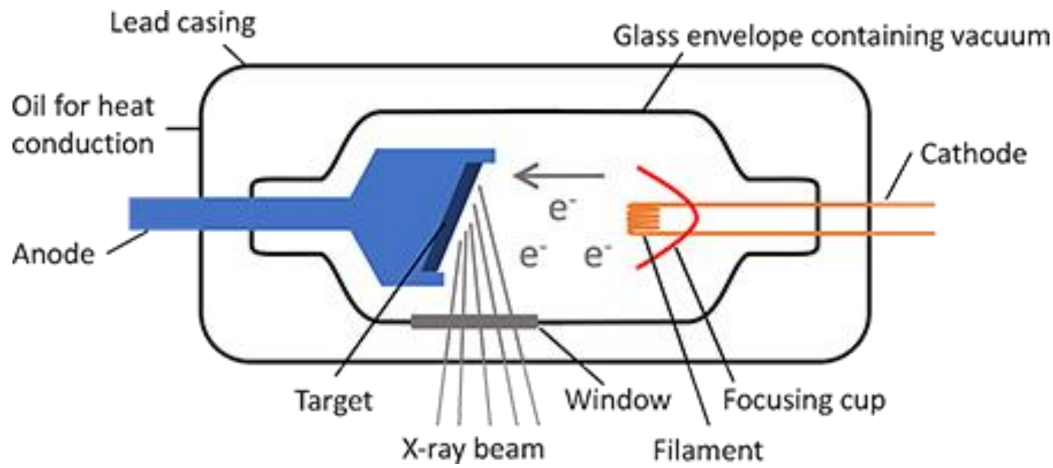


Figure 2.1 Schematic of Coolidge hot cathode X-ray tube

The output from an X-ray tube, therefore, is a combination of the shell and bremsstrahlung X-rays and can be considered as a 'white light' source. Achieving the production of X-rays requires that these physical processes occur within a vacuum enclosure so that the electrons are not absorbed by the air before they strike the target material. The device that achieves this is usually referred to as an X-ray tube.

At left is a schematic of an x-ray tube similar to Cu tubes used in our laboratory. The (é) arrow from the bottom indicates the direction of electrons generated from a tungsten filament (not in the diagram). The filament current is typically set in the range between 25 and 40 ma (milliamps).

The anode is a pure metal. Cu, Mo, Fe and Cr are in common use in XRD applications. In our lab we use a Cu tube. In one of the XRD systems in Chemistry, a Cr tube is used. Mo is in common use in metallurgical laboratories. The table below lists the common anodes in use in XRD and their particular advantages and disadvantages.

Cooling water (usually kept at about 20 °C) is circulated through the x-ray tube (and sprayed on the back side of the anode) to keep operating temperatures low.

A high potential voltage (typically 30 to 40 KV) is maintained on the anode so that the generated electrons are accelerated and interact with it to generate x-rays. Electronics are usually designed so that the anode is maintained at ground and a high negative potential placed on the cathode (filament).

Thin metal windows of a light metal (typically Be) that are effectively transparent to x-rays are used to allow x-rays generated to exit in the direction of the specimen and maintain the vacuum in the tube. X-ray tubes used for XRD typically have four Be windows to enable multiple ports for output. On our Scintag diffractometer (and most modern automated systems), only one window is used.

Common Anode Materials are listed in the table below:

Table 4: Characterisitic Wavelength values (in Å) for Common Anode Materials

Anode	$K\alpha_1$ (100)	$K\alpha_2$ (50)	$K\beta$ (15)
Cu	1.54060	1.54439	1.39222
Cr	2.28970	2.29361	2.08487
Fe	1.93604	1.93998	1.75661
Co	1.78897	1.79285	1.62079
Mo	0.70930	0.71359	0.63229

The descendants of the Coolidge tube are still used today. They are often called sealed, or closed, tubes, indicating that the vacuum is self-contained, and therefore maintained, within an enclosed glass, or other, vessel. In the early days, this was the best method to achieve the high level of vacuum necessary for long term, optimal X-ray production. Although still useful for many applications, including in the medical field, closed tubes have limitations on the quantity, or flux, of X-rays that they can provide at the highest image resolution and the image magnification that they can achieve.

2.7 Efficiency of X-Ray production

The efficiency of X-Ray production depends on various factors, including the voltage applied, the target material used, and the thickness of the target. Tungsten is commonly used as the anode material due to its high atomic number and ability to withstand intense heat. The high voltage applied between the cathode and anode determines the energy of the X-Rays produced, with higher voltages generating higher-energy X-Rays.

In addition to traditional X-Ray tubes, modern methods like laser-driven X-Ray sources and synchrotron radiation have been developed for advanced imaging applications.

2.8 X-Ray Attenuation

Like all radiation, X-Rays can be absorbed by the material they pass through; this is known as attenuation. This property is crucial as it forms the basis of medical imaging using X-Rays.

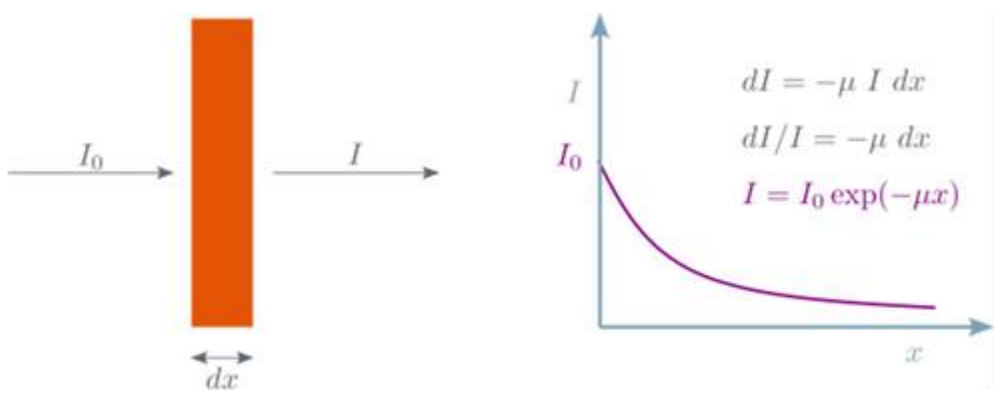


Figure 2.2 X-ray Attenuation

I_0 and **I** represent the intensity of the incident beam and the transmitted beam, respectively.

x is the thickness of the medium traversed.

μ is the linear attenuation coefficient of the medium.

The attenuation coefficient μ depends on the chemical composition of the tissues being traversed. It is high for bone, moderate for soft tissues, and low for fat. Bones contain mineral salts (phosphorus, calcium, magnesium), which are elements with a higher atomic number than the main components of soft tissues (oxygen, carbon, hydrogen, nitrogen, etc.). Their higher density means they absorb more X-rays.

2.9 Applications of X-Rays in Medicine

X-rays are indispensable in modern medicine, playing a crucial role in diagnostics, treatment, and research. Some of the most common applications include:

- Radiography: Radiography is an imaging technique that uses X-rays to visualize an organ or part of the body on a photosensitive film. By extension, the term 'radiography' also refers to the radiographic image itself.

  Its principle is based on recording differences in the density of an organ on a radiographic film. An X-ray beam, produced by an X-ray tube, is directed toward the area of the human body to be examined and passes through the patient's body. Since X-rays penetrate matter, the radiographic film captures the impression and provides an image of our internal anatomy.

  During radiography, X-rays encounter tissues, muscles, or bones. X-rays easily pass through air-filled cavities of the body and soft tissues but are blocked by bones, teeth, etc., which have a higher density. The photographic plate, placed opposite the X-ray source and behind the subject, will therefore be highly exposed in areas corresponding to soft tissues and less exposed in areas corresponding to bones and dense tissues. Depending on the density of the radiographed organ, the image will appear more or less dark. Bone structures appear white, while organs containing significant amounts of air, like the lungs, allow X-rays to pass through and appear black. Between these two extremes, all shades of gray exist.

The X-ray beam, produced by an X-ray tube, is directed toward the area of the human body to be examined. Its intensity is 'modulated' by the differential absorption of the traversed organs. The image is captured at the exit on a detector (such as a photographic plate).

Figure 2.3 Radiology

- Computed Tomography (CT scans): A CT scan is a diagnostic imaging exam that uses X-ray technology to produce images of the inside of the body.

  A CT scan produces detailed cross-sectional images of internal organs and tissues.

  It can show detailed images of any part of the body, including the bones, muscles, organs and blood vessels.

  It can also be used for fluid or tissue biopsies, or as part of preparation for surgery or treatment.

  CT scans are frequently done with and without contrast agent to improve the radiologist's ability to find any abnormalities.

  One of the most significant advancements in X-ray technology has been the development of computed tomography (CT). CT scans provide highly detailed cross-sectional images of the body, allowing for accurate diagnosis of internal injuries, tumors, and other abnormalities. The introduction of digital radiography has further improved the efficiency and precision of X-ray imaging, reducing radiation exposure while enhancing image quality.

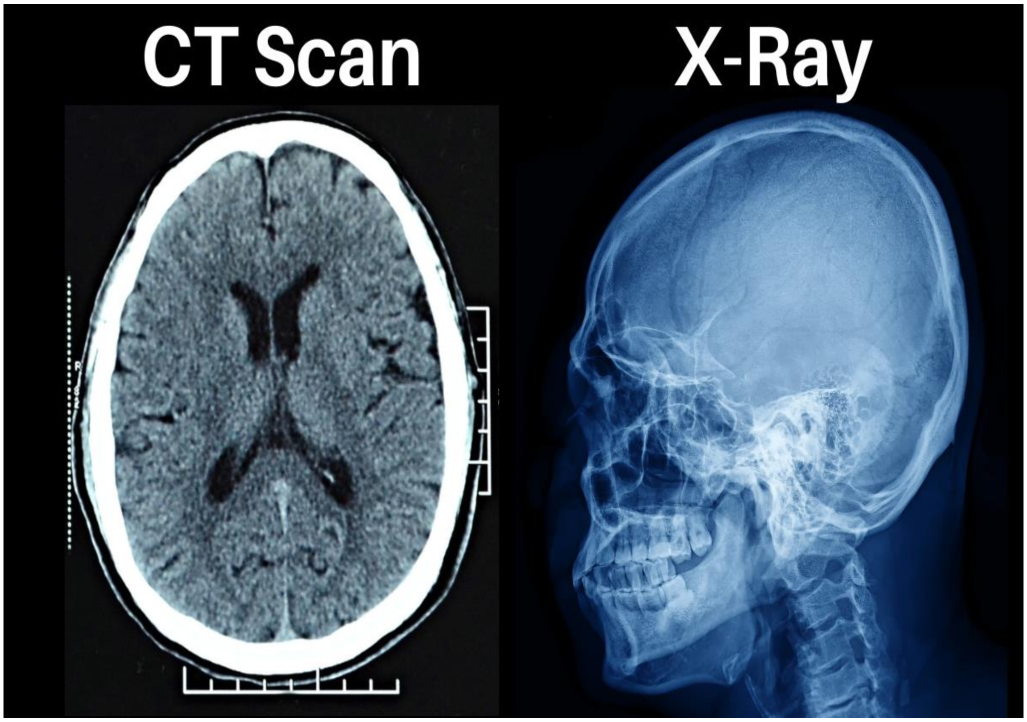


Figure 2.4 Computed Tomography (CT scans)

- Fluoroscopy:

Fluoroscopy is a type of medical imaging that shows a continuous X-ray image on a monitor, much like an X-ray movie. Enables real-time imaging, used in procedures like barium swallows and angiography.

During a fluoroscopy procedure, an X-ray beam is passed through the body. The image is transmitted to a monitor so the movement of a body part or of an instrument or contrast agent ("X-ray dye") through the body can be seen in detail.

Fluoroscopy is used in a wide variety of examinations and procedures to diagnose or treat patients. Some examples are:

1- Barium X-rays and enemas (to view the gastrointestinal tract)

2- Catheter insertion and manipulation (to direct the movement of a catheter through blood vessels, bile ducts or the urinary system)
3- Placement of devices within the body, such as stents (to open narrowed or blocked blood vessels)
4- Angiograms (to visualize blood vessels and organs)
5- Orthopedic surgery (to guide joint replacements and treatment of fractures)

Figure 2.5 Fluoroscopy

- Mammography: Mammography is specialized medical imaging that uses a low-dose x-ray system to see inside the breasts. A mammography exam, called a mammogram, aids in the early detection and diagnosis of breast diseases in women.

An x-ray exam helps doctors diagnose and treat medical conditions. It exposes you to a small dose of ionizing radiation to produce pictures of the inside of the body. X-rays are the oldest and most often used form of medical imaging.

Three recent advances in mammography include digital mammography, computer-aided detection and breast tomosynthesis.

Figure 2.6 Mammography

- Radiotherapy: Radiation therapy or radiotherapy is a cancer treatment that uses high doses of radiation to kill cancer cells and shrink tumors. At low doses, radiation is used in x-rays to see inside your body, as with x-rays of your teeth or broken bones. It uses high-energy X-rays to treat cancer by targeting and destroying malignant cells.

  At high doses, radiation therapy kills cancer cells or slows their growth by damaging their DNA. Cancer cells whose DNA is damaged beyond repair stop dividing or die. When the damaged cells die, they are broken down and removed by the body. Radiation therapy does not kill cancer cells right away. It takes days or weeks of treatment before DNA is damaged enough for cancer cells to die. Then, cancer cells keep dying for weeks or months after radiation therapy ends.

There are two main types of radiation therapy, external beam and internal.

The type of radiation therapy that you may have depends on many factors, including:

1- The type of cancer
2- The size of the tumor
3- The tumor's location in the body
4- How close the tumor is to normal tissues that are sensitive to radiation
5- The general health and medical history
6- Whether there are other types of cancer treatment
7- Other factors, such as the age and other medical conditions

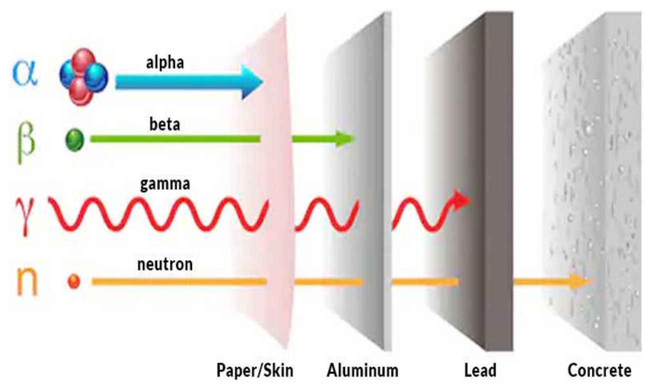
Figure 2.7 Radiotherapy

2.10 Safety and Radiation Protection

Despite their numerous benefits, X-rays pose potential health risks if not used correctly. Prolonged exposure to radiation can lead to cellular damage and increase the risk of cancer. Therefore, strict safety measures are in place to minimize exposure.

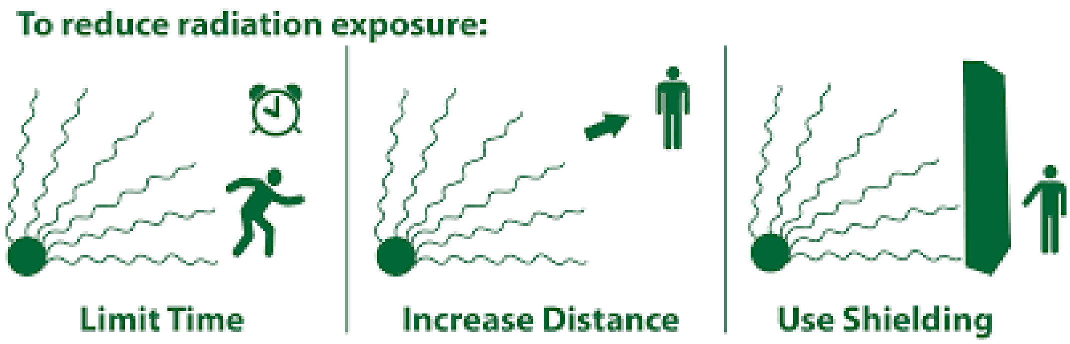
Some key safety measures include:

- Lead shielding: Protective barriers, such as lead aprons, minimize radiation exposure.



- Dosimetry monitoring: Radiation exposure levels are regularly measured for healthcare workers.

- Optimized exposure settings: Modern X-ray equipment is designed to use the lowest radiation dose possible.



➤ Strict regulatory guidelines: Organizations such as the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP) establish safety protocols.

Studies have shown that proper safety measures significantly reduce the risks associated with X-ray exposure. For instance, lead aprons can block up to 95% of radiation, minimizing exposure to vital organs. Additionally, advancements in technology, such as automatic exposure control (AEC) in digital radiography, help optimize radiation doses without compromising image quality.

Chapter 3: Radioactivity

3.1 Definition

Radioactivity is a fundamental natural phenomenon in which unstable atomic nuclei emit radiation to attain stability. Discovered by Henri Becquerel and further studied by Marie and Pierre Curie, radioactivity has revolutionized various fields, particularly medicine. It involves the emission of alpha, beta, and gamma radiation, each with unique properties and applications. In the medical field, controlled radioactive emissions are widely used for diagnostic imaging and therapeutic treatments, such as cancer radiotherapy and nuclear medicine techniques.

3.2 Discovery:

Radioactivity, discovered around 1898 by Marie Curie, is the property of unstable atomic nuclei to spontaneously transform, directly or indirectly, into stable nuclei. These transformations emit radiation, including helium nuclei (alpha particles), electrons or positrons (beta particles), and high-energy photons (gamma rays). Radioactivity can be natural (due to cosmic and terrestrial radiation) or artificial (produced by nuclear reactions). An isotope, whether natural or artificial, has identical radioactive properties.

3.3 Types of Radioactivity: Alpha, Beta, and Gamma Decay

Many nuclei are radioactive; that is, they decompose by emitting particles and in doing so, become a different nucleus. In our studies up to this point, atoms of one element were unable to change into different elements. That is because in all other types of changes discussed, only the electrons were changing. In these changes, the nucleus, which contains the protons that dictate which element an atom is, is changing. All nuclei with 84 or more protons are radioactive, and elements with less than 84 protons have both stable and unstable isotopes. All of these elements can go through nuclear changes and turn into different elements.

In natural radioactive decay, three common emissions occur. When these emissions were originally observed, scientists were unable to identify them as some already known particles and so named them:

Alpha particles (α), Beta particles (β), Gamma rays

These particles were named using the first three letters of the Greek alphabet. Some later time,

- Alpha particles were identified as Helium-4 nuclei,
- Beta particles were identified as electrons.
- Gamma rays as a form of electromagnetic radiation like x-rays, except much higher in energy and even more dangerous to living systems.

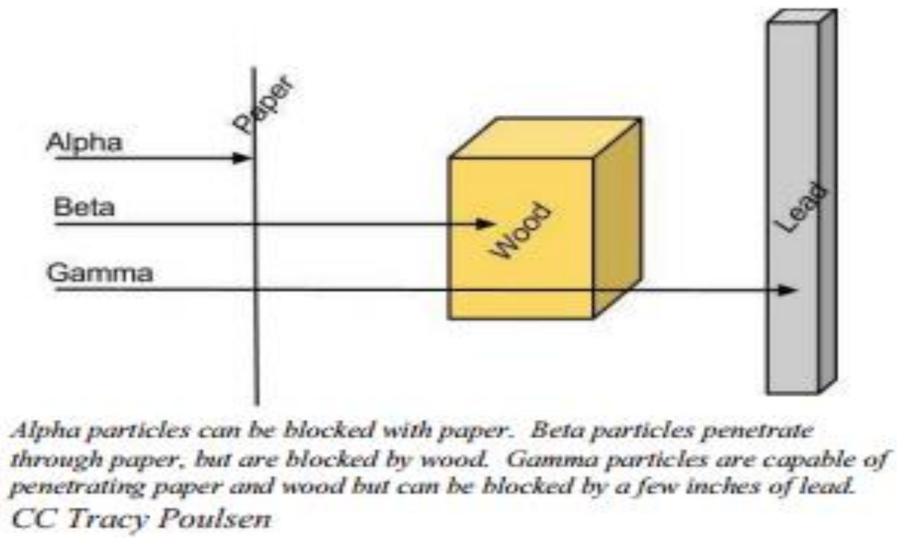


Figure 3.1 Alpha, Beta and Gamma Particles penetration's through different materials

3.4 The Ionizing and Penetration Power of Radiation

With all the radiation from natural and man-made sources, we should quite reasonably be concerned about how all the radiation might affect our health. The damage to living systems is done by radioactive emissions when the particles or rays strike tissue, cells, or molecules and alter them. These interactions can alter molecular structure and function; cells no longer carry out their proper function and molecules, such as DNA, no longer carry the appropriate information. Large amounts of radiation are very dangerous, even deadly. In most cases, radiation will damage a single (or very small number) of cells by breaking the cell wall or otherwise preventing a cell from reproducing.

The ability of radiation to damage molecules is analyzed in terms of what is called ionizing power. When a radiation particle interacts with atoms, the interaction can cause the atom to lose electrons and thus become ionized. The greater the likelihood that damage will occur by an interaction is the ionizing power of the radiation.

Comparing only the three common types of ionizing radiation, alpha particles have the greatest mass. Alpha particles have approximately four times the mass of a proton or neutron and approximately 8,000 times the mass of a beta particle. Because of the large mass of the alpha particle, it has the highest ionizing power and the greatest ability to damage tissue. That same large size of alpha particles, however, makes them less able to penetrate matter. They collide with molecules very quickly when striking matter, add two electrons, and become a harmless helium atom. Alpha particles have the least penetration power and can be stopped by a thick sheet of paper or even a layer of clothes. They are also stopped by the outer layer of dead skin on people. This may seem to remove the threat from alpha particles, but it is only from external sources. In a nuclear explosion or some sort of nuclear accident, where radioactive emitters are spread around in the environment, the emitters can be inhaled or taken in with food or water and once the alpha emitter is inside you, you have no protection at all. Beta particles are much smaller than alpha particles and therefore, have much less ionizing power (less ability to damage tissue), but their small size gives them much greater penetration power. Most resources say that beta particles can be stopped by a one-quarter inch thick sheet of aluminum. Once again, however, the greatest danger occurs when the beta emitting source gets inside of you. Gamma rays are not particles, but a high energy form of electromagnetic radiation (like x-rays, except more powerful). Gamma rays are energy that has no mass or charge. Gamma rays have tremendous penetration power and require several inches of dense material (like lead) to shield them. Gamma rays may pass all the way through a human body without striking anything. They are considered to have the least ionizing power and the greatest penetration power.

3.5 Major Forms of Radioactivity

a) Alpha Particle (α):

Rutherford's experiments demonstrated that there are three main forms of radioactive emissions. The first is called an alpha particle, which is symbolized by the Greek letter α. An alpha particle is composed of two protons and two neutrons and is the same as a helium nucleus. (We often use 24He to represent an alpha particle.) It has a 2+ charge. When a radioactive atom emits an alpha particle, the original atom's atomic number decreases by two (because of the loss of two protons), and its mass number decreases by four (because of the loss of four nuclear particles). We can represent the emission of an alpha particle with a chemical equation—for example, the alpha-particle emission of uranium-235 is as follows:

$$^{235}_{92}U \rightarrow {}^{4}_{2}He + {}^{231}_{90}Th$$

Where $^{4}_{2}He$ is α particle.

Rather than calling this equation a chemical equation, we call it a nuclear equation to emphasize that the change occurs in an atomic nucleus. How do we know that a product of this reaction is 90231Th? We use the law of conservation of matter, which says that matter cannot be created or destroyed. This means we must have the same number of protons and neutrons on both sides of the nuclear equation. If our uranium nucleus loses 2 protons, there are 90 protons remaining, identifying the element as thorium. Moreover, if we lose four nuclear particles of the original 235, there are 231 remaining. Thus we use subtraction to identify the isotope of the Th atom in this case, $^{231}_{90}Th$.

b) Beta Particle (β)

The second type of radioactive emission is called a beta particle, which is symbolized by the Greek letter β. A beta particle is an electron ejected from the nucleus (not from the shells of electrons about the nucleus) and has a (-1) charge. We can also represent a beta particle as (-e). The net effect of beta particle emission on a nucleus is that a neutron is converted to a proton. The overall mass number stays the same, but because the number of protons increases by one, the atomic number goes up by one. Carbon-14 decays by emitting a beta particle:

$$^{14}_{6}C \rightarrow\ ^{14}_{7}N +\ _{-1}^{0}e$$

Where $_{-1}^{0}e$ is β particle.

Again, the sum of the atomic numbers is the same on both sides of the equation, as is the sum of the mass numbers. (Note that the electron is assigned an "atomic number" of −1, equal to its charge.)

c) Gamma Radiation (γ)

The third major type of radioactive emission is not a particle but rather a very energetic form of electromagnetic radiation called gamma rays, symbolized by the Greek letter γ. Electromagnetic radiation can be characterized into different categories based on the wavelength and photon energies. The electromagnetic spectrum shown in figure 3.2 shows the major categories of electromagnetic radiation. Note that the human sensory adaptations of sight and hearing have evolved to detect electromagnetic radiation, with radio waves having wavelengths between 1 mm and 100 km and visible light having wavelengths between 380 – 700 nm. Technological advances have helped humankind utilize other forms of electromagnetic radiation including X-rays and microwaves.

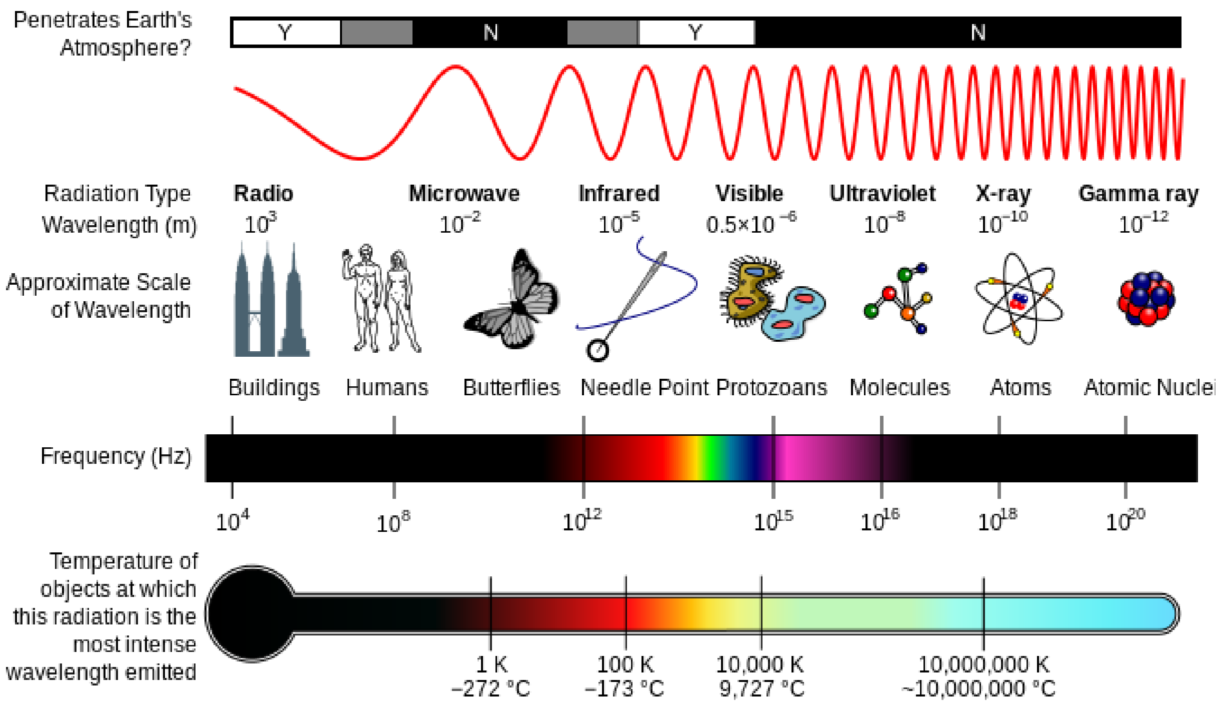


Figure 3.2 Gamma radiation in the electromagnetic spectrum

Some electromagnetic radiation with very short wavelengths are active enough that they may knock out electrons out of atoms in a sample of matter and make it electrically charged. The types of radiation that can do this are termed ionizing radiation. X-rays and Gamma rays are examples of ionizing radiation. Some radioactive materials, emit gamma radiation during their decay. For example, in the decay of radioactive technetium-99, a gamma ray is emitted. Note that in radioactive decay where the emission of gamma radiation occurs, that the identity of the parent material does not change, as no particles are physically emitted.

$$^{99m}_{43}Tc \rightarrow \, ^{99}_{43}Tc + \, ^{0}_{0}\gamma$$

Where $^{0}_{0}\gamma$ is a ray.

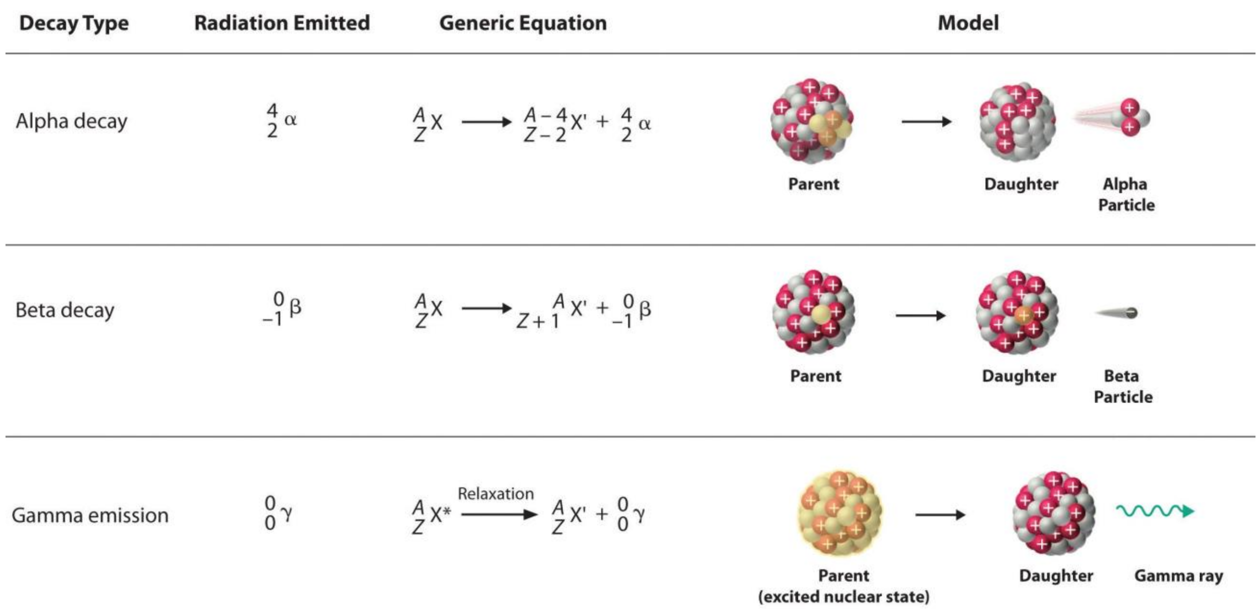


Figure 3.3 Representation of Alpha, Beta and Gamma emmision

3.6 Radioactive Decay

The main sources of particulate radiation (Electrons, Protons, Alpha particles, etc.) and Gamma radiation (R γ) are the decay of radioactive elements. The decay of unstable nuclei follows the law:

$$dN = -\lambda N\,dt \Rightarrow dN/N = -\lambda\,dt + C$$

where **N** is the number of undecayed nuclei at time t, $\mathbf{N_0}$ is the initial number of nuclei, and **λ** (in s^{-1}) is the probability of decay per unit time, also called the decay constant.

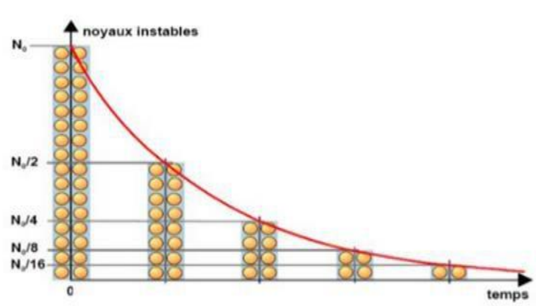


Figure 3.4 Radioactive Decay

To calculate the integration constant C, we return to the initial conditions:

$A\ t = 0,\ N = N_0 \Rightarrow C = \text{Log}\ N_0 \Rightarrow \text{Log}\ N = -\lambda\ t + \text{Log}\ N_0 \Rightarrow$

$$\text{Log}\ N/N_0 = -\lambda\ t$$

$$\Rightarrow N = N_0\ e^{-\lambda\ t}$$

3.7 Radioactive Half-Life

The radioactive half-life ($T_1/_2$) is the time required for half of the initial atoms to decay, meaning the activity is reduced by half. It is defined by:

$$\lambda = \log 2\ /\ T\ (\lambda \text{ in } s^{-1})$$

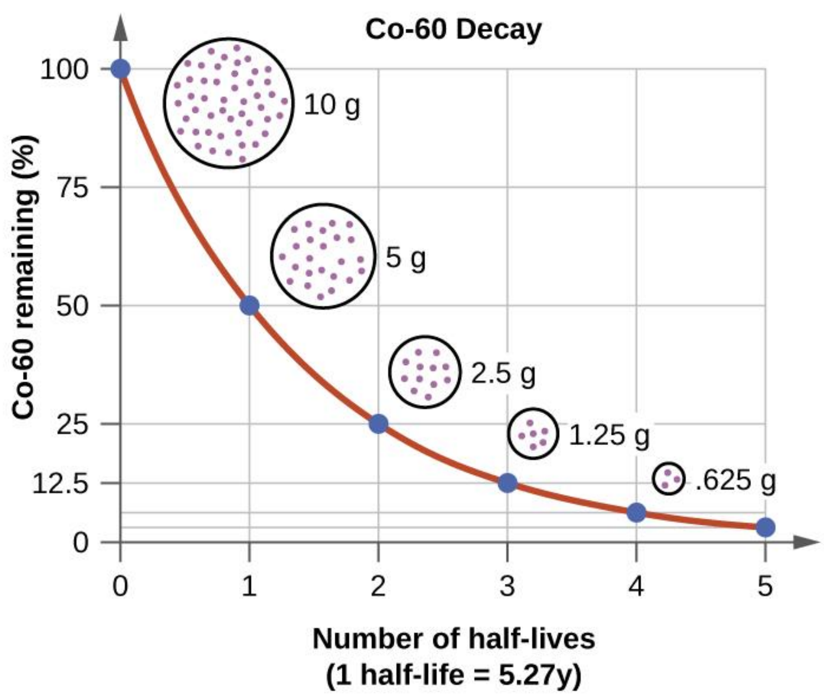


Figure 3.5 The Decay of Cobalt 60

3.8 Activity and the Becquerel Unit

A radioactive substance is characterized by its "activity," which represents the number of decays occurring per second. This activity is given by:

$$A = dN/dt,\ R = dN/dt = \lambda N = \lambda N_0 e^{-\lambda t}$$

The becquerel (**Bq**) is the SI unit of activity, defined as one decay per second. Previously, activity was measured in curies (**Ci**),

Where: $1\ Ci = 3.7 \times 10^{10}\ Bq.$

3.9 Biological Effects of Radiation

Radiation exposure has several biological effects on living tissues, including physical effects, DNA damage, and cellular impact. The severity of these effects depends on the type of radiation and the dose absorbed. High-dose exposure causes immediate cellular death, while lower doses can induce long-term genetic mutations.

3.10 Target Theory

The target theory suggests that cell damage is concentrated on critical molecules such as DNA. If radiation hits the DNA molecule, cell survival is compromised. The number of surviving cells follows an exponential decay:

$$N = N_0 e^{-D/D_0}$$

Where $\mathbf{D_0}$ is the dose required to leave 37% of cells surviving.

3.11 Medical Applications of Nuclear Physics

Applications of nuclear physics have become an integral part of modern life. From the bone scan that detects one cancer to the radioiodine treatment that cures another, nuclear radiation has diagnostic and therapeutic effects on medicine.

Single-photon-emission computer tomography (SPECT) used in conjunction with a CT scanner improves on the process carried out by the gamma camera. Figure 3.6 shows a patient in a circular array of SPECT detectors that may be stationary or rotated, with detector output used by a computer to construct a detailed image. The spatial resolution of this technique is poor, but the three-dimensional image created results in a marked improvement in contrast.

Figure 3.6 SPECT uses a rotating camera to form an image of the concentration of a radiopharmaceutical compound.

Positron emission tomography (or PET) scans utilize images produced by β^+ emitters. When the emitted positron β^+ encounters an electron, mutual annihilation occurs, producing two γ rays. Those γ rays have identical 0.511 MeV energies (the energy comes from the destruction of an electron or positron mass) and they move directly away from each other, allowing detectors to determine their point of origin accurately (as shown in Figure 3.7). It requires detectors on opposite sides to simultaneously (i.e., at the same time) detect photons of 0.511 MeV energy and utilizes computer imaging techniques similar to those in SPECT and CT scans. PET is used extensively for diagnosing brain disorders. It can note decreased metabolism in certain regions that accompany Alzheimer's disease. PET can also locate regions in the brain that become active when a person carries out specific activities, such as speaking, closing his or her eyes, and so on.

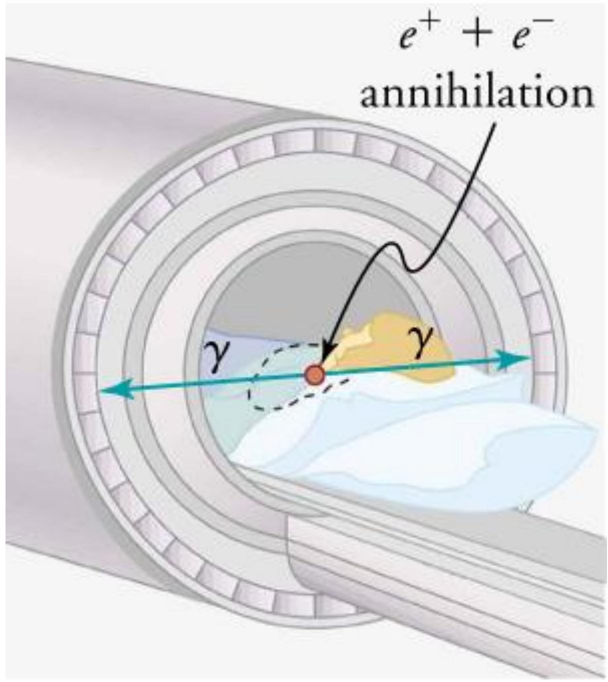


Figure 3.7 A PET system takes advantage of the two identical γ -ray photons produced by positron-electron annihilation.

3.12 Ionizing Radiation on the Body

We hear many seemingly contradictory things about the biological effects of ionizing radiation. It can cause cancer, burns, and hair loss, and yet it is used to treat and even cure cancer. How do we understand such effects? Once again, there is an underlying simplicity in nature, even in complicated biological organisms. All the effects of ionizing radiation on biological tissue can be understood by knowing that ionizing radiation affects molecules within cells, particularly DNA molecules. Let us take a brief look at molecules within cells and how cells operate. Cells have long, double-helical DNA molecules containing chemical patterns called genetic codes that govern the function and processes undertaken by the cells. Damage to DNA consists of breaks in chemical bonds or other changes in the structural features of the DNA chain, leading to changes in the genetic code. In human cells, we can have as many as a million individual instances of damage to DNA per cell per day. The repair ability of DNA is vital for maintaining the integrity of the genetic code and for the normal functioning of the entire organism. A cell with a damaged ability to repair DNA, which could have been induced by ionizing radiation, can do one of the following:

- ✓ The cell can go into an irreversible state of dormancy, known as senescence.
- ✓ The cell can commit suicide, known as programmed cell death.
- ✓ The cell can go into unregulated cell division, leading to tumors and cancers.

Since ionizing radiation damages the DNA, ionizing radiation has its greatest effect on cells that rapidly reproduce, including most types of cancer. Thus, cancer cells are more sensitive to radiation than normal cells and can be killed by it easily. Cancer is characterized by a malfunction of cell reproduction, and can also be caused by ionizing radiation. There is no contradiction to say that ionizing radiation can be both a cure and a cause.

3.13 Radiation Dosage

To quantitatively discuss the biological effects of ionizing radiation, we need a radiation dose unit that is directly related to those effects. To do define such a unit, it is important to consider both the biological organism and the radiation itself. Knowing that the amount of ionization is proportional to the amount of deposited energy, we define a radiation dose unit called the rad. It 1/100 of a joule of ionizing energy deposited per kilogram of tissue, which is

$$1\text{rad} = 0.01\text{J/kg}.$$

Example:

If a 50.0-kg person is exposed to ionizing radiation over her entire body and she absorbs 1.00 J, then her whole-body radiation dose is

$$(1.00\text{J})/(50.0\text{kg}) = 0.0200\text{J/kg} = 2.00\text{rad}.$$

If the same 1.00 J of ionizing energy were absorbed in her 2.00-kg forearm alone, then the dose to the forearm would be

$$(1.00\text{J})/(2.00\text{kg}) = 0.500\text{J/kg} = 50.0\text{rad},$$

and the unaffected tissue would have a zero rad dose. When calculating radiation doses, you divide the energy absorbed by the mass of affected tissue. You must specify the affected region, such as the whole body or forearm in addition to giving the numerical dose in rads. Although the energy per kilogram in 1 rad is small, it can still have significant effects. Since only a few eV cause ionization, just 0.01 J of ionizing energy can create a huge number of ion pairs and have an effect at the cellular level.

The effects of ionizing radiation may be directly proportional to the dose in rads, but they also depend on the type of radiation and the type of tissue. That is, for a given dose in rads, the effects depend on whether the radiation is α, β, γ, X-ray, or some other type of ionizing radiation. The relative biological effectiveness (RBE) relates to the amount of biological damage that can occur from a given type of radiation and is given in Table 3.1 for several types of ionizing radiation.

Table 3.1: Relative Biological Effectiveness

Type and Energy of Radiation	RBE
X-Ray	1
Gamma Ray	1
Beta Ray greater than 32 KeV	1
Beta Ray less than 32 KeV	1.7
Neutrons, thermal to slow (<20KeV)	2-5
Neutrons, fast (1-10 MeV)	10 (body), 32 (eyes)
Protons (1-10 MeV)	10 (body), 32 (eyes)
Alpha Rays from radioactive decay	10-20
Heavy ions from accelerators	10-20

The discovery and application of radioactivity have significantly contributed to modern medicine, particularly in diagnostics and treatment. Techniques such as radiotherapy, PET scans, and radioactive tracers have enhanced our ability to detect and treat diseases effectively. However, careful handling and regulation of radioactive substances are essential to ensure safety and minimize exposure risks.

General Conclusion

Conclusion

The study of biophysics of radiation is crucial in understanding the fundamental principles governing electromagnetic radiation, X-rays, and radioactivity, as well as their interaction with biological systems. Radiation is an integral part of both natural and artificial processes, with applications spanning medicine, industry, scientific research, and environmental studies. However, despite its numerous benefits, radiation exposure also poses risks, necessitating a careful balance between utilization and protection.

Throughout this paper, we have explored the properties and significance of radiation in three key areas:

Electromagnetic Radiation, which encompasses a broad spectrum of waves, from radio waves to gamma rays. We have seen how these waves interact with matter and biological tissues, leading to applications in imaging technologies such as MRI and infrared thermography, as well as potential risks, particularly from UV radiation and ionizing forms of EM radiation.

X-Rays, which revolutionized medical diagnostics and treatment, allowing non-invasive visualization of internal structures. However, due to their ionizing nature, X-rays can damage biological tissues, making radiation protection strategies essential for both patients and healthcare workers. Advances in X-ray technology continue to improve image quality while minimizing exposure, ensuring safer and more effective diagnostic techniques.

Radioactivity, a natural and artificial phenomenon with vast implications in medicine, energy production, and environmental science. While radioactive isotopes are indispensable in nuclear medicine (e.g., PET scans, radiotherapy), uncontrolled exposure to ionizing radiation can lead to cellular damage, mutations, and radiation-related diseases. Understanding the principles of radioactive decay, half-life, and radiation shielding is vital for ensuring safe applications.

Radiation-based technologies have played a transformative role in modern healthcare. Medical imaging techniques such as X-rays, CT scans, and nuclear medicine imaging allow for early disease detection, improving diagnosis and treatment planning. Radiotherapy has been a major breakthrough in cancer treatment, using controlled doses of ionizing radiation to target and destroy malignant cells while sparing healthy tissues.

Beyond medicine, radiation finds applications in sterilization, industrial testing (non-destructive testing - NDT), environmental monitoring, and space exploration. In research, radiation-based techniques such as spectroscopy and radiocarbon dating provide valuable insights into materials and historical artifacts.

Despite its benefits, exposure to high levels of radiation can be hazardous. Ionizing radiation has the potential to cause cellular mutations, increasing the risk of cancers and genetic damage. For this reason, radiation safety guidelines have been established to protect workers, patients, and the environment

The field of radiation biophysics continues to evolve with technological advancements aimed at enhancing imaging precision, improving radiation therapy techniques, and developing safer ways to harness radioactive materials. Emerging areas of research include:

Artificial Intelligence (AI) in medical imaging, improving diagnostics with automated image analysis.

Targeted radiotherapy (e.g., proton therapy and heavy ion therapy), which minimizes damage to healthy tissues.

Radioprotection innovations, including new materials and pharmaceuticals that protect against radiation damage.

Radiation is a double-edged sword while it provides invaluable benefits in medicine, science, and industry, it also requires careful management to avoid its harmful effects. By understanding the biophysical principles of radiation, we can optimize its applications, harnessing its potential for the benefit of humanity while ensuring safety and sustainability.

This manuscript serves as a foundational guide for students, researchers, and professionals interested in the biophysics of radiation. By integrating scientific knowledge, technological advancements, and safety measures, we can continue to explore and expand the positive impact of radiation in the modern world.

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