BIOPHYSICS

Electromagnetic and Particulate Radiation

Course Notes – Academic Year 2025–2026

Prepared for: ***1st-Year Veterinary Medicine Students***

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A concise overview of electromagnetic and particulate radiation and their importance in veterinary medicine, particularly in diagnostic imaging, radiation safety, and clinical applications.

1. General Introduction

Biophysics is a compelling field that bridges physics and biology to unravel the mechanisms of biological systems, ranging from individual molecules to entire organisms. This course provides a comprehensive introduction to the fundamental principles of biophysics, exploring the methodologies and techniques utilized in the study of living systems.

By the end of this curriculum, you will have gained a thorough understanding of how biophysical principles explain both **electromagnetic and particulate radiation**, as well as the interactions between radiation and matter. You will also be introduced to **dosimetry**, various **radiological modalities**, the principles of **acoustics and ultrasound**, and the fundamentals of **sonography**. Furthermore, the course covers an introduction to **fluid dynamics** and **geometric optics**. You will discover how these biophysical tools are applied across diverse fields, including human and veterinary medicine, biotechnology, and pharmacology.

This course is designed to foster a deep understanding of biophysics and its critical role in deciphering biological systems. You will have the opportunity to explore current research frontiers and see how biophysics addresses global health challenges and environmental issues. I trust you will find this journey both intellectually stimulating and professionally rewarding.

1.1.Defining Biophysics

Biophysics is a scientific discipline that investigates biological phenomena through the lens of physical principles and quantitative methods.

This field of study involves analyzing the effects of **vibrations, radiation, electricity, and acoustics** on living beings. It also encompasses the evaluation of diagnostic and therapeutic techniques based on physical methods, alongside the study of internal physiological processes—such as fluid exchange and dynamics, membrane transport, hemodynamics (blood flow), and respiratory mechanics.

1.2.Review of Fundamental Constants and Physical Laws in Biology

The tables provided below outline the measurement systems and fundamental constants commonly utilized in biological calculations. These values form the quantitative foundation of the concepts we will cover extensively throughout this course.

Quantity	Unit	Symbol	Definition
Length	Meter	**m**	The length of the path traveled by light in a vacuum during a time interval of 1/299,792, 458 of a second.
Mass	Kilogram	**kg**	The mass of the international prototype of the platinum-iridium alloy, as sanctioned by the General Conference on Weights and Measures.
Time	Second	**s**	The duration of 9,192, 631,770 periods of the radiation

			corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.
Electric Current	Ampere	**A**	That constant current which, if maintained in two straight parallel conductors of infinite length and negligible circular cross-section, placed 1 meter apart in a vacuum, would produce a force equal to 2.10^{-7} newtons per meter of length.
Temperature	Kelvin	**K**	The unit of thermodynamic temperature, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water.
Amount of Substance	Mole	**mol**	The amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12.
Luminous Intensity	Candela	**cd**	The luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540.10^{12} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

Parameter	**Formula / Value**
Half-life / Period	$T = 0.693 / \lambda$
Speed of Light (Electromagnetic wave)	$c = 3\ 10^8$ m/s
Frequency (υ)	1 Hertz (Hz) = 1 cycle (vibration) per second
Planck's Constant	$h = 6, 6.\ 10^{-34}$ J.s
Avogadro's Number	$N = 6, 023.\ 10^{23}$
Electron Rest Mass	me = 0,000550 a.m.u
Proton Rest Mass	mp = 1, 007596 a.m.u

Quantity	**Unit**	**Symbol**	**Dimensional Definition**
Energy	Joule	**J**	$Kg\ m^2\ s^{-2}$
Force	Newton	**N**	$Kg\ m\ s^{-2}$
Pressure	Pascal	**Pa**	$N\ m^{-2}$
Electric Charge	Coulomb	**C**	A s
Electric Potential	Volt	**V**	$J\ C^{-1}$

Table 1: Units of Measurement and Their Definitions

2. Electromagnetic and Particulate Radiation

2.1. Definition of Radiation

Radiation can be defined as the transfer of energy in the form of waves or particles. This process occurs through **electromagnetic radiation** (such as infrared) or via **radioactive decay** (such as alpha or beta radioactivity). Notably, this energy transfer can occur in a vacuum; the most common example is solar radiation traveling through space.

In physics, the terms "radiation" or "radiant energy" refer to the emission or transmission of energy as particles, electromagnetic waves, or acoustic waves. This encompasses:

- **Electromagnetic radiation:** Radio waves, infrared, visible light, X-rays, and gamma rays.
- **Particulate radiation:** Alpha particles, beta particles, and neutrons.

2.2. Classification of Radiation

Radiation is classified either by its physical nature or by its interaction with matter.

A. Classification by Nature:

- **Electromagnetic Radiation (EMR):** Examples include radio waves, visible light, infrared (IR), ultraviolet (UV), X-rays, and gamma rays.
- **Particulate Radiation (PR):** Composed of particles with non-zero mass.
    - **Charged particles:** Electrons and positrons, which interact with the electrons of the target matter.
    - **Neutral particles:** Neutrons, which interact primarily with the nuclei of the target matter.
    - **Heavy particles:** Alpha and beta radiation.

B. Classification by Interaction with Matter:

- **Ionizing Radiation:** Radiation with enough energy to displace electrons from atoms, creating ions.
    - *Examples:* X-rays and gamma rays.
- **Non-Ionizing Radiation:** Radiation that lacks the energy to ionize atoms but can cause excitation (heat).
    - *Examples:* Radio waves, visible light, and infrared.

2.3. Electromagnetic Radiation (EMR)

Electromagnetic radiation propagates through space as oscillating **Electric (E)** and **Magnetic (B)** fields that are perpendicular to each other and to the direction of travel (Figure 1). These waves vary in wavelength, ranging from long radio waves to extremely short gamma rays.

EMR carries both energy and information and is essential in numerous applications such as medicine (diagnostic imaging), telecommunications, broadcasting, and remote sensing. Furthermore, electromagnetic radiation is produced naturally by celestial bodies, including the sun and stars.

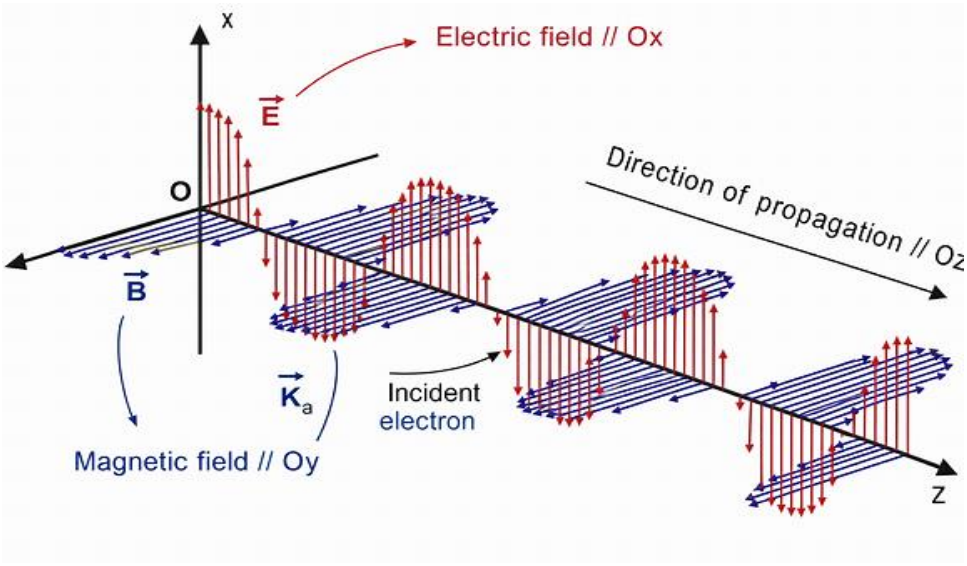

Figure 1. Propagation of an electromagnetic wave.

2.3.1. The Electromagnetic Spectrum

The electromagnetic spectrum is a representation of all possible wavelengths of electromagnetic waves, typically ordered by increasing frequency or energy. This spectrum forms a continuous range, starting from low-frequency radio waves, moving through the visible light spectrum, and reaching high-frequency X-rays and gamma rays.

Each type of electromagnetic radiation possesses unique properties, such as the ability to penetrate matter or be reflected/absorbed by specific materials. Different regions of the spectrum have specialized applications in science, medicine, and technology.

The intensity of EMR can be represented graphically. The resulting plots are known as **wavelength spectra**, **frequency spectra**, or **energy spectra** (Figure 2).

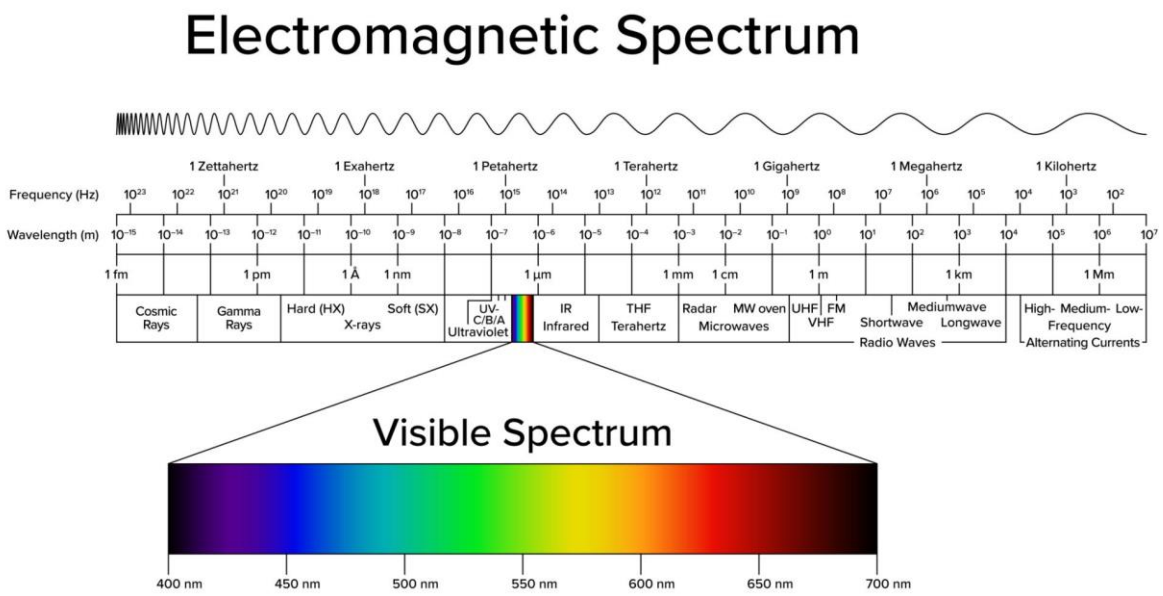

Figure 2. Representation of electromagnetic spectra.

NOTE: Key Characteristics of Electromagnetic Waves

- A **monochromatic electromagnetic wave** is defined as having a single, constant frequency; it is often referred to as a **sinusoidal wave**. This wave propagates by generating a disturbance (or perturbation) within space. This disturbance can be mathematically described by a complex function known as the **"wave function,"** which depends on both spatial coordinates and time.
- Electromagnetic waves are unique in that they facilitate the **transfer of energy without requiring any physical medium**; they propagate effectively in a vacuum.
- Electromagnetic waves are classified as **plane waves**. This signifies that in a vacuum, the direction of propagation is always mutually perpendicular (orthogonal) to the entire plane defined by the oscillating Electric (E) and Magnetic (B) fields.
- In a vacuum, the velocity of an electromagnetic wave is a constant, denoted by the symbol **c** (widely recognized as the **Speed of Light**).

2.3.2. Velocity of Electromagnetic Wave Propagation in a Vacuum

The velocity at which electromagnetic waves propagate in a vacuum is a fundamental physical constant, denoted by the symbol "**c**" and commonly referred to as the "**speed of light**." It is derived from the following relationship:

$$v = \frac{1}{\sqrt{\mu_0 \, \varepsilon_0}} = c$$

Where ε_0 and ε_0 are constants representing the **permittivity** and **permeability** of free space (vacuum), respectively.

- $\varepsilon_0 = 8.84\ 10^{-12}$ F/m (or SI units)
- $\mu_0 = 1.26\ 10^{-6}$ H/m (or SI units)

Consequently, the speed of light is calculated as:

$c = 3.10^8$ m/s

2.3.3. Propagation of Electromagnetic Waves Through Matter

Electromagnetic waves can propagate through certain physical media but not others. Based on their frequency and the properties of the material, matter can be classified as:

- **Transparent:** Propagation through the medium is possible.
- **Opaque:** No propagation occurs; the waves are entirely absorbed, scattered, or reflected.

Within a transparent medium, the velocity of propagation (v) is variable. It depends not only on the chemical composition of the medium but also on physical parameters such as temperature, pressure, and density.

Every transparent medium is characterized by its **refractive index**, denoted by "**n**" (which may be frequency-dependent). The refractive index is used to express the velocity of propagation within that medium as a ratio to the speed of light in a vacuum:

$n = c_{vacuum}/v_{medium}$

2.3.4. Characteristics of Electromagnetic Radiation

Like all periodic waves, electromagnetic radiation is characterized by the following fundamental properties:

- **Period (T):** Expressed in seconds (s) (less commonly used).
- **Frequency (ν):** Expressed in Hertz (Hz).
- **Wavelength (λ):** Expressed in meters (m).
- **Amplitude:** In this context, the preferred measure is **Luminous Intensity (I)**.
- **Velocity (c):** Expressed in meters per second ($m.s^{-1}$ or m/s).
- **Energy (E):** Expressed in Joules (J).

These physical quantities are interrelated through standard mathematical relationships:

- Frequency is the mathematical reciprocal of the period: **ν = 1 / T**

- **Period (T):** Consequently, the period is defined as the reciprocal of the frequency:

T = 1\ **ν**

- **Wavelength (λ):** The wavelength is the distance over which the wave propagates during one full period. This is expressed by the relation λ= c .T.

It can also be defined in terms of frequency as:

λ= 1\ ν

-

2.3.5. Period and Frequency of an Electromagnetic Wave

The duration of a complete vibration is called the **Period (T)**. Frequency (ν) measures the number of vibrations per second.

T = 1\ ν

Where **T** is in seconds (s) and ν is in inverse seconds (s^{-1}) or Hertz (Hz).

2.3.6. Wavelength

Wavelength represents the physical distance covered by an electromagnetic wave during one period of oscillation (Figure 3).

In a vacuum, the wavelength is given by the relation:

λ = c.T = c\ ν

Where λ is in meters (m) and **c** is the speed of light in meters per second ($m.s^{-1}$ or m/s).

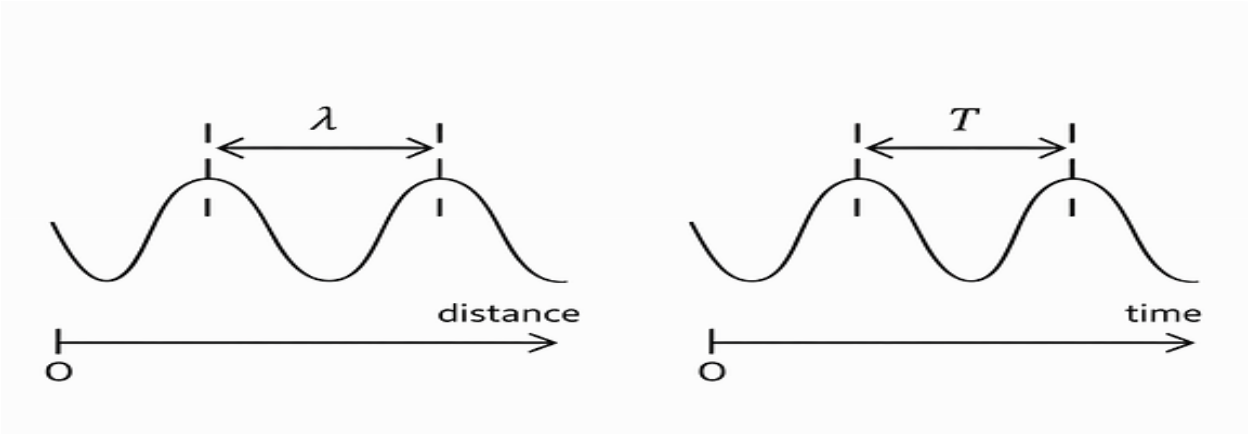

Figure 3. . Wavelength of an electromagnetic wave.

2.3.7. Energy of an Electromagnetic Wave

Like all waves, electromagnetic waves propagate energy. This energy depends on the frequency: the higher the frequency, the greater the energy propagated. Given that $\lambda = c/\nu$ the shorter the wavelength, the higher the energy. Consequently, the most energetic radiations in the electromagnetic spectrum are **gamma rays**, while the least energetic are **radio waves**. Within the visible spectrum, violet light is more energetic than red light.

An electromagnetic wave enables the transport of energy in the form of discrete (discontinuous) packets called **quanta**. Each quantum carries an energy E such that:

$E = h .\nu$

Where h is **Planck's constant**: $h = 6.62 \times 10^{-34}$ J.s and E is in Joules (J). At the atomic scale, it is customary to express energy in **electronvolts (eV)**.

2.3.8. Emission and Absorption of an Electromagnetic Wave

The emission or absorption of electromagnetic waves by matter is possible during transitions between different "energy levels":

- Transitioning to a **lower energy level** releases energy, thereby **emitting** an electromagnetic wave.
- Transitioning to a **higher energy level** requires an energy gain, resulting in the **absorption** of an electromagnetic wave.

2.3.9. Particle-like Nature of Electromagnetic Radiation

Under certain conditions, electromagnetic waves can be interpreted as a stream of particles called **photons**. This concept of the "photon" is useful for understanding the properties of light, particularly how it interacts and exchanges energy with matter. In other words, the photon concept allows the specific characteristics of light to be explained in terms of particles rather than waves.

2.3.9.1. A Breach in Wave Theory: The Photoelectric Effect

Towards the end of the 19th century, the scientific community was convinced that the wave model was sufficient to explain all the properties of light in any experiment. However, difficulties were encountered, notably in 1887, with the discovery of the **photoelectric effect** by Heinrich Hertz (1857–1894) (Figure 4).

The photoelectric effect was observed in a famous experiment involving the illumination of a zinc plate (acting as a cathode) subjected to a negative potential with a light source (UV, X-rays, etc.). An electric current is observed (detected by the deflection of an ammeter needle) as electrons are ejected from the plate and collected by the anode. However, the production of this current could not be explained by the classical interaction between an electromagnetic wave and the zinc plate.

In 1905, Albert Einstein (1879–1955) explained the photoelectric effect by revisiting the **corpuscular model**. He postulated that light delivers energy in sufficient discrete quantities—photons—to dislodge electrons from the metal, thus allowing the electroscope to discharge. The concept of the photon had previously been introduced in 1900 by Max Planck (1858–1947) within his model of **blackbody radiation**.

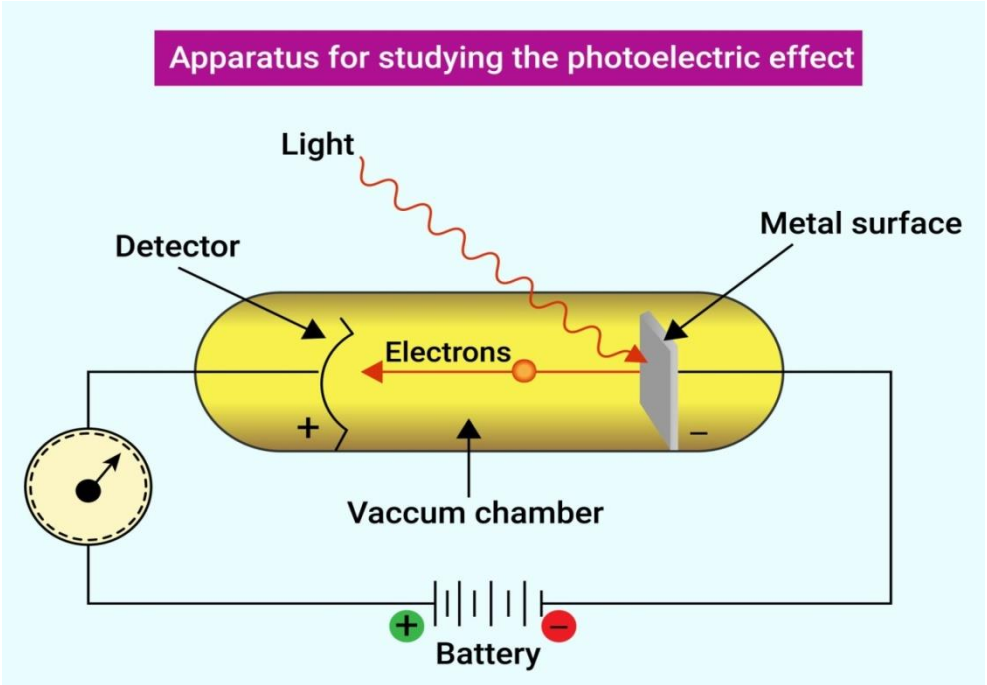

Figure 4. The Photoelectric Effect Experiment

Due to the **quantization** of electron energy levels within an atom, the release of an electron can only occur as a single-event process; that is, it requires a single photon providing sufficient energy.

According to the relation

$E = E = h.\nu = h.c \setminus \lambda$

This process involves high-frequency (ν) / short-wavelength (λ) photons, such as the UV photons used in the experiment. Consequently, radiation devoid of UV photons (the effect produced by the glass slide) is incapable of generating an electric current.

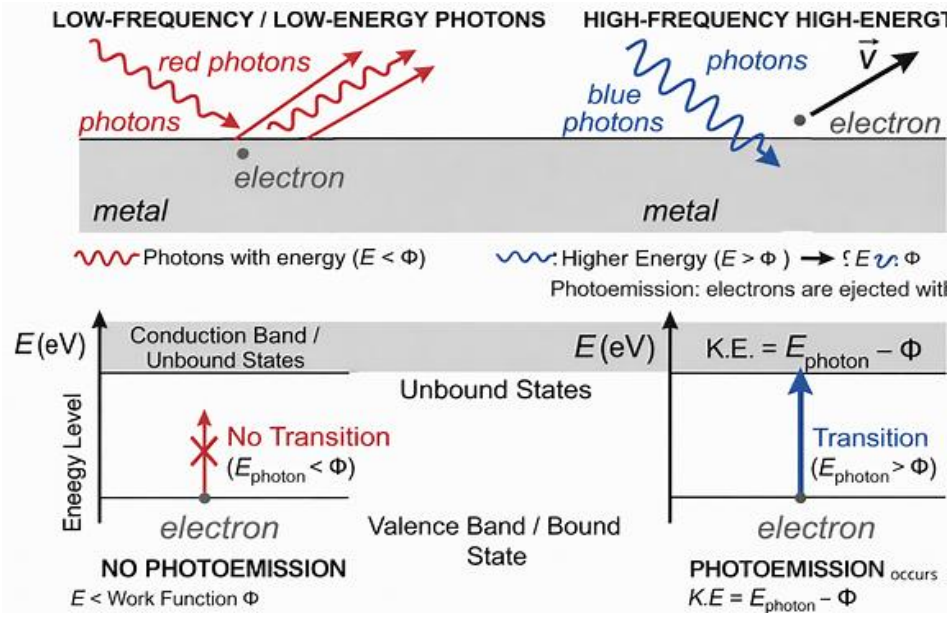

Figure 5. Electronic Transitions

The relationship between energy and wavelength is defined by the **Duane-Hunt law**:

$E\ (eV) = 12400 \setminus \lambda\ (Å)$

Where 1 eV = 1.6 $x10^{-19}$ J and 1 (Å) = 10^{-10} m.

These photons collide with the electrons within the metal. When their energy exceeds the **binding energy** (or **work function**) W_0, the electrons are ejected with a specific **kinetic energy** (Figure 5). This condition is expressed by the **photoelectric effect equation**:

$h.\nu = W_0 + ½.mv^2$

This qualitative aspect of electromagnetic radiation (photon energy) cannot be described by the classical wave model.

2.3.9.2. Louis de Broglie's Solution: Wave-Particle Duality

The wave model is suitable for describing light in **diffraction** and **interference** experiments, whereas the corpuscular model is better suited to explain the photoelectric effect. However, Louis de Broglie resolved this dilemma in 1923. He proposed that the two models are not necessarily in opposition but rather coexist. Light and electromagnetic waves exhibit a dual nature, acting as both waves and particles—a concept known as **wave-particle duality**.

To illustrate this concept, scientific literature often employs the **cylinder metaphor**: a cylinder may appear as either a circle or a rectangle depending on the angle of observation, without being exclusively one or the other (Figure 6).

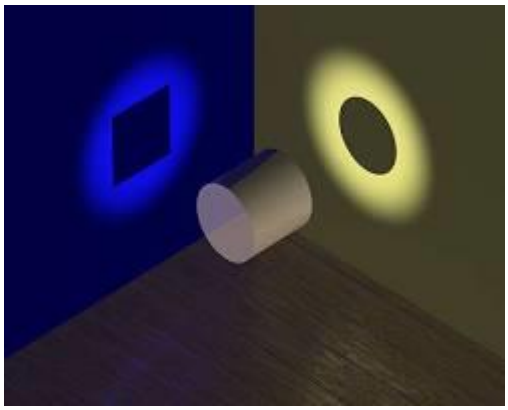

Figure 6.The Cylinder Metaphor

2.3.9.3. Louis de Broglie Wavelength of a Quantum Object

Why is light afforded such unique treatment? According to Louis de Broglie, this dual behavior is not exclusive to light. Indeed, any object can be considered as both a wave and a particle. In macroscopic objects, this wave-like behavior is imperceptible; however, for objects such as electrons, **diffraction** and **interference** phenomena can be observed, allowing them to exhibit wave-like properties. Generally, objects with dimensions less than or equal to the atomic scale are described by **quantum mechanics** and exhibit this **wave-particle duality**.

The wave nature of a non-zero mass quantum object is expressed by its **de Broglie wavelength** (λ), given by the following relation:

$$\lambda = h/p$$

Where:

- λ is the wavelength in meters (m);
- h is **Planck's constant** (6.62×10^{-34} J.s);
- p is the **momentum** of the particle in $kg.m.s^{-1}$.

⟶ In the **non-relativistic regime** ($v \ll c$): $p = m.v$.

→ In the **relativistic regime**: $p = \frac{mv}{\sqrt{1-\frac{v^2}{c^2}}}$ where c is the speed of light.

Note: For a massless particle, the relation λ = h/p *remains valid, with* $p=\frac{E}{c}$*, where E represents its energy (in Joules).*

2.4. Ionizing and Non-Ionizing Radiation

Given that hydrogen atoms—abundant in organic matter—possess an **ionization energy** of 13.6 eV, radiation is classified based on its interaction with matter:

1. **Non-ionizing radiation** lacks sufficient energy to ionize atoms or molecules (i.e., to cause the gain or loss of electrons). Various types exist, including **near-ultraviolet (near-UV)**, visible light, infrared radiation, microwaves, and radio waves. Although these cannot ionize atoms, they are not entirely harmless; for instance, microwaves possess enough energy to cook food, and ultraviolet rays can induce erythema (sunburn).
2. **Ionizing radiation** possesses sufficient energy to eject electrons from their parent atoms, thereby creating **ions**. **Far-ultraviolet (far-UV)**, **X-rays**, and **gamma rays** are highly energetic forms of ionizing radiation. They can induce rapid cellular damage or lead to carcinogenesis. This explains the use of lead aprons during radiography and why technicians remain in shielded rooms during radiological procedures. While the radiation dose from a single X-ray is typically not harmful, cumulative exposure can be hazardous.

3. Particulate Radiation

Particulate radiation consists of atomic or subatomic particles—such as protons, neutrons, and electrons—that possess **kinetic energy** (energy associated with the motion of mass). Unlike massless elementary particles, these particles have a non-zero **rest mass** and are characterized by:

- **Charge**
- **Rest mass** (m_0)
- **Velocity** (v)
- **Relativistic mass** $m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$
- **Momentum** (or quantity of motion) p = m.v
- **Total energy** $E = m.c^2$
- **Kinetic energy** = $E_k = \left[\frac{m_0 c^2}{\sqrt{1-\frac{v^2}{c^2}}} - 1\right]$

There are three primary subatomic particles: two "heavy" particles (**neutrons** and **protons**) and one "light" particle (**electrons**). To these, we can add the **positron** (β^+) and the **negatron** (β^-).

Directly vs. Indirectly Ionizing Radiation

Alpha and beta particles emit **directly ionizing radiation** because they are charged. They interact directly with atomic electrons via **Coulombic forces** (i.e., like charges repel, while opposite charges attract).

- **Alpha particles (α):** These consist of two protons and two neutrons. They are relatively large, slow-moving, and positively charged. An alpha particle is identical to the nucleus of a helium atom.
- **Beta particles (β):** These are small and fast-moving. They can carry either a negative charge (electrons/negatrons) or a positive charge (positrons).

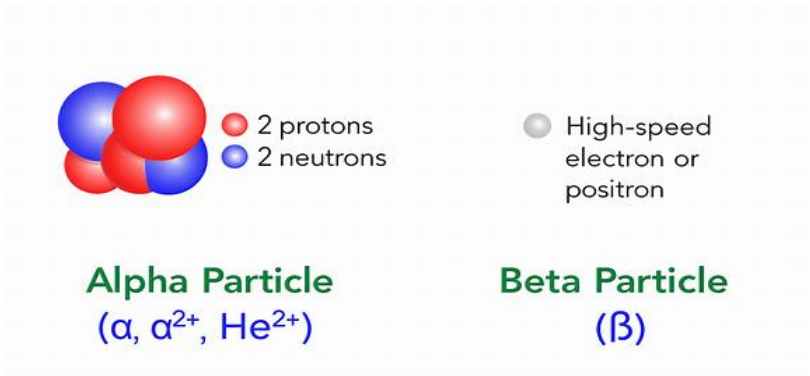

Figure 7. Alpha and Beta Particles

Each alpha particle consists of two protons and two neutrons. A beta particle can be either a high-speed electron or a positron.

Neutrons and Indirect Ionization

Neutrons are located within the atomic nucleus and, unlike protons and electrons, are **uncharged particles**.

Neutron radiation is classified as **indirectly ionizing radiation**. It is composed of free neutrons that have been released from atoms. These free neutrons can react with the nuclei of other atoms to form new isotopes, which may then emit radiation, such as **gamma rays**. Neutron radiation is termed "indirectly ionizing" because it does not ionize atoms through the same electromagnetic mechanisms as charged particles.

When a neutron strikes a heavier nucleus during an inelastic collision, the energy acquired by the nucleus is released in the form of gamma photons. Despite this interaction, the neutron retains a significant amount of its initial energy.

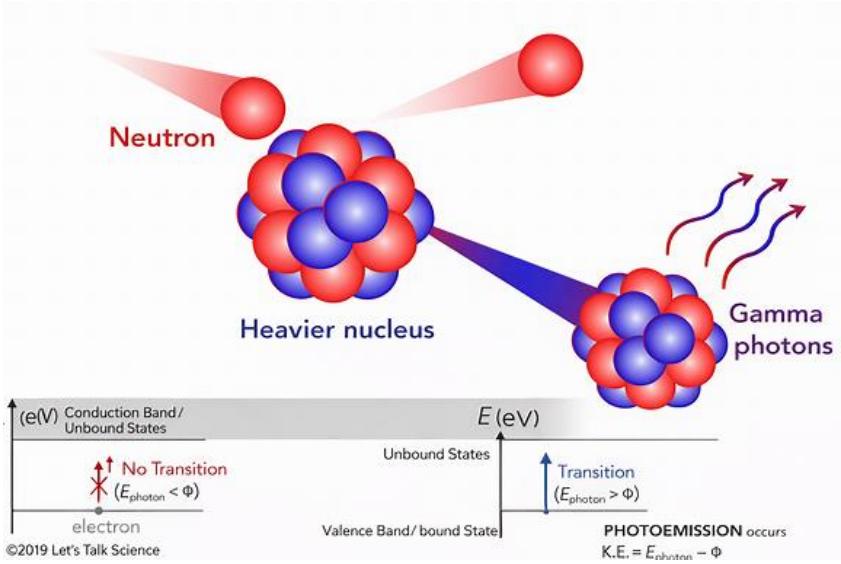

Figure 8. Nuclear Reaction and Gamma Emission

4. X-Rays

4.1. Introduction

Most of us will, at some point in our lives, require one or more X-rays, whether at the dentist's office or during a medical consultation. Therefore, it is essential to understand the underlying principles of X-ray radiation, which forms the basis of radiography.

4.2. Discovery

In 1895, the German physicist Wilhelm Conrad Röntgen made a nearly serendipitous discovery by uncovering **X-rays**, a breakthrough that radically altered our understanding of the physical world. This discovery was rapidly integrated into the medical field, giving birth to the specialty of **radiology**, and ultimately earned Röntgen the inaugural Nobel Prize in Physics in 1901.

4.3. Nature

X-rays are electromagnetic waves widely utilized in various applications, most notably in medical imaging via **conventional radiography**. They occupy a specific region of the electromagnetic spectrum, similar to visible light, but possess significantly shorter wavelengths, ranging from 10^{-12} m to 10^{-8} m.

X-rays are invisible to the naked eye as they fall outside the visible light spectrum. Characterized by high frequencies—ranging from $3x10^{16}$ Hz to $3x10^{19}$Hz —X-rays are highly energetic and can penetrate material objects with varying degrees of ease. Although they are slightly less hazardous than gamma rays, X-rays remain dangerous due to their high energy levels.

4.4. Production of X-Rays

How are they produced?

X-rays are generated using an **X-ray tube** (such as Coolidge or Crookes tubes), which consists of two primary electrodes: the **anode** (or target) and the **cathode**.

The cathode, connected to a low-voltage negative terminal, consists of a **tungsten filament** that emits electrons via the **thermionic effect** (thermionic emission). These electrons are then accelerated toward the anode, which is connected to a high-voltage positive terminal. The interaction of these high-speed electrons with the anode material generates X-rays.

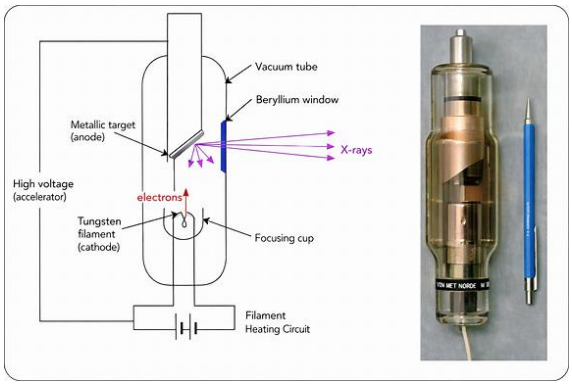

Figure 9. X-ray Tube (Coolidge tube)

4.4.1. Principle of X-ray Production

- **Thermoelectronic effect**: A tungsten filament (cathode, negative pole) is heated to a very high temperature using a low-intensity, low-voltage electric current.
- **Electron acceleration**: The heated tungsten filament emits electrons that are accelerated by a voltage (U) (typically several tens of keV). These electrons rush toward a metallic target (anode, positive pole). Under the influence of the electric field (U), they acquire kinetic energy:
  [$\mathbf{E = ½\ mv^2 = e.\ U}$]
- **Beam focusing**: To prevent excessive divergence caused by mutual electron repulsion, the filament is surrounded by a negatively charged cylinder. This focusing device concentrates the electron beam toward the target.
- **Radiation emission**: X-rays are emitted perpendicular to the incident electron beam and exit the tube through a beryllium window.
- **Generator power** (in watts) is given by:
  [**P = U.I**]
  where (U) is the accelerating voltage (in kV) and (I) is the electronic current (in mA).

Only about **1%** of this power is effectively used to produce X-rays. If (**Ø**) represents the radiated flux (energy per second), the energy efficiency of the tube is:

$$R = Ø/P=(k.i.U^2.Z)/(U.i) = k.U.Z$$

where:

- ($k = 10^{-10}$) is a proportionality constant
- (U) is the accelerating voltage (in volts)
- (Z) is the atomic number of the target material

Key effects:

- Increasing (I) → more electrons emitted → more X-ray photons produced
- Increasing (U) → higher electron energy → higher maximum photon energy

Most of the electrical power (**P = U.I**) is dissipated as heat. The actual radiated X-ray power is:

[$\emptyset = P_R = k .I . U^2 . Z$]

Typical accelerating voltages:

- 50 kV → fluoroscopy
- 100 kV → radiography
- 200 kV → radiotherapy

4.5. X-ray Spectrum

The **continuous spectrum**, also known as **Bremsstrahlung radiation**, is produced when electrons pass near an atomic nucleus without causing ionization, resulting in a sudden deceleration. Most of the energy is converted into heat during collisions with atoms in the **target (anticathode)**. However, according to electromagnetic theory, this deceleration is accompanied by the emission of electromagnetic radiation.

The energy lost by the electron during this braking process, denoted as **ΔW**, is transferred to an emitted photon with energy **hν**. The value of **ΔW** can vary continuously and must be less than or equal to the initial kinetic energy of the electron, **e·U**, upon reaching the target. Therefore, the wavelength of the emitted photon can take any value satisfying the condition:

$e \cdot U \geq h\nu$

The continuous spectrum arises from the deceleration of electrons interacting with the target. Some electrons undergo abrupt stopping after a single collision, transferring their entire energy to a single X-ray photon. The energy of this photon, **hν**, is thus less than or equal to the incident electron energy **e·U**.

The **minimum wavelength** of the emitted X-ray photons is given by:

$\lambda_{min} = hc/e \cdot U \rightarrow \lambda min(A^\circ) = 12400/U(volts)$

This minimum wavelength decreases as the accelerating voltage increases. Notably, λ_{min} **depends only on the accelerating voltage**, not on the target material.

For example, consider a **molybdenum target** bombarded by electrons at increasing voltages. For each accelerating voltage, we can examine the resulting spectrum distribution—how the intensity of emitted X-rays varies with wavelength. Up to **20 kV**, only a continuous spectrum is observed, ending at short wavelengths. Starting from **25 kV**, intense emission lines appear, standing out from the continuous background. These are known as **characteristic lines**.

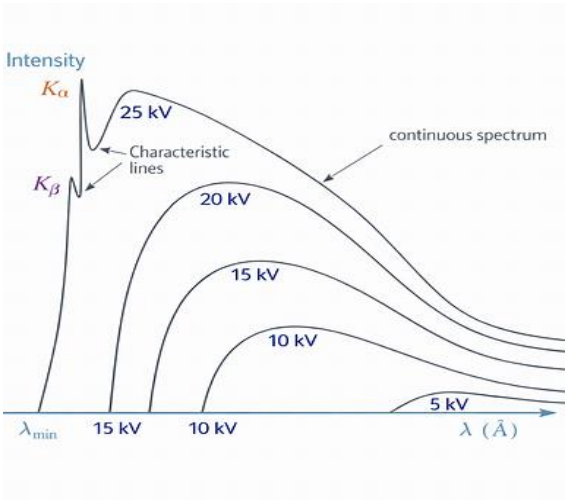

Figure 10. X-ray Emission Spectrum of Molybdenum as a Function of Accelerating Voltage U.

Characteristic X-ray Spectrum

When a high-energy electron enters an atom, it may eject an electron from one of the atom's inner shells (K, L, etc.). Within a very short time, an electron from a higher shell drops down to fill the vacancy. This transition is accompanied by the emission of electromagnetic radiation, whose frequency is directly proportional to the energy difference between the initial and final states of the electron.

Example: If an electron is ejected from an energy level W_1 and replaced by an electron from a higher level W_2 (with $W_2<W_1$), the emitted X-ray photon will have an energy E given by:

$E=W_1-W_2=hc/\lambda \rightarrow \lambda=hc/W_1-W_2$

Note: The energy difference between two electrons belonging to adjacent shells is greatest for the innermost shells. Therefore, transitions involving inner shells (e.g., K and L) produce higher-energy (shorter-wavelength) X-ray photons.

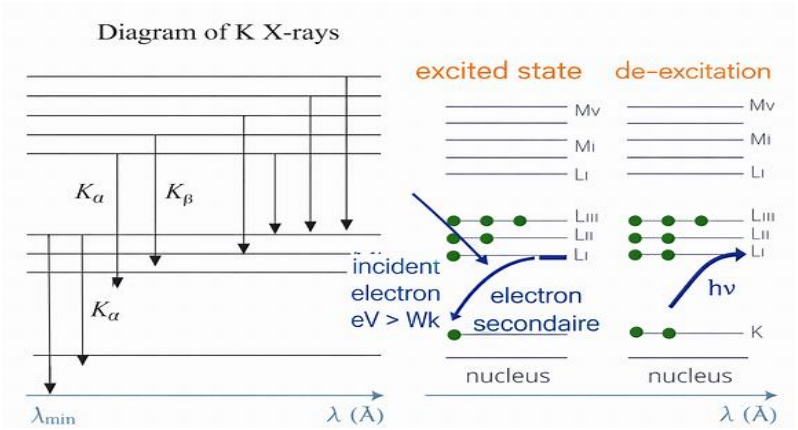

Figure 11. Diagram of the First X-ray Lines

The **K shell** is historically defined by n=1. If the electron that fills the vacancy in the K shell comes from the **L shell** (n=2), the emitted line is called **Kα**. If the electron comes from the **M shell** (n=3), the emitted line is called **K_β**, and so on. The electron that fills a vacancy in the **L** or **M** shell originates from a higher shell of the atom.

Note: X-rays produced by ionization therefore exhibit a **line spectrum**.

Remark: This line spectrum is used in **crystallography** and in **chemical analysis by X-ray fluorescence**. It has **little relevance in medicine**.

The **overall spectrum** results from the **superposition** of:

- the **continuous Bremsstrahlung spectrum** (which is predominant), and
- the **characteristic line spectrum**.

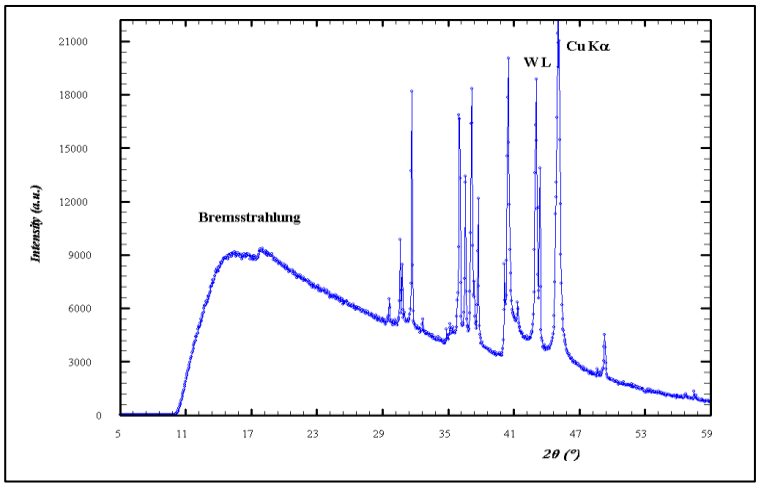

Figure 12. Total spectrum resulting from the superposition of the continuous Bremsstrahlung

5. Radioactivity

5.1 Introduction

Radioactivity was not created by humans; it is a natural phenomenon identified at the end of the 19th century. In 1896, the French physicist **Henri Becquerel** investigated whether the rays emitted by fluorescent uranium salts were identical to the X-rays discovered in 1895 by the German physicist **Wilhelm Roentgen**. Becquerel believed that uranium salts emitted X-rays after being stimulated by light. However, in March 1896, he was surprised to find that a photographic plate had been exposed **without any exposure to sunlight**. He concluded that uranium **spontaneously emitted invisible radiation**, different from X-rays, without being discharged. This phenomenon was named **radioactivity** (from the Latin *radius*, meaning "ray").

In 1898, **Pierre and Marie Curie** isolated **polonium** and **radium**, previously unknown radioactive elements present in uranium ore, following Becquerel's discovery. In nature, some nuclei are **stable**, while others are **unstable or radioactive**.

5.2 Nuclear Stability

A nucleus is **unstable (radioactive)** when the repulsive forces between nucleons exceed the cohesive forces that hold them together.

5.2.1 Stability and Binding Energy

The mass of a nucleus is **lower** than the sum of the masses of its individual constituents (protons and neutrons):

Z protons+N neutrons $\longrightarrow$ nucleus

$Z_{mp}+N_{mn} > m_{nucleus}$

The **mass defect** is defined as:

$\Delta m=(Z_{mp}+N_{mn}) - m_{nucleus}$

This mass defect corresponds to the **binding energy** released during the formation of the nucleus:

$\mathbf{\Delta E=\Delta m.c^2}$

- **ΔE**: energy released during the formation of the nucleus
- **ΔE / A**: average binding energy per nucleon
- **A**: total number of nucleons

The **greater** the binding energy per nucleon, the **more stable** the nucleus.

5.2.2 Stability and Number of Nucleons

Positively charged protons repel one another. The addition of neutrons stabilizes nuclides through a "dilution" effect: by increasing the number of neutrons, the positively charged protons become more widely spaced, which reduces their mutual repulsion.

5.2.3 The N–Z Chart

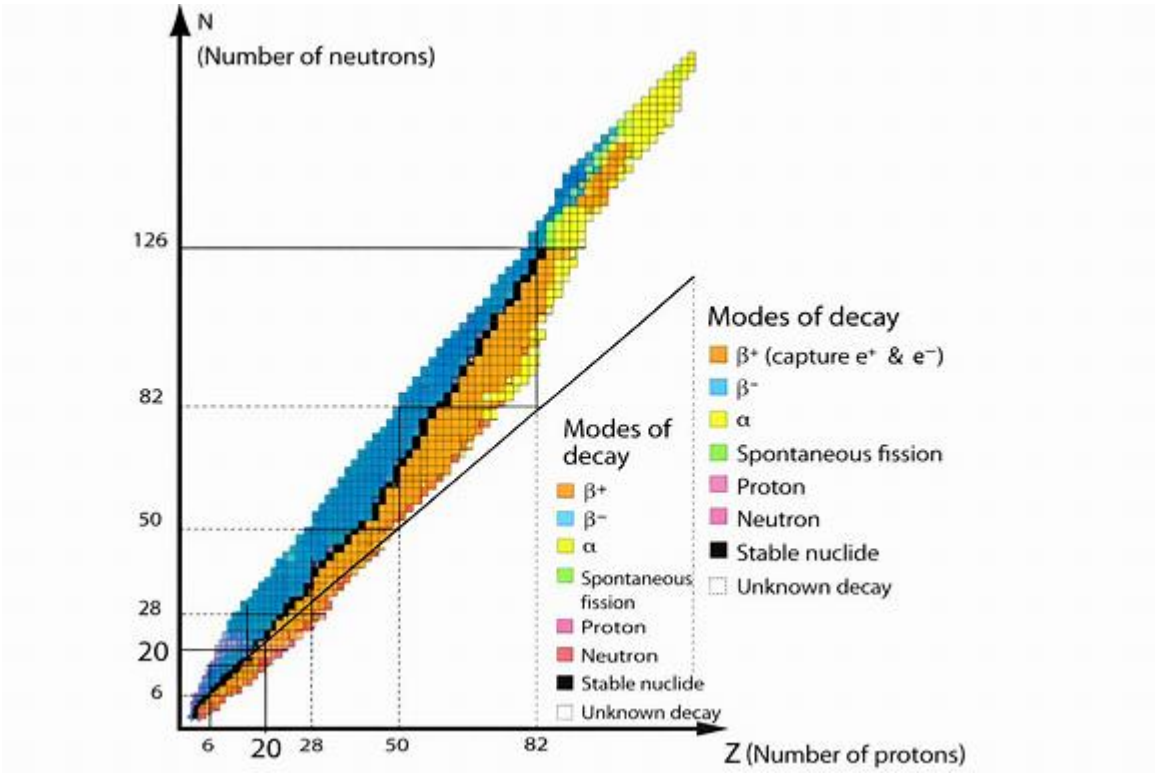

Figure 13.N–Z Chart of Nuclear Stability and Decay Modes

The graph representing the number of neutrons (N) as a function of the number of protons (Z) is called the **N–Z chart**. It reveals several distinct regions:

Stable Nuclei ("Valley of Stability")

These nuclei are shown in **black** on the chart.

- For **Z < 20**, stable nuclei lie near the line **Z = N**.
- For **Z > 20**, the number of neutrons increases faster than the number of protons, and stable nuclei lie **above** the Z = N line.

Unstable Nuclei

These are divided into three categories:

1. **Neutron Excess** (above the valley of stability) – **blue zone**
    - Radionuclides in this region undergo **β^- decay** (electron emission).

2. **Neutron Deficiency** (below the valley of stability) – **orange zone**
   - Radionuclides in this region undergo **β^+ decay** (positron emission).
3. **Heavy Nuclei with Neutron Deficiency** (A > 170)
   - These nuclei undergo **α decay**.

5.3 Properties of Radioactive Decay

1. **Conservation Laws**

Radioactive decay respects the conservation of **electric charge (Z)** and **mass number (A)**. After decay, both Z and A must remain conserved:

$${}^{A}_{Z}X \rightarrow {}^{A1}_{Z1}Y + {}^{A2}_{Z2}Y \quad \text{with} \quad A = A_1 + A_2 \text{ and } Z = Z_1 + Z_2$$

2. **Spontaneity**

Decay occurs **spontaneously**, without any external intervention. It does **not require specific conditions** such as temperature, pressure, etc.

3. **Randomness**

For a given nucleus, it is **impossible to predict** when it will decay. In a sample, we cannot determine **which nucleus** will decay.

4. **Inevitability**

Nothing can **stop**, **slow down**, or **accelerate** the rate of decay of a radioactive sample.

5.4 Natural Radioactivity

- In **1896**, **Henri Becquerel** discovered that uranium compounds emit a radiation capable of exposing photographic plates and ionizing air.
- In **1898–1899**, **Pierre and Marie Curie** isolated two elements that were even more radioactive than uranium: **polonium** and **radium**.
- In **1900**, Marie Curie proposed a hypothesis about radioactivity: *"Atoms undergo a metamorphosis, a transmutation accompanied by the emission of considerable energy."*

In natural radioactivity, three types of radiation are distinguished: **α, β, and γ**.

5.4.1 α Decay (Helium Emission) or α Emission

α decay results in the emission of an **α particle**, which corresponds to a **helium nucleus** (${}^{4}_{2}He$).

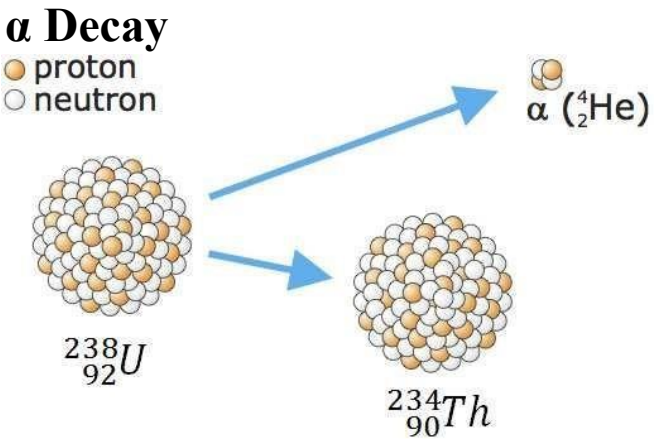

Figure 14.α Decay

α decay is a type of radioactive transformation in which an unstable nucleus emits an **α particle**, corresponding to a **helium-4 nucleus** (^4_2He). This process reduces:

- the **mass number** by 4
- the **atomic number** by 2

General equation

$$^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + {}^4_2He$$

Example

$$^{238}_{92}U \rightarrow {}^{34}_{90}Th + {}^4_2He$$

During α decay, the nucleus becomes **lighter** and moves closer to the **valley of stability**. **α decay occurs in heavy nuclei with Z > 82.**

5.4.2 β Decay

β decay involves the emission of a **β radiation**. A β particle can be either an **electron (e^-)** or a **positron (e^+)**. Therefore, there are two types of β decay:

- **β^- decay** (electron emission)
- **β^+ decay** (positron emission)

The radioactive half-lives associated with β decay are generally **short**, and in some cases **very short**.

5.4.2.1 β^- Decay (Negatron Emission)

When the **N/Z ratio is too high**, a neutron tends to transform into a proton. This transformation produces a particle with the same characteristics as an electron, called a **β^- particle** (negatron).

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + \nu$$

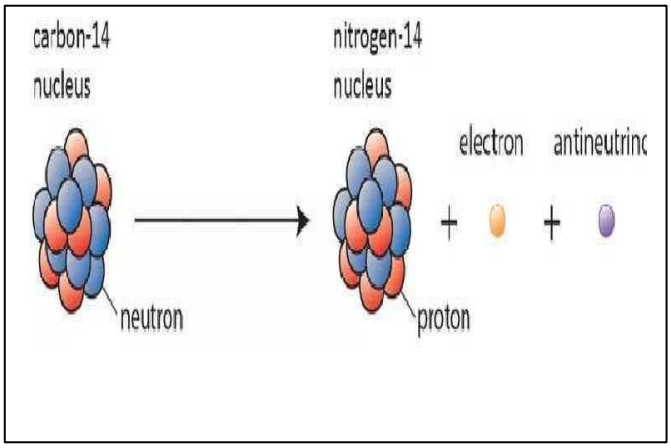

Figure 15. β^- decay

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

The electron cannot exist inside the nucleus and is therefore emitted.

During β^- decay, the neutron transforms into a proton, an electron, and an antineutrino. Since an electron **cannot remain confined within the nucleus**, it is immediately **ejected** with high kinetic energy.

5.4.2.2 β^+ Decay (Positron Emission)

When there is an excess of protons in the nucleus, one of them transforms into a neutron. A positron and a neutrino are then emitted.

$$^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + \nu$$

Example

$$^{7}_{4}Be \rightarrow {}^{7}_{3}Li + {}^{0}_{+1}e + \nu$$

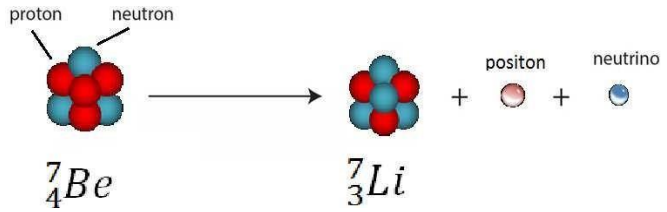

Figure 16.β^+ Decay

β particles are **more penetrating** but **less ionizing** than α particles. They can penetrate the skin to a depth of a **few millimeters**, which makes them **dangerous for the skin**.

5.4.3 γ Radiation

The emission of α or β particles is often accompanied by an **electromagnetic radiation** of extremely short wavelength (λ<1 A°), similar in nature to **X-rays** or **visible light**. This radiation is called **γ rays**.

γ rays are produced because nuclei formed after radioactive decay are often in an **excited state**. They tend to release this excess energy in order to reach a **more stable (lower-energy) state**, emitting a γ photon in the process.

γ Emission

$^{m}X \longrightarrow X + \gamma$

Example

$^{99m}Tc \longrightarrow {}^{99}Tc + \gamma$

In this process, the nucleus transitions from a **metastable excited state** (noted *m*) to a **lower-energy stable state**, releasing the excess energy as a **γ photon**.

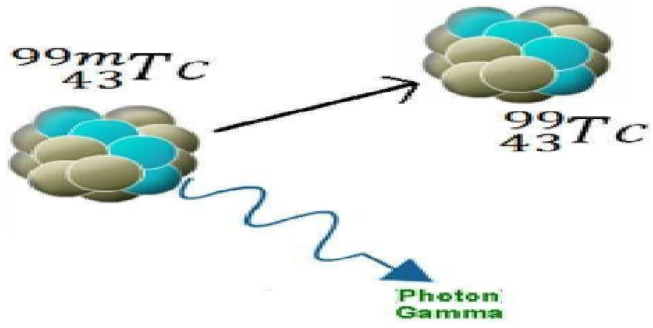

Figure 17. γ Emission

The emission of γ radiation does **not** produce any change in mass or charge.

γ rays are **not directly ionizing**, but they are **highly penetrating**.

Natural Radioactivity

Natural radioactivity is **spontaneous**, and it is called *natural* because radioactive nuclei are found in nature without any human intervention.

Important: α and β decays are often accompanied by the emission of **one or several γ rays**.

5.5 Law of Radioactive Decay

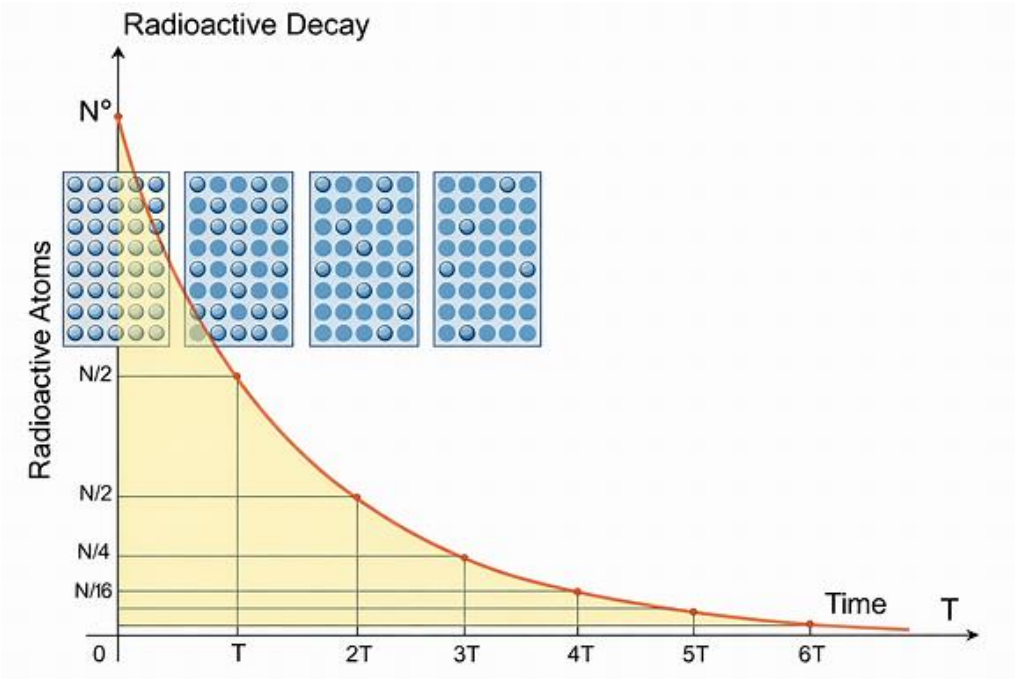

Figure 18. Radioactive Decay

The law of radioactive decay applies to **all types of radioactive isotopes**, whether **natural or artificial**. It states that the number of radioactive atoms in a sample **decreases exponentially over time**, according to the equation:

$N(t)=N_0 \cdot e^{-\lambda t}$

This decay is **independent of pressure, temperature**, or **chemical reactions** involving the radioactive atoms. This fundamental property allows scientists to use the decay law to:

- **measure the age** of samples containing radioactive isotopes
- perform various **scientific and medical applications**

When the resulting nuclide is stable

If the product of the decay is **not radioactive**, the transformation is:

$X \longrightarrow Y$

Where:

- X is the **radioactive parent nuclide**
- Y is the **stable daughter nuclide**

The activity A of a radioactive sample is defined as:

$$\mathbf{A=-dN/dt=\lambda N}$$

Where:

- **A** : absolute activity, the number of decays per unit time
- **N** : number of radioactive atoms at time t
- **λ** : decay constant of the radioactive element

Starting from the decay law:

$$-dN/dt=\lambda N$$

We separate variables:

$$-dN/N=\lambda\, dt$$

Integrating from N_0 to N_t and from 0 to t:

$$\int -dN/N = \lambda \int t dt$$

This gives:

$$\ln(N_t/N_0)=-\lambda t$$

Finally:

$$N(t)=N_0\, e^{-\lambda t}$$

Where:

- N_0 : initial number of radioactive atoms
- **N(t)** : number of atoms remaining at time t

Mass Form of the Radioactive Decay Law

The number of radioactive nuclei decreases **exponentially** with time.

If **1 mole** of a radioactive element has a molar mass M, then:

1 mole ⟶ N_A atoms

m(g) ⟶ N atoms

So the number of atoms in a mass m_0 is:

$N_0= (m_0 /M) \times N_A$

At time t, the remaining number of atoms is:

$N(t) = (m(t)/M)\, N_A$

Since:

$N(t)=N_0\, e^{-\lambda t}$

We obtain:

$(m(t)/M)N_A = (m_0M)/N_A \,.\, e^{-\lambda t}$

The constants cancel out, giving the **mass decay law**:

$$\mathbf{m(t)=m_0\, e^{-\lambda t}}$$

Where:

- $\mathbf{m_0}$: initial mass of the radioactive sample
- **m(t)** : remaining mass at time t
- **M** : molar mass of the radioactive element
- $\mathbf{N_A}$: Avogadro's number
- **λ** : decay constant

5.6 Activity

The activity of a radioactive sample is defined as the **number of disintegrations per unit time** occurring within it at any given moment. This activity is a fundamental characteristic of the sample, together with the nature of the emitted radiation. It represents its **"intrinsic radioactivity."**

When the sample contains several radioactive elements, the **total activity** is the **sum of the activities** of each individual element.

Officially, the activity of a radioactive sample is defined as the **number of disintegrations occurring per second**.

Units of Activity (A)

Activity can be expressed in:

- **disintegrations per second (dps)** or **Becquerels (Bq)**
- **disintegrations per minute (dpm)**
- **Curies (Ci)**

A source of **1 Curie** undergoes:

1 Ci=3.7×1010 dps

(For reference: **1 g of radium (Ra)** has an activity of **1 Ci**.)

Example

$$^{11}_{6}C \rightarrow {}^{11}_{5}B + {}^{0}_{+1}e + \nu$$

If at time t=0 the sample contains **only nuclei of** ^{11}C, then:

- N represents the **number of carbon-11 nuclei remaining** at time t (i.e., those that have **not** decayed).
- The number of 11C nuclei that **have decayed** is equal to the number of **boron-11 nuclei** formed.

Thus, the number of nuclei that have decayed is:

$N_0 - N$

Where:

- **N_0** = initial number of 11C nuclei
- **N** = number of 11C nuclei remaining at time t

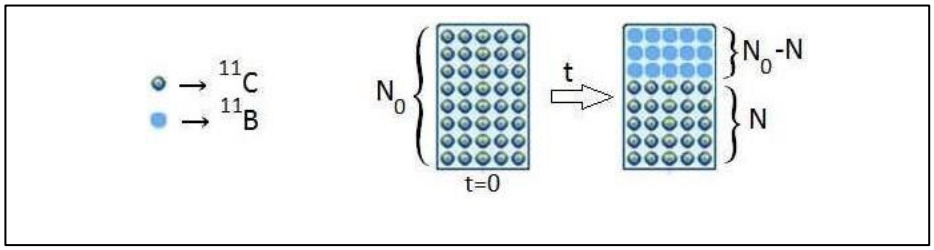

Figure 19. The Decay of

5.7 Radioactive Half-Life

Some radioactive nuclides remain stable for **billions of years**, while others decay in a **fraction of a second**. A decay process is characterized by its **period** T, also called the **half-life** t1/2.

The half-life is defined as the **time required for half of the radioactive substance to decay**.

Derivation of the Half-Life Formula

Starting from the decay law:

$N=N_0e^{-\lambda T}$

At the half-life, the number of remaining nuclei is:

$N=N_0/2$

Substituting:

$$N_0/2=N_0e^{-\lambda T}$$

Dividing both sides by N_0:

$$1/2=e^{-\lambda T}$$

Taking the natural logarithm:

$$\ln(1/2)=-\lambda T$$

Since:

$$\ln(1/2)=-\ln 2$$

We obtain the half-life:

$$T=\ln 2/\lambda$$

Or numerically:

$$T=0.693/\lambda$$

Important Properties of the Half-Life

- **The half-life does not depend on the initial number of nuclei.**
- **Temperature and pressure do not affect the value of the half-life.**
- **Each nuclide has its own characteristic half-life.**

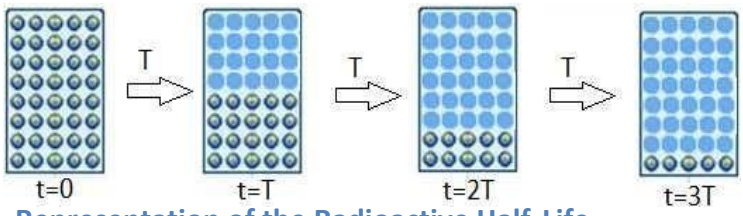

Figure 20. Representation of the Radioactive Half-Life

If we set n=t/T, then we obtain:

Starting from the decay law:

$$N=N_0e^{-\ln 2\ t/T}$$

Since n=t/T, this becomes:

$$N=N_0e^{-\ln 2\ n}$$

And because:

$$e^{-\ln 2\, n} = (e^{-\ln 2})n = (1/2)n$$

We get the compact form:

$$N = N_0/2^n$$

Similarly, for the activity:

$$A = A_0 e^{-\ln 2\, t/T}$$

Thus:

$$A = A_0/2^n$$

Where:

- **n** represents the **number of half-lives** that have elapsed.

Examples

- ^{14}C (β decay): T=5700 years
- $^{226}_{88}Ra$: T=1620 years
- ^{40}K (β decay): T=1.3×109 years
- ^{15}O: T=125 s

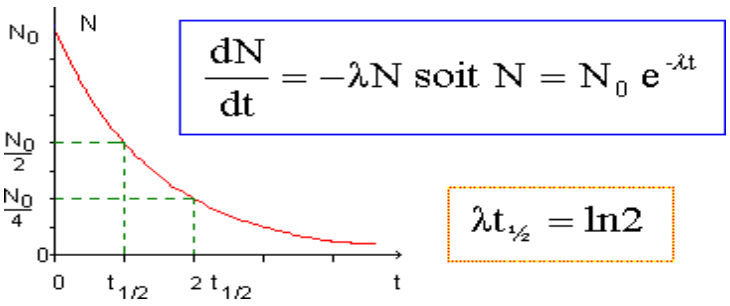

Figure 21. Demonstration of the Half-Life

5.8 Relationship Between the Mass of a Radionuclide and Its Activity

We have:

$$m(g) = (N \times M)/N_A$$

Where:

- **m** : mass of the radionuclide
- **N** : number of radioactive nuclei
- **M** : molar mass

- N_A : Avogadro's number

Since:

$$N=A/\lambda$$

We obtain:

$$m(g)=A/\lambda \cdot M/N_A$$

Using the relation:

$$\lambda=\ln 2/T$$

We substitute:

$$m(g)=(A \cdot M \cdot T)/(N_A \ln 2)$$

Thus, the mass of a radionuclide can be expressed as:

$$m(g) = (A .M .T)/(N_A \ln 2)$$

Important Note

The **unit of time** used in the activity A and in the half-life T must be the **same**.

5.9 Physical, Biological, and Effective Half-Lives

A radionuclide present in the human body undergoes two simultaneous processes:

1. **Radioactive decay**, governed by its **physical half-life**
2. **Biological elimination**, governed by its **biological half-life**

These two mechanisms combine to determine how quickly the activity of the radionuclide decreases inside the organism.

Physical Half-Life

The **physical half-life** is the radioactive half-life of the nuclide. It is the time required for **half of the radioactive nuclei** to decay due to their intrinsic nuclear instability.

Biological Half-Life

The **biological half-life** of a chemical element is the time required for the body to eliminate **half of the ingested or inhaled quantity** through natural biological processes such as:

- urine
- sweat

- respiration
- metabolic pathways

This elimination is **independent of radioactivity**.

Effective Half-Life

For a radionuclide inside the body, both processes occur simultaneously:

- radioactive decay (physical half-life)
- biological elimination (biological half-life)

The **effective half-life** is defined as the time required for the **activity inside the organism** to be reduced by half due to the **combined effect** of these two mechanisms.

It satisfies the relation:

$$1/T_{eff}=1/T_{phys}+1/T_{bio}$$

Where:

- T_{phys} = physical half-life
- T_{bio} = biological half-life
- T_{eff} = effective half-life

$$A(t) = A_0 e^{-\lambda_{pt}\, t} \cdot {}^{-\lambda_{bt}\, t}$$

$$A(t) = A_0 e^{-(\lambda_{p}+ + \lambda_{bt})t)}$$

$$A(t) = A_0 e^{--\lambda_{eff}\, t}$$

$$A(t) = A_0 e^{--\lambda_{eff}\, t}$$

Examples of Physical, Biological, and Effective Half-Lives

Element	Physical Half-Life Tp	Biological Half-Life Tb	Effective Half-Life Te
Iodine-131	8.0 days	30 days (thyroid)	6.3 days
Technetium-99m	6 hours	1 day	4.8 hours
Cesium-137	10,950 days	150 days	148 days

5.10 Disintegration Rate and Radiation Emission Rate

Radioactive activity is measured based on the **number of radiation emissions per unit time**. This means that the **more radioactive** a substance is, the **more radiation it emits**.

Radioactive activity can be broken down into:

- **Alpha activity**: number of alpha particles emitted per unit time
- **Beta activity**: number of beta particles emitted per unit time
- **Gamma activity**: depends on the **average number of gamma rays emitted per disintegration**

In most cases, when **every disintegration produces an alpha or beta particle**, the **number of disintegrations** is **equivalent** to the **alpha or beta activity**.

5.11 Radioactive Decay Chains

Up to this point, we have considered only the case in which a radionuclide decays into a **stable** element. However, in most situations, the nuclide produced during the first decay is **not stable**. It therefore becomes another **unstable radionuclide**, which will in turn undergo its own radioactive decay.

This sequence of successive decays is called a **radioactive decay chain**.

In natural radioactivity, a decay chain may include **up to 15 successive disintegrations** before reaching a stable nuclide.

Exemple :

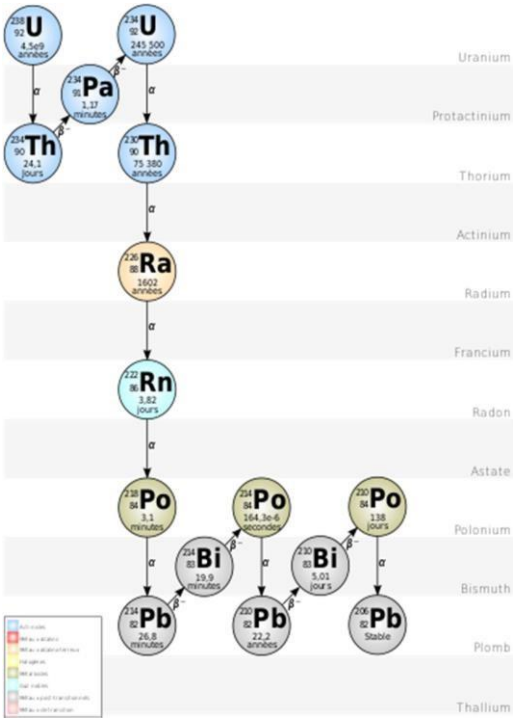

Figure 22. Decay Chain of 238U Containing 14 Successive Disintegrations

In what follows, we restrict ourselves to the case where only two successive disintegrations occur, leading to a stable element.

$X_1 \longrightarrow X_2 \longrightarrow X_3$

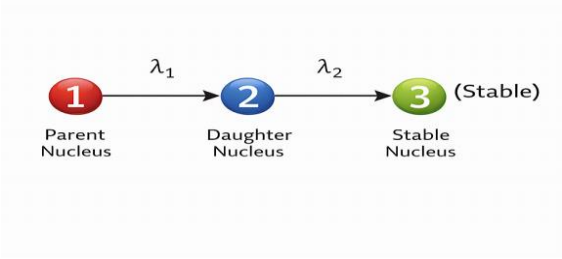

Figure 23. Decay of the parent radionuclide into the daughter radionuclide.

X_1 is called the **parent radionuclide**.

- X_2 is called the **daughter radionuclide**.
- X_3 is the **stable nuclide**.

Let us assume that in a sample, at time t=0, only nuclei of the parent nuclide X_1 are present:

$N_{10} \neq 0$, $N_{20}=0$, $N_{30}=0$

Thus, at t = 0:

$N_1(t=0) = N_{10}$

$N_2(t=0) = 0$

Differential Equations for a Two-Step Radioactive Decay Chain

At time t=0, we assume the sample contains only nuclei of the **parent nuclide** X_1:

$N_1(0)=N_{10} \neq 0$, $N_2(0)=0$, $N_3(0)=0$

Between time t and t+dt, the number of nuclei N_1, N_2, N_3 undergo variations dN_1, dN_2, dN_3 due to radioactive decay:

- **$\lambda_1 N_1 dt$** nuclei of the parent nuclide X_1 **disappear**
- **$\lambda_1 N_1 dt$** nuclei of the daughter nuclide X_2 **appear**
- **$\lambda_2 N_2 dt$** nuclei of the daughter nuclide X_2 **disappear**
- **$\lambda_2 N_2 dt$** nuclei of the stable nuclide X_3 **appear**

Differential Equations

$\frac{dN_1}{dt} = -\lambda_1 N_1$

$\frac{dN_2}{dt} = \lambda_1 N_1 - \lambda_2 N_2$

$\frac{dN_3}{dt} = \lambda_2 N_2$

Solutions

By integrating these equations, we obtain:

$N_1(t)=N_{10}\cdot e^{-\lambda 1 t}$

$\mathbf{N_2(t)=N_{10}\cdot\lambda_1/(\lambda_2-\lambda_1)\,(e^{-\lambda 1 t}-e^{-\lambda 2 t})}$

$\mathbf{N_3(t)=N_{10}-(N_1(t)+N_2(t))}$

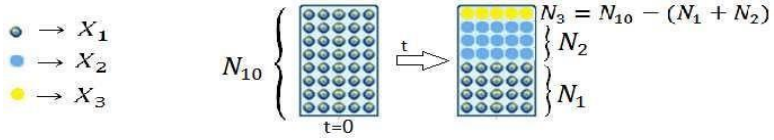

Figure 24. Example: Decay of a Parent Radionuclide into a Daughter Radionuclide

Corresponding Radioactive Activities

For the parent radionuclide:

$\mathbf{A_1=\lambda_1 N_1=A_{10}\,e^{-\lambda 1 t}}$

For the daughter radionuclide:

$\mathbf{A_2=\lambda_2 N_2}$

Using the expression of $N_2(t)$:

$\mathbf{A_2(t)=\lambda_2 N_2=N_{10}\cdot\lambda_1/(\lambda_2-\lambda_1)(e^{-\lambda 1 t}-e^{-\lambda 2 t})}$

Or equivalently:

$\mathbf{A_2(t)=A_{10}\cdot\lambda_1/(\lambda_2-\lambda_1)\,(e^{-\lambda 1 t}-e^{-\lambda 2 t})}$

For the stable nuclide:

$\mathbf{A_3=0}$

since X_3 is stable and does not undergo radioactive decay.

5.11.1 Maximum of N_2 and A_2

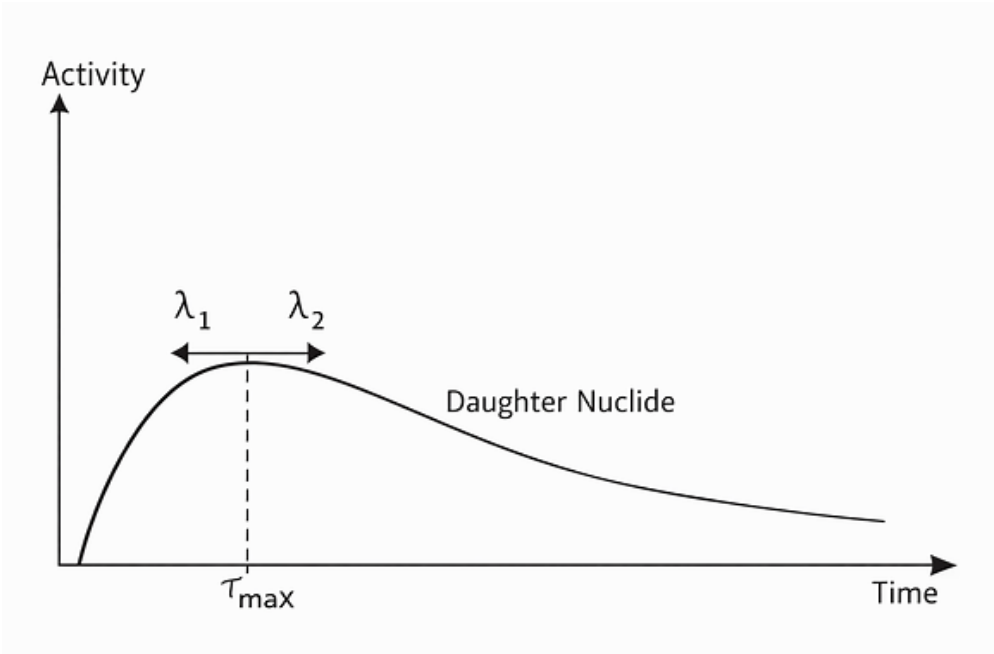

Figure 25. Evolution of the daughter nuclide activity and calculation of T_{max}

At times t= 0 and t→∞, the number of daughter nuclei $N_2(t)$ and their activity $A_2(t)$ are both equal to zero. Therefore, they must reach a **maximum** at some intermediate time t=tmax.

To determine this maximum, we set the derivative of $N_2(t)$ or $A_2(t)$ to zero:

$$\mathbf{(dN_2/dt)t=t_{max}=0 \text{ or } (dA_2/dt)t=t_{max}=0}$$

Solving this condition yields:

$$\mathbf{t_{max}= \ln(\lambda_2/\lambda_1)/(\lambda_2-\lambda_1)}$$

This expression gives the time at which the **daughter activity** reaches its peak. It depends only on the **decay constants** of the parent (λ_1) and daughter (λ_2) radionuclides.

5.11.2 Equilibrium Between Parent and Daughter Activities

We consider two radioactive nuclides with half-lives T_1 and T_2. Depending on the relative magnitudes of these half-lives, three situations may occur:

- $\mathbf{T_1>T_2}$: an equilibrium is reached
- $\mathbf{T_1<T_2}$: no equilibrium is possible
- $\mathbf{T_1\approx T_2}$: case of comparable half-lives

An equilibrium exists when the ratio

$A_2(t)/A_1(t)$=constant

If this ratio is not constant, then no equilibrium is established.

5.11.3 Case T1>T2 (i.e., λ1<λ2) — Transient Equilibrium

When the parent nuclide has a **longer half-life** than the daughter ($\mathbf{T_1 > T_2}$), the decay constant of the parent is **smaller**:

$\mathbf{\lambda_1 < \lambda_2}$

In this situation, a **transient equilibrium** (also called *secular regime equilibrium*) is established.

In transient equilibrium:

- The activity of the daughter nuclide $A_2(t)$ increases until it becomes **almost equal** to the activity of the parent $A_1(t)$.
- After this point, both activities decrease **in parallel**, with the same effective decay constant (that of the parent).

Mathematically, after a sufficiently long time:

$\mathbf{A_2(t) \approx A_1(t)}$ and the ratio becomes nearly constant:
$\mathbf{A_2(t)/A1(t) \approx \lambda_2/(\lambda_2 - \lambda_1)}$

This is the signature of **transient equilibrium**.

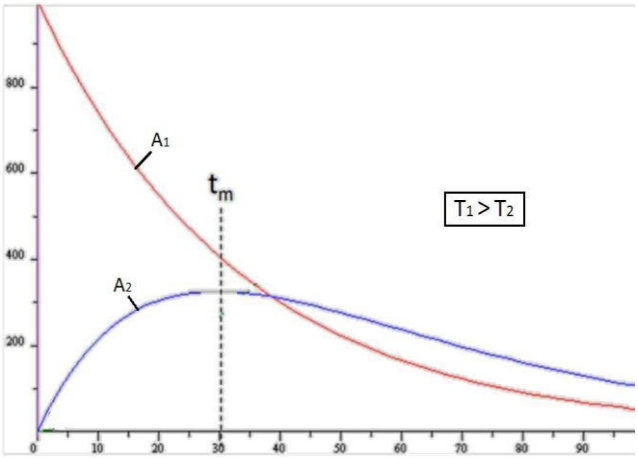

Figure 26. Transient Equilibrium

Transient Equilibrium

After a sufficiently long decay time ($t \gg t_{max}$), and since

$\lambda_1 < \lambda_2$, the activity of the daughter nuclide becomes:

$\mathbf{A_2(t)/A_1(t) = \lambda_2/(\lambda_2 - \lambda_1) = constant > 1}$

This means that the daughter activity becomes **proportional** to the parent activity. From this moment on, the daughter nuclei decay with the **same effective half-life as the parent**, because the production rate of daughter nuclei (from the parent) compensates for their faster decay.

In this situation, the system reaches what is called a **transient equilibrium**.

5.11.4 When T1≫T2 (i.e., λ1≪λ2) secular equilibrium

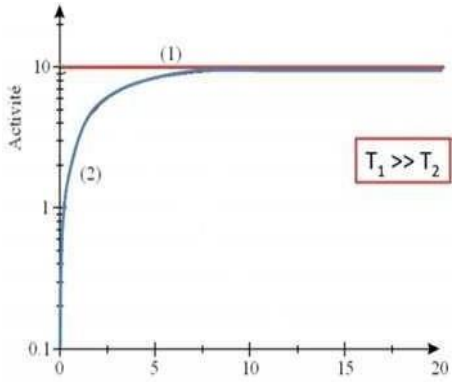

Figure 27. Secular Equilibrium

For small values of time t, and when the parent half-life is much longer than the daughter half-life (**$T_1 \gg T_2$, i.e., $\lambda_1 \ll \lambda_2$**), the activities of the parent and daughter nuclides become:

$A_2(t)/A_1(t) \approx 1$

In this situation, the two activities are essentially **equal**. The daughter nuclide is produced so rapidly (because the parent decays very slowly) that its activity follows that of the parent almost instantaneously.

Thus, the system reaches what is called a **secular equilibrium**.

5.11.5 When T1≈T2 (i.e., λ1≈λ2)

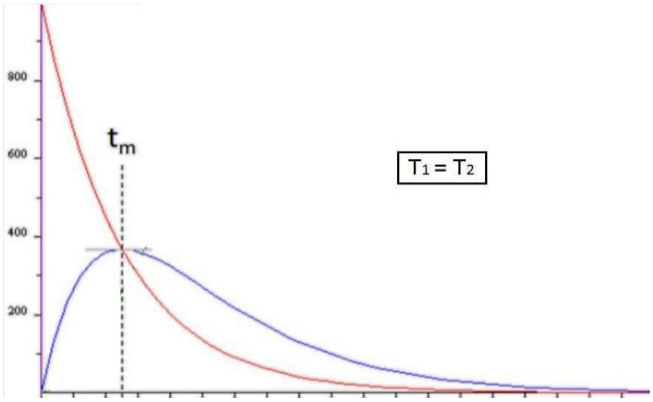

Figure 28. Absence of Equilibrium

Absence of Equilibrium

For this case, the ratio of the daughter activity to the parent activity is:

$$A_2(t)/A_1(t) = \lambda_2/(\lambda_2-\lambda_1)\,[1-e^{-(\lambda 2-\lambda 1)t}]$$

Since this ratio **depends on time**, it is **not constant**, and therefore **no equilibrium is established** between the parent and daughter activities.

Remark

In this specific case, when A_2 reaches its maximum, it becomes equal to A_1: $t=t_m \rightarrow A_2=A_1$ or equivalently: $A_2(t_{max})=A_1(t_{max})$.

5.11.6 When T1<T2 (i.e., λ1>λ2) — Non-Equilibrium

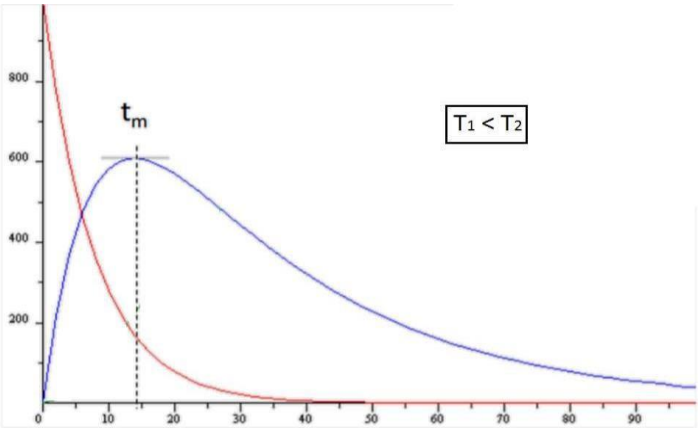

Figure 29.Non-Equilibrium

Radioactive equilibrium is **never reached** in this case because, for sufficiently large times t, only the **daughter nuclei** remain; the parent nuclide has completely disappeared.

5.12 Artificial Nuclear Reactions

These reactions occur when nuclei are bombarded with subatomic particles such as protons, neutrons, electrons, or helium nuclei (alpha particles).

5.12.1 Aston Curve

A nucleus is more stable when its **binding energy** is high. The **average binding energy per nucleon**, E/A, is plotted as a function of the mass number A.

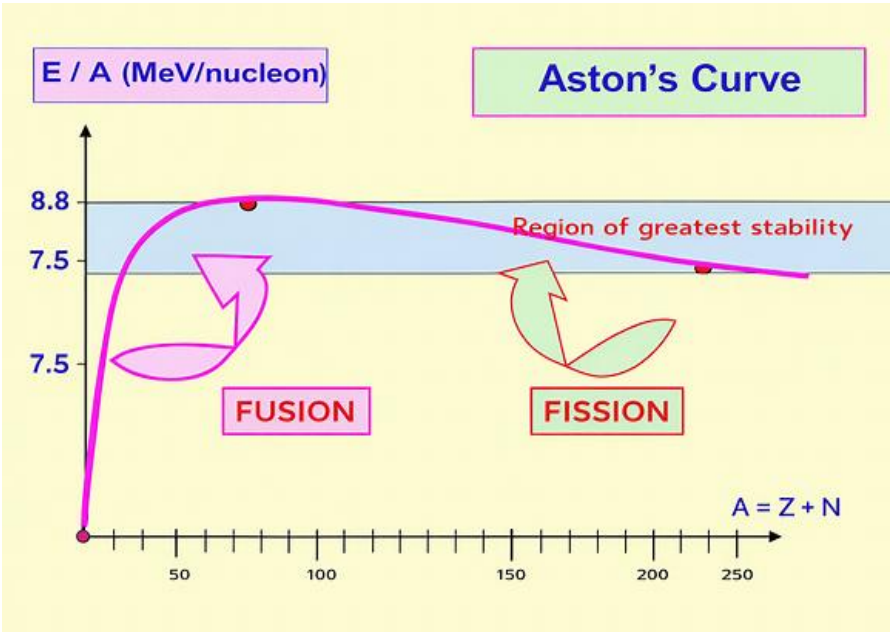

Figure 30. Aston Curve

The resulting curve exhibits a **maximum near** A=60. The nuclei corresponding to this region are the **most stable** known in nature.

Atoms with a **low average binding energy per nucleon** (E/A<7.5 MeV/nucleon) tend to **stabilize** by moving toward the **zone of maximum stability** near A=60.

Two distinct processes can lead to this stabilization:

- **Stabilization of light nuclei → Fusion**
- **Stabilization of heavy nuclei → Fission**

5.12.2 Fission Reaction

A fission reaction involves the **splitting of certain heavy nuclei** into two fragments of comparable mass, triggered by the impact of a projectile (typically a neutron), and accompanied by the release of a large amount of energy.

Example:

$$^{235}_{92}U + ^{1}_{0}n ==> ^{87}_{35}Br + ^{146}_{57}La + 3^{1}_{0}n + E$$

Where:

- A>200: heavy nucleus
- 72<A<162: resulting fragments

Once initiated, the reaction becomes **self-sustaining**, and the energy released **suddenly** is **explosive** — as in the case of an **atomic bomb**.

5.12.3 Fusion Reaction

Fusion is the **combination of two very light nuclei** into a heavier nucleus, with the **ejection of a neutron or proton**, and the release of a **very large amount of energy**.

Example:

$$^{3}_{1}H + ^{2}_{1}H ==> ^{4}_{2}He + ^{1}_{0}n + E$$

The energy released is **considerable**, but the reaction requires **extremely high temperatures**, around **1 million °C**. The **hydrogen bomb** is a direct application of these **thermonuclear reactions**. However, **controlling** the energy released remains **largely unresolved**.

5.12.4 Nuclear Transmutations

These reactions produce **nuclides** whose **mass number** is very close to that of the **target nucleus**.

Examples:

$$^{14}_{7}N + ^{4}_{2}He ==> ^{17}_{8}O + ^{1}_{1}H$$

$$^{27}_{13}Al + ^{4}_{2}He ==> ^{30}_{15}P + ^{1}_{0}n$$

5.13 Energy and Mass Defect

The energy released during nuclear reactions is calculated using **Einstein's principle**:

$\Delta E = \Delta m \cdot c^2$

Where:

- Δm is the **mass defect**
- c is the **speed of light**

5.14 Applications of Radioactivity

5.14.1 In Chemistry

Radioactivity is used in several chemical applications, including:

- Determination of molecular structures
- Study of reaction mechanisms
- Investigation of absorption and diffusion phenomena
- Control of the efficiency of separation and purification methods

- Measurement of the solubility of substances considered insoluble
- Study of metabolic processes, such as:
  - establishing the carbon cycle in chlorophyll photosynthesis
  - the biosynthesis of hemoglobin

By introducing into a molecule an isotope (e.g. ^{12}C, ^{1}H) in place of a specific atom (^{13}C, ^{2}H), these isotopes can be **traced** thanks to their radiation.

5.14.2 In Medicine and Biology

Medical applications of radioactivity were theoretically considered shortly after its discovery, but it is mainly during the past half-century that radioactivity has become fully integrated into diagnostic (medical imaging) and therapeutic (radiotherapy) techniques.

Radioisotopes are used for:

- diagnosing and treating diseases
- providing valuable information on the mechanisms of biological reactions

For example, **iodine-131** reduces thyroid hyperactivity and is used to treat goiters.

Nuclear medicine is the medical field that uses radioactivity both to explore the human body and to treat it.

Among the medical imaging techniques in nuclear medicine are:

- **scintigraphy**
- **positron emission tomography (PET)**

5.14.3 Dating of Rocks

This method relies on determining the ratio of 206Pb to 207Pb in a uranium ore.

5.14.3 Dating of Rocks

This method relies on determining the ratio of 206Pb to 207Pb in a uranium ore.

5.15 Dangers of Radioactivity

- **Pathological effects:** cancers, leukemia, damage to mucous membranes…
- **Genetic effects:** these effects impact future generations.

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