University IBN KHALDOUN of Tiaret

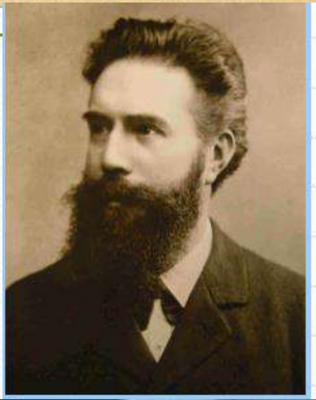
Biophysic Radiation

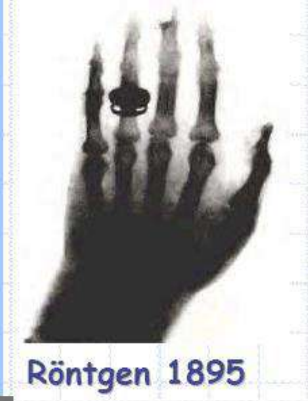
Mrs CHIBANI F

Introduction:

1895

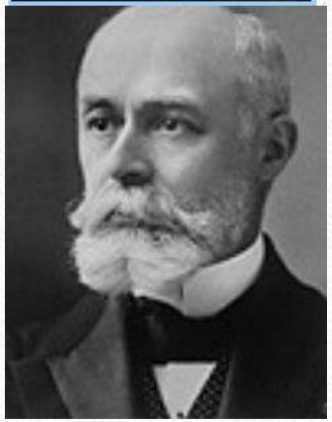
On December 28, Wilhelm Conrad Röntgen publishes the paper "On a New Kind of Rays" announcing the discovery of X-rays (X symbolizes the unknown).





1896

Henri Becquerel discovers the spontaneous emission of a new type of ionizing radiation by the element uranium, meaning it produces electric charges as it passes through air.



1897

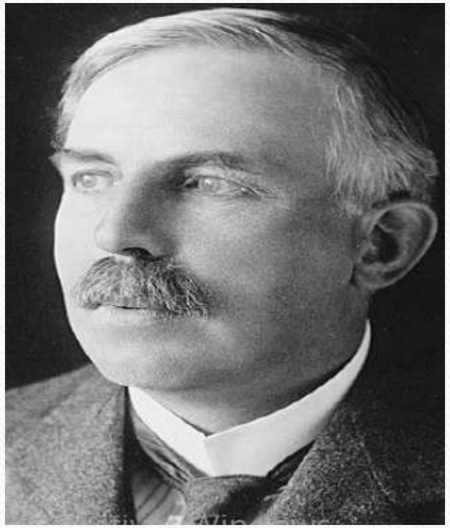
J.J. Thomson characterizes cathode rays and determines that electrons are elementary constituents of atoms, for which he proposes the "plum pudding" model.

1898

Marie and Pierre Curie discover polonium and radium. Marie Curie introduces the term radioactivity to describe the rays emitted by uranium, thorium, polonium, radium, and others.

1899

Several scientists demonstrate the existence of two types of radiation emitted by uranium. Rutherford would later name them alpha and beta rays.



1900

Paul Villard identifies a third type of radioactivity: gamma radiation.

What, then, is the difference between radiation and radioactivity?

Radiation is the process of transmitting energy in the form of waves (electromagnetic or acoustic) or particles through space.

Radioactivity is the process of the spontaneous disintegration of unstable atomic nuclei, usually accompanied by the emission of ionizing radiation.

Definition of Radiation:

It is the process of emitting or transmitting energy in the form of:

Electromagnetic waves (radio waves, infrared, light, X-rays, gamma rays)

Particles (alpha particles, beta particles, neutrons)

Acoustic waves.

Certain types of radiation can:

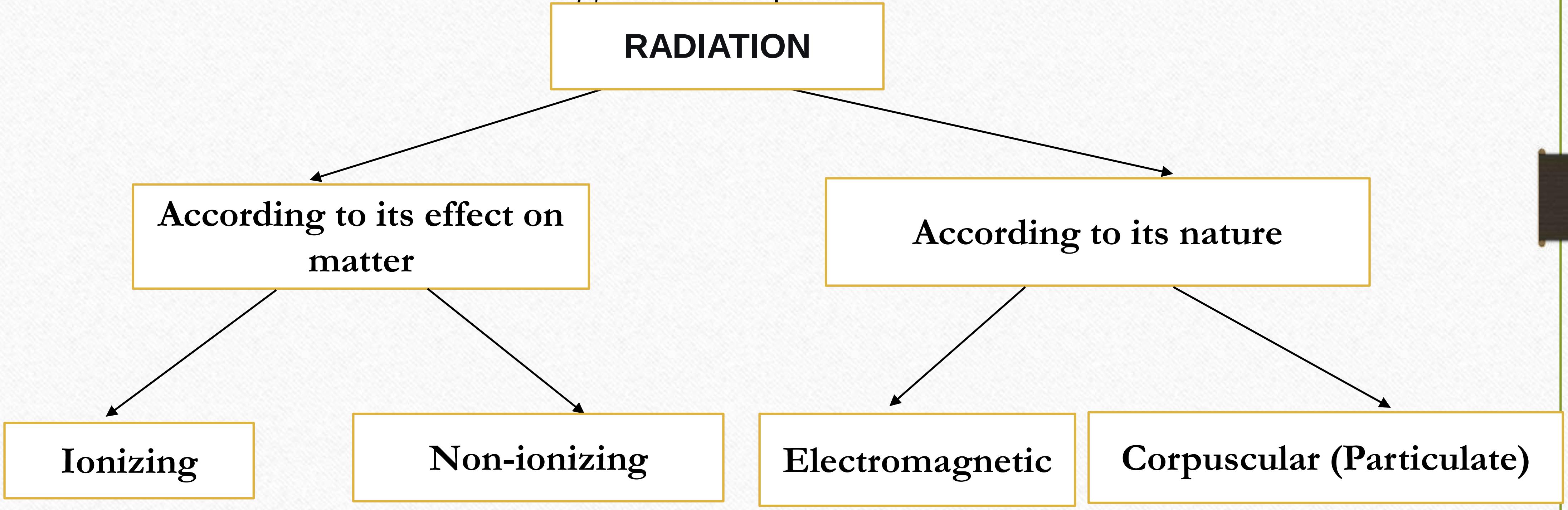
Penetrate matter, including biological tissues, making them useful for diagnostic imaging (bone X-rays, mammography, scintigraphy, etc.).

Destroy cells or inhibit their multiplication, which justifies their use in certain treatments (radiotherapy, laser therapy, etc.).

Classification of Radiation:

Based on their effect on matter: ionizing, non-ionizing.

Based on their nature: electromagnetic and particulate.



Electromagnetic Radiation (EMR) corresponds to the propagation of an electric field $\vec{E}$ and a magnetic field $\vec{B}$ perpendicular to each other. This propagation occurs at a constant speed C (the speed of light), with zero mass.

The vectors $(\overrightarrow{E}; \overrightarrow{B}; \vec{k})$ form a right-handed coordinate system (trihedron):

$\vec{E}$: Electric field

$\vec{B}$: Magnetic field

$\vec{k}$: Wave vector

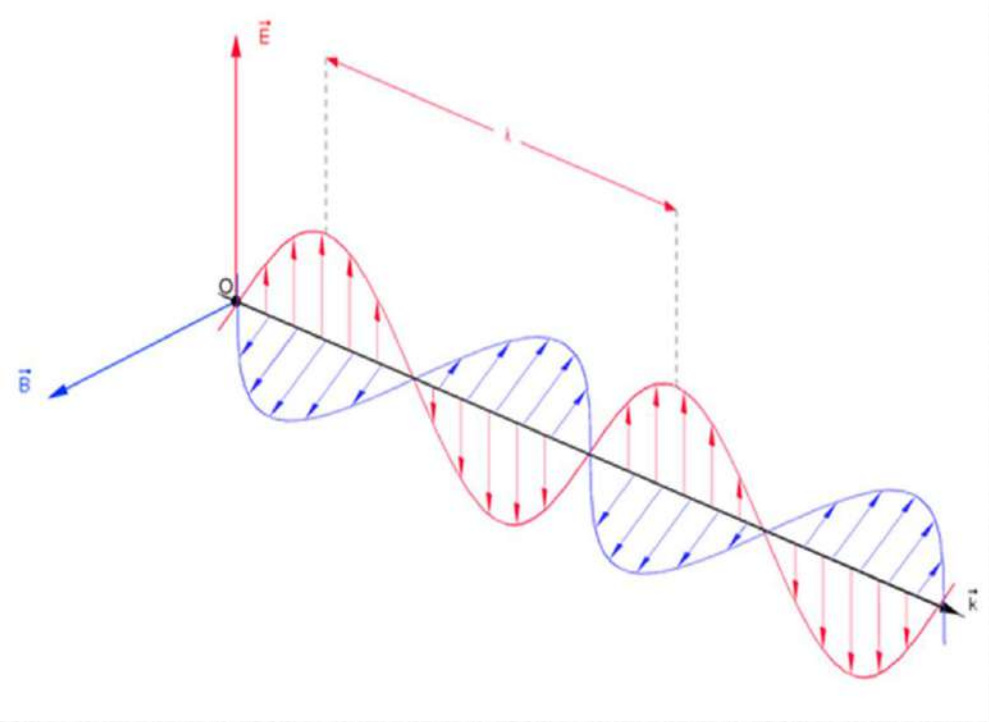
The wavelength λ is given by:

$\lambda = C / \nu = C\,T$

where $\nu = \frac{1}{T}$ and $C = 3.10^8 ms^{-1}$

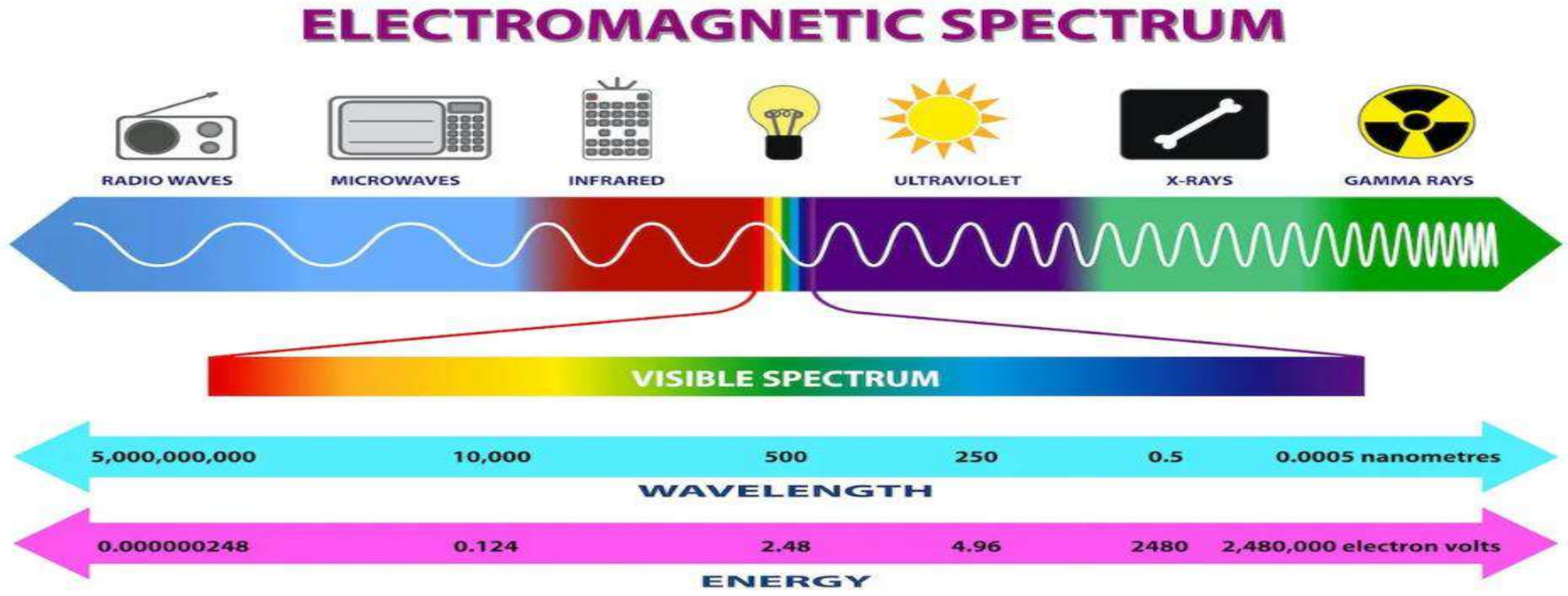
ν: Frequency of the electromagnetic wave

T: Period



The electromagnetic spectrum (EMR) encompasses a whole range of energies, from very low energy, such as radio waves, to very high energy, such as gamma rays. The energy of the radiation varies according to its frequency.

The electromagnetic spectrum is divided into non-ionizing radiation and ionizing radiation, based on the frequency of the electromagnetic waves.



A diagram of the electromagnetic spectrum. (Image credit: Getty Images)

Why is the electromagnetic spectrum important?
The EM spectrum is the means by which our universe transfers energy and information from one location to another. Depending on the type of radiation, however, different knowledge can be gleaned.

Most of the waves we are exposed to in our daily lives fall into the categories of low and extremely low frequencies. The electrical current supplied by the power grid, as well as all the electrical devices it powers, is limited to 50 Hz in most European countries (60 Hz in the United States and Japan).

Corpuscular (Particulate) Radiation (PR) consists of subatomic particles moving at very high speeds. These particles have mass and may possess an electric charge, such as electrons, protons, neutrons, alpha particles (He^{++}), and positrons (e^{+}).

Wave–Particle Duality - Particles and light behave both as waves and as particles.

A wavelength can be associated with particles, known as the de Broglie wavelength. An important experiment that confirmed the wave nature of light is Young's double-slit experiment.

In 1905, Einstein introduced the idea that light is composed of small packets of energy, which can be likened to particles.

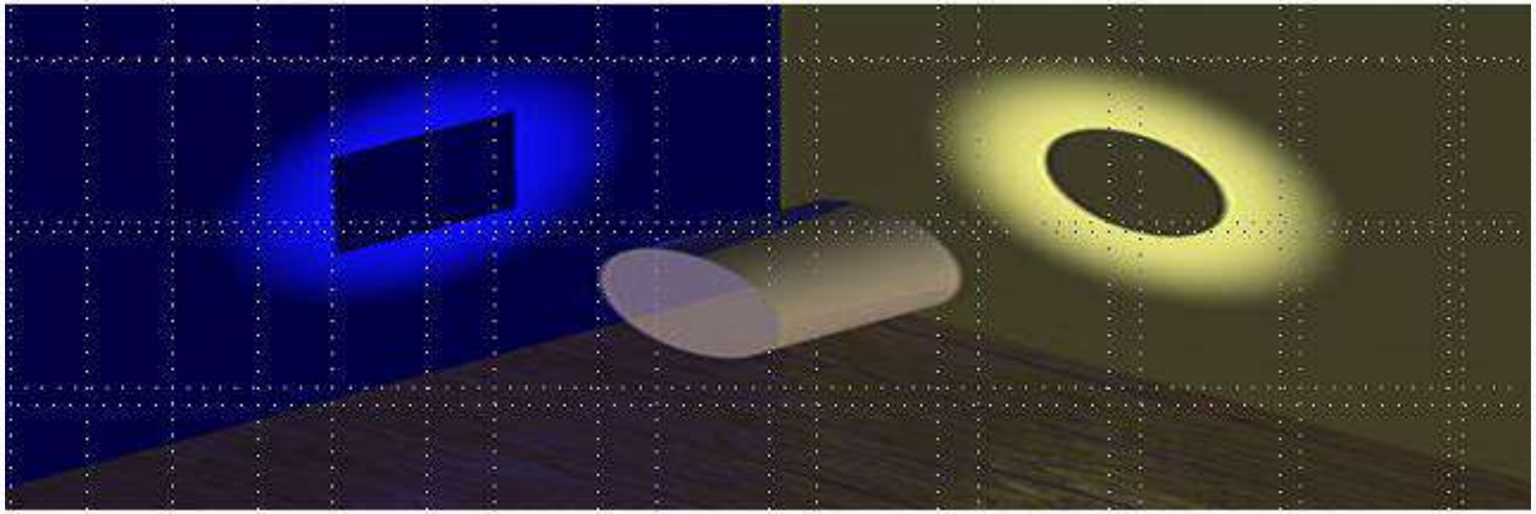
Wave–particle duality was experimentally discovered by several scientists, but it was de Broglie in 1924 who introduced the concept of a particle's wavelength.

The wavelength of a particle is inversely proportional to its momentum.

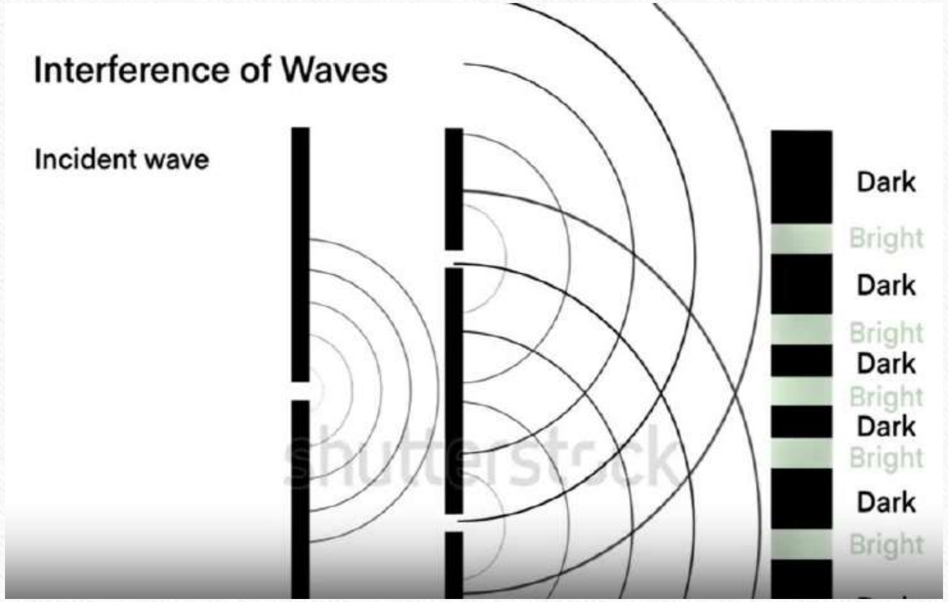
Light is both a wave and a particle because:

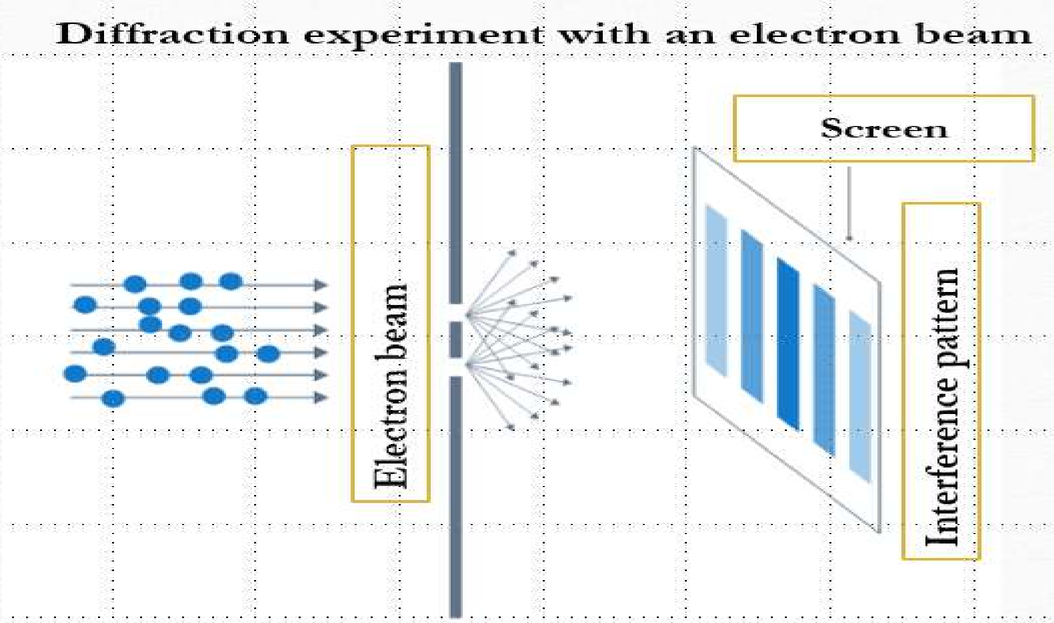
It is composed of packets of energy, which are particles called photons.

At the same time, light is a wave, as it interferes with itself and undergoes diffraction.



Metaphor of the Cylinder: an object possessing both the properties of a disc and a rectangle.





The interference of light and the diffraction of electrons are two wave phenomena that illustrate the wave nature of both light and particles like electrons.

These two phenomena show that light and matter can behave as both waves and particles, depending on the conditions of observation, which is a cornerstone of modern physics.

What is the relationship between waves and particles?

De Broglie discovered that if electrons behave like waves, then particles must have a wavelength. He related this wavelength to the momentum of the particles.

Energy of a wave and of a photon

In the case of light, which is an electromagnetic wave, the quantum of energy is inversely proportional to the wavelength.

$E_{photon} = h\nu$ avec $\nu = \frac{C}{\lambda}$

E: Energy in Joules

h : Planck's constant, $h = 6{,}63.10^{-34} m^2.\frac{kg}{s}$

C : Speed of light, $C = 3.10^8 m/s$

Energy of a particle:

According to Einstein, the energy of a particle with mass m is:

$$E_{particule} = mC^2$$

Momentum:

- For a photon:

$$E_{photon} = \text{h}\nu = \frac{hC}{\lambda}$$

- For a particle with mass:

$$E_{particule} = mC^2$$

- From the photon energy relation, we have:

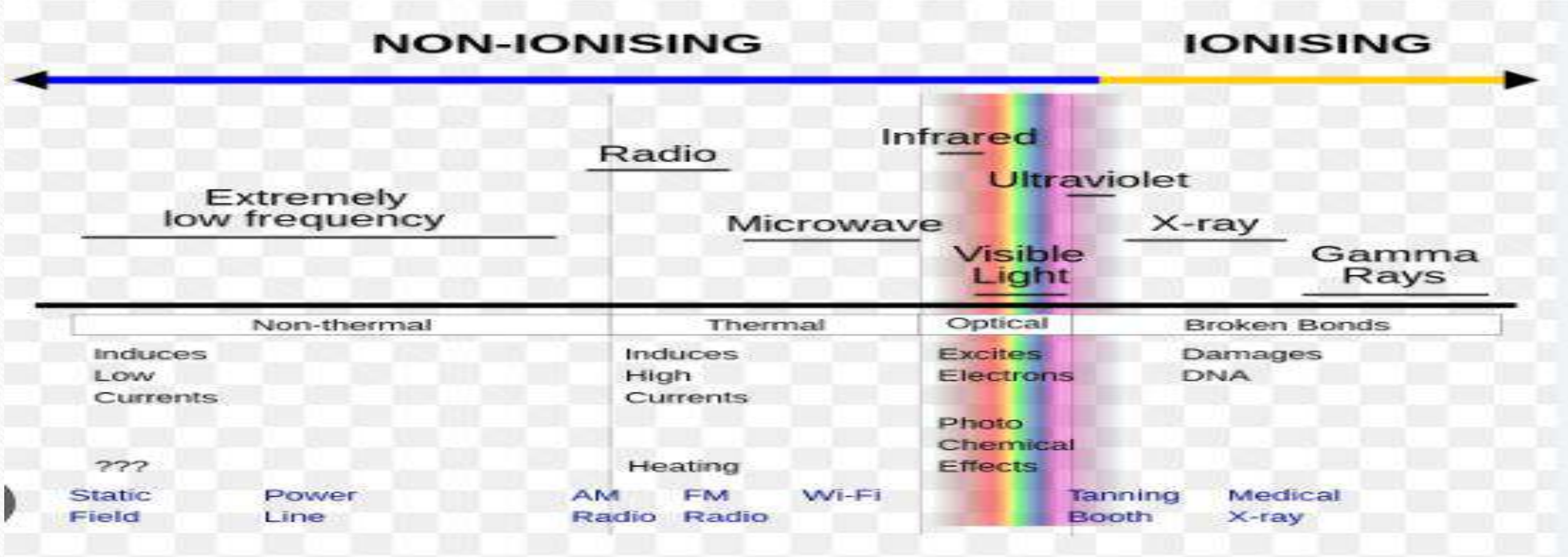
$$\frac{h}{\lambda} = mC = \frac{E}{C} = P\text{(momentum)}$$

Another unit for measuring energy is:

1 eV=1.6×10−19

Ionizing and Non-Ionizing Radiation:

Ionizing radiation, such as X-rays and gamma rays, has enough energy to remove electrons from atoms, thereby creating ions. In contrast, non-ionizing radiation, such as microwaves and radio waves, does not have enough energy to ionize matter.



Ionizing Radiation

Ionizing radiation can be particulate (alpha particles, beta particles, electrons, neutrons) or electromagnetic (X-rays, gamma rays). It is considered ionizing when it is capable of removing electrons from matter.

Element	First Ionization Energy (eV)
Hydrogen	13,54
Oxygen	13,57
Carbon	11,24
Nitrogen	14,24

Minimum energy values required to remove electrons from the main atoms

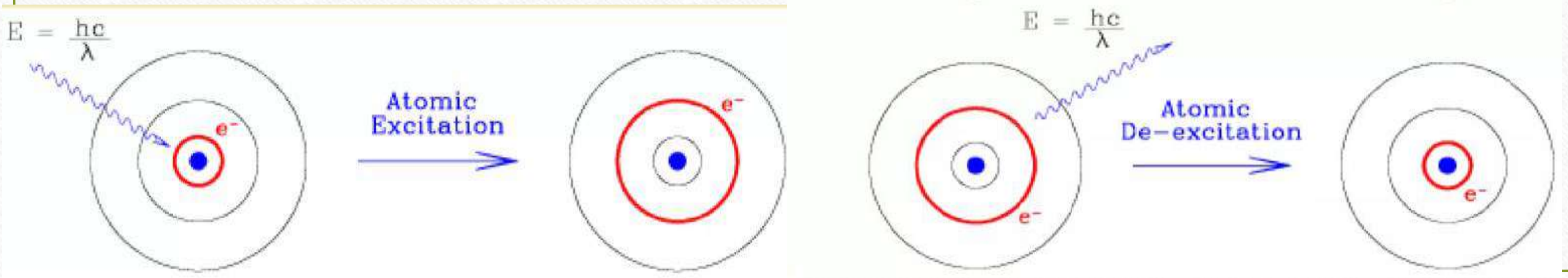
Interaction of Electromagnetic Radiation (X-rays and Gamma Rays) with Matter
X-ray and gamma-ray photons (electromagnetic radiation) interact with matter in three primary ways.

Mechanism of Interaction of Electromagnetic Waves (Photons) with Matter:

1) Atomic Excitation:

The electromagnetic radiation transfers energy to the atom.

- Electrons are then moved to orbits farther from the nucleus than their ground state.
- The atom is thus in an excited state.
- Return to the normal state occurs through the emission of fluorescence.

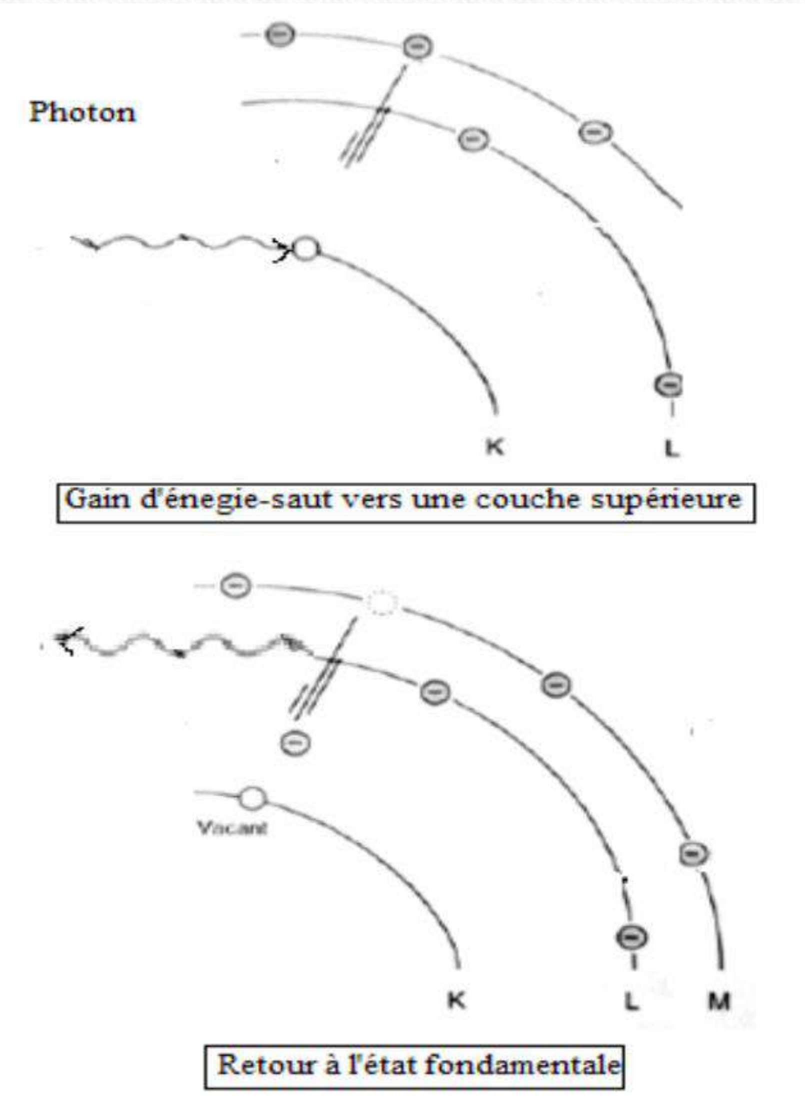


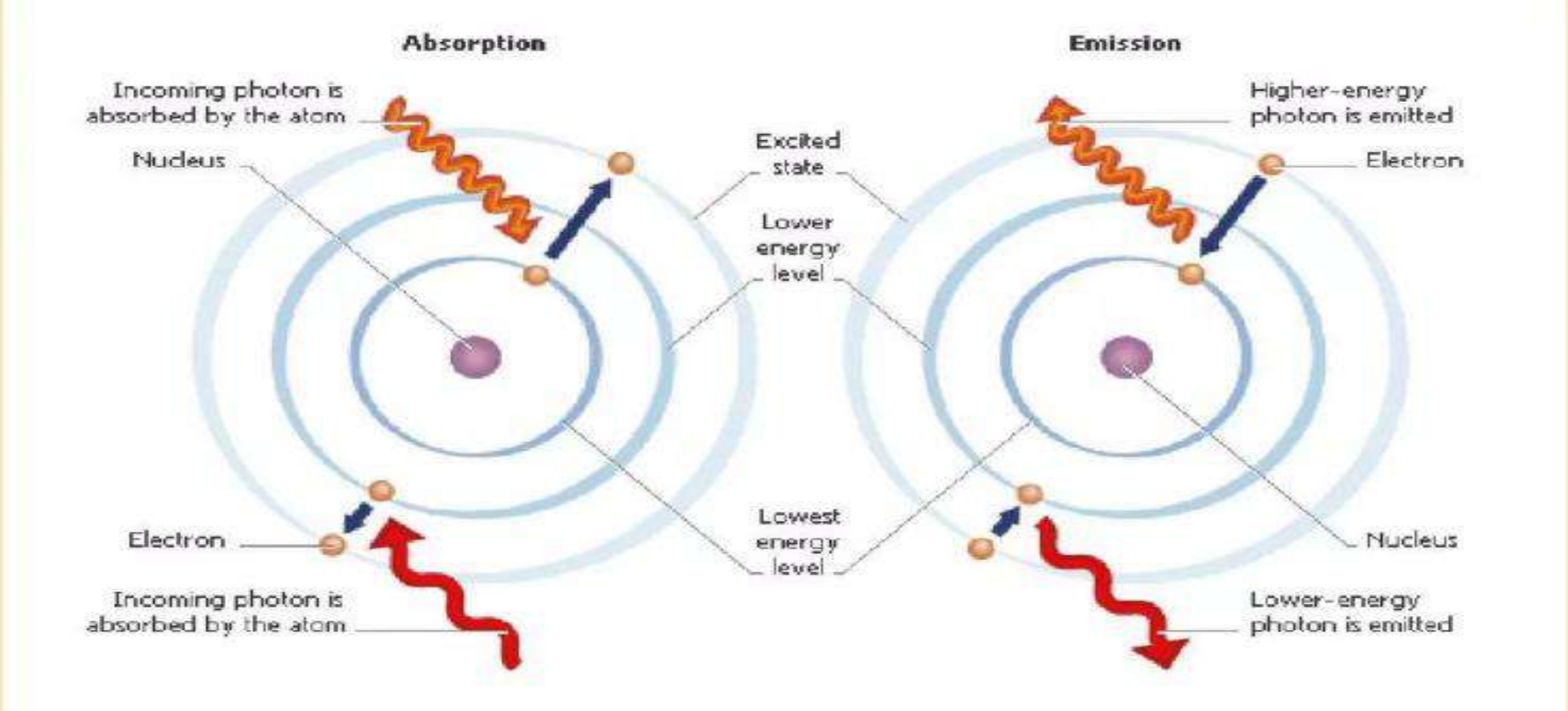
This occurs when
$E_{h\nu} < E_L$

The electron absorbs the photon and is elevated to a higher energy level.

The energy absorbed by the electron is not sufficient to remove it from the atom.

When the electron returns to its lower energy level, it releases the same energy as the absorbed photon$E_{h\nu}$.




Absorption
Emission
Incoming photon is absorbed by the atom
Nucleus
Excited state
Lower energy level
Electron
Incoming photon is absorbed by the atom
Lowest energy level
Higher-energy photon is emitted
Electron
Nucleus
Lower-energy photon is emitted

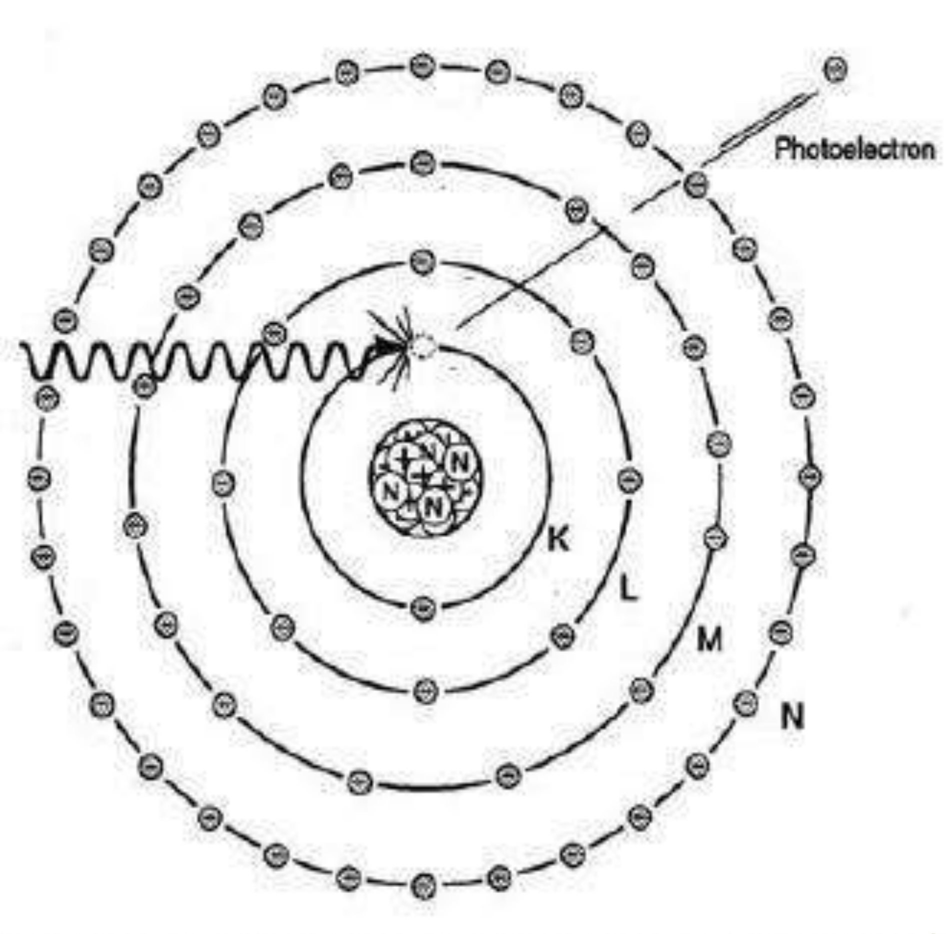
2) The Photoelectric Effect:

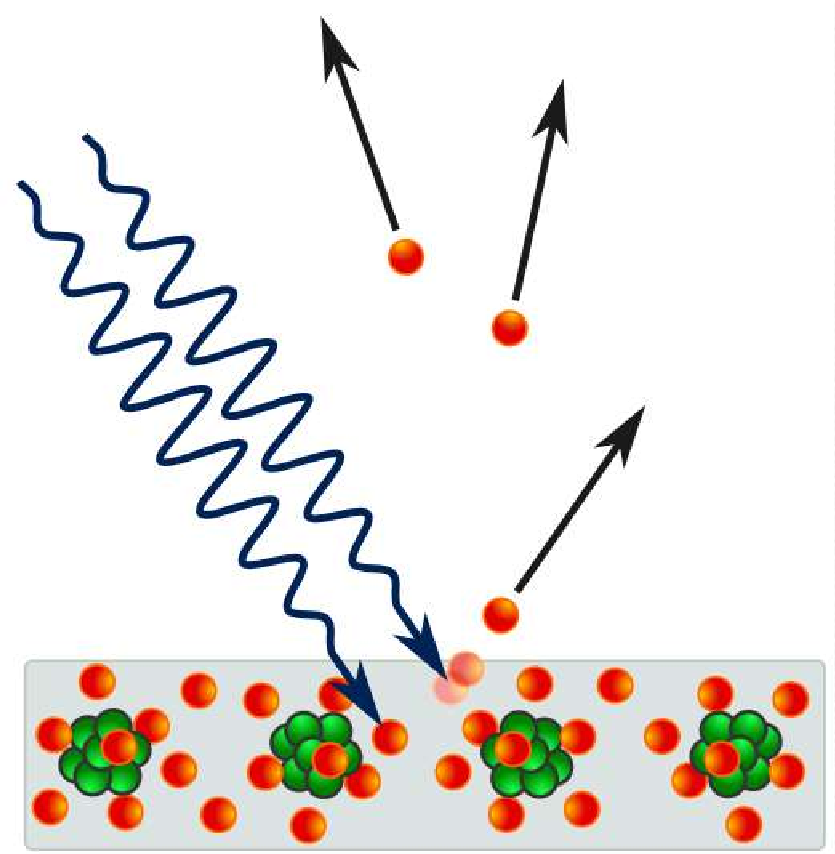
The photon interacts with an electron bound to the atom, where$E_{h\nu} \geq E_L$

•The incident photon disappears after transferring all its energy to the electron.

•The ejected electron carries away a kinetic energy $E_C = E_{h\nu} - E_L$

This mechanism is predominant for photons with relatively low energies when they interact with electrons in the inner (deep) shells.

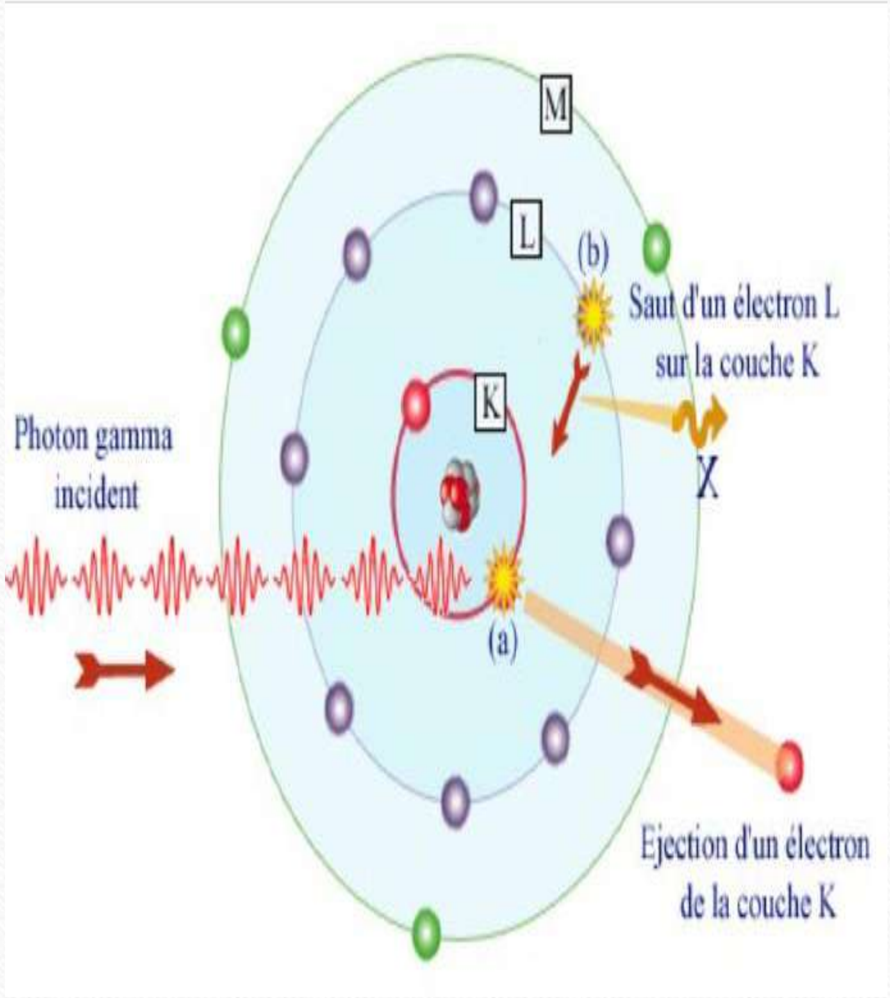


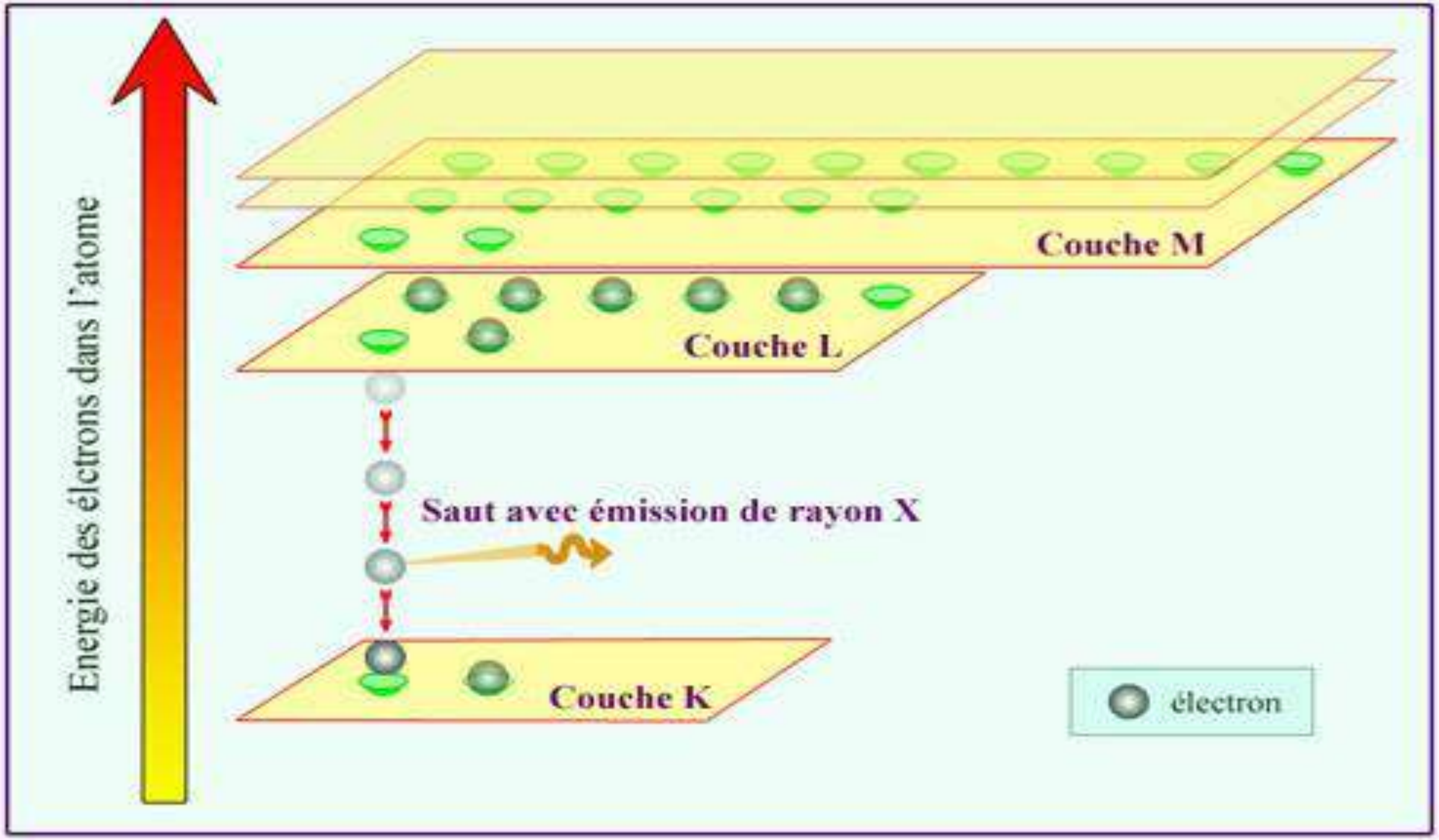


The diagram shows the emission of electrons from a metal plate. The emission of each electron (red particles) requires a minimum amount of energy, which is supplied by a photon (blue waves).

Absorption of a Gamma Ray by an Atom

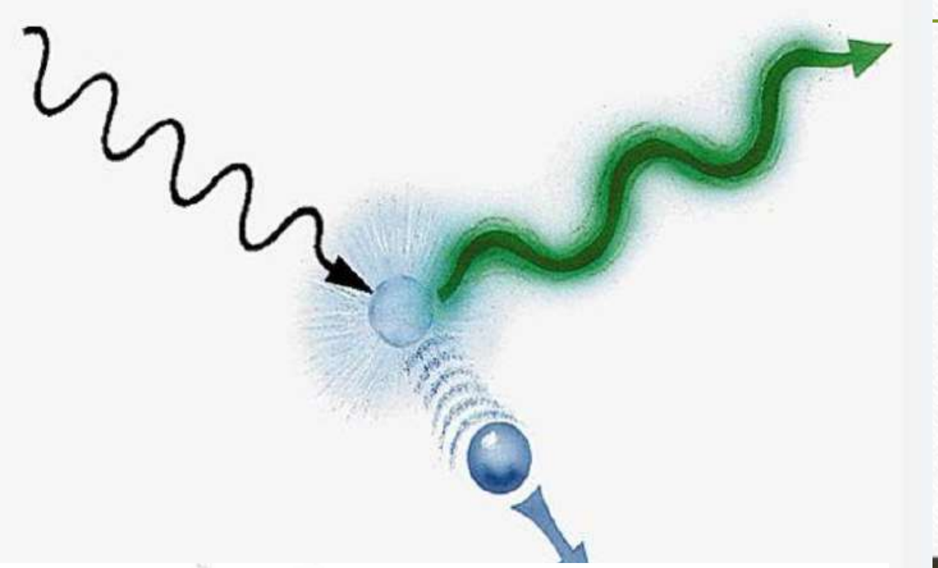
The photoelectric effect occurs in two steps. First, the photon ejects (a) a bound electron from an atom. In the case of a gamma ray, this is typically an electron from the innermost shells, such as the K or L shell (as shown in the figure). Subsequently, the atom, having lost one of its inner electrons, enters an excited state. An electron from a higher, outer shell (b) then fills the vacancy left by the ejected electron. If the ejected electron was from the K shell, as illustrated, an X-ray is emitted during this transition.

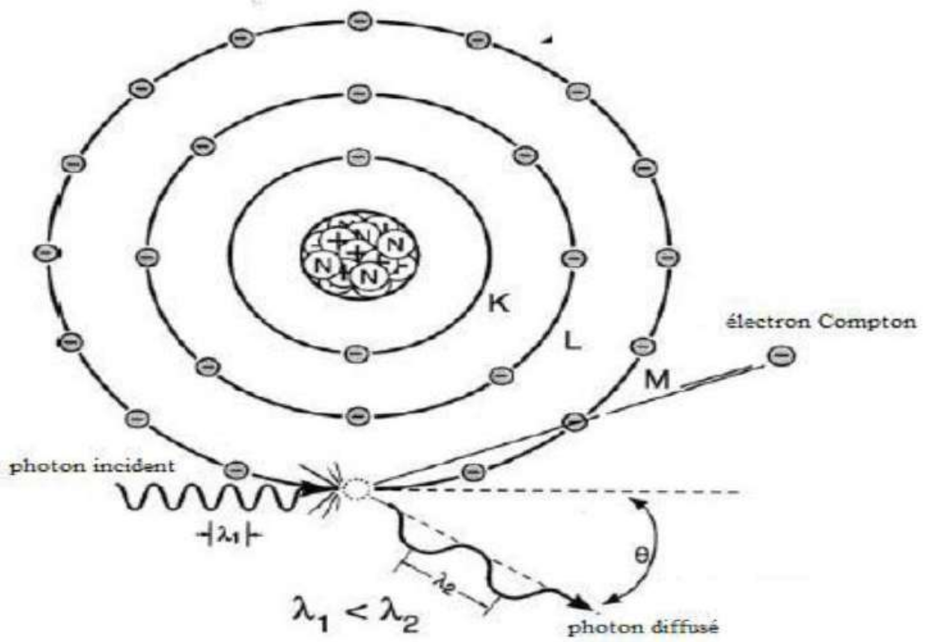



Energie des élctrons dans l'atome
Couche M
Couche L
Saut avec émission de rayon X
Couche K
électron

3) The Compton Effect:

This is a phenomenon in which photons, the particles of light, interact with free electrons. During this interaction, photons transfer a portion of their energy and change direction. This energy transfer results in a change in the wavelength of the scattered photons. This wavelength shift is proportional to the scattering angle and the amount of energy transferred during the collision. This discovery, made by Arthur Compton in 1923, was crucial evidence for the particle nature of light, thereby confirming quantum theory.





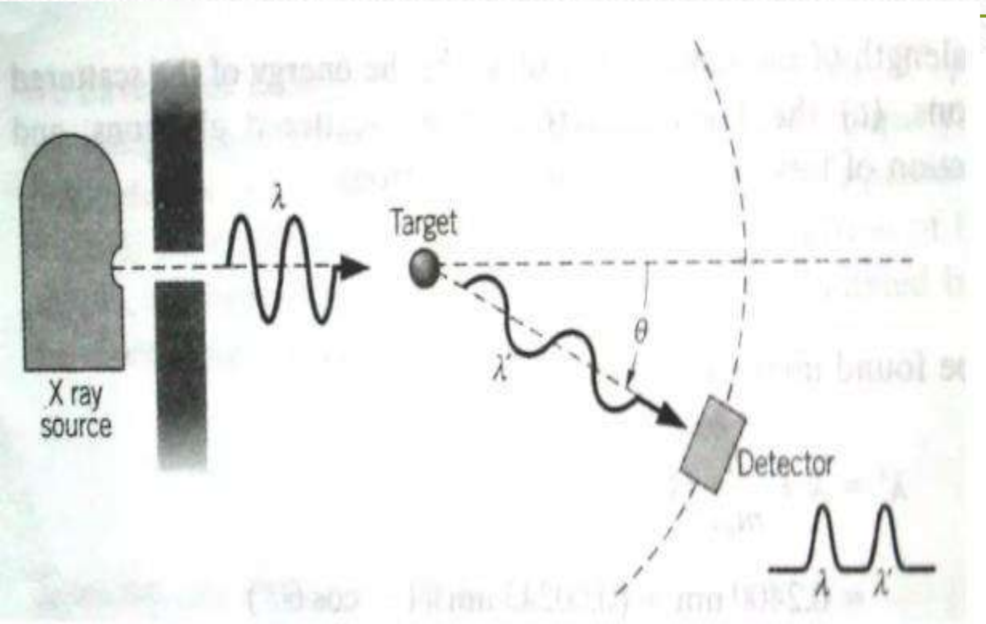
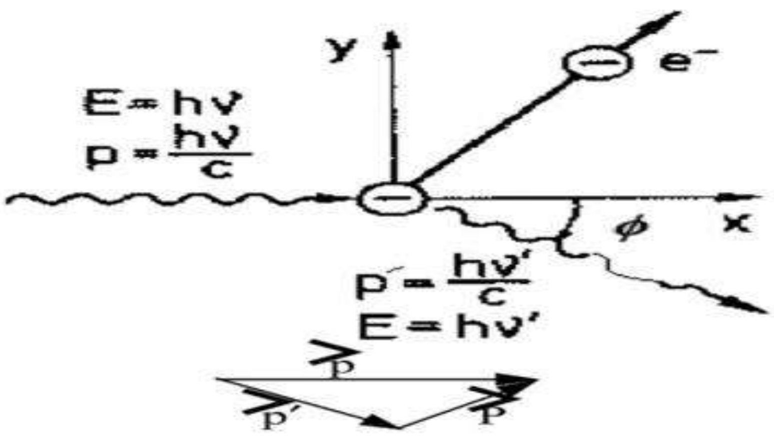


Fig. 4: A Compton effect experiment



(a) An incident photon with wavelength λ, energy E and momentum $\vec{p}$ approaching an electron e at rest.
(b) The incident photon is scattered through an angle ϕ and the struck electron recoils.
(c) Vector diagram for the conservation of momentum.

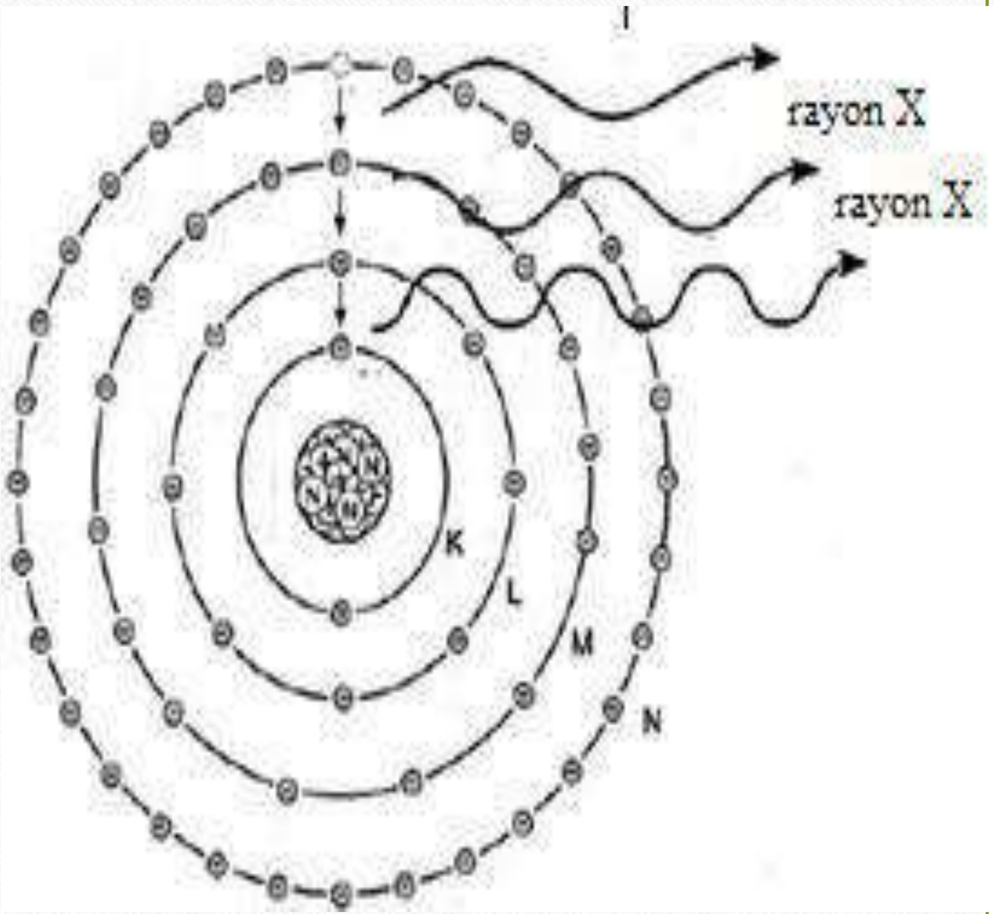
The higher the energy of the incident photon, the more the scattered photons and ejected electrons are emitted in the forward direction—this is referred to as forward scattering.

The cascade of electron jumps from outer shells to inner shells, followed by the emission of radiation, is known as "characteristic radiation".

The atom undergoes electronic rearrangement.

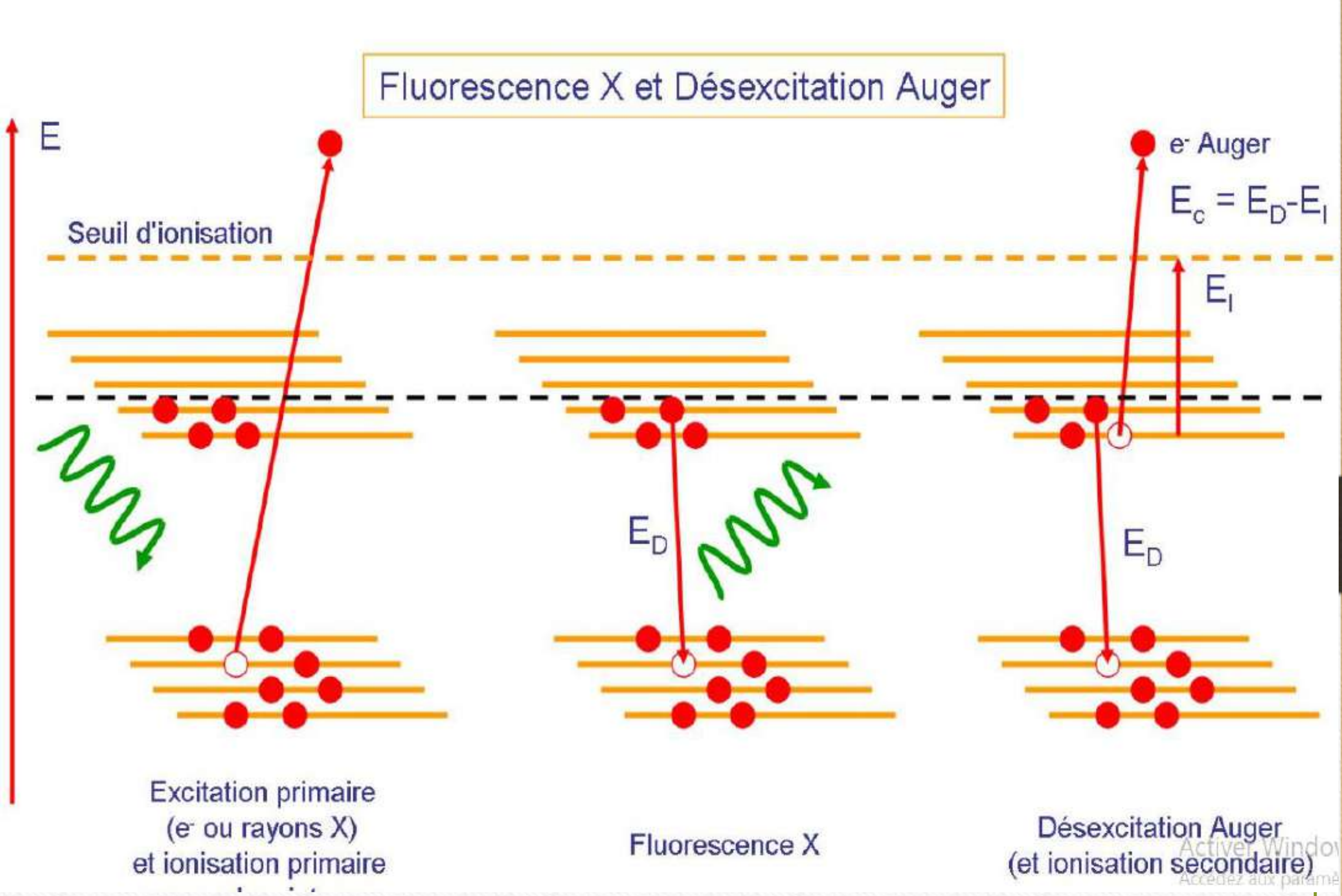
The rule is that electrons occupy the lowest energy levels.

This phenomenon is the fundamental principle behind the generation of X-rays.



Auger Effect:

- This is the interaction of a fluorescence photon, resulting from electronic rearrangement, with an electron in the same atom, when the photon has an energy greater than E_L.
- This results in the ejection of an Auger electron.

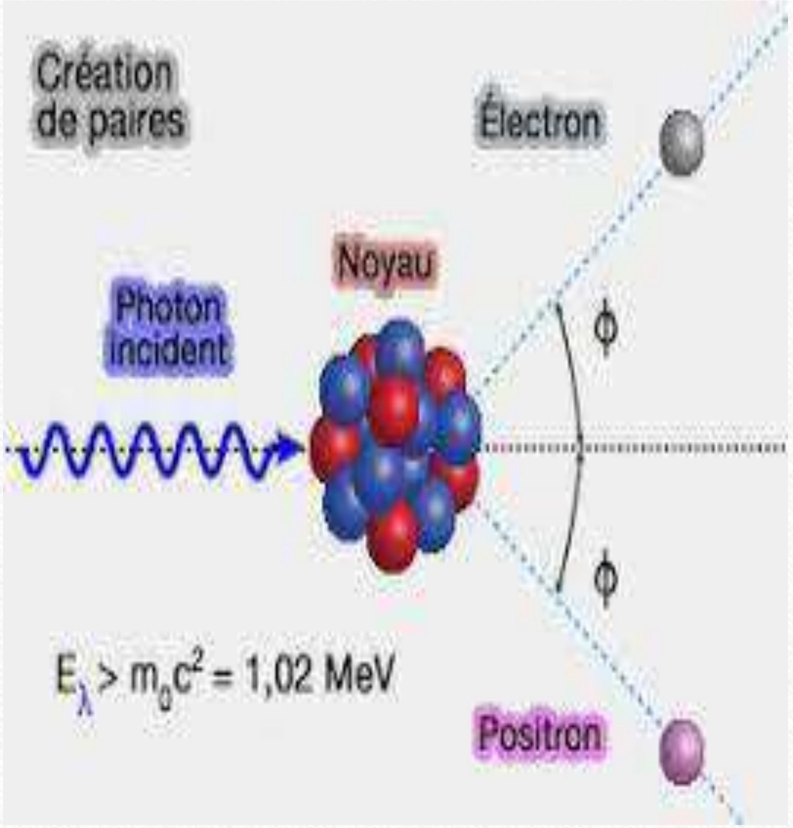


Pair Production or Materialization Effect:

When a high-energy photon interacts with an atomic nucleus, it creates an electron-positron pair.

The energy required for this pair materialization is equal to 1.022 MeV. Below this threshold, this effect is energetically impossible.

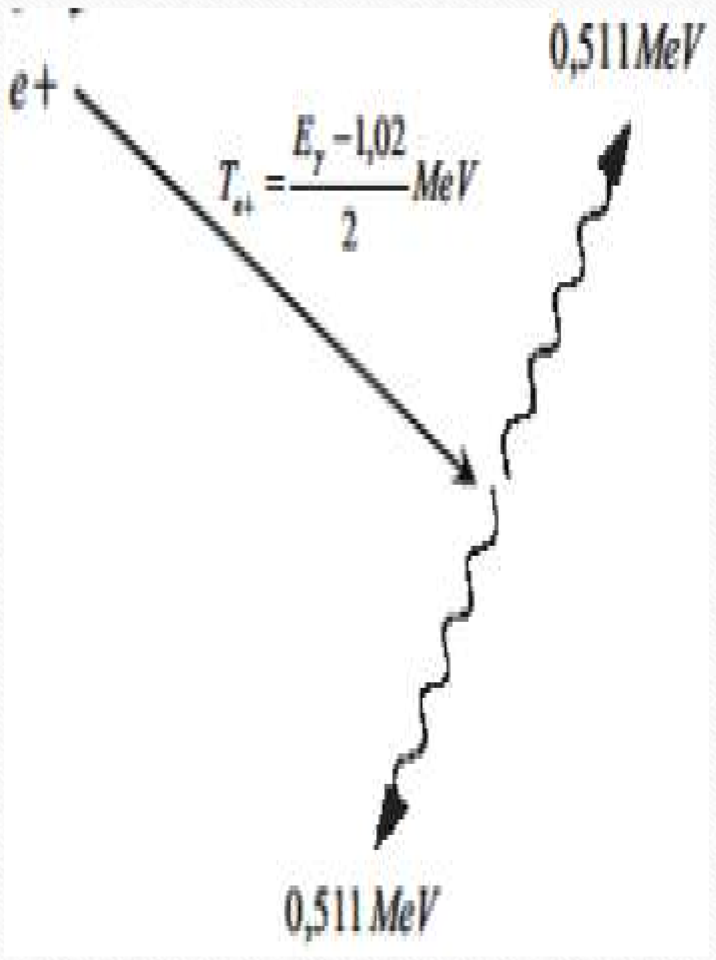
Energy can be converted into mass according to the equation: $\boldsymbol{E = mC^2}$



Fate of the Pair:

The negatron (electron), being more stable, can remain free or attach itself to an atom to form a negative ion.

The positron, being less stable, once slowed down, encounters a negative electron in the surrounding matter. This encounter triggers a dematerialization phenomenon, resulting in the emission of two photons, each of energy 0.511 MeV, emitted at 180° relative to each other.



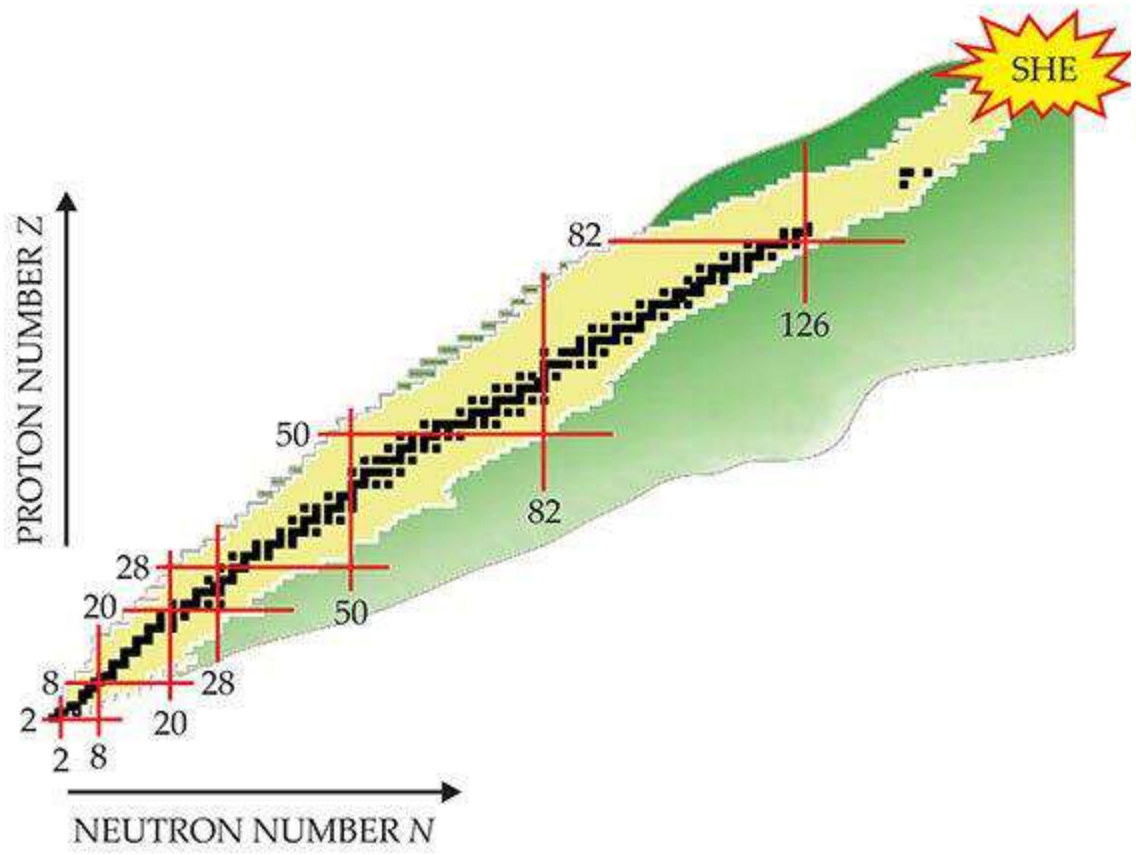
Characteristic	Ordinary Electron	Negatron (electron from beta decay)
Origin	Present around the nucleus in an atom	Result of beta decay of a neutron
Energy	Variable (orbital, thermal)	High kinetic energy (from a few keV to MeV)
Use of the term	General in physics and chemistry	Specific to nuclear physics

Particulate Radiation–Matter Interaction:

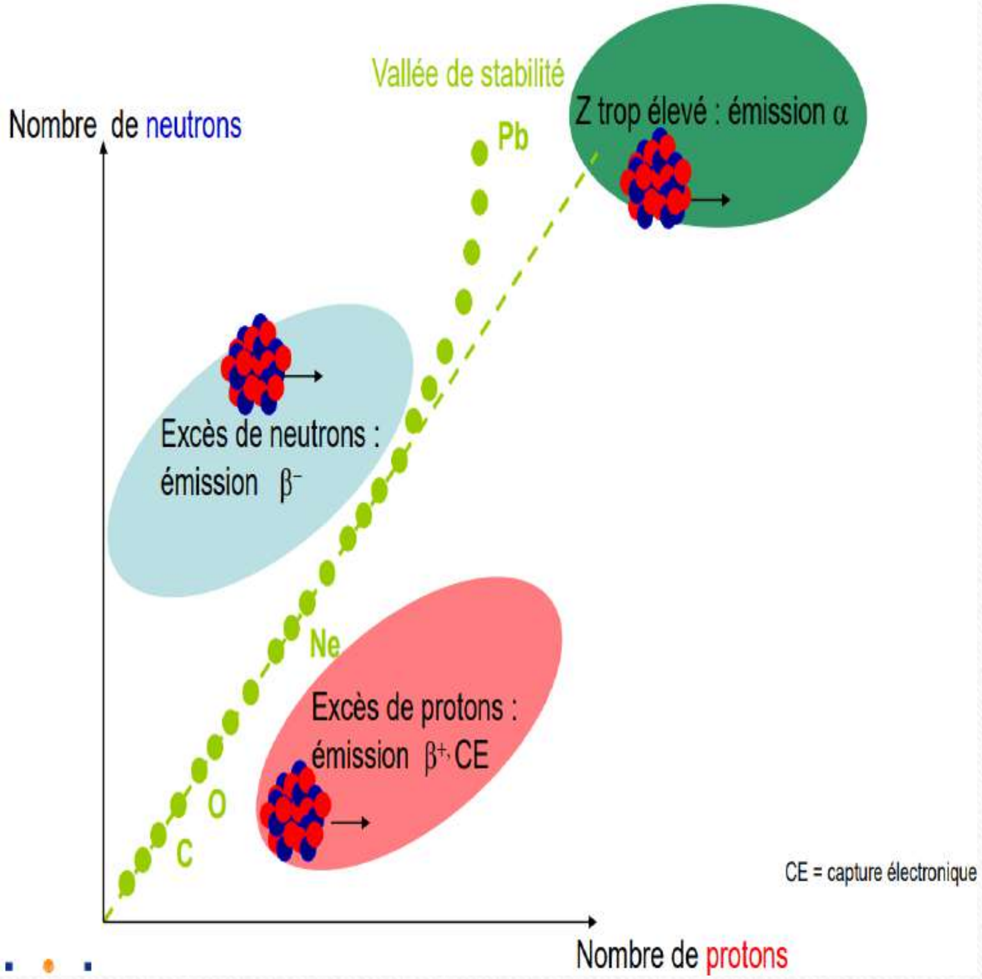
There are three elementary particles: two heavy particles (neutron and proton) and one light particle (electron), to which we can add the positron ($\beta+$) and negatron ($\beta-$).

The interaction of an ionizing material particle with matter is characterized by an energy transfer due to direct or distant impacts (collisions). This transfer causes the particle to slow down on one hand, and produces physical effects (ionization) on the other, continuing until the particle comes to a stop.

Their radiobiological effects are more significant compared to those of electromagnetic radiation (EMR).

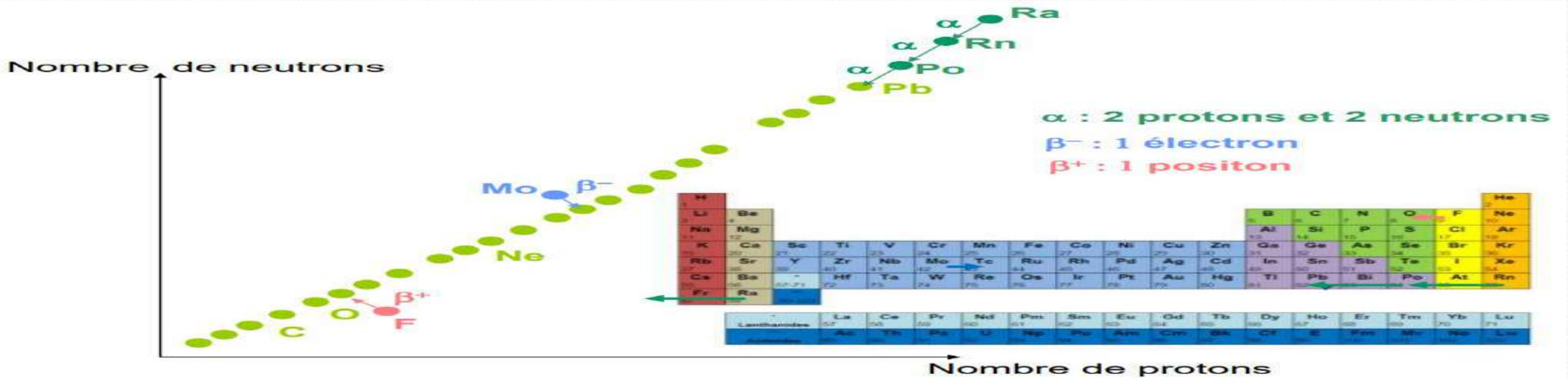


Origine des rayonnements alpha, beta, gamma



Alpha and Beta Radiation:

- α and β radiation come from the nuclear decay of unstable nuclei.
- These decays are almost always followed, after a highly variable amount of time, by de-excitation.
- The daughter nucleus Y de-excites by emitting a photon, called a γ photon.
- The daughter nucleus Y may itself be unstable and decay in turn (radioactive filiation / decay chain).



Uranium-238 Decay Chain (Short Form)

238U**(Uranium)** α→ 234Th(**Thorium)** β→ 234Pa (**Protactinium)** β→ 234U α→ 230Th → 226Ra(**Radium)** α→ 222Rn(**Radon)** α→ 218Po(**Polonium)** → 214Pb(**Lead)** β→ 214Bi(**Bismuth)** β→ 214Po α→ 210Pb β→ 210Bi β→ 210Po α→ 206Pb (stableEnd of chain)

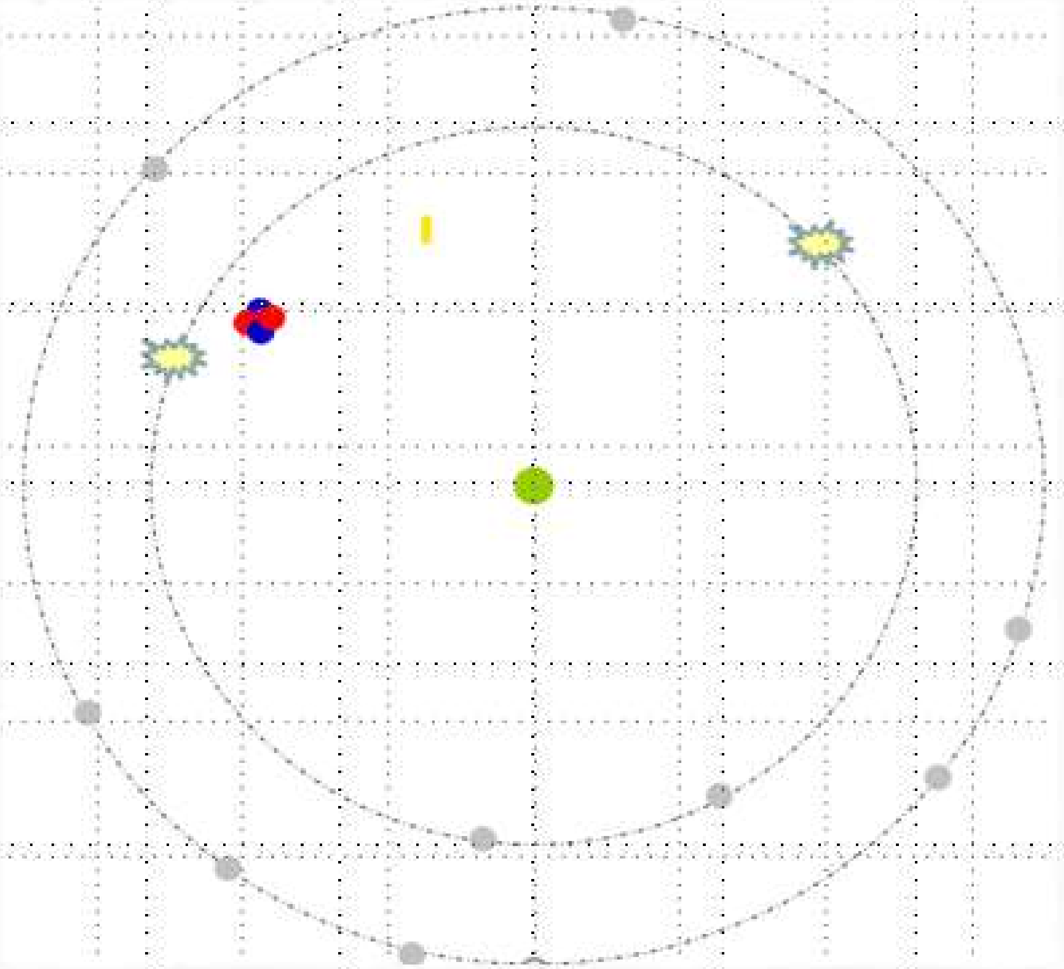
Even Shorter (Major Steps Only):

$^{238}U \rightarrow {}^{234}U \rightarrow {}^{230}Th \rightarrow {}^{226}Ra \rightarrow {}^{222}Rn \rightarrow {}^{210}Pb \rightarrow {}^{210}Po \rightarrow {}^{206}Pb$

It decays by emitting alpha particles with a typical energy of 5.3 MeV.

Alpha vs matter

Ionization



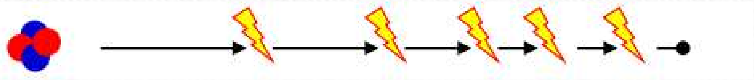
Interaction of Alpha Radiation with Matter:

Alpha radiation is highly ionizing but has little to no penetrating power.

The alpha particle is massive and strongly charged (2+), so it interacts very intensely with the electron shells of the material it passes through.

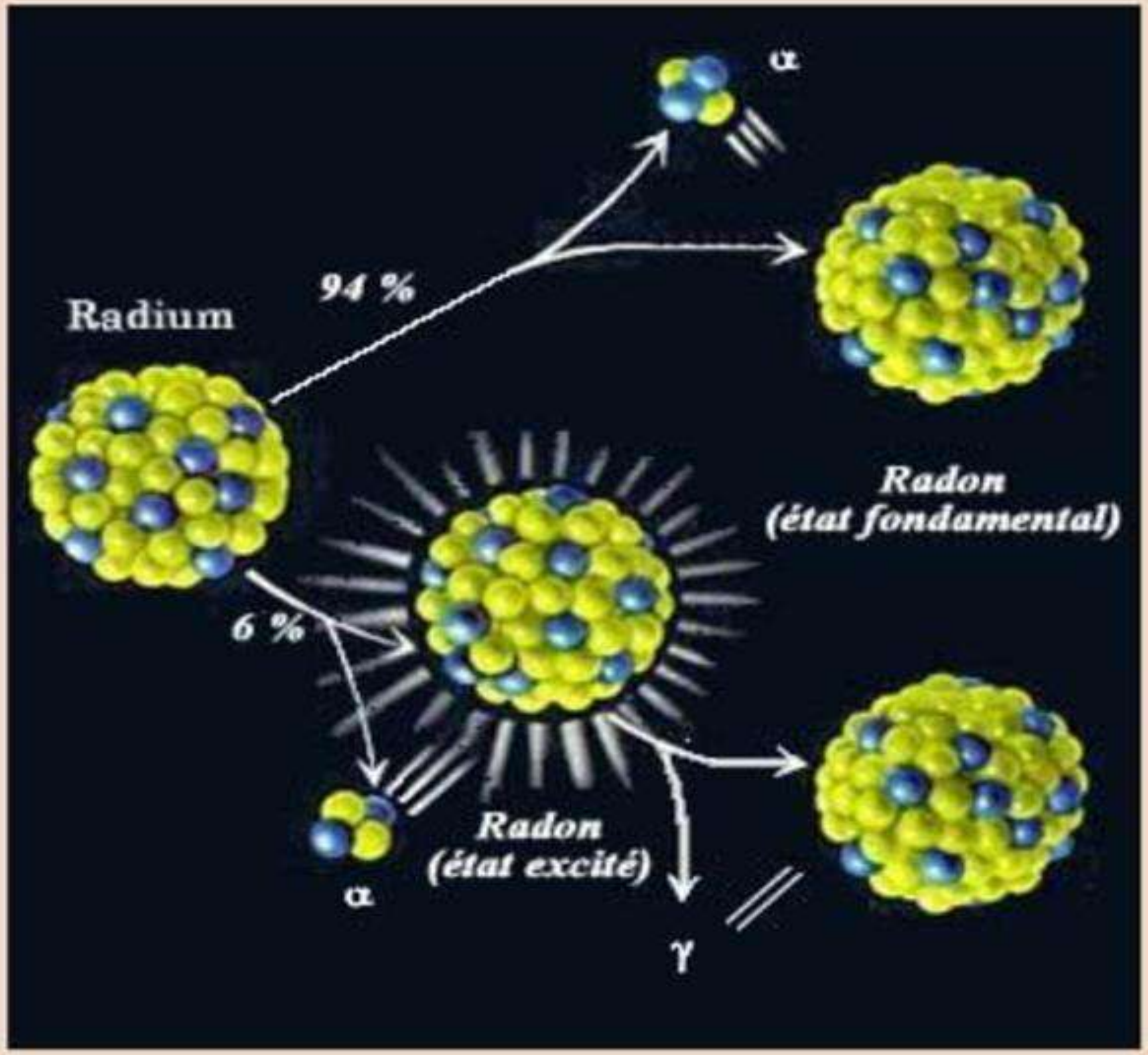
By gradually losing its kinetic energy, it is slowed down.

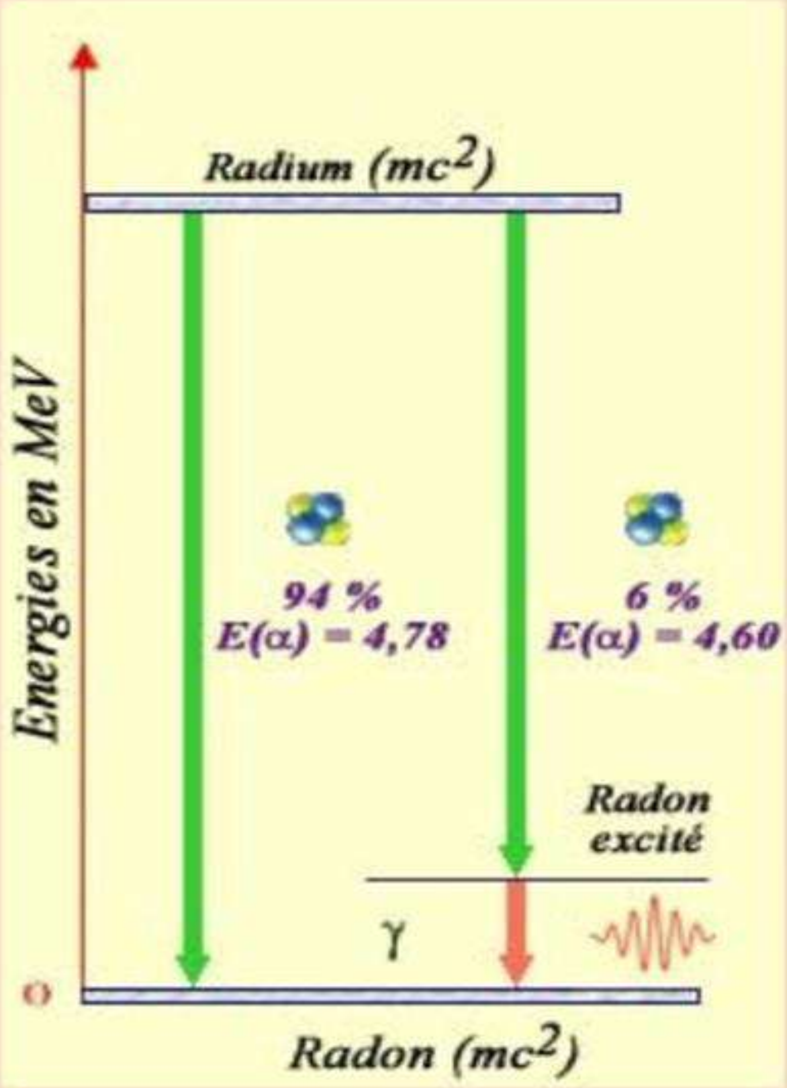
At each interaction, the energy transferred causes ionization.

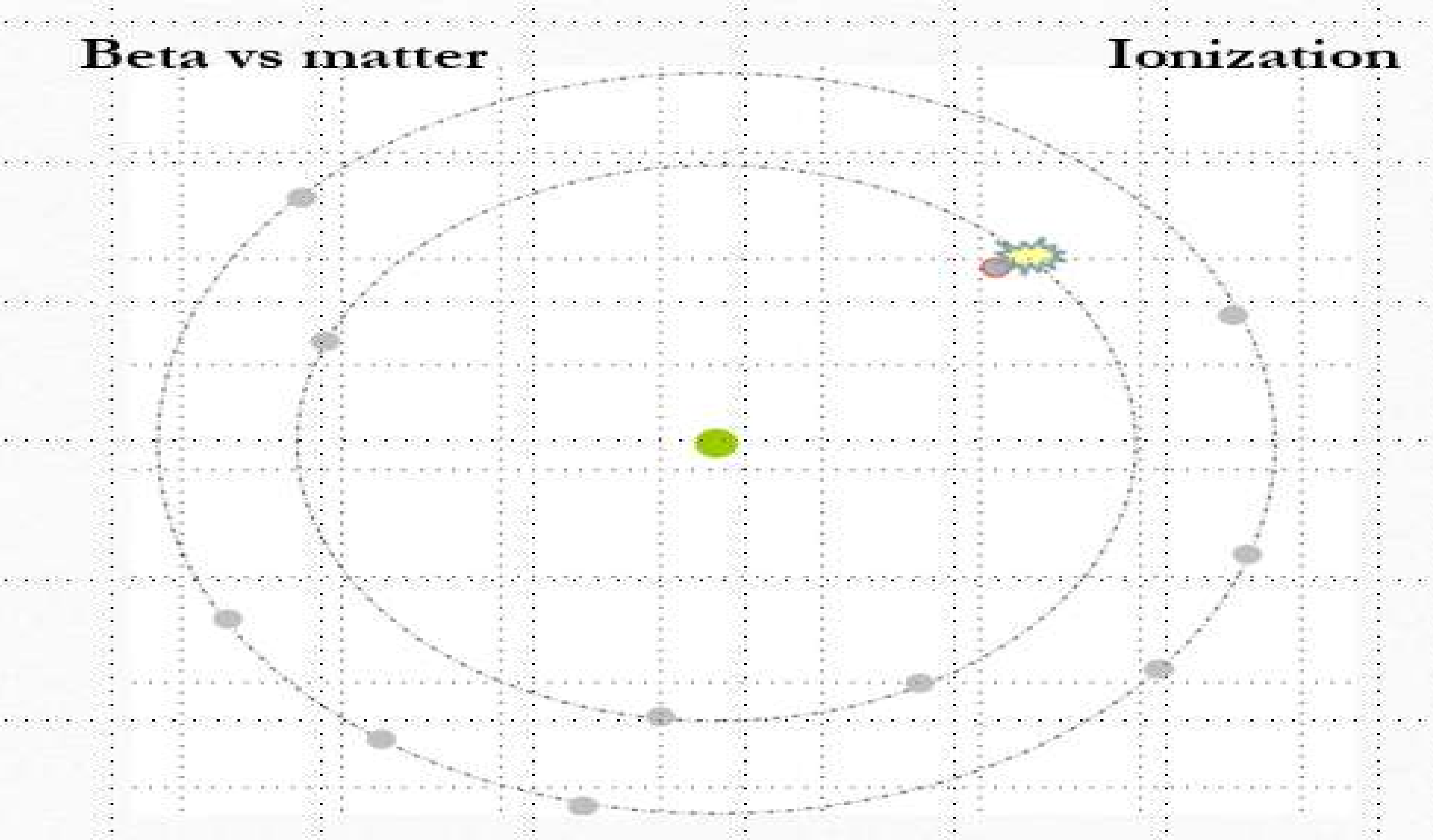


The probability of interaction between an alpha particle and a nucleus is very low.

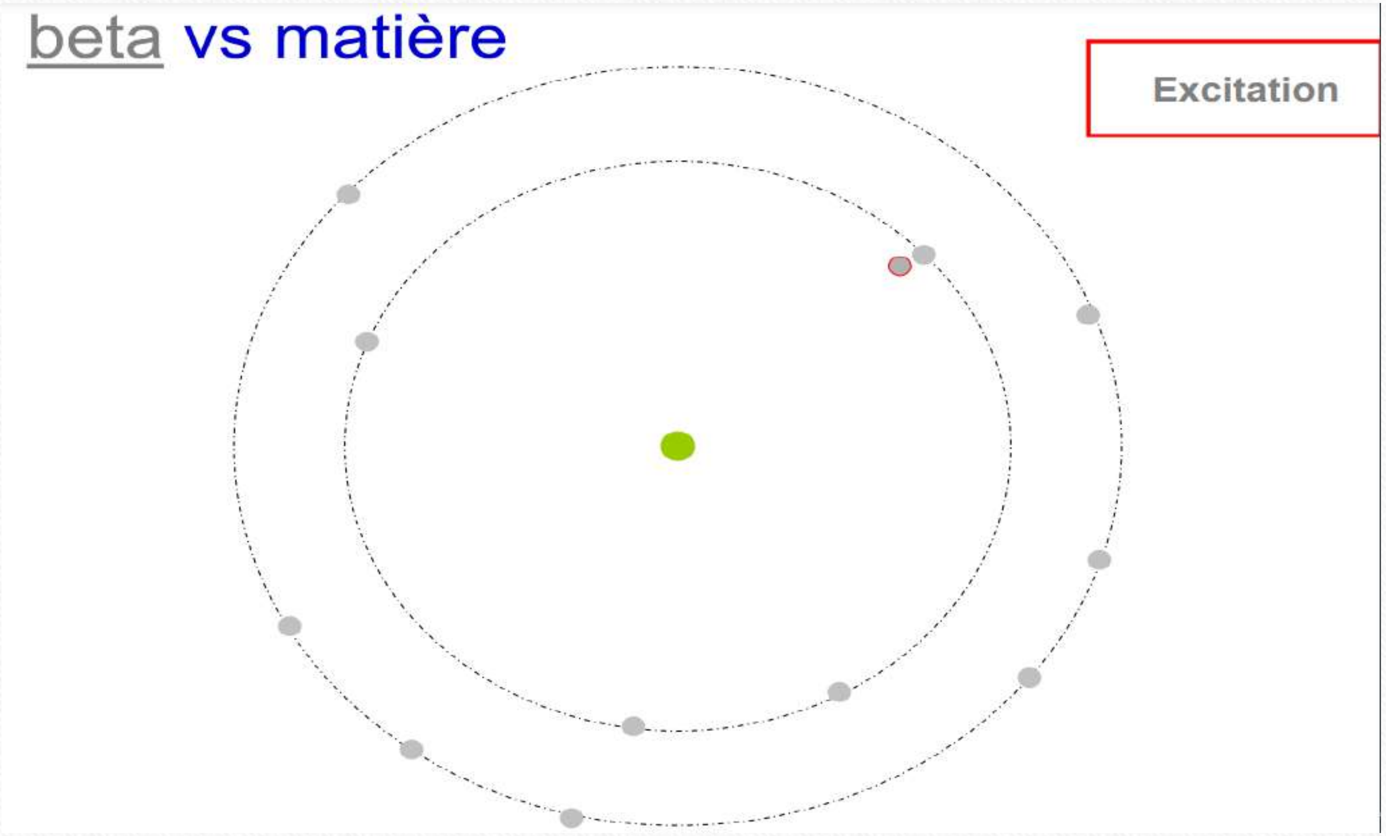
Alpha particles are stopped by a sheet of paper, but they are dangerous when they enter the body (e.g., through a skin wound).


α
94 %
Radium
Radon
(état fondamental)
6 %
Radon
(état excité)
α
γ

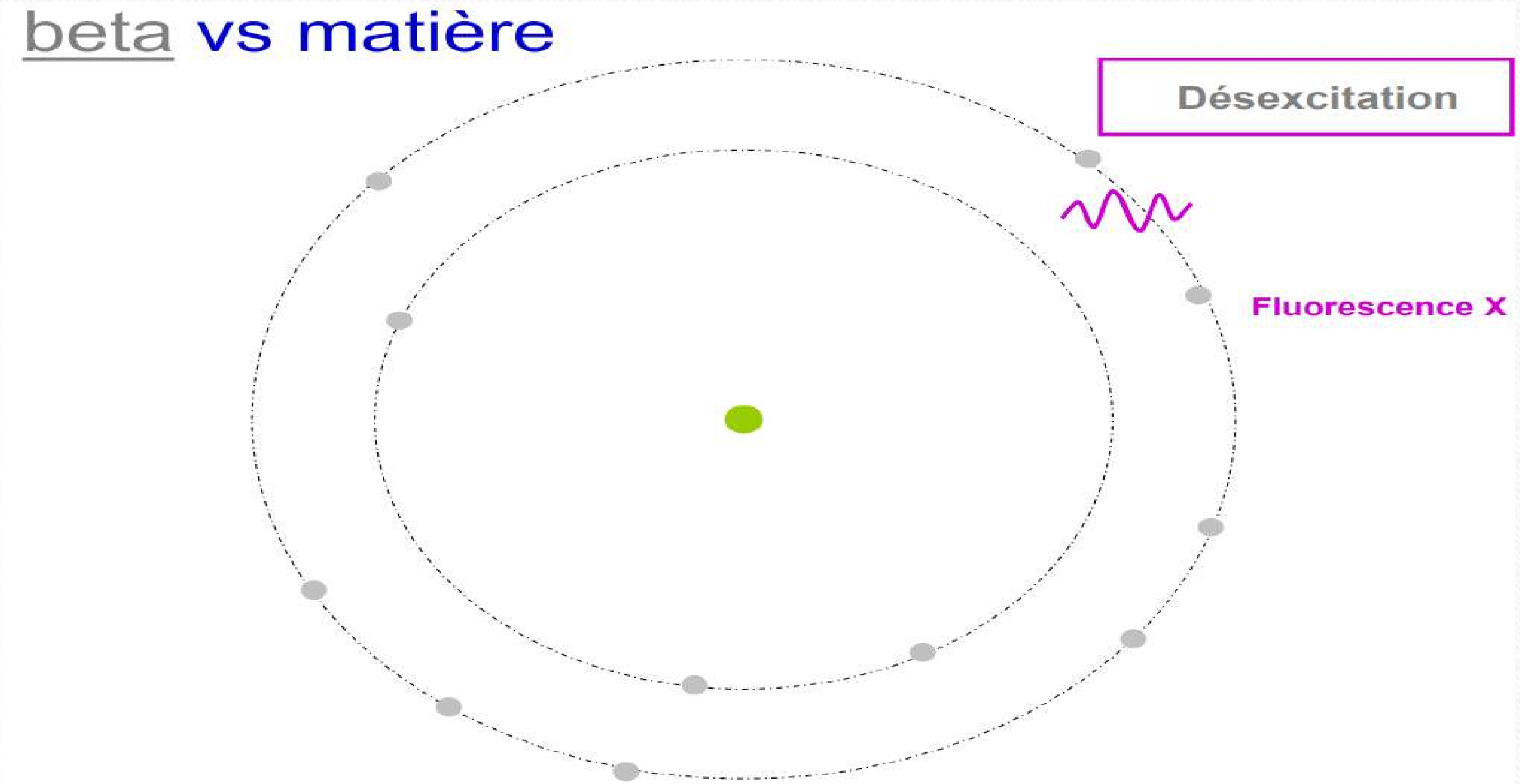

Radium (mc²)
Energies en MeV
94 %
E(α) = 4,78
6 %
E(α) = 4,60
Radon
excité
γ
0
Radon (mc²)



The incident electron loses kinetic energy without significant interaction (as heat).



Interaction with the nucleus and emission of braking radiation (X-rays).
In physics, "rayonnement de freinage" is specifically called Bremsstrahlung (from German), which refers to radiation produced when a charged particle is decelerated or deflected by another



Interaction with the electrons of atoms (Compton scattering and ionization)

(1) Negative beta decay (β^-)

A neutron transforms into a proton by emitting an electron (β^-) and an electron antineutrino ($\overline{\nu}_e$).

$n \rightarrow p^+ + e^- + \overline{\nu}_e$

Example: ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^- + \overline{\nu}_e$

Carbon-14 transforms into nitrogen-14.

(2) Positive beta decay (β^+) (positron emission)

A proton transforms into a neutron by emitting a positron (β^+) and an electron neutrino (ν_e).

$p^+ \rightarrow n + e^+ + \nu_e$

Example: ${}^{11}_{6}C \rightarrow {}^{11}_{5}B + e^+ + \nu_e$

Carbon-11 transforms into boron-11.

(3) Electron Capture (EC)

A proton in the nucleus captures an electron from an inner shell (often the K shell) and transforms into a neutron, emitting an electron neutrino (ν_e).

$p^+ + e^- \rightarrow n + \nu_e$

Example: $^{40}_{19}K + e^- \rightarrow {}^{40}_{18}Ar + \nu_e$

Potassium-40 transforms into argon-40.

Interaction of Beta Radiation with Matter:

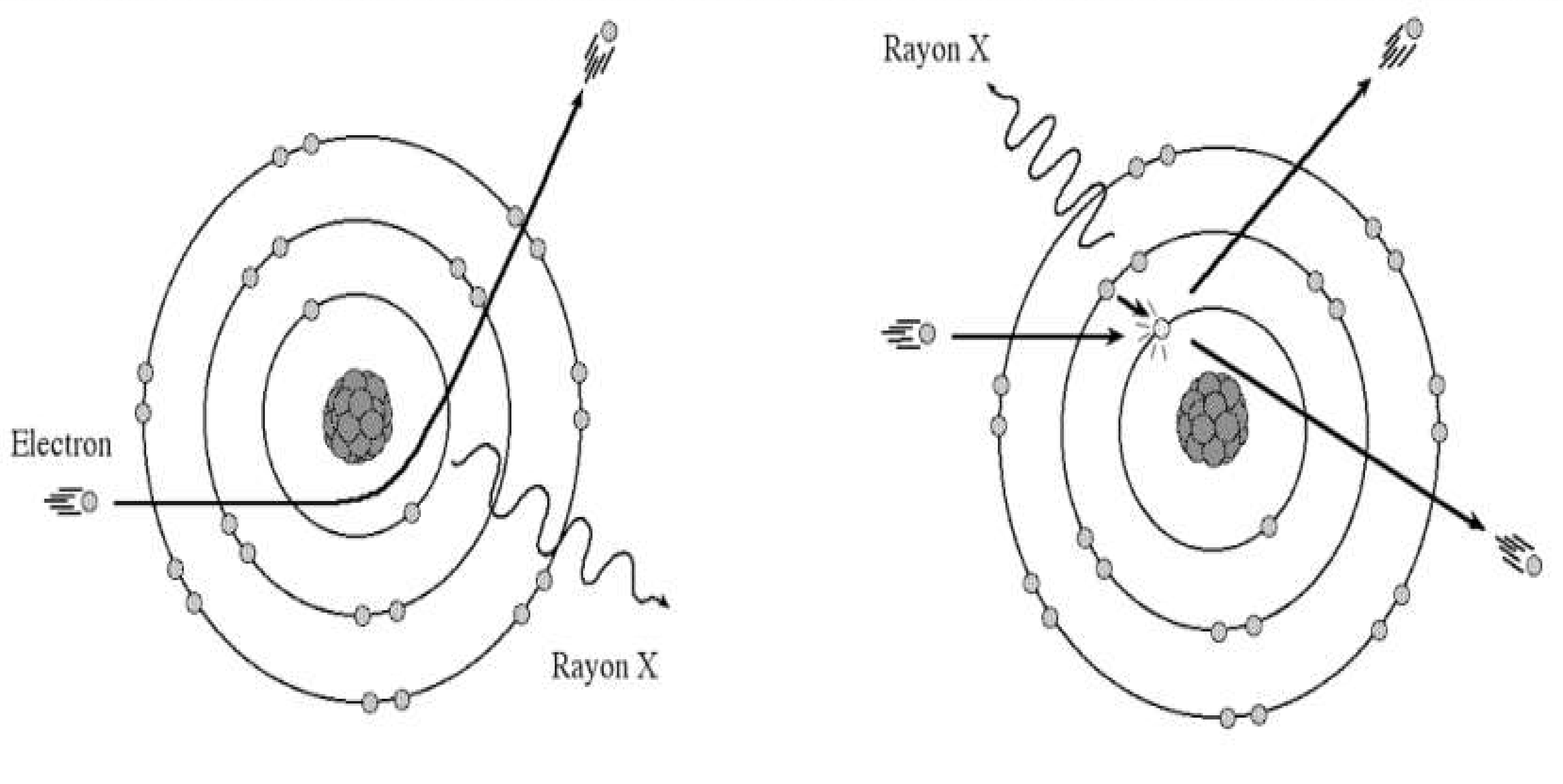
- Beta radiation is weakly ionizing.
- Its path through matter is therefore a broken line, with each segment decreasing in length with each interaction. Its range can reach up to 1.5 cm.
- Three possible interaction cases with β radiation:

Loss of kinetic energy of the incident electron without significant interaction (heat),

Deceleration (braking) in the vicinity of the nucleus,

Interaction with the electrons of atoms (Compton scattering and ionization).

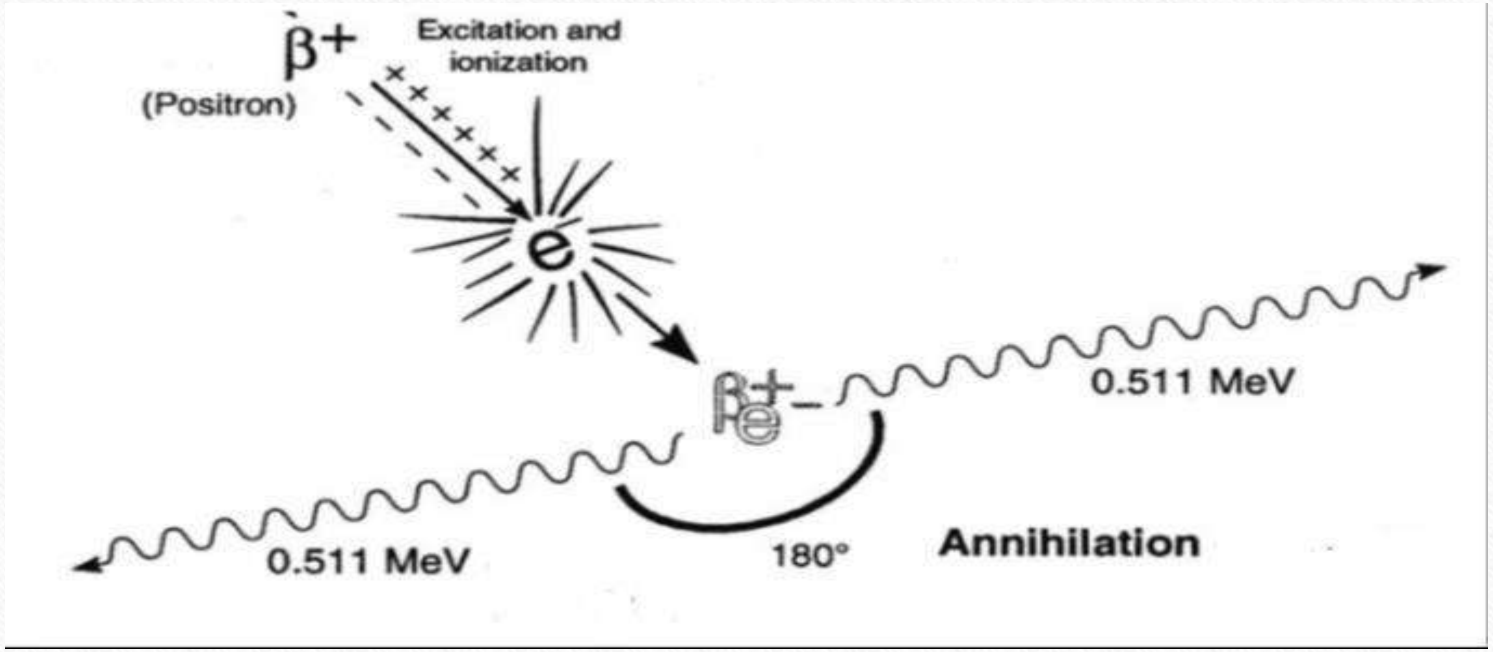
Both phenomena result in the formation of X-rays.



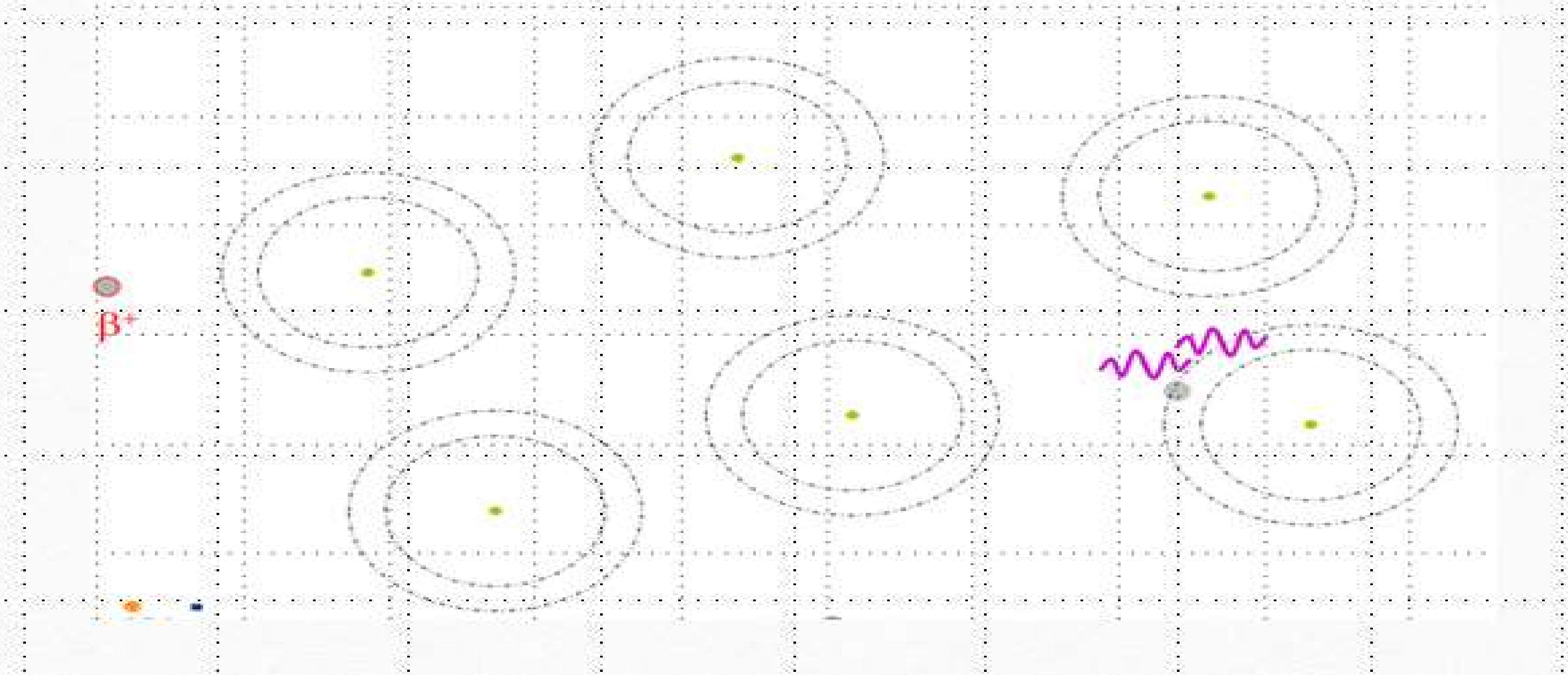
Electron
Rayon X
Rayon X

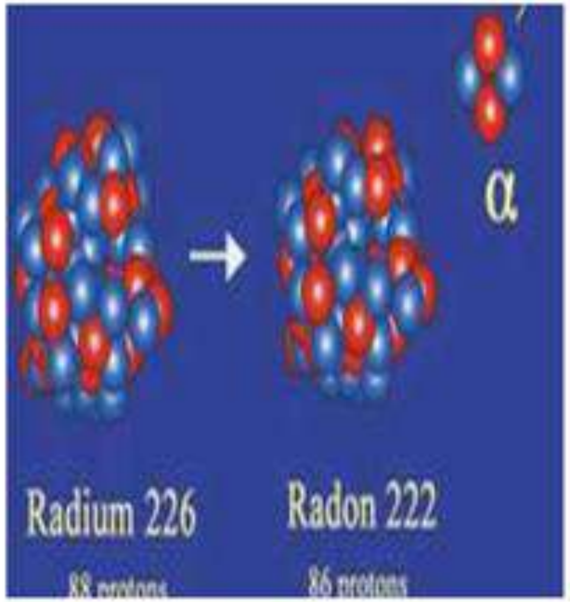
Annihilation:

When a positron meets an electron in matter, they can mutually annihilate, thereby releasing energy in the form of gamma photons.
Gamma photons are highly energetic electromagnetic particles that can further ionize matter or induce nuclear reactions.

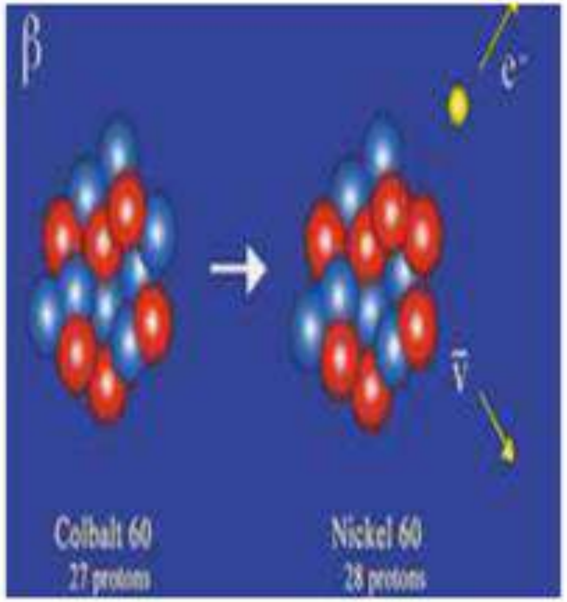


Annihilation in the case of β^+

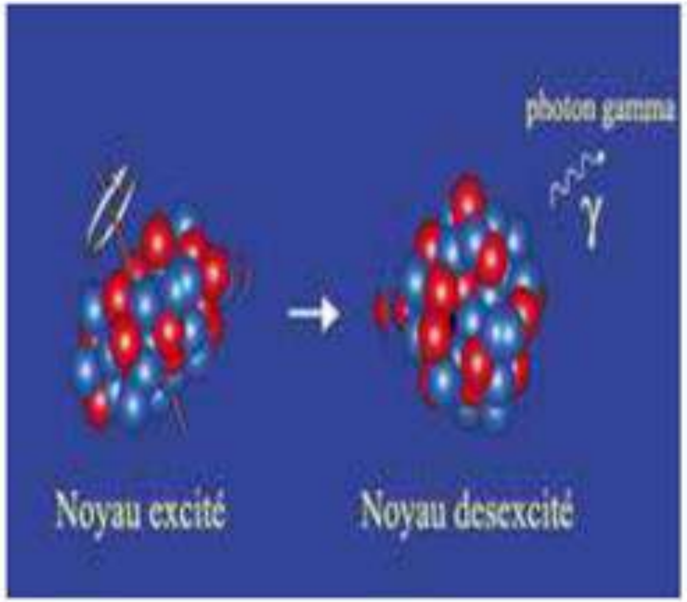




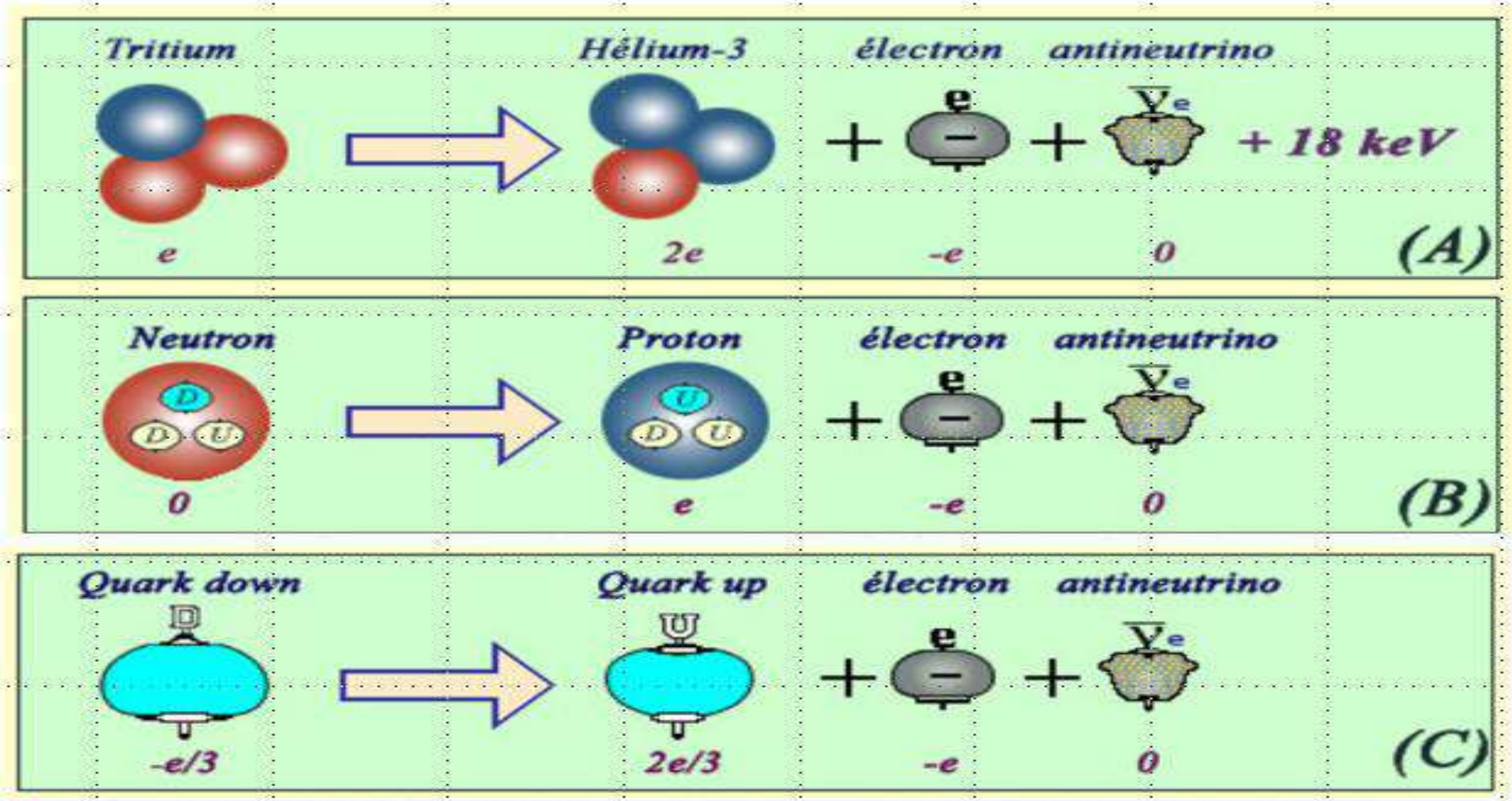
RADIOACTIVITE ALPHA (A)



RADIOACTIVITE BÊTA (B)



RADIOACTIVITÉ GAMMA (Γ)



Tritium
Hélium-3
électron
antineutrino
e
+ 18 keV
e
2e
-e
0
(A)
Neutron
Proton
électron
antineutrino
D
D
U
U
D
U
0
e
-e
0
(B)
Quark down
Quark up
électron
antineutrino
D
U
-e/3
2e/3
-e
0
(C)

Linear Energy Transfer (LET):

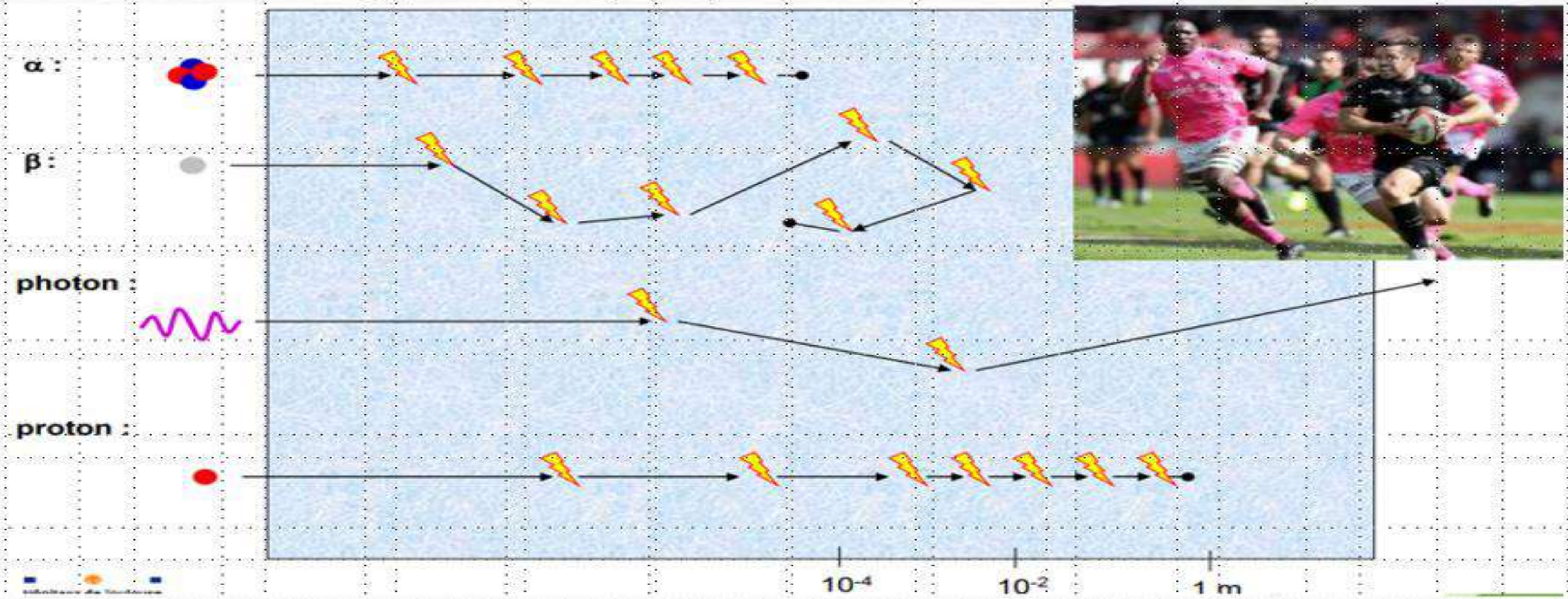
This is the amount of energy transferred to the medium by the particle along its path. It is measured by the linear ionization density (LID).

$$LET = LID \times \omega$$

Where ω is the average ionization energy ($\omega = 34eV$ in air).

Penetration into Matter

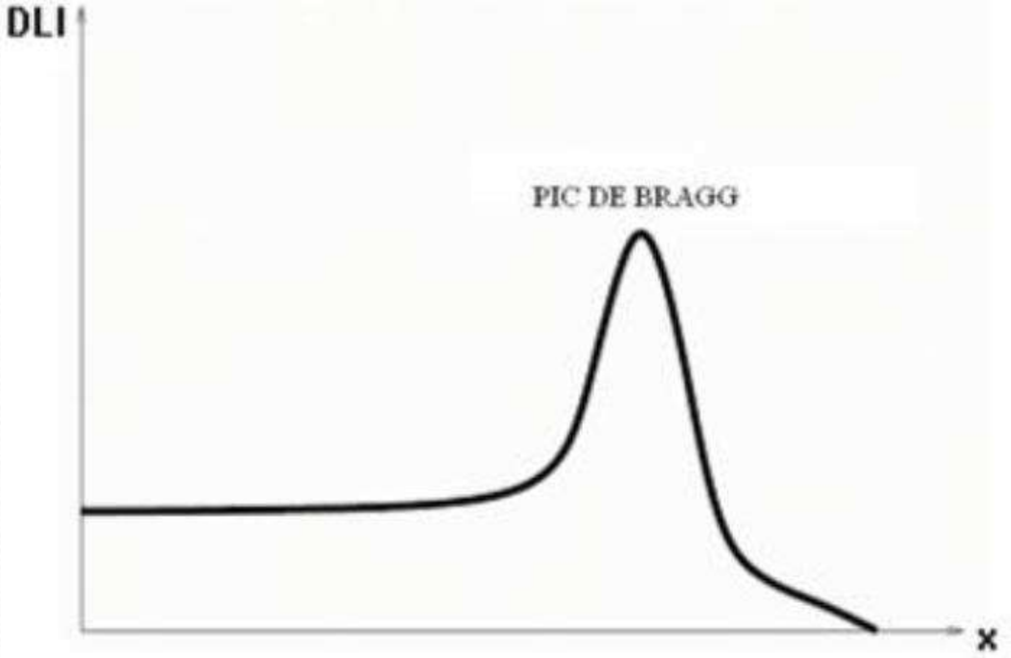
Linear Energy Transfer (LET) — Mean Free Path

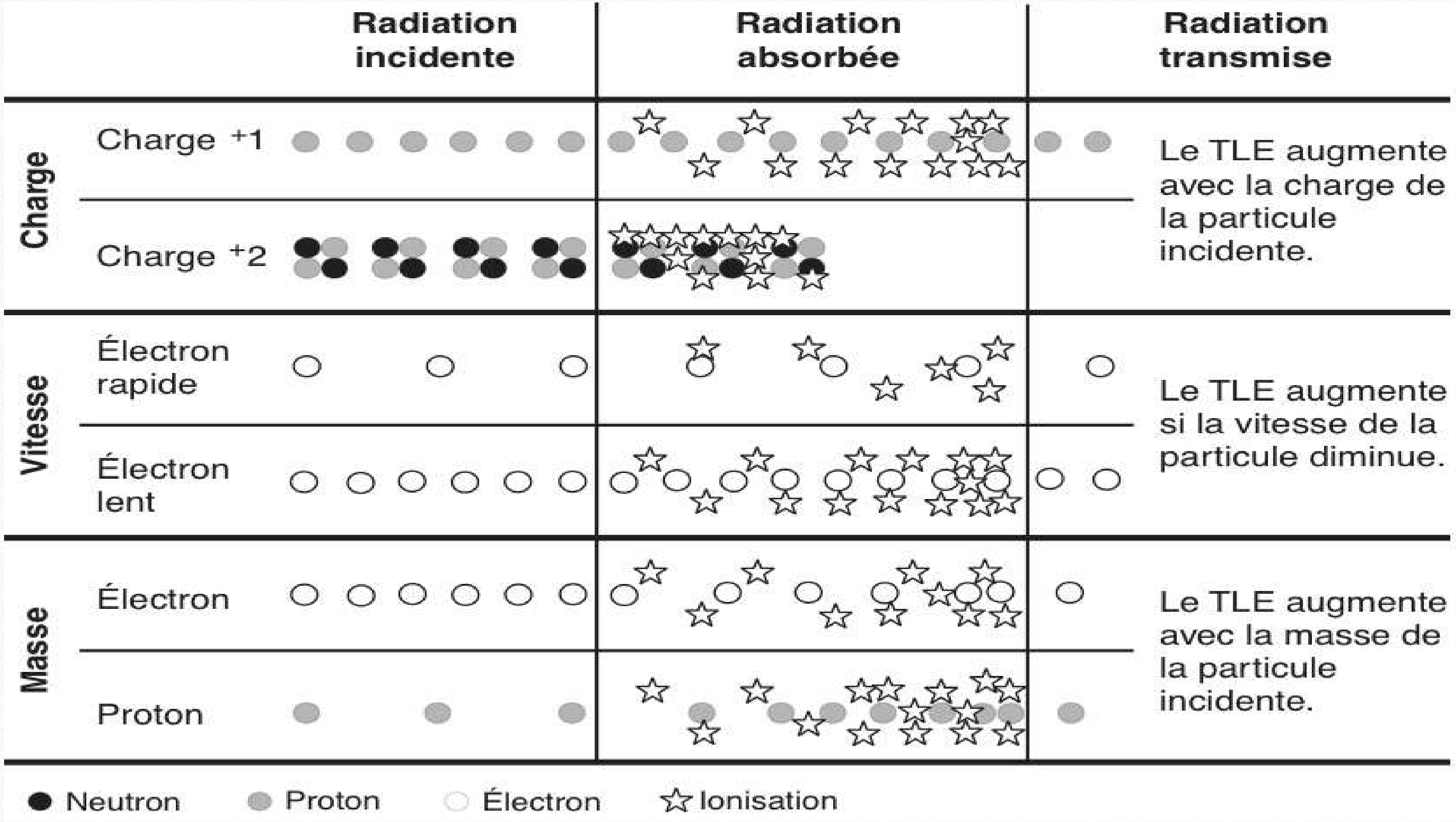


Linear Ionization Density (LID):

Number of ion pairs created per unit length (in ion pairs/µm).

The LID increases at the end of the path, so the maximum ionization occurs at the end of the range, as shown by the Bragg curve.

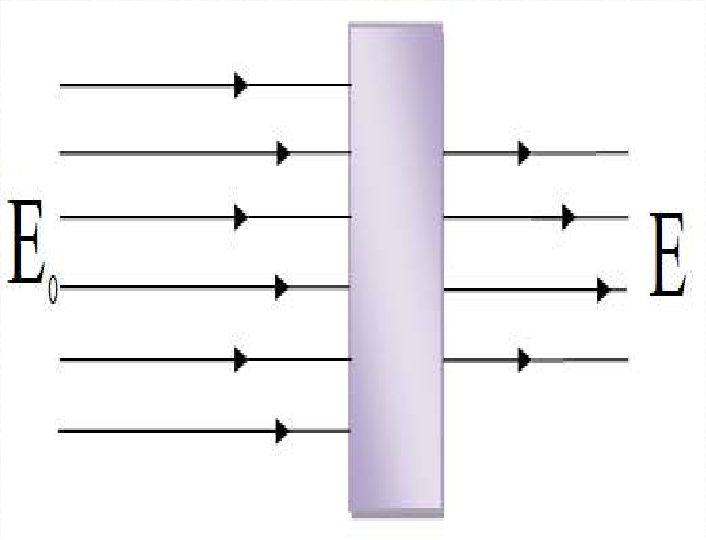



Radiation incidente
Radiation absorbée
Radiation transmise
Charge
Charge +1
Charge +2
Le TLE augmente avec la charge de la particule incidente.
Vitesse
Électron rapide
Électron lent
Le TLE augmente si la vitesse de la particule diminue.
Masse
Électron
Proton
Le TLE augmente avec la masse de la particule incidente.
Neutron
Proton
Électron
Ionisation

Photon Beam Attenuation Laws:

These laws describe how the intensity of light decreases as it passes through a material, taking into account factors such as the material's concentration, its thickness, its absorption properties, and the specific interactions between photons and the electrons of the material.

When a source emits radiation, this emission often occurs in all directions of space, which we will consider as isotropic and homogeneous.



In a vacuum, photons propagate without interaction, therefore in a straight line from the source.

This is a purely geometric law, which is not only applicable to electromagnetic radiation.

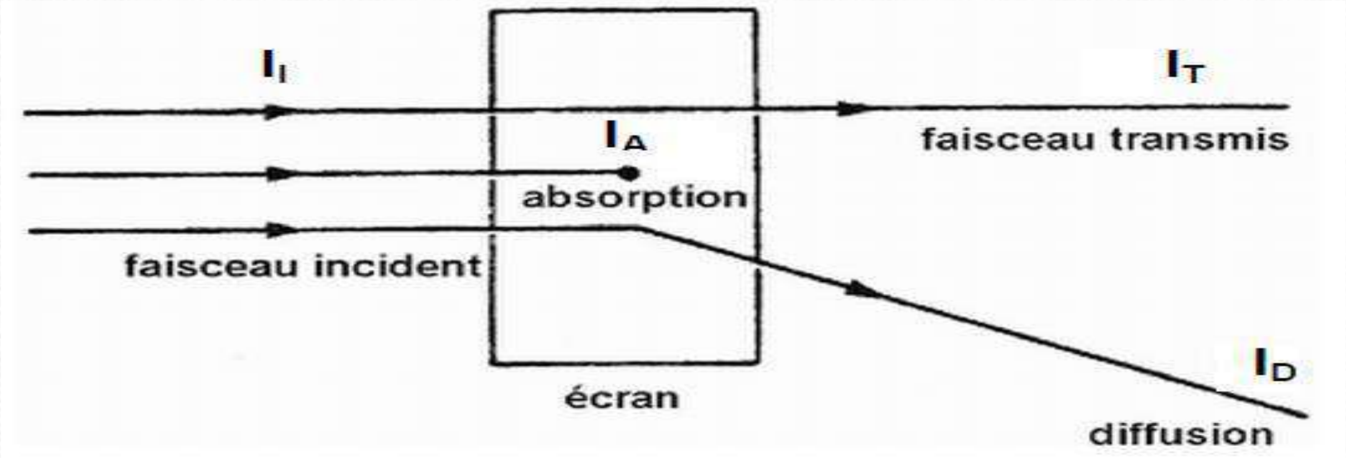
It is called the inverse square law. It follows the law:

$$I = \frac{I_0}{d^2}$$

When a thin, unidirectional beam of monoenergetic photons passes through a material medium:

- A portion of the photons is stopped,
- Another portion is deflected (scattered),
- Another portion is transmitted, remaining in the same direction of propagation as the beam without being deflected.

The total energy of the beam will be reduced or attenuated.



Attenuation Law:

- The random nature of photon interactions with matter leads to an exponential attenuation law.
- If we consider a screen of thickness x , characterized by a linear attenuation coefficient μ, and receiving N_0 photons, the number N that passes through is given by: $N = N_0 e^{-\mu . x}$

N and N_0 can easily be replaced by the beam intensity *I* or by the beam energy *E*

Half-Value Layer (HVL)or (CDA)

This is the thickness a screen must have to allow only half of the incident photons to pass through. In other words, it is the thickness that reduces the number of photons in the beam by half.

The HVL depends on the absorbing medium and the energy of the photons.

An important fact is that it is impossible to completely stop a photon beam. However, with a suitable screen, its energy can be limited to values that do not present a biological hazard.

$$N_{CDA} = N_0 e^{-\mu . CDA}$$

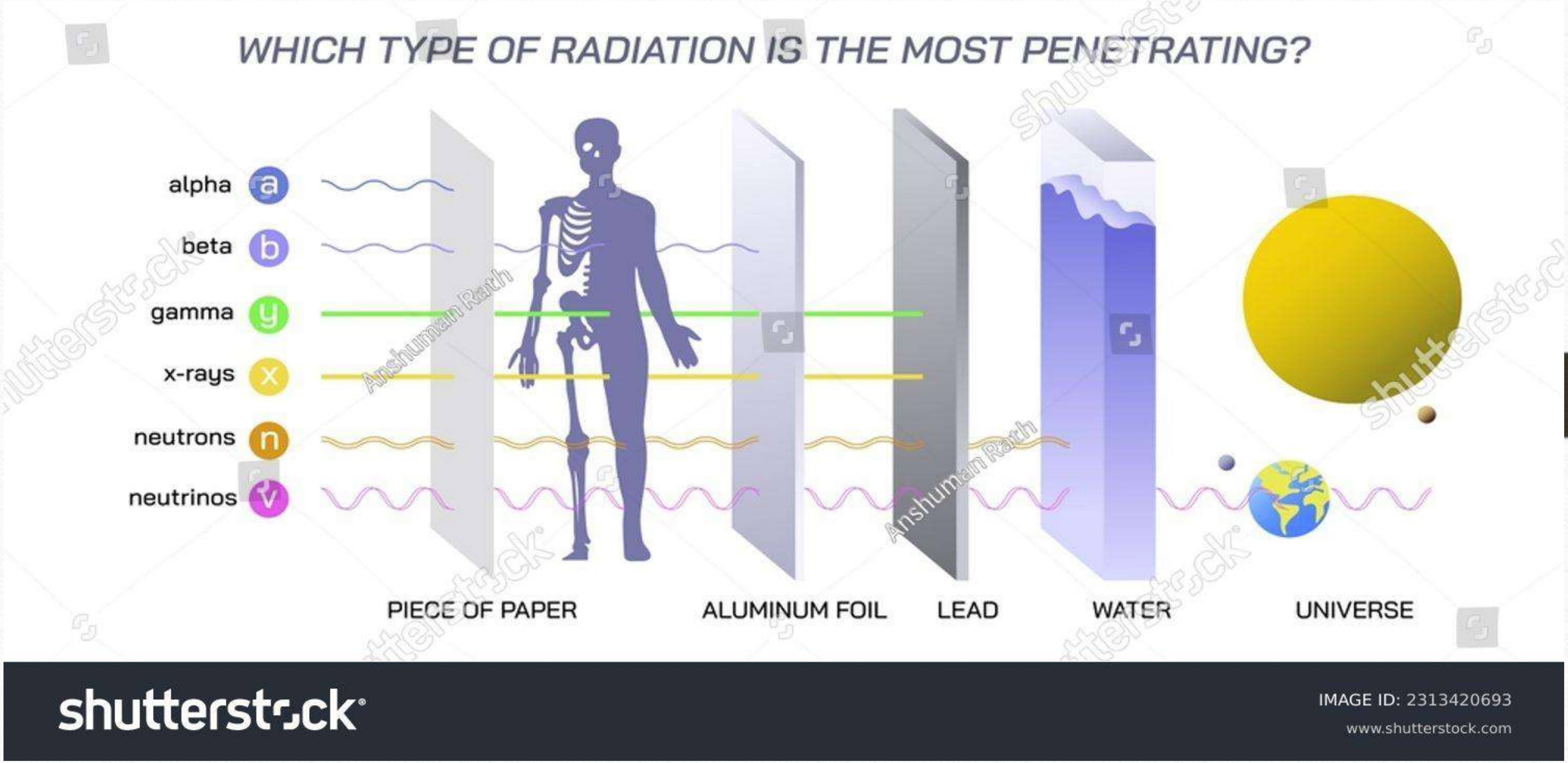
$$\frac{N_0}{2} = N_0 e^{-\mu . CDA}$$

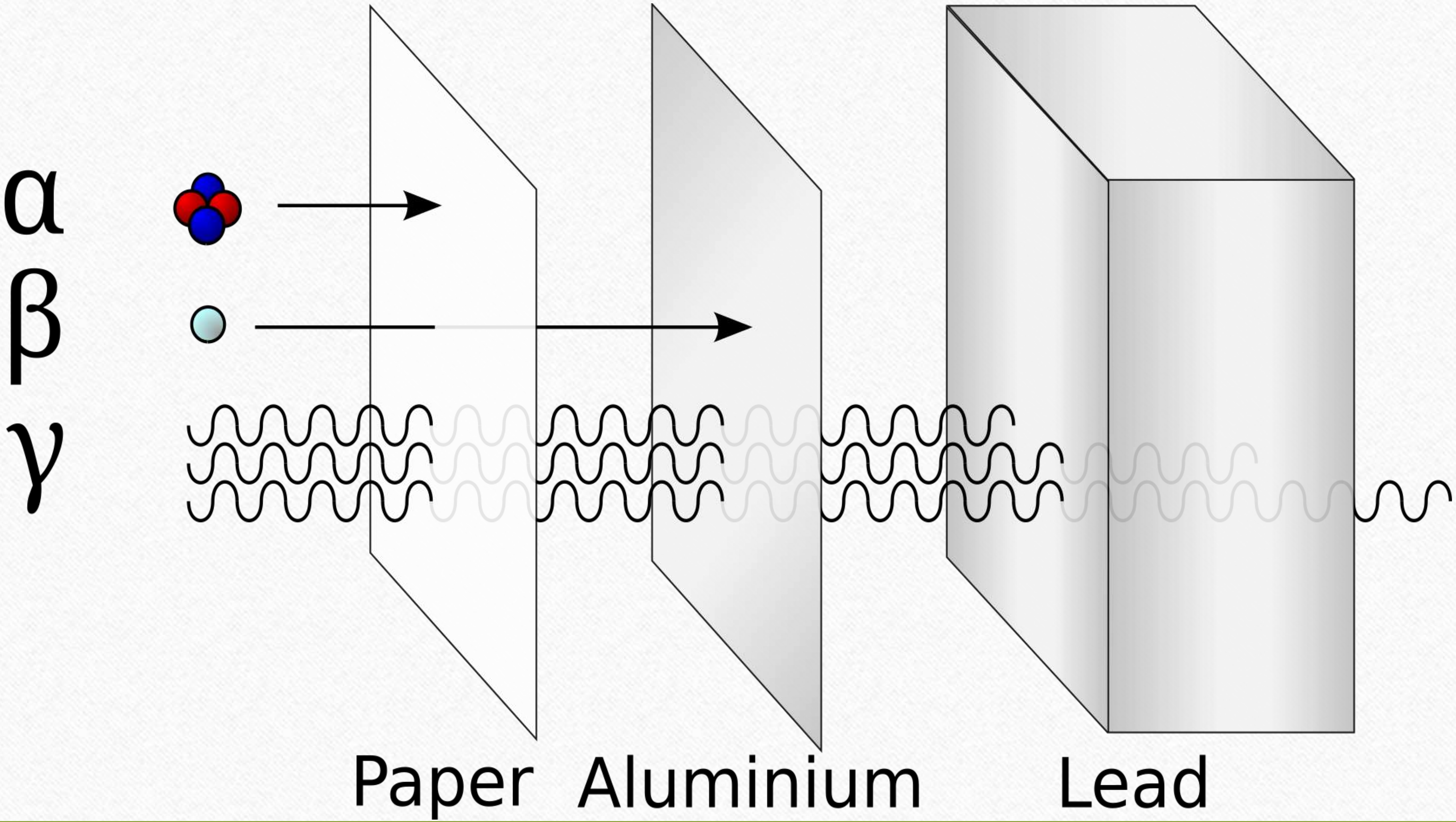
$$\mu \, CDA = Ln\, 2$$

$$CDA = \frac{Ln\, 2}{\mu}$$

Type	Symbol	When Emitted	Affect on Mass	Affect on Atomic Number	Ionising Strength	Stopped By	Travel
α	${}^{4}_{2}\alpha$	Too few n	-4	-2	Strong	Paper	<5cm
β	β^{-}	Too many n	0	+1	Weak	3mm Al	<1m
γ	${}^{0}_{0}\gamma$	Excess energy	0	0	Weakest	Pb	<1Km
n	${}^{1}_{0}n$	Specific Events	-1	0	Strongest	H_2O	>1Km

Radiation tape information


WHICH TYPE OF RADIATION IS THE MOST PENETRATING?
alpha
beta
gamma
x-rays
neutrons
neutrinos
PIECE OF PAPER
ALUMINUM FOIL
LEAD
WATER
UNIVERSE
shutterstock
IMAGE ID: 2313420693
www.shutterstock.com


α
β
γ
Paper
Aluminium
Lead

Conclusion:

- The study of phenomena related to radiation-matter interaction has enabled the advancement of several disciplines in medicine.
- In radiological diagnosis, the photoelectric effect is the basis for the formation of X-rays, and annihilation is the principle behind PET (Positron Emission Tomography; an imaging examination in nuclear medicine).
- Also, the ionizing and destructive power of electrons is the basis of radiotherapy and radiobiology.
- Other phenomena, such as the Compton effect for the formation of scattered radiation and the attenuation of the photon beam, have made it possible to develop radiation protection.

Thank you. I look forward to your comments or questions.