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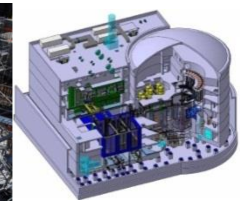
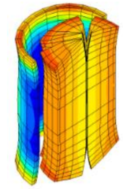

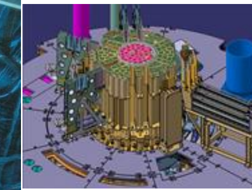
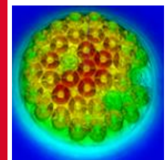

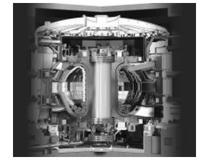




Radiation detection and measurement for non-destructive characterization and control in nuclear media.

Abdallah Lyoussi (CEA)
IEEE DL
Capetown, July 7-17, 2018

IEEE NPSS International School for Real Time Systems in Particle Physics 2018

A. LYOUSSI (CEA/DEN/CAD)
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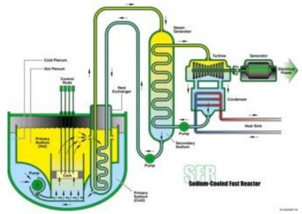
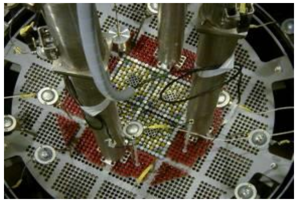
Key figures of the CEA Cadarache Centre

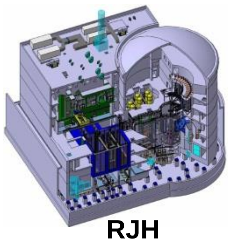
- 2 400 employees on a site that actually involves the activities of 5 500 people
- 480 buildings and laboratories of which 20 are licensed facilities (BNF: Basic Nuclear Facilities and 1 Basic Nuclear Defence Facility)
- 200 active patents (20 per year)
- A training centre (160 teaching researchers, 130 PhD students and post-docs,…)
- Partnerships and international collaborations
- a Mixed Research Unit in Biotechnologies and a joint laboratory LIMMEX with Aix-Marseille University in the field of instrumentation exposed to extreme environments
- Approximately 300 scientific publications per year
- One of the major employment zones in the Provence/Côte d'Azur region (PACA) and one of the greatest concentrations of scientific experts.

DE LA RECHERCHE À L'INDUSTRIE



Nuclear radiation detection : basics, principles and applications





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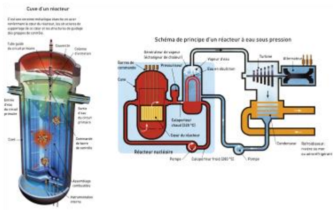

Abdallah LYOUSSI CEA/DEN/CAD/DER; abdallah.lyoussi@cea.fr

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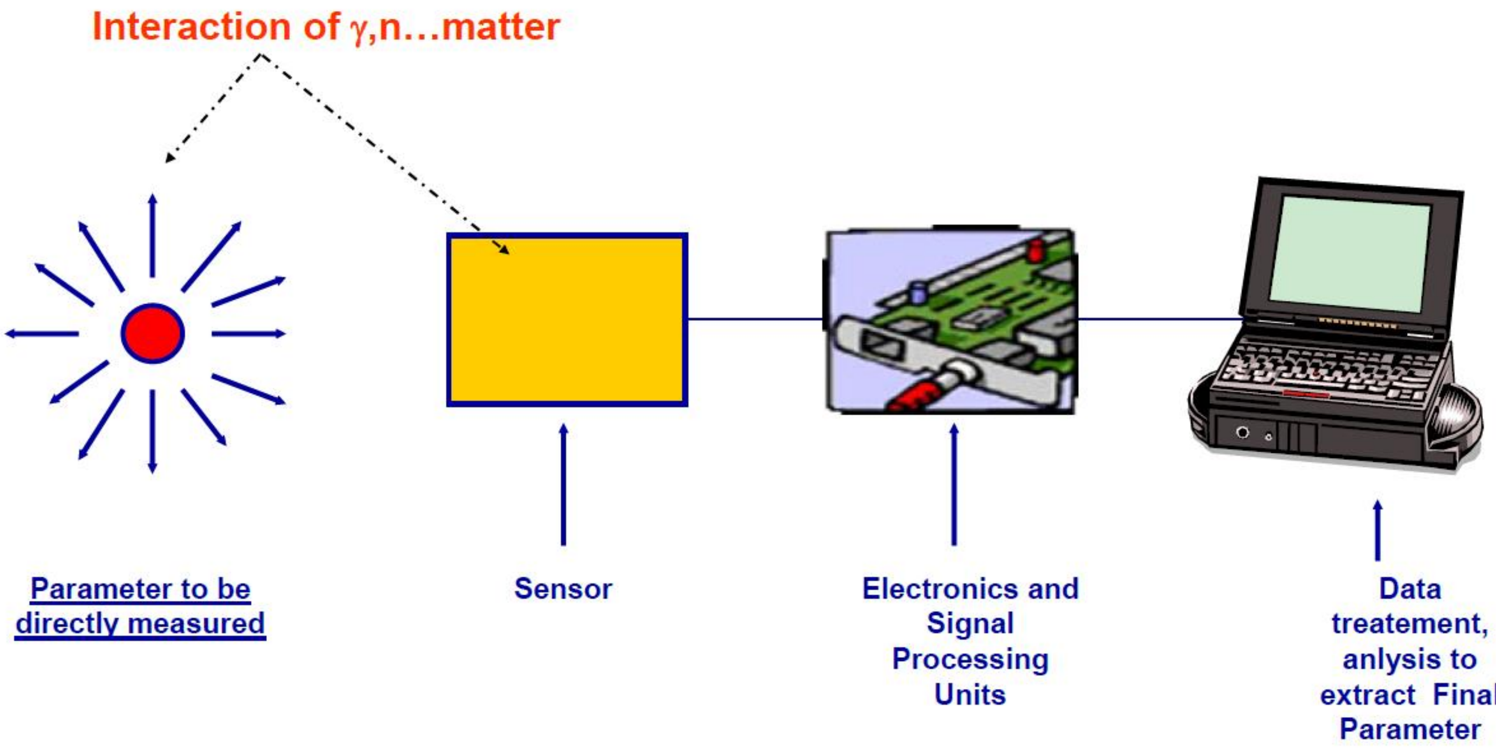
Radiation needs to interact before being detected



The Menu…

1 – Introduction

2 - Nuclear Radiations : Basic Concepts and Terminologies

3 - Interaction of charged particles with matter
- Interaction of heavy charged particles
- Interaction of light charged particles

4 – Interaction of neutral particle with matter
- Interaction of photons
- Interaction of neutrons

5 – Nuclear Radiation Detectors

6 - Examples of nuclear measurement techniques

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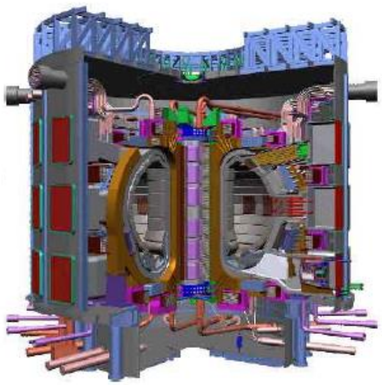
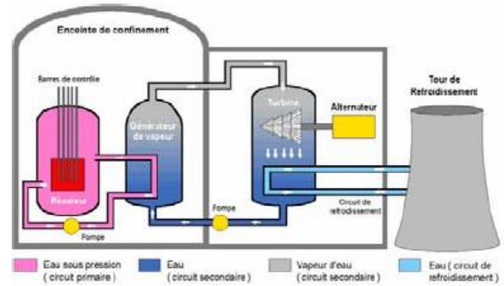
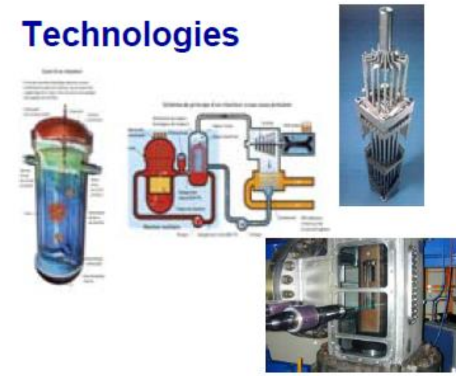
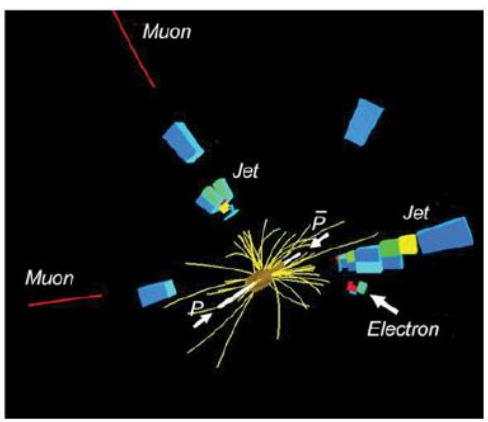
Radiation Interaction with Matter

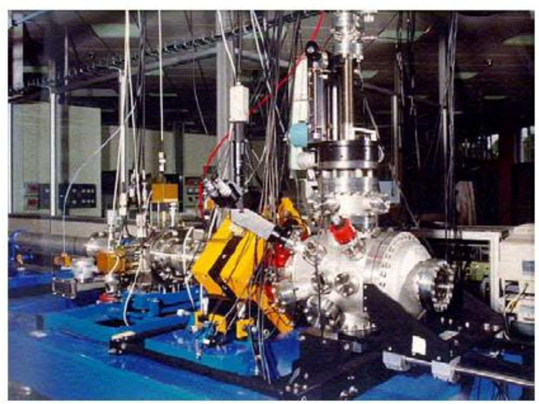


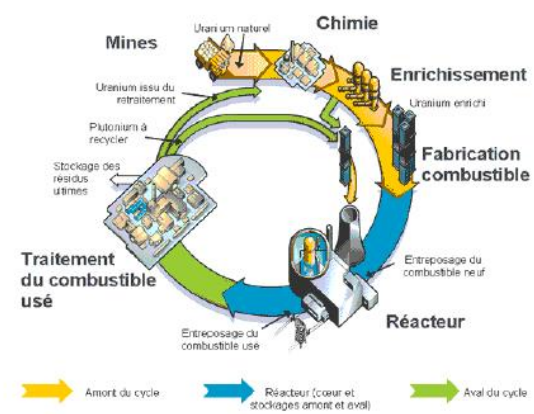




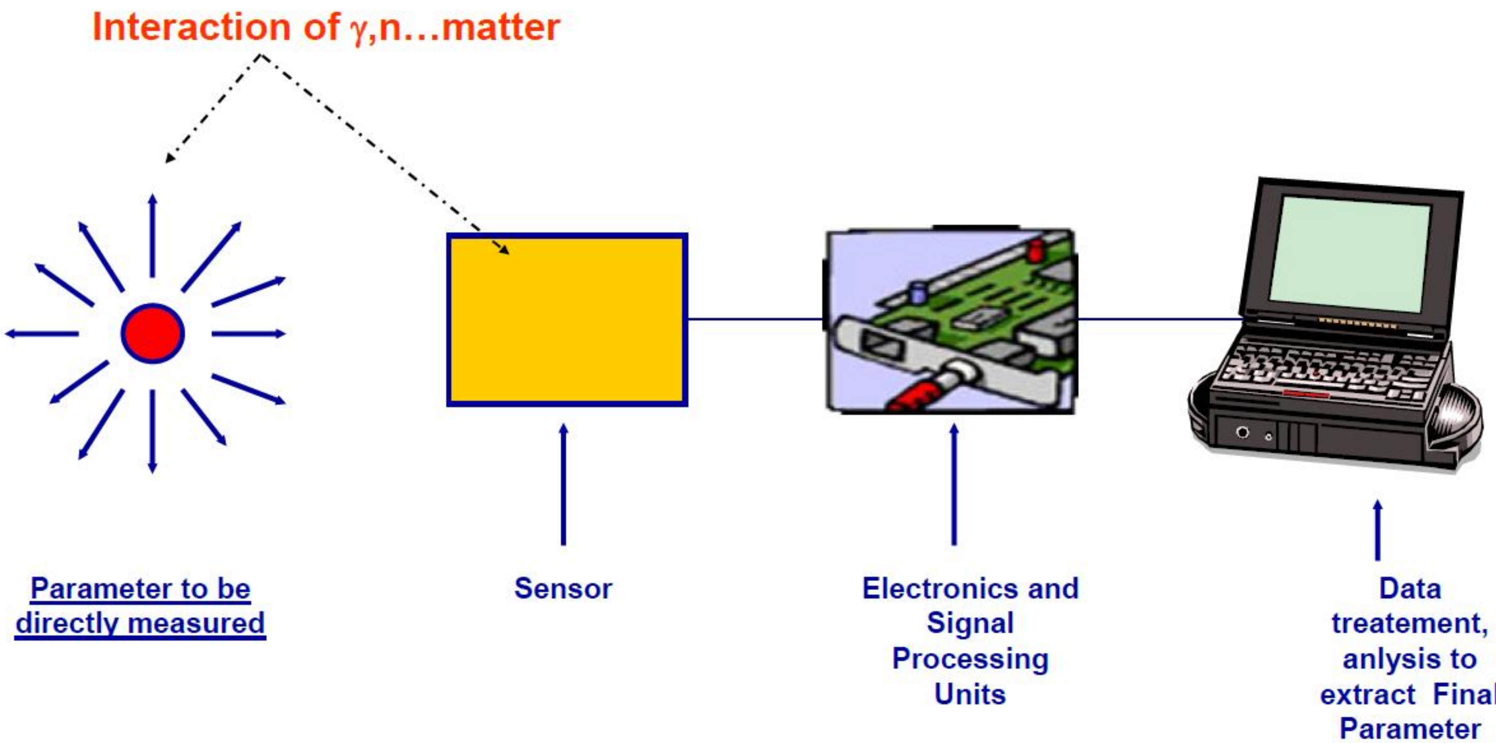
INTERACTION OF RADIATION WITH MATTER



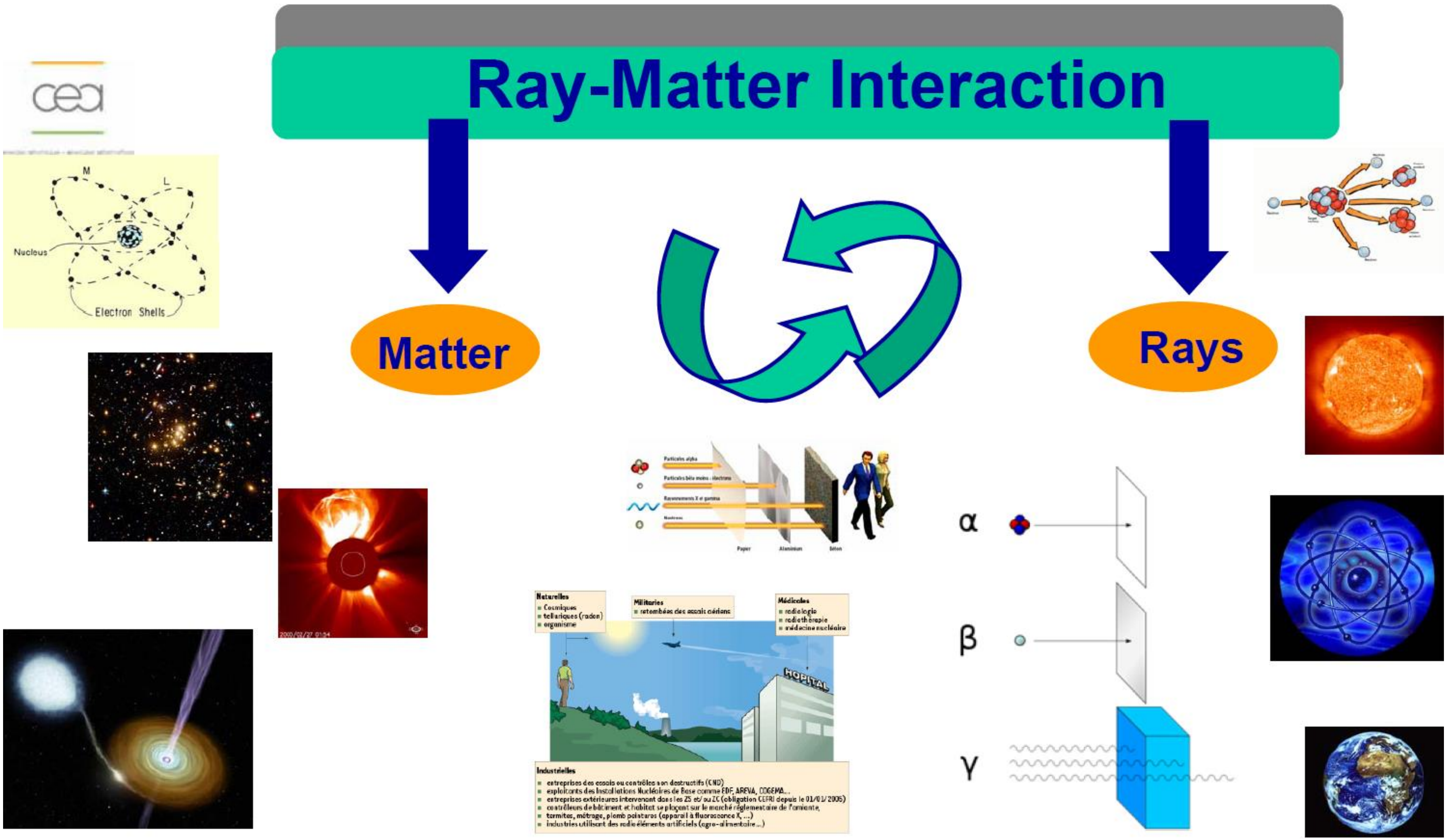




What about Ray vs. Matter interaction ?

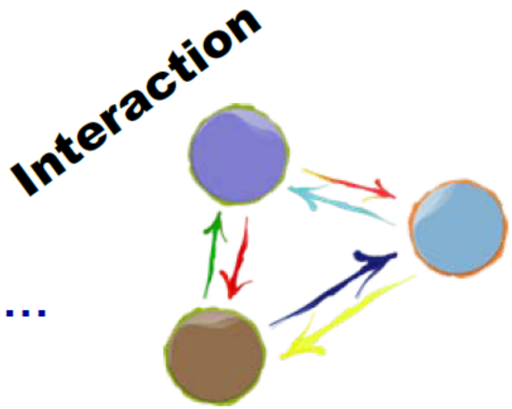


Radiation Interaction with Matter

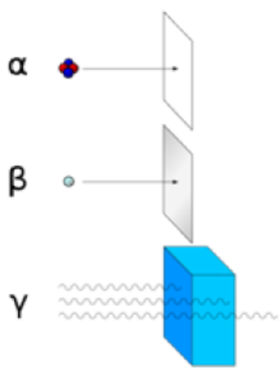


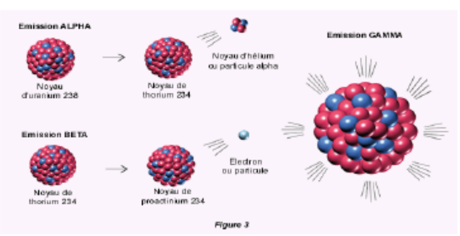
Interaction of Radiation with Matter

*- Whenever we want to detect or measure radiation, we have **<u>to make it interact</u>** with some material and then study the resulting **change in the system configuration**. So, in general, it is not possible to <u>detect radiation</u> or measure its properties without <u>letting it interact with measuring device.</u>*

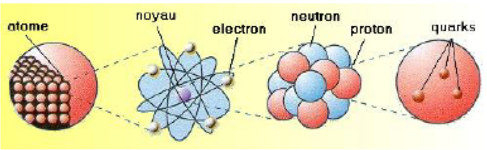


Radiation/Rays …

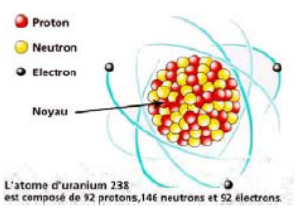


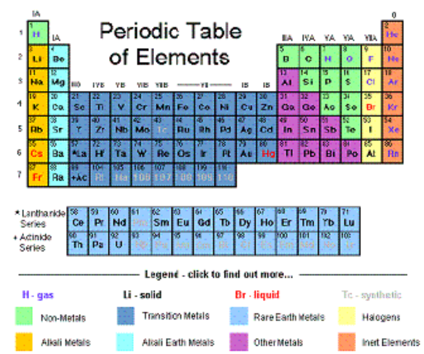


In our case …Matter is



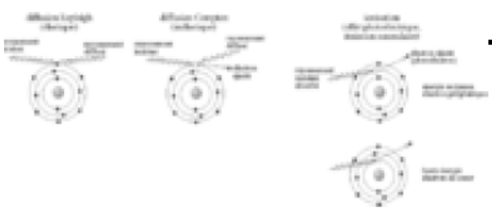
In Physics, Matter is considered as an association of electrons, nucleus, atoms and/or Molecules



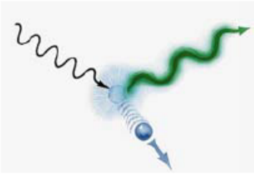


Interaction of Radiation with Matter

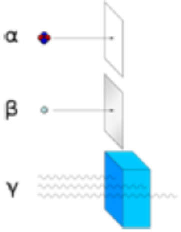
Every particle carries some energy with it and is, therefore, capable of exerting force on other particles through process called particle interactions. These particle interactions may or may not change the state and properties of the particles involved.

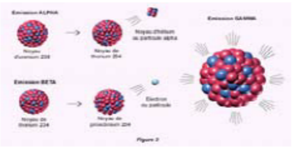


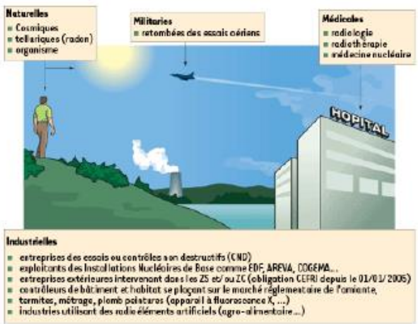
The way particles interact with matter (detector) depends not only on the types of incident and target particles but also their properties, such as energy and momentum.

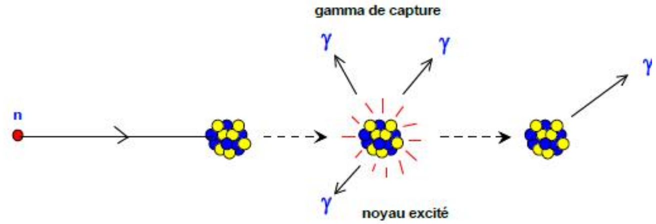


So, knowledge of basics theory of interaction mechanisms and understanding the gross properties that have been empirically and experimentally determined is very important for particle detection discipline

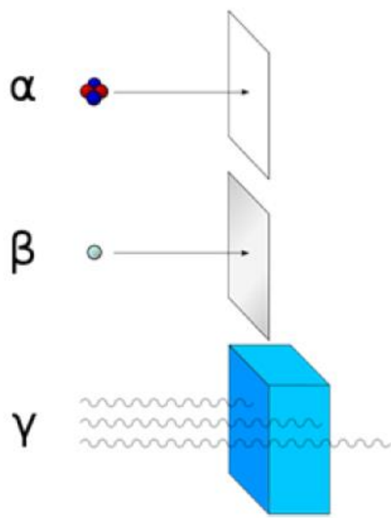








What is meant by radiation?...



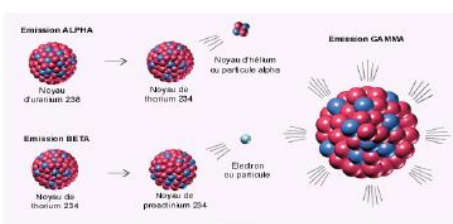
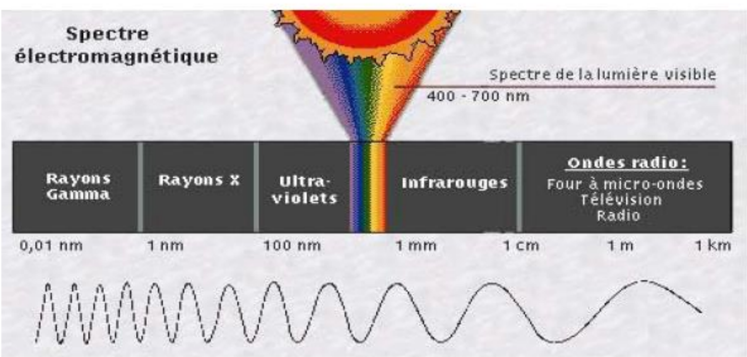
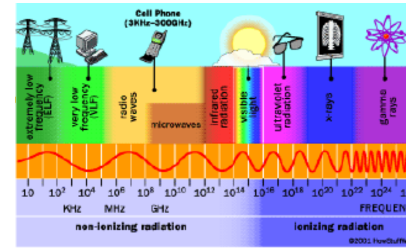


Figure 3



Radiation Interaction with Matter



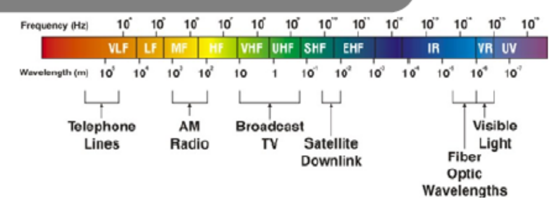
The word *RADIATION*…

Was used until about beginning of 1900s to describe electromagnetic waves. Around the turn of the century, electons, X-rays, and natural radioactivity were discovered and were included under the term radiation. The newly discovered radiation showed characteristics of particles which was initially treated as a wave

Duality of matter has been proved (L. De Broglie) and the distinction between particles and waves ceased to be important.

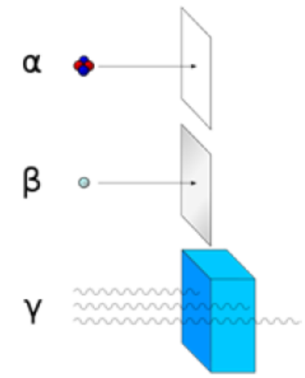
TODAY…

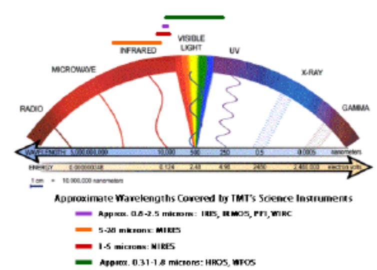
Radiation refers to the whole electromagnetic spectrum as well as to all the atomic and subatomic particles that have been discovered …



What are the main/basics characteristics of radiation?

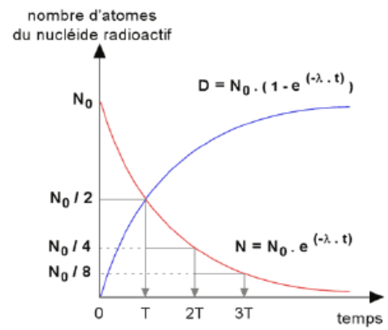
Type	:	atomic, nuclear
Nature	:	elementary, nuclei, heavy nucleus, photons
Charge	:	negative, zero, positive
Energy	:	low, intermediate, high
Period	:	short, long
Intensity	:	low, high
Type of reactions	:	with atom, with nucleus
Cross section	:	low, high



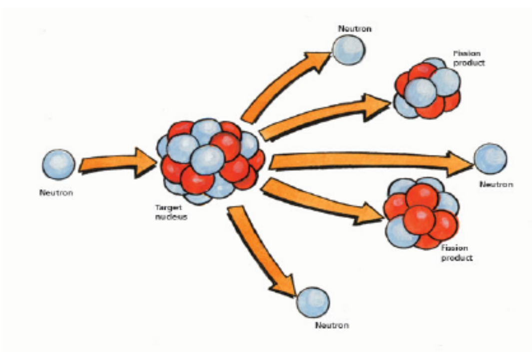


In our Case...

We will focus on radiations/particles directly or indirectly emitted following radioactive disintegration and/or nuclear (atomic) reaction..



Nuclear/Atomic Reactions/Interactions



Radioactive Disintegration

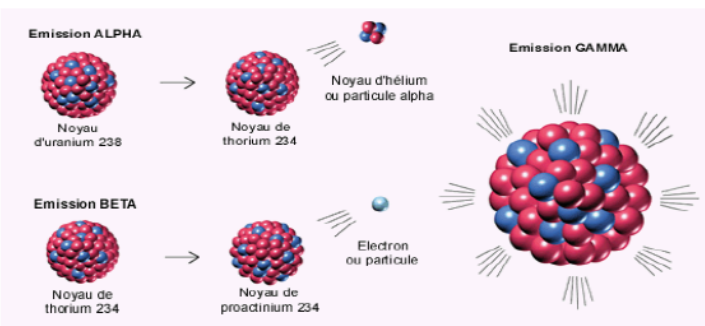
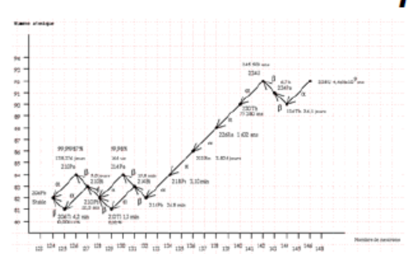


Figure 3

Neutrons, Gamma, FP, AP, RP



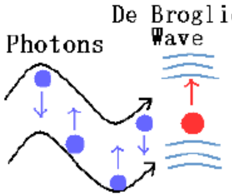
Radiation Interaction with Matter

The word *RADIATION*…

Different types of radiation are grouped in many ways

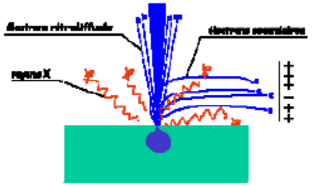
Ionizing and nonionizing radiation

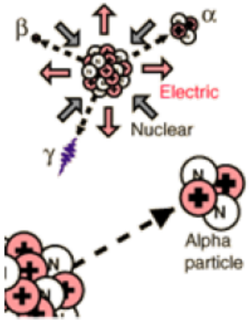
Charged Particles



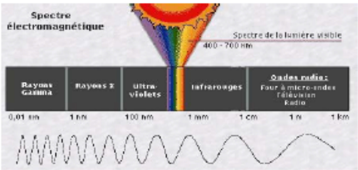
Non Charged Particles

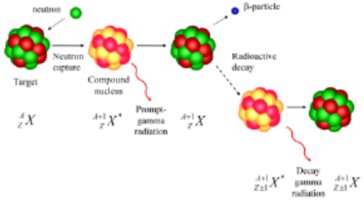
- Heavy Charged Particles (p, α, PF, PR)
- Light Charged Particles (e-, e+, β-, β+)





- Photons (visibles, IR, UV, X, gamma, freinage)
- Neutrons (thermal, epithermal, fast)
- Neutrinos





Two main famillies…

Radiation	Form	mass	charge	Energy
α	^4He	$7340.m_e$	$2\ q_e$	3 to 10 MeV
β	β^+ : positon β^- : électron	m_e m_e	q_e q_e	0 to some MeV 0 to some MeV
Heavy Ions	Protons Fission Products Reaction Products	$1836.m_e$ - -	q_e - -	0,1 to some MeV some MeV to 100 MeV -
γ - X	photons	none	none	some keV to some MeV
n	neutrons	$1838.m_e$	none	some % of eV to qq MeV

$q_e = 1.6\ 10^{-19}$ C

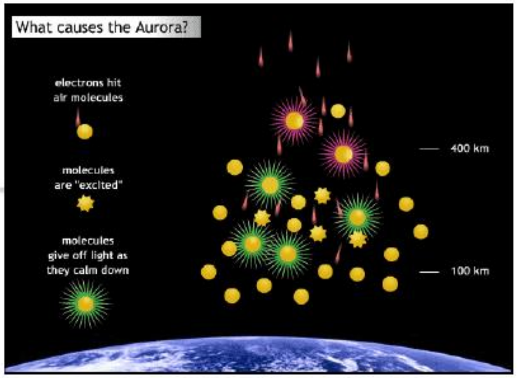
$m_e = 511$ keV/c2

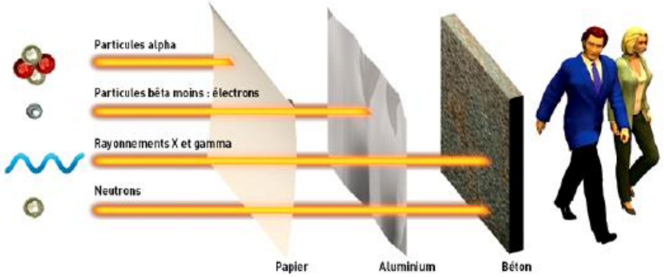
$m_p = 938{,}3$ MeV/c^2

$m_n = 939.6$ MeV/c^2

1 eV = $1{,}6\ 10^{-19}$ J

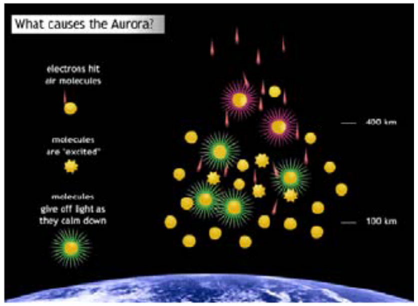
Radiation Interaction with Matter



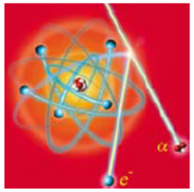


Interaction of charged particles with matter

Interaction of Charged Particles with Matter

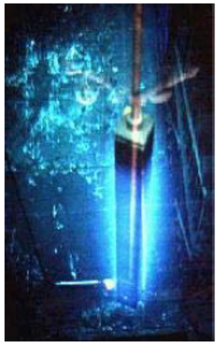


Main and fundamental characteristics of charged particles are :



- ✓ Electric charge in Coulomb (n.(± qe)), n ∈ Z
- ✓ Rest Mass M_0 (u.m.a.)
- ✓ Total Energy Mc^2
- ✓ or relativistic mass given by Lorentz formula :

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$



- ✓ or Velocity v
- ✓ or Kinetic Energy ($T = (m-m_0)\, c^2$)

Interaction of Charged Particles with Matter

Interaction of charged particles (low and intermediate energies) with matter mainly occurs by mean of Coulomb Forces with Atomic Electrons and/or electromagnetic field of atomic nucleus.

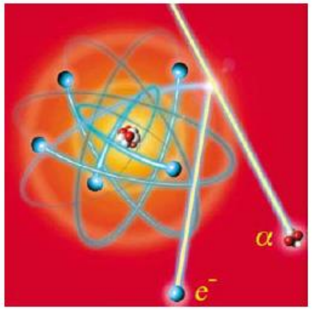
Energies of particles we deal with in our field of activities generally do not lead to interaction with atomic nucleus.

Interaction of heavy charged particles

Interaction of Light Charged Particles

Slowing Down; Energy Loss, Loss of charges

Interaction of heavy charged particles with matter



Interaction of heavy charged particles

By heavy charged particles we mean : (p ($^{1}H^{+}$), D ($^{2}H^{+}$), α($^{4}He^{2+}$), PF, PR)

Mass M is larger than electron mass m_e ($M/m_e \cong A.1836$)

For 100 MeV>Ec > 1 MeV ⇨ slowing Down without strong deviation of H.C.P.*

Heavy Charged Particle loss its energy gradually

H.C.P. energy is gradually transferred to electrons

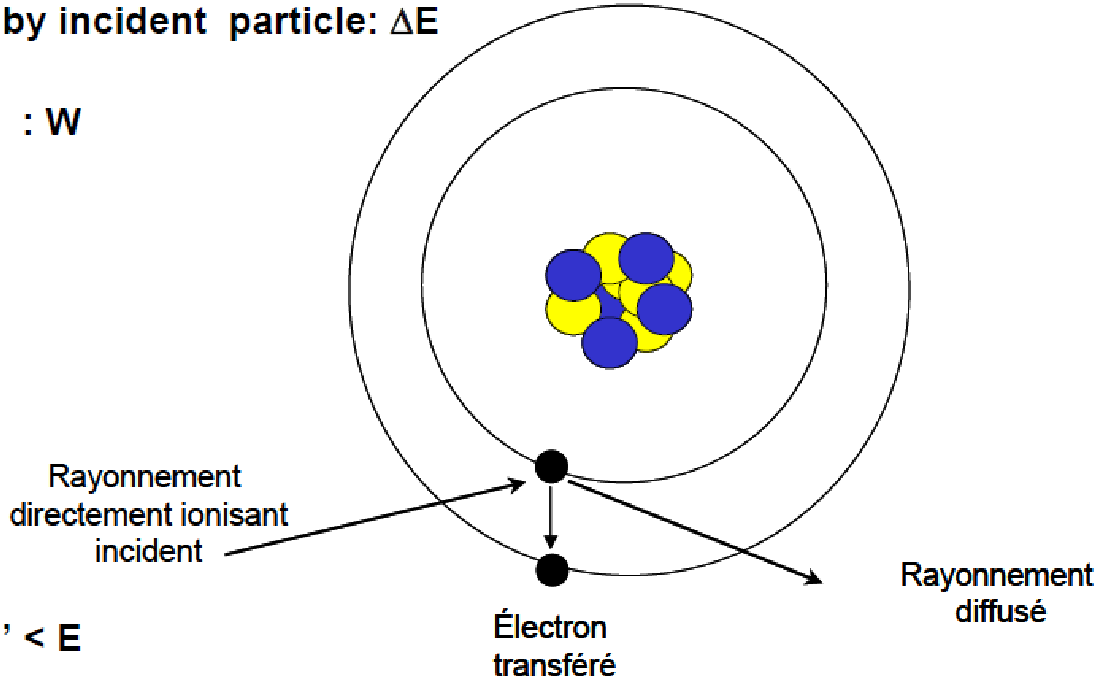
Energy transfer is mainly done via excitation and/or ionization process

Interaction of heavy charged particles

Basic Excitation phenomena

- Kinetic Energy transferred by incident particle: ΔE
- Binding Energy of electron : W

Excitation occurs if $\Delta E < W$



Scattered Ray with energy E' < E

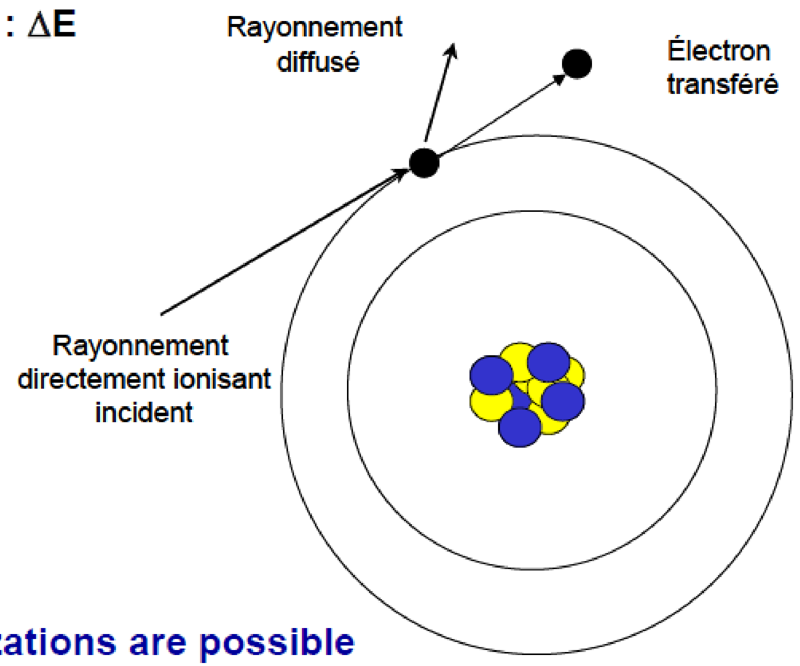
Désexcitation ⇔ Emission of electromagnetic rays (X , U.V. , visible)

Interaction of heavy charged particles

Basics of Ionization Phenomena

- Kinetic Energy transferred by incident particle : ΔE
- Binding Energy of electron : W

- Ionization occurs if ΔE > W



$E_{\text{électron éjecté}} = \Delta E - W$

If E of emitted electron > W ⇒ secondary ionizations are possible (Auger effect)

Interaction of heavy charged particles

The rate at which a charged particle loses energy as it passes through a material depends on the nature of both the incident and the target particles. This quantity is generally referred as the stopping power of the material which could considered as the sum of the electronic and nuclear stopping powers.

$$-\frac{dE}{dx} = S_{elect.} + S_{nucl.} \approx S_{elect.}$$

Bethe and Bloch expression for stopping power given in keV.µm^{-1} :

$$\left| -\frac{dE}{dx} \right| = \frac{z^2 e^4}{4\pi\varepsilon_0^2 m_0 v^2} nZ \ \ln \frac{2 m_0 v^2}{I}$$

Interaction of heavy charged particles

Bethe formula in classical mechanic :

$$\left| -\frac{dE}{dx} \right| = \frac{z^2 e^4}{4\pi\varepsilon_0^2 m_0 v^2} nZ \ln \frac{2 m_0 v^2}{I}$$

Where :

- **z** et **v** respectively atomic number (charge) and velocity of incident particle
- $\mathbf{m_0}$ and **e** rest mass and charge of electron respectively
- **n** number of atoms per volume unit of target material.
- **Z** atomic number of the medium
- **I** Ionization potential of the medium

Remarks :

- ✓ **Stopping power is independent of incident particle mass**
- ✓ **for particles of same charge z, dE/dx only depends on their velocities**
- ✓ **for low energy, due to recombination ⇨ Bethe formula is not applicable.**

Interaction of heavy charged particles

In relativistic mechanic, Bethe formula becomes :

$$\left| -\frac{dE}{dx} \right| = \frac{z^2 e^4}{4\pi\varepsilon_0^2 m_0 v^2} nZ \left[\ln \frac{2 m_0 v^2}{I} - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2} \right]$$

Where c is light celerity in the void.

Using Bethe formula is often complicated

One commonly use simple formula :

$$\left| -\frac{dE}{dx} \right| = I_s \omega$$

With Is : number of ionizations produced per cm traveled by incident particle.

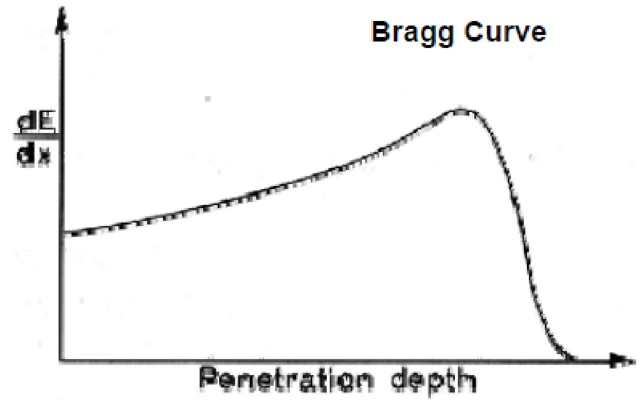
ω : Average ionization energy of the medium.

Interaction of heavy charged particles

ω Is a characteristic of medium

GAZ	$\omega\alpha$(eV)	ωp(eV)	ωe-(eV)
Air	35	36	37
Argon	26	26	26
Nitrogen	36	36	35
Hydrogen	36	- - - - -	

$$\left| -\frac{dE}{dx} \right| = I_s \omega$$

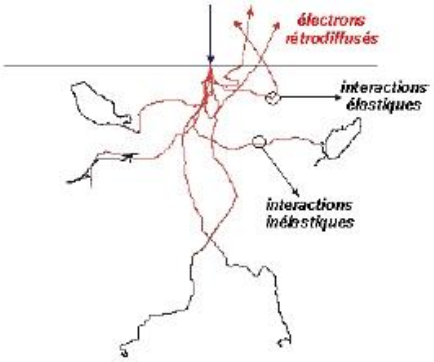


Variation of stopping power with respect of residual energy

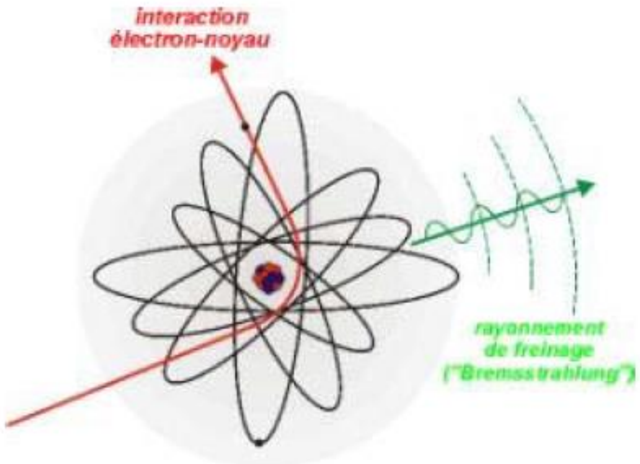
As a heavy charged particle moves through matter it looses energy and consequently it stopping power changes.

The range of a particle traveling through a material depends on its instantaneous energy.

Energy deposit of particle is finally very localized



Interaction of light charged particles



Interaction of light charged particles

Light charged particles ⇔ (e-, e+, β-, β+)

Concerns mainly interactions of electrons with matter

The way an electron beam would behaves when passing through matter depends, to a large extent, on its energy. At low to moderate energies, the primary modes of interaction are:

- Ionization
- Elastic scattering of an electron from another electron (Moeller scattering)
- Electron positron annihilation
- Inelastic scattering on nucleus (Bremsstrahlung)
- Cherenkov Radiation

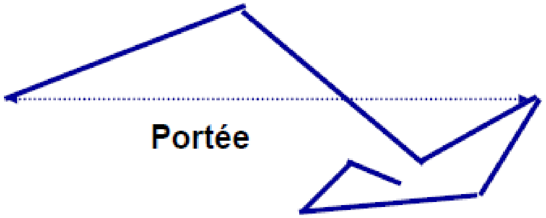
Interaction of light charged particles

ELECTRONS

There is a significant difference between electrons and H.C.P. behaviours when passing through matter.

Actually :

- ✓ Electrons become relativistic from 50 keV energy when proton and α-particles need respectivelly 90 MeV and 350 MeV
- ✓ Electrons loose their energie in matter via :
  - Excitation and ionisation for low and moderate energies
  - Electromagnetic radiations for high electron energies



Interaction of light charged particles

ELECTRONS

At low to moderate energies the collisional energy loss of electrons is quite significant and up to a certain energy is higher than the radiative energy loss. Hence the stopping power of a material for electrons consists of two components : collisional and radiatice:

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{coll} + \left(\frac{dE}{dx}\right)_{rad}$$

Where :

$$-\frac{dE}{dx}\bigg|_{ray} = \frac{\rho EZ(Z+1)e^4}{137\, m_e^2 c^4}\left[4\ln\left(\frac{2E}{m_e c^2} - \frac{4}{3}\right)\right]$$

In first approximation radiative energy loss behaves as Z^2E when collisional energy loss varies like Z.LnE.

Interaction of light charged particles

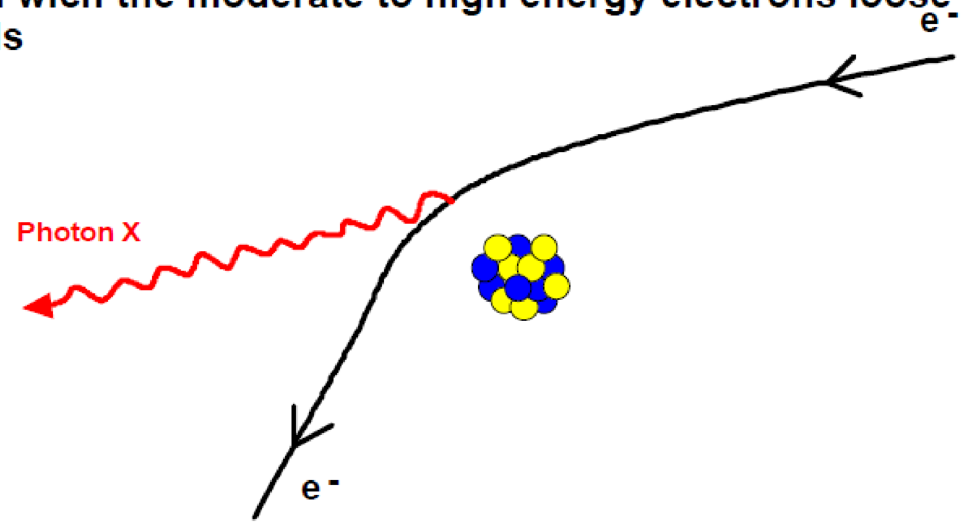
Bremsstrahlung

Bremsstrahlung process refers to the emission of radiation when a charged particle accelerates in a material.

⇒ Abrupt variation of velocity and déviation of trajectory

⇒ Dominant mode through wich the moderate to high energy electrons loose energy in high Z materials

$$\frac{\dfrac{dE}{dx(\text{freinage})}}{\dfrac{dE}{dx(\text{ionis.+excit.})}} = KZE$$

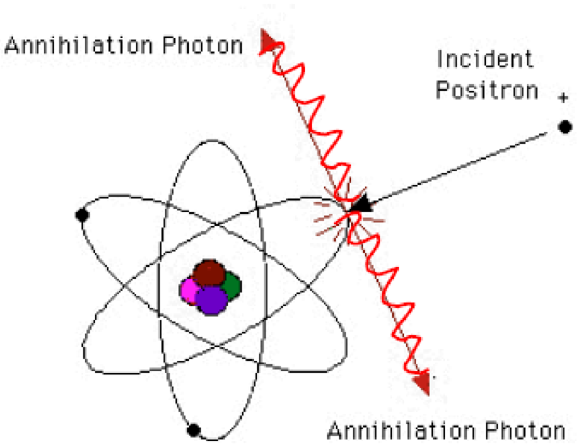


Interaction of light charged particles

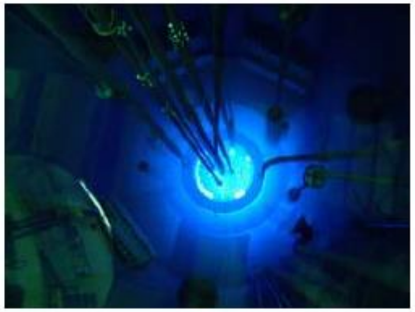
POSITRONS

- Coulomb attraction with atomic electrons
- Energy loss as electron enrgy loss behaviour
- At low energy, positron could disappear following annihilation process

2 photons are created each of de 511 keV energy



Interaction of light charged particles



CHERENKOV effect

Charged particle in general and electron in particular can emit Cherenkov radiation when accelerated to high energies in a medium. Its energy should be so high that its velocity becomes higher than the velocity of light in medium.

c : speed of light in vaccum 3 10^8 m/s

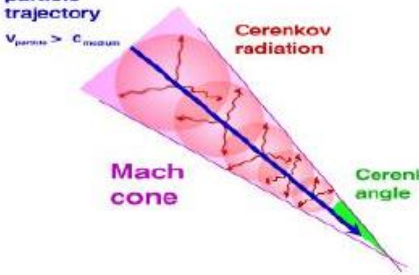
n : refractive index of medium ⇒

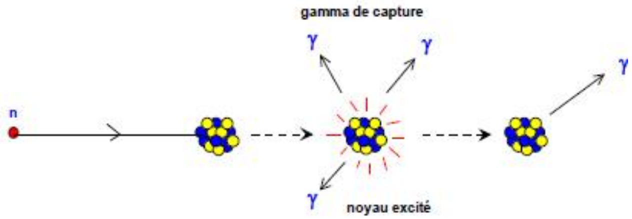
$$v > \frac{c}{n}$$

⇒ émission of light (continium spectrum)

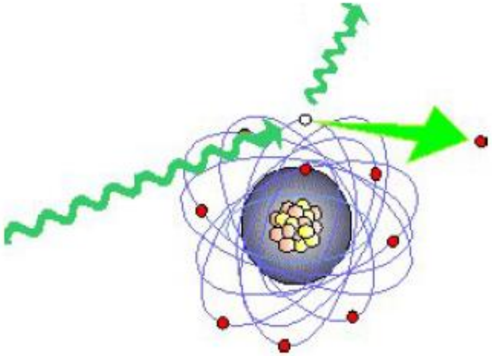
In practical cases, this phenomenon cocerns electrons mainly.

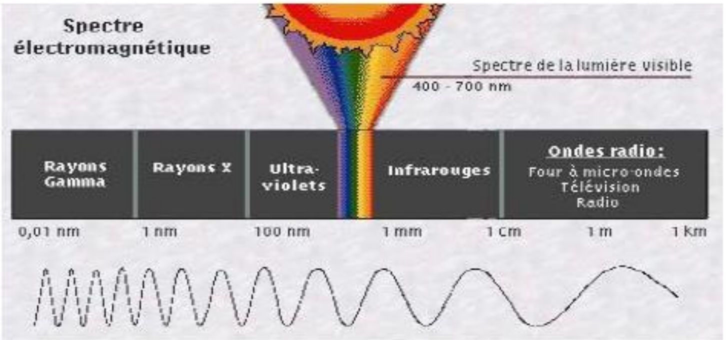
(Example : in watter n=4/3 compute the minimum energy of electron Eelectron and proton to induce Cherenkov effect.
v > 3/4 c So, Energy $E_{électron}$ > 0.26 MeV E proton > 478 MeV)



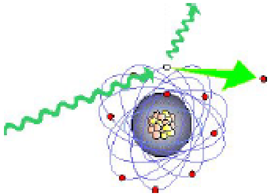


Interaction of Non Charged particles with matter

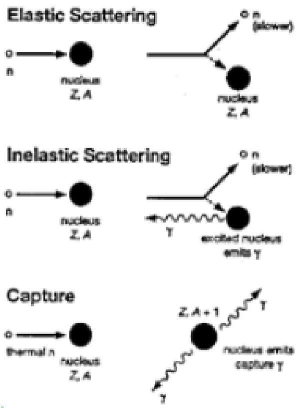




Interaction of non charged particles



- Interaction of photons
- Interaction of neutrons



Socrates argued that a statue inferred the existence of a sculptor

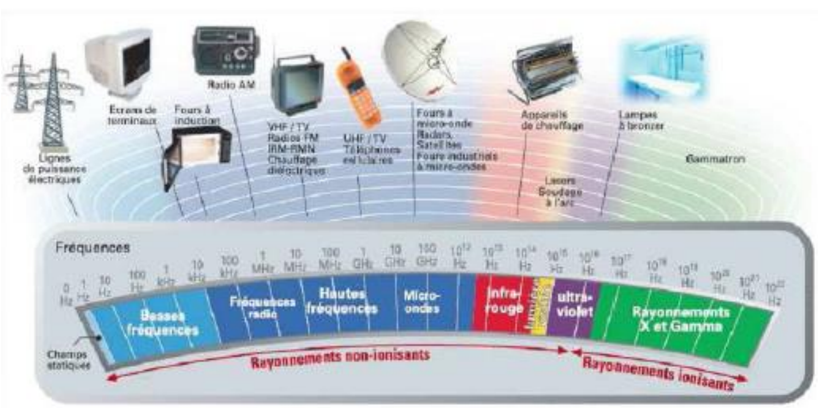
Interaction of photons with matter

PHOTONS

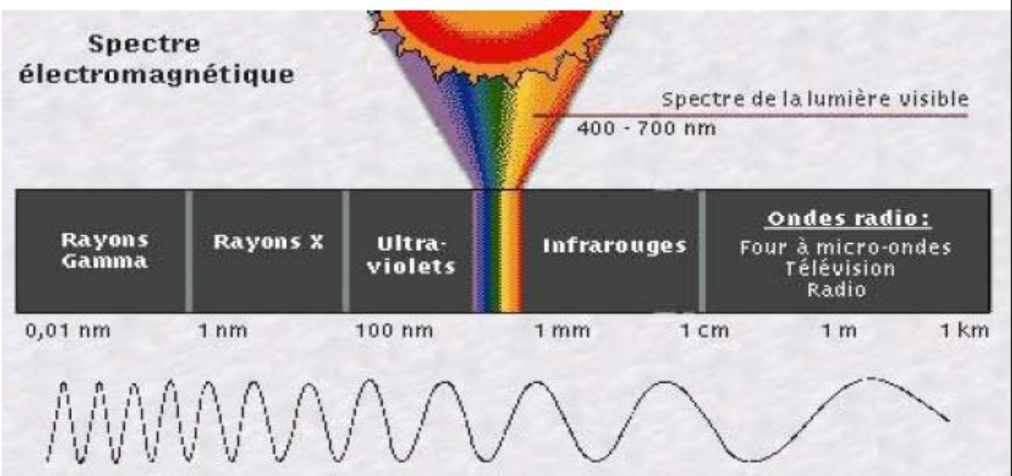
- Charge = 0, Mass = 0
- Energy : $E_{photon} = h\nu = hc/\lambda$
- Momentum : $P_{photon} = E/c = h/\lambda$

h constant ofPlanck (quantum d'énergie) equals to 6,626 10^{-34} J. s^{-1}

ν et λ respectively frequency (s^{-1}, Hz) and wavelength (m) of photon



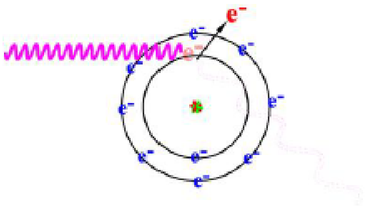
Spectre des ondes électromagnétiques (source INRS).



Interaction of X and γ with matter

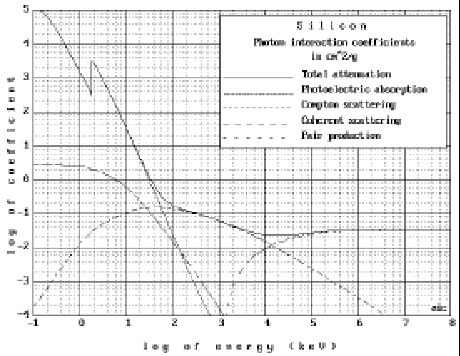
4 Main Process :

Interaction with electrons :



- Photoelectric effect (Einstein 1905)
- Compton effect (Compton 1923)

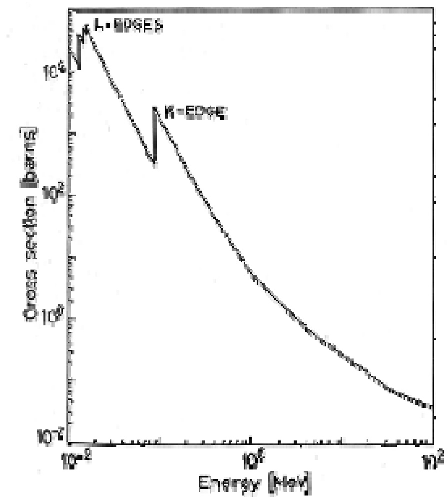
Interaction with nucleus :



- Pair production (Planck 1932)
- Photonuclear reactions (γ,n);(γ,p);(γ,f)

Interaction of X and γ with matter

Photoelectric Effect

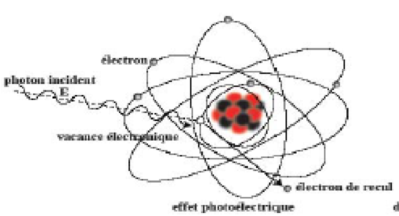


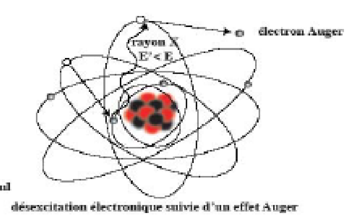
Total Absorption of Photon by Atomic Electron

$$\gamma + atom \rightarrow atom^{+} + e^{-}$$

A positive ion is created following emission of photoelectron,.
After what, X Rays are emitted and hence sometimes Auger electron(s).

Photoelectric effect takes place predominatly in the K atomic shell.





$$\sigma_{photo}^{K} = \left(\frac{32}{\gamma^{7}}\right)^{1/2} .\alpha^{4}.z^{4}.\sigma_{T}$$

$$\alpha = \frac{1}{137};\gamma = \frac{E_{\gamma}}{m_{e}c^{2}}$$

$\cong$ **Proportional to Z^4 / E^3**

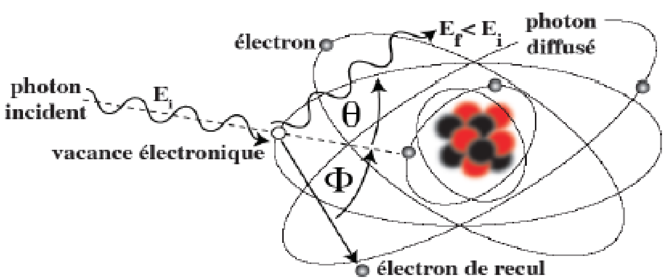
Interaction of X and γ with matter

Compton scattering

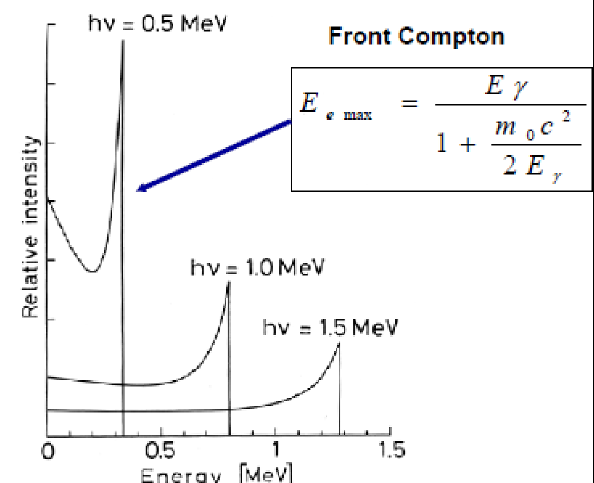
Refers to inelastic scattering of photons from free or loosely bound electrons which are at rest.

Process : $\gamma + e^- \rightarrow \gamma' + e^-$

Compton scattering becames significant
(0.1 MeV < E < 5 MeV)



$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

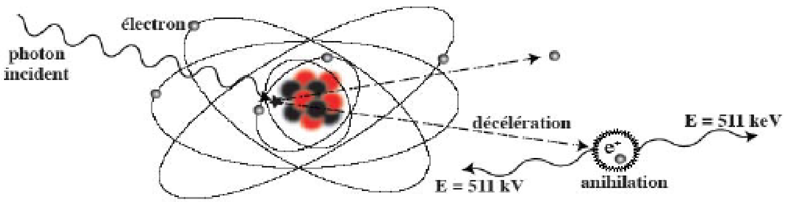


Interaction of X and γ with matter

Paire production

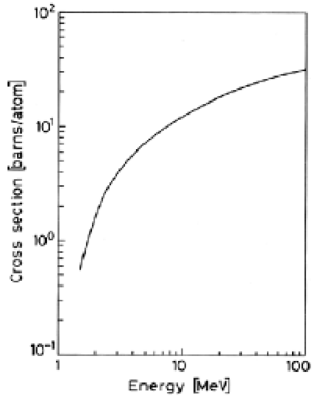
- Process that results in the conversion of a photon into *electron-positron* pair
- Actual threshold energy of reaction : $E_{th} = 2m_0c^2(1+(m_0/M))$
- Photon disapears and hence production of [e-,e+] pair
- Electron and positron interact with matter
- Positron quickly combines with a nearby electrons to produce photons through the process of annihilation (2 photons of 511 keV energy)

Cross section for E>20 MeV has roughly Z^2 dependence.



$$\sigma_{paire} = \frac{Z^2}{137}\left(\frac{e^2}{4\pi\varepsilon_0 m_0 c^2}\right)^2\left(\frac{28}{9}Log\frac{2h\gamma}{m_0c^2}-\frac{218}{27}\right)$$

If $2m_0c^2 << h\gamma << 137 m_0c^2 Z^{-1/3}$



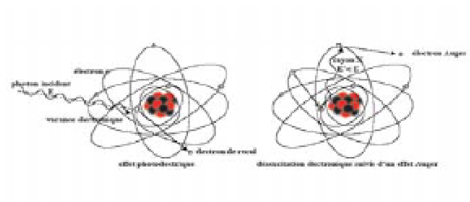
Interaction of X and γ with matter

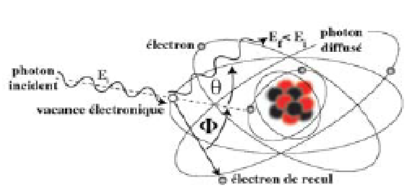
Finally

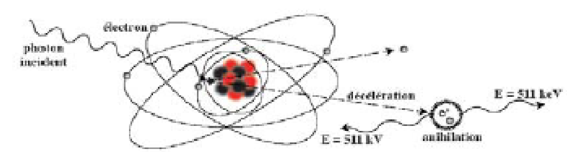
With photons there is no direct ionizations

$\Rightarrow$ Most of ionization are induced by primary e^- (p-e, Compton, p-p) :

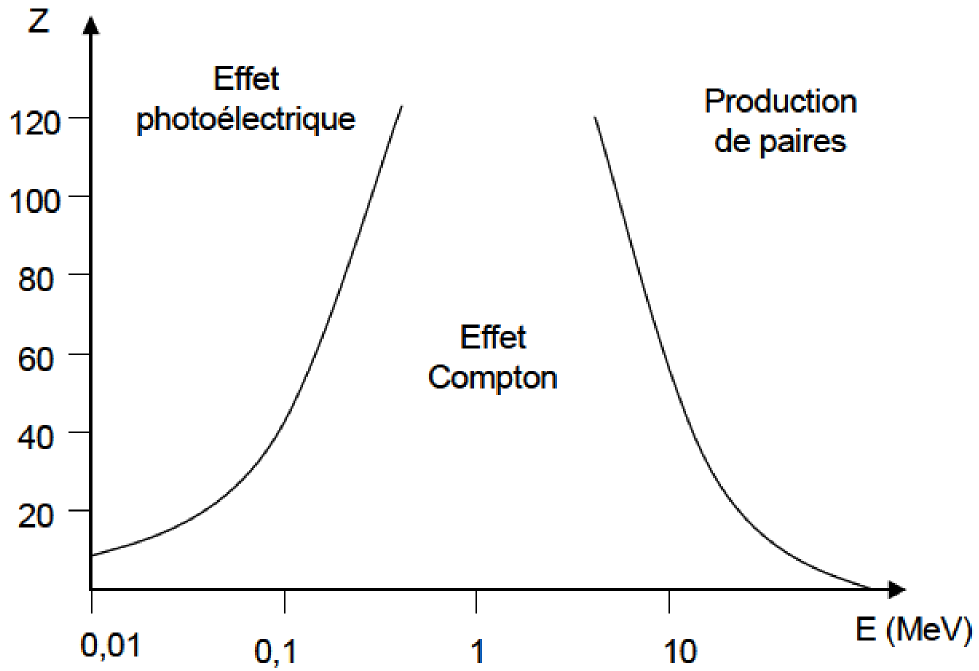
Photoelectric effect
Compton scattering $\Rightarrow$ e^- $\Rightarrow$ ionization and excitations
Paire production







Interaction of X and γ with matter



Cross section behaviour v.s. energy

$$\sigma_T = \sigma_{Ph} + Z\sigma_C + \sigma_{p\text{-}p}$$

Photonuclear reactions

For photons of high energy i.e. above certain reaction threshold(s), photonuclear réactions could occur

Typical reactions

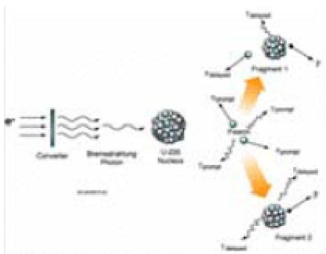
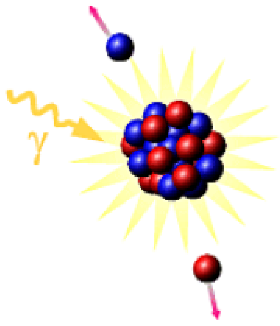


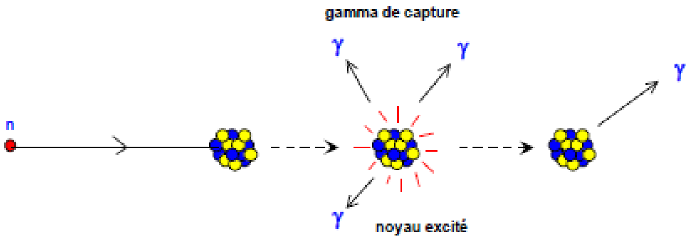
Figure 1. Schematic illustration of relevant neutron emission processes in photofission

(γ,n); (γ,2n), (γ,xn)

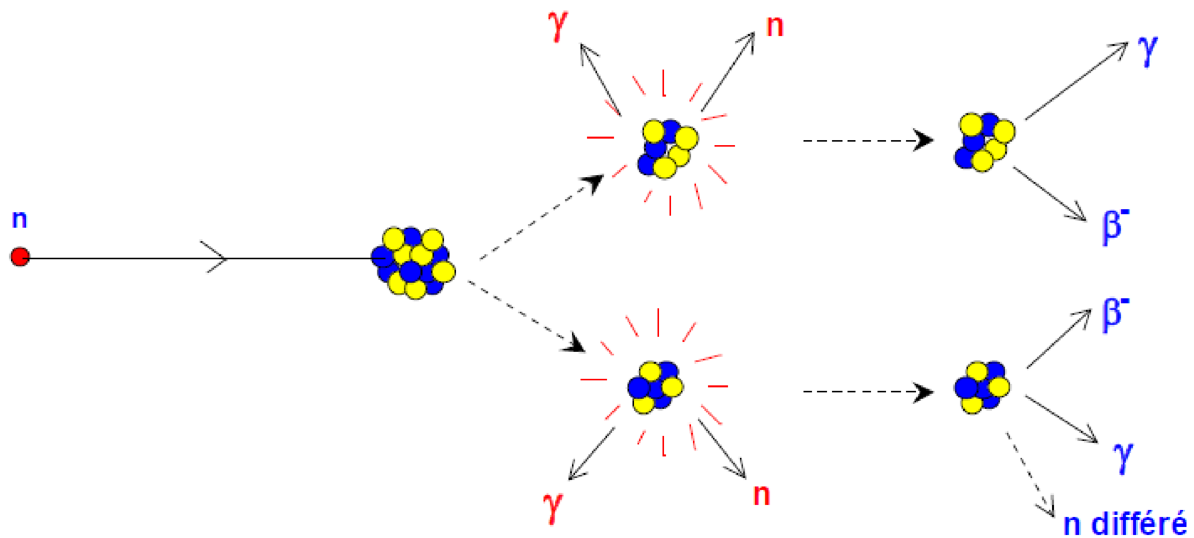
(γ,p); (γ,xp)

(γ,f)



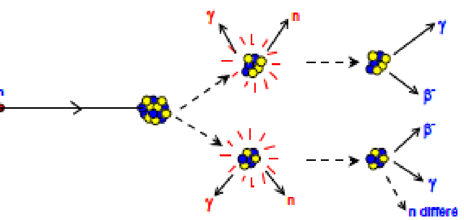


Interaction of neutrons with matter



Interaction of neutrons with matter

- The neutron interacts **with nucleus**
- In general heavy **charged particles are produced**
- Secondary particles **ionize medium/matter**.
- The interaction type **strongly depends** on neutron **energy**



Classification of neutrons

Thermal neutrons E = 0.025 eV

Epithermal neutrons 0.6 eV <E<10 keV

Intermediate neutrons 10 keV<E<0.5 MeV

Fast neutrons E>0.5 MeV

Interaction of neutrons with matter

Main neutron-nucleus reactions

scattering

- inelastic: (n , n' γ)
- elastic: (n , n)

prominent for fast neutrons

The neutron is kept

absorption

- capture: (n , γ)
  - (n , α)
  - (n , p)
- fission: (n , fission)

prominent for thermal/epithermal neutron

The neutron disapears

Interaction of neutrons with matter

Examples of radiative capture reaction

$${}^{1}_{1}H + n \rightarrow {}^{2}_{1}H + \gamma_c$$

Les écrans contenant de l'hydrogène (eau, béton) sont des sources de rayonnement de capture (γ_c).

$${}^{113}_{48}Cd + n \rightarrow {}^{114}_{48}Cd + \gamma_c$$

Utilisée (de - en -) pour la détection des neutrons thermiques (σ_{th} = 2450 b)

$${}^{238}_{92}U + n \rightarrow {}^{239}_{92}U + \gamma_c$$

forte résonance à ≈ 7 eV

$${}^{239}_{92}U \rightarrow {}^{239}_{93}Np + \beta^-$$

$${}^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + \beta^-$$

Interaction of neutrons with matter

Non Radiative capture (n , α)

Neutron is absorbed , an α-particle is emitted

$$^{10}_{5}\mathrm{B} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{7}_{3}\mathrm{Li} + 2.79\ \mathrm{MeV} \quad (6\%)$$

$$\rightarrow {}^{4}_{2}\mathrm{He} + {}^{7}_{3}\mathrm{Li} + \gamma(0.48\mathrm{MeV}) + 2.31\ \mathrm{MeV} \quad (94\%)$$

frequently used for neutron detection (σ = 3900 barns for thermal neutrons et σ = 0.4 barns for fast neutrons)

$$^{7}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{3}_{1}\mathrm{H} + 4.8\ \mathrm{MeV}$$

Used for neutron detection and production of Tritium (σ = 950 barns pour n_{th}. et σ = 0.3 barns pour n $_{fst}$.)

Interaction of neutrons with matter

Finally

With neutron, il n'y there is no direct ionization

$\Rightarrow$ Ionizations are induced by :

Heavy charged particles emitted by non radiative captures $\Rightarrow$ (n , p) ; (n , α)...
The photons emitted $\Rightarrow$ radiative capture
Fission products $\Rightarrow$ réactions de fission

Interaction of radiations with matter

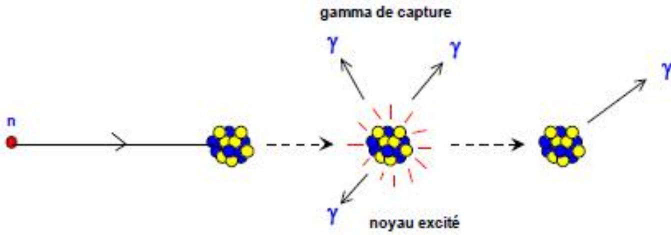
Radiation directely ionizing ⇒ Charged particles α, β, p ⟶ ionizations

Radiations indirectely ionizing

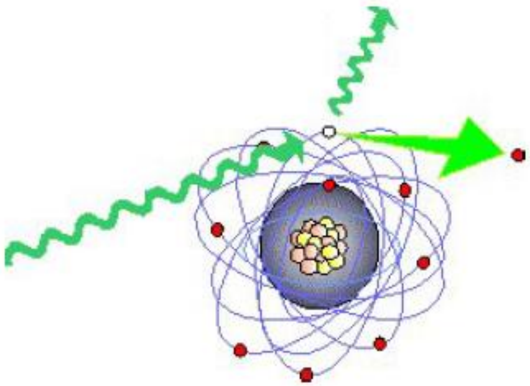
X , γ ⇒ photoelectric effect
Compton scattering
Pair production ⟶ e- ⟶ ionizations

n ⇒ (n,f) P.F.
(n, α) α
(n,p) p
(n, γ) γ

Finally (α, β, p,X,γ,n) ⇒ « ionizing radiations »



"WHENEVER A NUCLEAR PHYSICIST OBSERVES A NEW EFFECT CAUSED BY AN ATOMIC PARTICLE, HE TRIES TO MAKE A COUNTER OUT OF IT".



McKAY,
1953

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