



# WHO I AM ?



Abdallah LYOUSSI

*PhD in Physics*

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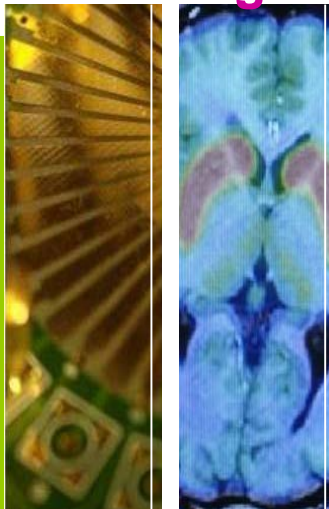
- **High Graduation from INSTN<sup>1</sup> (Engineer/Master in *Génie Atomique*).**
- **PhD in Nuclear Physics**
- **HDR in Experimental Physics**
- **International Expert in Nuclear Instrumentation & Measurements**
- **Research Director**
- **International R&D Project Manager**
- **Professor at INSTN and Aix Marseille University**
- **ANIMMA<sup>2</sup> General Chairman ([www.animma.com](http://www.animma.com))**
- **IEEE Distinguish Lecturer**
- **Founder and Coordinator of the Joint Research Lab. LIMMEX (CEA & AMU-CNRS)**  
Instrumentation and Measurement in harsh media Lab.
- **Chevalier dans l'Ordre des Palmes Académiques**

# The strategic pillars of the CEA

## Low carbon energies



## Health and information technologies



## The great research infrastructures



## Global Defence and Security



Fundamental Research  
≈ 30 % of the subsidies

## Higher education and Training

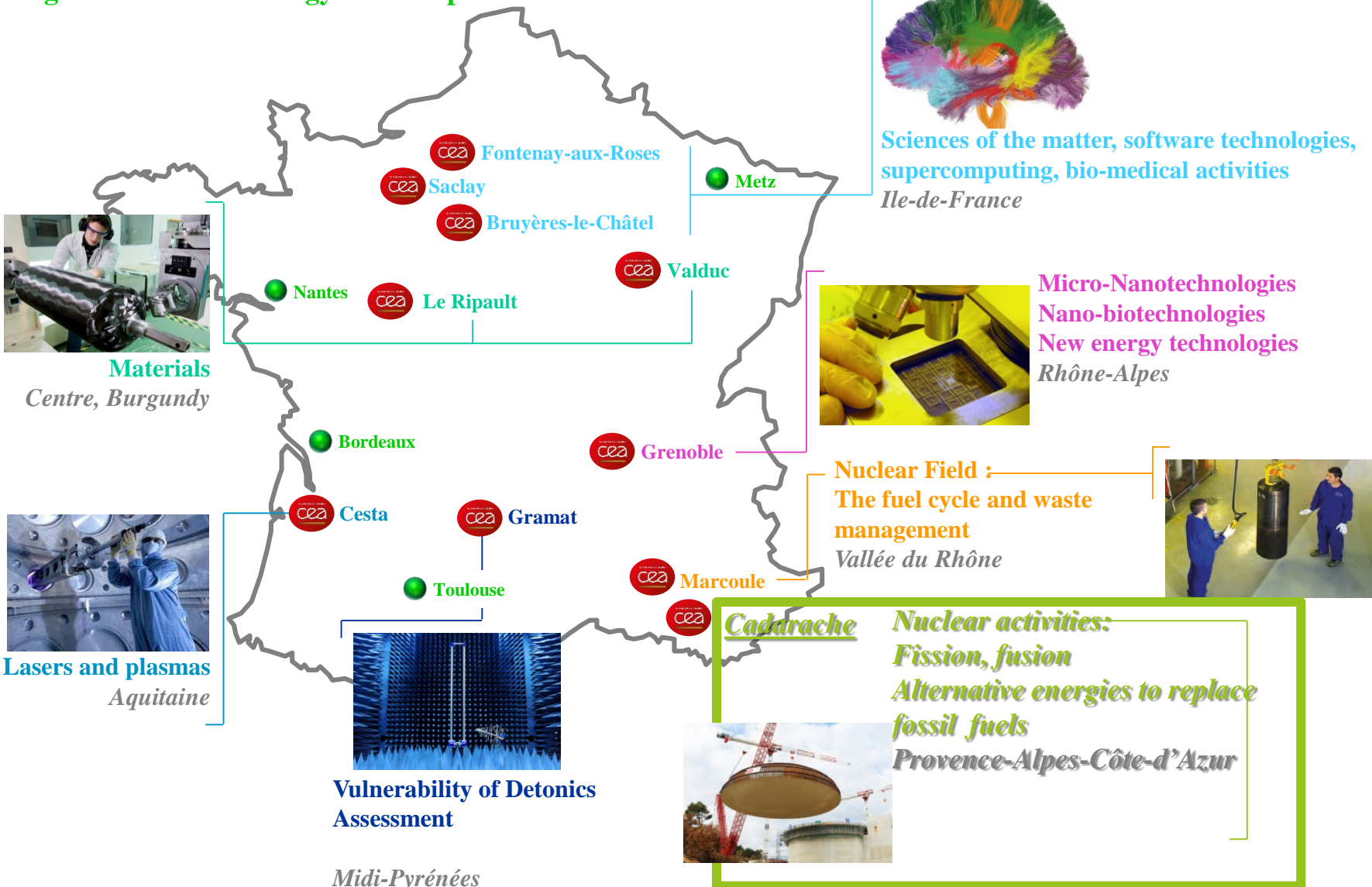


## Technological Development and Dissemination

# The CEA is located in 9 different regions in France (~16000 persons)

## There are 10 research centres in France

● 4 Regional CEA Technology transfer platforms



# The Cadarache Research Area

*1600 hectares of which 900 are enclosed*



2400



800

700  
80 Intercontrôle



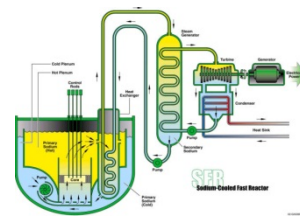
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*The largest European Research Centre involved in Low Carbon Energy Research*

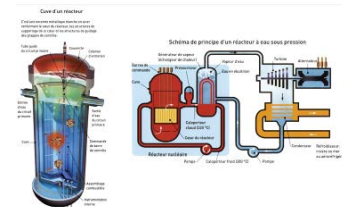
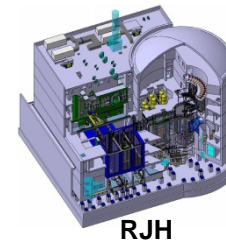
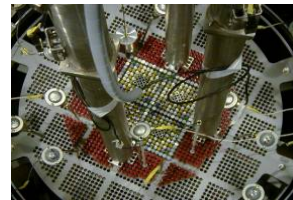
DE LA RECHERCHE À L'INDUSTRIE



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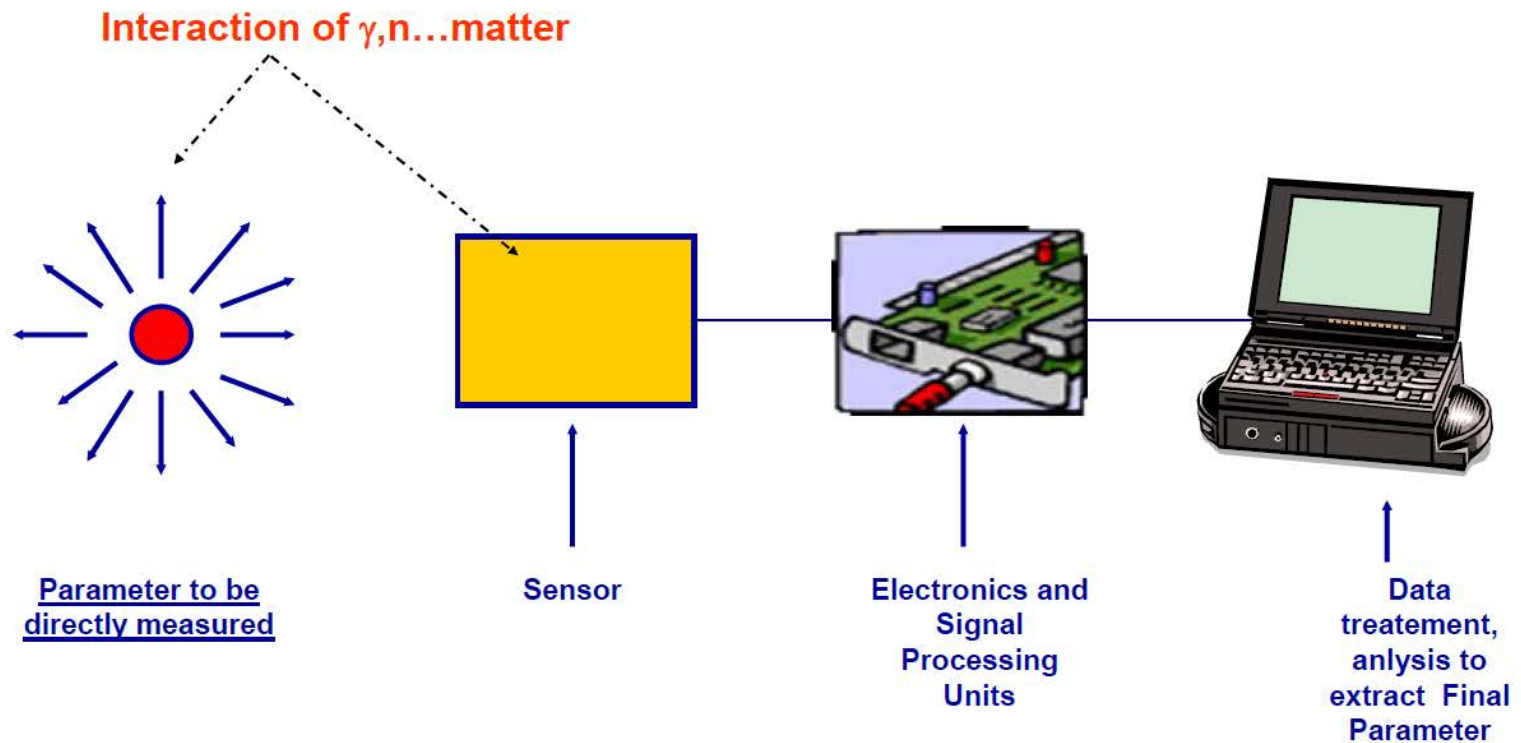


# Nuclear radiation detection : basics, principles and applications



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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



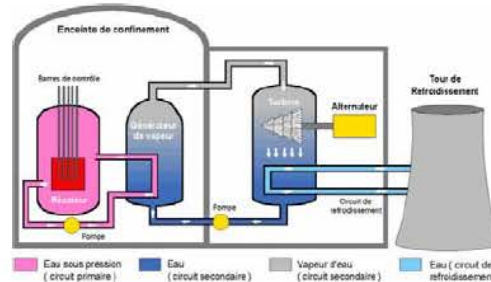
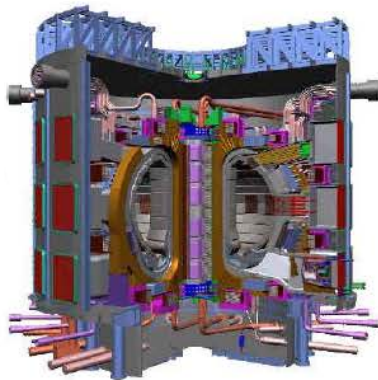


## Bibliography and references

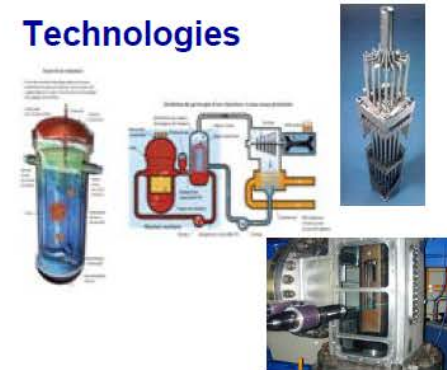
- [1] S. N. AHMED “*Physics & Engineering of Radiation Detection*” Academic Press in an imprint of Elsevier, UK 2007.
- [7] R.D. EVANS : “*The Atomic Nucleus*” MacGraw-Hill Book Company, Inc, New-York, 1955.
- [12] G.F. KNOLL : “*Radiation Detection and Measurement*”, 3<sup>rd</sup> Edition, John Wiley & Sons, New-York 2000, ISBN 0-471-073385.
- [19] H. Van HAERINGEN “*Charged-Particle Interactions*”: Theory and Formulas” Coulomb Press Leyden, 1985.
- [13] – A. LYOUSSI & al.: “*Transuranic waste assay detection by photon interrogation and on-line delayed neutron counting*”, Nuclear Instruments and Methods in Physics Research B 160 (2000) pp 280-289.

**Abdallah Lyoussi : « Détection des rayonnements et instrumentation nucléaire » EDP Sciences, ISBN:978-2-7598-0018-6, March 2010.**

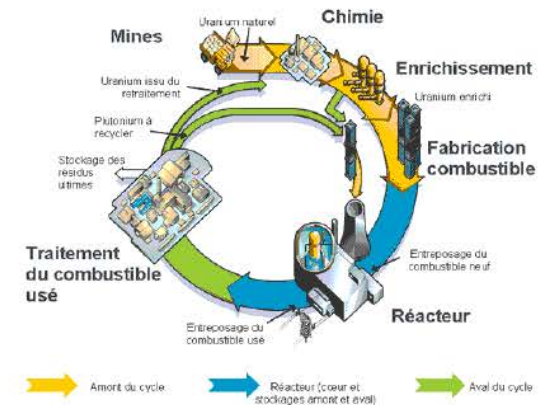
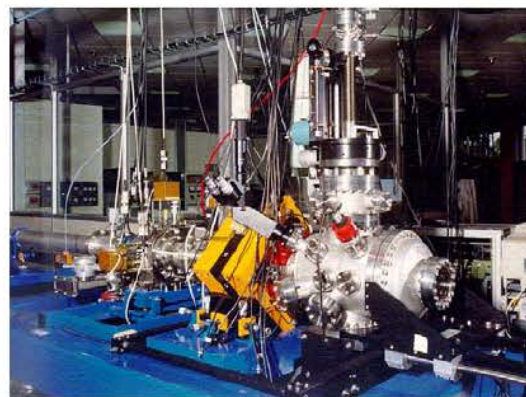
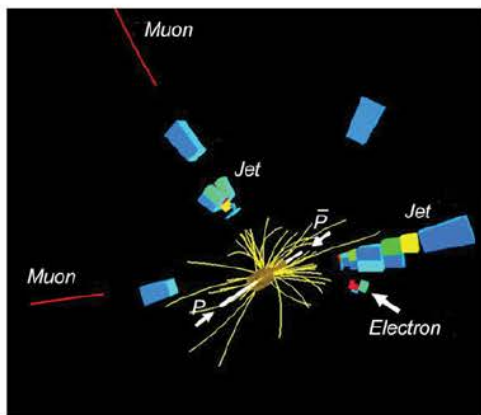




## Technologies



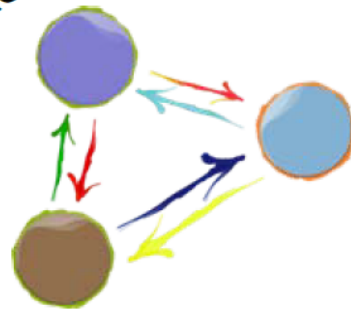
# INTERACTION OF RADIATION WITH MATTER



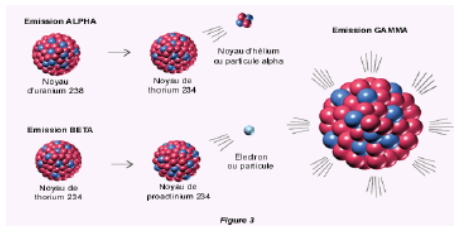
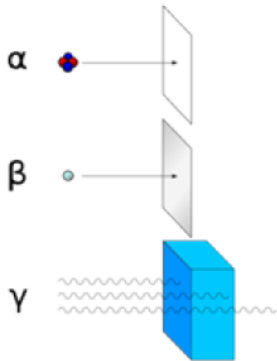
## Interaction of Radiation with Matter

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

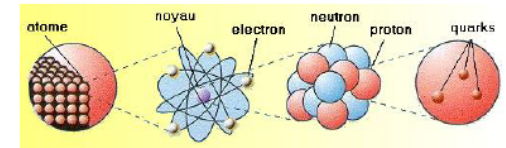
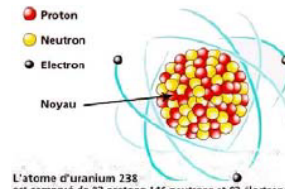
**Interaction**



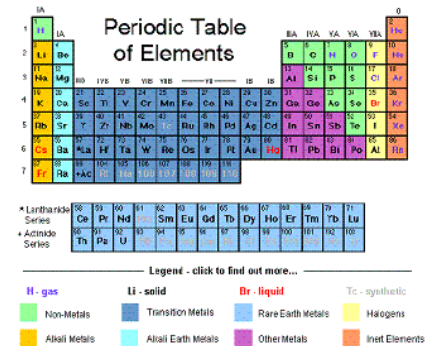
**Radiation/Rays ...**



**In our case  
...Matter is**

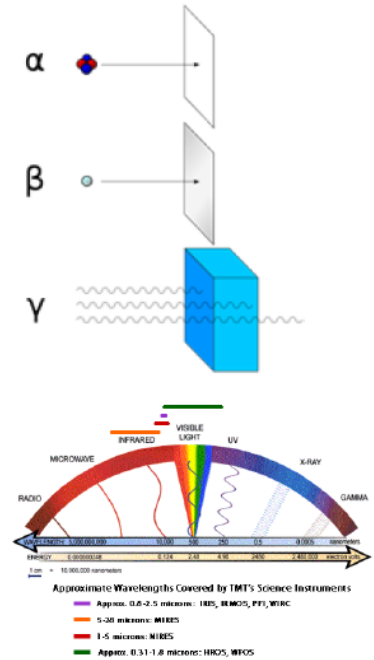


In Physics, Matter is considered as an association of electrons, nuclei, atoms and/or Molecules



## What are the main/basics characteristics of radiation?

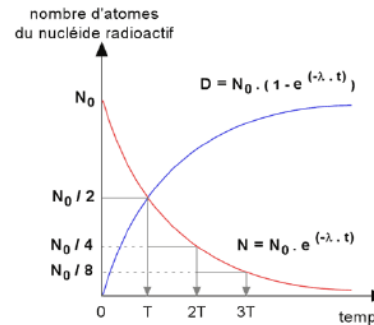
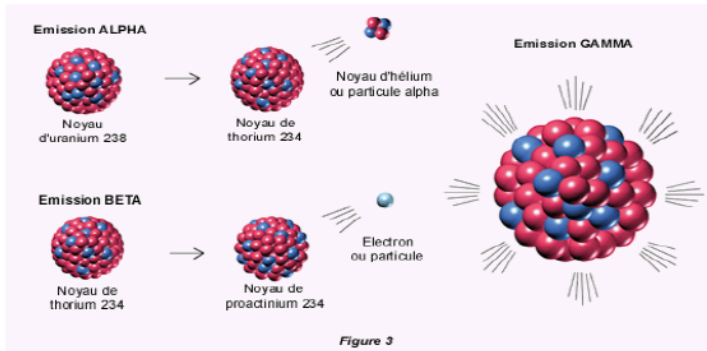
Type	:	atomic, nuclear
Nature	:	elementary, nuclei, heavy nucleus, photons
Charge	:	negative, zero, positive
Energy	:	low, intermediate, high
Period	:	short, long
Intensity	:	low, high
Type of reactions	:	with atom, with nucleus
Cross section	:	low, high



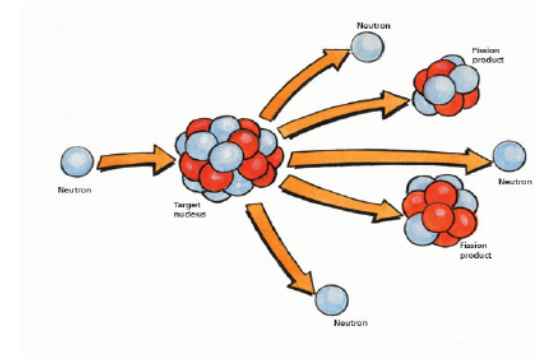
## In our Case...

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

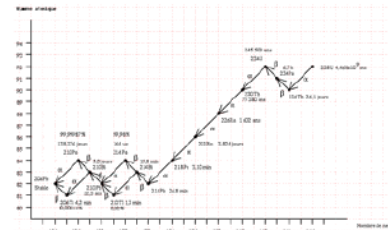
### Radioactive Disintegration



### Nuclear/Atomic Reactions/Interactions



Neutrons, Gamma, FP, AP, RP



## The word *RADIATION*...

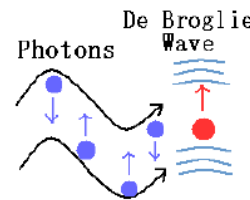
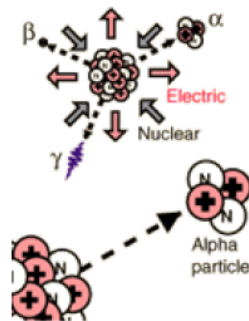
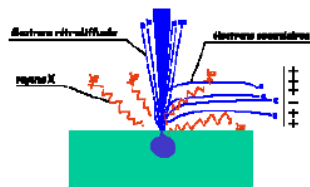
Different types of radiation are grouped in many ways

## Ionizing and nonionizing radiation



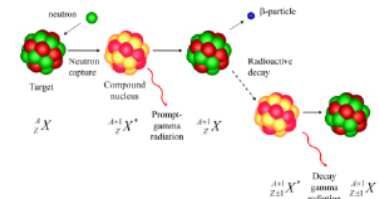
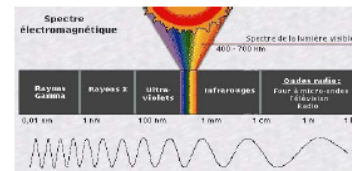
### Charged Particles

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



### Non Charged Particles

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



## Two main families...

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

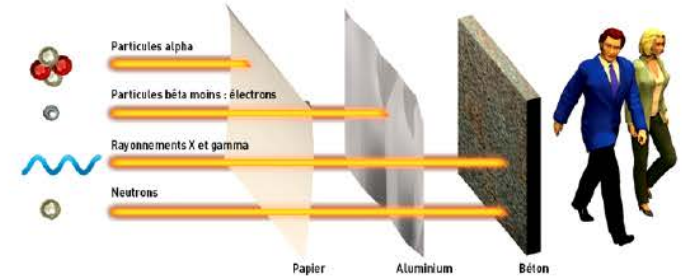
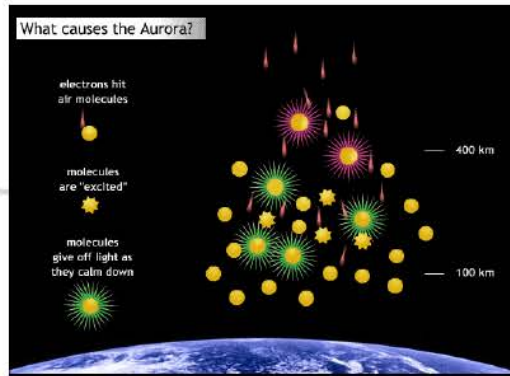
$$q_e = 1.6 \cdot 10^{-19} \text{ C}$$

$$m_e = 511 \text{ keV}/c^2$$

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

$$m_n = 939.6 \text{ MeV}/c^2$$

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



## Interaction of charged particles with matter





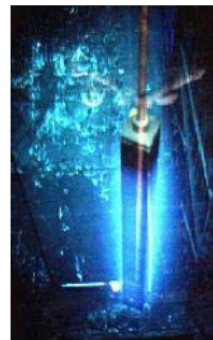
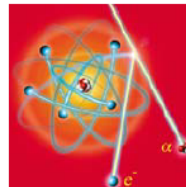
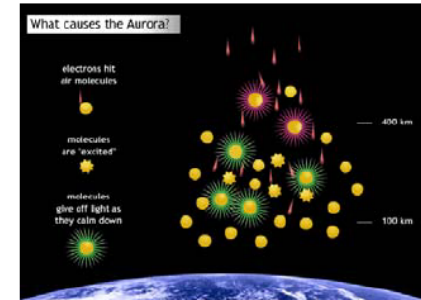
## Interaction of Charged Particles with Matter

Main and fundamental characteristics of charged particles are :

- ✓ Electric charge in Coulomb ( $n \cdot (\pm q_e)$ ),  $n \in \mathbb{Z}$
- ✓ 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.

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Interaction of heavy  
charged particles

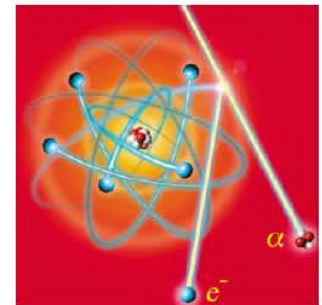


Interaction of Light  
Charged Particles



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 ( ${}^1\text{H}^+$ ), D ( ${}^2\text{H}^+$ ),  $\alpha$ ( ${}^4\text{He}^{2+}$ ), PF, PR)

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

For  $100 \text{ MeV} > E_c > 1 \text{ MeV} \Rightarrow$  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

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 be 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<sup>-1</sup> :

$$\left| -\frac{dE}{dx} \right| = \frac{z^2 e^4}{4 \pi \epsilon_0^2 m_0 v^2} nZ \ln \frac{2 m_0 v^2}{I}$$

## 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
- $m_0$  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

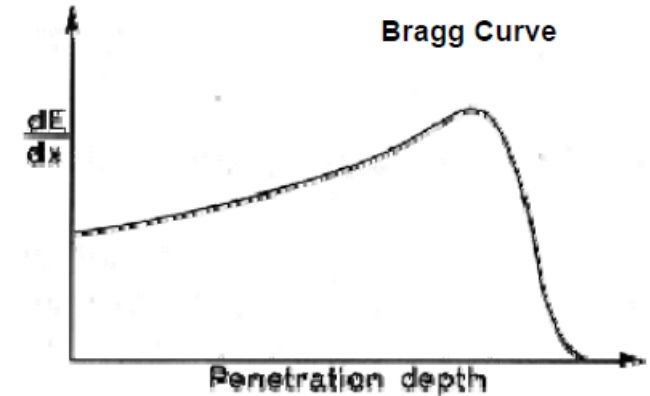
**Remarks :**

- ✓ 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  $\Rightarrow$  **Bethe formula is not applicable.**

## Interaction of heavy charged particles

$\omega$  is a characteristic of medium

GAZ	$\omega_{\alpha}(eV)$	$\omega_p(eV)$	$\omega_e(eV)$
Air	35	36	37
Argon	26	26	26
Nitrogen	36	36	35
Hydrogen	36	-----	



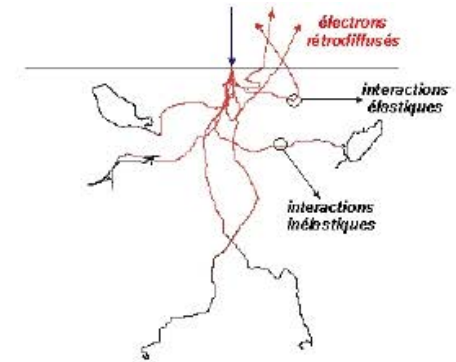
Variation of stopping power with respect of residual energy

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

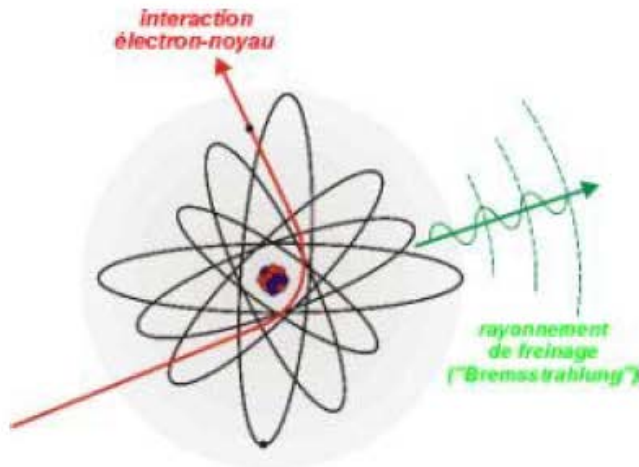
As a heavy charged particle moves through matter it loses energy and consequently its stopping power changes.

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  $\Leftrightarrow$  (e<sup>-</sup>, e<sup>+</sup>,  $\beta^-$ ,  $\beta^+$ )



Concerns mainly interactions of electrons with matter

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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

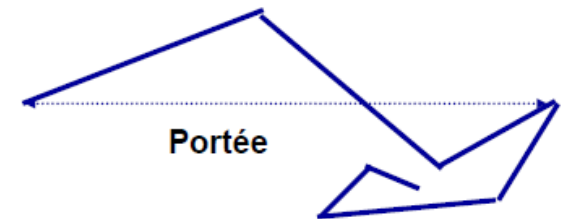
## Interaction of light charged particles

### 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  $\alpha$ -particles need respectively 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 radiative:

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

Where :

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

In first approximation radiative energy loss behaves as  $Z^2 E$  when collisional energy loss varies like  $Z \cdot \ln E$ .

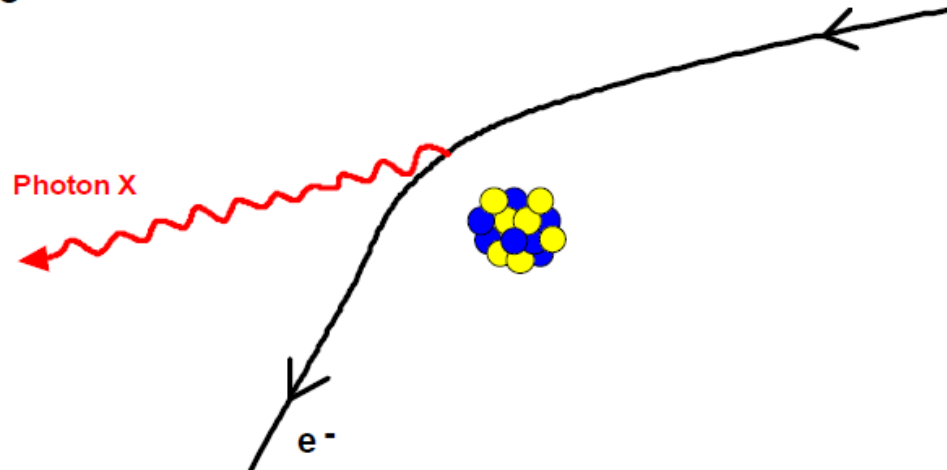
## Interaction of light charged particles

### 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 which the moderate to high energy electrons lose energy in high Z materials

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



## 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 vacuum  $3 \cdot 10^8$  m/s

$n$  : refractive index of medium

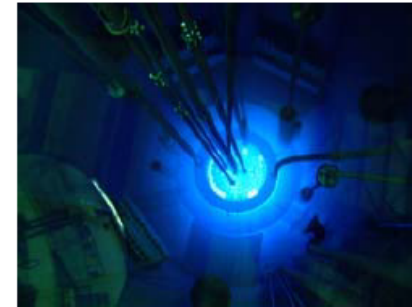
⇒

⇒ émission of light (continuum spectrum)

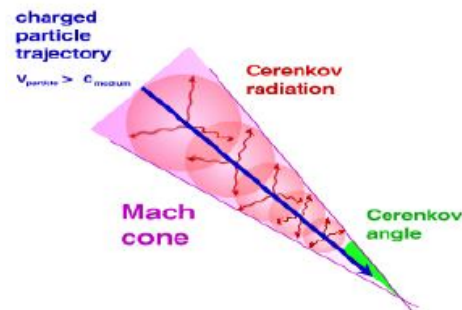
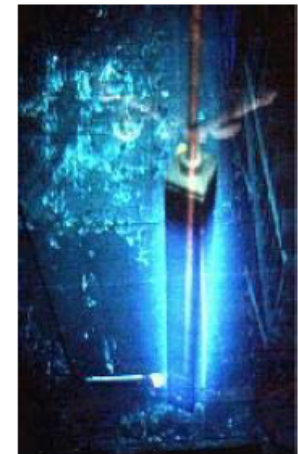
In practical cases, this phenomenon concerns electrons mainly.

( Example : in water  $n=4/3$  compute the minimum energy of electron and proton to induce Cherenkov effect.

$v > 3/4 c$  So, Energy  $E_{\text{electron}} > 0.26$  MeV  $E_{\text{proton}} > 478$  MeV )



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

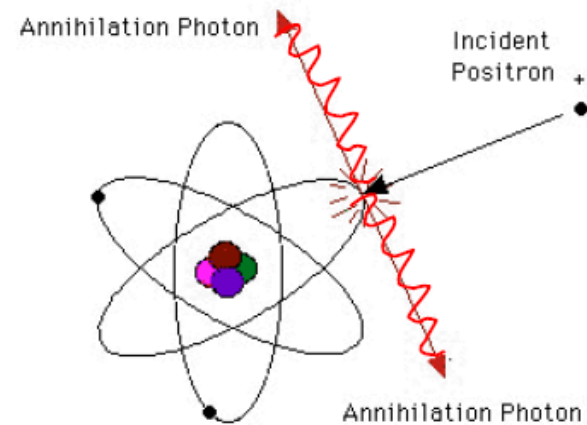


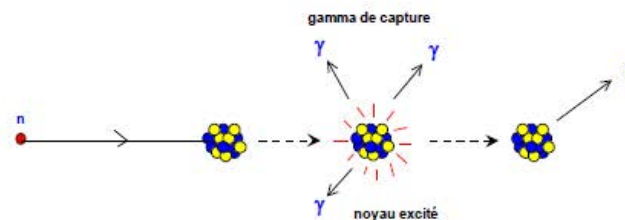
## Interaction of light charged particles

### POSITRONS

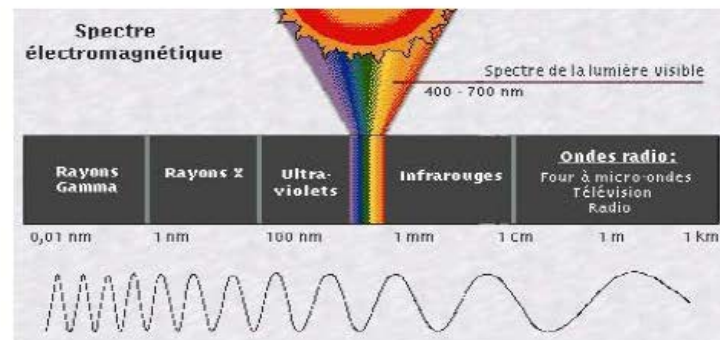
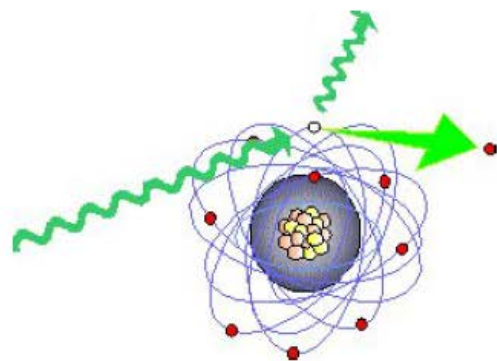
- \* Coulomb attraction with atomic electrons
- \* Energy loss as electron energy loss behaviour
- \* At low energy, positron could disappear following annihilation process

2 photons are  
created each of de  
511 keV energy

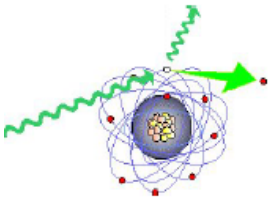




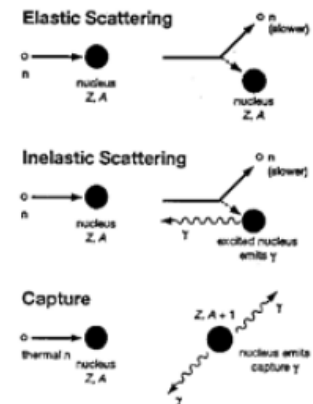
## Interaction of Non Charged particles with matter



## Interaction of non charged particles



- Interaction of photons
- Interaction of neutrons



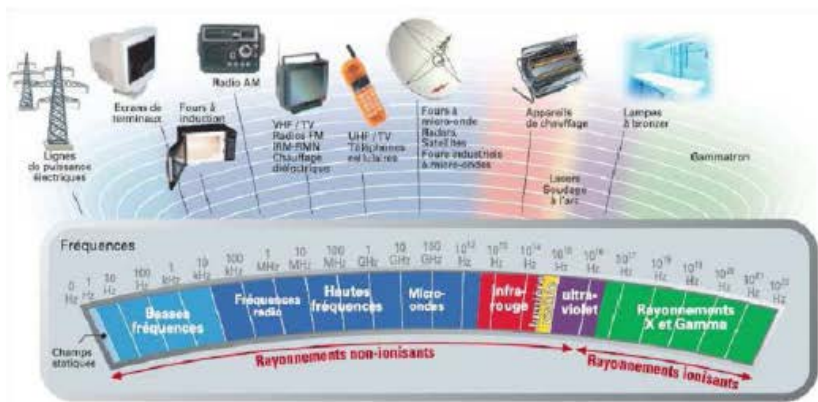
***Socrates argued that a statue inferred the existence of a sculptor***



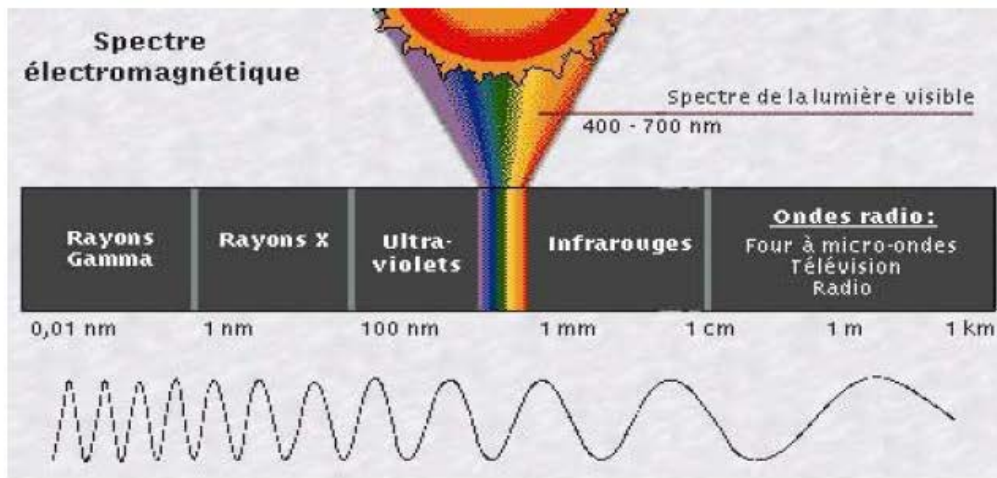
## Interaction of photons with matter

### PHOTONS

- ◆ Charge = 0, Mass = 0
  - ◆ Energy :  $E_{\text{photon}} = h\nu = hc/\lambda$
  - ◆ Momentum :  $P_{\text{photon}} = E/c = h/\lambda$
- $h$  constant of Planck (quantum d'énergie) equals to  $6,626 \cdot 10^{-34} \text{ J} \cdot \text{s}^{-1}$
- $\nu$  et  $\lambda$  respectively frequency ( $\text{s}^{-1}$ , Hz) and wavelength (m) of photon



Spectre des ondes électromagnétiques (source INRS).

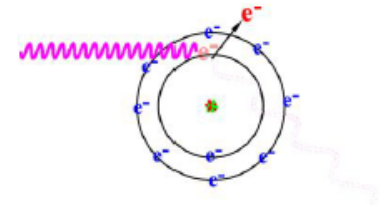


## Interaction of X and $\gamma$ with matter

4 Main Process :

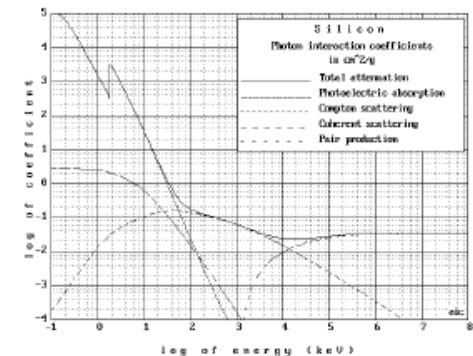
### Interaction with electrons :

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



### Interaction with nucleus :

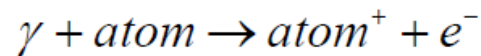
- Pair production (Planck 1932)
- Photonuclear reactions ( $\gamma, n$ ); ( $\gamma, p$ ); ( $\gamma, f$ )



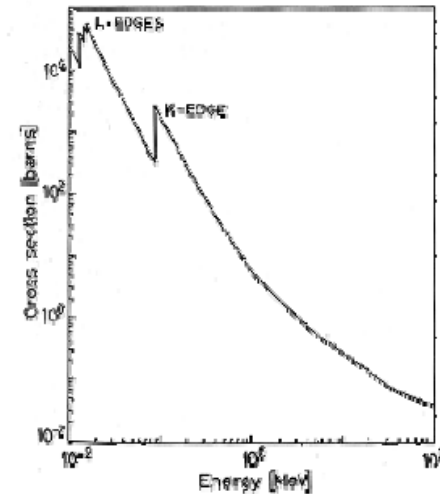
## Interaction of X and $\gamma$ with matter

### Photoelectric Effect

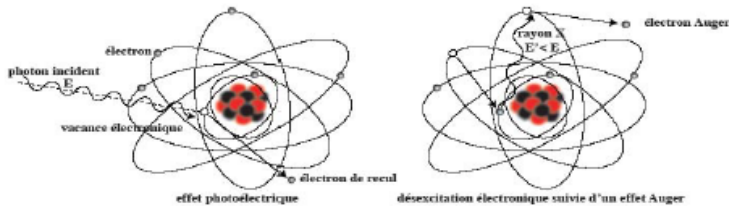
#### Total Absorption of Photon by Atomic Electron



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 predominately in the K atomic shell.



$$\sigma_{photo}^K = \left( \frac{32}{\gamma^7} \right)^{1/2} \cdot \alpha^4 \cdot Z^4 \cdot \sigma_T$$

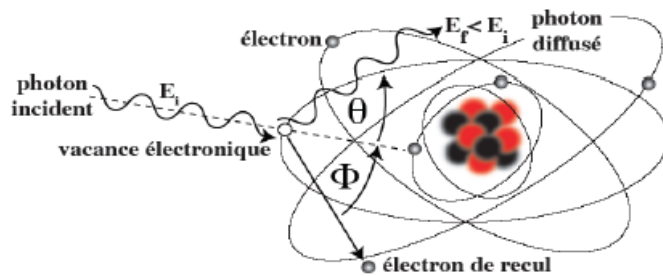
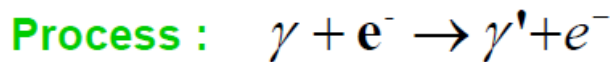
$$\alpha = \frac{1}{137}; \gamma = \frac{E_\gamma}{m_e c^2}$$

≡ Proportional to  $Z^4 / E^3$

## Interaction of X and $\gamma$ with matter

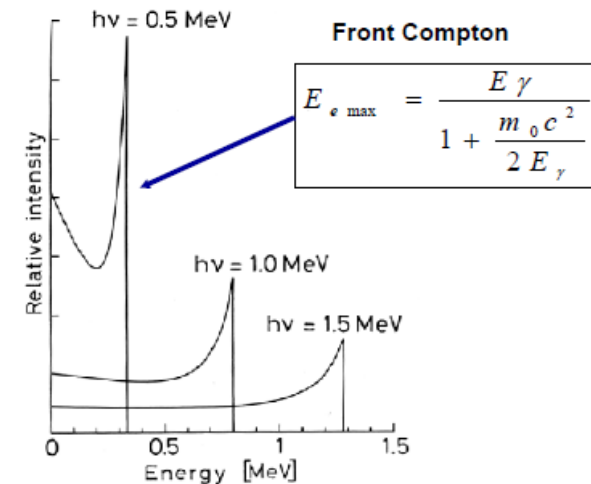
### Compton scattering

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



Compton scattering becomes significant  
(  $0.1 \text{ MeV} < E < 5 \text{ MeV}$  )

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

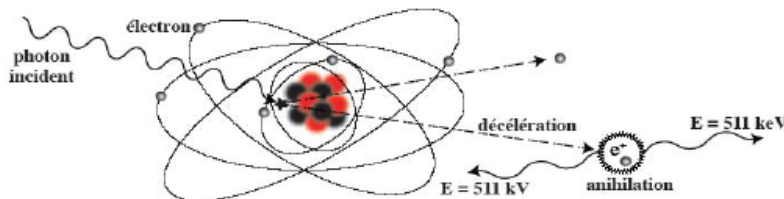


## Interaction of X and $\gamma$ with matter

### Paire production

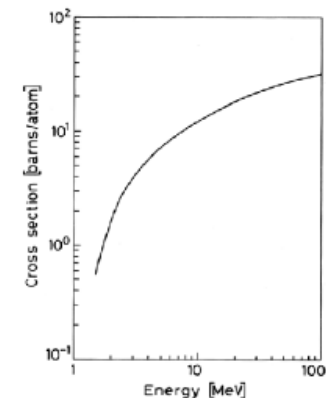
- ◆ Process that results in the conversion of a photon into *electron-positron* pair
- ◆ Actual threshold energy of reaction :  $E_{th} = 2m_0c^2(1+(m_0/M))$
- ◆ Photon disappears and hence production of  $[e^-,e^+]$  pair
- ◆ Electron and positron interact with matter
- ◆ Positron quickly combines with 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.

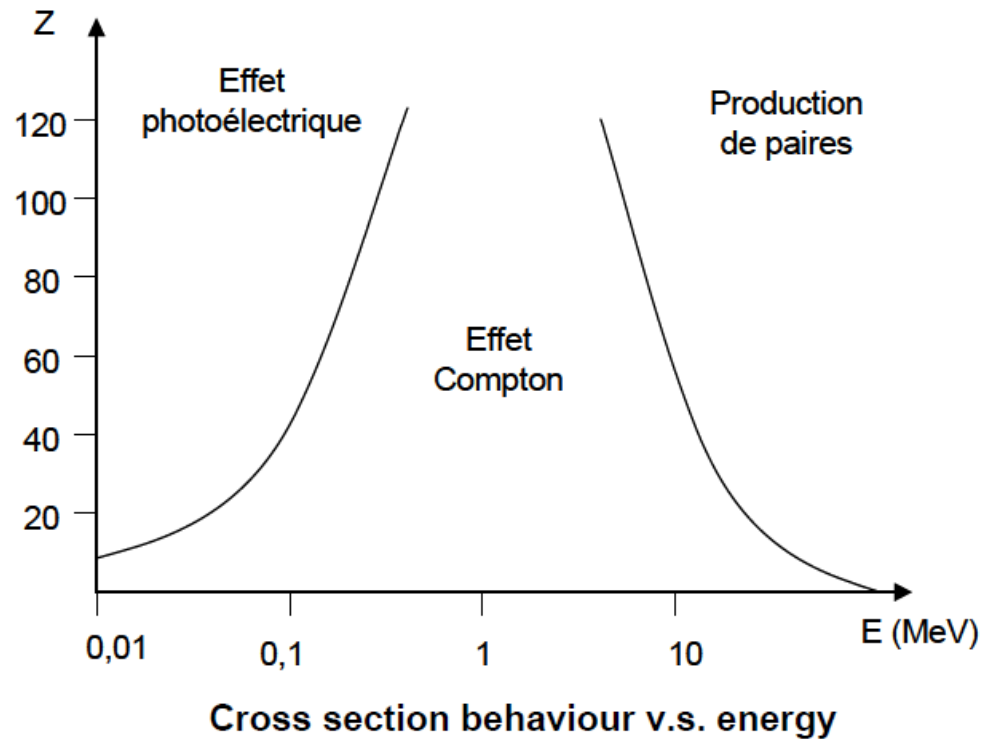


$$\sigma_{paire} = \frac{Z^2}{137} \left( \frac{e^2}{4\pi\epsilon_0 m_0 c^2} \right)^2 \left( \frac{28}{9} \text{Log} \frac{2h\gamma}{m_0 c^2} - \frac{218}{27} \right)$$

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



## Interaction of X and $\gamma$ with matter



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

## Interaction of X and $\gamma$ with matter

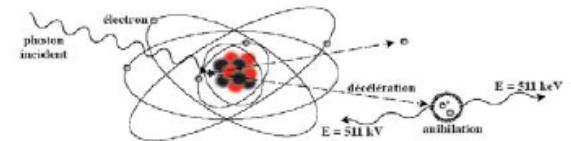
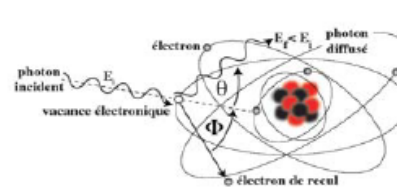
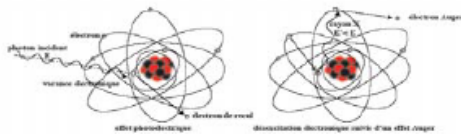
### Finally

With photons there is **no direct ionizations**

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

Photoelectric effect  
Compton scattering  
Paire production

⇒  $e^-$  ⇒ **ionization and excitations**



## Photonuclear reactions

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

### Typical reactions

$(\gamma, n)$ ;  $(\gamma, 2n)$ ,  $(\gamma, xn)$

$(\gamma, p)$ ;  $(\gamma, xp)$

$(\gamma, f)$

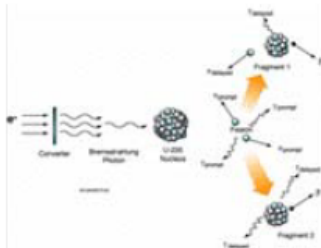
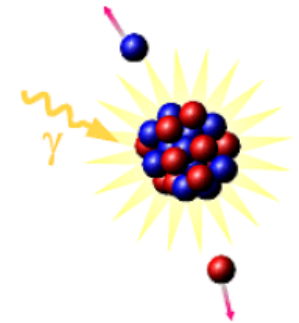
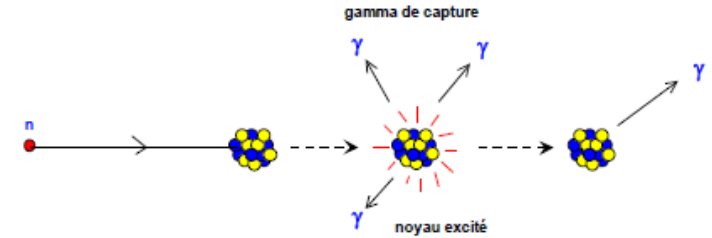
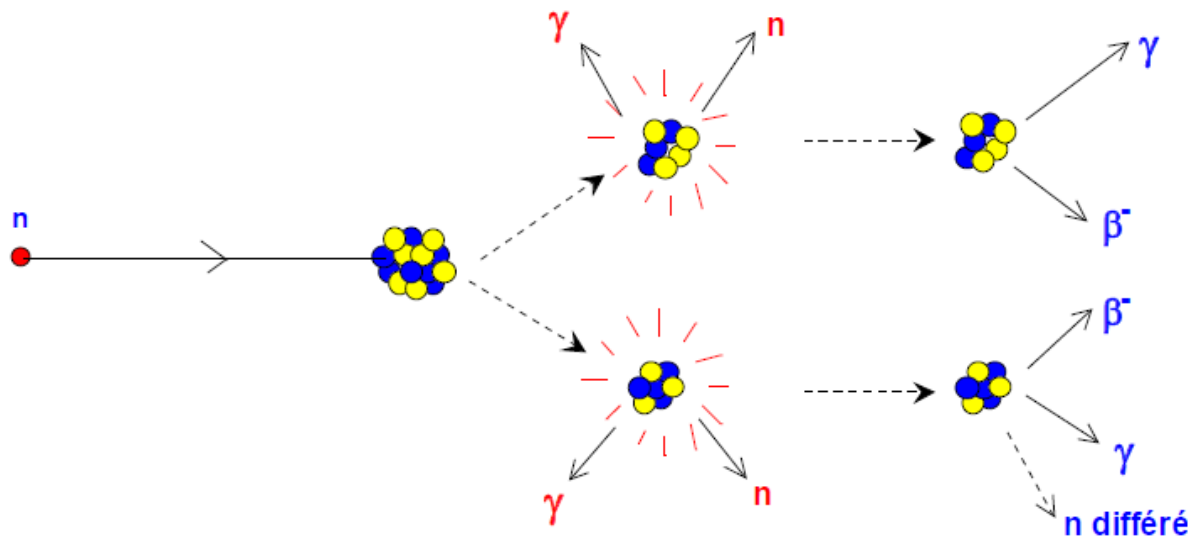


Figure 1. Schematic illustration of relevant neutron emission processes in photofission



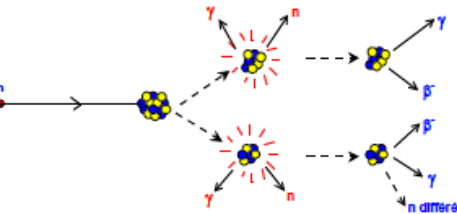


## Interaction of neutrons with matter



## 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

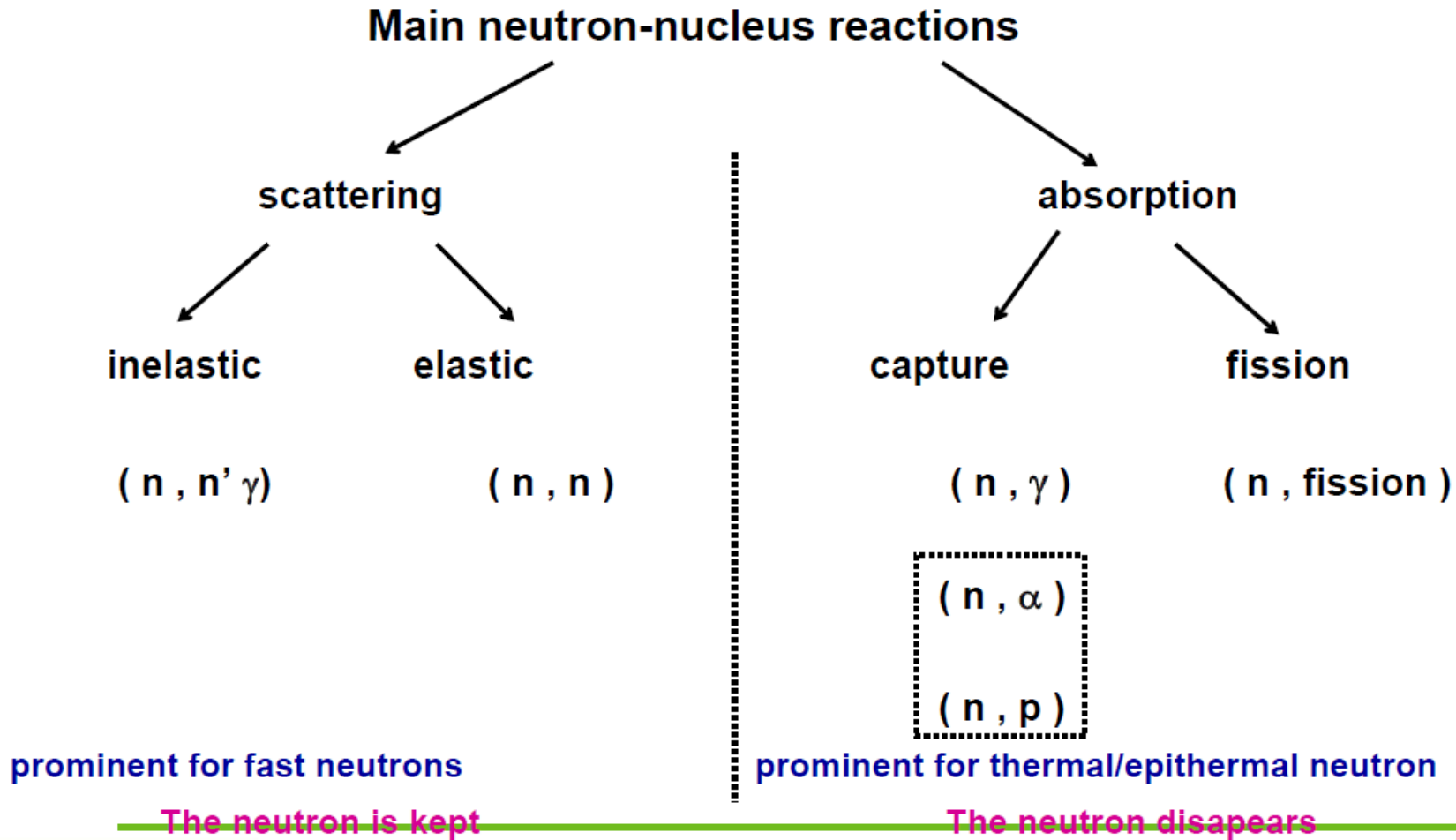
Thermal neutrons  $E = 0.025 \text{ eV}$

Epithermal neutrons  $0.6 \text{ eV} < E < 10 \text{ keV}$

Intermediate neutrons  $10 \text{ keV} < E < 0.5 \text{ MeV}$

Fast neutrons  $E > 0.5 \text{ MeV}$

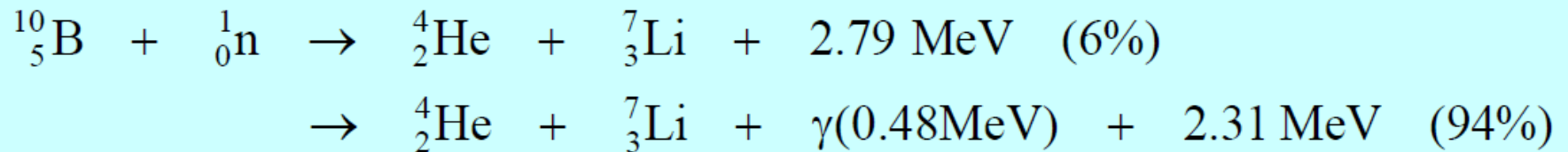
## Interaction of neutrons with matter



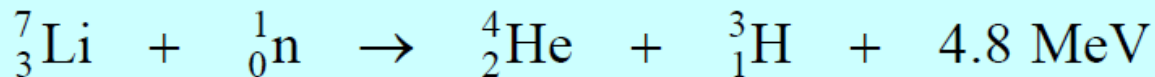
## Interaction of neutrons with matter

### Non Radiative capture ( n , α )

Neutron is absorbed , an α-particle is emitted



frequently used for neutron detection (  $\sigma = 3900$  barns for thermal neutrons  
et  $\sigma = 0.4$  barns for fast neutrons)



Used for neutron detection and production of Tritium (  $\sigma = 950$  barns pour  $n_{\text{th}}$ .  
et  $\sigma = 0.3$  barns pour  $n_{\text{fst}}$ .)

## Interaction of neutrons with matter

### Finally

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

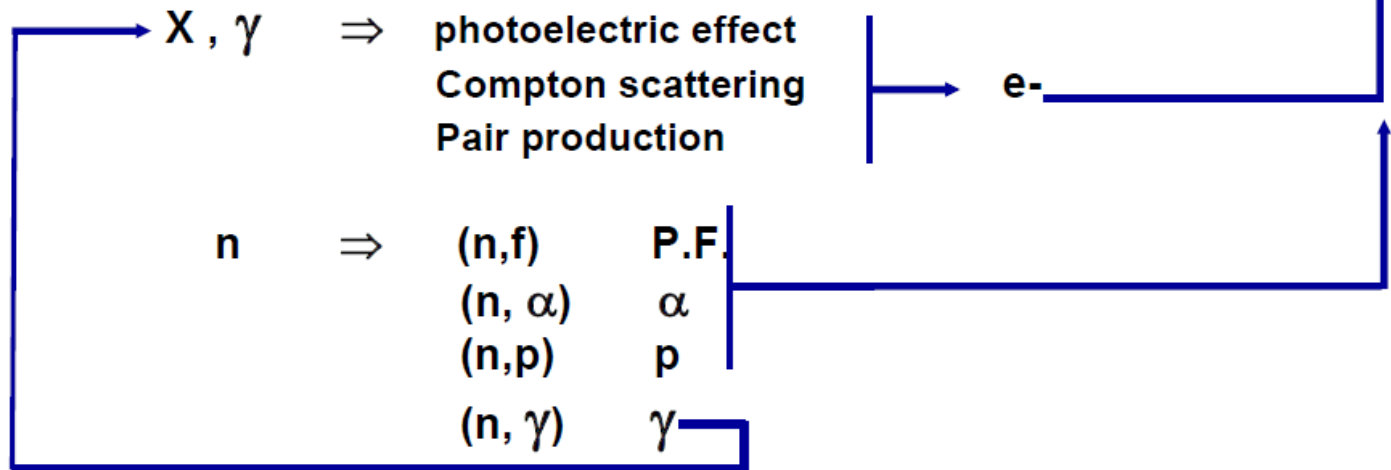
⇒ Ionizations are induced by :

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

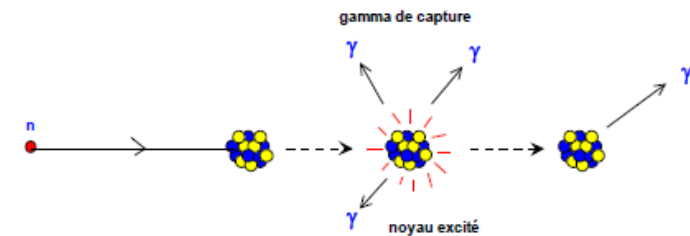
## Interaction of radiations with matter

Radiation **directly ionizing**  $\Rightarrow$  Charged particles  $\alpha, \beta, p \rightarrow$  **ionizations**

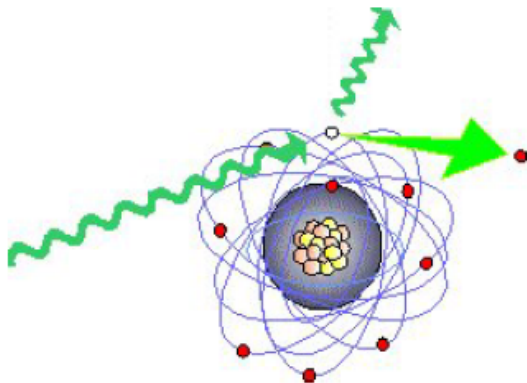
Radiations **indirectly ionizing**



Finally  $(\alpha, \beta, p, X, \gamma, n) \Rightarrow$  « **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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