Radiation biology, protection and applications

PHYS-450

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Radiation Protection Lectures

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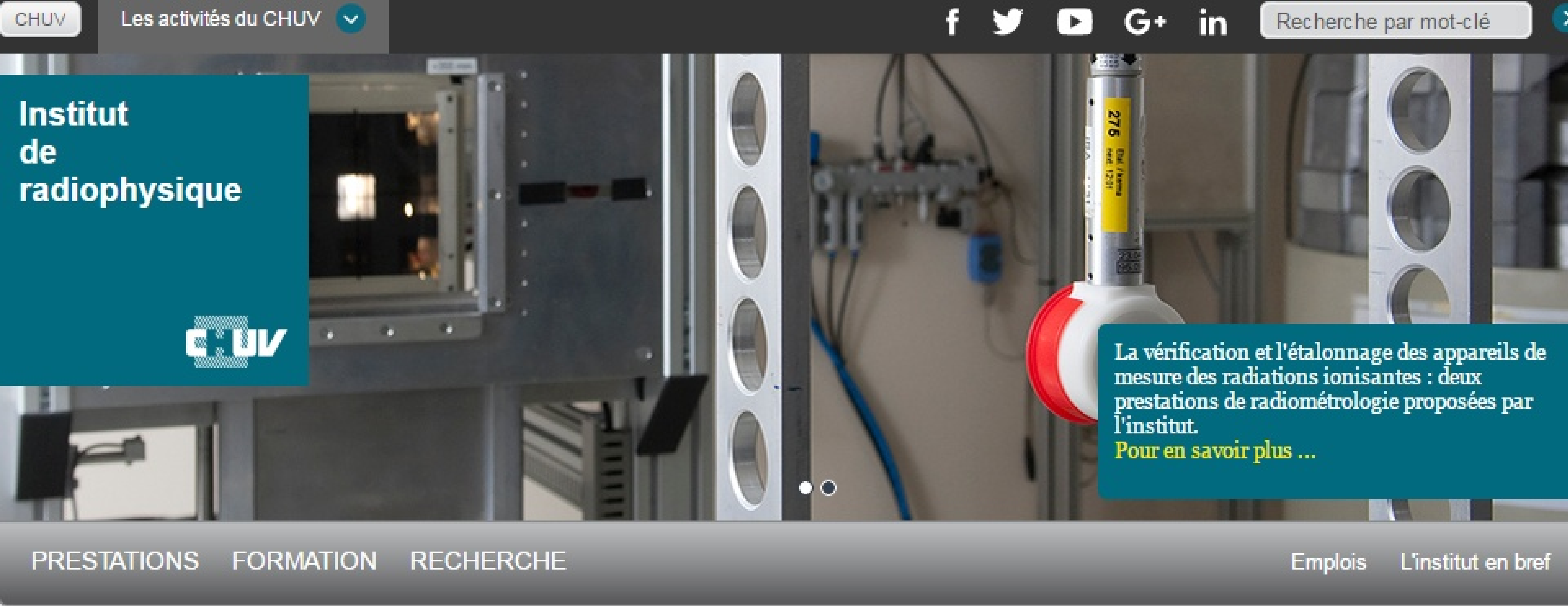
University of Otago, Christchurch, New Zealand



Institut
de
radiophysique

La vérification et l'étalonnage des appareils de mesure des radiations ionisantes : deux prestations de radiométrologie proposées par l'institut.
Pour en savoir plus ...

The Institute of Radiation Physics (IRA) is an affiliated institute of the Department of Radiology at the CHUV. Institute activities are chiefly focused in two disciplines: medical physics, which involves the use of ionizing radiation in medicine, and radiation protection, which deals with methods and practices of protecting both workers and the general population from the effects of ionizing radiation. Within the context of these two disciplines, the institute provides an array of services for, primarily, various departments at the CHUV, as well as for any entity or person working with ionizing radiation in the canton of Vaud. IRA is also responsible for teaching medical physics and radiation protection within the framework of the Department of Medicine at the University of Lausanne.
IRA’s main fields of expertise, which correspond to several working groups within the institute, are indicated and explained below.

MEDICAL PHYSICS

physics of radiation therapy; this group is responsible for providing technical and scientific support in radio-oncology
radio-pharmaceutical chemistry; this group works to support nuclear medicine departments: radiopharmaceutical monitoring, product labeling
medical imaging; this group collaborates with radiodiagnostic departments with respect to image quality and patient protection

RADIATION PROTECTION

radiation protection; this group provides technical support for any entity or person working with ionizing radiation: individual dosimetry, consulting and certification
radioecology; this group works in close collaboration with the Swiss Federal Office of Public Health to guarantee monitoring of radiation activity levels in the environment by taking soil, grass, milk and other samples

Radiation Protection Group @ IRA

Jérôme DAMET, PhD

Andreas PITZSCHKE, PhD

Reiner GEYER, PhD

Nicolas CHERBUIN

Camille LEMESRE

Mélanie PATONNIER

Marie NOWAK, PhD student

Siria MEDICI, PhD student (from EPFL, via TP4 and Masters programme)

Valentin BONVIN, PhD student

+ 7 technicians for the dosimetry service (external and internal exposure)

At Lausanne University hospital, IRA provides consulting and support services to local RP experts

Radiation Protection Lectures @ EPFL

Radiation biology, protection and applications

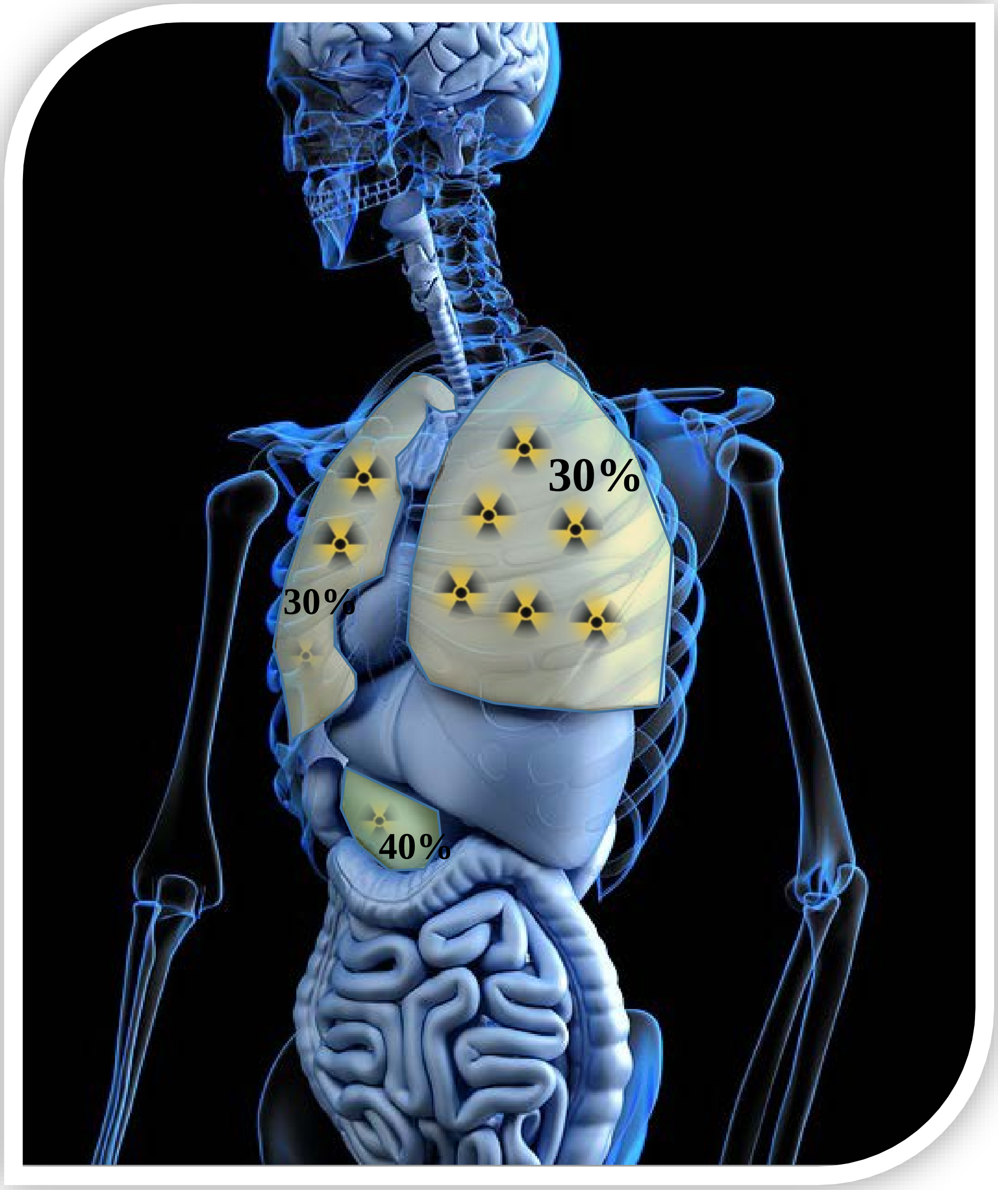
1st lecture on 01.10 Basis of radiophysics and Dosimetry
2nd lecture on 08.10 Dosimetry, radiation measurement and instrumentation
3rd lecture on 15.10 Radiobiology
4th lecture on 22.10 Individual dosimetry – External and internal exposures
5th lecture on 29.10 Operational radiation protection – external exposure
6th lecture on 05.11 RP physicists in hospitals
7th shared lecture on 12.11 Waste/Transport and accident management / Start of Pavel’s lecture

fall semester 2018: 2+1:
Monday 09h15-11h00 C Radiation protection & radiation applications
Monday 11h15-12h00 E Radiation protection & radiation applications

What’s that?
Is that dangerous?
Is that a radioactive waste?
…..

What do you want to measure?
What does that mean?

What happens if a person incorporate a radioactive substance?



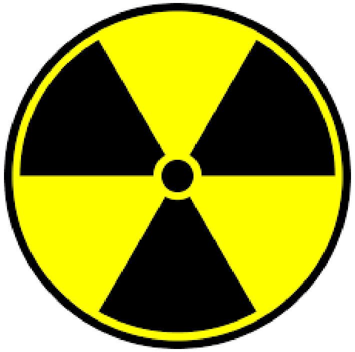
Based on the presentation of

Prof **François Bochud**
Institute of Radiation physics (IRA)
UNIL - CHUV

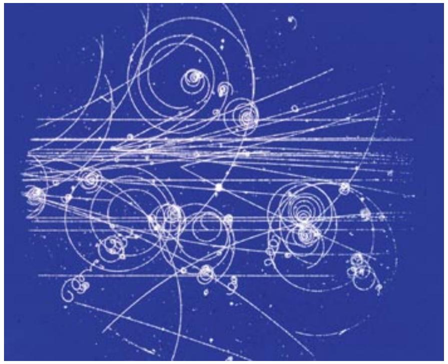
Master of Science EPF-ETH degree in **Nuclear Engineering**
RPRA : **Radiation protection** and radiation applications

Basis of radiation physics
*1st **October, 2018***

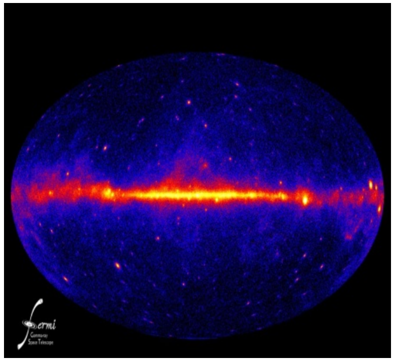
Overview



Radioactivity



Interaction of particles with matter



Interaction of photons with matter

Objectives

- Become familiar with radiation physics
- Understand the main concepts:
  - Radioactivity and different types of decay
  - Interaction of radiation with matter

→ Useful for Radiobiology, Dosimetry and eventually RP

Prof **François Bochud**

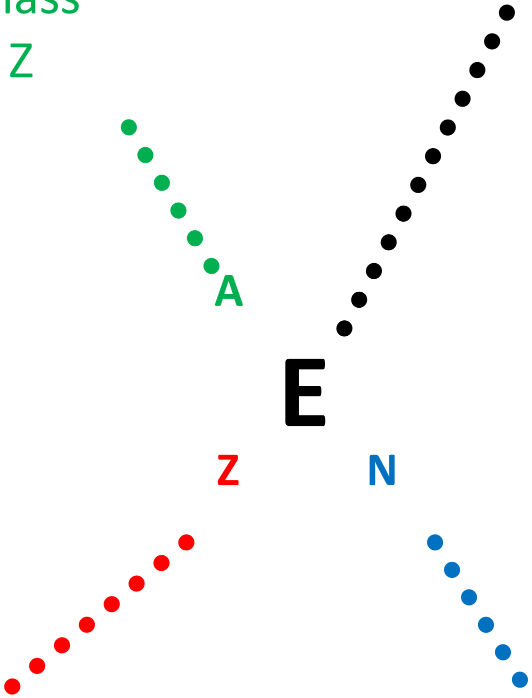
Institute of Radiation physics (IRA)

UNIL - CHUV

Master of Science EPF-ETH degree in **Nuclear Engineering**
RPRA : **Radiation protection** and radiation applications

Basis of radiation physics
Radioactivity

Nomenclature



Mass number
characterizes the mass
of the nucleus: N + Z

Element
characterized by the
number of protons
C = carbon
i.e. Z = 6 protons

Number of protons
chemical characteristics of the
element

Number of neutrons
different N for a given Z
= isotopes

$${}^{A}_{Z}\mathbf{E}_{N}$$

- Whay can we right either ${}^{14}_{6}C_{8}$ ${}^{14}C$

- Element = C

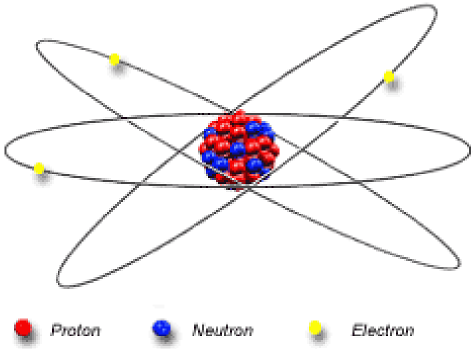
  $\Rightarrow$ **Z=6**

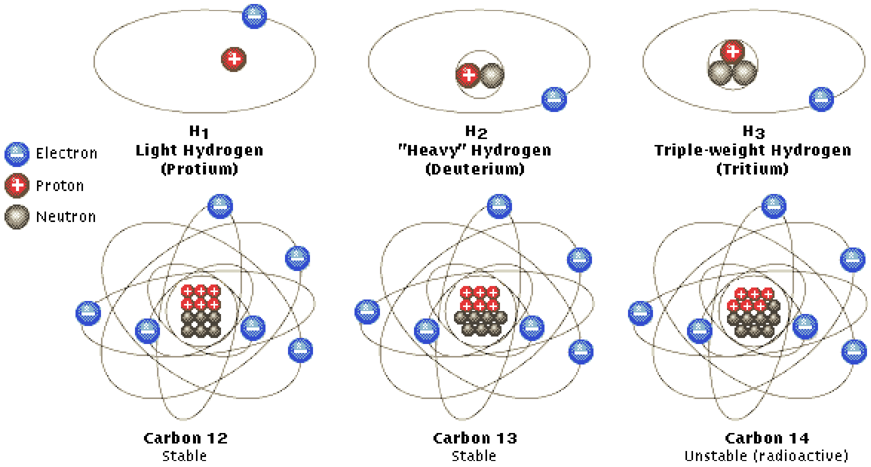
- Knowing that A equals 14 and Z equals 6

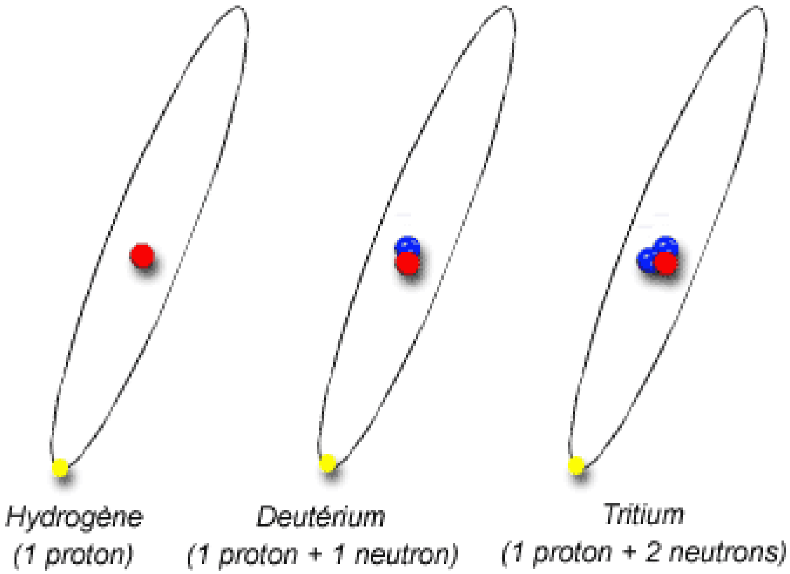
  $\Rightarrow$ **N=8**

$${}^{A}_{Z}E_{N} \equiv {}^{A}E \equiv E - A$$

Isotopes



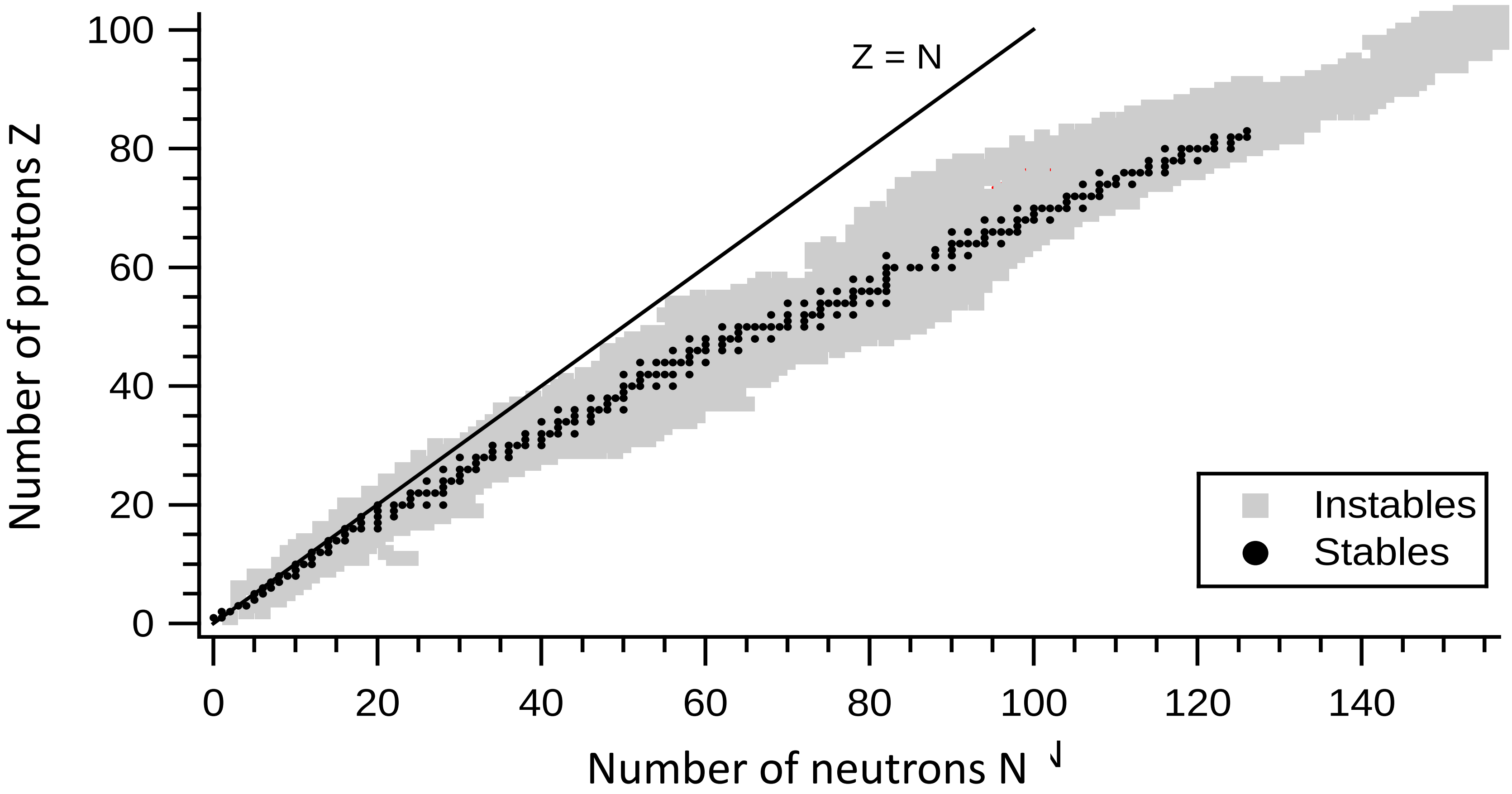




hydrogène has three isotopes :

- **hydrogene**: 1 p, 1 e^-
- **deuterium**: 1 p, 1 n, 1 e^-
- **tritium**: 1 p, 2 n, 1 e^-

Chart of the nuclides

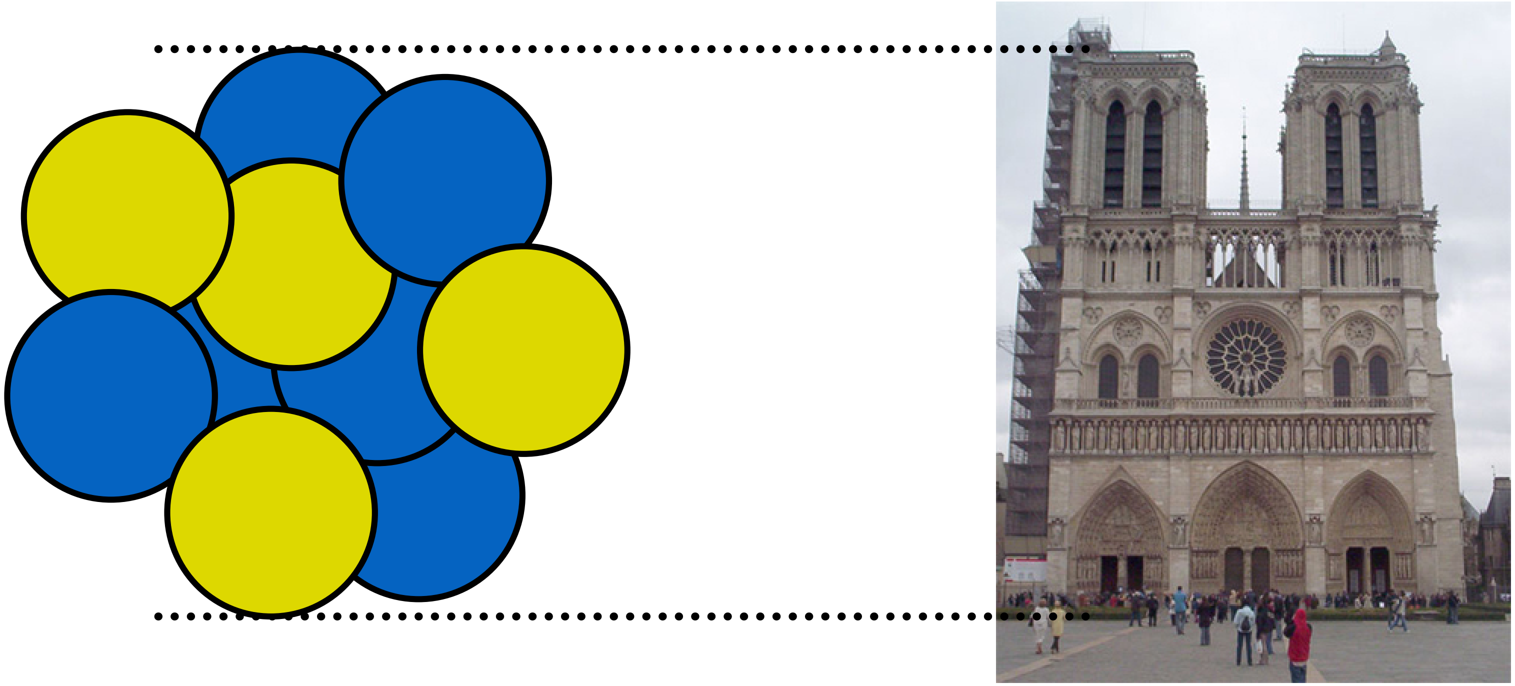


Solution : Size of a carbon atom

<u>Scale</u>

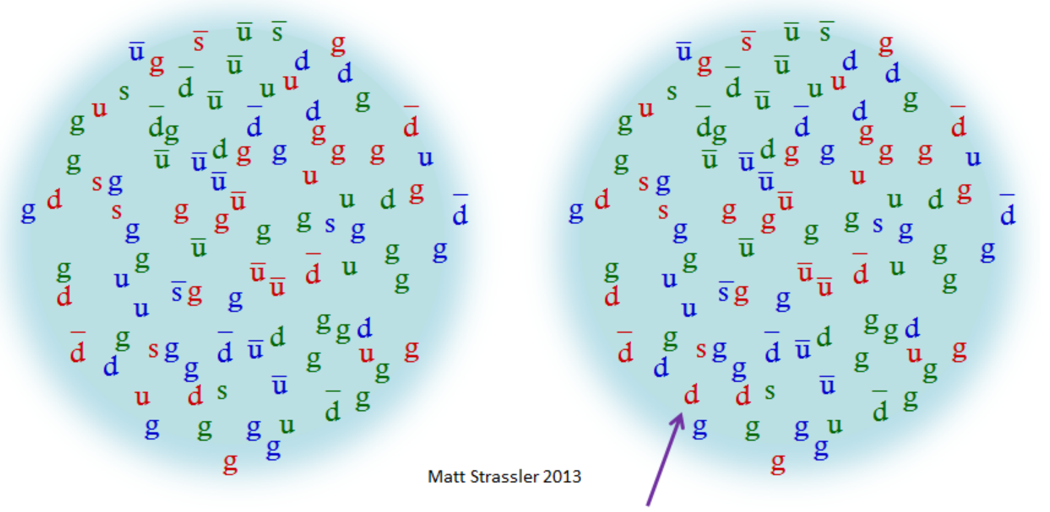
1 electron = 1 ant

Solution : Size of carbon nucleus



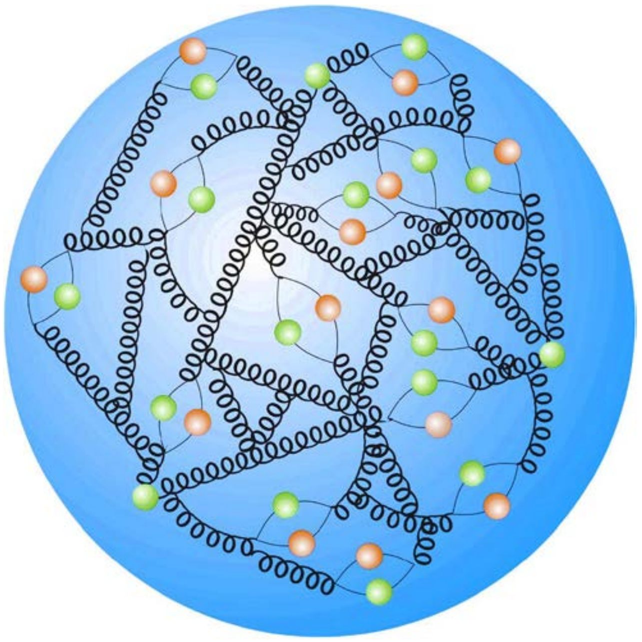
<u>Scale</u>
1 electron = 1 ant

"More modern" vision of the nucleus


proton

neutron

Matt Strassler 2013



Radioactive decay

Radioactive decay

- Alpha

emission of 2 p & 2 n

- Beta
  - Beta -
  - Beta +
  - Electron capture

emission of an electron
or a positron
from the nucleus

- Gamma

emission of a photon
from the nucleus

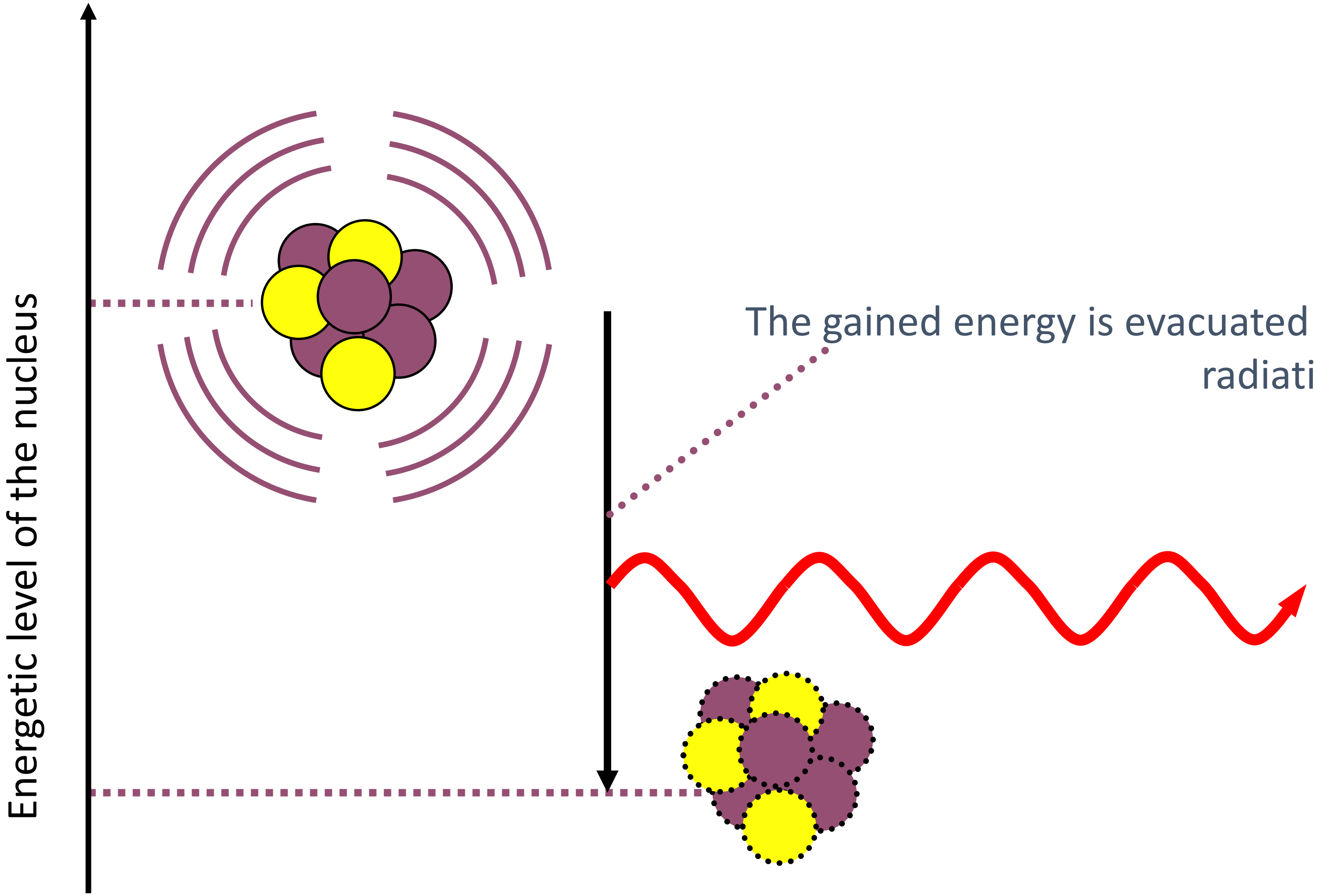
Radioactivity

- Radioactive decay
  - **Spontaneous** and **random** mechanism
  - Transformation of the nucleus

- Probability of decay per unit of time
  - Decay constant λ [s^{-1}] :
    - Specific to the considered nucleus
    - Does not vary with time

The nucleus is looking for stability

If a lower level exists and is reachable, the nucleus will tend to go there spontaneously.



The gained energy is evacuated by radiation

Radioactivity

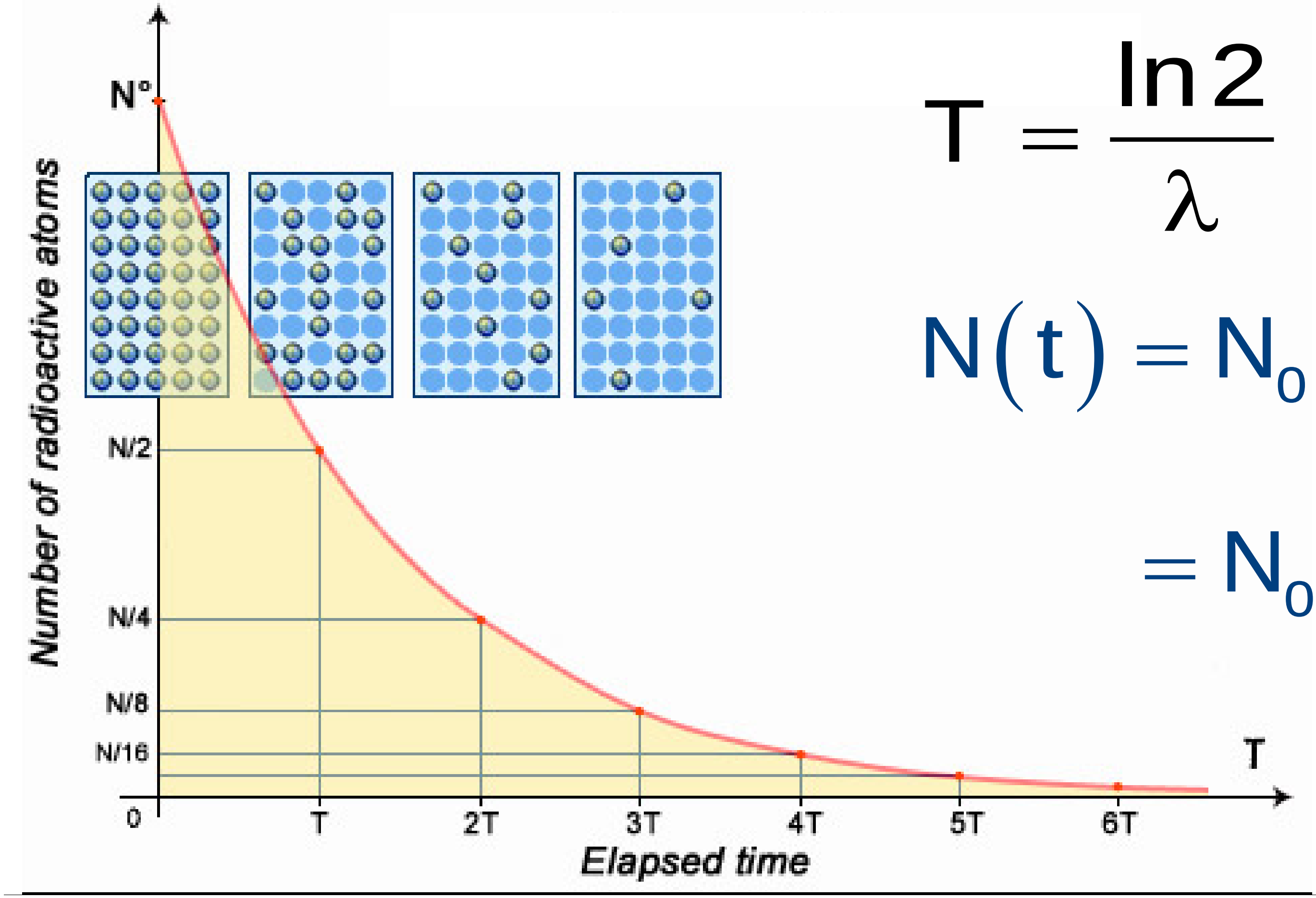
$$dN(t) = -\lambda N(t)\,dt \quad \Rightarrow \quad \frac{dN(t)}{dt} = -\lambda N(t)$$

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

Exponential decay

Half-life

T (half-life): time necessary to reduce N by 2

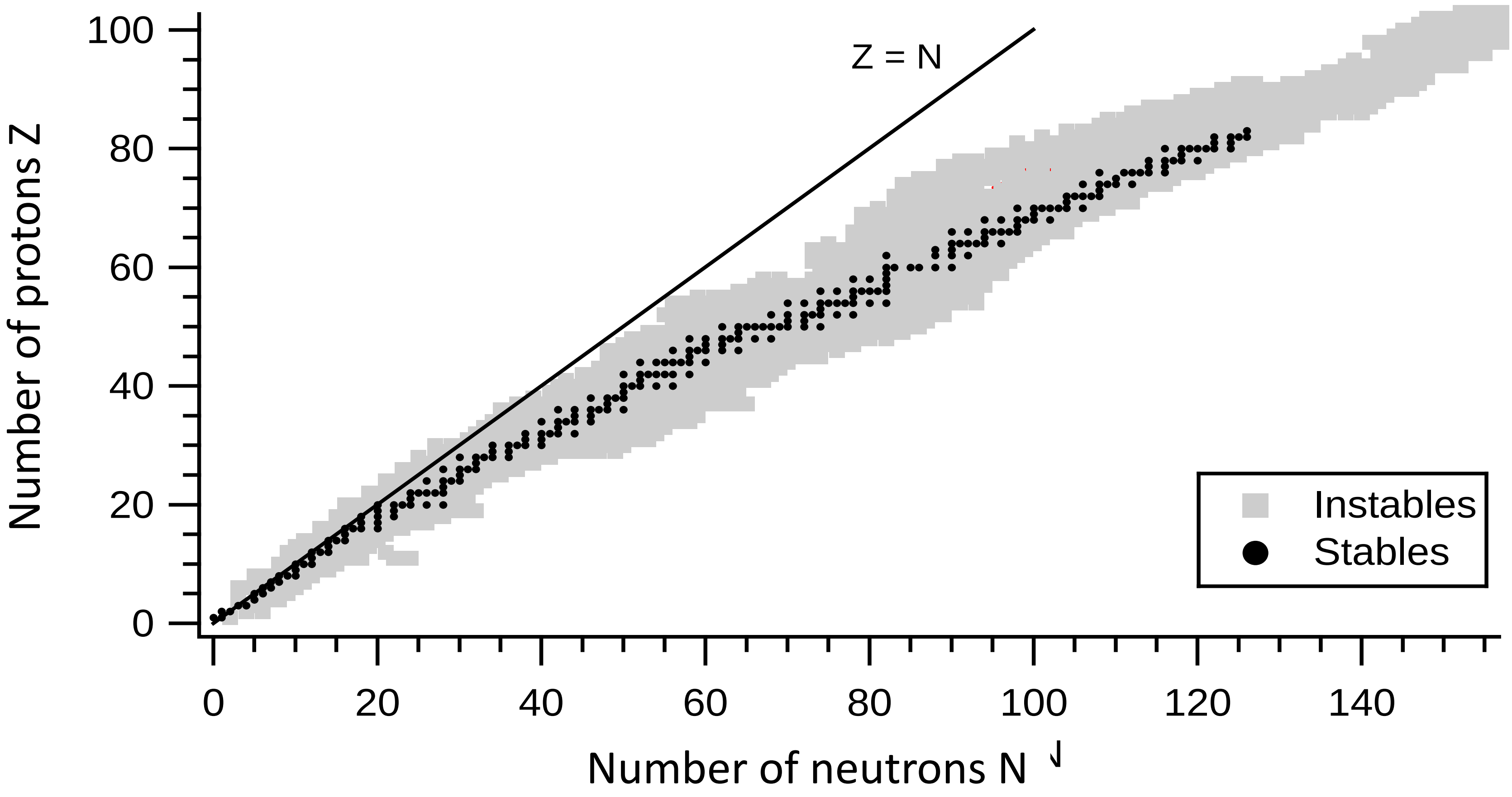


$$T = \frac{\ln 2}{\lambda}$$

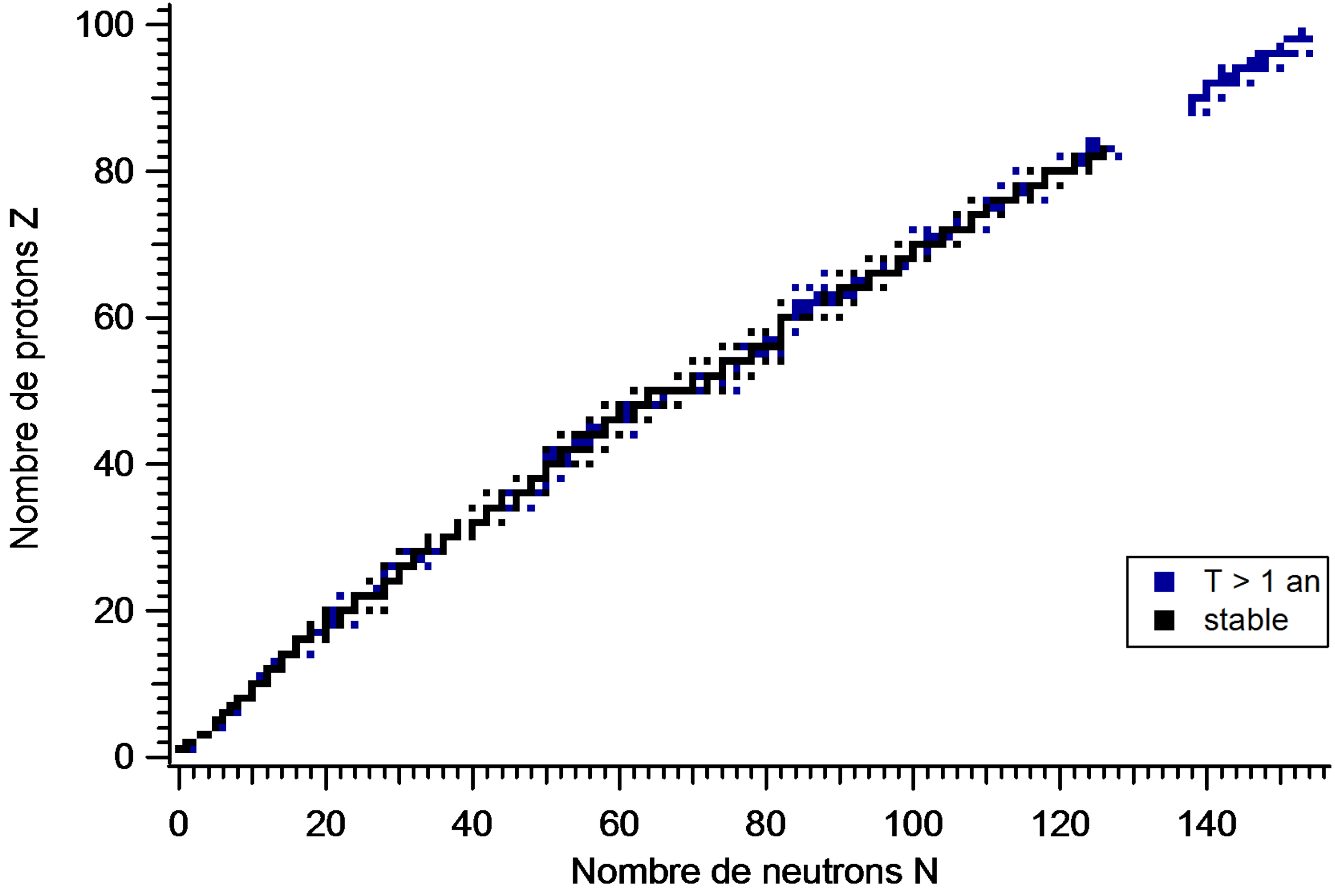
$$N(t) = N_0\ e^{-\lambda t}$$

$$= N_0 e^{-\frac{\ln(2)}{T}t}$$

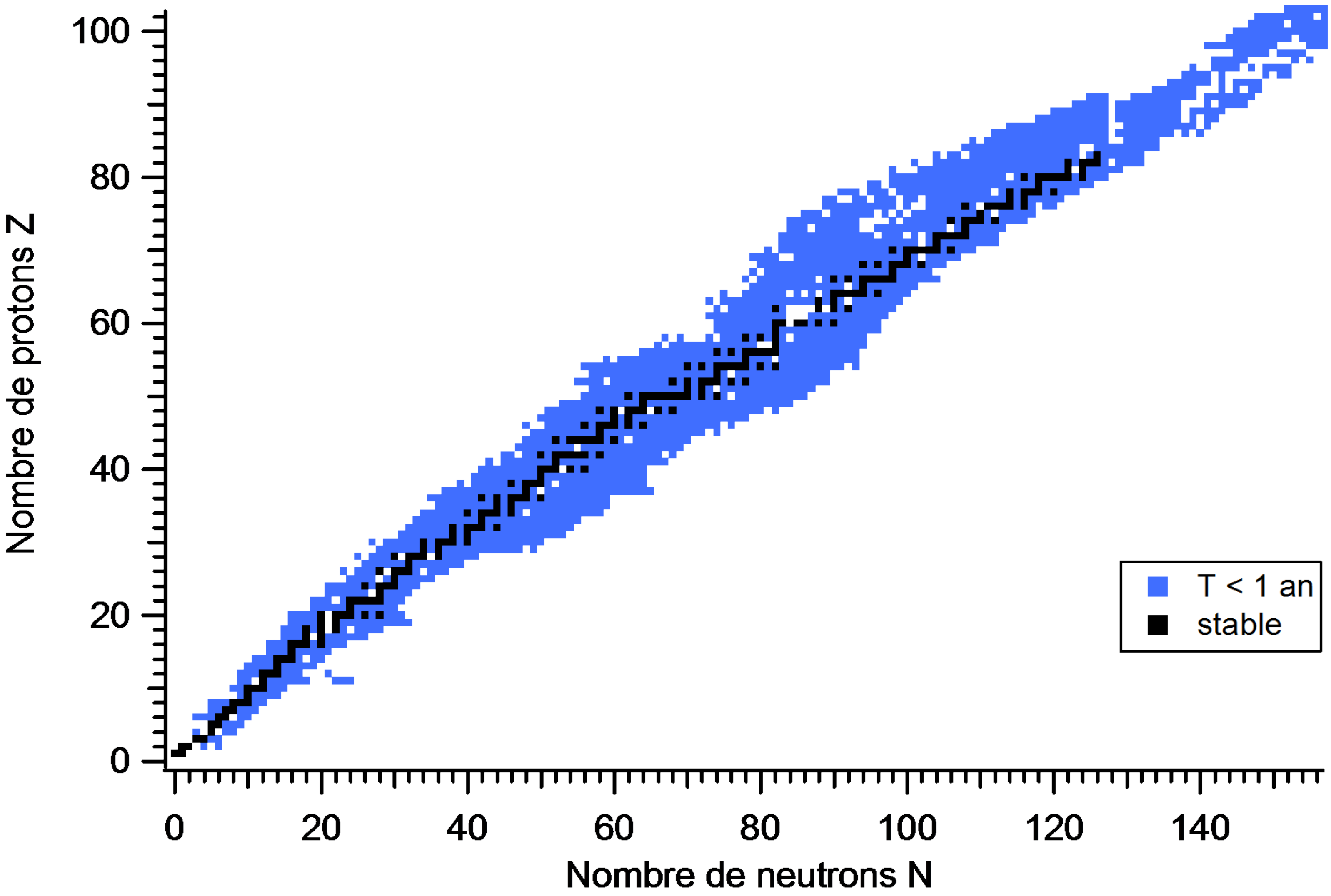
Chart of the nuclides



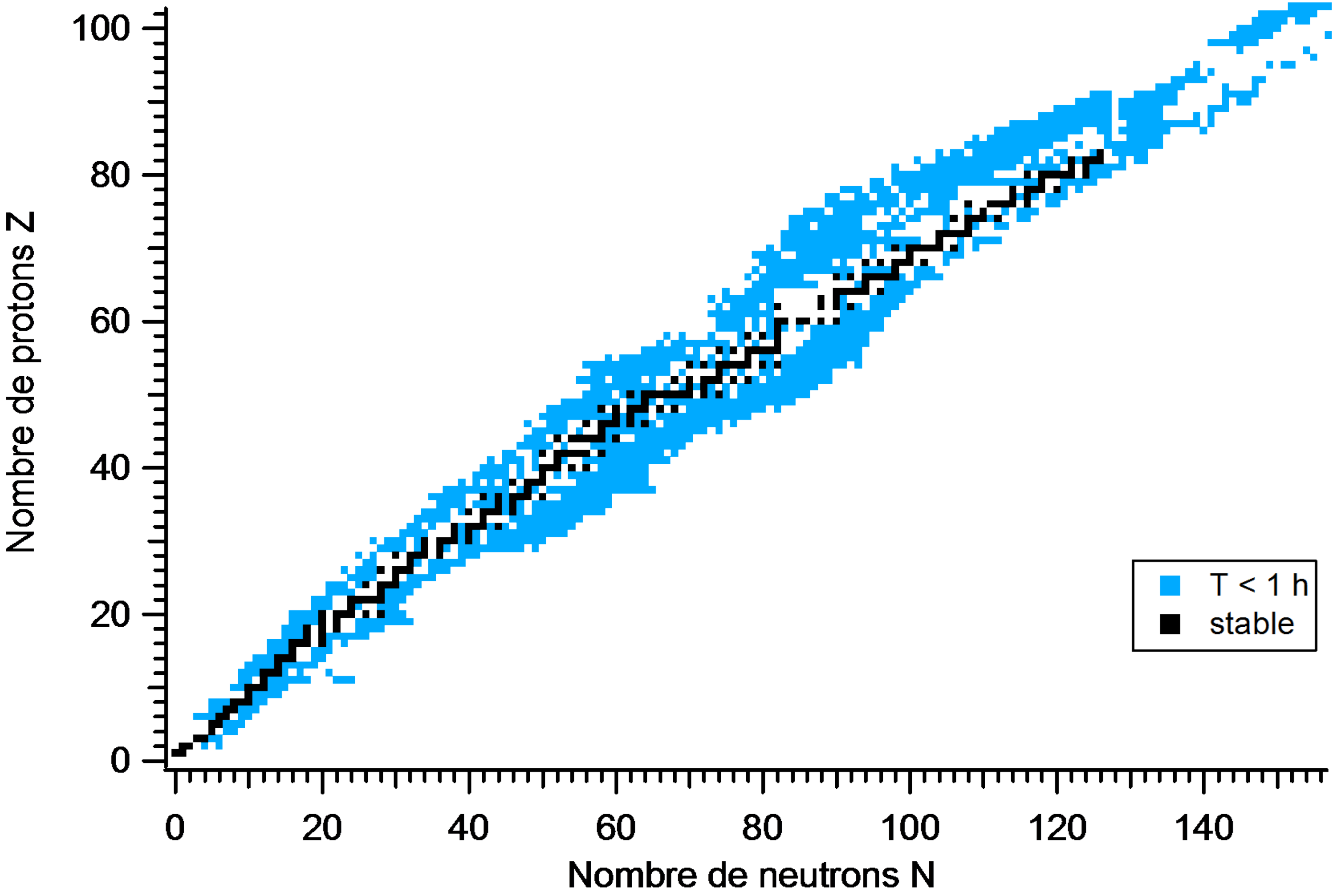
Half-life: most stable elements



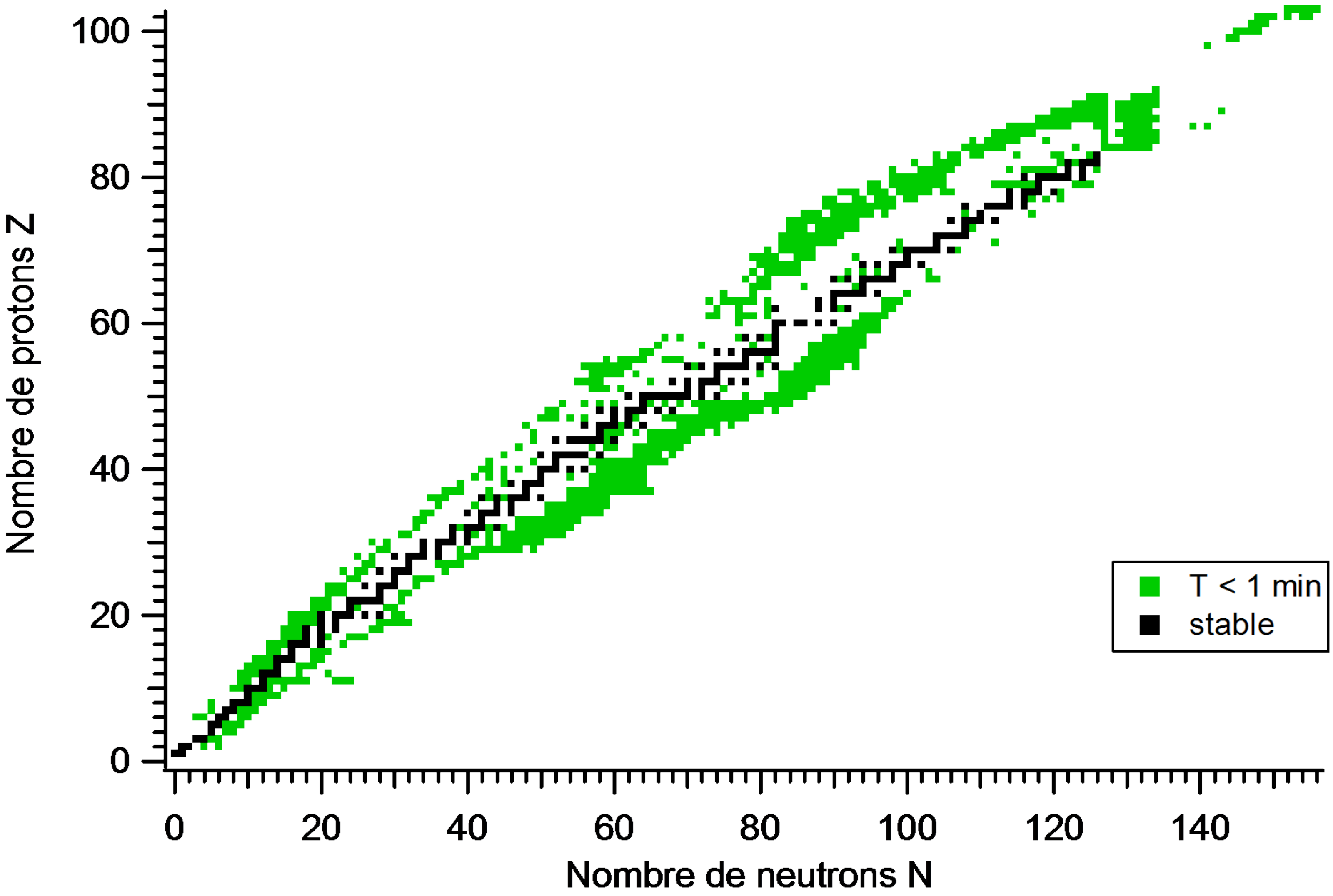
Half-life


Nombre de protons Z
100
80
60
40
20
0
0
20
40
60
80
100
120
140
Nombre de neutrons N
🟦 T < 1 an
■ stable

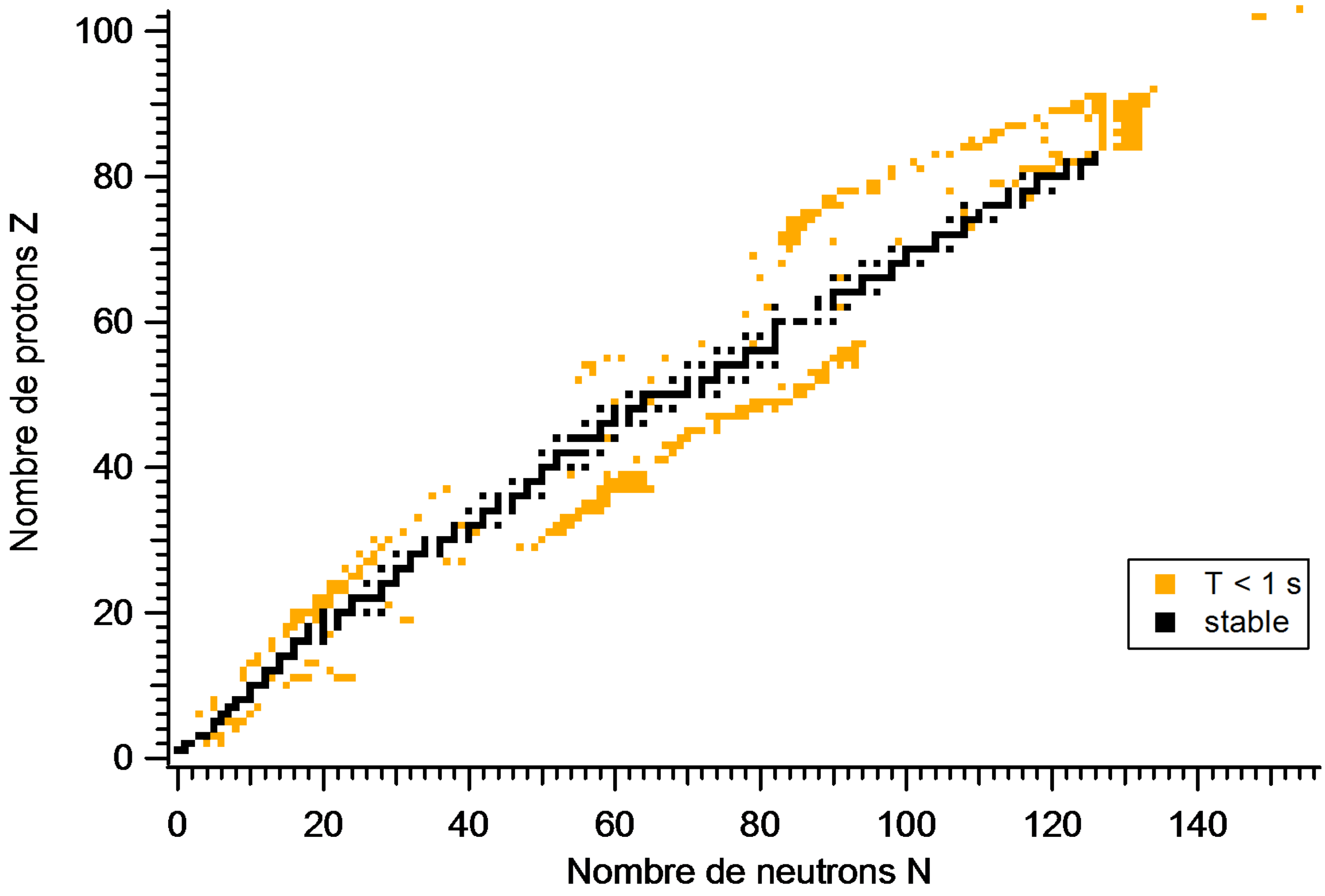
Half-life


100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
T < 1 h
stable

Half-life


100
80
60
40
20
0
Nombre de protons Z
0
20
40
60
80
100
120
140
Nombre de neutrons N
🟩 T < 1 min
■ stable

Half-life: least stable elements



Activity

- Number of unstable nucleus N(t) difficult to measure
  - Number of decays per unit of time

Unit : s^{-1} = Bq = becquerel

$$A = \lambda N$$

- A(t) evolves as N(t):
  - Exponential decay with half-life T

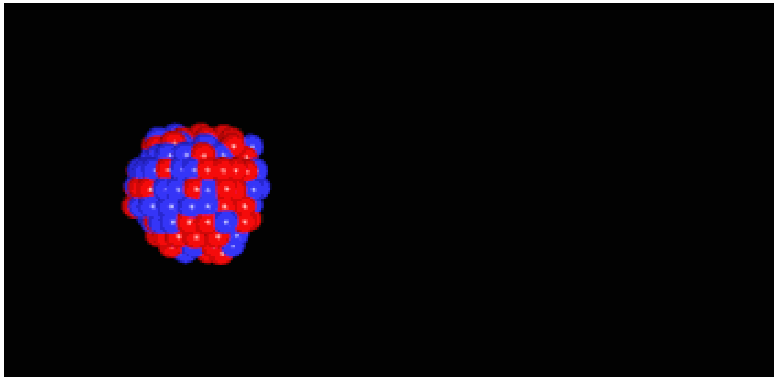
$$A(t) = A_0 e^{-\frac{\ln(2)\,t}{T}}$$

Exercise : Activity

- You have a solution of Tc-99m with an activity of 96 MBq/ml delivered at 7:00 :
  - You have to prepare a sample of 96 MBq at 19:00 the same day
  - Which volume do you extract ?

Solution : Activity

- You have a solution of Tc-99m with an activity of 96 MBq/ml delivered at 7:00 :
  - You have to prepare a sample of 96 MBq at 19:00 the same day
  - Which volume do you extract?
- 2 half-lives between 7:00 and 19:00
- The activity of the stock solution decayed by approximately a factor of 4
- To get 96 MBq, you need ≈ **4 ml**

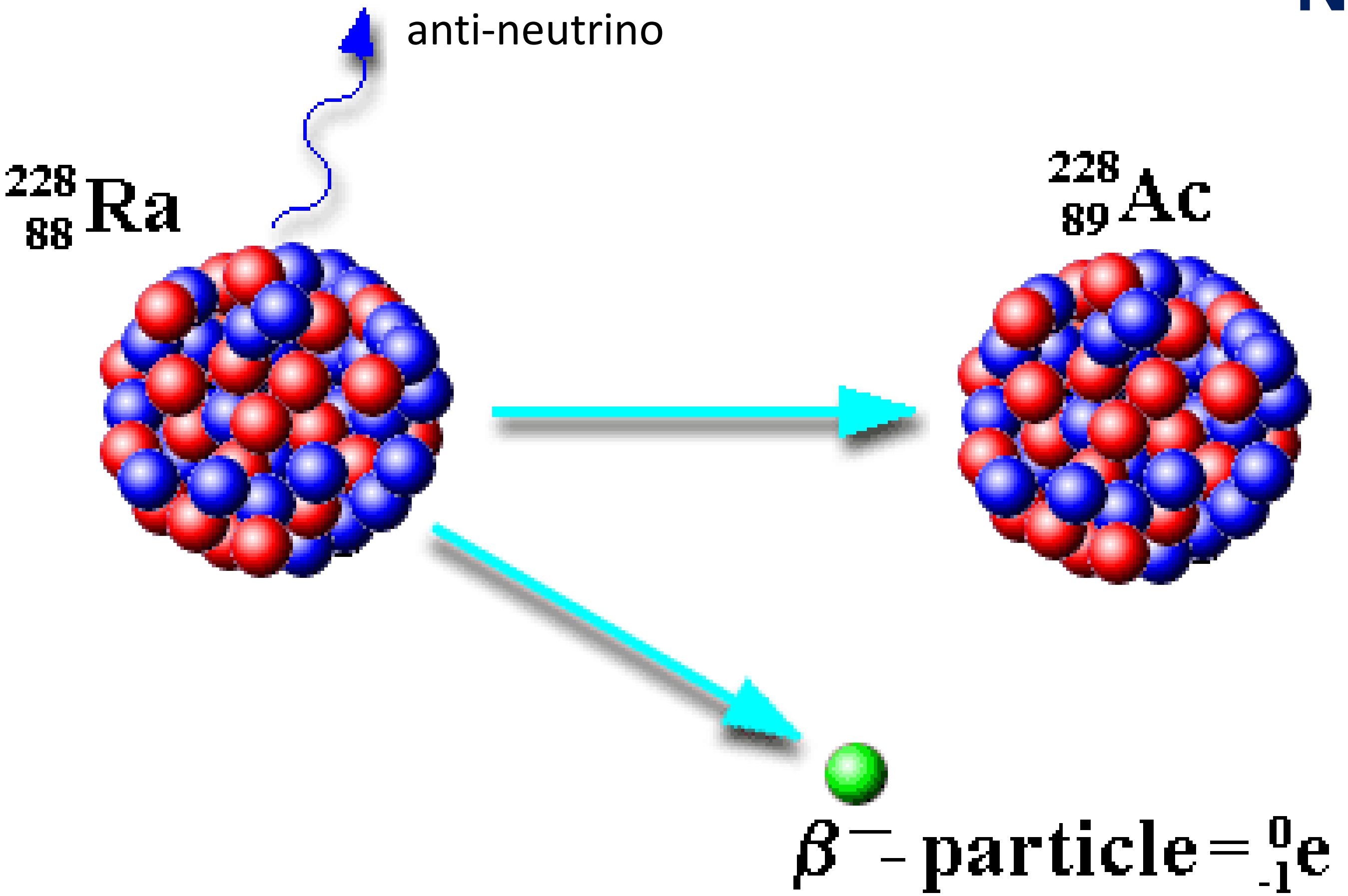


Beta minus decay

β^- decay

Z+1
N-1

Z
N



anti-neutrino

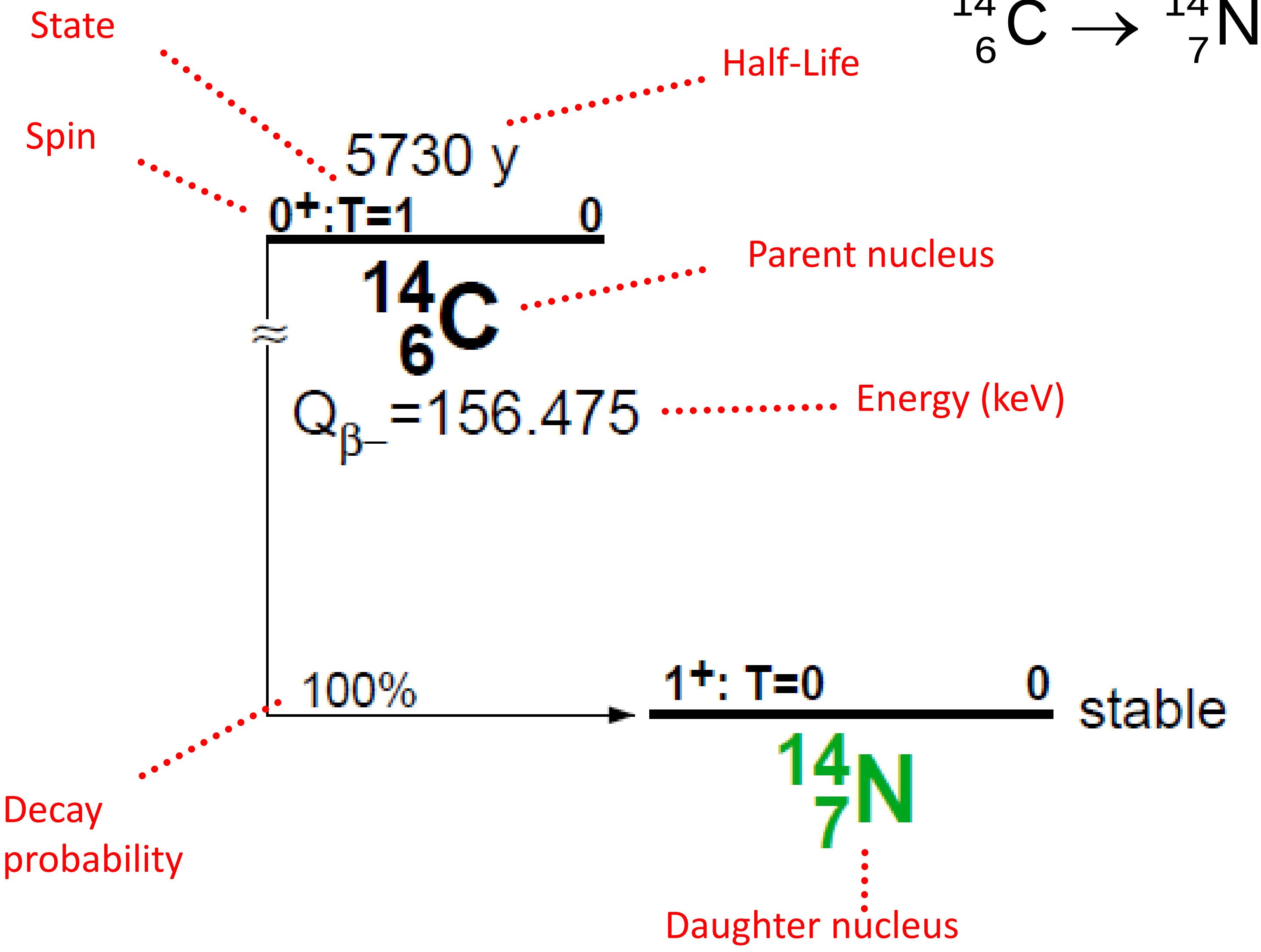
$^{228}_{88}\mathrm{Ra}$

$^{228}_{89}\mathrm{Ac}$

β^-- particle = $^{0}_{-1}\mathrm{e}$

Example of pure beta decay

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



State

Spin

Half-Life

Parent nucleus

Energy (keV)

Decay probability

Daughter nucleus

Example of beta spectrum

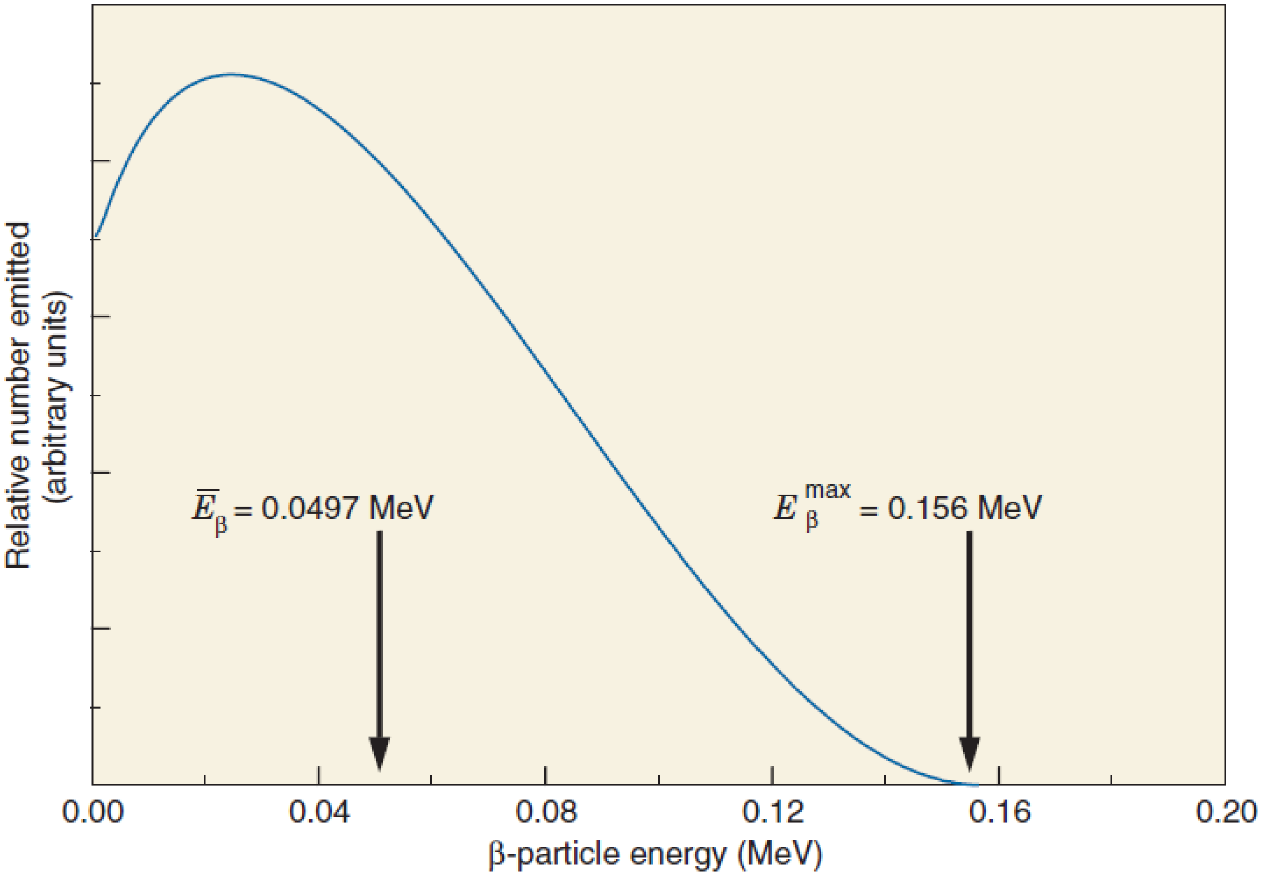
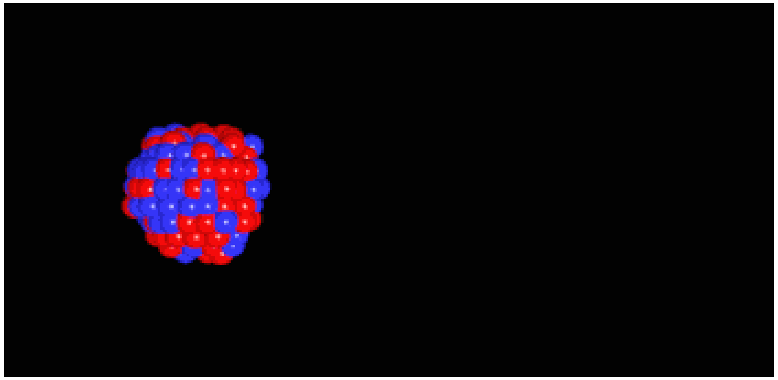


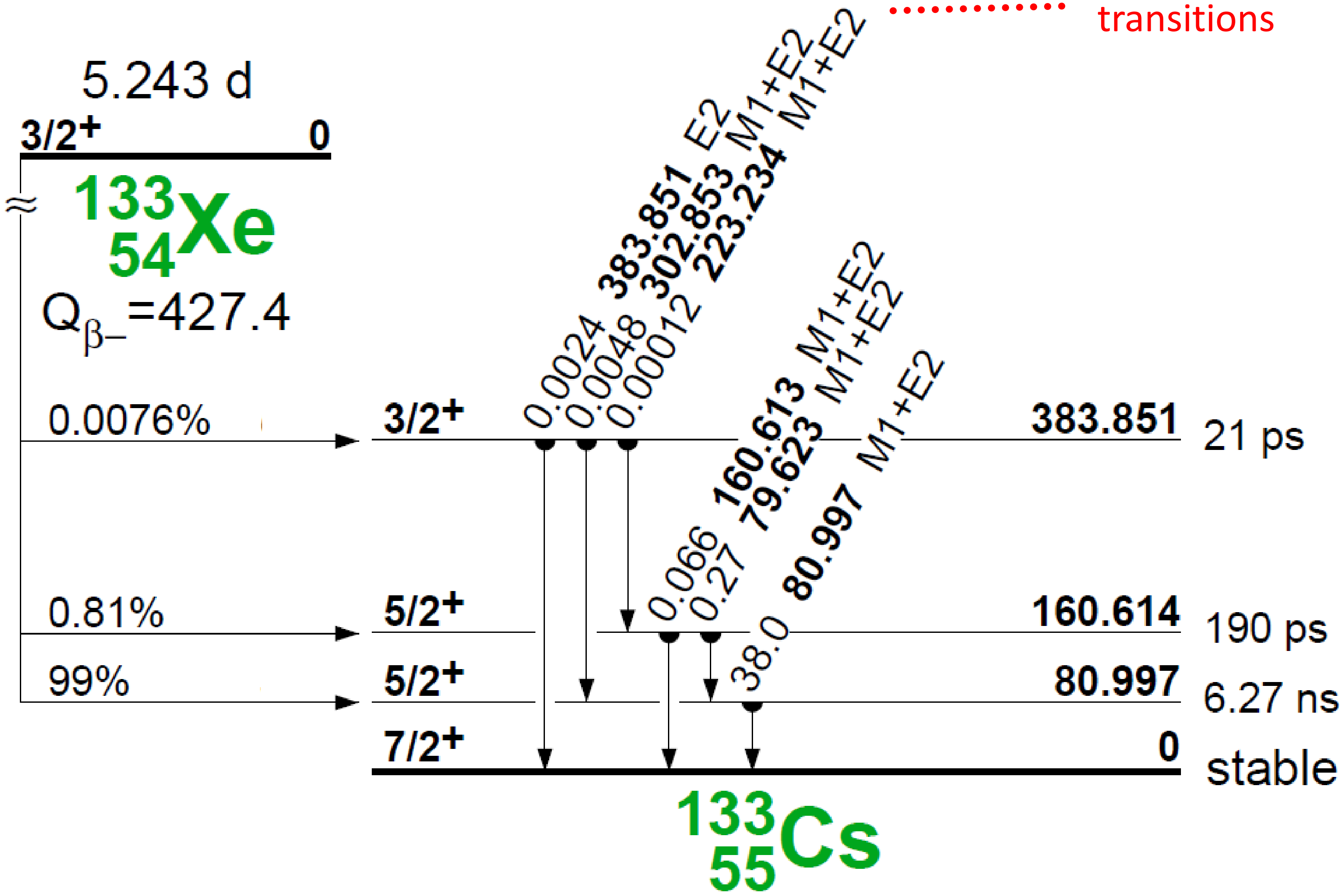
FIGURE 3-2 Energy spectrum (number emitted vs. energy) for β particles emitted by ^{14}C. Maximum β^--particle energy is Q, the transition energy (see Fig. 3-1). Average energy $\bar{E}_\beta$ is 0.0497 MeV, approximately $(\frac{1}{3})\,E_\beta^{max}$. (*Data courtesy Dr. Jongwha Chang, Korea Atomic Energy Research Institute.*)

Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012



Gamma emission &
Internal conversion
(competitive processes)

Example of beta decay with gamma emissions

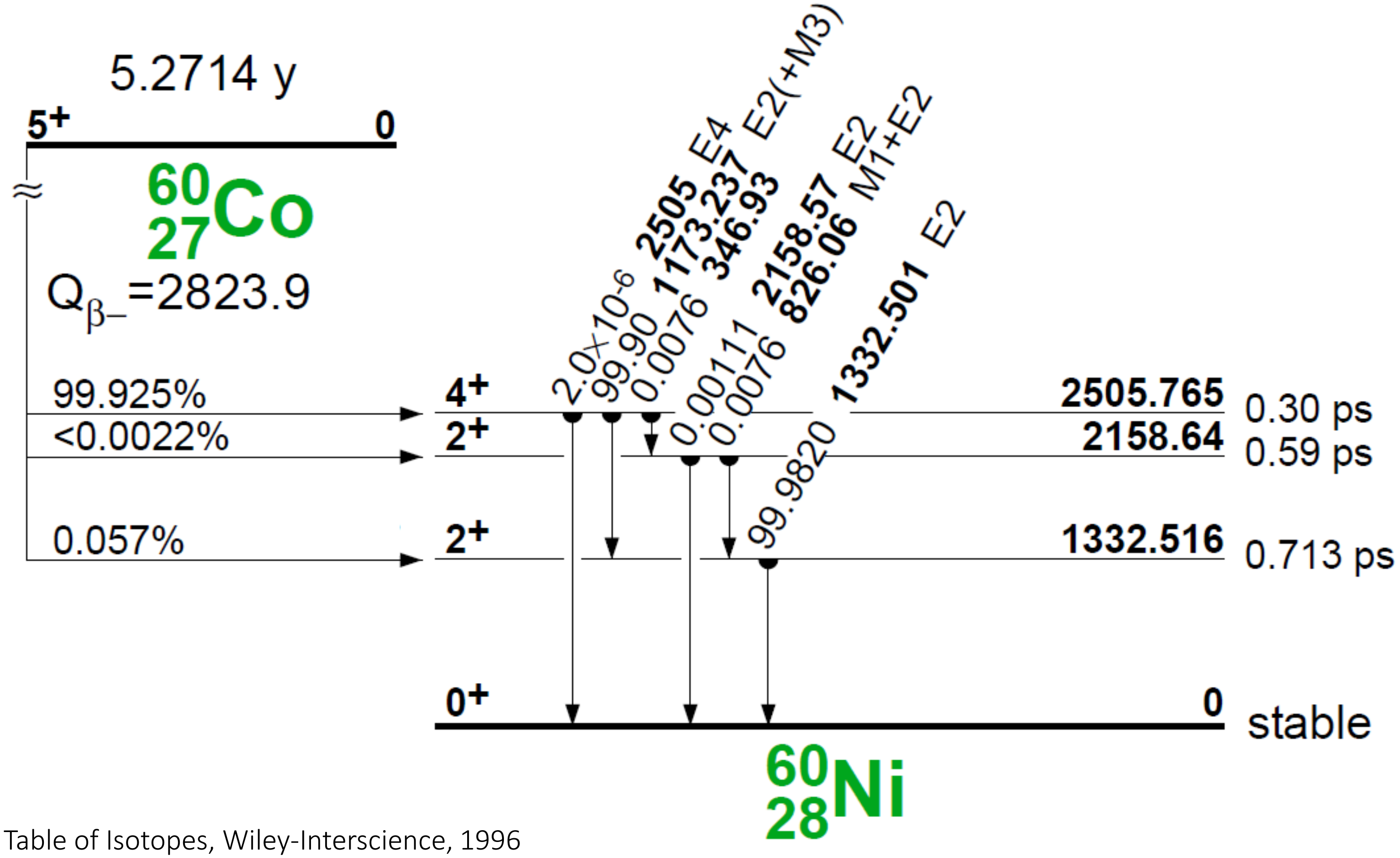


Multipole transitions

Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Exercise : decay of Co-60

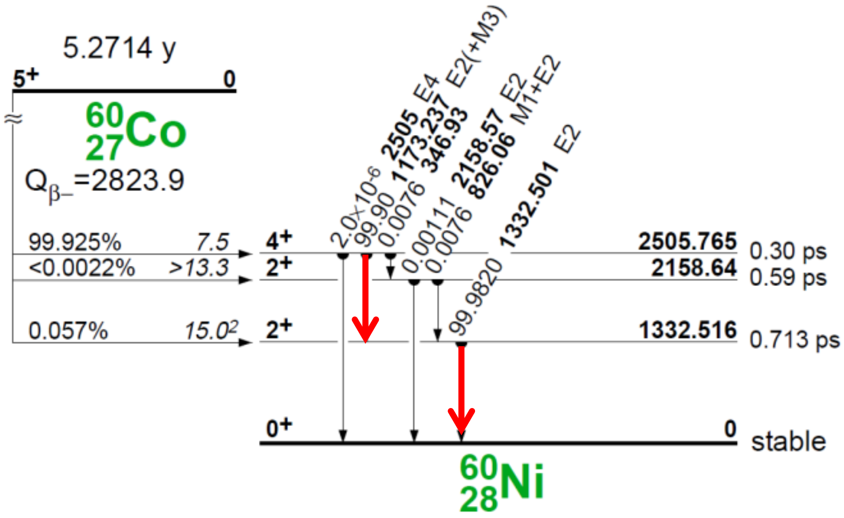
What is the mean number of photons emitted after 10'000 decays of Co-60?



R. B. Firestone, Table of Isotopes, Wiley-Interscience, 1996

Solution : decay of Co-60

What is the mean number of photons emitted after 10'000 decays of Co-60?



Only two gamma rays are significant

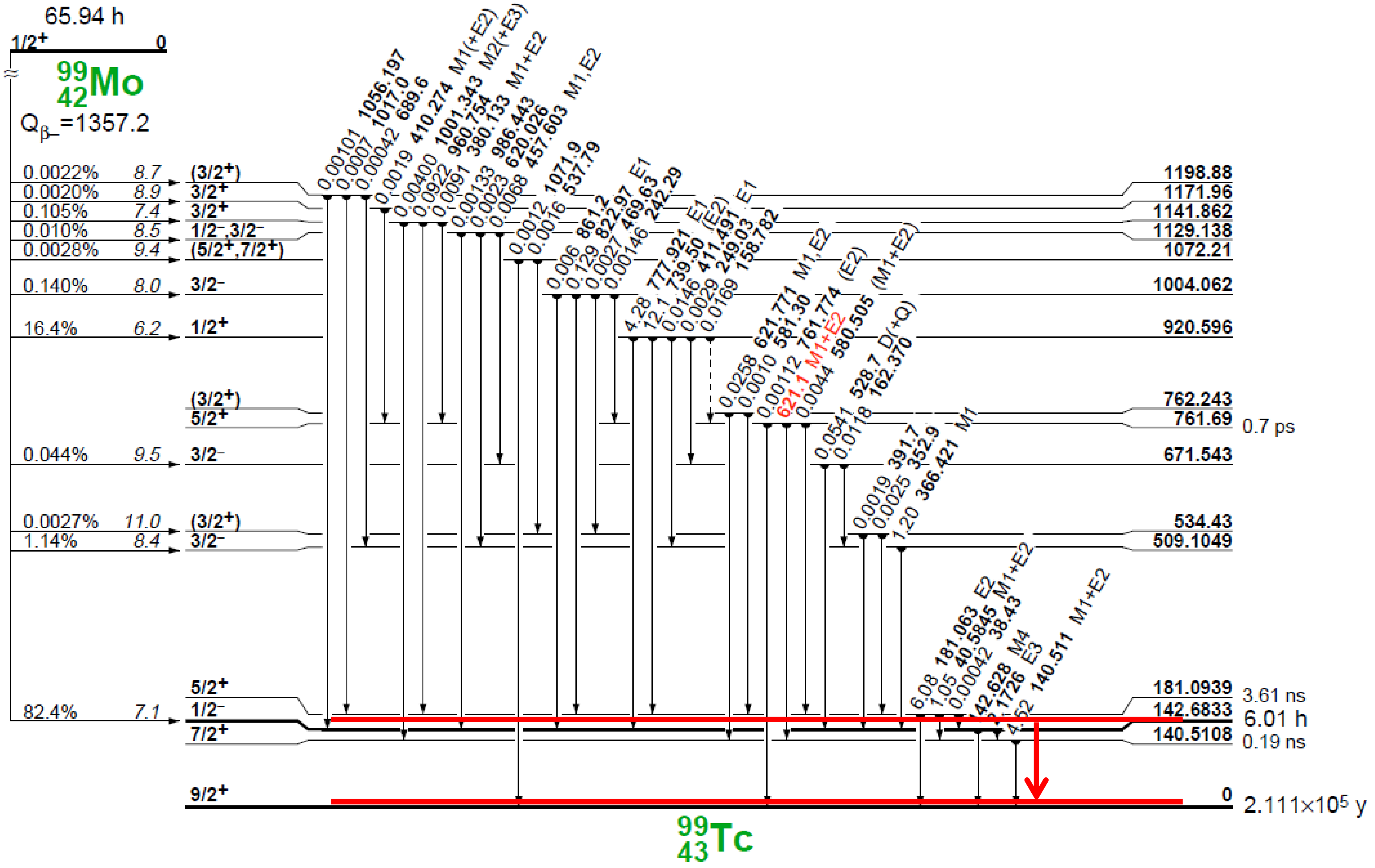
9990 photons of 1173 keV
(2505 keV – 1332 keV)

9998 photons of 1332 keV
(1332 keV – 0 keV)

Mean number of photons:
9990 + 9998 = 19998

Isomeric transition (delayed gamma emission)

metastable state

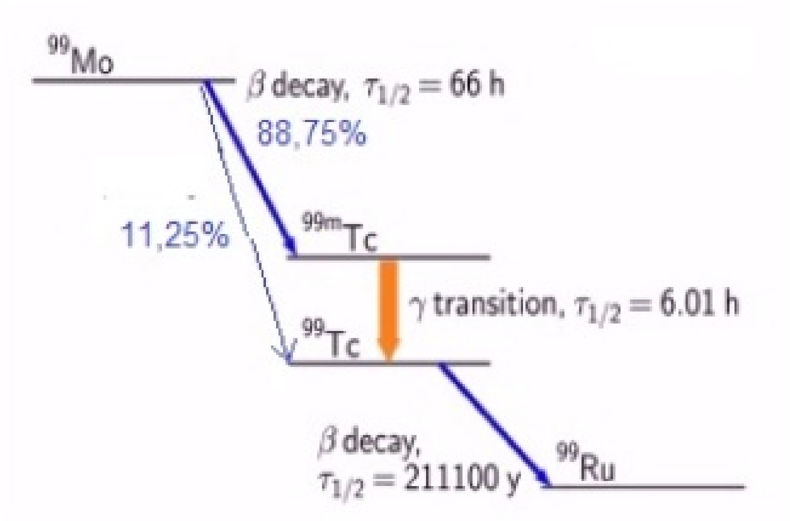


Tc-99m
(exp decay)

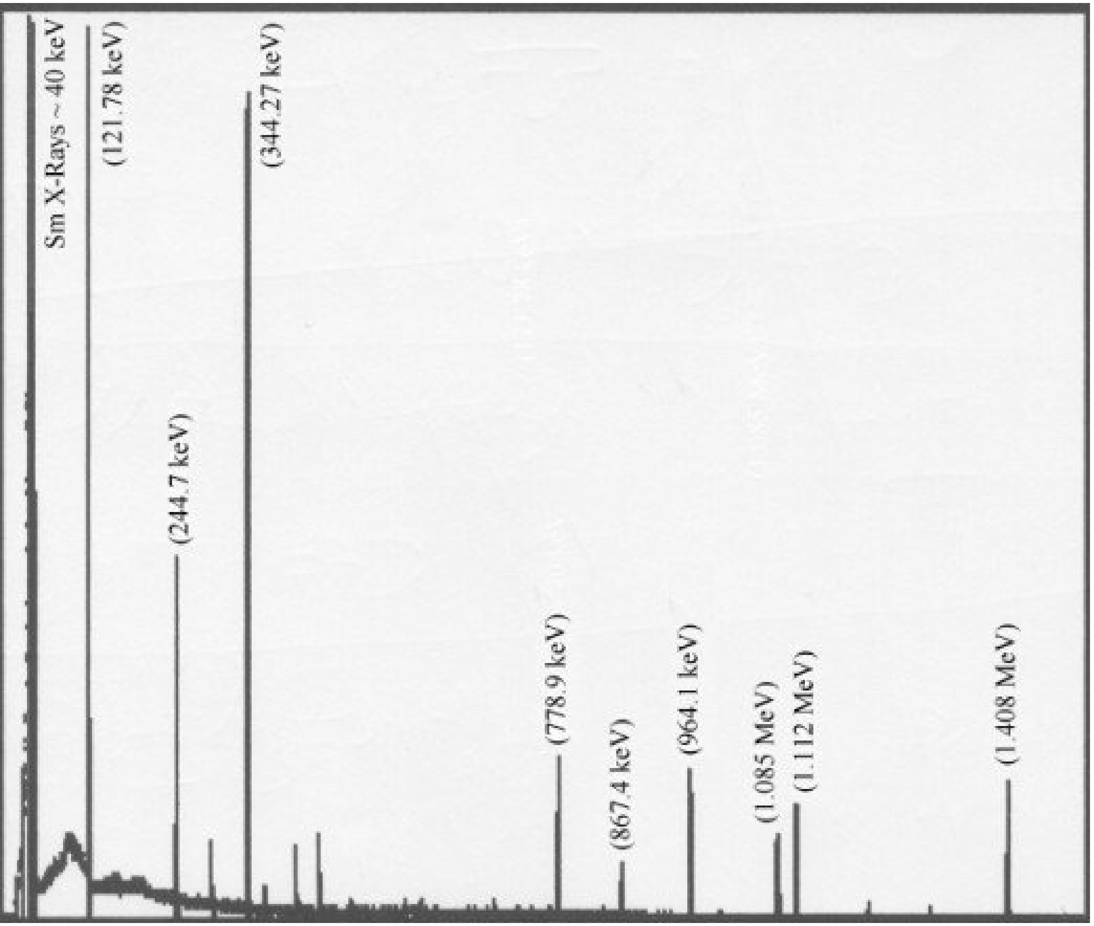
Tc-99m Radionuclide properties for in Nuclear Medicine

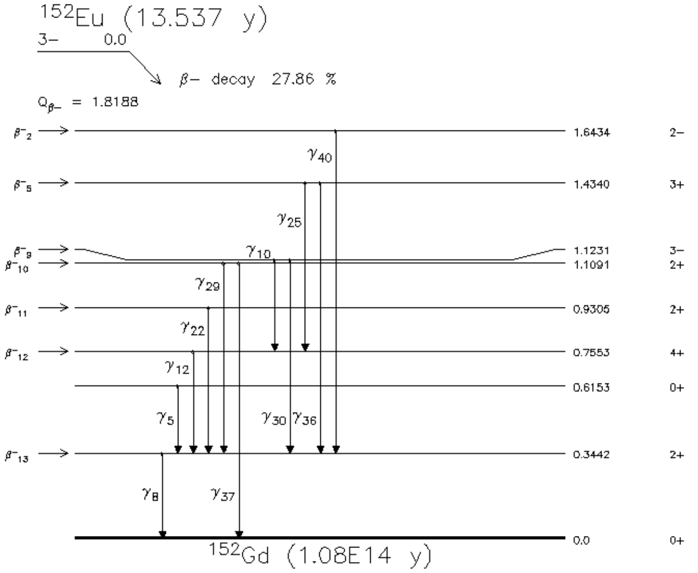
Nuclear diagnostics SPECT (single photon emission computer tomography)
requirements: gamma emitters 100-200 keV, $T_{1/2}$ = hours-days

- Tc^{99m} nuclear isotope is used for medical imaging in 90% of cases all over the world due to its near ideal nuclear characteristics of a 6 h halflife and γ-ray emission energy of 142 keV

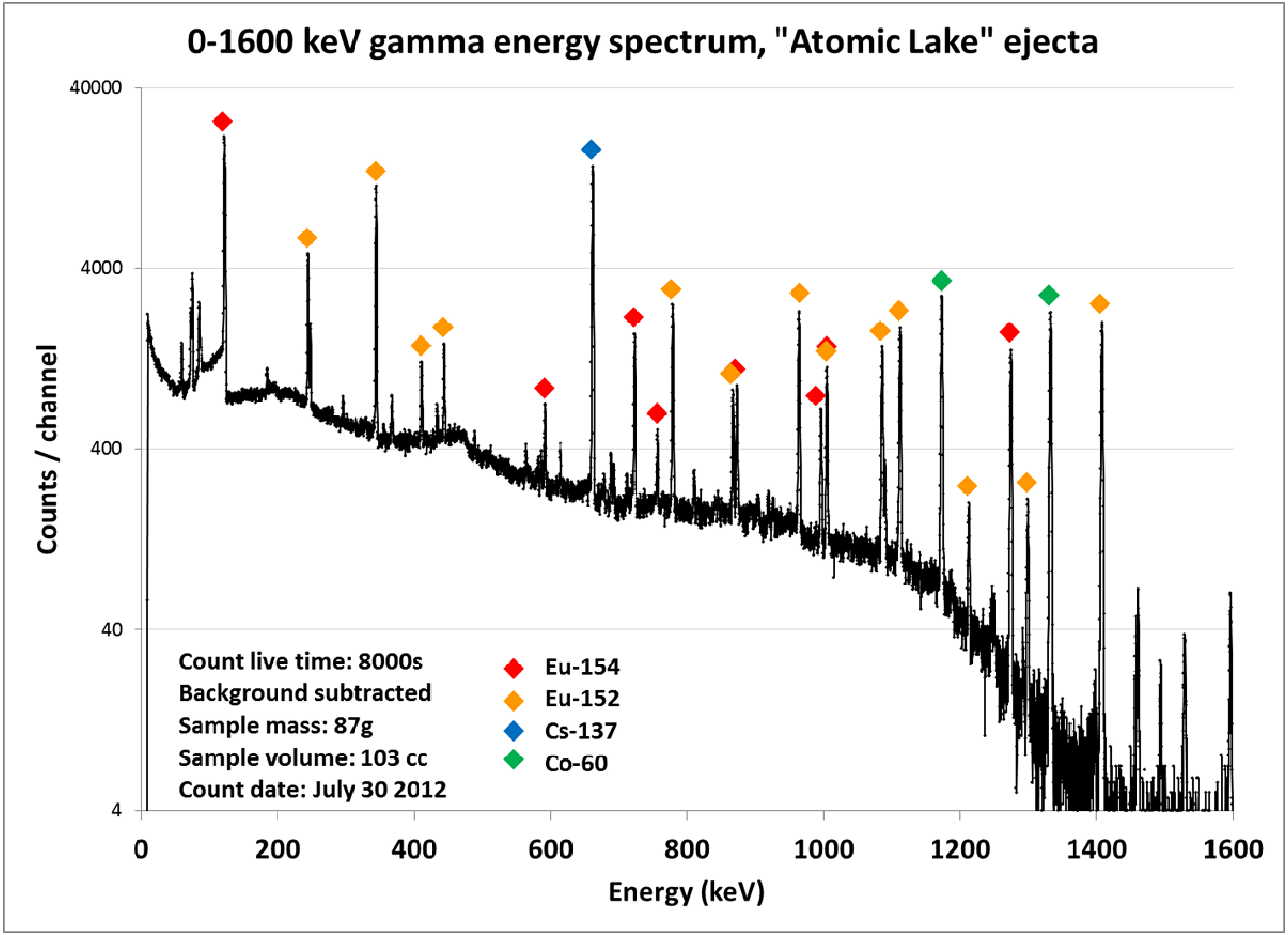


Eu-152


Sm X-Rays ~ 40 keV
(121.78 keV)
(244.7 keV)
(344.27 keV)
(778.9 keV)
(867.4 keV)
(964.1 keV)
(1.085 MeV)
(1.112 MeV)
(1.408 MeV)

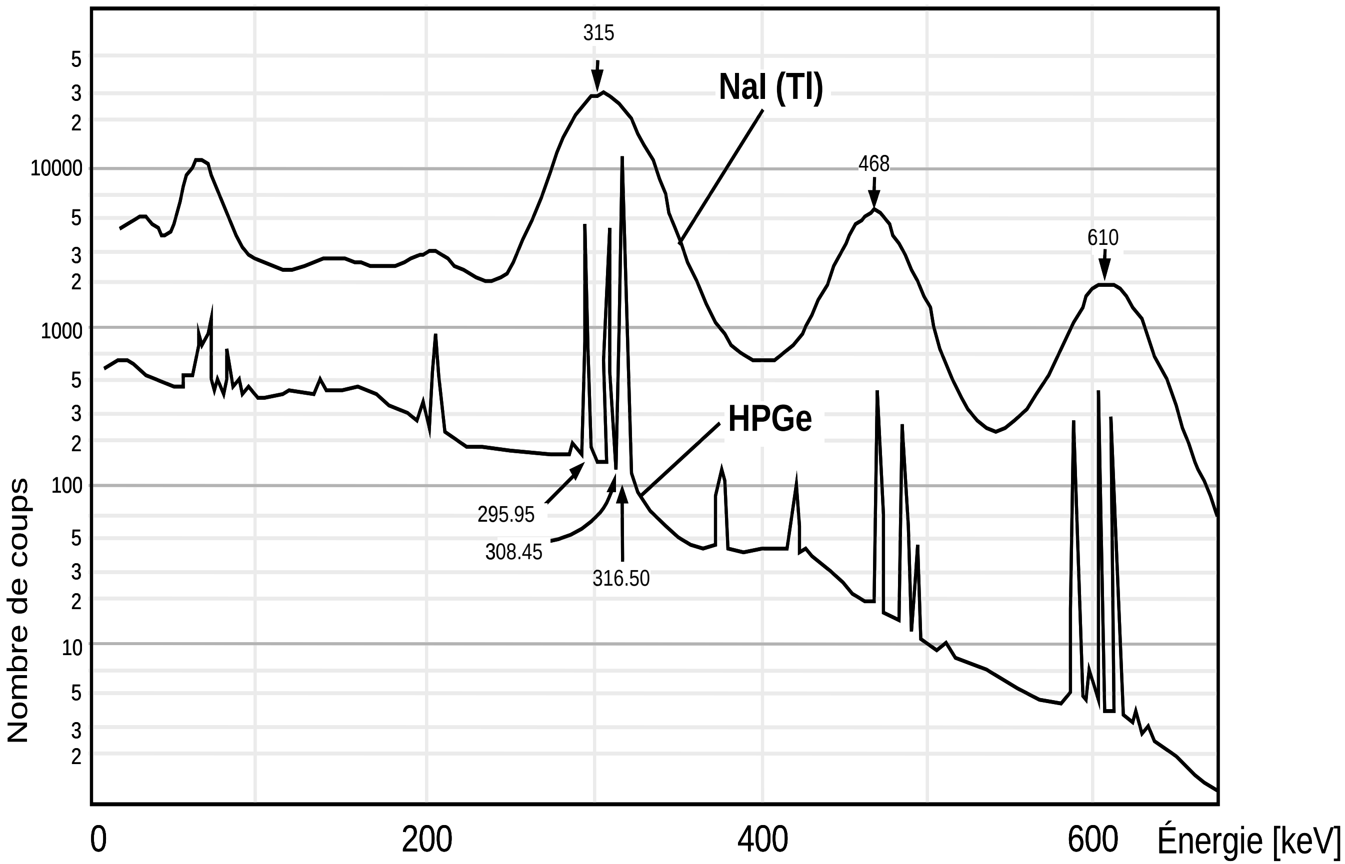

^{152}Eu (13.537 y)
3− 0.0
β− decay 27.86 %
$Q_{\beta-}$ = 1.8188
β^-_2 1.6434 2−
β^-_5 1.4340 3+
β^-_9 1.1231 3−
β^-_{10} 1.1091 2+
β^-_{11} 0.9305 2+
β^-_{12} 0.7553 4+
0.6153 0+
β^-_{13} 0.3442 2+
0.0 0+
γ_{40}
γ_{25}
γ_{10}
γ_{29}
γ_{22}
γ_{12}
γ_5
γ_{30}
γ_{36}
γ_8
γ_{37}
^{152}Gd (1.08E14 y)


automess
S/N 126805
µSv/h
0.05
0.1
0.2
0.5
1
2
5
10



0-1600 keV gamma energy spectrum, "Atomic Lake" ejecta

Count live time: 8000s
Background subtracted
Sample mass: 87g
Sample volume: 103 cc
Count date: July 30 2012

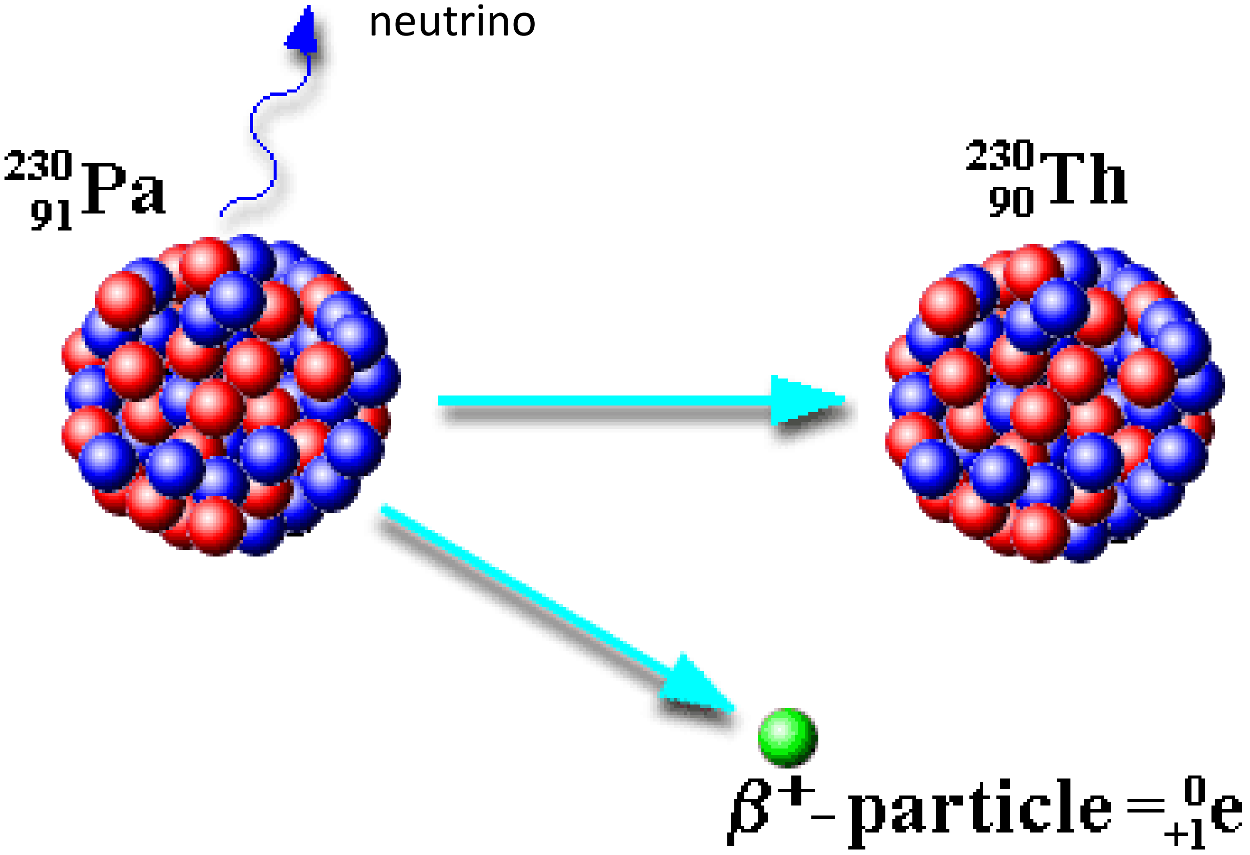


Comparison of Iridium-192 spectrum measured with
a crystal scintillator (NaI) vs. a semi-conductor detector (HPGe).

⇒ Choice of the instruments

Beta plus decay &
Electron capture
(competitive processes)

β^+ decay



neutrino

$^{230}_{91}\mathrm{Pa}$

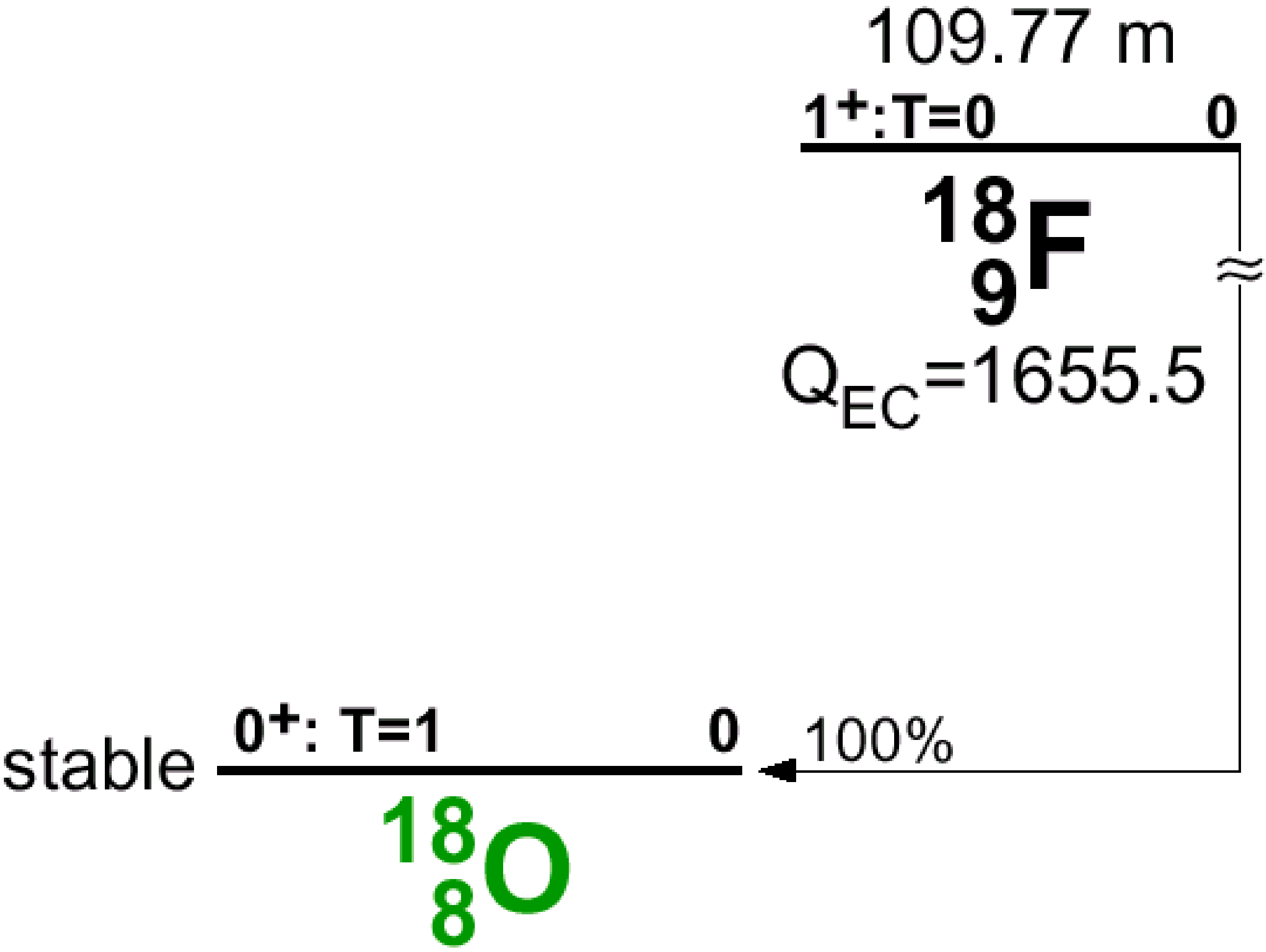
$^{230}_{90}\mathrm{Th}$

Z
N

Z-1
N+1

β^+-particle $= {}^{0}_{+1}\mathrm{e}$

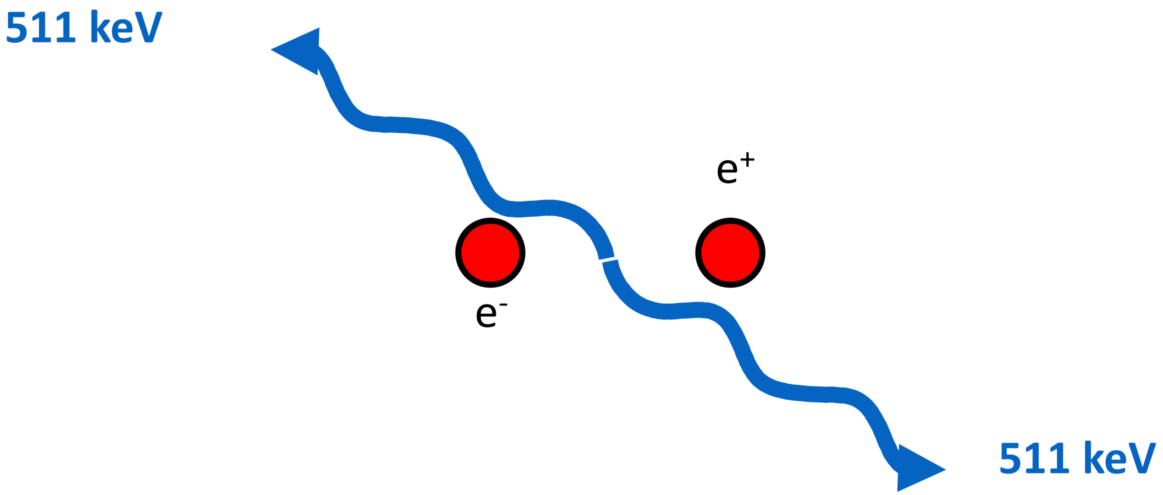
Example of β⁺ decay



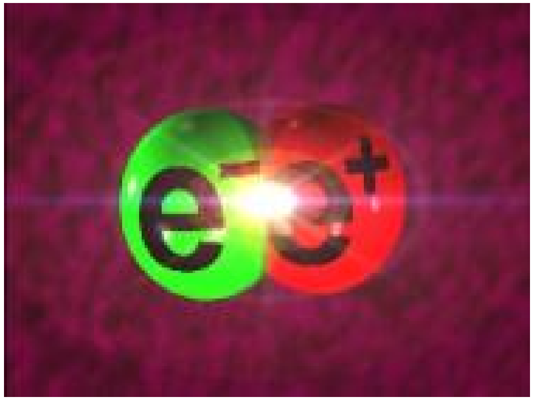
R. B. Firestone, Table of Isotopes, Wiley-Interscience, 1996

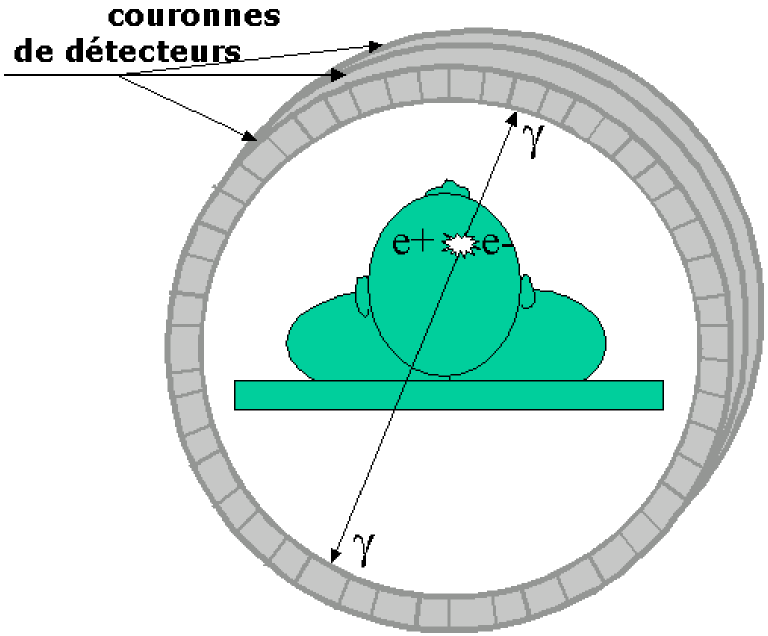
Positron-electron annihilation

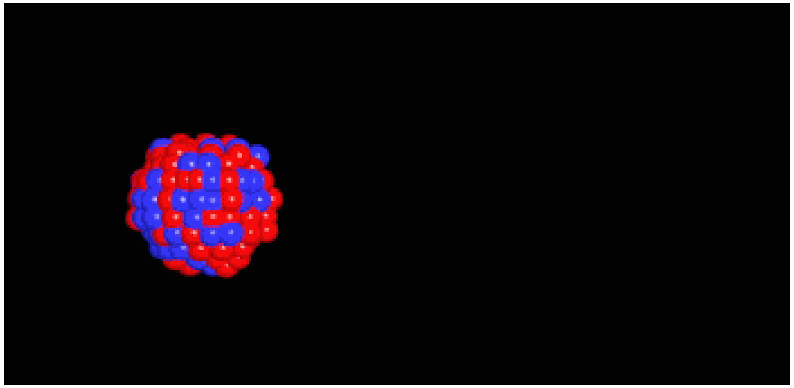
- The positron slows down in matter
- At slow speed: annihilation with an electron
- Result: 2 photons of 511 keV emitted at 180°
- Application : PET



Positron-electron annihilation

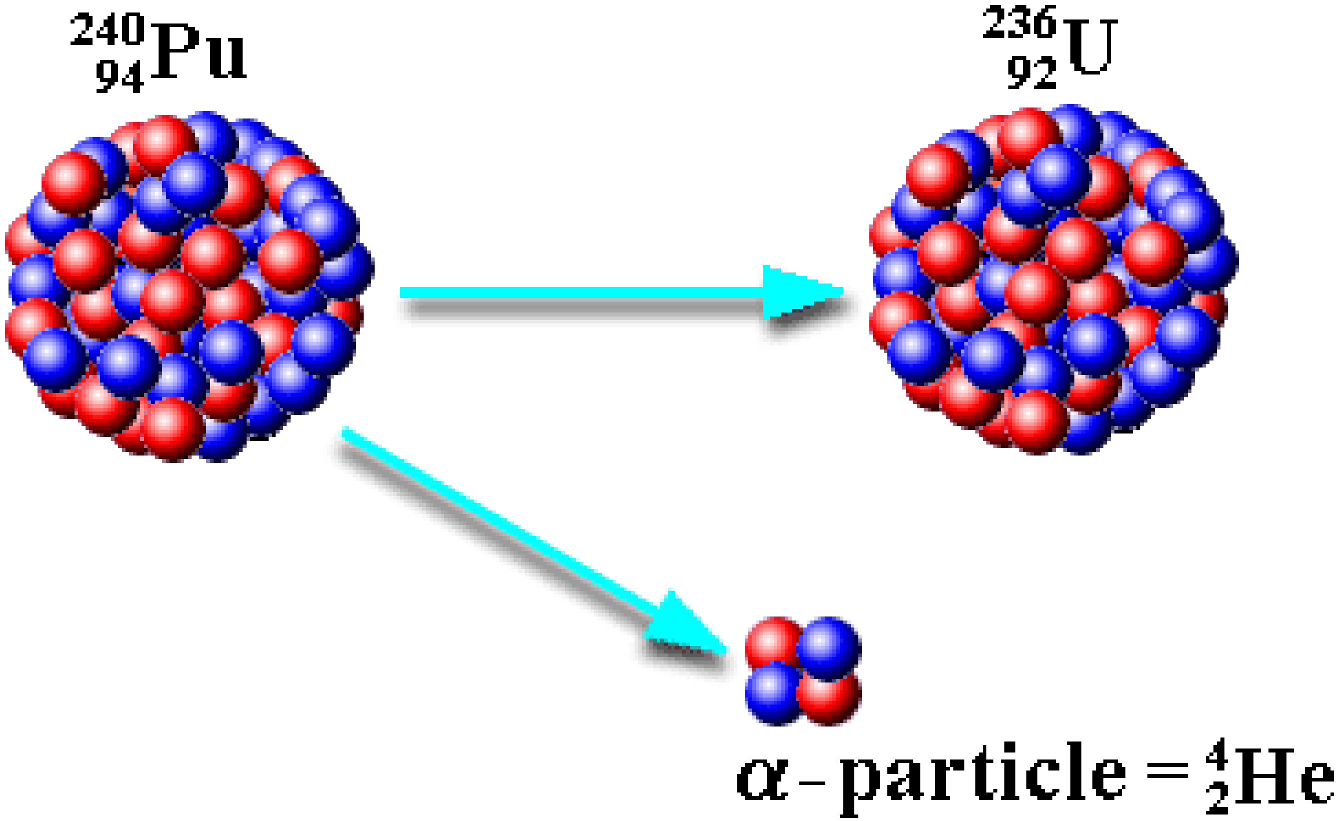






Alpha decay

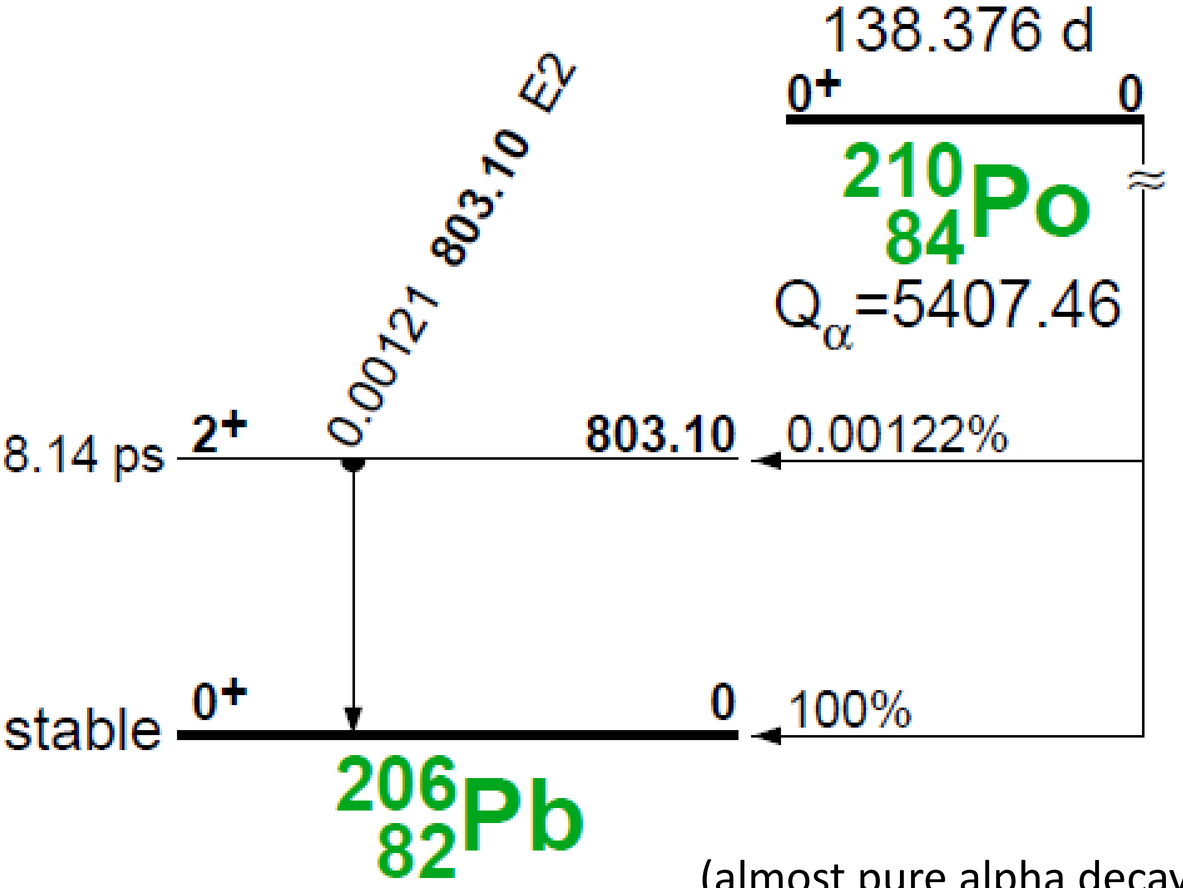
α decay



Z
N

Z-2
N-2

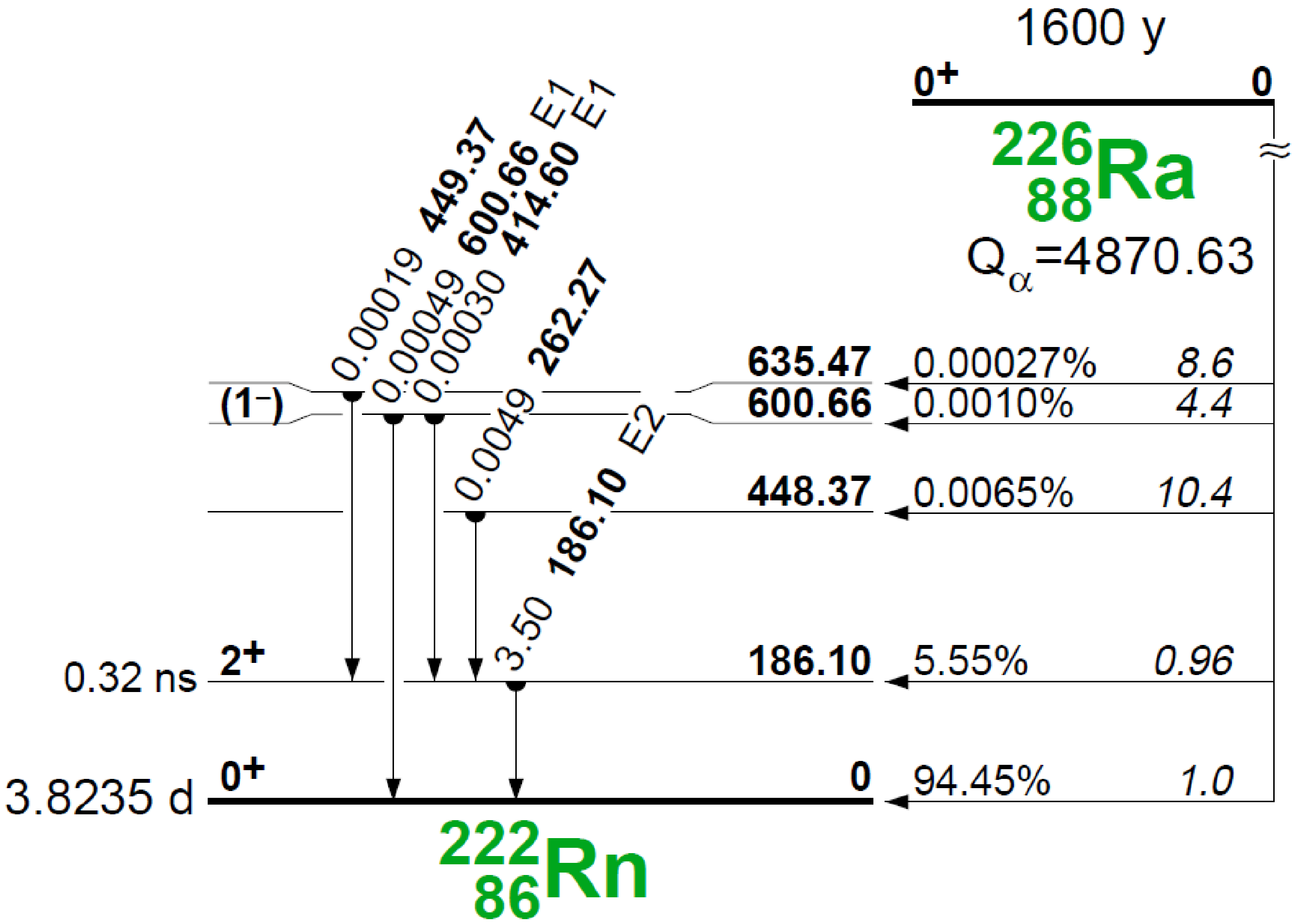
Example of alpha decay



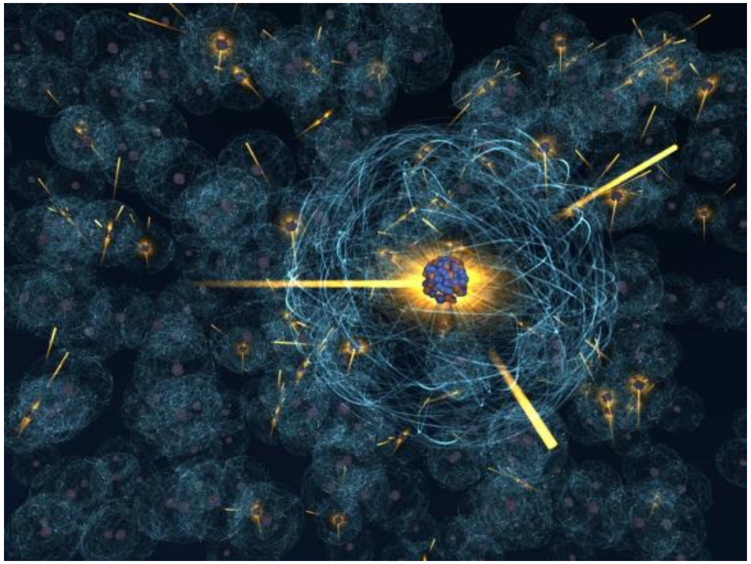
(almost pure alpha decay)

R. B. Firestone, Table of Isotopes, Wiley-Interscience, 1996

Radium decay



R. B. Firestone, Table of Isotopes, Wiley-Interscience, 1996



Fission

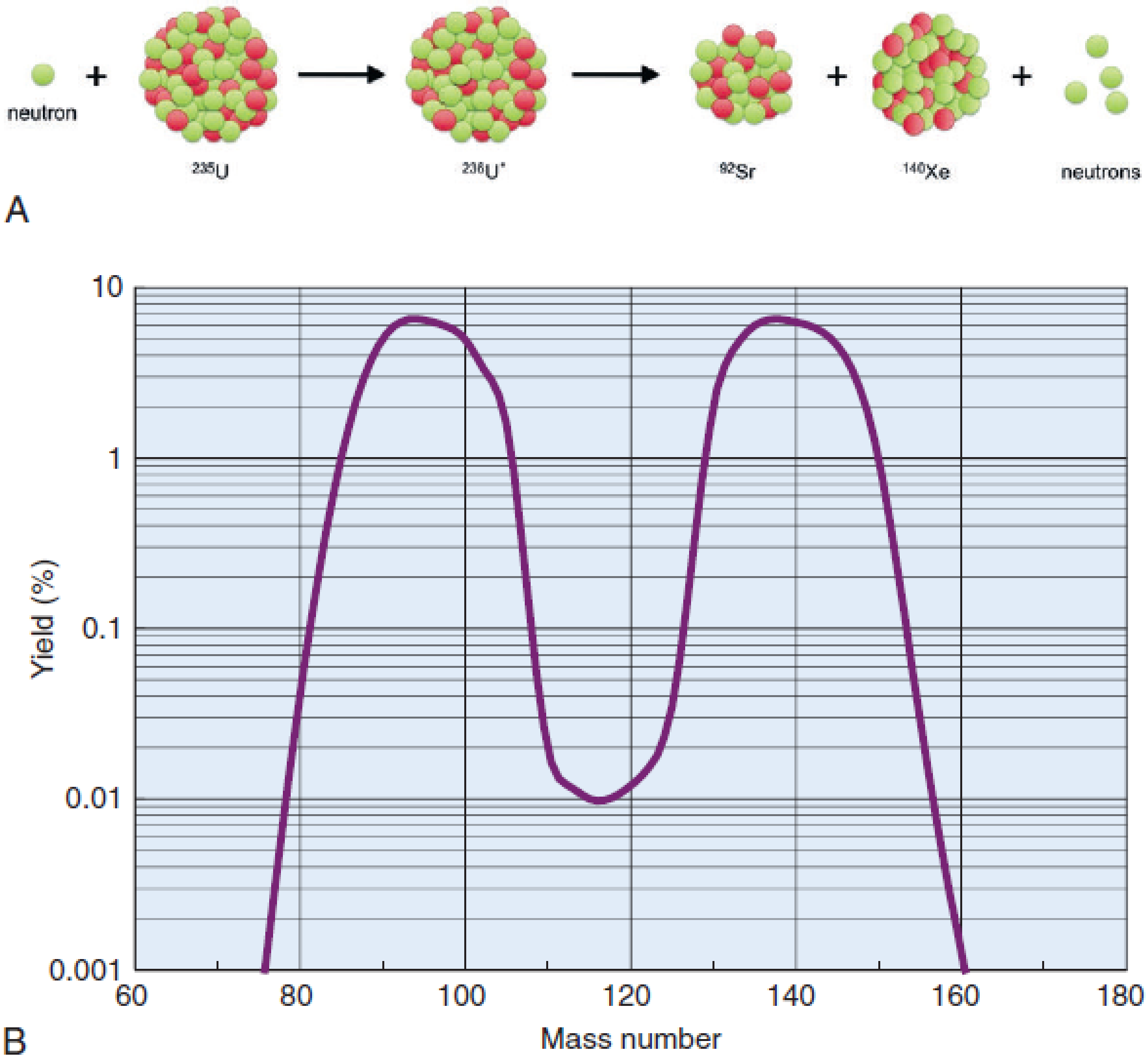
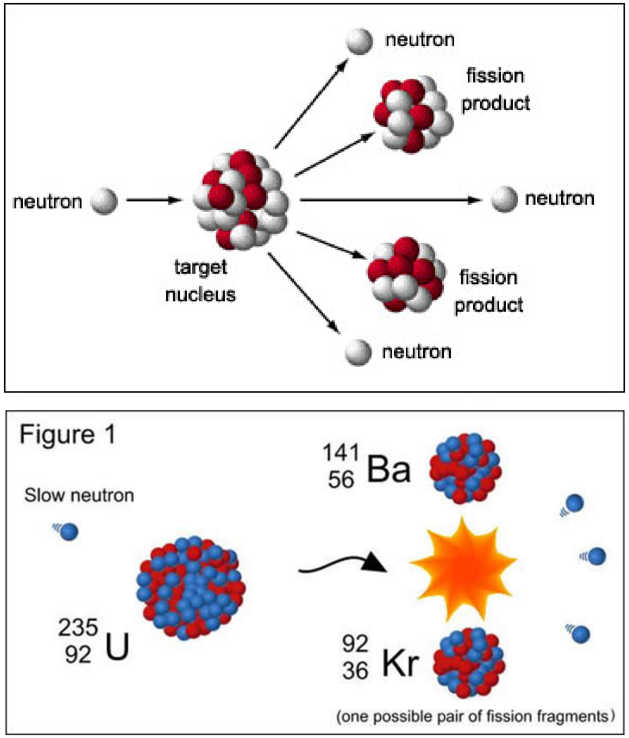


FIGURE 5-2 *A*, Example of production of fission fragments produced when neutrons interact with ^{236}U*. *B*, Mass distribution of fragments following fission of ^{236}U*.

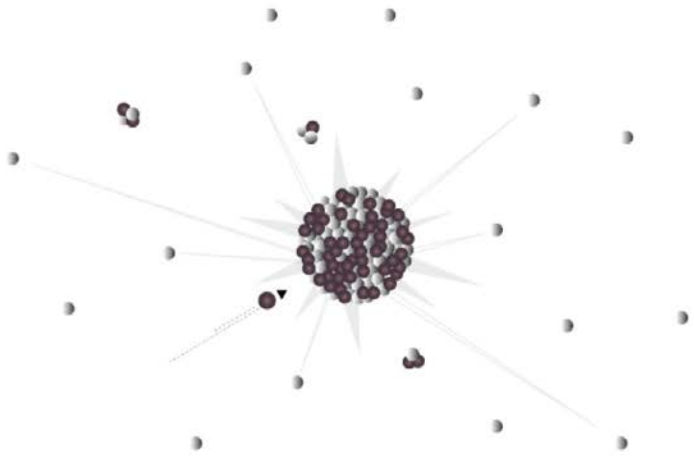
Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Fission — production of two elements of similar size

Spallation — fragmentation in light elements

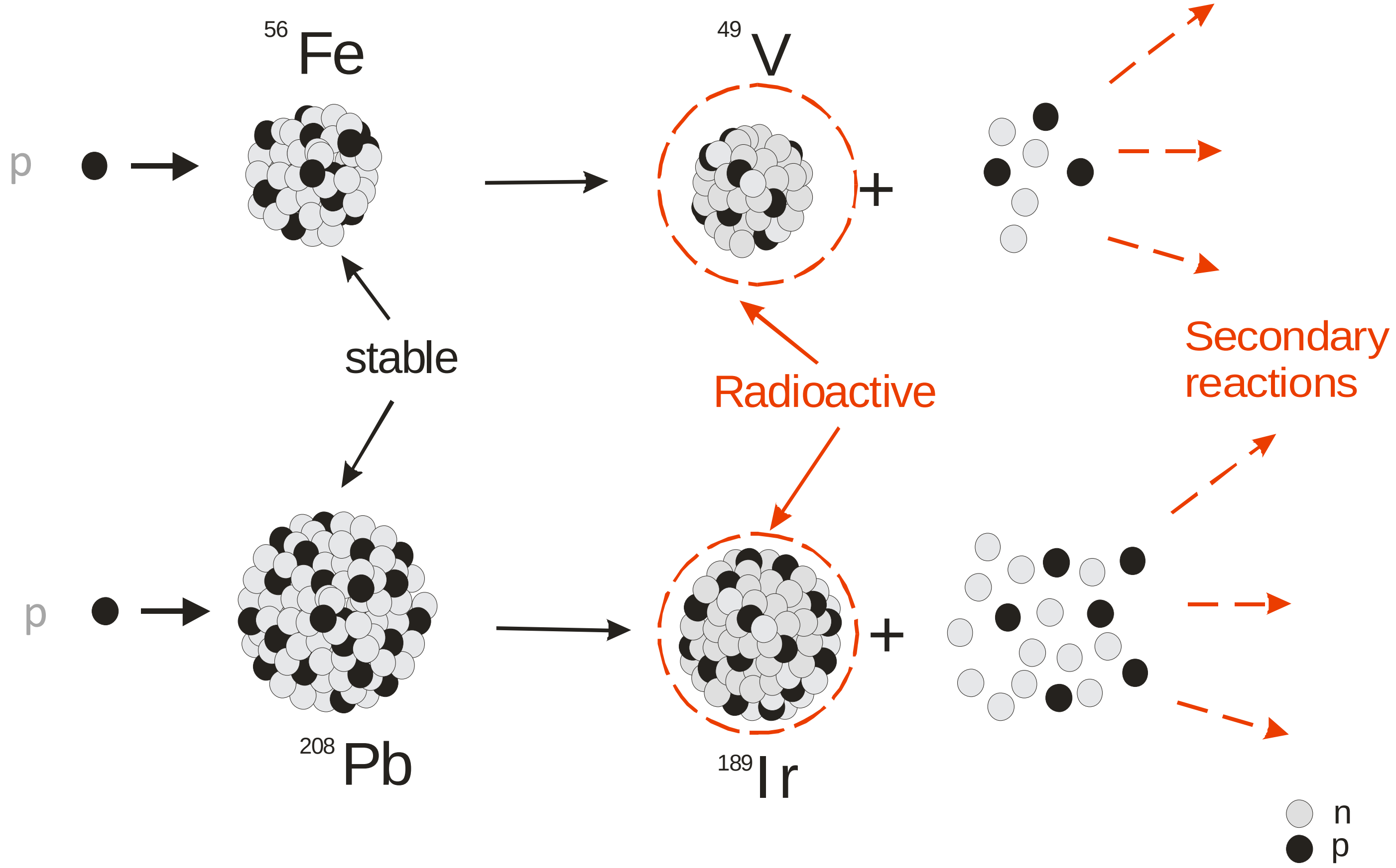


Fission

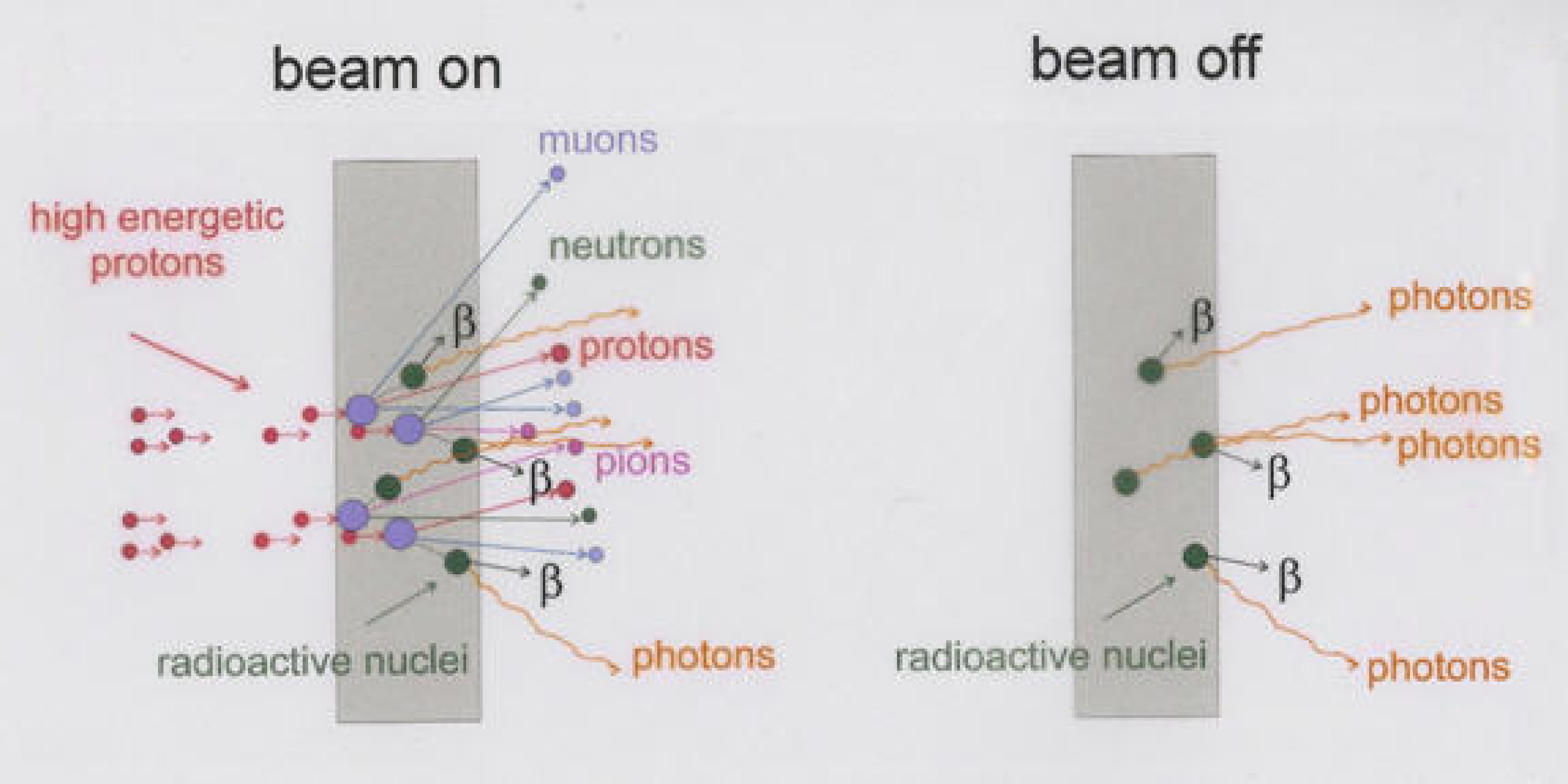


Spallation

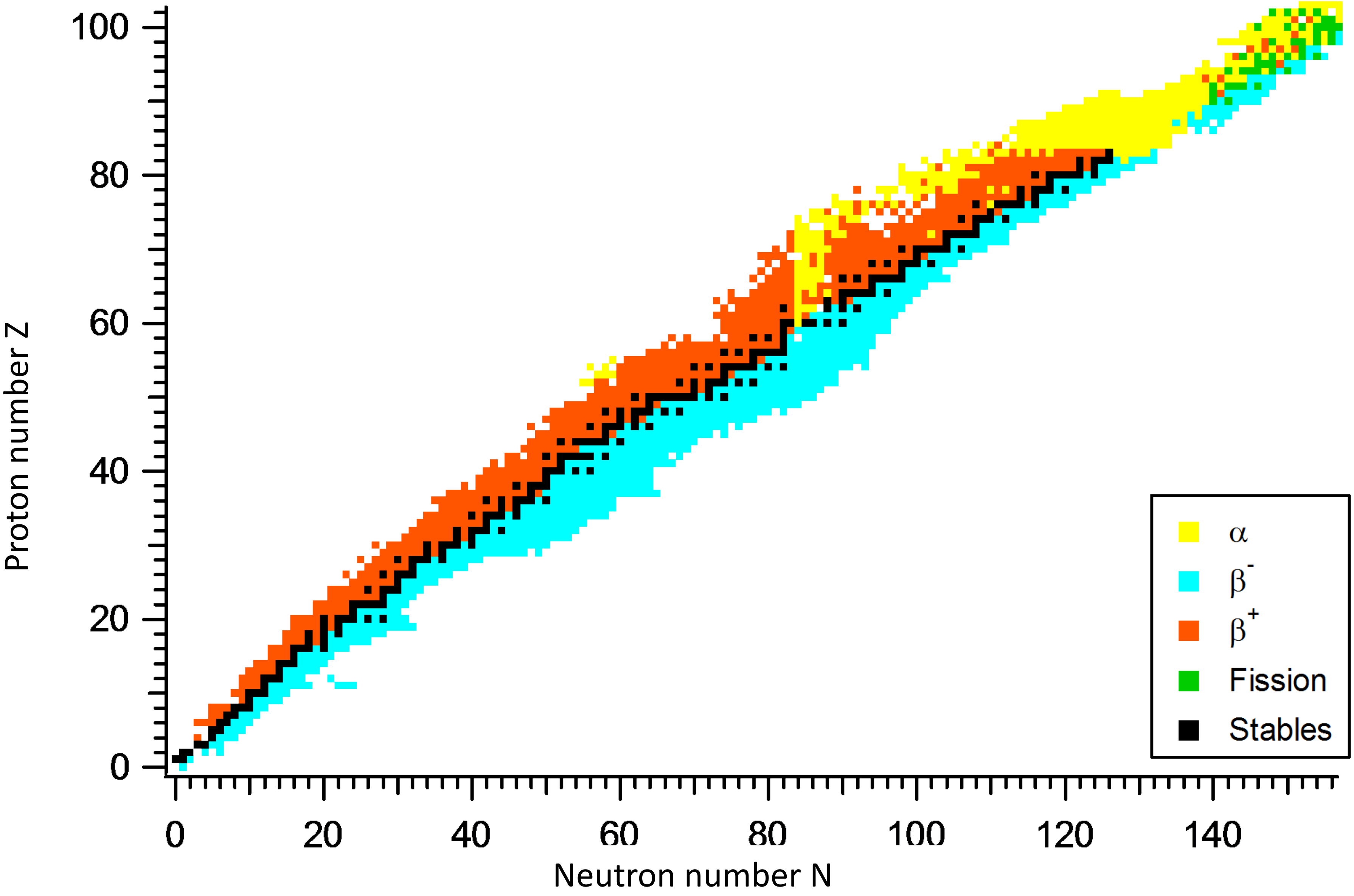
Spallation

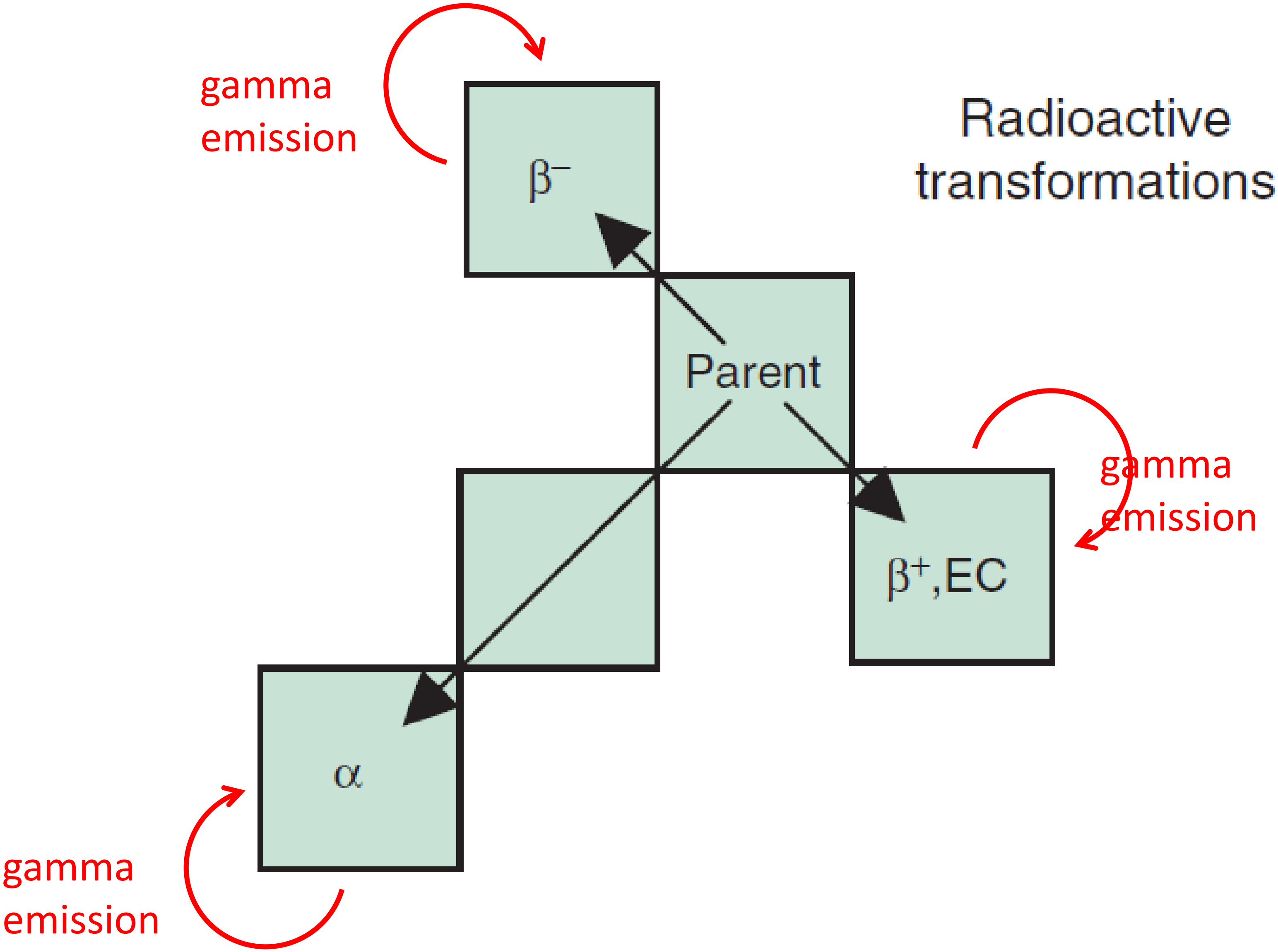

^{56}Fe
p
stable
^{49}V
+
Radioactive
Secondary reactions
p
^{208}Pb
^{189}Ir
+
n
p

Activation

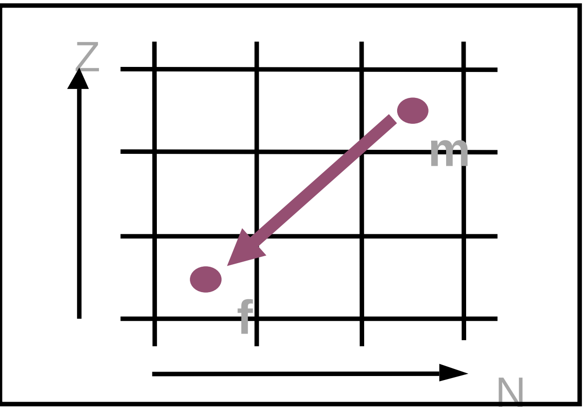

beam on
beam off
muons
high energetic protons
neutrons
β
protons
pions
β
β
radioactive nuclei
photons
photons
β
photons
photons
β
β
radioactive nuclei
photons

How do you move on the chart with the different decays?





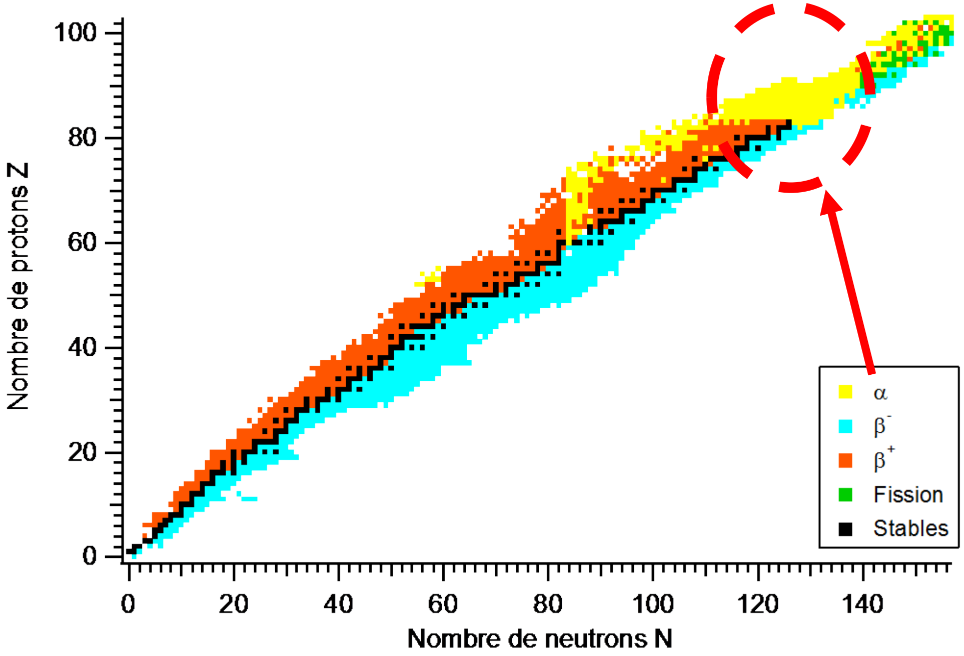
Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012



$${}^{A}_{Z}E_{N} \rightarrow {}^{A-4}_{Z-2}E_{N-2} + \underbrace{{}^{4}_{2}He_{2}}_{\text{particule } \alpha}$$

:

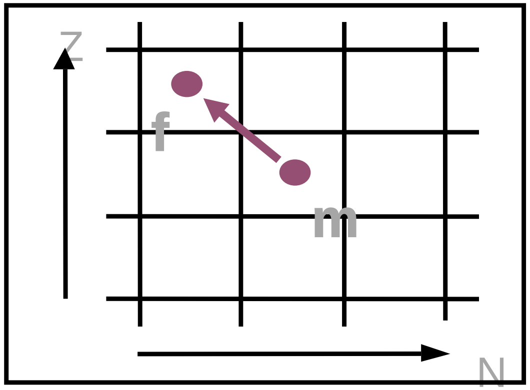
2 neutrons + 2 protons



Rn-222

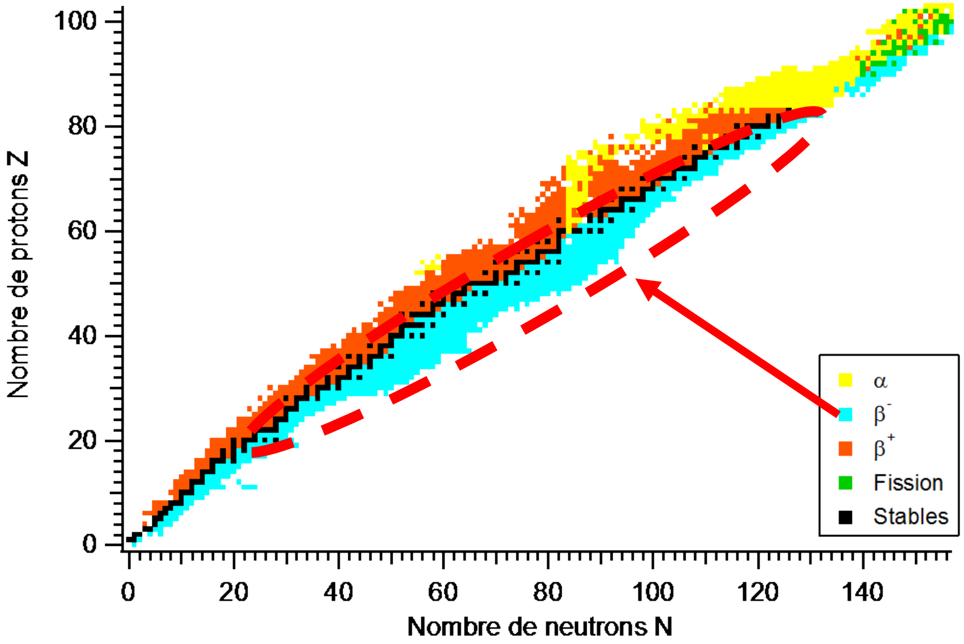
Am-241

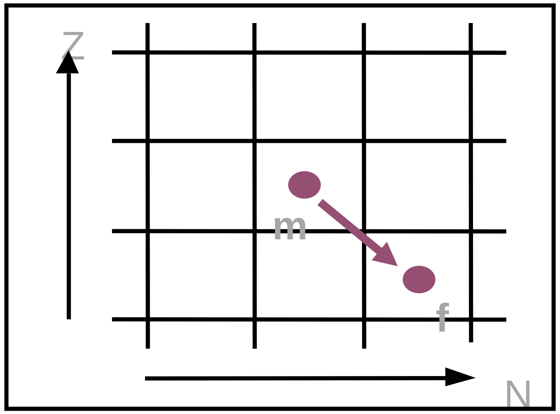
U-238



$$ {}^{A}_{Z}E_{N} \rightarrow {}^{A}_{Z+1}E_{N-1} + \underbrace{\beta^{-}}_{\text{électron}} + \underbrace{\bar{\nu}}_{\text{anti-neutrino}} $$

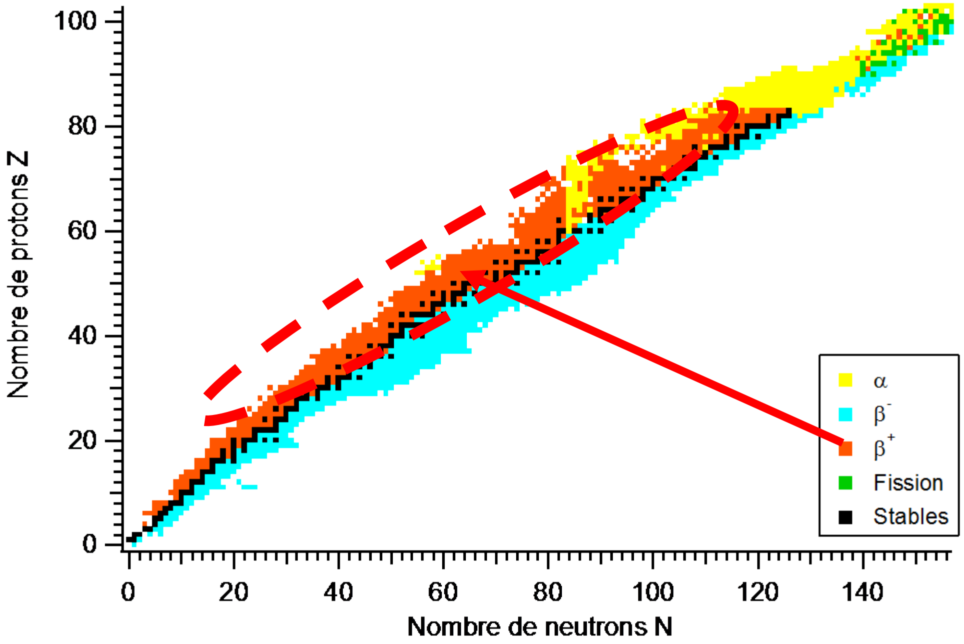
Neutron turns into a **proton**





$$ {}^{A}_{Z}E_{N} \rightarrow {}^{A}_{Z-1}E_{N+1} + \underbrace{\beta^{+}}_{\text{positron}} + \underbrace{\upsilon}_{\text{neutrino}} $$

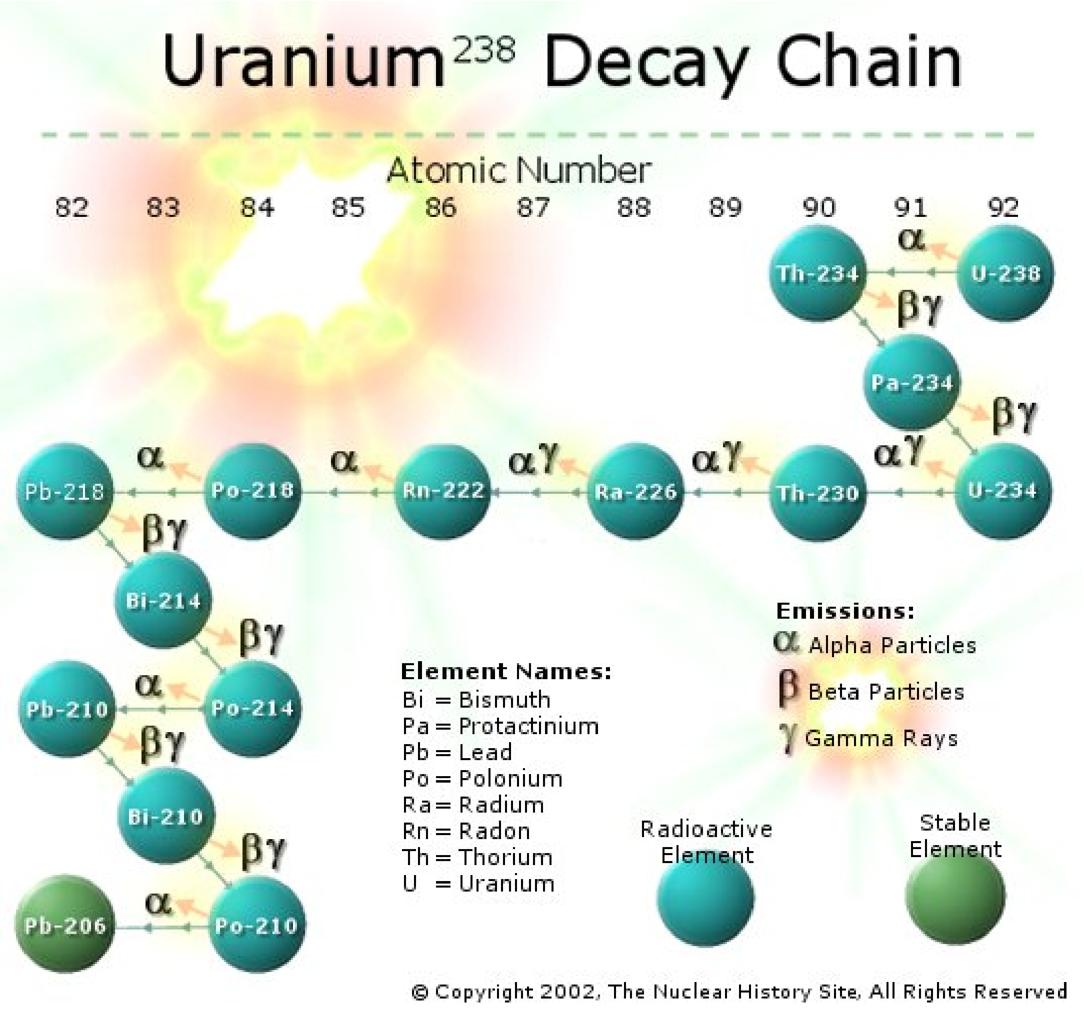
Proton turns into a **neutron**

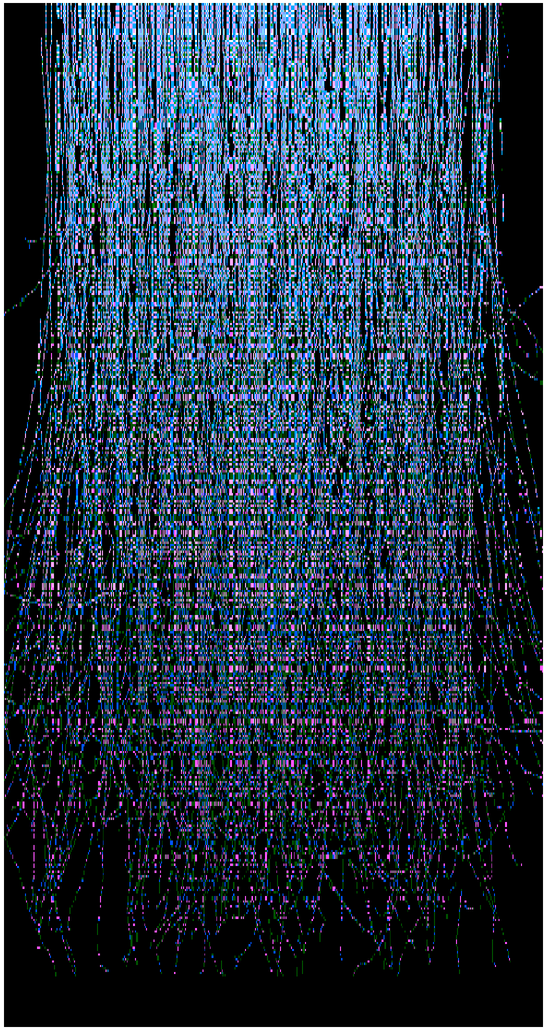


^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{124}I

Radioactivity

α, β± γ





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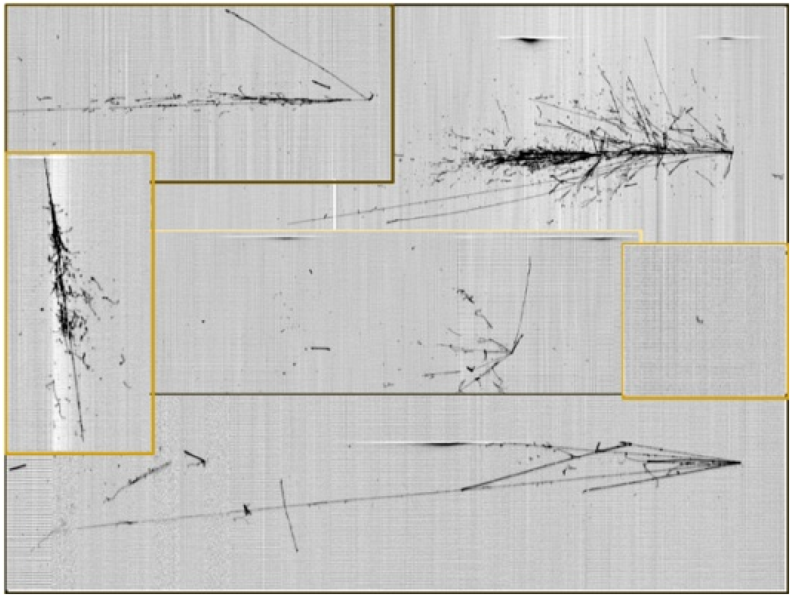
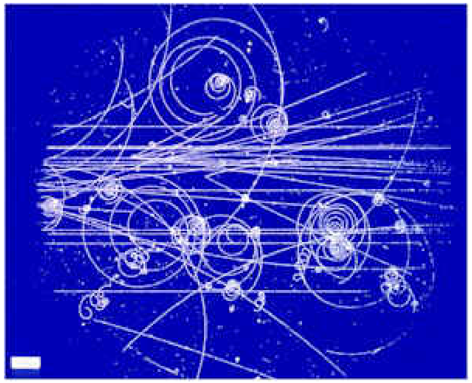
RPRA : **Radiation protection** and radiation applications

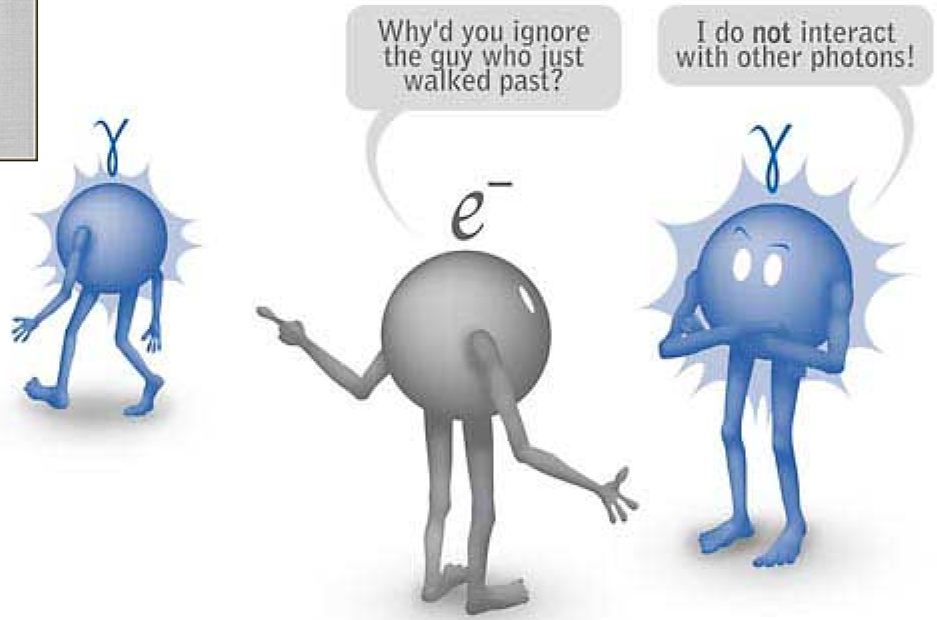
Basis of radiation physics

Interactions of charged particles

Interaction with matter





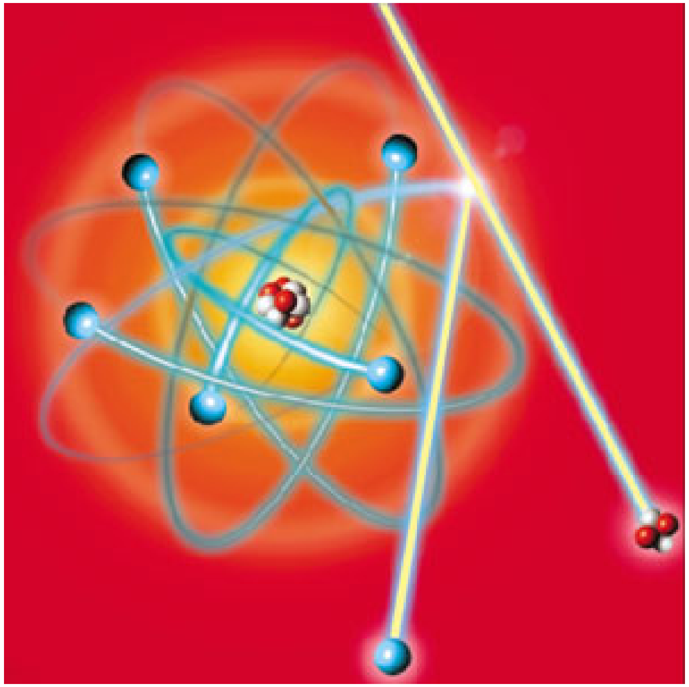


Ionizing radiation

Ionising radiation

High energy radiation are able to remove electrons from atoms, which is why they are called "ionising radiation".

Electromagnetic radiation can cause ionisation if the wavelength is less than 100 nanometers, because in these limits, the photon has enough energy to eject an electron.



Several types of ionising radiation:

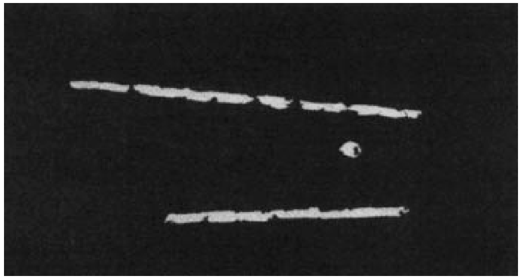
1. **Particles**

(neutrons, protons, α, β)

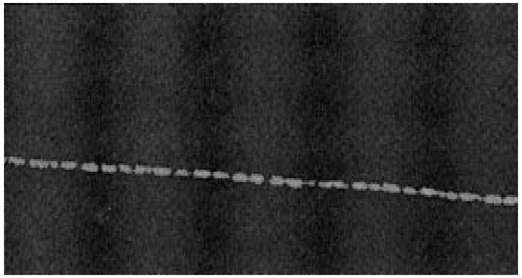
2. **Electromagnetic waves**

(γ, X –rays)

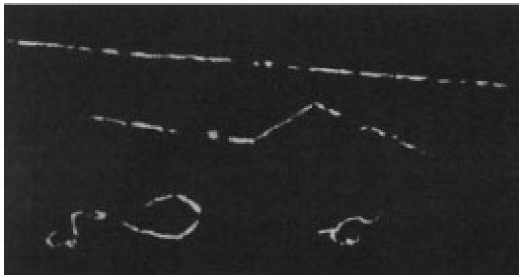
Interaction avec la matière



protons

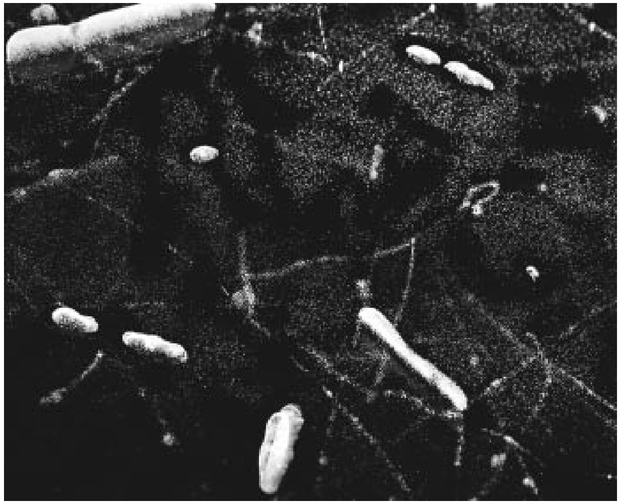


muon

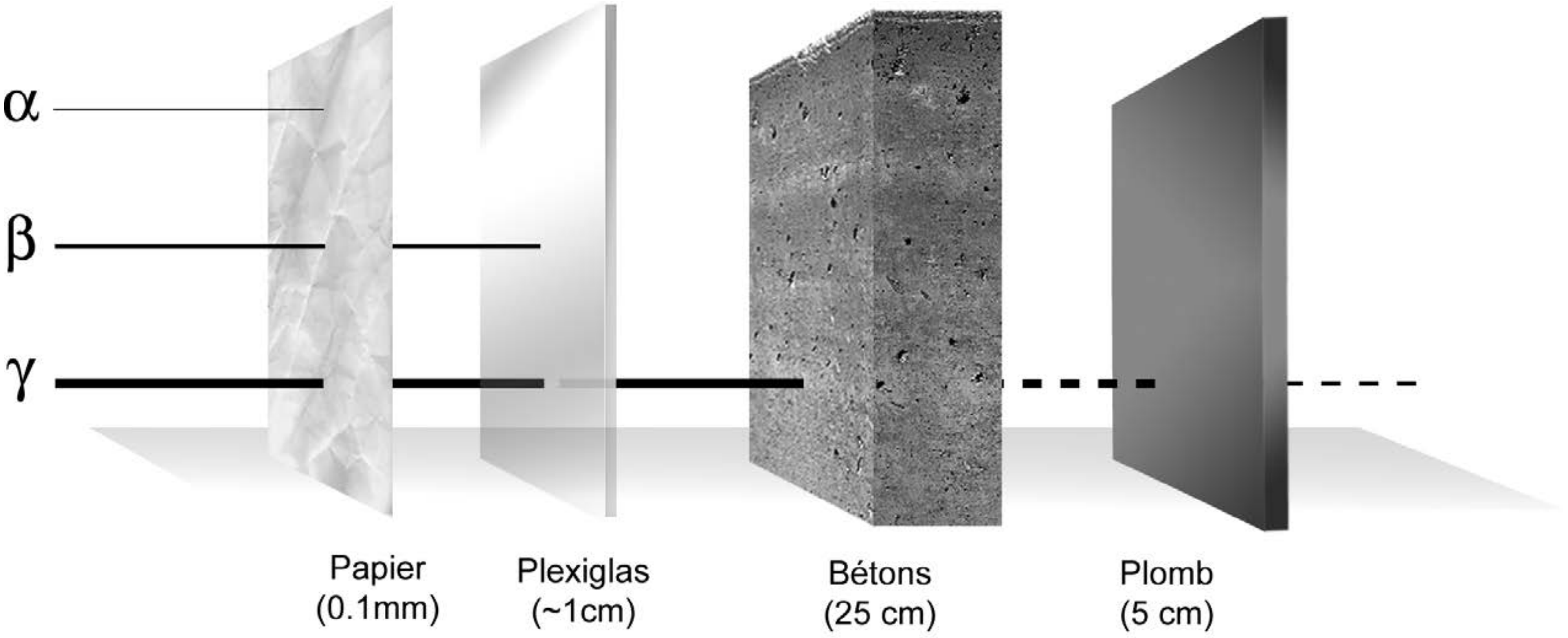


β

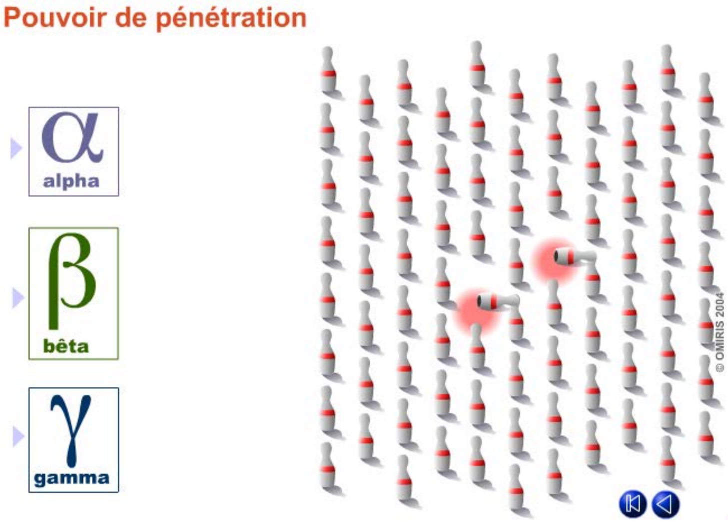
particule α



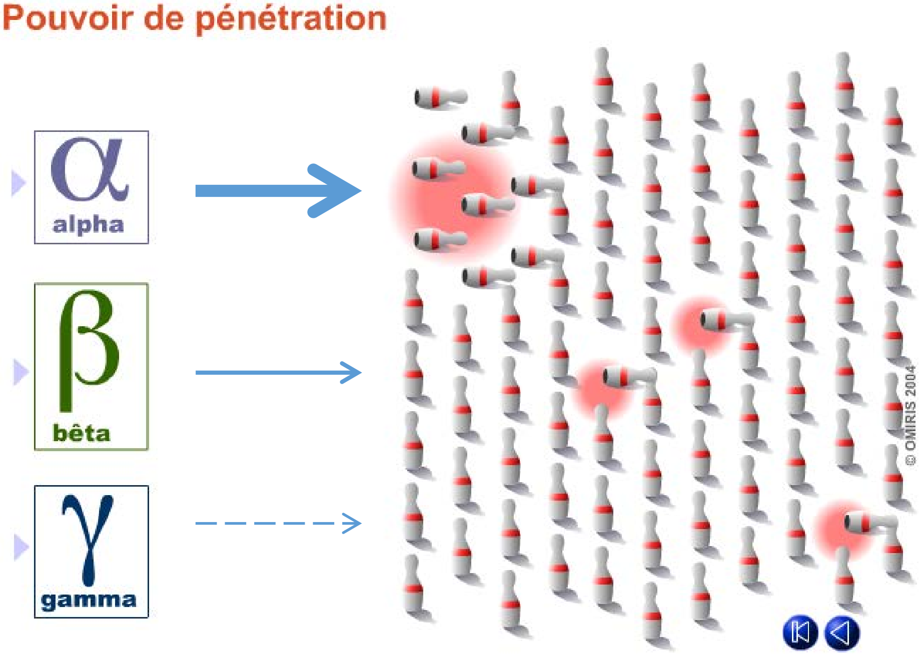
Path length in matter



⇒ Radiation Protection



α, β, γ ???

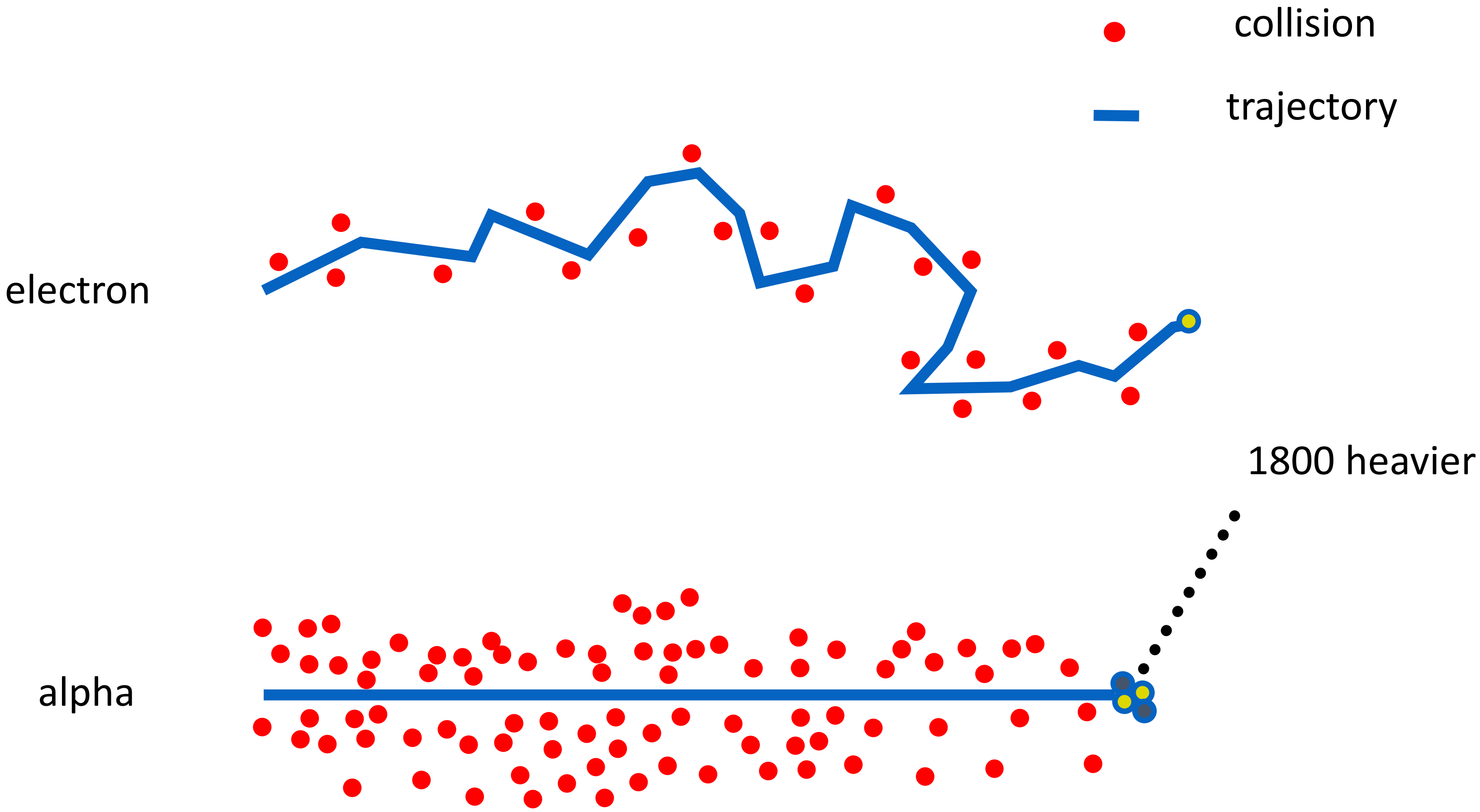


⇒ Dosimetry

Photon-matter interaction

	Charged particles	**Non-charged particles**
Typical example	Electrons, protons, α	Neutrons, RX, γ
Slowing down	Continuous	Random mechanism
Frequency of interactions	Many small interactions	Long journey without interaction
Quantity of energy loss	Weak for each interaction	Major modification (production of charged particles)
Path	Finite	Exponential weakening

Charged particles interactions



Electrons

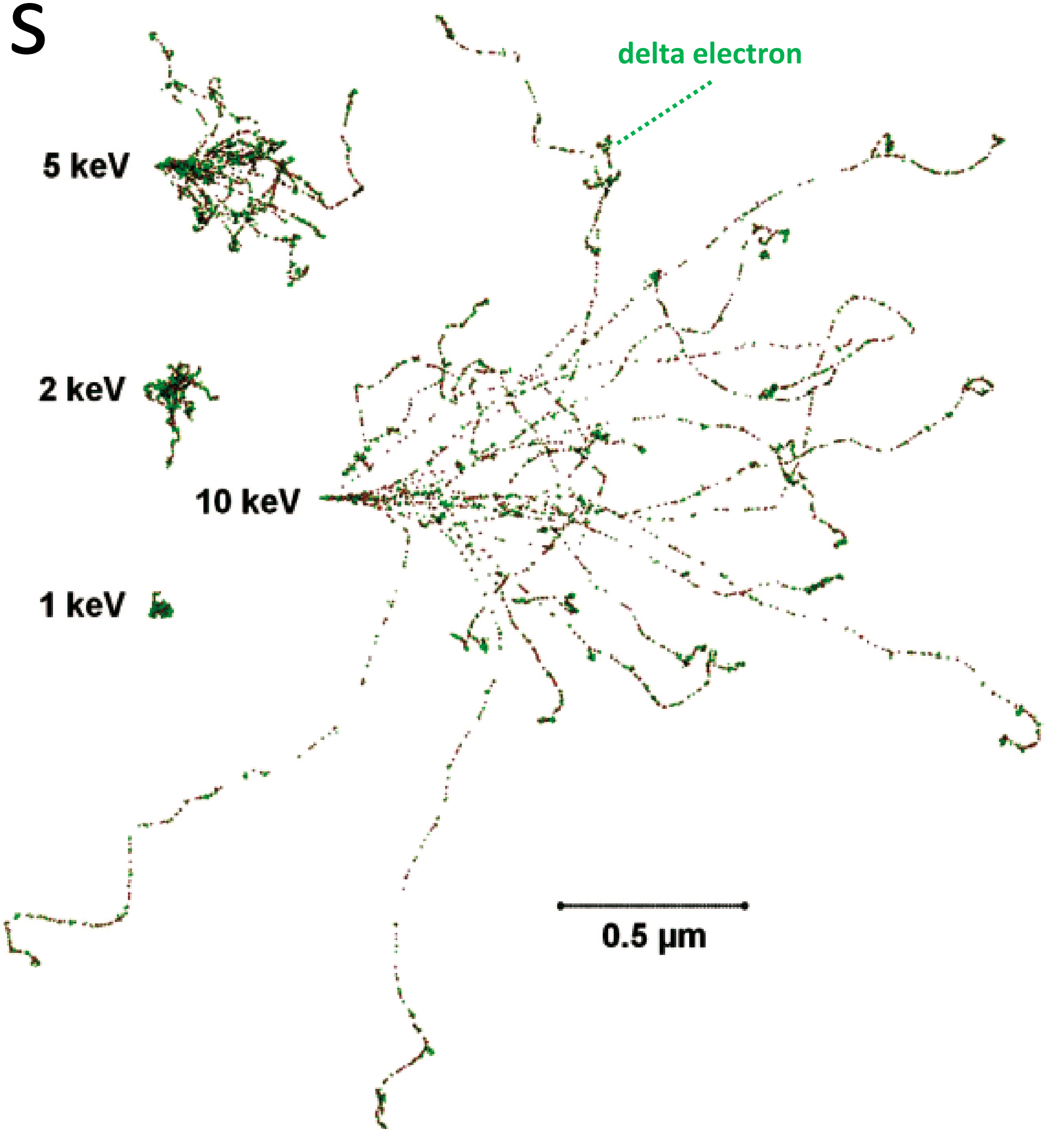
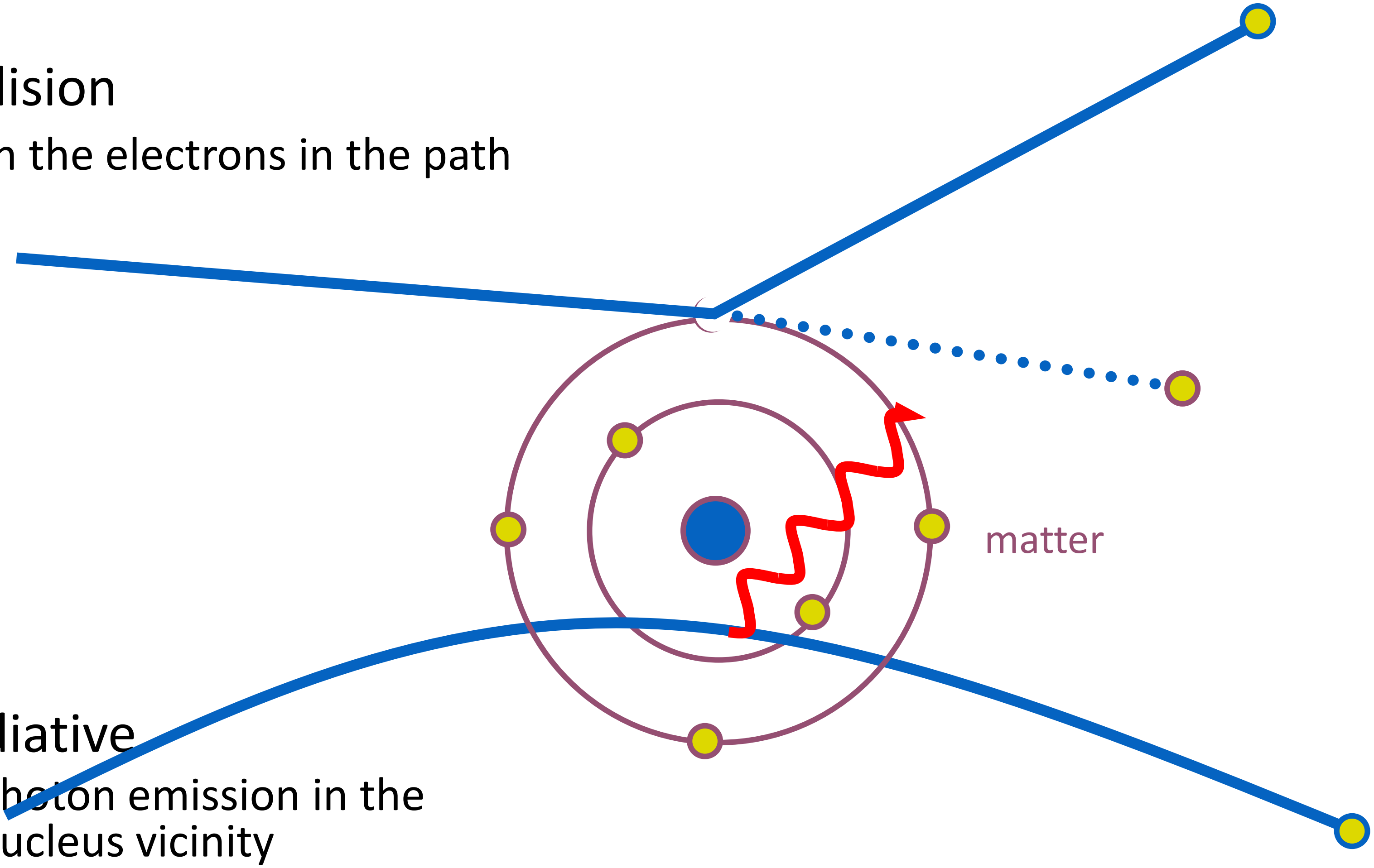


Figure 2.3. Twenty randomly generated electron tracks for initial kinetic energies of 1 keV, 2 keV, 5 keV, and 10 keV. Red points represent ionizations, and green points represent excitations. All tracks of the same energy start at the same point and initially proceed in the same direction (left to right in the figure).

ICRU-86

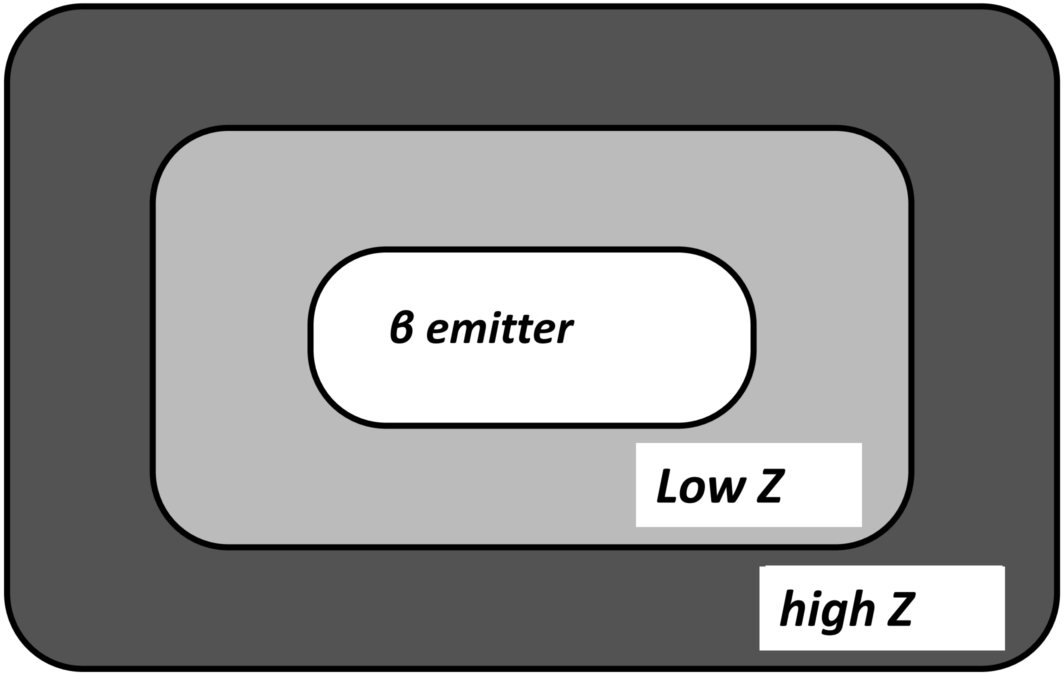
Electron slowing down

1. Collision
   - with the electrons in the path



2. Radiative
   - photon emission in the nucleus vicinity (bremsstrahlung)

Protection against beta radiation



β emitter

Low Z

high Z

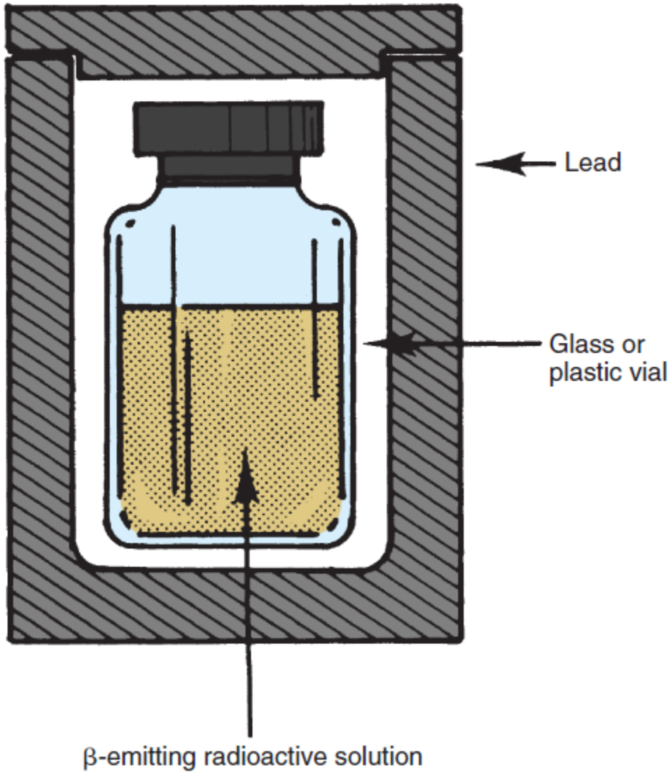
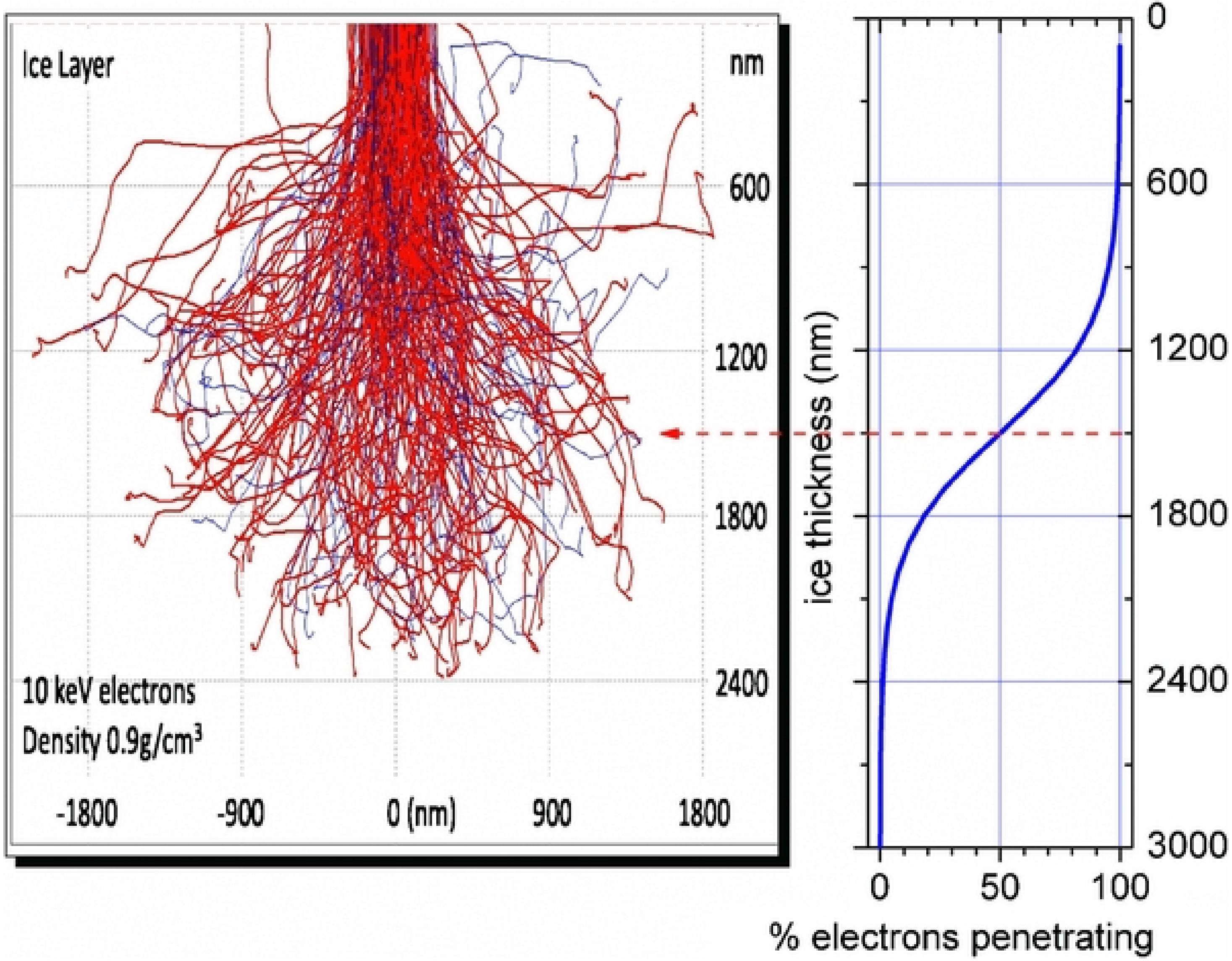


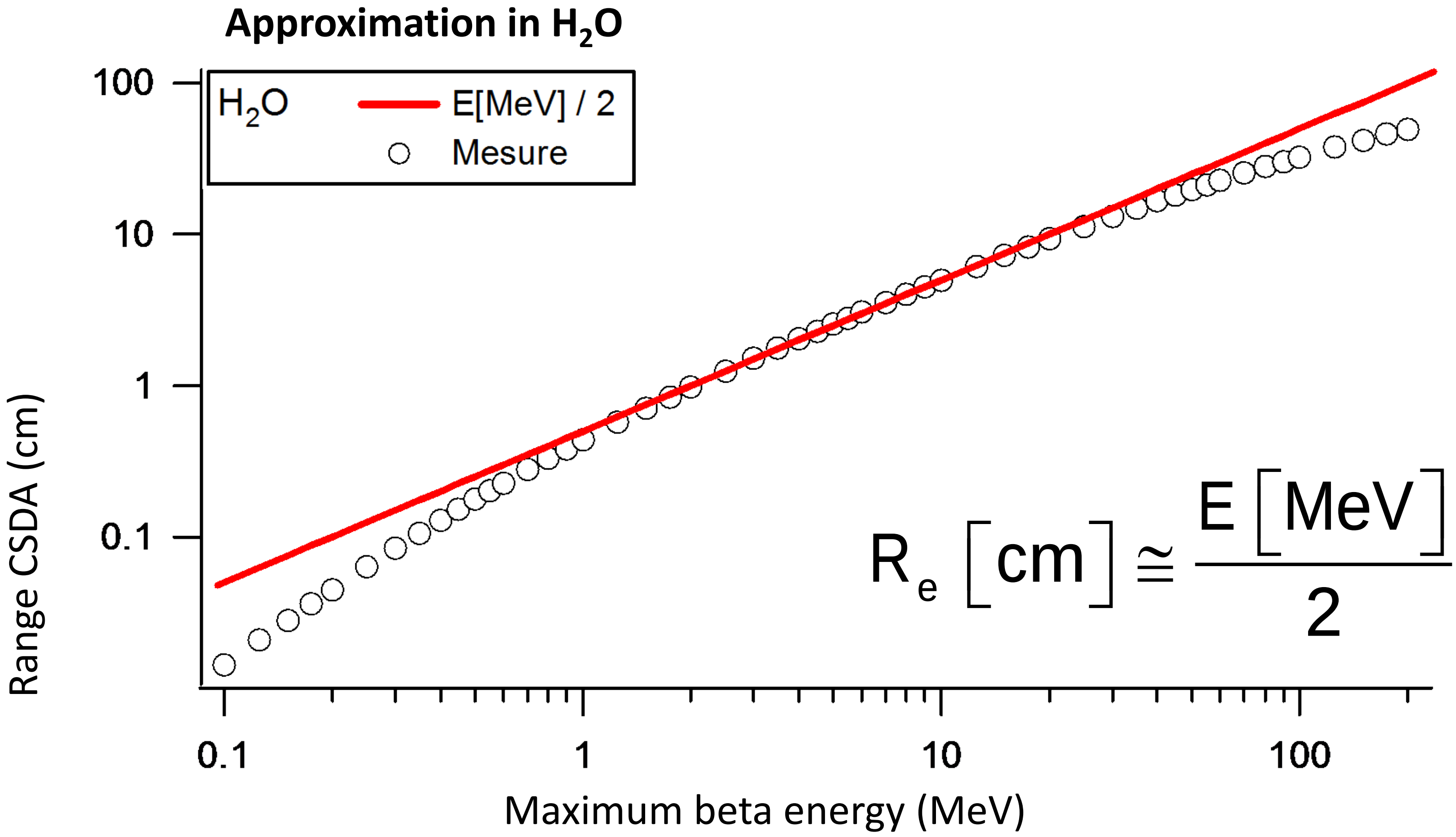
FIGURE 6-3 Preferred arrangement for shielding energetic β-emitting radioactive solution. Glass or plastic walls of a vial stop the β particles with minimum bremsstrahlung production, and a lead container absorbs the few bremsstrahlung photons produced.

Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012



The Astrophysical Journal 747(1), 13 (2012)
doi:10.1088/0004-637X/747/1/13

Electrons range



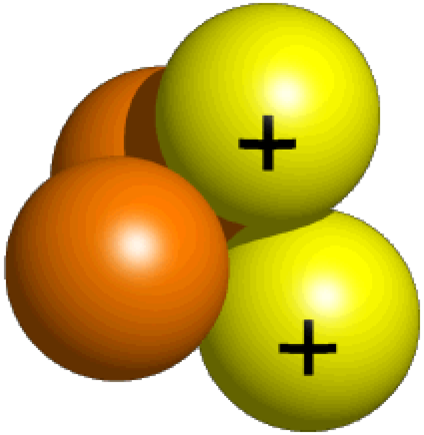
Approximation in H_2O

$$R_e\left[\text{cm}\right] \cong \frac{E\left[\text{MeV}\right]}{2}$$

Exercise: Electron range in matter

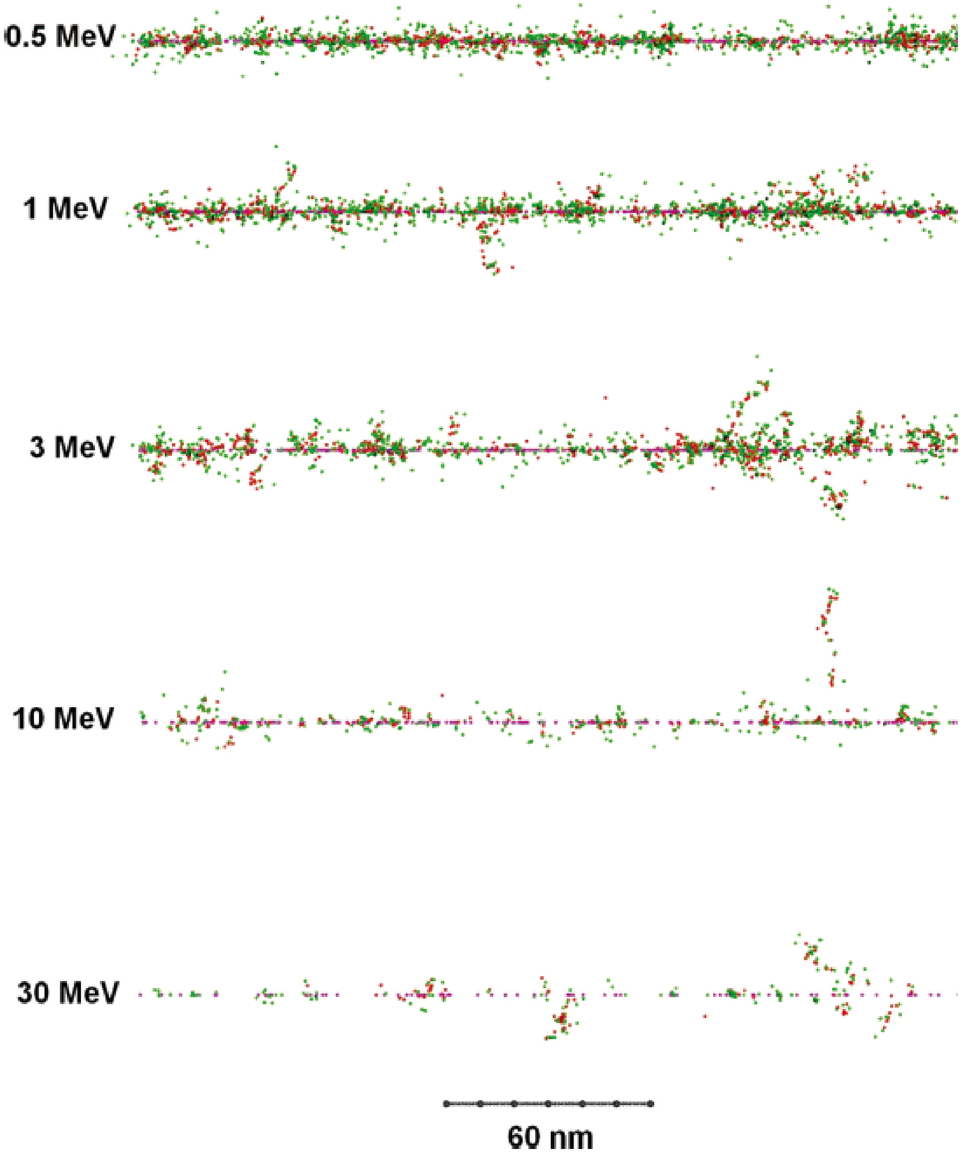
What is the maximum range of the electrons emitted by P-32 in tissue?
(E_{max} = 1.7 MeV)

$$R_e\left[\text{cm}\right] \cong \frac{E\left[\text{MeV}\right]}{2} \approx 0.9\ \text{cm}$$



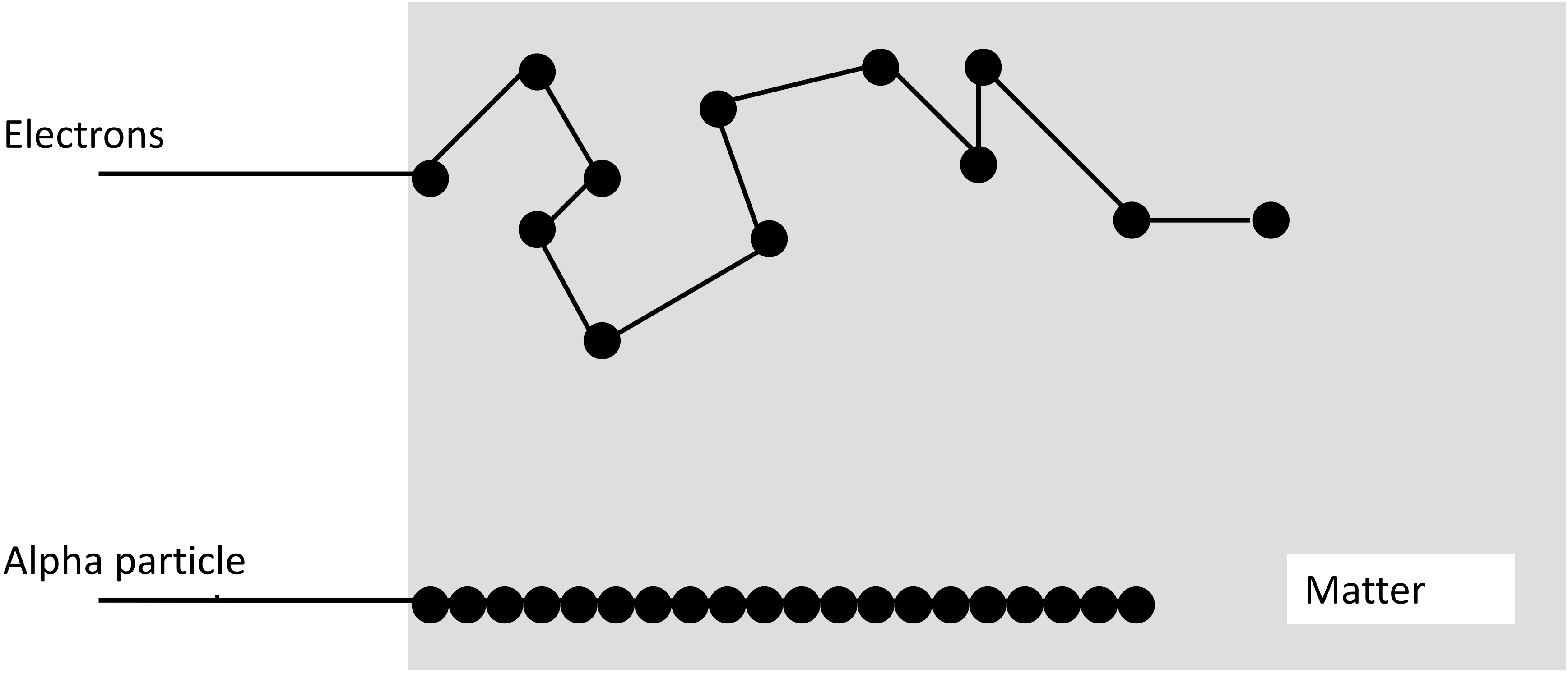
Heavy charged particles (protons ou alpha)

Alphas



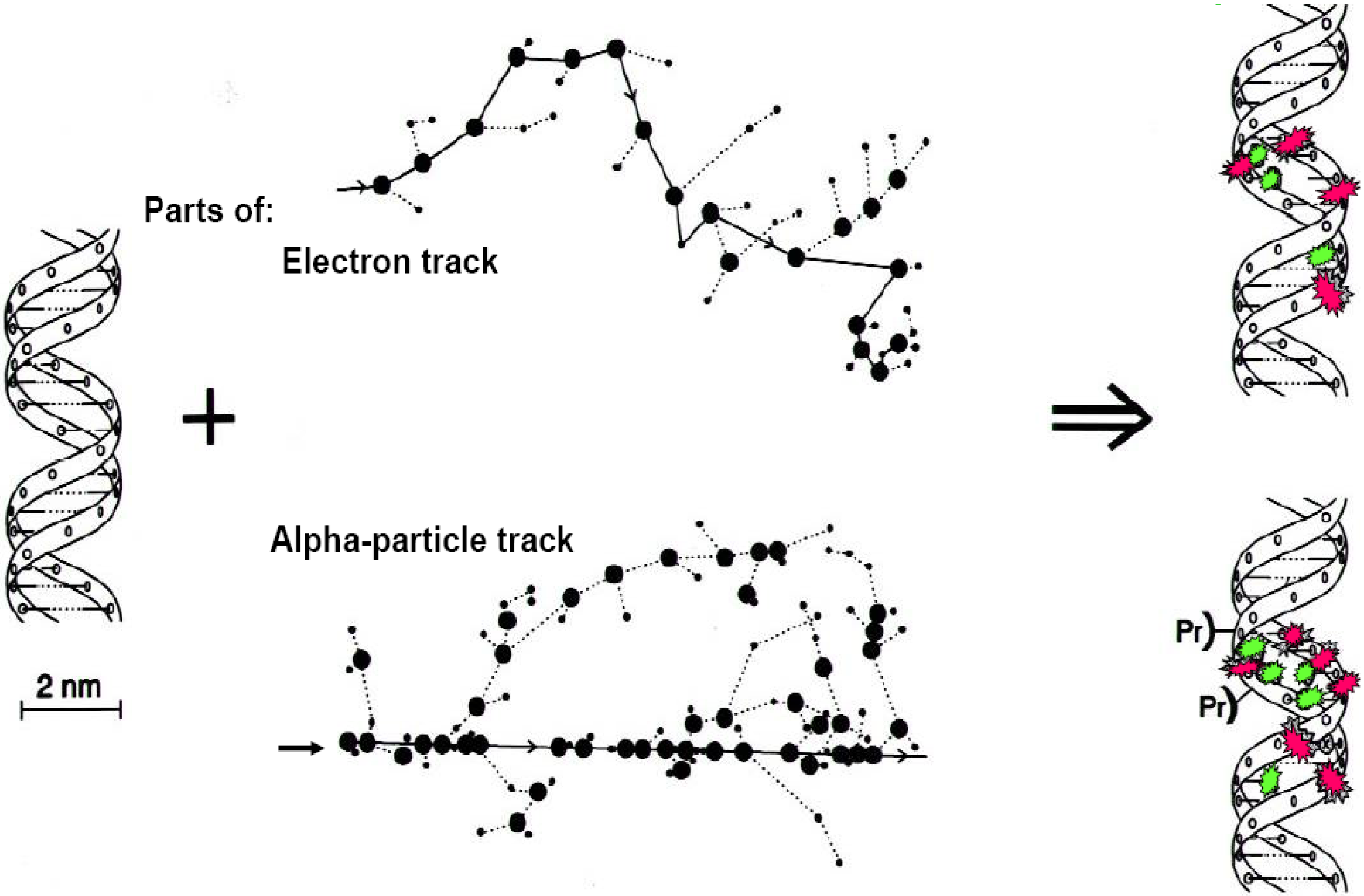
ICRU 86

Figure 2.5. Calculated 230 nm track segments for 0.5 MeV, 1 MeV, 3 MeV, 10 MeV, and 30 MeV alpha particles in water. Red points represent ionizations, and green points represent excitations.



Linear trajectory
More energy lost per unit of distance

Type of radiations



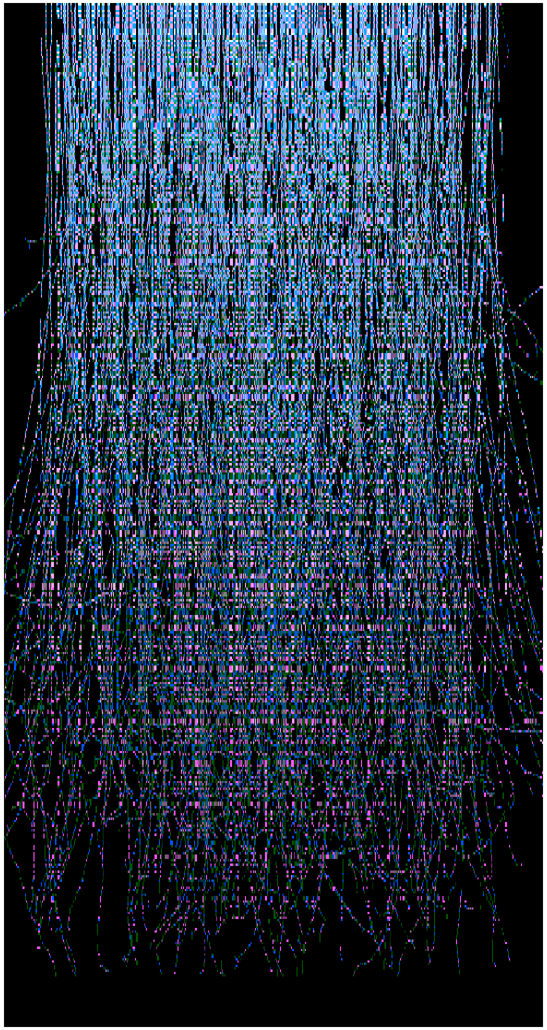
⇒ RadioBiology and Effects on humans

Heavy charged particles

- Protection
  - Easily protected from alpha
    - paper or gloves

  - Range of 5 MeV alpha in soft tissue is about 0.03 mm (about 10 cells)

  - When direct contact → Important effects
    - Must avoid ingestion!



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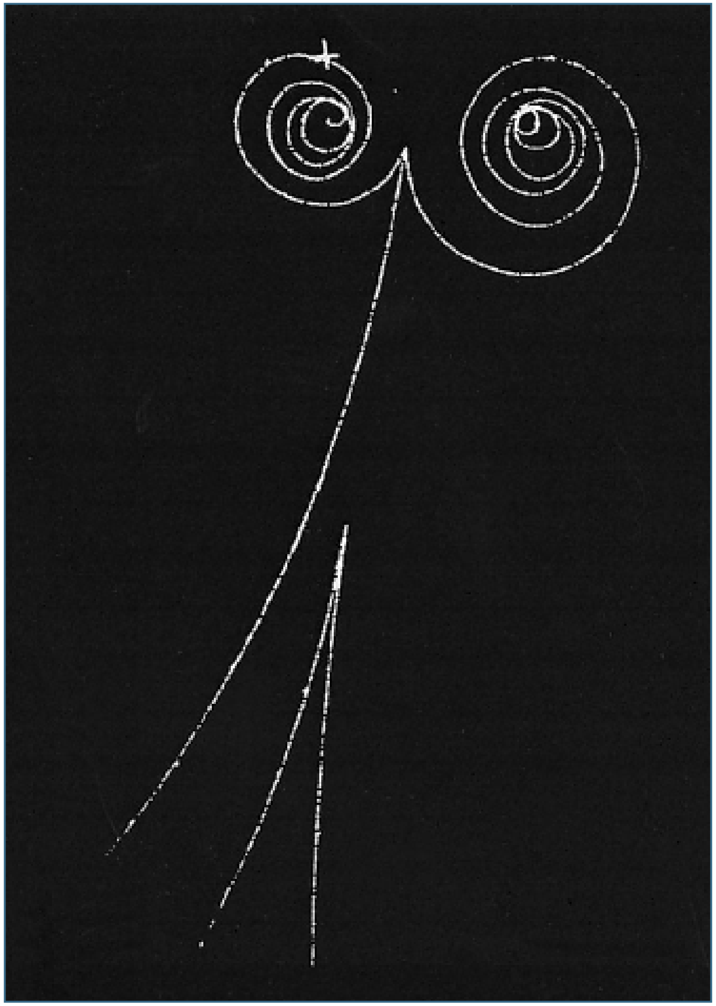
Basis of radiation physics

Interactions of photons with matter



Photons interactions with matter

Photoelectric effect

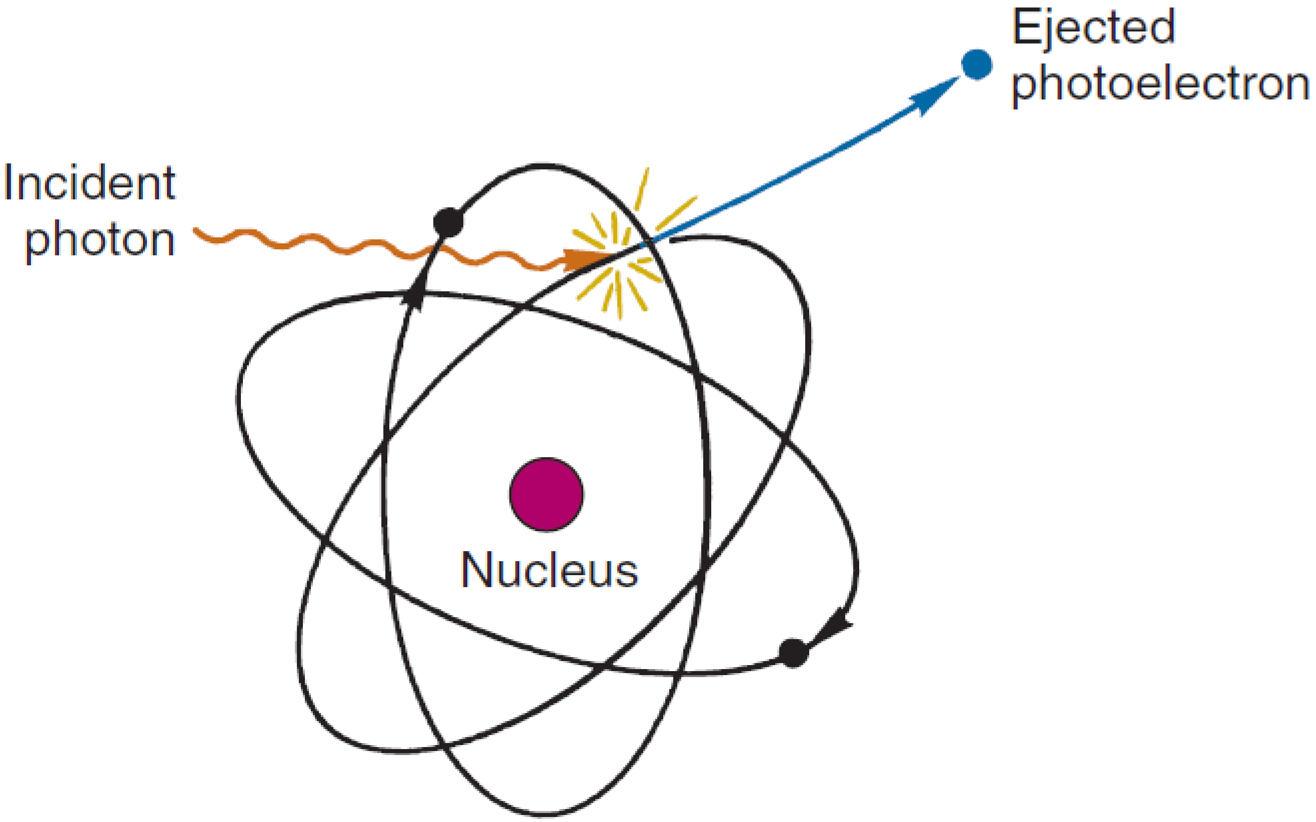
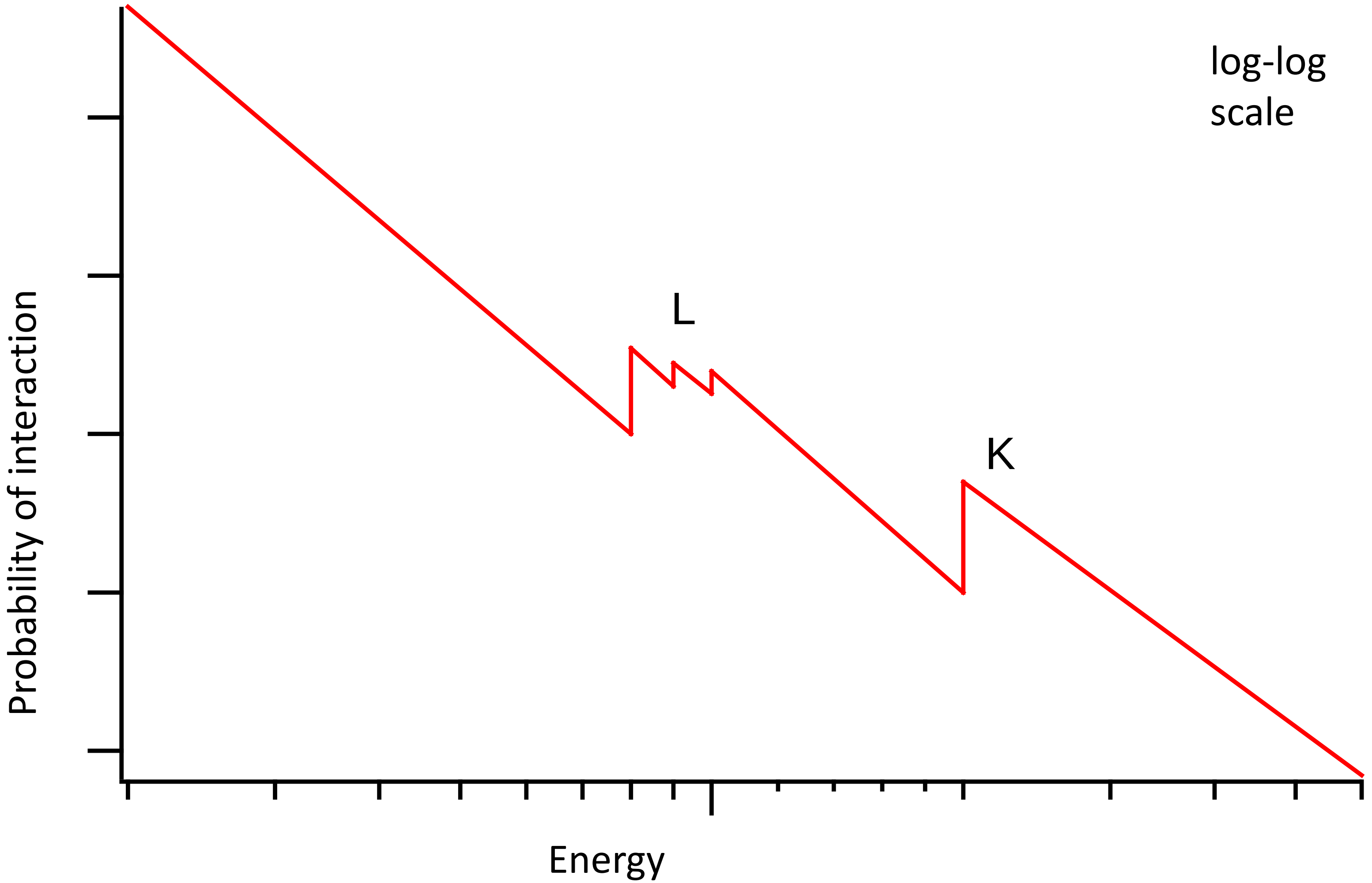


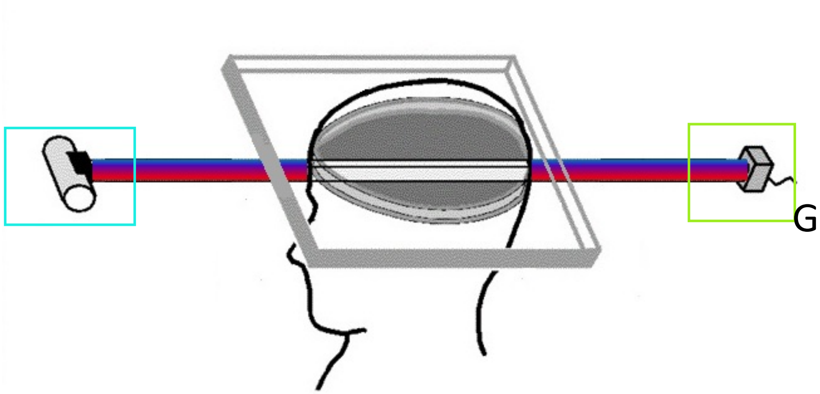
FIGURE 6-11 Schematic representation of the photoelectric effect. The incident photon transfers its energy to a photoelectron and disappears.

Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Photoelectric effect

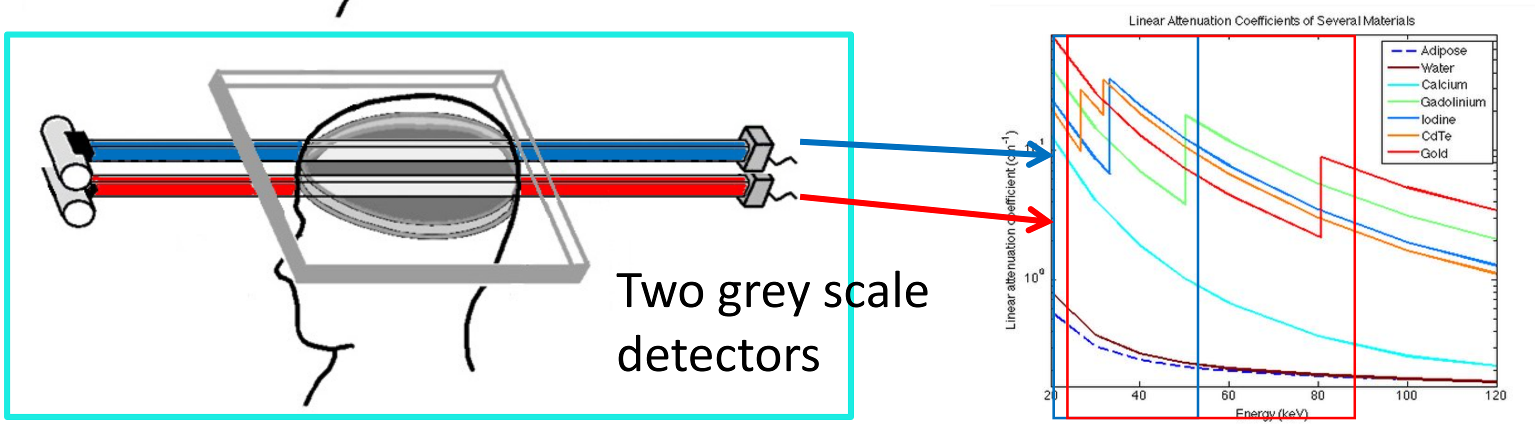


Single energy CT



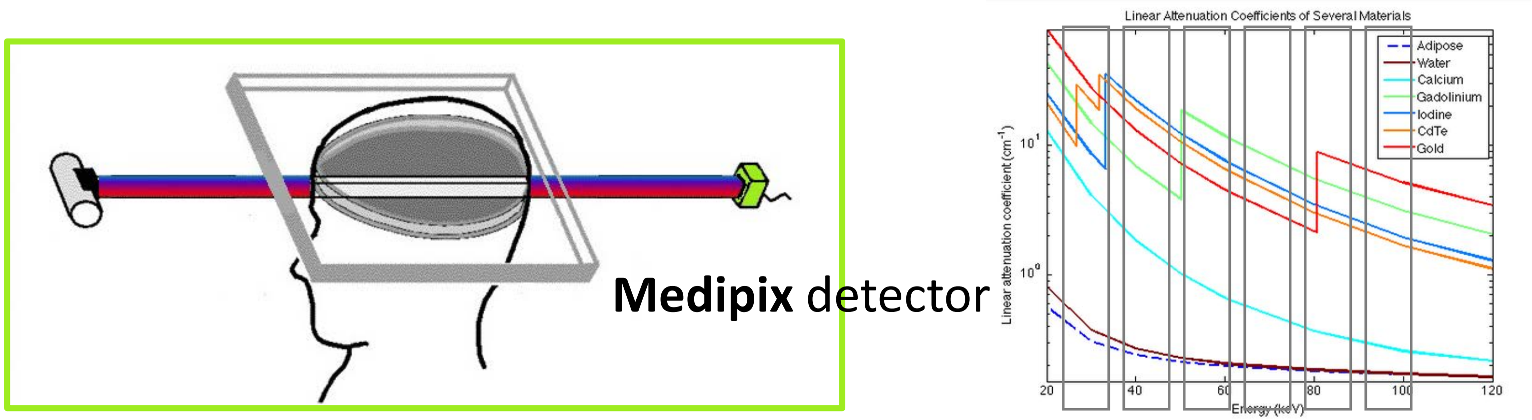
Grey scale detector

Dual energy CT



Two grey scale detectors

MARS spectral CT



Medipix detector

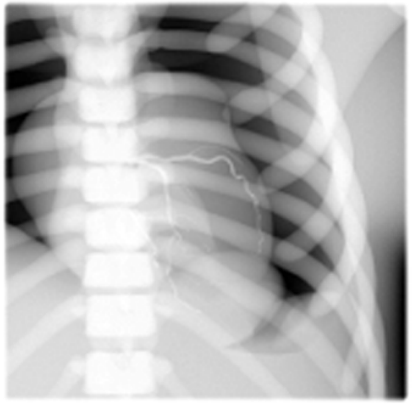
Photoelectric effect

- Important at high Z

- Important at low energies

- Jumps at electron binding energies
  - resonance phenomenon

- Fundamental effect for
  - Radiography
  - Lead shielding



Compton effect

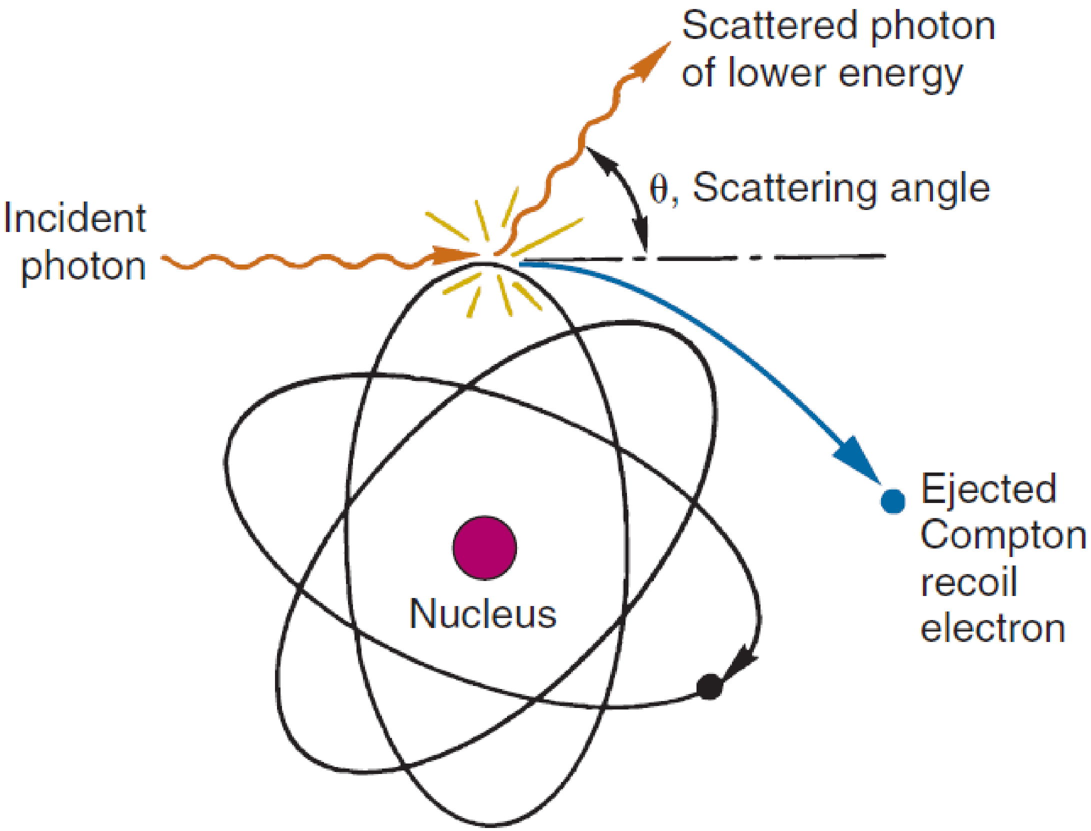
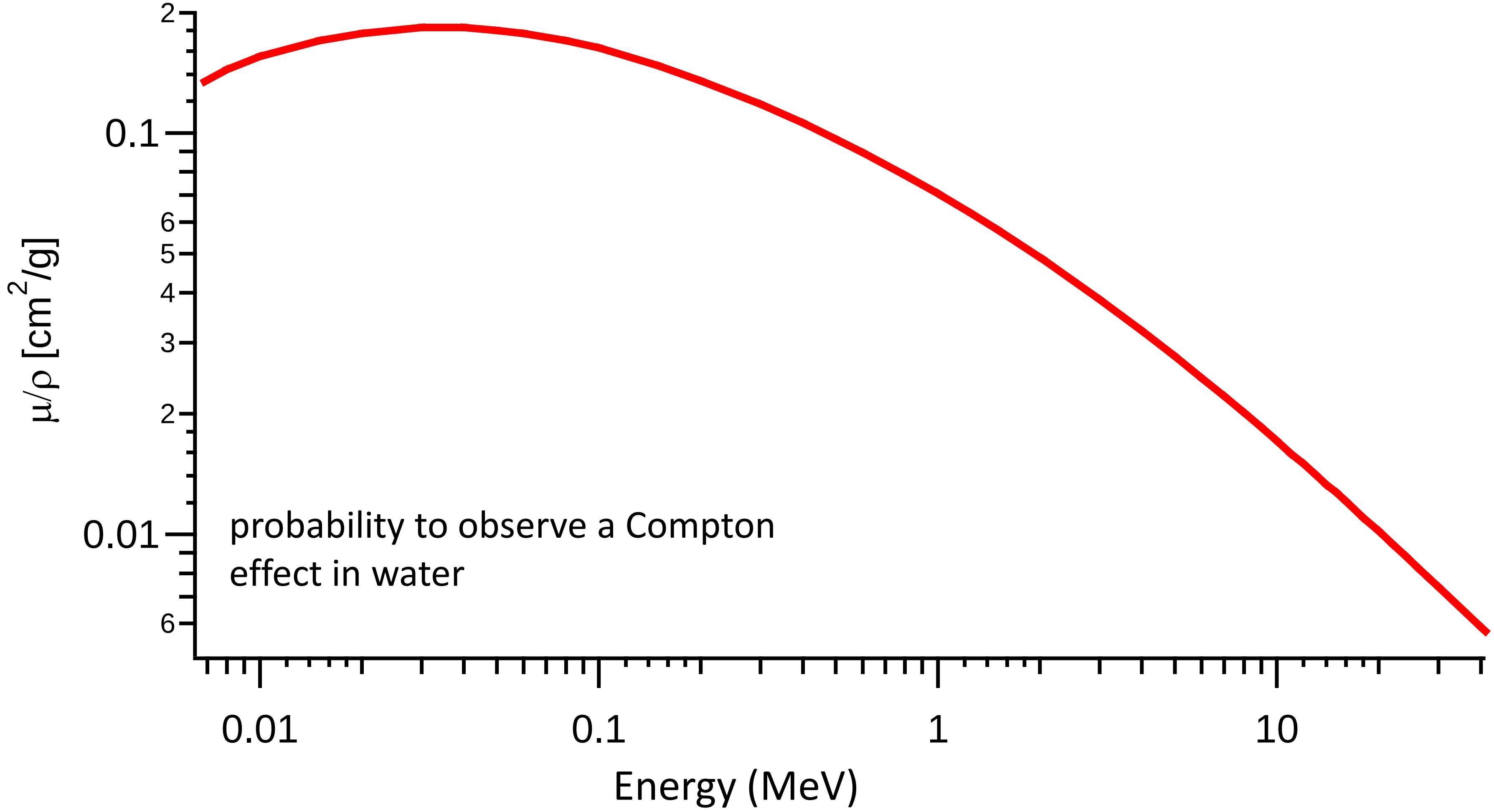


FIGURE 6-12 Schematic representation of Compton scattering. The incident photon transfers part of its energy to a Compton recoil electron and is scattered in another direction of travel (θ, scattering angle).

Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Compton effect



probability to observe a Compton effect in water

Compton effect

- Independent of Z
  - Depends on the number of electrons in matter (much less on how they are grouped within the atoms)
- Dominant medium energy
- Tend to diminish with energy
- At high energy
  - Particles tend to be projected forward

Pair production

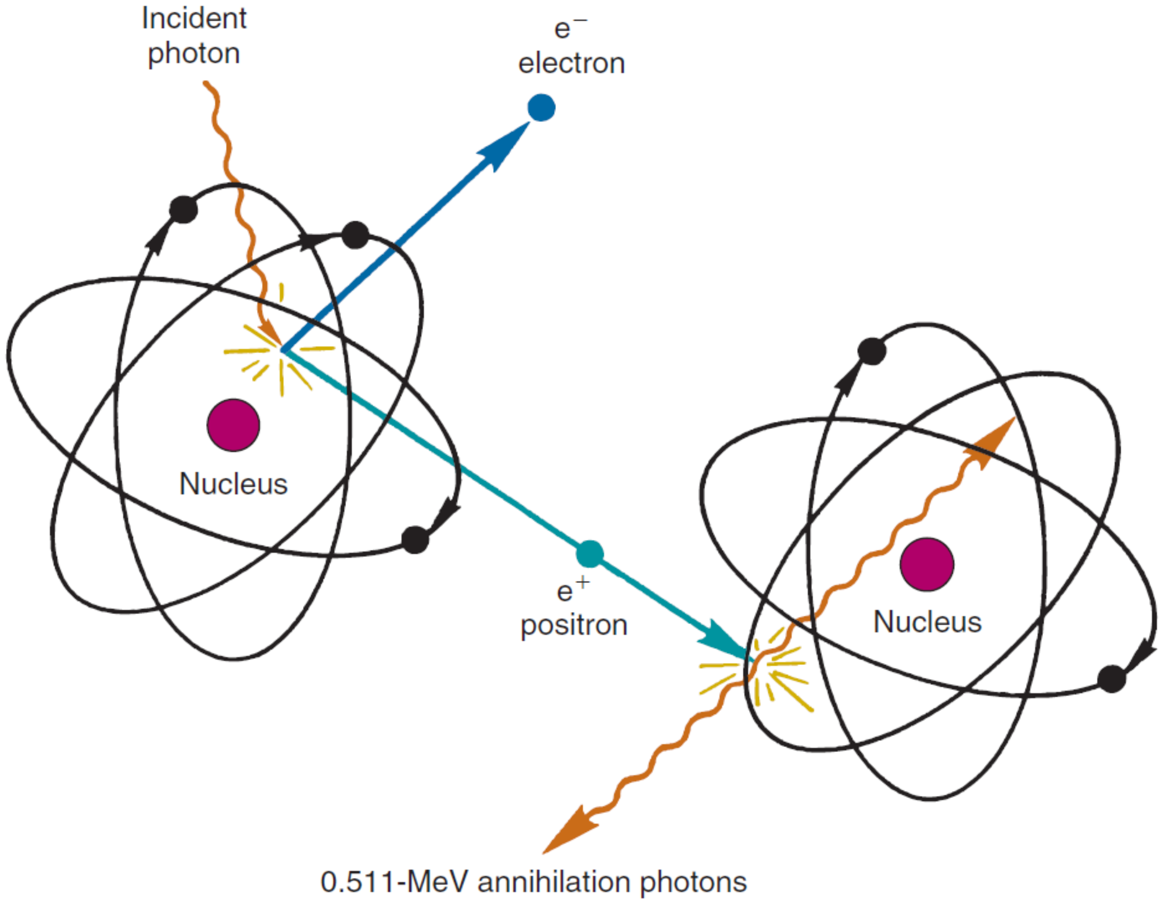
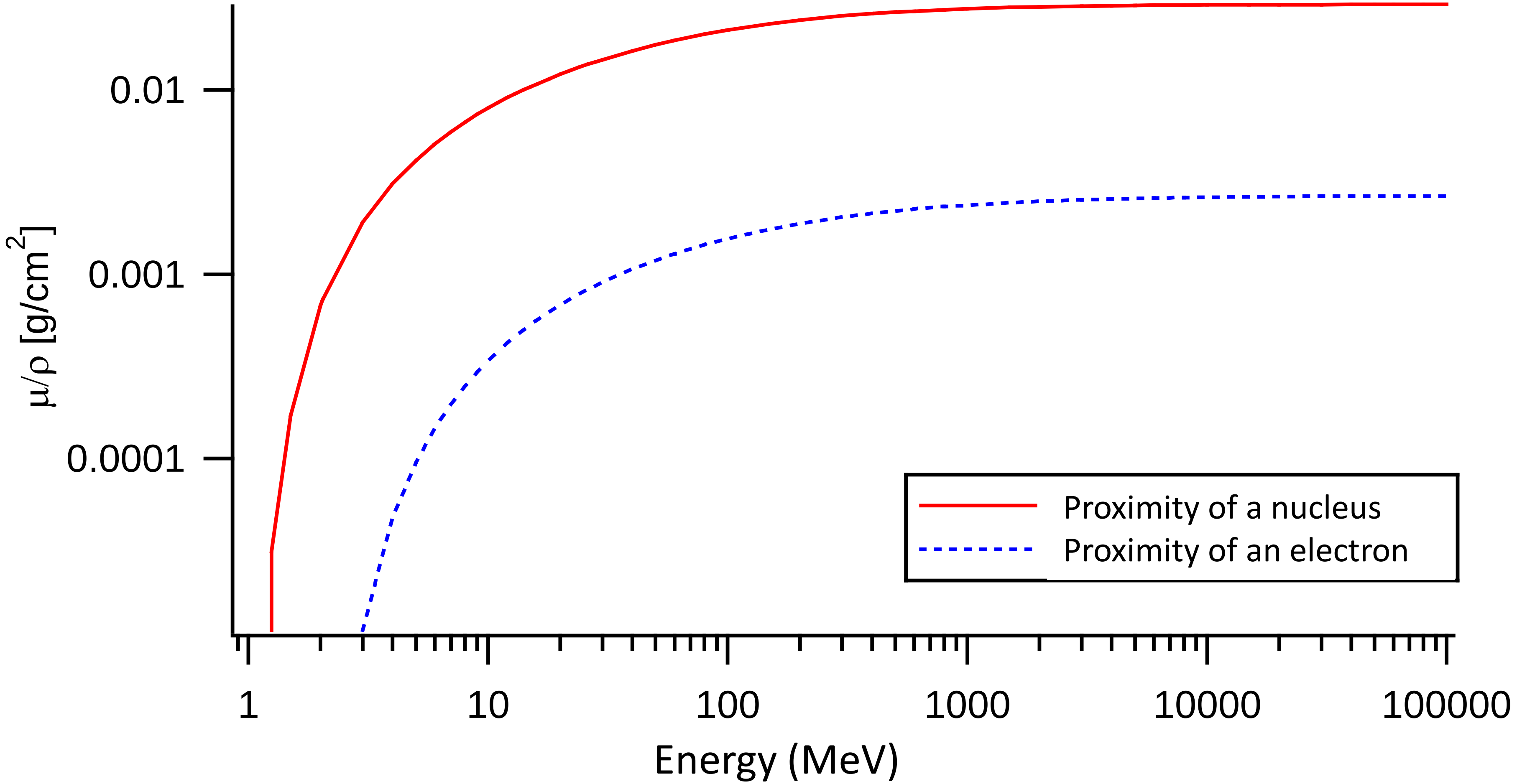


FIGURE 6-14 Schematic representation of pair production. Energy of incident photon is converted into an electron and a positron (total 1.022-MeV mass-energy equivalent) plus their kinetic energy. The positron eventually undergoes mutual annihilation with a different electron, producing two 0.511-MeV annihilation photons.

Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Pair production



Probability to produce an electron/positron pair in aluminum

Pair production

- Threshold: E_{gamma} = 1.022 MeV
  - 2 x 0.511 MeV
- Important at high Z ($\sim Z^2$)
- Important at high energies
- Annihilation of positron

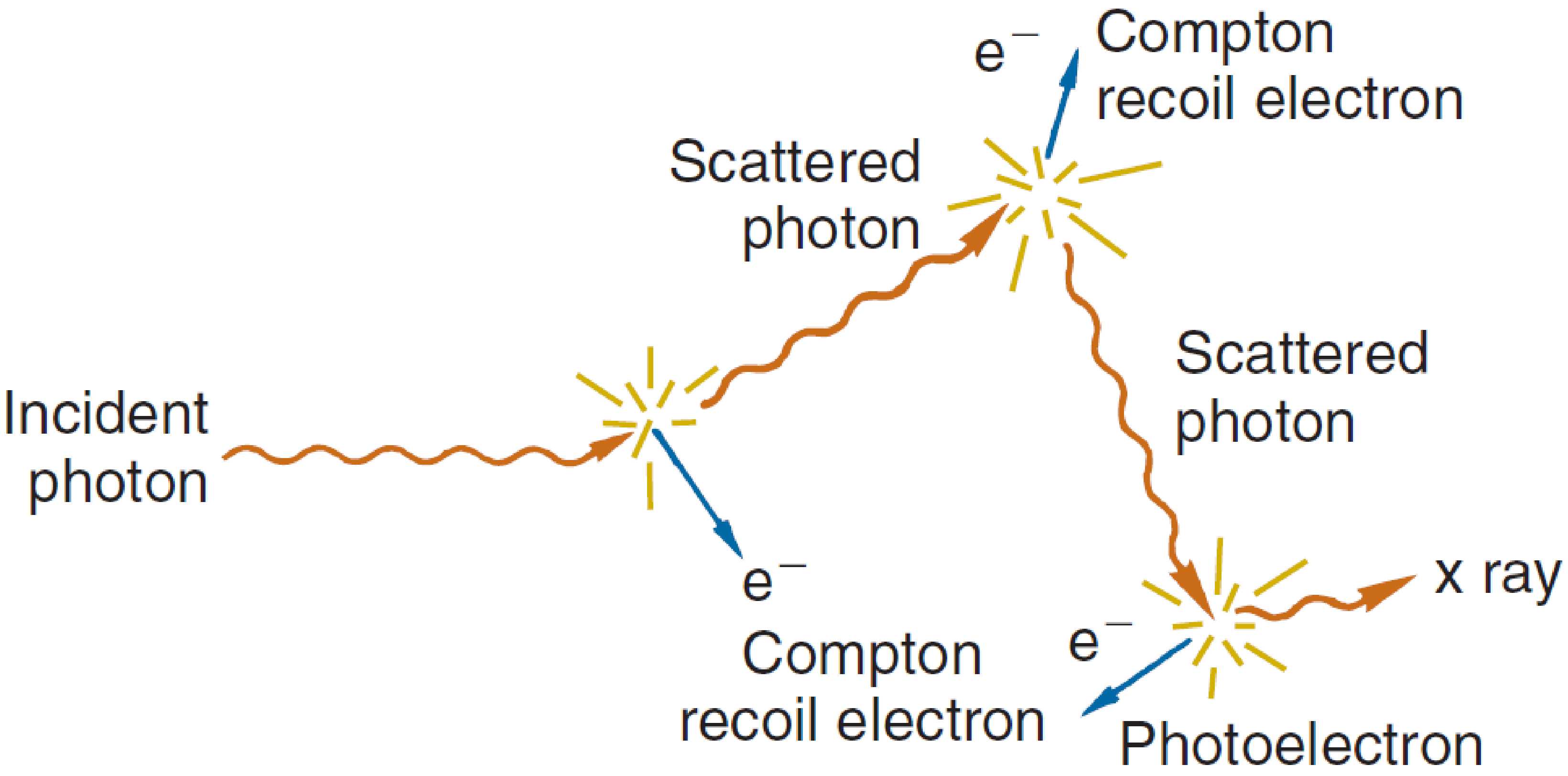
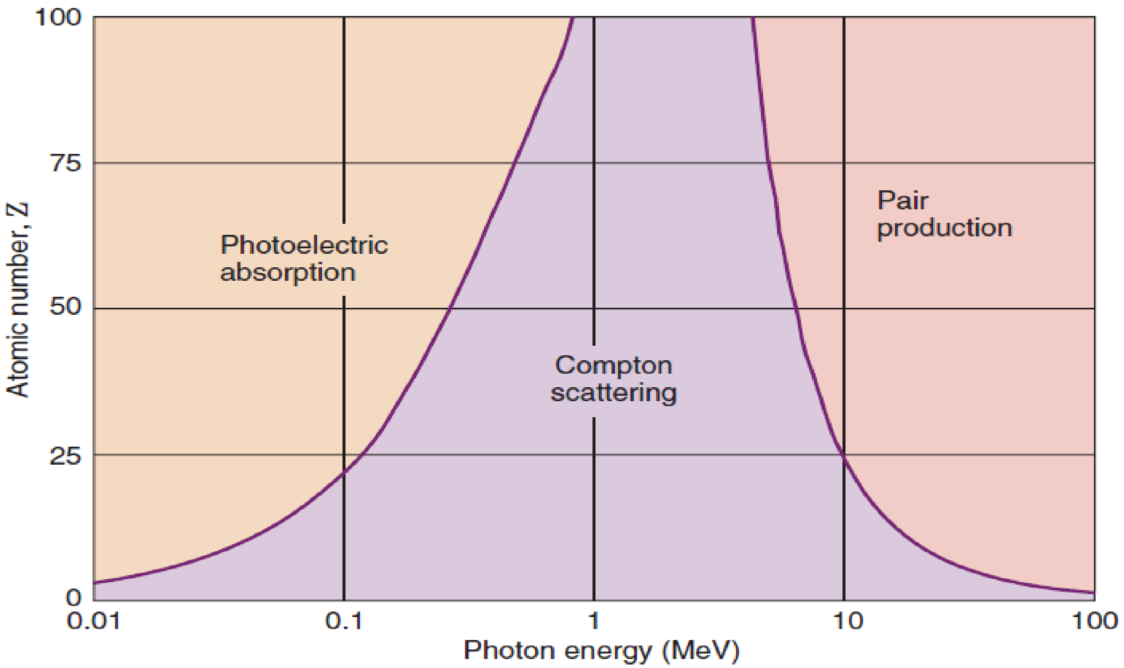
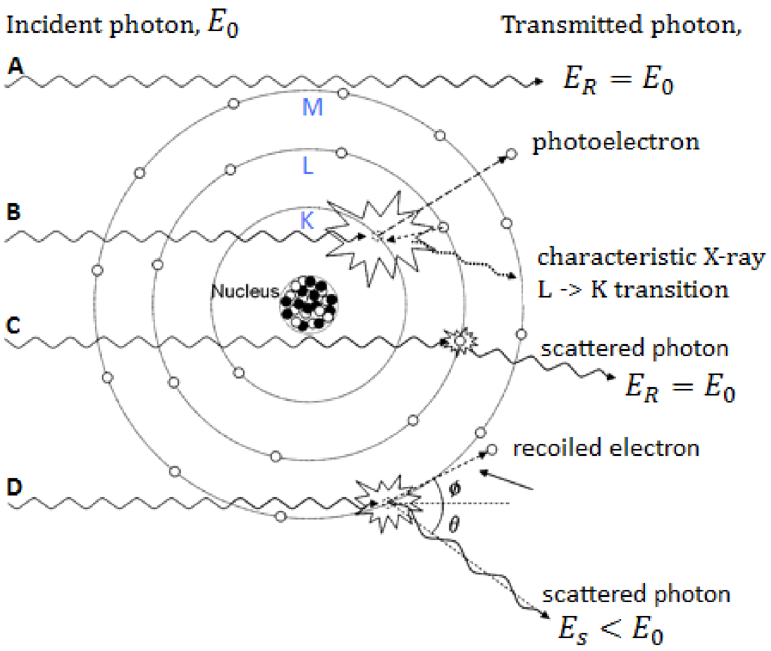


FIGURE 6-15 Multiple interactions of a photon passing through matter. Energy is transferred to electrons in a sequence of photon-energy degrading interactions.

Cherry, Sorenson, Phelps, Physics in Nuclear Medicine, Sauders Elsevir, 2012

Photons





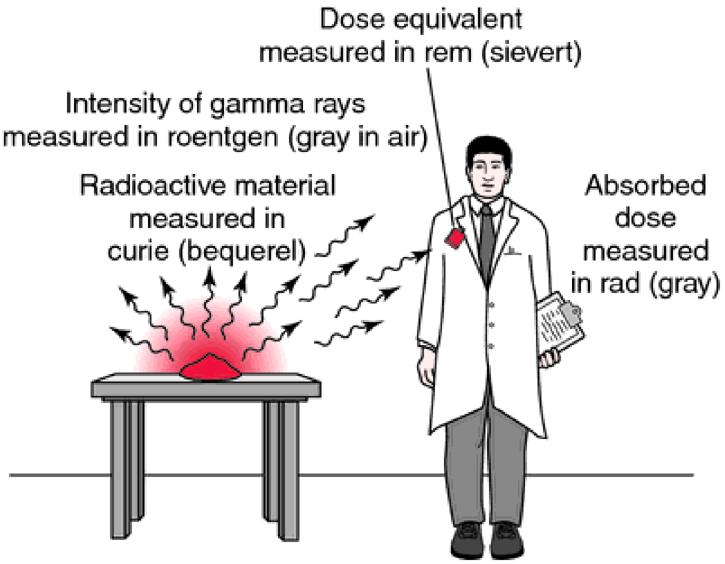
A. TRANSMITTED UNAFFECTED
No interaction

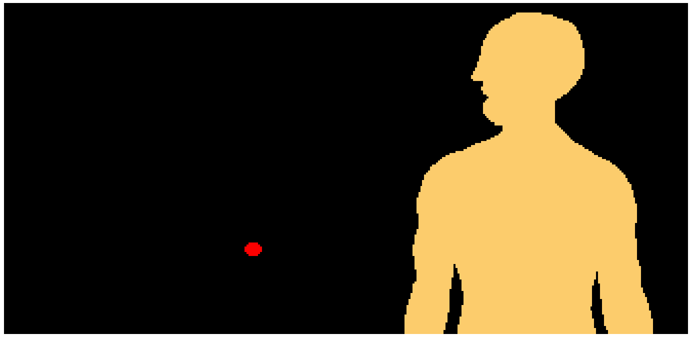
B. PHOTOELECTRIC ABSORPTION
Collision with a tightly bound inner-shell electron

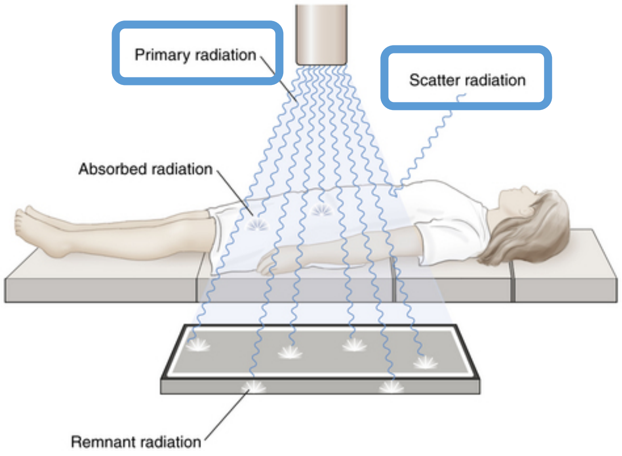
C. RAYLEIGH SCATTERING
Elastic collision with a bound outer-shell electron

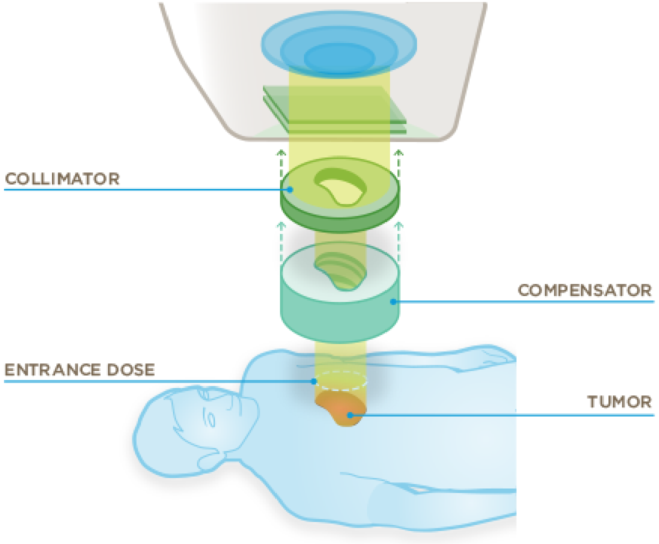
D. COMPTON SCATTERING
Inelastic collision with weakly bound outer-shell electron

Primary

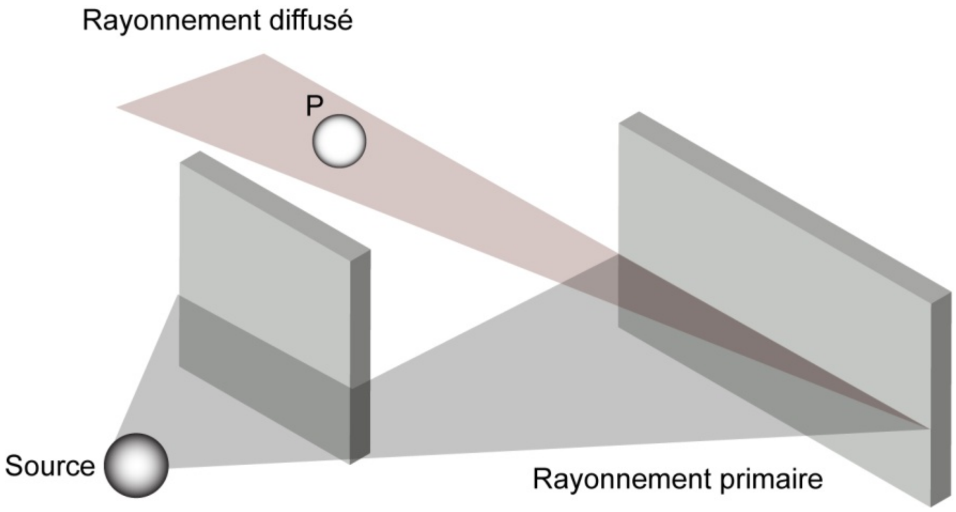

Dose equivalent
measured in rem (sievert)
Intensity of gamma rays
measured in roentgen (gray in air)
Radioactive material
measured in
curie (bequerel)
Absorbed
dose
measured
in rad (gray)




Primary radiation
Scatter radiation
Absorbed radiation
Remnant radiation

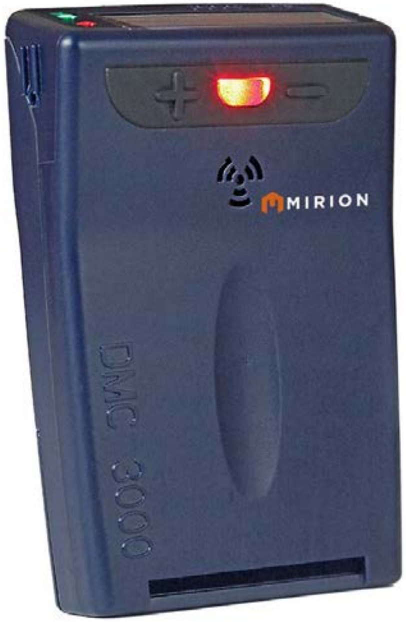

COLLIMATOR
COMPENSATOR
ENTRANCE DOSE
TUMOR

Scattered radiation



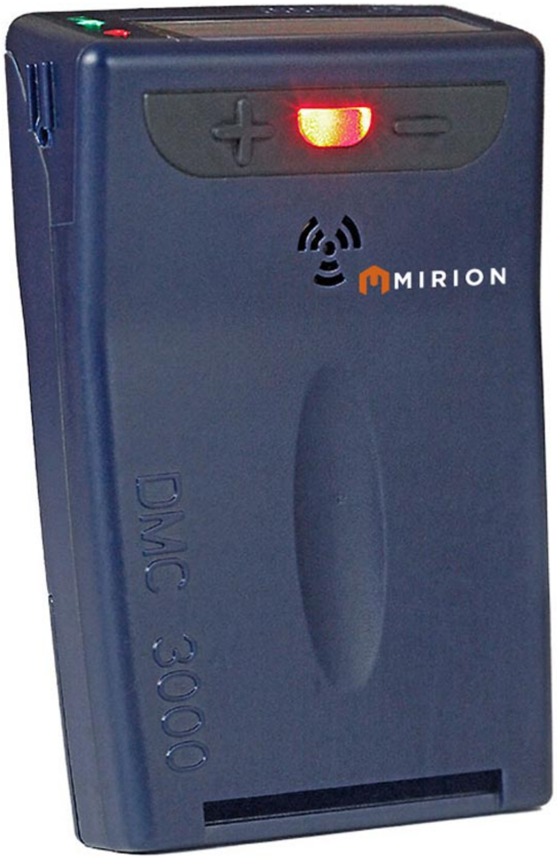
Objectives

- Become familiar with radiation physics
- Understand the main concepts:
  - Radioactivity and different types of decay
  - Interaction of radiation with matter



Introduction to Dosimetry

What’s dosimetry?



Absorbed dose

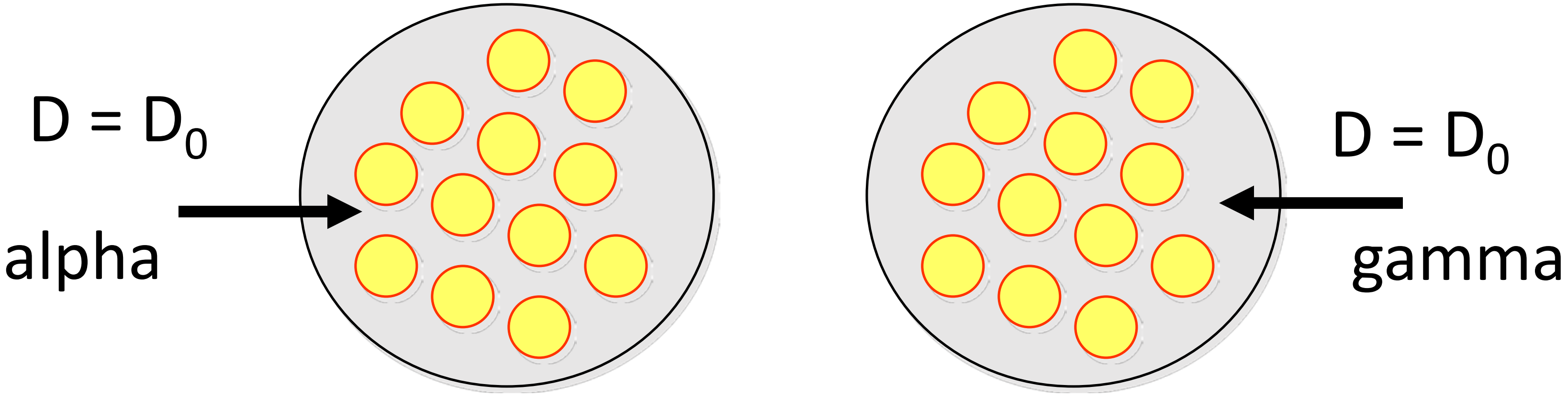
$$\boxed{D = \frac{d\overline{\varepsilon}}{dm} \quad \left[J \cdot kg^{-1}\right] = [Gy]}$$

Absorbed energy
per mass unit

Main effect : heat
2 Gy in water → about 0.5 mK

Absorbed dose and biological effects

- The absorbed dose is not always directly related to the biological risks



$D = D_0$

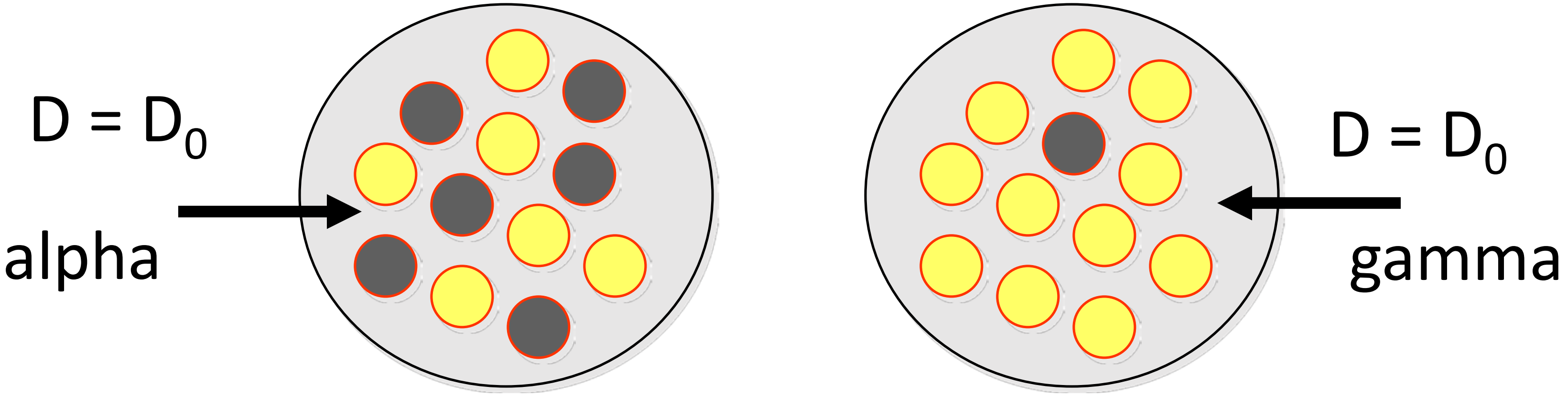
alpha

$D = D_0$

gamma

Absorbed dose and biological effects

- The absorbed dose is not always directly related to the biological risks



D = D_0

alpha

D = D_0

gamma

Biological effects are different

Equivalent dose

$$\mathrm{H} = \sum_{\mathrm{R}} \mathrm{w}_{\mathrm{R}}\, \mathrm{D}_{\mathrm{R}} \qquad \left[\mathrm{J} \cdot \mathrm{kg}^{-1}\right] = [\mathrm{Sv}]$$

Radiation type

Radiation weighting factor

Absorbed dose delivered to target organ

Dose weighted by a biological factor

Radiation weighting factor w_R

Radiation type	W_R
X-ray, γ, electrons	1
protons	5
neutrons	5-20
α-particules	20

Effective dose

- Synthetic dose indicator

$$E = \sum_{T} w_T H_T \quad [\mathrm{Sv}]$$

tissue weighting factor

Tissue or organ	w_T
Bone surface, skin	0.01
Bladder, breast, liver, oesophagus, thyroide, rest	0.05
Bone marrow, colon, lung, stomac	0.12
Gonads	0.20

Summary of dosimetric quantities

- KERMA **K**
  - Photon kinetic energy released per unit of mass
    - unit: gray, 1 Gy = 1 J/kg
- Absorbed dose **D**
  - Energy deposited per unit of mass
    - unit: gray, 1 Gy = 1 J/kg
- Equivalent dose **H**
  - Mean absorbed dose weighted by radiation-specific factor (w_R)
    - unit: sievert, 1 Sv = 1 J/kg
- Effective dose **E**
  - Sum of the organ equivalent doses weighted by organ-specific factors (w_T)
    - unit : sievert

Physics

Biology