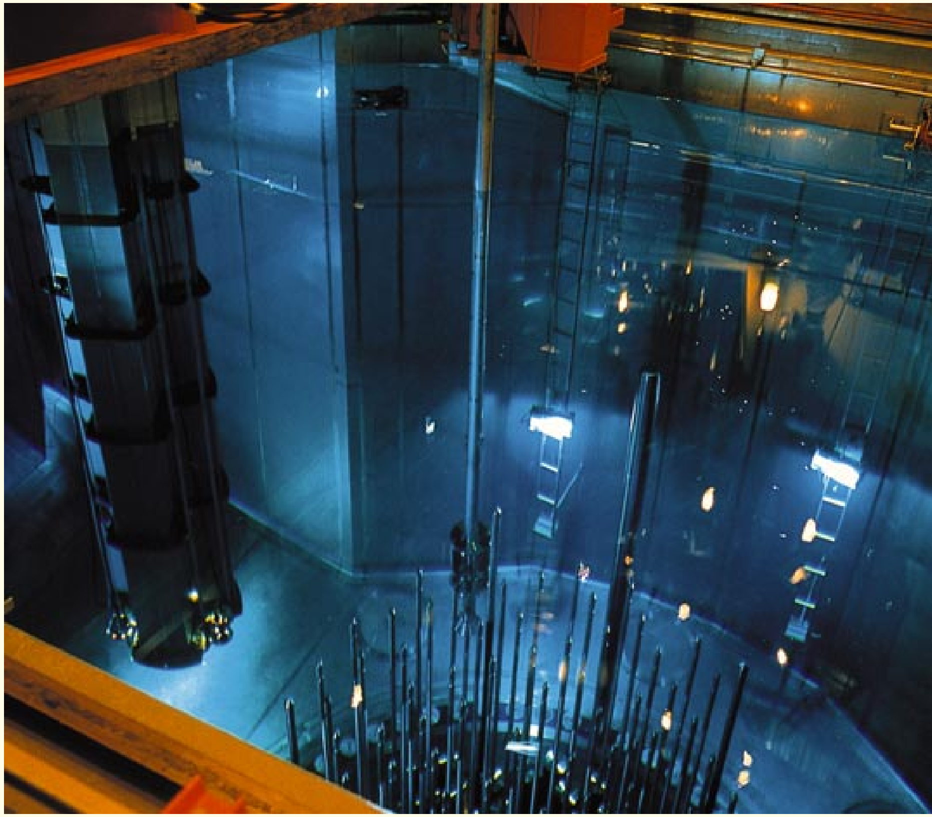
WILL THE NEUTRONS HELP SAVING THE CLIMATE ?



The fabulous destiny of the neutron

Gérard RUDOLF European Summer University Strasbourg July 4th 2009

In2p3

WHICH WORLD IN 2050 ?

In 2006, the population of the world was **6.5 Ghab**. The mean consumption of energy per habitant all over the world was **70 GJ/year**

70 GJ correspond to about 2 tons of fossil fuel, and to 5-6 tons of CO_2

In 2050, the population of the world is expected to rise to **9 Ghab**. The mean consumption of energy is expected to rise to **90 GJ/year**
(S. Bouneau, S. David, J-M. Loiseaux, O. Méplan)

If 80% of the energy is still produced by fossile fuel, the total production of CO_2 may rise from 29 Gt/year in 2006 to **52 Gt/year** in 2050. The maximum admissible if one wants to save the climate is **14 Gt/year !!!**

Energy / waste
Fossil / nuclear

1 chemical reaction generates a few eV
1 Uranium fission generates ~ 180 MeV
1 D+T fusion generates ~ 17.6 MeV

70 GJ correspond to :

- **Fossil** : 1.7 tons of oil, which produces 4.7 tons of CO_2, plus NO_2, SO_2 … (coal is worse)

- **Fission** : 1 g of ^{235}U (200 g Uranium), which produces 1 g of fission fragments, among which many are very short lived, plus Pu and minor actinides

- **Fusion** : 0.08 g of Deuterium, 0.12 g of Tritium and 0.26 g ^{6}Li (3.5 g of Lithium) and produces … ?

The Tremendous Power of the Neutrons

Neutrons may save the climate since they allow :

- fissionning heavy nuclei
- fusioning light nuclei
- transmuting nuclear waste

and also :

- producing elements heavier than Fe in stars
- finding oil fields (also water)

HOW ?

The interaction with nuclei: Mechanisms and Cross Sections

Because neutrons have no charge, they interact with all nuclei at any energy.

Different microscopic **reaction mechanisms** can occur:

- Elastic scattering
- Capture
- Fission
- (n,p), (n,α), … reactions
- (n,2n) reactions, etc …

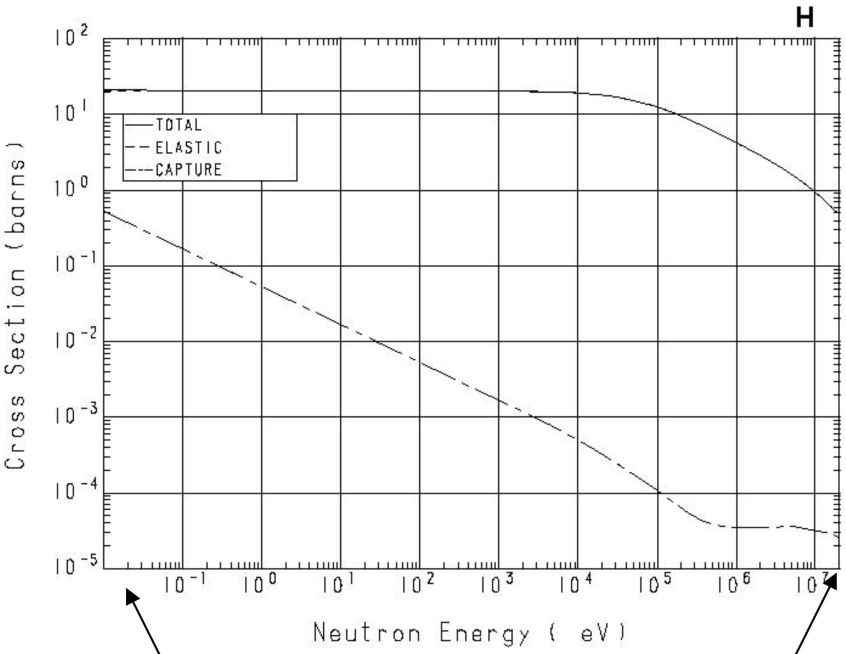
These mechanisms induce **macroscopic phenomena** :

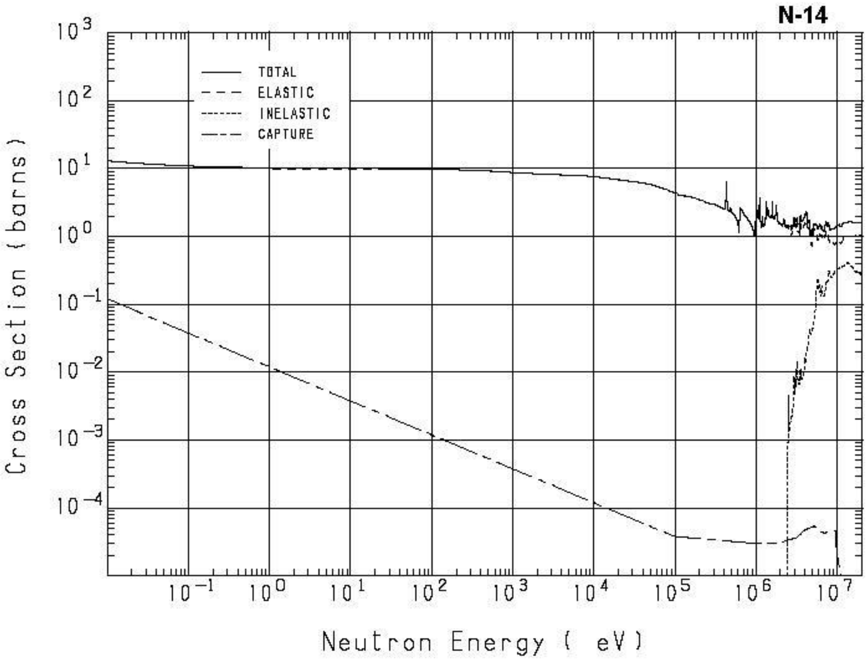
- Diffusion
- Multiplication
- Transmutation
- Moderation
- Energy production
- etc…

Each mechanism can occur with a given **probability**. This probability is measured by a **cross section** (effective surface).

If you want to understand the world you should understand neutron cross sections !!!

Simple cases



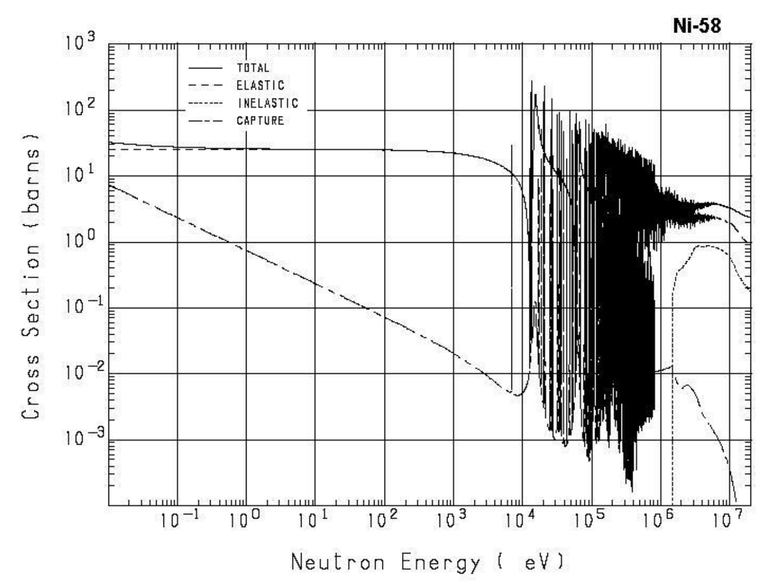


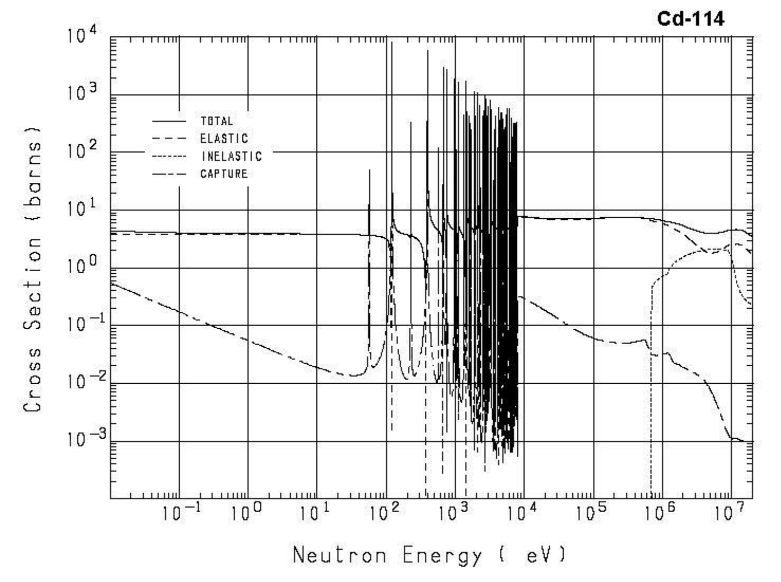
0.025 eV

20 MeV

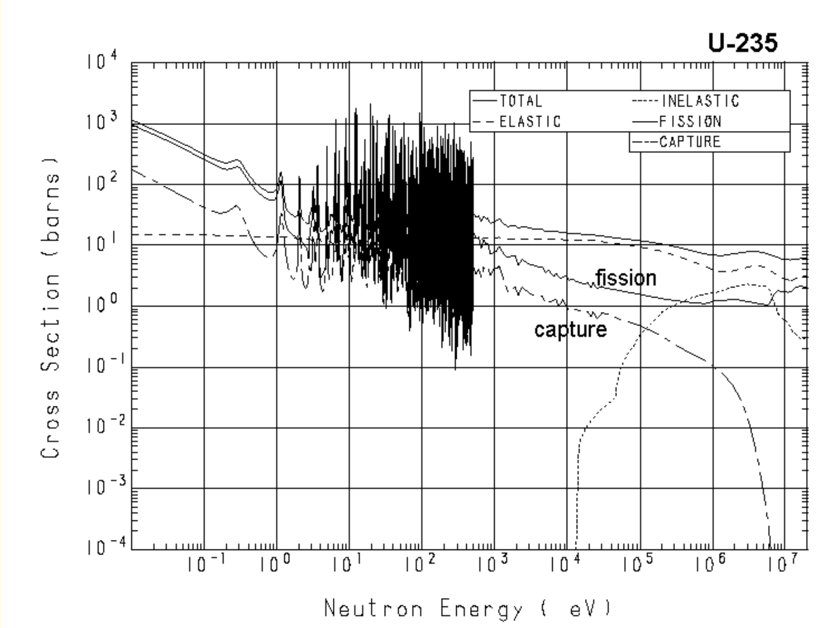
Data bases cover energies between
0.025 eV (the thermal energy) and 20 MeV
i.e. the limits of the neutron energy in a present day reactor

General cases





The cross sections may vary over
6 orders of magnitude within a few eV

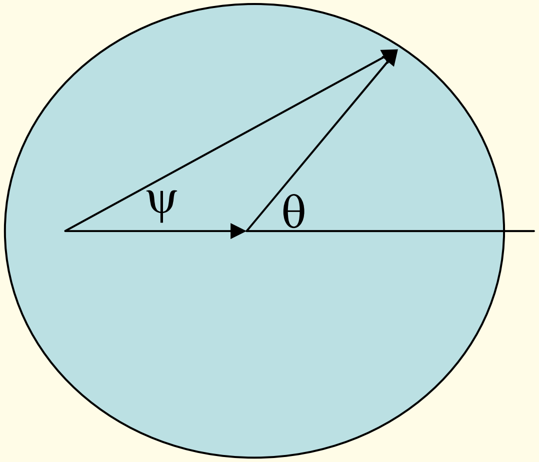


1) ELASTIC SCATTERING

n+ A ➞ n + A

The nucleus is scattered by a nucleus with atomic mass A

The diffusion angle in the C.M. is θ



The energies in the lab system before and after the collision are E_0 et E_1 :

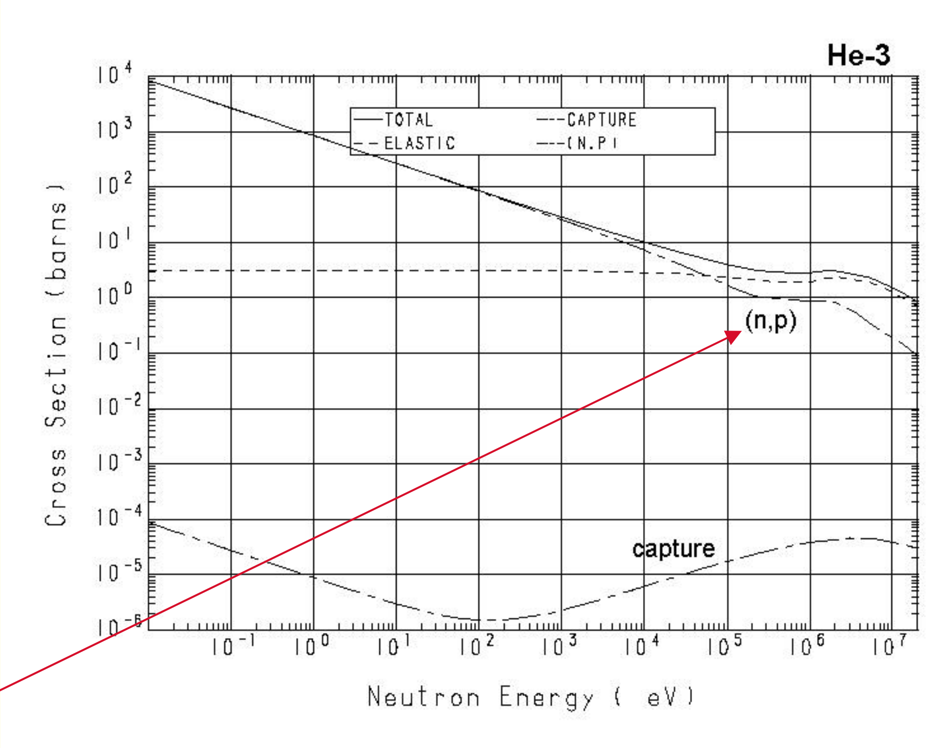
$$\frac{E_1}{E_0} = \frac{A^2 + 2A\cos\theta + 1}{(A+1)^2}$$

Particular case : if A $= 1$ and $\theta = 180°$ $E_2 = 0$

Backscattering on protons

Because it has almost the same mass as the proton, the neutron can lose all its energy in one single collision with it.

If the neutron is produced at 1 MeV and scattered at 179.9°
it will have energy E_1 :
- 0.98 MeV if scattered by ^{208}Pb
- 0.11 MeV if scattered by ^{2}D
- 0.77 eV if scattered by the proton



At such a low energy, its cross section with many materials is much higher, which favors its detection.

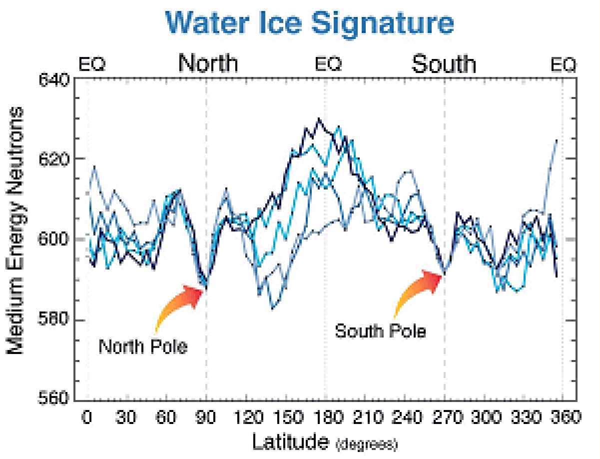
An enhanced neutron rate at backward angles reveals the presence of hydrogen, and thus water, hydrocarbonates or explosives.

Backscattering on Hydrogen

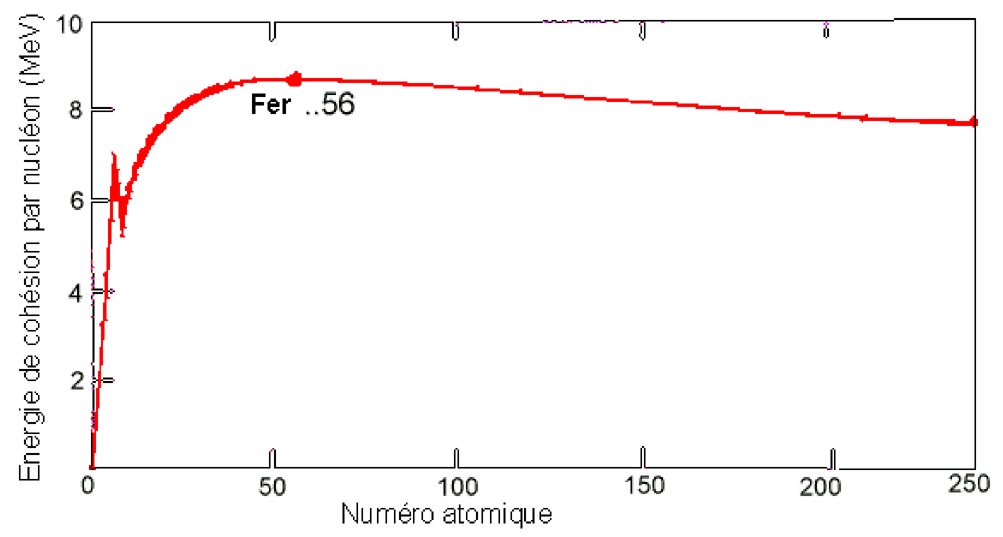
Mars Water Finder developped by the
Federal Space Agency of Russia,
to equip the Mars Science Laboratory

Landmine detector (Delft University, 2002)

Lunar
Prospector
(Nasa)



2) CAPTURE n + $^{A}A \rightarrow ^{A+1}A$

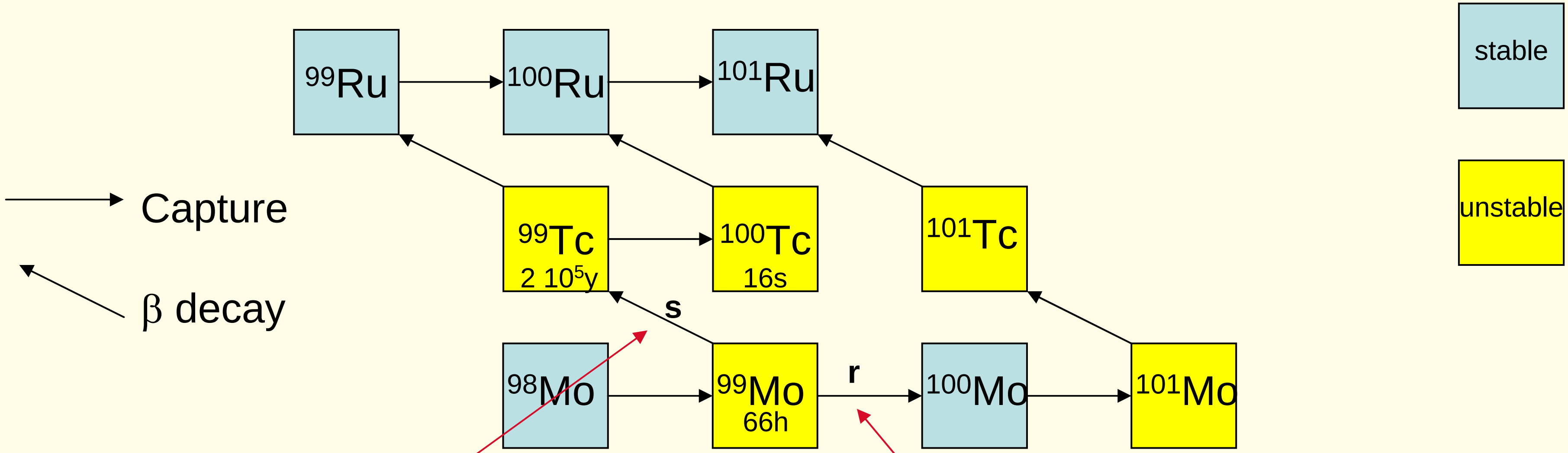


The capture of a neutron by a stable nucleus is allways exothermic.

Fusion is exothermic only up to Z=56.

In stars, only elements with Z smaller than 56 can be produced by fusion. Elements with Z larger then 56 are produced by neutron capture.

Nucleosynthesis

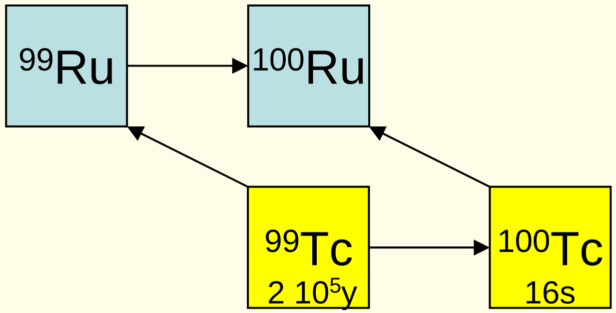


The nucleosynthesis has been demonstrated in 1952 by the observation of Tc isotopes in some stars

The **s-process** occurs when the neutron density is of the order of 10^7-10^9n/cm^3 . Then the rate of captures is sufficiently high to build a sizeable amount of Tc isotopes, all of which are unstable with live-times less then 10^6 years.

When the neutron density is much higher (10^{20}n/cm^3) the **r-process** occurs. This happens in supernovae explosions.

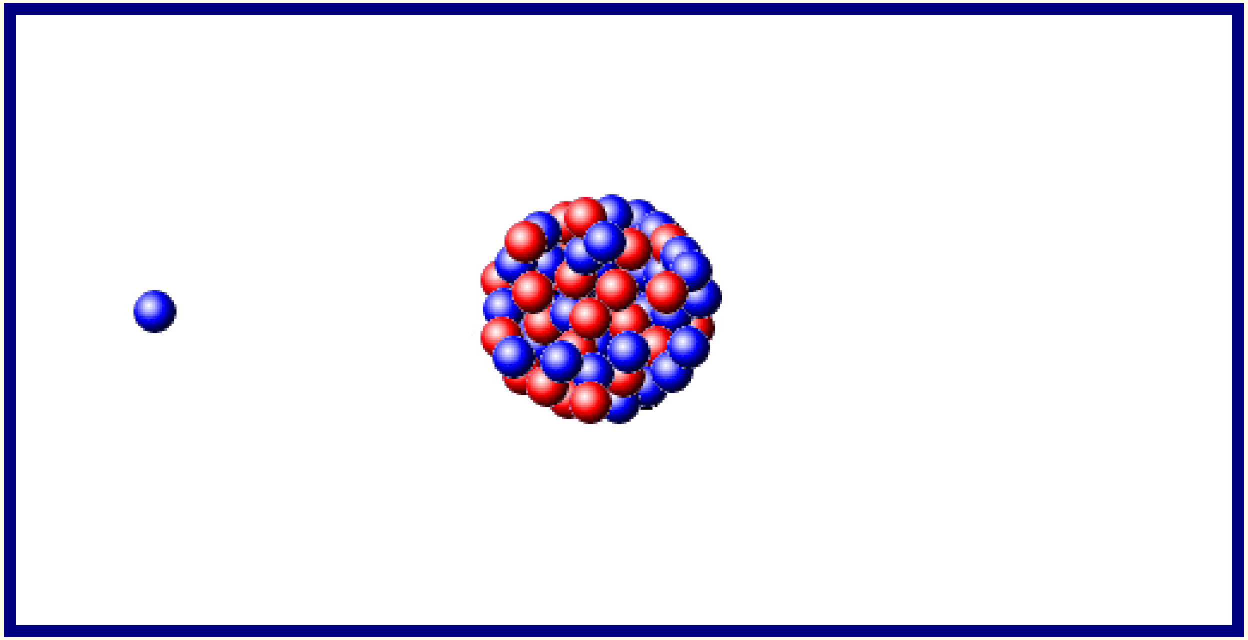
Transmutation of nuclear waste: ^{99}Tc as an example



^{99}Tc is a **fission fragment** with long live time and is therefore a **nasty nuclear waste**. It could be transmuted in an intense neutron flux provided by dedicated reactors

^{99m}Tc is a tracer intensively used in medicine. It decays to ^{99}Tc with a half-live of 6h. Between 5 and 1000 MBq are injected in a patient for analysis

3) FISSION n + A → B + C + 2…n



Emprunté à http://www.hpwt.de/

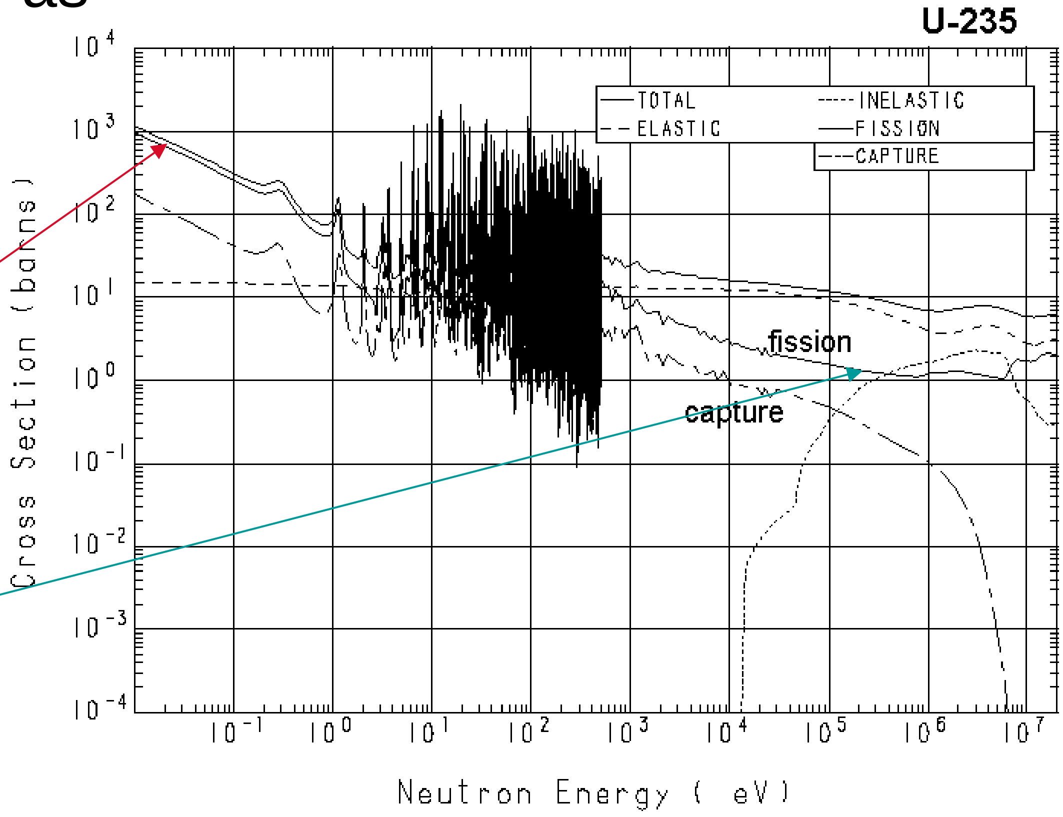
When a ^{235}U nucleus fissions after having been hit by a neutron, two fragments with about 200 MeV kinetic energy are produced, as well as 2 to 3 neutrons

The ^{235}U cycle

^{235}U exists in nature.

Therefore, present days reactors use this isotope as fissile element.

Because the fission cross section of ^{235}U exceeds largely the capture cross section at any energy, the neutron balance is possible in a thermal spectrum
as well as in a fast spectrum



The weak side of the ^{235}U cycle

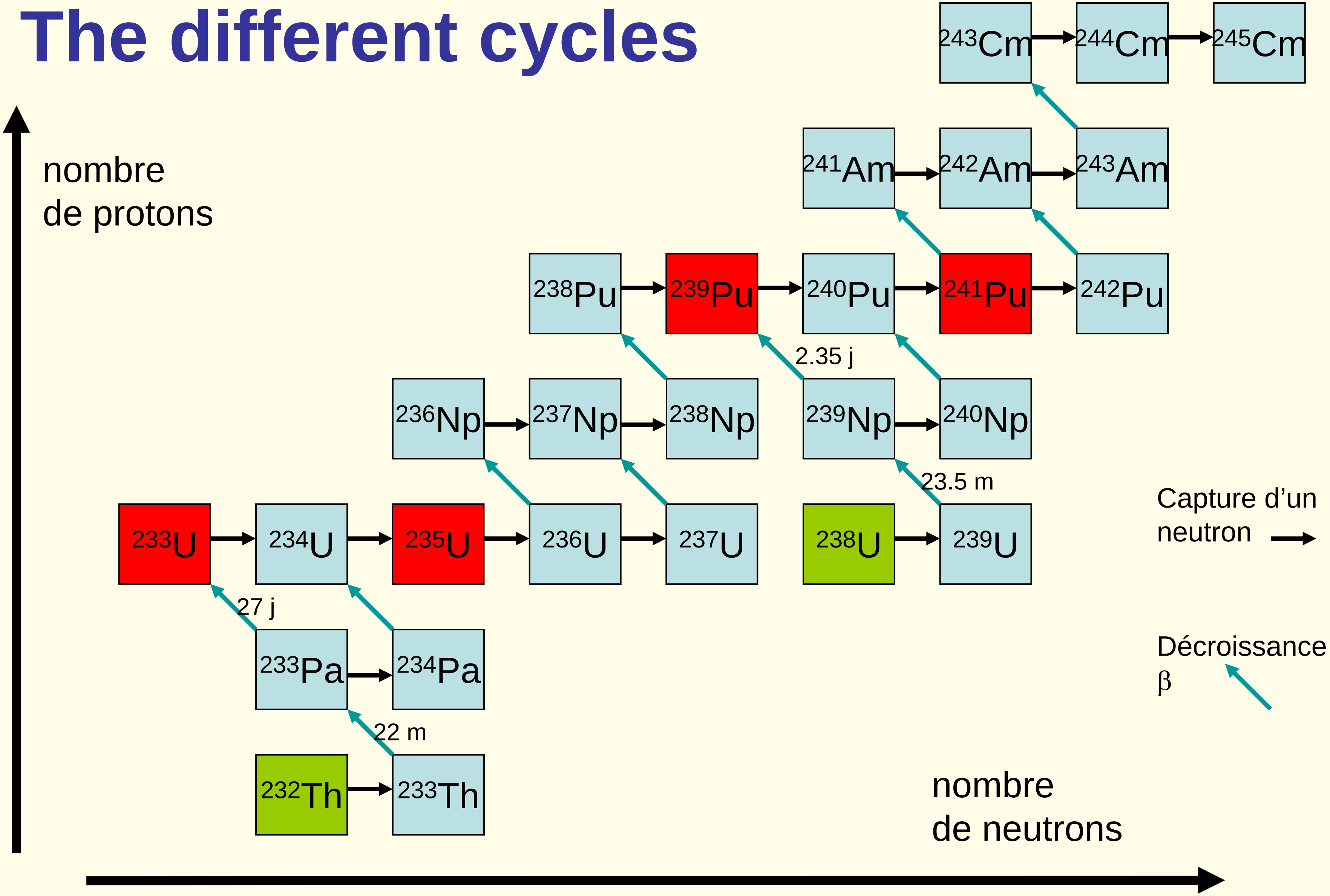
The stock of ^{235}U is limited !!!

The abundance of ^{235}U is only 0.7%. To ensure the neutron balance, the fuel has to be enriched in almost all types of reactors (in a PWR to about 3.5%).

The 96.5% remaining ^{238}U nuclei capture neutrons, which leads to the built up of ^{239}Pu. Part of this ^{239}Pu will fission in the reactor and contribute to the energy production. ^{239}Pu is considered as a waste in some countries, as a fuel in others (and allows to make a bomb if purified !)

But Pu can also capture neutrons, which leads to the built up of the “minor actinides” (Am, Ci, etc…) i.e. of toxic waste.

The different cycles



^{243}Cm ^{244}Cm ^{245}Cm

^{241}Am ^{242}Am ^{243}Am

^{238}Pu ^{239}Pu ^{240}Pu ^{241}Pu ^{242}Pu

2.35 j

^{236}Np ^{237}Np ^{238}Np ^{239}Np ^{240}Np

23.5 m

^{233}U ^{234}U ^{235}U ^{236}U ^{237}U ^{238}U ^{239}U

27 j

^{233}Pa ^{234}Pa

22 m

^{232}Th ^{233}Th

nombre
de protons

nombre
de neutrons

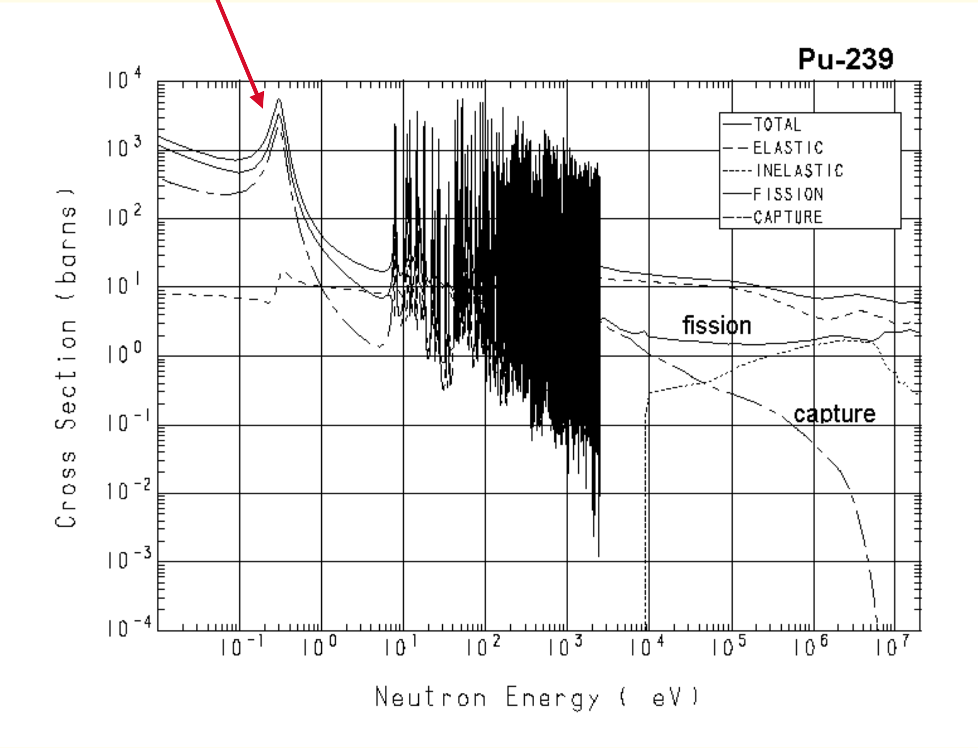
Capture d'un
neutron →

Décroissance
β

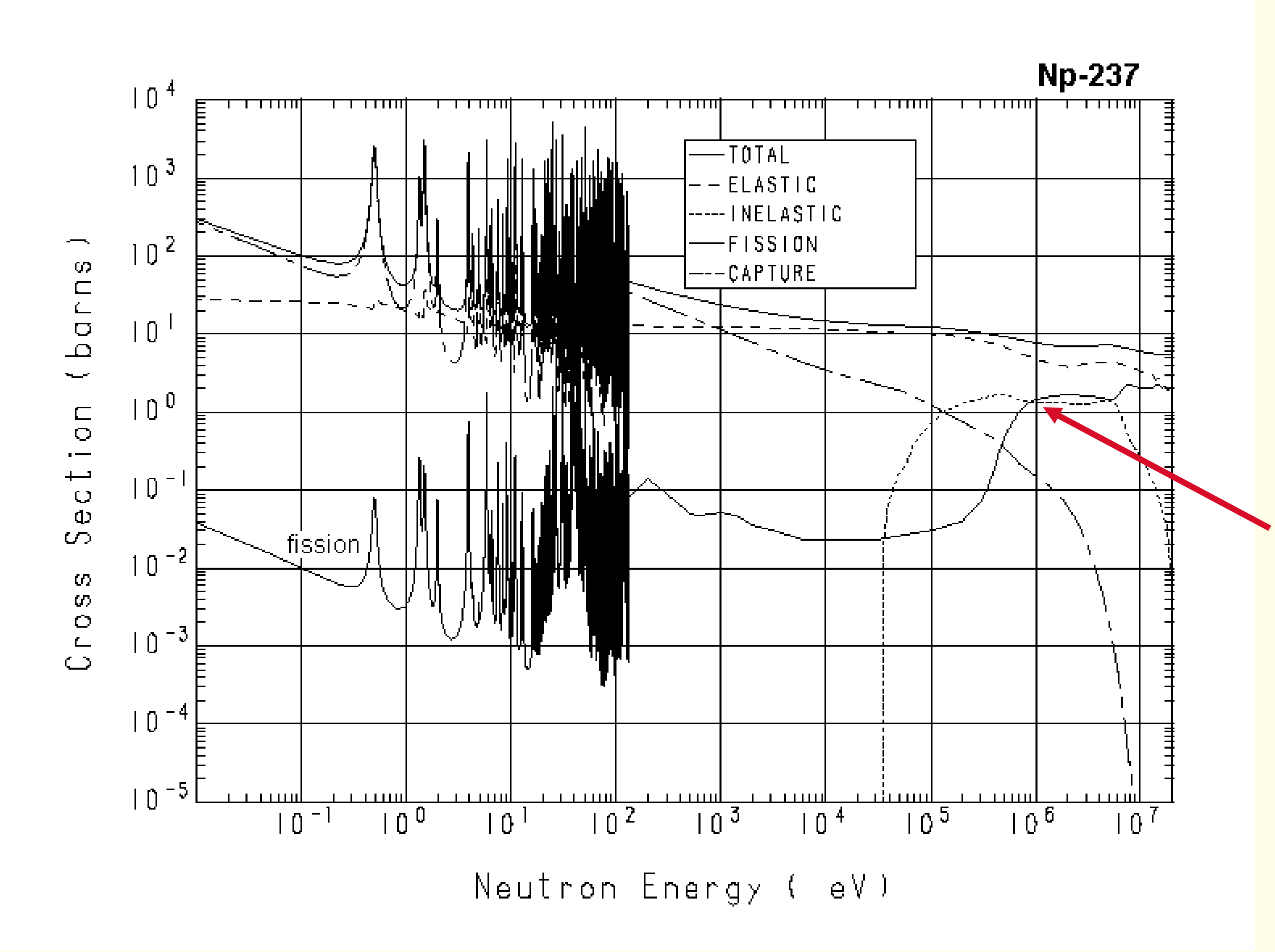
The U/Pu cycle

The U/Pu cycle or the Th/U cycle can replace the ^{235}U cycle
The U/Pu is the most advanced one (Phenix, Superphenix, Monju, reactors in Russia and soon in India). It works only in a fast spectrum

One cannot use water to cool the core if one wants a fast spectrum



The good side of a fast spectrum



^{237}Np and the other minor actinides can be fissionned in a fast spectrum

^{237}Np: Production : 8.8 kg/year in a typical PWR Life time : 2 10^{6} years

Separation and transmutation

La Hague,
Sellafield,
…

Once
through

Fast
reactors

If we keep our policy and we don't recycle in the United States, we will have to build nine Yucca Mountains over the course of the century, if we just keep Yucca Mountain at 20 percent of our -- if we just keep nuclear power at 20 percent of our electricity generation. If we recycle and can burn down those wastes in a way that we are proposing, we will be able to use -- that one Yucca Mountain will be able to last for the entirety of the century.

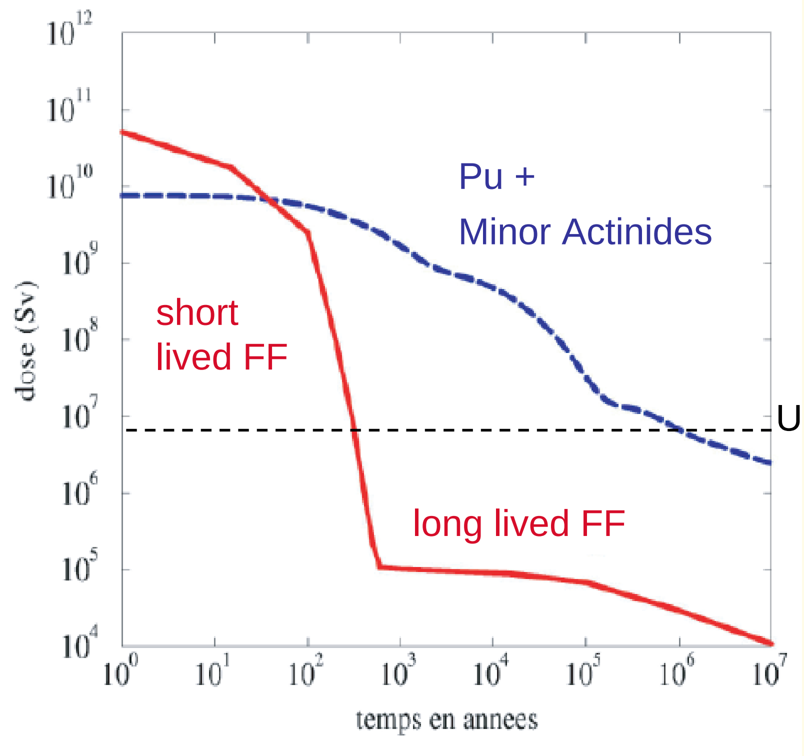
The first element is to expand dramatically the use of nuclear power here in the United States. We think -- today, we have 100 nuclear reactors; many of those are going to start phasing out in the coming decades. We think we really need to be, from a public policy standpoint we're shooting for 300 reactors in 2050; that's a significant increase. That's what we think would be appropriate to meet our energy needs as well as to manage our greenhouse gas emissions and that's going to require significant advances in technology.

Minor Actinides and Fission- Fragment decays

🔵	**^{237}Np**	$2\ 10^{6}$y
🔴	^{233}Pa	2d
🔵	^{233}U	$1.6\ 10^{5}$
🔵	^{229}Th	7340y
🔴	^{225}Ra	15d
🔵	^{225}Ac	10d
🔵	^{221}Fr	4.9m
🔴	^{217}At	32ms
🔵	^{217}Rn	0.54 ms
🔵	^{213}Po	4.2μs
🔴	^{209}Pb	3.2h
⚪	^{209}Bi	stable

🔴	**^{93}Zr**	$1.5\ 10^{6}$y	0.00014%
⚪	^{93}Nb	stable	

🔴	**^{90}Kr**	32.3s	4.4%
🔴	^{90}Rb	158s	
🔴	^{90}Sr	28.8y	
🔴	^{90}Y	64.1h	
⚪	^{90}Zr	stable	

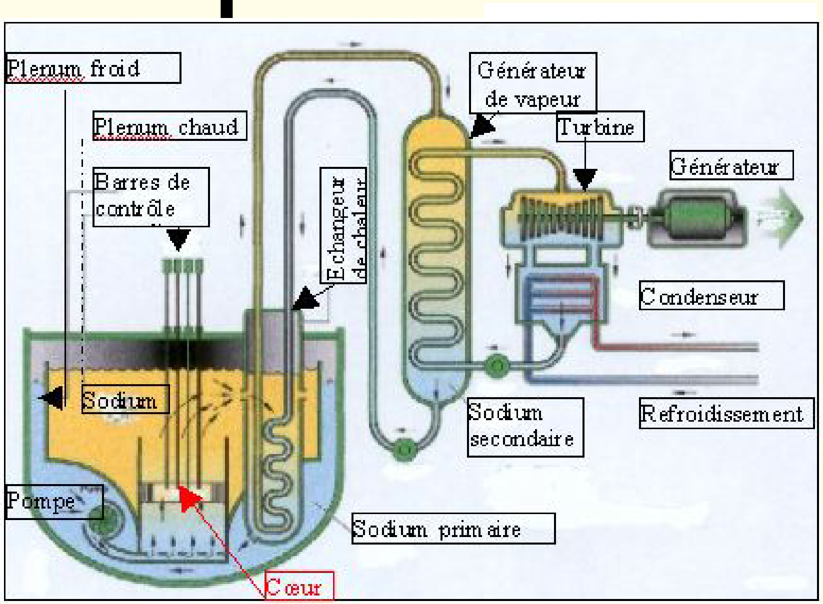


Radiotoxicity of a typical PWR core

🔵 α
🔴 β

“Closed” Cycle

Used fuel



Fast Reactor

Fission Fragments

U + Pu + Minor Actinides

Génération IV

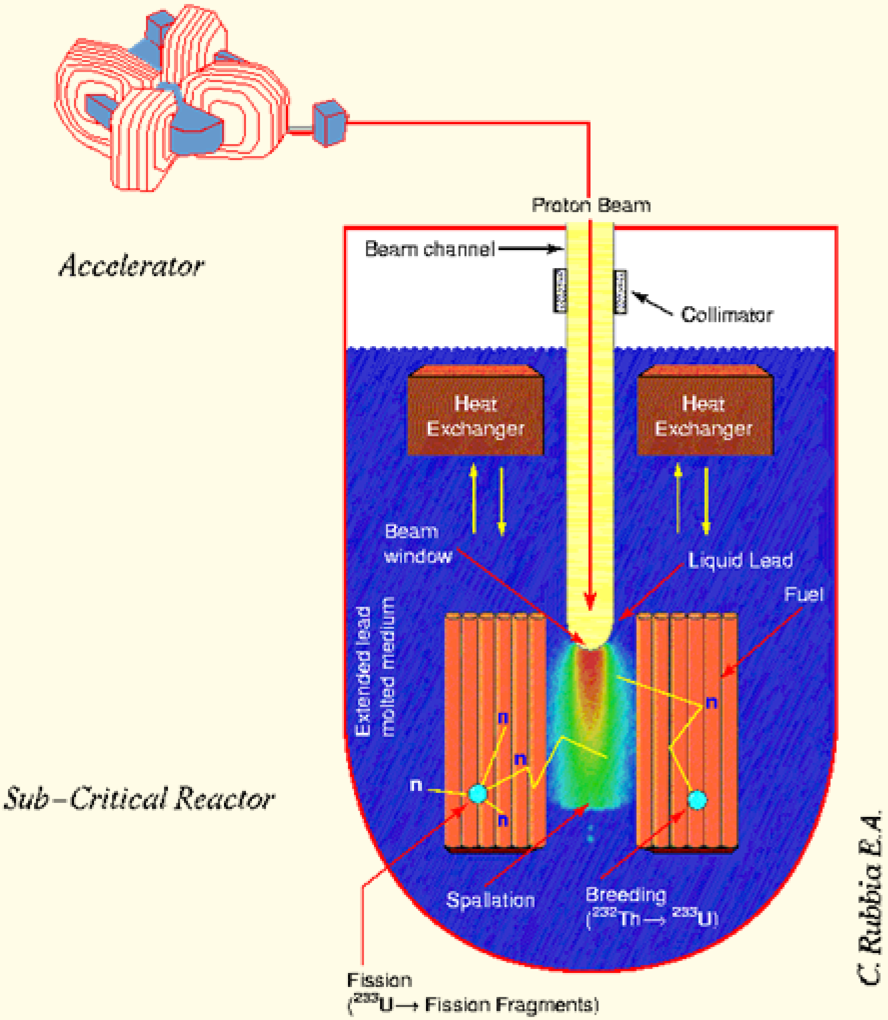
Six systems which could provide CO_2-free energy in 2040 :

Type	Spectrum	Cycle	
Sodium Cooled Fast Reactor	Fast	Closed	U/Pu
Lead Cooled Fast Reactor	Fast	Closed	U/Pu
Gas Cooled Fast Reactor	Fast	Closed	U/Pu
Very High Temperature Reactor	Thermal	Open	^{235}U
Supercritical Water cooled Reactor	Fast/Thermal	Closed/Open	^{235}U
Molten Salt Reactor	Fast/Epithermal	Closed	U/Pu or Th/U

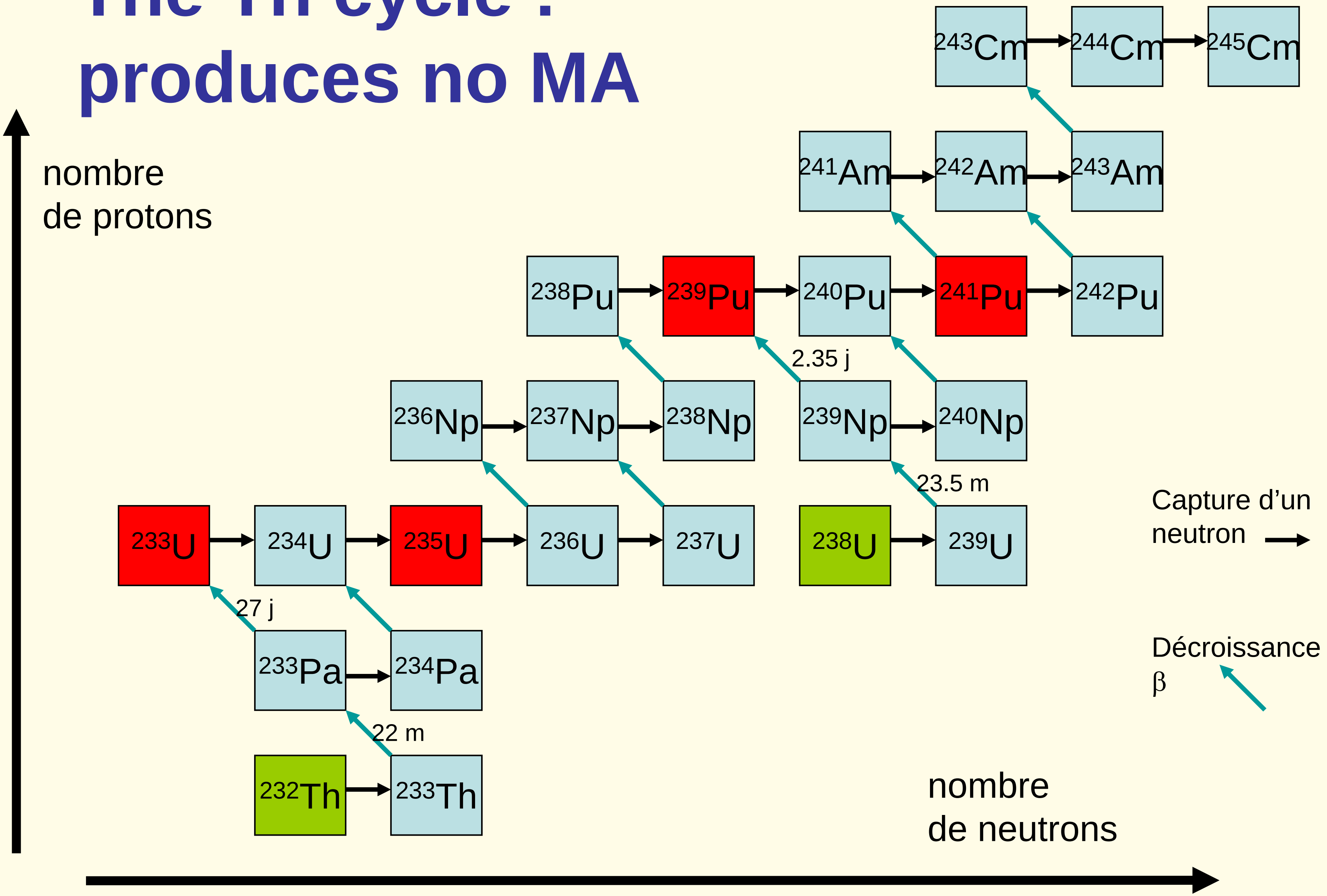
Accelerator Driven System

The reactor is sub-critical reactor. The neutron balance is obtained with the help of spallation reactions between a proton beam and a heavy element (Pb ?)

Projected demonstator:
Myrrha
(Mol, Belgique)



The Th cycle : produces no MA



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23.5 m

^{233}U → ^{234}U → ^{235}U → ^{236}U → ^{237}U

^{238}U → ^{239}U

27 j

^{233}Pa → ^{234}Pa

22 m

^{232}Th → ^{233}Th

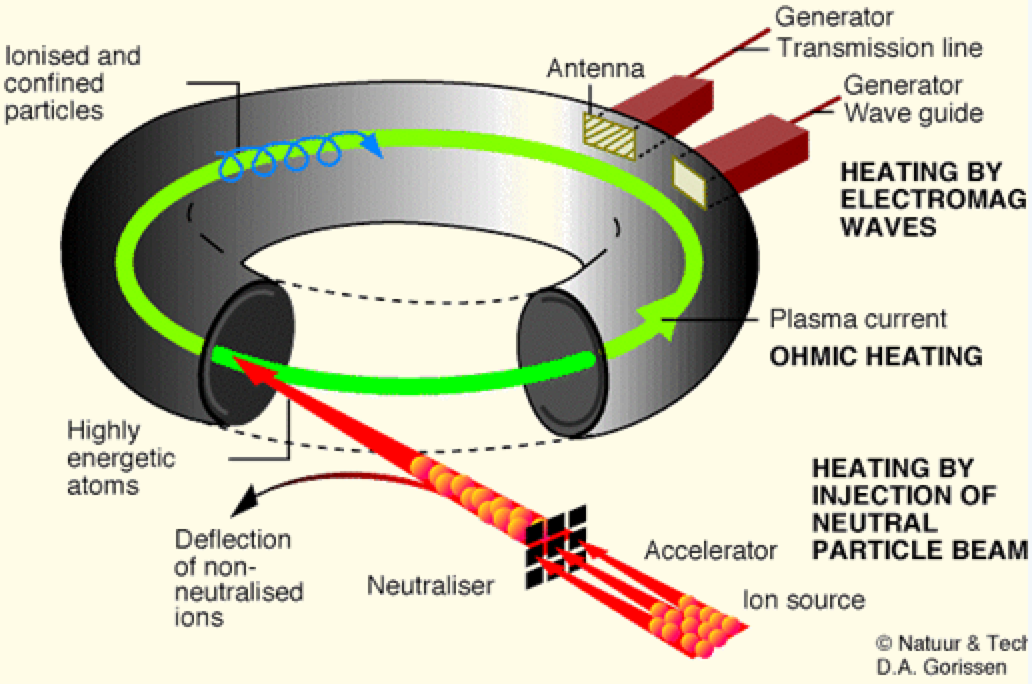
nombre
de protons

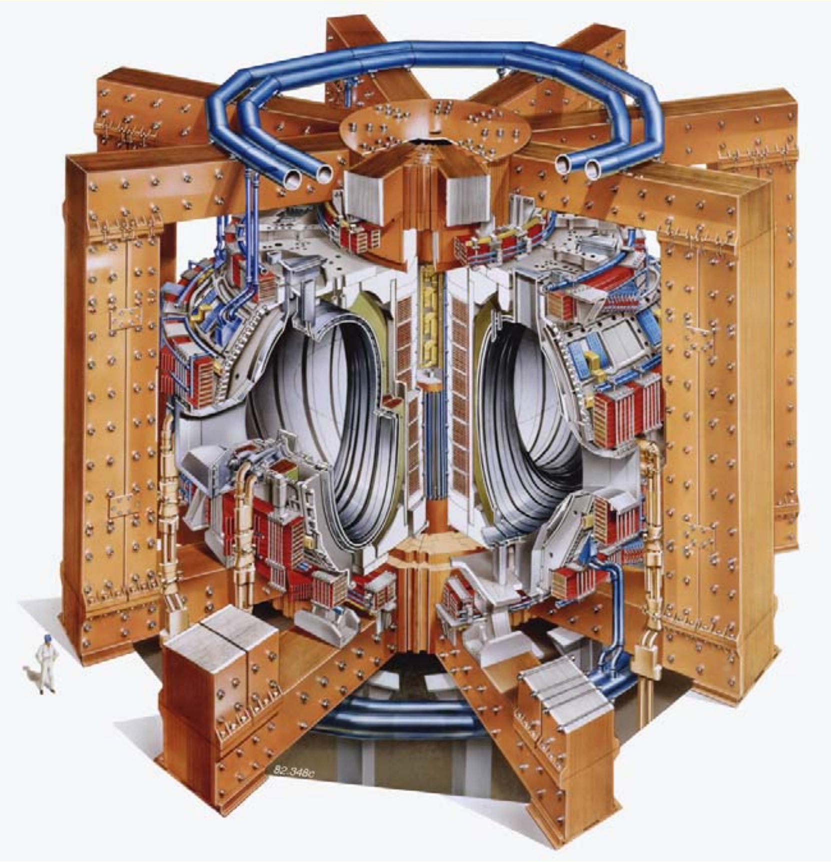
nombre
de neutrons

Capture d’un neutron →

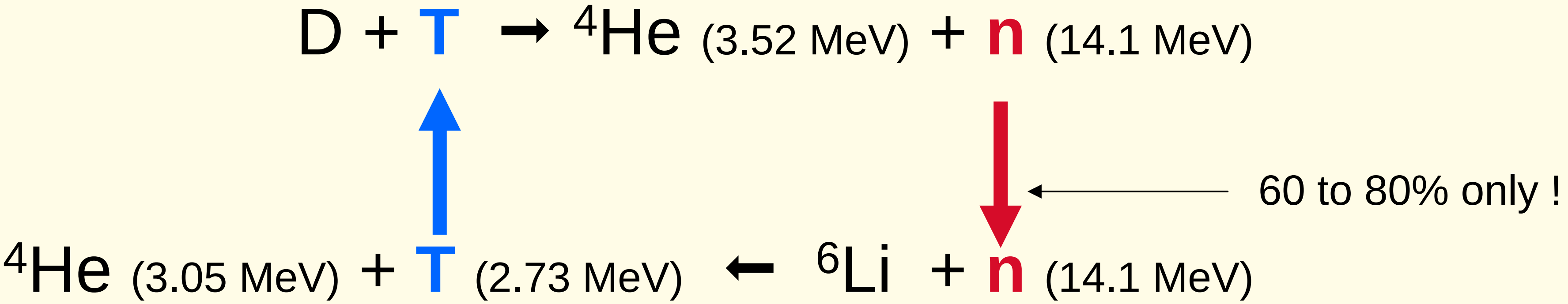
Décroissance β

4) FUSION $D + T \rightarrow {}^{4}\mathrm{He} + n$





$D + {}^{6}Li \rightarrow 2\ {}^{4}He$



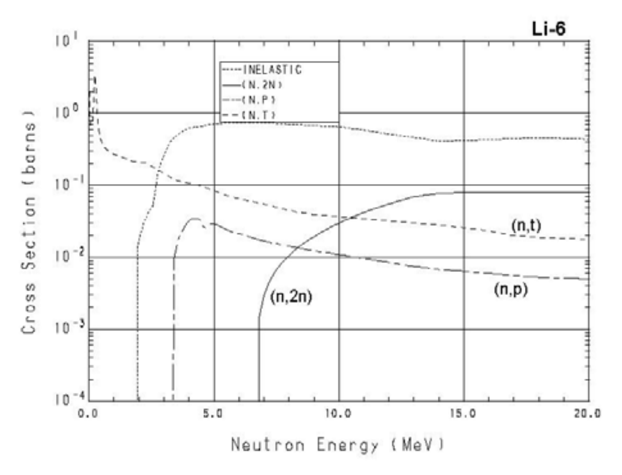
$D + T \rightarrow {}^{4}He$ (3.52 MeV) + n (14.1 MeV)

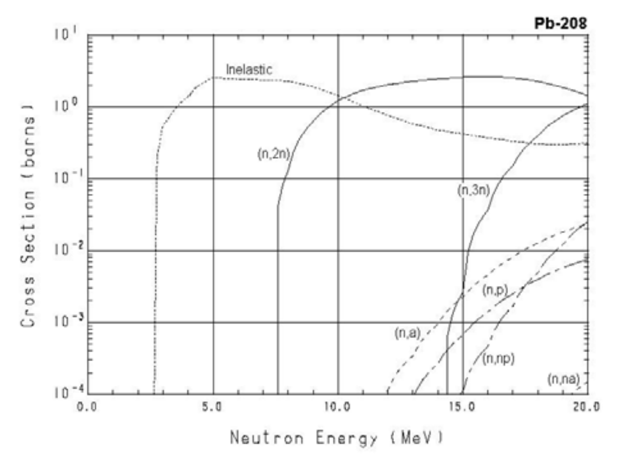
60 to 80% only !

${}^{4}He$ (3.05 MeV) + T (2.73 MeV) ← ${}^{6}Li$ + n (14.1 MeV)

The first wall will be made of ${}^{6}Li$ but the loss of neutrons must be compensated by :

- Lead through the **${}^{206,207,208}Pb(n,2n)$ reaction**
- ${}^{7}Li$ through the ${}^{7}Li(n,nt)\ {}^{4}He$ reaction





The Research in the Grace Group of IPHC Strasbourg

^{206,207,208}Pb(n,2n)
^{235}U(n,n')
…
^{233}U(n,2n)
cross sections

The experiments are performed mostly at IRMM Geel (Be)