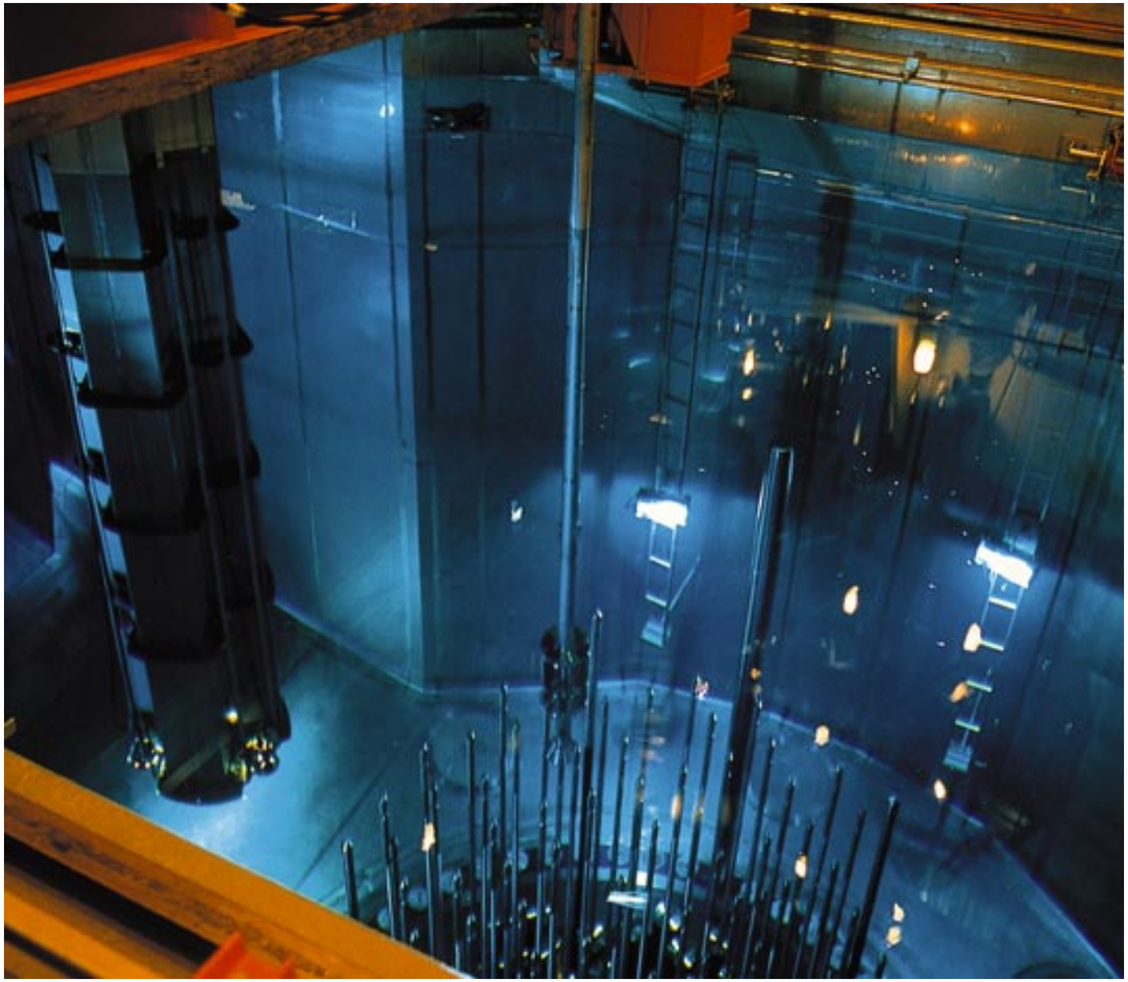
PHYSICS OF NUCLEAR FISSION REACTORS



European Summer Campus 2013 Gérard RUDOLF

In2p3

UNIVERSITÉ DE STRASBOURG

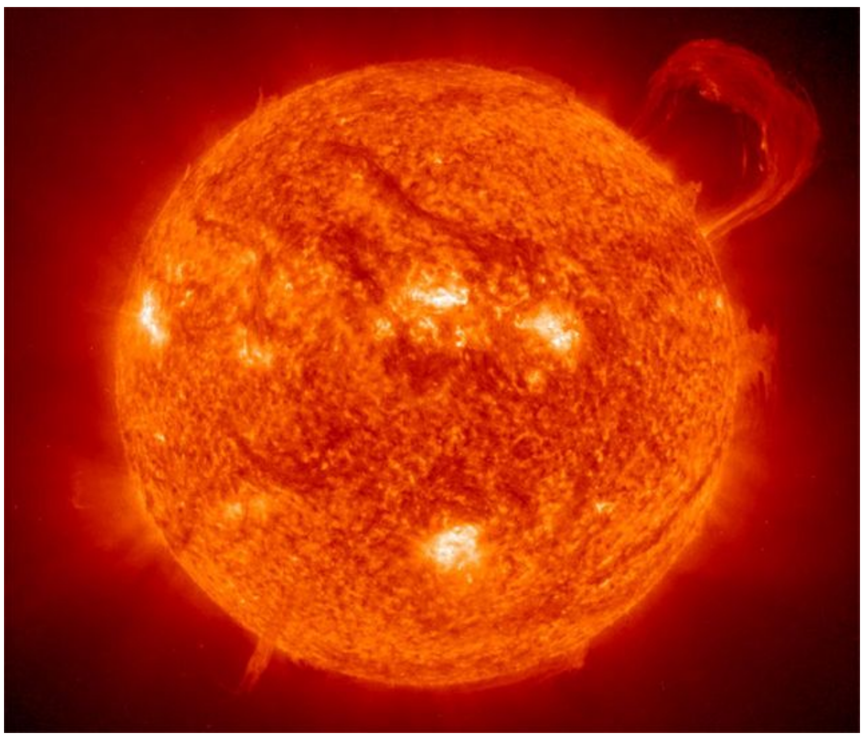
Where does our energy come from ?

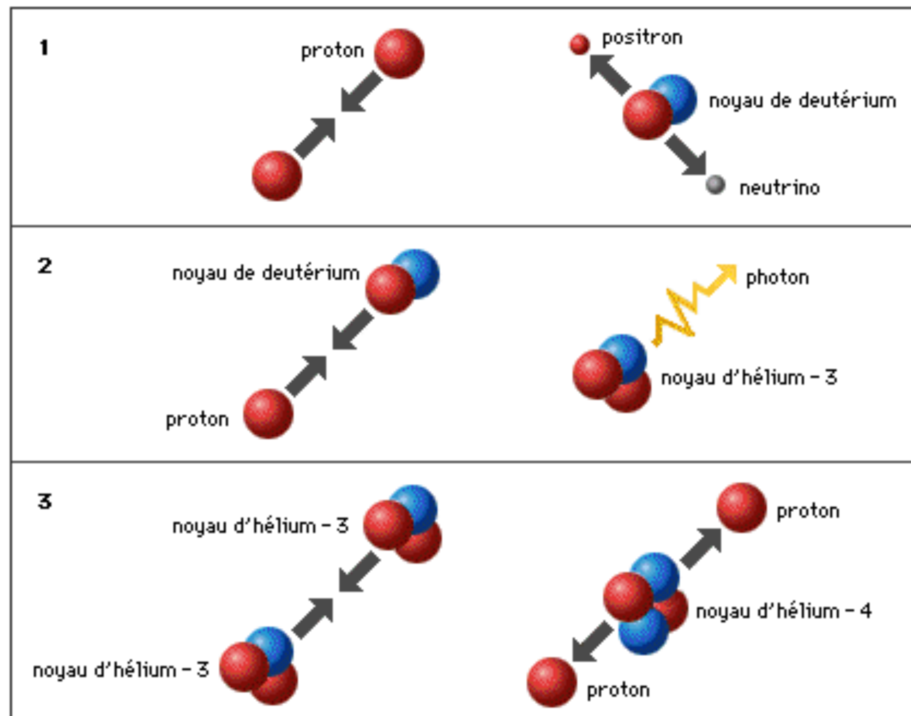
« Nuclear forces are at the origin of all sources of energy available on earth »

Actually, nearly all our energy sources have a solar origin.

Sun →
- Wind
- Oil
- Coal
- Wood
- Hydroelectricity
- …
- Photovoltaic !

Nuclear forces in action
1) the Sun

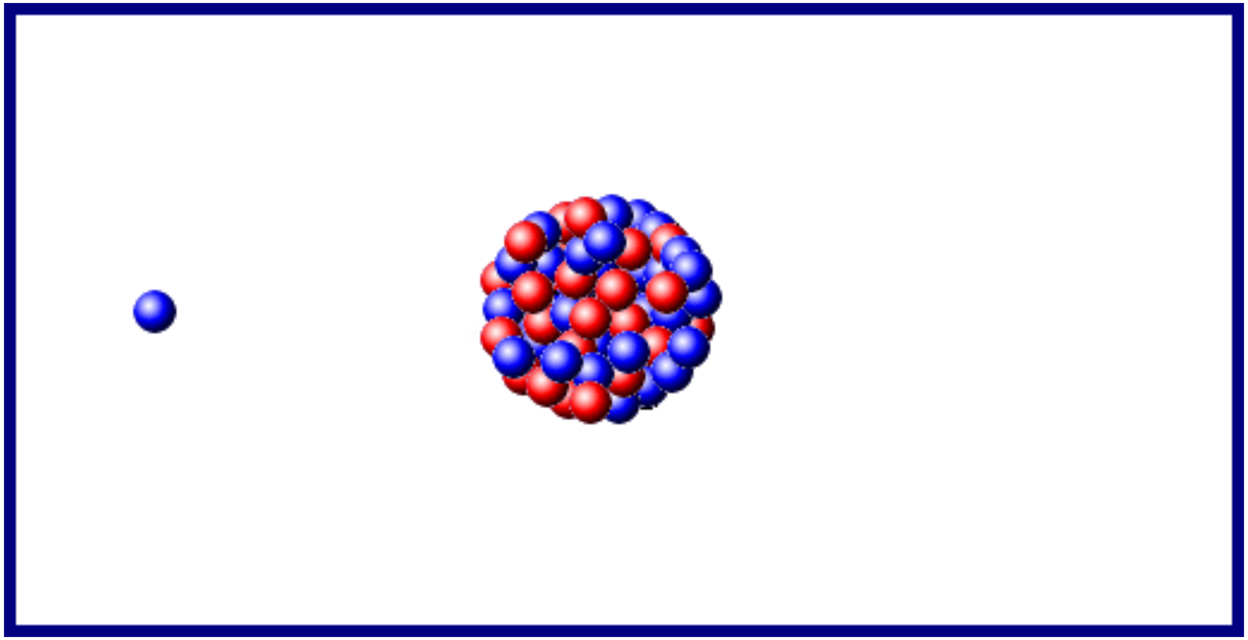




Where does the nuclear energy in a fission reactor come from

?

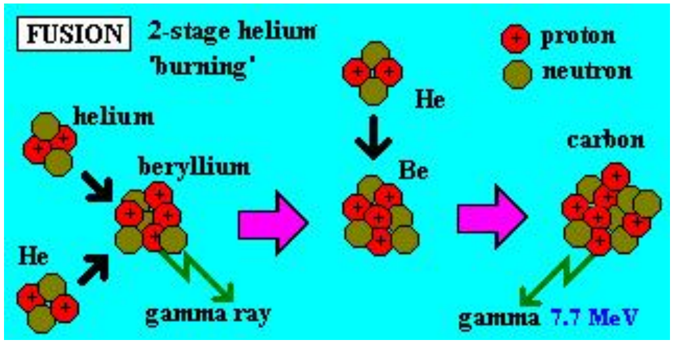
The fission reaction

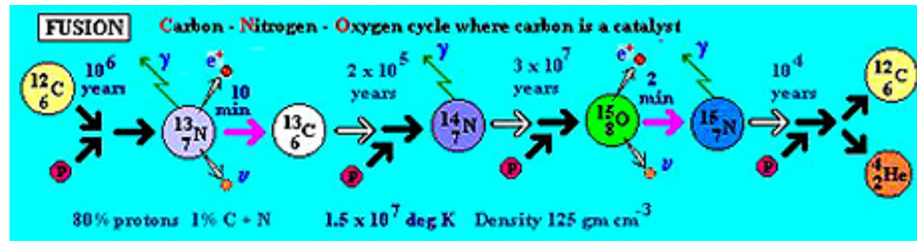


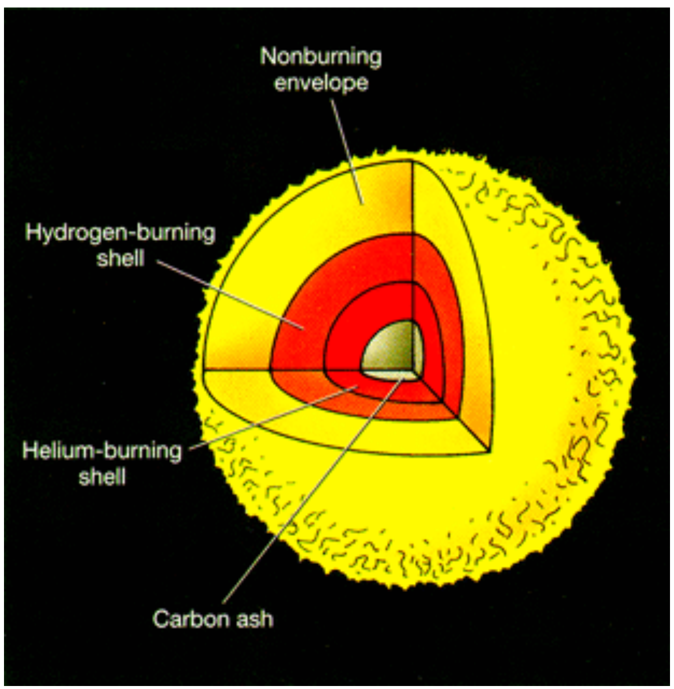
From http://www.hpwt.de/

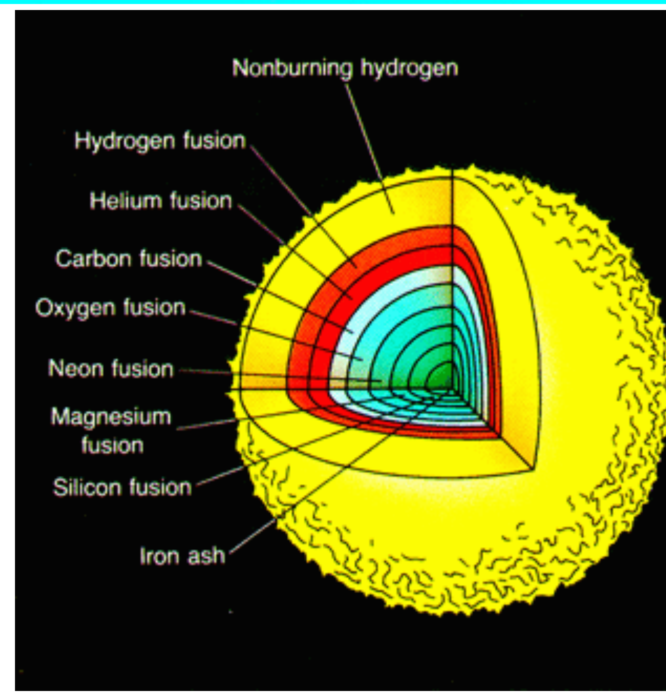
The interaction between one neutron and a ^{235}U nucleus produces about 170 MeV and 2-3 neutrons

Nuclear forces in action
2) larger stars

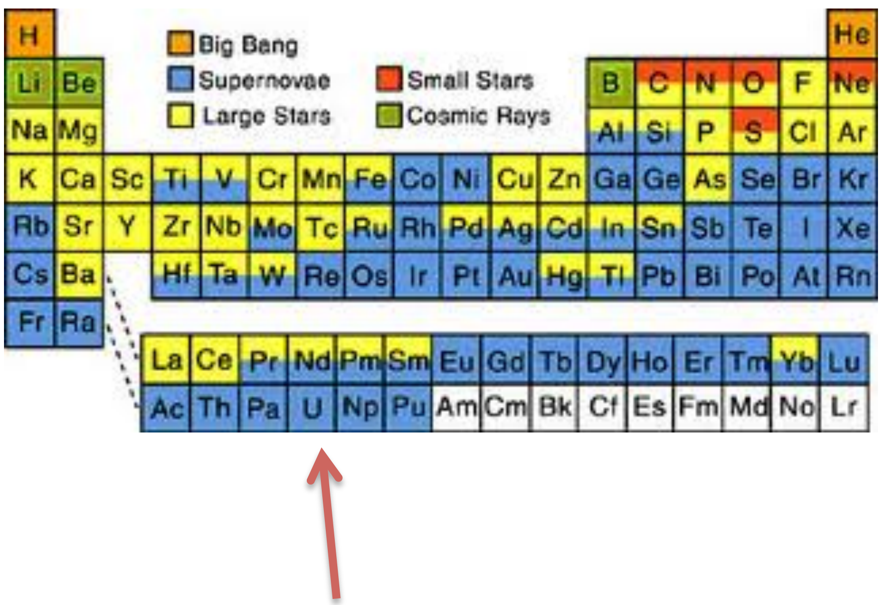








Nuclear forces in action
3) Supernovae



Uranium is formed in supernovae explosions

Energy stored in one ^{235}U nucleus

Binding energy of ^{235}U

$m(^{235}U)=235.043929918$ u

$m(p)=1.007276$ u

$m(n)=1.008665$ u

$\Delta m= 92*m(p)+143*m(n) -m(^{235}U)$

$=1.864557$ u

$=> 1.864*931.5 = 1736$ MeV

Energy released in fission

$m(^{135}Cs)=134.9059770$

$m(^{98}Rb) = 97.941790668$

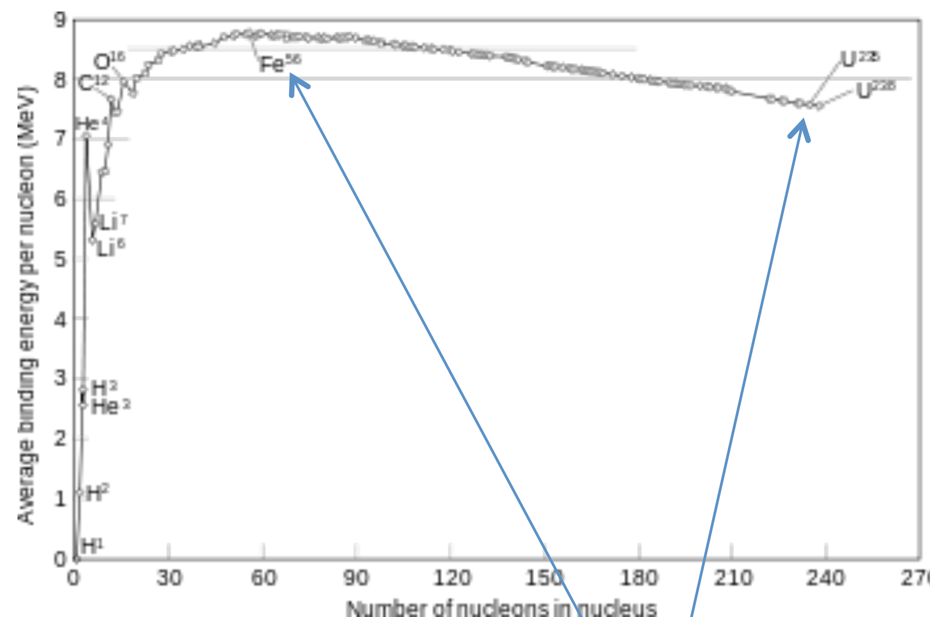
$\Delta m= m(^{235}U) - m(^{135}Cs)-m(^{98}Rb)-2m(n)$

$=0.179$ u

$=> 0.179*931.5=166$ MeV

Energy to change 143 protons in 143 neutrons

$143 * (1.007276 - 1.008665) * 931.5 = -185$ MeV



But → 10^8 times less U than Fe

But → A/Z has changed

Nuclear forces in action : nuclear fission

The energy released in the fission of one ^{235}U nucleus is about 10% of the energy released during its synthesis, including the supernova phase.

Today, nuclear fission reactors are the most compact source of energy on earth

Energy / waste
Fossil / nuclear

A chemical bonding energy correspond to a few eV
A nuclear binding energy corresponds to a few MeV

70 GJ correspond to :

- **Fossil** : 1.7 tons of oil, which produces 4.7 tons of CO_2, plus NO_2, SO_2 …
  or 3 tons of coal, which produces 11 tons of CO2, plus …

- **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 … ?

PART 1

Basic approach

Interactions between neutrons and nuclei

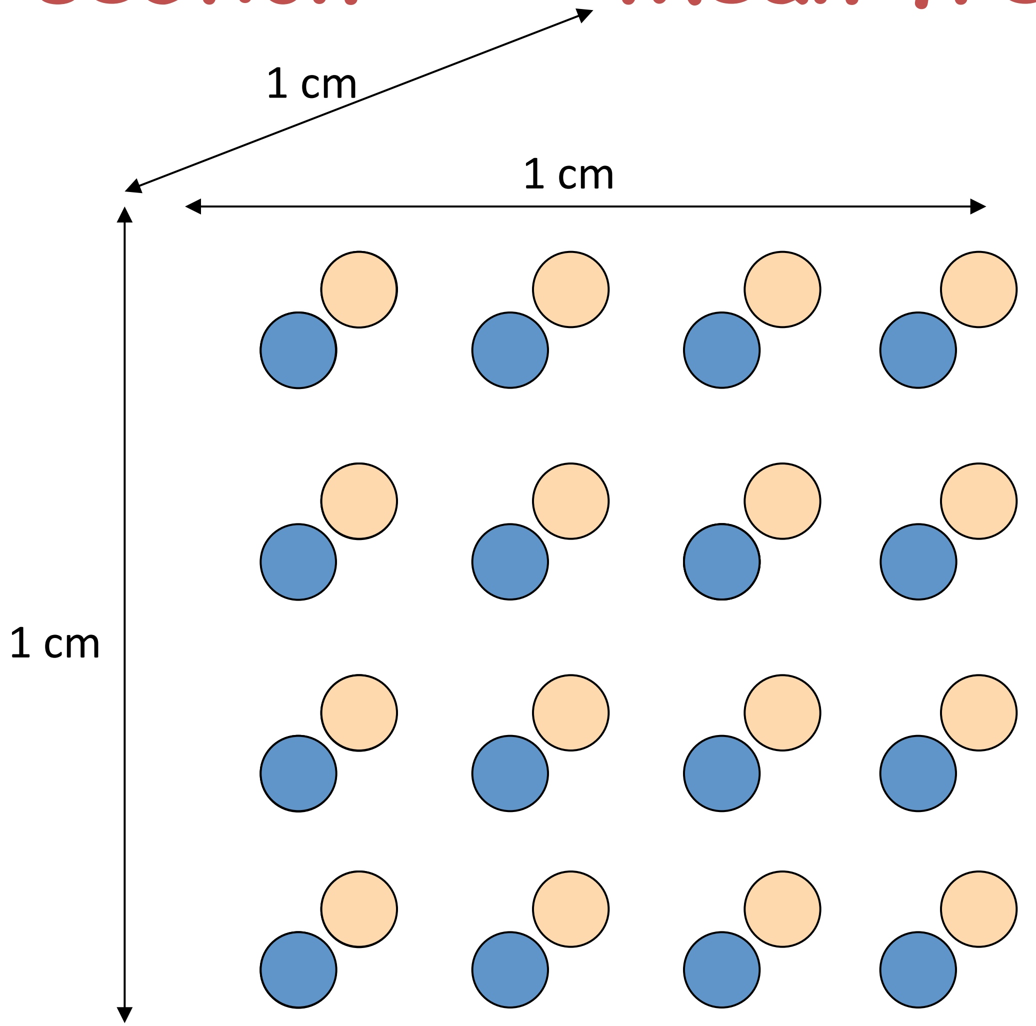
Neutrons interact with nuclei through different reaction mechanisms:

- Fission
- Capture
- Elastic scattering

and also

- Inelastic scattering
- Reactions producing protons, alpha particles, …
- Reactions producing several neutrons

The microscopic scale
Cross section <-> Mean free path



From the microscopic to the macroscopic scale

Total power

The power of the reactor is

$$\sigma_f N_{^{235}\mathrm{U}} \Phi E_f V$$

Microscopic fission cross section (cm^2)

Atomic density of ^{235}U (atoms cm^{-3})

Neutron flux (neutrons cm^{-2} s^{-1})

Energy released by one fission (MeV or Joules)

Volume of the core (cm^3)

From the microscopic to the macroscopic scale

Fuel consumption

The total fuel consumption per sec is

$$\sigma_f N_{^{235}\mathrm{U}} \Phi \frac{235}{N_{Avogadro}} V$$

- σ_f: Microscopic fission cross section (cm^2)
- $N_{^{235}\mathrm{U}}$: Atomic density of ^{235}U (atoms cm^{-3})
- Φ: Neutron flux (neutrons cm^{-2} s^{-1})
- $\frac{235}{N_{Avogadro}}$: Mass disappeared by one fission (MeV or Joules)
- V: Volume of the core (cm^3)

From the microscopic to the macroscopic scale

^{239}U production

The total ^{239}U (which leads to ^{239}Pu) production per sec is

$$\sigma_c N_{^{238}\mathrm{U}} \Phi \frac{239}{N_{Avogadro}} V$$

Microscopic capture cross section by ^{238}U (cm^2)

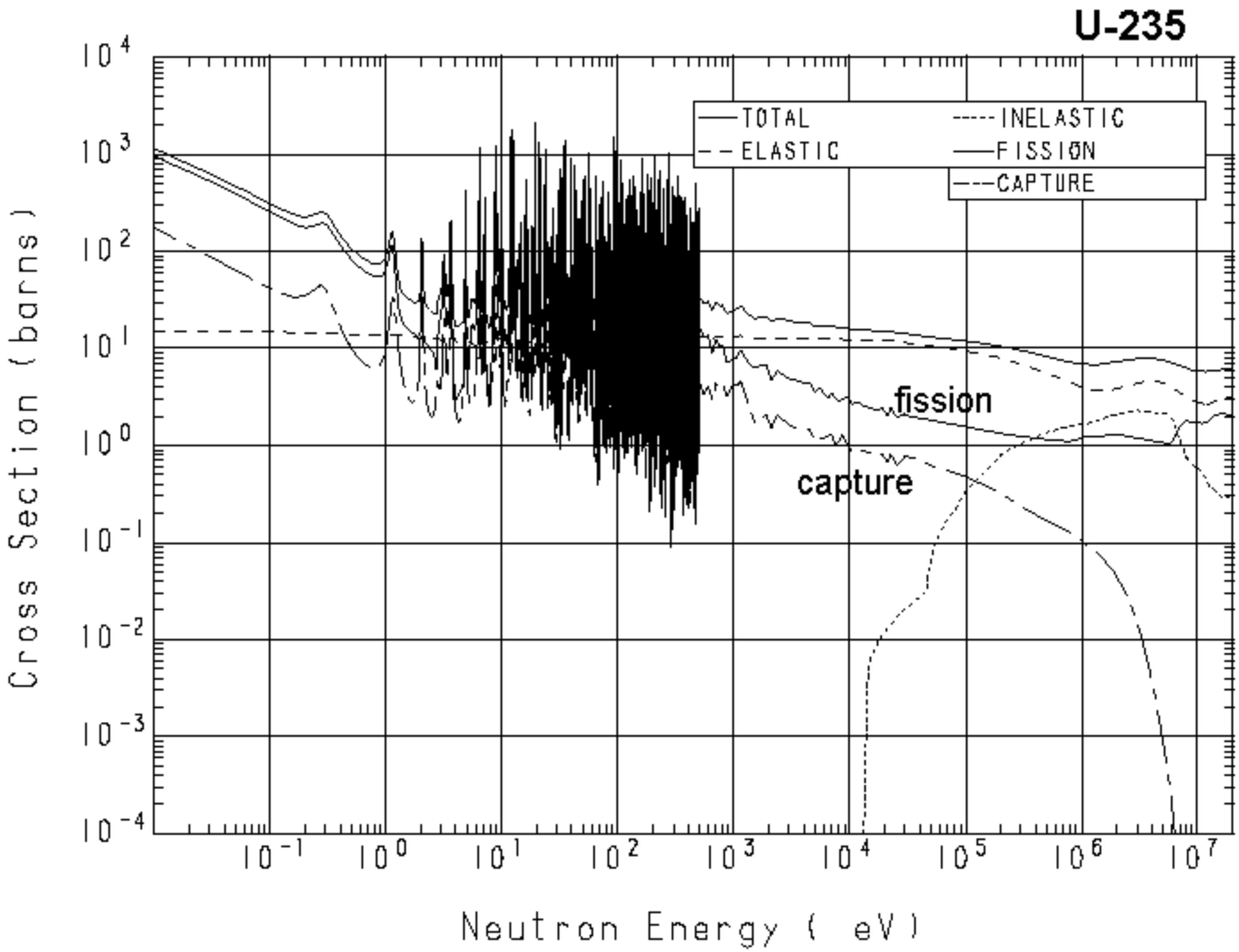
Atomic density of ^{238} U (at cm^{-3})

Neutron flux (neutrons cm^{-2} s^{-1})

Mass of ^{239}U produced by one capture (grammes)

Volume of the core (cm^3)

Neutron cross sections



Fission reactions

Capture

Diffusion

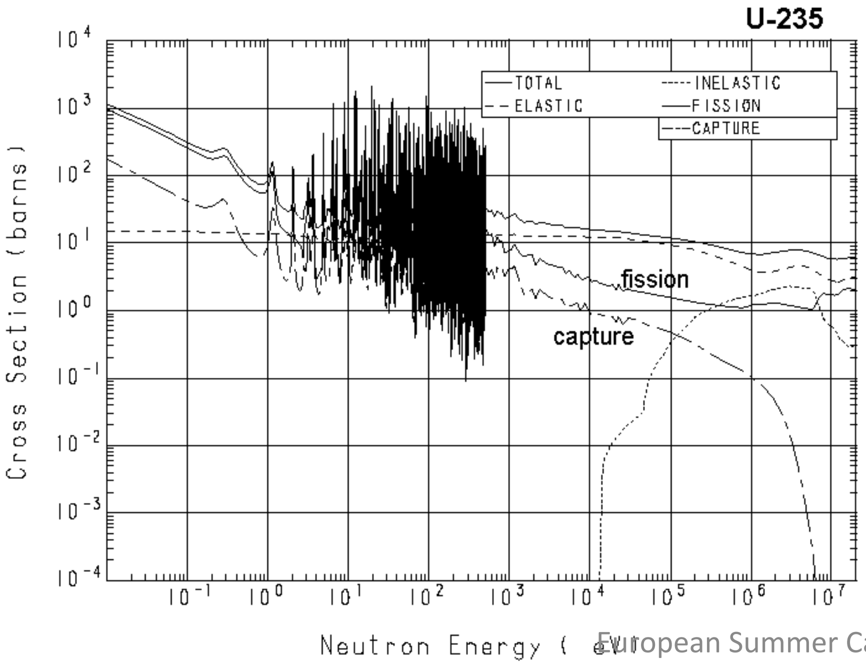
Fissile nuclei

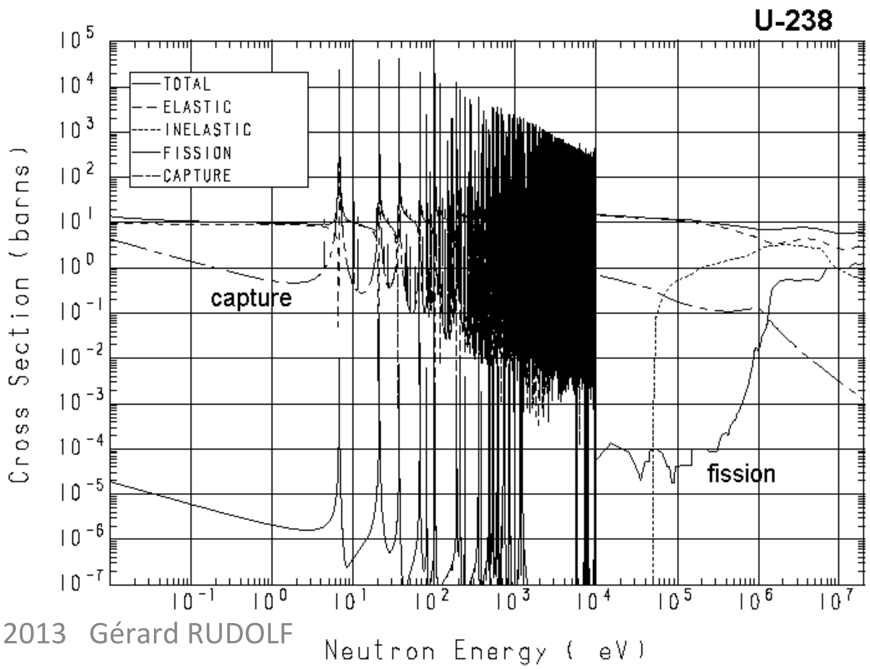
All heavy nuclei can fission when they are bombarded by high energy neutrons.

Only ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu are fissile.

Among them, only ^{235}U exists in nature.

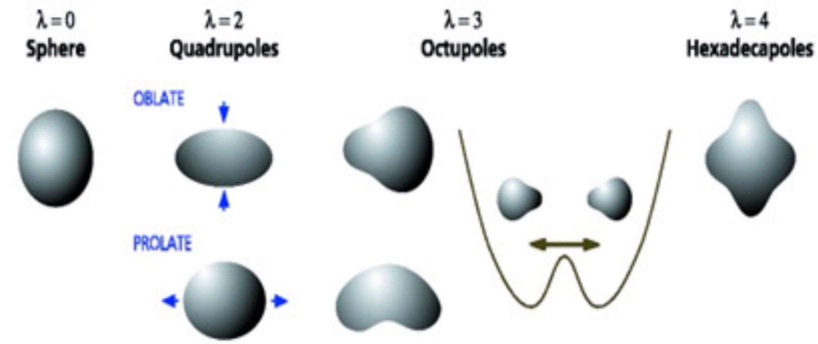
The abundance of ^{235}U in natural Uranium is about 0.7%



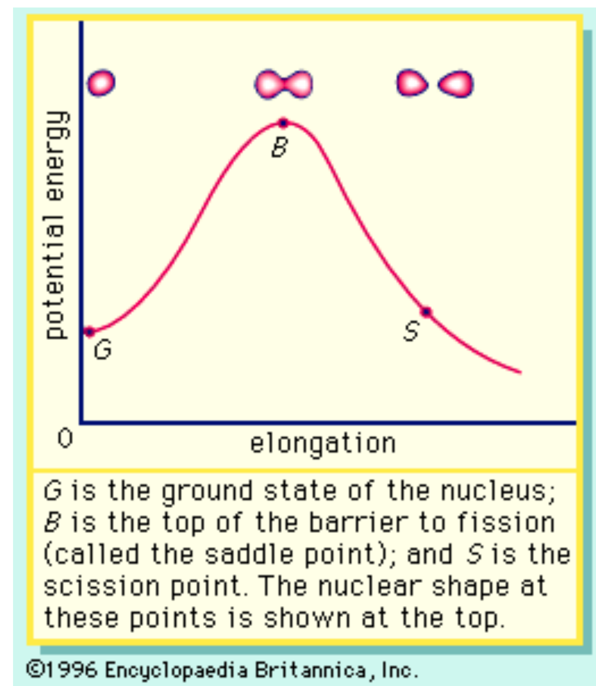


Energy production by fission

Very heavy nuclei behave like soap bubles: they oscillate between fancy shapes.

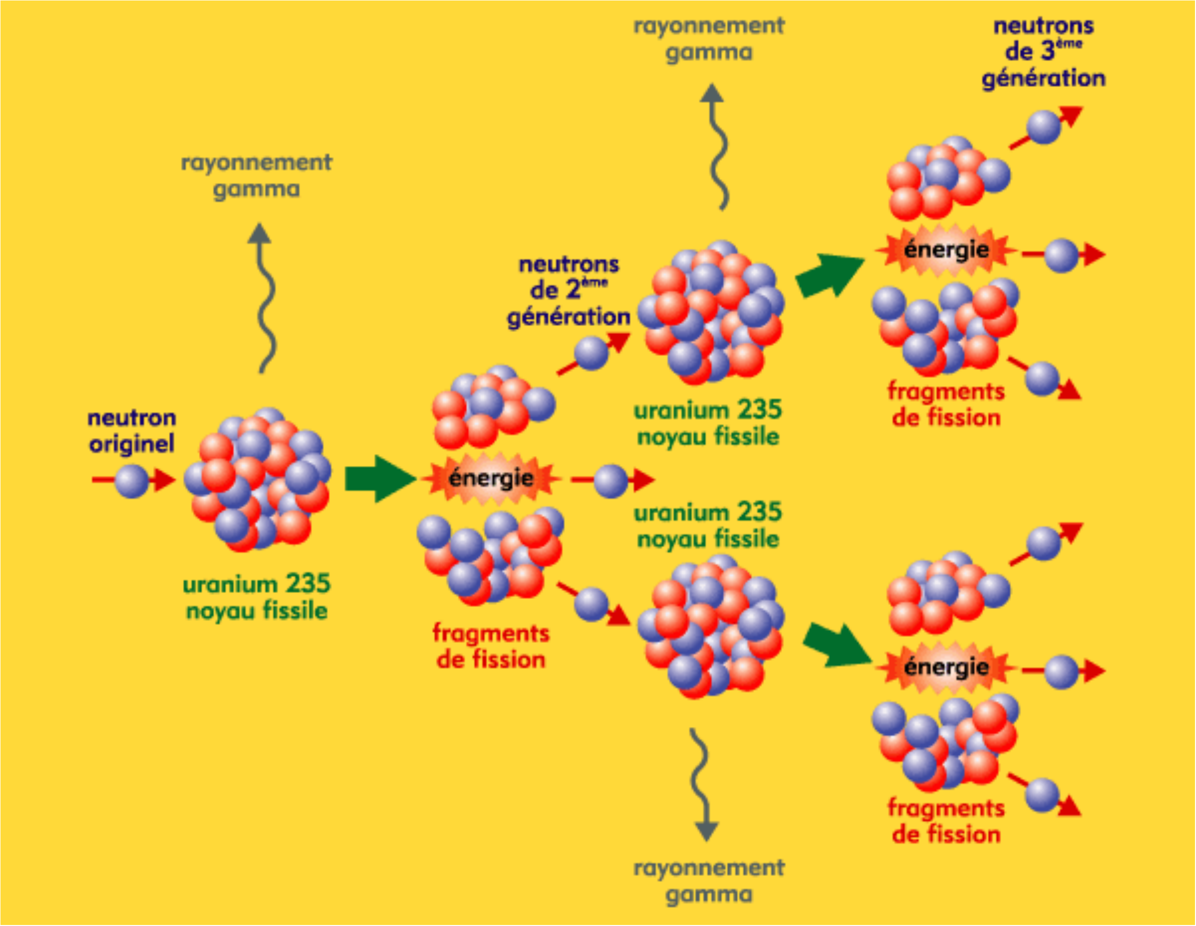


For some of them, these oscillations my lead to their fission, and then the Coulomb repulsion recovers part of the nuclear forces.



Two fission fragments are accelerated, and later loose their kinetic energy in the medium.

Chain reaction



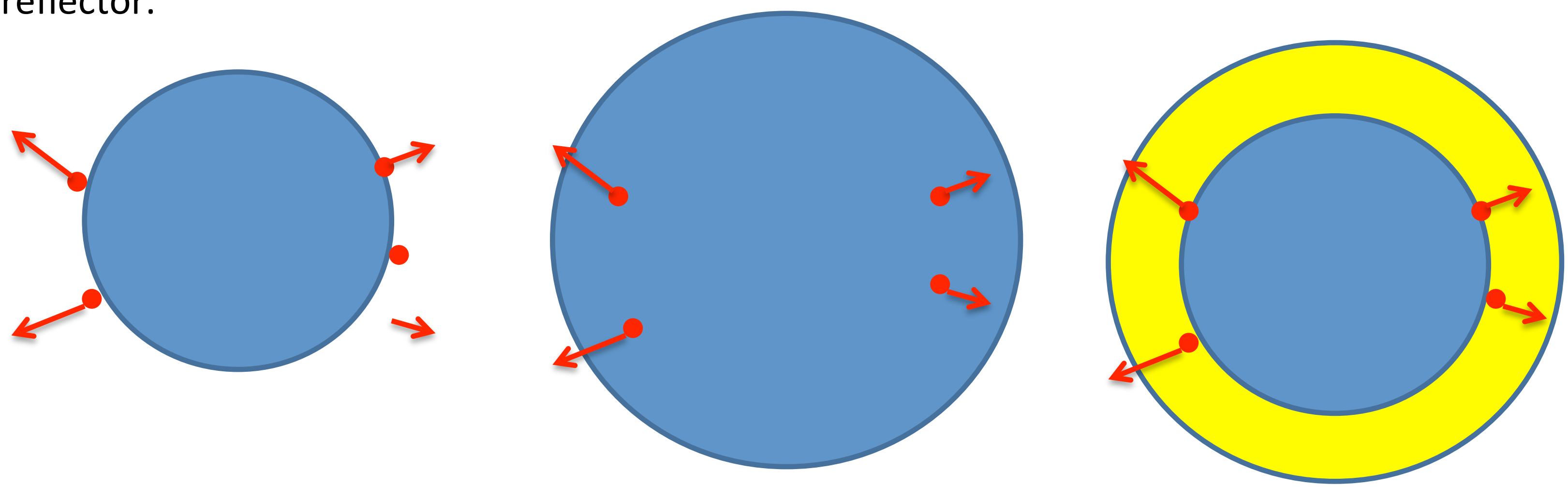
Criticality

The fission of one ^{235}U creates about 2.5 neutrons.
Among them, some escape. Among those which remain in the core, some induce a new fission, the others are capture by ^{235}U, ^{238}U or structure material.

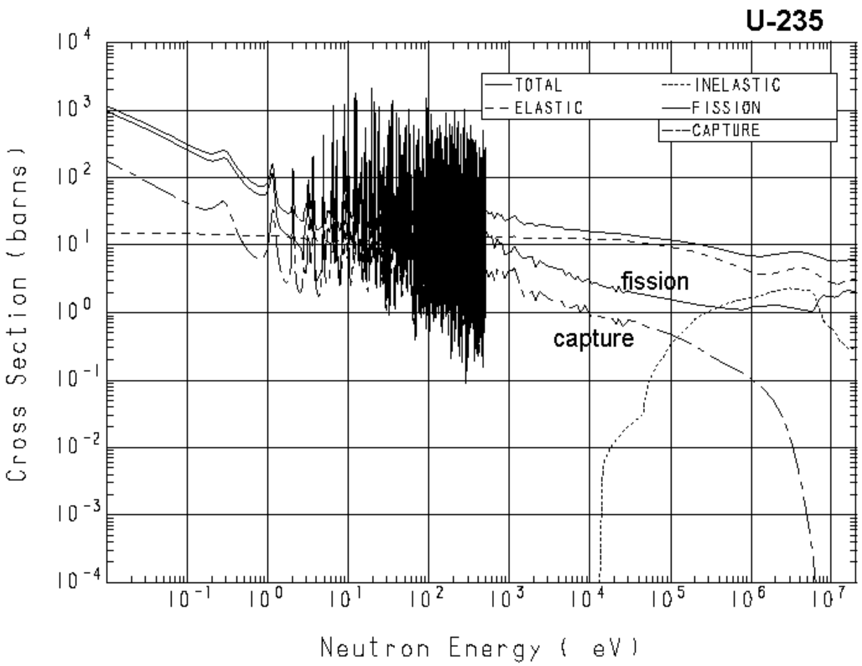
Criticality is obtained the chain reaction remains constant in intensity, i.e. if exactly 1 neutron among the 2.5 produced induces a new fission.

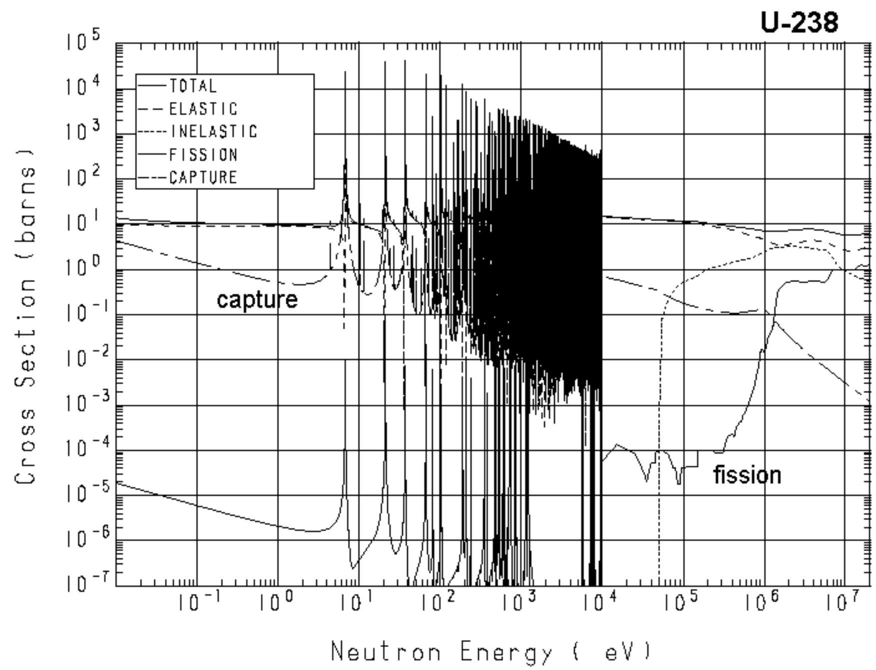
Since the proportion of escaping neutrons decreases when the volume increases, criticality is obtained for a given volume or mass, called critical mass.

Criticality can also be obtained by ajusting the enrichment, i.e. the proportion of neutrons which fission or are captured, or by using a better moderator (heavy water), or by adding a reflector.



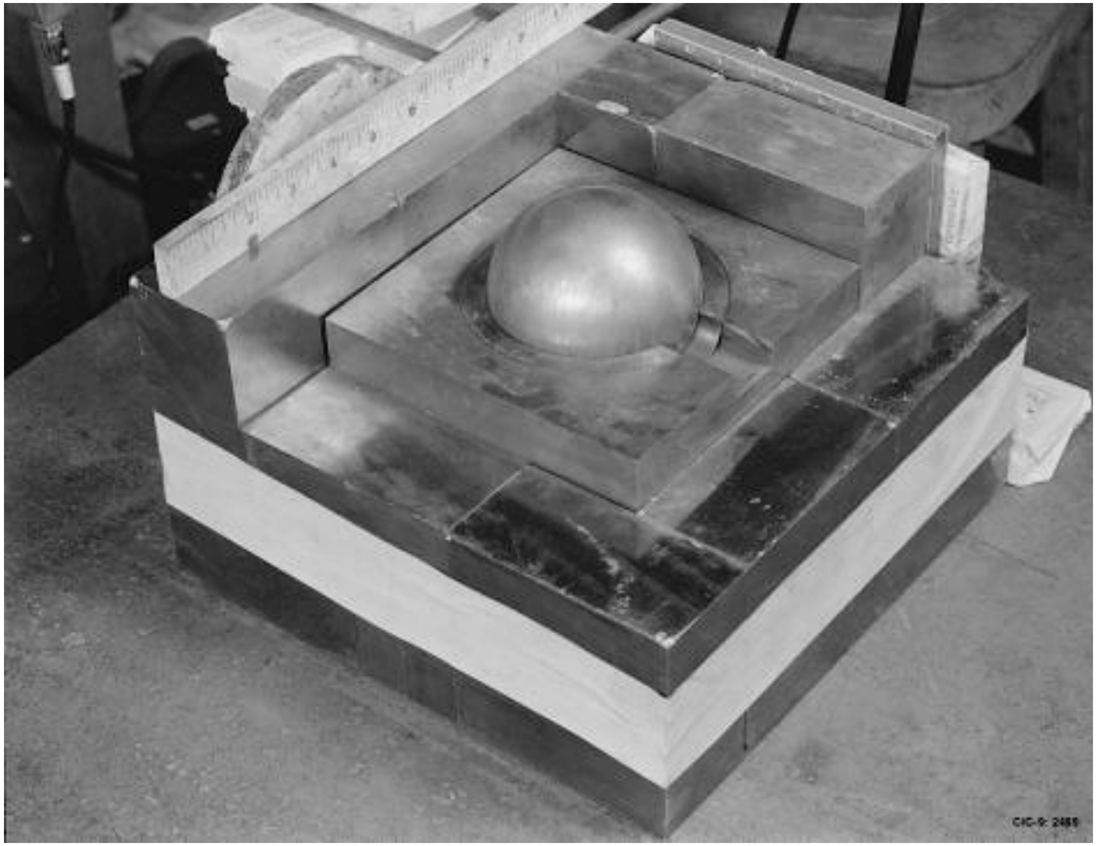
Criticality by enrichment





In a thermal reactor, most of the neutrons have a kinetic energy of 0.025 eV. At this energy, ^{235}U has a fission cross section much larger than capture, but ^{238}U only captures neutrons. In natural U, there is only 0.7% of ^{235}U. Therefore the fuel of a reactor has generally to be **enriched** in ^{235}U to reach the criticality.

Criticality by mass or by reflector



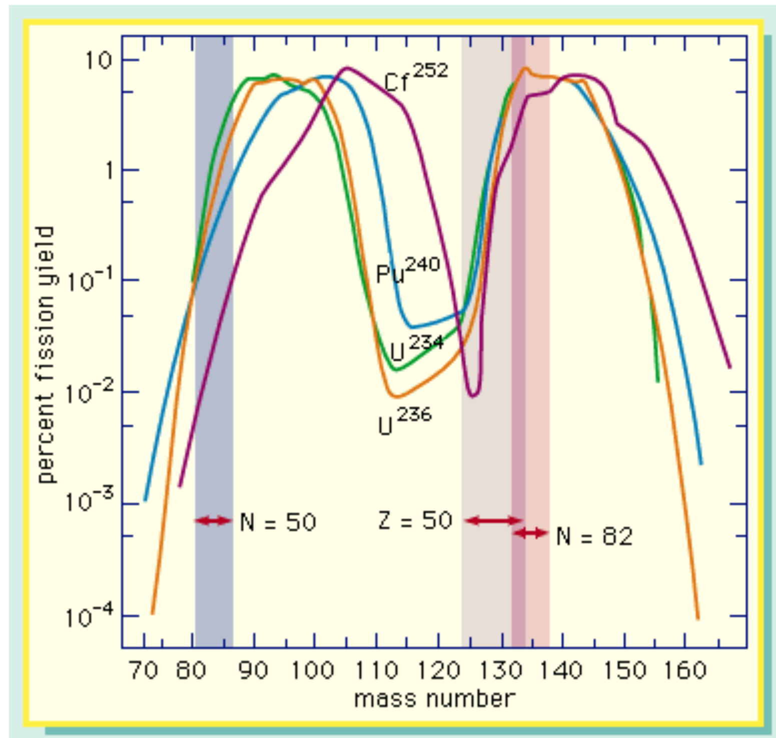
Harry Daghlian 21 août 1945

Louis Slotin 21 mai 1946

^{239}Pu 6,2 kg reflector: Tungstène carbide

Waste from fission : fission fragments

Because of shell effects in the nuclei, the mass distribution of fission fragments is not symmetric. Generally, a heavier fragment (mass about 140) and a lighter fragment (mass about 95) are produced



The light mass group shifts to higher masses as the mass of the fissioning nucleus increases, while the heavy group remains nearly stationary. The shaded areas show the location of the closed shells of 50 protons, 50 neutrons, and 82 neutrons (see text).

Isotopic distribution of fission fragments

When a nucleus fissions, it tends to break in two fragments with equal $\frac{A}{Z}$ ratios

the same as that of the fissioning nucleus.

This ratio is equal to 2,565 for ^{235}U

In the case of a fission in Rubidium (Z = 37) and Cesium (Z = 55)

this ratio corresponds to ^{95}Rb + ^{141}Cs but 2 - 3 neutrons are also produced.

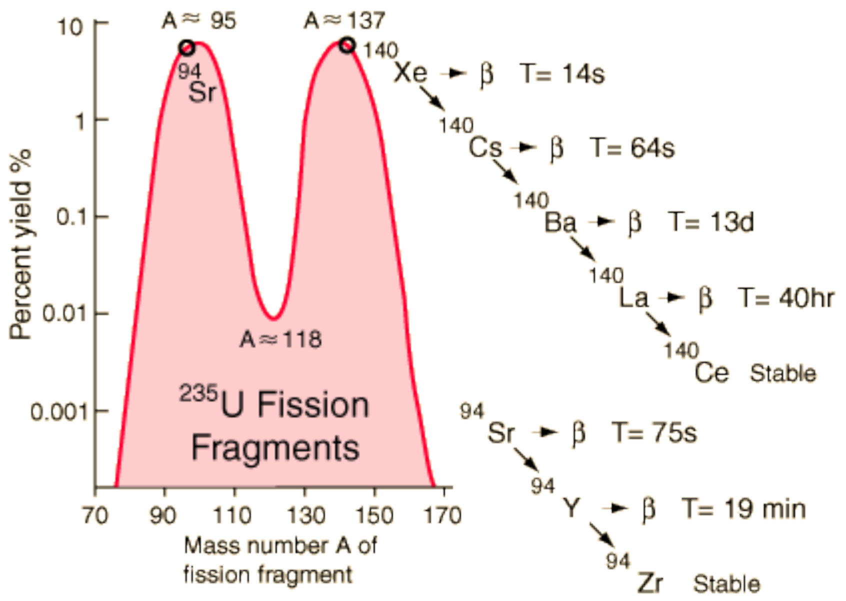
Actually, the proportion of isotopes of this two elements are:

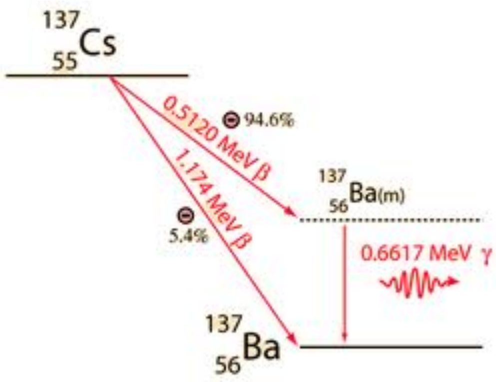
^{98}Rb	0,00024%		^{135}Cs	0,0004%	$2,3 10^{6}$ years
^{97}Rb	0,0038%				
^{96}Rb	0,168%		^{137}Cs	0,060%	30 years
^{95}Rb	0,764%		^{138}Cs	0,24%	
^{94}Rb	1,57%		^{139}Cs	1,31%	
^{93}Rb	3,07%		^{140}Cs	2,07%	
^{92}Rb	3,13%	4.49 s	^{141}Cs	2,92%	25 sec
^{91}Rb	2,23%		^{142}Cs	2,28%	
^{90}Rb	0,139%		^{143}Cs	1,40%	
^{89}Rb	0,205%		^{144}Cs	0,42%	
^{88}Rb	0,022%	17.8 min	^{145}Cs	0,076%	
^{87}Rb	0,0025	$4.9*10^{10}$ y	^{146}Cs	0,0076%	
			^{148}Cs	0,00013%	

while the only stable isotopes of Rb et de Cs are ^{85}Rb et ^{133}Cs

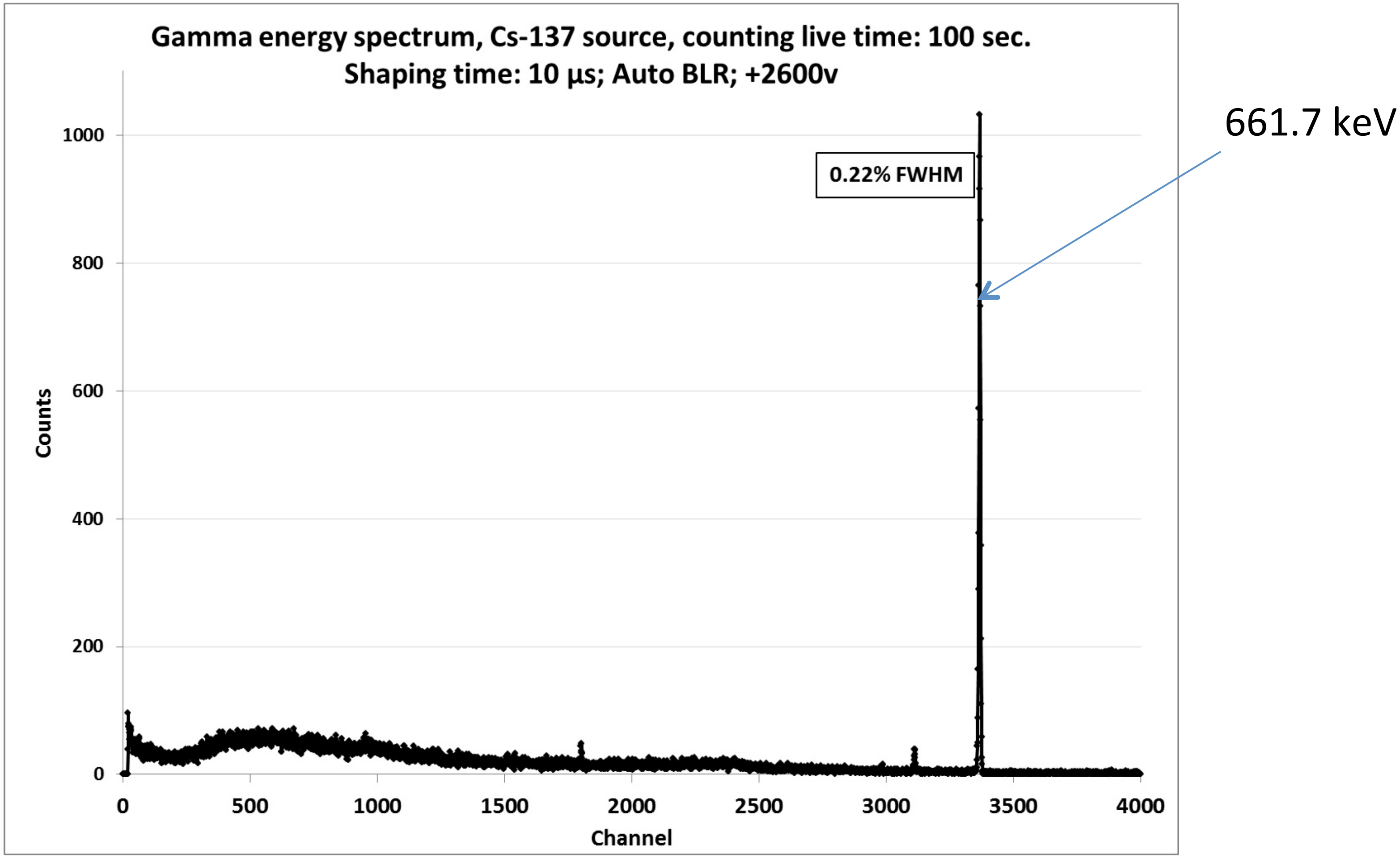
The isotopes produced with highest probability have generally short live times

Decay of fission fragments





^{137}Cs γ spectrum measured by HPGe detector



^{137}Cs in Bordeaux wine

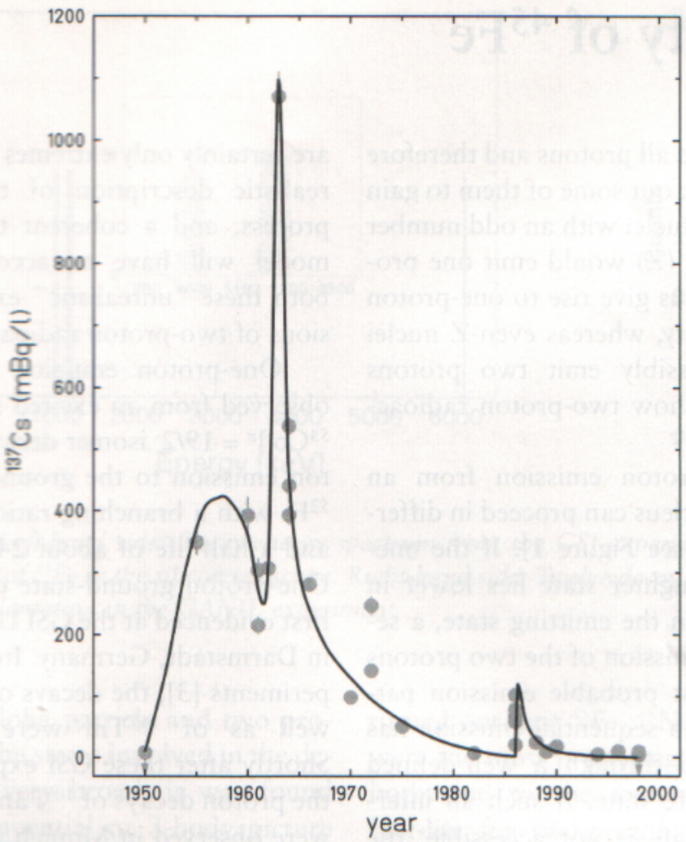
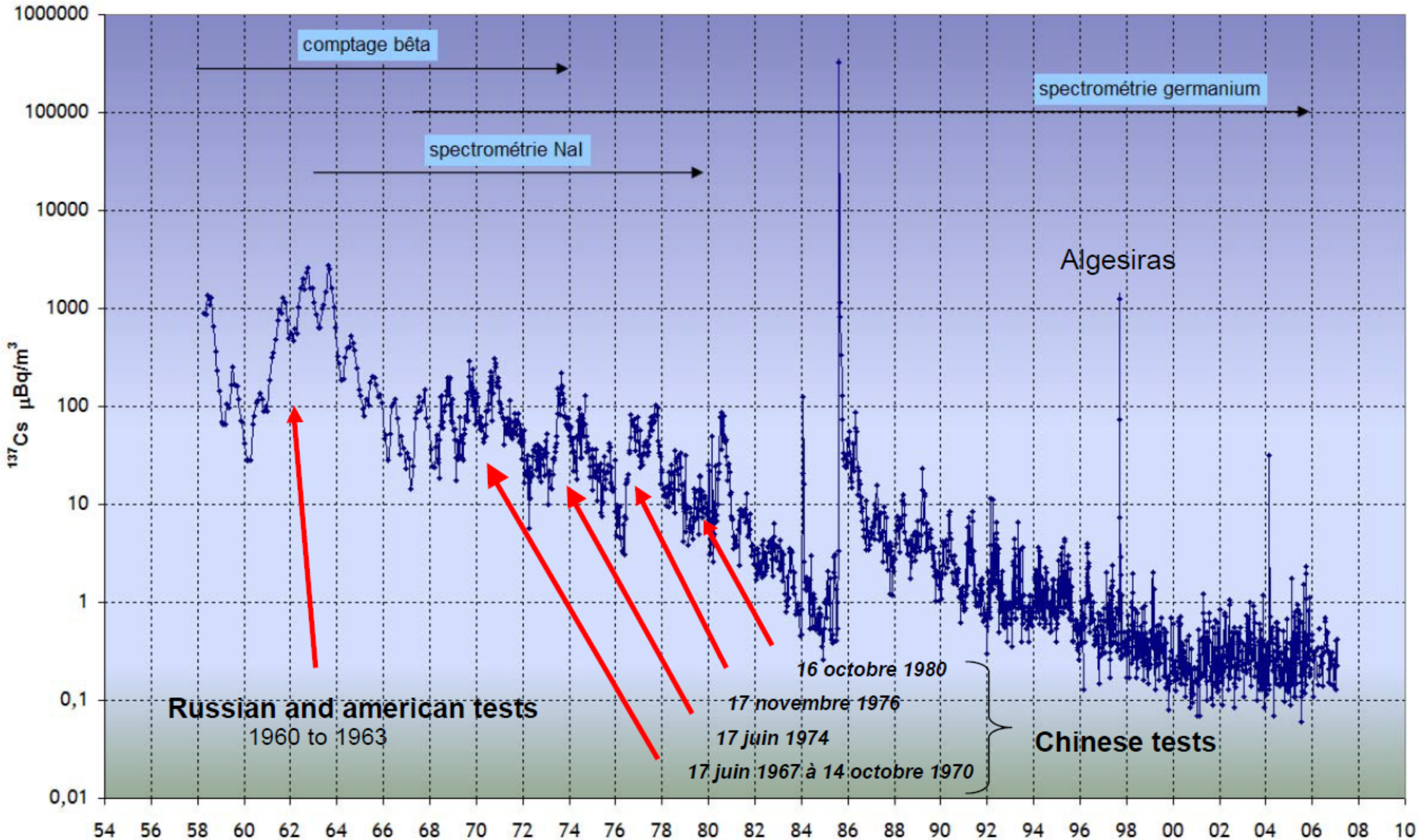


Figure 1. *Cesium activity in the Bordeaux wine as a function of the millésime.*

^{137}Cs in air at Orsay



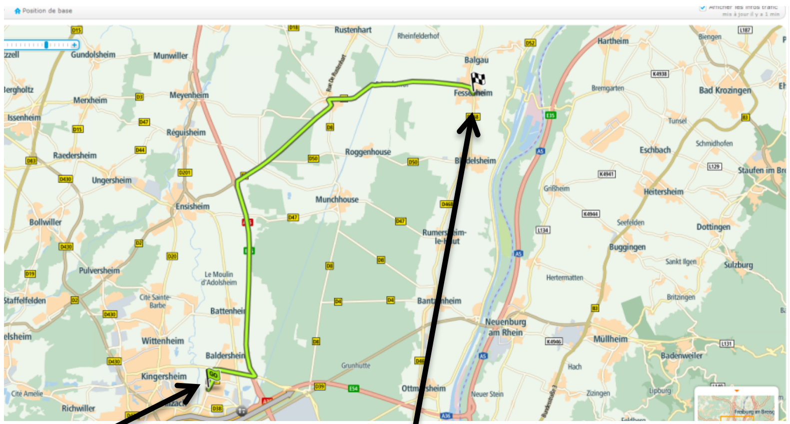
From Gurriaran, IRSN,European Summer Campus 1999

Diapers in the garbage

^{99}Tc

^{131}I

5 x 0.75 µSv/h



Sausheim

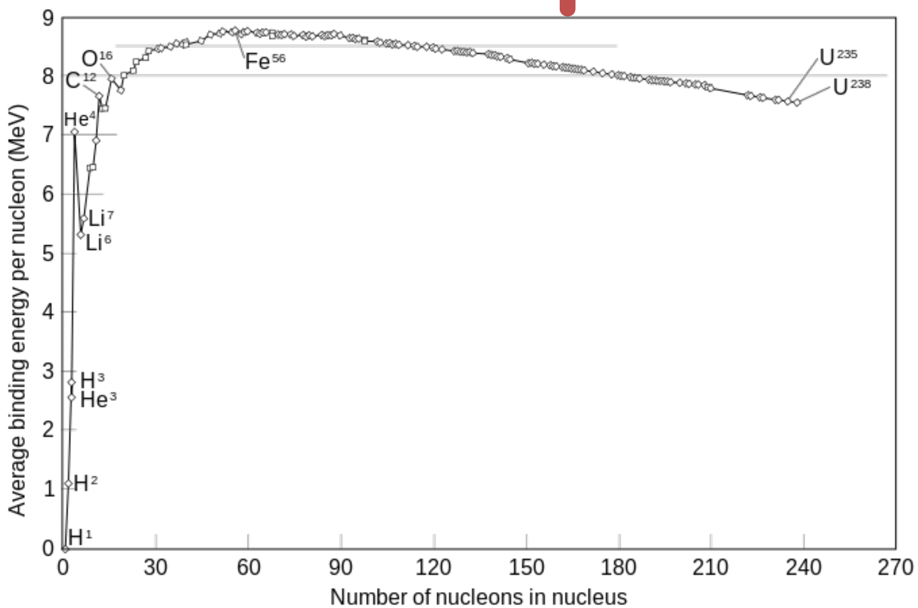
Fessenheim

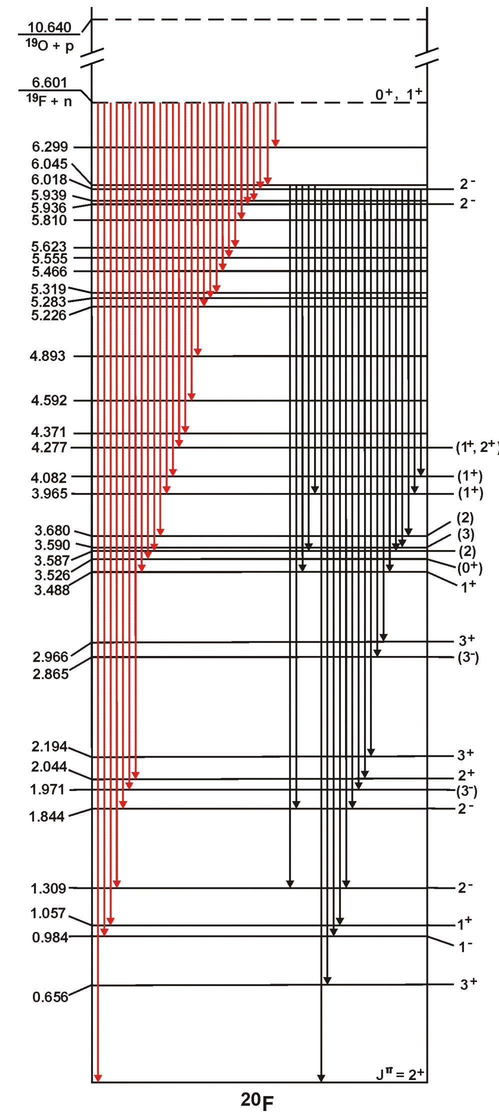
Fission reactions

Capture

Diffusion

The capture reaction





When a nucleus A (here ^{19}F) is hirt by a neutron, the nucleus A+1(here ^{20}F) may be formed. It will be created with an excitation energy of the order of 6-8 MeV, and will emit γ rays until it reaches the ground state. The path toward it is variable.

Bateman's Equation

Atomic density of the isotop with atomic number Z and atomic mass A :

$$\frac{dN_i}{dt} =$$

$P(Z,A)\Sigma_f \Phi$ — Production by fission

$-\lambda(Z,A)N_i$ — Loss by decay

$-\Sigma_a(Z,A)\Phi$ — Loss by capture

$+\Sigma_c(Z,A-1)\Phi$ — Production by capture by nucleus A-1

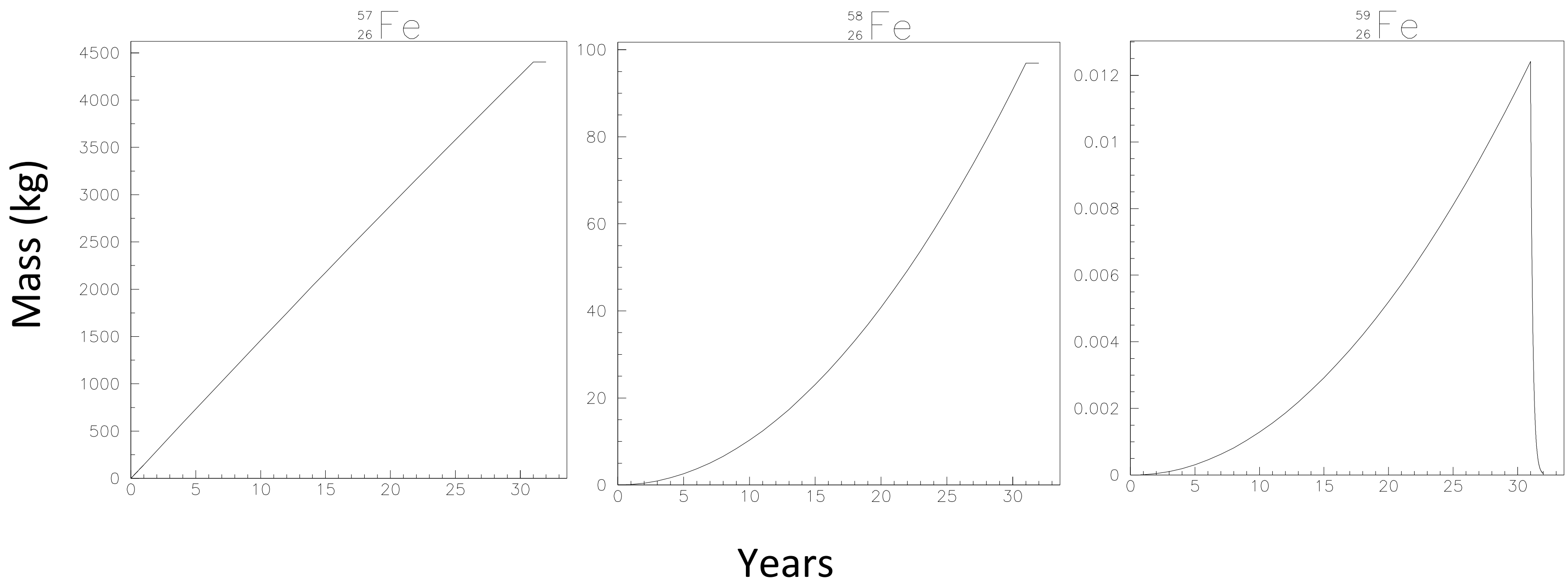
$+\lambda_\beta(Z-1,A)N(Z-1,A)$ — Production by β- decay

$+\lambda(Z+2,A+4)N(Z+2,A+4)$ — Production by α decay

$+\ldots$

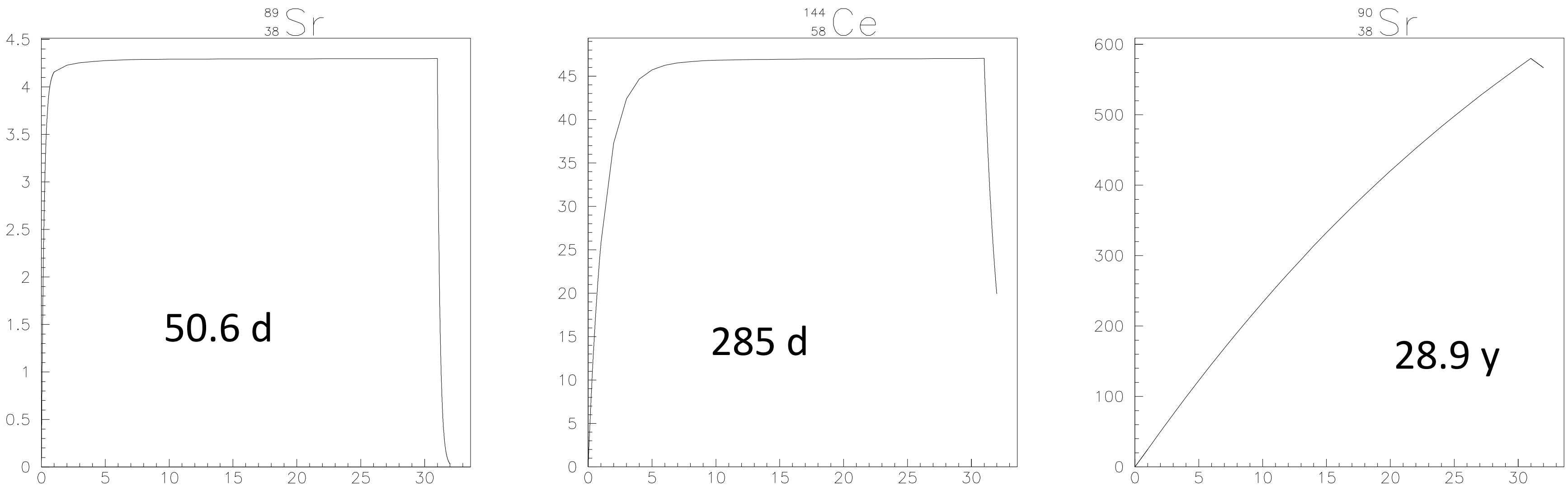
Structure material

Example : transmutation of ^{56}Fe



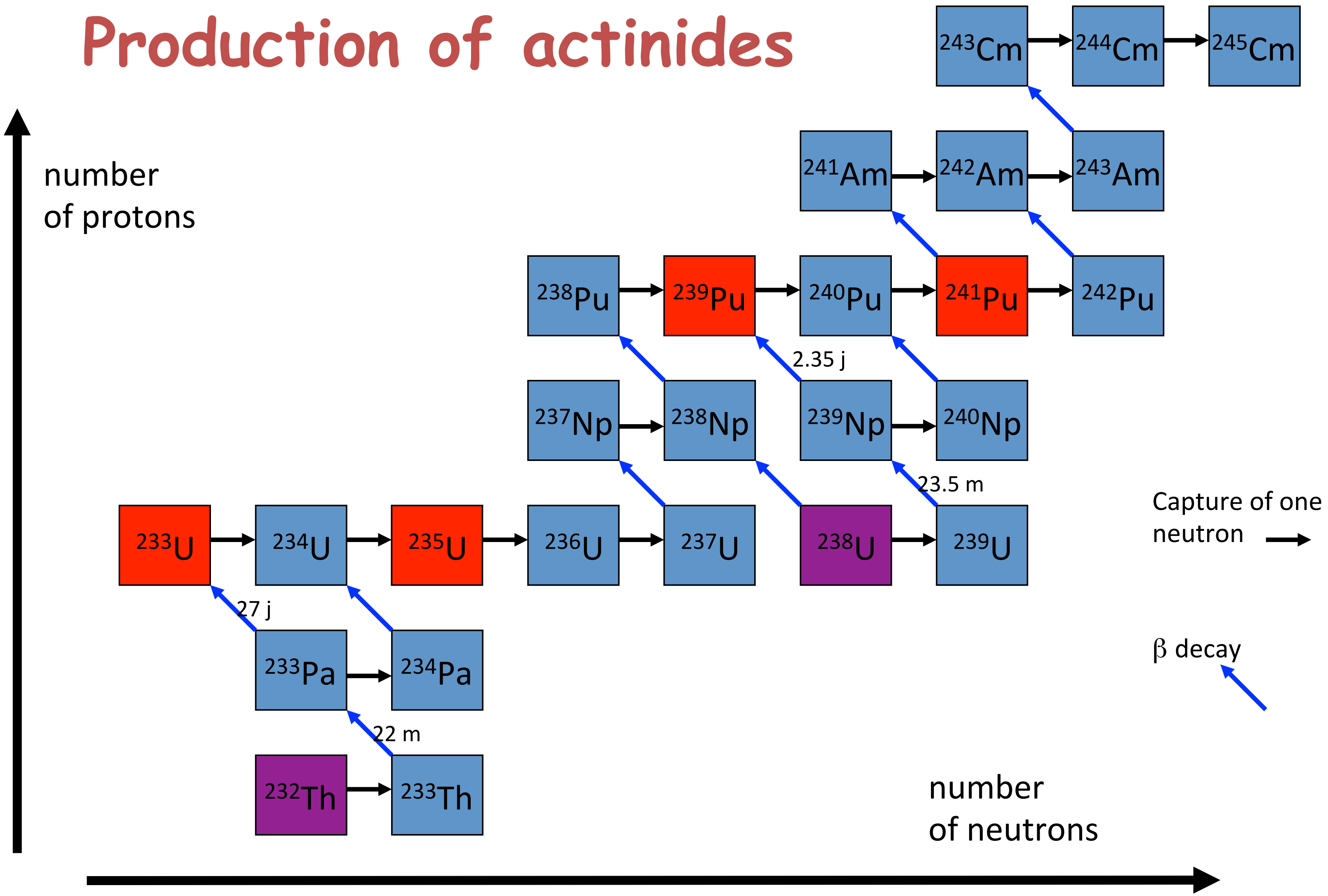
^{59}Fe decreases to ^{59}Co, which is stable. After a few years, pure iron extracted from a nuclear reactor is less radioactive than concrete, or … the human body.

Radioactive elements

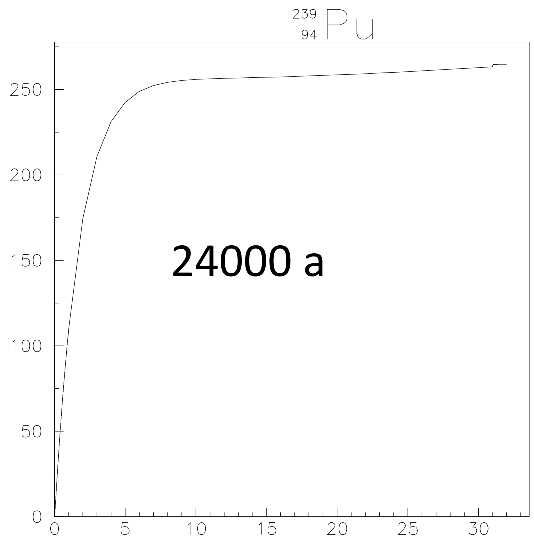


The atomic density of unstable isotopes is the result of a competition between production and decay. It reaches a plateau after several periods. Once the reactor is stopped, they **continue to heat** the core also during several periods.

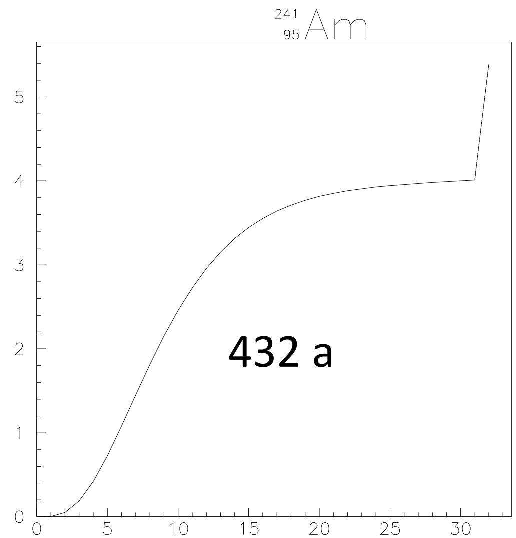
Production of actinides



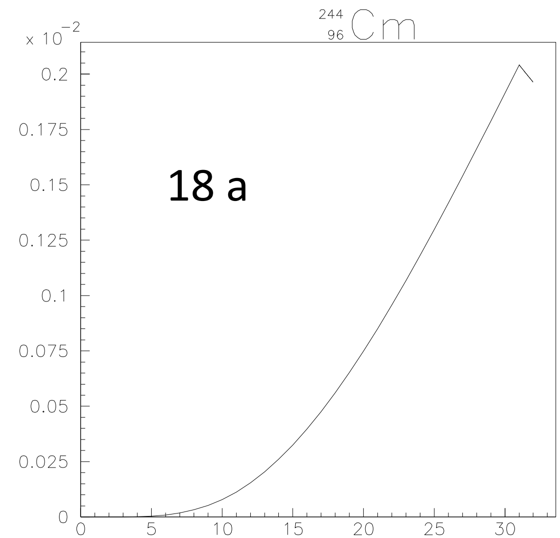
Actinides



σ_f=747 b



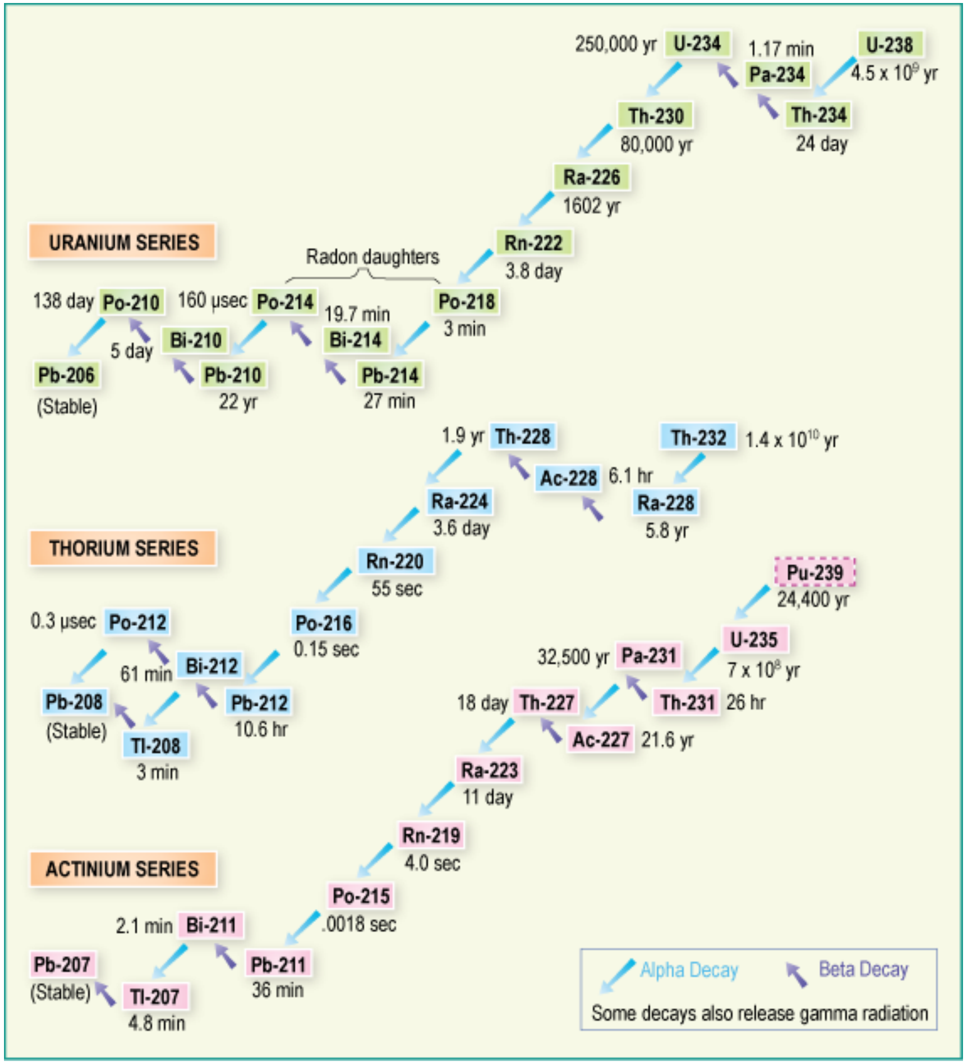
Produced by the decay of ^{241}Pu (90 years) which has σ_f=1000 b
Its σ_c=639 b



Produced after capture by^{243}Am σ_c=77 b

The atomic density of certain isotopes is the result of the competition between several mechanisms. Since some of these isotopes have a large capture cross section, the fuel must be recycled regularly.

Decay of actinides



Fission reactions
Capture
Diffusion

Elastic scattering

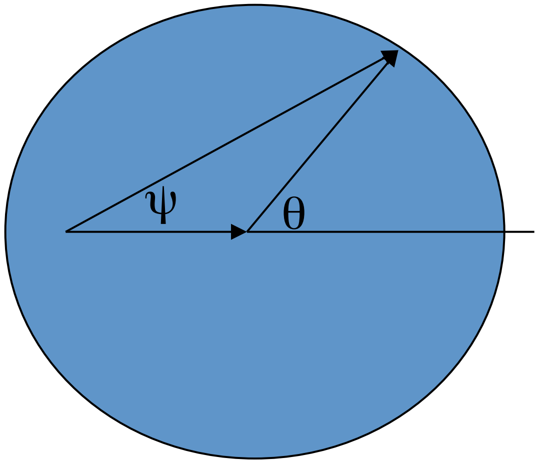
The nucleus is scattered by a nucleus with atomic mass A

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 :

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

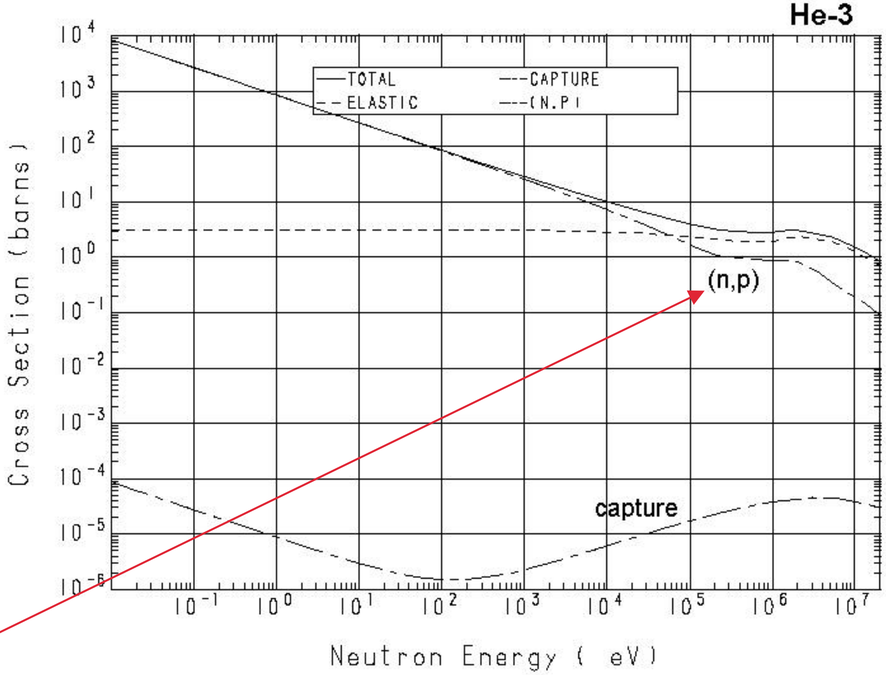
Particular case : if $A = 1$ and $\theta = 180°$ $E_2 = 0$



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.

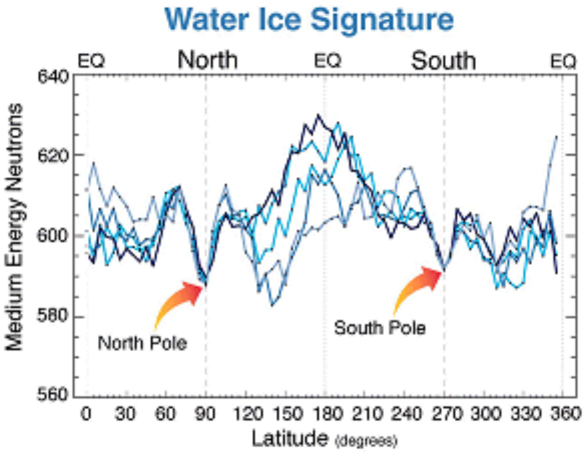
An enhanced neutron rate at backward angles reveals the presence of hydrogen, and thus water, hydrocarbonates or explosives.

Backscattering on Hydrogen

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

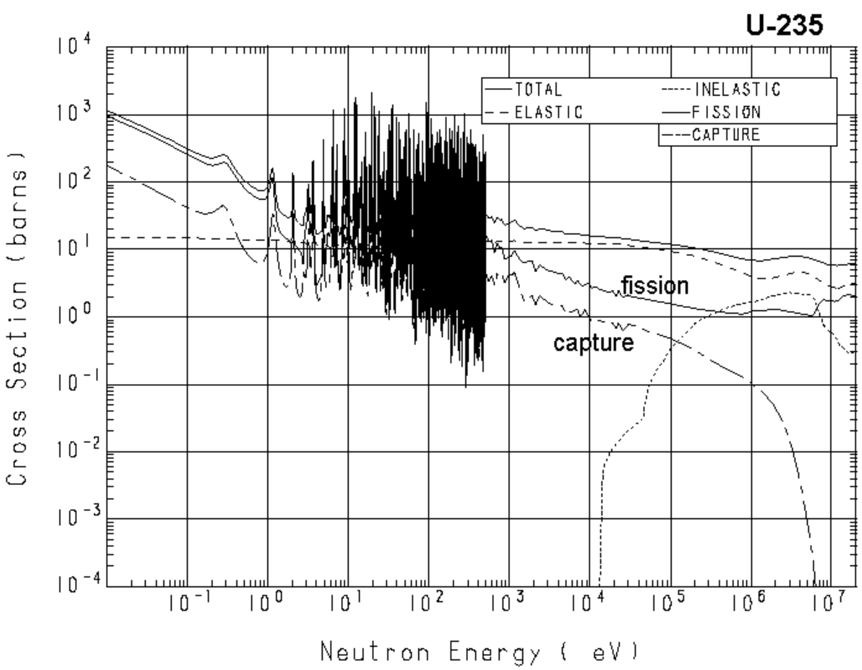
Landmine detector (Delft University, 2002)

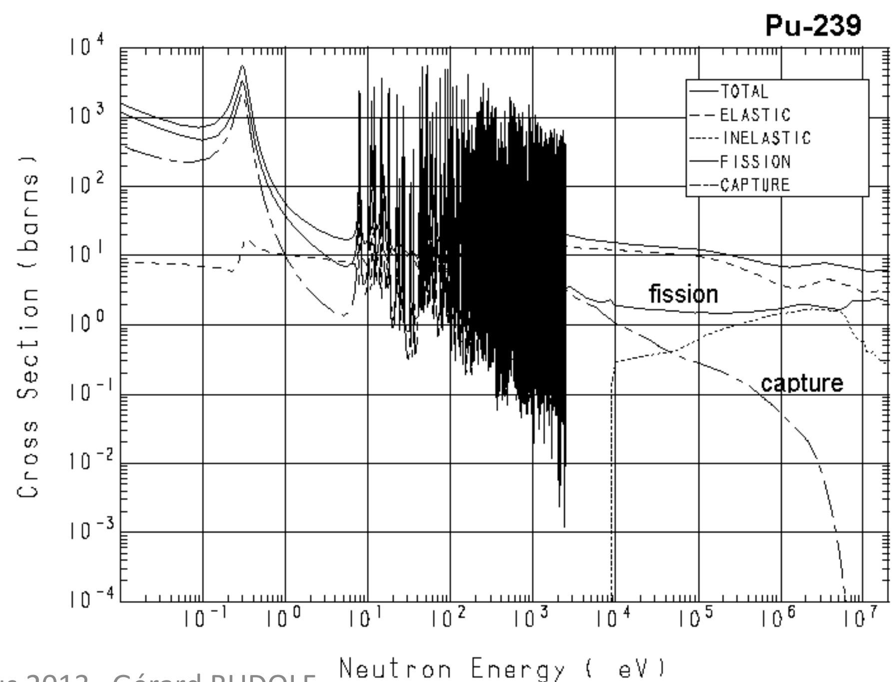
Lunar
Prospector
(Nasa)



Moderation

To reach criticality, the fission cross section must be sufficiently larger than the capture cross section.
All ^{235}U fueled reactors presently in operation work in the thermal region. It would have been possible to build reactors working in the fast region.
^{239}Pu fueled reactors can only work in the fast region.
To reach the thermal region, one uses **moderators**.

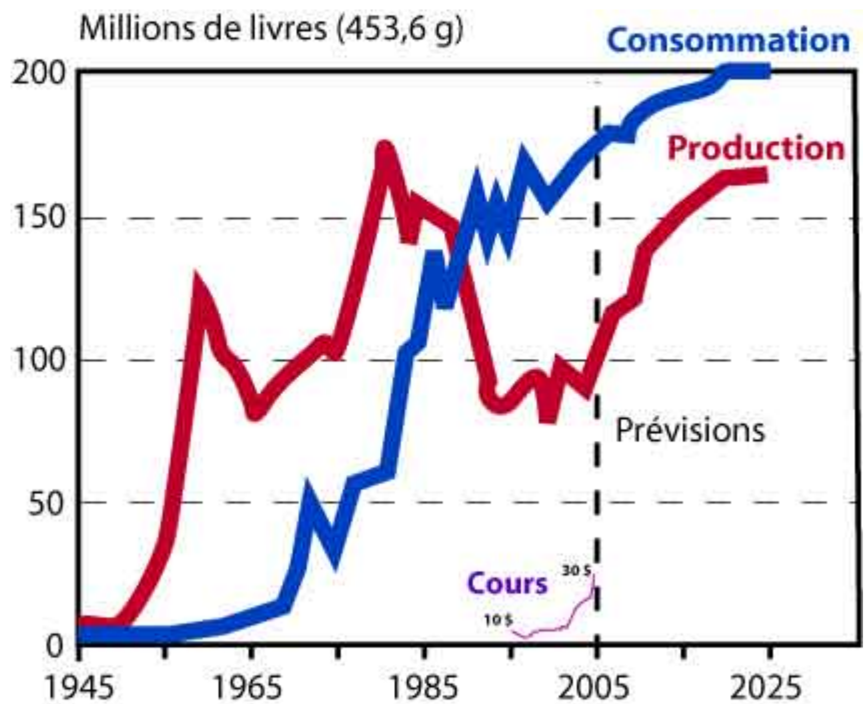




PART 2

Perspectives

Uranium Reserves To Be Over By 2050 ?



L'Expansion, Paris, octobre 2005, n °701

The proven reserves of uranium will last less than 30 years. Current nuclear plants consume around 67,000 tons of high-grade uranium per year. With present uranium deposits in the planet having been estimated at 4-5 million tons, this means the present resources would last 42 years.

February 1st, 2012 | HumanEconomics |

Recycling and transmutation

La Hague

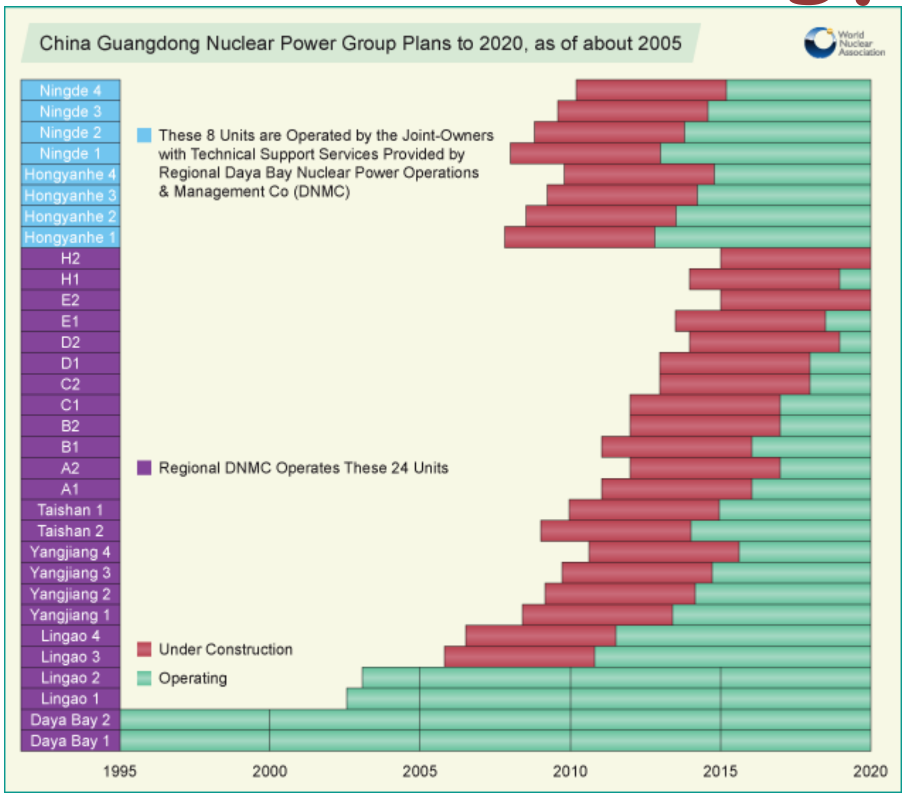
Once through

Fast reactor

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 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.

The future of nuclear fission energy



(In China) by around 2040, PWRs are expected to level off at 200 GWe and fast reactors progressively increase from 2020 to at least 200 GWe by 2050 and 1400 GWe by 2100.

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Categorised | Nuclear Power
Tags | Barack Obama, GE Hitachi, Gen4 Energy, General Atomics, westinghouse

US Government provides $3.5m for nuclear reactor projects

Posted on 01 July 2013 by Priyanka Shrestha

The US Government has announced funding worth $3.5 million (£2.3m) for four advanced nuclear reactor projects in the country.

Led by GE Hitachi, General Atomics, Gen4 Energy and Westinghouse, the projects will address key technical challenges to designing, building and operating the "next generation" of nuclear reactors.

The US Department of Energy's latest move is part of President Barack Obama's plans to cut carbon pollution and spark innovation across a wide variety of energy technologies.

Energy Secretary Ernest Moniz said: "Public-private research in advanced nuclear reactors will help accelerate American leadership in the next generation of nuclear energy technologies and enable low carbon nuclear power to be a significant contributor to the US energy economy."

General Atomics will conduce research and development on the material used for fuel rod cladding – the outer layer of the fuel rods, standing between the coolant and the nuclear fuel – and GE Hitachi's project will include the development of high temperature insulation materials and analysis tools to help design and manufacture electromagnetic pumps for liquid-metal-cooled nuclear reactors.

Gen4 Energy will conduct research and development on natural circulation designs for advanced nuclear reactors and develop computer models that will help visualise natural circulation flow and integrate it into safe, reliable reactor designs.

A recent survey found more than a third of the British public said they would support Government subsidy for the construction of new nuclear power plants in the UK.

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July 2013

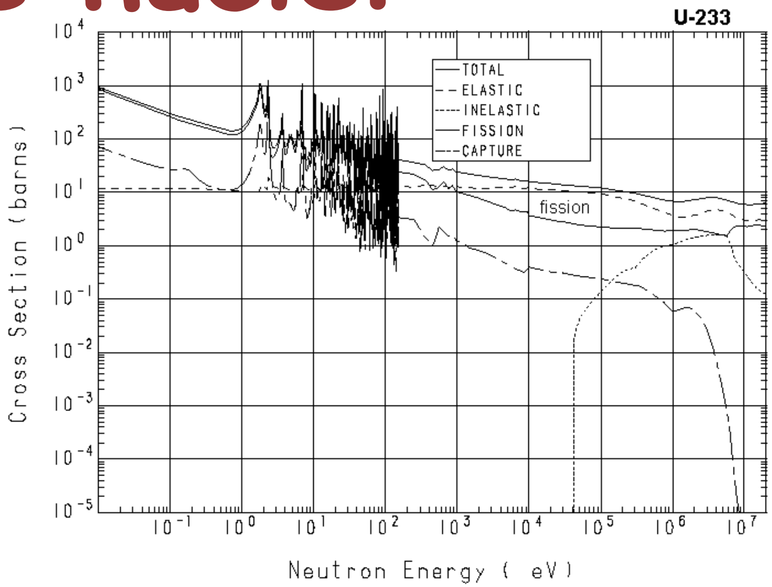
Other fissile nuclei

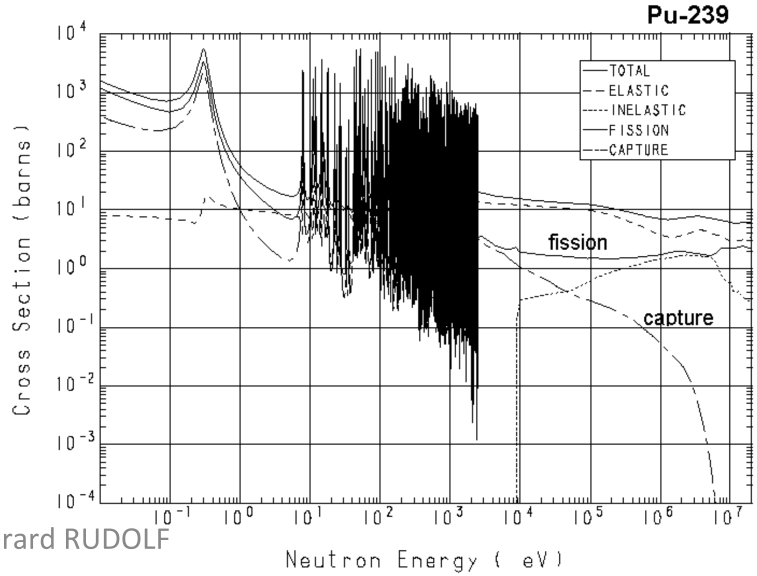
^{233}U, ^{239}Pu and ^{241}Pu are also fissile.
They do not exist in nature.

^{239}Pu has been produced in large quantities for military purposes

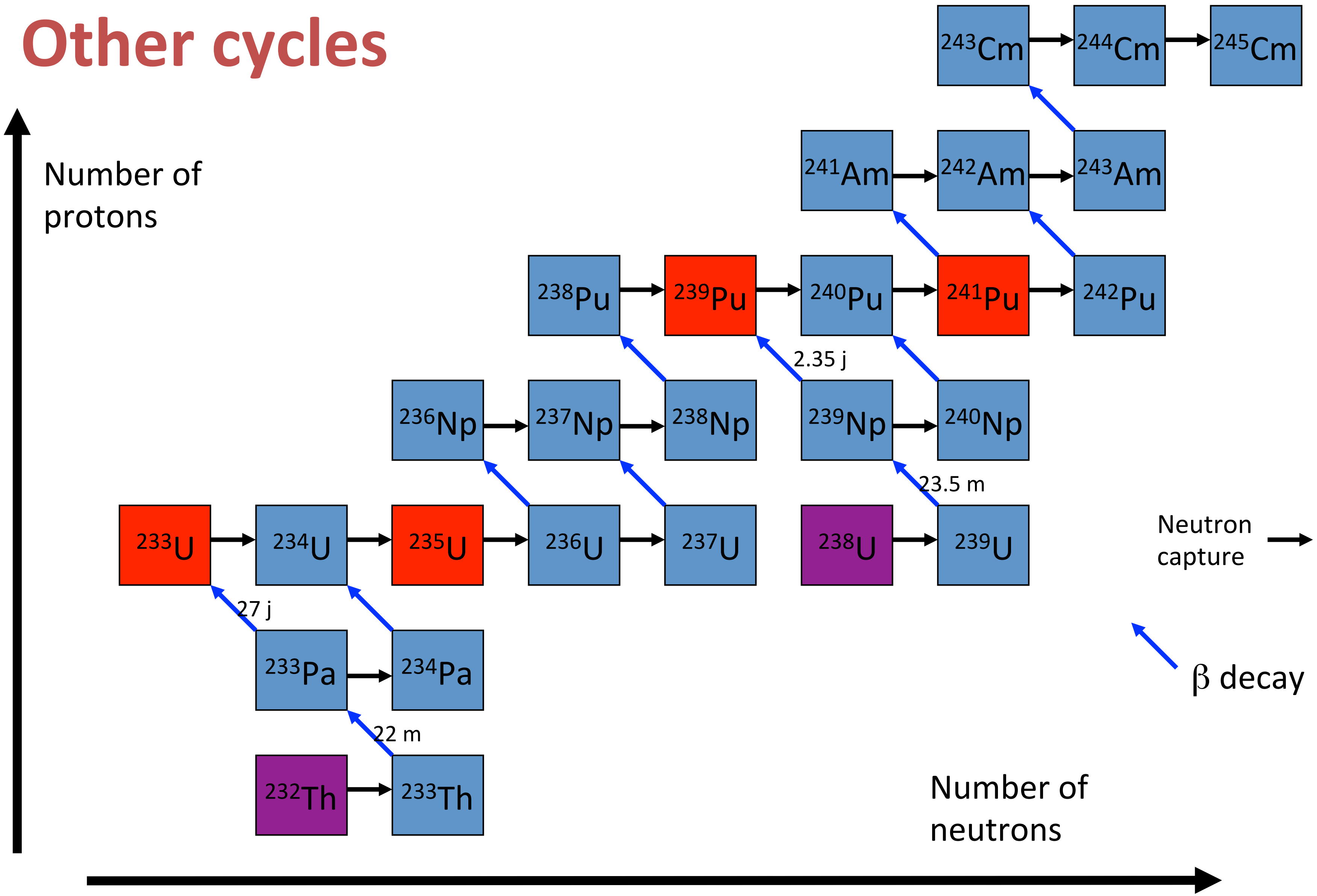
^{239}Pu is produced through neutron capture by ^{238}U
^{233}U is produced through neutron capture by ^{232}Th

Reactors which produce electricity and ^{239}Pu or ^{233}U from ^{238}U or ^{232}Th are called breeder (surgenerator)





Other cycles



Economy of neutrons

^{235}U burning thermal reactor

100 fissions create 250 neutrons, among which

•100 neutrons fission 100 ^{235}U nuclei

•70 neutrons are captured by ^{238}U and form 70 ^{239}Pu nuclei

•75 neutrons are captured by ^{235}U or by the structure material

•5 neutrons escape the core

^{239}Pu burning fast reactor

100 fissions create 300 neutrons, among which

•100 neutrons fission 100 ^{239}Pu nuclei

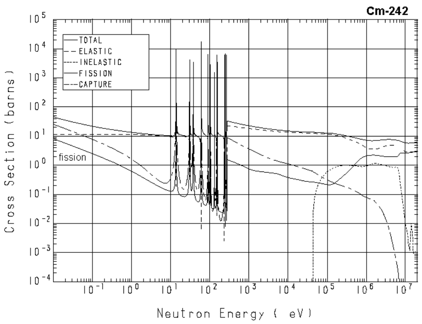
•100 neutrons are captured by ^{238}U and form 100 ^{239}Pu nuclei

•40 neutrons are lost by capture on other material

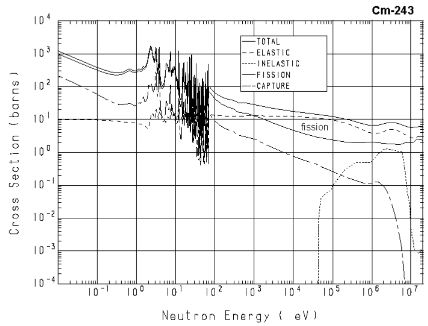
•60 neutrons escape the core, and can be captured in the coverage

The 60 escaping neutrons can either form more ^{239}Pu **or transmute waste**

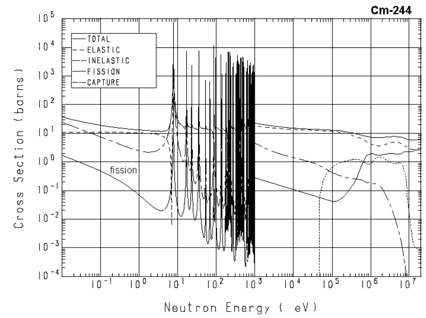
All minor actinides produced by a PWR fission at high energy



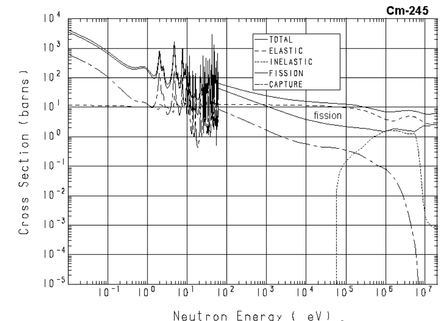
163 d



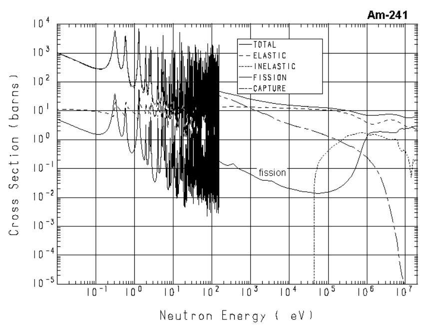
28.5 years



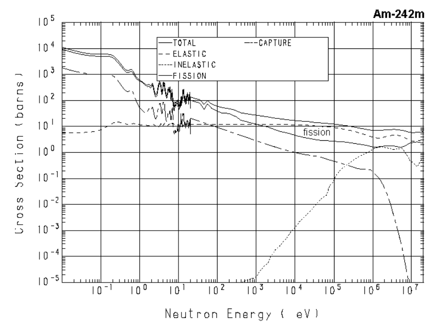
18.1 years, 0.5 kg/year



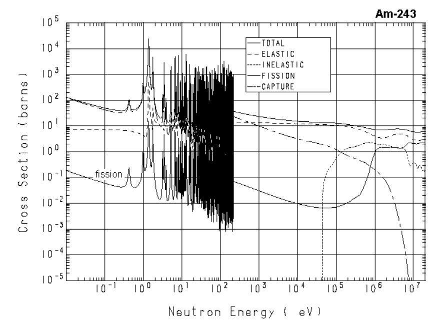
8500 ans, 0.1 kg/year



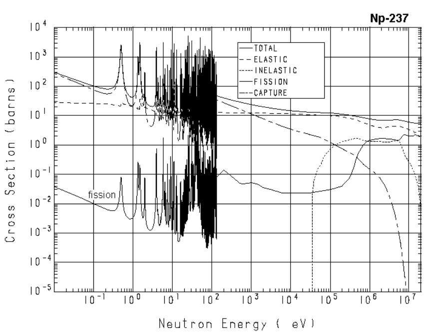
432 years, 4.4 kg/year



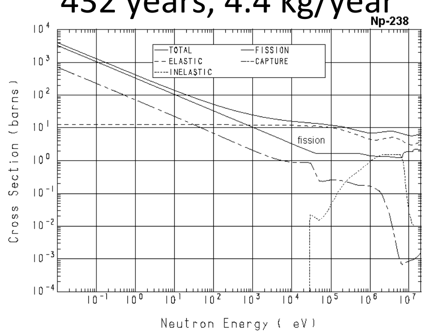
141 years



7380 years, 2.3 kg/year



$2*10^6$ years, 8.8 kg/year



2.1 d

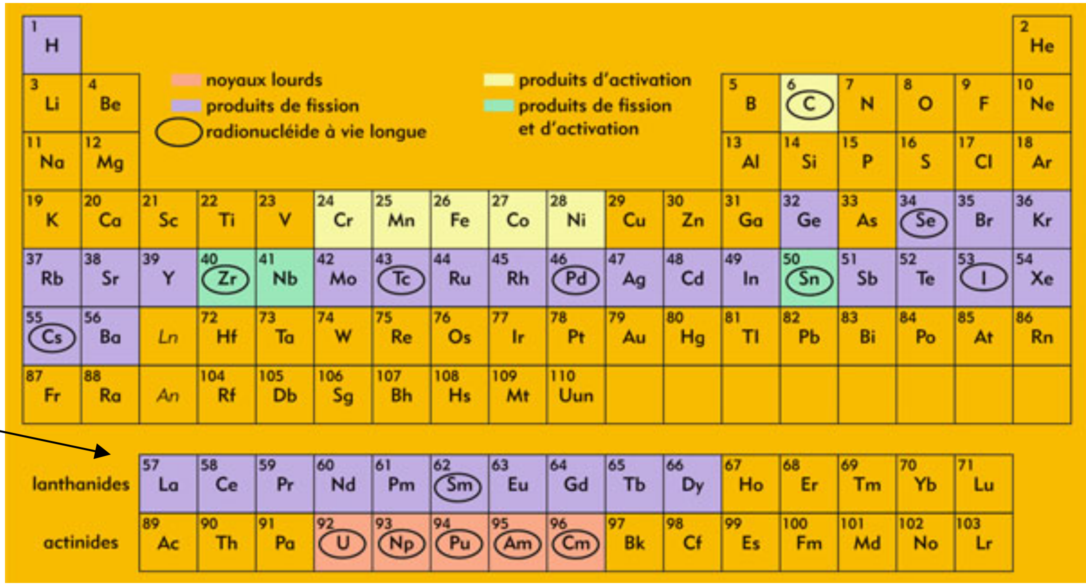
Waste

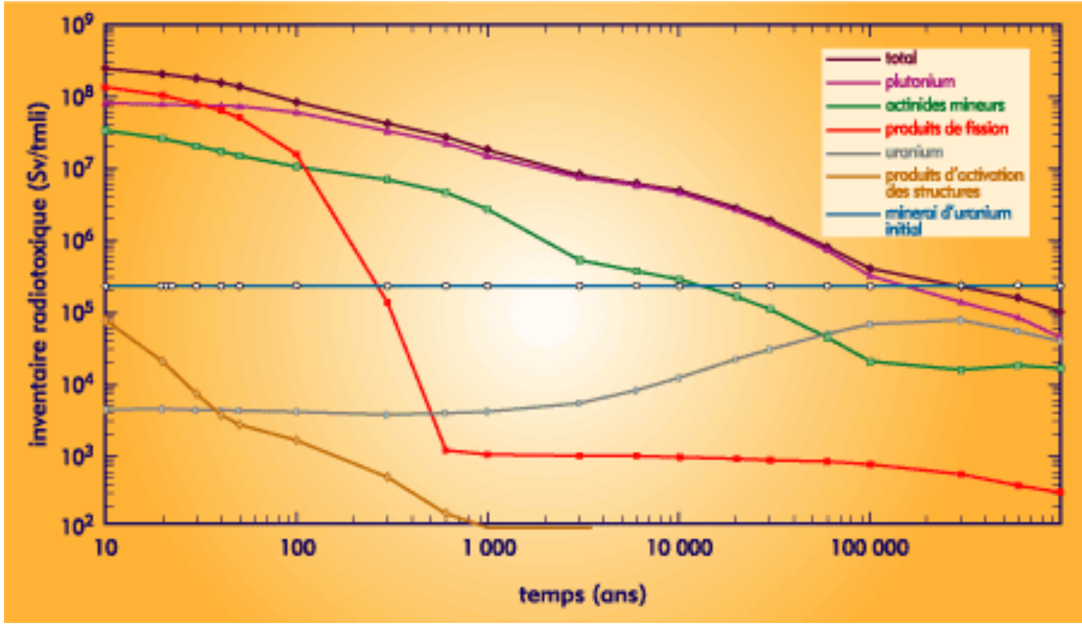
Structure material

Fission fragments

Actinides

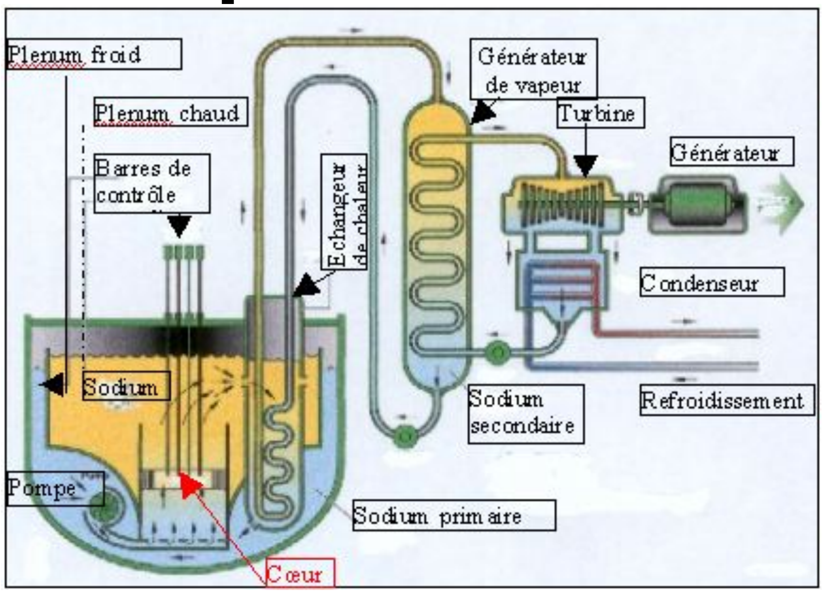
Biologic effect in Sieverts





“Closed” Cycle

Used fuel



Fast Reactor

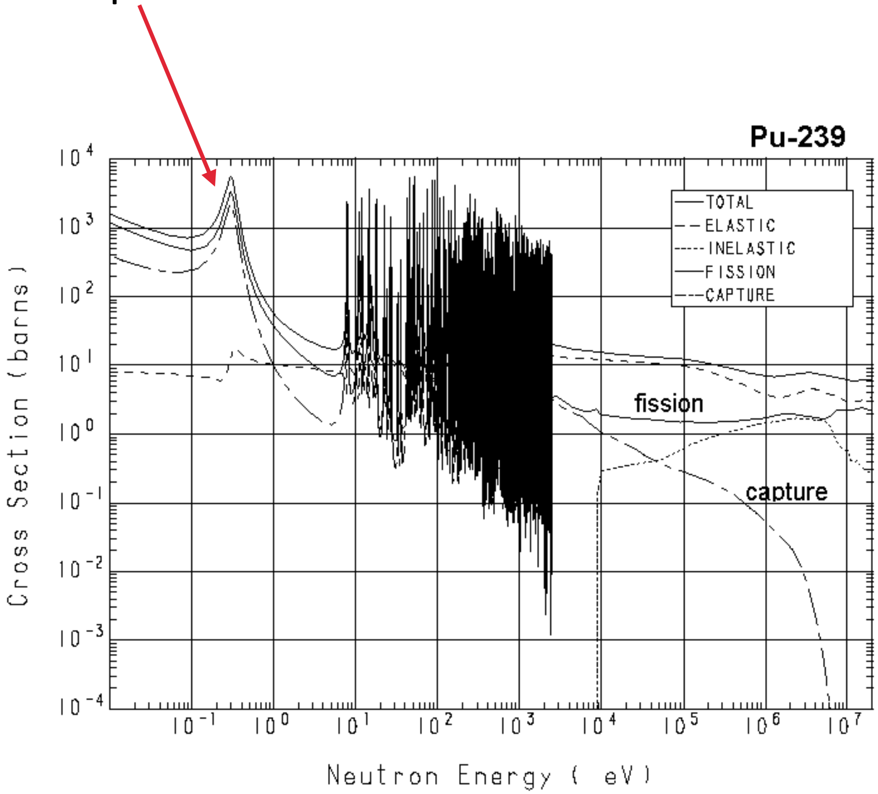
U + Pu + Minor Actinides

Fission Fragments

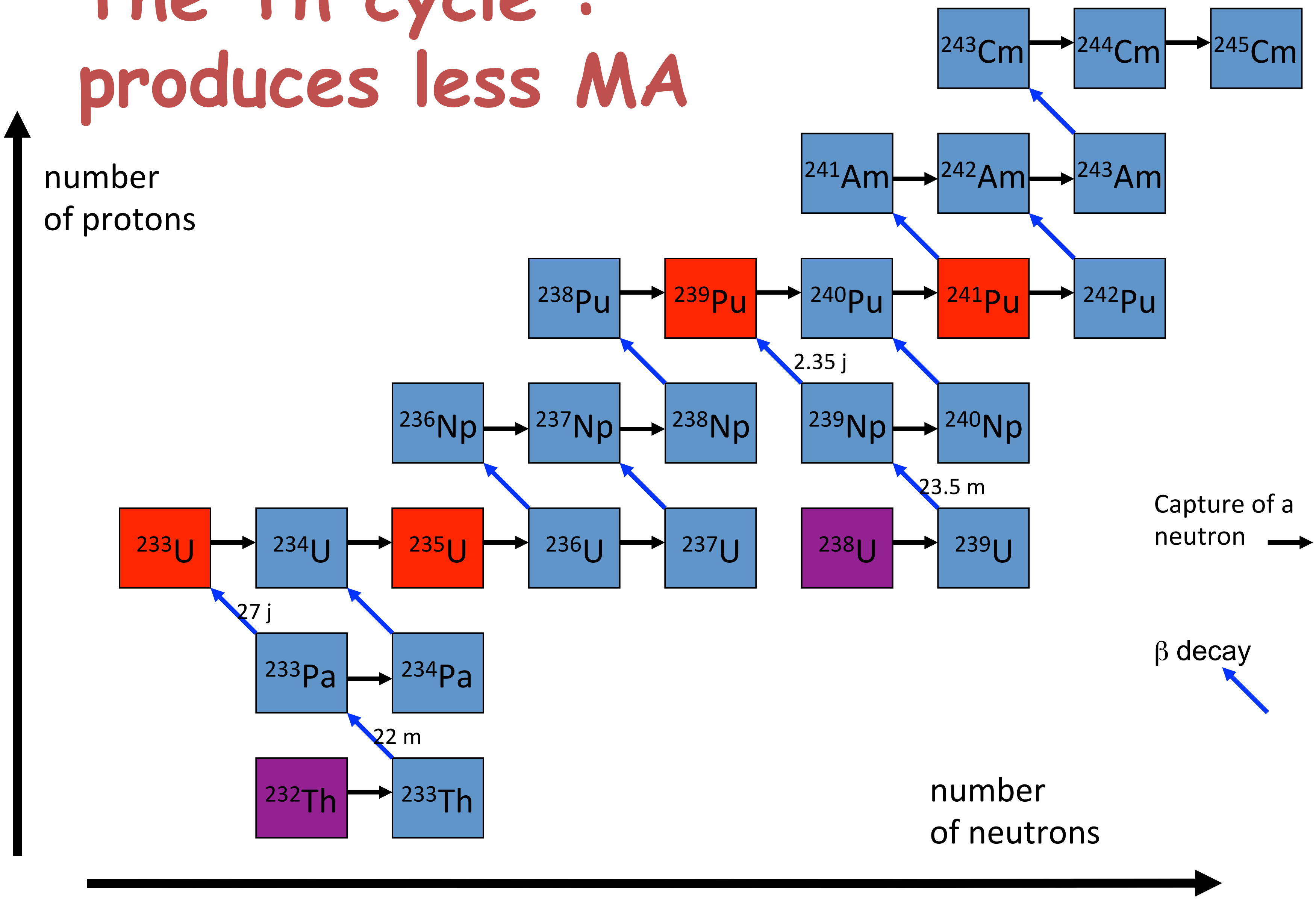
The U/Pu cycle

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 because one needs a fast spectrum



The Th cycle : produces less MA

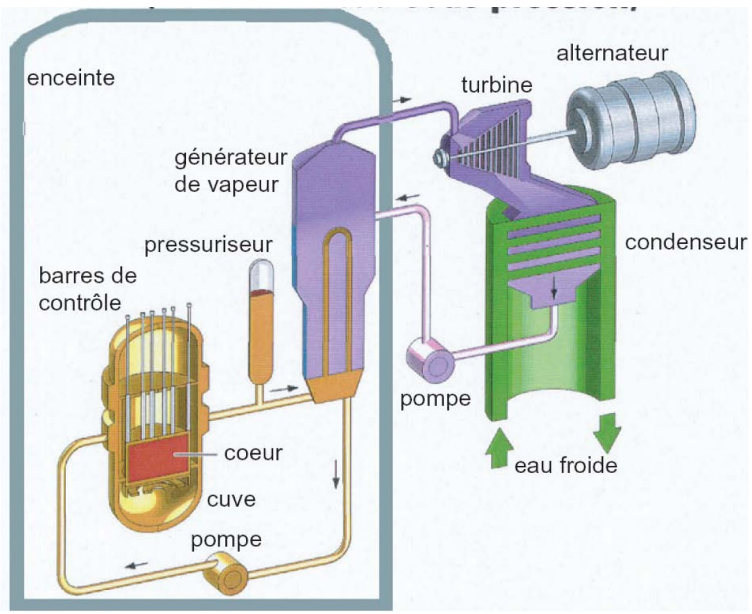


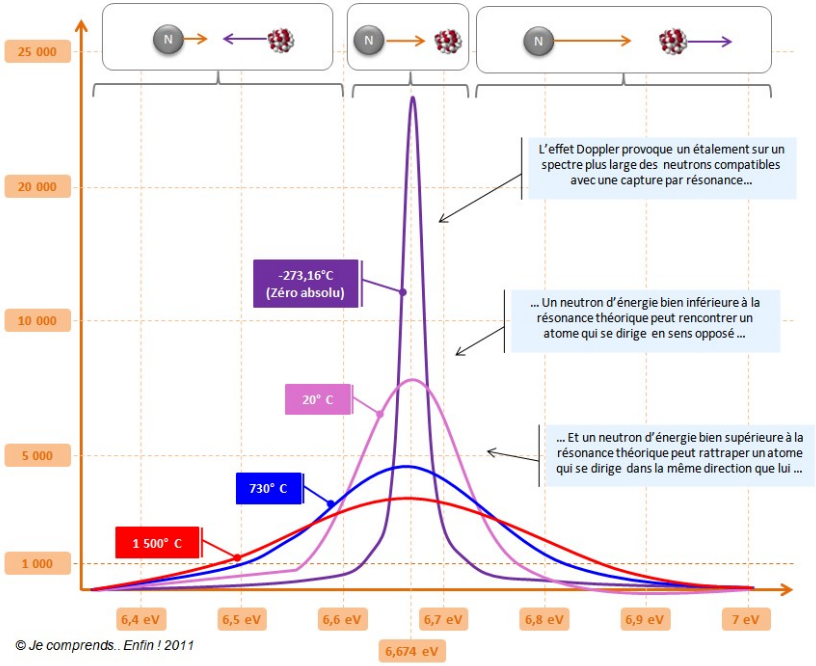
Safety of reactors

Active safety:
relies on sensors, automated or manual intervention

Passive safety:
relies on basic laws of the reactor physics

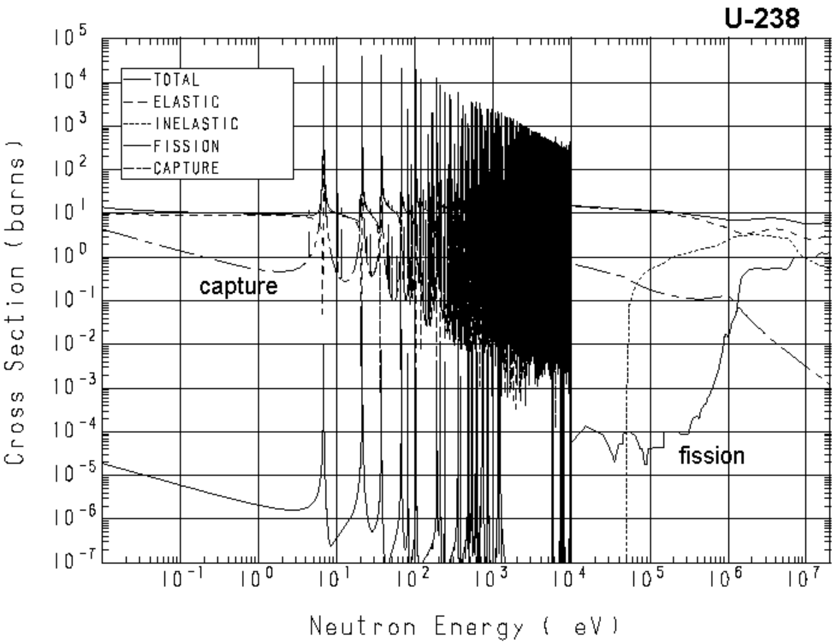
Doppler effect

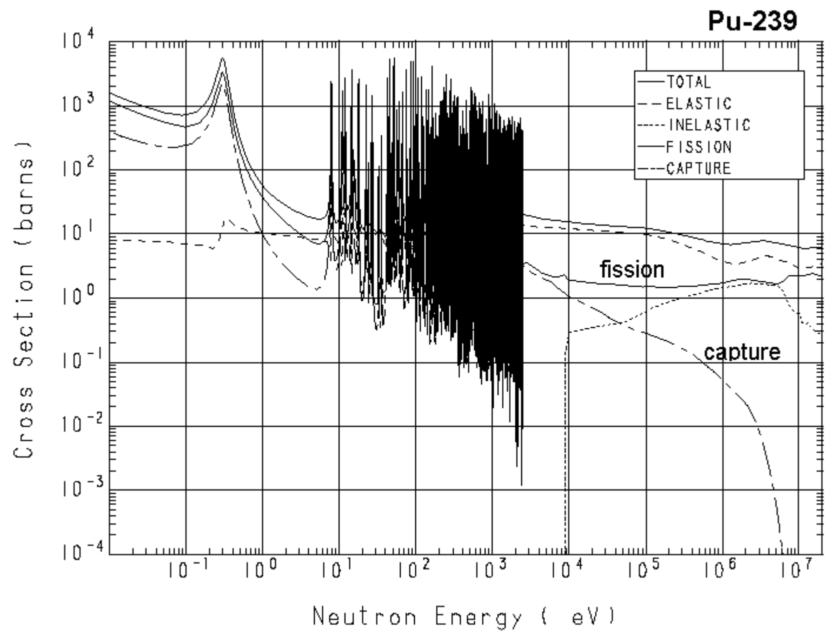




When the secondary circuit has to produce more energy, its temperature decreases, the resonance in the capture cross section by ^{238}U becomes narrower, more neutrons are thermalised.
This effect is helpful for the operation of the reactor, and is an important factor for safety.

Doppler auto-stabilisation with ^{239}Pu





In ^{239}Pu, both capture and fission cross sections have a resonance.
The auto-stabilisation is less effective.

Reactor kinetics at 1st order

If

- τ is the live time of a neutron, i.e. the delay between two generations,
- n is the number of neutrons in a given volume,
- k is the effective multiplication factor of the reactor

then the number of neutrons generated in this volume is $kn\,dt/\tau$

and that of neutrons absorbed $-n\,dt/\tau$

So :

$$dn = -n\,dt/\tau + kn\,dt/\tau$$

$$\frac{dn}{dt} = \frac{k-1}{\tau} n$$

$$n(t) = n(0)\exp\left((k-1)\frac{t}{\tau}\right)$$

$T = \dfrac{\tau}{k-1}$ is the period of the reactor

Example

In a PWR, the live time of a neutron is about 10^{-4} s.

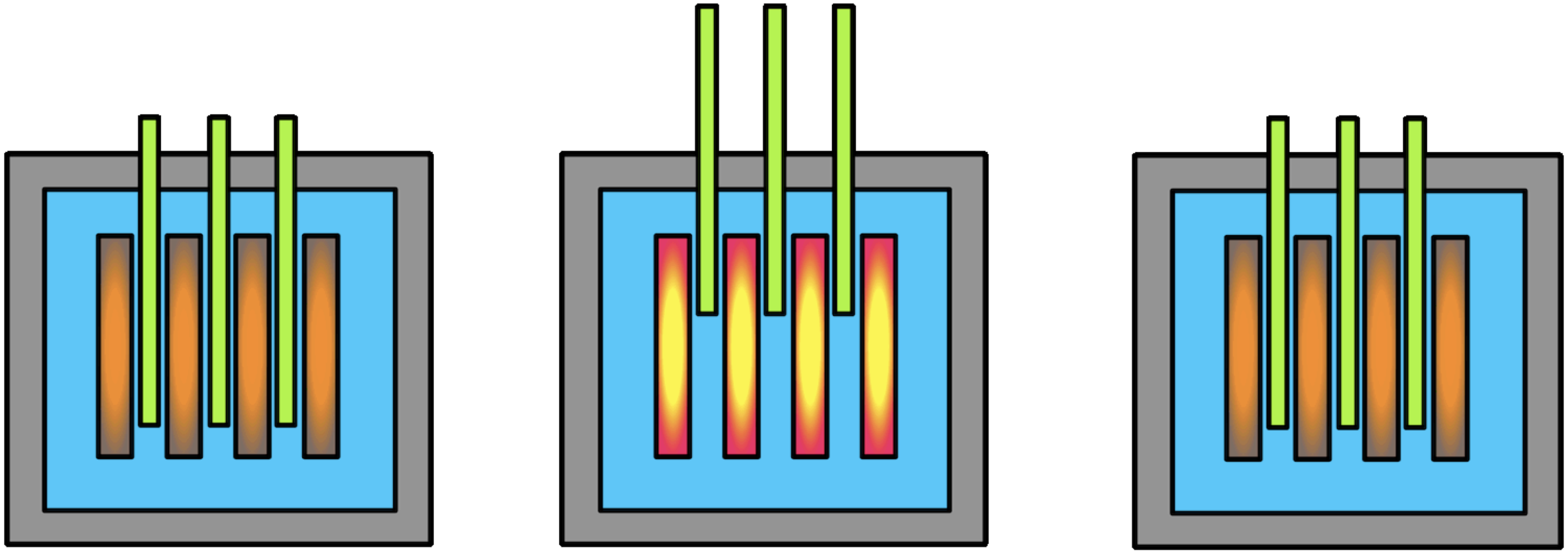
If k = 1.00010 instead of 1.00000

$$n(t) = n(0)\exp\left[\frac{(k-1)t}{\tau}\right] = n(0)\exp\left[\frac{10^{-4} * t}{10^{-4}}\right]$$

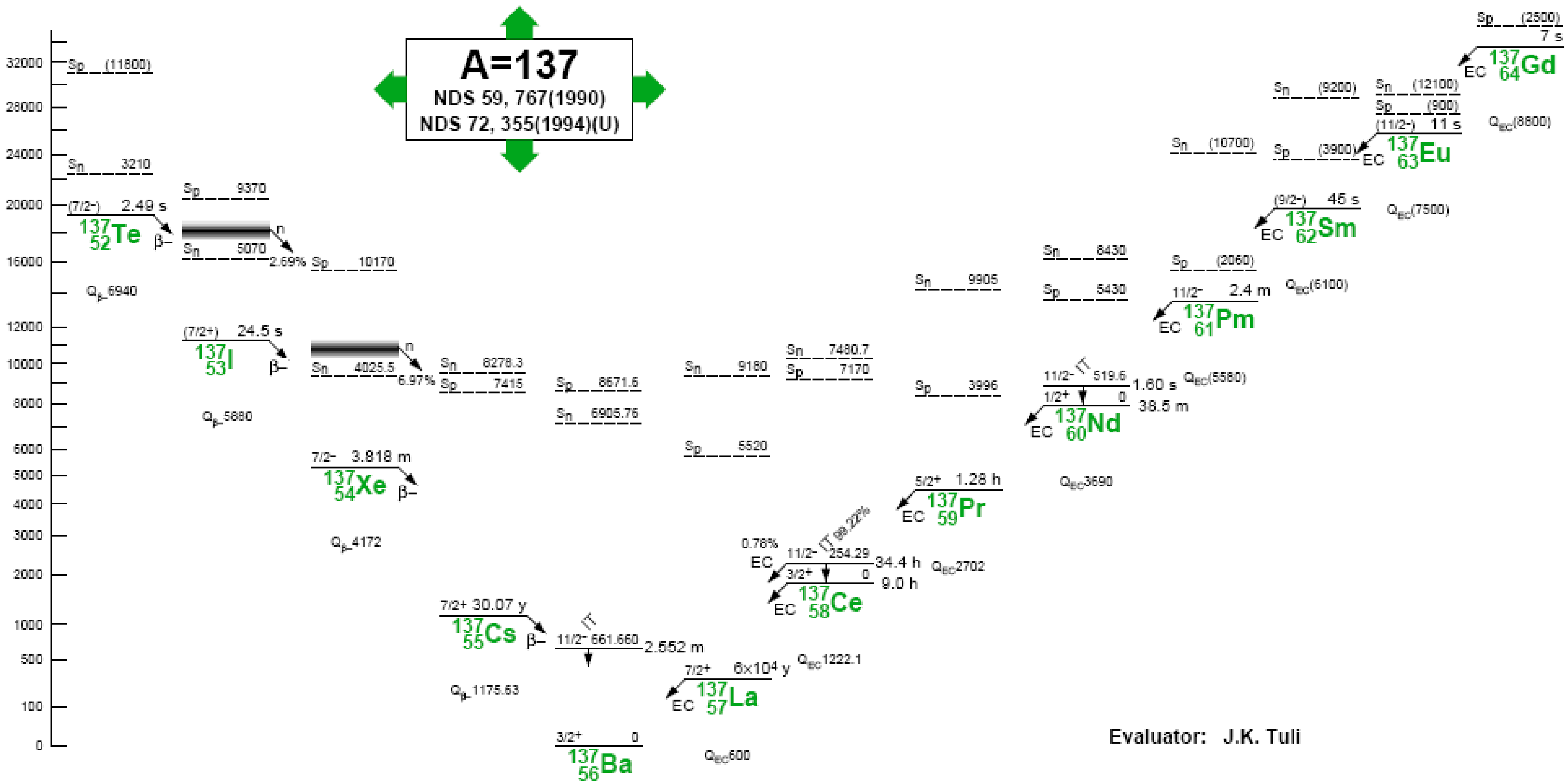
In 1sec the neutron flux, and thus the power, is multiplied by 2.7

Kinetics without delayed neutrons

If $k = 1$, the period is infinit, the reactor is stable.
But small variation of k are unavoidable, and even needed to control the reactor.
Since τ is quite small (10^{-4} sec or so) it would be impossible to control the reactor.



Delayed neutrons : the origin



Slow kinetics

β=proportion of delayed neutrons

Fast neutrons

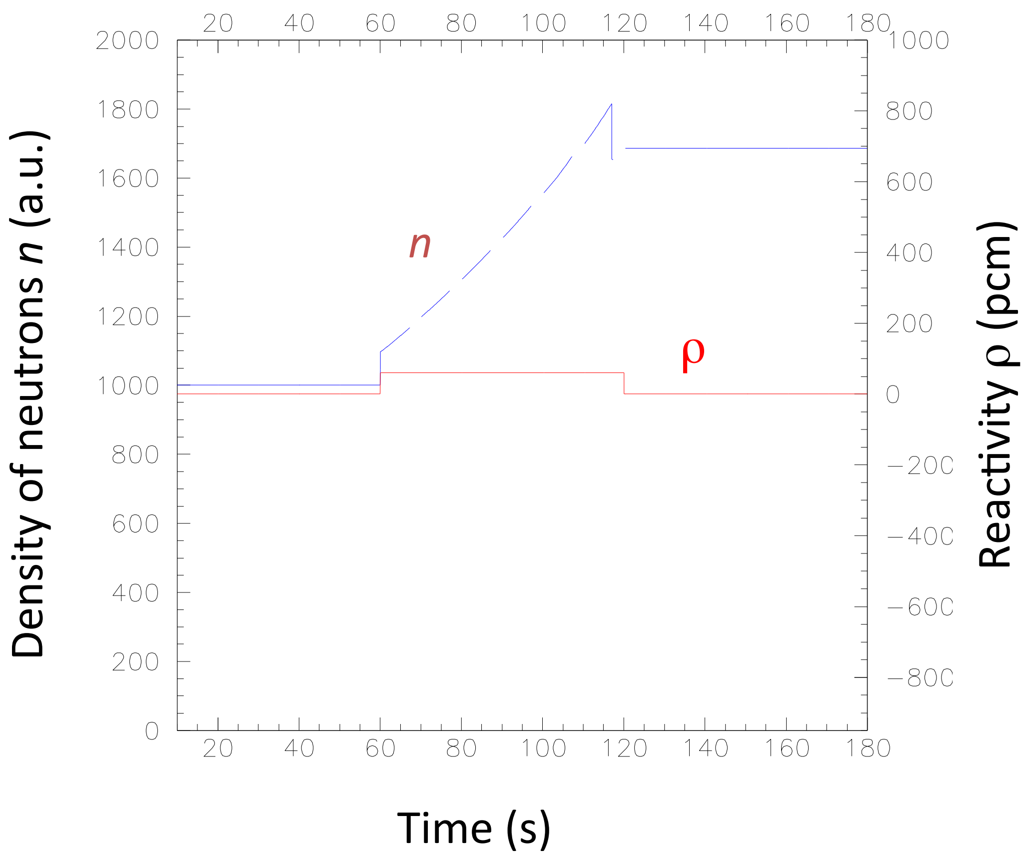
Delayed neutrons from β decay

$$\frac{dn}{dt} = \frac{k(1-\beta)-1}{\tau} n + \sum_i \lambda_i C_i$$

$$\frac{dC_i}{dt} = \frac{k\beta_i}{\tau} n - \lambda_i C_i$$

Production of β emitters

Decay of the β emitters



Proportion of delayed neutrons

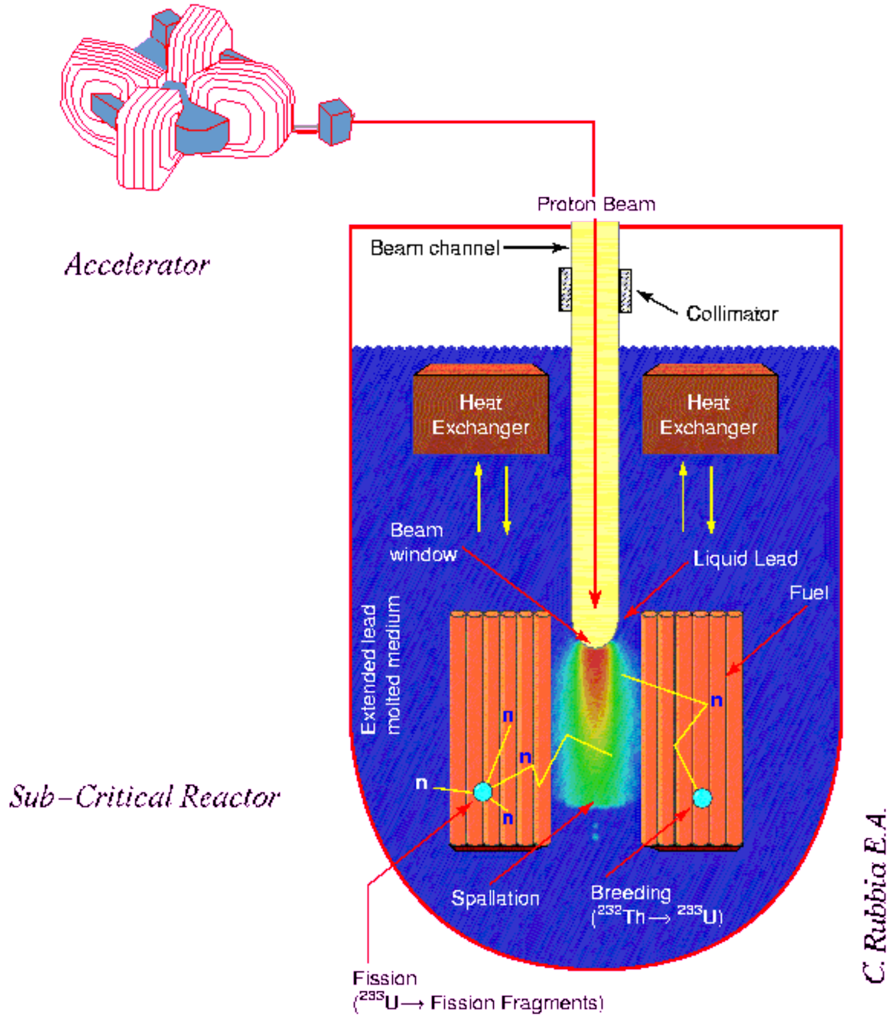
isotope	$\beta(\%)$	$\beta\tau_r(sec)$
^{232}Th	2,03	0,14
^{233}U	0,26	0,03
^{235}U	0,64	0,06
^{238}U	1,48	0,08
^{239}Pu	0,2	0,02
^{241}Am	0,24	0,013
^{242}Cm	0,04	0,004

In the U/Pu cycle, the proportion of delayed neutrons **is much lower** than in the ^{235}U one.
The addition of minor actinides lowers even more this proportion.

Accelerator driven system

An ADS is the coupling between an accelerator and a sub-critical (k<1) reactor.

The proton beam of the accelerator produces up to 30 neutrons by a spallation process.



Kinetics of an ADS

$\beta = 0.00679$ (values for a PWR)

$\lambda^{-1} = 11\ s$

$\ell = 10^{-4}\ s$

$n_0 = 1000$ (arbitrary)

Top:

$k = 0.994$ ($\rho = 600$ pcm)

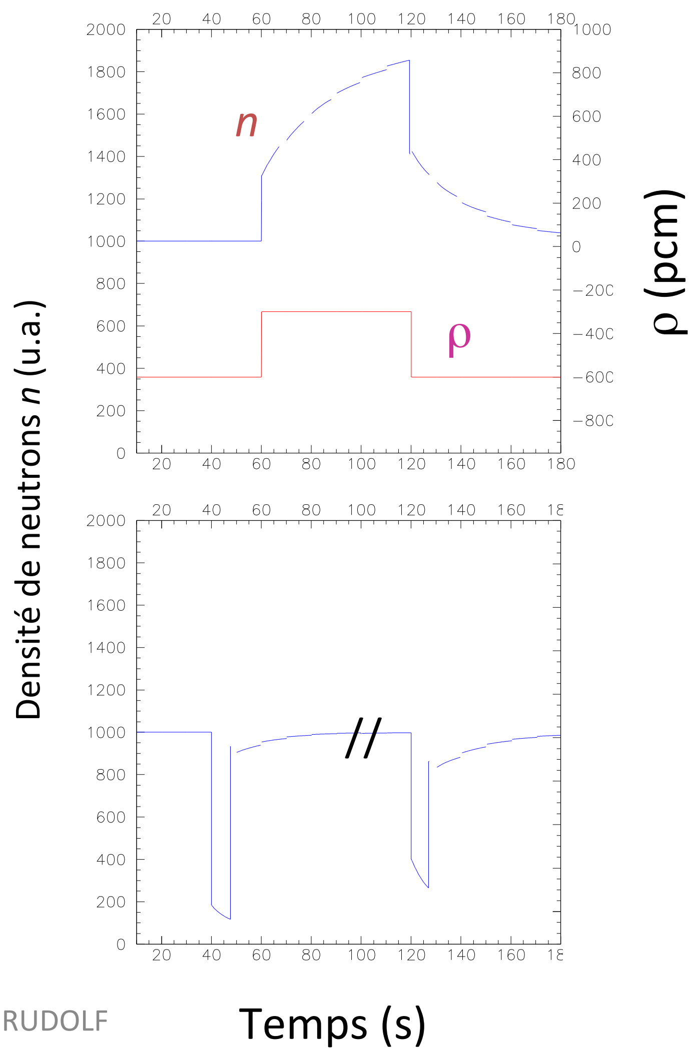
increases to 0.997 during one minute and comes back

Bottom:

$k = 0.97$ (left)

$k = 0.99$ (right)

the accelerator shuts down during 10 s



ADS : what for ?

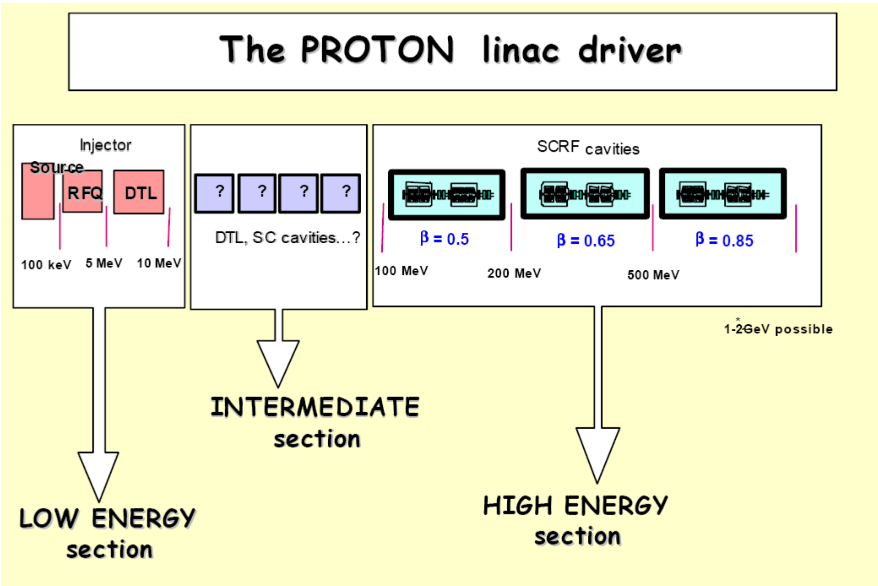
An ADS can produce much more energy than needed by the accelerator. However, since the technique will take long to be operationnal, ADS are no more believed for energy supply in a fairly narrow future.

Instead, they appear now as a safe way to fission the minor actinides accumulated so far.

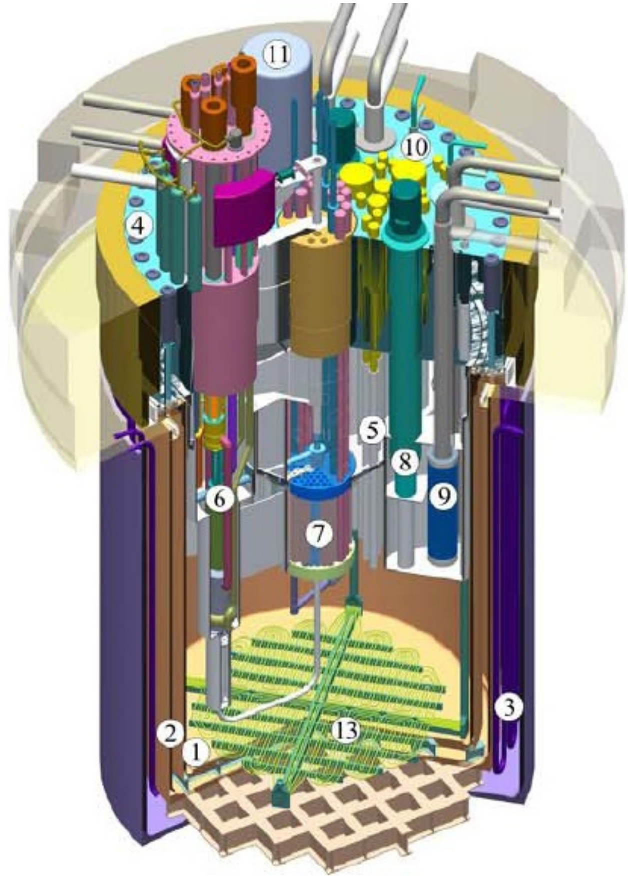
Safety is due to the fact that the accelerator is sub-critical, and also to the fact that delayed neutrons are replaced (and even surpassed) by neutrons produced by the accelerator.

Beacause a fast spectrum is needed to fission the actinides, water cannot be the coolant. Instead, Pb or PB/Bi are envisaged.

THE MYRRHA PROJECT



Linear proton accelerator



Sub critical Pb/Bi cooled reactor