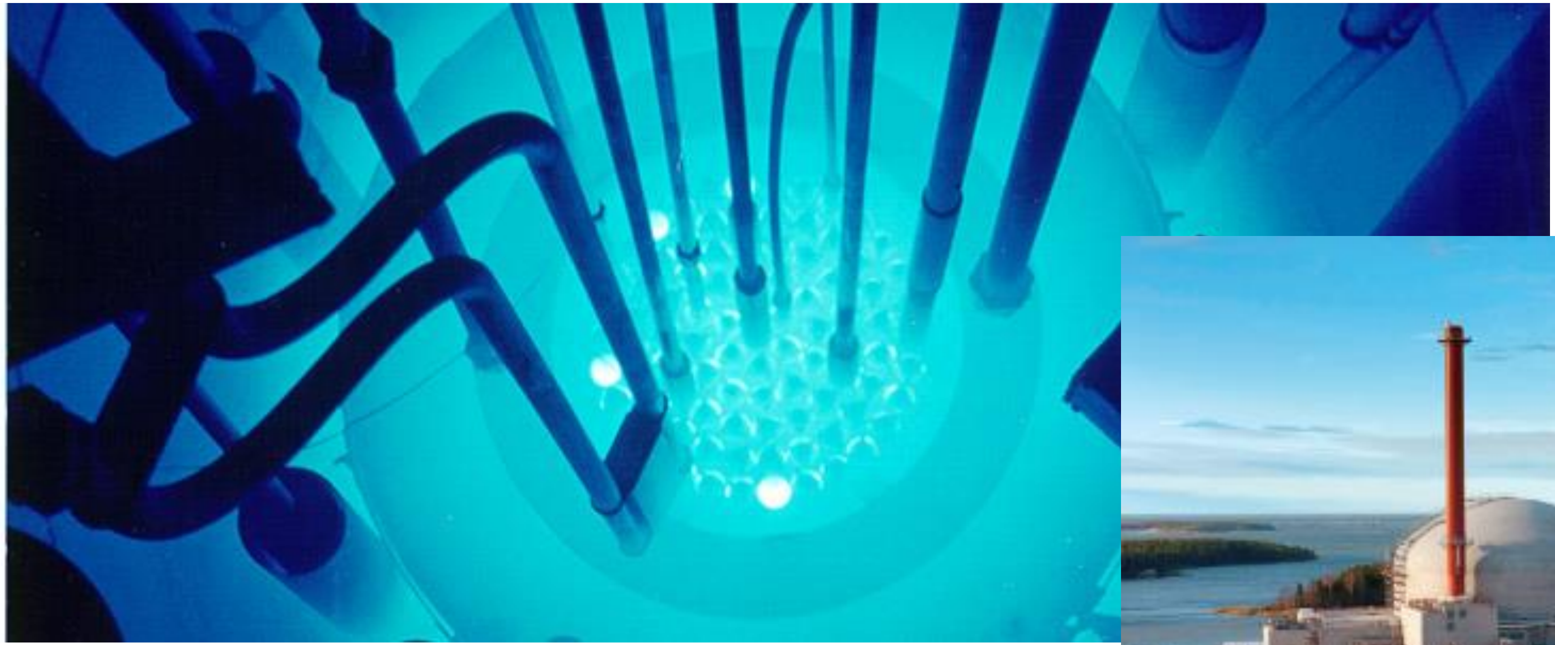
Energy from nuclear fission



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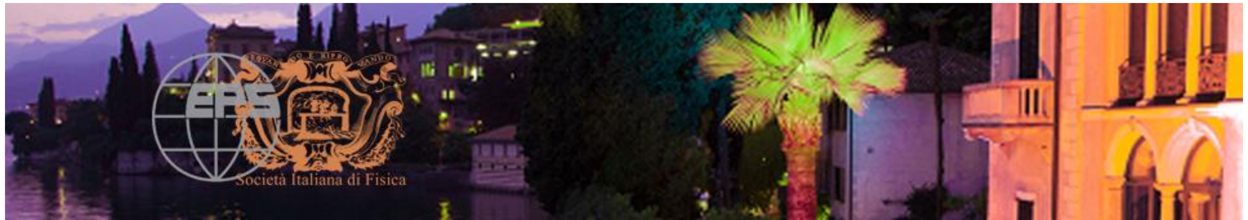
Joint EPS-SIF International School on Energy 2023



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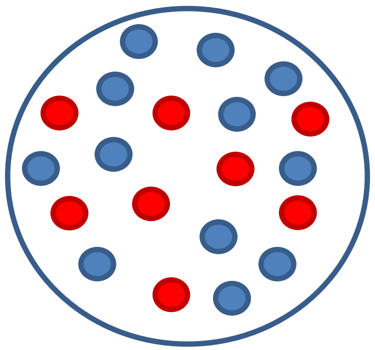
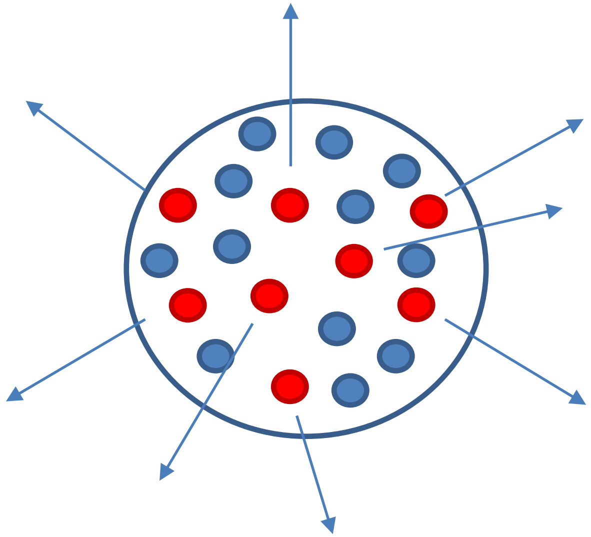
The atomic nucleus



Protons (positive electric charge)

Neutrons (no electric charge)



Electric charges with the same sign repel each other

Neutrons act as the "glue" that holds the nucleus together
(it's called «strong nuclear force»)

The larger the nucleus, the more neutrons it needs

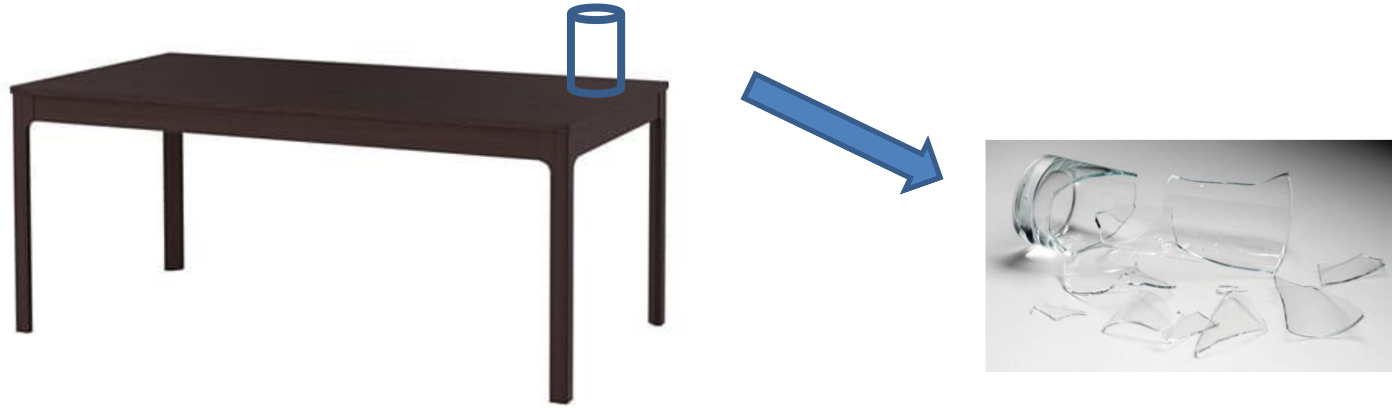
For example, Oxygen has 8 protons and 8 neutrons

The most abundant type of Lead in nature has 82 protons and 126 neutrons

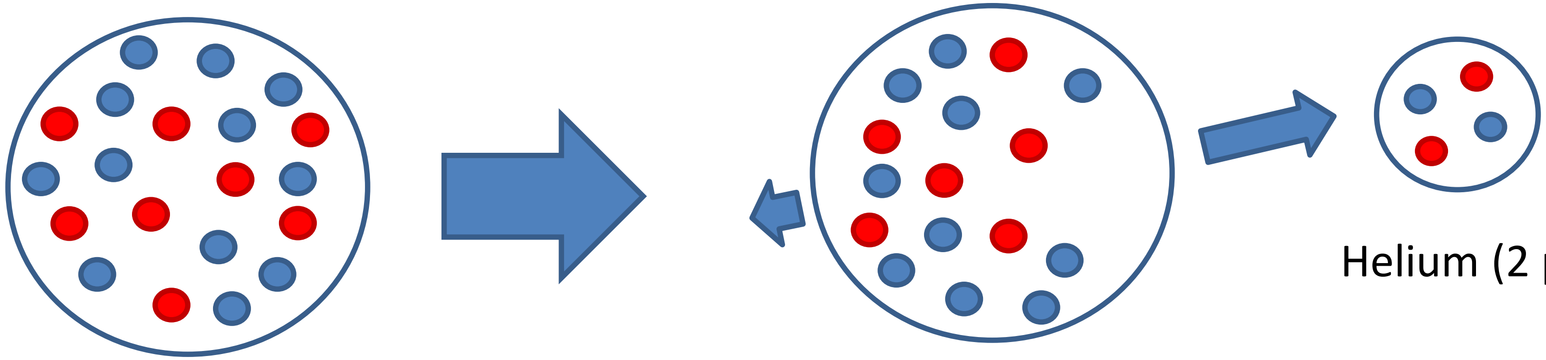
But there is also Lead with 124 and 125 neutrons → "isotopes“ → same chemical properties, different nuclei

Radioactivity

Certain atomic nuclei are «unstable», that is, they tend to break up, <u>releasing energy</u>



Alpha (α) decay

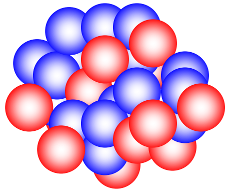


Helium (2 p, 2 n)

Uranium 238 (92 protons, 146 neutrons) Thorium 234 (90 protons, 144 neutrons)

Elements and isotopes

There are many nuclear species



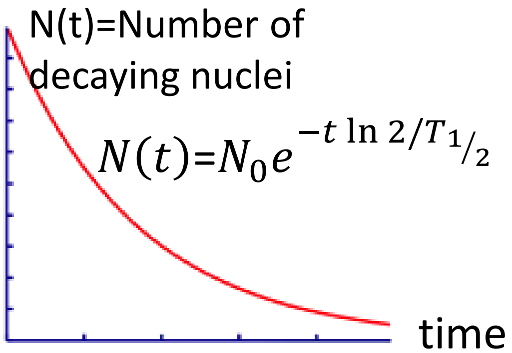
They are classified with two numbers:

Z = number of protons, which determines the chemistry

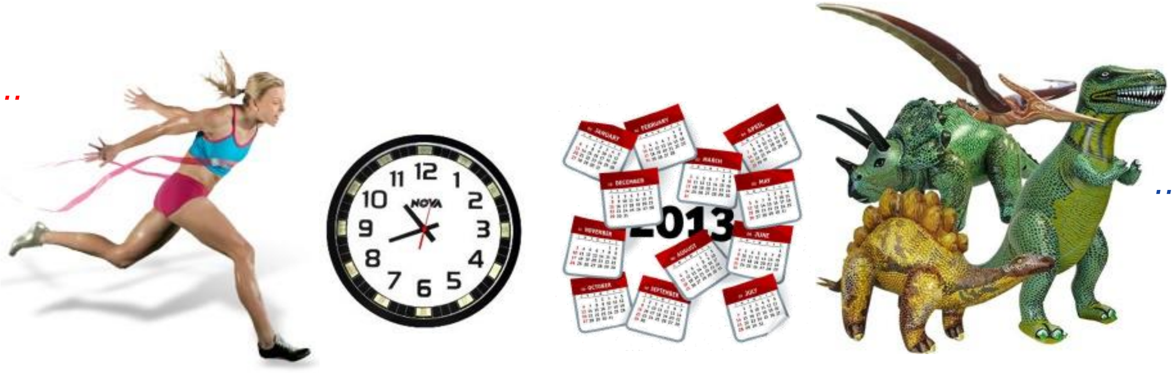
A = total number of nucleons (protons + neutrons)

- *each nuclear species is uniquely determined by its A and Z*
- *about 1700 known (A,Z) combinations (species)*
- *about 300 stable (minimum energy: equilibrium)*
- *the rest: radioactive (unstable)*

Each radioactive substance has a *characteristic time $T_{1/2}$* in which its radioactivity is halved.



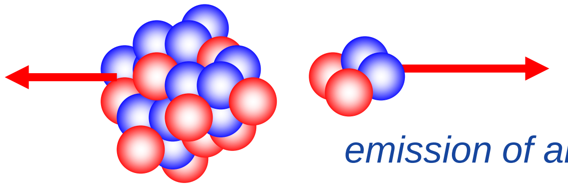
Some species decay in seconds...



...others in million (or even billion) years

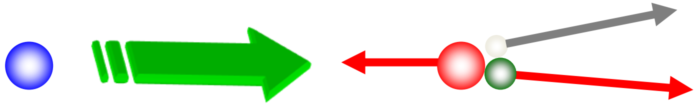
The three main types of radioactivity

alpha



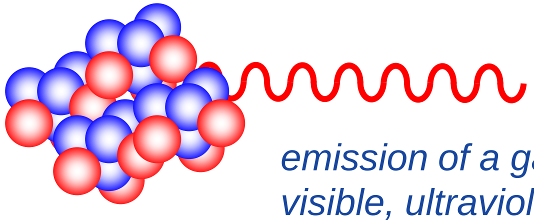
emission of an alpha particle (= helium nucleus)

beta(+)



a neutron transforms into a proton (or a nucleus with N neutrons and Z protons transforms into a nucleus with N-1 (N+1) neutrons and Z+1 (Z-1) protons, emitting an electron (positron, or beta/+ particle) and an antineutrino(neutrino)

gamma

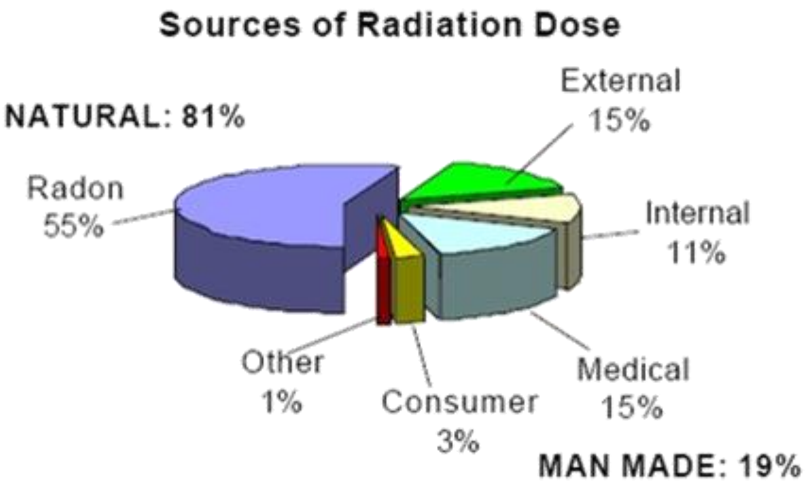


emission of a gamma ray (=photon, such as radio waves, microwaves, infrared, visible, ultraviolet, X-rays:
the only difference is the wavelength or, if you prefer, the energy)

Very often, alpha and beta radiation lead to the formation of nuclei in excited states which decay by gamma radiation

Radiation is part of our everyday life on earth

Radiation around us



From the sky: about 30 neutrons and 120 cosmic rays pass through our body per second

From air: about 10 atoms per second (Radon, Polonium, Bismuth, Lead) disintegrate in the lungs releasing alpha, beta, gamma

From diet: about 4500 atoms per second (Potassium-40) disintegrate in our body, releasing beta and gamma; also, about 2 atoms per second of natural uranium release alpha

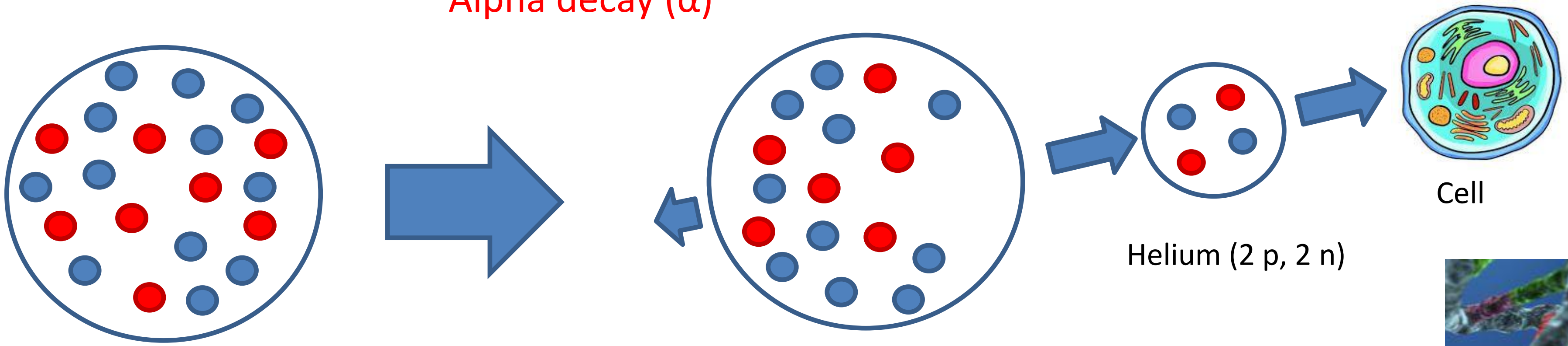
From the ground and buildings: about 56,000 gamma per second pass through our body

≈ 6000 decays per second of Potassium-40 (^{40}K) per m^3 of sea water

Biological effects of radioactivity

Radioactivity can be dangerous to the environment and humans due to cell damage (by *direct exposure* or by *inhalation or ingestion*)

Alpha decay (α)



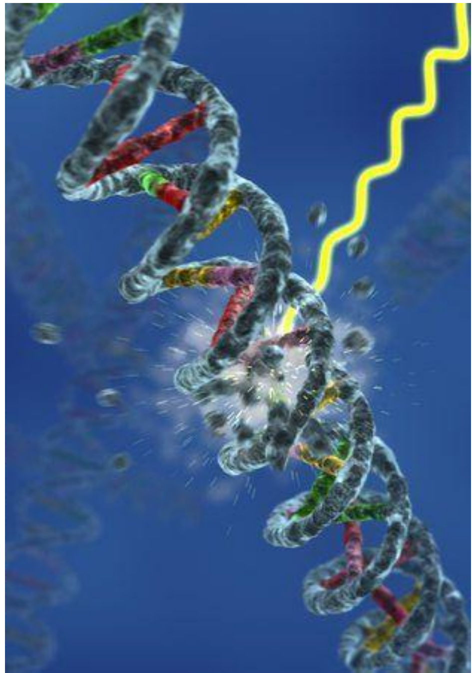
Cell

Helium (2 p, 2 n)

Uranium 238 (92 protons, 146 neutrons)

Thorium 234 (90 protons, 144 neutroni)

radiation can break DNA and cause mutations
probably plays a role in evolution

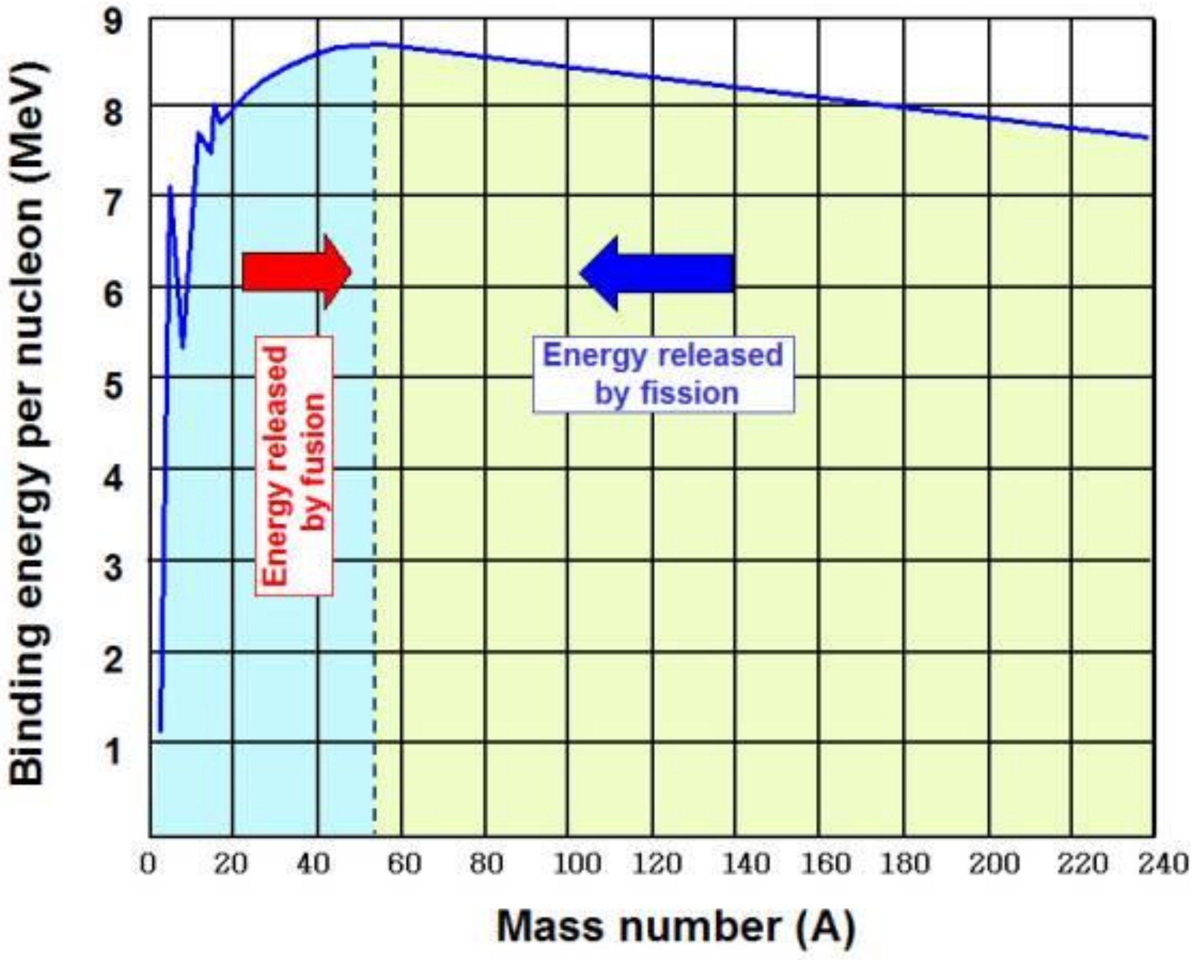


Why can fission produce energy ?

Nuclear mass and **nuclear binding energy** $M(Z,A) = ZM_p + (A - Z)M_n + B(Z,A)$

B(Z,A) < 0 !!! i.e. a nucleus weighs <u>less</u> than the sum of proton and neutron masses

$$\varepsilon \equiv \frac{|B(Z,A)|}{A}$$



How can fission produce energy ?

Nucleus splits into 1 and 2: $M(Z_0, A_0) \rightarrow M(Z_1, A_1) + M(Z_2, A_2)$; $Z_0 = Z_1 + Z_2$; $A_0 = A_1 + A_2$

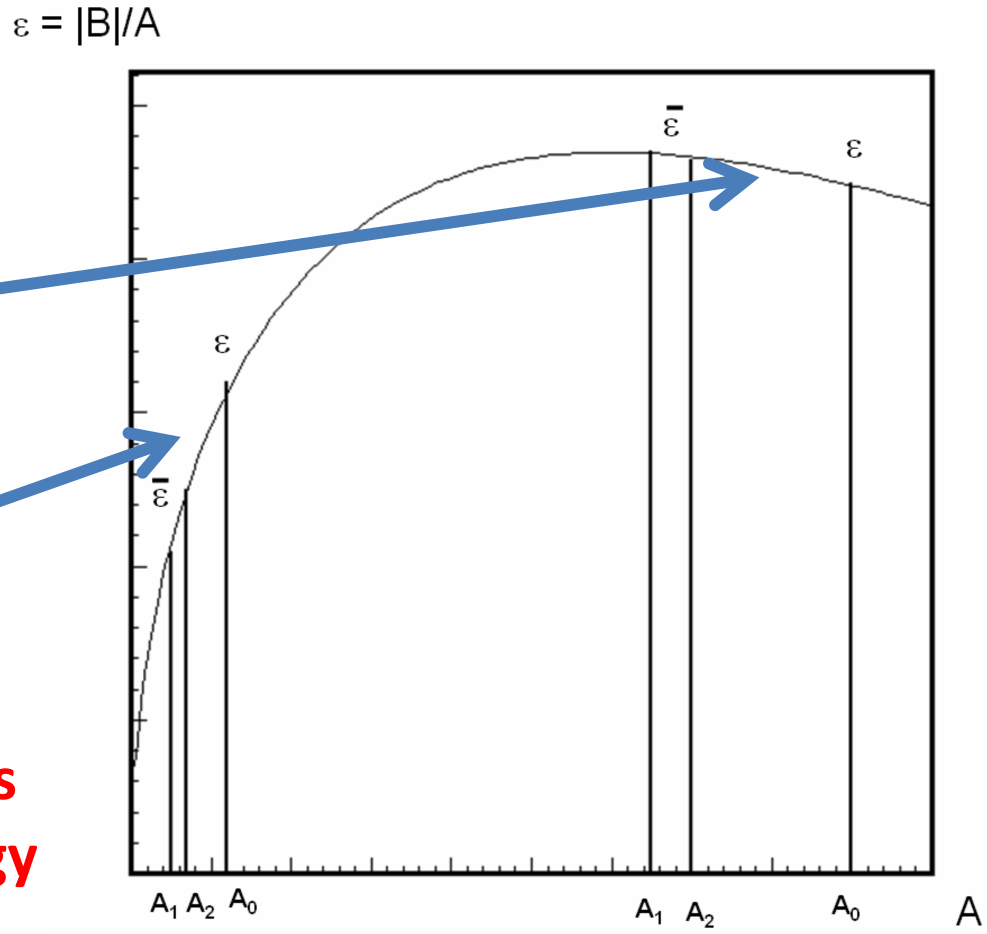
Energy balance (Q-value) $Q_{fiss} = M(Z_0, A_0) - M(Z_1, A_1) - M(Z_2, A_2)$

$$= B(Z_0, A_0) - B(Z_1, A_1) - B(Z_2, A_2) = -\varepsilon A + \varepsilon_1 A_1 + \varepsilon_2 A_2 = -\varepsilon A + \bar{\varepsilon} A = (\bar{\varepsilon} - \varepsilon) A$$

$$\bar{\varepsilon} = \frac{\varepsilon_1 A_1 + \varepsilon_2 A_2}{A_1 + A_2}$$

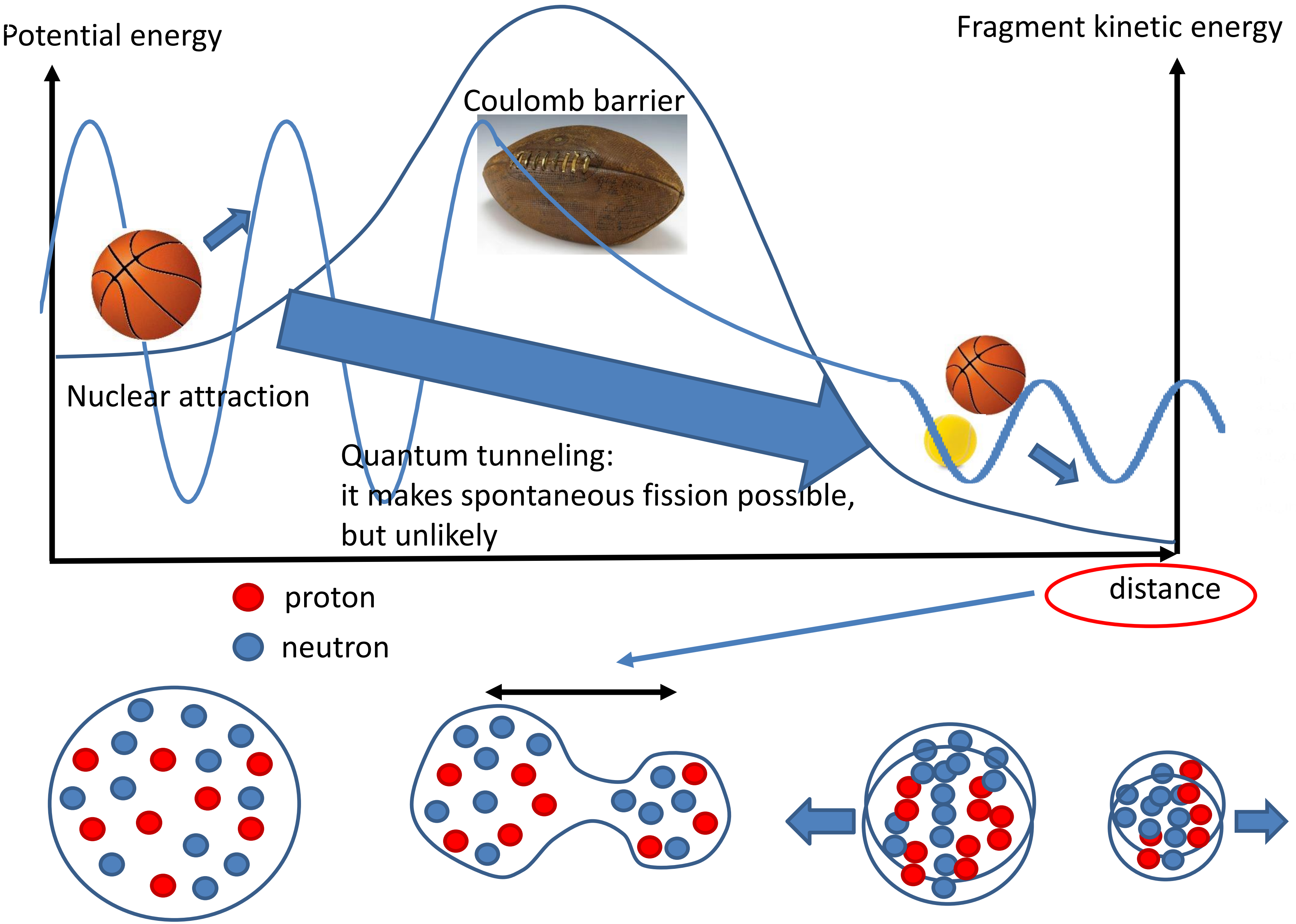
$Q_{fiss} > 0$

$Q_{fiss} < 0$

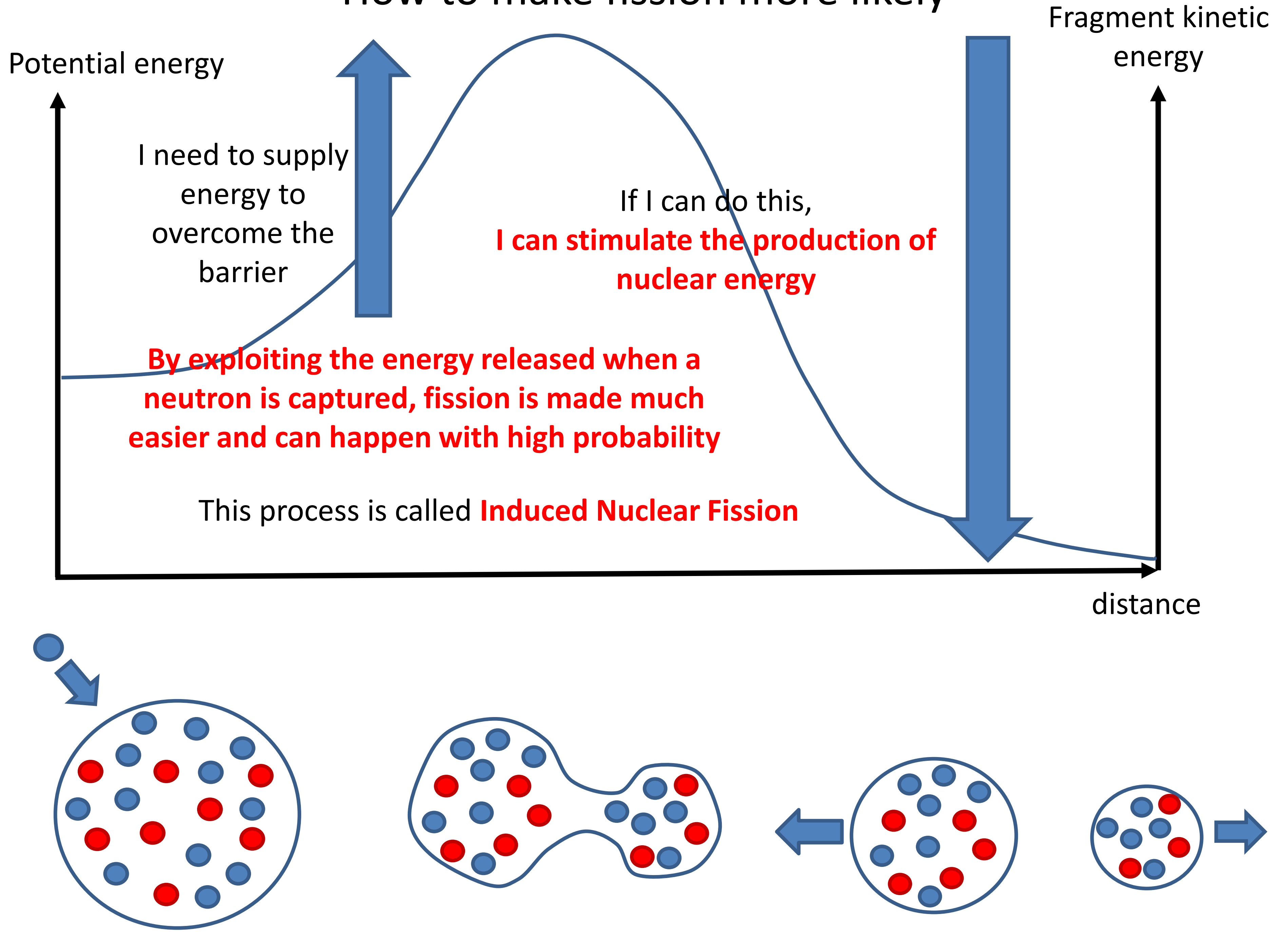


Q > 0 means that the reaction is spontaneously producing energy

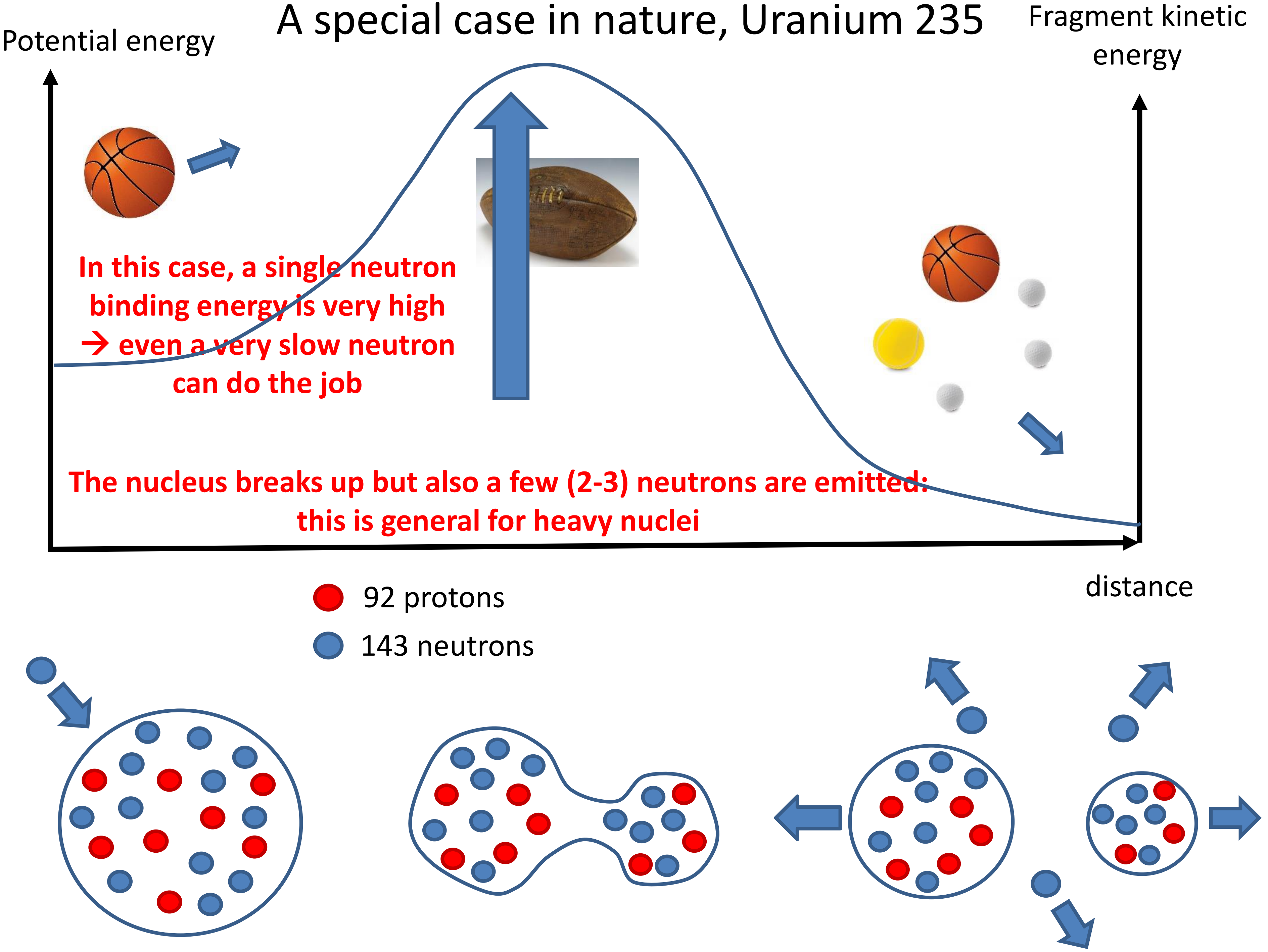
Energy balance is not the whole story, what is the reaction dynamics ?



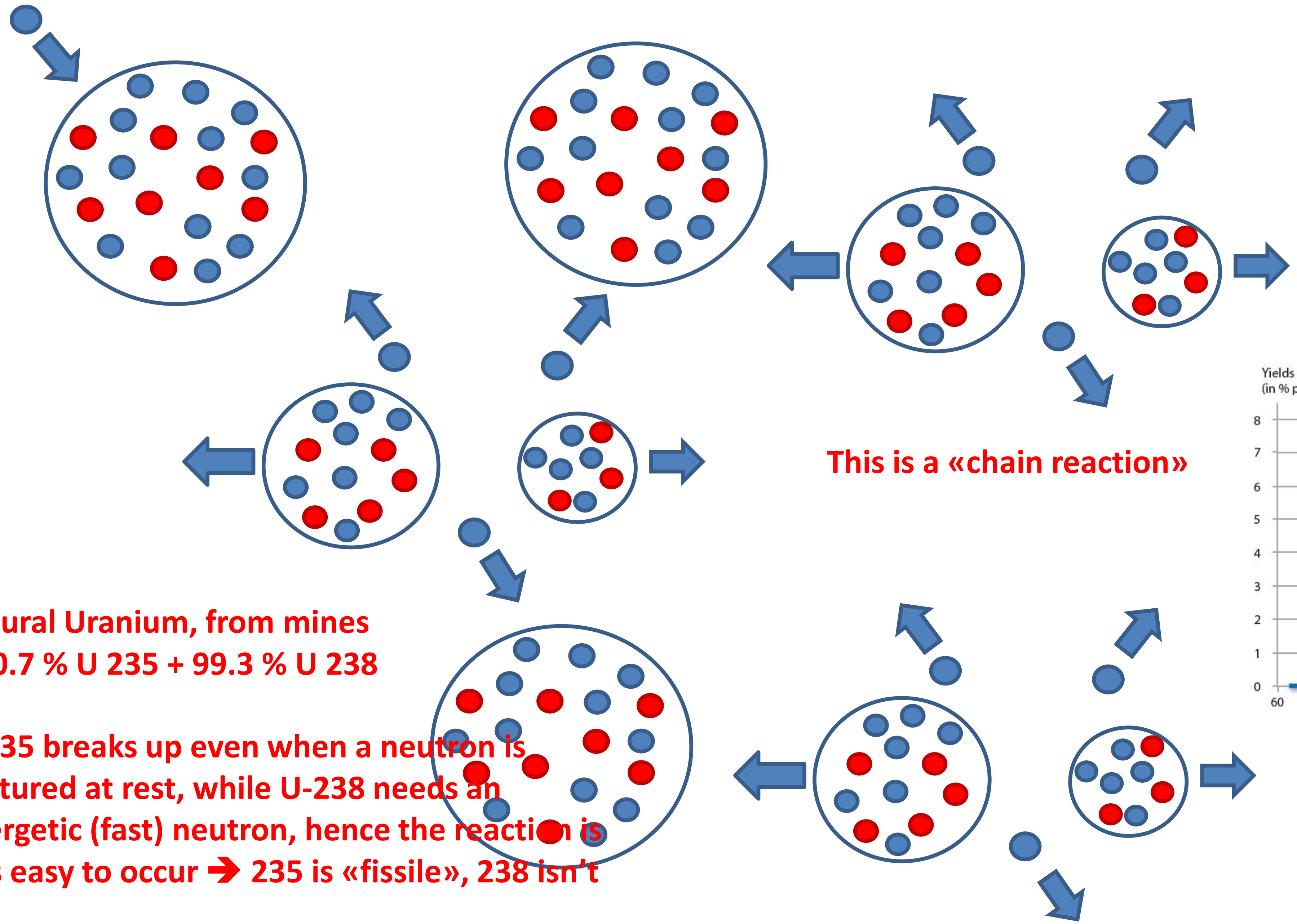
How to make fission more likely



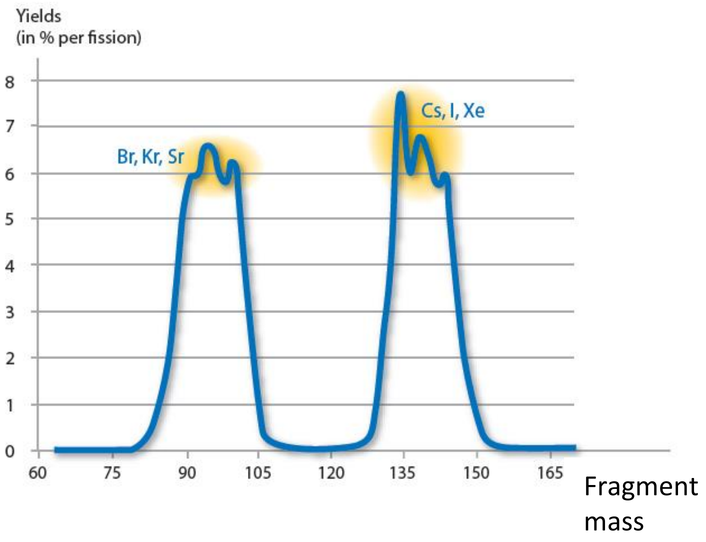
A special case in nature, Uranium 235



The chain reaction



This is a «chain reaction»



Natural Uranium, from mines
→ 0.7 % U 235 + 99.3 % U 238

U-235 breaks up even when a neutron is captured at rest, while U-238 needs an energetic (fast) neutron, hence the reaction is less easy to occur → 235 is «fissile», 238 isn't

Fragments are moving → kinetic energy → transferred to atoms → heat

How much energy is produced ?
And what are the reaction products ?

The mass of the two fragments plus the mass of the neutrons makes a little less than the mass of the initial uranium nucleus ➔ about a thousandth of the mass of the nucleus has been transformed into energy, according to Einstein's famous relationship

$$E = m c^2$$

This energy is shared among

- **Kinetic energy of the two fragments**
- **Kinetic energy of the 2-3 emitted neutrons**
- **Gamma rays (electromagnetic energy)**
- **antineutrinos** (practically massless particles that pass through matter as if it was transparent)

The biggest part of the energy released by the fission process **is converted into heat**

Fission provides 20 to 50 million times more energy than a chemical reaction

With 1 gram of U-235, about 7,000 washing machines run for an hour

The same job would require almost 3 tons of coal

Amount of energy and reaction products

When a uranium nucleus fissions into two daughter nuclei fragments, about **0.1 % of uranium mass appears as fission energy of ~200 MeV(*) ($E=Mc^2$)**

➔ **much bigger than any other exoenergetic nuclear reaction** (in absolute terms)

- ~**170 MeV** appears as the **kinetic energy of the daughter nuclei**,
-which fly apart at about 3% of the speed of light

- an **average of 2.5 <u>prompt</u> neutrons are emitted**, with a **mean kinetic energy per neutron of ~2 MeV** (total of 4.8 MeV)
- the **average number of neutrons emitted is called ν (order of 2-3)**

- **~25 MeV** are released in form of **prompt gamma ray photons and fission product β decay**

Chemical reactions vs nuclear fission

$C+O_2 = CO_2 + Q$ *(Q = 3.6 eV)*,
$CH_4 + 2O_2 = CO_2 + 2H_2O + Q$ *(Q = 9.22 eV)*,
$^{235}U+n = F_1+F_2+ \nu n + Q$ *($Q \sim$ 200 MeV)*
→ *Fission gives between 20 and 50 million times more energy*

(*) 1 eV = energy acquired by an electron crossing a potential difference of 1 V = 1.6×10^{-19} Joule
1 MeV = 1 million eV = 1.6×10^{-13} Joule

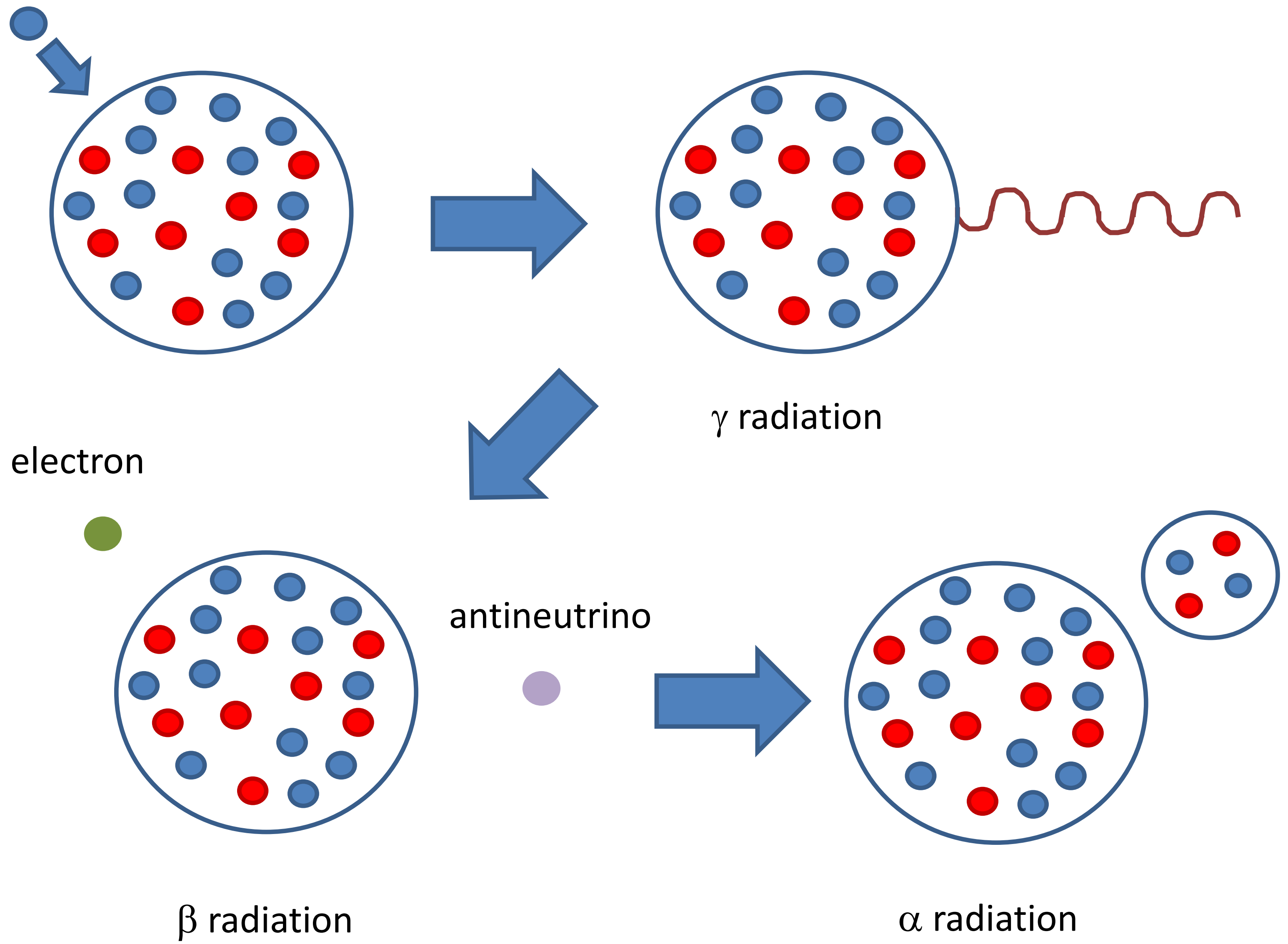
Comparison of energy sources

Material	Specific energy (MJ/kg)	Energy density (MJ/L)
Deuterium-Tritium (50 % mix)	3.4×10^8	7.65×10^4 (at room temperature and standard pressure)
Uranium	8.2×10^7	1.56×10^9
Hydrogen	142	8.9 (at room temperature and 700 bar pressure)
Methane	55.6	0.0378 (at 15 ^oC and atmospheric pressure)
Diesel / Fuel oil	48	35.8
LPG (including Propane / Butane)	46.4	26
Gasoline (petrol)	46.4	34.2
Ethanol fuel (E100)	26.4	20.9
Coal, anthracite	26-33	34-43
Wood	~13-20	~10-16

Source: Wikipedia plus some changes and corrections

Yellow background: nuclear energy (fusion and fission)

Radiative neutron capture



Nuclear energy and radioactive products

The two nuclei resulting from fission are called **«fragments or fission products»** → most of them are **radioactive**

Furthermore, we have seen that it is Uranium 235 that produces fission. **Uranium 238** instead, with high probability absorbs the neutron, giving rise to a **transformation chain that produces heavier elements, including Plutonium** (that doesn't exist in Nature)

However, plutonium can also give rise to fission, so it can be used as fuel

Other materials of the plant, subjected to the intense flux of neutrons, can also become radioactive *(activation)*

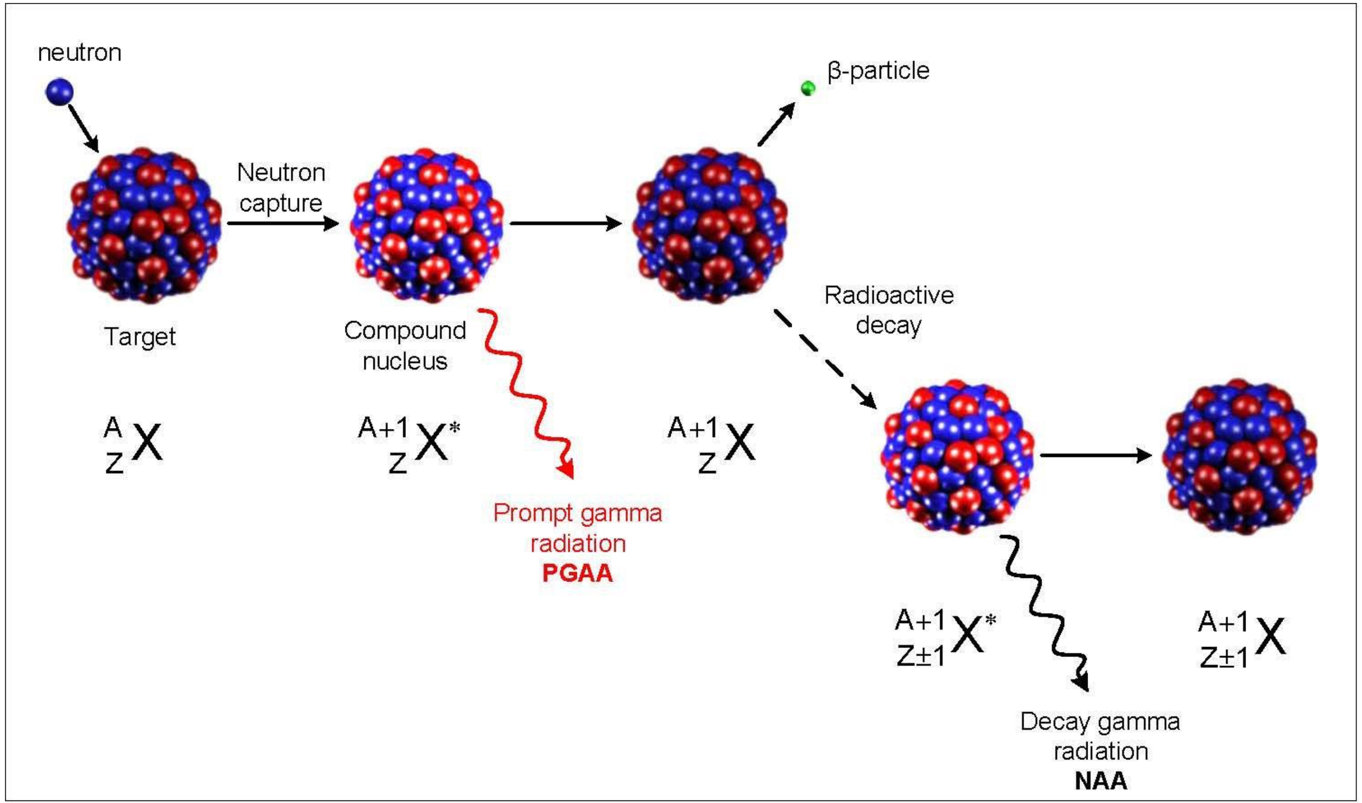
Example: Plutonium production from Uranium

$n + {}^{238}U \rightarrow {}^{239}U + \gamma \rightarrow {}^{239}Np + \beta + \text{anti-}\nu \rightarrow \mathbf{{}^{239}Pu} + \beta + \text{anti-}\nu$

Other elements (*Transuranics: elements heavier than Uranium)* not existing in Nature are formed beyond Plutonium: the so-called *Minor Actinides* (Americium, Curium, etc.), typically with very long lives → they make handling and disposing of spent fuel more challenging

Example: ^{60}Co production in steel

$n + {}^{59}Co \rightarrow \mathbf{{}^{60}Co} + \gamma \rightarrow {}^{60}Ni + \beta + \text{anti-}\nu$



Physics: nuclear cross sections

Cross section: quantity that characterizes a nuclear reaction (elastic, inelastic scattering, etc.) connected to the range of the involved forces; **effective area of a nuclear target**

Here we will consider the **total cross section**, defined as follows:

Given a **flux** $\frac{dN_{in}}{dSdt}$

number of incident particles per unit surface and unit time on a single nucleus (target)

and given an **interaction rate** $\frac{dN_{reac}}{dt}$

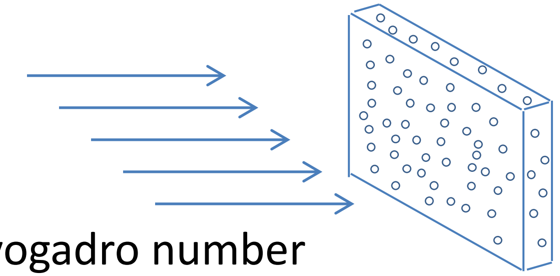
number of interacting particles (scattered or absorbed projectiles) per unit time, then

$$\sigma = \frac{\frac{dN_{reac}}{dt}}{\frac{dN_{in}}{dSdt}}$$

σ → physical dimensions of a surface

Nuclear cross sections

Macroscopic target comprising several nuclei with **density ρ (es. gr/cm3) and thickness x**, struck by a particle beam of intensity I (particles/sec) →



$$R = \frac{dN_{reac}}{dt} = I\,\frac{\rho\, x}{A} N_A \sigma$$

where A is the target atomic weight (es. in gr.) e N_A is the Avogadro number

$\frac{\rho}{A} N_A$ is the **number density of nuclei** in the target (i.e. number of nuclei per unit volume)

This is all valid for a <u>small thickness</u> x

For a target of <u>arbitrary thickness</u>, first divide it in thin slices of thickness dx →

$$dR = \frac{dN_{reac}}{dt} = I(x)\frac{\rho}{A} N_A \sigma\, dx$$

$$dI = -I(x)\frac{\rho}{A} N_A \sigma\, dx$$

$$I(x) = I(0)\exp(-\frac{\rho}{A} N_A \sigma\, x)$$

$$\Rightarrow \boxed{\Sigma \equiv \frac{\rho}{A} N_A \sigma}$$ **Macroscopic cross section = prob.ty of interaction per unit length**

$1/\Sigma$ **= Mean free path** $\Sigma\, v =$ **Frequency with which reactions occur, v= projectile speed**

Nuclear cross sections

Since the nuclear radius is a few 10^{-13} cm, the geometrical cross-sectional area of the nucleus is close to **10^{-24} cm^2 = 1 barn (1 b)**

Hence, we might expect nuclear cross sections to be of the order of 1 b

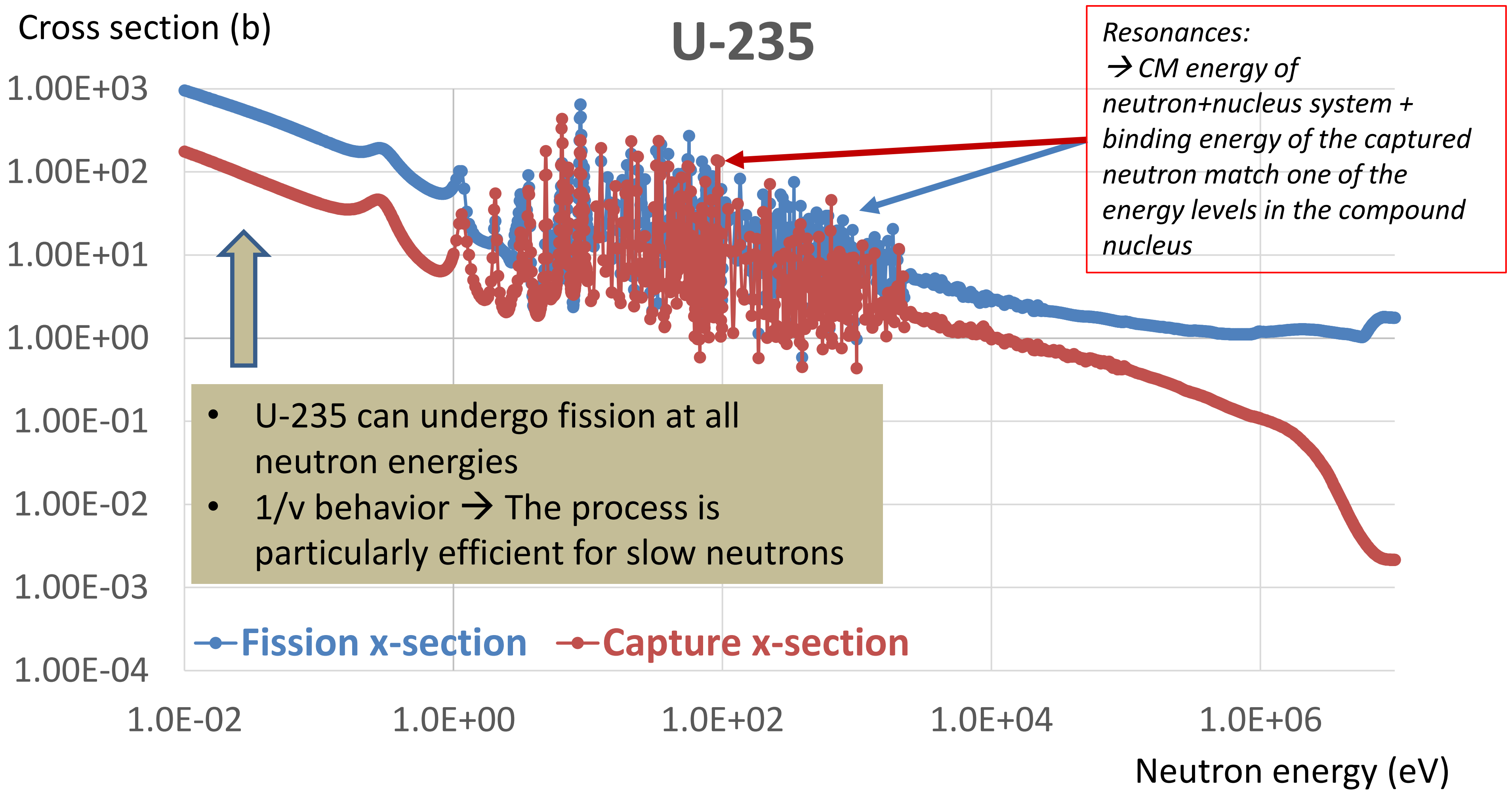
However, for both fission and radiative neutron capture, due to quantum mechanical effects

→ cross section follows a 1/v law, with v being the relative speed (essentially the n speed)

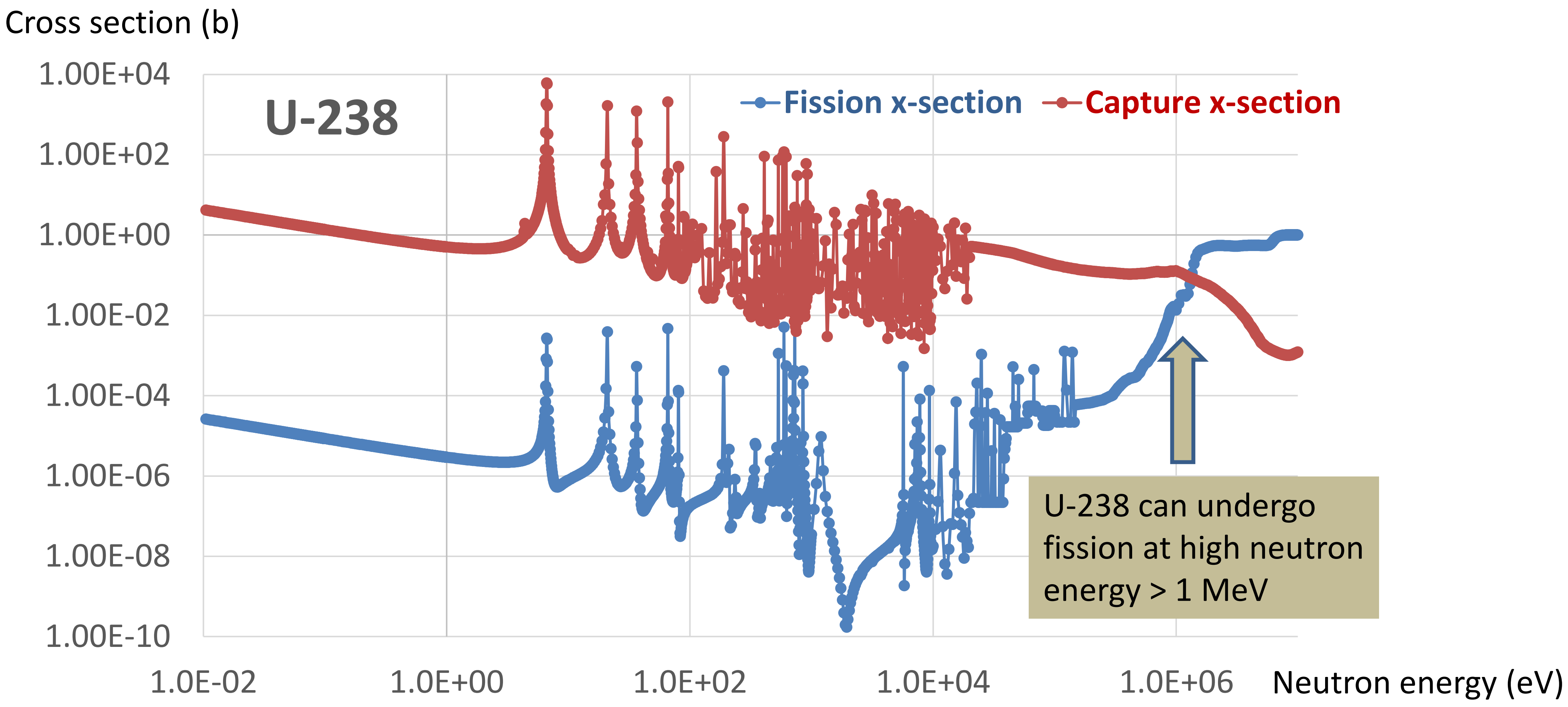
→ "slow" neutrons are much more effective at producing fission or radiative capture

→ however, for certain nuclei <u>fission</u> can have a <u>threshold</u>, i.e. it happens only if the neutron energy is above some minimum value (e.g. ^{238}U)

Nuclear cross sections



Heavy nuclei with a high fission cross section at low (thermal) neutron energies are called **fissile** (e.g. ^{233}U, ^{235}U, ^{239}Pu,…)

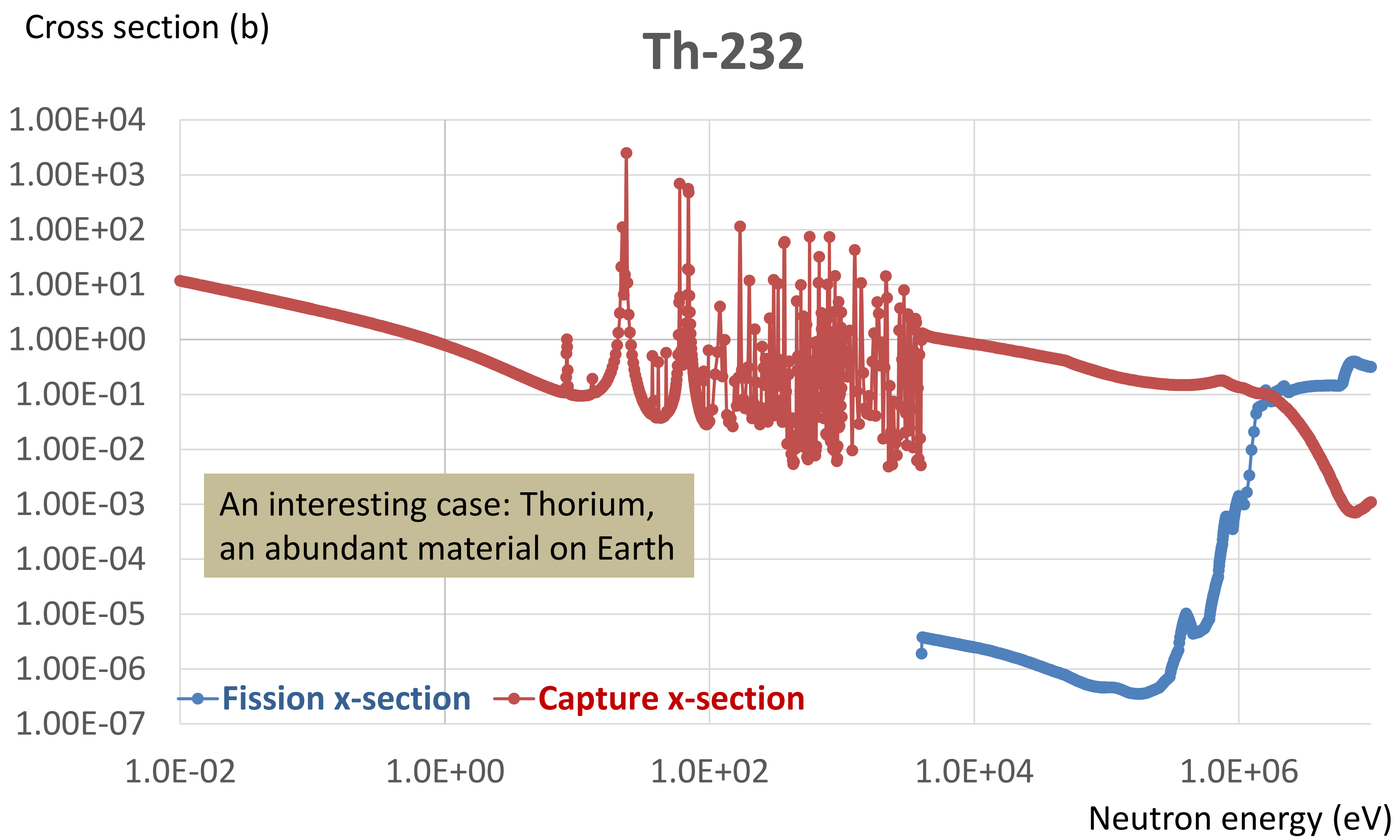


Those that can produce a fissile isotope via neutron radiative capture and β decay are called **fertile**, i.e. they can be used to **produce fuel** (e.g. ^{238}U,…)

fissile

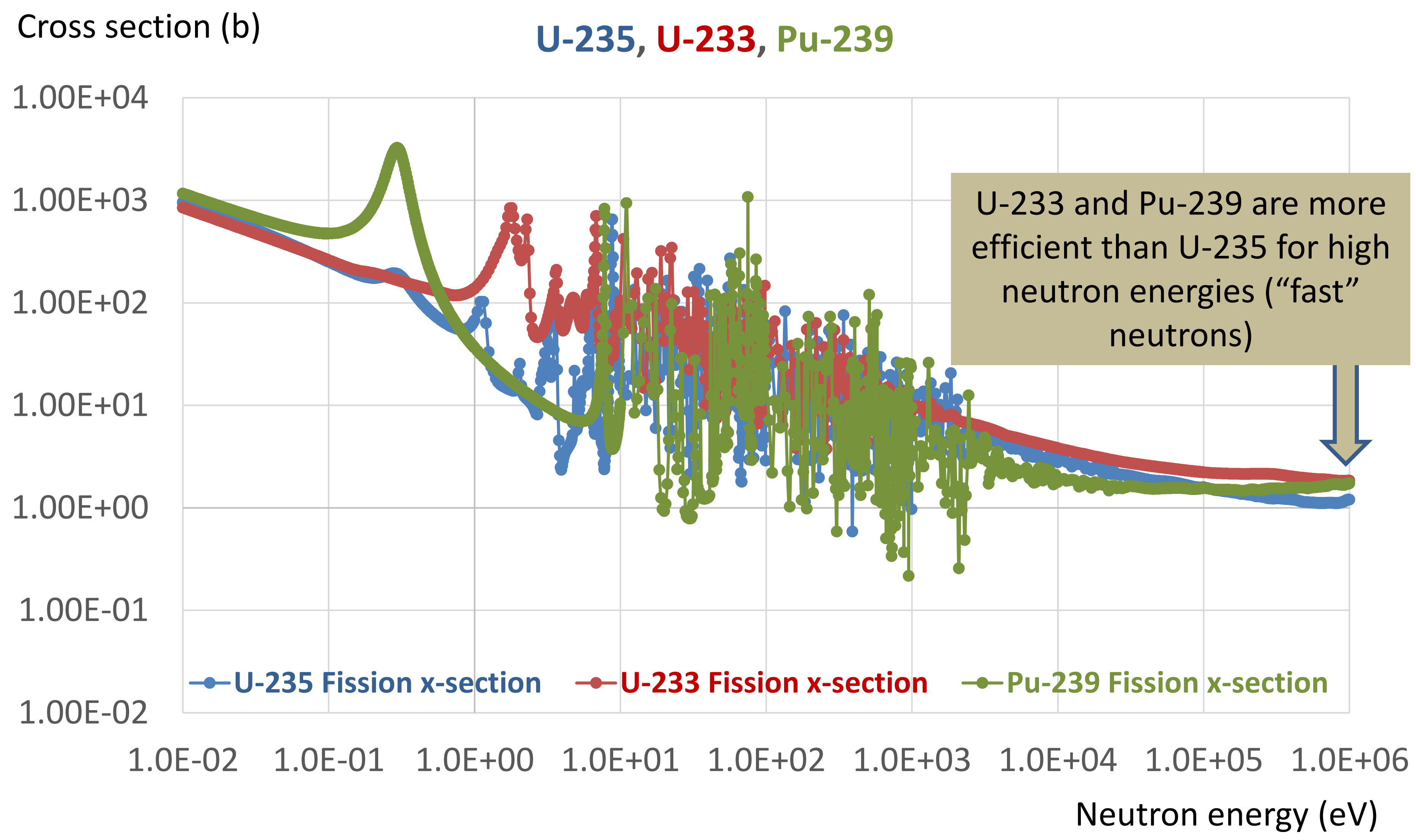
n+ ^{238}U → ^{239}U + γ → ^{239}Np + β + anti-ν → $\boxed{^{239}\text{Pu}}$ + β + anti-ν

- ✓ Natural Uranium → 0.7 % ^{235}U + 99.3 % ^{238}U → **most reactors need 3-5 % ^{235}U → "enrichment" process**
- ✓ Plutonium production is also called "breeding"
- ✓ **When exposed to fast neutrons, a reactor can produce more Pu than it consumes → it is called "breeder"**

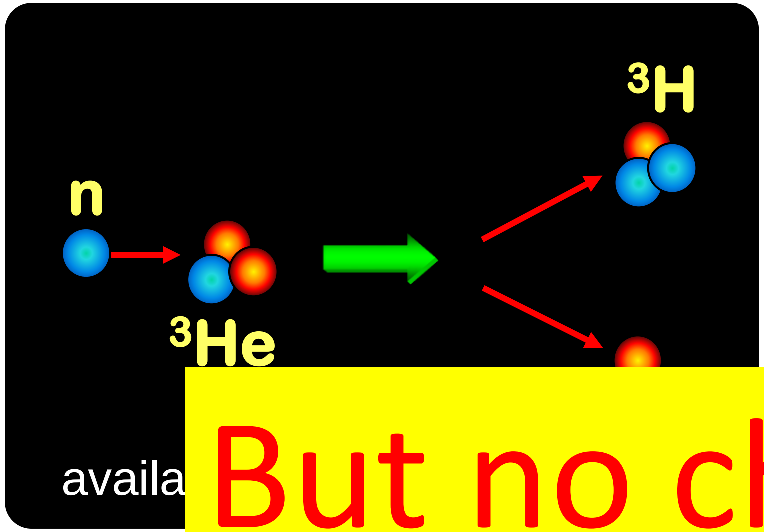


fissile

n+ ^{232}Th → ^{233}Th + γ → ^{233}Pa + β + anti-ν → $\boxed{^{233}U}$ + β + anti-ν


Cross section (b)
U-235, U-233, Pu-239
1.00E+04
1.00E+03
1.00E+02
1.00E+01
1.00E+00
1.00E-01
1.00E-02
U-233 and Pu-239 are more efficient than U-235 for high neutron energies ("fast" neutrons)
U-235 Fission x-section
U-233 Fission x-section
Pu-239 Fission x-section
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
1.0E+03
1.0E+04
1.0E+05
1.0E+06
Neutron energy (eV)

Other neutron absorption processes yielding energy



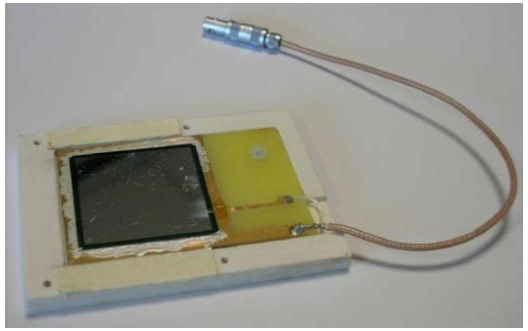
σ(thermal neutrons)
≈ 5330 b (barn, 1 b=10^{-24} cm^2, σ is proportional to the reaction probability, see later)

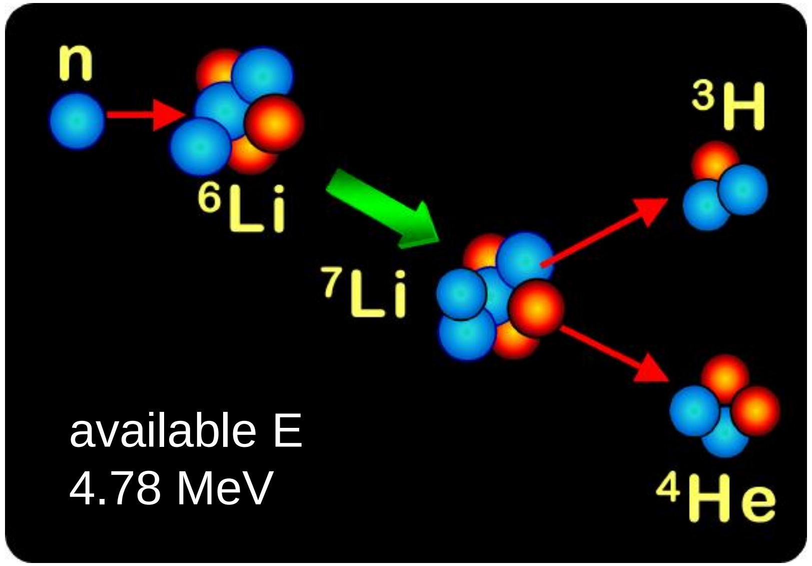
But no chain reaction

≈ 940 b

^{3}He neutron detector

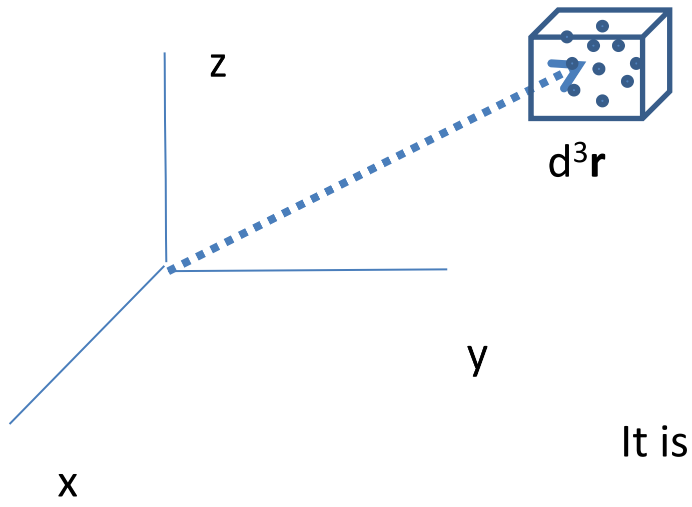
neutron detector based on a LiF film





Neutron density and flux

Neutron density ≡ $n(\mathbf{r},E,t)$ [cm^{-3}] ≡
expected number of neutrons with energy between E and E+dE, in the volume $d^3\mathbf{r}$ about $\mathbf{r}$, at a time t



Reaction density ≡ $R(\mathbf{r},E,t)$ ≡
Number of reactions in the volume $d^3\mathbf{r}$ about $\mathbf{r}$, at a time t, initiated by neutrons with energy between E and E+dE = $n(\mathbf{r},E,t)\,\Sigma v$

We give a <u>special name</u> to the quantity $n(\mathbf{r},E,t)v$

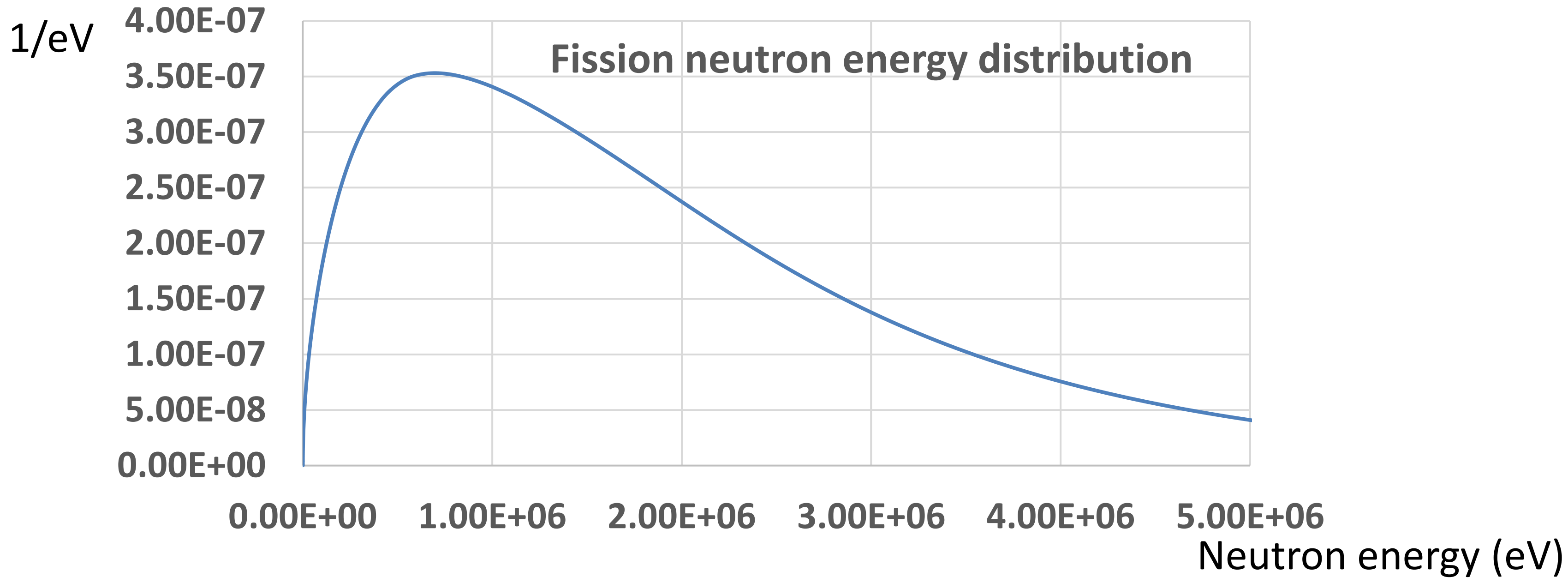
It is called the **neutron "flux" $\phi(r,E,t) \equiv n(r,E,t)v$ [$cm^{-2}\ s^{-1}$]**

Reaction density ≡ number of reactions per unit volume ≡ $R(r,E,t) = \Sigma\,\phi$

Suppose you've got a reactor with 1 GW thermal power* = 10^9 Joule/sec
Assume each fission releases order of 200 MeV energy = 3.2×10^{-11} Joule
→ In the reactor the fission rate is about 3×10^{19} fissions/sec
→Almost 10^{20} neutrons/sec emitted, about 2×10^{20} neutrinos/sec
→ $\phi \sim 10^{14}$ neutrons $cm^{-2}\ s^{-1}$ (by using the cross section for neutrons at room temperature)

(*) 1 GW(th) = 1 GW thermal power, 1 GW(e) = 1 GW electrical power; typically, for a fossil-fueled or nuclear power plant, a conversion factor between ~ 30 to 60 % has to be applied to go from thermal to electrical power

Fission spectrum, fast and slow neutrons



It is customary to adopt the following classification:

- **slow neutrons**: those with kinetic energy T_n < 1 eV
- in particular **thermal neutrons** have T_n around 0.025 eV or 25 meV (the value of kT, where k is the Boltzmann constant and T is the temperature
- **epithermal neutrons**: 1 eV < T_n < 100 keV (0.1 MeV)
- **fast neutrons**: 0.1 MeV < T_n < 20 MeV

Obviously neutrons in general can have energies above 20 MeV but this is an extreme limit in reactor physics (e.g. neutrons from D+T fusion have 14 MeV fixed energy)

Slowing down neutrons (moderation)

It is easy to show in non-relativistic kinematics that **after a scattering off a nucleus with mass number A**, the kinetic energy of the neutron changes according to the ratio

$$\frac{T_n'}{T_n} = \frac{m_n^2 + m_A^2 + 2m_n m_A cos\theta_{CM}}{(m_n + m_A)^2}$$

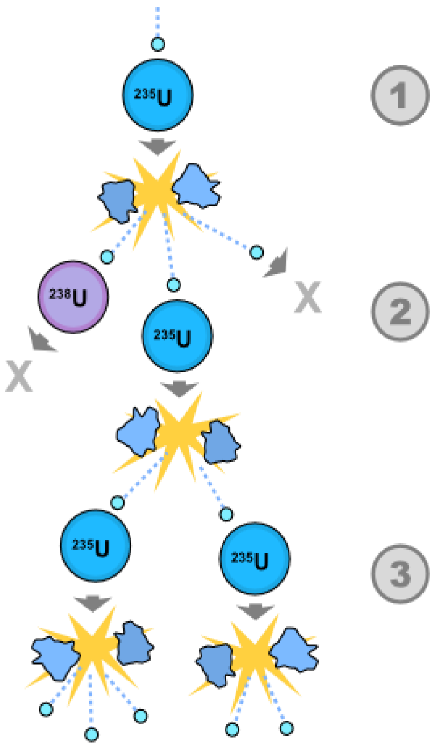
Assuming an isotropic CM cross section that does not depend on $\cos\theta_{CM}$, the corresponding term averages out to zero, so that we can write <u>on average</u>

$$\frac{T_n'}{T_n} = \frac{m_n^2 + m_A^2}{(m_n + m_A)^2}$$ ➔ Assuming $M_A \cong Am_n$ ➔ $$\frac{T_n'}{T_n} = \frac{1 + A^2}{(1 + A)^2}$$

For a **heavy nucleus A>>1 → $T_n' \cong T_n$** or in other words, the neutron has to undergo many collisions in order to significantly lose energy.
Consider instead the case **A=1** → (target containing hydrogen, i.e. protons as nuclei) **$T_n' = T_n/2$** i.e. on average a neutron will lose half of its energy at each collision and therefore few collisions are sufficient to rapidly decrease its energy

➔ **Moderators = light materials containing hydrogen = water, paraffin or graphite**

The chain reaction and the critical reactor



The chain reaction:
- must not diverge (more and more fissions at each "generation")
- must not die away (less and less fissions at each generation)

→precisely one neutron from each fission has to induce another fission event

The remaining fission neutrons will then either be
- absorbed (e.g. by radiative capture) or
- will leak out from the system

Suppose we can count the number of neutrons in one generation and in the next one

$$k \equiv \frac{\text{number of neutrons in one generation}}{\text{number of neutrons in the preceding generation}}$$

- The condition **k=1** corresponds to a **critical reactor** (steady state)
- **k>1** is a **supercritical reactor** (chain reaction diverges)
- **k<1** is a **subcritical reactor** (chain reaction dies away)

In "simple-minded" reactor kinetics →

$$\boxed{n(t) = n_0(t)\exp\left(\frac{k-1}{\tau}t\right)}$$

n(t)=neutron population at time t
τ = neutron "survival time" in the reactor

$$\text{Time constant} \equiv \mathrm{T} \equiv \text{Reactor period} \equiv \frac{\tau}{k-1}$$

Delayed neutrons: crucial for reactor control

Typical neutron lifetime in a thermal power reactor ~ 10^{-4} sec

If k=1.001 ➡ **T=0.1 sec** ➡ **power will increase by 2.7 in 0.1 sec !! Not manageable…**

Actually, **we neglected** the very small amount (< 1 %) of **delayed neutrons**

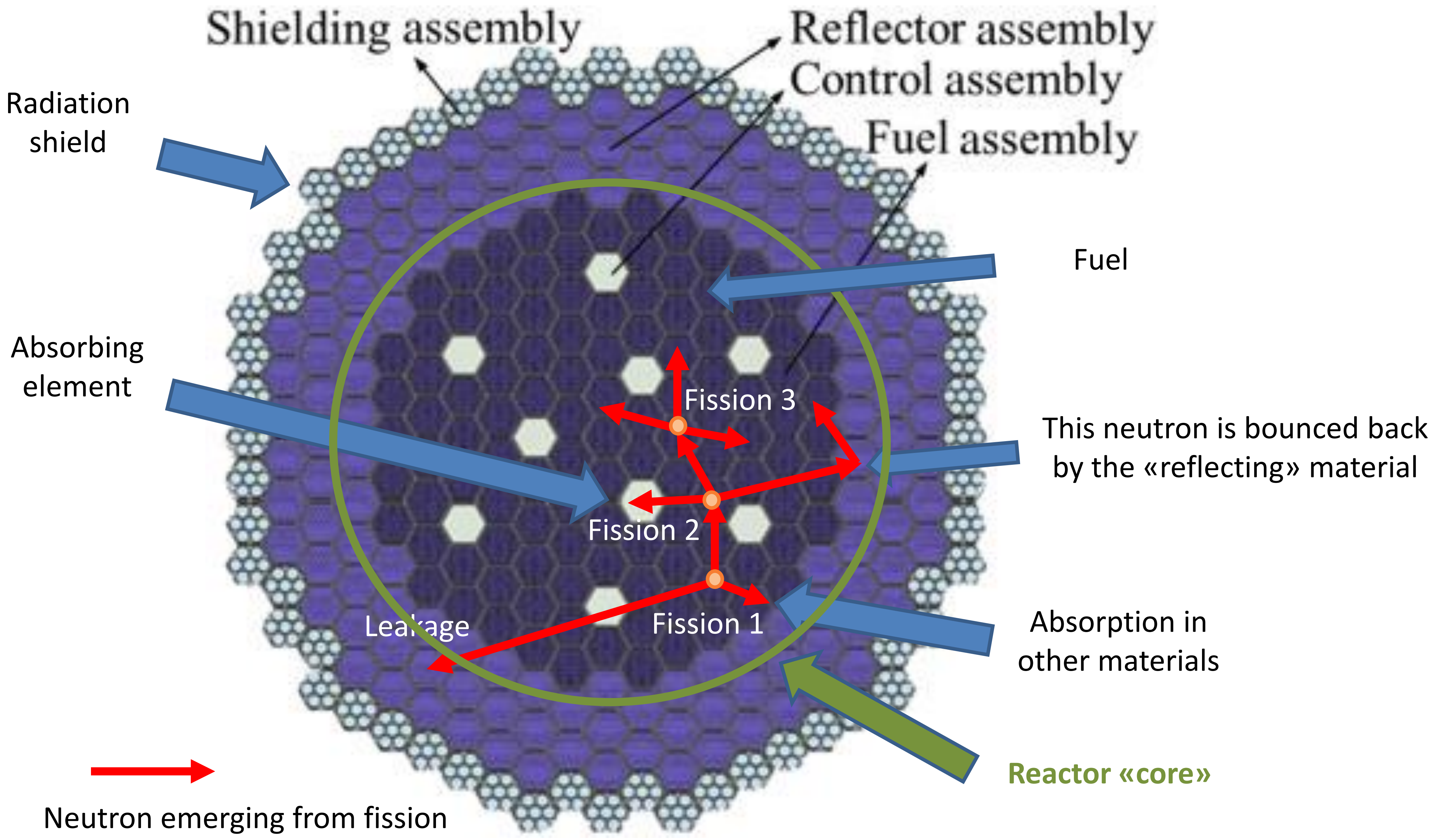
They are emitted by fragments after fission on **time scale from ms to sec**

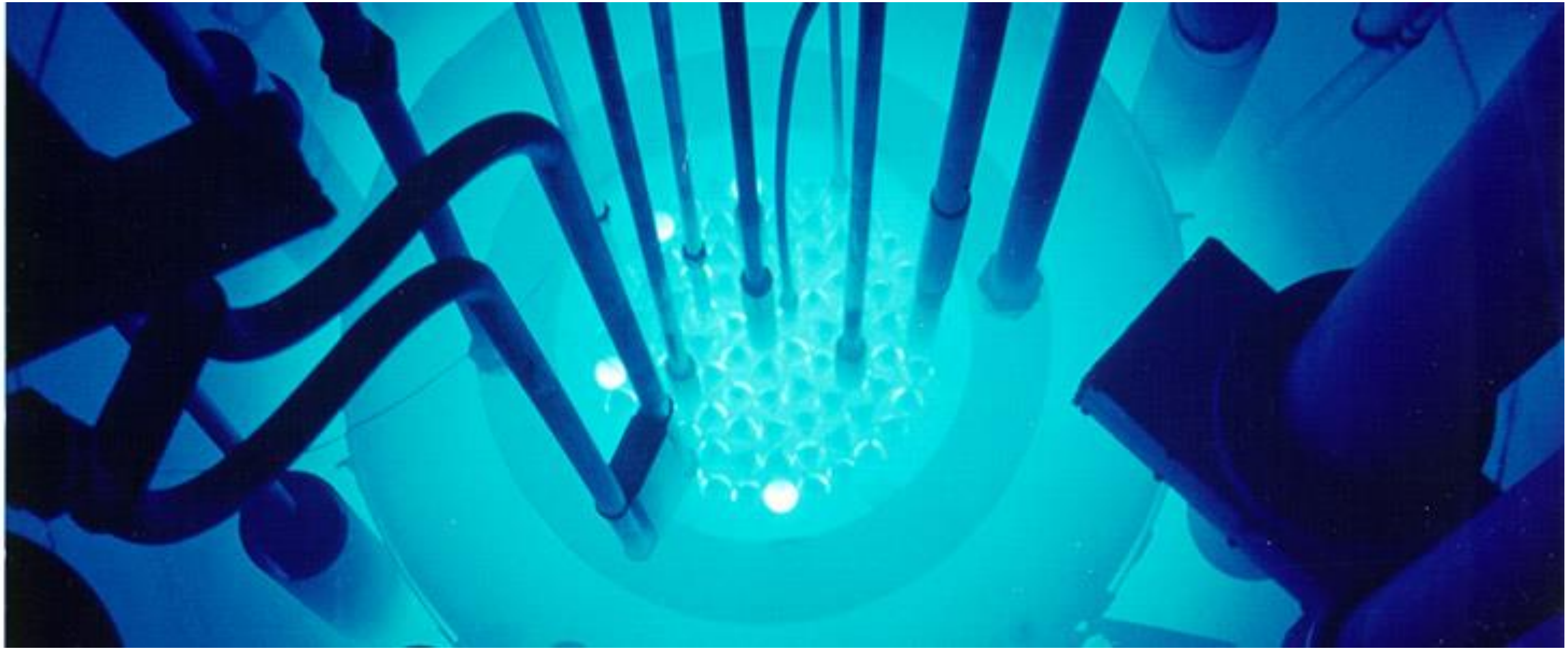
The trick is to **make the reactor critical thanks to that small fraction of neutrons**

→ Delayed neutrons **dominate the reactor response time** making it much longer

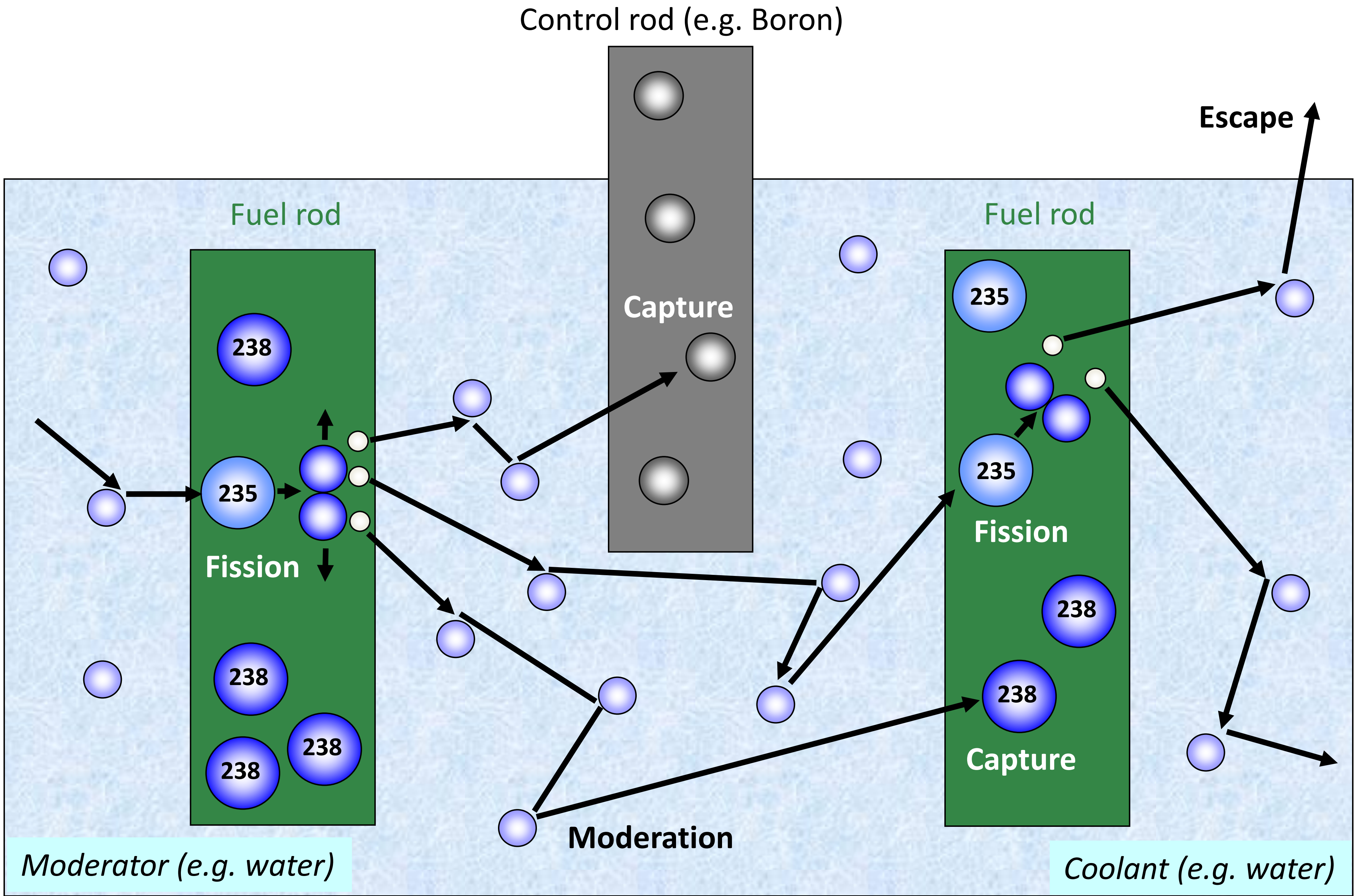
➡ Reactor control manageable by absorbers: "control rods"

Physics of multiplication: visual representation

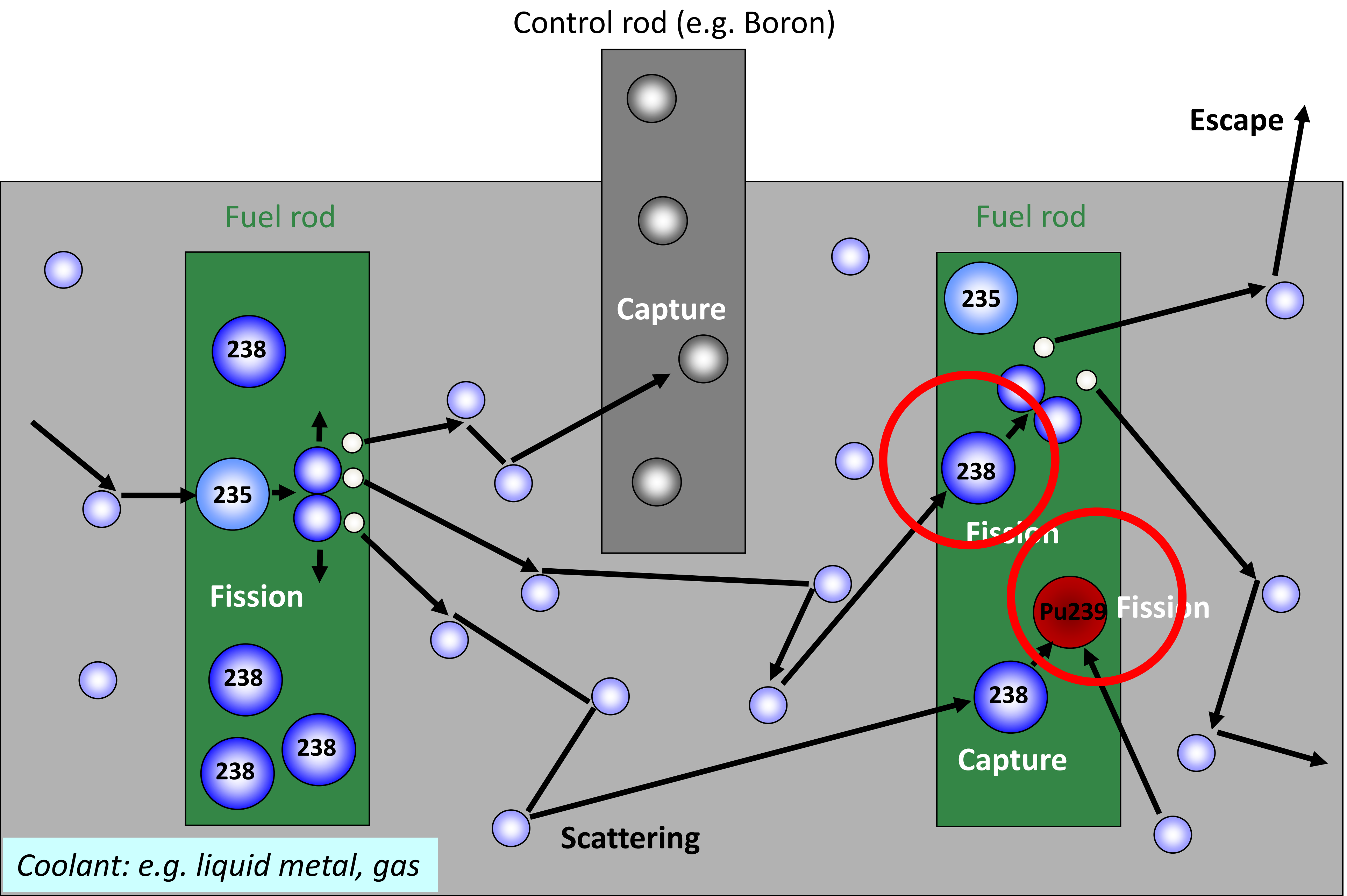




The thermal reactor

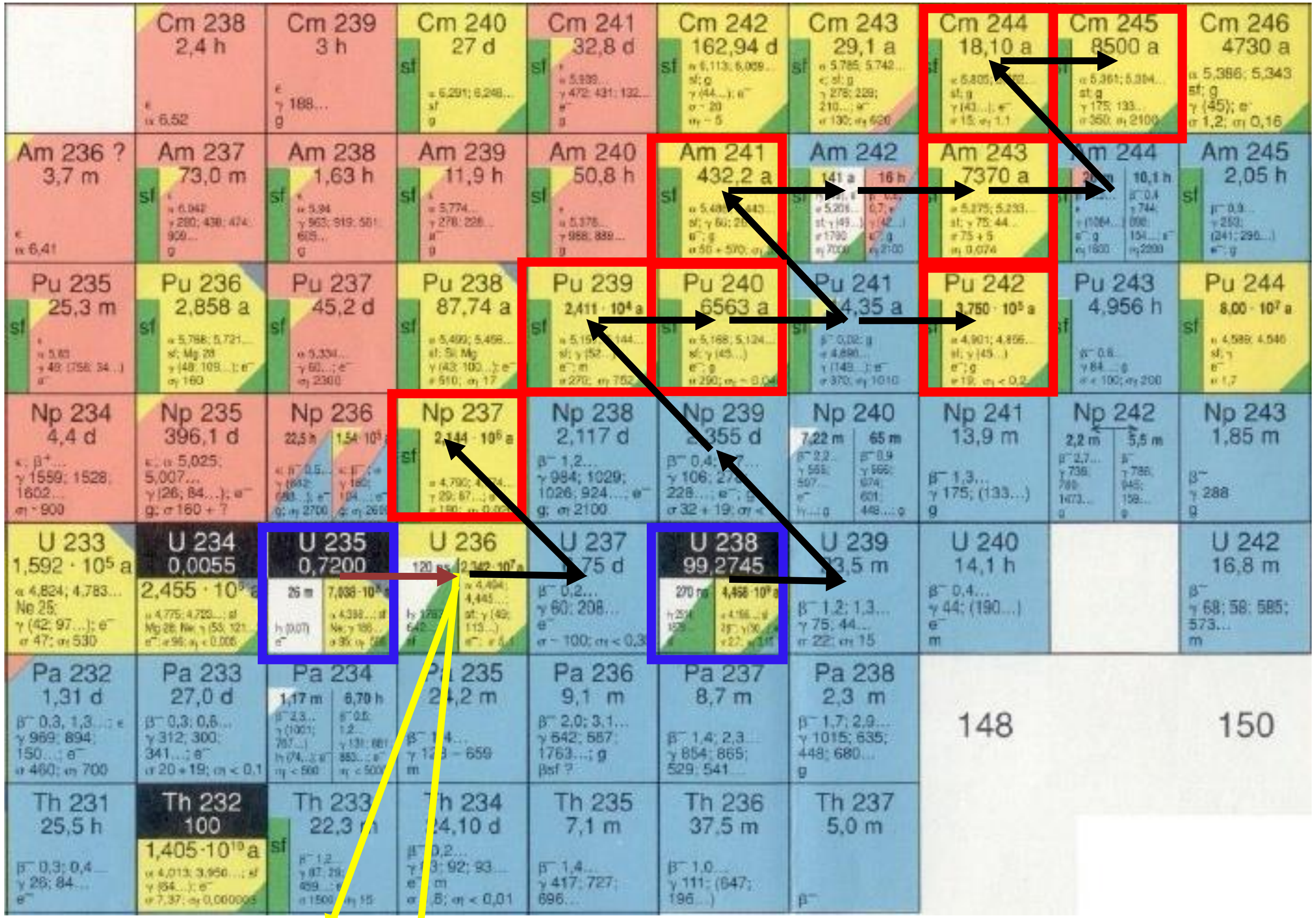


The fast reactor



In the fast reactor, neutrons are not slowed down → possibility to produce and burn more Plutonium and also to burn other radioactive nuclei beyond Plutonium formed by neutron capture

Burning-breeding-burning: Uranium-Plutonium cycle and radioactive waste production (1 GW_e LWR)



$^{244,245}Cm$ 1.5 Kg/yr

^{241}Am: 11.6 Kg/yr
^{243}Am: 4.8 Kg/yr

^{239}Pu: 125 Kg/yr

^{237}Np: 16 Kg/yr

LLFP 76.2 Kg/yr

See S. Leray's, V. Montoya's and A. Mariani's lectures for more info

Nuclide	Half-life $T_{1/2}$ (years)
Pu-239	24,000
Pu-242	3.7×10^5
Am-241	433

Fissile fuel

Fission Products (e.g. ^{90}Sr, ^{137}Cs → β emitters)
LLFP=Long Life Fission Products

Transuranics = Minor Actinides + **Pu** (mostly α)

Breeding and burning: the Thorium-Uranium cycle

Fission products

Fission products

- Use an abundant element to «breed» new fuel
- Much lower production of Transuranics

How much fuel ?

Suppose you've got a **reactor with 1 GW thermal power (1 GW_{th}* → ~ 300 MW_e*) = 10^9 Joule/sec**
Assume each fission releases order of 200 MeV energy = 3.2×10^{-11} Joule
→In the reactor the fission rate is about 3×10^{19} fissions/sec
→ which means that e.g. 3×10^{19} (nuclei of ^{235}U)/sec disappear (actually a bit more because of radiative capture)

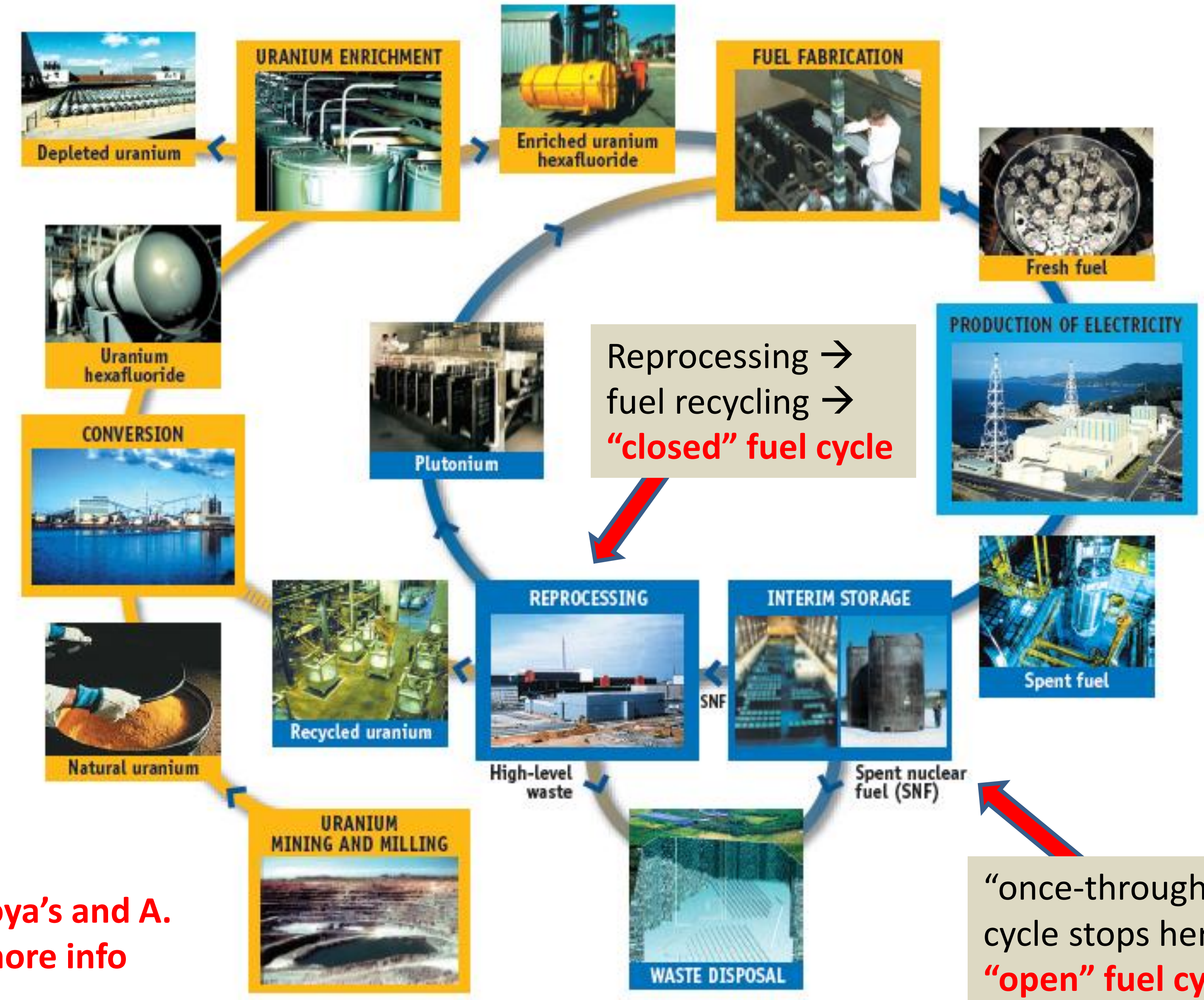
Fuel	Instantaneous consumption (per second)	Yearly consumption (@90 % load factor**)
Uranium-235	**0.012 g**	**340 Kg**
Natural Gas	27 m^3	766 million m^3
Crude oil (average)	22.5 Kg	0.6 million tons
Lignite (average)	67 Kg	1.9 million tons
Coal (average)	34 Kg	1 million tons

For a thermal reactor (see later) loaded with mixed UO_2 fuel (density about 11 gr/cm^3) comprising 4 % ^{235}U and 96 % ^{238}U, the yearly consumption corresponds to 8500 Kg of fuel → 0.8 m^3

In practice, there has to be much more as the chain reaction needs the presence of fissile nuclei at all times → the reactor has to be critical at all times
However, ^{235}U consumption is partly compensated by Plutonium (^{239}Pu) burn up

(*) 1 GW(th) = 1 GW thermal power, 1 GW(e) = 1 GW electrical power; typically, for a fossil-fueled or nuclear power plant, a conversion factor between ~ 30 to 60 % has to be applied to go from thermal to electrical power
(**) load factor=percentage of time when the reactor is actually producing electricity

How does it actually work ? The nuclear fuel cycle

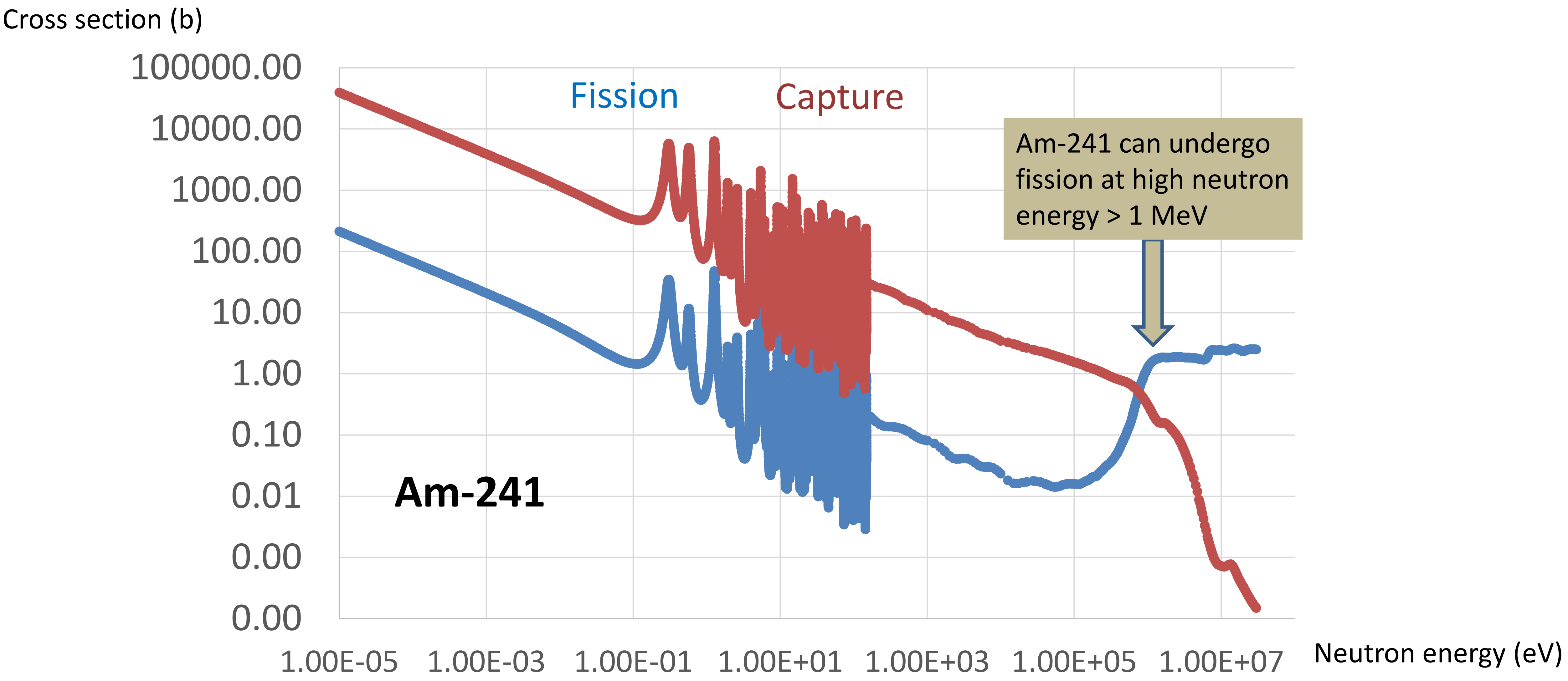


Reprocessing → fuel recycling → **"closed" fuel cycle**

"once-through" cycle stops here → **"open" fuel cycle**

See S. Leray's, V. Montoya's and A. Mariani's lectures for more info

Fast spectrum systems and waste incineration (transmutation)

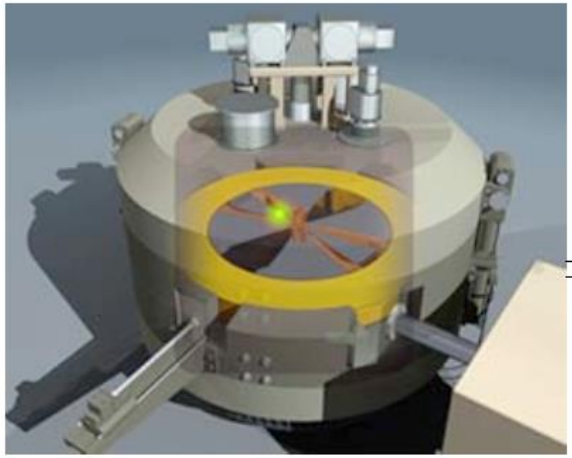


Also other **Minor Actinides** are characterized by a **fission threshold** around the **MeV**

➔ Such isotopes can be burnt in **fast reactors or in fast Accelerator Driven Systems (ADS)**

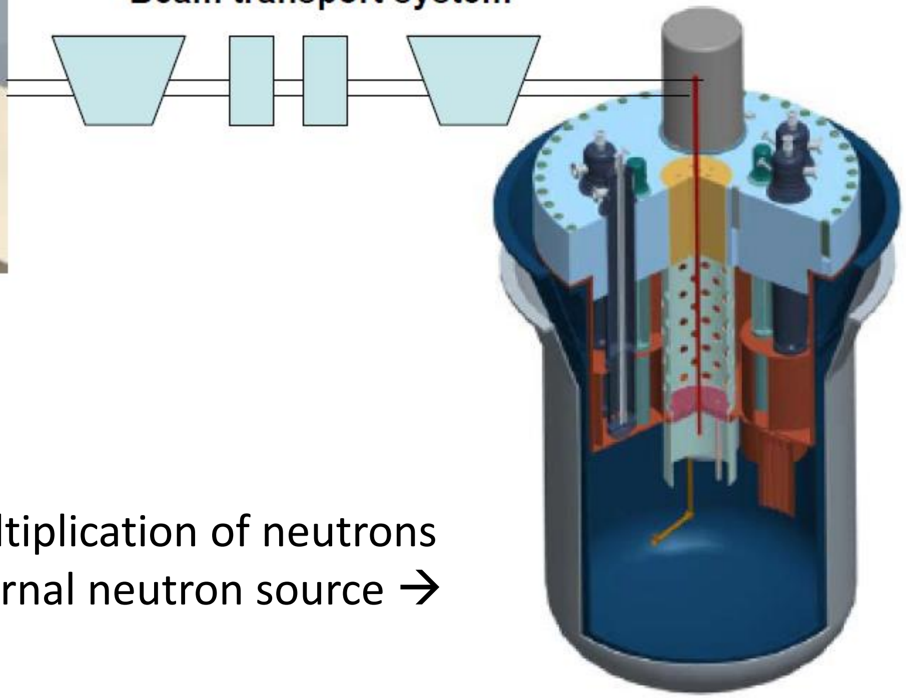
➔ BUT, MAs have less delayed neutrons: cannot load too much in FRs, ADS has no such limitation

ADS: a 3-component infrastructure

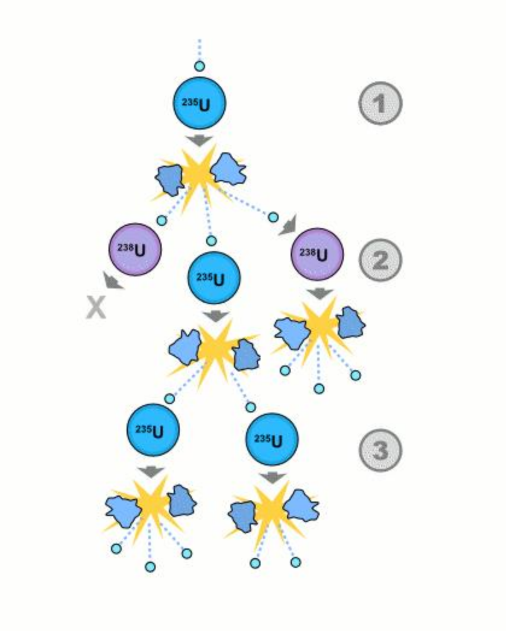


Proton accelerator

Beam transport system



Subcritical reactor

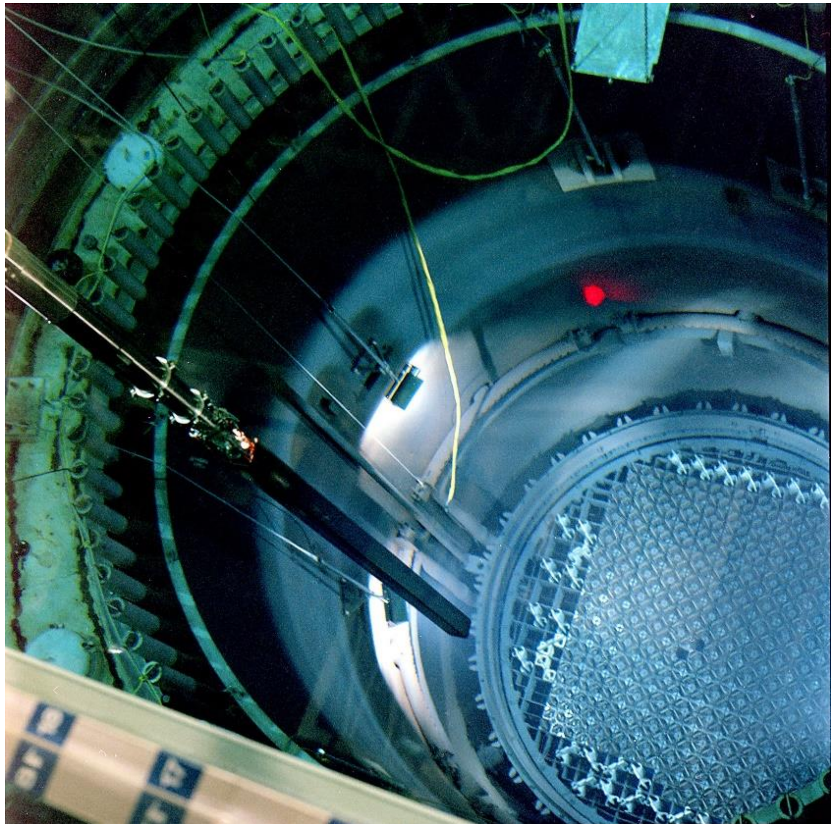


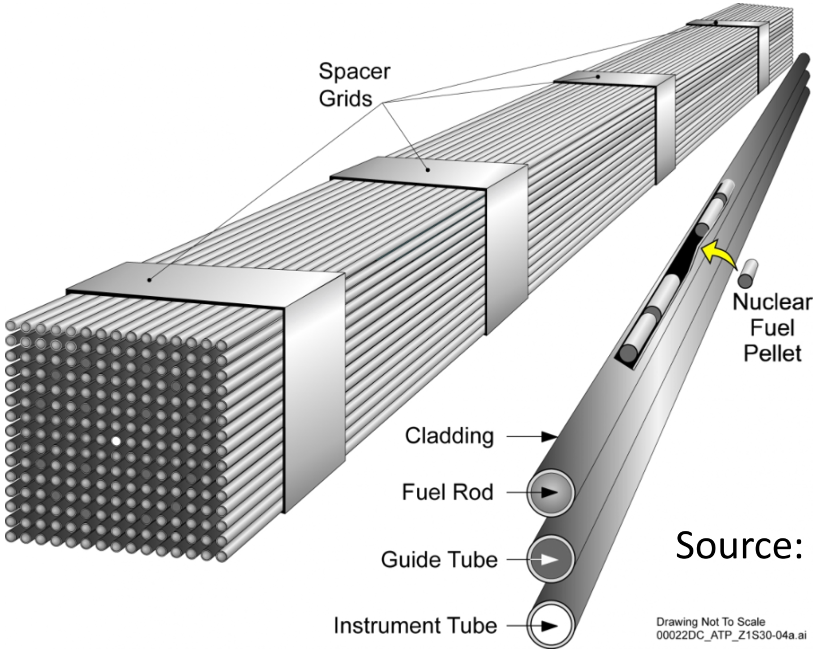
In ADS, effective multiplication of neutrons is < 1→ need an external neutron source → accelerator+target

The maximum thermal power P_{th} from the subcritical reactor is limited (and controlled !) by the input beam power P_{beam}

How do fuel, core and reactor actually look like ?

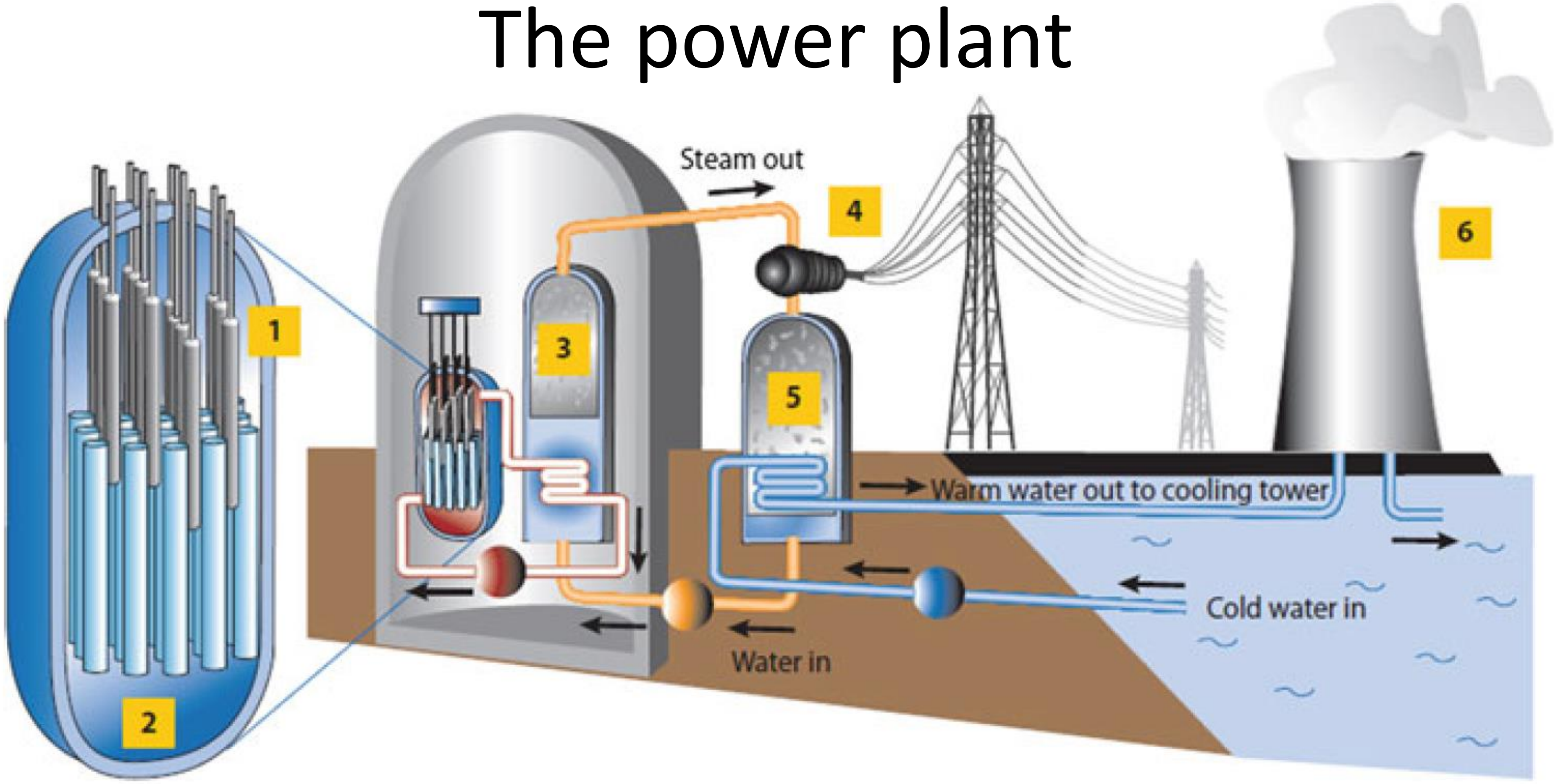
Fuel pellets. Photo: Areva/US NRC





Source: US DOE

The power plant



Basic components of a thermal nuclear power reactor (pressurised water reactor):
1-Reactor: fuel rods (light blue) heats up pressurised water. Control rods (grey) absorb neutrons to control or halt the fission process
2-Coolant and moderator: fuel and control rods are surrounded by water (primary circuit) that serves as coolant and moderator
3-Steam generator: water heated by the nuclear reactor transfers thermal energy through thousands of pipes to a secondary circuit of water to create high-pressure steam
4-Turbo-generator set: steam drives the turbine, which spins the generator to produce electricity just like in a fossil-fuel plant
5-Condenser: removes heat to convert steam back to water, which is pumped back to the steam generator
6-Cooling tower: removes heat from the cooling water that circulates through the condenser, before returning it to the source at near-ambient temperature

Source: OECD-NEA Nuclear Energy Today, 2nd edn. (2012), ISBN 978-92-64-99204-7. NEA Report No. 6885

Decay heat

Decay heat is the heat released as a result of radioactive decay: the energy of the alpha, beta or gamma radiation is converted into atomic motion

In nuclear reactors **decay of the radioisotopes created in fission continues** for a long time after shut down

A practical approximation is given by the formula
$$\frac{P}{P_0} = 6.6 \cdot 10^{-2} \left[\frac{1}{(\tau - \tau_s)^{0.2}} - \frac{1}{\tau^{0.2}} \right]$$

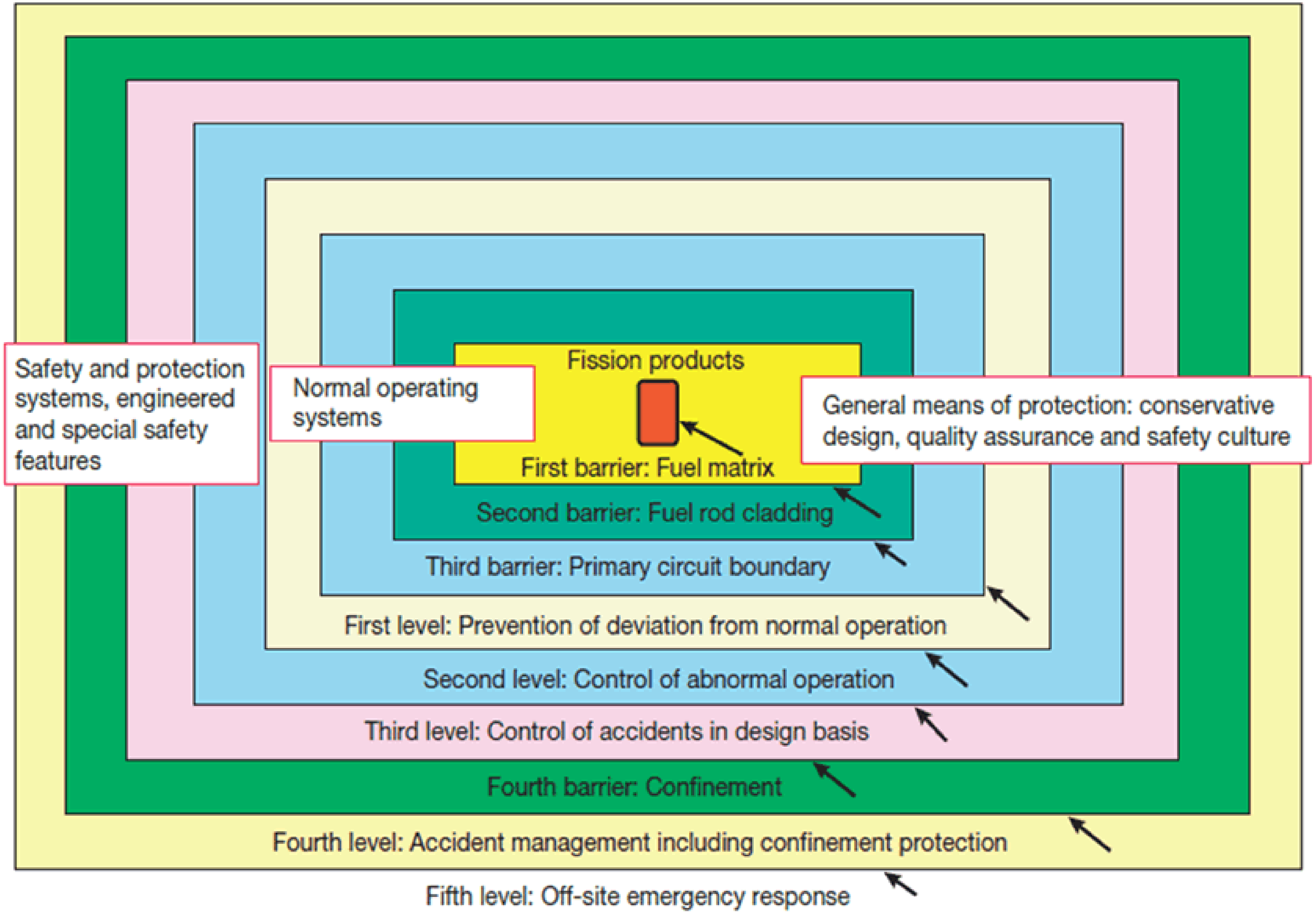
Where P is the decay power, P_0 is the reactor power before shutdown, τ is the time since reactor startup and τ_s is the time of reactor shutdown measured from the time of startup (in seconds)

At shutdown, the heat power is about 6.5 % (~200 MWth for a 1 GWe reactor)
Sufficient to melt the core….

About 1 hour after shutdown, the decay heat will be about 1.5% of the previous core power. After a day, the decay heat falls to 0.4%, and after a week it will be only 0.2%, which still requires cooling, though…
Spent fuel rods are kept for long time in water pools, before storage or reprocessing.

Removal of decay heat very important → Fukushima…
"Heat sink" must not be compromised

Safety: defence in depth



Control of operation should include some (negative) feedback mechanisms:
e.g. if temperature (power) goes up, reaction cross section goes down

Nuclear accidents

The fission process creates radioactive substances that can be dangerous for the environment and for human health→ they **must** be contained as much as possible

Chernobyl, Soviet Union, 1986

Fukushima, Japan, 2011

Safety measures are essential and are subject of continuous research and improvement

Accidents in perspective…

Train carrying liquid gas explodes in Italy killing 12

At least 50 injured as freight train derails in Viareggio and hits homes of sleeping families

▲ The aftermath of the explosion of gas tanks on a derailed train in the Italian town of Viareggio. Photograph: Olycom SPA /Rex Features

The Guardian, 30 June 2009

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Mozambique fuel truck explosion: 73 dead, 100s injured

with AFP 17/11/2016

Los Angeles Times

CALIFORNIA

‘Avian incident’ knocks out 84% of massive California solar farm

A solar power facility in Borrego Springs, Calif., on Feb. 11. (Al Seib / Los Angeles Times)

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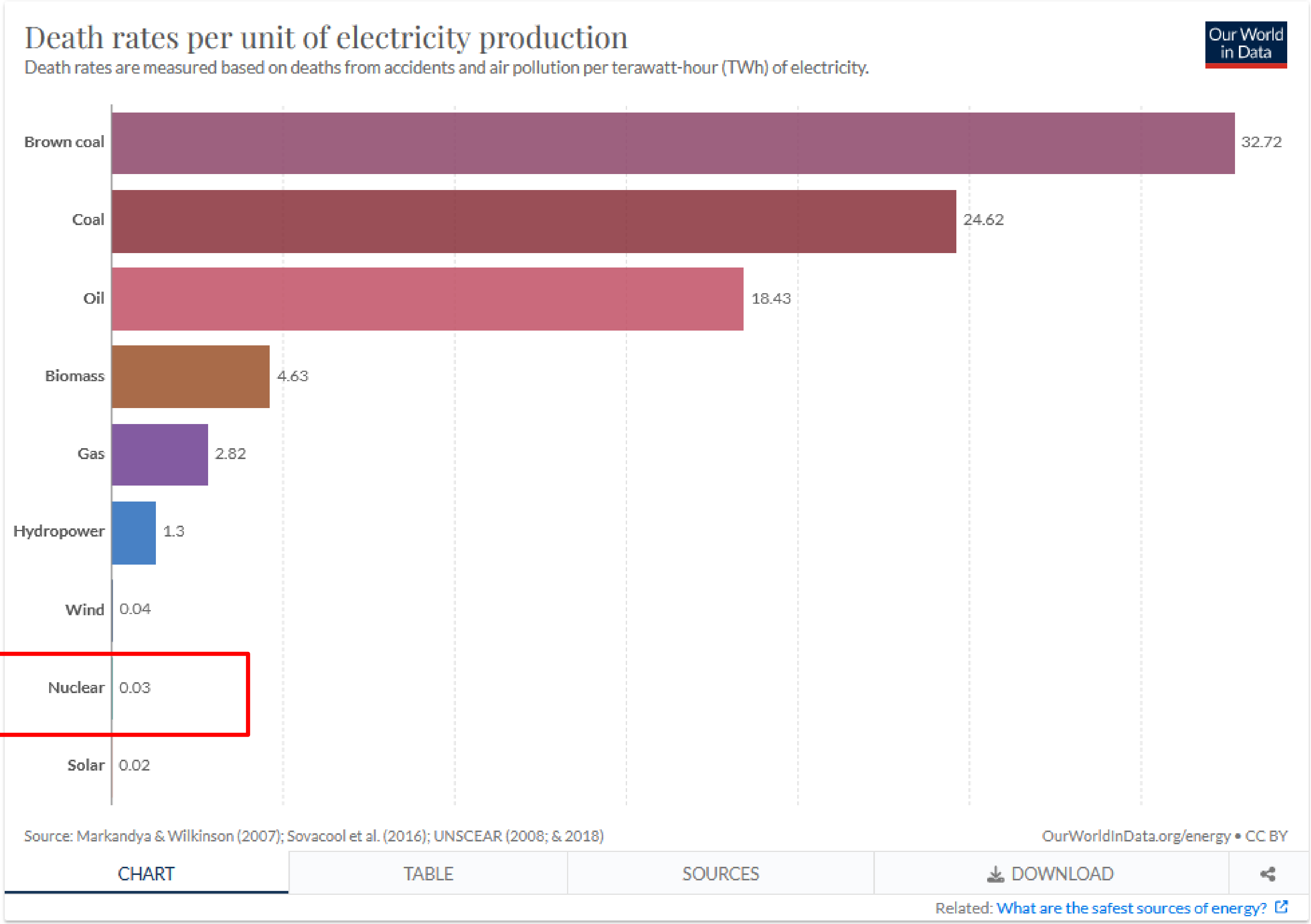
By BLOOMBERG JUNE 20, 2019 | 8:05 AM

An “avian incident” sparked a fire at one of California’s biggest solar farms, affecting 1,200 acres and knocking out 84% of the California Valley Solar Ranch’s generating capacity.

The June 5 incident didn’t damage solar panels at the 250-megawatt power plant, but distribution poles and cables need to be replaced, according to a regulatory filing Wednesday from owner Clearway Energy Inc. The company didn’t say exactly how the blaze was ignited. …

About 40 megawatts of the San Luis Obispo County facility are in operation, and it’s expected to return to full service by July 1. Clearway expects the incident to cost $8 million to $9 million this year, after estimated insurance recovery.

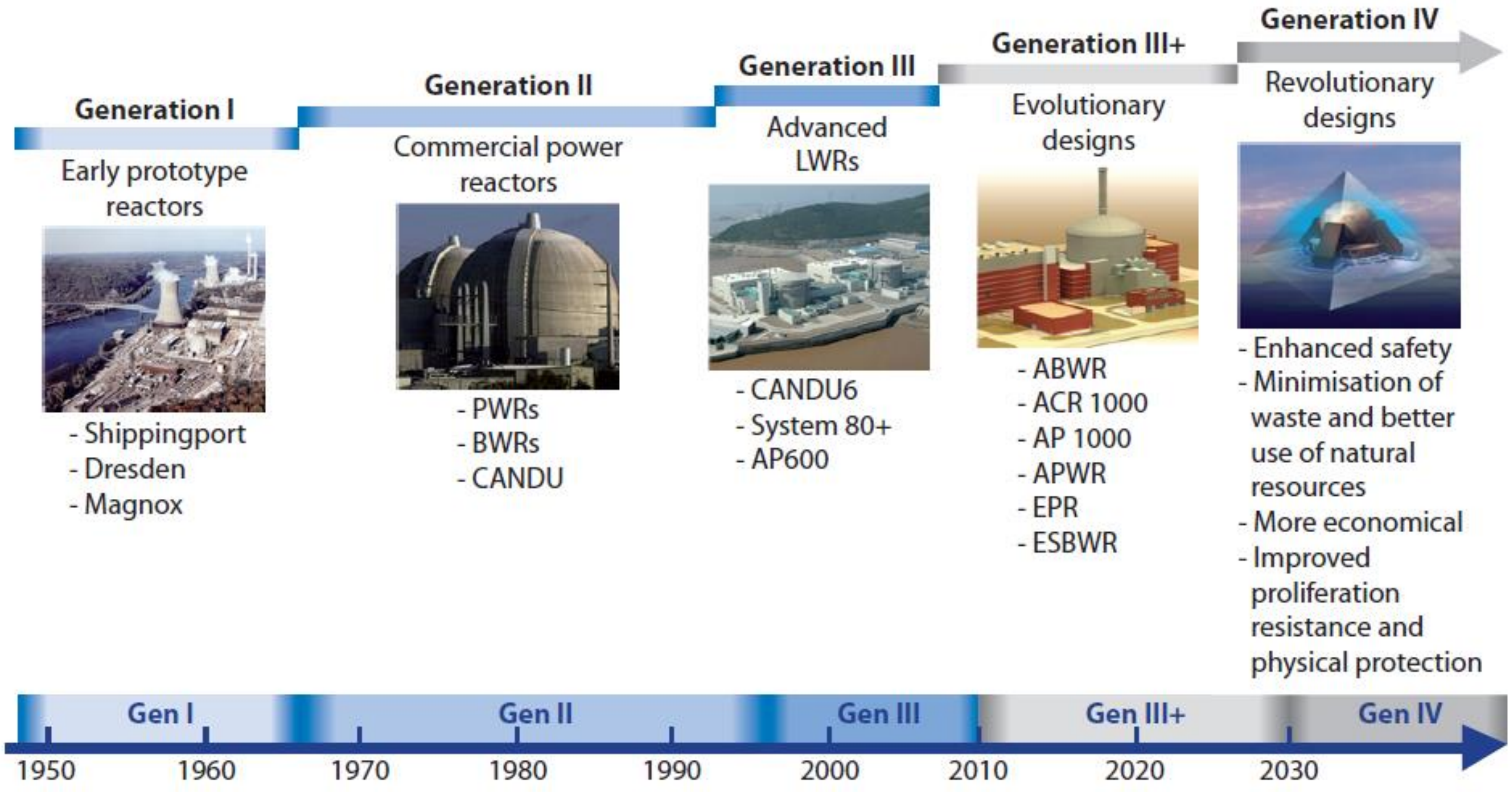
How dangerous is nuclear energy ?



From: https://ourworldindata.org/grapher/death-rates-from-energy-production-per-twh

Past and future

Please look at Sylvie Leray’s lecture for the global picture on nuclear energy from fission



+ SMR

Thank you !