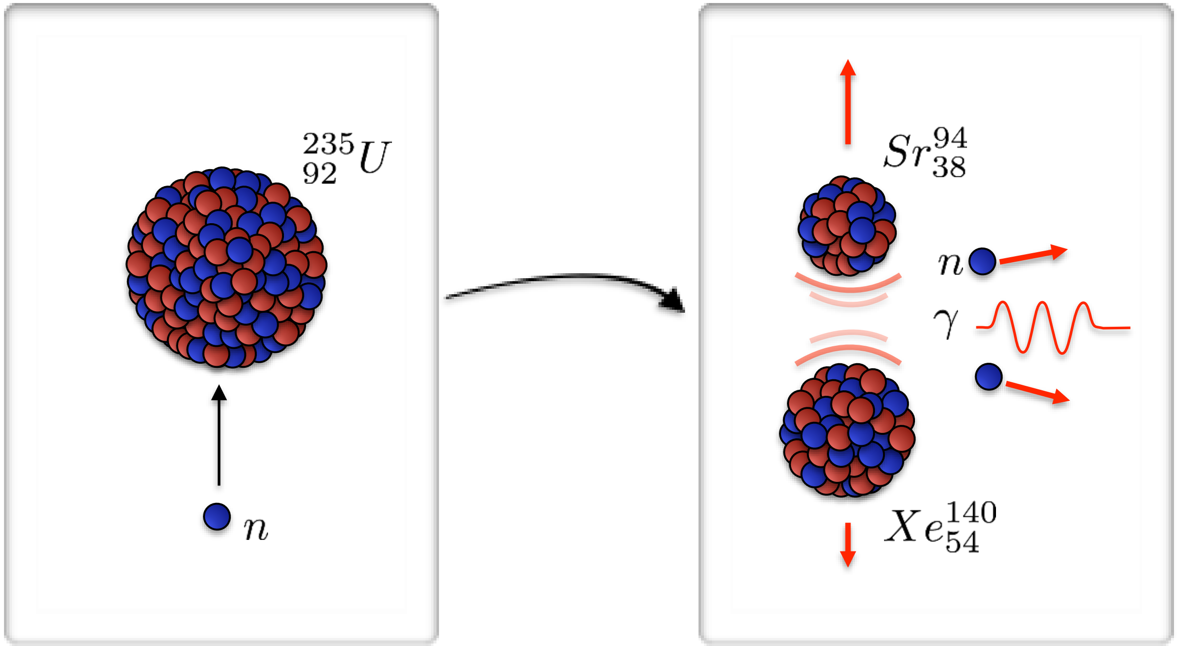
EPFL

Broad topic	Lecture title
Basic principles of NPP	Introduction / Review of nuclear physics
	Interaction of neutrons with matter
	Nuclear fission
	Fundamentals of nuclear reactors
	LWR plants
Modeling the beast	The diffusion of neutrons - Part 1
	The diffusion of neutrons - Part 2
	Neutron moderation without absorption
	Neutron moderation with absorption
	Multigroup theory
	Element of lattice physics
	Neutron kinetics
	Depletion
Reactor Concepts Zoo	Advanced LWR technology
	Breeding and LFR
	AGR, HTGR
	Channels, MSR and thorium fuel
Review session	

- Fission reaction.
- Fission products.
- Energy release from fission. Fission and burnup rates.
- Fission fragments. Yields, decay, poisoning, residual heat.
- Fission neutrons (prompt and delayed).
- Delayed neutrons.
- Practical fission fuels. Fissile and fertile fuels.
- Fuel fission and capture cross sections vs. energy.
- Comparison of cross sections of fissile and fertile fuels.

- A heavy nucleus after absorption of a neutron can fission into two (fission) fragments
- Release of considerable energy (mainly kinetic energy of the repulsing fragments)
- Emission of 2 – 3 high-energy neutrons, γ-rays and neutrinos



A fission results in a number of products:

- fission fragments (often called Fission Products = FP)
- fission neutrons
- γ rays
- β^- rays
- neutrinos

prompt (at the moment of fission) or **delayed** (as a result of decay of fission fragments)

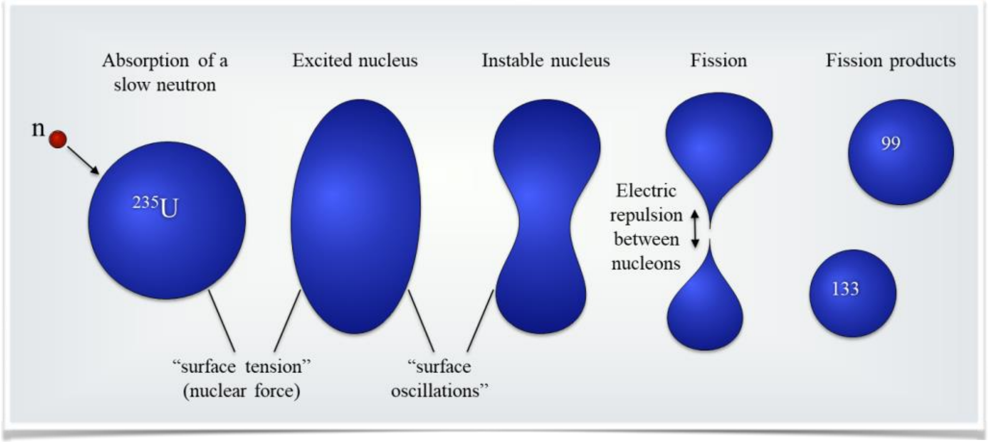
A reminder what β^--decay is:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^- + \bar{\nu}_e \quad \text{e.g.} \quad n \rightarrow p + e^- + \bar{\nu}_e$$ (electron antineutrino)

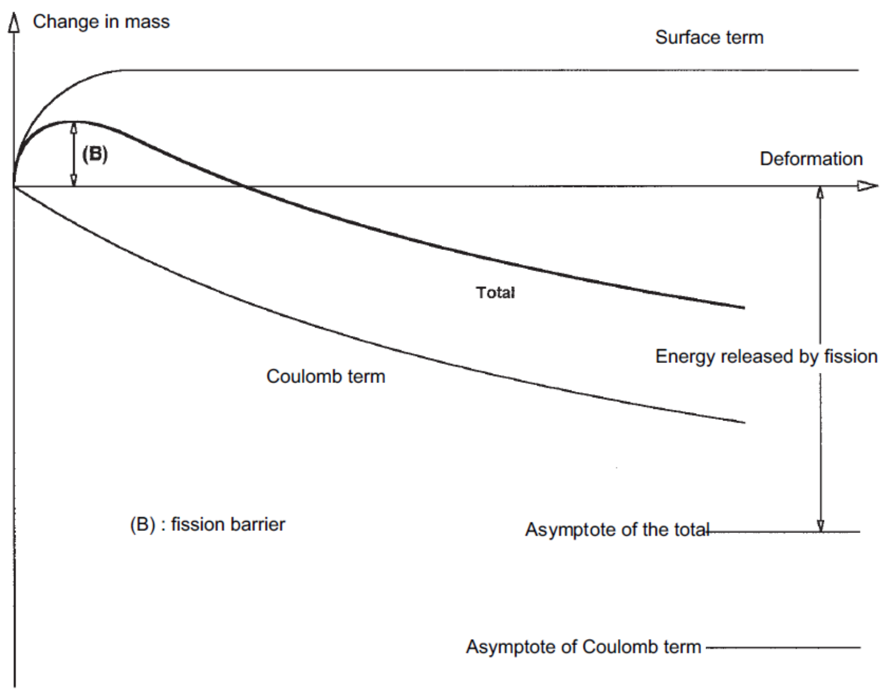
A process which allows the atom to obtain the optimal ratio of protons and neutrons: Z/N increases

Fission Barrier

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \Delta(Z,N)$$



- Neutron-induced fission can occur only if the energy brought into the compound nucleus exceeds the fission barrier (B).
- The height of this barrier depends on the actinide



Fission Barrier

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \Delta(Z,N)$$

- The energy brought in by the absorbed neutron consists of:

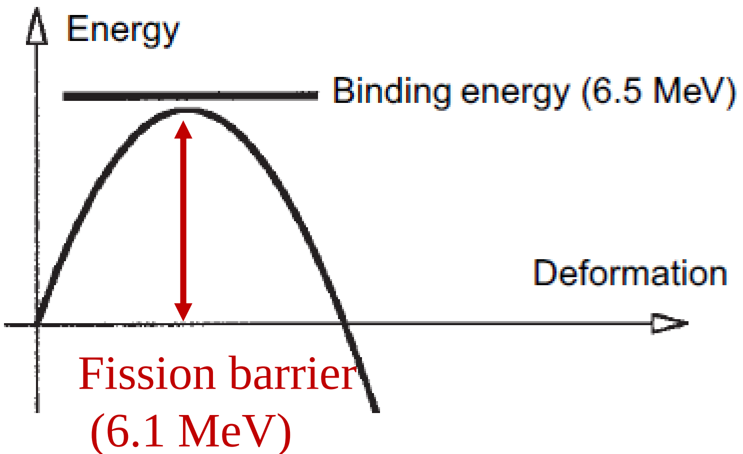
1) Binding energy component

2) Kinetic energy component

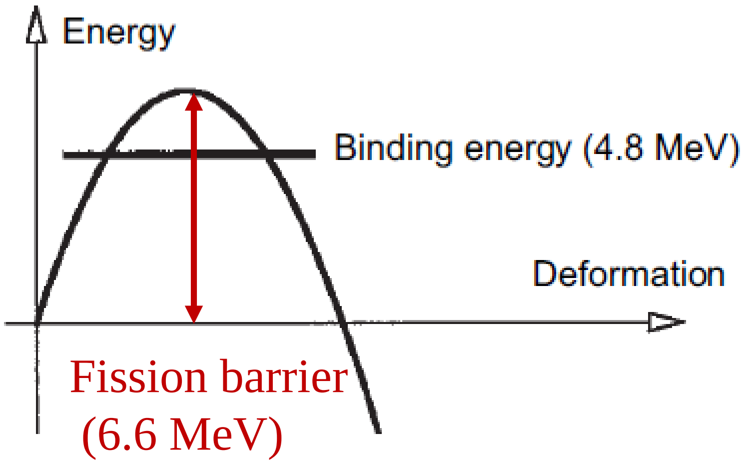
- The binding energy of a nuclide depends on its nucleon configuration, and nuclides with even number of protons (even-Z) or neutrons (even-N) tend to be more tightly bound (parity effect)

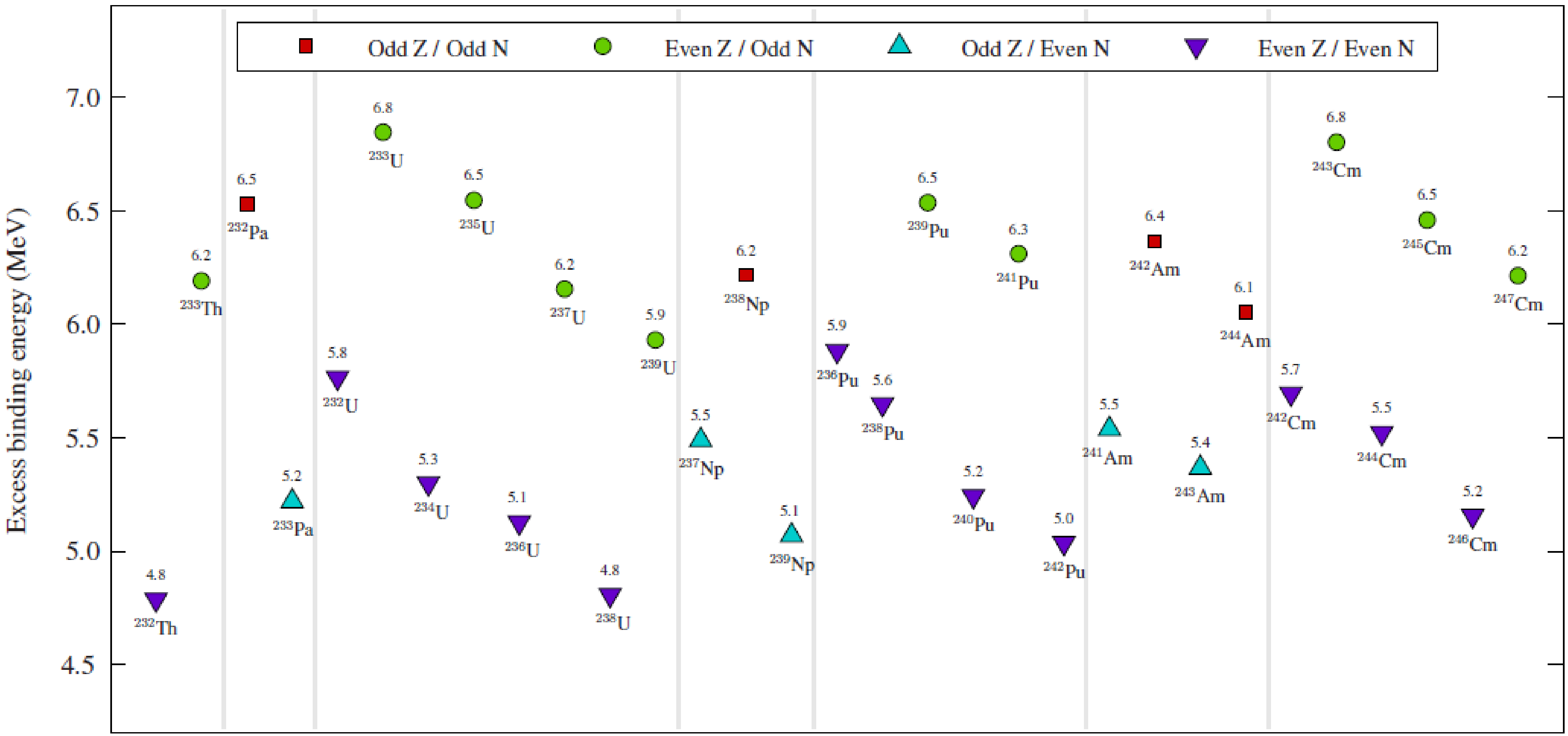
- Neutron absorption in odd-N nuclides releases more energy, as the resulting even-N isotope is more tightly bound.

URANIUM 235



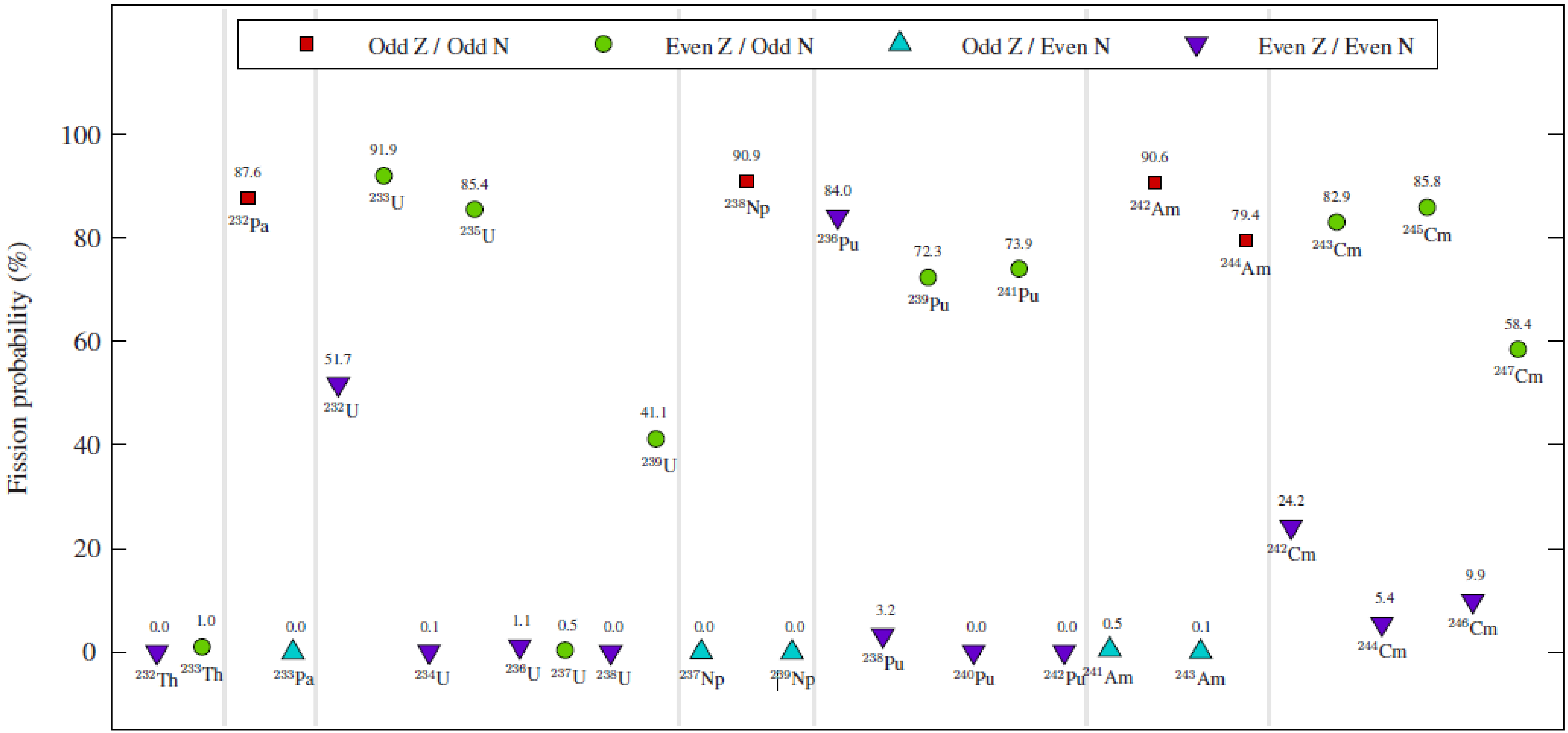
URANIUM 238



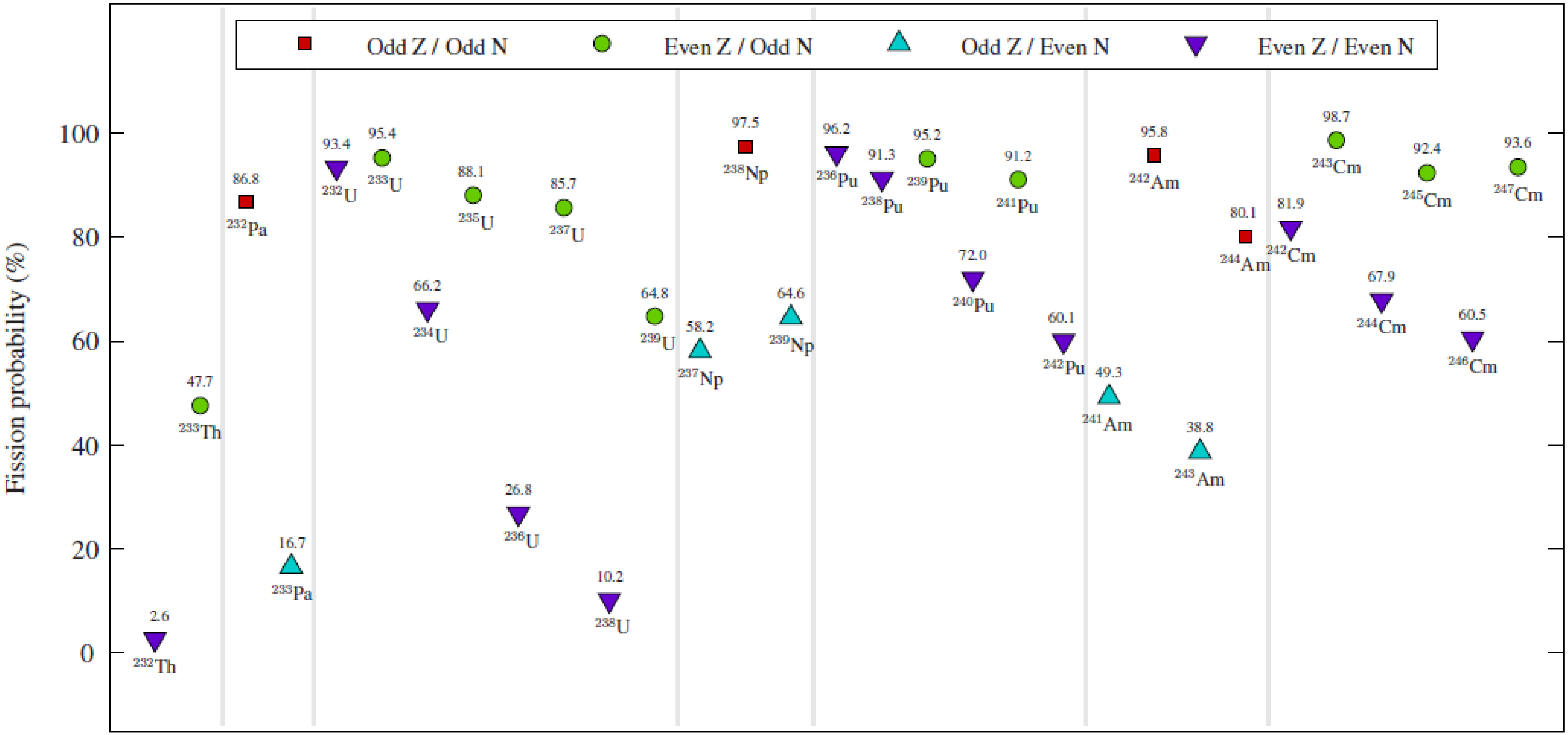


Odd Z / Odd N
Even Z / Odd N
Odd Z / Even N
Even Z / Even N
Excess binding energy (MeV)
7.0
6.5
6.0
5.5
5.0
4.5
4.8 232Th
6.2 233Th
6.5 232Pa
5.2 233Pa
5.8 232U
6.8 233U
5.3 234U
6.5 235U
5.1 236U
6.2 237U
4.8 238U
5.9 239U
5.5 237Np
6.2 238Np
5.1 239Np
5.9 236Pu
5.6 238Pu
6.5 239Pu
5.2 240Pu
6.3 241Pu
5.0 242Pu
5.5 241Am
6.4 242Am
5.4 243Am
6.1 244Am
5.7 242Cm
6.8 243Cm
5.5 244Cm
6.5 245Cm
5.2 246Cm
6.2 247Cm

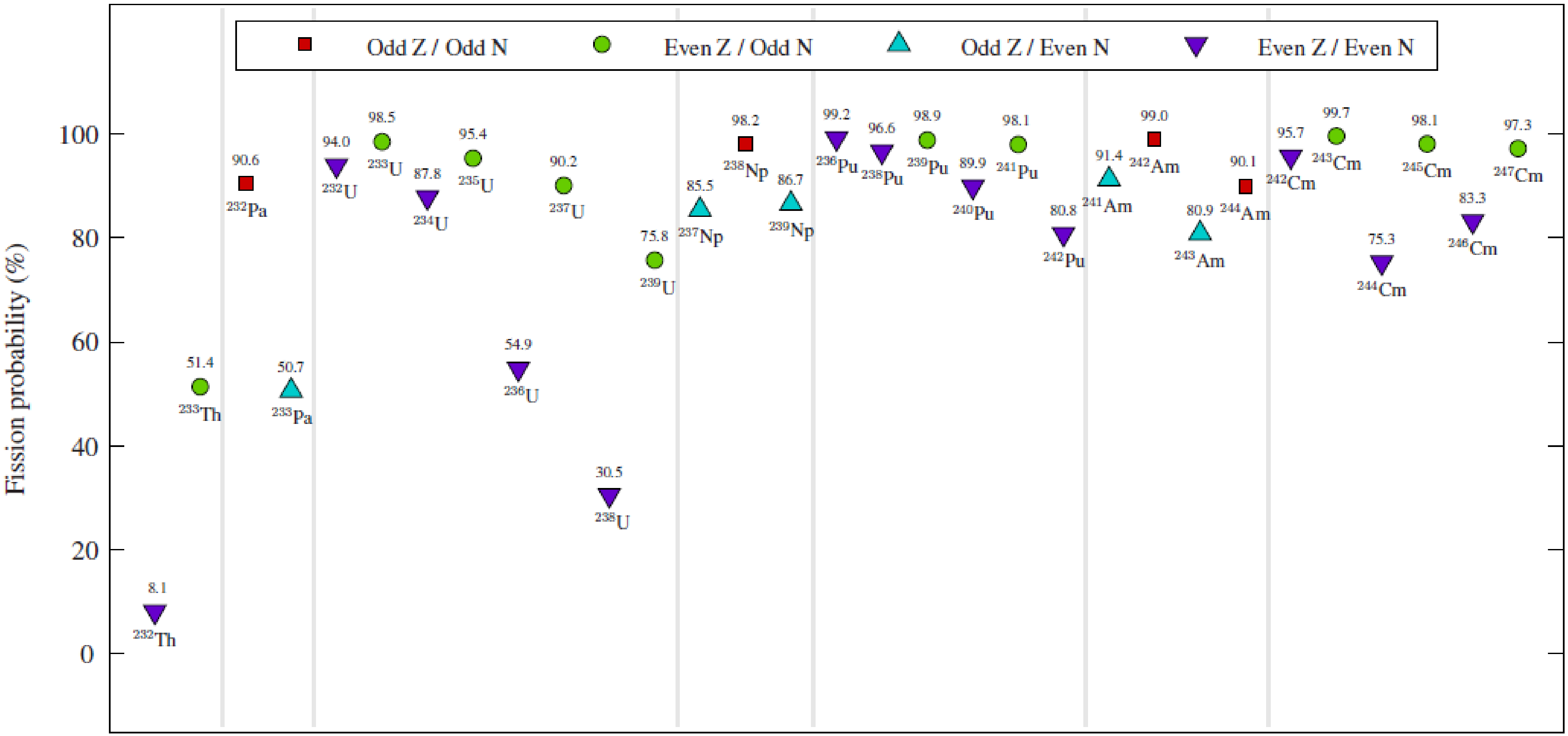
PROBABILITY OF FISSION WITH THERMAL NEUTRONS



PROBABILITY OF FISSION WITH FAST (1.3 MEV) NEUTRONS



PROBABILITY OF FISSION WITH VERY FAST (14 MEV) NEUTRONS



Fission Barrier

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \Delta(Z,N)$$

- Actinides are divided into fissile and fissionable nuclides, depending on whether they can undergo fission by low-energy neutron absorption.
- Most of the fissile isotopes are odd-N nuclides (^{235}U, ^{239}Pu, etc.).
- Fissionable isotopes (^{238}U, ^{240}Pu, etc.) require 1 MeV of additional kinetic energy for fission to occur.

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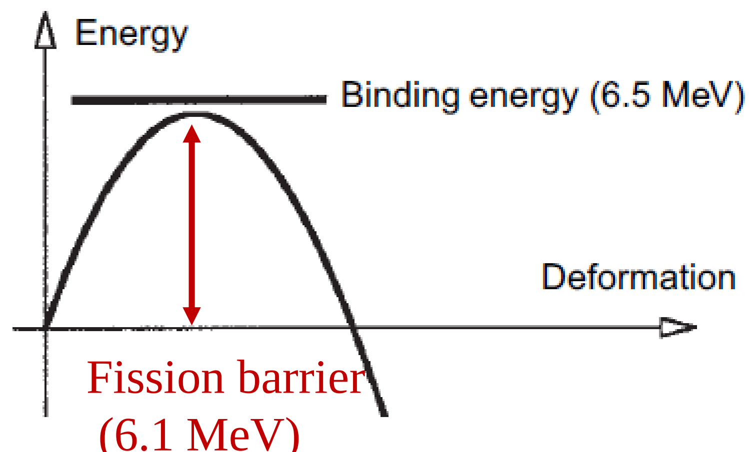

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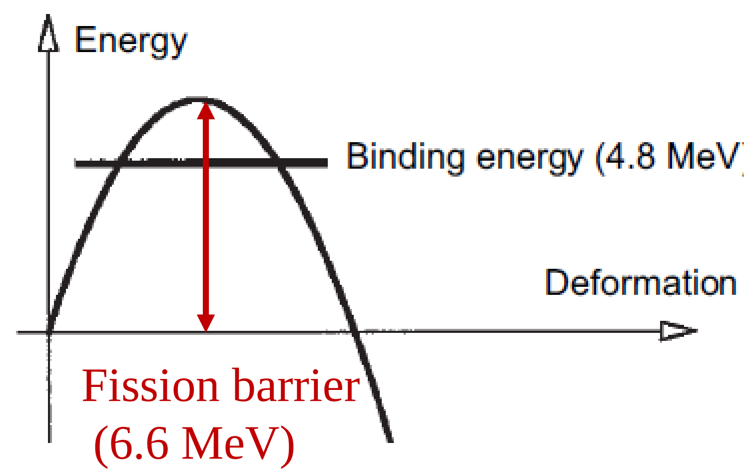


Uranium, Thorium, Plutonium

90	91	92	93	94	95	96
Th	**Pa**	**U**	**Np**	**Pu**	**Am**	**Cm**
Thorium	Protactinium	Uranium	Neptunium	Plutonium	Americium	Curium
232.0381	231.03588	238.0289	(237)	(244)	(243)	(247)

- U, Th : the 2 "natural" nuclear fuels
  → Natural uranium: 99.3% of ^{238}U + 0.7% of ^{235}U + ^{234}U (traces).
  → Natural thorium: 100% ^{232}Th (more abundant than uranium).

- Only U contains *fissile* material: 0.7% of ^{235}U (can be enriched)
  → *Fissile* nuclei can be fissioned by slow (thermal) neutrons with a very high probability

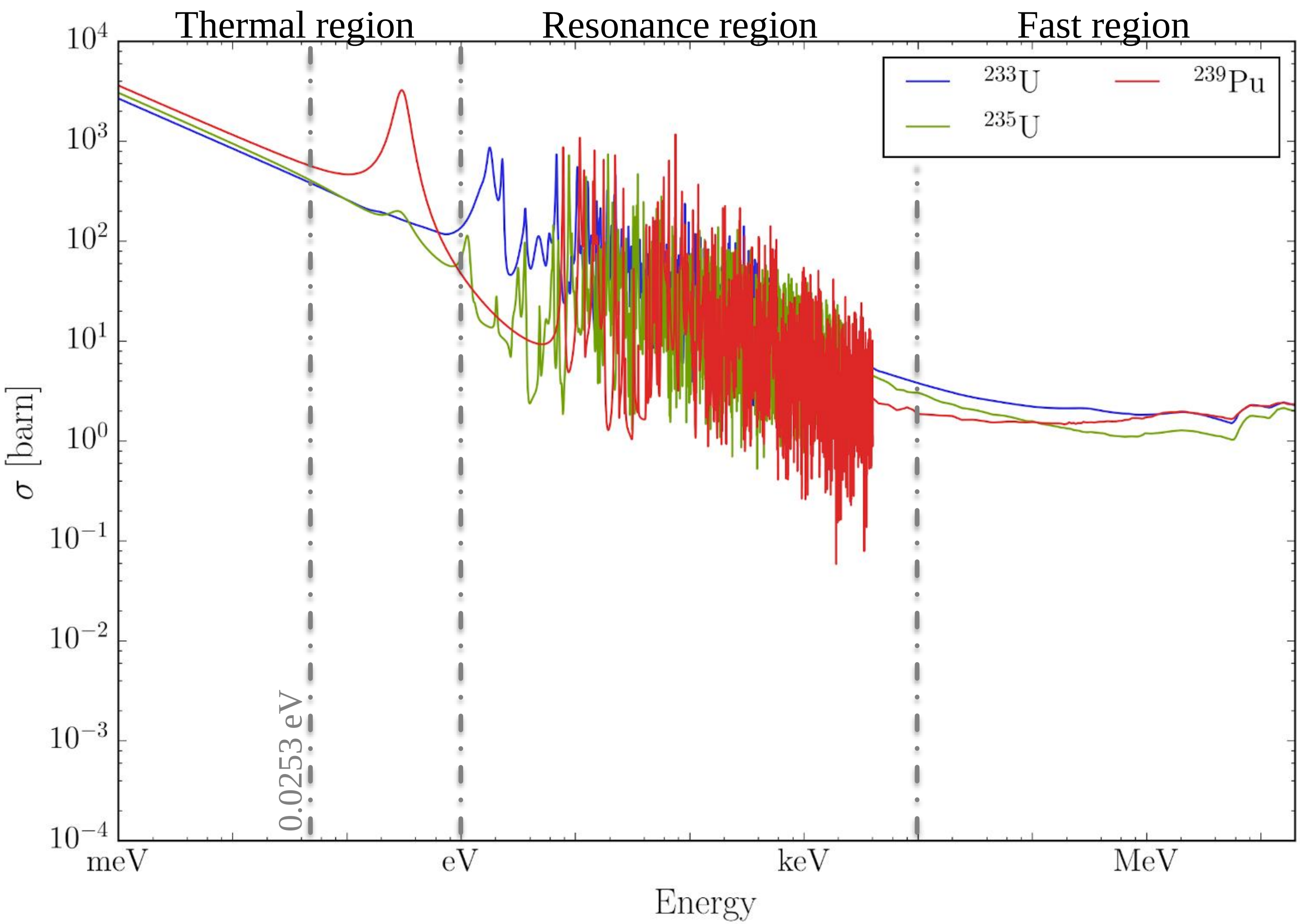
- Rest of U_{nat}, as also all Th_{nat}, are *fertile*
  → *Fertile* nuclei give rise, via neutron capture, to the "artificial" fissile isotopes: ^{239}Pu, ^{233}U

$$^{238}U(n,\gamma)^{239}U \xrightarrow[23\,m]{\beta^-} {}^{239}Np \xrightarrow[2.3\,d]{\beta^-} {}^{239}Pu \qquad T_{1/2}\left(^{239}Pu\right) = 2.4\,10^4\,y$$

$$^{232}Th(n,\gamma)^{233}Th \xrightarrow[22\,m]{\beta^-} {}^{233}Pa \xrightarrow[27.4\,d]{\beta^-} {}^{233}U \qquad T_{1/2}\left(^{233}U\right) = 1.6\,10^5\,y$$

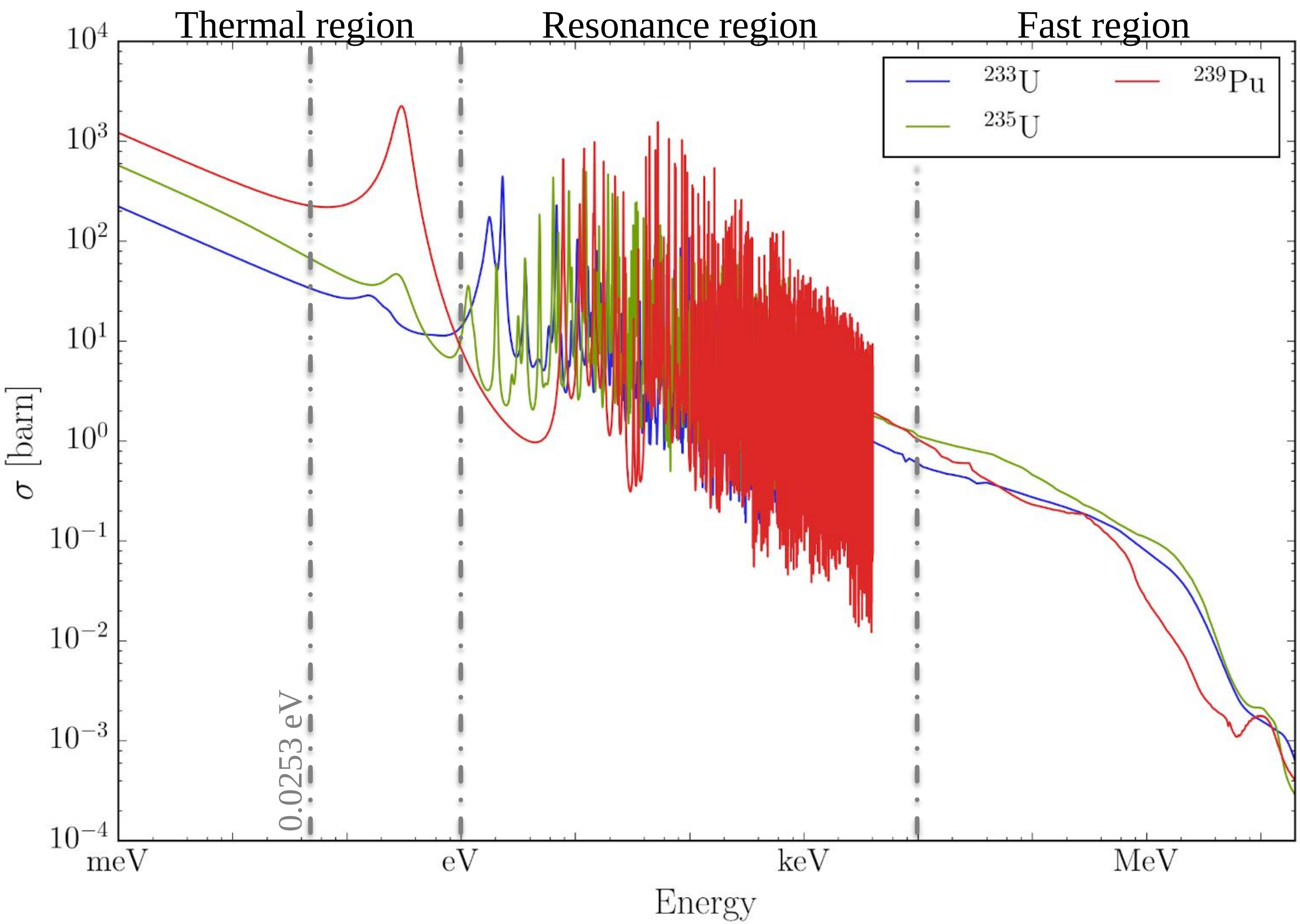
Fissile fuels - Fission

- Very high in thermal region



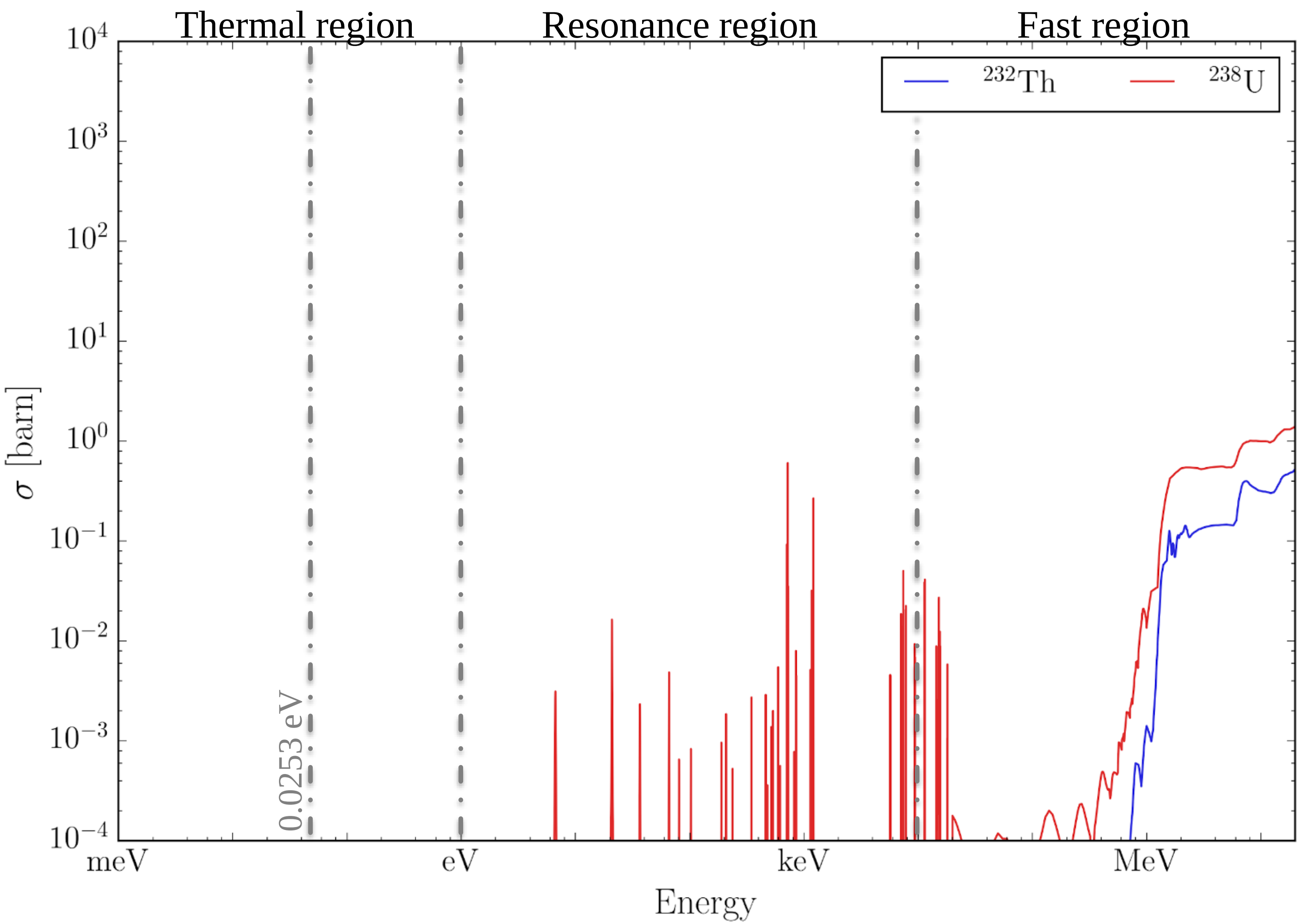
Fissile fuels - Capture

- Wide resonances for all cross sections



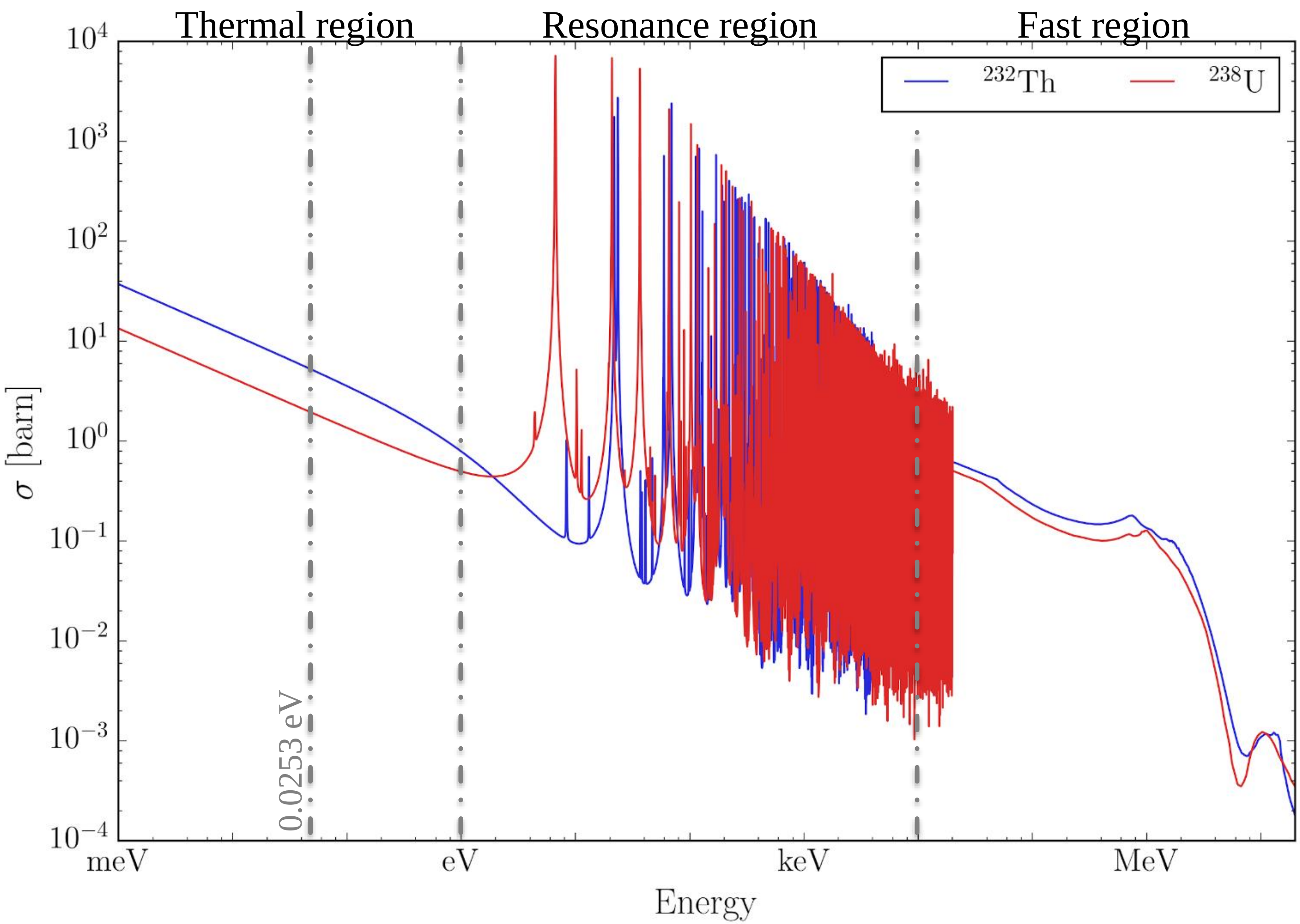
Fertile fuels - Fission

- Threshold reaction



Fertile fuels - Capture

- Very high and sharp resonances



Comparison of Cross Sections of Fissile and Fertile Fuels

- Fissiles… σ_f goes up for low neutron energies
- Fertiles… only fissionable with neutrons of E > 1 MeV
- Captures "parasitic" for fissiles, useful for fertiles, e.g.

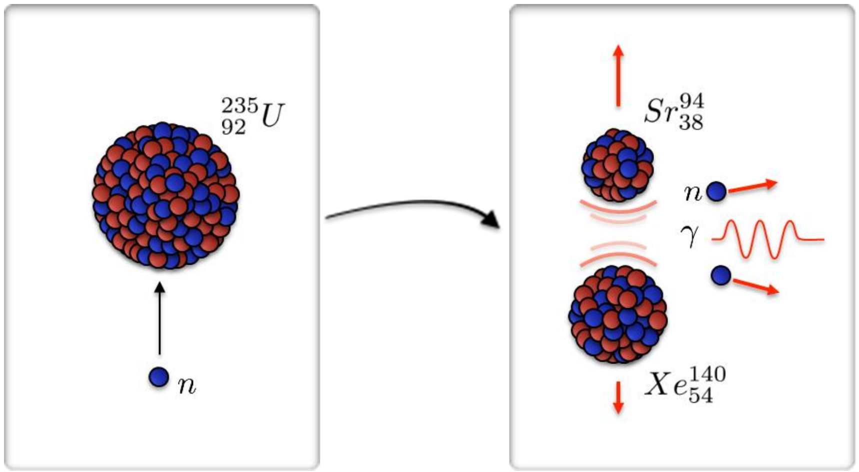
$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{236}_{92}U$$ "useless"

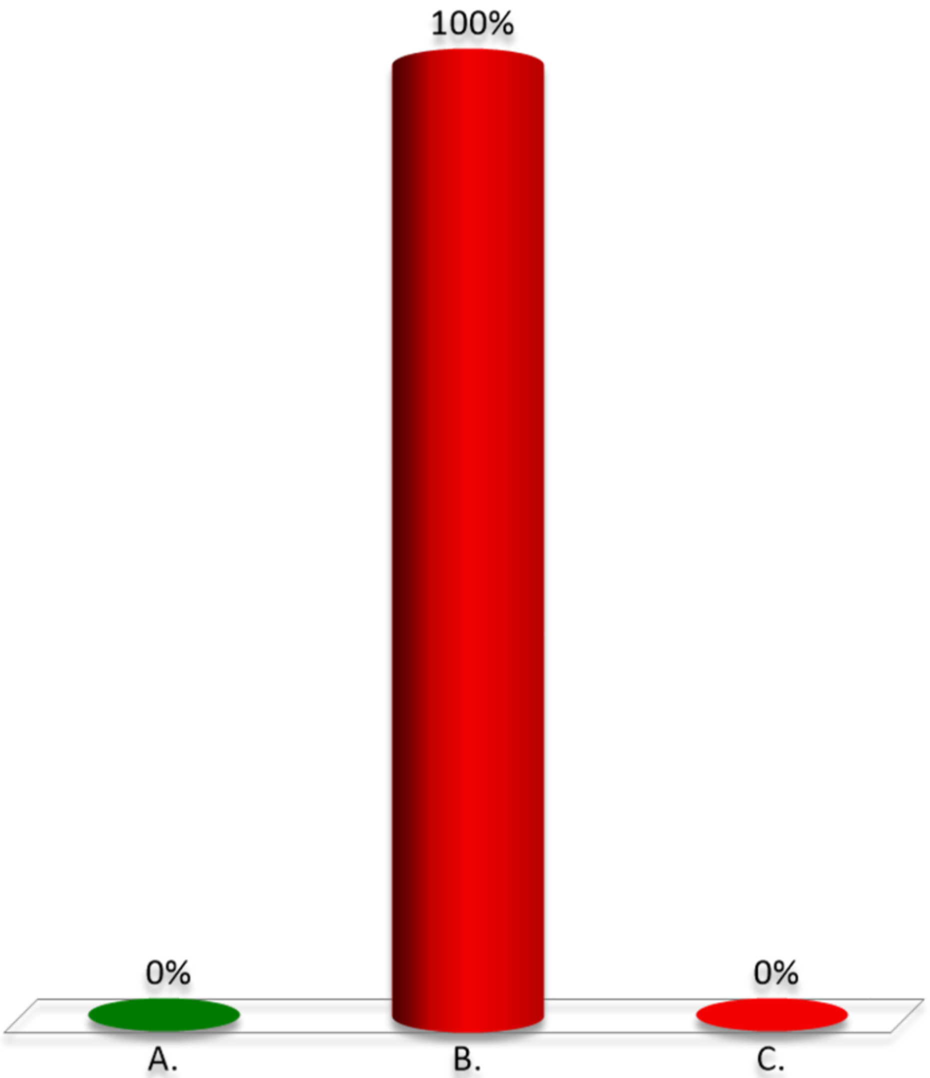
$${}^{238}_{92}U + {}^{1}_{0}n \rightarrow {}^{239}_{94}Pu$$ "useful"

	Fissiles ^{235}**U**, ^{239}**Pu**, ^{233}**U**	**Fertiles** ^{238}**U**, ^{232}**Th**
Thermal fissions	strong	zero
Fast fissions	weak	weak
Captures (thermal, resonance)	parasitic	useful (new fissiles produced)

Where is most of the energy released by fission deposited?

A. In the fuel
B. In the cladding
C. In the coolant / moderator
D. In the control rods
E. None of the above





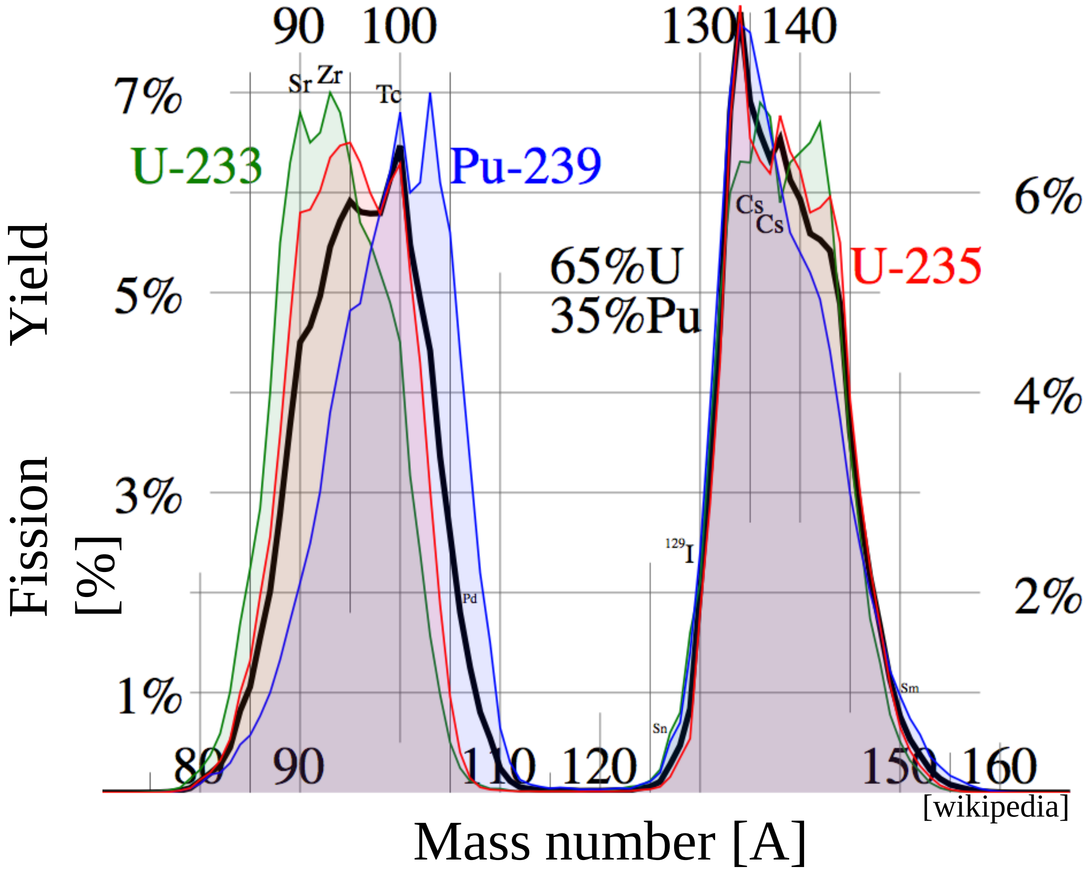
- Most, absorbed in the fuel: ~ 180 to 190 MeV (FP's, β^{-}'s, part of γ's), in form of heat (recovered by coolant). Partly absorbed in coolant and structural materials (γ's)

- Following reactor shutdown: component "FP-radioactivity" remains
  ~ 7% immediately after shutdown, slowly decreasing
  (*Decay heat*: very important factor for nuclear safety)

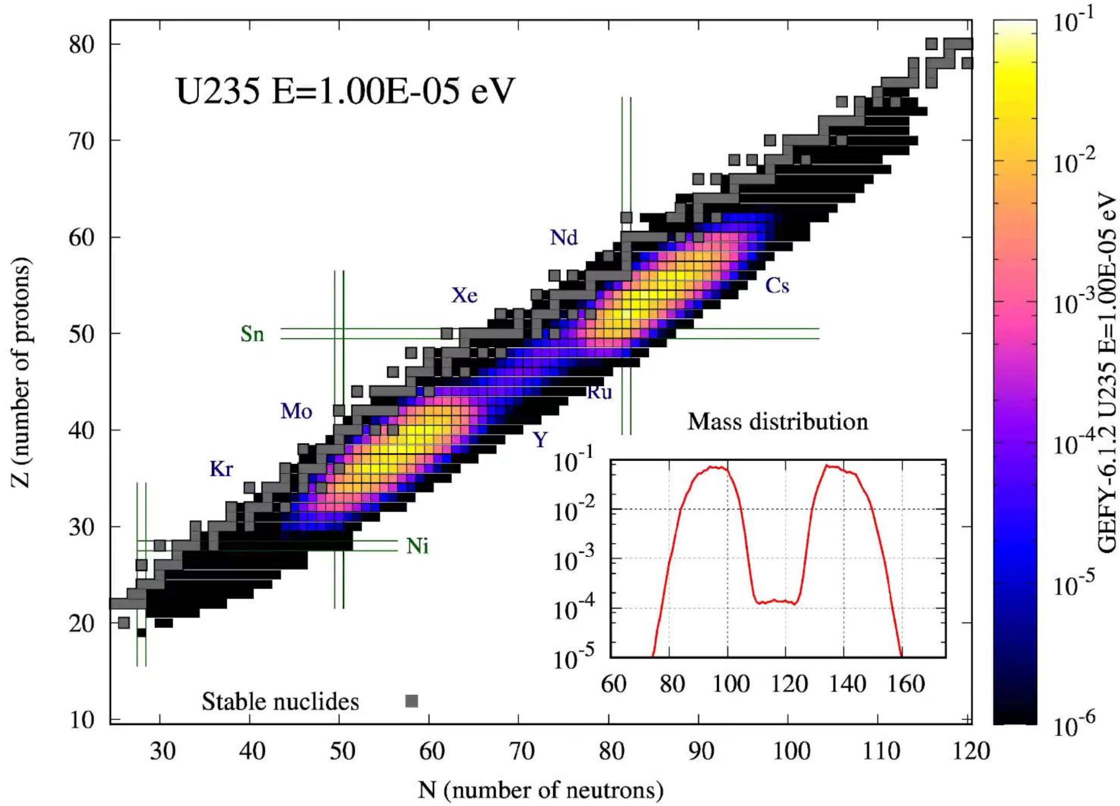
Components	**Released (MeV)**	**Recoverable (MeV)**
FP's	168	168
n's	5	5
Prompt γ's	7	7
FP-radioactivity (β^{-})	8	8
FP-radioactivity (γ)	7	7
Neutrinos	12	-
Radiative capture of fission neutrons (γ)	-	5 to 10
TOTAL	~ 207	200 to 205

- Fission yield—probability that a fission fragment of a given A is produced in fission
- Sum is 200 % (A1 + A2 = A)
- Asymmetric “double-hump” curve
- Depends on fissioning nuclei

…



- Fission yield—probability that a fission fragment of a given A is produced in fission
- Sum is 200 % (A1 + A2 = A)
- Asymmetric "double-hump" curve
- Depends on fissioning nuclei and neutron energy



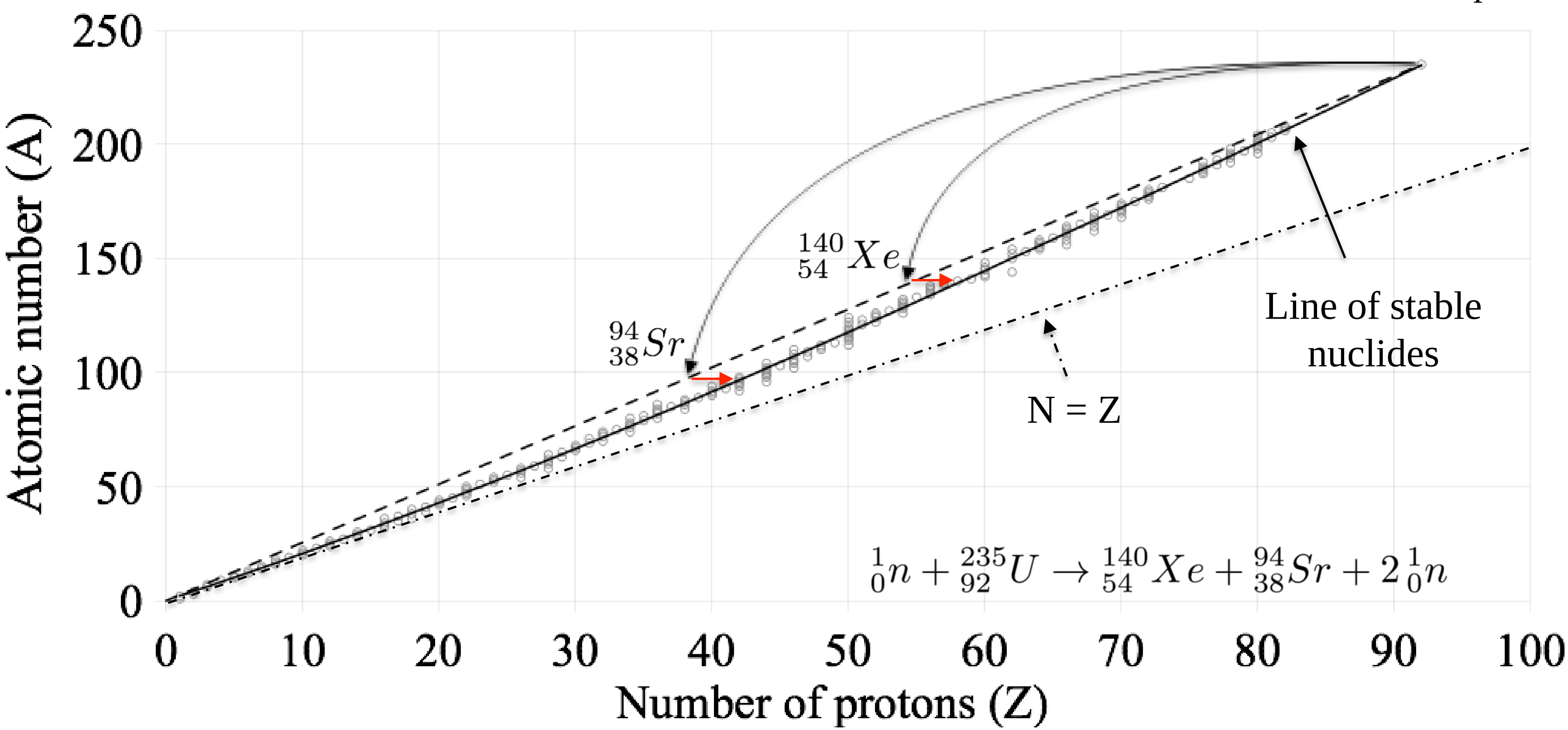
[https://fispact.ukaea.uk/nuclear-data/fission-yields/]

- Fission products excessively “neutron rich” (too many neutrons for stability).
- Decay with emission of
  - one or more negative β^- rays,
  - γ rays and
  - possibly (delayed) neutrons.

$$^{140}_{54}Xe \xrightarrow{\beta^-} {}^{140}_{55}Cs \xrightarrow{\beta^-} {}^{140}_{56}Ba \xrightarrow{\beta^-} {}^{140}_{57}La \xrightarrow{\beta^-} {}^{140}_{58}Ce$$

$$^{94}_{38}Sr \xrightarrow{\beta^-} {}^{94}_{39}Y \xrightarrow{\beta^-} {}^{94}_{40}Zr$$

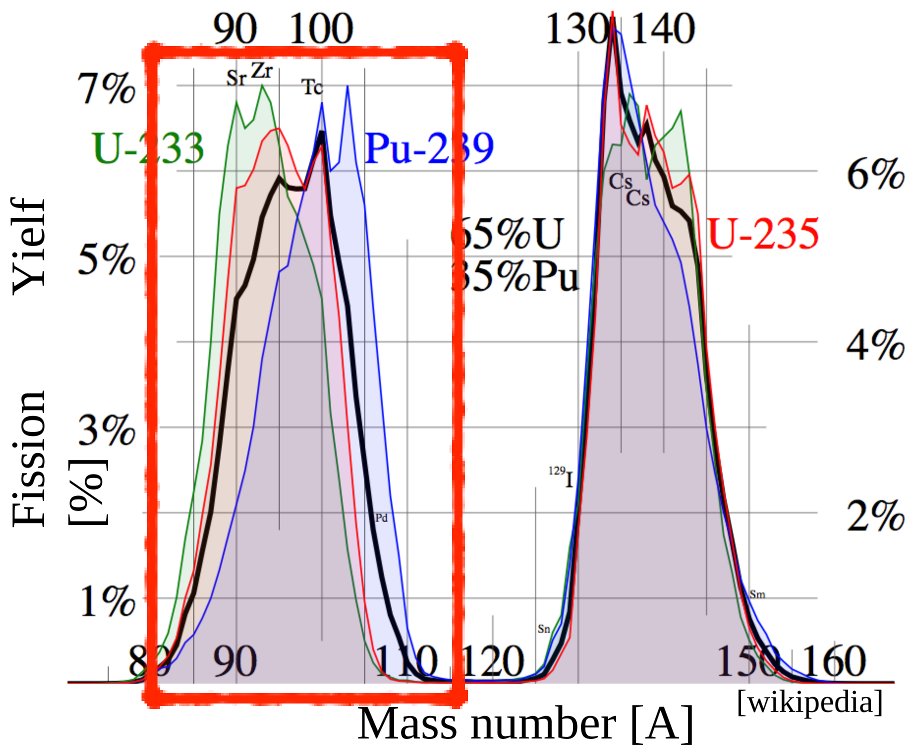
⚠⚠⚠ *Xe and Sr are examples*



Some important nuclides

	Se	Br	Kr	Rb	Sr	Y	Zr	Nb	Mo
Z	34	35	36	37	38	39	40	41	42
A	86	87-89	88-92	91-94	92-97	95-99	97-102	101-103	104

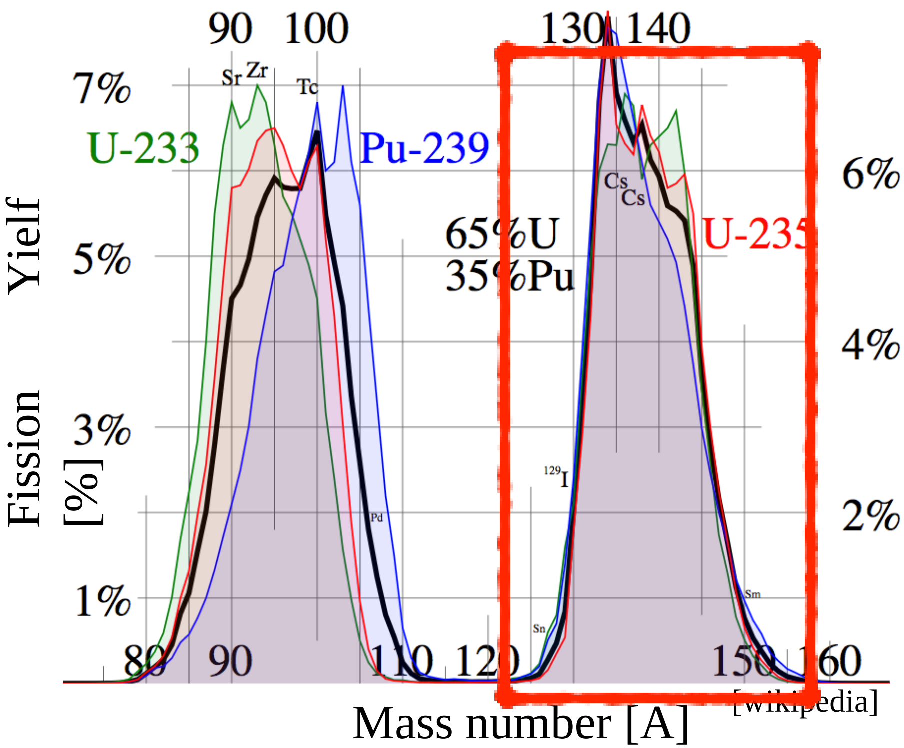
- *Bromine*:
  one of the precursors of delayed neutrons
- *Krypton*:
  gaseous fission product
  → fuel swelling and fission gas release
- *Strontium*:
  long-lived fission product
  → radiologically relevant



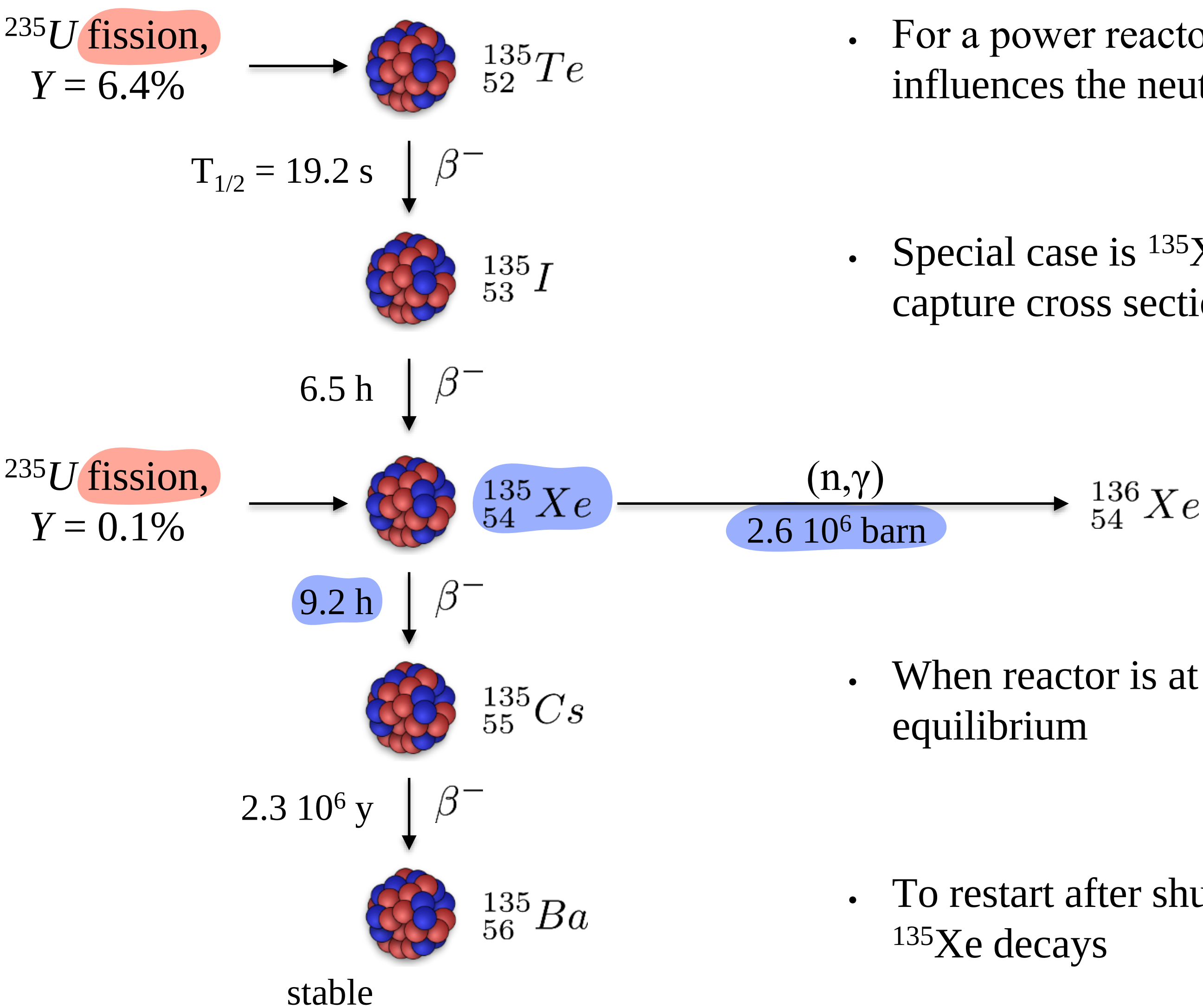
Some important nuclides

	Ce	La	Ba	Cs	Xe	I	Te	Sb	Sn
Z	58	57	56	55	54	53	52	51	50
A	148-149	144-146	141-145	139-143	136-141	134-138	132-136	131-133	130-131

- *Tellurium*:
  precursors of ^{135}Xe
  strongest neutron poison
- *Xenon*:
  gaseous fission product
  → fuel swelling and fission gas release
- *Cesium, Iodine*:
  medium/long-lived fission product
  → radiologically relevant



Xenon poisoning



- For a power reactor, accumulation of FP's influences the neutron balance

- Special case is ^{135}Xe with a huge radiative capture cross section

- When reactor is at full power ^{135}Xe is at equilibrium

- To restart after shutdown one should wait until ^{135}Xe decays

Why is the decay of FPs so important?

During normal operation:

- β^{-} and γ rays from decay of FPs contribute to the recoverable energy of fission (~7 %)
- some FPs are precursors of delayed neutrons – *important for neutron kinetics*

After reactor shutdown (stop of chain reaction):

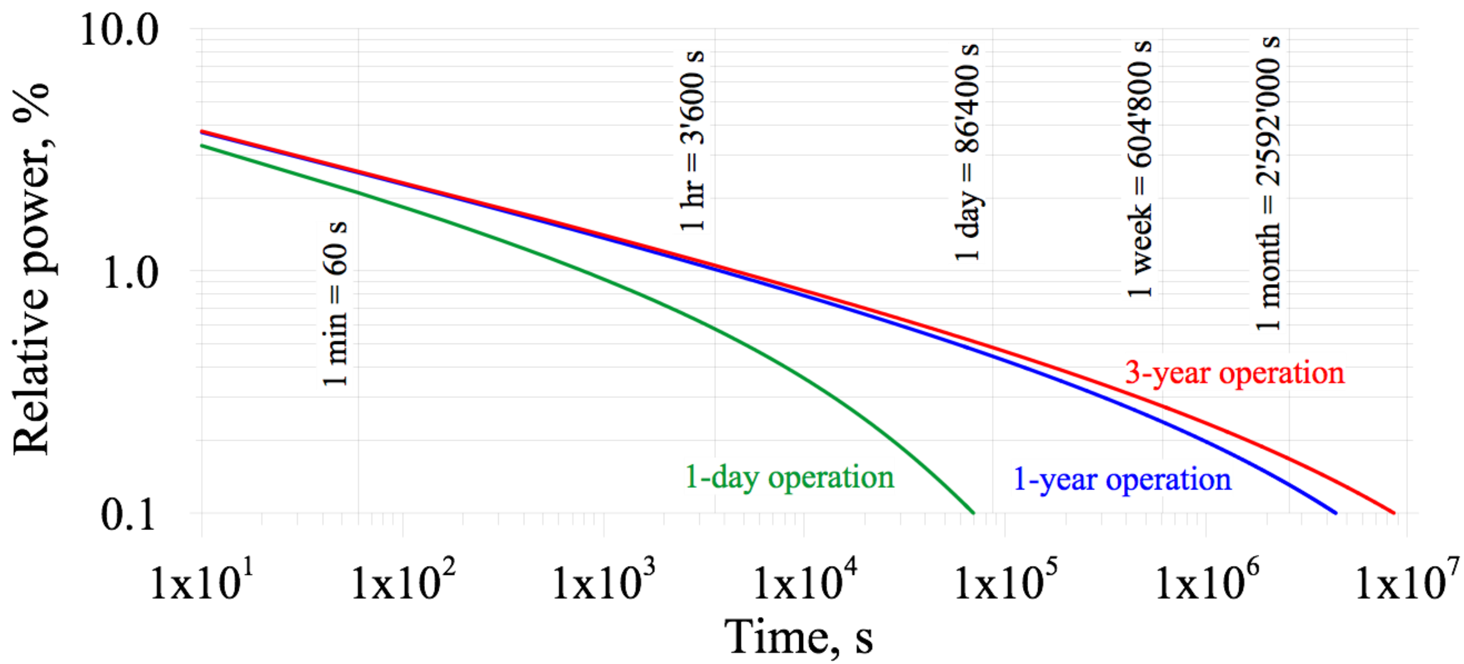
- β^{-} and γ rays from decay of FPs are a source of *radiation* (biological hazard) as well as of *decay heat = residual heat*
- some radioactive FPs are strong neutron absorbers (poisons): the reactor can restart only after their decay

Decay (residual) heat

- The *decay heat removal* (DHR) at acceptable T and for sufficiently long time is an important engineering problem to be properly foreseen in the reactor design.

- *Wigner-Way formula* gives the power from decay of FPs after t sec after the shutdown in a reactor that has been operated for T sec at a power of P_0:

$$P(t,T) / P_0 = 6.22\,(t^{-0.2} - (t + T)^{-0.2})\ (\%)$$



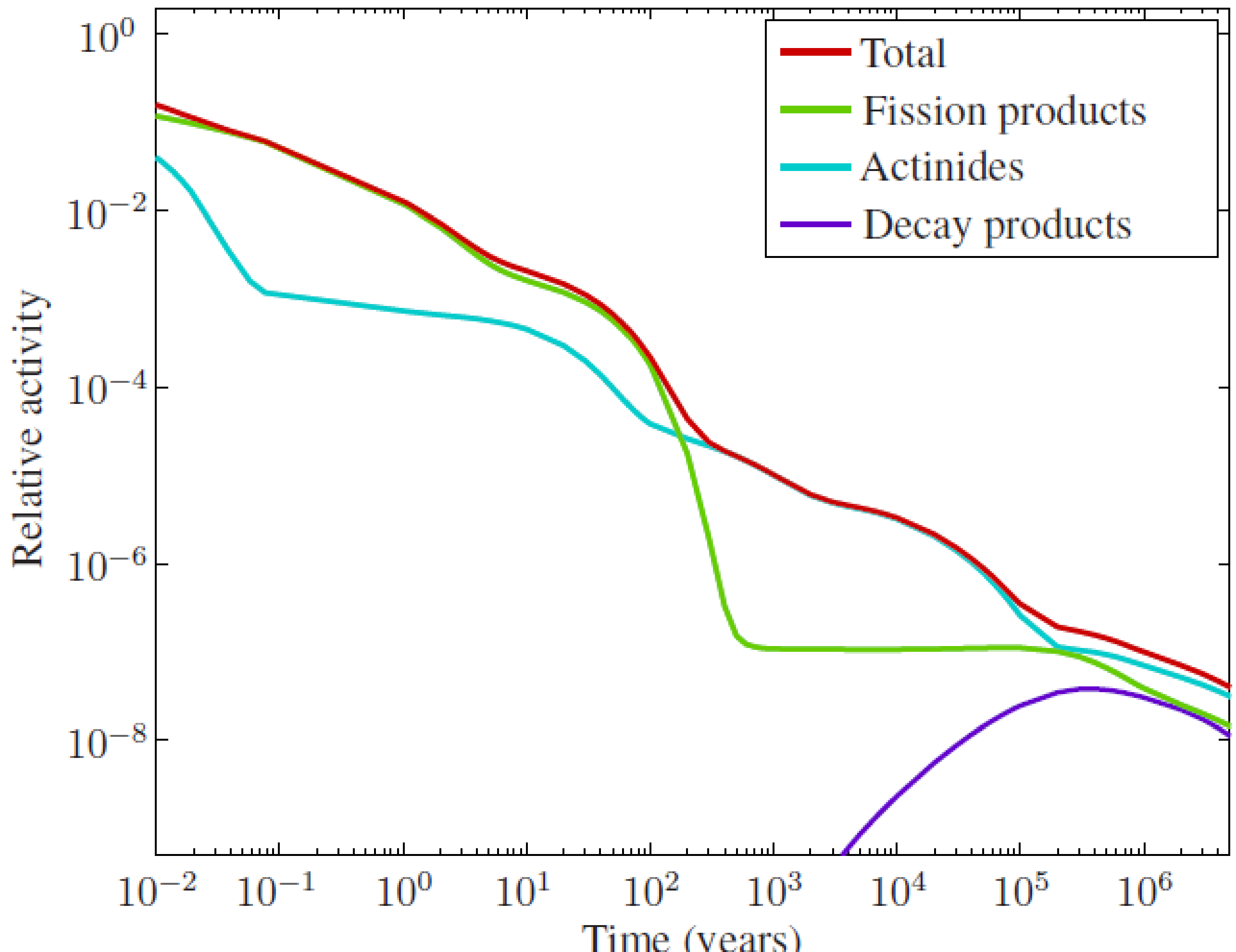
- Short-lived fission products that are released at low temperature form the most significant radiological source term in nuclear accidents:
  - Noble gases (released from the gas gap once the cladding is burst, and not easily contained)
  - ^{131}I (some iodine compounds are gaseous at 240°C)
  - ^{137}Cs (gaseous compounds at 1300 °C)
  - Melting of fuel at about 2600-3000°C releases ^{90}Sr and isotopes of barium, ruthenium and lanthanum.

- The most significant contributor to radiation dose for inhabitants living within the fallout zone is ^{131}I ($T_{1/2}$ = 8 days). Long-term exposure and limitations to land cultivation are mainly due to contamination by ^{137}Cs ($T_{1/2}$ = 30 years).

- The activity of ^{131}I in the fuel saturates within 30 days of continuous reactor operation. The saturation of ^{137}Cs takes much longer than the fuel is irradiated in the reactor, which means that the core inventory depends on burnup.

- Long-lived radionuclides in spent fuel form the radiological hazard in nuclear waste.

- Important
  - Pluto
  - Mino ... 400 years)
  - Long ... s ($T_{1/2}$ = 2
    milli

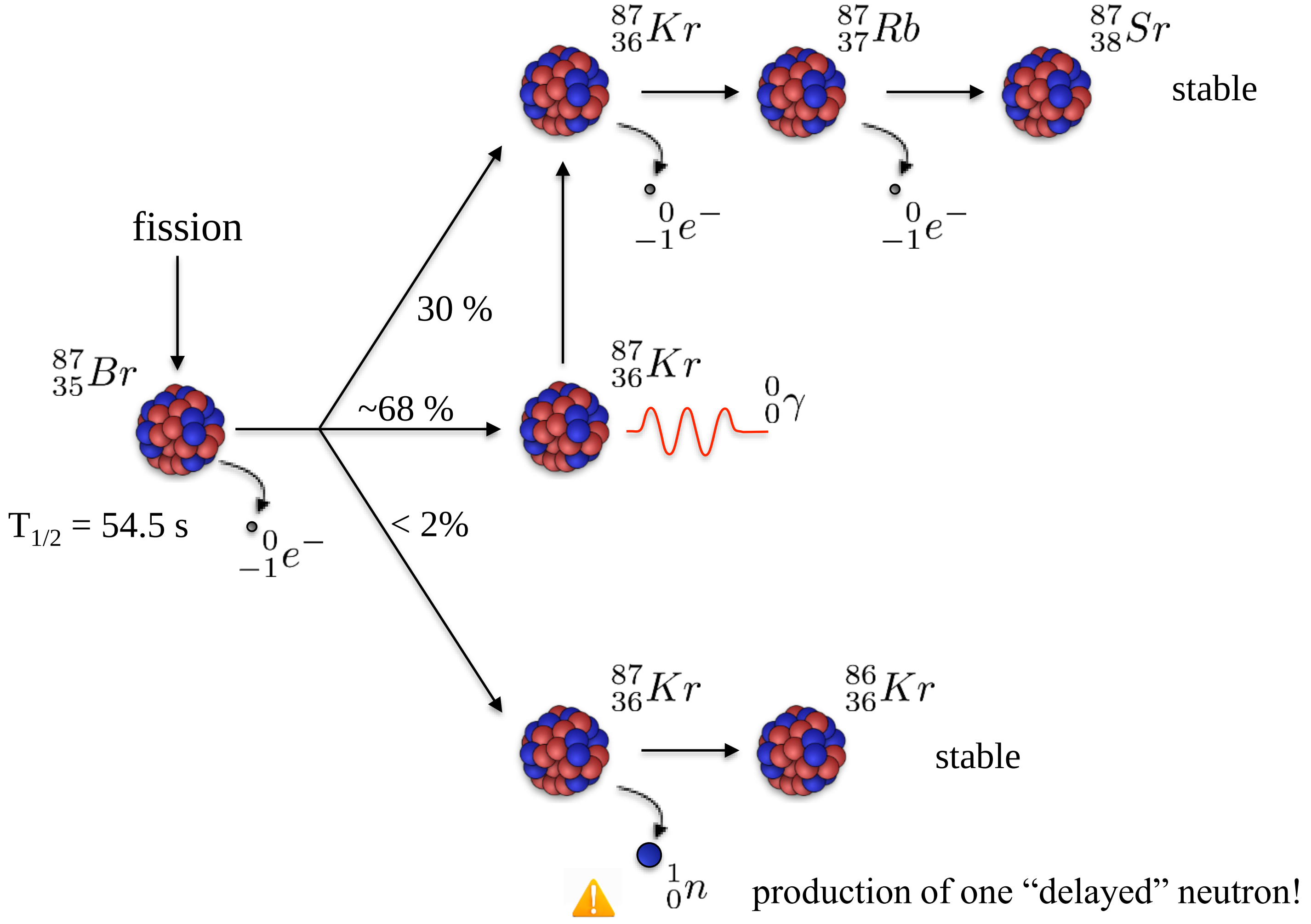


- For the fi ... products,
  such as 13

- Radioacti ... ological
  hazard is ... chain.

Example

- Small fraction of the neutrons, not prompt (~ 0.65 % for ^{235}U)
- Produced by decay of FP's, e.g.



Precursor

- Fission products which decay with emission of delayed neutrons are called delayed-neutron precursors.
- About 20 precursors are grouped in 6 (time) groups according to their half-lives.

Gp	Precursor	$T_{1/2}$ (s)
1	Br87	55.7
2	I137, Br88	22.7
3	I138, Br89, …	6.2
4	I139, Cs, …	2.3
5	I140, Kr, …	0.61
6	Br, Rb, …	0.23

- In practical calculations for every group (i = 1, …, 6) the delayed neutron precursors are described with

delayed neutron fractions: $\beta_i = \nu_{D_i}/\nu$, and

decay constants λ_i = ln(2) / $T_{1/2}$

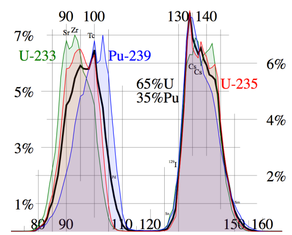
for ^{235}U

Gp	Precursor	$T_{1/2}$ (s)	λ_i (1/s)	β_i (%)
1	Br87	55.7	0.012	0.022
2	I137, Br88	22.7	0.031	0.142
3	I138, Br89, …	6.2	0.11	0.127
4	I139, Cs, …	2.3	0.30	0.257
5	I140, Kr, …	0.61	1.14	0.075
6	Br, Rb, …	0.23	3.01	0.027

β = Sum(β_i)
= 0.65 %

- Spectrum of delayed and prompt neutrons often assumed the same but delayed neutrons have in general a lower energy

- λ_i's relatively constant



- β_i's depend on nuclide, e.g.

β = Sum (β_i) = 0.65% for ^{235}U
= 0.21% for ^{239}Pu
= 0.26% for ^{233}U … other "fissiles"

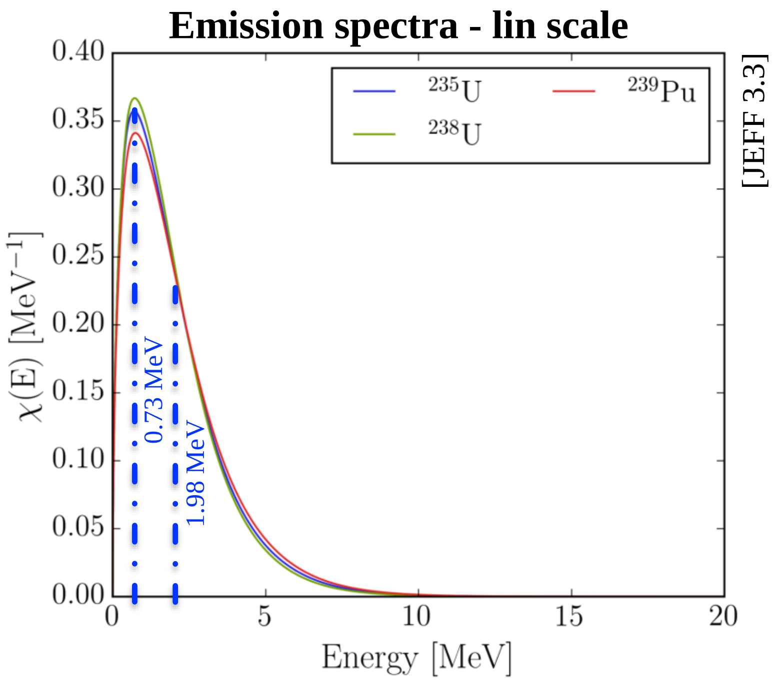
- β small, but very important for control of the chain reaction → kinetic behaviour

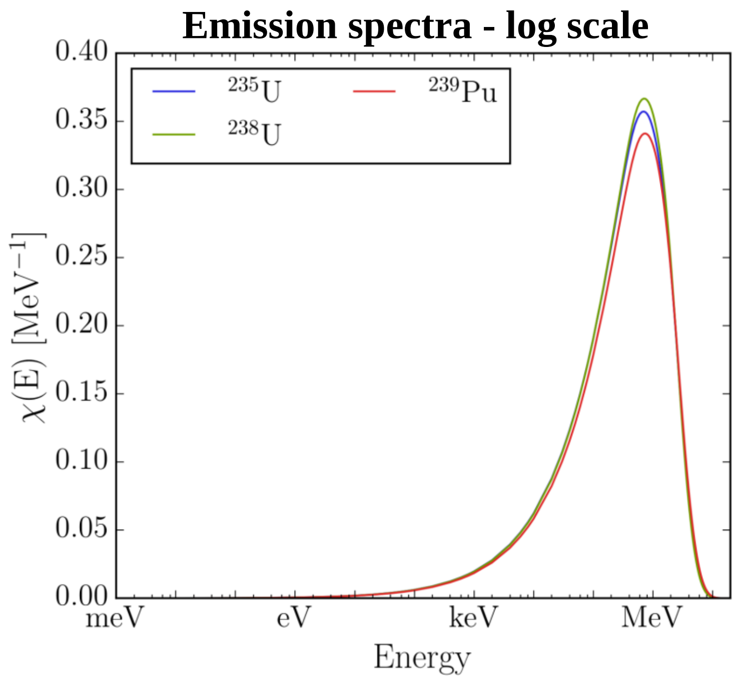
→ The delay between the fission and emission of delayed neutrons is between a second and a minute, while it is only 10^{-17} s for prompt neutrons

→ Response of a reactor which becomes slightly supercritical, much slower

Fission spectrum

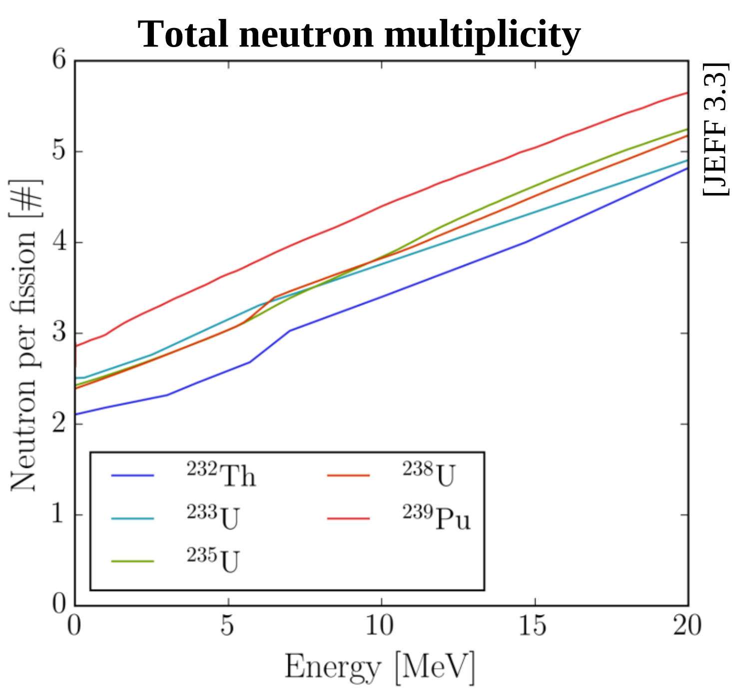
- Energy of the fission neutrons varies… Spectrum $\chi(E)$
- $\chi(E)\mathrm{d}E$ – number of neutrons with energy between E and $E+\mathrm{d}E$ emitted per fission: $\int_0^\infty \chi(E)\mathrm{d}E = 1$
- Empirical correlation for ^{235}U: $\chi(E) = 0.453\exp(-1.036E)\sinh\sqrt{2.29E}, \quad E$ in MeV
- Most probable energy: E_{max} = 0.73 MeV
- Average energy: $\overline{E} = \int_0^\infty E\,\chi(E)\mathrm{d}E = 1.98\,\mathrm{MeV}$

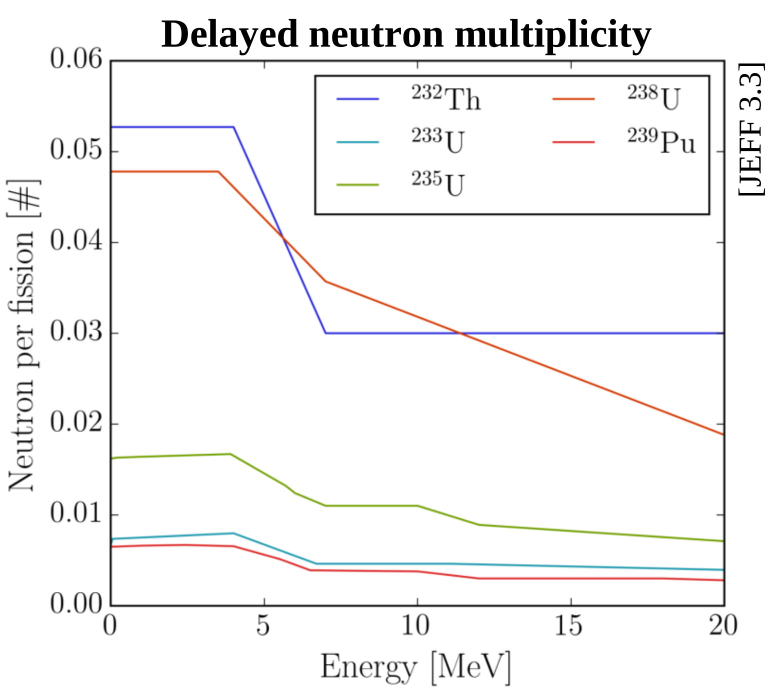




Neutron multiplicity

- ν neutrons (prompt+delayed) created per fission (~ from 0 to 5, per event)
- ν always expressed as an average, depends on nuclide and incoming neutron energy
- $\nu = \nu_0 + a.E$ with a in MeV^{-1}
- For a mixture of nuclides $\nu_{eff} = Sum(\nu_i\Sigma_{fiss}) / Sum(\Sigma_{fiss})$





Fission and burnup rates

- Consider a reactor, operating at *constant* thermal power of P
- Fission rate: number of nuclei “burned” per unit time:

$$F = \frac{\text{Reactor thermal power, } P}{\text{Average recoverable energy released per fission, } E_R}$$

For ^{235}U: F [fissions/day] = $2.7\times10^{21} \times P$ [MW]

- Burnup rate: mass of fuel “burned” per unit time:

$$B = \frac{\text{Fission rate (number of nuclei “burned” per unit time)}}{\text{Atomic number density of fuel (number of nuclei per g)}}$$

For ^{235}U: B [g/day] = $1.05\times P$ [MW] 

Fuel burnup. Two units.

- Fuel burnup: energy generated per unit mass of loaded fuel

$$Bu_1 = \frac{\text{Reactor thermal power, } P \times \text{Time of operation, } T}{\text{Initial mass of heavy metal, } M_0}$$

Units: megawatt-day per kg of heavy metal [MWd/kgHM] or [GWd/tHM]

- Fuel burnup: fraction of heavy metal nuclei which was burned

$$Bu_2 = \frac{\text{Mass of “burned” HM, } \Delta M}{\text{Initial mass of HM, } M_0} = \frac{\text{Number of HM nuclei “burned”}}{\text{Initial number of HM nuclei}}$$

Units: atomic % [at%]

$$\frac{Bu_1}{Bu_2} = \frac{PT}{\Delta M} = \frac{P}{B}$$

For ^{235}U: Bu_1 [MWd/kgHM] = 9.5×Bu_2 [at%]

- The products of fission include fission fragments, neutrons, γ and β rays, neutrinos
- Most of fission energy deposited in fuel (as heat)
- Large variety of FP combinations possible ("double-hump curve")
- FP's radioactive (β^- decay): decay heat, important safety factor
- On average, ν (2 to 3) n's emitted per fission… chain reaction rendered possible
- Delayed neutrons: n's resulting from decay of certain FP's, crucial for reactor kinetics and control

- Nuclear fuels: U, Th… only ^{235}U fissile; ^{238}U, ^{232}Th fertile (yield fissile ^{239}Pu, ^{233}U)
- Neutron cross-sections: thermal, intermediate (=resonance) and fast regions of neutron spectrum
- Absorptions ~1/v + wide resonances in thermal range, strong peaks (resonances) in resonance range, threshold fission reaction for ^{238}U and ^{232}Th