Neutron production and moderation

Ulli Köster, ILL
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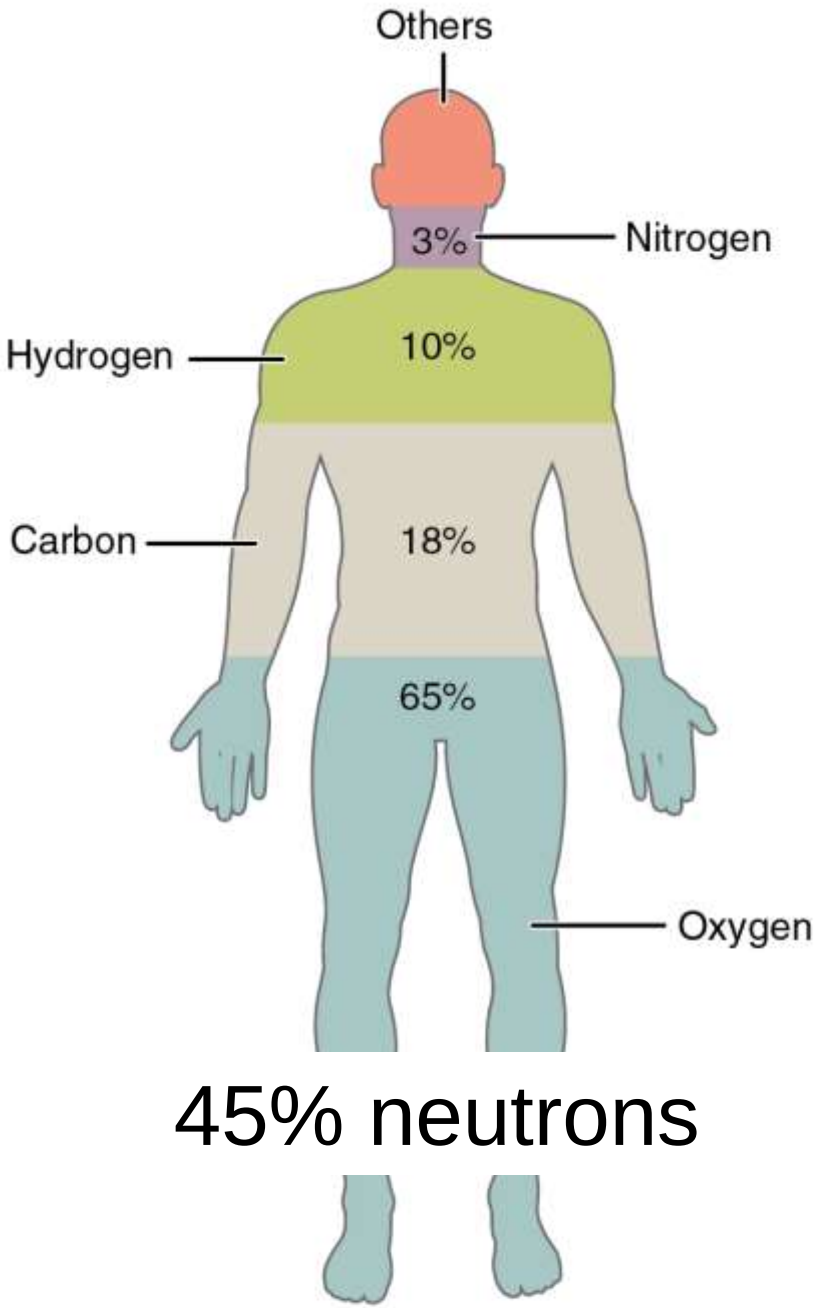
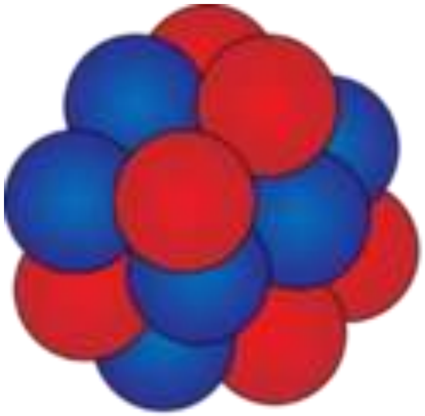
neutrons are everywhere

13% neutrons

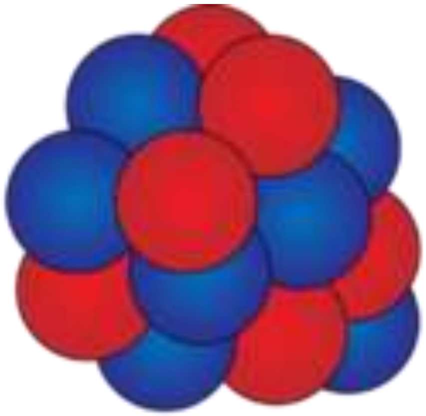
Bound neutrons are everywhere



45% neutrons

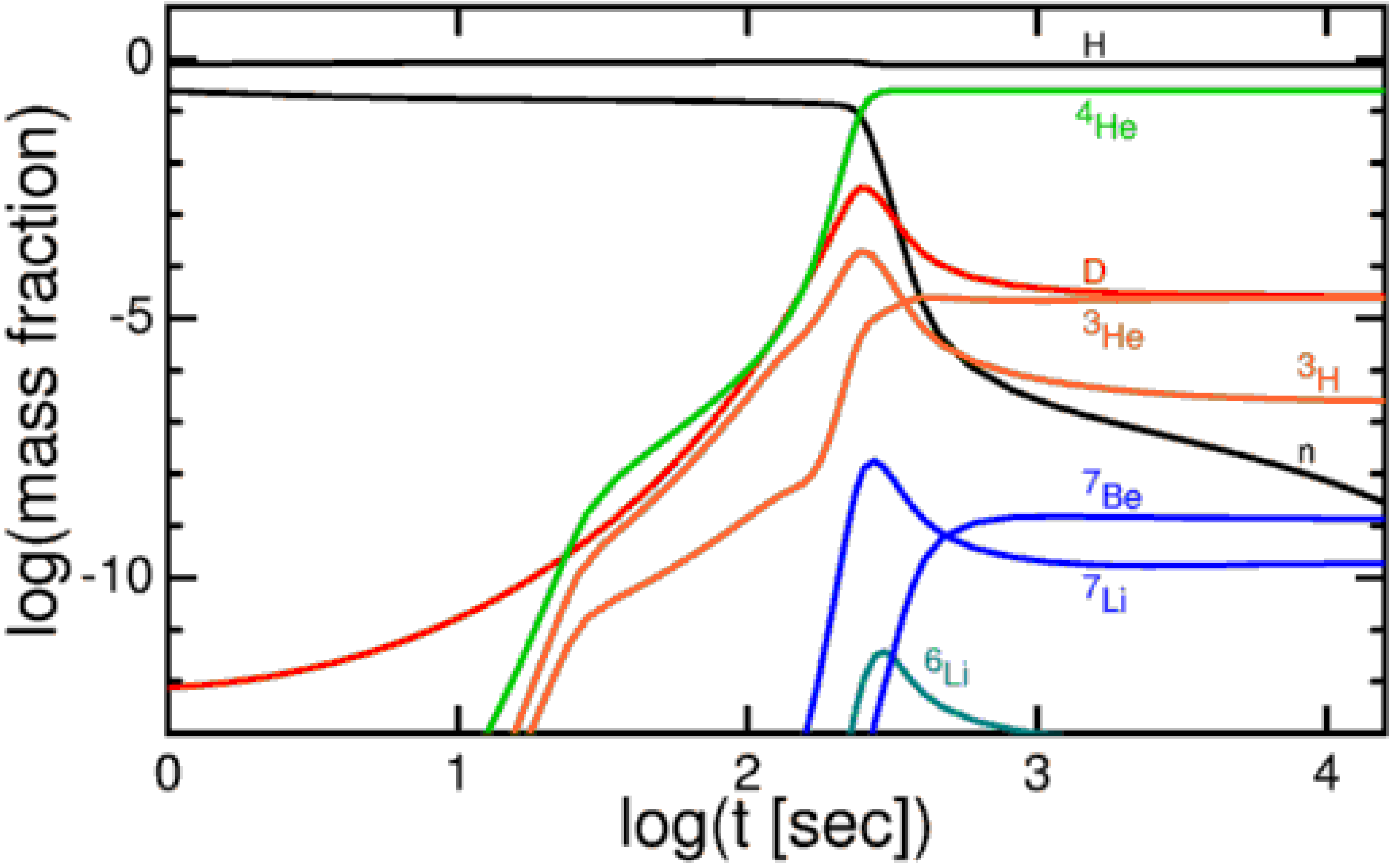


Carbon-12
98.9%
6 protons
6 neutrons



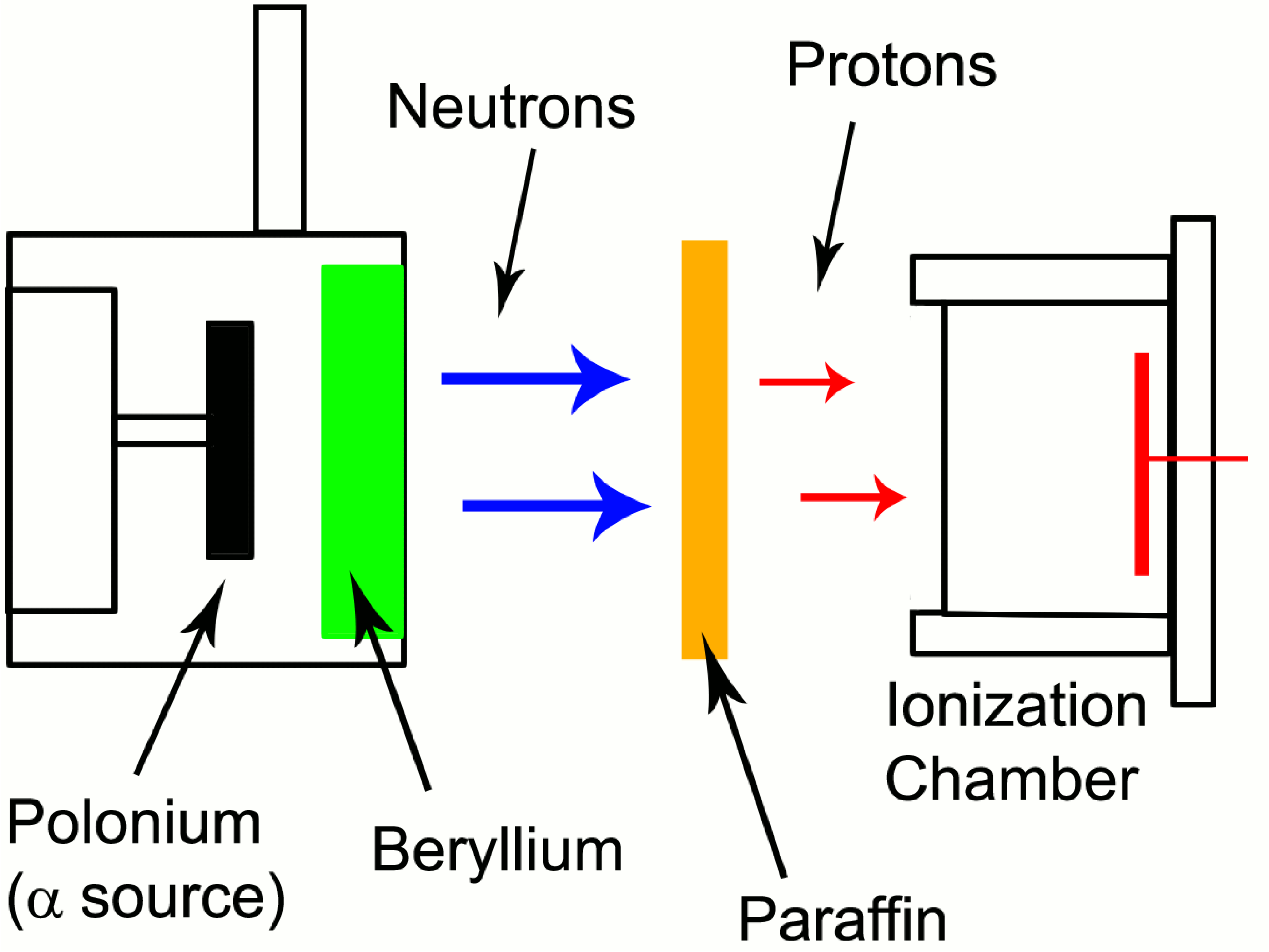
Carbon-13
1.1%
6 protons
7 neutrons

Big Bang Nucleosynthesis



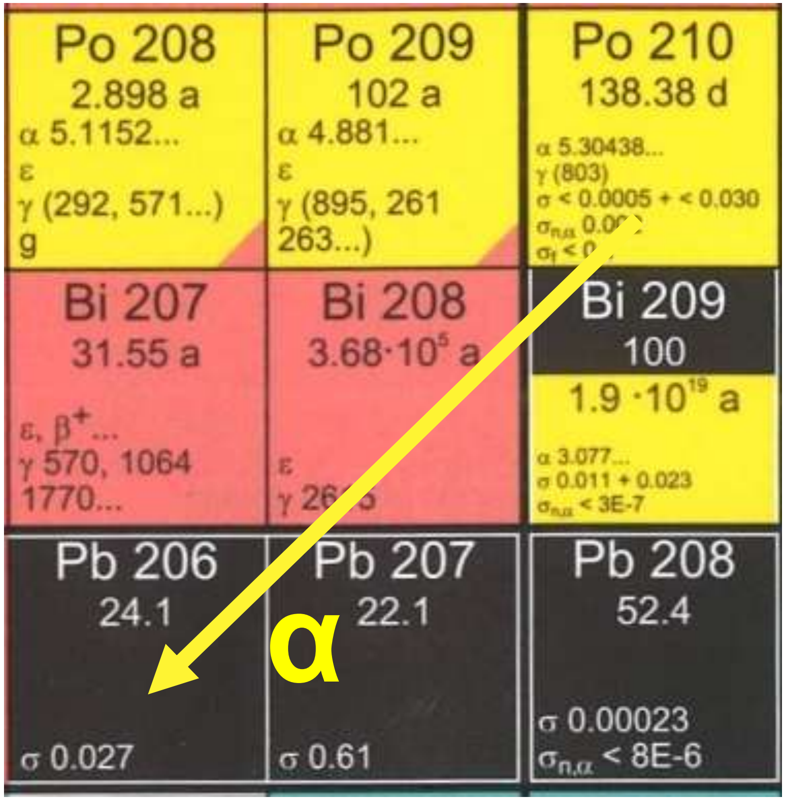
Free neutrons have become rare

Discovery of the neutron

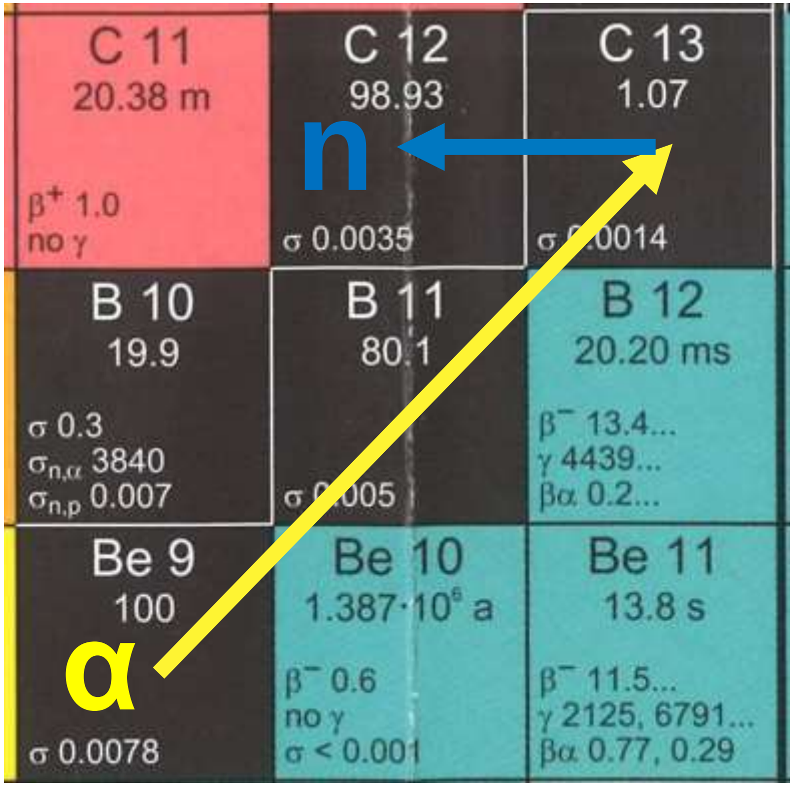


How neutrons are born

1. **Alpha-induced reactions: ^{9}Be(α,n)^{12}C** +5.7 MeV



Po 208 2.898 a α 5.1152... ε γ (292, 571...) g	Po 209 102 a α 4.881... ε γ (895, 261 263...)	Po 210 138.38 d α 5.30438... γ (803) σ < 0.0005 + < 0.030 $σ_{n,α}$ 0.0 $σ_f$ < 0
Bi 207 31.55 a ε, $β^+$... γ 570, 1064 1770...	Bi 208 $3.68 \cdot 10^5$ a ε γ 26	Bi 209 100 $1.9 \cdot 10^{19}$ a α 3.077... σ 0.011 + 0.023 $σ_{n,α}$ < 3E-7
Pb 206 24.1 σ 0.027	Pb 207 22.1 σ 0.61	Pb 208 52.4 σ 0.00023 $σ_{n,α}$ < 8E-6



C 11 20.38 m $β^+$ 1.0 no γ	C 12 98.93 σ 0.0035	C 13 1.07 σ 0.0014
B 10 19.9 σ 0.3 $σ_{n,α}$ 3840 $σ_{n,p}$ 0.007	B 11 80.1 σ 0.005	B 12 20.20 ms $β^-$ 13.4... γ 4439... βα 0.2...
Be 9 100 σ 0.0078	Be 10 $1.387 \cdot 10^6$ a $β^-$ 0.6 no γ σ < 0.001	Be 11 13.8 s $β^-$ 11.5... γ 2125, 6791... βα 0.77, 0.29

How neutrons are born

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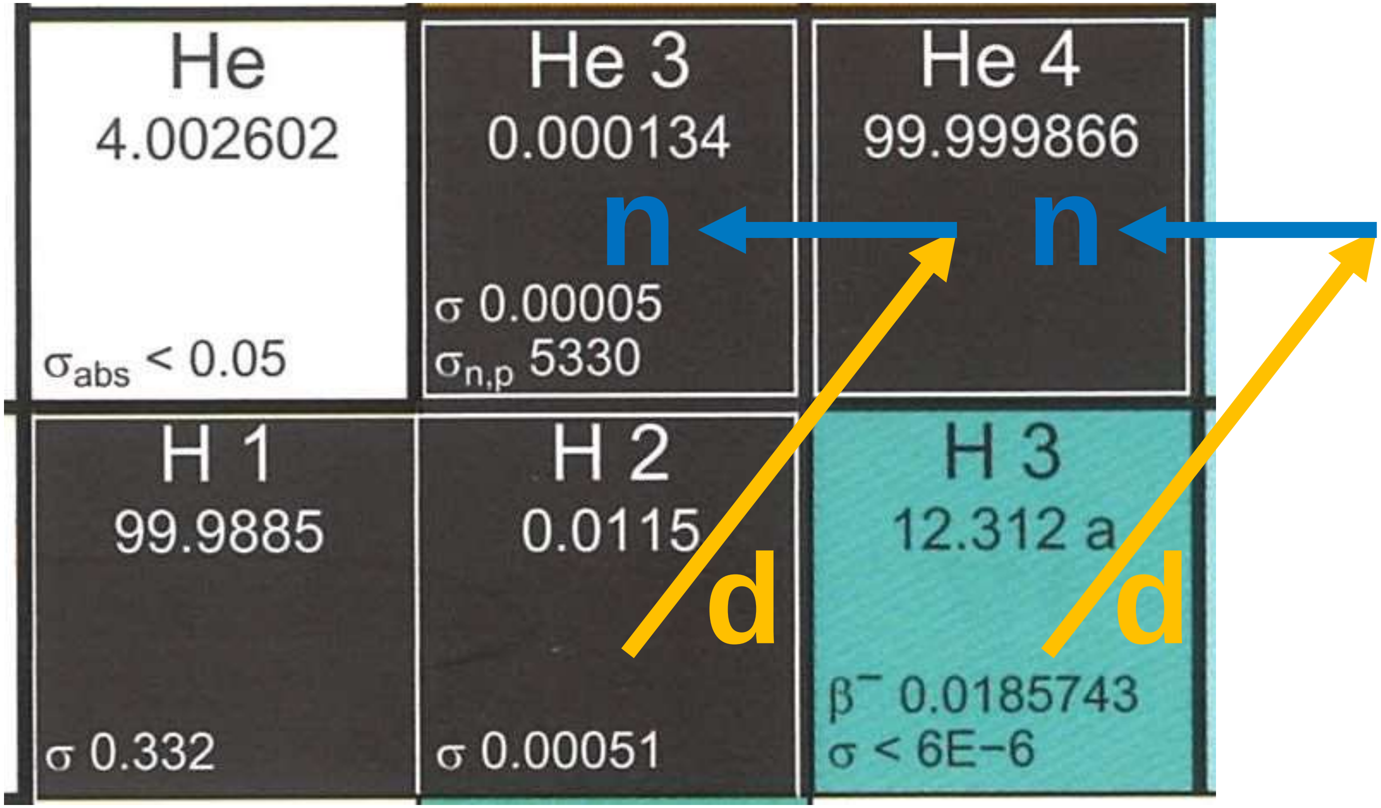

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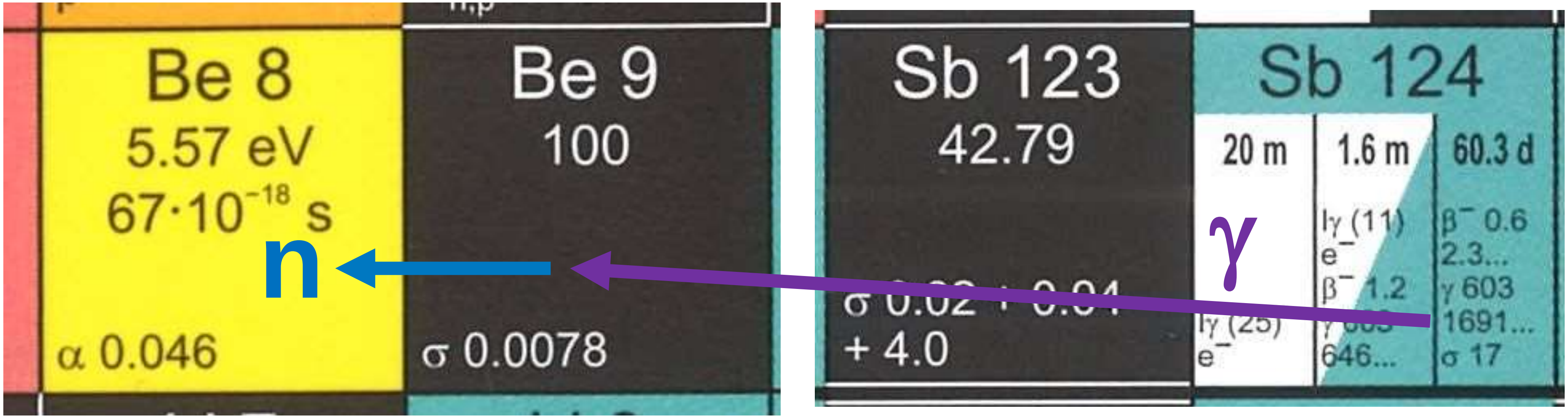

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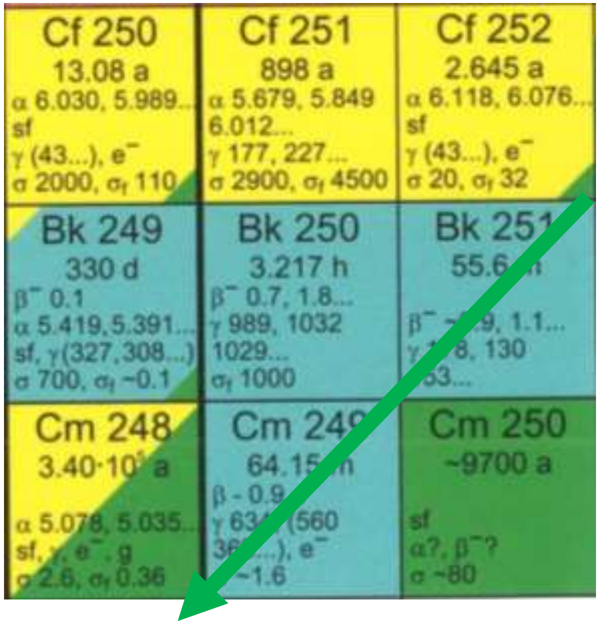
4. **Spontaneous fission: ^{252}Cf(sf)^{134}Te+^{115}Pd+3n** +212 MeV



Cf 250 13.08 a α 6.030, 5.989... sf γ (43...), e^- σ 2000, σ_f 110	Cf 251 898 a α 5.679, 5.849 6.012... γ 177, 227... σ 2900, σ_f 4500	Cf 252 2.645 a α 6.118, 6.076... sf γ (43...), e^- σ 20, σ_f 32
Bk 249 330 d β^- 0.1 α 5.419, 5.391... sf, γ(327,308...) σ 700, σ_f ~0.1	Bk 250 3.217 h β^- 0.7, 1.8... γ 989, 1032 1029... σ_f 1000	Bk 251 55.6 β^- ~ .9, 1.1... γ 8, 130 53...
Cm 248 3.40·10 a α 5.078, 5.035... sf, γ, e^-, g σ 2.6, σ_f 0.36	Cm 249 64.15 β - 0.9 γ 63 (560 36...), e^- ~1.6	Cm 250 ~9700 a sf α?, β^-? σ ~80

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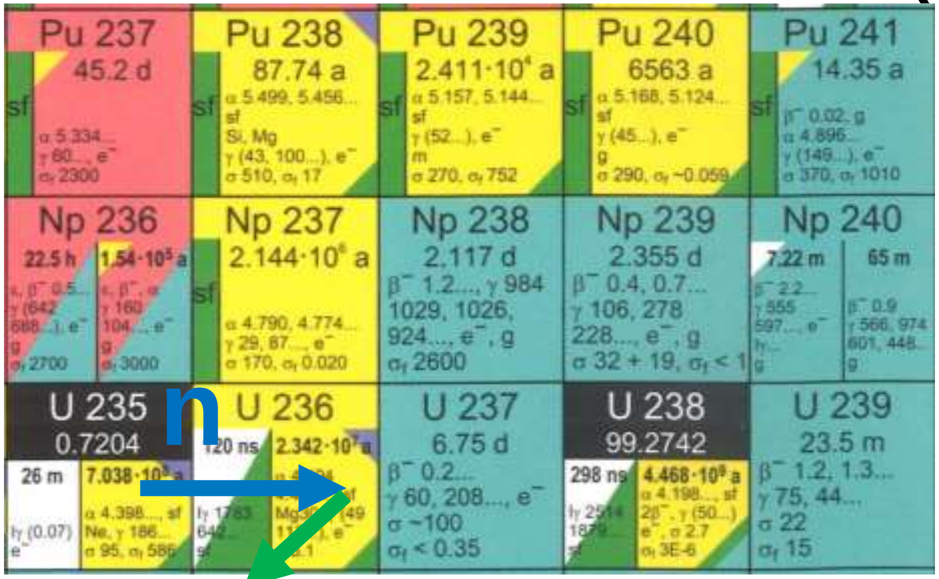
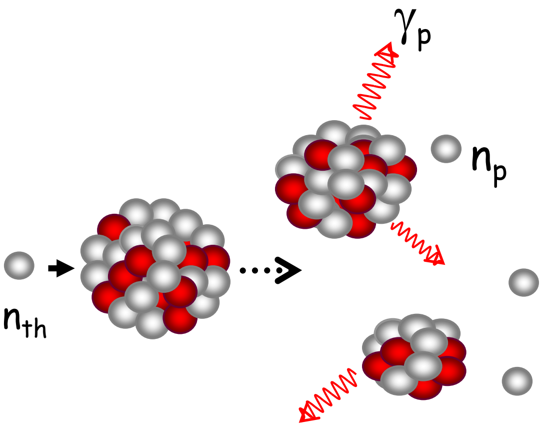


Pu 237 45.2 d sf α 5.334... γ 60..., e⁻ σf 2300	Pu 238 87.74 a sf α 5.499, 5.456... sf Si, Mg γ (43, 100...), e⁻ σ 510, σf 17	Pu 239 2.411·10⁴ a sf α 5.157, 5.144... sf γ (52...), e⁻ m σ 270, σf 752	Pu 240 6563 a sf α 5.168, 5.124... sf γ (45...), e⁻ g σ 290, σf ~0.059	Pu 241 14.35 a sf β⁻ 0.02, g α 4.896... γ (149...), e⁻ σ 370, σf 1010
Np 236 22.5 h | 1.54·10⁵ a σf 2700 | σf 3000	Np 237 2.144·10⁶ a sf α 4.790, 4.774... γ 29, 87..., e⁻ σ 170, σf 0.020	Np 238 2.117 d β⁻ 1.2..., γ 984 1029, 1026, 924..., e⁻, g σf 2600	Np 239 2.355 d β⁻ 0.4, 0.7... γ 106, 278 228..., e⁻, g σ 32 + 19, σf < 1	Np 240 7.22 m | 65 m β⁻ 2.2... | β⁻ 0.9 γ 555 | γ 566, 974 597..., e⁻ | 601, 448... g
U 235 0.7204 26 m | 7.038·10⁸ a α 4.398..., sf Ne, γ 186... σ 95, σf 586	U 236 120 ns | 2.342·10⁷ a sf	U 237 6.75 d β⁻ 0.2... γ 60, 208..., e⁻ σ ~100 σf < 0.35	U 238 99.2742 298 ns | 4.468·10⁹ a α 4.198..., sf 2β⁻, γ (50...) e⁻, σ 2.7 σf 3E-6	U 239 23.5 m β⁻ 1.2, 1.3... γ 75, 44... σ 22 σf 15



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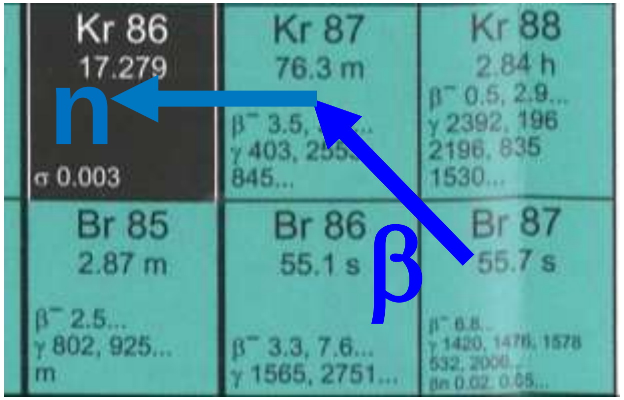

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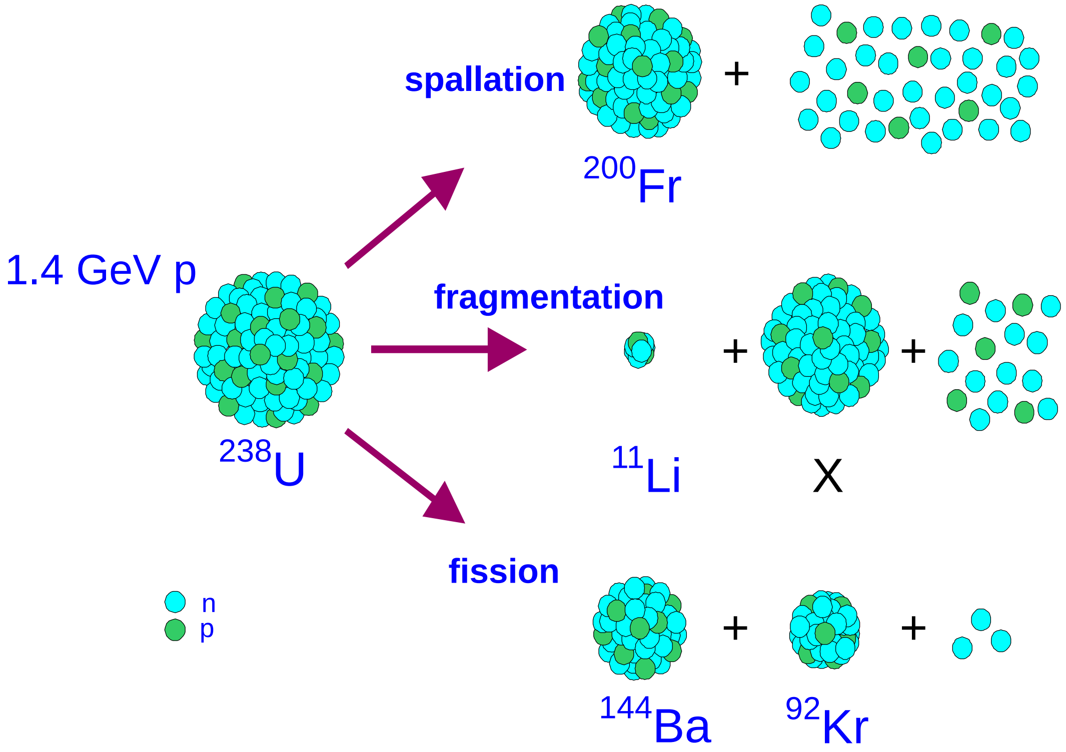
High energy nuclear reactions



1.4 GeV p

^{238}U

spallation

^{200}Fr +

fragmentation

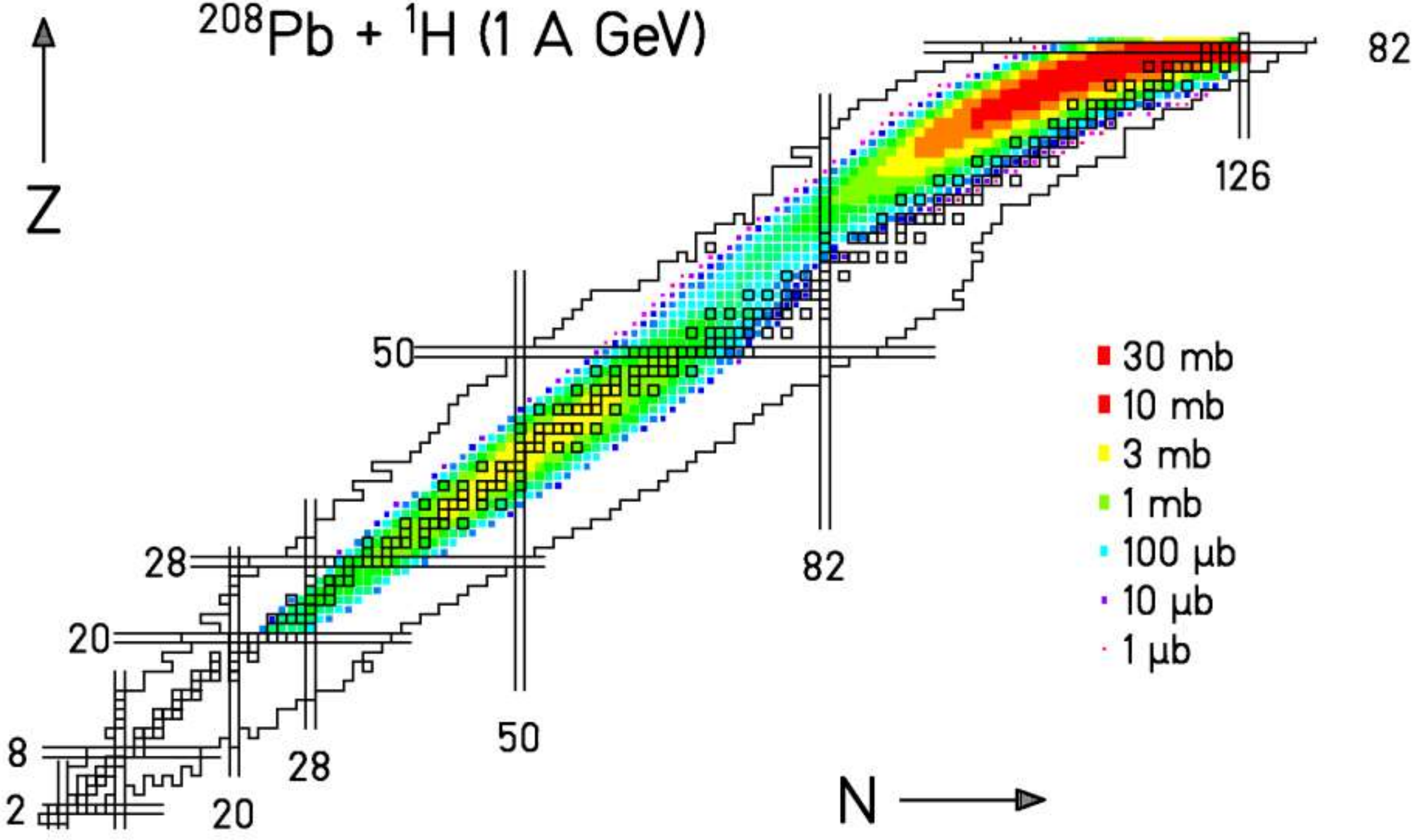
^{11}Li + X +

fission

^{144}Ba + ^{92}Kr +

n
p

Spallation + Fragmentation + Fission



W. Wlazło et al., Phys. Rev. Lett. 84 (2000) 5736.

T. Enqvist et al., Nucl. Phys. A 686 (2001) 481.

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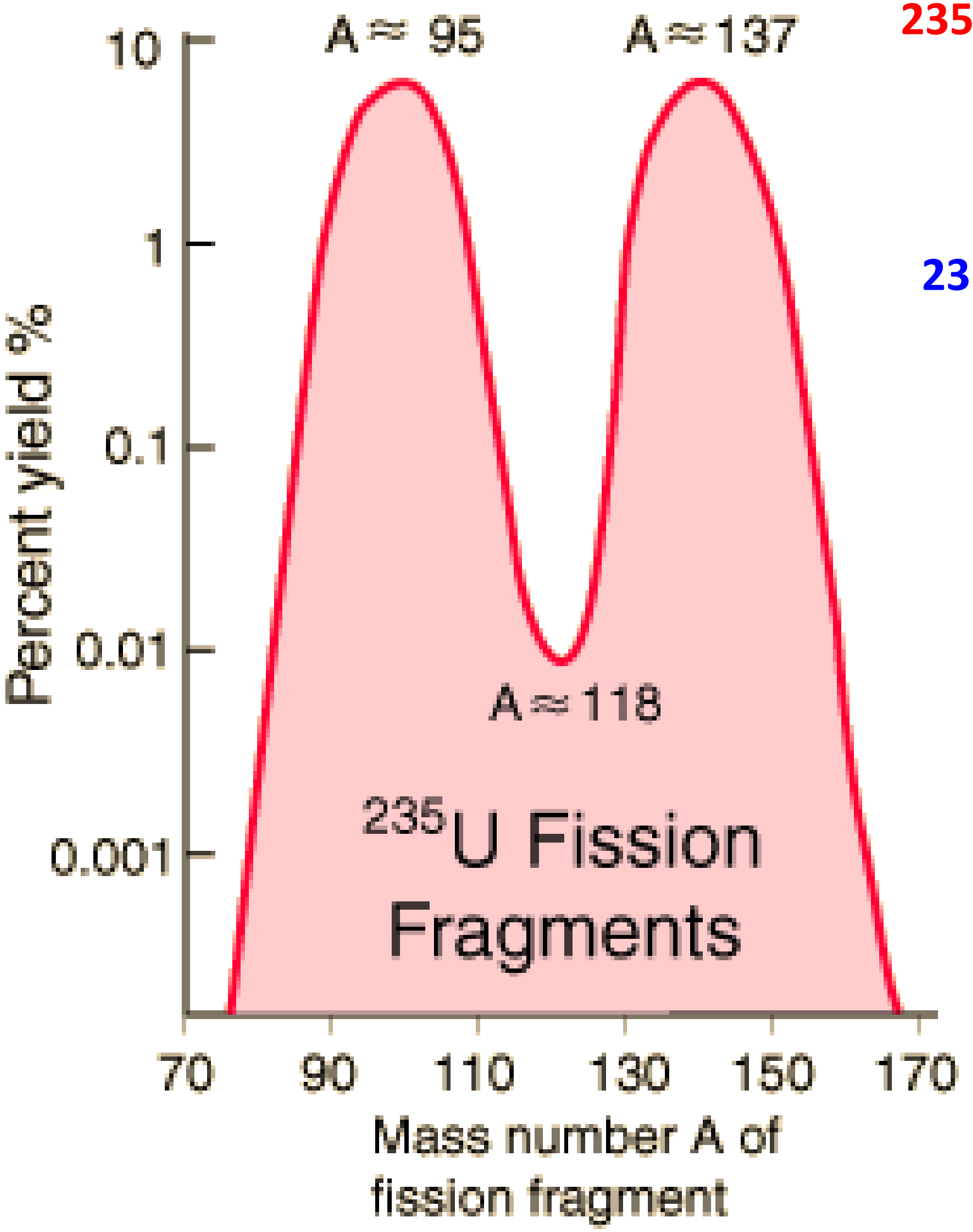
Mass yields of fission fragments

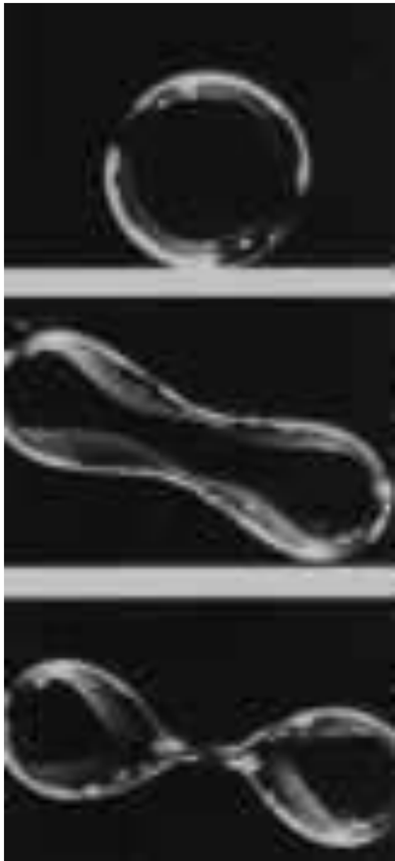


$$^{235}\mathrm{U} + n \rightarrow {}^{118}\mathrm{Pd} + {}^{118}\mathrm{Pd}$$

$$Q_{LDM} = +184\ \mathrm{MeV}$$

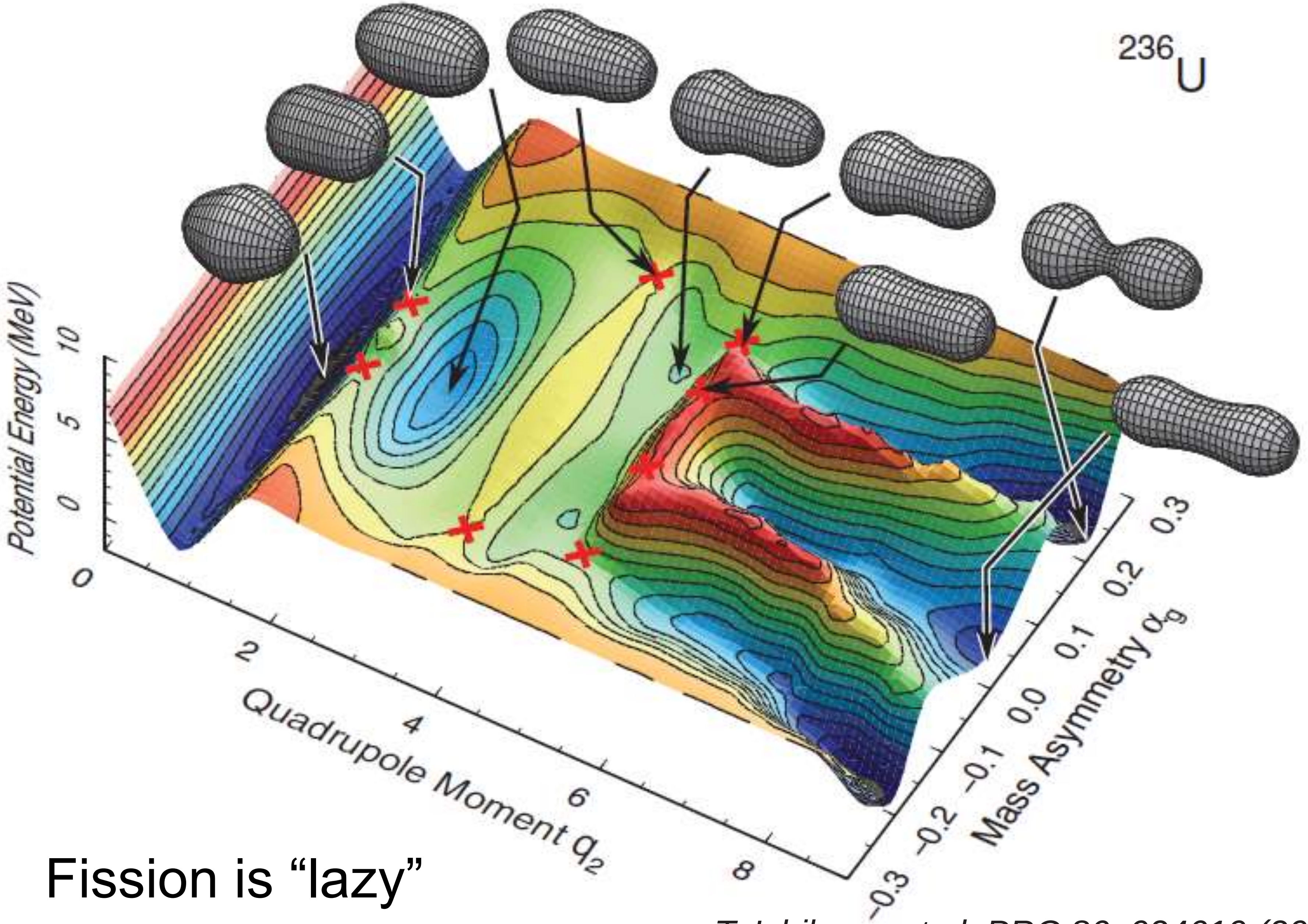
$$^{235}\mathrm{U} + n \rightarrow {}^{138}\mathrm{Xe} + {}^{98}\mathrm{Sr}$$

$$Q_{LDM} = +176\ \mathrm{MeV}$$



T.G. Wang et al.
J Fluid Mech
354, 43 (1994)
STS-50 flight

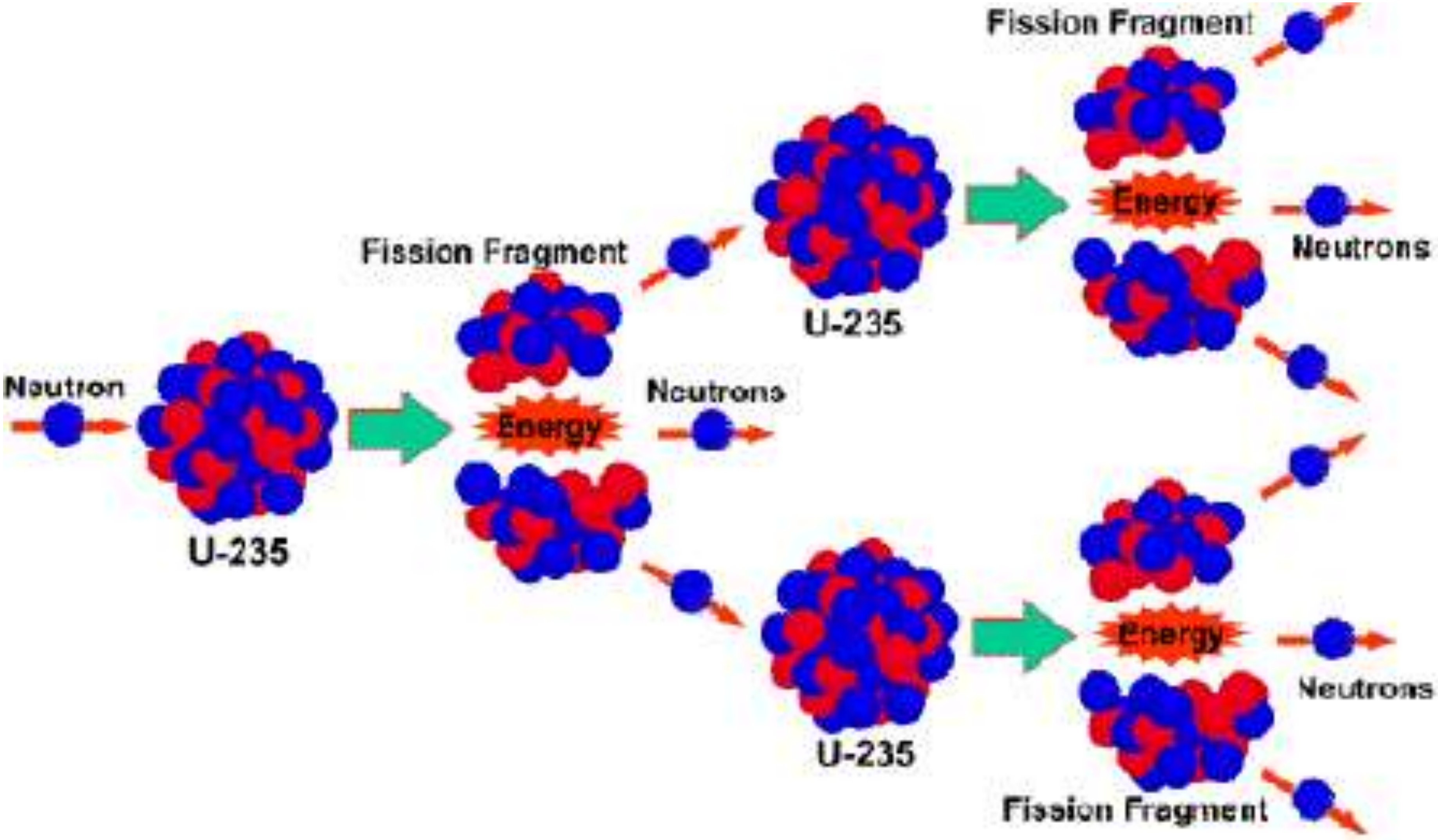
Understanding fission yields of ^{236}U



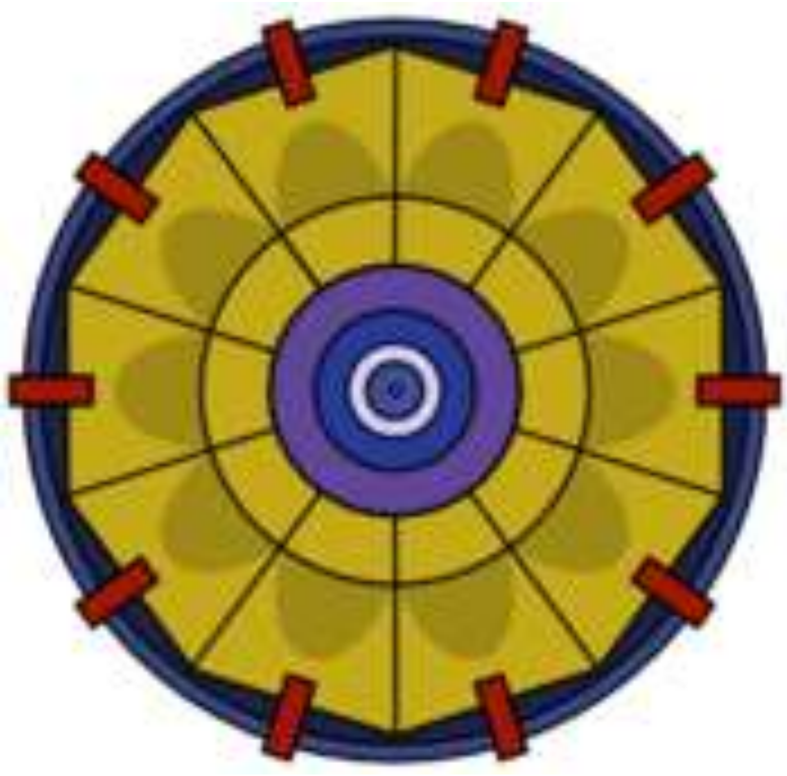
Fission is "lazy"

T. Ichikawa et al. PRC 86, 024610 (2012)

A nuclear chain reaction

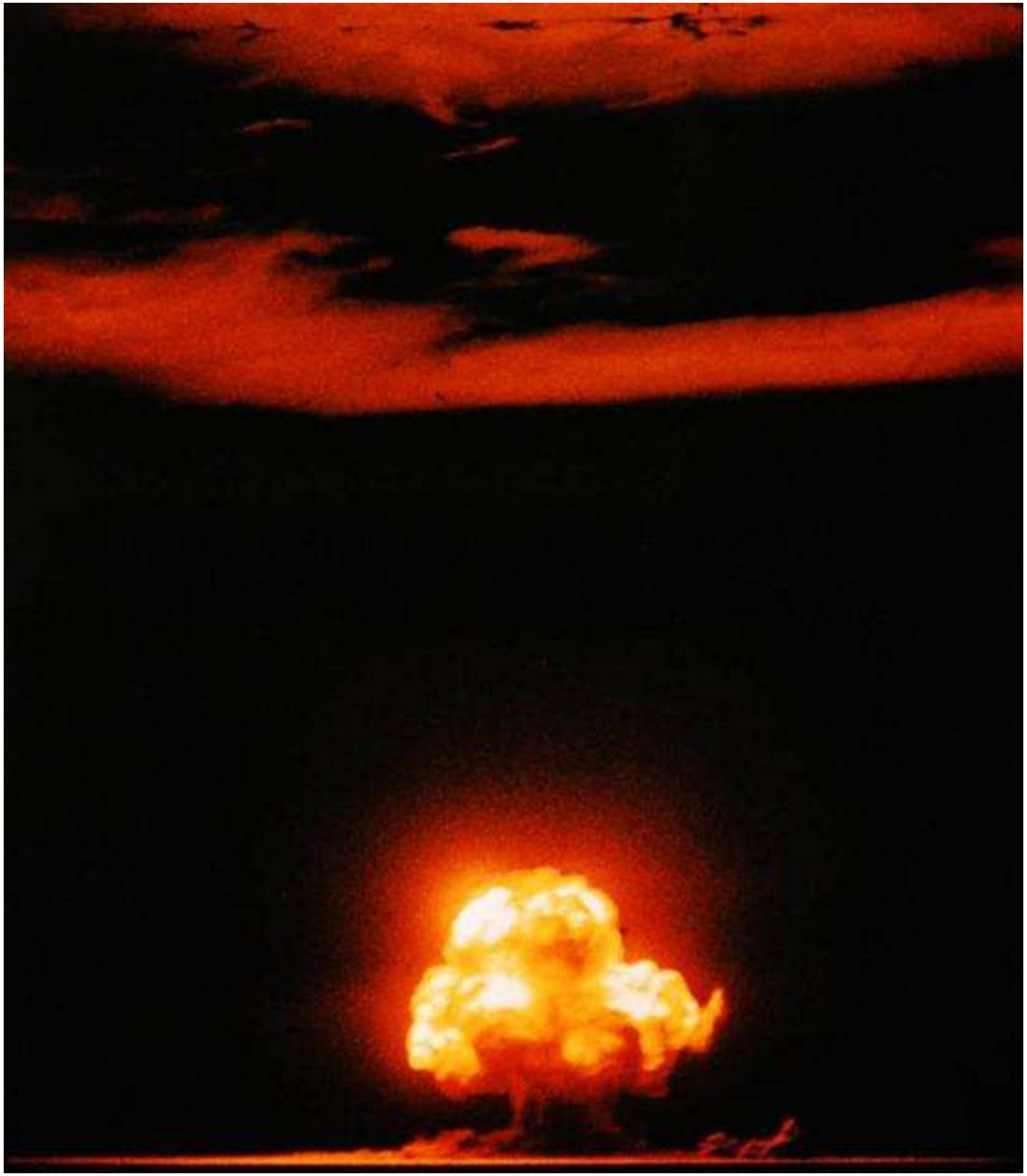


A single-pulse neutron source

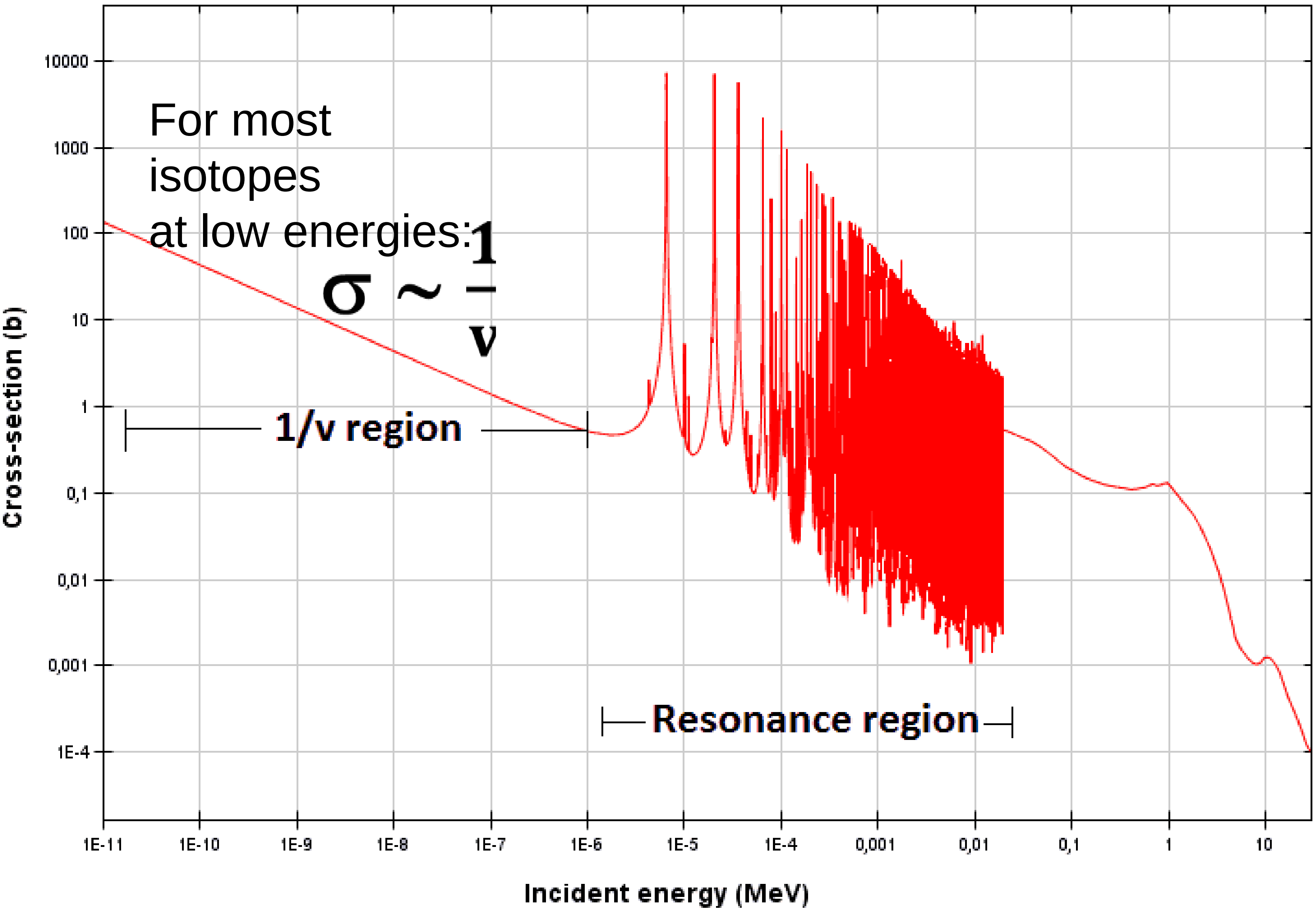


Uncontrolled
chain reaction
of fast-neutron
induced fission

≈25 kg of 93% ^{235}U



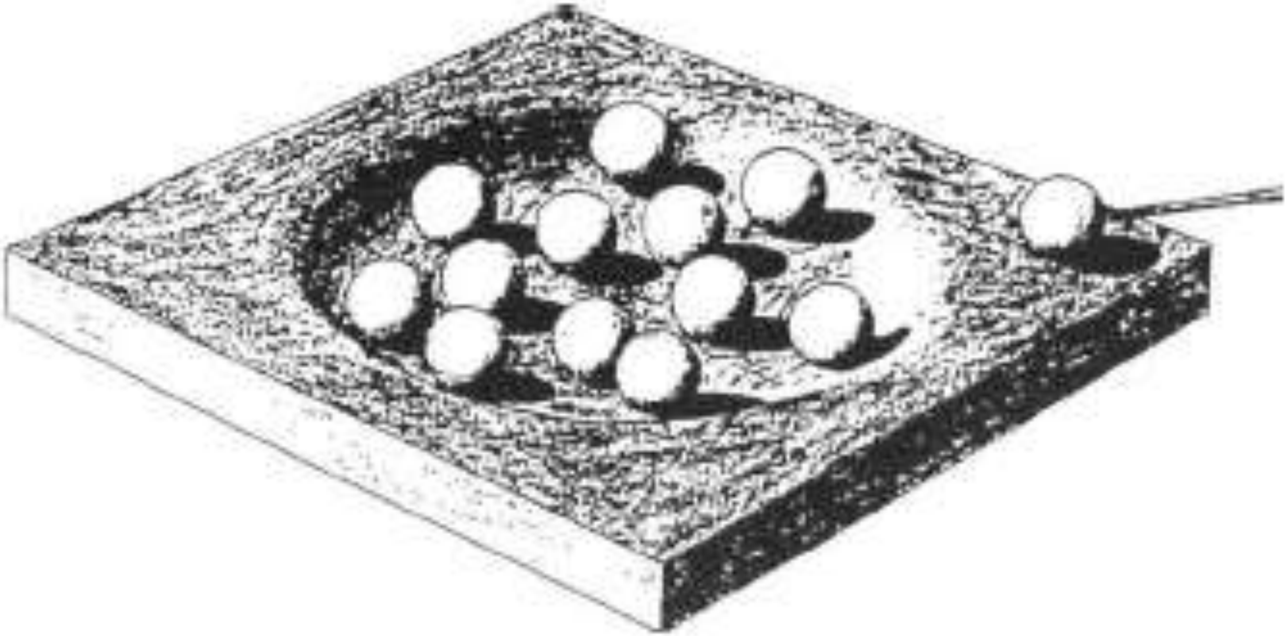
Energy dependence of cross-section



For most
isotopes
at low energies:

$$\sigma \sim \frac{1}{v}$$

Bohr’s compound nucleus model



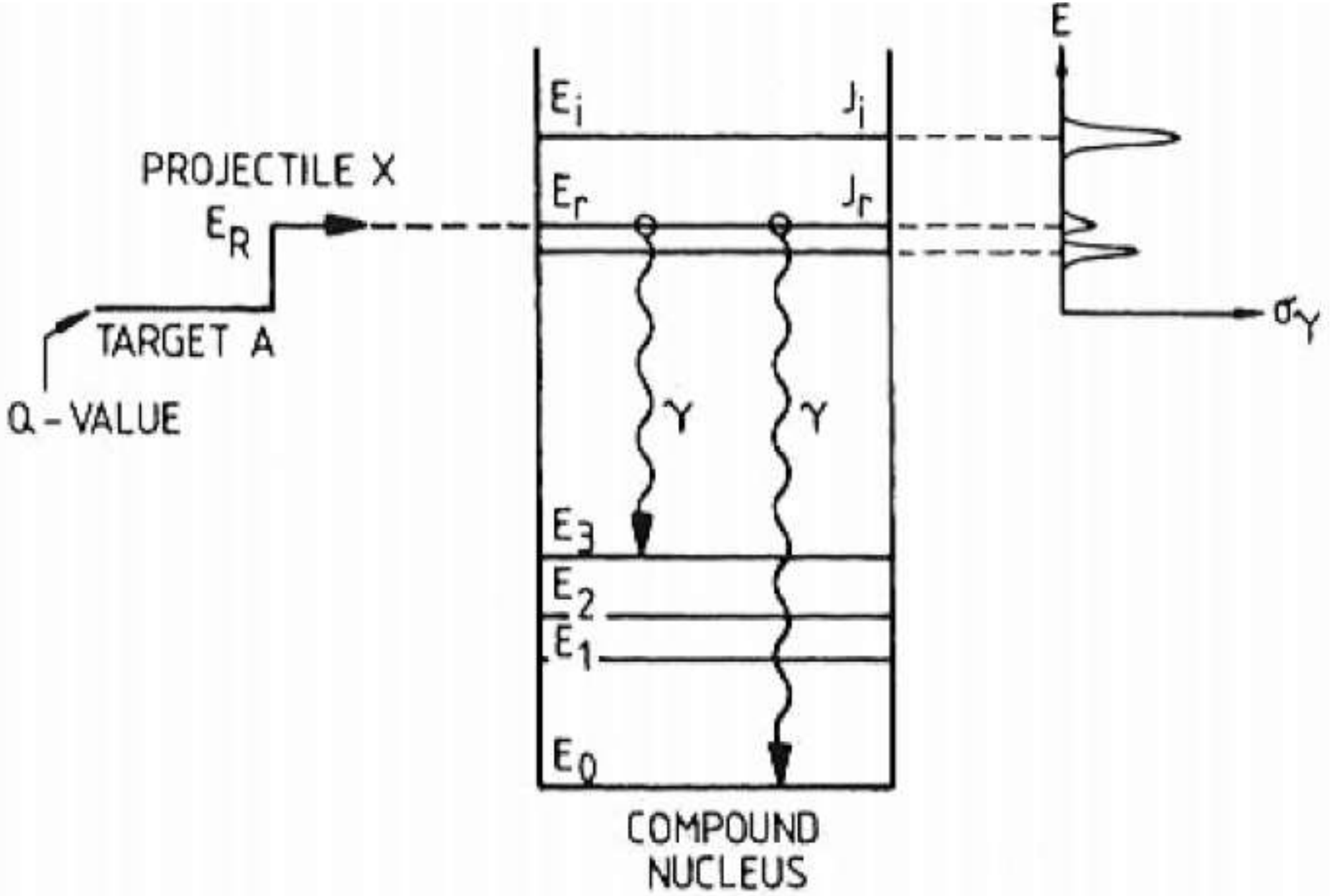
Two separable steps:

1. Incident particle merges with target to form a compound nucleus.
   Intermediate state lives “long” (fs – as) ⇒ thermal equilibrium

2. The compound nucleus deexcites by emitting gammas or particles.

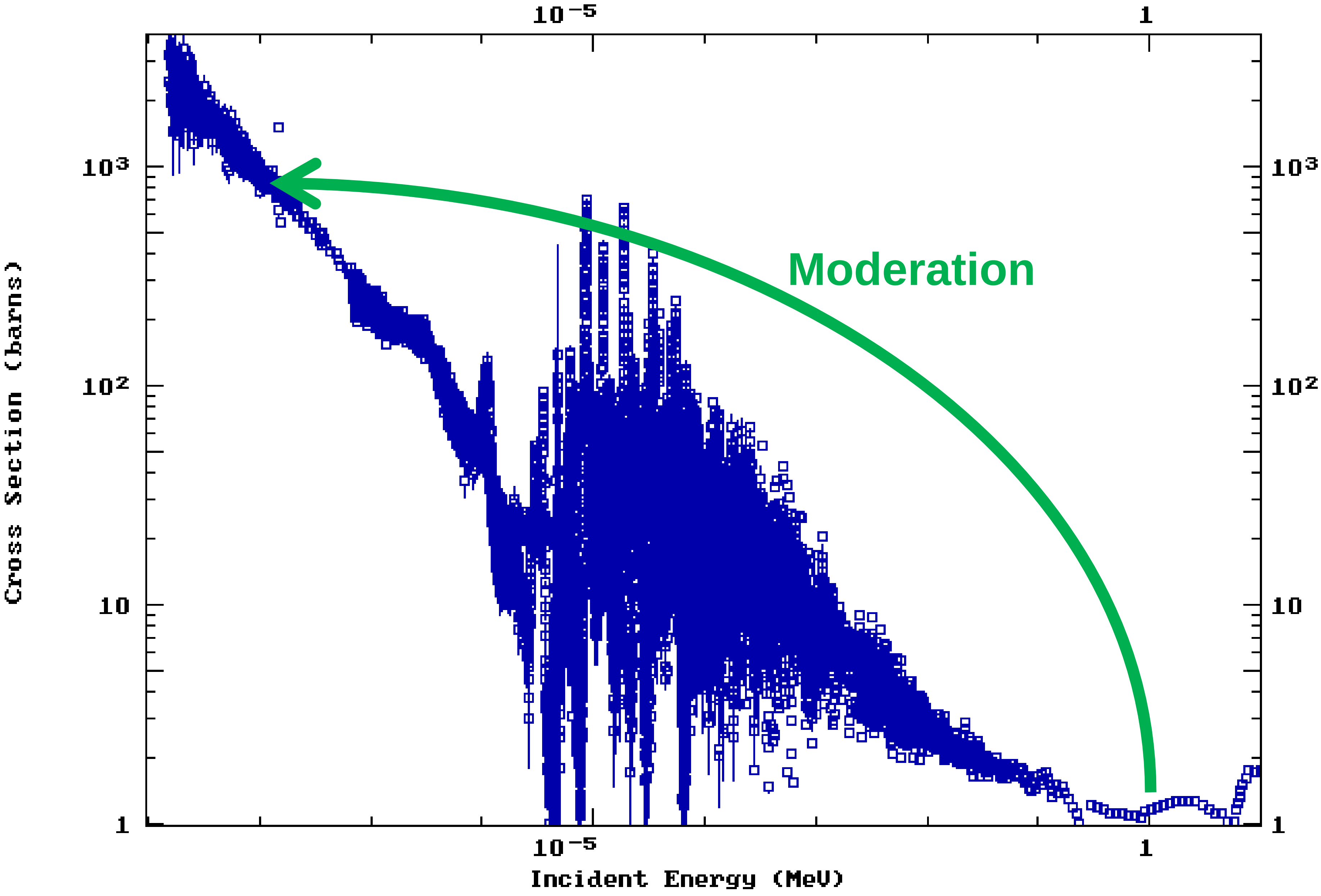
The mode of decay (2.) is independent from the way the compound nucleus was initially formed (1.).

Resonance reactions

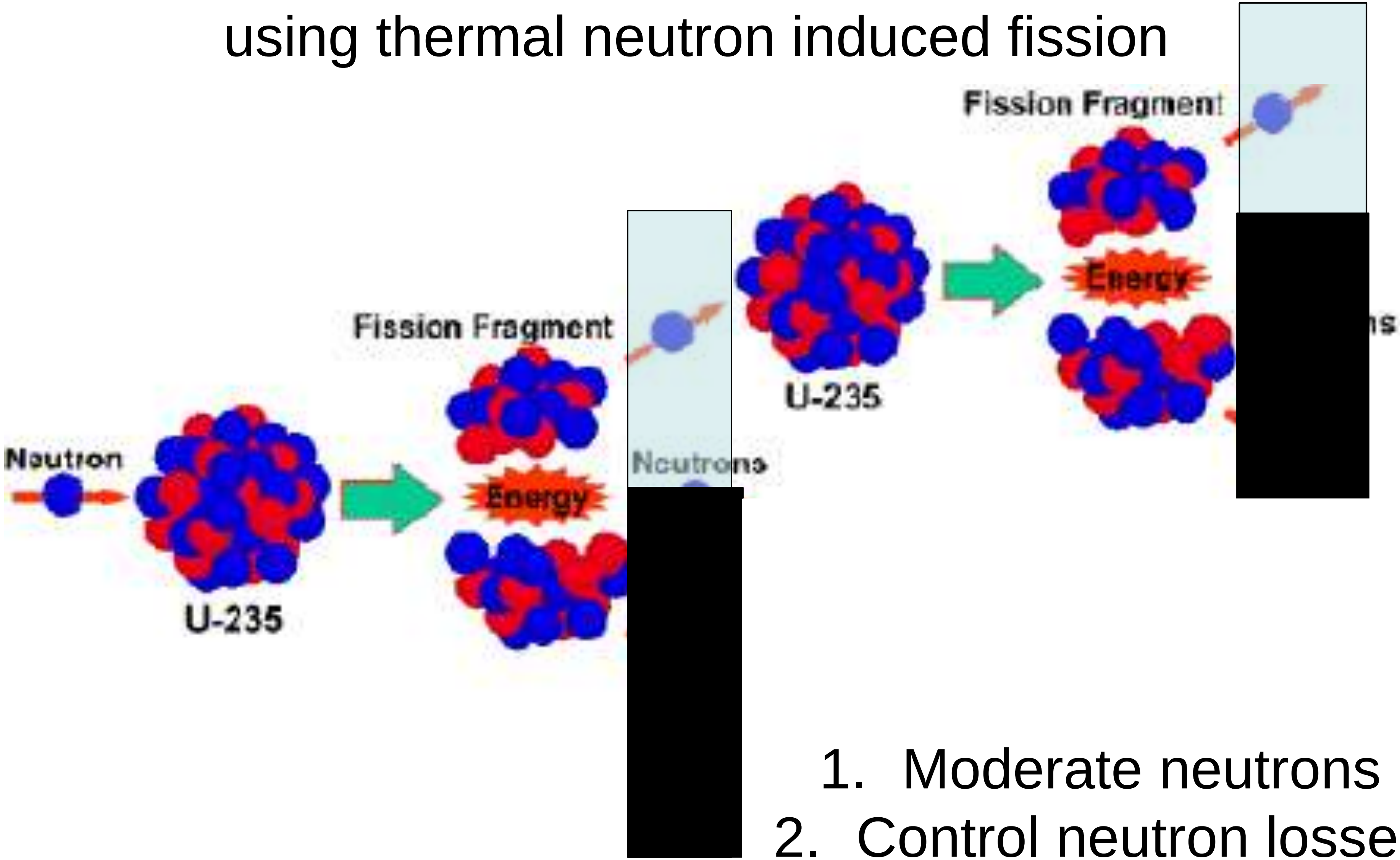


Enhanced cross-section (resonance) when energy matches excited state in compound nucleus.

^{235}U(n,f) cross-section as function of energy



A controlled nuclear chain reaction using thermal neutron induced fission



1. Moderate neutrons
2. Control neutron losses

k = multiplication factor = (neutrons produced in one generation) / (neutrons produced in previous generation)

Prompt neutron kinetics

Prompt neutron lifetime τ_p is the average time between the birth of prompt fission neutrons and their final absorption.

Assumptions:

-No delayed neutrons

-Infinite reactor, multiplication factor $k_\infty = k$

time	N(t)
0	n
τ_p	kn
$2\tau_p$	k^2n
$3\tau_p$	k^3n

$$\frac{dn}{dt} = \frac{k-1}{\tau_p} n \Rightarrow n(t) = n(0) e^{\frac{(k-1)}{\tau_p} t}$$

Time constant $$\boxed{T = \frac{\tau_p}{k-1}}$$

Exponential decrease (k<1)
or exponential growth (k>1)

cf. demographic projections for Germany
Fertility: 1.5 child/women -> k=0.75
T=25 years / (1-0.75) =100 years

Prompt neutron kinetics

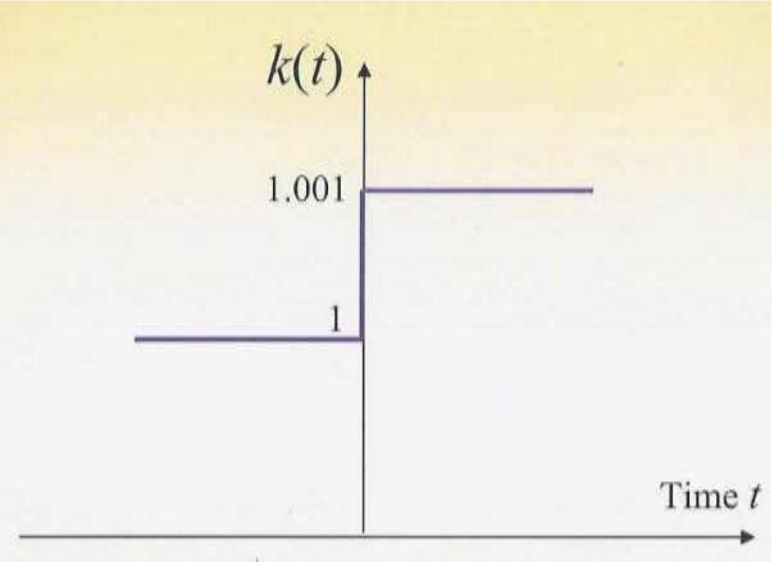
$\tau_p = \tau_s + \tau_d$ = slowing down time + diffusion time

In thermal reactors: $\tau_s << \tau_d$, i.e. $\tau_p \cong \tau_d$

$\tau_d \cong \lambda_a / v \cong 10$ cm / (2000m/s)

$\tau_p \cong \tau_d \cong 50\ \mu$sec

Example: step of reactivity from k=1.000 to k=1.001



$$T = \frac{\tau_p}{k-1} = \frac{50.10^{-6}}{10^{-3}} = 0.05\text{sec}$$

$$n(t) = n_0 e^{\frac{t}{0.05}}$$

$$\frac{n(1\text{sec})}{n_0} = e^{20} = 5E8$$

“Prompt” control is not possible!

Chernobyl: a criticality accident

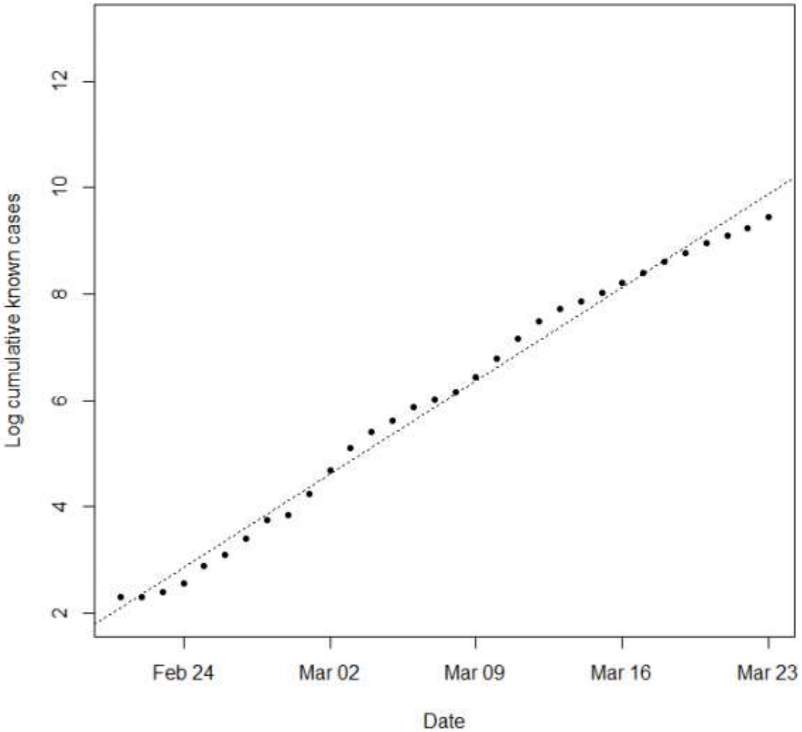
An interesting equation

$n(t) = n(0)\exp((k-1)/\tau_{\mathrm{cycle}}\, t)$

$T_2 = \ln(2)\,\tau_{\mathrm{cycle}} / (k-1)$

$k = R_0$ basic reproduction number

$\tau_{\mathrm{cycle}} \approx$ incubation period



$k<1$: $T_{1/2} = \ln(2)\,\tau_{\mathrm{cycle}} / (k-1)$

$\tau_{\mathrm{cycle}} = 7$ d; $k = 0.8 \Rightarrow T_{1/2} = 3.5$ weeks

$\tau_{\mathrm{cycle}} = 7$ d; $k = 0.9 \Rightarrow T_{1/2} = 7$ weeks

$\tau_{\mathrm{cycle}} = 7$ d; $k = 0.99 \Rightarrow T_{1/2} = 70$ weeks

The greatest shortcoming of the human race is our inability to understand the exponential function. [Prof. Al Bartlett]

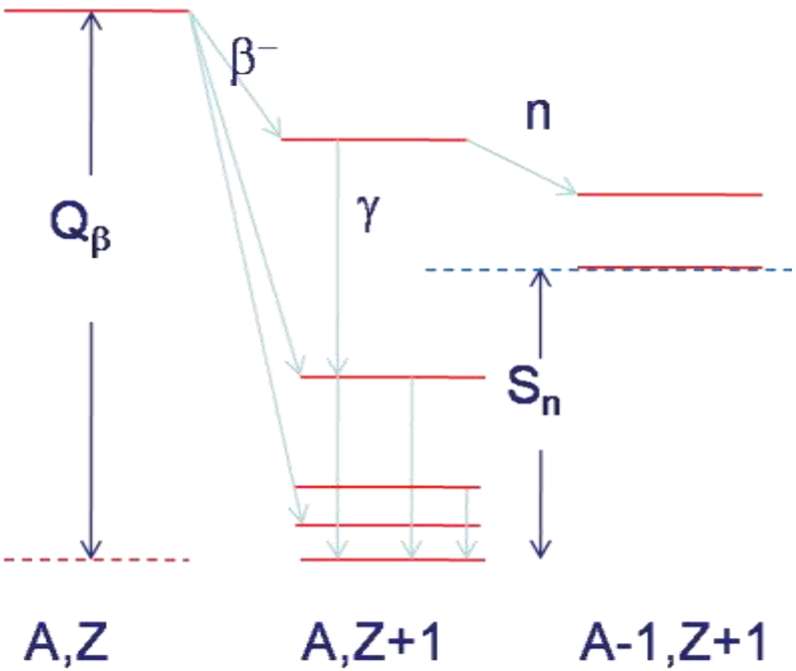
“Just stay calm. It will go away.”

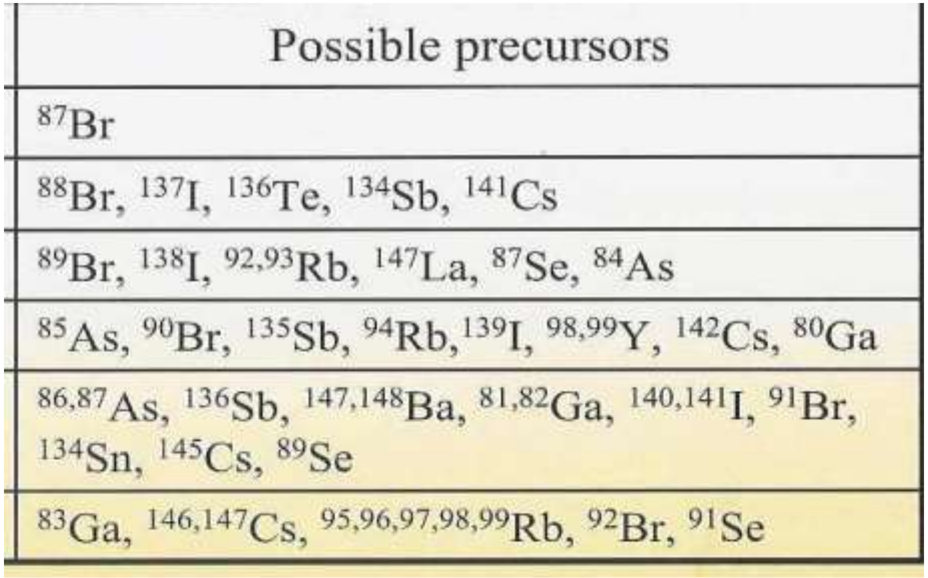
"I continue to shake hands."

“Everything passes and this will pass.”

“Brazilians never catch anything.”

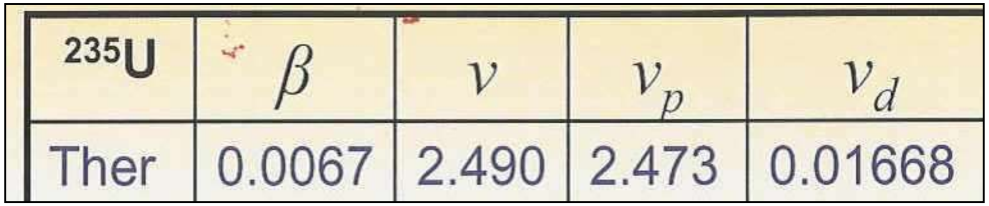
Delayed neutron emission from fission products





Possible precursors
^{87}Br
^{88}Br, ^{137}I, ^{136}Te, ^{134}Sb, ^{141}Cs
^{89}Br, ^{138}I, ^{92,93}Rb, ^{147}La, ^{87}Se, ^{84}As
^{85}As, ^{90}Br, ^{135}Sb, ^{94}Rb, ^{139}I, ^{98,99}Y, ^{142}Cs, ^{80}Ga
^{86,87}As, ^{136}Sb, ^{147,148}Ba, ^{81,82}Ga, ^{140,141}I, ^{91}Br, ^{134}Sn, ^{145}Cs, ^{89}Se
^{83}Ga, ^{146,147}Cs, ^{95,96,97,98,99}Rb, ^{92}Br, ^{91}Se

β= percentage of delayed neutrons

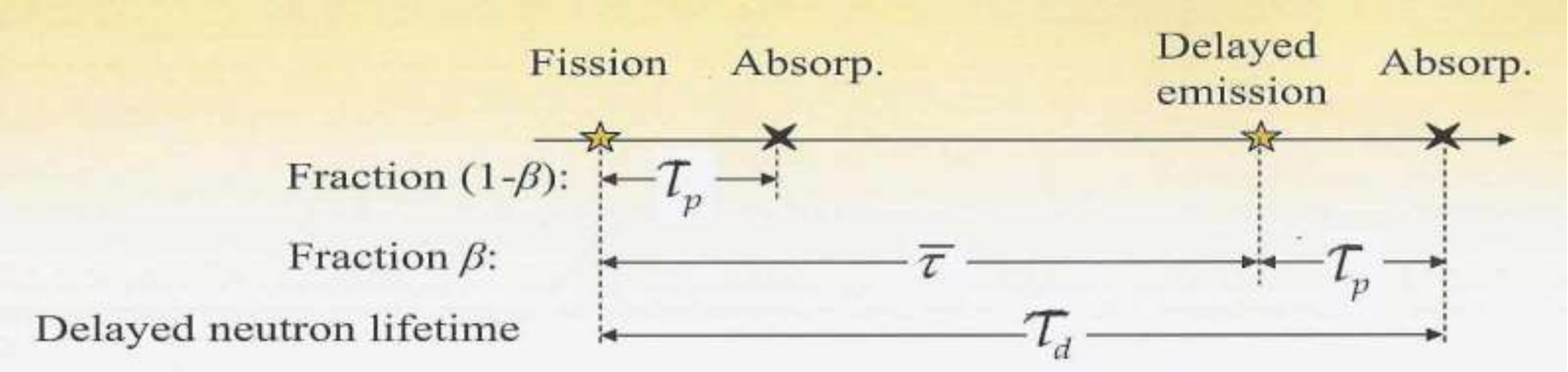


^{235}U	β	ν	ν_p	ν_d
Ther	0.0067	2.490	2.473	0.01668

average emission time

$$\tau_{delayed} = \frac{1}{\beta}\sum_i \beta_i \tau_i \approx 12\,\mathrm{sec}$$

Neutron lifetime,
taking into account delayed neutrons



$$k = k_{prompt} + k_{delayed} = 1 = (1-\beta) + \beta$$

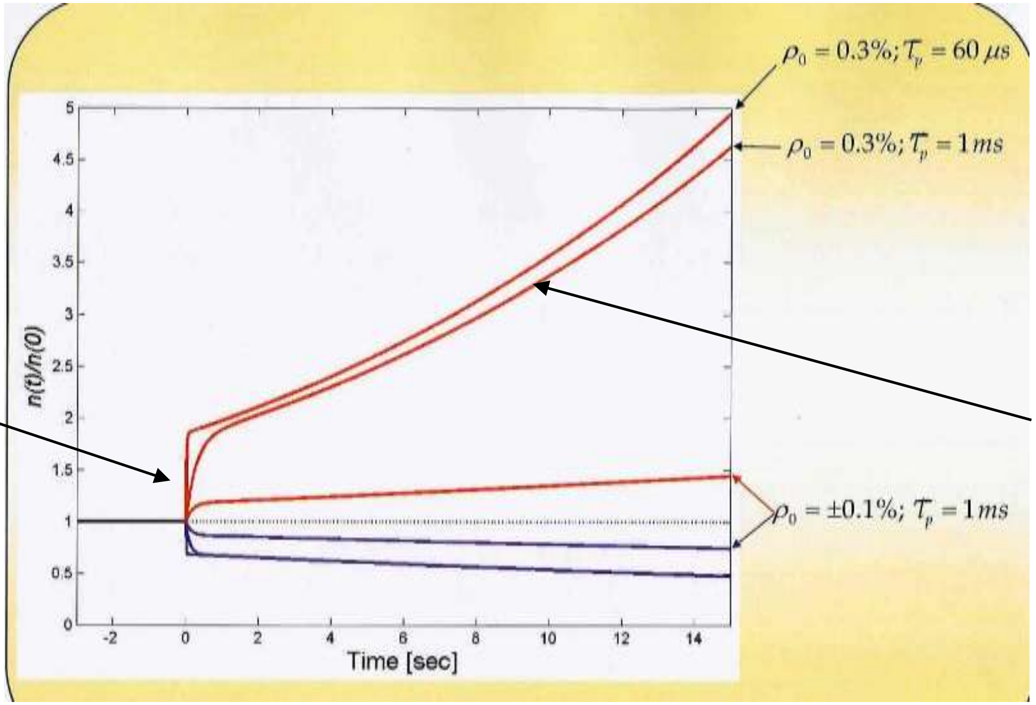
$$\tau = (1-\beta)\tau_p + \beta(\tau_{delayed} + \tau_p) \approx \beta\tau_{delayed} = 0.08\,\mathrm{sec}$$

Now for step from k=1.000 to k=1.001

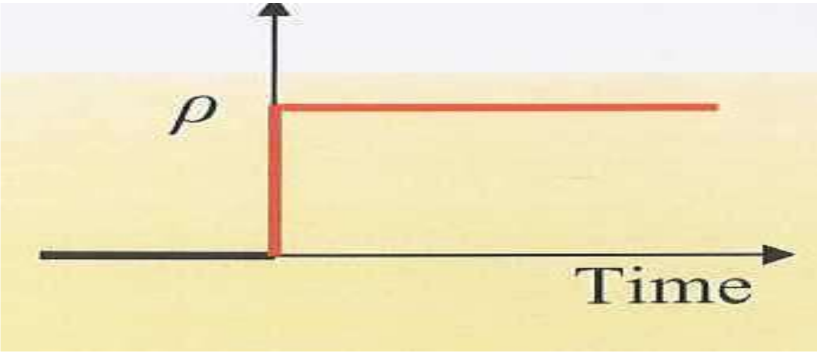
$T = \beta\tau_{delayed}/(k-1) =$ 80 seconds

Reactor response to a step of reactivity

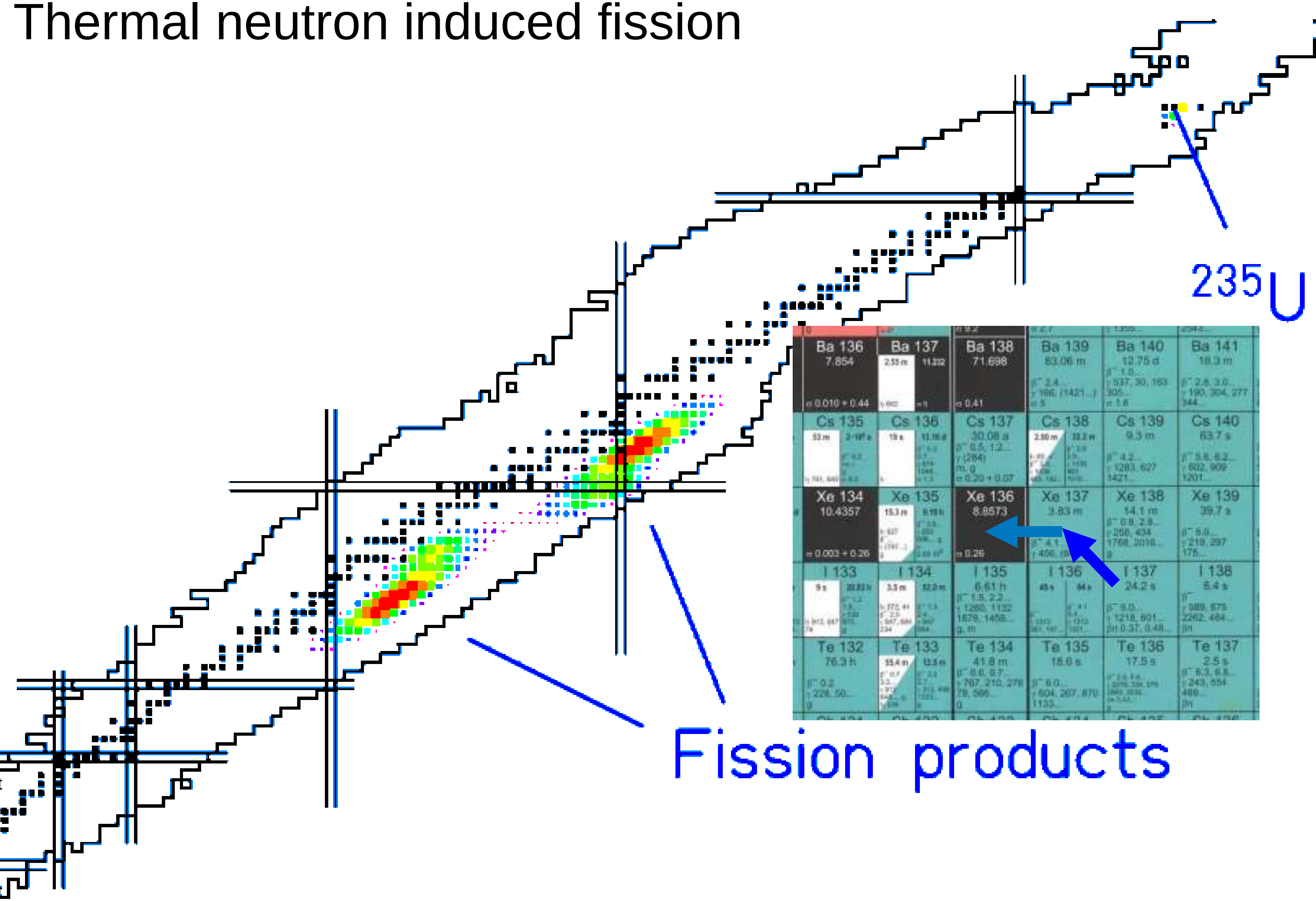
Prompt jump



Slow increase due to Delayed neutrons



Thermal neutron induced fission

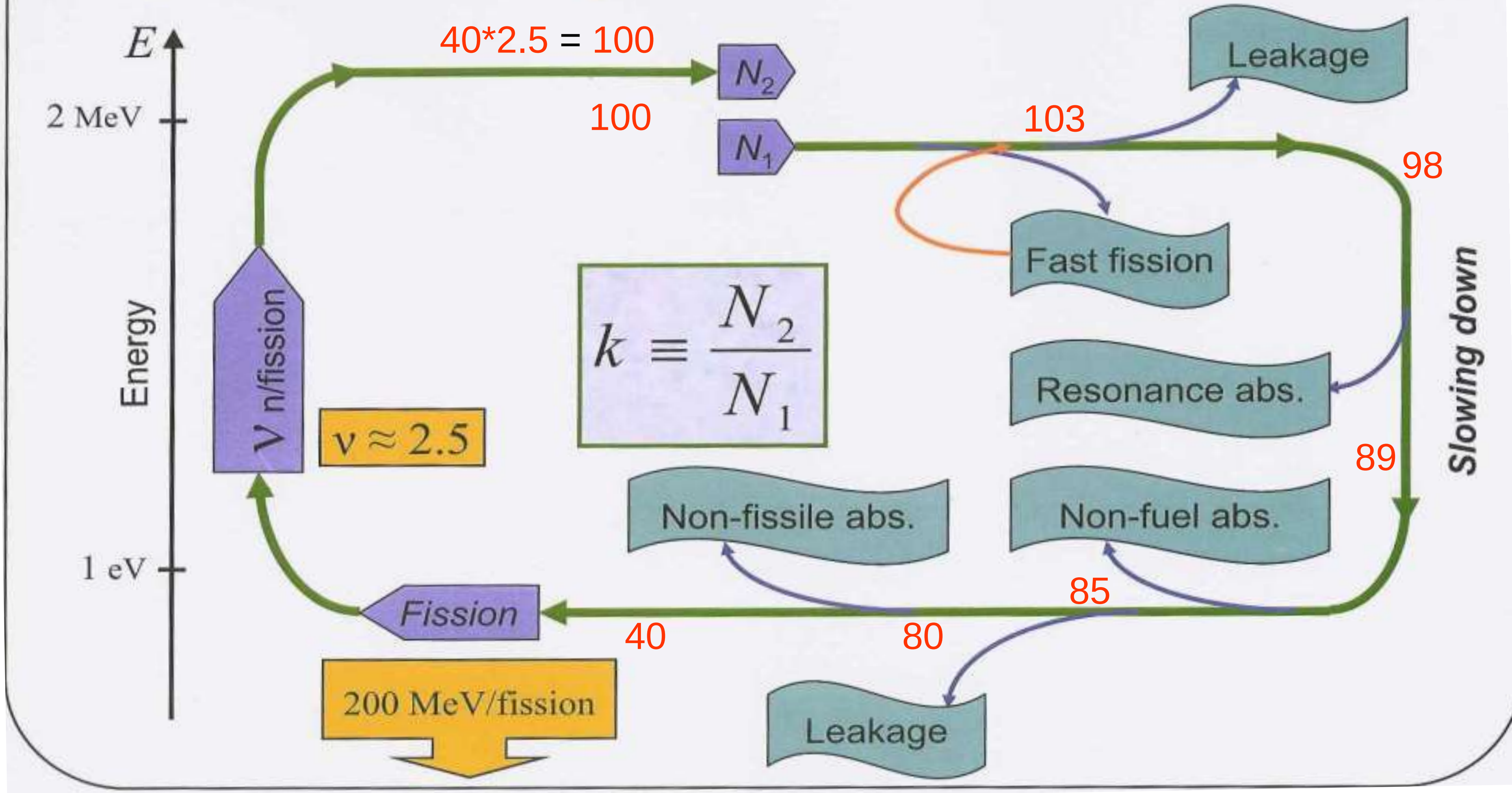


Ba 136 7.854 σ 0.010 + 0.44	Ba 137 2.55 m 11.232	Ba 138 71.698 σ 0.41	Ba 139 83.06 m	Ba 140 12.75 d	Ba 141 18.3 m
Cs 135	Cs 136 19 s 13.16 d	Cs 137 30.08 a σ 0.20 + 0.07	Cs 138 2.90 m 32.2 m	Cs 139 9.3 m	Cs 140 63.7 s
Xe 134 10.4357 σ 0.003 + 0.26	Xe 135 15.3 m 9.10 h	Xe 136 8.8573 σ 0.26	Xe 137 3.83 m	Xe 138 14.1 m	Xe 139 39.7 s
I 133 9 s 20.83 h	I 134 3.5 m 52.0 m	I 135 6.61 h	I 136 45 s 84 s	I 137 24.2 s	I 138 6.4 s
Te 132 76.3 h	Te 133 55.4 m 12.5 m	Te 134 41.8 m	Te 135 18.6 s	Te 136 17.5 s	Te 137 2.5 s

^{235}U

Fission products

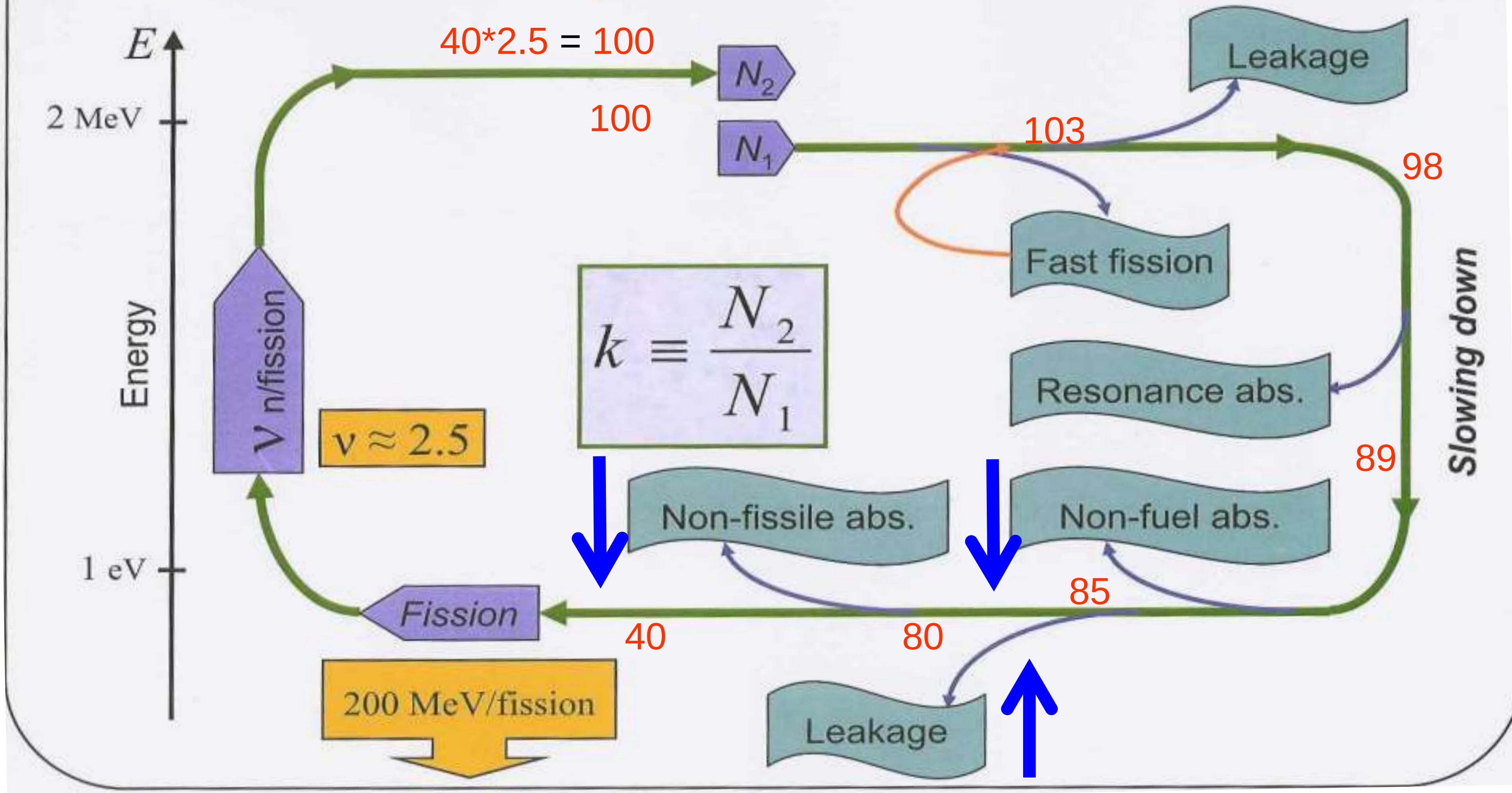
Physical Principles of a Nuclear Reactor



$$k \equiv \frac{N_2}{N_1}$$

neutron numbers are given for a typical PWR reactor

Physical Principles of a Nuclear Reactor



$$k \equiv \frac{N_2}{N_1}$$

Research reactor

Components of a nuclear reactor

1. Fuel
2. Moderator
3. Control rods
4. Coolant
5. Pressure vessel
6. Containment
7. Steam generator (for power plants) or experimental facilities (for research reactors)

Moderator

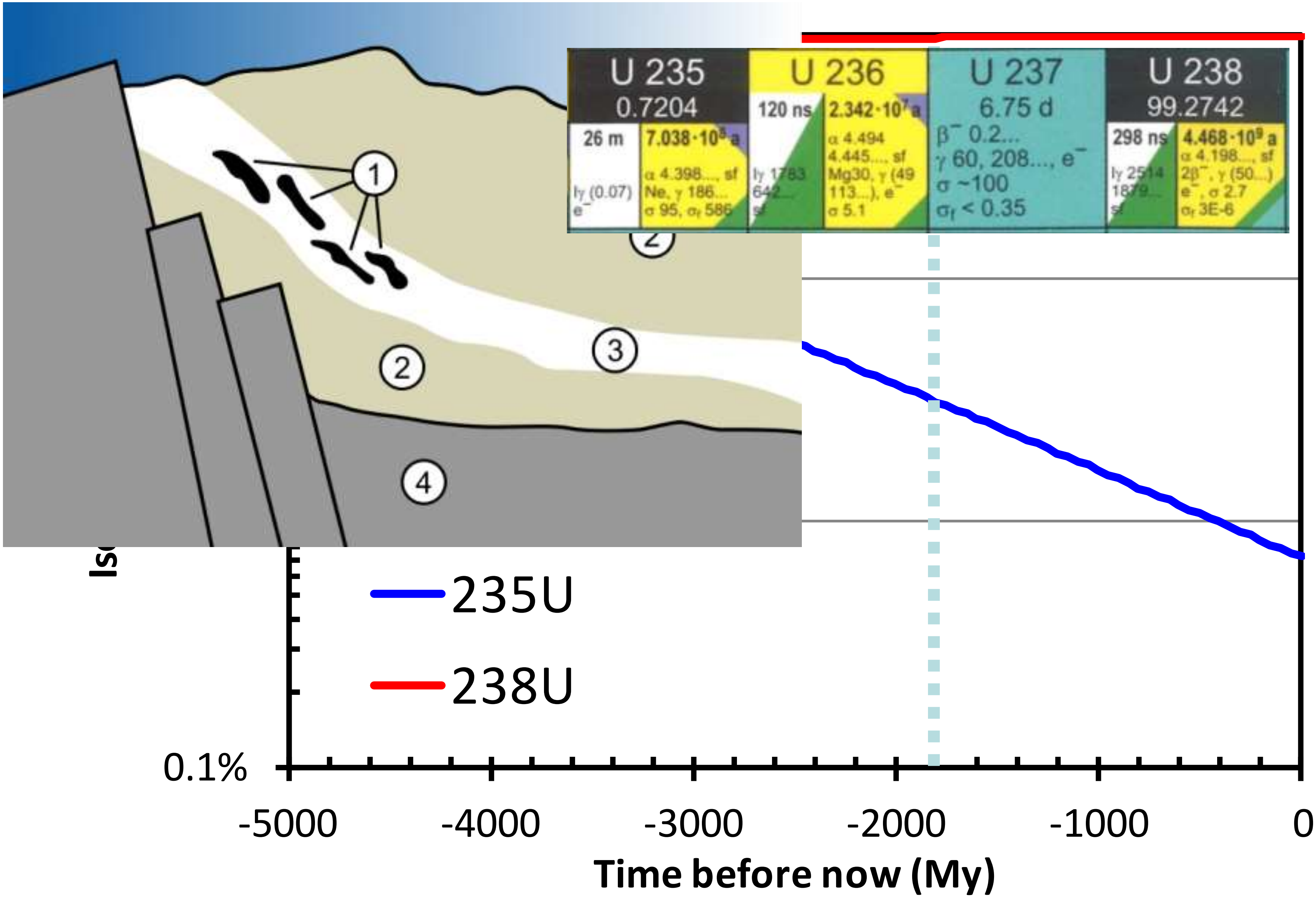
elastic collisions with light atoms (mass A):
average energy loss $E_{n+1} - E_n = 2\,E_n\,A/(A+1)^2$

$$\ln(E_n) - \ln(E_{n+1}) = \xi = 1 - (A-1)^2/(2A) * \ln[(A+1)/(A-1)]$$

$$\Sigma = n\,\sigma = m/M\,\sigma$$

Moderating power:	$\xi\Sigma_{\text{scatter}}$	
Moderating ratio:		$\xi\Sigma_{\text{scatter}}/\Sigma_{\text{abs.}}$
Light water (H_2O)	1.28	58
Heavy water (D_2O)	0.18	21000
Beryllium (Be)	0.16	130
Graphite (C)	0.064	200
Polyethylene $(CH_2)_x$	3.26	122

Q4: The moderator of the first nuclear reactor



Choice of coolant

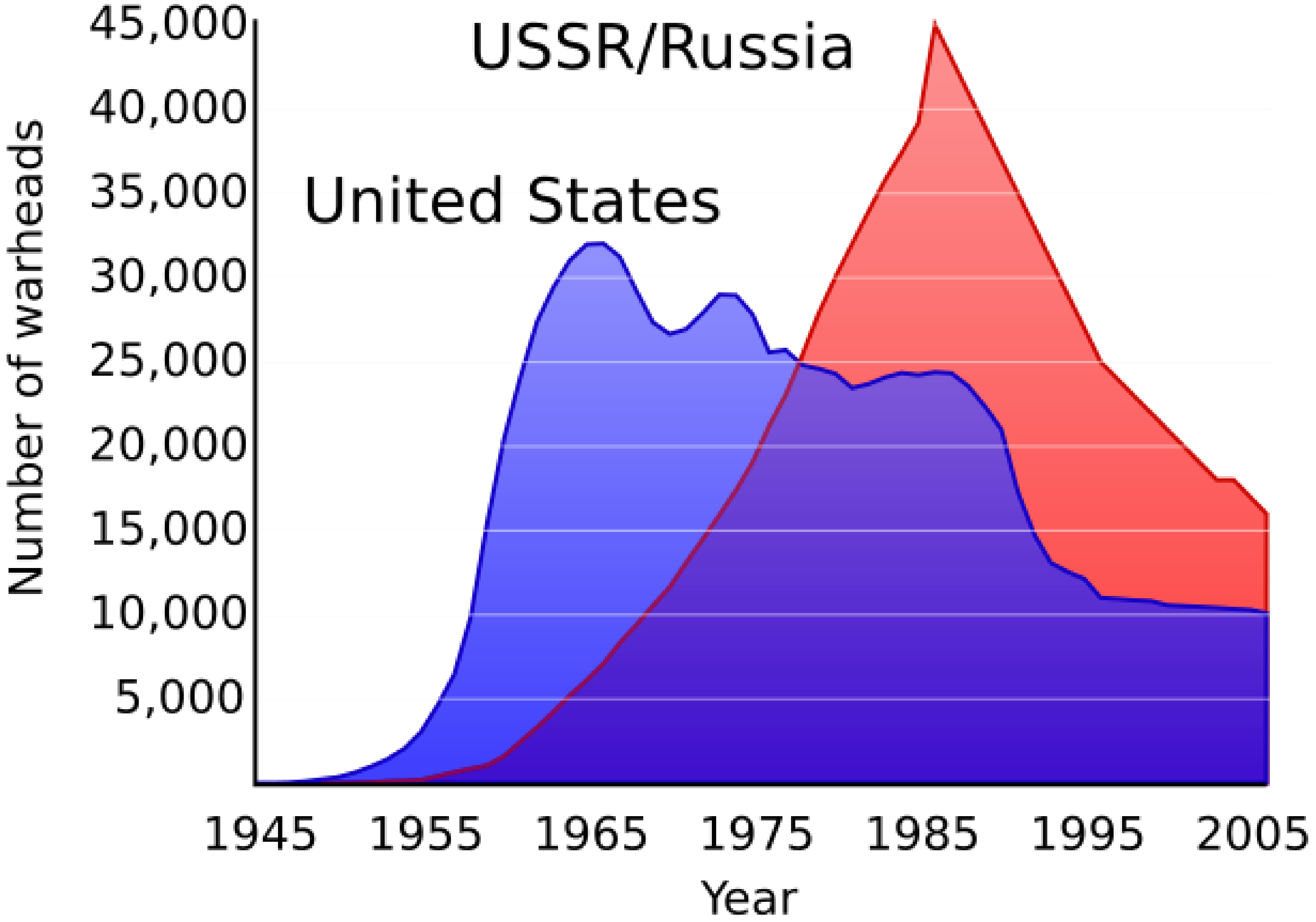
coolant = moderator
⇒ passive regulation
⇒ intrinsic safety

RBMK:
graphite moderator
water cooling
⇒ positive void
coefficient !

RHF fuel element

8.6 kg ^{235}U, 93% enriched

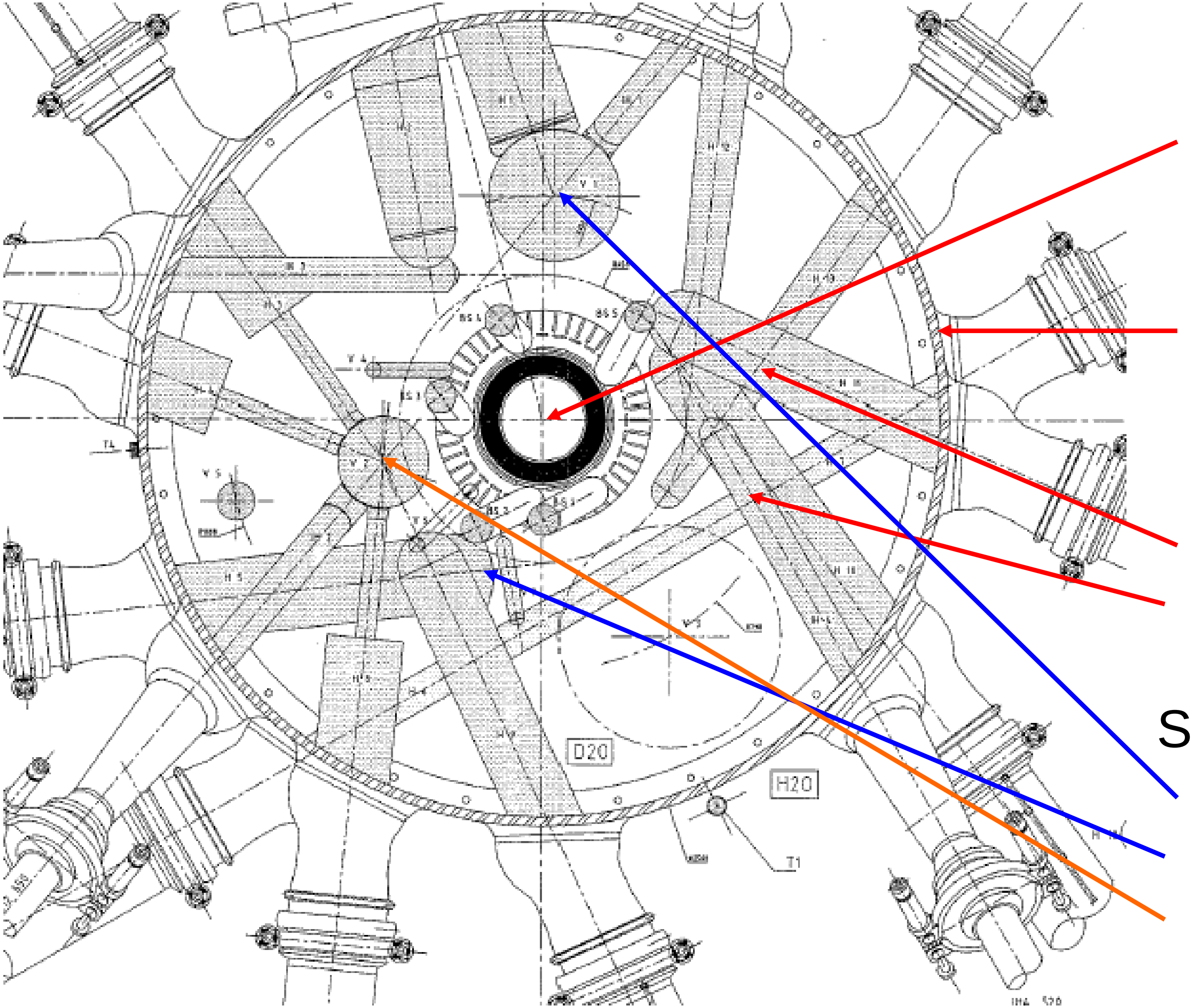
8 December 1987: Intermediate-Range Nuclear Forces Treaty



1 warhead = 25 kg HEU = 3 fuel elements for ILL

The ILL reactor contributes to permanent disarmament!

The reactor core and vessel



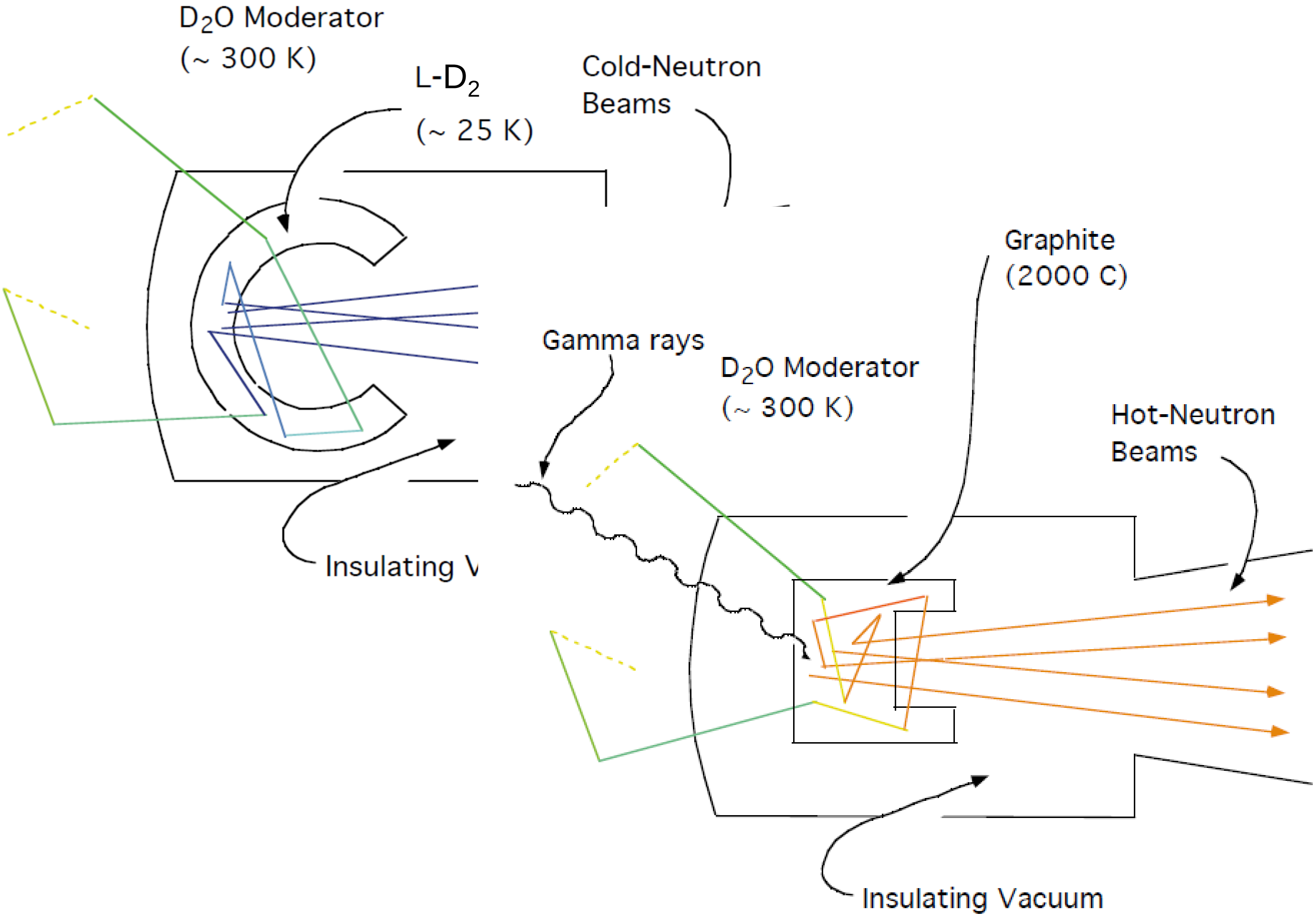
Fuel element :
-R_i = 14 cm
-R_e = 19 cm

Vessel:
- R = 125 cm

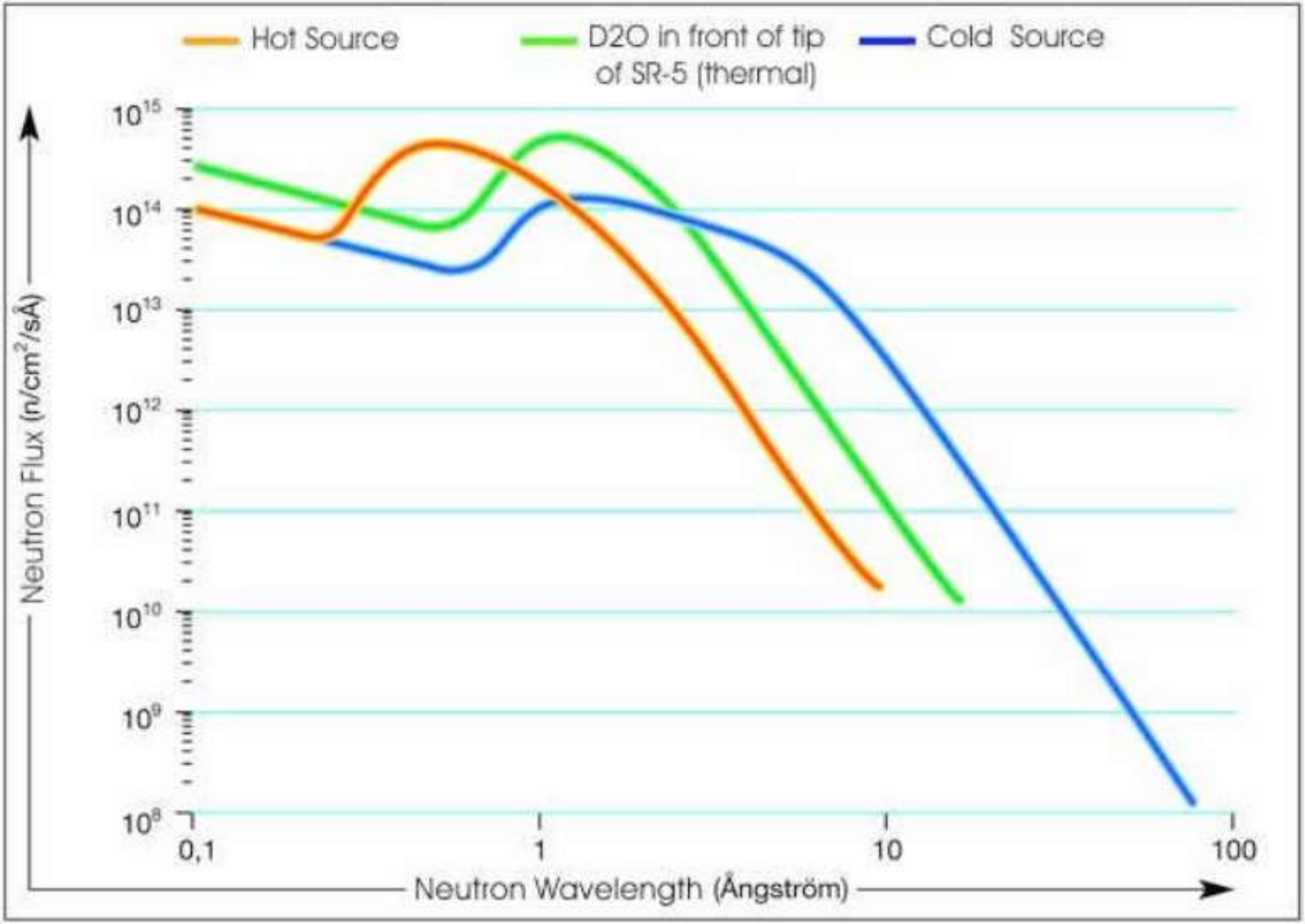
Beam tubes :
-13 Horizontal
-4 inclined

Sources
-VCS
-HCS
-HS

Spectral shaping with dedicated moderators



Spectral shaping with dedicated moderators



Power reactor ⇔ Research reactor

- heat used to produce electricity
- neutrons just to maintain chain reaction
- needs high power, high temperature and high pressure for good thermal efficiency
- BWR: 75 bar, 285°C
- PWR: 155 bar, 315°C
- 25 cm thick steel pressure vessel ⇒ defines lifetime (40..60 y)

- neutrons used for applications
- heat not used
- operates at lower power, low temperature (ILL 30-48°C) and low pressure (<14 bar)
- vessel and all inserts made from pure Al-alloy
- modular and exchangeable ⇒ no finite lifetime

ILL: Replacement of the reactor vessel 1990-94