MSc Energy (2019/20)

NUCLEAR REACTOR TECHNOLOGY (LECTURE 1)

P. STAMENOV

Synopsys

- Why nuclear energy – advantages and disadvantages. Proliferation and Impact. General principles of reactor design – neutron and thermal considerations. Common components.
- Reactor types and classifications. Reactor generations. Historical notes, current status and planned future reactors worldwide.
- Elements of reactor theory. Neutron reactions and characteristics. Scattering of neutrons. Nuclear fission. Chain reactions. Neutron flux and cross-sections.
- Neutron transport and diffusion equation. Dynamic characteristics. Xenon and other poisoning. Burn-up. Equilibrium state. Fuel cycle.
- Pressurized Water Reactors (PWRs). Boiling Water Reactors (BWRs). Pressurised Heavy Water Reactors (PHWRs and Candu).
- Gas-cooled reactors (AGR & Magnox).
- Light water graphite moderated reactors (RBMK).
- Fast neutron reactors and breeders (FBR).
- Back-end and auxiliary equipment. Fuel types and fuel handling equipment.
- Control strategies and algorithms. Passive and active control. Safety aspects and measures. Construction, deployment, use and decommissioning of nuclear reactors.

Books & Other Literature

- 1. Nuclear Reactor Theory (*Hiroshi Sekimoto*, **TIT**)
- 2. Nuclear Reactor Physics (*Weston M. Stacey* , **Wiley-VCH, Berlin**)
- 3. An introduction to Nuclear Materials (*Linga K. Murty and Indrajit Charit*, **Wiley-VCH, Berlin**)

- 4. Nuclear Physics – Principles and Applications (*John Lilley*, **Wiley**)
- 5. Fundamentals in Nuclear Physics – From Nuclear Structure to Cosmology (*Jean-Louis Basdevant, James Rich, Michael Spiro*, **Springer, Berlin**)
- 6. Introductory Nuclear Physics (*Kenneth S. Krane*, **Willey**)
- 7. Introduction to Nuclear Science(*Jeff C. Bryan*, **CRC Press**)

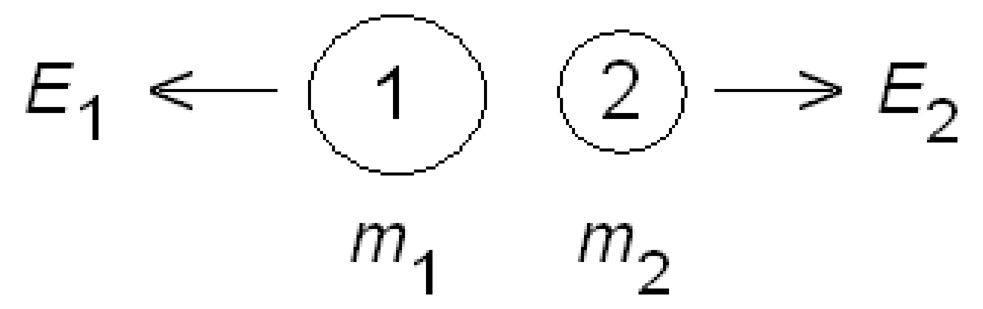
- 8. SF Nuclear Physics (*Maria Stamenova*, **TCD**)

History – Brief Aspects

- 1808 Dalton: Atomic theory
- 1876 Goldstein: Cathode rays
- 1891 Stoney: Prediction of electrons
- 1895 Roentgen: X-rays
- 1896 Becquerel: Radioactivity
- 1897 Thomson: Cathode rays = electrons
- 1898 Rutherford: a-rays and β-rays
- 1900 Planck: Quantum theory
- 1905 Einstein: Special relativity theory
- 1911 Rutherford: Atomic model
- 1912 Thomson: Isotope
- 1914-1918 World War 1
- 1919 Aston: Mass spectrometer
- 1921 Harkins: Prediction of neutrons
- 1930 Bothe: Be (a, ?)
- 1932 Irene and Frederic Joliot-Curie: Be (a, γ)
- **Chadwick: Neutron discovery**
- 1934 Fermi: Delayed neutrons
- Szilard: Chain reaction
- 1939-1945 World War 2
- 1939 **Hahn, Strassman, Meitner: Discovery of nuclear fission**
- 1942 **Fermi: CP–1 made critical**
- 1944 First plutonium production reactor made critical (Hanford, USA)
- 1945 Test of atomic bomb (USA)
- 1945 Natural uranium heavy water research reactor (ZEEP) made critical (Canada)
- 1946 Fast reactor (Clementine) made critical (USA)
- 1950 Swimming pool reactor (BSR) made critical (USA)
- 1951 Experimental fast breeder reactor (EBR-1) made critical and generates power (USA)
- 1953 Test of hydrogen bomb (USSR)
- "Atoms for Peace" Initiative (United Nations, USA)
- 1954 Launch of the nuclear submarine "Nautilus" (USA)
- Graphite-moderated water-cooled power reactor (AM-1) generates power (USSR)

Nuclear fission

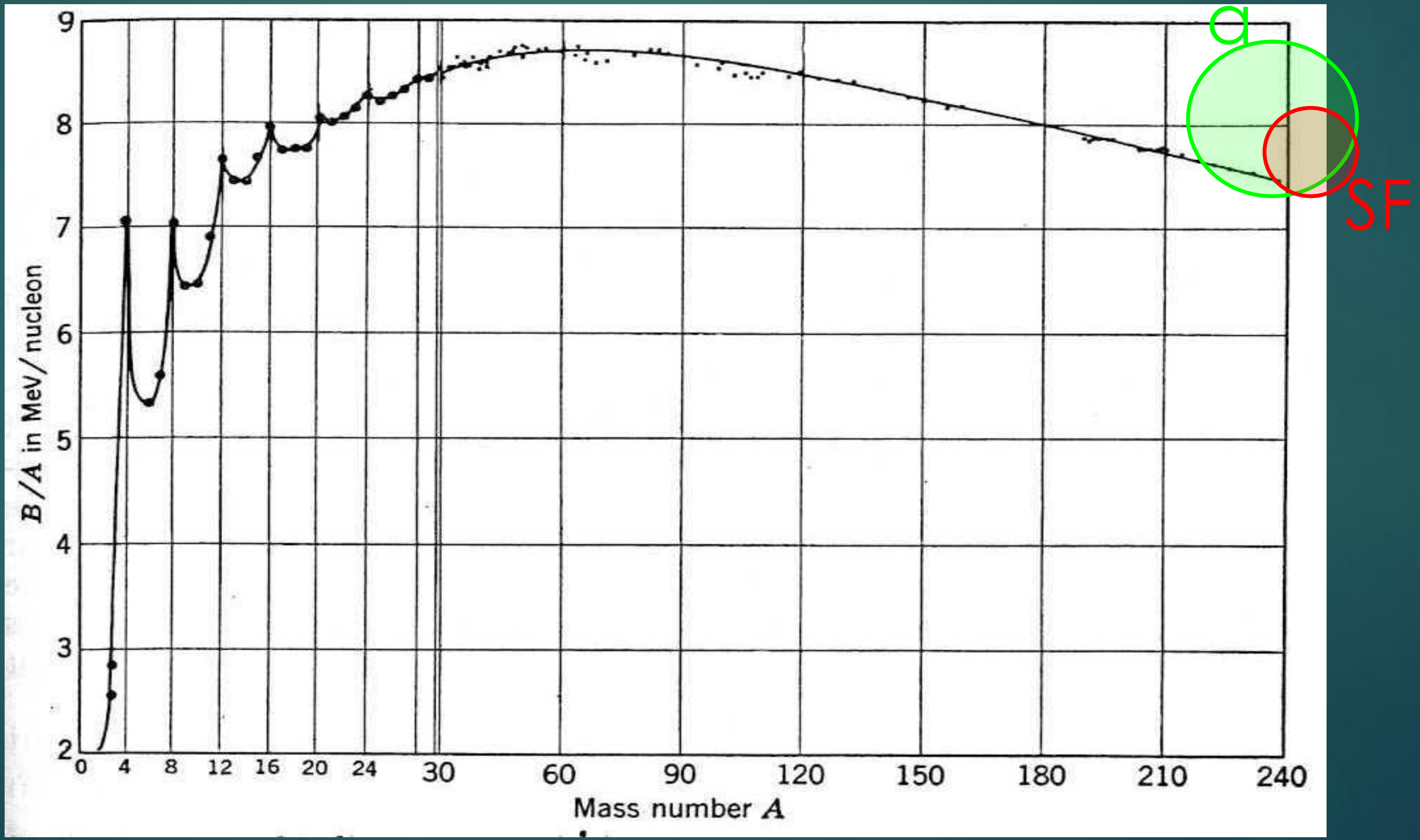
- The process in which a nucleus splits into (usually) two fragments of similar mass, together with an energy release.



- For the same reasons as in alpha decay: $m_1E_1 = m_2E_2$
- Two types will be considered:
  - *spontaneous fission* (radioactive decay)
  - *induced fission* (by particle bombardment).
- Many aspects of the theories of alpha decay and spontaneous fission are similar…..

Spontaneous fission

- Like alpha decay – occurs only for very heavy nuclei *A*>230, in region where *B*/*A* decreases as *A* increases:



Spontaneous fission – conditions

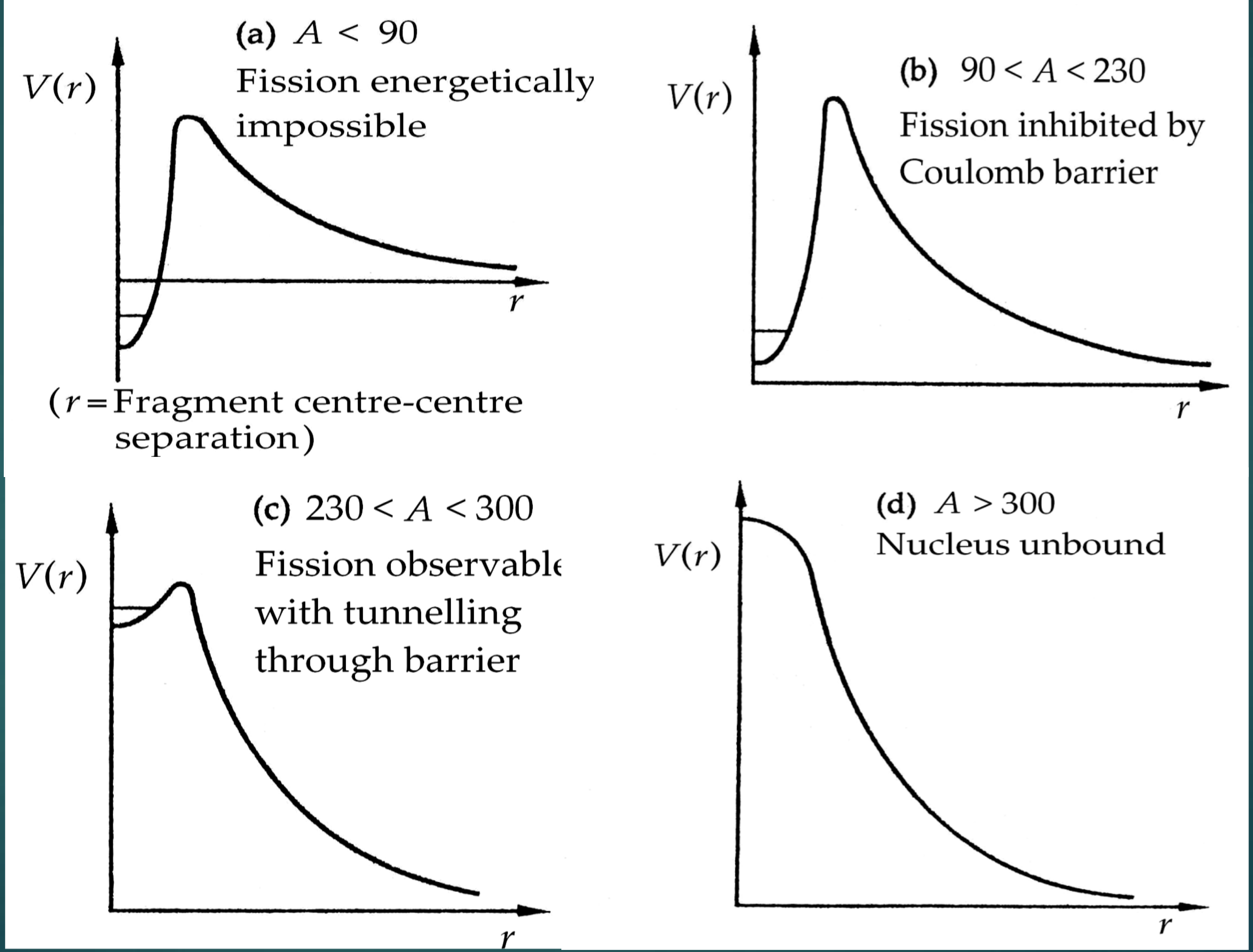
- For the decay: $\boxed{{}^{A}_{Z}\mathrm{X} \rightarrow {}^{A_1}_{Z_1}\mathrm{Y} + {}^{A_2}_{Z_2}\mathrm{Z} + k\,\mathrm{n}}$ to occur it is required that

$$\boxed{Q > 0 \;\Rightarrow\; m_{\mathrm{X}} > m_{\mathrm{Y}} + m_{\mathrm{Z}}\ ,\ \text{i.e.}\ \ B_{\mathrm{X}} < B_{\mathrm{Y}} + B_{\mathrm{Z}}}$$

(neutron emission, neglected above, will be considered later)

- From this and von Weizsäcker's SEM formula it can be shown that, for fission to be energetically possible, $A > 90$.
- However, because of the mechanism of the process, spontaneous fission is unmeasurably slow until $A \sim 230$.
- Analogous to the *α*-decay → a quantum-mechanical tunnelling process.
- As *A* increases further, spontaneous fission very rapidly becomes more likely.

Fission barriers from liquid drop model



Spontaneous fission – examples

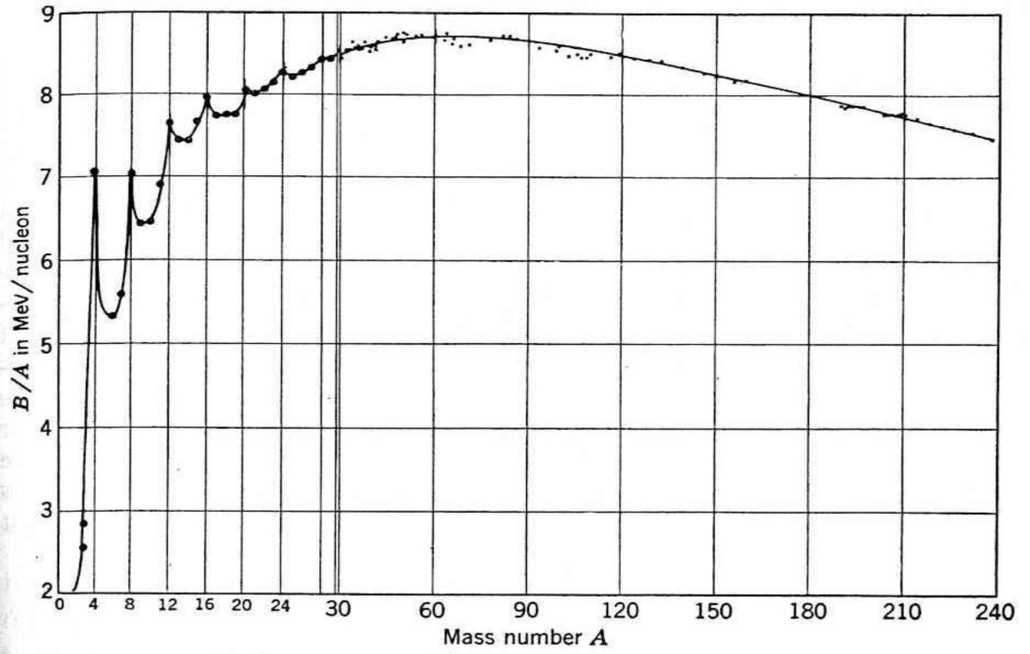
- The rate of spontaneous fission (SF) increases exceptionally rapidly with *A*:

Nuclide	**A, Z**	**$t_{1/2}$ (y)**	**SF (%)**
^{232}Th	232, 90	1.4×10^{10}	1.2×10^{-8}
^{238}U	238, 92	4.5×10^{9}	4×10^{-5}
^{252}Cf	252, 98	2.6	3.1

- Increasing *A*, both $t_{1/2}$ decreases and the SF % increases.
- For each of these three nuclides the rest of the decays occur by alpha emission.
- ^{252}Cf is a very useful source of neutrons.

Energy release in fission

- For example, B/A (^{252}Cf) = 7.4 MeV/nucleon, but for fragments with A = 126, B/A = 8.4 MeV/nucleon.
- Energy release is ~ 1 MeV/nucleon or about 200 MeV !
- These values increase only very slowly with A.

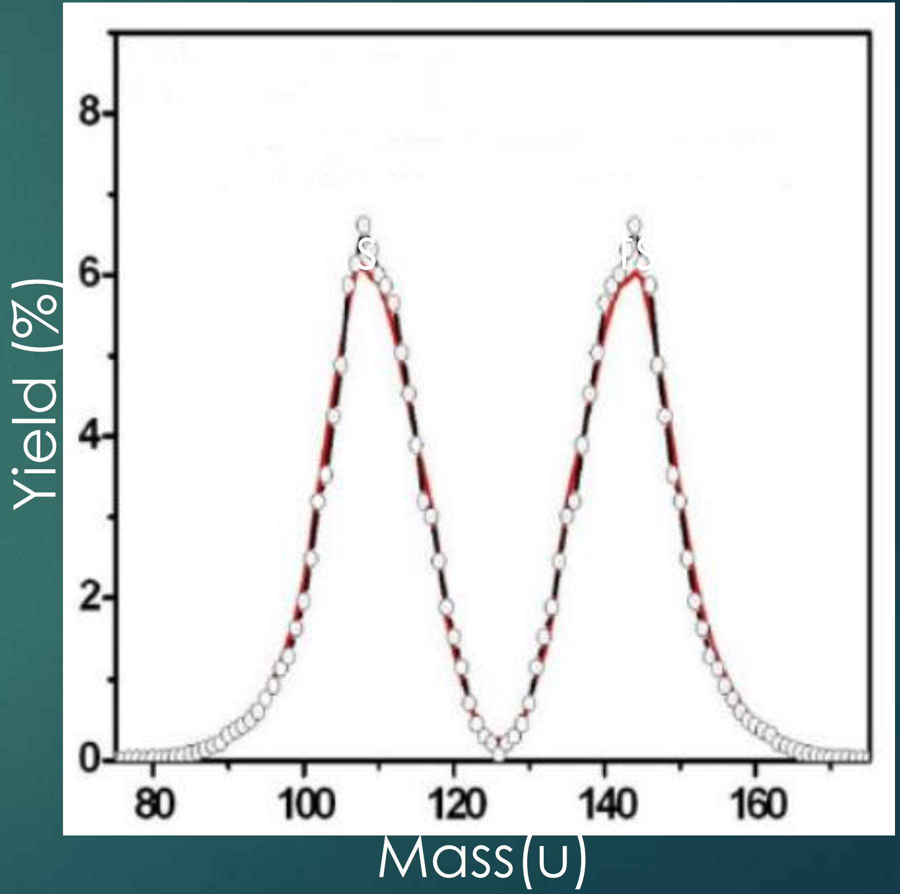


Fission fragment masses distribution

- Fission is normally asymmetrical, i.e. the fragment masses are unequal.

$$\text{Fission of } ^{252}_{98}\mathrm{Cf} \rightarrow$$

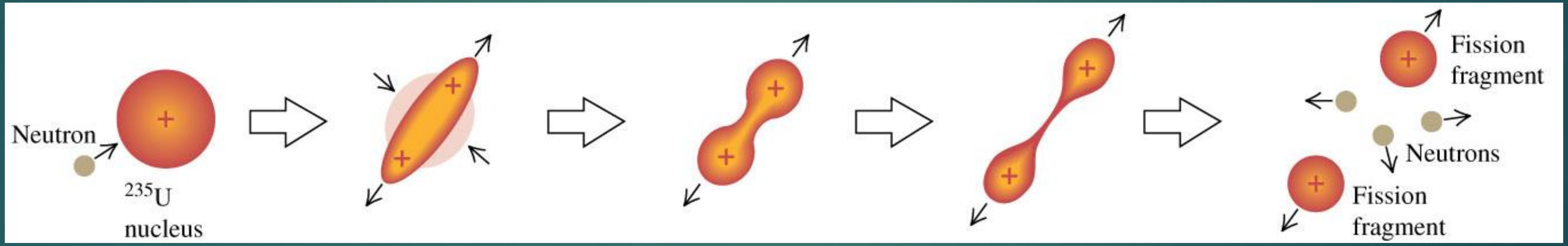
- The SEM formula fails to predict this, even the energy release in fission is maximised when each fragment has the same mass
- This paradox remained unsolved for many years to be explained by magic numbers.



Induced fission

- The almost instantaneous fissioning of a nucleus when struck by radiation – usually a neutron, i.e. no Coulomb barrier to be overcome.
- Induced fission always proceeds in two steps.

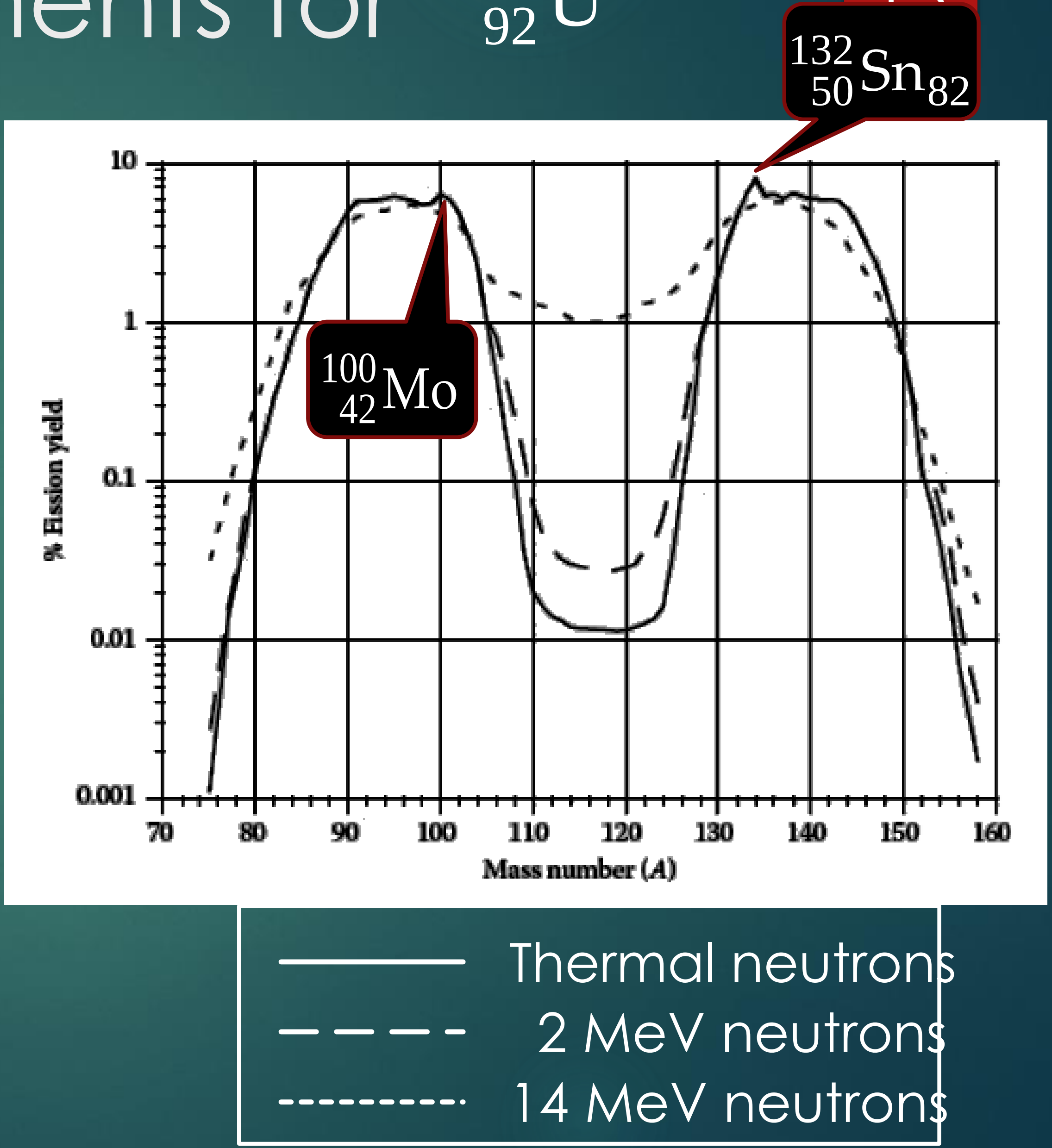
$$\boxed{{}^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U}^{*} \rightarrow \ 2\ \text{fragments} + k\,\mathrm{n}}$$



- Discovered in 1938 by Hahn and Strassmann, then explained by Meitner and Frisch.
- First observed by Fermi in 1934 – but famously misinterpreted by him.

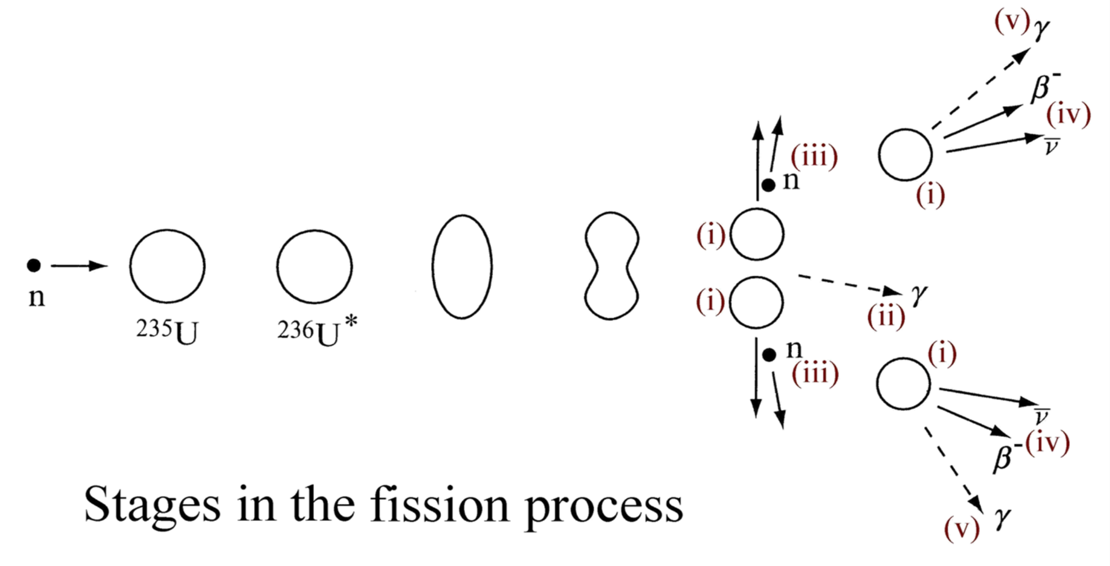
Induced fission fragments for $^{235}_{92}U$

- Similarly to spontaneous fission an <u>asymmetric</u> distribution of fragment masses →
- Doubly magic fragments more likely.
- Increasing the energy of the neutron the gap is filled – nucleus has more energy to release and less time to form magic fragments →

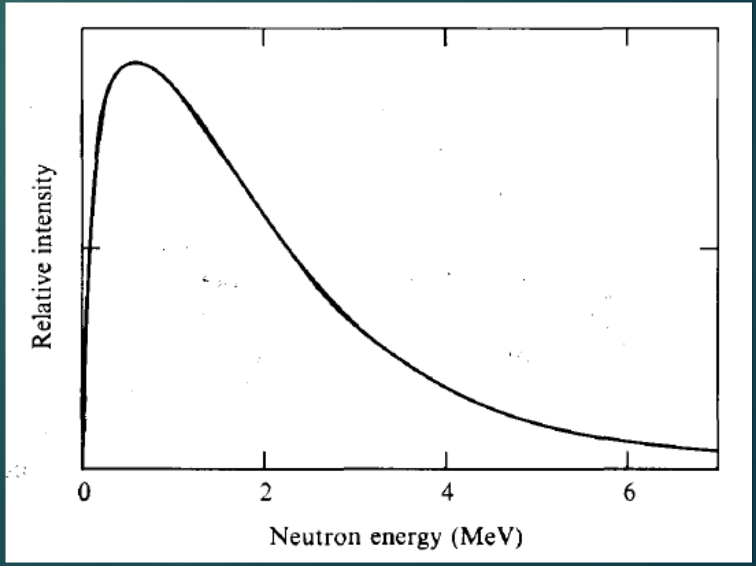


Stages of the induced fission - 1

- Fission fragments: E_{kin} ~ 170 MeV
- γ-rays emitted immediately with the fission process; ~ 6 MeV.
- Prompt neutrons emitted from neutron-rich fragments ~ 10^{-14} s after fission



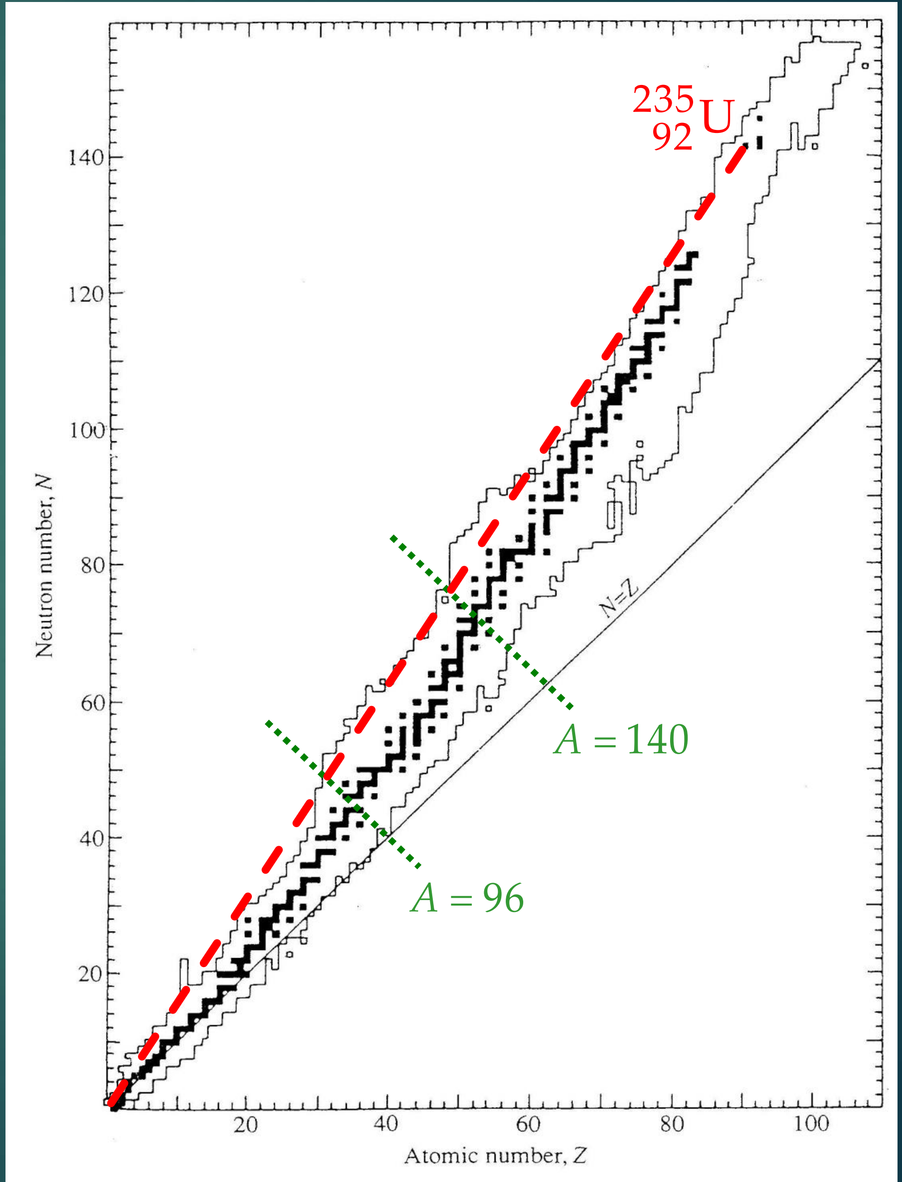
Stages in the fission process



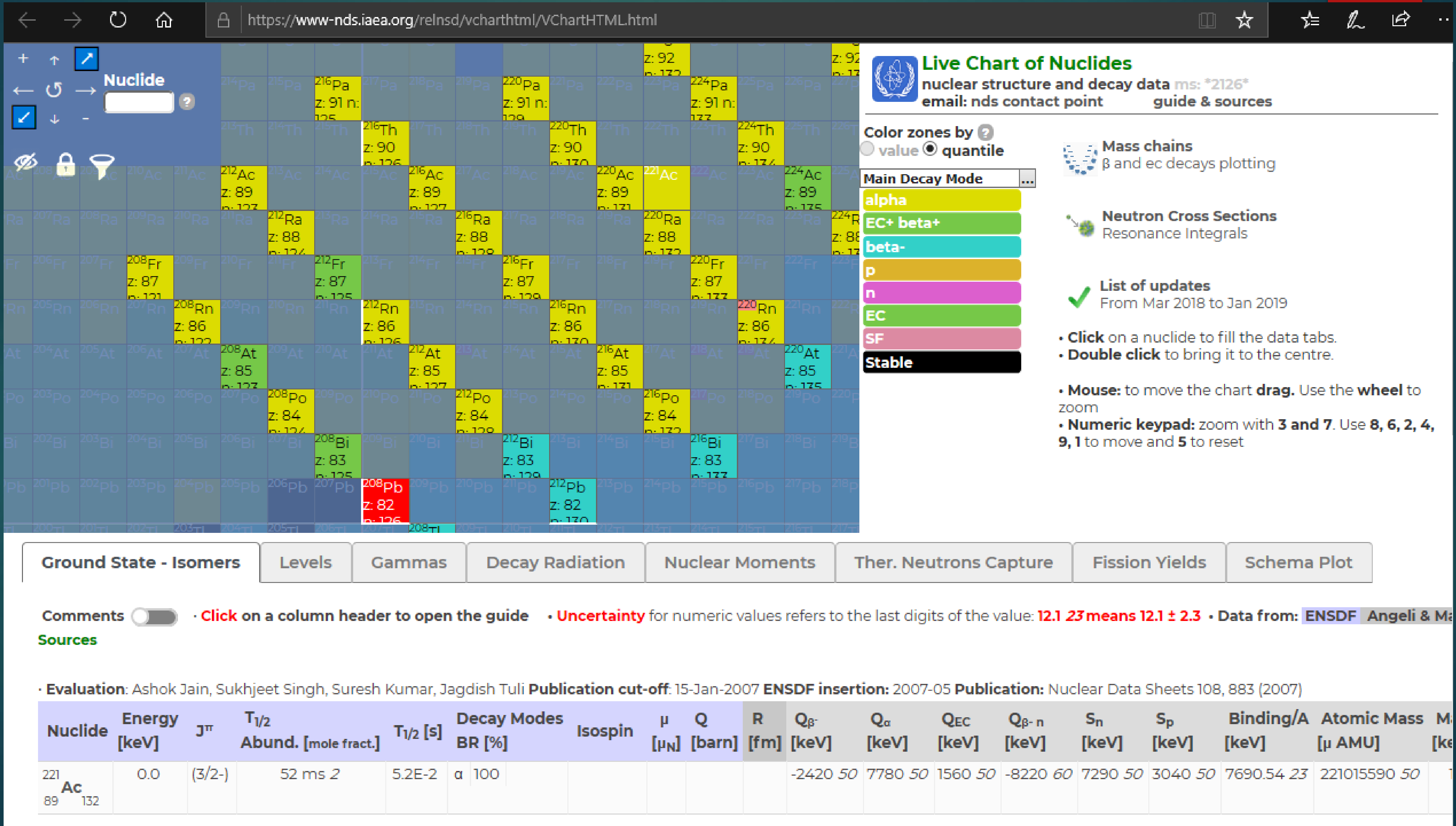
Average number of prompt neutrons emitted per fission = 2.5 × 2 MeV ≈ 5 MeV.

Stages of the induced fission - 2

- Electrons: from three or four beta decays of each fragment; ~ 5 MeV total (also neutrinos).
- Fragments from ^{235}U fission are initially formed on the red dashed line joining ^{235}U to the origin – neutron rich.
- β-decays along the isobaric lines, shown are a typical light and heavy fragments



Sagre chart fragment



Live Chart of Nuclides

nuclear structure and decay data ms: *2126*

email: nds contact point **guide & sources**

Color zones by ?
○ value ● quantile

Main Decay Mode ...

alpha
EC+ beta+
beta-
p
n
EC
SF
Stable

Mass chains
β and ec decays plotting

Neutron Cross Sections
Resonance Integrals

✓ **List of updates**
From Mar 2018 to Jan 2019

- **Click** on a nuclide to fill the data tabs.
- **Double click** to bring it to the centre.

- **Mouse:** to move the chart **drag.** Use the **wheel** to zoom
- **Numeric keypad:** zoom with **3 and 7**. Use **8, 6, 2, 4, 9, 1** to move and **5** to reset

Ground State - Isomers | Levels | Gammas | Decay Radiation | Nuclear Moments | Ther. Neutrons Capture | Fission Yields | Schema Plot

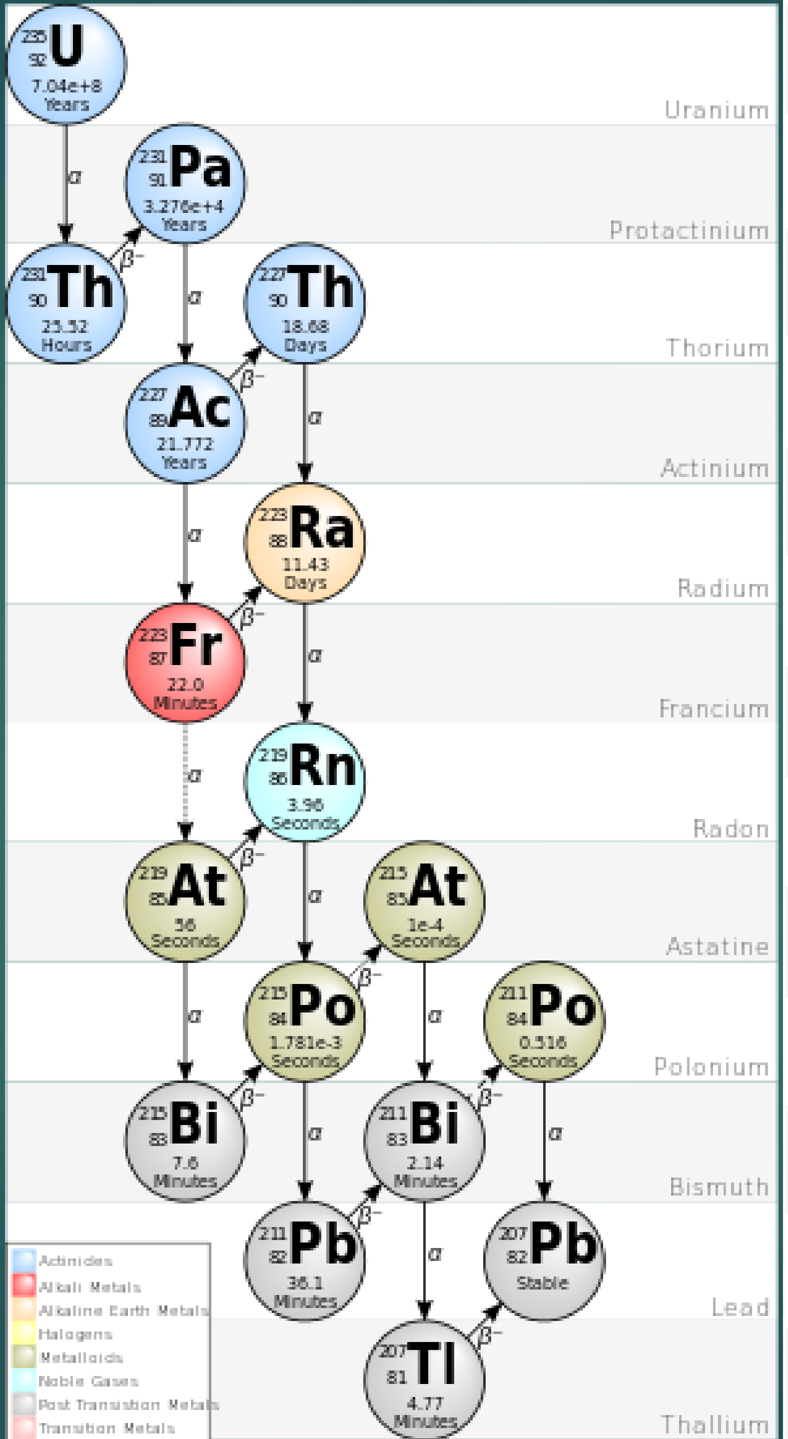
Comments · **Click on a column header to open the guide** · **Uncertainty** for numeric values refers to the last digits of the value: 12.1 *23* means 12.1 ± 2.3 · **Data from:** ENSDF Angeli & Ma

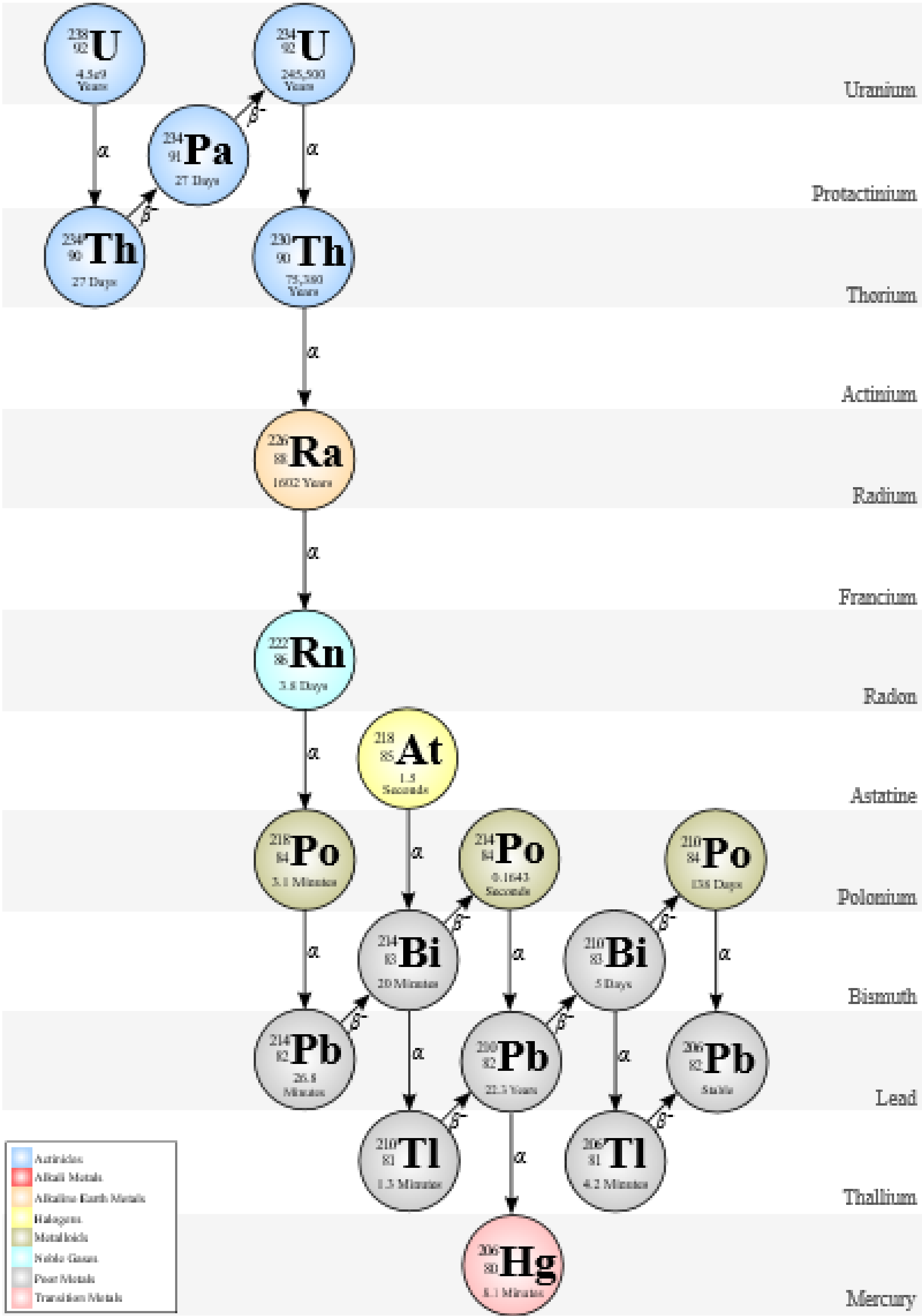
Sources

· **Evaluation**: Ashok Jain, Sukhjeet Singh, Suresh Kumar, Jagdish Tuli **Publication cut-off**: 15-Jan-2007 **ENSDF insertion:** 2007-05 **Publication:** Nuclear Data Sheets 108, 883 (2007)

Nuclide	Energy [keV]	Jπ	$T_{1/2}$ Abund. [mole fract.]	$T_{1/2}$ [s]	Decay Modes BR [%]	Isospin	μ [μ_N]	Q [barn]	R [fm]	Q_{β^-} [keV]	Q_α [keV]	Q_{EC} [keV]	Q_{β^-n} [keV]	S_n [keV]	S_p [keV]	Binding/A [keV]	Atomic Mass [μ AMU]	M [ke
$^{221}_{89}\mathrm{Ac}_{132}$	0.0	(3/2-)	52 ms *2*	5.2E-2	α 100					-2420 *50*	7780 *50*	1560 *50*	-8220 *60*	7290 *50*	3040 *50*	7690.54 *23*	221015590 *50*	

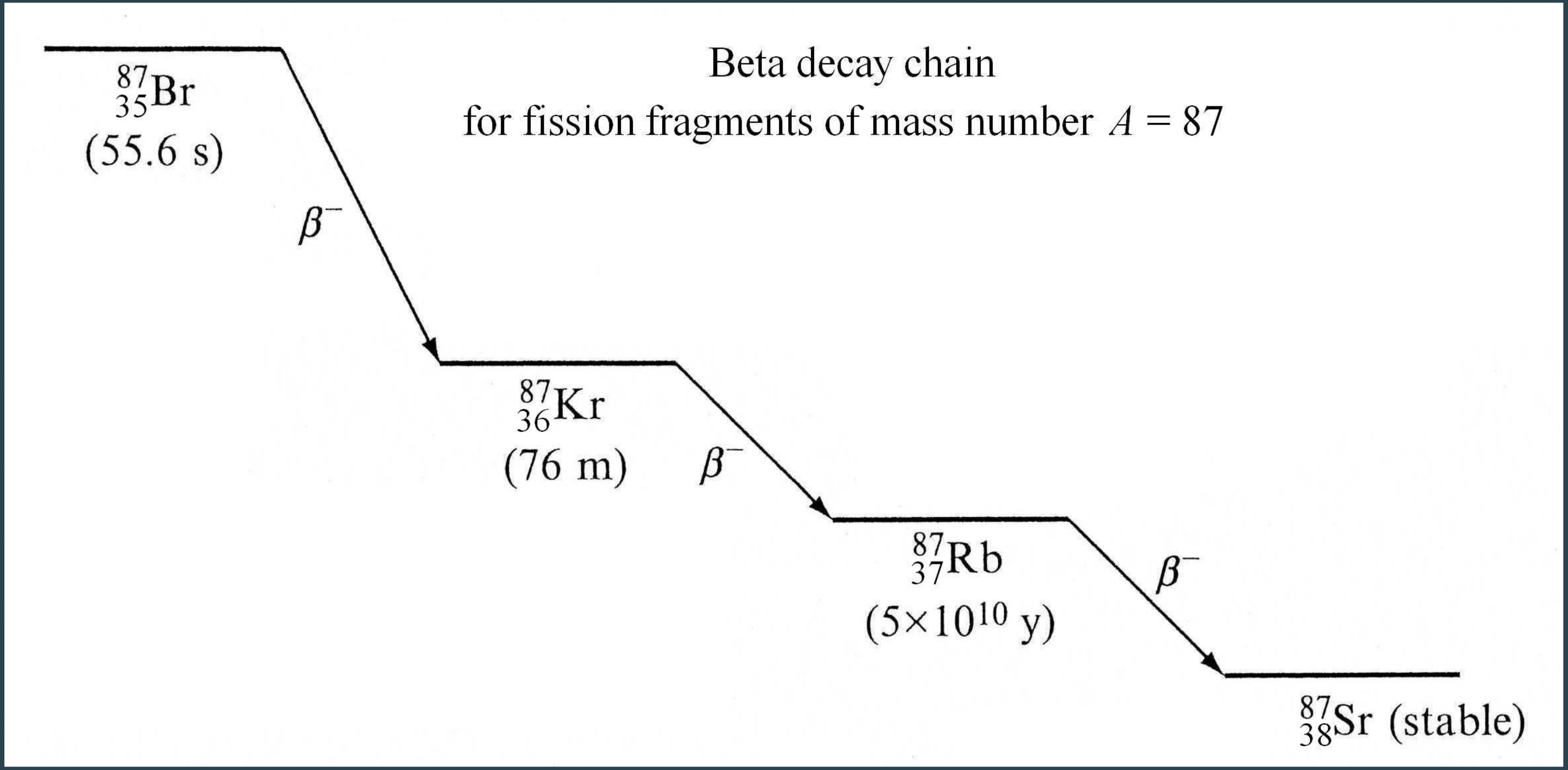
Decay Chains





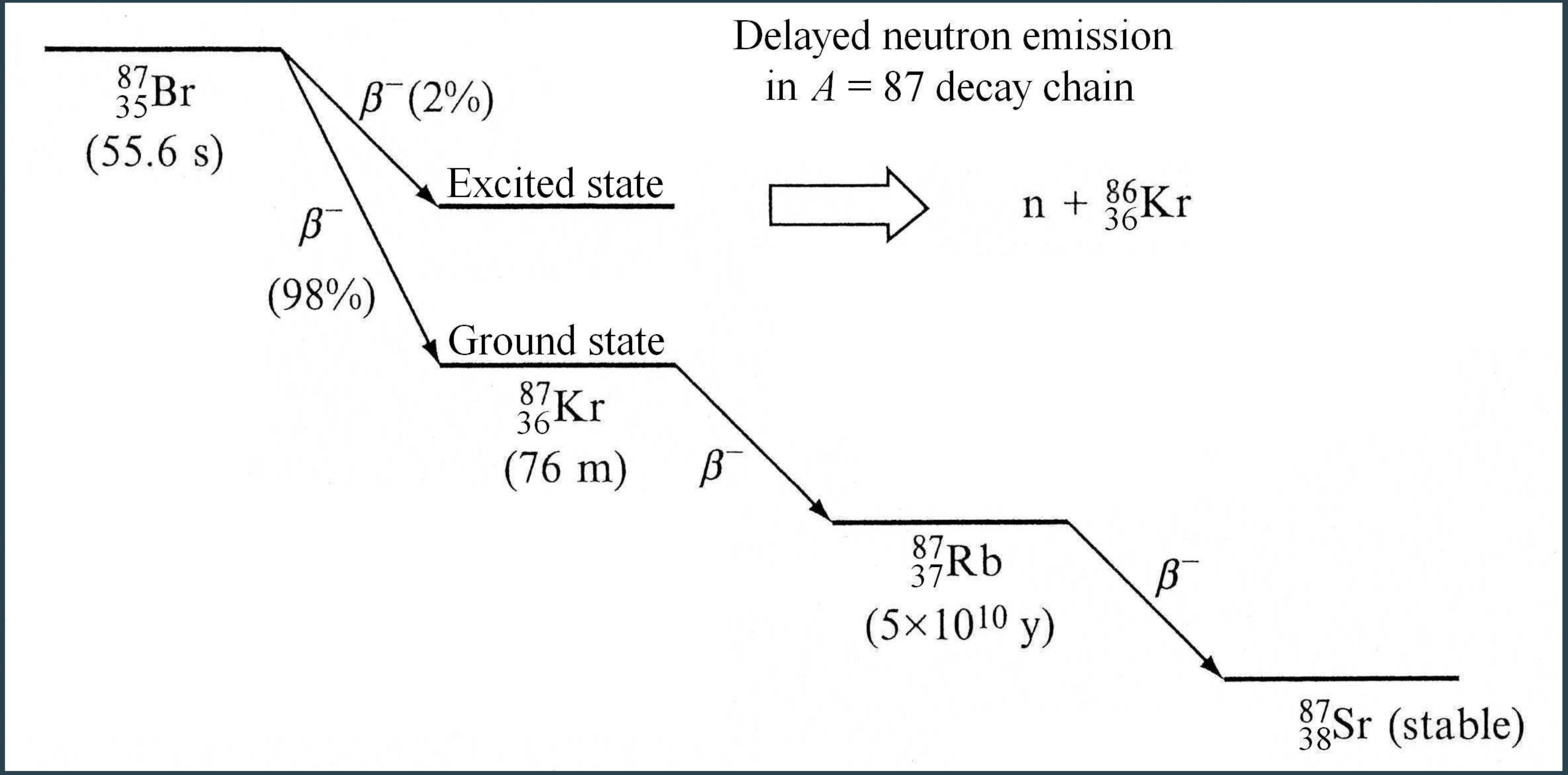
Isobaric fragment decay chains – 1

- Some 80 of those are known, for instance:



Isobaric fragment decay chains – 2

- Notice the second β-decay branch leading to n emission:



More fission products

- More γ rays from fragments, *after* both fission and β-decay; ~ 7 MeV.
- Delayed neutrons occasionally emitted from fragments ~ 1 min after fission during the β-decay process.
  - The neutrons are *delayed* with respect to the original fission event, but are emitted *immediately* once the excited state of the ^{86}Kr nucleus is formed (instead of γ-emission).
- Average #(d. n. per fission) = only 1% (but essential for reactors control, avr. lifetime of prompt n is ~1ms, exponential instability)

		Energy (MeV)
Prompt energy	Fission fragments	170
	Prompt neutrons	5
	γ-emission	6
Radioactivity	β-decay (electrons + neutrino)	7 + 12
	γ-emission	7

Nuclear fission reactors

- Basic reaction:

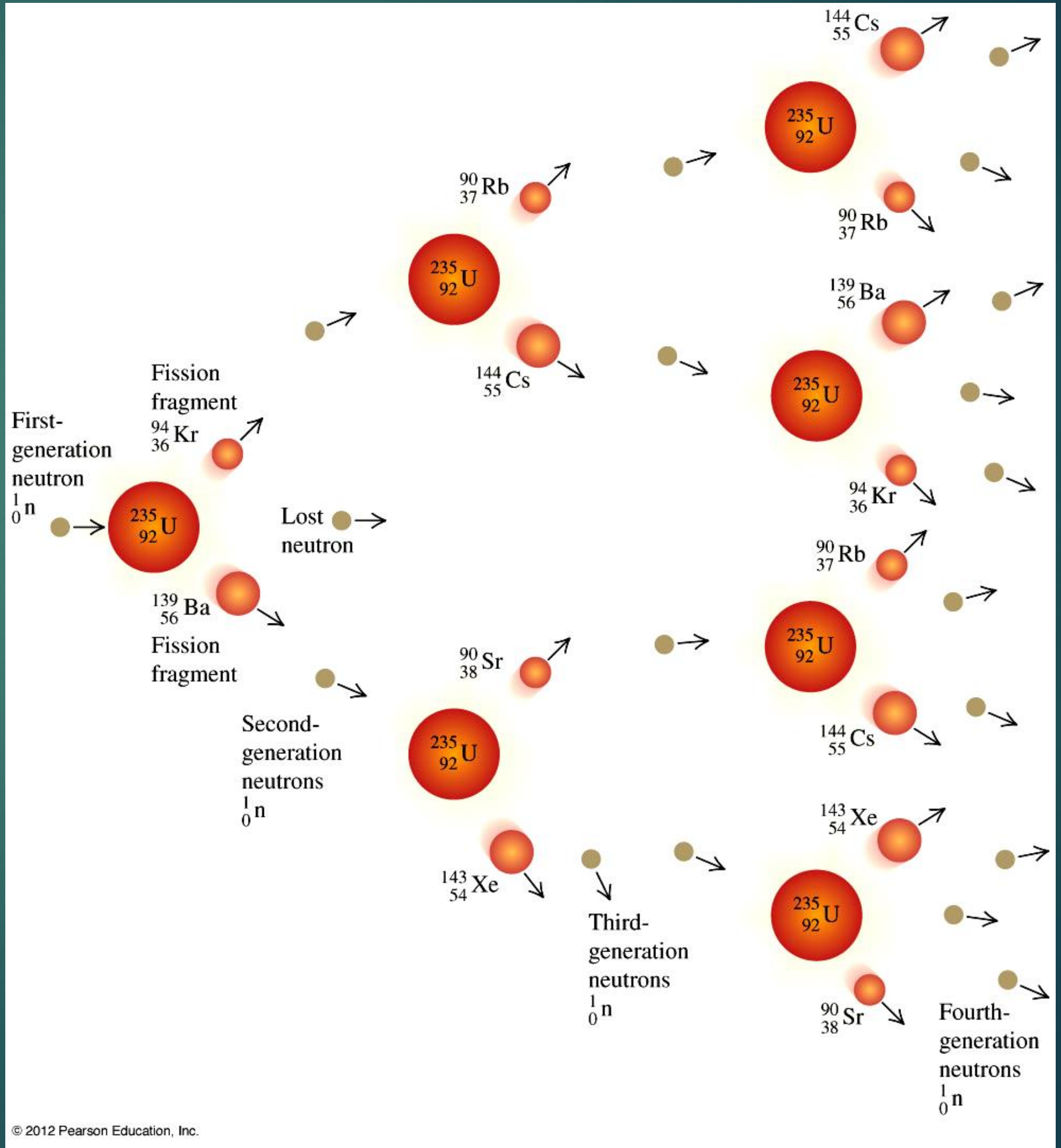
$$\boxed{{}^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow \text{(two fragments)} + 2.5\,\mathrm{n} + 200\ \mathrm{MeV}}$$

- Most of the 200 MeV immediately appears as heat when the fragments stop within the uranium fuel (range ~ 10 μm).
- More than 1 neutron emitted, so further fissions can occur, leading to a *chain reaction* and large-scale power production (without CO_2).
- *Neutron multiplication factor* (k) is the ratio of number of fission-causing neutrons between subsequent generations:

  $k < 1$ – subcritical, $k \approx 1$ – critical (reactor), $1 < k < 1/(1-\beta_{\mathrm{d.n.}})$ (delayed supercritical, control), $k > 1/(1-\beta_{\mathrm{d.n.}})$ – bomb.

Fission chain reaction

- First four generations of a fission chain reaction.
- If yield *k* >1 the neutron numbers increase exponentially.



Possible neutron life histories

- Escape from reactor:
  - minimum physical reactor core size
  - neutron reflector (e.g. graphite) around core.
- Capture by non-fissile material:
  - coolants must have low capture cross section (also to minimise induced radioactivity)
  - neutron absorbents used to control/stop chain reaction
- Capture by uranium without fission.
- Capture by uranium with fission.

Natural uranium

- Contains: $$\boxed{0.7\%\left({}^{235}_{92}\mathrm{U}\right)+99.3\%\left({}^{238}_{92}\mathrm{U}\right)}$$
- Only ^{235}U can undergo fission with 'thermal neutrons'.
- ^{235}U is *fissile* and ^{238}U is *fertile*!
- Neutrons emitted in ^{235}U fission are fast: $E_{kin} \approx 1\text{–}2$ MeV
- The fission cross-sections σ_f for fast neutrons are too low for a natural uranium 'fast reactor':

$$\sigma_{\mathrm{f}}\left({}^{235}\mathrm{U}\right)=1\ \mathrm{b}\ \text{and}\ \sigma_{\mathrm{f}}\left({}^{238}\mathrm{U}\right)=0.5\ \mathrm{b}$$

- Either *enrich* (to > 20%) in ^{235}U – difficult and expensive (UF_6 diffusion, or centrifuging, or laser separation)
- Or *thermalize* neutrons – slow them down → thermal equilibrium with the surroundings, i.e. their kinetic energies ~ $kT = 0.025$ eV at room temperature.

Fissile vs Fertile

- Fissile – can undergo fission with thermal neutrons
- Fertile – can breed to produce fissile nucludes
- ^{235}U is *fissile* and ^{238}U is *fertile*!
- The cross-section for fission of ^{238}U induced by thermal neutrons, $\sigma_f \approx 0$ b.
- But ^{238}U can initiate breeder reactions

$$\boxed{{}^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U}\,(23\,\mathrm{m}) \rightarrow {}^{239}_{93}\mathrm{Np}\,(2.4\,\mathrm{d}) \rightarrow {}^{239}_{94}\mathrm{Pu}\left(2.4\times10^{4}\ \mathrm{y}\right)}$$

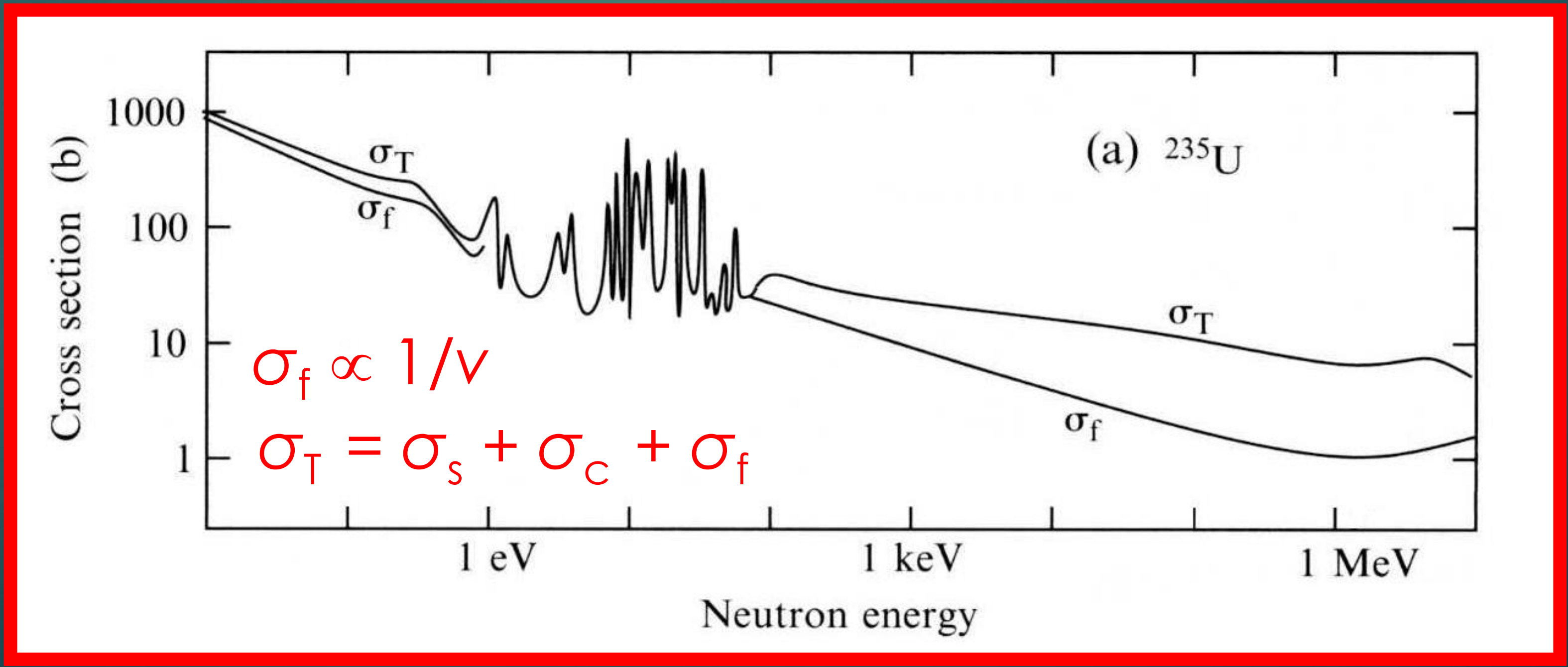
- ^{239}Pu is fissile too, just like ^{235}U!
- As neutrons are uncharged a general trend applies:

$$\boxed{\sigma_\mathrm{f} \propto \left\{ \begin{array}{c} \text{the time spent} \\ \text{close to nucleus} \end{array} \right\} \propto \frac{1}{v}}$$

- For thermal neutrons v = 2.2 km/s, and σ_f rises to 580 b.

Neutron interaction cross-sections of ^{235}U

- Three processes involved: scattering, radiative capture [or (n,γ)-reaction] and fission:
- Large fission cross-section $\propto 1/v$ below 1eV (incl. thermal n).
- Resonances from 1eV to 100 eV (from metastable ^{236}U).
- Scattering : $\sigma_s \approx 10$ b (almost independent of energy).

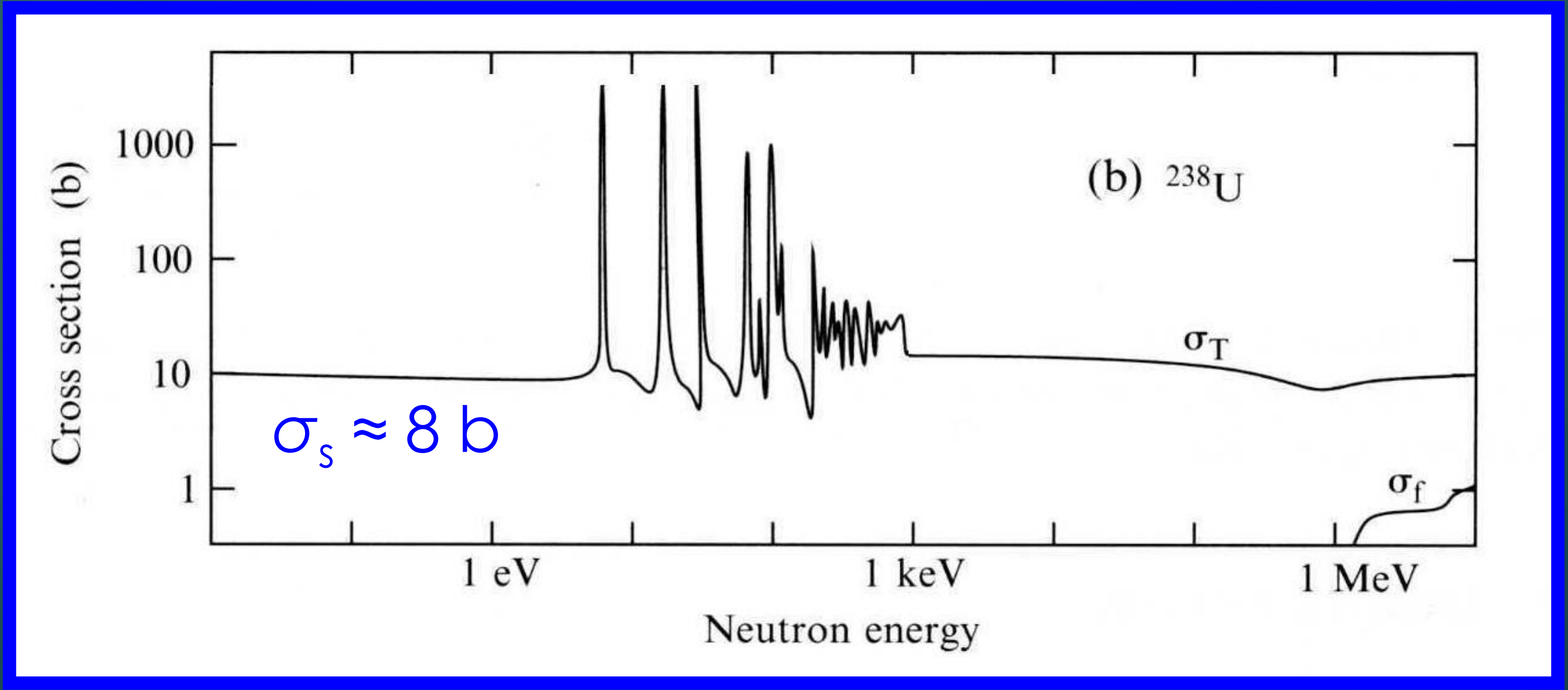


$\sigma_f \propto 1/v$

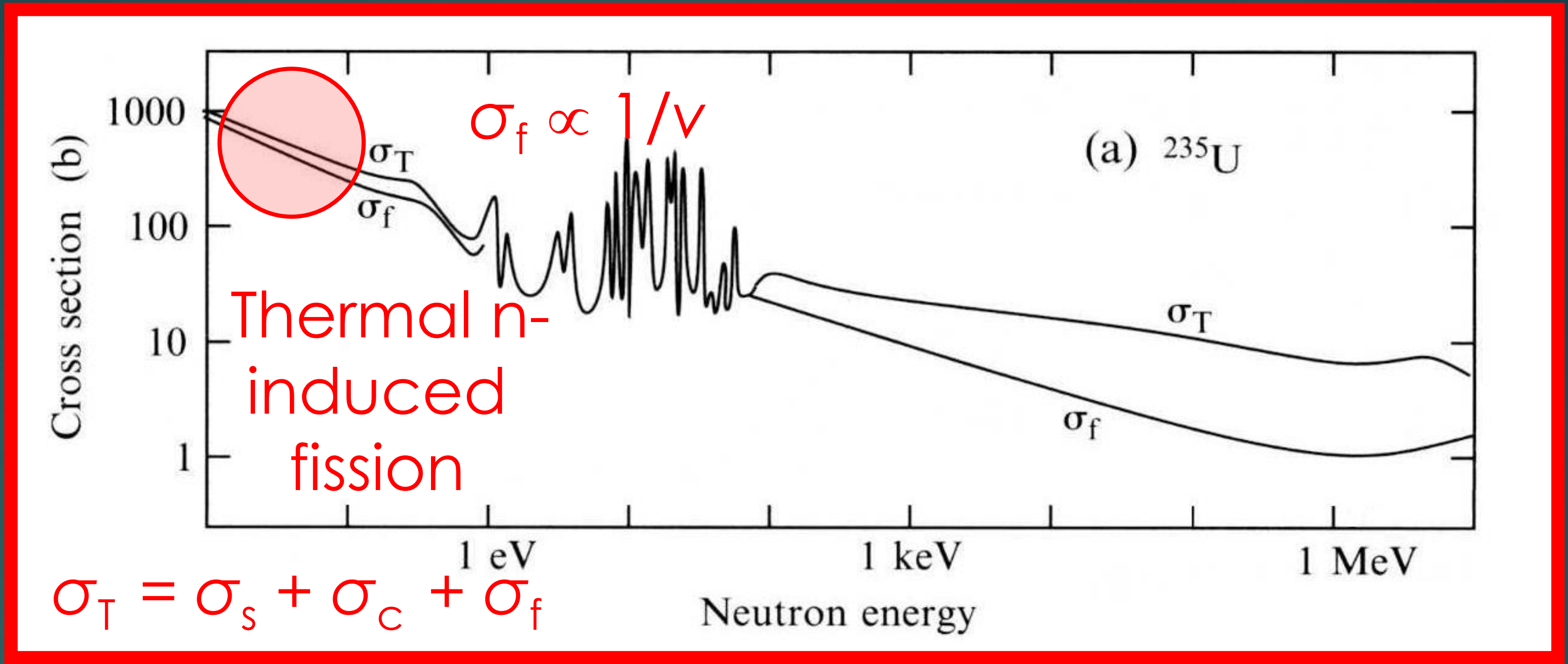
$\sigma_T = \sigma_s + \sigma_c + \sigma_f$

Neutron interaction cross-sections of ^{238}U

- Scattering cross-section $\sigma_s \approx 8$ b dominates for most energies.
- At resonances the radiative capture (n,γ) prevails (no fission) – important source of absorption in reactors.
- Some non-zero fission cross-section for energetic neutrons (above 1 MeV).



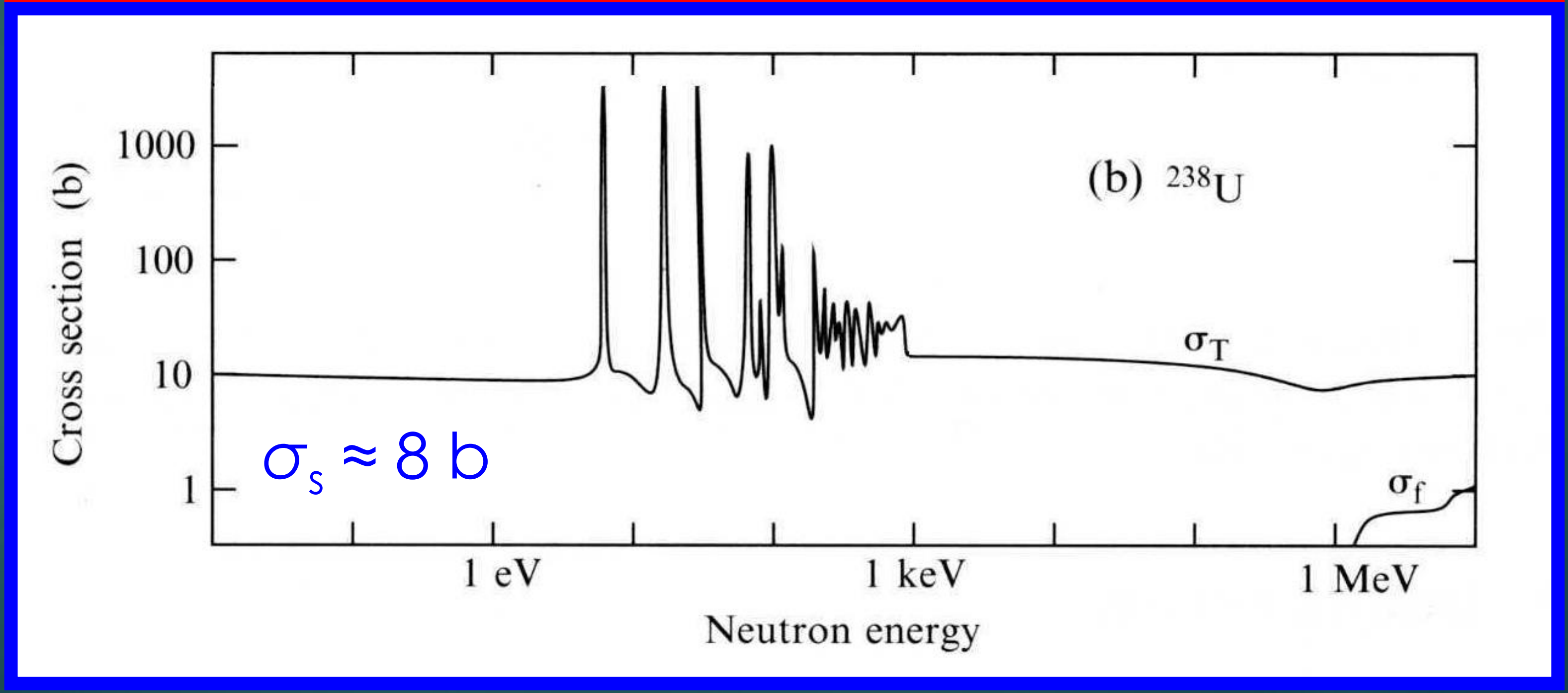
Scattering + fission cross-sections



$\sigma_f \propto 1/v$

Thermal n-induced fission

$\sigma_T = \sigma_s + \sigma_c + \sigma_f$



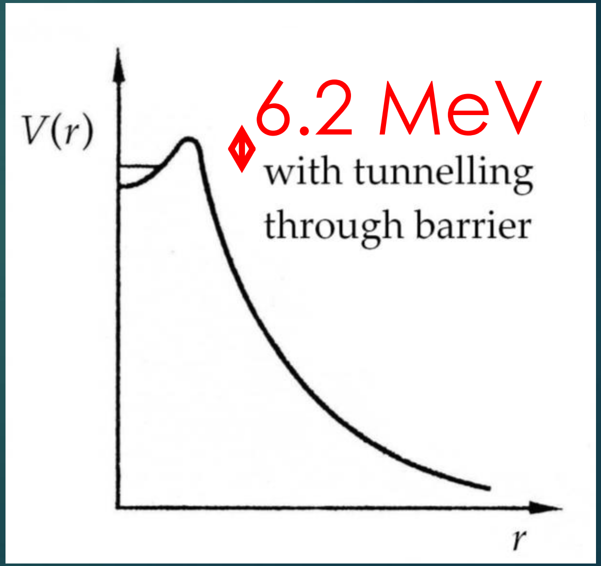
$\sigma_s \approx 8$ b

Critical energy for induced fission

- Cross-sections for fission (and other neutron-induced nuclear reactions) are largest for slow neutrons *only* if enough energy is available for the reaction to proceed.
- For both ^{235}U and ^{238}U fission, the intermediate ^{236}U* and ^{239}U* must be excited by a *critical energy* of 6 MeV or more in order to achieve tunnelling through the potential barrier.
- We know nucleon *separation energy* is about 7 MeV :

$$^{236}_{92}\mathrm{U} + 7\ \mathrm{MeV} \rightarrow {}^{235}_{92}\mathrm{U} + \text{slow neutron}$$

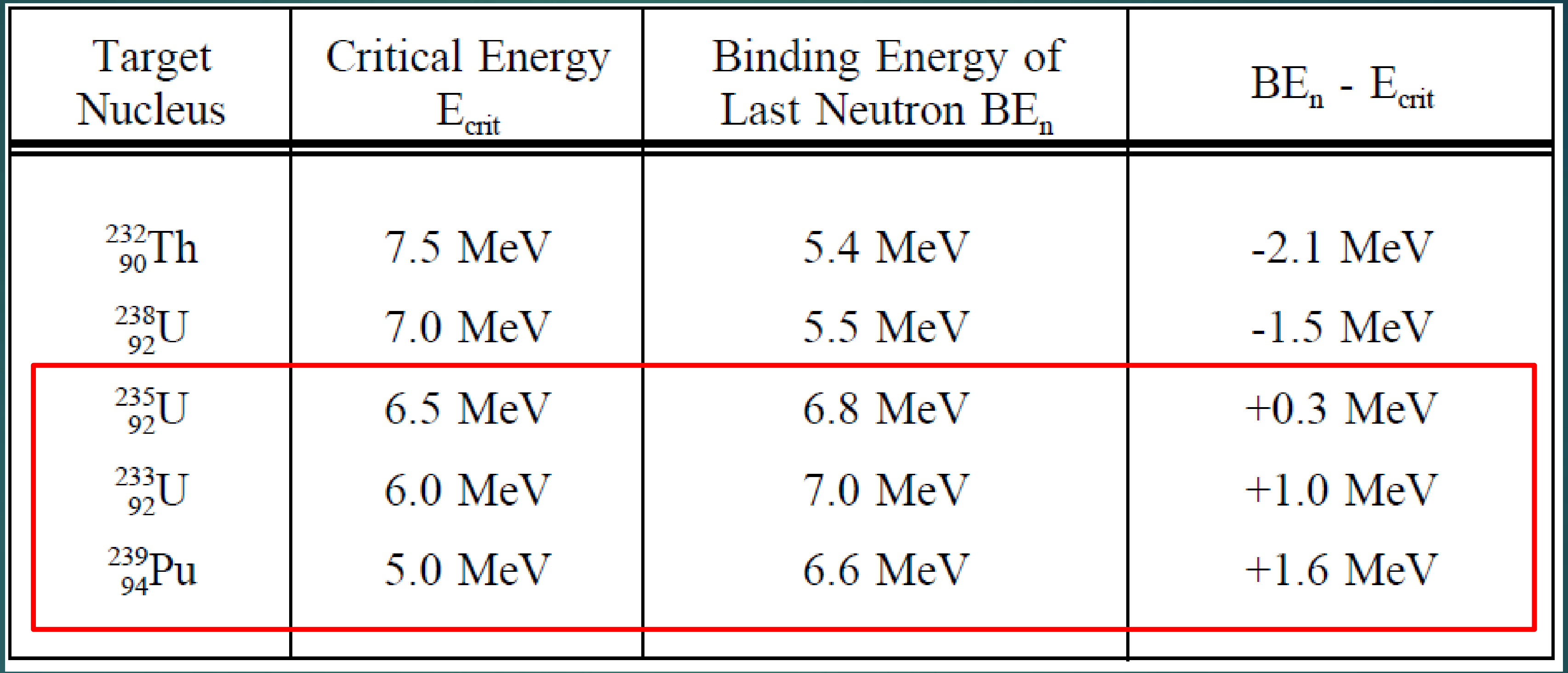
$$^{235}_{92}\mathrm{U} + \text{slow n} \rightarrow {}^{236}_{92}\mathrm{U}^{*}\ (\text{excited by 7 MeV})$$



6.2 MeV with tunnelling through barrier

- To fission ^{238}U, neutron kinetic energies of at least 1 MeV are required.

Comparison of critical energies

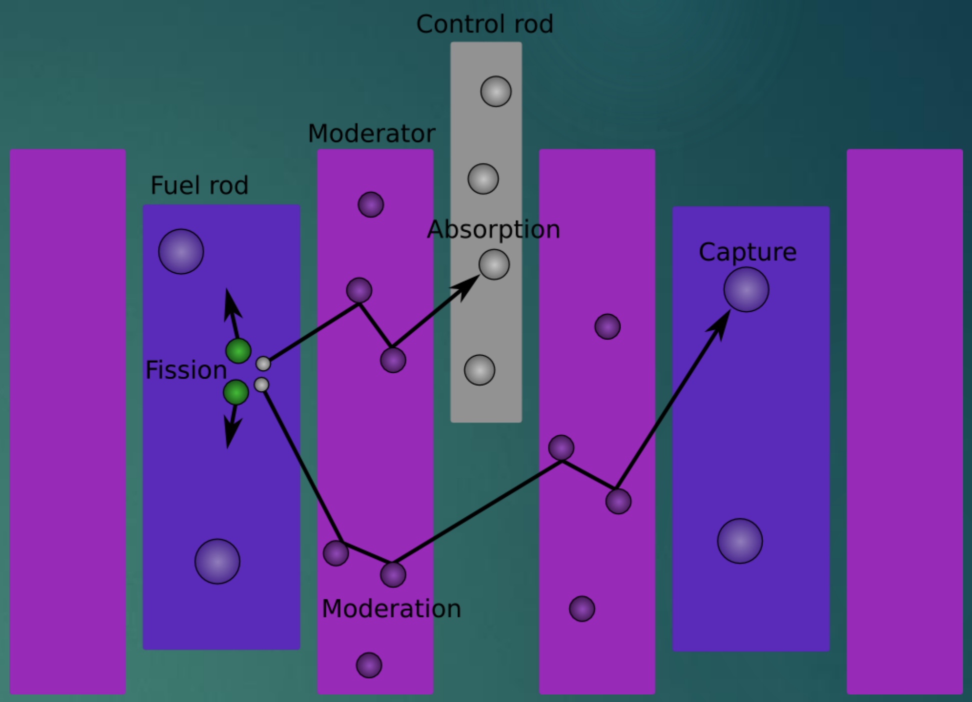


Target Nucleus	Critical Energy E_{crit}	Binding Energy of Last Neutron BE_n	$BE_n - E_{crit}$
$^{232}_{90}\mathrm{Th}$	7.5 MeV	5.4 MeV	-2.1 MeV
$^{238}_{92}\mathrm{U}$	7.0 MeV	5.5 MeV	-1.5 MeV
$^{235}_{92}\mathrm{U}$	6.5 MeV	6.8 MeV	+0.3 MeV
$^{233}_{92}\mathrm{U}$	6.0 MeV	7.0 MeV	+1.0 MeV
$^{239}_{94}\mathrm{Pu}$	5.0 MeV	6.6 MeV	+1.6 MeV

- The bottom three do not need the kinetic energy of the neutrons to undergo fission. They are fissile.

Moderators

- Bulk material surrounding the uranium fuel rods, designed to slow down fission neutrons from fast to thermal speeds.

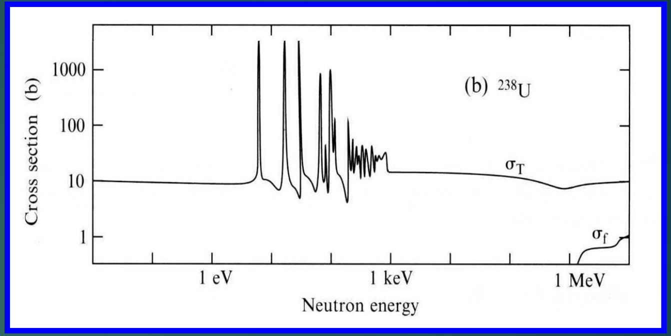


  - Thermalisation by elastic collisions with moderator nuclei within ~ 10^{-1} m (avoid capture by ^{238}U).
  - Ideally, in fewer collisions, with large energy losses per collision – moderator made of light nuclei (low *A*).
  - This geometry was first thought of in 1939 by the transistor pioneer, William Shockley.

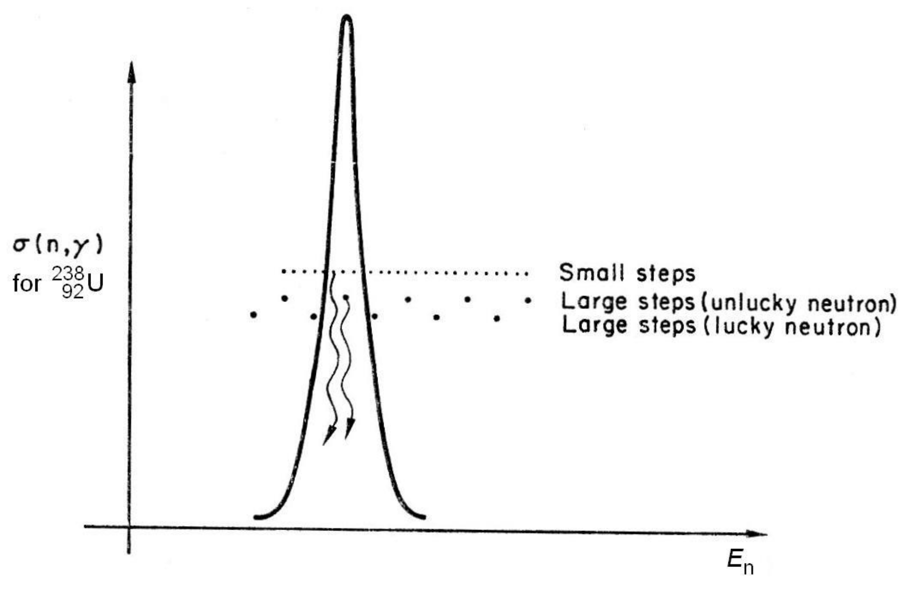
Moderators – more facts

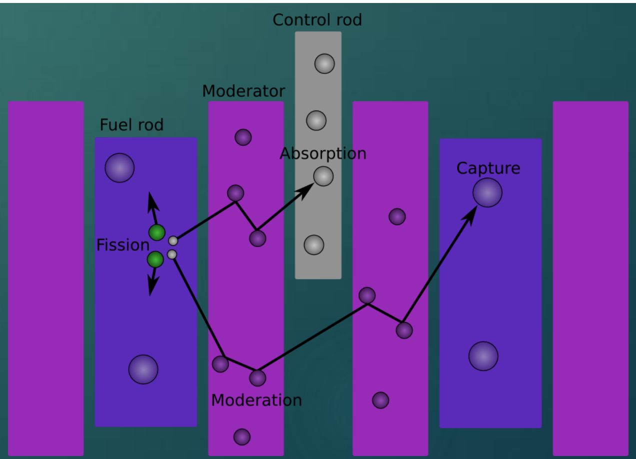
- In graphite (^{12}C) to moderate E_n from 1 MeV to 0.1 eV, ~ 100 collisions are required.
- But in ^{238}U (without a separate moderator) ~ 2000 collisions would be required.
- Many of the neutrons would instead be captured by ^{238}U and cause no fission.
- Even with a moderator, any neutron which happens to acquire an energy falling within a ^{238}U resonance peak (width 2 – 4 eV) may still be captured without fission occurring.
- To minimise this, moderation must occur in large steps >> 4 eV (next slide), i.e. in a separate light moderator not mixed in with the fuel.

Moderators – more facts



- With this geometry, the fuel interior can be effectively shielded from neutrons of any ^{238}U resonance energies by the surface layer of fuel itself as it captures such neutrons.
  - Spatial self-shielding effect relies on the small amount of neutron moderation in the fuel.
  - It cannot happen if the fuel and moderator were a homogeneous mixture.





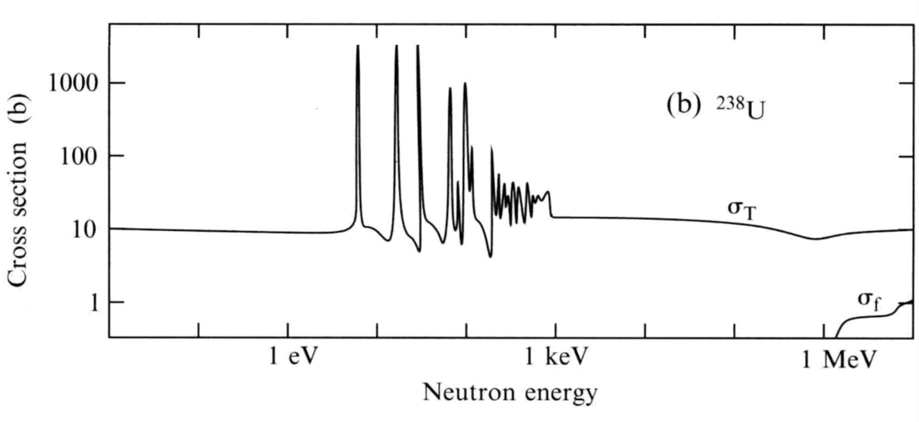
Light water as moderator

- Light water: H_2O, where the hydrogen atom is ^1H.
- Heavy water: D_2O, where the *deuterium* (D) atom is ^2H.
- Both are used as neutron moderators.
- Deuterium is a stable isotope of hydrogen, present naturally to 0.015 atomic %.
- It can be shown that the average fraction, f, of energy lost by a neutron (mass m_n) per elastic collision with a nucleus of mass m, is given by

$$\boxed{f = \frac{2m_n m}{(m_n + m)^2}}$$

- For ^1H (in light water) $m = m_n = 1$, so $f = 0.5$.

Light water moderator + natural uranium ?



- For, say, E_n = 100 eV, energy lost = 50 eV.
- This is >> than the widths of ^{238}U resonance peaks in this energy region.
- Few neutrons are lost through capture by ^{238}U as they slow down.
- *But* the cross section for the neutron absorption reaction $p + n \rightarrow d + \gamma$ (0.3 b at 0.025 eV) is too high for operation of reactors fuelled by natural uranium and with a light water moderator. (d is for deuteron, nucleus of deuterium)
- Natural uranium salt solutions can't go 'critical' (no chain reaction growth).

Moderators compared

Slowing-down power

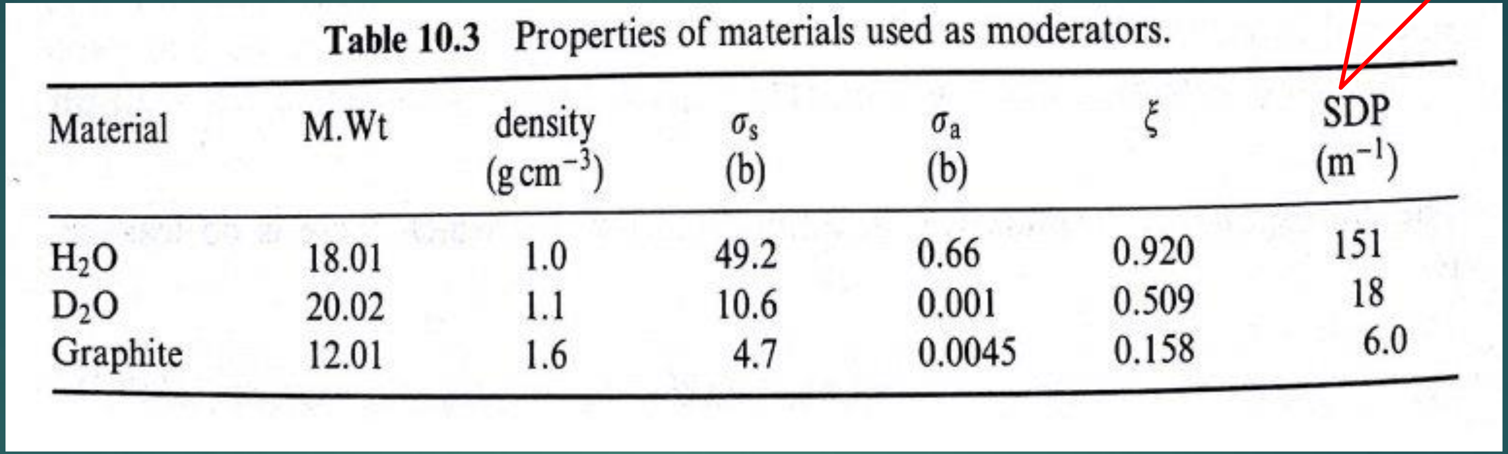


Table 10.3 Properties of materials used as moderators.

Material	M.Wt	density $(\mathrm{g\,cm^{-3}})$	σ_s (b)	σ_a (b)	ξ	SDP $(\mathrm{m^{-1}})$
H_2O	18.01	1.0	49.2	0.66	0.920	151
D_2O	20.02	1.1	10.6	0.001	0.509	18
Graphite	12.01	1.6	4.7	0.0045	0.158	6.0

- Uranium enriched to 2 – 3% (or more) in ^{235}U if light water is to be used as a moderator.
- *Pressurised water reactor* (PWR) – light water moderator and coolant.
- *Boiling water reactor* (BWR) – light water moderator and boiling water coolant
- From commercial power reactors in service (by 2012): 60% PWRs and 20% BWRs.

Heavy water as moderator

- Average fraction *f* of neutron energy lost by collision with a deuteron = 0.44, so, once again, energy lost >> resonance peak widths.
- But this time the neutron absorption cross section = only 0.5 mb at 0.025 eV.
- Reactors using heavy water moderators can, if wished, be fuelled by natural uranium.
- This avoids the expense of enrichment. Heavy water is expensive, but an operating reactor does not consume it.
- Example of heavy water moderated reactors are the CANDU reactors (about 30 in the world).

WWII examples

- The 1945 attempts of Heisenberg and von Weizsäcker in Haigerloch, Germany…..

- 664 natural U cubes, 5 cm edge, total mass 1.5 tons
- Graphite-lined vessel for heavy water moderator →

Graphite as a moderator

- Low neutron absorption, refractory and relatively cheap.
- It can be used with natural uranium as fuel.
- First critical assembly: the “Chicago Pile” (Fermi, Chicago, 1942).
- U.K. Gas-cooled Magnox reactors (being phased out).
- Eastern European power reactors (LWGR).
- U.K. AGRs (advanced gas-cooled reactors) – these use enriched uranium.
- With graphite, the fraction *f* of neutron energy lost by collision with a carbon nucleus = 0.14 (still larger than the resonance peak widths).
- A moderator does not 'slow down the reaction rate' – in fact it speeds it up!