Nuclear Fusion and Fission

Nuclear and Reactor Physics Fundamentals
(BMETE80MX00)

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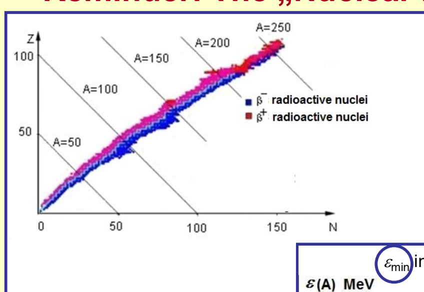
Contents

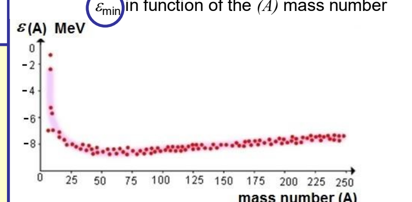
Reminder: The „Nuclear Energy Valley"



The place of Z_{min} on the (N,Z) „map" is between the blue and purple region

This helped to understand the radioactive decays!

ε_{min} in function of the (A) mass number



This helps to understand the energy production from the nuclei (nuclear energy production)

Options for releasing nuclear energy

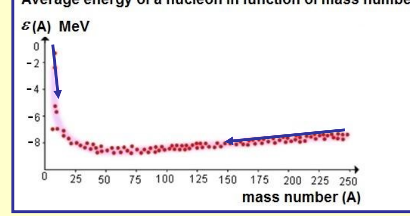
Fusion (make larger nuclei from smaller ones)

Fission (make smaller nuclei from larger ones)

For example:
$^2H + ^3H \longrightarrow ^4He + n$

$(Q = 17,6 \text{ MeV})$

Average energy of a nucleon in function of mass number



Fusion:
- big change in (energy/nucleon) (~ 2 … 5 MeV/nucleon)
- few nucleon (~ 2 ... 5),

Total energy gain ~ 2–18 MeV

Fission:
- small change in (energy/nucleon) (~ 0,85 MeV/nucleon)
- many nucleons (~236),

Total energy gain ~ 200 MeV

The fusion process

There are many possibilities to gain energy via fusion processes

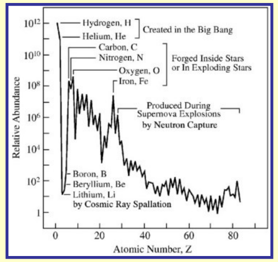
Stars

- „Sun-like" stars,
- „Red Giants",
- „White Dwarfs",
- Supernovae

etc.

} Different reaction chains (stellar nucleosynthesis)

Big Bang: primordial nucleosynthesis



Main composition of „Sun-like" stars:
75% ^{1}H, 25% ^{4}He, <0,1% other

Hydrogen-burning

But…. $^{1}H + {}^{1}H \rightarrow {}^{2}He$ impossible! (^{2}He does not exist!)

The weak interaction (β-transition) helps:

$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$ (this way a neutron is „made" inside ^{2}H)

Once a deuteron is made, the following steps are easy:

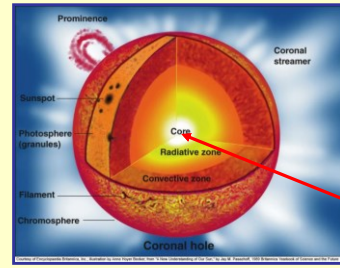
$^{2}H + {}^{1}H \rightarrow {}^{3}He$, and from two ^{3}He we have: $^{3}He + {}^{3}He \rightarrow {}^{4}He + 2 \cdot {}^{1}H$

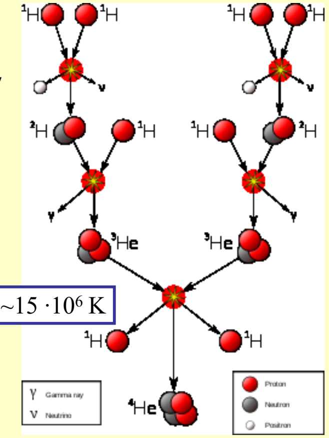
The fusion process

Summarizing the fusion p-p chain:

$$4 \cdot {}^{1}H \rightarrow {}^{4}He + 2 \cdot e^{+} + 2 \cdot \nu + Q$$

Q =26,22 MeV total reaction energy





High temperature needed: to overcome the Coulomb-barriers for the charged particles.

The fusion process

Why can **not** we do it on the Earth?

- Because of the **high temperature**?

  False! We can create even higher temperatures

- Because we cannot **confine** this high temperature plasma, like the Sun's gravitation can?

  False! We can confine even higher temperature plasma!

- Because of the **weak interaction** involved at the starting step?

  True! The weak interaction is so weak, that a proton wanders around in the very dense core of the Sun during **~4,5·10^{9} years** in average, until it can fusion with another proton:
  $^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu$

Note: that is the brake in the Sun, why it can operate billions of years!

Conclusion: here on the Earth fusion energy can be gained **only** from reactions **without** involving any weak interaction!

The fusion process

Possible reactions of light nuclei not involving any weak interaction:

p = ^{1}H (proton)
D = ^{2}H (deuteron)
T = ^{3}H (tritium)

Which one to choose??

D + T	→	^{4}He (3.5 MeV) + n (14.1 MeV)
D + D	→	T (1.01 MeV) + p (3.02 MeV) (50%)
	→	^{3}He (0.82 MeV) + n (2.45 MeV) (50%)
D + ^{3}He	→	^{4}He (3.6 MeV) + p (14.7 MeV)
T + T	→	^{4}He + 2 n + 11.3 MeV
^{3}He + ^{3}He	→	^{4}He + 2 p
^{3}He + T	→	^{4}He + p + n + 12.1 MeV (51%)
	→	^{4}He (4.8 MeV) + D (9.5 MeV) (43%)
	→	^{4}He (0.5 MeV) + n (1.9 MeV) + p (11.9 MeV) (6%)
D + ^{6}Li	→	2 ^{4}He + 22.4 MeV
p + ^{6}Li	→	^{4}He (1.7 MeV) + ^{3}He (2.3 MeV)
^{3}He + ^{6}Li	→	2 ^{4}He + p + 16.9 MeV
p + ^{11}B	→	3 ^{4}He + 8.7 MeV

The fusion process

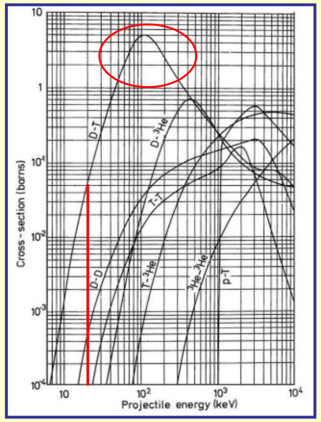
Which one to choose?

The one, with the highest cross-section at the lowest particle energy

$${}^{2}_{1}\mathrm{H}+{}^{3}_{1}\mathrm{H}\rightarrow{}^{4}_{2}\mathrm{He}+\mathrm{n}+17{,}6\ \mathrm{MeV}$$

Seems easy, because it occurs already at projectile energy 20 keV.

Here electrons are accelerated to more than 20 keV!

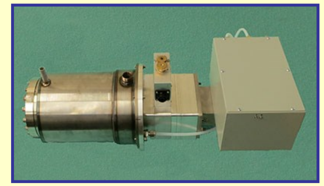


The fusion process

Indeed, there are devices (accelerators) that make this reaction happen
They are called „**neutron generators**”

$${}^{2}_{1}\mathrm{H}+{}^{3}_{1}\mathrm{H}\rightarrow{}^{4}_{2}\mathrm{He}+\mathrm{n}+17{,}6\ \mathrm{MeV}$$
(14,4 MeV)

Small, „table-top” neutron generators



High-intensity neutron generator producing about 10^{12} neutron/s
(**~ 2,8 W** fusion power)
Consumed power to operate: **~40 kW**

The fusion process

Why is not possible to get positive energy balance this way?

Possible reactions of an accelerated ^{2}H ion in ^{3}H target:

- **Fusion**: ${}^{3}_{1}\mathrm{H}(\mathrm{D,n}){}^{4}_{2}\mathrm{He}$ ($\sigma \sim 1...50$ mb, depends on the energy)
- ~~Elastic scattering:~~ ${}^{3}_{1}\mathrm{H}(\mathrm{D,D'}){}^{3}_{1}\mathrm{H}$
- ~~Ionization:~~ ${}^{3}_{1}\mathrm{H}_{\mathrm{atom}}(\mathrm{D,D',e^-}){}^{3}_{1}\mathrm{H}^{+}$

The deuteron **looses energy**!! Much **larger cross sections** than for the fusion

The only solution: **high temperature**

Atoms are already ionized (plasma state)

Also ^{3}H ions have high (thermal) kinetic energy → no slow down via scattering

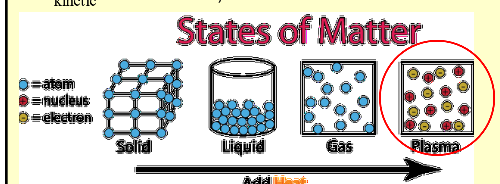
How high temperature needed? $E_{\mathrm{kin}} = \frac{3}{2}kT \approx 10\ \mathrm{keV} \approx 116\cdot 10^{6}\ \mathrm{K}$!!!

The fusion process

At this temperature the matter is in **plasma** state

$E_{\mathrm{ionisation}}$ of hydrogen: 13,9 eV.

If E_{kinetic} ~ 10000 eV, almost all atoms are ionized



Some characteristics of the **plasma** state

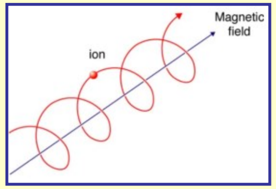
- Globally electrically neutral (as many ions as electrons)
- „Freely” moving charged particles → **conductor**
- Charged **particles can be manipulated** by electrical and magnetic fields

The fusion process

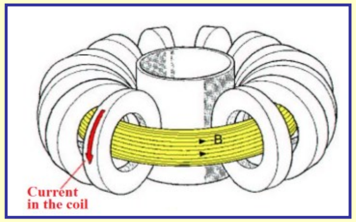
Magnetic confinement

The hot plasma can be confined with the help of magnetic field.

The charged particles „follow” the field lines (Larmor-precession)



The field lines should be „closed” ⇒ **toroidal** geometry

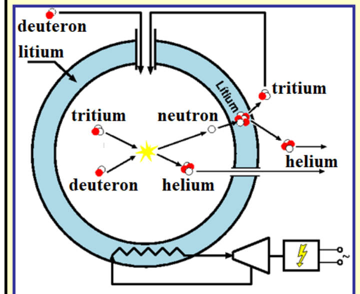


There are other important details how to shape the magnetic field.

But we stop here, at the main principle.

The fusion process

The fuel cycle of a future fusion power reactor



No radioactive isotopes are created in the fusion reaction!

(But… neutrons make the reactor material radioactive!)

$${}^{2}_{1}\mathrm{H}+{}^{3}_{1}\mathrm{H}\rightarrow{}^{4}_{2}\mathrm{He}+\mathrm{n}+17{,}6\ \mathrm{MeV}$$

Fuel resources

Deuterium: large quantities in the ocean (heavy water)

Tritium: only small amount in nature. Radioactive: $T_{1/2}$=12,32 y

Tritium breeding in the blanket:

$$\mathrm{n}+{}^{6}_{3}\mathrm{Li}\rightarrow{}^{3}_{1}\mathrm{H}+{}^{4}_{2}\mathrm{He}+4{,}78\ \mathrm{MeV}$$

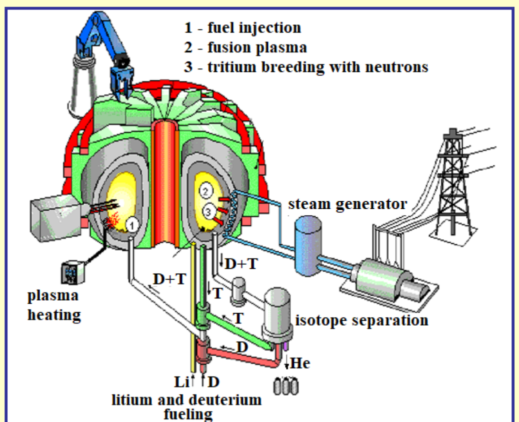
$$\mathrm{n}+{}^{7}_{3}\mathrm{Li}\rightarrow{}^{3}_{1}\mathrm{H}+{}^{4}_{2}\mathrm{He}+\mathrm{n}'-2{,}47\ \mathrm{MeV}$$

Large quantity in Earth's crust

only with high energy neutrons

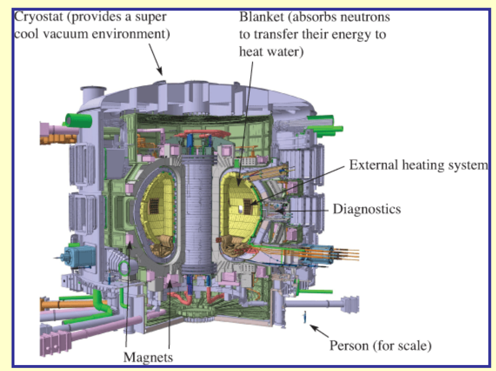
The fusion process

Possible scheme of a future fusion power reactor



The fusion process

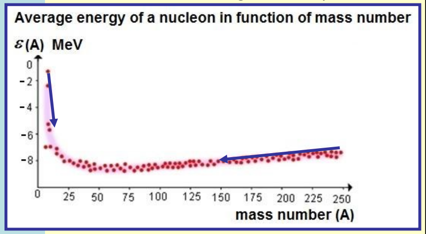
The ITER experimental device (in construction)



The first plasma is expected around 2025-2026…

Options for releasing nuclear energy

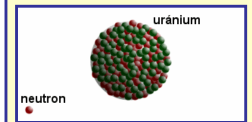
Fission
(make smaller nuclei
from larger ones)



Fission:
- small change in (energy/nucleon) (~ 0,85 MeV/nucleon)
- many nucleons (~236),

Total energy gain ~ 200 MeV

The fission process



1) The nucleus gets excited (e.g. after neutron absorption)
2) It gets **deformed**, …
3) …then **scissions** and splits into 2 parts, and **emits a few neutrons**

Some heavy nuclei undergo spontaneous fission
(step 1 is missing for them)

The „equation" of the fission reaction:

$$^{235}\mathrm{U} + \mathrm{n} \longrightarrow \mathrm{Fragment}_1 + \mathrm{Fragment}_2 + 2{,}43\ \mathrm{n}$$

Two obvious questions:
1) Why don't we write down the results (the daughter nuclei) exactly?
2) What does 2,43 n signify? Number of neutrons can be only integer number!

The answers:

1) The composition *(Z,A)* of the fragments cannot be defined more precisely, since **the fission process is stochastic** also in this respect!

The nucleus splits into two parts as if a blind cook would cut the onion. In most cases the two parts will not be equal sized.

The fission is not a deterministic process and mostly occurs asymmetrically!

The „equation" of the fission reaction:

$$^{235}\mathrm{U} + \mathrm{n} \longrightarrow \mathrm{Fragment}_1 + \mathrm{Fragment}_2 + 2{,}43\ \mathrm{n}$$

Two obvious questions:
1) Why don't we write down the results (the daughter nuclei) exactly?
2) What does 2,43 n signify? Number of neutrons can be only integer number!

The answers (contd.):

2) Since fission is a stochastic process, the **actual** number of emitted neutrons cannot be determined either. There is a distribution in the number of the emitted neutrons (see later).

Only the **average** number of emitted neutrons can be determined. Therefore it is not necessary an integer

We could write the fission „equation" more precisely:

$$^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{A_1}_{Z_1}\mathrm{X} + {}^{A_2}_{92-Z_1}\mathrm{Y} + (236 - A_1 - A_2)\cdot \mathrm{n}$$

Here the 3 variables (A_1, A_2, Z_1) all have some stochastic nature, although with some constraints (e.g. $A_1 + A_2 \le 236$, $Z_1 < 92$, etc.)

Mass distribution of the fragments

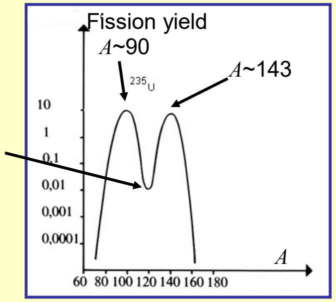
Symmetric fission would be:

$^{236}_{92}\mathrm{U} \rightarrow {}^{118}_{46}\mathrm{Pd} + {}^{118}_{46}\mathrm{Pd}$

According to the graph A~120 is ~1000 times less probable

The fission is most probably asymmetric! ($^{235}\mathrm{U} + \mathrm{n}_{thermal}$)

The mass distribution depends on the fissile material as well as on the energy of the neutrons !

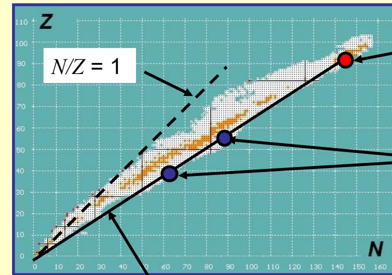


During the fission process
- neutrons are emitted (in average 2,43)
- highly radioactive fission fragments are produced

Fission on the (N,Z) „map"

$^{236}_{92}\mathrm{U}_{144}$

$N/Z = 144/92 = 1{,}56$



Starting point: ($N/Z \sim 1{,}56$) (stable nucleus)

Final points if $N/Z \sim 1{,}56$ remains (asymmetric fission)

$N/Z = 1{,}56$

As compared to the stable nuclei the fragments are NEUTRONRICH nuclei

Highly radioactive (β^- decay) fission products

Neutron emission is necessary ($\bar{\nu}$ ~ 2,43)

Energy balance of the fission ^{235}U(n,f)

Energy is released by several processes. This influences the **time-** and **spatial** distribution of the heat source

Kinetic energy of the fragments	168 MeV (82,0 %)
Energy of the β-particles of the fragments	8 MeV (3,9 %)
Total energy of the fission neutrons	5 MeV (2,4 %)
Total energy of the prompt γ-rays	7 MeV (3,4 %)
Energy of the γ –radiation of the fragments	7 MeV (3,4 %)
Energy of the antineutrinos emitted during the β-decay of the fragments	10 MeV (4,9 %)
TOTAL	**205 MeV** (100%)

Short range (in the fuel and close to it)
Medium range (coolant, reactor vessel, shielding)
Very long range (escaping)
— **spatial**

Instantly (prompt)
Later (determined by their half-lives)
— **time**

Example: suppose that the fission of ^{236}U occurs the following way: $^{236}\mathrm{U} \longrightarrow {}^{90}\mathrm{Kr} + {}^{143}\mathrm{Ba} + 3\mathrm{n}$

Calculate the distance of the two fragments, at the scission point, when only Coulomb-forces act on them!

Their total kinetic energy will be 168 MeV.

Solution:

At the scission point they have only Coulomb potential energy, this is transformed to kinetic energy:

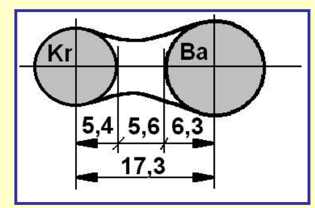
$$\frac{1}{4\pi\varepsilon_0}\cdot\frac{Z_1 Z_2 e^2}{d} = 168\cdot 1{,}6\cdot 10^{-13}\ \mathrm{J}$$ Here Z_1=36 (Kr), Z_2=56 (Ba)

From this: $d \sim 17{,}3$ fm

Using $R = r_0\sqrt[3]{A}$ we get for the radius of the two nuclei:

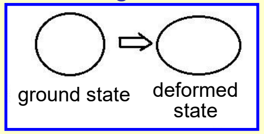
$R_{Kr} = 5{,}4$ fm, $R_{Ba} = 6{,}3$ fm

The geometry of the „scission" is:



The fission barrier

The fission **begins** with a small deformation of the nucleus



(deformation parameter: ε)

How much energy is needed?

The energy change is estimated using the Weizsäcker-formula

$$B = b_V A - b_F \cdot A^{2/3} - b_C \cdot \frac{Z^2}{A^{1/3}} - b_A \cdot \frac{(N-Z)^2}{A} + b_P \cdot \delta \cdot A^{-3/4}$$

During the deformation

- volume = constant (uncompressible nuclear matter)
- asymmetry, pairing energy = assumed to be constant
- surface ⟶ increases $\quad b_F A^{2/3} \Rightarrow b_F A^{2/3}(1 + a_F \cdot \varepsilon)$
- Coulomb-energy ⟶ decreases (protons get further away) $\quad b_C \frac{Z^2}{A^{1/3}} \Rightarrow b_C \frac{Z^2}{A^{1/3}}(1 - a_C \cdot \varepsilon)$

The coefficients (according to precise calculations):

$a_F \sim 0{,}025$ és $a_C \sim 0{,}012$.

The change in energy: $\Delta E = \left(0{,}025 \cdot b_F \cdot A^{2/3} - 0{,}012 \cdot b_C \frac{Z^2}{A^{1/3}}\right) \cdot \varepsilon$

If $\Delta E < 0$, then every small ε deformation decreases the energy, the nucleus spontaneously fissions!

$$\left(0{,}025 \cdot b_F \cdot A^{2/3} - 0{,}012 \cdot b_C \frac{Z^2}{A^{1/3}}\right) < 0 \quad \Rightarrow \quad \frac{Z^2}{A} \geq \frac{0{,}025 \cdot b_F}{0{,}012 \cdot b_C} \approx 54$$

(since b_F=2,85 ·10^{-12} J, b_C=0,11 ·10^{-12} J)

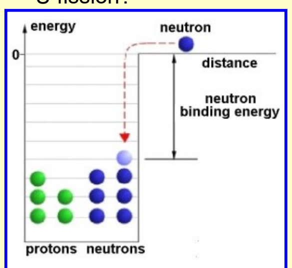
For heavy nuclei $Z/A \sim 0{,}39$, therefore for $Z > 136$ there is no „activation energy" for the fission. (In fact, already around $Z \sim 110$ the activation energy is so small, that the nuclei spontaneously fission quickly by the quantum-mechanical tunnel effect.)

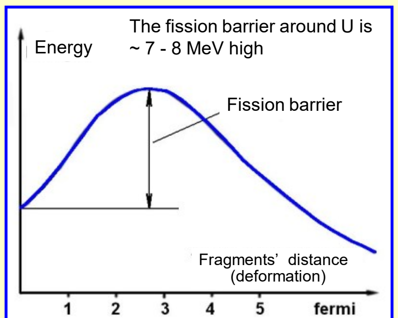
The Periodic System is finished because of the fission!!

The fission barrier

If $\Delta E > 0$, then small ε deformations need some energy. This leads to the formation of a fission (energy) barrier.

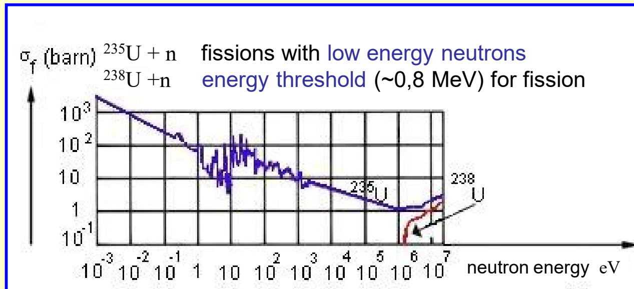
How can a slow neutron (kinetic energy~0) make ^{235}U fission?





The binding energy of the neutron can make the nucleus climb over the fission barrier!

Fission cross sections



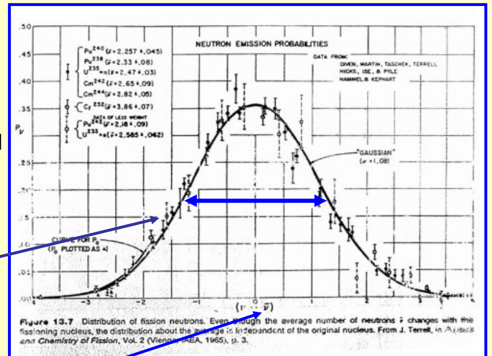
^{235}U and ^{238}U fission cross sections in function of the neutron energy

The cause of the difference is in the pairing energy. $^{235}_{92}U_{143}$ is even-odd (less bound), and $^{238}_{92}U_{146}$ is even-even (strongly bound). For the other heavy nuclei in the region the fission cross-sections behave similarly.

Fission neutrons

The number of emitted neutrons is not constant, it is scattered around a mean value. Can be well approximated by a Gaussian-distribution

The mean value depends on the energy of the incoming neutron and also on the fissile isotope



FWHM:
~ 2,5
(not depending on the fissile isotope)

Mean value $\bar{\nu} = 2,43$ (for $^{235}U+n_{th}$ fission)

Time and energy of the fission neutrons (emission time after the fission)

a) Prompt neutrons

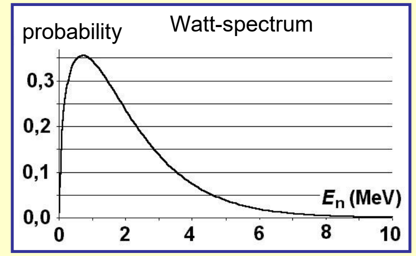
Most of the neutrons are emitted „immediately” at the fission. These are the prompt neutrons ($t < 10^{-16}$ s).

Their average energy ~ **2 MeV**

Energy-distribution: „Watt-spectrum”

$$N(E_n) \sim 0,484 \cdot e^{-E_n/E_0} \cdot \sinh\sqrt{2\frac{E_n}{E_0}}$$

($E_0 = 1$ MeV)

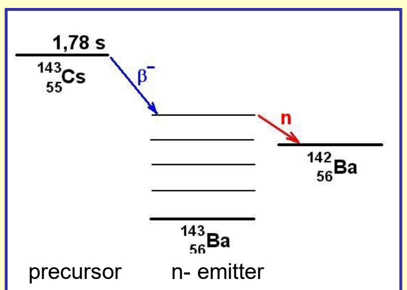


b) Delayed neutrons

The fission fragments necessarily contain **more neutrons** than the stable isotopes.
Consequently they all undergo β^--decays.

In some cases after the β^--decay also the daughter nucleus can emit neutrons → **delayed neutrons**

A possible example:
(The neutron will be emitted with 1,78 s half life!)



There are many similar decay chains, with different half lives (T_i), different yields (β_i)

Delayed neutrons are grouped into 6 groups
(according to their half lives)

	E_n(MeV)	T_i(s)	β_i(%)	Typical precursor
1	0,25	56	0,020	^{87}Br, ^{142}Cs
2	0,56	23	0,143	^{88}Br, ^{137}I
3	0,43	6,2	0,128	^{89}Br, ^{138}I
4	0,62	2,3	0,255	^{94}Kr, ^{139}I, ^{143}Cs
5	0,42	0,6	0,074	^{140}I, ^{145}Cs
6	0,51	0,2	0,030	^{87}As, ^{143}Xe

Total yield: $\beta = 0,65$ %

Delayed neutron ratio: $\beta = \frac{\text{(delayed n)}}{\text{(total n)}} \sim \frac{\text{(delayed n)}}{\text{(prompt n)}}$

Delayed neutrons' emission rate after the fission:

$$N(t) = \sum_{i=1}^{6} \beta_i \cdot e^{-\ln 2 \cdot \frac{t}{T_i}}$$

Their role is very important in the control of the chain reaction!!

Thank you for your attention !

These slides are **uploaded** in the „Files" menu item of the Teams Group: *Nuclear and Reactor Physics Fundamentals*,
in Channel: *Nuclear Physics 4.*
Nuclear Fusion and Fission (29. October)

At the end of the slides there are some „*Self-test questions*". Please try to answer them to check your own understanding.

Self-test questions

1. The average energy of a nucleon depends both on the nucleon number A and on the proton number Z: $\varepsilon(Z,A)$. How is it possible that the graph on slide 4 depends only on A? What happened with the Z dependence?
2. Why is neutron emission necessary in fission process? (Use the „energy valley" picture in the explanation)
3. Why is it necessary that the fission fragments are radioactive? What kind of radiation they emit?
4. What percentage of the energy released in fission heats the fuel rods and its close environment?
5. What percentage of the fission energy heats the reactor later (not promptly, after the fission)? What determines its time-behaviour?
6. Which terms of the Weizsäcker formula play a role in the existence of the fission barrier? Which role they play?

Self-test questions (cont.)

7. The height of the fission barrier is about 7-8 MeV for the uranium isotopes. How is it possible that a thermal neutron (energy ~0,03 eV) can induce fission in ^{235}U?
8. Why can a thermal neutron induce fission in ^{235}U, and can not induce fission in ^{238}U, if the fission barrier is about the same height for both isotopes?
9. How does the fission cross section depend on the neutron velocity for very slow neutrons, and for the $^{235}U(n,f)$ reaction?
10. What kind of distribution describes the number of emitted neutrons? What is the mean value for $^{235}U(n_{th},f)$?
11. How are the delayed neutrons produced? How much is their proportion? What determines their „delay"?