Nuclear fission - history

1932 – The English physicist James Chadwick discovered the neutron

1934 - Enrico Fermi and his colleagues in Rome studied the results of bombarding uranium with slow-moving neutrons and found radioactive isotopes in the decay products

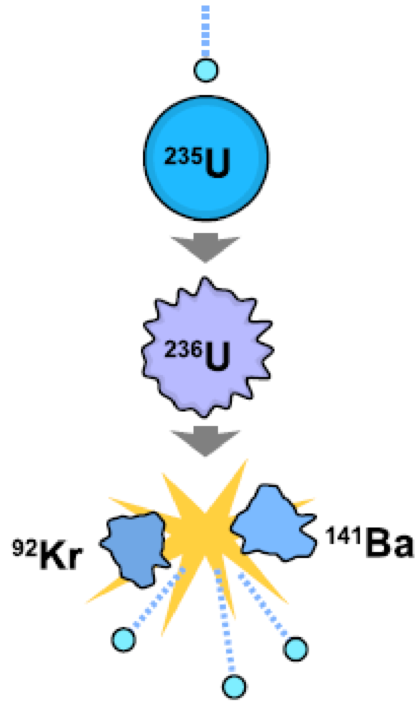
1939 - Otto Hahn and Fritz Strassmann detected the element barium after bombarding uranium with neutrons

1939 - Lise Meitner and Otto Robert Frisch correctly interpreted these results as being nuclear fission

1944 – Otto Hahn received the Nobel Prize for Chemistry for the discovery of nuclear fission

1939 - the Hungarian physicist Leo Szilárd, then in the United States, realized that fission could be used to create a nuclear chain reaction (an idea he had first formulated in 1933)

1940 – The Russian physicists Georgy Flerov and Konstantin Peterzhak discovered the spontaneous fission of uranium ^{235}U

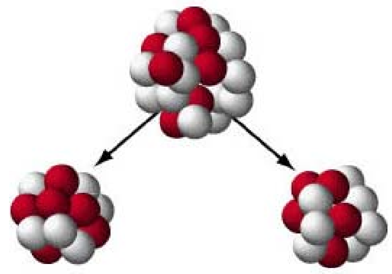


Nuclear fission

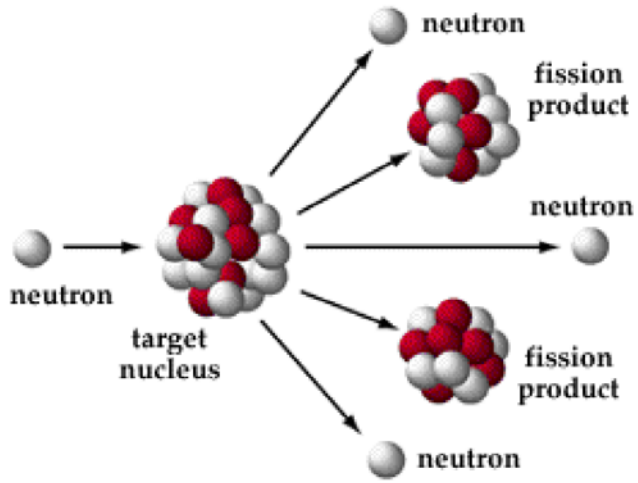
Nuclear fission

- decay into two or more lighter nuclei :

❑ spontaneous fission (tunneling effect)

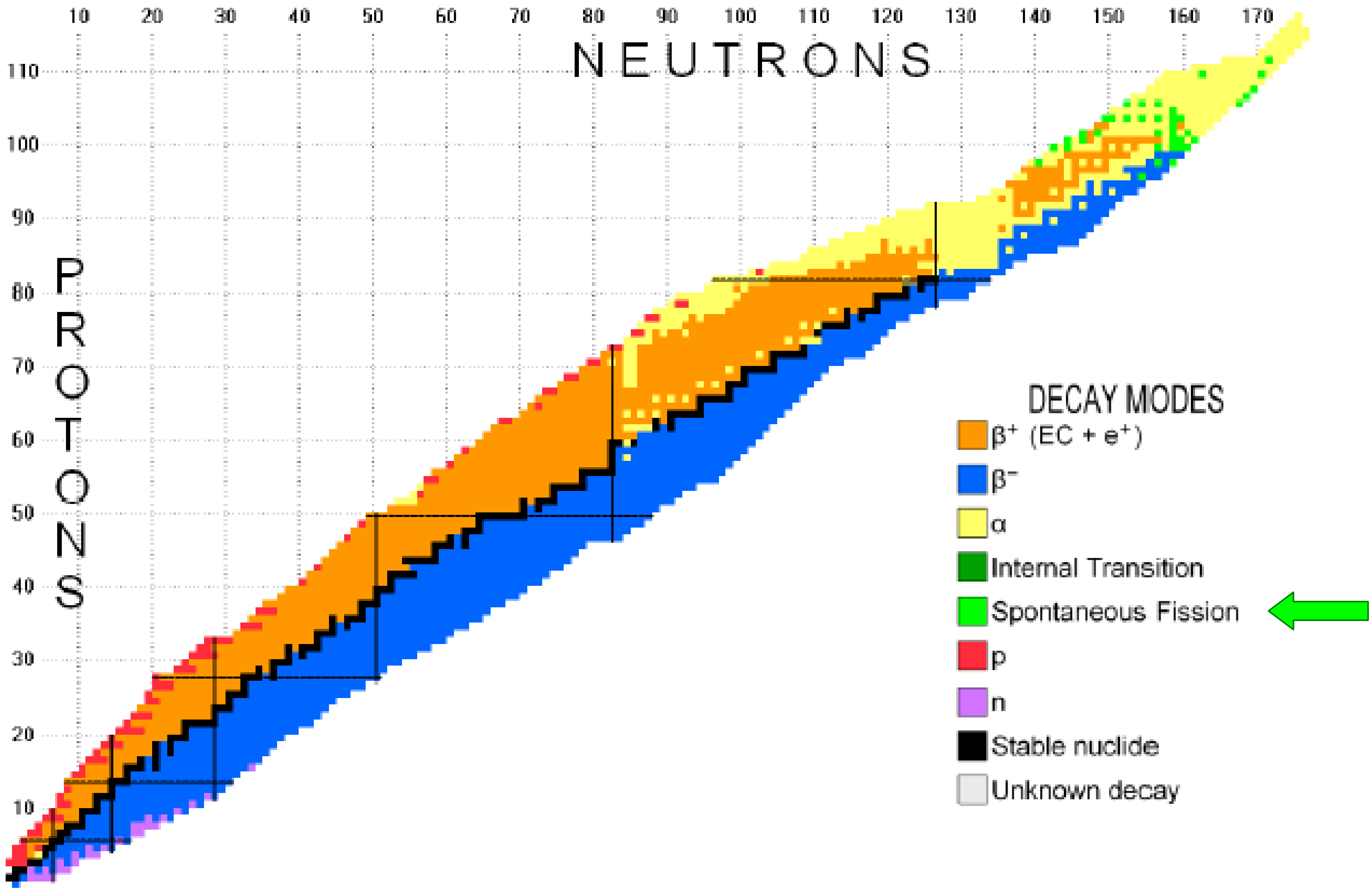


❑ induced fission – due to nuclear reactions, e.g. under neutron bombardment



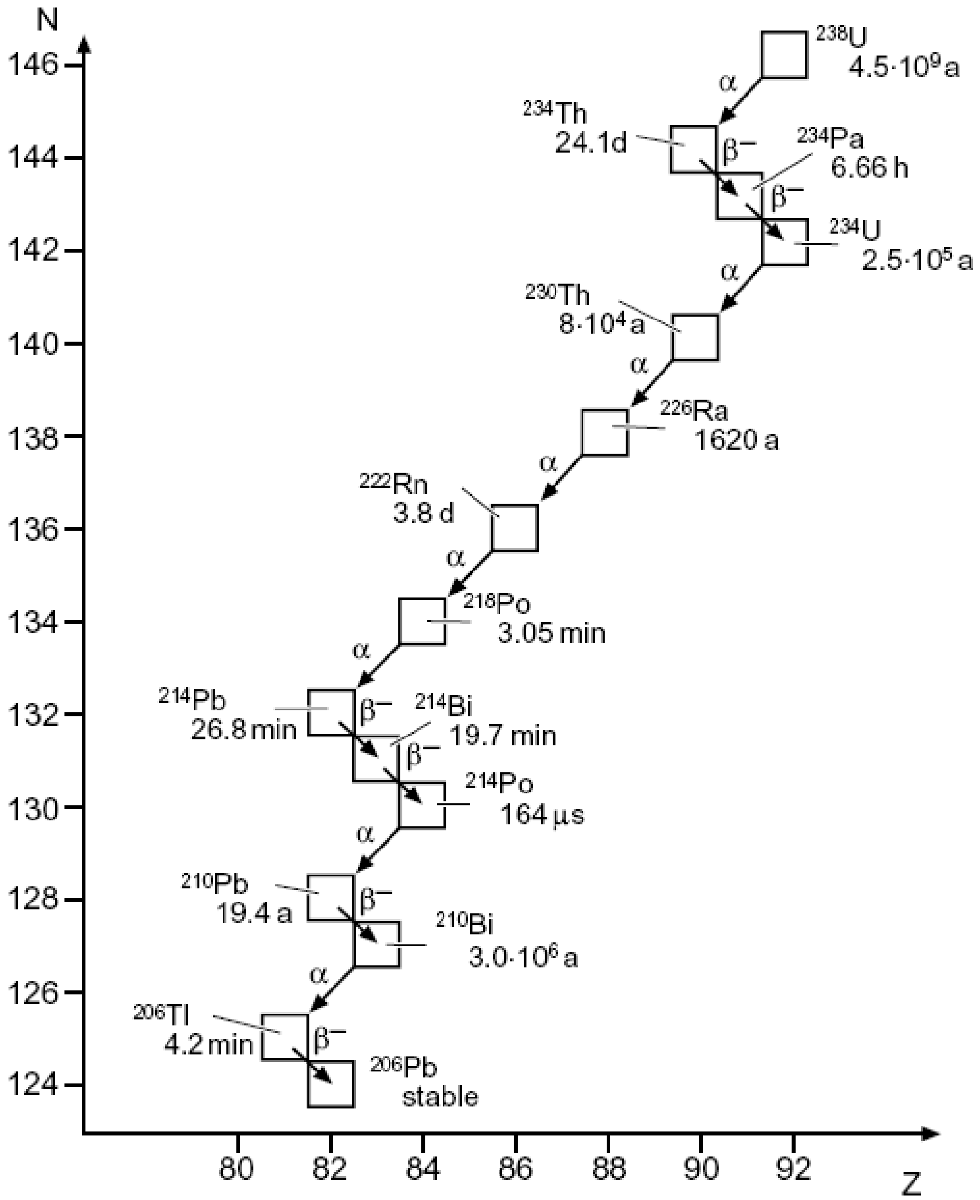
- Fission is energetically more favourable for heavy isotopes
- Fission products: the two nuclei produced are most often of comparable size, typically with a mass ratio around 3:2 for common fissile isotopes.

Decay modes



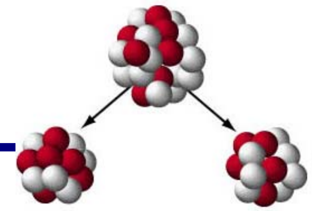
NEUTRONS
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170
PROTONS
110 100 90 80 70 60 50 40 30 20 10
DECAY MODES
β+ (EC + e+)
β−
α
Internal Transition
Spontaneous Fission
p
n
Stable nuclide
Unknown decay

Decay modes



The ^{238}U decay chain in the N-Z plane.

Spontaneous fission



Nuclei	Half-life (years) Spont. Fission	α-decay
$^{232}_{90}Th$	$1,3 \cdot 10^{18}$	$1,41 \cdot 10^{10}$
$^{235}_{92}U$	$1,9 \cdot 10^{17}$	$7,1 \cdot 10^{8}$
$^{238}_{92}U$	$5,9 \cdot 10^{15}$	$4,5 \cdot 10^{9}$
$^{238}_{94}Pu$	$4,9 \cdot 10^{10}$	$89,6$
$^{239}_{94}Pu$	$5,5 \cdot 10^{15}$	$24,3 \cdot 10^{3}$
$^{240}_{94}Pu$	$1,3 \cdot 10^{11}$	$6,6 \cdot 10^{3}$
$^{242}_{94}Pu$	$7 \cdot 10^{10}$	$3,5 \cdot 10^{5}$
$^{241}_{95}Am$	$2,3 \cdot 10^{14}$	$432,6$

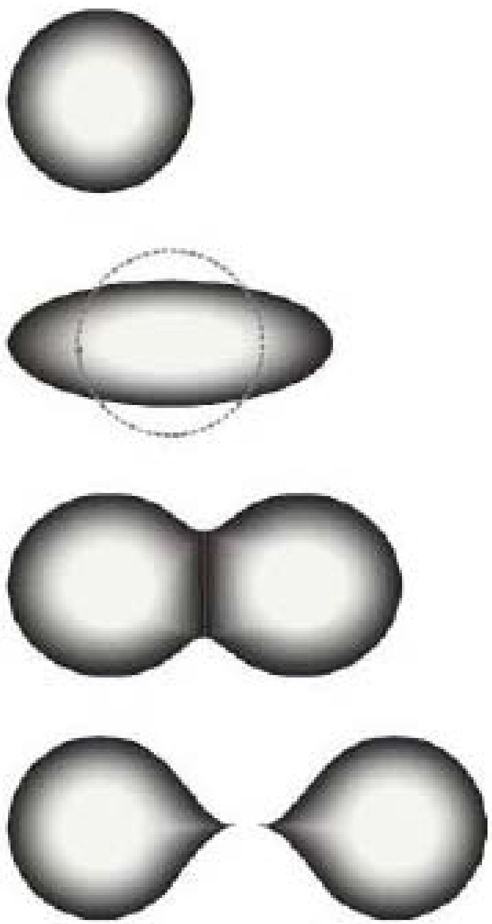
- **Half-life for the spontaneous fission is much longer than for radioactive α-decay and only for superheavy elemens it is comparable**

E.g.: spontaneous fission of ^{238}U:

$\tau_{1/2}(^{238}U) = 5 \cdot 10^{15}$ years

→ there are ~35 spontaneous decays of ^{238}U in 1 gram of ^{238}U during 1 hour

Mechanisms of nuclear fission



- **The fission of a heavy nucleus requires a total input energy of about 7 to 8 MeV to initially overcome the strong force which holds the nucleus into a spherical or nearly spherical shape**
- **deform it into a two-lobed ("peanut") shape**
- **the lobes separate from each other, pushed by their mutual positive charge to a critical distance, beyond which the short range strong force can no longer hold them together**
- **the process of their separation proceeds by the energy of the (longer range) electromagnetic repulsion between the fragments. The result is two fission fragments moving away from each other (+ a few neutrons)**

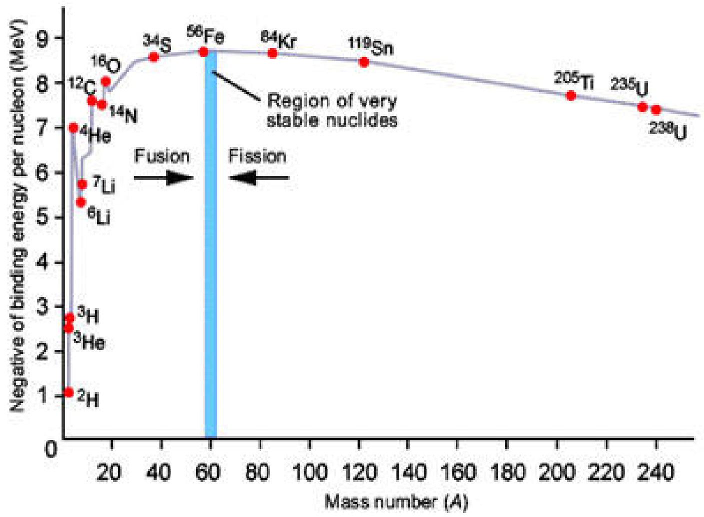
Fission energy

- Fission of heavy elements is an exothermic reaction which can release a large amount of energy (~1 MeV per nucleon) both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place).

- In order that fission produces energy, the total binding energy of the resulting elements must be larger than that of the starting element.

- Fission is a form of nuclear transmutation because the resulting fragments are not the same elements as the original one.

Binding energy



- Typical fission events release about two hundred million eV (200 MeV) of energy for each fission event , e.g. for ^{235}U : ~235 MeV
- By contrast, most chemical oxidation reactions (such as burning coal) release at most a few eV per event

➔ So nuclear fuel contains at least ten million times more usable energy per unit mass than chemical fuel

E.g.: 1 gramm of ^{235}U is equivalent to 1 tonn of coal (=> 3.5 tonn CO_2)!

Fission energy

Fission energy is the release energy from the fission of the nucleus of mass M(A,Z) to fragments with masses $M_1(A_1,Z_1)$ and $M_2(A_2,Z_2)$:

$$Q_f = M(A, Z)c^2 - [M_1(A_1, Z_1)c^2 + M_2(A_2, Z_2)c^2] =$$
$$= W_1(A_1, Z_1) + W_2(A_2, Z_2) - W(A, Z),$$

where W(A,Z) is the total binding energy (binding energy per nucleon: ε=W(A,Z)/A)

The binding energy – from the liquid drop model - Weizsäcker formula: $W=E_B$

$$E_B = \underbrace{a_V \cdot A}_{\text{Volum term}} - \underbrace{a_S \cdot A^{\frac{2}{3}}}_{\text{Surface term}} - \underbrace{a_C \cdot \frac{Z^2}{A^{\frac{1}{3}}}}_{\text{Coulomb term}} \underbrace{- a_{Sym} \cdot \frac{(N-Z)^2}{A}}_{\text{Assymetry term}} - \underbrace{\frac{\delta}{A^{1/2}}}_{\text{Pairing term}}$$

Empirical parameters:

$$a_V \approx 16MeV$$
$$a_S \approx 20MeV$$
$$a_C \approx 0,75MeV$$
$$a_{Sym} \approx 21MeV$$

$$\delta = \begin{cases} -11.2\ \text{MeV}/c^2 & \text{for even } Z \text{ and } N \text{ (even-even nuclei)} \\ 0\ \text{MeV}/c^2 & \text{for odd } A \text{ (odd-even nuclei)} \\ +11.2\ \text{MeV}/c^2 & \text{for odd } Z \text{ and } N \text{ (odd-odd nuclei).} \end{cases}$$

Symmetric and asymmetric fission

1) Symmetric fission to equal fragments with masses $M_1(A_1,Z_1) = M_2(A_2,Z_2)=M(A/2,Z/2)$:

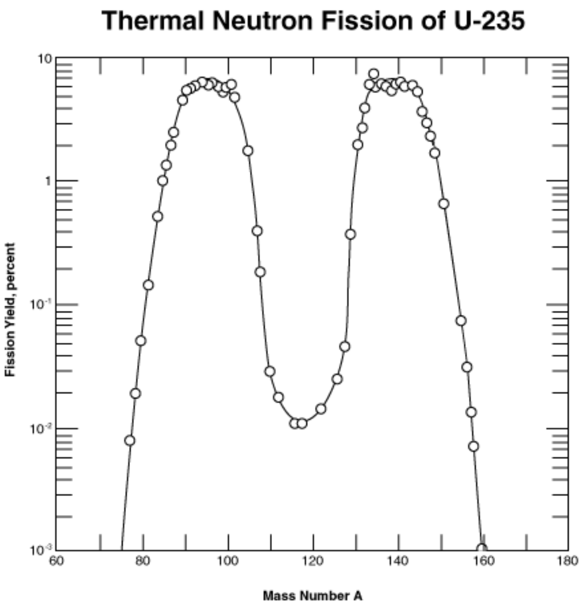
$$Q_f = 2W(A/2, Z/2) - W(A, Z) \approx [E_s(A, Z) + E_c(A, Z)] - 2[E_s(A/2, Z/2) + E_c(A/2, Z/2)]$$

E_S - surface energy
E_C – Coulomb energy

Fission is energetically favourable if $Q_f > 0$ ➔

fission parameter $\frac{Z^2}{A} \geq 17$ for nuclei with $A > 90$

2) Asymmetric fission to fragments with nonequal masses $M_1(A_1,Z_1)$, $M_2(A_2,Z_2)$,



it produces the fission products at
$A_{light}=95\pm15$ and $A_{heavy}=135\pm15$.

The reason:
to form closed shells for the fission products!

$$\frac{A_{light}}{A_{heavy}} \approx \frac{Z_{light}}{Z_{heavy}} \approx \frac{2}{3}$$

$$n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U \rightarrow {}^{95}_{38}Sr + {}^{139}_{54}Xe + 2n.$$

Potential energy of fission

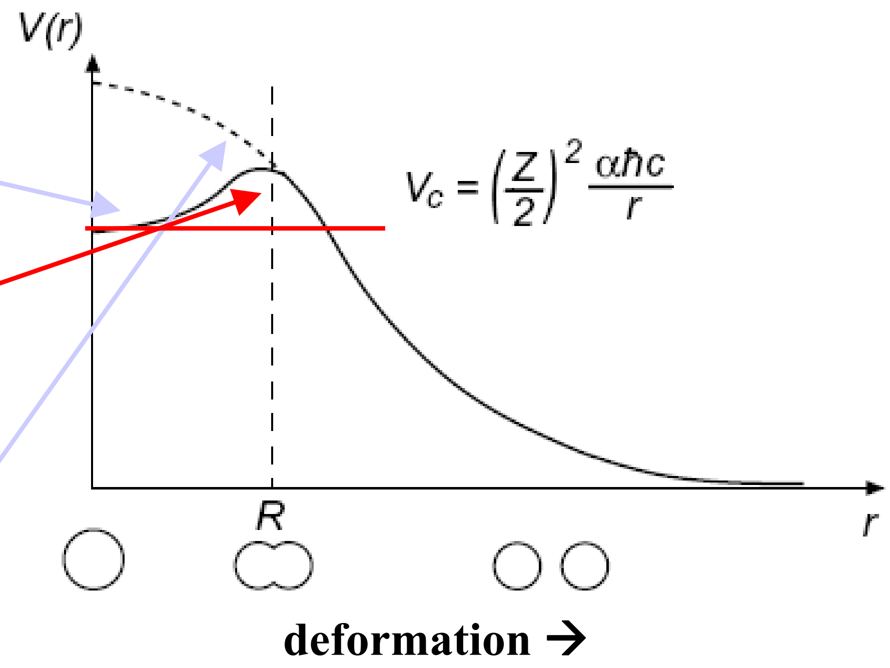
Let‘s find the charge number Z above which nuclei become fission unstable, i.e., the point from which the mutual Coulombic repulsion of the protons outweights the attractive nature of the nuclear force.

An estimate can be obtained by considering the surface and the Coulomb energy during the fission deformation. As the nucleus is deformed the surface energy increases, while the Coulomb energy decreases. If the deformation leads to an energetically more favourable configuration, the nucleus is unstable.

Potential energy during different stages of a fission reaction:

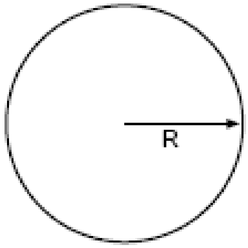
A nucleus with charge Z decays spontaneously into two daughter nuclei. The solid line corresponds to the shape of the potential in the parent nucleus.

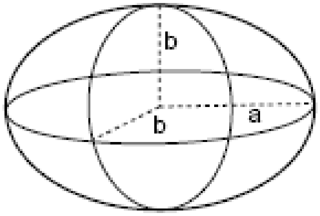
The height of the barrier for fission determines the probability of spontaneous fission. The fission barrier disappears for nuclei with Z^2/A >48 and the shape of the potential then corresponds to the dashed line.



Fission barrier

Quantitatively, this can be calculated as follows: keeping the volume of the nucleus constant, we deform its spherical shape into an ellipsoid with axes $a = R(1 + \varepsilon)$ and $b = R(1 - \varepsilon/2)$





ε - deformation

$$V = 4\pi R^3/3 = 4\pi ab^2/3$$

The surface energy then has the form:

$$E_\mathrm{s} = a_\mathrm{s} A^{2/3}\left(1 + \frac{2}{5}\varepsilon^2 + \cdots\right)$$

while the Coulomb energy is given by:

$$E_\mathrm{c} = a_\mathrm{c} Z^2 A^{-1/3}\left(1 - \frac{1}{5}\varepsilon^2 + \cdots\right)$$

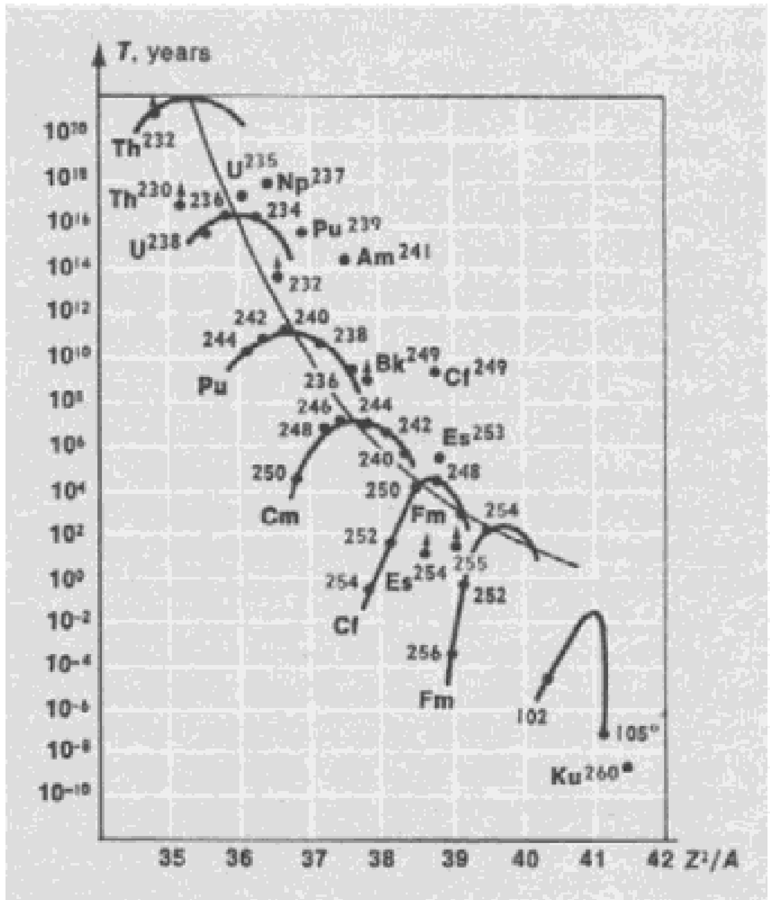
Hence a deformation ε changes the total energy by:

$$\Delta E = \frac{\varepsilon^2}{5}\left(2a_\mathrm{s} A^{2/3} - a_\mathrm{c} Z^2 A^{-1/3}\right)$$

- **If ΔE is negative, a deformation is energetically favoured.**
- **The fission barrier disappears for:**

$$\frac{Z^2}{A} \geq \frac{2a_\mathrm{s}}{a_\mathrm{c}} \approx 48$$

This is the case for nuclei with $Z > 114$ and $A > 270$



Fission barrier

Fission energy Q_F

Fission parameter Z^2/A

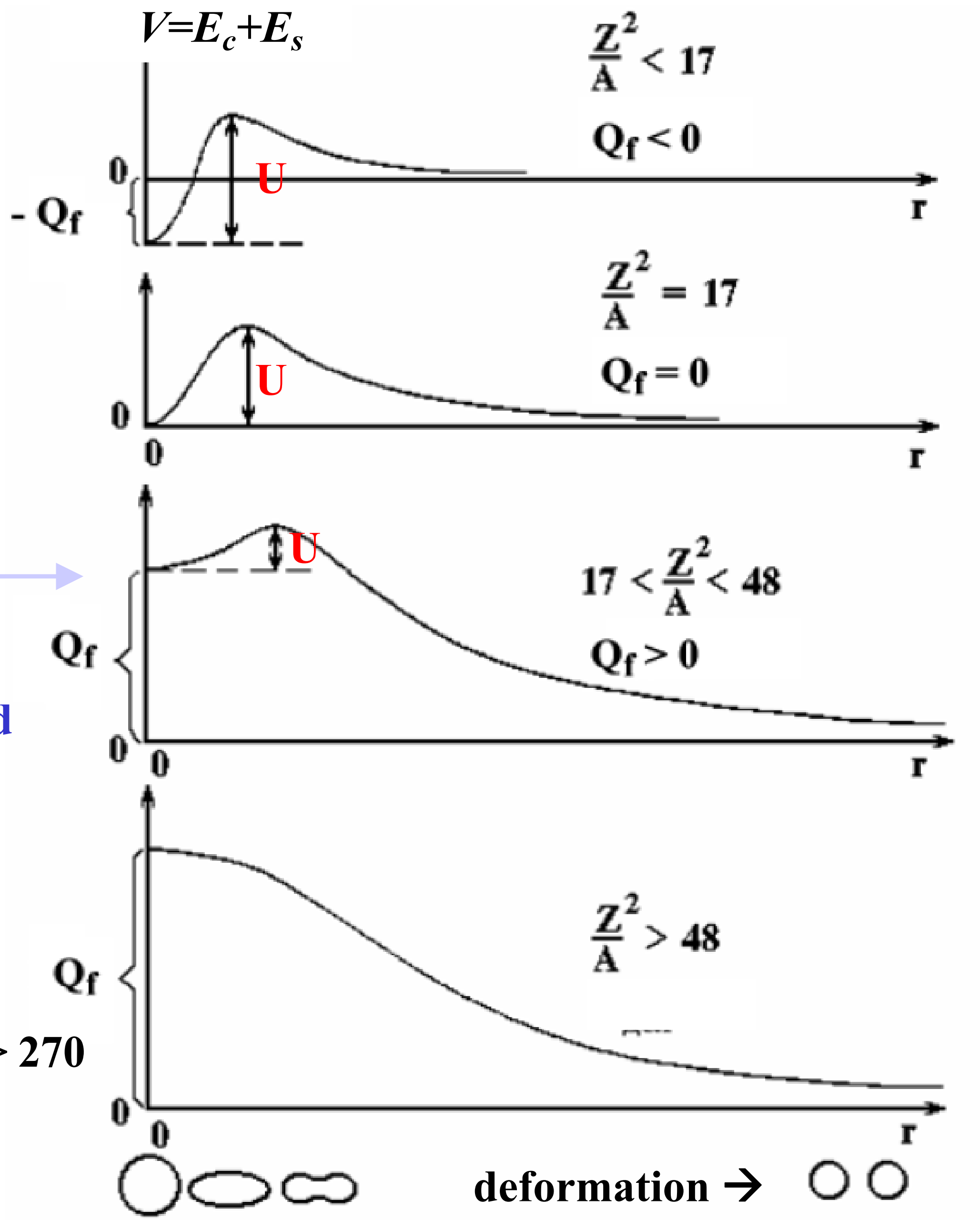
Fission barrier U:

$$U(r) = V|_{max} - V|_{r=0}$$

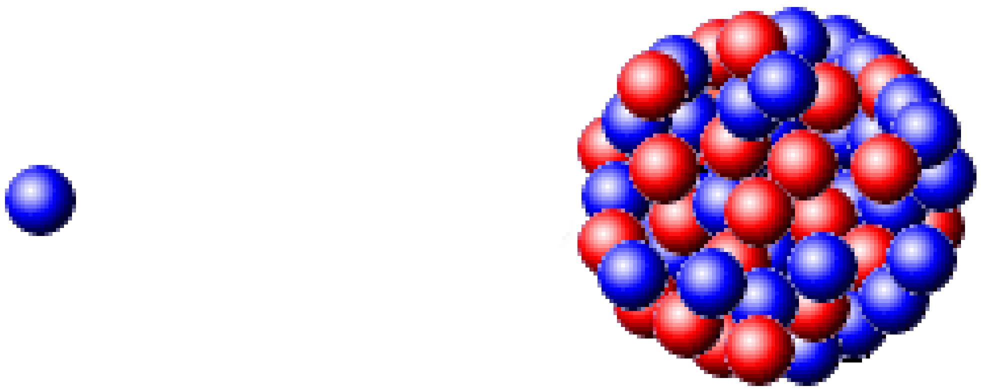
e.g. ^{235}U →

$Q_f > 0$:
Fission is energetically favoured

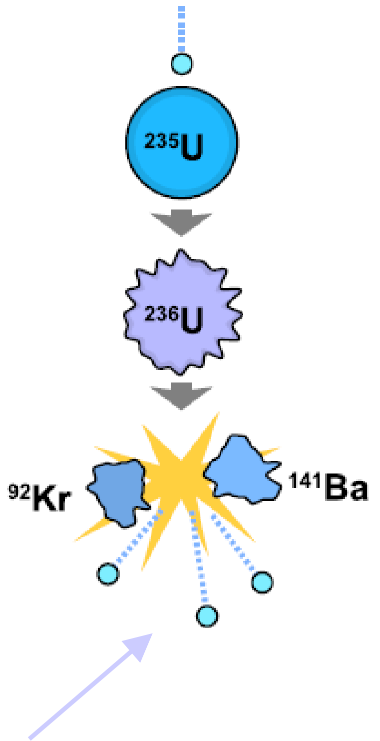
nuclei with $Z > 114$ and $A > 270$



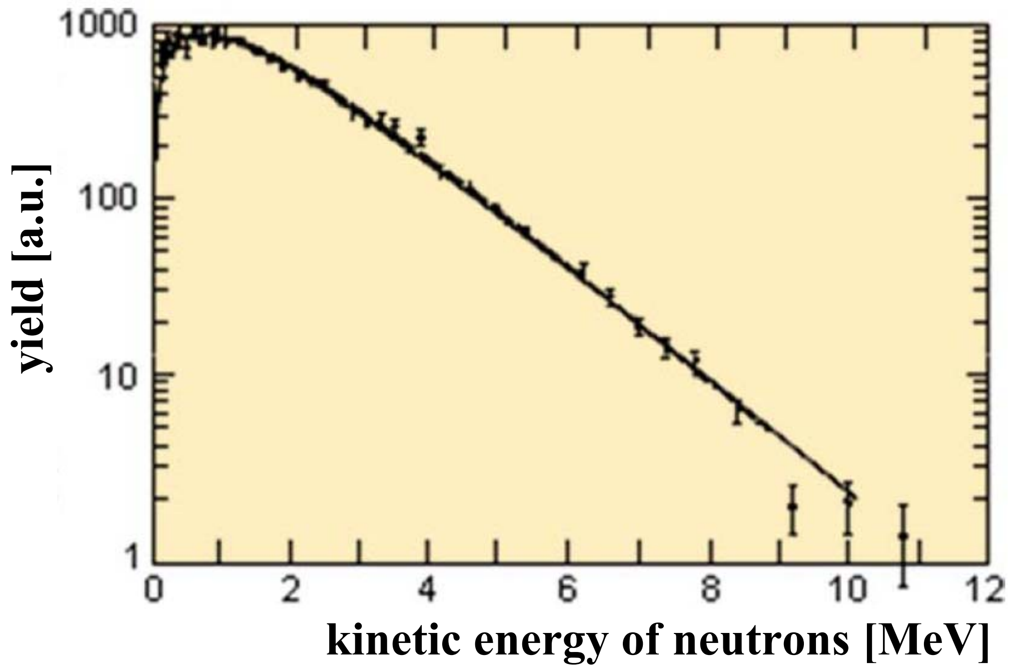
Nuclear fission



Neutrons from nuclear fission



Spectrum of neutrons from nuclear fission:



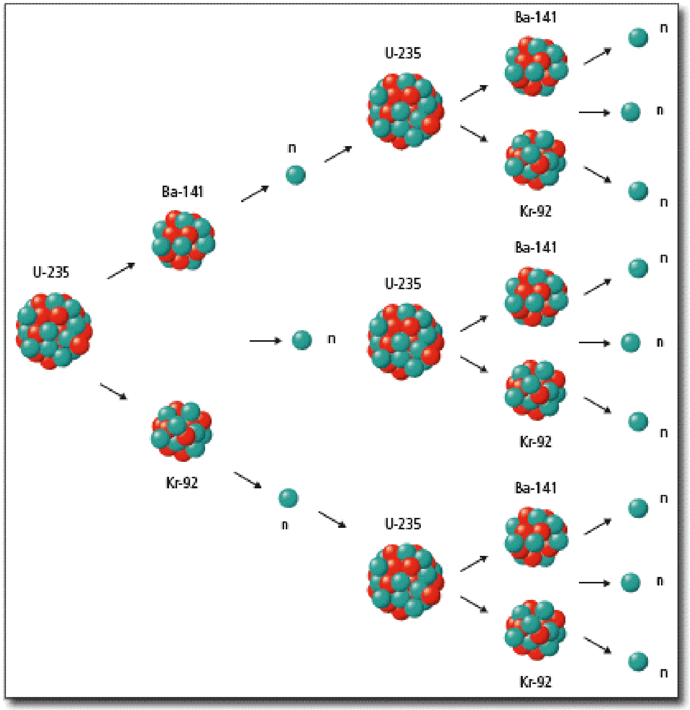
2-3 neutrons are produced in each fission event ➔

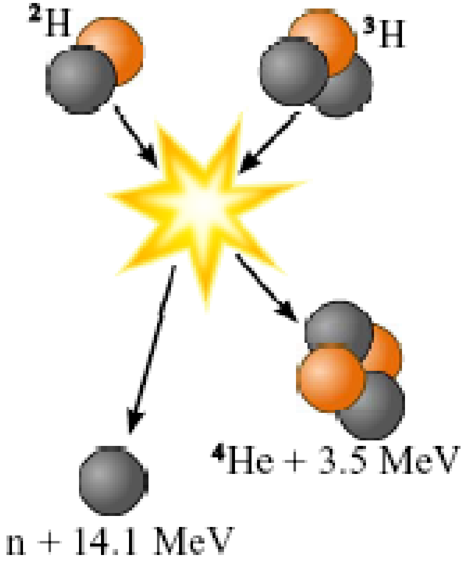
- continuum energy spectrum of produced neutrons with the maximum at 1 MeV
- a prompt neutron is a neutron immediately emitted by a nuclear fission event
- about 1% of neutrons – so-called delayed neutrons – are emitted as radioactive decay products from fission-daughters from a few milliseconds to a few minutes later

Nuclear chain reactions

A nuclear chain reaction occurs when one nuclear reaction causes on the average one or more nuclear reactions, thus leading to a self-propagating number of these reactions.

The specific nuclear reaction may be:
the fission of heavy isotopes (e.g. ^{235}U) or the fusion of light isotopes (e.g. ^{2}H and ^{3}H)

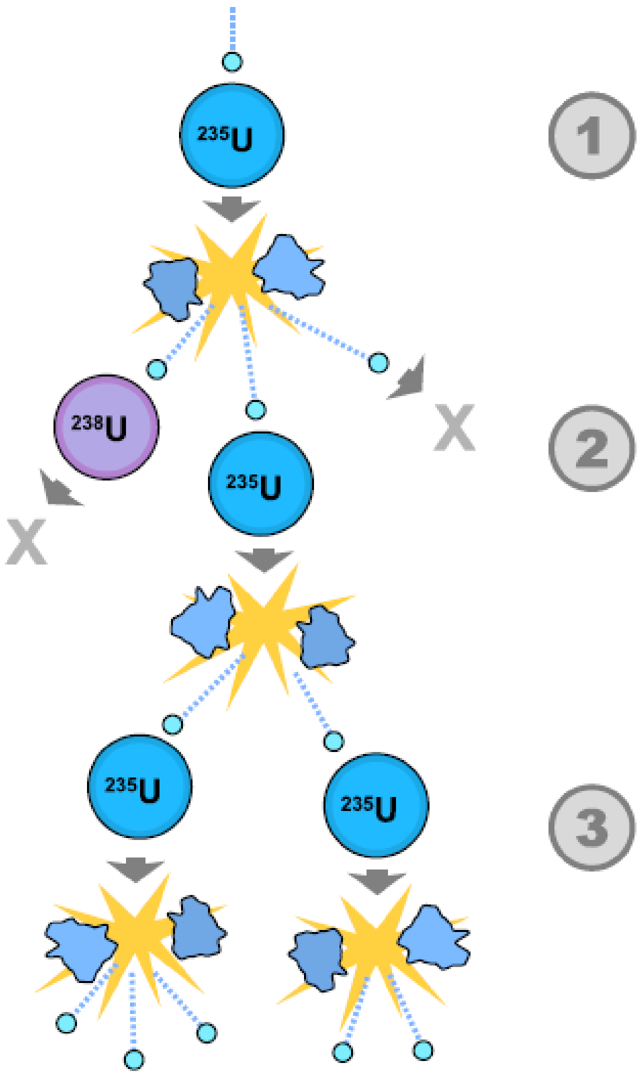




The nuclear chain reaction releases several million times more energy per reaction than any chemical reaction!

Fission chain reactions

➢The production of 2-3 neutrons in each fission event makes it possible to use fission chain reactions for the production of energy!



A schematic nuclear fission chain reaction:

1. A uranium-235 atom absorbs a neutron and fissions into two new atoms (fission fragments), releasing three new neutrons and some binding energy.

2. One of these neutrons is absorbed by an atom of uranium-238 and does not continue the reaction. Another neutron is simply lost and does not collide with anything, also not continuing the reaction. However one neutron does collide with an atom of uranium-235, which then fissions and releases two neutrons and some binding energy.

3. Both of these neutrons collide with uranium-235 atoms, each of which fissions and releases between one and three neutrons, which can then continue the reaction.

Fission chain reactions

1^{st} Generation: on average 2 neutrons

….

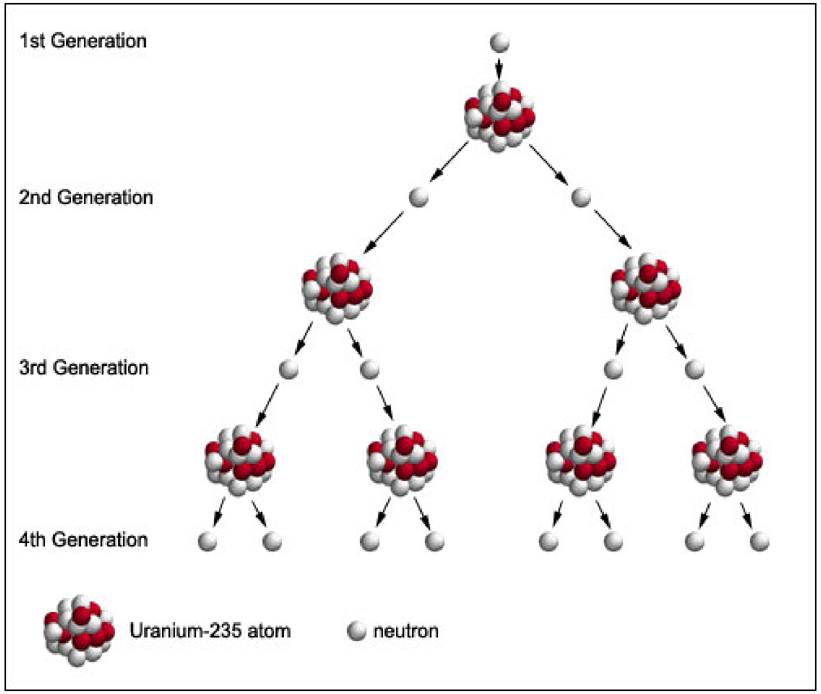
k^{th} Generation: 2^k neutrons

Mean generation time Λ is the average time from a neutron emission to a capture that results in a fission Λ $=10^{-7}$-10^{-8} c

⇒ e.g. 80^{th} generation in 10^{-5}-10^{-6} c :

during this time $2^{80}=10^{24}$ neutrons are produced which lead to

- the fission of 10^{24} nulei (140 g) of ^{235}U
- = release of $3{\cdot}10^{13}$ Watt of energy
  (1W=1J/c, 1 eV = $1.602{\cdot}10^{-19}$ J)
- which is equivalent to 1000 tonns of oil!

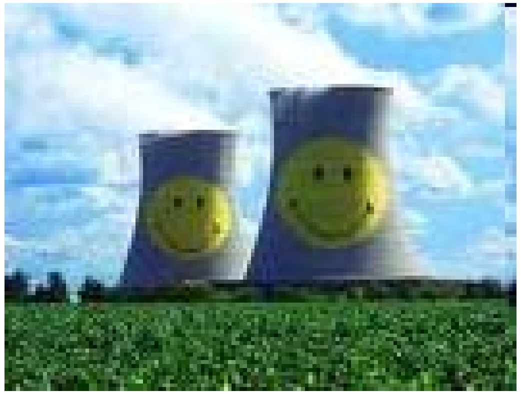


- Controlled chain reactions are possible with the isotops ^{235}U, ^{233}U and ^{239}Pu

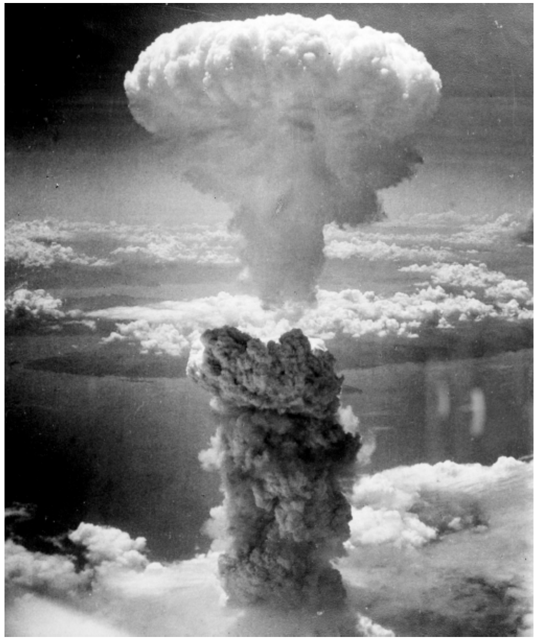
- The chemical element isotopes that can sustain a fission chain reaction are called nuclear fuels, and are said to be fissile.
- The most common nuclear fuels are ^{235}U (the isotope of uranium with an atomic mass of 235 and of use in nuclear reactors) and ^{239}Pu (the isotope of plutonium with an atomic mass of 239).

Fission chain reactions

Fission chain reactions are used:



Nuclear power plants operate by precisely controlling the rate at which nuclear reactions occur, and that control is maintained through the use of several redundant layers of safety measures.
Moreover, the materials in a nuclear reactor core and the uranium enrichment level make a nuclear explosion impossible, even if all safety measures failed.



Nuclear weapons are specifically engineered to produce a reaction that is so fast and intense that it cannot be controlled after it has started.
When properly designed, this uncontrolled reaction can lead to an explosive energy release.

Nuclear chain reactions

The **effective neutron multiplication factor, k**, is the average number of neutrons from one fission that causes another fission:

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

The remaining neutrons either are absorbed in non-fission reactions or leave the system without being absorbed.
The value of k determines how a nuclear chain reaction proceeds:

- **$k < 1$ (subcriticality):** The system cannot sustain a chain reaction, and any beginning of a chain reaction dies out in time. For every fission that is induced in the system, an average total of $1/(1 - k)$ fissions occur.

- **$k = 1$ (criticality):** Every fission causes an average of one more fission, leading to a fission (and power) level that is constant. Nuclear power plants operate with $k = 1$ unless the power level is being increased or decreased.

- **$k > 1$ (supercriticality):** For every fission in the material, it is likely that there will be k fissions after the next mean generation time. The result is that the number of fission reactions increases exponentially, according to the equation $e^{(k-1)t/\Lambda}$, where t is the elapsed time. Nuclear weapons are designed to operate in this state.

Nuclear chain reactions

1) Consider an idealized case – an infinite nuclear medium:

k => neutron multiplication factor in an infinite medium k_∞

$$k_\infty = \eta f p \varepsilon$$

η - reproduction factor - the number of fission neutrons produced per absorption in the fuel

f - the thermal utilization factor - probability that a neutron that gets absorbed does so in the fuel material

p - the resonance escape probability - fraction of fission neutrons that manage to slow down from fission to thermal energies without being absorbed

ε - the fast fission factor = $\dfrac{\text{total number of fission neutrons}}{\text{number of fission neutrons from just thermal fissions}}$

2) For the final size medium (as a reactor zone) the neutron will escape from the reaction zone =>

$$k = k_\infty P$$

P is a probability for neutrons to stay in the reaction zone – depends on the interia of the reaction zone, geometrical form of reaction zone and surrounding material

Nuclear chain reactions

		$^{234}_{92}\mathrm{U}$	$^{236}_{92}\mathrm{U}$	$^{240}_{94}\mathrm{Pu}$
Thermal neutrons E=0.025 eV	ν	2.52	2.47	2.91
	η	2.28	2.07	2.09
Fast neutrons E=1 MeV	ν	2.7	2.65	3.0
	η	2.45	2.3	2.7

ν– average number of neutrons per one fission event
η - reproduction factor - the number of fission neutrons produced per absorption in the fuel

Possible reactions with neutrons:

- **fission reactions (n,f) – cross section σ_{nf}**
- **radioactive capture (n,γ) - cross section $\sigma_{n\gamma}$**

$$\eta = \nu \frac{\sigma_{nf}}{\sigma_{nf} + \sigma_{n\gamma}}$$

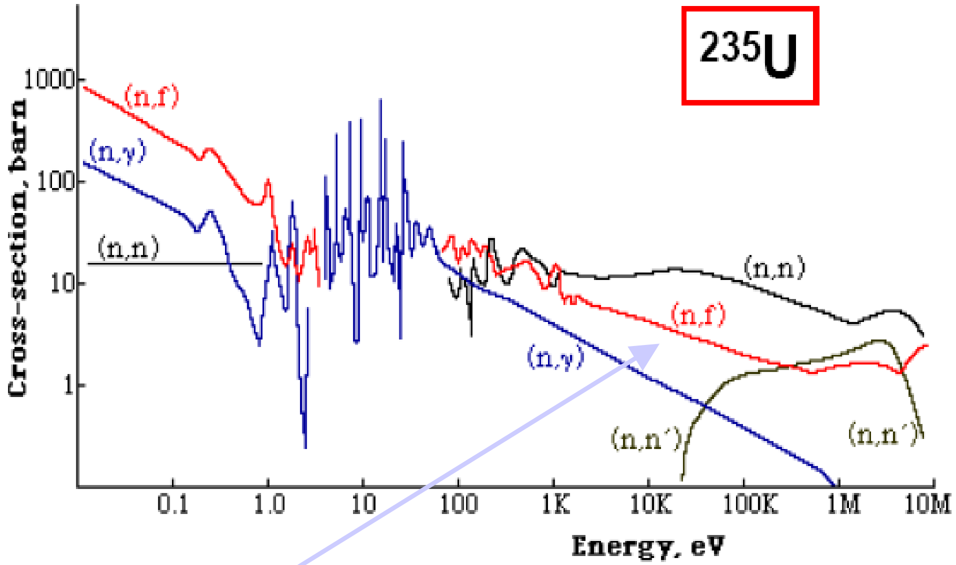
➔ **The chain reactions are possible only if η>1**

η depends on the quality of the fuel: the larger η the better is the fuel

Reactions with neutrons

Produced neutrons:

- thermal E=0.02-0.5 eV
- resonant E=0.5eV-1.0 keV
- fast E =100 keV –14 MeV



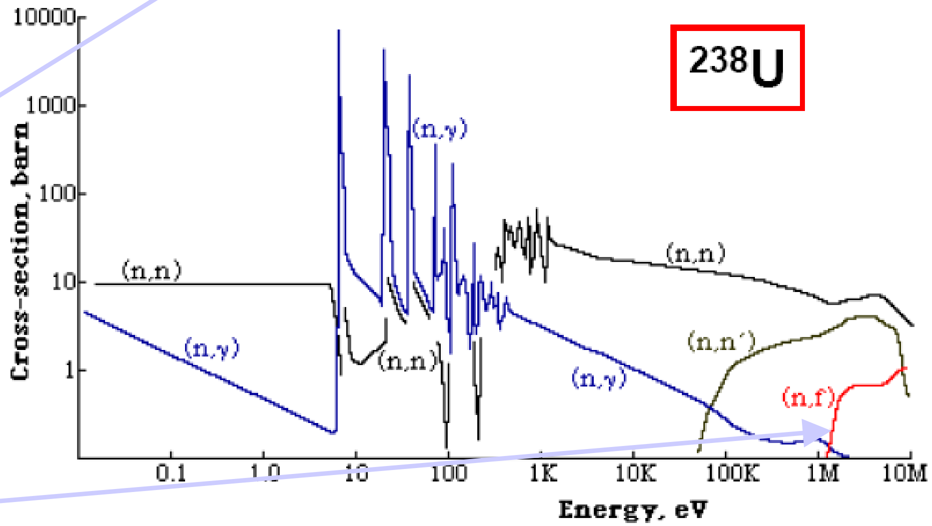
Possible reactions with neutrons:

- fission reactions (n,f)
- radioative capture (n,γ)
- (n,n), (n,n‘)

Radioative capture vs. fission reactions:

1) n + ^{235}U → ^{236}U

radioative capture energy E_{cap} (^{235}U)=6.5 MeV
energy of the fission barrier for ^{236}U is
E_{fb} (^{236}U)= 6.0 MeV → $E_{fb} < E_{cap}$
→the fission of ^{236}U is possible for all energies of incoming neutrons (thermal and fast)



2) n + ^{238}U → ^{239}U

E_{cap} (^{238}U)=6.0 MeV; E_{fb}(^{239}U)=7.0 MeV
→ $E_{fb} > E_{cap}$
→the fission of ^{239}U is possible for fast neutrons with kinetic energy >1 MeV

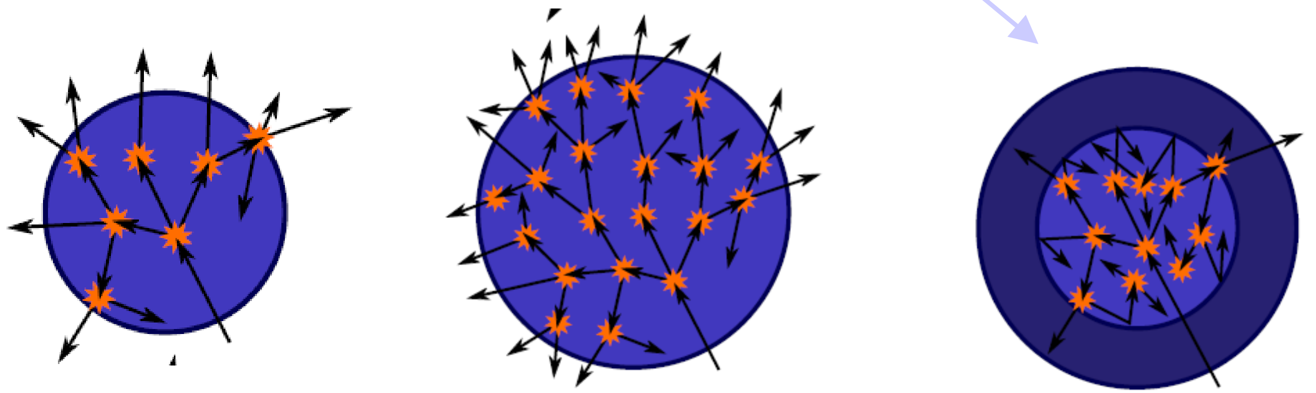
Critical mass, size

Since the neutrons can escape from the reaction zone =>

- **critical size** - the size of the reaction zone such that k=1
- **critical mass** - the mass in the reaction zone such that $P_{crit} = 1/k_{\infty}$

- if $M < M_{crit}$ the chain reactions are impossible
- if $M > M_{crit}$ ➔ uncontrolled reaction => explosion

E.g.: the critical mass for the pure ^{235}U isotop is 47 kg,
however, for ^{235}U surrounded by a reflecting material it is only 242g



Nuclear fuel

Radioactive capture of neutrons by ^{238}U or ^{233}Th decreases the efficiancy of the chain reactions, however, leads to the manufacturing of fuel, i.e. the production of ^{233}U and ^{239}Pu :

$$n + {}^{238}_{92}U \longrightarrow {}^{239}_{92}U \xrightarrow[\beta^-,23min]{} {}^{239}_{93}Np \xrightarrow[\beta^-,2,3days]{} {}^{239}_{94}Pu$$

$$n + {}^{232}_{90}Th \longrightarrow {}^{233}_{90}Th \xrightarrow[\beta^-,22min]{} {}^{233}_{91}Pa \xrightarrow[\beta^-,27days]{} {}^{233}_{92}U$$

In nature there are only 3 isotops - ^{235}U, ^{238}U and ^{232}Th – which can be used as nuclear fuel (^{235}U) or reproduction of fuel (as $^{238}U \rightarrow {}^{239}Pu$; $^{232}Th \rightarrow {}^{233}U$)

- Naturally occuring uranium consists 99.3% of ^{238}U and only 0.7% of ^{235}U, i.e. for 1 nucleus of ^{235}U there are 140 nuclei of ^{238}U

- Consider fission of naturally occuring uranium:

1) by fast neutrons

If the energy of a neutron is larger than 1.4 MeV, the fission of ^{238}U becomes possible →

η reproduction factor: $\eta_{fast}\ (^{238}U) = \frac{140 \cdot \nu \sigma_{nf}^{238}}{\sigma_{nf}^{235} + \sigma_{n\gamma}^{235} + 140(\sigma_{nf}^{238} + \sigma_{n\gamma}^{238})} \cdot 0,6 \cdot \frac{1}{5} \approx 0,27$

$\nu = 2.65, \quad \sigma_{nf}^{235} = 1.2\text{–}1.3\ \text{barn}$

$\eta_{fast}(natur) = \eta_{fast}\ (^{238}U) + \eta_{fast}\ (^{235}U) = 0.27 + 0.03 = 0.3 < 1$

$\sigma_{nf}^{238} = 0.6\ \text{barn}, \quad \sigma_{n\gamma}^{235} \approx \sigma_{n\gamma}^{238} \approx 0.6\ \text{barn}$

→ Chain reactions by fast neutrons on naturally occuring uranium are impossible!

Nuclear fuel

2) fission by thermal neutrons on naturally occuring uranium:

$$\eta_{thermal}\,(\text{nature}) = \frac{\nu\sigma_{nf}^{235}}{\sigma_{nf}^{235} + \sigma_{n\gamma}^{235} + 140(\sigma_{n\gamma}^{238} + \sigma_{nf}^{238})}$$

$\nu = 2.47, \quad \sigma_{nf}^{235} = 580\,\text{barn}$

$\sigma_{n\gamma}^{235} = 112\,\text{barn}, \quad \sigma_{n\gamma}^{238} = 2.8\,\text{barn}, \quad \sigma_{nf}^{238} = 0$

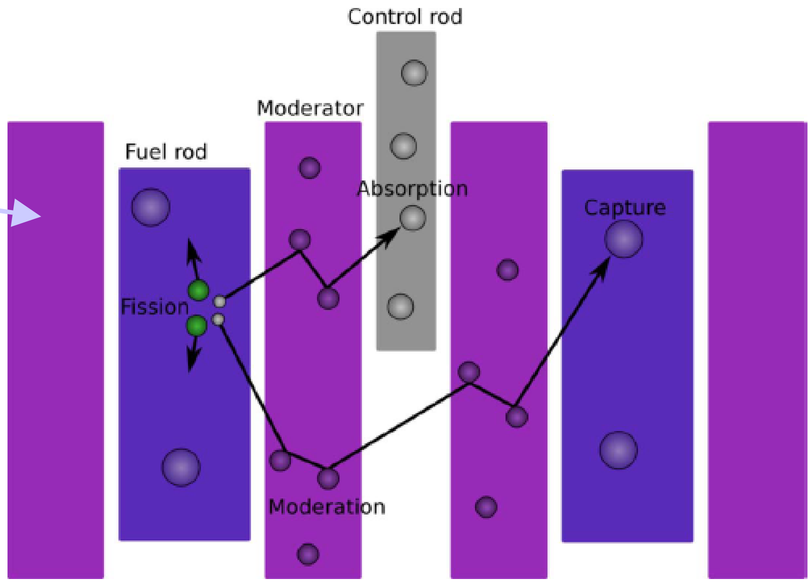
$\eta_{thermal}\,(\text{nature}) = 1.32 > 1$

➔ Chain reactions by thermal neutrons on naturally occuring uranium are possible !

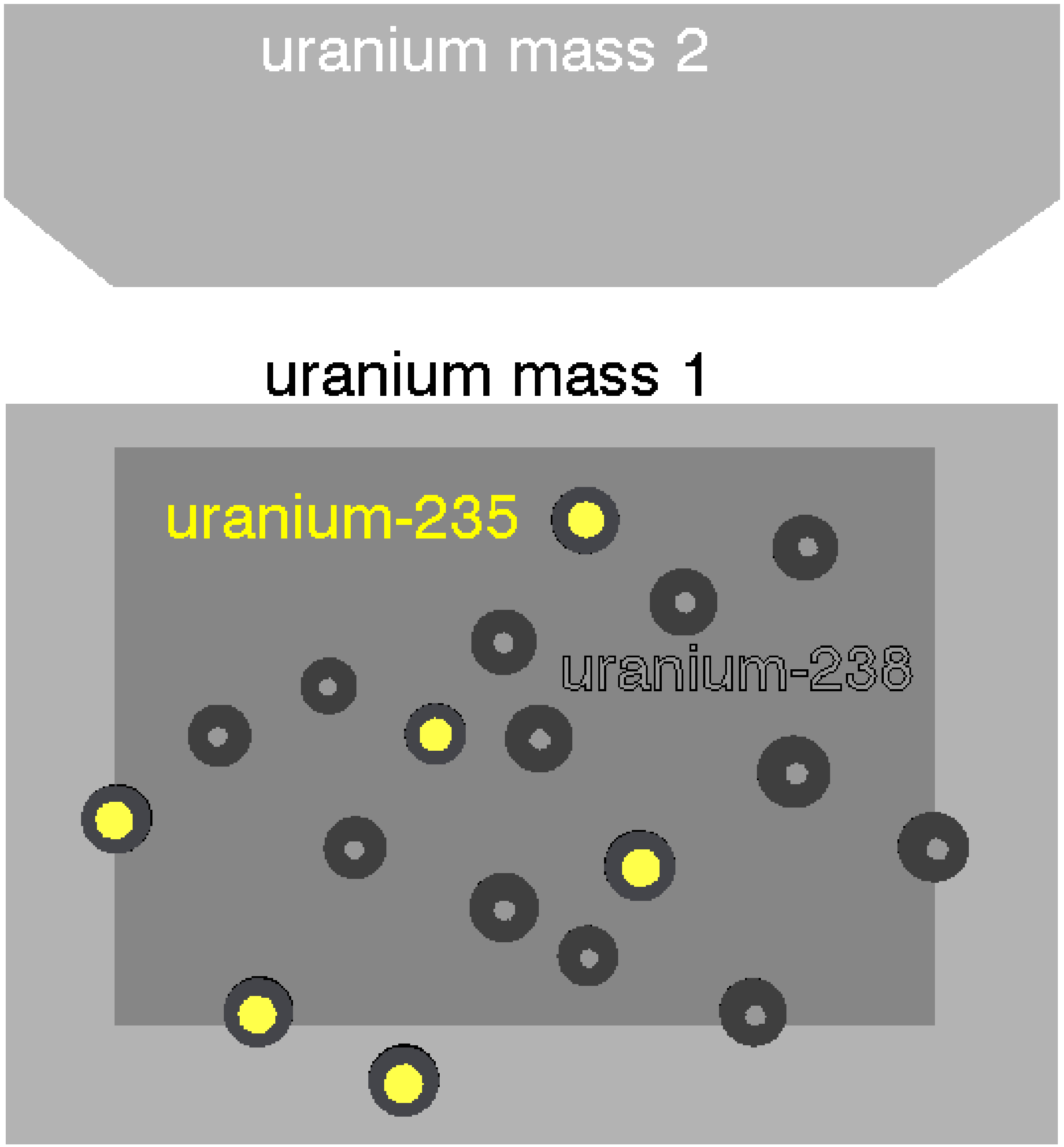
In order to use the naturally occuring uranium as a nucler fuel, one needs to slow down the fast neutrons to thermal energies

❑ In nuclear reactors there are neutron moderators, which reduce the velocity of fast neutrons, thereby turning them into thermal neutrons

Moderator materials: graphite, water

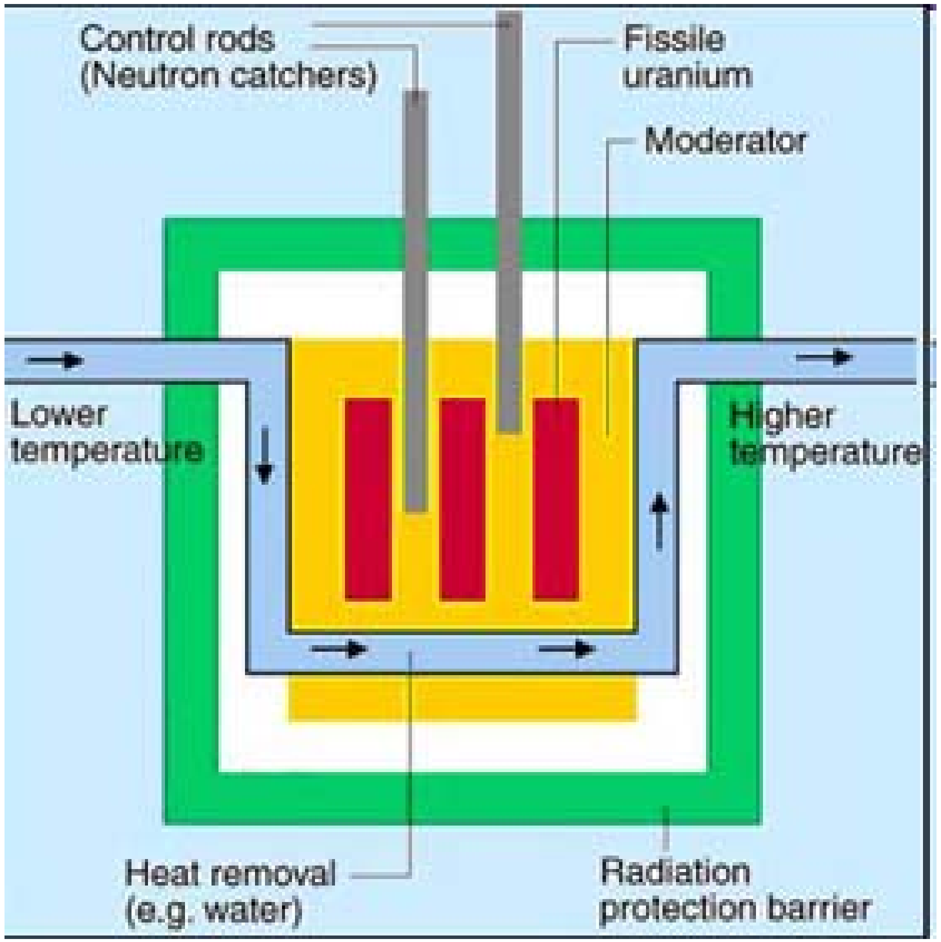


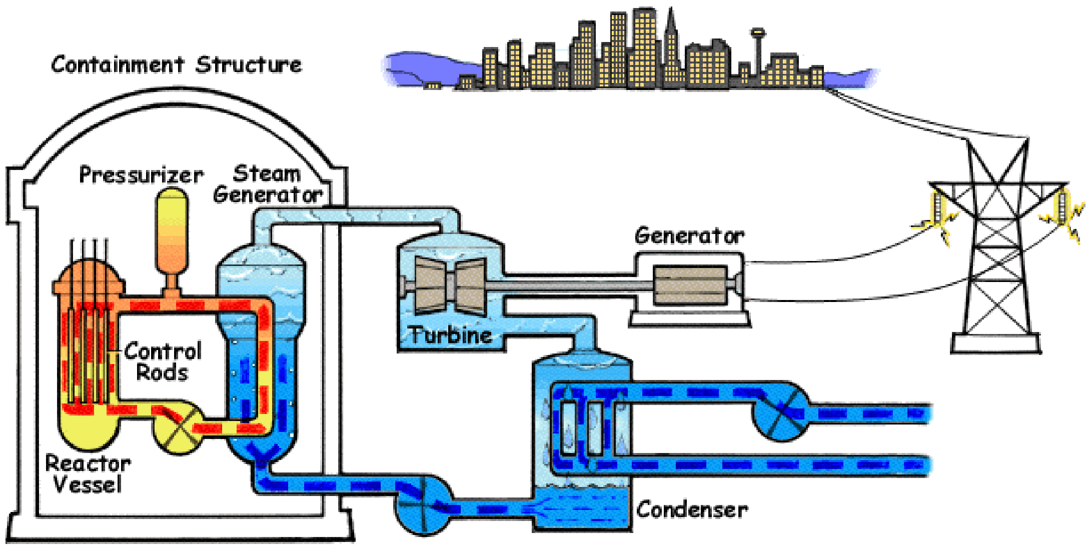
Nuclear reactor



Nuclear reactor

A nuclear reactor is a device to initiate and control a sustained nuclear chain reaction for the generation of electric energy. Heat from nuclear fission is used to producecreate electri steam, which runs through turbines and create electrity.

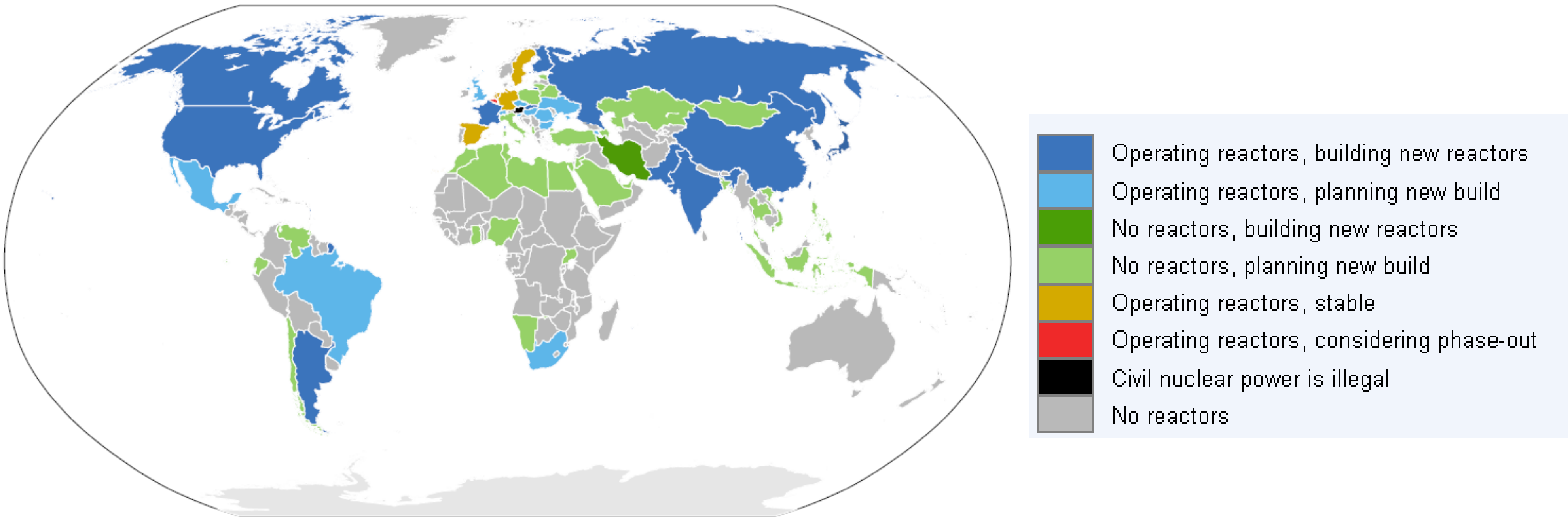




Nuclear power plants

Nuclear power plants currently use nuclear fission reactions to heat water to produce steam, which is then used to generate electricity

Nuclear power provides about 6% of the world's energy and 13–14% of the world's electricity.



Nuclear and radiation accidents

Nuclear power plant accidents include :

- **three Mile Island accident, US (1979)**
- **the Chernobyl disaster, Ukrain (1986),**
- **Fukushima I nuclear accidents, Japan (2011)**