# Nuclear physics

Radioactive decay – alpha, beta, gamma, radioactive decay law, half-life, detectors of radioactive radiation, binding energy of nucleus, absorbed and effective dose.

# Nuclear physics

Nuclear physics is specialized on the processes in nucleus

- nucleus decay and its transformation
- fusion and fission reactions
- nucleus structure by elementary particles
- reaction between elementary particles
- medical and industrial applications
-…

# Atom structure

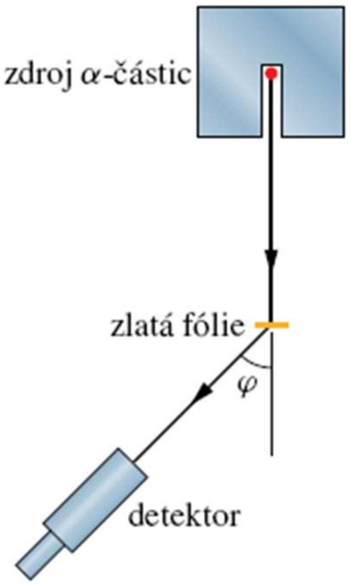
- Nucleus ($10^{-15}$m), nucleons (proton, neutron), most of the atom mass
- Electron orbitals ($10^{-12}$m), elektrons with specific energy levels (shells, subshells), electrons are responsible for the radiation spectra, periodic table of elements – ordering by atom number Z

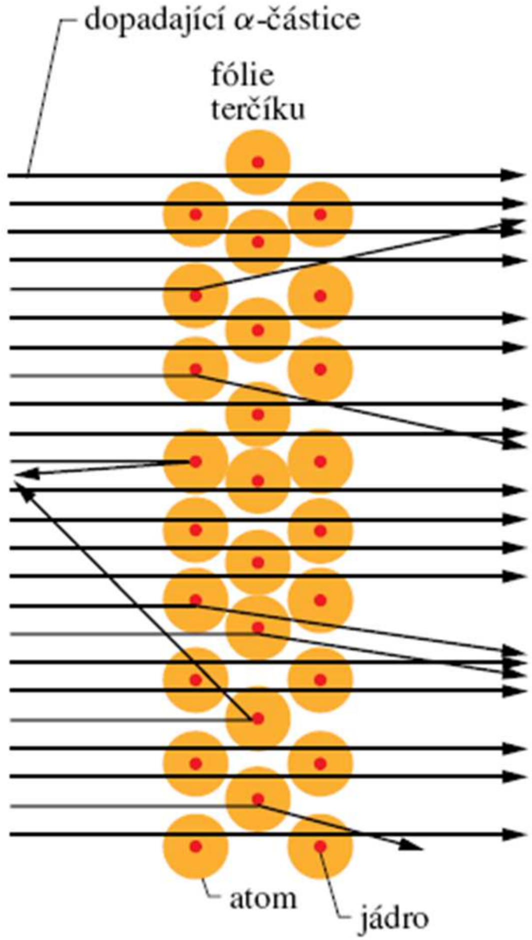
# Atom nucleus

Rutherford 1911

α-particle scattering

at Au-foil



# Nucleus size

Scattering experiments by E.Rutherford – nucleus size of the order $5\cdot10^{-14}$m

Electron is located inside bigger region of the diameter $5\cdot10^{-11}$m because of Heisenberg uncertainty principle

No information about nucleus structure from scattering experiment

# Nucleus properties

- Mass – atomic mass number A=Z+N
- Electric charge – atomic number Z

$$^{A}_{Z}X$$

Nuclide – radioactive nuclide (radionuclide)

Example: $^{12}C$, $^{13}C$, $^{14}C$ – different masses of nuclei

Separation of nuclei in mass spectrometer – possibility to measure specific charge of particle (ratio of charge per mass)

Neutron number N = number of neutrons in nucleus

# Nucleus structure

Hydrogen $^1_1H$ – single proton

Helium $^4_2He$ - charge +2$e$, but mass higher than two protons

1932 – J.Chadwick suggested new nuclear particle without charge – neutron

Electrically neutral, mass approximately the same as proton, spin ½

Neutron is not stable outside nucleus, it decomposes during 10.8 min into proton, electron and antineutrino $n \to p^+ + e^- + \bar{\nu}$

# Stability of nucleus

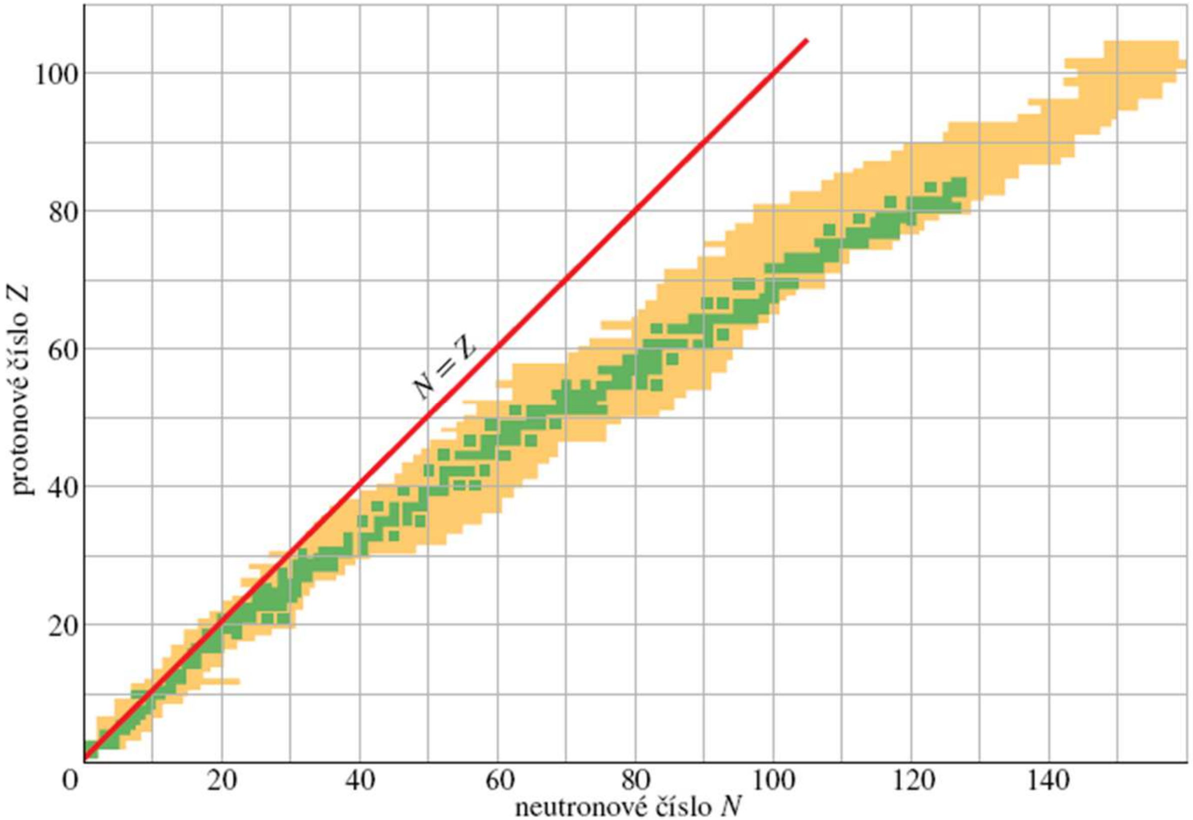
Very close packing of charged protons require very strong nuclear forces (short range forces) – compensation of electrostatic repulsive forces

Nucleons must follow Pauli exclusion principle, i.e. nuclei with higher number of nucleons have higher energies

Neutrons stabilize nucleus structure – stability of nuclei with approximately the same number of neutrons and protons

# Nuclides chart

Stability up to Z=83 (Bi) – no stability above



# Nuclear binding energy

Energy of particular nucleons alone minus energy of nucleus

$$Q = \Delta m c^2$$

Comparison by the binding energy per nucleon

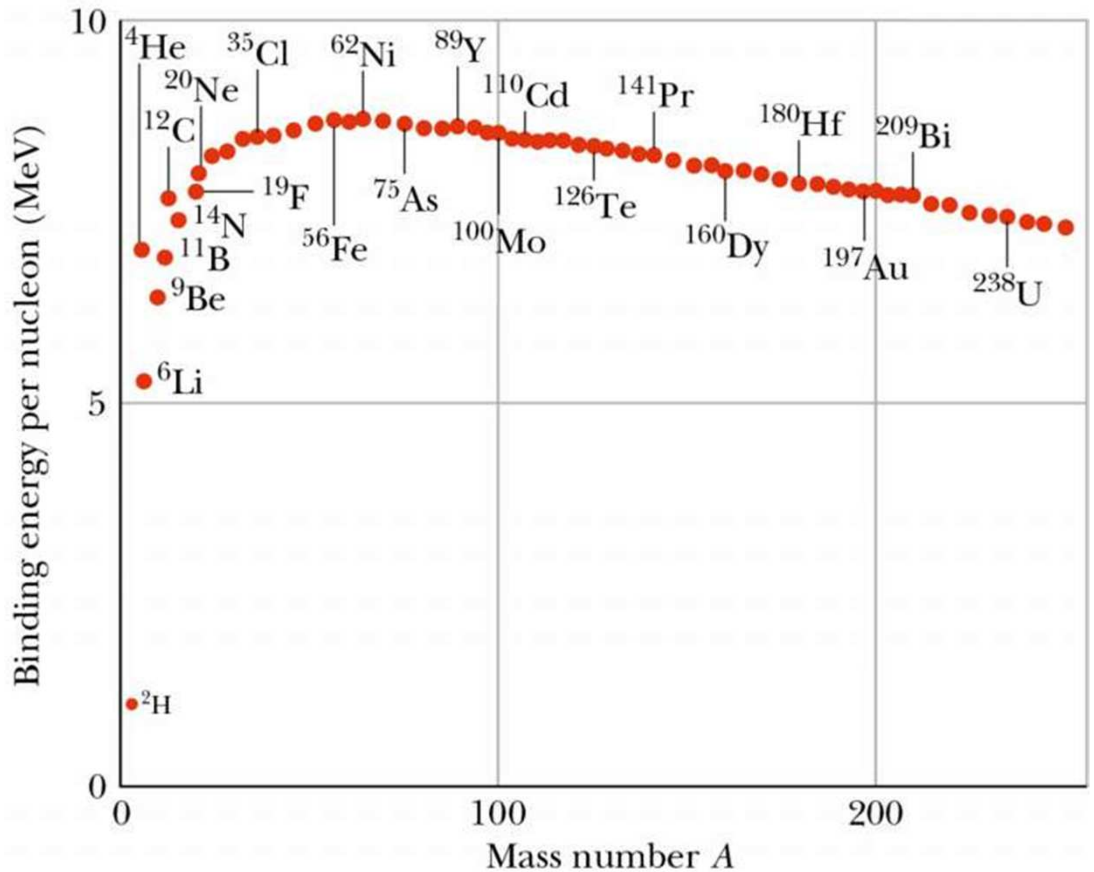
Most stable isotope ${}^{62}_{28}Ni$, $Q = 8.8$MeV/nucleon

# Binding energy

$^{62}_{28}Ni$

fission

fusion



# Radioactive decay

Nucleus changes its energy

Decay rate

$$-\frac{\mathrm{d}N}{\mathrm{d}t} = \lambda N$$

$$N = N_0 \mathrm{e}^{-\lambda t}$$

Activity

$$R = -\frac{\mathrm{d}N}{\mathrm{d}t} = \lambda N_0 \mathrm{e}^{-\lambda t}$$

Unit 1Bq = 1 decay per second (Becquerel)

Probability law – no way how to find out what nucleus will decay and when

# Half-life

Defined as the time it takes for half the original amount of parent isotope in a given sample to decay.

Half-life and decay constant relationship

$$\tau = \frac{\ln 2}{\lambda}$$

# Types of radioactive decay

- α-decay

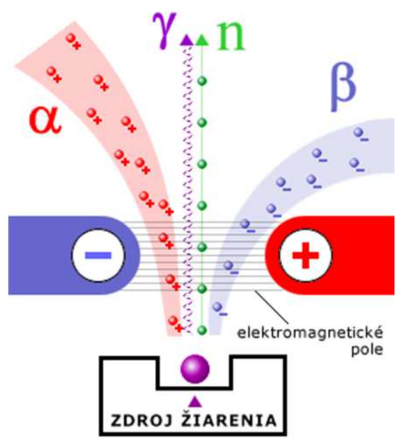
Charged α-particles $He^{2+}$ $^{238}U \rightarrow {}^{234}Th + {}^{4}He, \quad Q = 4{,}25\ MeV$

- β-decay ($\beta^{+}$, $\beta^{-}$)

Charged particles – electron, positron

$$^{32}P \rightarrow {}^{32}S + e^{-} + \nu \quad (\tau = 14{,}3\ d)$$

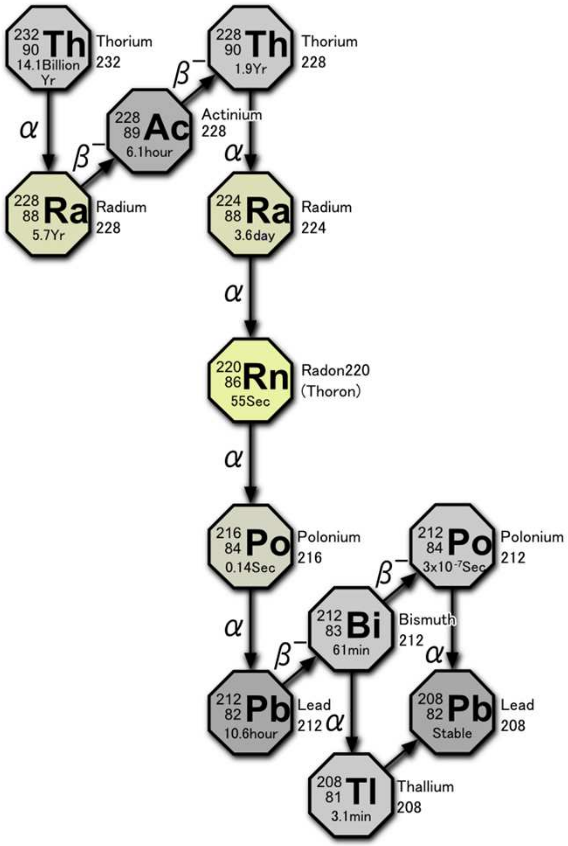
$$^{64}Cu \rightarrow {}^{64}Ni + e^{+} + \nu \quad (\tau = 12{,}7\ h)$$

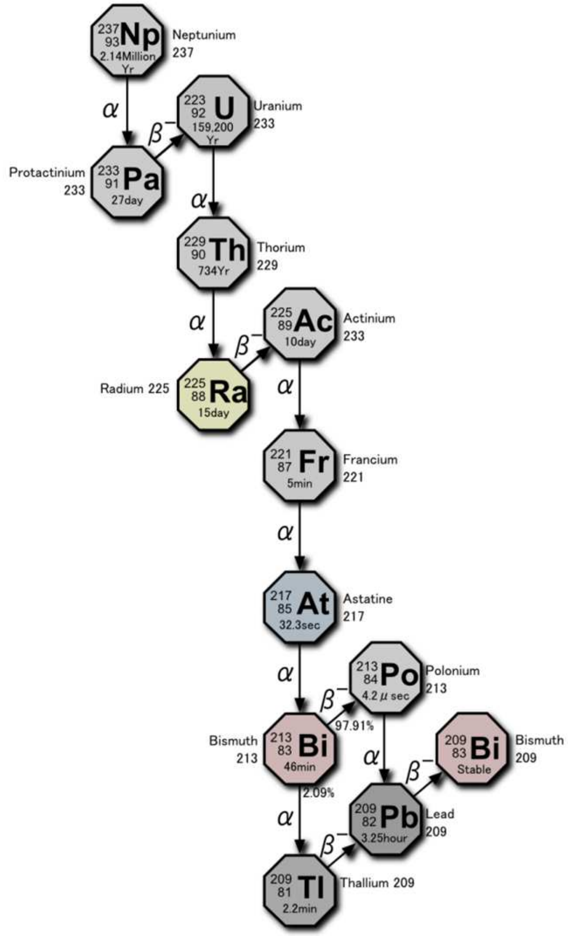


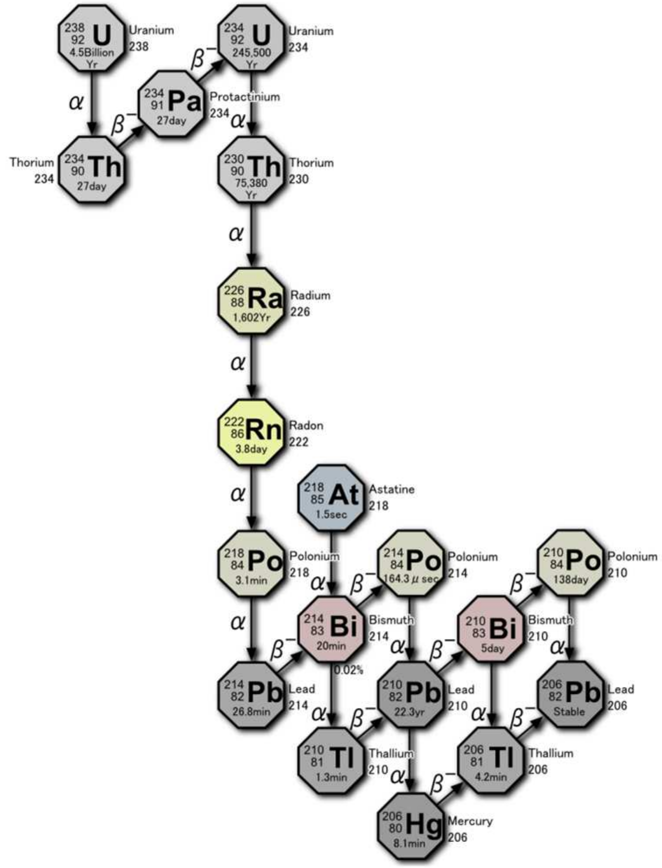

- γ-decay

Neutral radiation – photons of short wavelength electromagnetic radiation

# Decay series



# Radioactive dating

Based on the measurement of ratio between isotopes – common $^{12}_{6}C$ and rare $^{14}_{6}C$

Half-life $^{14}_{6}C$ is 5730 years

Commonly 1 nucleus of $^{14}_{6}C$ is found per $10^{13}$ nuclei of common isotope $^{12}_{6}C$

$^{14}_{6}C$ is created in atmosphere from nitrogen nuclei during their collisions with cosmic radiation particles

# Dosimetry

- Absorbed dose = absorbed energy of radiation per unit mass (units gray)

Natural radioactive background = 0.002Gy

$$1\,\mathrm{Gy} = 1\,\mathrm{J/kg} = 100\,\mathrm{rad}.$$

- Effective dose = absorbed dose multiplied by the factor of relative biological effectiveness (RBE) - RBE=1 (units sievert)

(RTG, elektrons), RBE=5 (neutrons), RBE=10 (α-particle)

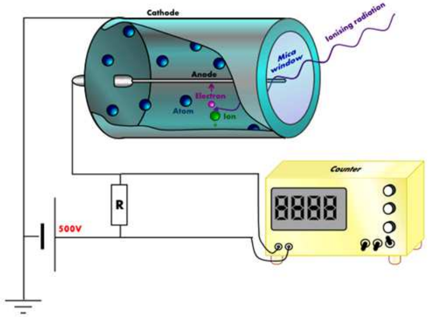
$$1\,\mathrm{Sv} = 100\,\mathrm{rem}.$$

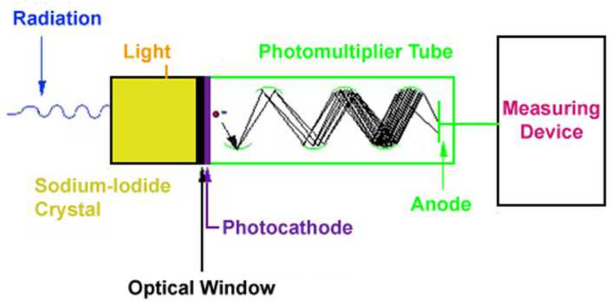
# Detection of particles

Geiger counter – charged capacitor is discharged by the current created at the interactions between particle and gas molecules in it

Wilson cloud chamber – condensation around path of particle in saturated vapour

Scintilators – recombination of particle and charge carrier in semiconductor, photon is multiplied



# Nuclear energy

- Fission of heavy nuclei into lighter fission fragments, radioactivity influenced by neutrons (used for about 60 years, radioactive waste )

- Fusion of very light nuclei (in small scale experiments)

# Chain reaction

Fission of uranium nuclei by neutrons – avalanche reaction $^{235}\mathrm{U} + \mathrm{n} \rightarrow {}^{236}\mathrm{U} \rightarrow {}^{140}\mathrm{Xe} + {}^{94}\mathrm{Sr} + 2\mathrm{n}$.

$$^{140}\mathrm{Xe} \rightarrow {}^{140}\mathrm{Cs} \rightarrow {}^{140}\mathrm{Ba} \rightarrow {}^{140}\mathrm{La} \rightarrow {}^{140}\mathrm{Ce}$$

| $\tau$ | 14 s | 64 s | 13 d | 40 h | stabilní |
|---|---|---|---|---|---|
| $Z$ | 54 | 55 | 56 | 57 | 58 |

$$^{94}\mathrm{Sr} \rightarrow {}^{94}\mathrm{Y} \rightarrow {}^{94}\mathrm{Zr}$$

| $\tau$ | 75 s | 19 min | stabilní |
|---|---|---|---|
| $Z$ | 38 | 39 | 40 |

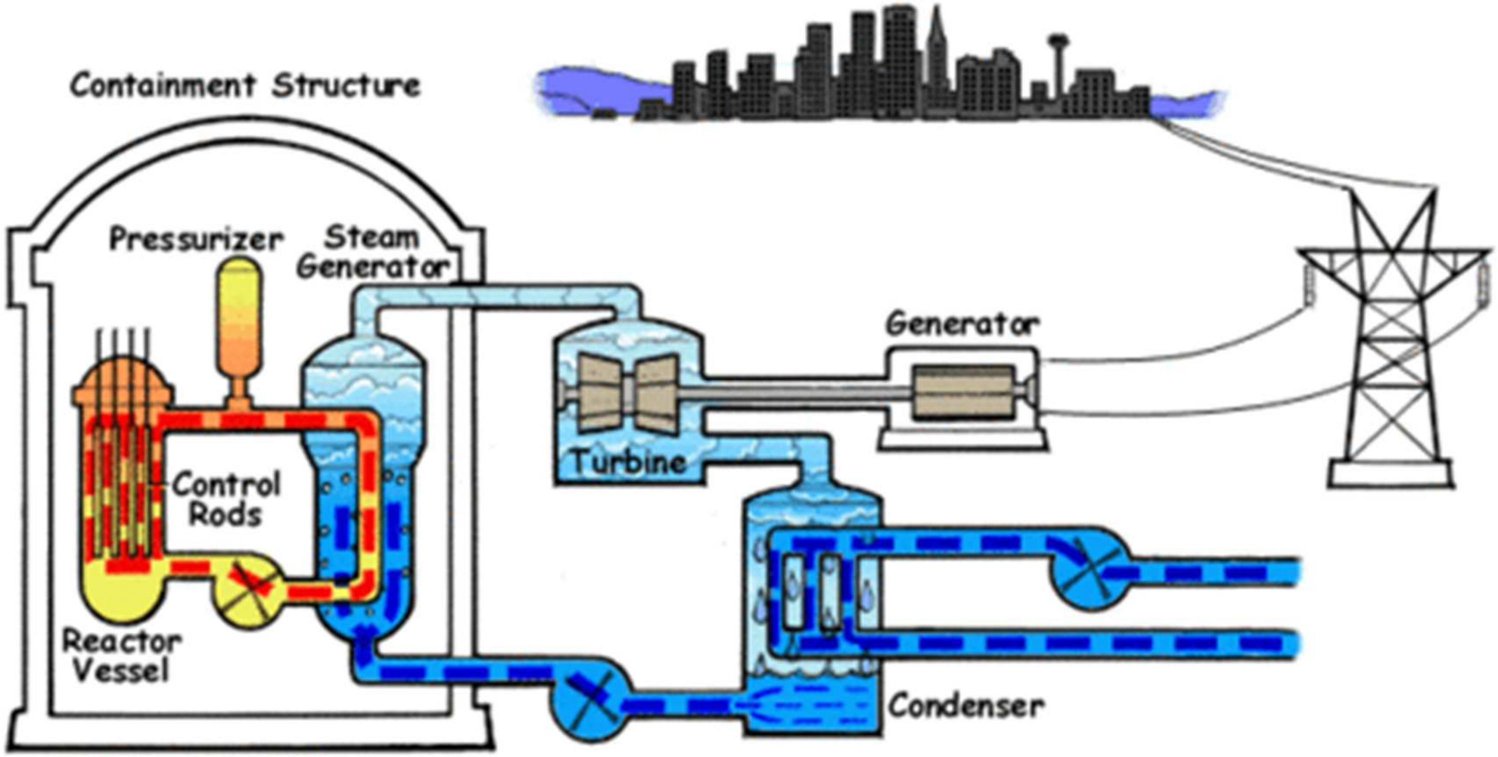
Energy created A≈240, 7.6MeV, A≈120, 8.5MeV

$$Q = 2(8{,}5\,\mathrm{MeV})(120) - (7{,}6\,\mathrm{MeV})(240) \doteq$$
$$\doteq 200\,\mathrm{MeV}.$$

# Chain reaction

- Critical mass – to ensure neutrons ratio
- Moderator – slow down of neutrons, higher probability of their absorption
- Uranium – enriched mixture of isotopes $^{238}_{92}U$ (99.3%) and $^{235}_{92}U$ (natural resources only 0.72%, increase up to 3%)
- Control rods – control of neutron number close to the critical state of reactor – control of chain reaction, absorptive material (boron, cadmium)

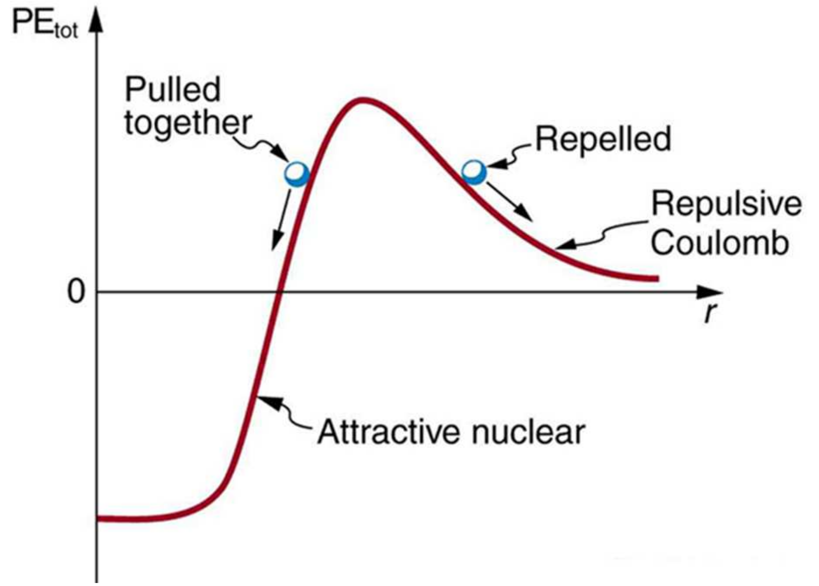
# Nuclear power station



# Thermonuclear fusion

Fusion of light nuclei – in Tokamak fusion reactor

Very high potential barrier when nuclei get into contact, e.g. hydrogen (400keV) - necessary to add high energy to particles by heating to very high temperature




Fusion in nature - Sun

# Thermonuclear fusion

Reactions

Deuterium – Tritium

$$ {}_1^2H + {}_1^3H \rightarrow {}_2^4He\,(3.5MeV) + {}_0^1n\,(14.1MeV) $$

Neutron – Lithium

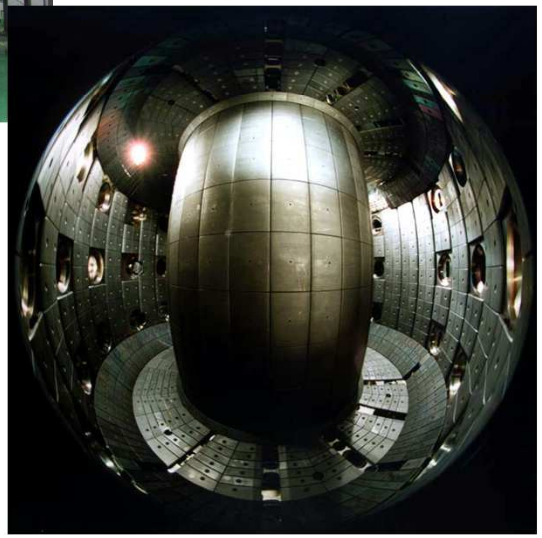
$$ {}_0^1n + {}_3^6Li \rightarrow {}_1^3H\,(2.75MeV) + {}_2^4He\,(2.05MeV) $$

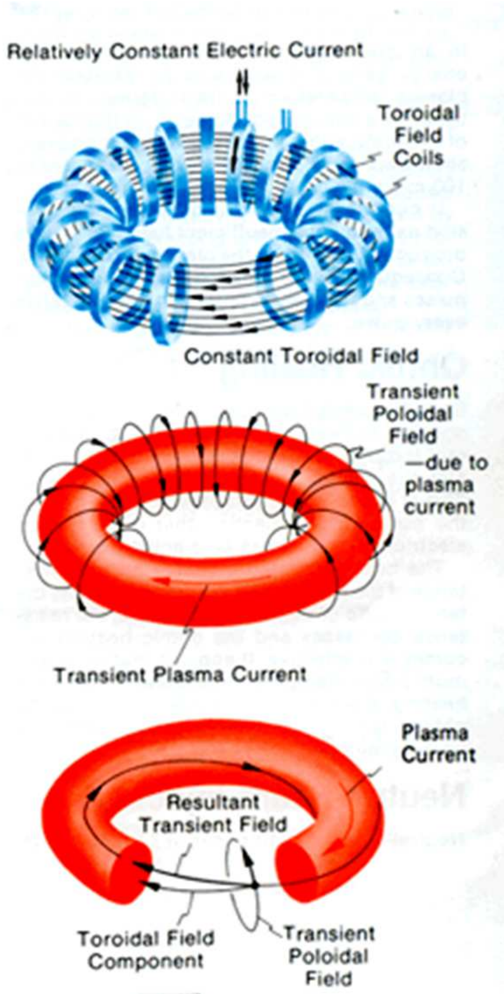
Total energy balance

$$ {}_1^2H + {}_3^6Li \rightarrow 2\ {}_2^4He + 22.4MeV $$

# Tokamak

„Toroidalnaja kamera s magnitnymi katuškami“





# Literature

Pictures used from the book:

HALLIDAY, D., RESNICK, R., WALKER, J.: Fyzika (část 5 – Moderní fyzika), Vutium, Brno 2000