Engineering Physics
Physics for Forestry

Nuclear Physics

Nuclear Physics

The structure of the atom

- atoms - nucleus - protons and neutrons

  - shell - electrons

- nuclear physics - processes at the level of atomic nuclei
- atomic physics - processes at the level of electron shells of atoms
- protons - one positive elementary electric charge
- electrons - one negative elementary charge
- neutrons - without electric charge
- the number of protons in the nucleus - the proton number Z - uniquely determines which element it is
- the number of neutrons in the nucleus - the neutron number N - can differ for individual atoms of the same element, then they are different isotopes of the same element

Nuclear Physics

- sum of protons and neutrons - nucleon number *A*

- schematic designation of the element nucleus: $^{A}_{Z}X$

- neutral atom - the number of electrons in the shell is the same as the number of protons in the nucleus

- positive ion - fewer electrons than protons - the positive charge of the nucleus predominates and the atom appears positively charged

- negative ion - more electrons than protons - the negative charge of the shell predominates and the atom appears negatively charged

- mass of protons and neutrons about 1800 times greater than the mass of electrons $\Rightarrow$ almost all the mass of an atom is concentrated in the nucleus

- atomic diameters – about 10^{-10} m

- nucleus diameters – about 10^{-15} m

Nuclear Physics

Radioactivity

- nuclide - a collection of atoms with the same number of protons and the same number of neutrons

- nuclide - e.g. a collection of atoms ${}^{235}_{92}U$ with 92 protons, 143 neutrons

- isotopes - nuclides of the same element (i.e. with the same number of protons), with different numbers of neutrons

- individual isotopes of elements either occur in nature or can be created artificially

- isotopes differ in physical properties, such as the stability of the nucleus

- stability of the nucleus - the ability of the core to remain in an unchanging state

- neutrons affect the distances of individual protons and thus the force ratios in the atomic nucleus – if the force conditions are unfavourable, the nucleus is unstable and will spontaneously transform into a more stable nucleus over time

Nuclear Physics

- radionuclides - unstable nuclides whose nuclei undergo spontaneous transformation accompanied by the emission of radiation

- radioactivity - the ability of unstable nuclei to spontaneously transmute

- the transformation can produce a nucleus that is again unstable or completely stable

General laws of radioactive transformations

- naturally occurring radioactive radionuclides - found in nature

x artificial radionuclides

- the conversion of radionuclides results in the emission of alpha particles (helium nuclei) or electrons or positrons, as well as high-energy photons (gamma radiation)

- radioactive transformations - in the nuclei of atoms, independent of external conditions

- random processes - governed by the laws of statistics; it is not possible to predict for individual nuclei whether they will transform or not in a certain time interval

Nuclear Physics

- decrease in the number of untransmuted radioactive nuclei -d*N* from the original number *N* in time d*t*: - dN = $N\lambda$ d$t \Rightarrow$

$\Rightarrow$ transformation (decay) law: $N = N_0 e^{-\lambda t}$, where

***N* - instantaneous number of original nuclei in time *t*,**

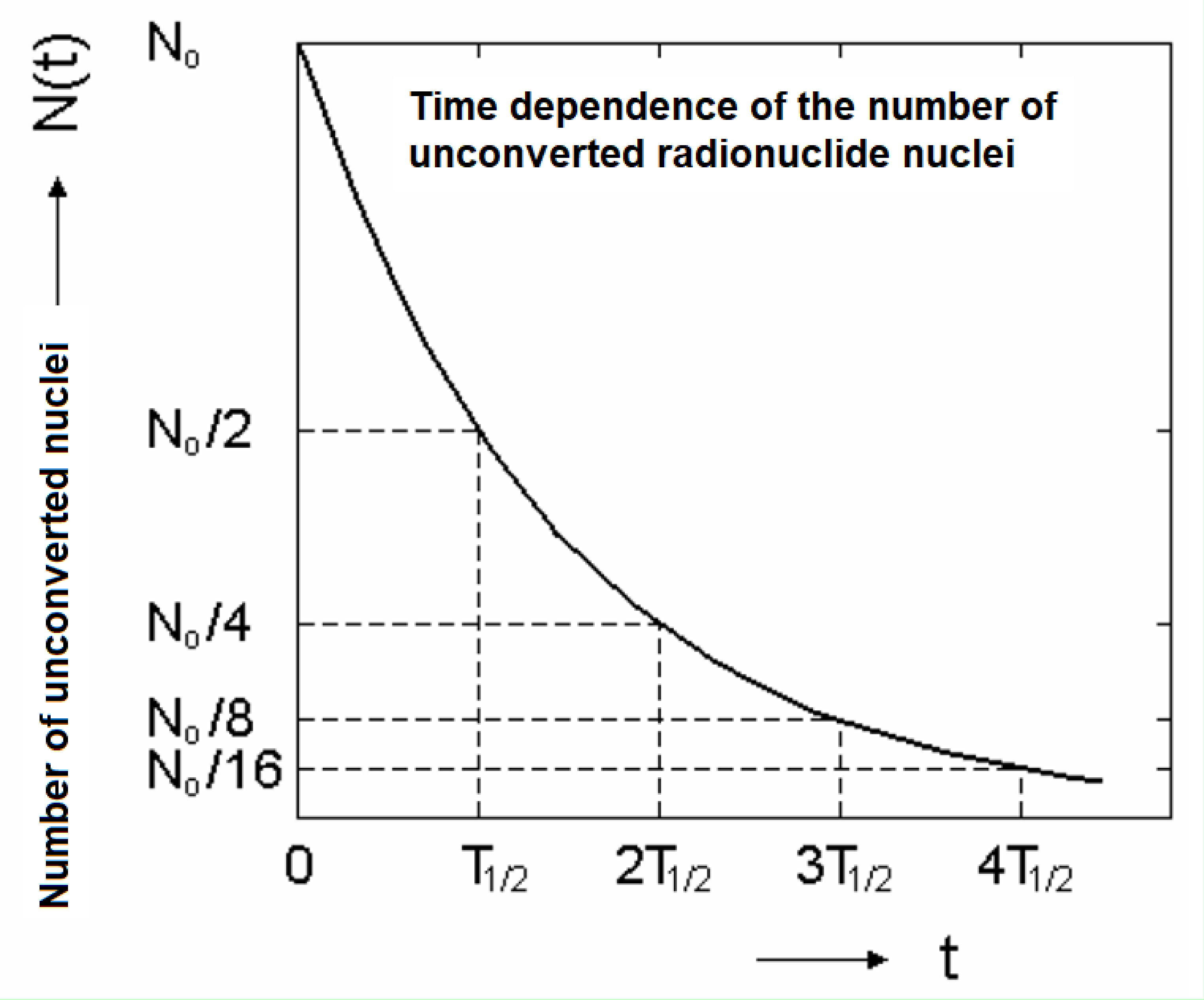
N_0 - original number of nuclei in time 0

λ - decay constant expressing the rate of conversion of a given radionuclide

- radionuclide characteristics - half-life $T_{1/2}$ - the mean time for the original number of atoms of a given radionuclide to be halved

- after substitution into the decay law: $T_{1/2} = \frac{\ln 2}{\lambda}$

Nuclear Physics



Nuclear Physics

Example 11.31:

The $T_{1/2}$ half-life of the radionuclide $^{90}_{38}Sr$ is 29 years. Calculate its decay constant λ.

[$\lambda = 7.58 \cdot 10^{-10}\ s^{-1}$]

Nuclear Physics

- the $T_{1/2}$ half-life value is characteristic of a particular radionuclide
- half-lives of known radionuclides over a wide range $T_{1/2} \approx 10^{-7} - 10^{22}$ s

Examples of half-life values for selected radionuclides:

Radionuclide	$^{232}_{90}Th$	$^{90}_{38}Sr$	$^{13}_{7}N$	$^{6}_{2}He$	$^{212}_{84}Po$
Halftime of conversion	$1,4 \,.\, 10^{10}$ years	28 years	0,9993 min	0,823 s	$3 \,.\, 10^{-7}$ s

- according to the mode of radioactive conversion, alpha conversion and beta conversion are distinguished

Alpha conversion

- particle α (nucleus $^{4}_{2}He$) emitted from the nucleus
- the nucleon number decreases by 4 and the proton number decreases by 2
- specific example: $^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}He$

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- energy of emitted α particles – in the range 4 - 9 MeV

- alpha conversion is exclusively for heavy radionuclides

<u>Beta conversion</u>

- the nucleon number of nucleus *A* does not change, only the proton number *Z* changes

***-* conversion of beta in two different ways:**

1) conversion of β^- **- electron and antineutrino emission from the nucleus**

- the neutron turned into a proton and the electron (electron is particle β^-)

- specific example: $^{60}_{27}Co \rightarrow {}^{60}_{28}Ni + {}^{0}_{-1}e + \overline{\nu}$, $T_{1/2}$ = 5.26 year

Nuclear Physics

Beta conversion

2) conversion of β^{+} **- positron and neutrino emission from the nucleus**

- positron - antiparticle to electron

- the proton turned into a positron and a neutron (positron is particle β^{+}**)**

- specific example: ${}^{22}_{11}Na \rightarrow {}^{22}_{10}Ne + {}^{0}_{1}e + \nu$, $T_{1/2}$ **= 2.58 year**

- energy of emitted β **particles max. units of MeV**

- beta conversion is even for lighter radionuclides

Nuclear Physics

Oxygen isotopes, their abundance in nature and, for unstable ones, the types of conversions:

Isotope	$^{13}_{8}O$	$^{14}_{8}O$	$^{15}_{8}O$	$^{16}_{8}O$	$^{17}_{8}O$	$^{18}_{8}O$	$^{19}_{8}O$	$^{20}_{8}O$
% representation in nature	0	0	0	99,40	0,40	0,20	0	0
Type of conversion	β^{+}	β^{+}	β^{+}	stable			β^{-}	β^{-}

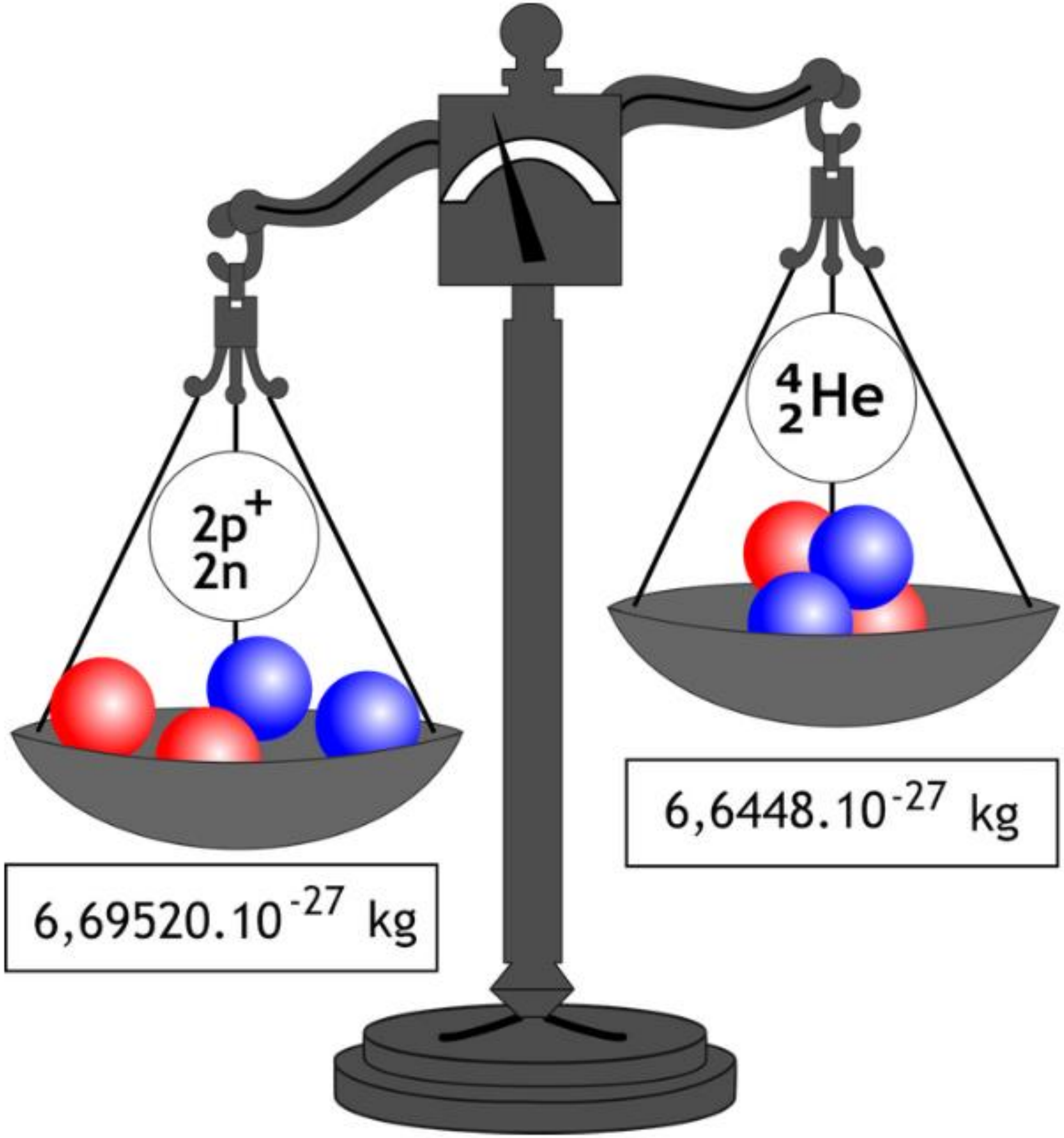
Nuclear Physics

Gamma ray emission

- usually accompanies alpha or beta transformations

- excess energy is emitted after the transition to the ground state in the form of gamma rays, i.e. photons with very short wavelengths and energies up to several MeV

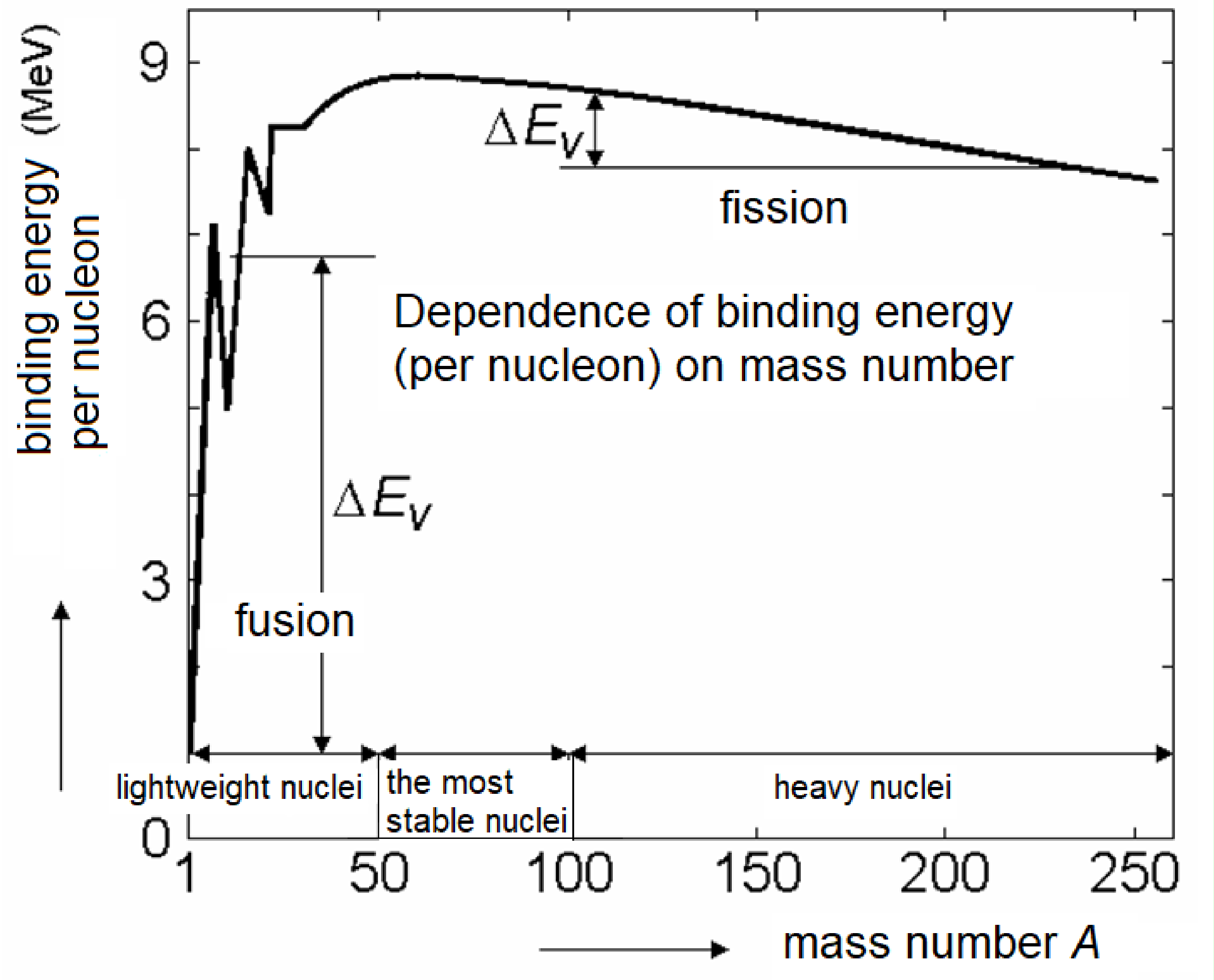
- specific example: $^{222}_{86}Rn(\text{excited state}) \rightarrow {}^{222}_{86}Rn(\text{basic state}) + \gamma$



The free nucleons are heavier than the nucleus formed from them.

Nuclear Physics

Release of nuclear energy



Example of fusion: $^{2}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He$

Example of fission: $^{235}_{92}U \rightarrow ^{144}_{57}La + ^{89}_{35}Br + 2\,^{1}_{0}n$

Nuclear Physics

- energy can be released by combining light nuclei into heavier ones, which are in the region of the most stable nuclei, or by splitting heavy nuclei into lighter ones again in the region of the most stable nuclei - see Fig.

- fusion of light nuclei - thermonuclear reaction or nuclear fusion - takes place spontaneously in the nuclei of stars

- the mass of the Sun consists mainly of hydrogen nuclei and free electrons; a small fraction of helium nuclei and traces of lithium nuclei

- a high temperature of the order of 10^7 K is necessary for nuclear fusion, because the nuclei are positively charged and must have sufficient energy to overcome the repulsive electrostatic forces and come within the range of the nuclear forces, i.e. at a distance of 10^{-15} m

Nuclear Physics

Example 11.19:

The deuteron consists of one proton and one neutron. When this particle is assembled from both simpler ones, the so-called mass loss Δm occurs, i.e. the sum of the rest masses of the proton m_p and the neutron m_n is just Δm greater than the rest mass of the deuteron m_d. Calculate the binding energy of the deuteron nucleus.

Values from the tables for the rest masses of the three particles and the speed of light c:

$m_p = 1.6722 \cdot 10^{-27}$ kg,

$m_n = 1.6744 \cdot 10^{-27}$ kg,

$m_d = 3.3426 \cdot 10^{-27}$ kg,

$c = 3 \cdot 10^8$ m/s.

[$E = 2.25$ MeV]

NUCLEAR FISSION AND FUSION

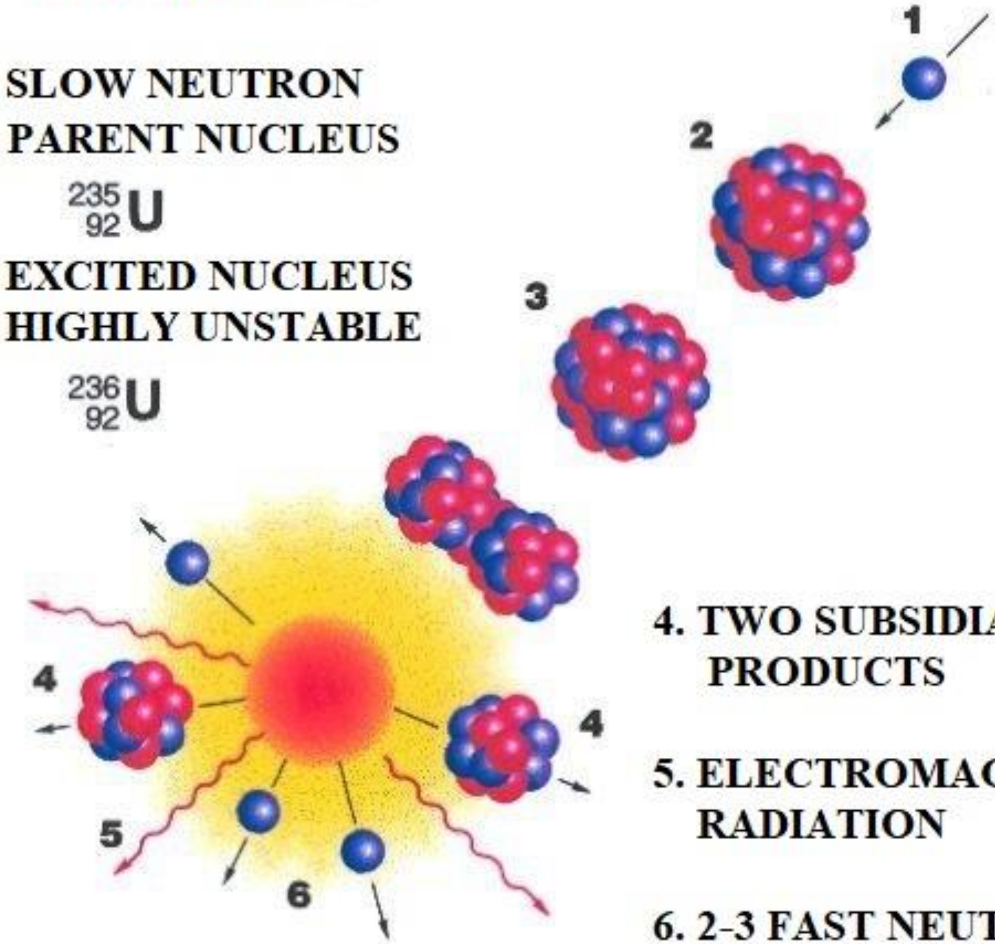
FISSION

1. SLOW NEUTRON
2. PARENT NUCLEUS

   $^{235}_{92}U$

3. EXCITED NUCLEUS HIGHLY UNSTABLE

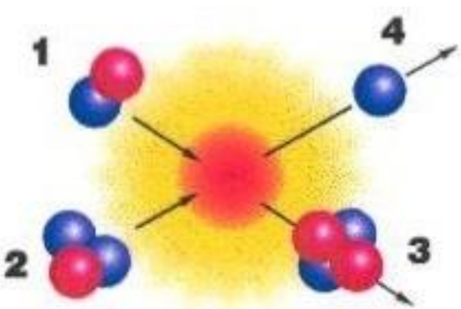
   $^{236}_{92}U$



4. TWO SUBSIDIARY PRODUCTS
5. ELECTROMAGNETIC RADIATION
6. 2-3 FAST NEUTRONS

FUSION

1. DEUTERON $^{2}_{1}D$
2. TRITIUM NUCLEUS $^{3}_{1}T$
3. HELIUM NUCLEUS (particle α) $^{4}_{2}He$
4. NEUTRON $^{1}_{0}n$



Nuclear Physics

Examples of some of the reactions taking place in the Sun's core and the amount of energy released:

${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}D + e^{+} + \nu_{e} + \gamma$
${}^{2}_{1}D + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + \gamma$
${}^{3}_{2}He + {}^{1}_{1}H \rightarrow {}^{4}_{3}Li + \gamma$
${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{2}He + {}^{1}_{0}n + 3{,}26\ \mathrm{MeV}$
${}^{2}_{1}D + {}^{2}_{1}D \rightarrow {}^{3}_{1}T + {}^{1}_{1}H + 4{,}03\ \mathrm{MeV}$
${}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + 17{,}6\ \mathrm{MeV}$
${}^{2}_{1}D + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + {}^{1}_{1}H + 18{,}4\ \mathrm{MeV}$
${}^{6}_{3}Li + {}^{2}_{1}D \rightarrow {}^{4}_{2}He + {}^{4}_{2}He + 22{,}4\ \mathrm{MeV}$
${}^{6}_{3}Li + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + {}^{4}_{2}He + 4{,}02\ \mathrm{MeV}$
${}^{7}_{3}Li + {}^{2}_{1}D \rightarrow {}^{4}_{2}He + {}^{4}_{2}He + {}^{1}_{0}n + 14{,}9\ \mathrm{MeV}$
${}^{7}_{3}Li + {}^{1}_{1}H \rightarrow {}^{4}_{2}He + {}^{4}_{2}He + 17{,}3\ \mathrm{MeV}$

Nuclear Physics

<u>Artificially achieving nuclear fusion</u>:

- uncontrolled reaction - by detonating a hydrogen bomb
- controlled reaction - in devices called tokamak
- the controlled reaction has not yet been technically mastered to the point where it can be used to produce energy

<u>Fission of heavy nuclei</u>:

- uncontrolled reaction - nuclear explosion
- controlled reaction - in fission nuclear reactors
- controlled fission chain reaction was technically mastered since 1942 (first nuclear reactor in the USA)
- fission nuclear reactors - in nuclear power stations for power generation or as a source of neutrons for scientific research