3) Natural and Artificial Radioactivity (1)

Natural Radioactivity

Cosmic Radiation

- Protons (93 %)
- Alpha-Particles (6.3 %)
- heavier nuclides (0.7 %)

Terrestrial Radiation

- without decay series
- 20 radioactive nuclides from the beginning of the earth
- long half-lifes
- most important representative ^{40}K

- Permanent formation of radioactive nuclides from decay series

- $^{232}Th \rightarrow {}^{208}Pb$
- $^{235}U \rightarrow {}^{207}Pb$
- $^{238}U \rightarrow {}^{206}Pb$

- 4th decay series:
  $^{241}Pu \rightarrow {}^{209}Bi$
  reactivated by the artificial production of Pu

3) Natural and Artificial Radioactivity (2)

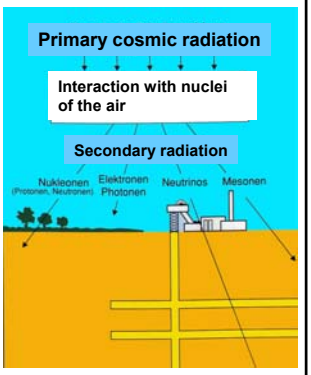
Natural Radioactivity

Cosmic Radiation

- Protons (93 %)
- Alpha-Particles (6.3 %)
- heavier nuclides (0.7 %)

- energy of the protons can be up to 10^{14} MeV
- initialisation of nuclear reactions

- Main products:
  Tritium, ^{7}Beryllium, ^{14}Carbon, ^{22}Sodium



^{14}C:

Formation $^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{14}_{6}C + {}^{1}_{1}p$

Decay $^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$

$T_{1/2} = 5730$ a

^{3}H:

Formation $^{14}_{7}N + {}^{1}_{0}n \rightarrow {}^{3}_{1}H + {}^{12}_{6}C$

$^{16}_{7}N + {}^{1}_{0}n \rightarrow {}^{3}_{1}H + {}^{14}_{7}N$

Decay $^{3}_{1}H \rightarrow {}^{3}_{2}He + {}^{0}_{-1}e$

$T_{1/2} =: 12.323$ a

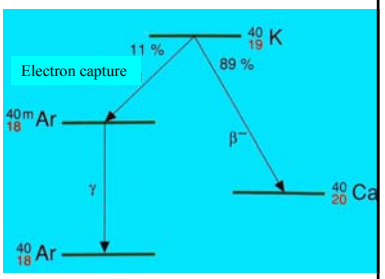
3) Natural and Artificial Radioactivity (3)

Natural Radioactivity
Terrestrial Radiation

Radioactive nuclides without decay series

- 20 radioactive nuclides
- from primordial ressources
- very long half-lifes
- most important representative is ^{40}K ($T_{1/2}$ = 1.28 x 10^9 y)

- **Other examples**:



Nuclide	$T_{1/2}$	Decay	Isotopic abundance
^{187}Re	5 x 10^{10} y	ß⁻	62.60
^{115}In	4.4 x 10^{14} y	ß⁻	95,7
^{123}Te	1.24 x 10^{13} y	K	0.908
^{87}Rb	4.8 x 10^{10} y	ß⁻	27.8
^{113}Cd	9.3 x 10^{15} y	ß⁻	12.2

3) Natural and Artificial Radioactivity (4)

Natural Radioactivity
Terrestrial Radiation

Decay series

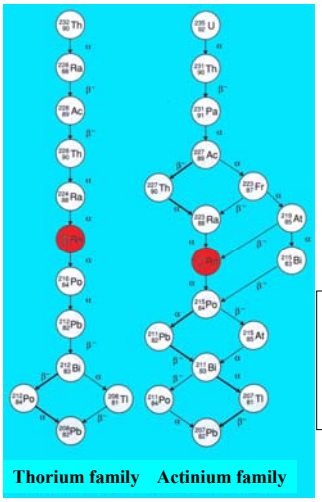
- Cascades of radioactive decays which origin from a certain radioactive nuclide and ends with a certain stable nuclide (lead or bismuth)
- Decay series include α-, ß- and γ-decays
- they can have branches but always end with the same final product
- four natural decay series were established:

$^{232}Th \rightarrow {}^{208}Pb$ (Thorium family)
$^{235}U \rightarrow {}^{207}Pb$ (Actinium family)
$^{238}U \rightarrow {}^{206}Pb$ (Uranium family)
$^{241}Pu \rightarrow {}^{209}Bi$ (Neptunium family)

- Pu/Bi series was decayed in nature due to the relatively short half-life of ^{237}Np

3) Natural and Artificial Radioactivity (5)

Natural Radioactivity
Terrestrial Radiation

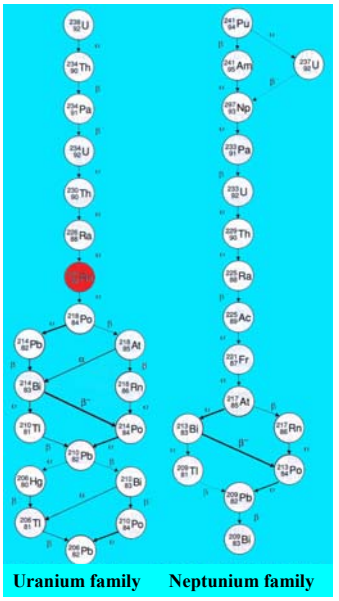


Decay series

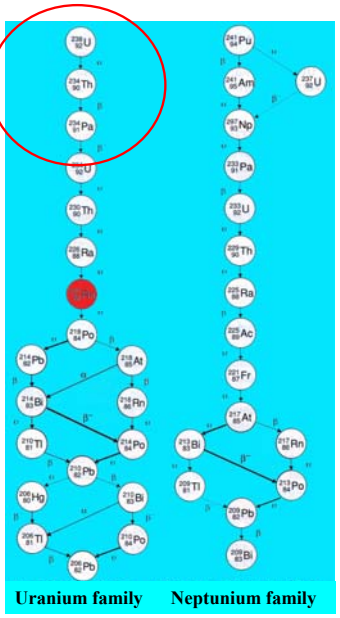
$^{232}Th \rightarrow {}^{208}Pb$
$^{235}U \rightarrow {}^{207}Pb$
$^{238}U \rightarrow {}^{206}Pb$
$^{241}Pu \rightarrow {}^{209}Bi$

Crucial Element:

- Radon
- inert gas
- can leave the compartment

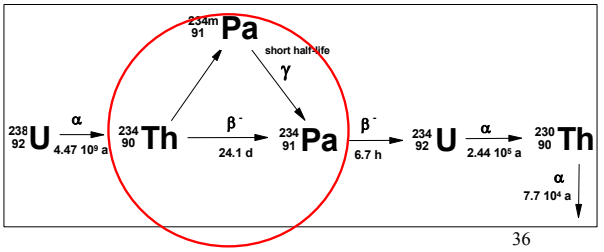


3) Natural and Artificial Radioactivity (6)

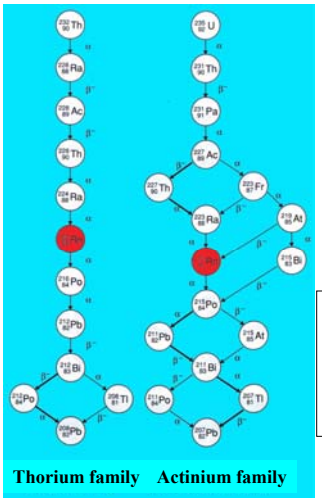


A part of the Uranium family series is important for the laboratory course:

- ^{238}U (99.27% natural abundance) decays into ^{234}Th (Half-life: 4.4 x 10^9 y, α-decay)
- ^{234}Th is radioactive itself and forms ^{234} Pa (Half-life 24.1 d, ß-decay)
- this disintegration passes a transient state with a certain half-life (the metastable isomer ^{234m}Pa which is a γ -emitter)
- This γ -emitter is the radioactive substance of almost all measuring experiments in the lab course



3) Natural and Artificial Radioactivity (7)



Decay series

$^{232}Th \rightarrow {}^{208}Pb$

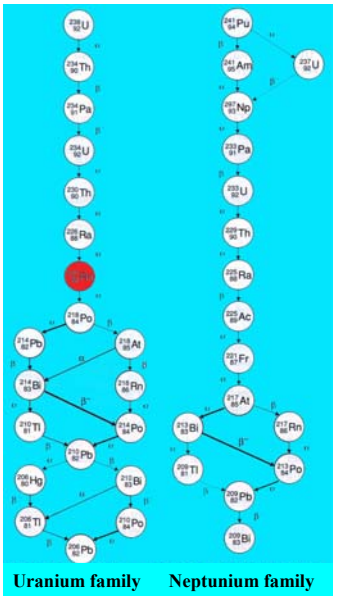
$^{235}U \rightarrow {}^{207}Pb$

$^{238}U \rightarrow {}^{206}Pb$

$^{241}Pu \rightarrow {}^{209}Bi$

Crucial Element:

- Radon
- inert gas
- can leave the compartment



4) Natural and Artificial Radioactivity (8)

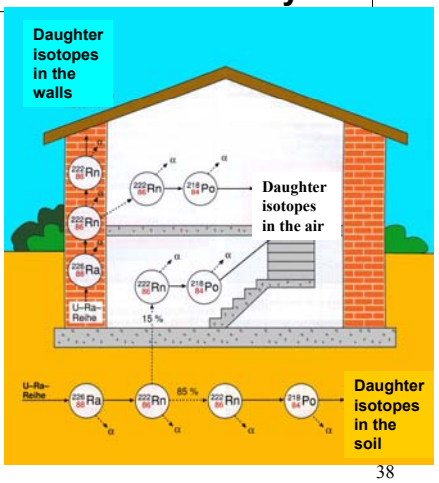
Natural Radioactivity
Terrestrial Radiation

Radon as main source of natural radioactivity

Radon is a mobile radioelement

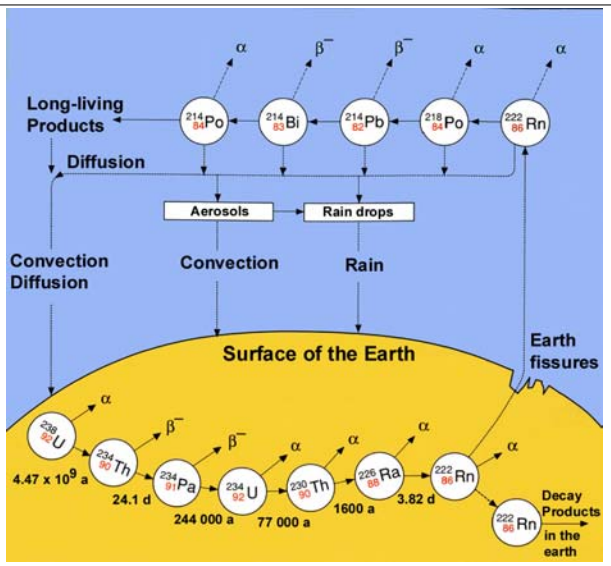
- formation by decay series:

  ^{228}Rn, ^{224}Rn, ^{220}Rn by thorium series
  ^{226}Rn, ^{222}Rn by uranium series
  ^{219}Rn by actinium series



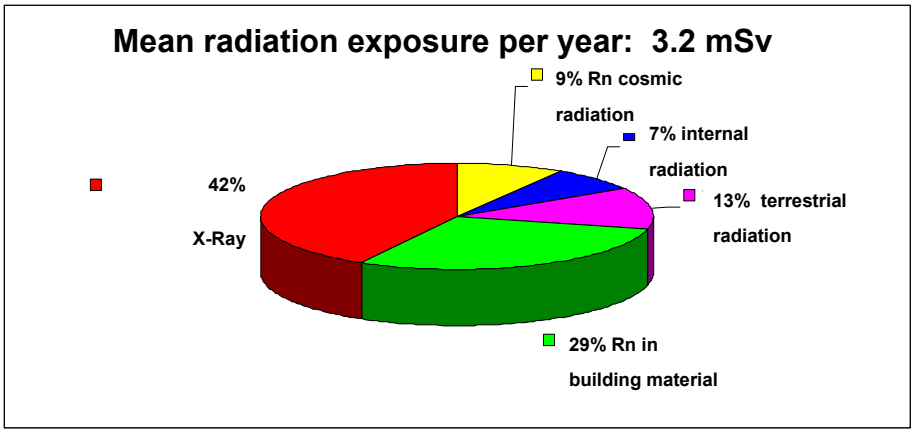
3) Natural and Artificial Radioactivity (9)

Radon distribution as main source of natural radioactivity



3) Natural and Artificial Radioactivity (10)

Mean radiation exposure to persons in industrial countries



3) Natural and Artificial Radioactivity (11)

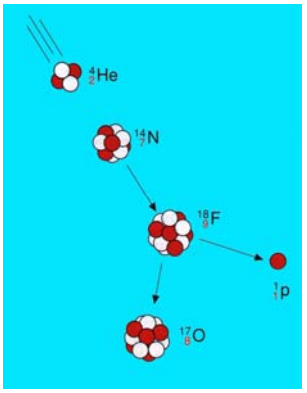
Artificial nuclear reactions

- first artificial nuclear reaction in 1919
- bombardment of nitrogen with α-particles
- transmutation of nitrogen into oxygen

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$$

$$^{14}_{7}N(\alpha, p)^{17}_{8}O$$

- all other particles are possible as projectiles (neutrons, protons, deuterons etc.)

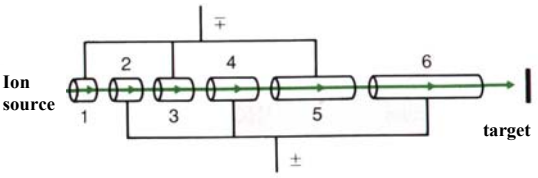


3) Natural and Artificial Radioactivity (12)

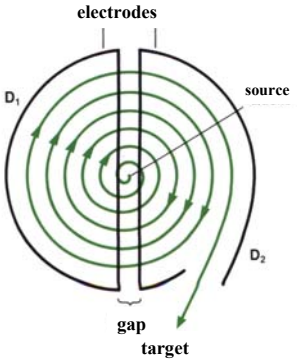
Artificial nuclear reactions

Facilities for nuclear reactions:

Linear accelerator



Cyclotron



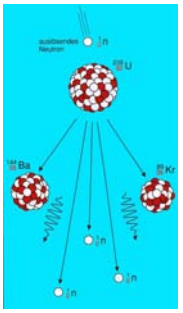
3) Natural and Artificial Radioactivity (13)

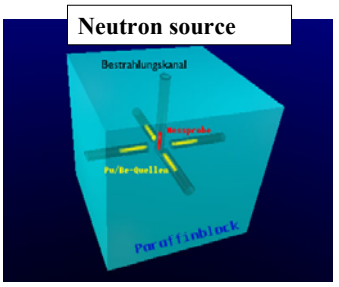
Artificial nuclear reactions

Neutrons as projectiles:
- neutral particles (no repulsion with the positively charged nucleus
- important projectile

Origin of the neutrons:

Nuclear reactor:
- speed of the neutrons must be decreased (moderated)
- moderators: water, hydrogen, deuterium



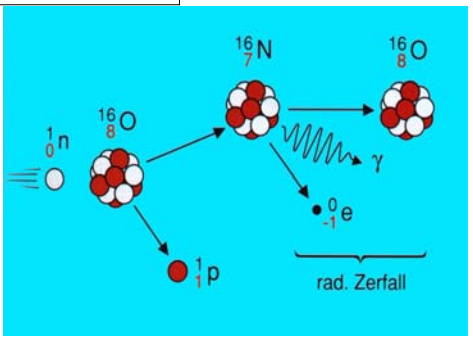


3) Natural and Artificial Radioactivity (14)

Artificial nuclear reactions

Neutrons as projectiles:
- neutral particles (no repulsion with the positively charged nucleus
- important projectile

- slow (moderated) neutrons react with many nuclei
- neutron capturing reactions
- radioactive isotopes of almost all elements can be produced this way

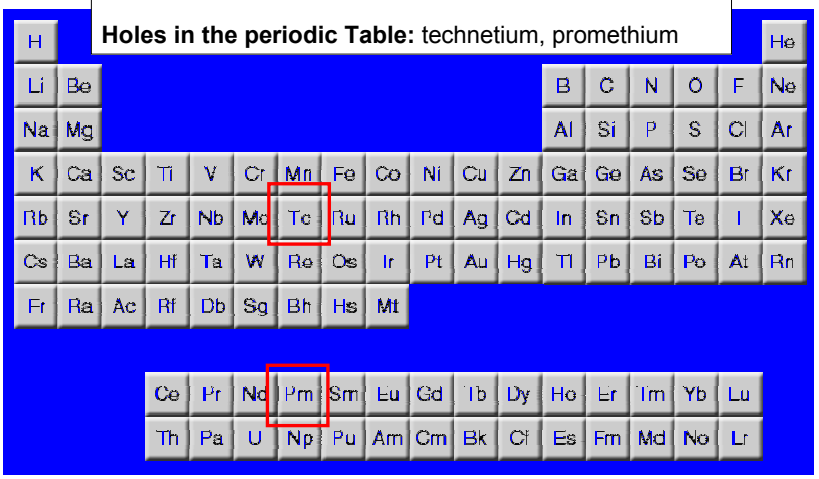


3) Natural and Artificial Radioactivity (15)

Artificial elements

Heaviest stable element is bismuth

Holes in the periodic Table: technetium, promethium



3) Natural and Artificial Radioactivity (16)

Artificial elements

$^{96}_{42}Mo + ^{2}_{1}H \rightarrow ^{97}_{43}Tc + ^{1}_{0}n$ (Molybdenum → Technetium)

$^{209}_{83}Bi + ^{4}_{2}He \rightarrow ^{211}_{85}At + 2\,^{1}_{0}n$ (Bismuth → Astat)

$^{230}_{90}Th + ^{1}_{1}H \rightarrow ^{223}_{87}Fr + 2\,^{4}_{2}He$ (Thorium → Francium)

Transuranium elements

$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U + \gamma$ (Uran → Uran)

$^{239}_{92}U \rightarrow ^{239}_{93}Np + ^{0}_{-1}e$ (Uran → Neptunium)

$^{239}_{93}Np \rightarrow ^{239}_{94}Pu + ^{0}_{-1}e$ (Neptunium → Plutonium)

$^{238}_{92}U + ^{12}_{6}C \rightarrow ^{244}_{98}Cf + 6\,^{1}_{0}n$ (Uran → Californium)

$^{249}_{98}Cf + ^{18}_{8}O \rightarrow ^{263}_{106}Sg + 4\,^{1}_{0}n$ (Uran → Seaborgium)

3) Natural and Artificial Radioactivity (17)

Examples for artificial nuclear reactions

Reaction Type	Nuclear Reaction	Radioactivity of the product
(α,n)	$^{75}_{33}As + {}^{4}_{2}He \rightarrow {}^{78}_{25}Br + {}^{1}_{0}n$ Arsen Bromine	β^+
(α,p)	$^{106}_{46}Pd + {}^{4}_{2}He \rightarrow {}^{109}_{47}Ag + {}^{1}_{1}H$ Palladium Silver	stable
(p,n)	$^{7}_{3}Li + {}^{1}_{1}H \rightarrow {}^{7}_{4}Be + {}^{1}_{0}n$ Lithium Beryllium	Electron capture
(p,γ)	$^{14}_{7}N + {}^{1}_{1}H \rightarrow {}^{15}_{8}O + \gamma$ Nitrogen Oxygen	β^+
(p,α)	$^{9}_{4}Be + {}^{1}_{1}H \rightarrow {}^{6}_{3}Li + {}^{4}_{2}He$ Beryllium Lithium	stable
(d,p)	$^{31}_{15}P + {}^{2}_{1}H \rightarrow {}^{32}_{15}P + {}^{1}_{1}H$ Phosphorus Phosphorus	β^-
(d,n)	$^{209}_{83}Bi + {}^{2}_{1}H \rightarrow {}^{210}_{84}Po + {}^{1}_{0}n$ Bismuth Polonium	α
(n,γ)	$^{59}_{27}Co + {}^{1}_{0}n \rightarrow {}^{60}_{27}Co + \gamma$ Cobalt Cobalt	β^-
(n,p)	$^{45}_{21}Sc + {}^{1}_{0}n \rightarrow {}^{45}_{20}Ca + {}^{1}_{1}H$ Scandium Calcium	β^-
(n,α)	$^{27}_{13}Al + {}^{1}_{0}n \rightarrow {}^{24}_{11}Na + {}^{4}_{2}He$ Aluminium Sodium	β^-

3) Natural and Artificial Radioactivity (18)

Nuclear fission

Remind! Nuclear binding energy
- Sum of the masses of nucleons is bigger than the nucleus of an atom
- Difference: nuclear binding energy

- Energy can be gained by fusion of light elements or **fission of heavy elements**

Nuclear binding energy per nucleon