Section 9: SOURCES of RADIOACTIVITY

This section briefly describes various sources of radioactive nuclei, both naturally occurring and those produced artificially (man-made) in, for example, reactors or accelerators.

1. NATURAL SOURCES OF RADIOACTIVITY

These can arise from extraterrestrial sources (cosmic rays) and from radioactive elements in the Earth's crust. The latter may be primordial radionuclides, whose half-lives are sufficiently long that they have survived since their creation or secondary radionuclides, which are products of their decay.

All other radioactive nuclei, produced prior to the formation of the earth, have decayed out of existence due to their short half-lives.

- Natural radioactivity generally varies little over the earth's crust.
- However, there can be wide local variations - concentration of certain radioactive minerals.

Nuclides produced by cosmic rays

Cosmic rays consist of high-energy particles: 87% protons, 11% α particles; 1% of nuclei with *Z* between 4 and 26; 1% of high-energy electrons.

Their mean energy is about 10^4 MeV up to about 10^{13} MeV.

Cosmic rays interact with the atmosphere via nuclear reactions forming radioactive products.

An example is ^{14}C: Protons interact in the upper atmosphere to produce **neutrons**. These interact with nitrogen nuclei to produce excited ^{15}N nuclei, which then decay by proton emission to yield ^{14}C:

$$^{14}N + n \rightarrow {}^{15}N^*$$

$$^{15}N^* \rightarrow {}^{14}C + p$$

^{14}C decays by $\beta-$ emission with a half-life of 5730 y.

Showers of electrons and mesons are also produced by cosmic-ray interactions.

At sea level, the meson component is the most important.

Table 9.1: Naturally occurring radionuclides produced by cosmic-ray interactions.

Radio-nuclide	Half-life	Tropospheric concentration (Bq/kg air)	Principal radiations and energies (MeV)
3H	12 y	1.2×10-3	β 0.019
7Be	53 d	0.01	γ 0.477
10Be	1.6×106 y	1.2×10-9	β 0.555
14C	5730 y	0.126	β 0.156
22Na	2.6 y	1.1×10-6	β 0.545, γ 1.27
24Na	15 h	–	β 1.4, γ 1.37, 2.75
32P	14 d	2.3×10-4	β 1.71
33P	25 d	1.3×10-4	β 0.249
35S	87 d	1.3×10-4	β 0.167
36Cl	3×105 y	2.5×10-10	β 0.71
38S	2.8 h	–	β 0.99, γ 1.94
38Cl	37 m	–	β 4.91, γ 1.64, 2.17
39Cl	56 m	–	β 1.91, γ 0.25, 1.27, 1.52

Radionuclides of terrestrial origin

Two classes:

- Those occurring **singly** - decay into stable nuclei.
- Those that are components of three different **decay chains**.

Nuclides occurring singly

Table 9.2: Primordial origin with long half-lives.

Radionuclide	Abundance (%)	Half-life (years)	Principal radiations and energy (MeV)	Specific activity (Bq/g)
40K	0.012	1.28×109	β 1.33, γ 1.46	32
87Rb	27.8	4.9×1010	β 0.27	888
115In	95.7	4.4×1014	β 0.48	0.18
142Ce	11.1	>5×1016	(α)	2×10-4
144Nd	23.8	2.1×1015	α 1.83	9×10-3
147Sm	15.0	1.1×1011	α 2.23	130
148Sm	11.3	7×1015	α 1.96	0.05
149Sm	13.8	>1×1016	–	0.012
176Lu	2.6	3.7×1010	β 0.57 γ 0.088, 0.202, 0.306	90
187Re	62.6	4.5×1010	β 0.003	1040

Nuclides occurring in chains

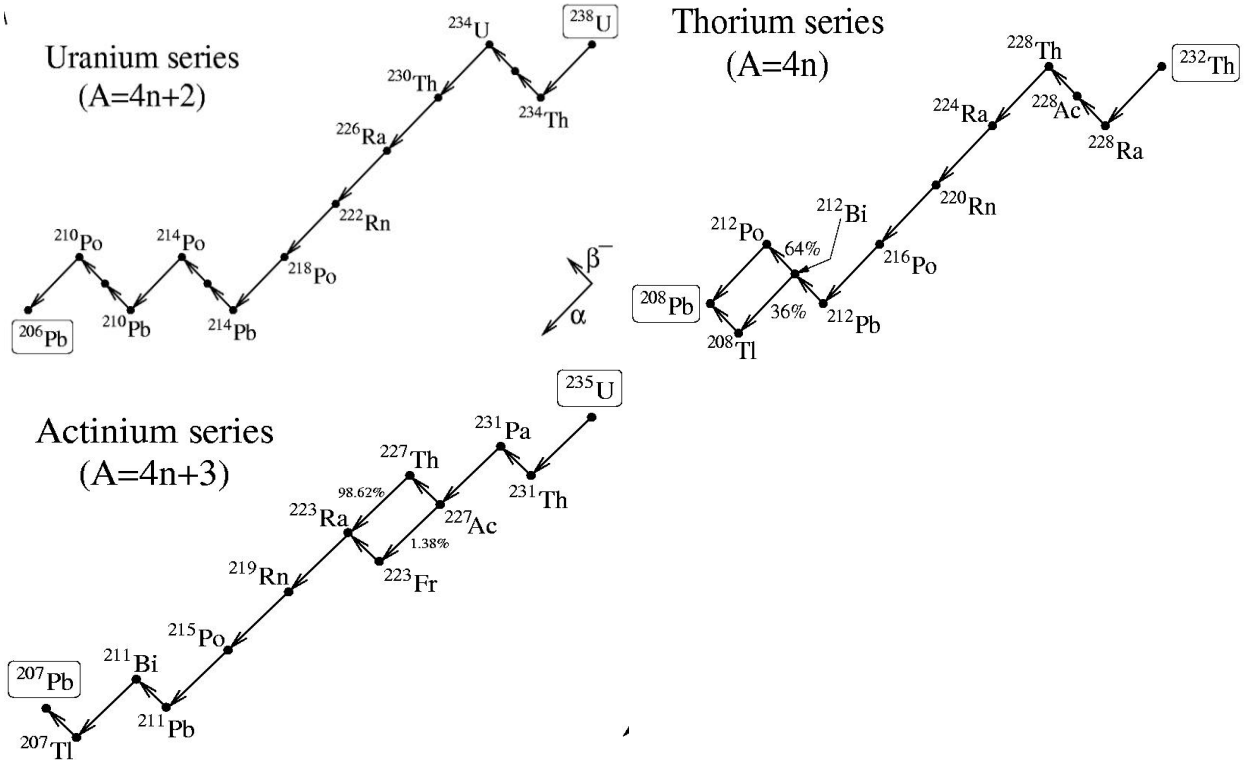
There are three chains of radioactive elements found in the earth's crust:

a) The **Uranium series** (A mod 2 series) - parent nucleus ^{238}U.

b) The **Thorium series** (A mod 4 series) - starting with ^{232}Th.

c) The **Actinium series** (A mod 3 series) - starting with ^{235}U.

Originally, there was a fourth series: **Neptunium series** (A mod 1).
Longest lived member : ^{237}Np - half-life 2×106 y, so the series died out.
The only surviving member is ^{209}Bi - stable (or very long half-life).



All active nuclei in the chains emit a combination of α, β, γ rays.

For none of the radioactive nuclei in the chains is proton or neutron decay energetically possible. The naturally occurring nuclei heading these decay chains, are isotopes of uranium and thorium.

- Uranium has three long-lived isotopes ^{238}U, ^{235}U and ^{234}U.
- Thorium has one naturally occurring isotope: ^{232}Th.
- Many of the heavier nuclei in the chains are α emitters. Examples are: ^{238}U, ^{235}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{222}Ra, ^{218}Po.
- Gamma emission often follows beta emission and the most prolific γ emitters are ^{214}Pb and ^{212}Pb.

- A decay chain stops when a stable isotope of **lead** is reached.

2. MAN MADE SOURCES OF RADIOACTIVITY

Radioactive nuclides can be produced artificially:

- Neutron induced fission - source of power in a nuclear reactor.
- Neutron activation - n capture by a stable target to produce an unstable product.
- Reactions using beams of charged particles, such as protons and α particles.

Reaction rate and cross section

In nuclear bombardment, the probability per unit time of a collision causing a reaction depends on

- Flux Φ of incident particles.
- Number N of irradiated nuclei.
- The constant of proportionality (for the reaction) is called the **cross section** σ.

Thus we can write the reaction rate as $$R = \sigma \Phi N \qquad (7.1)$$

A typical cross section for a collision of a light particle with a medium-mass nucleus is a barn (10^{-24} cm^2). Many different reactions can occur - each with its own partial cross section. The total cross section for the collision is the sum of the partial cross sections.

Induced nuclear fission

A heavy nucleus (e.g. uranium) is caused to split into two lighter nuclei – plus several neutrons. The fission process is highly exothermic.

Example: ^{235}U fission induced by a slow (thermal) neutron.
One possible mass partition (out of many): is

$$^{235}\mathrm{U} + \mathrm{n} \rightarrow {}^{145}\mathrm{La} + {}^{87}\mathrm{Br} + 4\mathrm{n}. \qquad (7.2)$$

Initial and final total mass numbers and atomic numbers balance.- i.e. the total number and type of nucleons are preserved:

Atomic mass: $235 + 1 = 145 + 87 + 4$.
Atomic number: $92 + 0 = 57 + 35 + 0$.

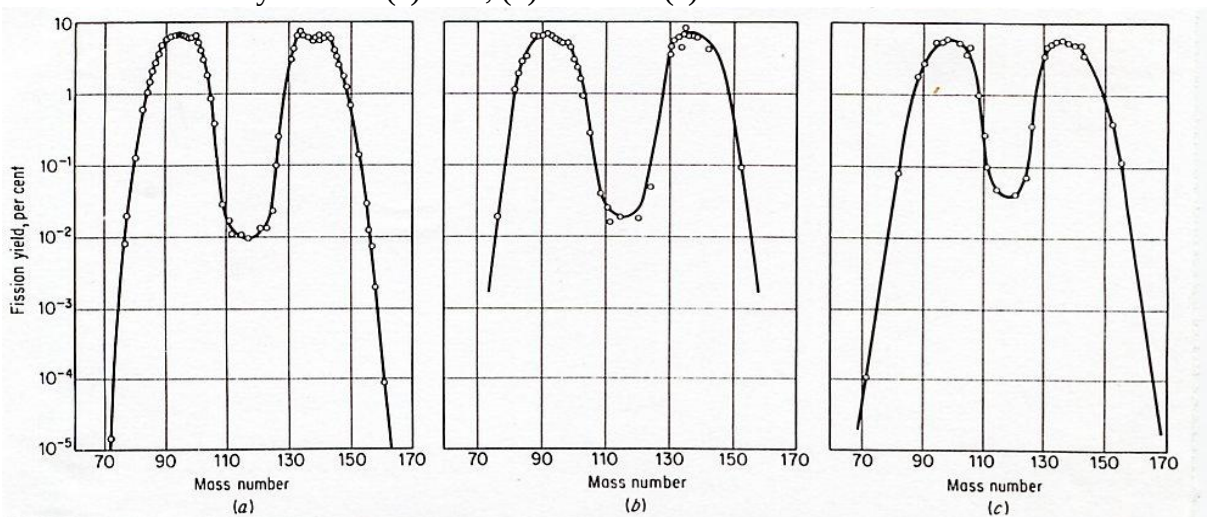
Mass-energies:

	Initial		Final
^{235}U	235.04392	^{145}La	144.92164
n	1.00867	^{87}Br	86.92069
		4n	4.03466
Sum	236.05259		235.87699

The mass difference is 0.1756 u = 163 MeV.

- The fission fragments are unstable and emit more energy as they decay towards stability. Overall, about 200 MeV of usable energy is generated.

Slow neutron fission yields for (a) ^{235}U, (b) ^{233}U and (c) ^{239}Pu:



- Double-humped mass yield - peaking at 85-105 and 130-150.

Activities of products in a reactor:

- The most important nuclides environmentally are those with long half-lives, e.g. the fission fragments: ^{90}Sr, ^{137}Cs and the transuranic nuclei ^{239}Pu, ^{240}Pu and ^{241}Am.

	Half-life (y)	**Initial activity**
^{90}Sr	28.84	0.037
^{137}Cs	30.07	0.047
^{239}Pu	24110	0.00021
^{240}Pu	6564	0.00021
^{241}Am	432.2	0.00017

Neutron activation

- A stable nuclide absorbs a neutron to produce a radioactive isotope of the same element.
- The product normally decays via β– emission with a half-life depending on the nuclide.

Example: $^{59}Co(stable) + n \rightarrow {}^{60}Co$.

^{60}Co has a half-life of 5.27 y - emitting a combination of β– and γ rays.

During irradiation, the number of radioactive nuclei gradually builds up with time.
After a long time (several half-lives), an equilibrium is reached:

Production rate = decay rate (activity)

Using Equation (7.1) for the production rate gives: **Activity = $\sigma \Phi N$** (7.3)

The number of target nuclei in the sample $N = \alpha mN\mathrm{A}/A$,
where α is the fraction of the target isotope (atomic mass A) in the sample (mass m) and NA is Avogadro's number.

In the cobalt example, we have:
$\sigma = 20.7$ b, $\Phi = 1012$ cm^{-2} s^{-1}, $\alpha = 1.0$, m = 1 g, $A = 59$.

Equilibrium activity = 2.11×10^{11} s^{-1}.

Charged-particle reactions

Radioactive nuclides can be made via charged-particle induced reactions.

Examples:

^{88}Y production:	$^{88}\mathrm{Sr} + \mathrm{p} \rightarrow {}^{88}\mathrm{Y} + \mathrm{n}$
^{56}Co production:	$^{56}\mathrm{Fe} + \mathrm{p} \rightarrow {}^{56}\mathrm{Co} + \mathrm{n}$
^{22}Na production:	$^{24}\mathrm{Mg} + \mathrm{d} \rightarrow {}^{22}\mathrm{Na} + \alpha$

Activities are obtained as for neutron activation - given that the cross sections are known.

- There may be several active products resulting from the nuclear collision.
- Need to choose the beam energy to maximize the yield of the product nuclei of interest and to minimize possible contaminant activities.
- Chemical separation can be used to eliminate unwanted species.
- Or, if the half-life of the contaminant is short enough, it can be allowed to decay away.