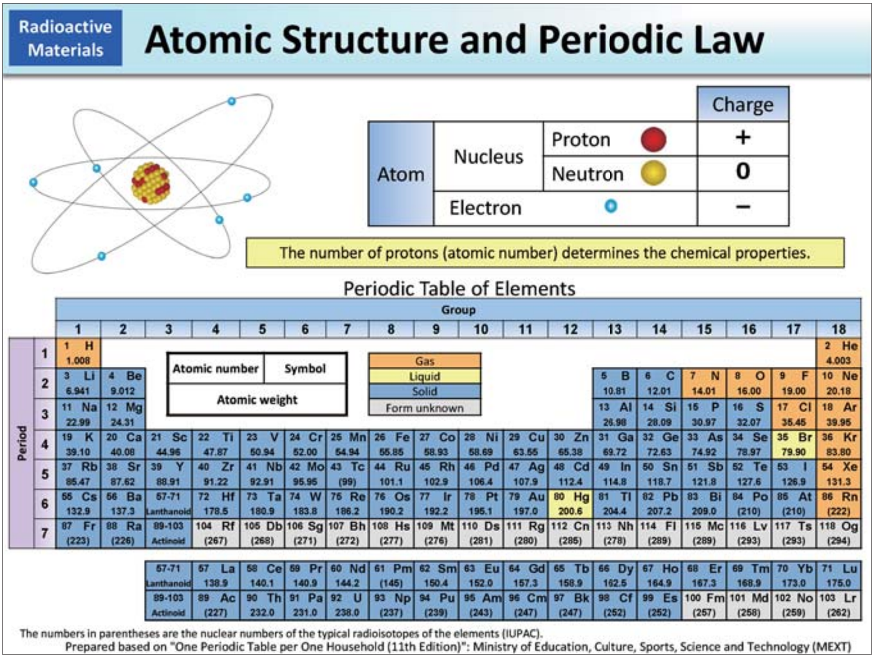

Radioactive Materials

Atomic Structure and Periodic Law

			Charge
Atom	Nucleus	Proton ●	+
		Neutron ●	0
	Electron	○	−

The number of protons (atomic number) determines the chemical properties.

Periodic Table of Elements

Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H 1.008																	2 He 4.003
2	3 Li 6.941	4 Be 9.012											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
3	11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.07	17 Cl 35.45	18 Ar 39.95
4	19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.63	33 As 74.92	34 Se 78.97	35 Br 79.90	36 Kr 83.80
5	37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.95	43 Tc (99)	44 Ru 101.1	45 Rh 102.9	46 Pd 106.4	47 Ag 107.9	48 Cd 112.4	49 In 114.8	50 Sn 118.7	51 Sb 121.8	52 Te 127.6	53 I 126.9	54 Xe 131.3
6	55 Cs 132.9	56 Ba 137.3	57-71 Lanthanoid	72 Hf 178.5	73 Ta 180.9	74 W 183.8	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.1	79 Au 197.0	80 Hg 200.6	81 Tl 204.4	82 Pb 207.2	83 Bi 209.0	84 Po (210)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89-103 Actinoid	104 Rf (267)	105 Db (268)	106 Sg (271)	107 Bh (272)	108 Hs (277)	109 Mt (276)	110 Ds (281)	111 Rg (280)	112 Cn (285)	113 Nh (278)	114 Fl (289)	115 Mc (289)	116 Lv (293)	117 Ts (293)	118 Og (294)

57-71 Lanthanoid	57 La 138.9	58 Ce 140.1	59 Pr 140.9	60 Nd 144.2	61 Pm (145)	62 Sm 150.4	63 Eu 152.0	64 Gd 157.3	65 Tb 158.9	66 Dy 162.5	67 Ho 164.9	68 Er 167.3	69 Tm 168.9	70 Yb 173.0	71 Lu 175.0
89-103 Actinoid	89 Ac (227)	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np (237)	94 Pu (239)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (252)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Atomic number	Symbol
Atomic weight	

- 🟧 Gas
- 🟨 Liquid
- 🟦 Solid
- ⬜ Form unknown

The numbers in parentheses are the nuclear numbers of the typical radioisotopes of the elements (IUPAC).

Prepared based on "One Periodic Table per One Household (11th Edition)": Ministry of Education, Culture, Sports, Science and Technology (MEXT)

An atom is composed of a nucleus and electrons that go around the former. The nucleus is composed of protons with a positive charge and neutrons without charge, and the number of protons (atomic number) determines the chemical properties of the atom (element type).

For example, carbon has six protons, but there are also types of carbon with five, six, seven or eight neutrons. All of them have the same chemical properties.

When calling them distinctively, they are called Carbon 11, Carbon 12, Carbon 13 and Carbon 14, adding the nuclear number (total of protons and neutrons) after the element name, which is a nominal designation that covers the same types of atoms. Carbon 12 is the one that most commonly exists in nature.

Carbon 14 is a radionuclide which exists in nature and is made through a process where a proton of Nitrogen 14 is hit and removed by a neutron created as a result of collisions of cosmic rays and the atmosphere. Carbon 14 has six protons and eight neutrons, and the state is energetically unstable because of the unbalance of both numbers.

If one neutron of Carbon 14 changes to a proton, the element becomes stable because the numbers of protons and neutrons are both seven. At this time, an electron is emitted as extra energy. This is the identity of β (beta)-particles. In other words, Carbon 14 returns to nitrogen having seven protons by emitting β-particles, and becomes energetically stable.

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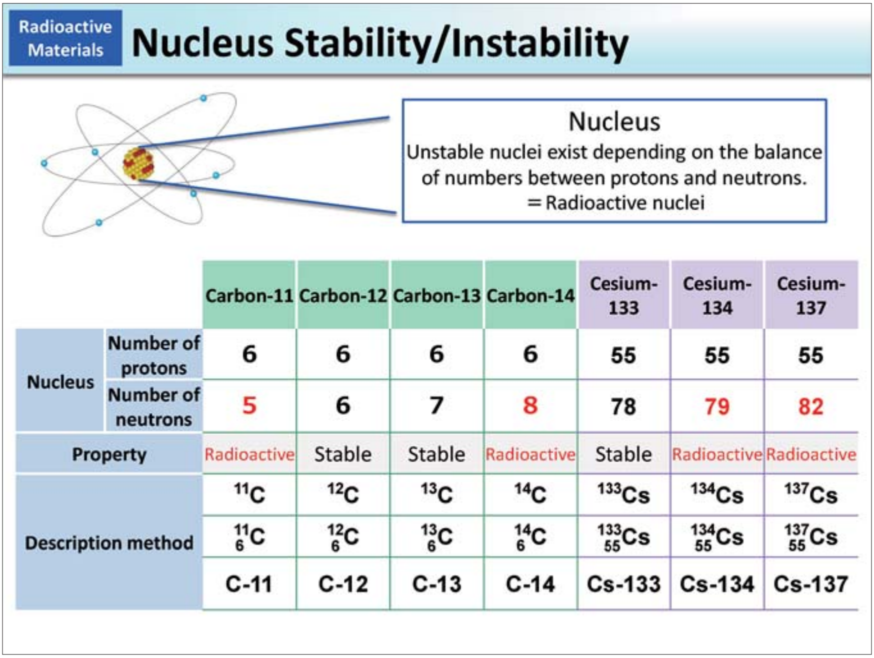

Radioactive Materials

Nucleus Stability/Instability

Nucleus

Unstable nuclei exist depending on the balance of numbers between protons and neutrons.
= Radioactive nuclei

		Carbon-11	Carbon-12	Carbon-13	Carbon-14	Cesium-133	Cesium-134	Cesium-137
Nucleus	Number of protons	6	6	6	6	55	55	55
	Number of neutrons	5	6	7	8	78	79	82
Property		Radioactive	Stable	Stable	Radioactive	Stable	Radioactive	Radioactive
Description method		$^{11}\mathrm{C}$	$^{12}\mathrm{C}$	$^{13}\mathrm{C}$	$^{14}\mathrm{C}$	$^{133}\mathrm{Cs}$	$^{134}\mathrm{Cs}$	$^{137}\mathrm{Cs}$
		$^{11}_{6}\mathrm{C}$	$^{12}_{6}\mathrm{C}$	$^{13}_{6}\mathrm{C}$	$^{14}_{6}\mathrm{C}$	$^{133}_{55}\mathrm{Cs}$	$^{134}_{55}\mathrm{Cs}$	$^{137}_{55}\mathrm{Cs}$
		C-11	C-12	C-13	C-14	Cs-133	Cs-134	Cs-137

Nuclei having the same atomic number (the number of protons) but differing in the number of neutrons are called "isotopes" to each other. There are "radioisotopes" that emit radiation upon radioactive disintegration and "stable isotopes" that do not emit radiation and so do not change in atomic weight.

Radionuclides emit radiation such as α (alpha)-particles, β (beta)-particles, and γ (gamma)-rays to mitigate or terminate their unstable states. Radionuclides turn into different atoms after emission of α-particles or β-particles but such change does not occur after emission of γ-rays. The radiation type to be emitted is dictated for each radionuclide (p.8 of Vol. 1, "Naturally Occurring or Artificial," and p.13 of Vol. 1, "Where does Radiation Come from?").

Carbon is an element having six protons but there are also variants having five to eight neutrons. Cesium is an element having fifty-five protons, and its variants having fifty-seven to ninety-six neutrons have been found so far. Among them, only Cesium-133 having seventy-eight neutrons (55 protons plus 78 neutrons = 133) is stable, and all the rest are radioisotopes that emit radiation. In the event of a nuclear plant accident, Cesium-137 and Cesium 134 that is made through a process where fission products are hit by a neutron may be released into the environment. They emit β-particles and γ-rays.
(Related to p.30 of Vol. 1, "Products in Nuclear Reactors")

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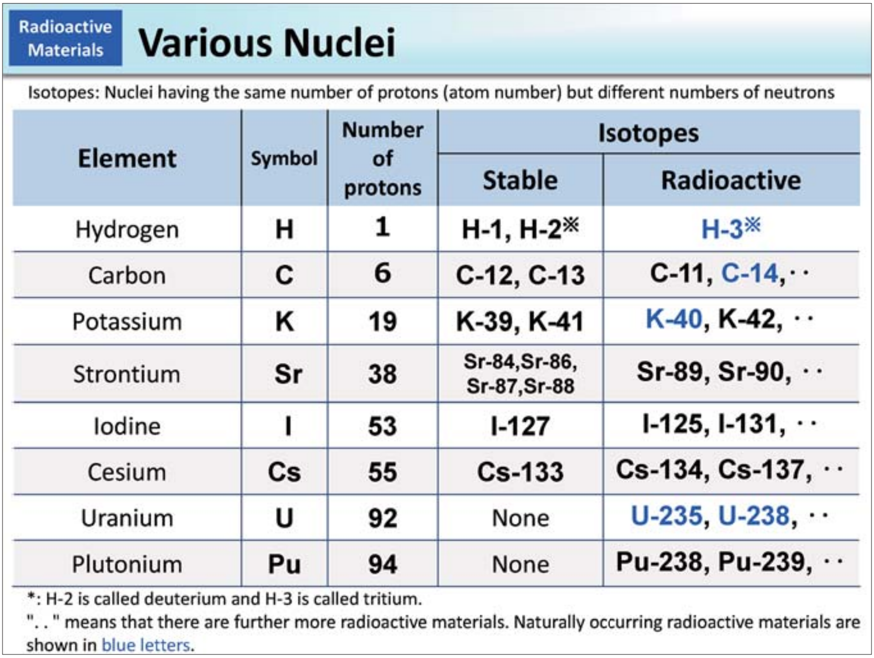

Radioactive Materials

Various Nuclei

Isotopes: Nuclei having the same number of protons (atom number) but different numbers of neutrons

Element	Symbol	Number of protons	Isotopes	
			Stable	Radioactive
Hydrogen	H	1	H-1, H-2※	H-3※
Carbon	C	6	C-12, C-13	C-11, C-14,・・
Potassium	K	19	K-39, K-41	K-40, K-42, ・・
Strontium	Sr	38	Sr-84,Sr-86, Sr-87,Sr-88	Sr-89, Sr-90, ・・
Iodine	I	53	I-127	I-125, I-131, ・・
Cesium	Cs	55	Cs-133	Cs-134, Cs-137, ・・
Uranium	U	92	None	U-235, U-238, ・・
Plutonium	Pu	94	None	Pu-238, Pu-239, ・・

*: H-2 is called deuterium and H-3 is called tritium.

". . " means that there are further more radioactive materials. Naturally occurring radioactive materials are shown in blue letters.

While most hydrogen atoms are H-1 whose nucleus has only one proton, there are also H-2 (deuterium) that has one proton and one neutron and H-3 (tritium) that has one proton and two neutrons. Only H-3 (tritium) emits radiation among these isotopes.

Like hydrogen, there are elements (collectively referring to the same type of atoms) having only one type of radioactive nucleus, but there are also many elements having multiple types of radioactive nuclei. Some elements with a large atomic number such as uranium and plutonium do not have stable nuclei that do not emit radiation.

While most naturally occurring radionuclides have existed since the birth of the earth, there are some that are still being created by the interaction between cosmic rays and the atmosphere, such as Carbon-14.

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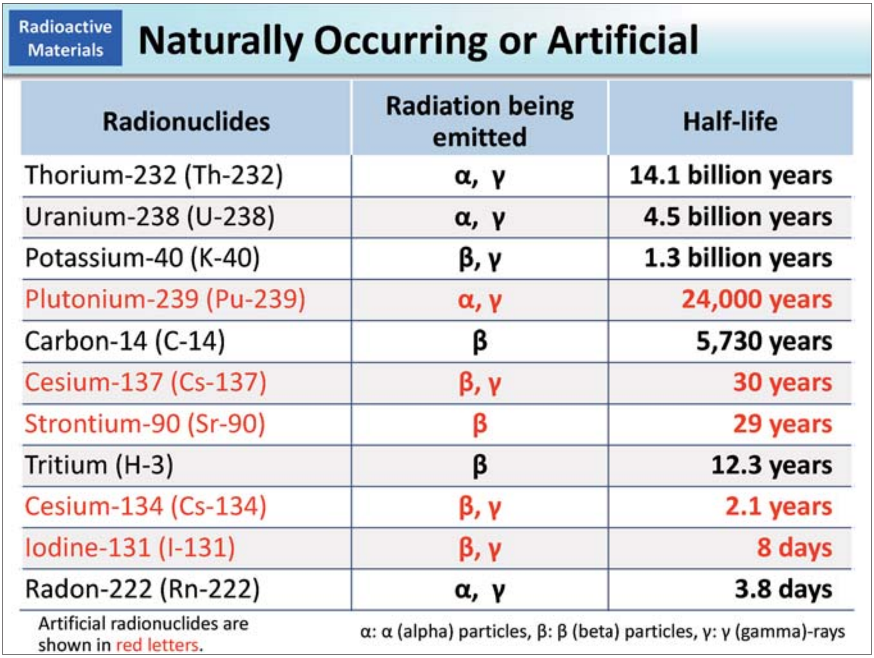

Radioactive Materials

Naturally Occurring or Artificial

Radionuclides	Radiation being emitted	Half-life
Thorium-232 (Th-232)	α, γ	14.1 billion years
Uranium-238 (U-238)	α, γ	4.5 billion years
Potassium-40 (K-40)	β, γ	1.3 billion years
Plutonium-239 (Pu-239)	α, γ	24,000 years
Carbon-14 (C-14)	β	5,730 years
Cesium-137 (Cs-137)	β, γ	30 years
Strontium-90 (Sr-90)	β	29 years
Tritium (H-3)	β	12.3 years
Cesium-134 (Cs-134)	β, γ	2.1 years
Iodine-131 (I-131)	β, γ	8 days
Radon-222 (Rn-222)	α, γ	3.8 days

Artificial radionuclides are shown in red letters.

α: α (alpha) particles, β: β (beta) particles, γ: γ (gamma)-rays

Radionuclides with long half-lives, such as Thorium-232 in the thorium series, Uranium-238 in the uranium series, and Potassium-40, were created in the universe in the distant past and taken into the earth when the earth was born.

Thorium-232 and Uranium-238 transform into various radionuclides by emitting α (alpha)-particles, β (beta)-particles, and γ (gamma)-rays before transforming into Lead-208 and Lead-206, respectively.

Carbon-14, which is also a naturally occurring radionuclide, is created when nitrogen that accounts for 78% of the atmosphere is hit by a neutron created as a result of collisions of cosmic rays and the atmosphere. Carbon-14 returns to nitrogen by emitting β-particles.

Cesium-134, Cesium-137, Strontium-90, Iodine-131, and Plutonium-239 can be released into the environment in the event of a nuclear plant accident. Some artificial radionuclides, such as Plutonium-239, have very long half-lives.

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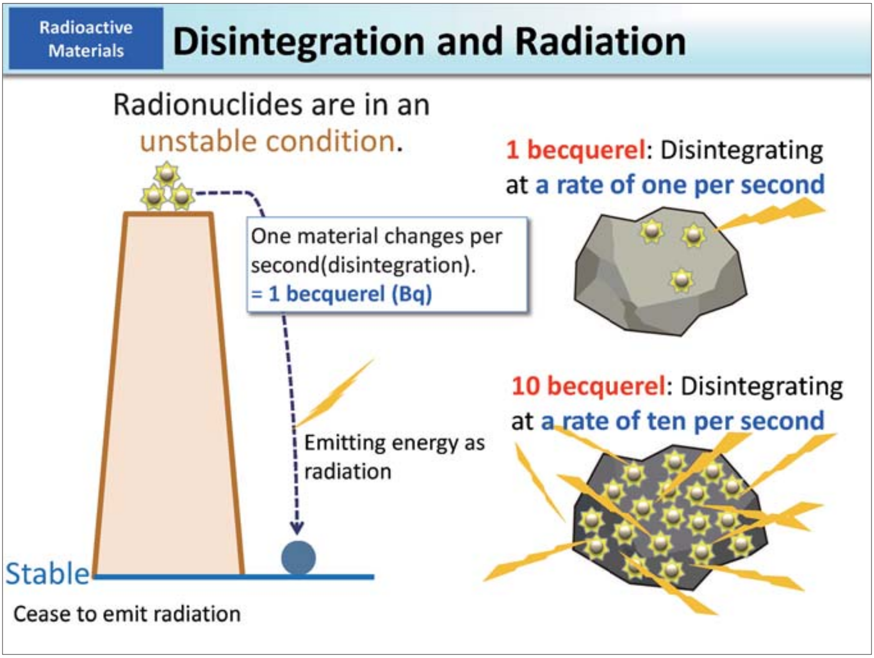

Radioactive Materials

Disintegration and Radiation

Radionuclides are in an unstable condition.

One material changes per second(disintegration).
= 1 becquerel (Bq)

Emitting energy as radiation

Stable

Cease to emit radiation

1 becquerel: Disintegrating at **a rate of one per second**

10 becquerel: Disintegrating at **a rate of ten per second**

A nucleus of a radionuclide is energetically unstable. In order to become stable, it releases extra energy in the form of radiation.

Becquerel is a unit used to quantify radiation intensity. One becquerel is defined as an amount that "one nucleus changes (disintegrates) per second." Since nuclei often emit radiation during disintegration, the becquerel is used as a unit to express the ability to emit radiation. In a rock with 1 Bq of radioactivity, for example, each nucleus of the radionuclide contained in the rock will disintegrate per second. 10 Bq means that 10 nuclei will disintegrate per second.

Once nuclei of a radionuclide disintegrate and the radionuclide becomes stable by emitting radiation, it will no longer emit radiation. Some types of radionuclides repeat disintegration multiple times until becoming stable.
(Related to p.10 of Vol. 1, "Parent and Daughter Nuclides")

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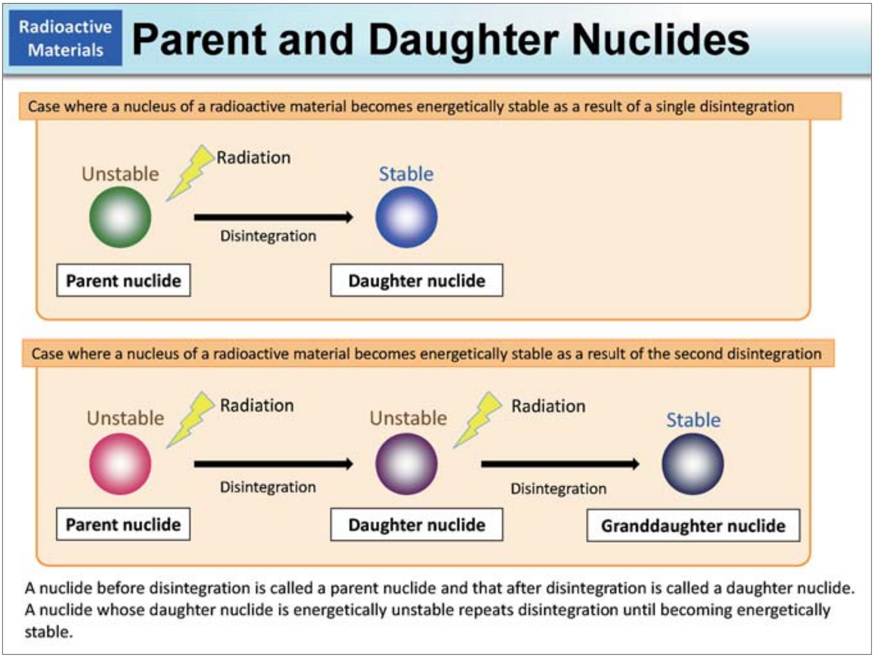

Radioactive Materials

Parent and Daughter Nuclides

Case where a nucleus of a radioactive material becomes energetically stable as a result of a single disintegration

Case where a nucleus of a radioactive material becomes energetically stable as a result of the second disintegration

A nuclide before disintegration is called a parent nuclide and that after disintegration is called a daughter nuclide. A nuclide whose daughter nuclide is energetically unstable repeats disintegration until becoming energetically stable.

Types of atoms and nuclei classified depending on the number of protons and neutrons are called nuclides. For example, Carbon-12 and Carbon-14 are both carbons but are different nuclides. Carbon-14 is a radionuclide as it is energetically unstable.

The phenomenon wherein a radionuclide emits radiation and transforms into a different nuclide is called disintegration. A nuclide before disintegration is called a parent nuclide and that after disintegration is called a daughter nuclide.

Some radionuclides remain energetically unstable even after disintegration, which means that the original radionuclides have transformed into other types of radionuclides. These types of radionuclides repeat disintegration until becoming energetically stable. A nuclide resulting from the disintegration of a daughter nuclide (seen from a parent nuclide) is sometimes called a granddaughter nuclide, and such daughter nuclide and granddaughter nuclide are collectively called progeny nuclides.

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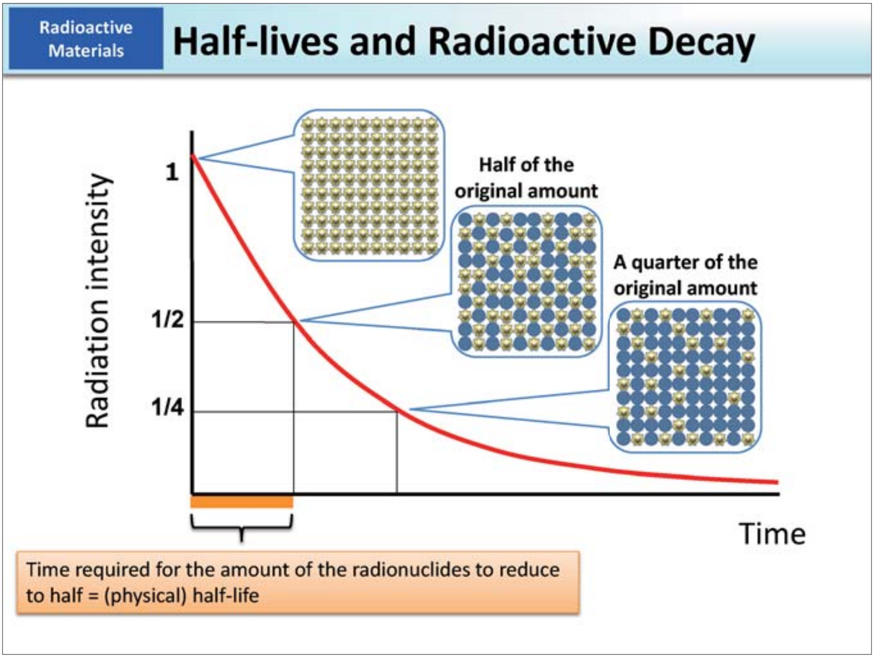

Radioactive Materials

Half-lives and Radioactive Decay

Time required for the amount of the radionuclides to reduce to half = (physical) half-life

An atom that has become stable in terms of energy by emitting radiation will no longer emit radiation. The amount of a radionuclide decreases over time and radioactivity weakens. The time required for radioactivity to weaken and reduce to half is called a (physical) half-life.

Upon the elapse of a period of time equal to the half-life, the radioactivity will be halved, and when a period of time twice as long as the half-life lapses, the radiation will reduce to a quarter of the original state. A graph with the horizontal axis representing the elapsed time and the vertical axis representing the radiation intensity demonstrates exponential radioactivity decreases in a curve as shown in the slide.

(Physical) half-lives vary depending on the types of radionuclides. For instance, the half-life is approximately 8 days for Iodine-131, approximately 2 years for Cesium-134, and approximately 30 years for Cesium-137.

Radioactive materials taken into the body will be excreted after being taken into various organs and tissues. The time required for the amount of radioactive materials in the body to reduce to half through excretion is called biological half-life and varies depending on their chemical forms and/or particle sizes (p.27 of Vol. 1, "Internal Exposure and Radioactive Materials").

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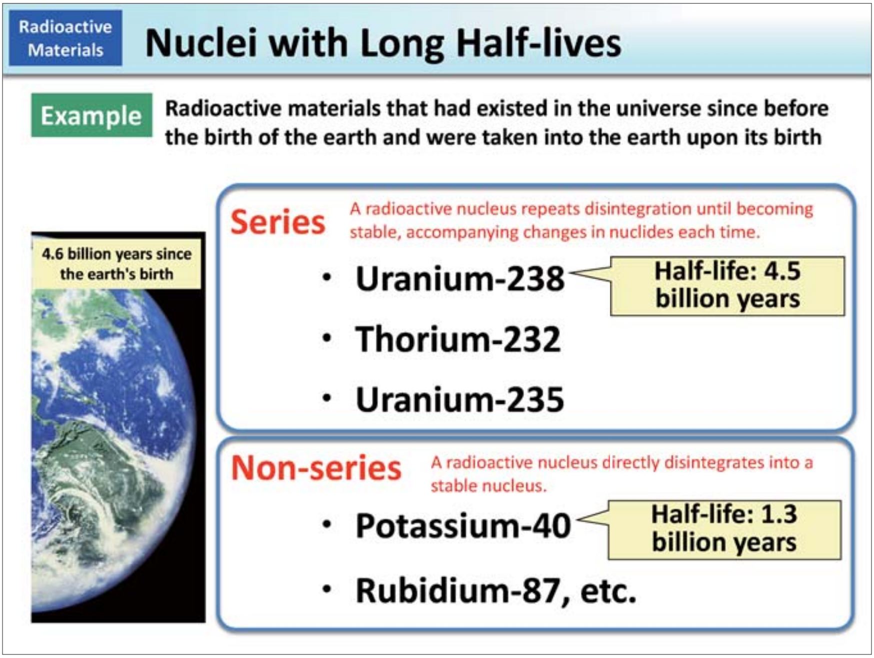

Radioactive Materials

Nuclei with Long Half-lives

Example Radioactive materials that had existed in the universe since before the birth of the earth and were taken into the earth upon its birth

4.6 billion years since the earth's birth

Series A radioactive nucleus repeats disintegration until becoming stable, accompanying changes in nuclides each time.

- Uranium-238 — Half-life: 4.5 billion years
- Thorium-232
- Uranium-235

Non-series A radioactive nucleus directly disintegrates into a stable nucleus.

- Potassium-40 — Half-life: 1.3 billion years
- Rubidium-87, etc.

Some nuclei that emit radiation have very long half-lives. Uranium-238 has a half-life of 4.5 billion years. Since the earth is about 4.6 billion years old, the amount of Uranium-238 that had existed at the time of the earth's birth has now reduced to half.

Some radionuclides become stable after a single emission of radiation, while some transform into various radionuclides as they disintegrate many times, until becoming stable.

For example, Uranium-238 emits α (alpha)-particles and transforms into Thorium-234, which is also a radionuclide. Thorium-234 further emits β (beta)-particles and transforms into Protactinium-234, which is also a radionuclide. They constitute a series in which the original element transforms into different atoms more than 10 times before becoming stable Lead-206.

Potassium-40 also has a long half-life of 1.3 billion years. This is another naturally occurring radionuclide that was taken into the earth upon its birth. Potassium-40 transforms into stable Calcium-40 or Argon-40 through a single disintegration without constituting a series.

(Related to p.10 of Vol. 1, "Parent and Daughter Nuclides," and p.11 of Vol. 1, "Half-lives and Radioactive Decay")

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