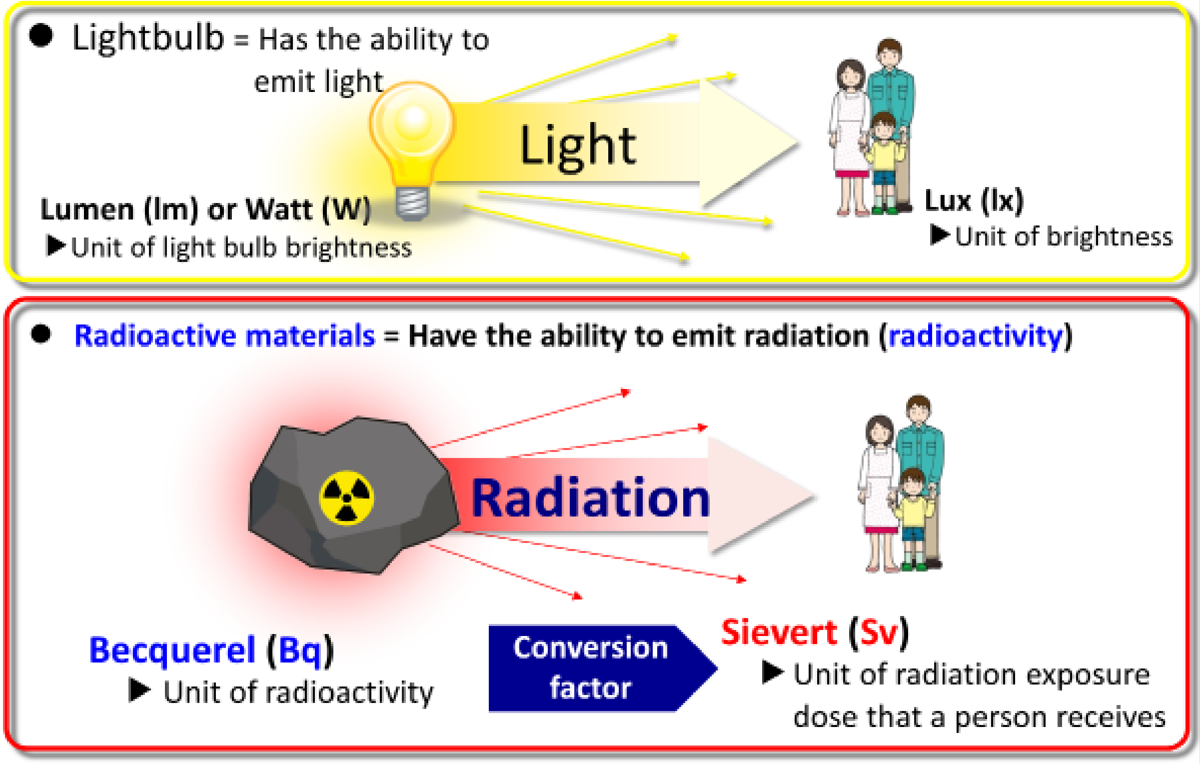
Radiation and Radioactivity

Radiation, Radioactivity and Radioactive Materials



*Sievert is associated with radiation effects.

Radiation, radioactivity and radioactive materials are outlined below.

A light bulb, an object familiar to everyone, has the ability to emit light. Light bulb brightness is expressed in the unit of “Lumens” or “Watts.” People receive the light and feel the brightness. The unit in this case is “Lux.”

The units related to radiation, such as becquerel and sievert, which we often hear about lately, also have a similar relation to the above. For example, when a rock emits radiation, this rock is called a “radioactive material” (p.3 of Vol. 1, “Units of Radiation and Radioactivity”).

Radioactive materials emit radiation, and this ability is called “radioactivity.” In this case, it is expressed as “This rock has radioactivity” or “This rock emits radiation.” This ability of emitting radiation is expressed in the unit of “Becquerel (Bq).”

“Sievert (Sv)” is used as the unit of the radiation exposure dose necessary to know the effect of radiation to which a person is exposed. There is a special conversion factor to calculate “Sv” from “Bq.”

Higher radioactivity (value expressed in becquerels) means that the relevant radioactive material emits more radiation, but radiation exposure dose (value expressed in sieverts) varies depending on the distance between the radioactive material and the person exposed thereto. The intensity of radiation rises when the person is closer to the thing emitting radiation, and the intensity weakens as the distance becomes larger. This is the same as a bright light bulb appearing dim at a distance.

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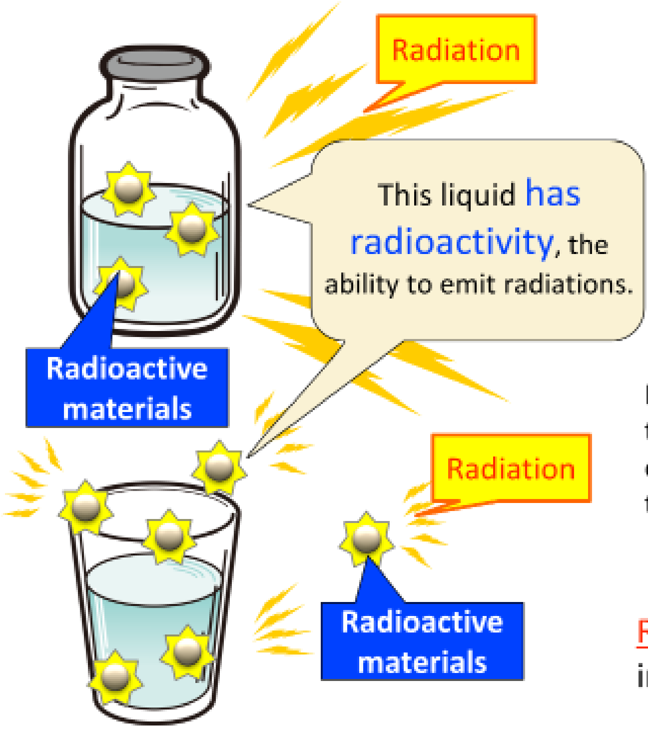
Radiation and Radioactivity

Difference between Radiation and Radioactive Materials



Radioactive materials themselves emit radiation.

If radionuclides are incorporated into the body, they will be partly removed outside the body (excreted) or be transferred to particular organs/tissues.

Radiation itself does not remain in the body.

Radioactive materials are materials that emit radiation. For example, the term is used as follows: “This water contains radioactive materials.” Although the term “radioactivity” is sometimes used in the meaning of radioactive materials, in the field of natural sciences, the term only refers to the ability to emit radiation.

If a sealed container contains water with radioactive materials, radiation may leak from the container, but radioactive materials do not come out. If a container without a lid contains water with radioactive materials, there is a possibility that radioactive materials may spread due to spilling, etc.

Radioactive materials incorporated into the body may remain in the body for a certain period of time and move between organs but some of them are excreted or lose radioactivity as a result of emitting radiation. Effects of radiation may partially remain in cells but radiation itself does not remain in the body. Health effects of radiation are detailed in Chapter 3.

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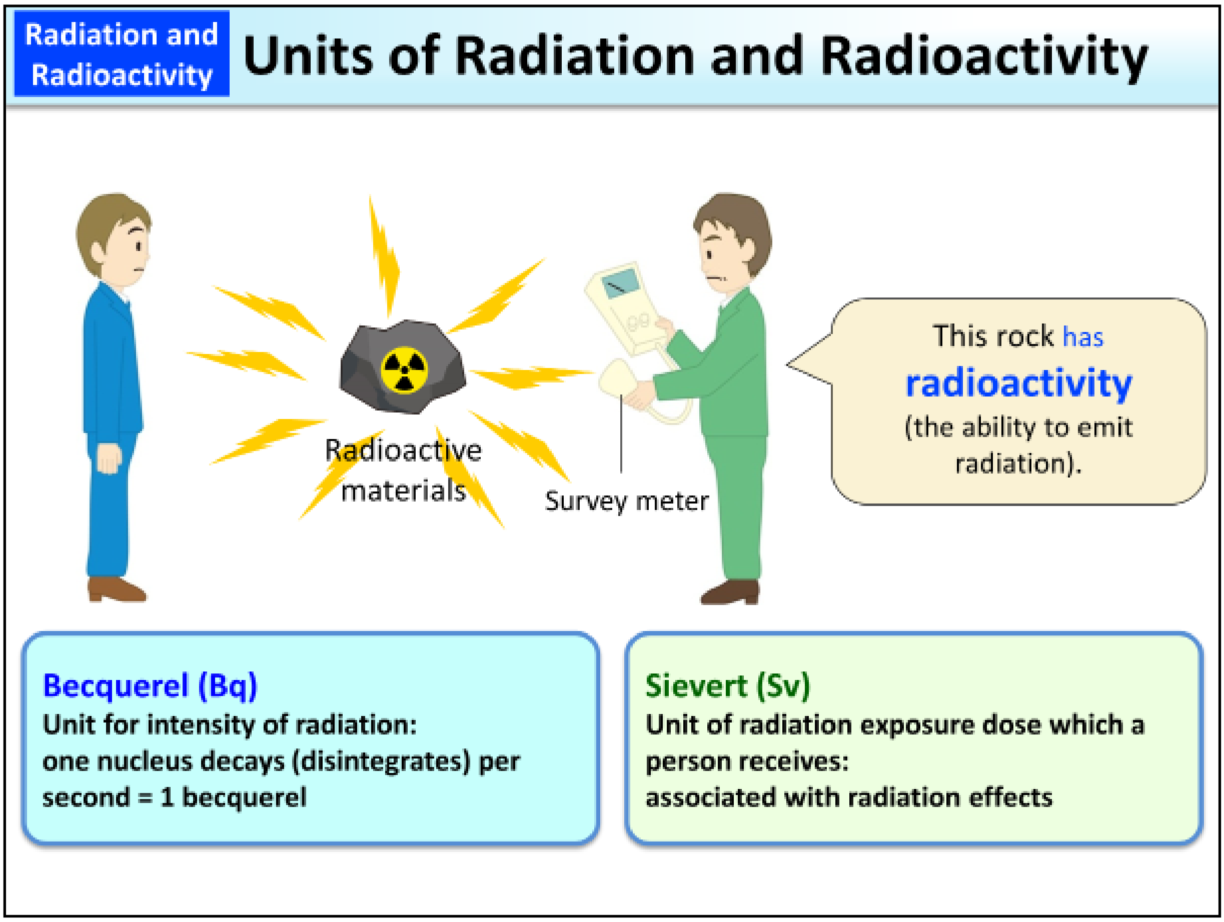

Radiation and Radioactivity

Units of Radiation and Radioactivity

This rock has **radioactivity** (the ability to emit radiation).

Becquerel (Bq)
Unit for intensity of radiation: one nucleus decays (disintegrates) per second = 1 becquerel

Sievert (Sv)
Unit of radiation exposure dose which a person receives: associated with radiation effects

Humans cannot sense radiation with their five senses because radiation is invisible and odorless. However, it has a feature that makes measuring easy.

"Becquerel" and "Sievert," which we have often heard about and seen recently, are units related to radiation. For example, radiation in soil or food can be measured using a special measuring device to find how much radioactive materials are contained in them. The becquerel is a unit to express the intensity of such radiation. The sievert is a unit to express the effect on the human body (for details, refer to Vol. 1, "2.3 Units of Radiation").

Places where a large amount of radioactive materials exist can be identified with a handheld survey meter. Additionally, the intensity and types of radiation emitted from radioactive materials, as well as personal exposure doses, can be checked with various types of survey meters (for details, refer to Vol. 1, "2.4 Dose Measurement and Calculation").

Furthermore, based on the results of various investigative studies, radiation doses due to the effect of the accident and natural radiation doses, as well as the total thereof, can be obtained separately.

Means for radiation management and radiation protection are devised taking advantage of this feature of radiation, i.e., the easiness of measurement.

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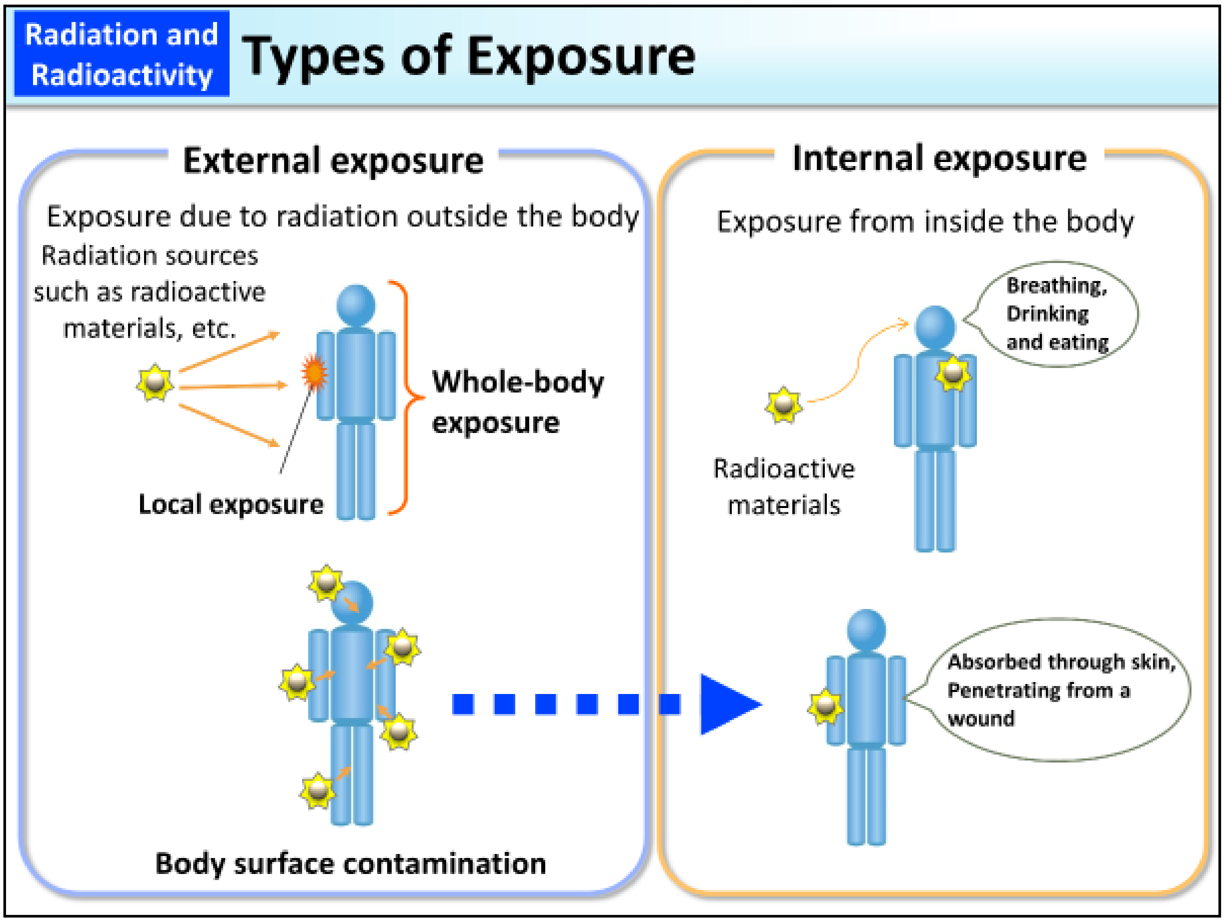

Radiation and Radioactivity

Types of Exposure

To receive radiation from radioactive materials is called radiation exposure. On the other hand, radioactive contamination means that matter, including people and places, is contaminated with radioactive materials. In other words, radioactive contamination suggests that some radioactive materials exist in places where radioactive materials do not usually exist.

To receive radiation from radioactive materials outside the body is called external exposure.

If a person breathes in radioactive materials in the air or takes contaminated food or drink into their body, he/she will be exposed to radiation from inside their body. In addition, radioactive materials can also enter the body from wounds. Receiving radiation in this way is called internal exposure.

For internal and external exposures, the relevant radiation types (α (alpha)-particles, β (beta)-particles and γ (gamma)-rays) (for details, refer to Vol. 1, “1.3 Radiation”) and radioactive materials (radionuclides) are different, because the ability to pass through the air or the body differs by radiation type.

In addition, the state in which radioactive materials adhere to the surface of the human body is called body surface contamination. If radioactive materials that adhere to the surface of the human body enter inside through the nose, mouth or wounds, internal contamination arises and this may cause internal exposure.

(Related to p.2 of Vol. 1, “Difference between Radiation and Radioactive Materials,” p.23 of Vol. 1, “Internal and External Exposure”)

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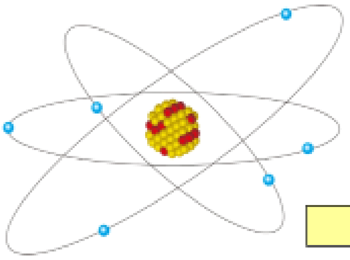
Radioactive Materials

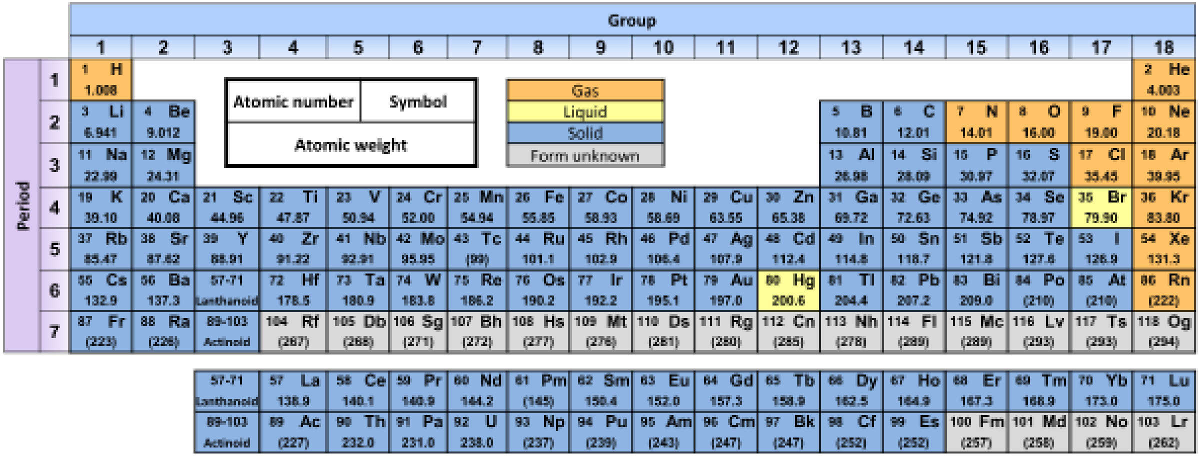
Atomic Structure and Periodic Law



			Charge
Atom	Nucleus	Proton 🔴	+
		Neutron 🟡	0
	Electron	🔵	−

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

Periodic Table of Elements



Atomic number	Symbol
Atomic weight	

Gas
Liquid
Solid
Form unknown

		Group																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period	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)

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 (13th 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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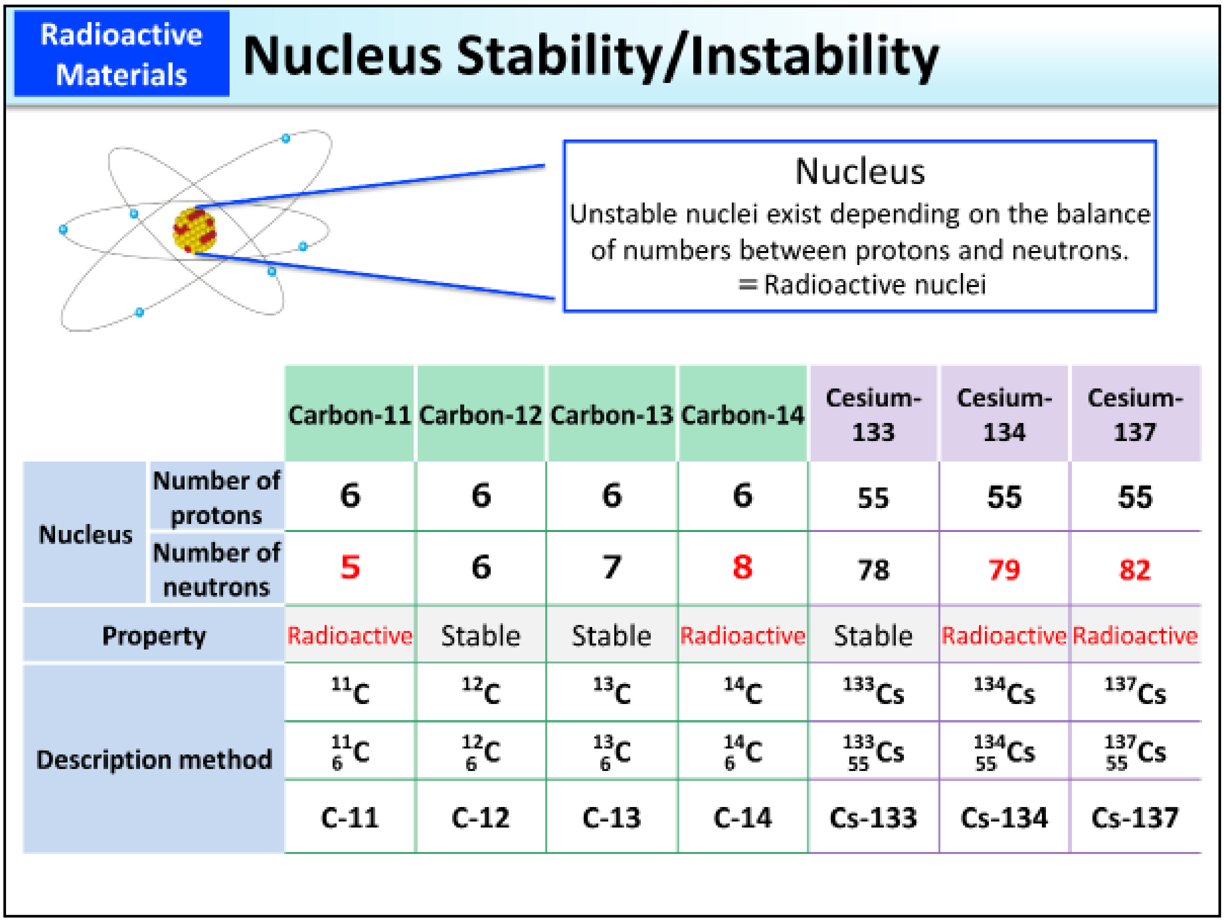

Radioactive Materials

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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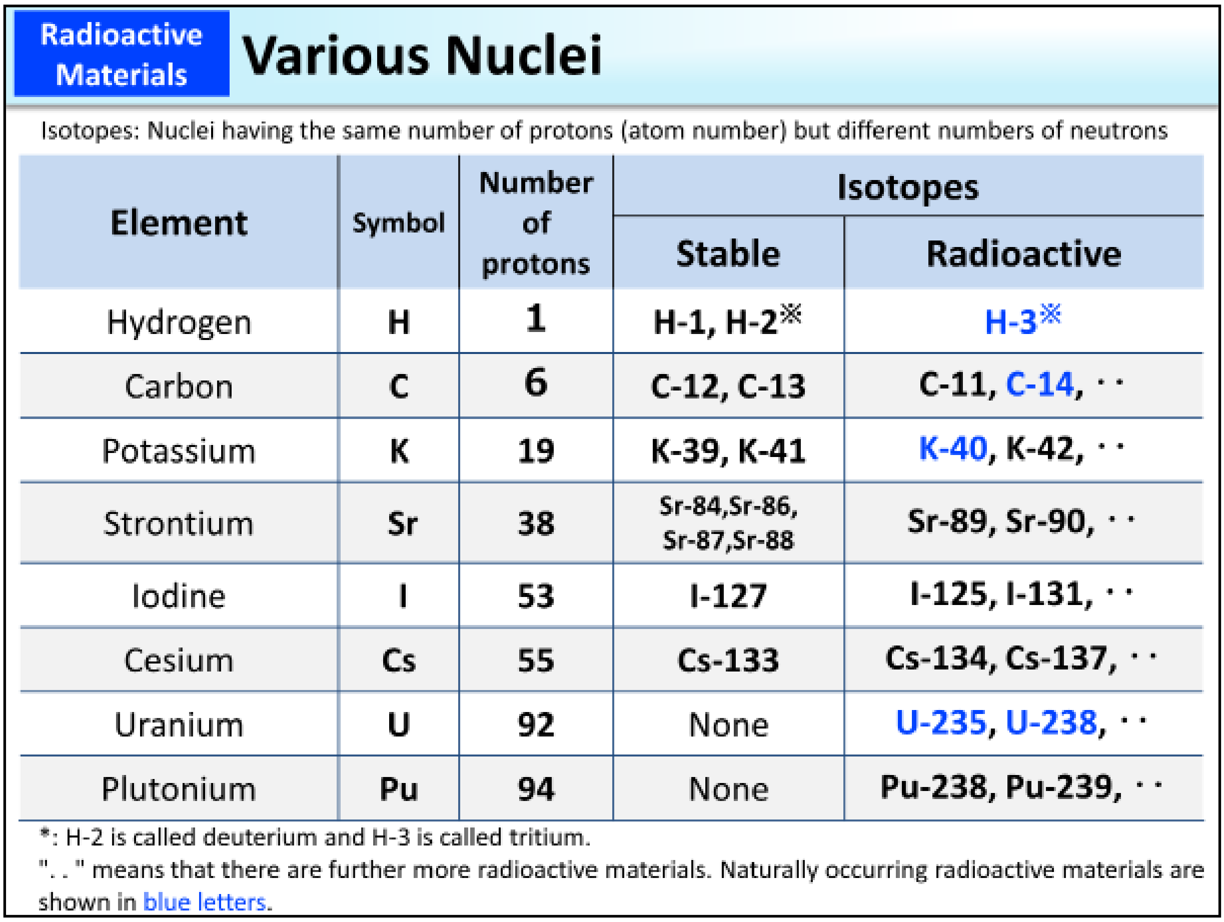

Radioactive Materials

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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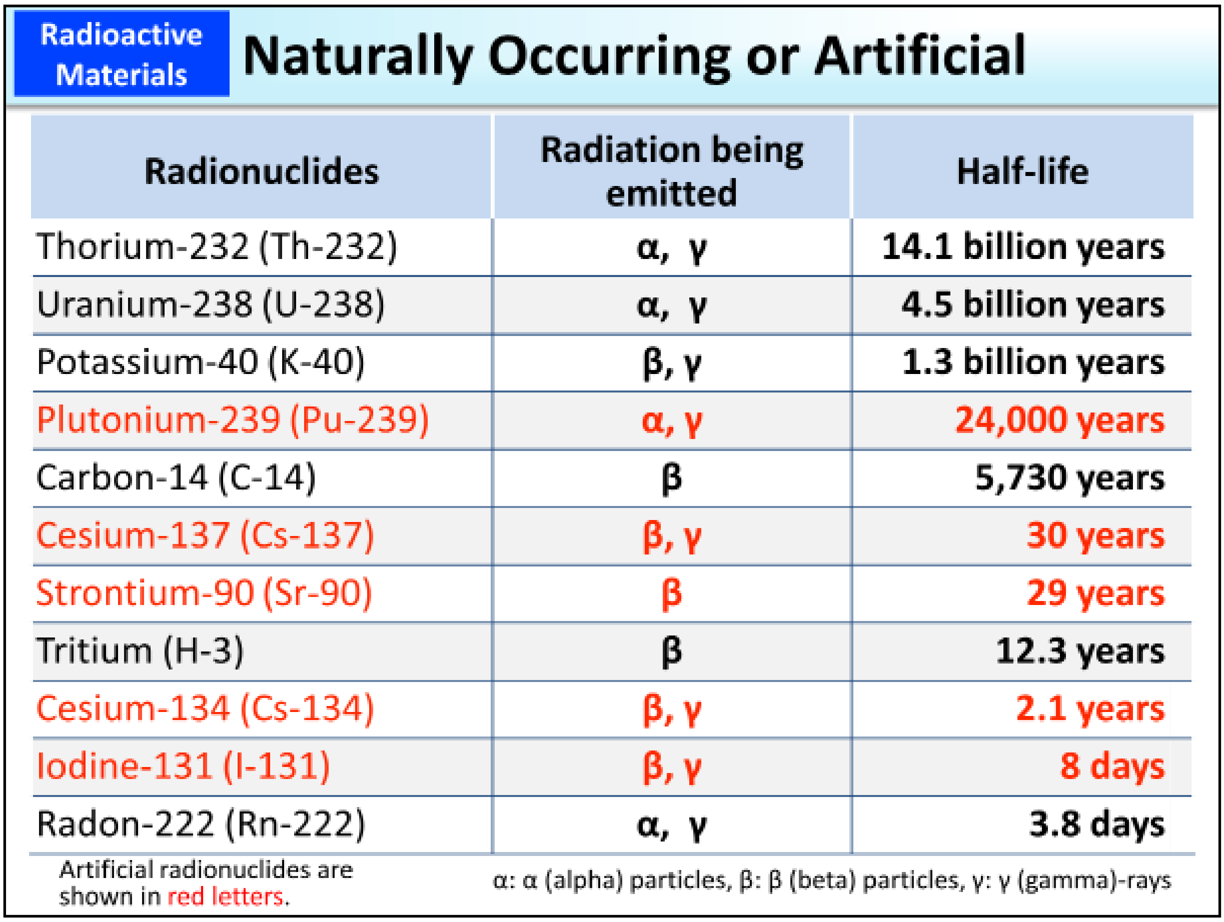

Radioactive Materials

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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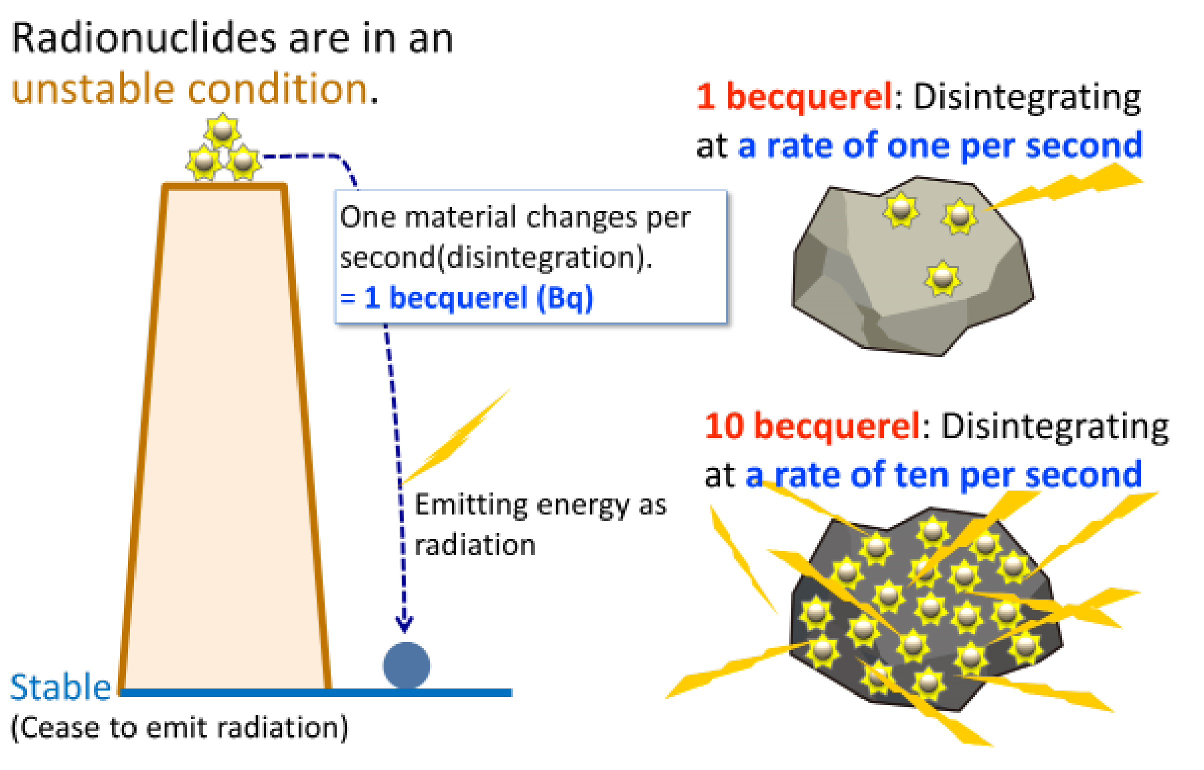
Radioactive Materials

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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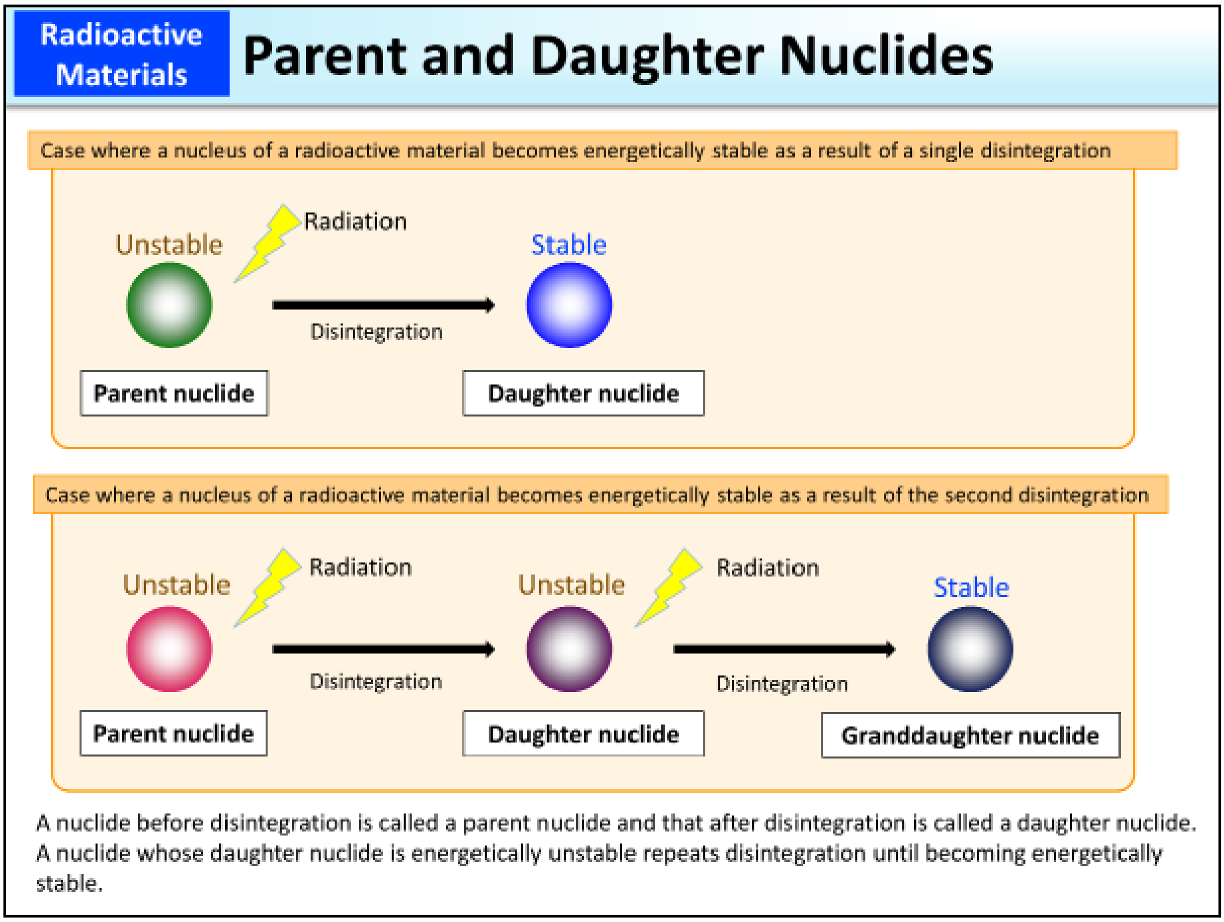

Radioactive Materials

Parent and Daughter Nuclides

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

Unstable

Radiation

Disintegration

Stable

Parent nuclide

Daughter nuclide

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

Unstable

Radiation

Disintegration

Unstable

Radiation

Disintegration

Stable

Parent nuclide

Daughter nuclide

Granddaughter nuclide

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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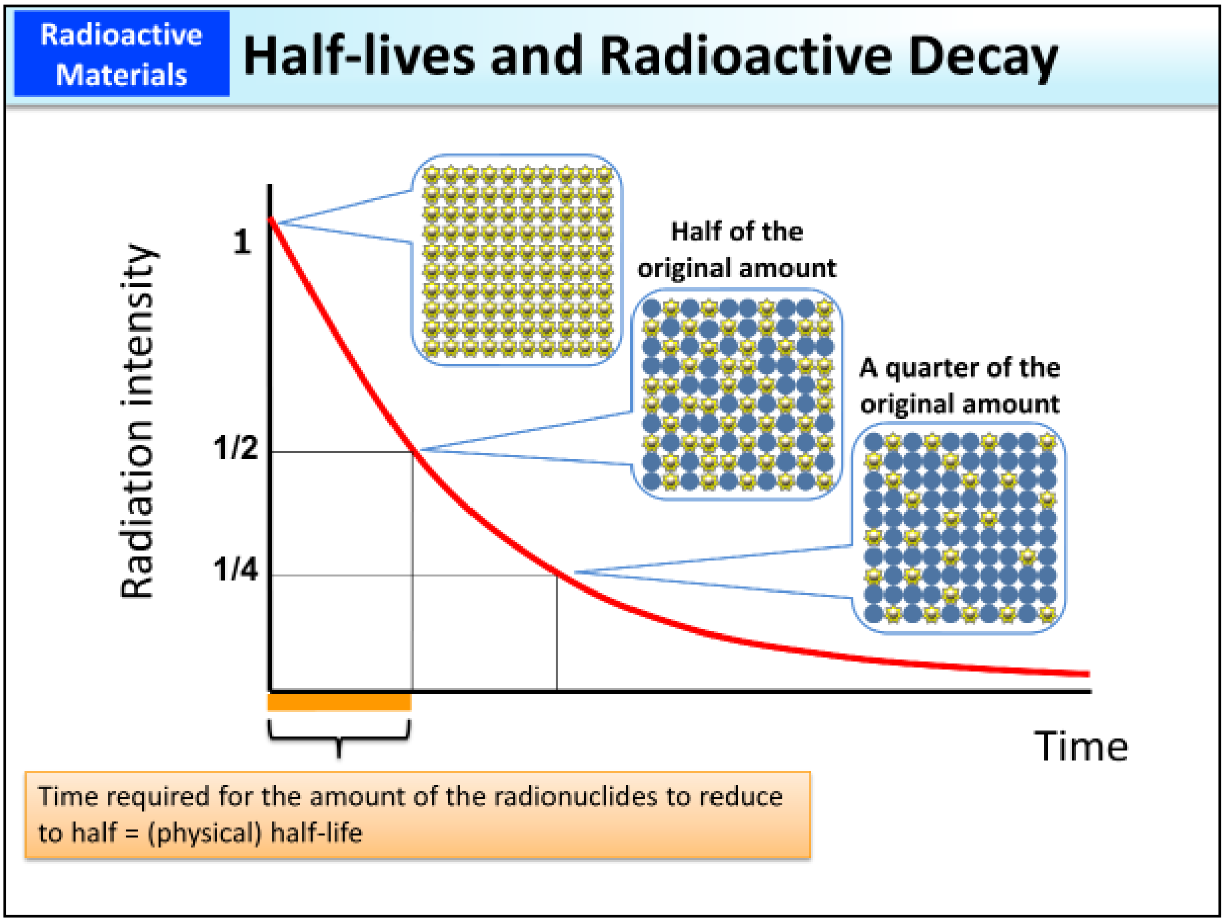

Radioactive Materials

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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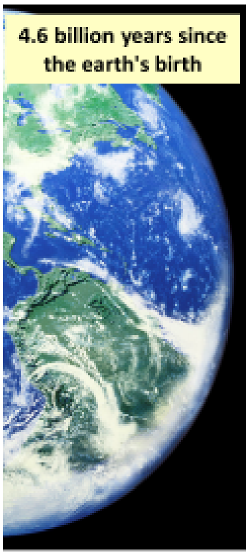
Radioactive Materials

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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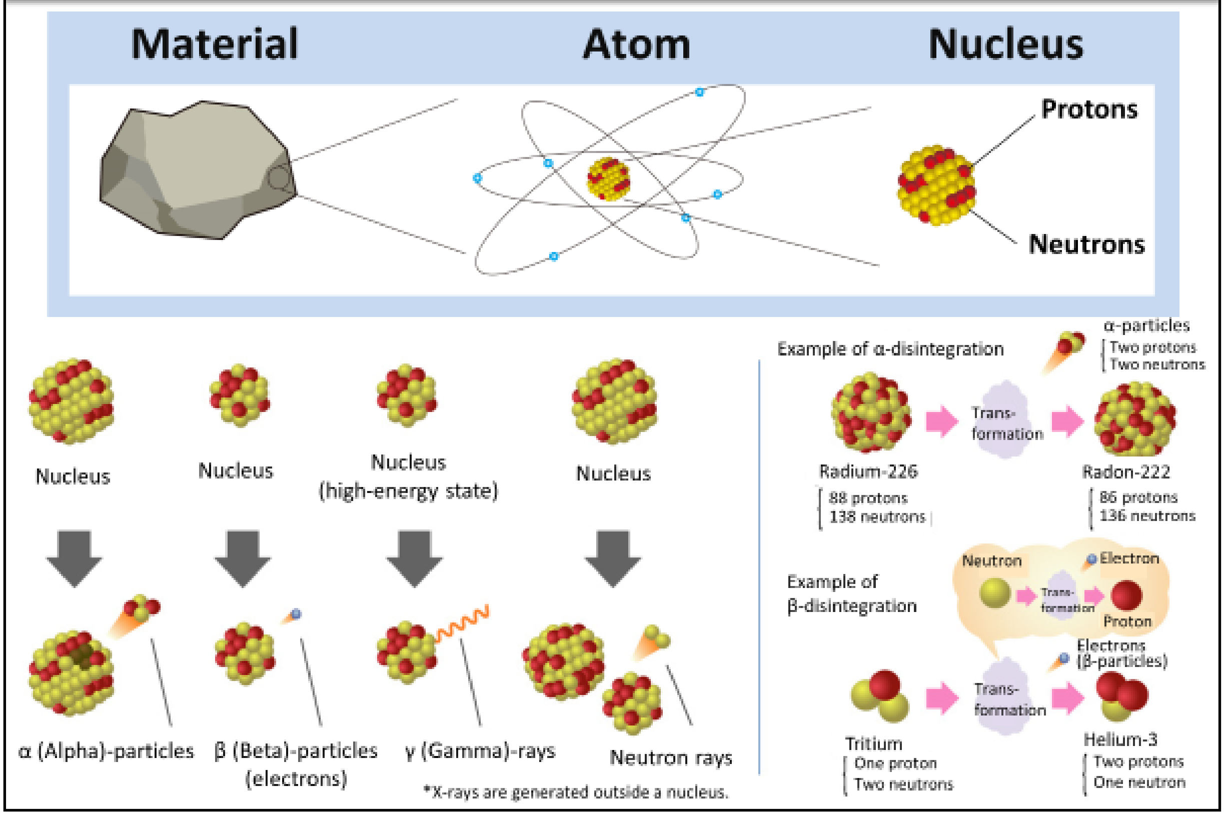
Radiation

Where does Radiation Come from?



α (alpha)-particles, β (beta)-particles, γ (gamma)-rays, and X-rays were the names given to them because they were not elucidated at the time of their discoveries. Today, α-particles are found to be helium nuclei with two protons and two neutrons, flying out at high speed; β-particles are electrons that are ejected from a nucleus. A helium nucleus weighs about 7,300 times more than an electron. Normally, nuclei have high energy and are therefore still unstable immediately after emission of α-particles or β-particles, so they will further emit γ-rays in order to become stable. However, some do not emit γ-rays.

While α-particles, β-particles, and γ-rays are emitted from a nucleus, X-rays are electromagnetic waves that are generated outside a nucleus. Unlike X-rays, γ-rays are generated from a nucleus, but both are electromagnetic waves. A neutron is a particle that constitutes a nucleus. Neutrons that are ejected from a nucleus with kinetic energy, e.g. during the fission of the nucleus, are called neutron beams.

(Related to p.14 of Vol. 1, “Types of Radiation,” and p.15 of Vol. 1, “Types of Ionizing Radiation”)

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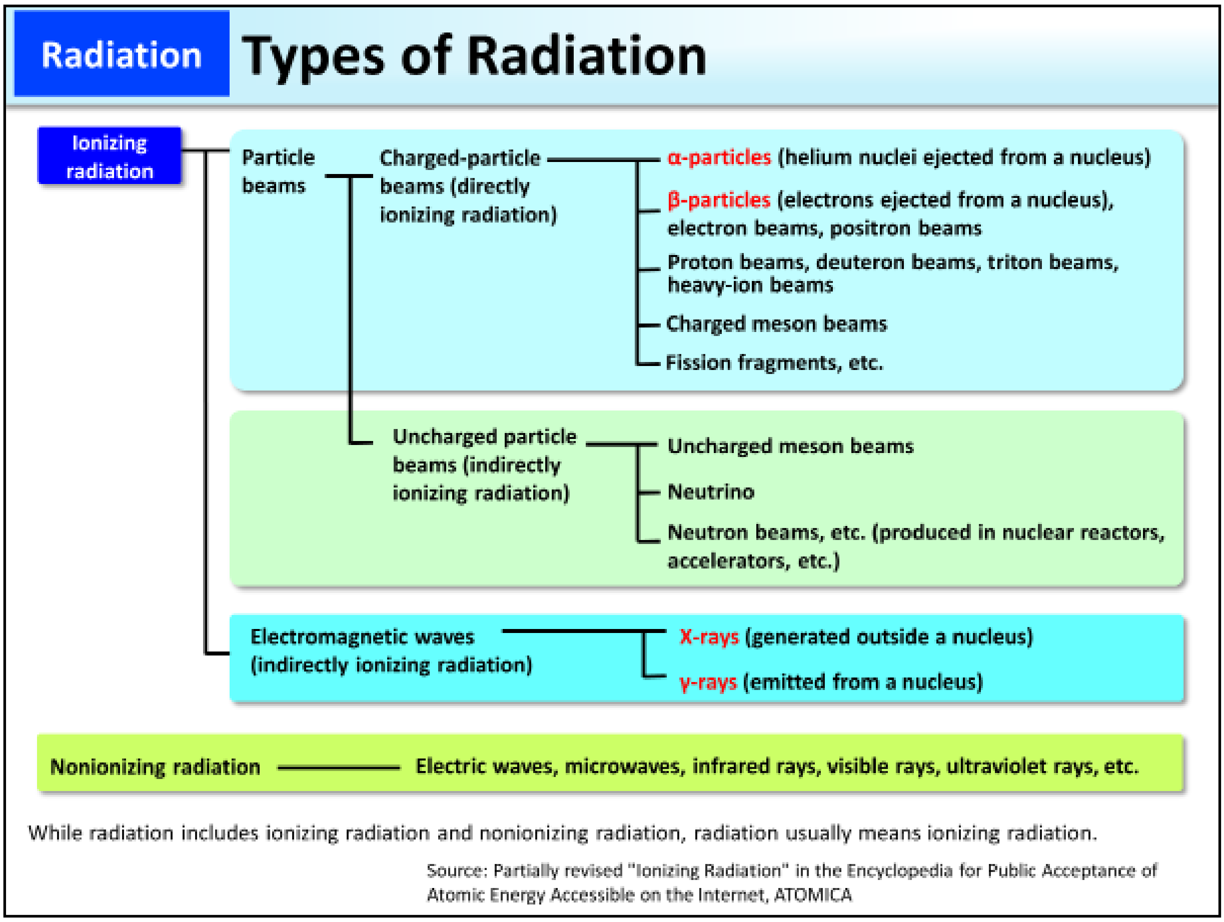

Radiation Types of Radiation

Ionizing radiation

Particle beams

Charged-particle beams (directly ionizing radiation)

- α-particles (helium nuclei ejected from a nucleus)
- β-particles (electrons ejected from a nucleus), electron beams, positron beams
- Proton beams, deuteron beams, triton beams, heavy-ion beams
- Charged meson beams
- Fission fragments, etc.

Uncharged particle beams (indirectly ionizing radiation)

- Uncharged meson beams
- Neutrino
- Neutron beams, etc. (produced in nuclear reactors, accelerators, etc.)

Electromagnetic waves (indirectly ionizing radiation)

- X-rays (generated outside a nucleus)
- γ-rays (emitted from a nucleus)

Nonionizing radiation — Electric waves, microwaves, infrared rays, visible rays, ultraviolet rays, etc.

While radiation includes ionizing radiation and nonionizing radiation, radiation usually means ionizing radiation.

Source: Partially revised "Ionizing Radiation" in the Encyclopedia for Public Acceptance of Atomic Energy Accessible on the Internet, ATOMICA

Radiation generally means ionizing radiation. Ionizing radiation, which has the ability to ionize atoms that make up a substance (separate the atoms into positively charged ions and negatively charged electrons), is categorized into particle beams and electromagnetic waves.

Particle beams include α (alpha)-particles, β (beta)-particles, neutron beams, etc. (p.13 of Vol. 1, "Where does Radiation Come from?"). Particle beams include charged (ionized) particle beams and uncharged particle beams. γ (gamma)-rays and X-rays are types of electromagnetic waves.

Some forms of electromagnetic waves, such as electric waves, infrared rays, and visible rays, do not cause ionization, and they are called nonionizing radiation. Ultraviolet rays are generally categorized as nonionizing radiation although some ultraviolet rays do cause ionization (p.15 of Vol. 1, "Types of Ionizing Radiation").

(Related to p.19 of Vol. 1, "Types of Radiation and Biological Effects," and p.20 of Vol. 1, "Penetrating Power of Radiation")

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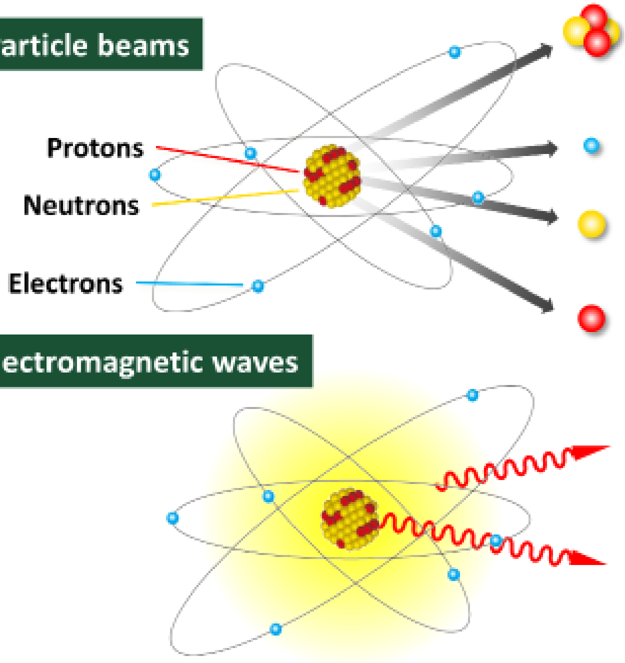
Radiation

Types of Ionizing Radiation

Ionizing radiation Radiation that causes ionization



Particle beams

α-particles (helium nuclei ejected from a nucleus)

β-particles (electrons ejected from a nucleus)

Neutron beams (produced in nuclear reactors, accelerators, etc.)

Proton beams (produced in accelerators, etc.)

Electromagnetic waves

X-rays (generated outside a nucleus)

γ-rays (emitted from a nucleus)

Particle beams include α (alpha)-particles, β (beta)-particles, neutron beams, etc.

α-particles are helium nuclei consisting of two protons and two neutrons that have been ejected at high speed, while β-particles are electrons ejected from a nucleus. Particle beams also include neutron beams and proton beams.

γ-rays and X-rays are types of electromagnetic waves. While α-particles, β-particles, and γ-rays are emitted from a nucleus, X-rays used in X-ray examination for medical checkups and the like are electromagnetic waves generated outside a nucleus. X-rays generated in X-ray tubes are used in X-ray examination. X-rays include braking X-rays and characteristic X-rays (p.16 of Vol. 1, “X-rays for Medical Use and Generators”).

(Related to p.13 of Vol. 1, “Where does Radiation Come from?,” and p.14 of Vol. 1, “Types of Radiation”)

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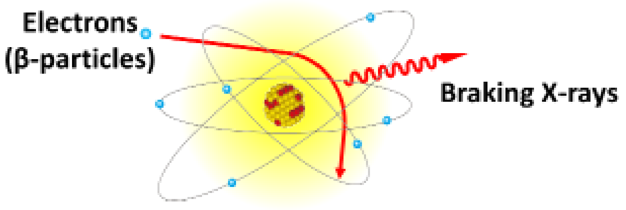
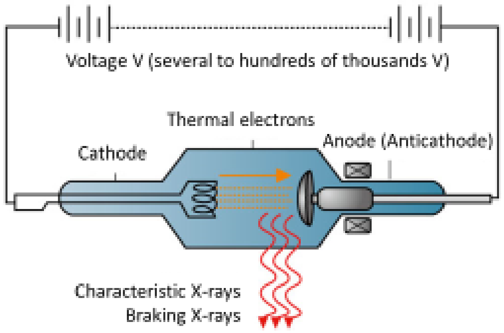
Radiation X-rays for Medical Use and Generators

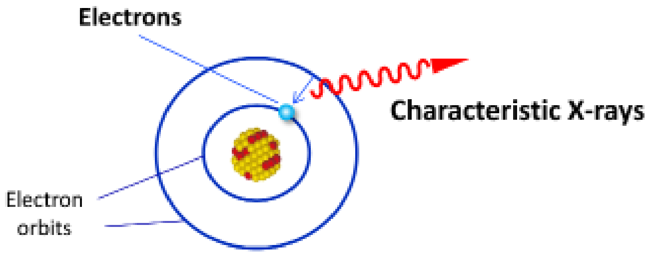
Braking X-rays



Structural drawing of an X-ray generator



Characteristic X-rays



X-ray examination uses X-rays generated in X-ray tubes. A high voltage is applied between a cathode and an anode (tungsten, molybdenum, copper, etc.) inside an X-ray tube so that thermal electrons migrate from the cathode to the anode in a vacuum at high speed. X-rays generated when the direction of propagation of the thermal electrons changes as they are attracted to the nucleus of the anode are called braking X-rays. When an electron is ejected from the inner electron orbit of the anode nucleus, another electron migrates (transitions) to this vacancy from the outer electron orbit. X-rays generated thereby are called characteristic X-rays. Most of the X-rays generated in X-ray tubes are braking X-rays.

Generation of X-rays stops when the X-ray tube is switched off.

X-ray generators used in the field of medicine are either for diagnosis or for treatment. The energy and amount of X-rays are adjusted to match the purpose of imaging and the part to be imaged. In chest roentgenography (diagnosis), the amount of radiation a patient receives in one imaging session is approx. 0.06 mSv.

(Related to p.63 of Vol. 1, “Exposure Dose from Natural and Artificial Radiation,” and p.76 of Vol. 1, “Radiation Doses from Medical Diagnosis”)

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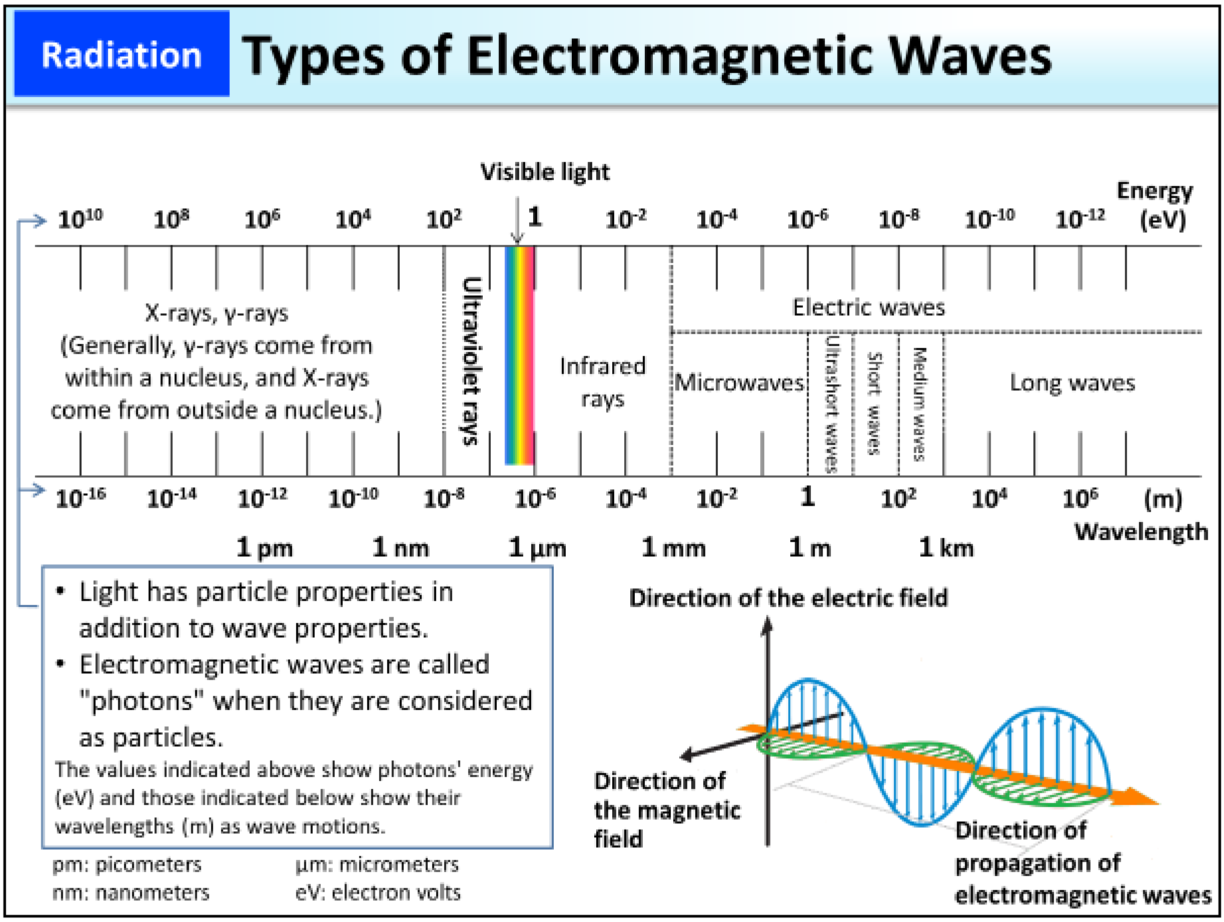

Radiation Types of Electromagnetic Waves

- Light has particle properties in addition to wave properties.
- Electromagnetic waves are called "photons" when they are considered as particles.

The values indicated above show photons' energy (eV) and those indicated below show their wavelengths (m) as wave motions.

pm: picometers
nm: nanometers
μm: micrometers
eV: electron volts

Electromagnetic waves are waves that propagate through space while an electric field and a magnetic field interact with each other. The shorter the wavelength is (the higher the frequency is), the higher the energy of an electromagnetic wave. The energy of radiation is expressed in electron volts (eV). 1 eV equals 1.6 x 10^{-19} Joule (J).

While X-rays and γ-rays differ in the mechanisms of how they are generated, they are both electromagnetic waves with high energy.

Thus, an electromagnetic wave sometimes behaves like a wave and may be expressed as a waveform perpendicular to its direction of propagation, as shown in the figure above.

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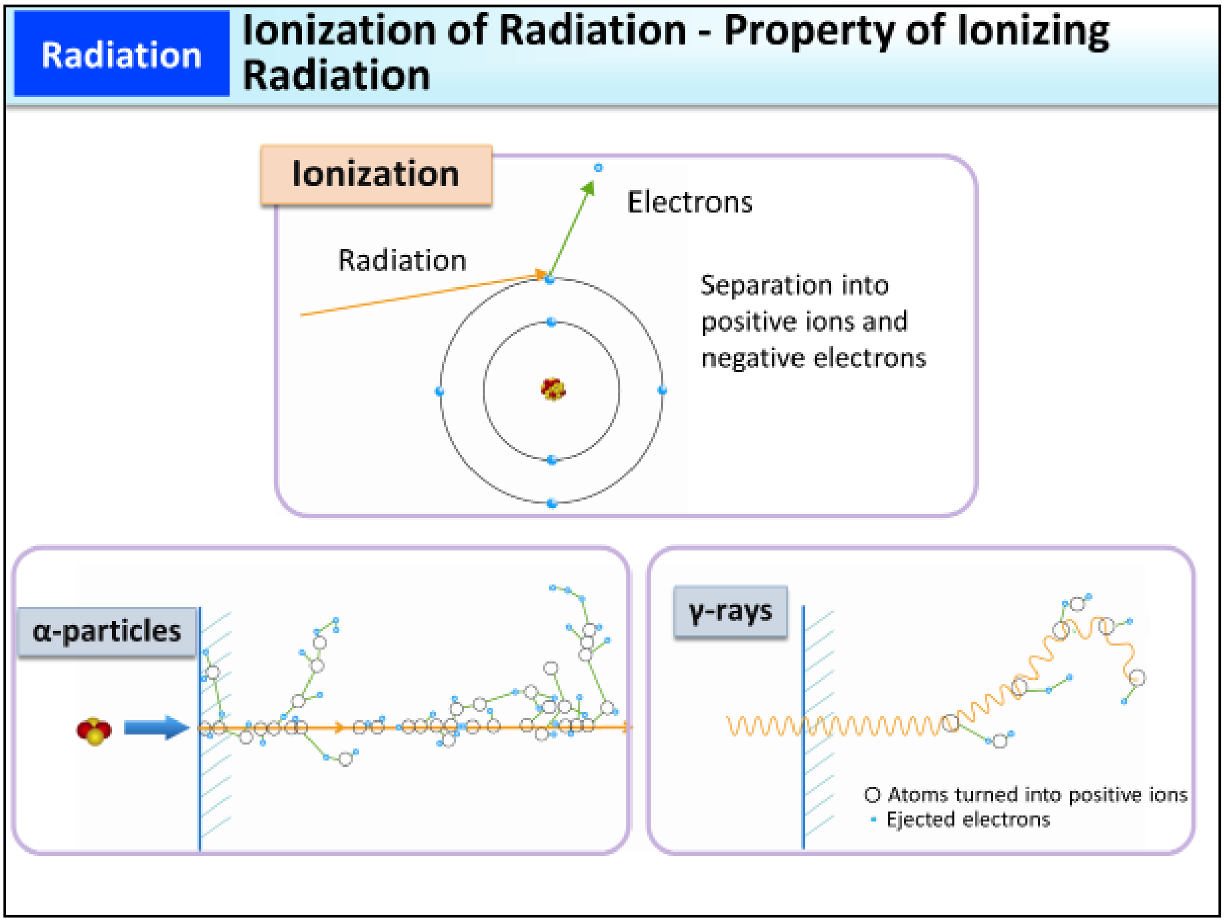

Radiation

Ionization of Radiation - Property of Ionizing Radiation

Ionization

Radiation

Electrons

Separation into positive ions and negative electrons

α-particles

γ-rays

○ Atoms turned into positive ions

▪ Ejected electrons

When radiation passes through a substance, its energy causes ejection of orbital electrons of the atoms that make up the substance, separating the atoms into positively charged atoms (or positive ion molecules) and free electrons. This is called ionization.

Ionizing radiation that causes ionization ionizes substances either directly or indirectly.

Charged particle beams, such as α-particles and β-particles, ionize substances directly. In particular, α-particles have high ionization density, causing ionization at a density hundreds of times as high as that of β-particles, etc.

γ-rays and X-rays ionize substances indirectly using secondary electrons generated through their interaction with the substances.

(Related to p.14 of Vol. 1, “Types of Radiation”)

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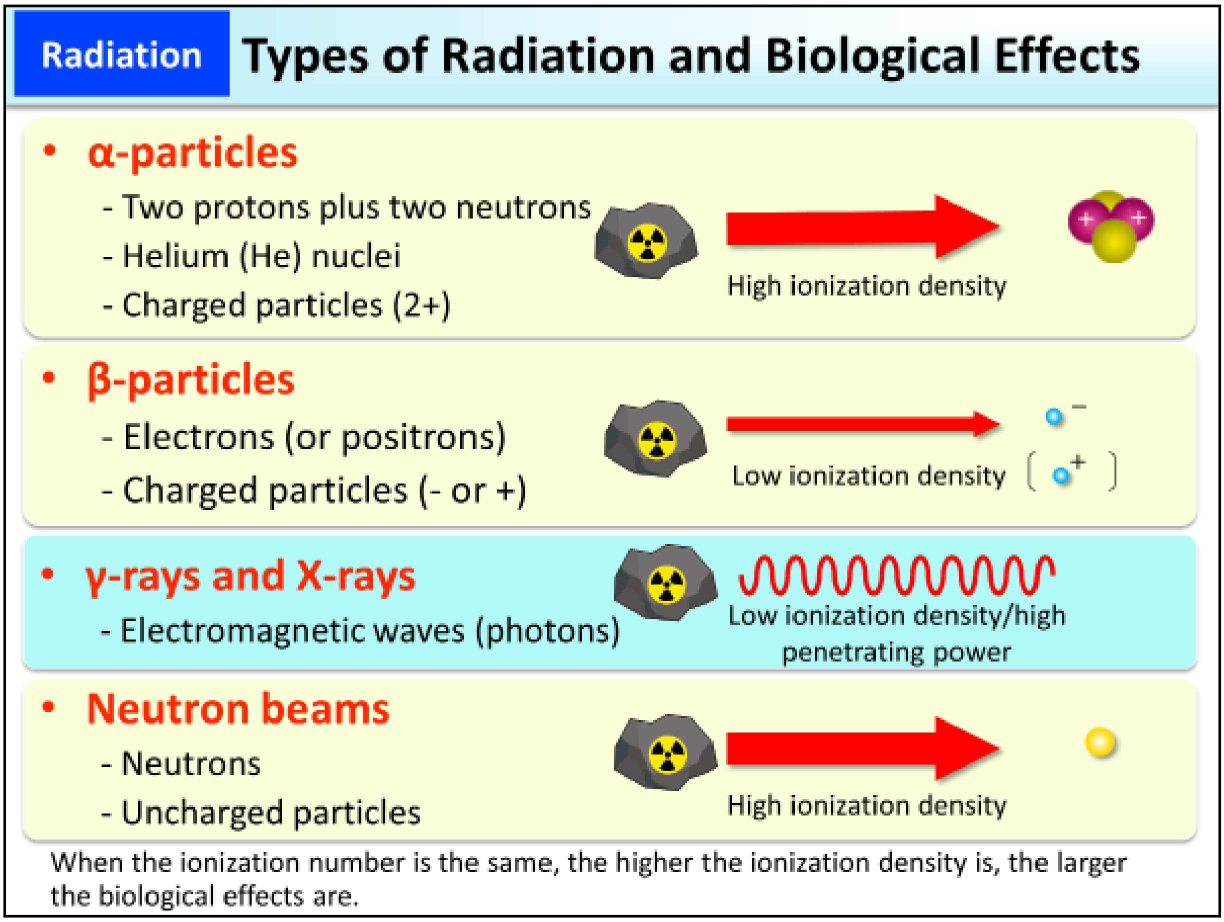

Radiation Types of Radiation and Biological Effects

- **α-particles**
  - Two protons plus two neutrons
  - Helium (He) nuclei
  - Charged particles (2+)

High ionization density

- **β-particles**
  - Electrons (or positrons)
  - Charged particles (- or +)

Low ionization density

- **γ-rays and X-rays**
  - Electromagnetic waves (photons)

Low ionization density/high penetrating power

- **Neutron beams**
  - Neutrons
  - Uncharged particles

High ionization density

When the ionization number is the same, the higher the ionization density is, the larger the biological effects are.

External exposure to α-particles does not cause problems because α-particles have weak penetrating power against biological tissues and cannot penetrate the horny layer of the skin (layer of dead cells on the skin surface). However, internal exposure to any radioactive material that emits α-particles causes large amounts of local ionization, i.e., high-density ionization, within tissues, providing concentrated energy. This significantly damages DNA and has strong biological effects.

β-particles cause direct ionization of the substance it passes through, as do α-particles, but because of their low ionization density, their biological effects are not as strong as those of α-particles. Penetrating power of β-particles is also weak but stronger than that of α-particles, and external exposure to β-particles could affect the skin and subcutaneous tissues.

γ-rays and X-rays reach deep organs and tissues because of their strong penetrating power but do not have high ionization density. Their biological effects are similar to those of β-particles.

Since a neutron has a mass almost equal to that of a proton, a neutron beam stops efficiently when colliding with a proton. Since the human body contains a large amount of water, neutrons lose their energy as they collide with hydrogen nuclei (protons) that make up water molecules.

(Related to p.15 of Vol. 1, “Types of Ionizing Radiation,” and p.18 of Vol. 1, “Ionization of Radiation - Property of Ionizing Radiation”)

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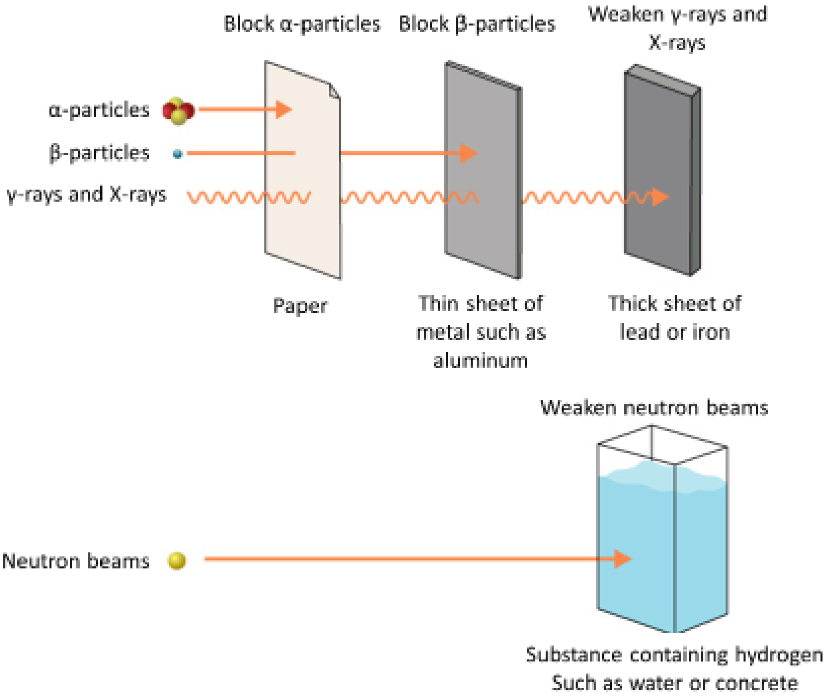
Radiation

Penetrating Power of Radiation

Radiation can be blocked by various substances.



Charged particles or electromagnetic waves interact with a substance, lose their energy (speed), and eventually stop.

Since α-particles cause a large amount of ionization, a sheet of paper is enough to stop them. β-particles travel several meters in the air, and a 1 cm thick plastic sheet or a 2-4 mm thick aluminum plate is enough to stop them, depending on how much energy they have. γ-rays and X-rays have higher penetrating power than α-particles or β-particles, travel several tens to hundreds of meters in the air (depending on their energy) and gradually lose their energy as they collide with atoms in the air. As γ-rays and X-rays can be shielded using thick plates of high-density lead or iron, those from radiation generators can be blocked using iron and the like.

Uncharged neutrons lose their energy through collision and are absorbed through interaction with substances. That is, neutrons lose their energy (speed) by directly colliding with nuclei that make up substances. They lose their energy most effectively by colliding with protons (hydrogen nuclei) that are almost equal in mass to them.
(Related to p.21 of Vol. 1, “Penetrating Power of Radiation within the Body”)

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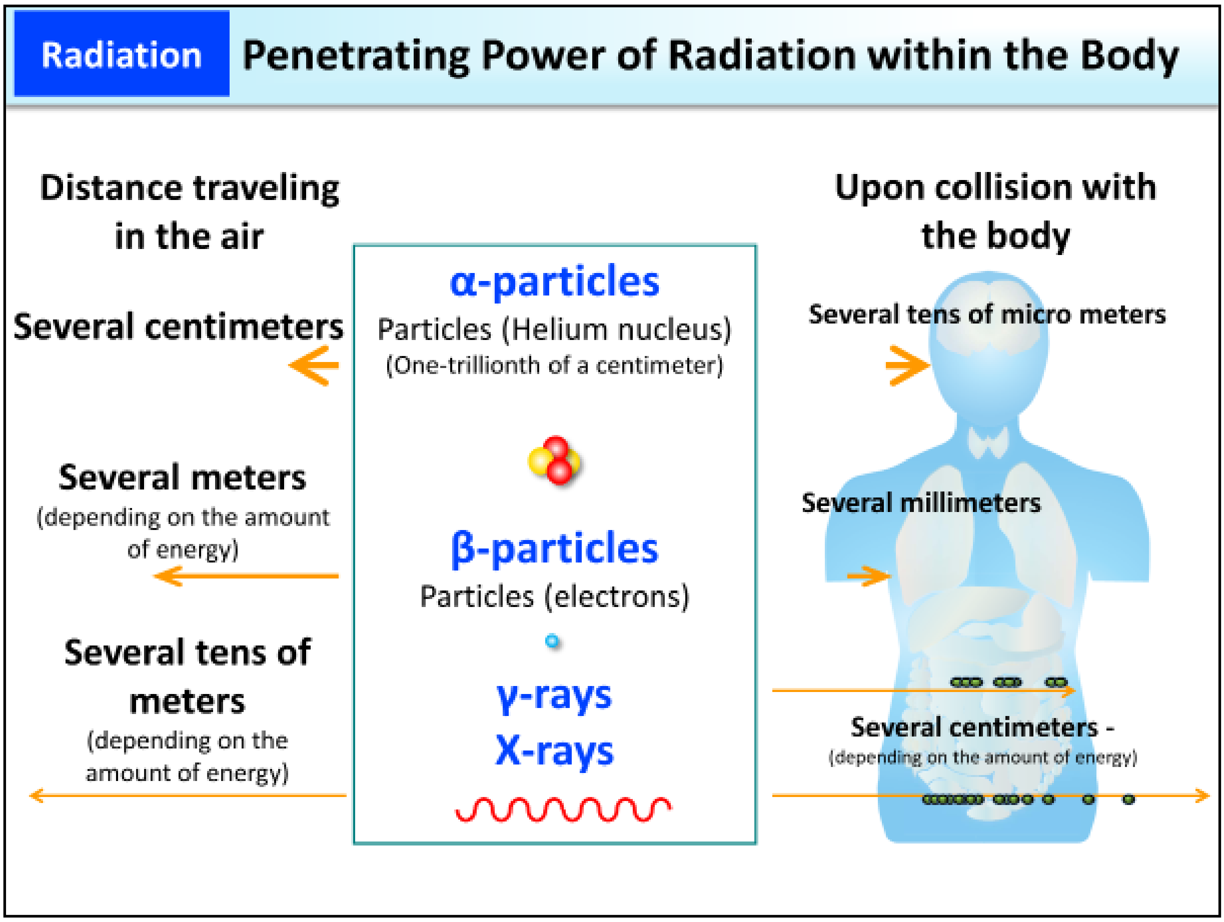

Radiation Penetrating Power of Radiation within the Body

Distance traveling in the air

Upon collision with the body

α-particles
Particles (Helium nucleus)
(One-trillionth of a centimeter)

β-particles
Particles (electrons)

γ-rays
X-rays

Several centimeters

Several meters
(depending on the amount of energy)

Several tens of meters
(depending on the amount of energy)

Several tens of micro meters

Several millimeters

Several centimeters -
(depending on the amount of energy)

The easiness to penetrate through the air or the human body varies depending on the types of radiation. Therefore, the types of radiation (α-particles, β-particles, or γ-rays) and radioactive materials (nuclides) that cause problems differ for external exposure and internal exposure.

α-particles can travel only several centimeters in the air and a sheet of paper is enough to stop them. In the case of external exposure, α-particles do not reach deeper than the layer of dead cells (horny layer) on the skin surface and do not cause effects. However, if an alpha-emitting radionuclide enters the body, it will provide energy intensively to nearby cells where it is deposited.

Since β-particles travel only several meters in the air, they hardly contribute to exposure when a radiation source is located away from the body. When the surface of the body is exposed to β-particles, their energy is imparted to the skin and subcutaneous tissues; when β-particles enter the body, their energy is imparted to a radius of several millimeters around the relevant spot.

γ-rays and X-rays have high penetrating power and travel several tens to hundreds of meters in the air. When they collide with the human body, they can reach deep into the body or sometimes pass through it. Their energy is imparted to the part they pass through. In X-ray examination, the parts of the body X-rays can easily pass through (lungs, etc.) appear in black while the parts they cannot easily pass through (bones, etc.) appear in white.
(Related to p.22 of Vol. 1, “Penetrating Power and Range of Effects on the Human Body”)

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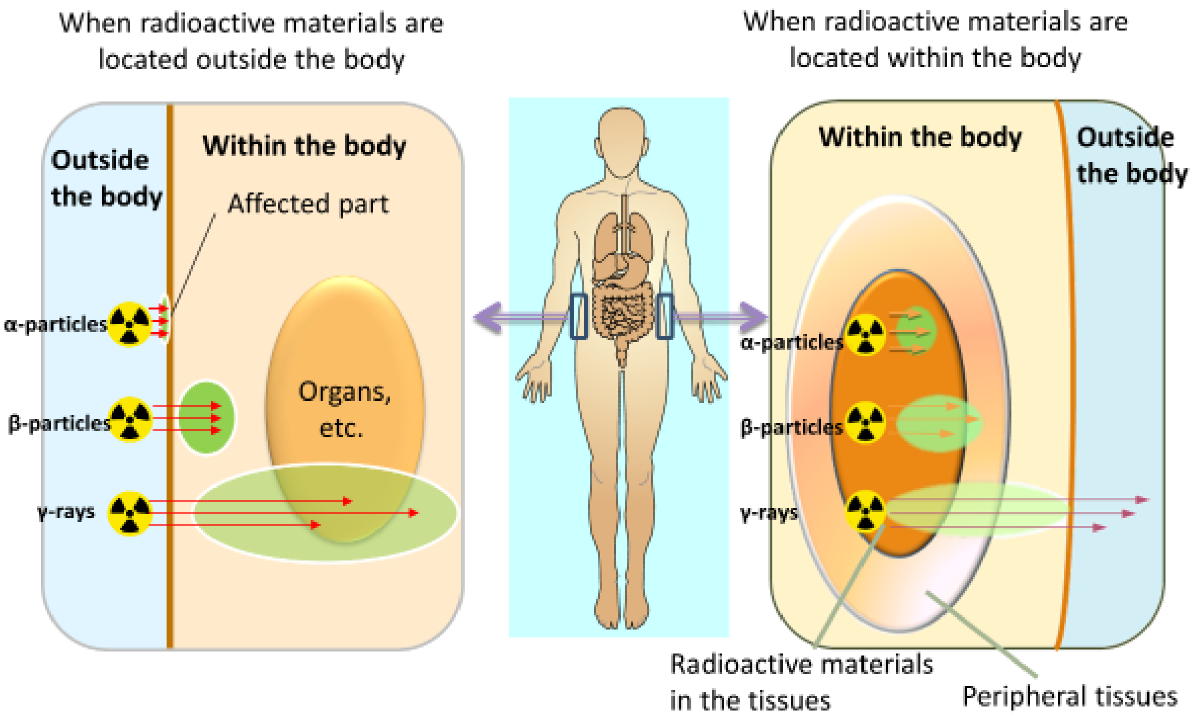
Radiation

Penetrating Power and Range of Effects on the Human Body



In the case of external exposure, α-particles do not have any effect as they stop at the horny layer on the surface of the body (the penetrating distance of α-particles is about several tens of micrometers). β-particles pass through the skin (their penetrating distance is about several millimeters) and can cause burn-like symptoms when doses are very high, but do not reach deep into the body. γ-rays reach important organs deep inside the body. Thus, the major concern in the case of external exposure is with γ-rays.

On the other hand, in the case of internal exposure, all radioactive materials that emit α-particles, β-particles, or γ-rays could affect cells within the body. Given the distance α-particles travel, their effects are confined to tissues where radioactive materials exist, but due to their significant biological effects, particular caution is required in relation to internal exposure. γ-rays can affect the entire body because they travel long distances.

Some radioactive materials such as uranium, once entering the human body, may also cause metallic toxicity, etc., in addition to causing internal exposure.
(Related to p.21 of Vol. 1, “Penetrating Power of Radiation within the Body”)

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