Chapter 17

# Radionuclide Sources of Ionizing Radiation

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## 17.1 ELEMENTS, ISOTOPES, AND NUCLIDES

When describing radionuclide sources, the terms "element," "isotope," "nuclide," "isobar," and "isomer" are used.

Chemical element is a collection of atoms with the same atomic number.

Nuclides are the nuclei with the definite atomic number and energy state.

Isotopes are the nuclei with the same number of protons but with the different total number of nucleons, i.e., neutrons. Different elements have different number of isotopes, some of them are stable and some are radioactive.

Isobars are the nuclei with the same total number of nucleons.

Isomers are the nuclei, that have different energy states of the same nucleus, with the half-life exceeding a part of a microsecond. For example, isomers of Technetium $^{99}$Tc and $^{99m}$Tc are two different nuclides.

There are 81 stable elements in nature, from hydrogen, H, No. 1, to bismuth, Bi, No. 83, without two short-lived radioactive elements technetium, Tc, No. 43, and promethium, Pm, No. 61.

In our world, the nuclei with all values of $Z$ from 1 up to 118 are known (June 2018). The region of stable nuclei ends up with bismuth ($Z = 83$). Recently, it has been proven that the single isotope, previously considered as a stable isotope of bismuth, is alpha-active with half-life $T_{1/2}$—$2 \cdot 10^{19}$ years that is much longer than the age of the Universe. Then up to uranium ($Z = 92$), the elements are radioactive. All elements with $Z > 92$ are artificially produced. They are called transuranic elements. There are no stable nuclei with $Z = 43$ (technetium) and $Z = 61$ (promethium). The stable nuclei, except $A = 5$ and $A = 8$, have mass numbers $A$ from 1 up to 209. The production of more and more heavy transuranic elements continues. The heaviest nucleus produced up to now is $^{294}_{118}$Og—oganesson. It got its name after Yuri Oganessian, a nuclear physicist from the Joint Institute for Nuclear Research in Dubna, Russia.


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Heavy nuclei with $Z > 92$, called transuranium nuclei, have a decreasing lifetime with increasing $Z$. The nuclei in the beginning of the transuranium row undergo mainly alpha decay, but with the increase of $Z$, spontaneous fission becomes the main decay process. So, for $^{238}$U, the half-life for spontaneous fission is about $10^{16}$ years, and for $^{258}$Fm (the isotope of fermium), it is small fractions of a second. However, it is assumed that with a further increase in the number of nucleons in the nucleus, a so-called "island of stability" can be detected, where the lifetimes would allow the accumulation of macroscopic amounts of matter. Calculations show that in heavy nuclei, magical numbers can be 114 protons and 184 neutrons and the lifetime of a nucleus with such nucleon numbers can be quite large. The nucleus $^{298}_{114}$Fl (flerovium) is expected to be double magic. Up to now seven isotopes of Fl have been synthesized with $A = 284-290$. The isotope $^{290}$Fl has the largest half-life of $\sim$19 s. More recent studies suggest that the true island of stability for spherical nuclei occurs around unbibium-306 (with 122 protons and 184 neutrons). The search for the "island of stability" continues.

At present, the list of transuranic elements, which have an official name, has 26 elements. This is the continuation of a number of actinides, beginning with $^{93}$Np and up to $^{103}$Lr (lawrence), which, like the lanthanides, are placed on a separate list. A row from rutherfordium $^{104}$Rf to oganesson $^{118}$Og is new, which is the seventh period of the periodic table. The work on the synthesis of superheavy transurans continues. It is assumed that oganesson is a member of the group of inert gases.

It is difficult or even senseless to count up the number of stable and radioactive nuclides because the boundary between them is quite artificial. In modern reference books, 254 nuclides are called stable, but it is pointed out that only 90 are considered theoretically stable. The rest (164) can, actually, undergo some form of decay, but so far their decays have not yet been discovered.

In the Mendeleev's periodic table, there are 56 pairs and 3 trios of "stable" isobars. It means that they, in principle, could undergo the so-called double beta decay. Now we know 13 nuclides for which the ordinal 2β decay has been confirmed, including double electron capture in $^{130}$Ba and $^{78}$Kr. The typical values of half-life are of the order of $10^{20}-10^{21}$ years. The longest half-life, $T_{1/2} = 7.2 \cdot 10^{24}$ years, has $^{128}$Te. Many others have a longer half-life. The question is: where is the boundary between stable and radioactive nuclides?

With $T_{1/2} = 10^{24}$ years, one could expect less than 1 decay per year in 1 kg of a pure nuclide. The age of the Universe is $13.8 \cdot 10^9$ years, and the age of the Earth is $4.54 \cdot 10^9$ years. During the life of the Earth, a negligible fraction of the substance, trapped within the Earth during its formation, has decayed.

On the site [1], one could find 37 nuclides with half-life from $1 \cdot 10^{16}$ s ($3.17 \cdot 10^8$ years) up to $10^{31}$ s ($3.17 \cdot 10^{25}$ years). They are isotopes of 30 elements. These nuclides have a half-life longer than the Earth's lifetime or shorter than the Earth's lifetime, but long enough, so that they are still preserved. Such nuclides are called natural long-lived or primordial radionuclides.

Thus, the planet Earth consists of about 300 nuclides, and, besides, about 50 radioactive nuclides with shorter half-life are constantly present in soil, water, and air. Although they are not natural, they, e.g., $^{3}$H, $^{7}$Be, $^{10}$Be, $^{14}$C, $^{22}$Na, are constantly formed by interaction of cosmic rays with the atmosphere. The others are produced in the decay of long-lived radioactive nuclides and products in decay chains, see Section 2.9 and Fig. 2.12A and B.

To date, more than 3000 radioactive nuclides have been detected and characterized, most of them were obtained artificially as a result of various nuclear reactions.

The most part of radioactive nuclides are short lived. Only about 650 nuclides have a half-life exceeding an hour, from them only 290 have a half-life longer than a day.

## 17.2 PHYSICAL CHARACTERISTICS OF RADIONUCLIDES

The half-life is one of the most important characteristics that determine the possibility of operating with nuclides and the danger that can be expected from them. Radionuclides with a very long lifetime have insignificant specific activity. For example, metal uranium can be picked up by hand, kept on a desk, drugs of uranium and thorium salts are widely used in chemistry and are in open sale. Depleted uranium ($^{235}$U content is 0.2%−0.4%, in natural mixture 0.71%), formed as waste when $^{235}$U is separated from the natural mixture, is a radioactive isotope $^{238}$U, and it has a wide range of applications. Having a high density (19.1 g/cm$^3$), it is used as counterweights in airplanes and missiles in various versions of radiation protection. The military industry uses it to produce armor sheets and armor-piercing subcaliber projectiles.

Nuclides with a short lifetime (<1 s) are very difficult to use, and they do not have time to bring significant harm. But short-lived nuclides with a lifetime of the order of tens of minutes and of several hours now attract a lot of interest and are increasingly used in medical diagnostics.

So, nuclides with a long lifetime have a small initial activity, and although they emit a long time, for human life, they are less dangerous than nuclides with intermediate half-lives. From practical use of radionuclides, it is clear that the most dangerous nuclides with $T_{1/2}$−30 years are $^{137}$Cs and $^{90}$Sr.

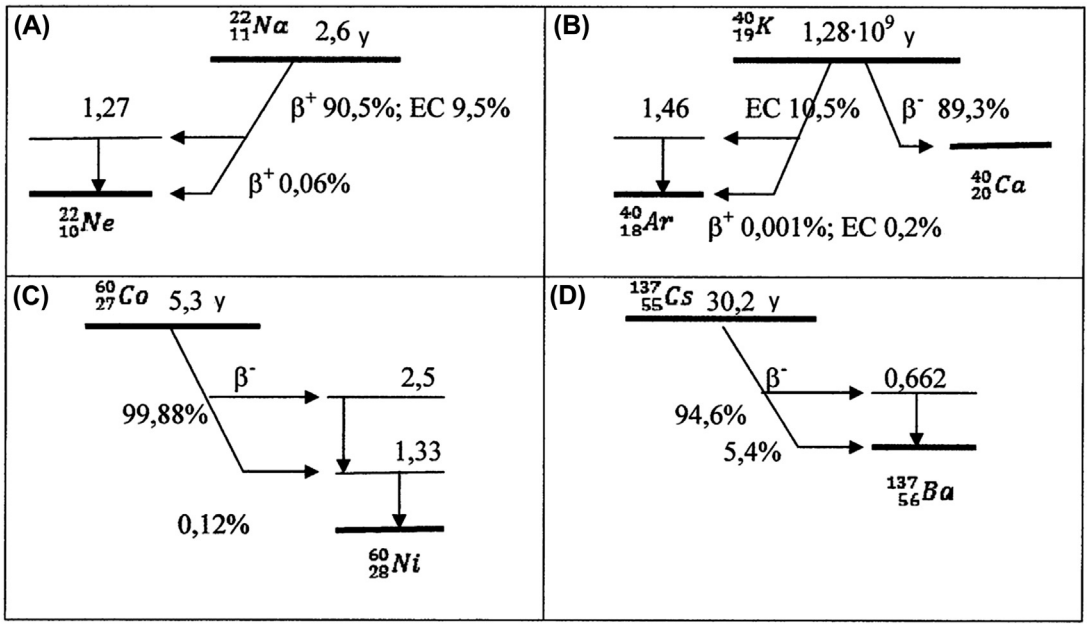


**FIGURE 17.1** Energy diagrams of decays: (A) $\beta^+$-decay of $^{22}$Na; (B) $\beta^-$- and EC-decays of $^{40}$K; (C) $\beta^-$-decay of $^{60}$Co and (D) $\beta^-$-decay of $^{137}$Cs. Energy of levels in MeV.

Other important characteristics of the nuclide are the decay mode, the type of radiation, and the set of particle and quantum energies. In most cases, nuclides experience one of the variants of beta decay with transition to the excited state of the daughter nucleus and with the subsequent emission of gamma quanta. This can be seen, for example, in the energy diagrams of the decay shown in Fig. 17.1. In decays, beta-plus and beta-minus particles of different energies and a whole gamma-ray spectrum can be emitted. Heavy nuclides ($A > 140$) mainly experience alpha decay.

For adjustment and calibration of equipment, it is convenient to have nuclides emitting either only alpha or only beta particles. For practical applications, it is desirable that at the subsequent gamma transitions one or at most two particle lines are emitted. Such sources are called model spectrometric. The number of pure alpha, and beta emitters is quite small.

The characteristic maximum energies of beta decay are in the order of magnitude from tens of keV to several MeV.

Excited nuclei are formed either in the processes of alpha or beta decay, or in nuclear reactions. Therefore, there are no pure gamma emitters among radioactive sources, and all of them simultaneously emit alpha or beta particles. However, because the range of alpha or beta particles is much smaller than the penetration depth of gamma radiation, the particles can stop in the walls of the source, and gamma quanta can come out of it. Thus, the packed nuclide becomes a "pure" gamma emitter.

Usually, the energies of the gamma quanta accompanying alpha decay do not exceed 0.5 MeV, and the energy of the gamma quanta accompanying beta decay can be higher. Gamma quanta of higher energy are emitted by $^{56}$Co ($T_{1/2} =$ 77 days). The decay scheme of this nuclide, which proceeds both by beta-plus decay or electron capture, gives rise to a complex spectrum of gamma quanta, whose energy extend up to 3.55 MeV.

As far as the gamma radiation, e.g., of the $^{60}$Co nucleus, is considered, the gamma quanta are emitted not by the $^{60}$Co nucleus but by the daughter nucleus $^{60}$Ni. $^{60}$Co undergoes beta-minus decay, turning into a $^{60}$Ni nucleus in the excited state; the selection rules for beta decay forbid decay to the ground state. With an overwhelming probability of 99.88%, the transition is carried out to the level of 2.5 MeV, from which the gamma transition to the ground state is also forbidden. Therefore, in the $^{60}$Ni nucleus, a cascade transition occurs through the level of 1.33 MeV: two gamma quanta are emitted, first a quantum with the energy of 1.17 MeV and second comes a quantum with the energy of 1.33 MeV through an average lifetime equal to 0.73 ps (Fig. 17.1).

In the case of beta-plus decay, the emitting positron annihilates with some electrons of matter in the encapsulation around the source. As a result of annihilation, the original positron and electron disappear and their rest energy transfers into two oppositely directed gamma quanta with the energy of 0.511 MeV each. So, all beta-plus sources practically, simultaneously with their gamma radiation, emit annihilation radiation.

Physical characteristics of some nuclides are presented in Appendix A5.

## 17.3 RADIOGENIC NUCLIDES

### 17.3.1 Radioactive Chains

As it is known (Section 2.9), there exist in nature three heavy radioactive nuclides with rather long half-life, which form chains from sequential radioactive nuclides. They are as follows: two isotopes of uranium, $^{235}$U and $^{238}$U, and one isotope of thorium, $^{232}$Th. The radioactive chains of $^{238}$U and $^{232}$Th are shown in Fig. 2.12A ($^{238}$U chain) and Fig. 2.12B ($^{232}$Th chain).

In equilibrium the activities of all members of the chain became equal, which is expressed by Eq. (2.34) (Chapter 2)

$$\lambda_1 N_1 = \lambda_2 N_2 = \cdots = \lambda_n N_n. \tag{2.34}$$

However, as the chemical properties of the nuclides in the decay chains differ, the daughter nuclides can enter into various chemical reactions, and if the medium allows, they can drop out of the chain and, consequently, break the balance. Such break of equilibrium can be realized, for example, during ore processing, during melting of the parent metal, under the influence of water on the charge containing the parent nuclide, and in other similar processes. Naturally, it takes time to break such chain. Therefore, equilibrium is more likely to be violated on long-lived nuclides. In the uranium series, this is $^{234}$U ($T_{1/2} = 2.45 \cdot 10^5$ years), $^{230}$Th ($T_{1/2} = 8 \cdot 10^4$ years), and $^{226}$Ra ($T_{1/2} = 1.6 \cdot 10^3$ years).

Another reason for the break of equilibrium is the presence of gaseous products in the chain of decay. Approximately, in the middle of each chain, there is an isotope of inert radioactive gas: in the $^{238}$U series it is radon ($^{222}$Rn), in the $^{232}$Th series it is thoron ($^{220}$Rn-Tn), because of the ability to volatilize these nuclides called "emanation." Due to the gaseous and inert nature of the emanations, their radioactive descendants can be easily separated from long-lived predecessors. The radioactivity of natural families in an open system, from which emanations easily escape, differs substantially from radioactivity in a closed system. For example, for a uranium family at a 100% yield of radon, the radioactivity decreases by 2/3 of the equilibrium value.

### 17.3.2 Radiation of Radiogenic Nuclides

Among the members of the radioactive chains, there are alpha, beta, and gamma emitters. The probability of spontaneous fission for all nuclides is extremely insignificant. Some nuclides are pure alpha emitters and pure beta emitters, and their decays are not accompanied by gamma radiation. The properties of the radiogenic nuclides are given according to D.C. Kocher [2].

Pure or almost pure alpha emitters in the $^{238}$U chain are $^{238}$U, $^{234}$U, $^{230}$Th, $^{222}$Rn, $^{218}$Po, $^{214}$Po, and $^{210}$Po and in the $^{232}$Th chain are $^{232}$Th, $^{228}$Th, $^{224}$Ra, $^{220}$Rn, $^{216}$Po, and $^{212}$Po.

The energy of alpha particles emitted by heavy nuclei from the ground states is 4—9 MeV. The energies of the alpha particles are clearly related to the half-life of the nuclide by the Geiger—Nuttall law (Section 2.7.1 and Fig. 2.7).

Pure or almost pure beta emitter in the $^{238}$U chain is $^{210}$Bi and in the $^{232}$Th chain is $^{228}$Ra.

Important role in formation of the radiation background is played by gamma emitters in the chains. In the $^{238}$U chain, they are $^{234}$Th, $^{234}$Pa, $^{226}$Ra. $^{214}$Pb, $^{214}$Bi, and $^{210}$Pb. Gamma emitters in the $^{232}$Th chain are $^{228}$Ac, $^{212}$Pb, $^{212}$Bi, and $^{208}$Tl

Let us indicate the main gamma emissions of the cosmogenic nuclides.

In the $^{238}$U chain, the gamma spectrum of $^{234}$Pa consists of 205 lines; several lines near 900 keV have intensity of ~12%; and maximum energy in the spectrum is 1926 keV (intensity ~ 0.5%). The spectrum of $^{226}$Ra has a gamma line with the energy of 186.2 keV and intensity of 3.28%. Two nuclides in the $^{238}$U chain are the gamma emitters of high intensity and high energy, and they are $^{214}$Pb—22 gamma lines and $^{214}$Bi—151 gamma lines, and the most important lines are 1764.5 keV, 15.8%; 1120.3 keV, 15.1%; and 609.3 keV, 46.3%.

Gamma emitters in the $^{232}$Th chain are $^{228}$Ac, $^{212}$Pb, $^{212}$Bi, and $^{208}$Tl. $^{228}$Ac emits 183 gamma lines, and the main gamma lines are 969.11 keV, 16.6%; and 911.7 keV, 27.7%.

$^{208}$Tl emits 27 gamma lines, and the main gamma lines are 2614.66 keV, 99.8%; and 583.1 keV, 8.2%.

$^{212}$Pb emits five gamma lines, and the main gamma line is 238.6 MeV 44.6%.

$^{212}$Bi is the famous nuclide that can undergo either alpha or beta decays, forming the so-called fork. The probability of the beta decay is 64% and of the alpha decay is 36%. After beta decay the daughter nucleus emits 11 gamma lines, after alpha decay—8. The main gamma line is 727.17 keV, 11.8%.

The presence of uranium and thorium in natural objects is determined not by the gamma radiation of the nuclides U and Th themselves but by the lines that are most convenient for measurements emitted by any member of the corresponding family.

It is seen that convenient for measurements, gamma quanta are emitted by nuclides located at the end of both decay chains. So in the family of thorium, the nuclide $^{208}$Tl (ThC"), standing at the very end of the chain, has a line of 2.62 MeV in its gamma-ray spectrum. The energy of gamma radiation of natural substances, as well as most of the basic nuclides that appeared in nature as a result of human activity, is less than this value. Therefore, the 2.62-MeV line is well distinguished against the background of radiation from other substances and can be easily detected.

The presence of uranium ($^{238}$U) is usually detected by the lines of 1.76 or 2.2 MeV, which are emitted by $^{214}$Bi (RaC). It is clear that the gamma radiation of these nuclides characterizes the presence of uranium and thorium, only if the equilibrium in the chains is not violated. Departed from the row, radon and thoron break the chain.

A special role in the formation of the radiation background is played by gaseous nuclides from radioactive series—radon $^{222}$Rn and thoron $^{220}$Rn. For more information on these nuclides and their health effects, see Chapter 47.

Terrestrial rocks also contain nuclides, the ancestor of the family of which is $^{235}$U. But because the concentration of $^{235}$U is less than the concentration of $^{238}$U by more than a 100 times, the nuclides from the $^{235}$U chain are neglected in this book.

## 17.4 TRANSURANIUM ELEMENTS

### 17.4.1 General Characteristics of the Problem of Transuranium Elements

All elements up to $Z = 92$ (uranium) can be found in nature (except technetium and promethium). However, with the help of accelerators and reactors, it occurred possible to obtain elements with $Z > 92$, the so-called transuranium elements, artificially, in nuclear reactions. So transuranium elements can be classified as a class of technogenic nuclides. All transuranium elements are radioactive with half-lives short in comparison with the Earth's lifetime, and if they were formed in cosmic processes of element synthesis, they would have disintegrated long ago.

Currently, the list of transuranic elements, with each having an official name, has 26 elements. They continue the row of actinides, starting from $^{93}$Np and up to $^{103}$Lr (Lawrencium), and the new, seventh row of the periodic table from $^{104}$Rf (rutherfordium) to $^{118}$Og (oganesson) (Table 17.1). The work on the synthesis of superheavy transurans continues.

**TABLE 17.1 Transuraniums (June 2018)**

| Actinides ($Z$ = 91–103) | | | | Seventh Row of the Periodic Table ($Z$ = 104–118) | | | |
|---|---|---|---|---|---|---|---|
| | | Most Heavy Isotope | | | | Most Long-Lived Isotope | |
| Element | Title | A | $T_{1/2}$ | Element | Title | A | $T_{1/2}$ |
| $_{92}$U | Uranium | 238 | $4.5 \cdot 10^9$ y | $_{104}$Rf | Rutherfordium | 267 | 1.3 h |
| $_{93}$Np | Neptunium | 237 | $2.2 \cdot 10^6$ y | $_{105}$Db | Dubnium | 268 | 28 h |
| $_{94}$Pu | Plutonium | 244 | $8.3 \cdot 10^7$ y | $_{106}$Sg | Seaborgium | 269 | 3.1 m |
| $_{95}$Am | Americium | 243 | $7.4 \cdot 10^3$ y | $_{107}$Bh | Bohrium | 278 | 11.5 m |
| $_{96}$Cm | Curium | 247 | $1.6 \cdot 10^7$ y | $_{108}$Hs | Hassium | 270 | 10 s |
| $_{97}$Bk | Berkelium | 247 | $1.4 \cdot 10^3$ y | $_{109}$Mt | Meitnerium | 282 | 67 s |
| $_{98}$Cf | Californium | 251 | 900 y | $_{110}$Ds | Darmstadtium | 281 | 14 s |
| $_{99}$Es | Einsteinium | 252 | 471.7 d | $_{111}$Rg | Roentgenium | 286 | 10.7 m |
| $_{100}$Fm | Fermium | 257 | 100.5 d | $_{112}$Cn | Copernicium | 285 | 28 s |
| $_{101}$Md | Mendelevium | 258 | 51.5 d | $_{113}$Nh | Nihonium | 286 | 9.5 s |
| $_{102}$No | Nobelium | 259 | 58 m | $_{114}$Fl | Flerovium | 290 | 19 s |
| $_{103}$Lr | Lawrencium | 266 | 10 h | $_{115}$Mc | Moscovium | 290 | 650 ms |
| | | | | $_{116}$Lv | Livermorium | 294 | 54 ms |
| | | | | $_{117}$Ts | Tennessine | 294 | 51 ms |
| | | | | $_{118}$Og | Oganesson | 295 | 181 ms |

There are 15 elements in the actinide group, but the first three, i.e., $^{89}$Ac, $^{90}$Th and $^{91}$Pa, are pre-uranium elements. The seventh row of the periodic table ends with the element $^{118}$Og, a chemical analog of inert gases. It was also reported about the synthesis of the unbiquadium ($Z = 124$), and there are indirect evidence of the elements unbinilium ($Z = 120$) and unbihexium ($Z = 126$), which have not yet been confirmed.

Transuranium elements show a certain trend in the decrease in the lifetime with an increase in the atomic number, as can be seen from Table 17.1. Physicists assume that by certain large values of the numbers of protons and neutrons in the nucleus, close to magical, the so-called island of stability can be discovered, where the lifetimes allow the accumulation of macroscopic amounts of matter. According to the shell model in the center of the island of stability, there may occur a nuclide $^{298}_{114}$Fl having a magic number of protons $Z = 114$, corresponding to the filled proton nuclear shell, and the magic number of neutrons $N = 184$. This should lead to the formation of an anomalously stable (doubly magic) nucleus with a half-life of about 10 min.

However, other theories that take relativistic effects into account give other magical numbers for the protons, $Z = 120$, 122, and 126, depending on the initial parameters adopted in the calculations.

Another feature of transuranium elements is the increase in the relative probability of spontaneous fission with the growth of the atomic number. Thus, the probability of spontaneous fission for $^{235}$U is $2 \cdot 10^{-9}$, for $^{238}$U is $5.4 \cdot 10^{-7}$, for $^{250}$Cm is 0.8, for $^{252}$Cf is $3.09 \cdot 10^{-2}$, and for $^{254}$Cf is 0.997. In the fermium isotope $^{256}_{100}$Fm, the half-life with respect to spontaneous fission is 2.7 h, and in $^{260}_{104}$Rf, it is 0.3 s. The isotopes of fermium with $A = 258$, 259, and 260 decay only due to spontaneous fission.

Transuranium elements can be obtained by capturing neutrons followed by beta decay. For example, this is how plutonium-239 is obtained. The following chain of nuclear reactions takes place:

$$^{238}_{92}\mathrm{U} + \mathrm{n} \rightarrow ^{239}_{92}\mathrm{U} \rightarrow ^{239}_{93}\mathrm{Np} \rightarrow ^{239}_{94}\mathrm{Pu} \tag{17.1}$$

The half-life for beta decay $^{239}$U is 23.5 min, and for $^{239}$Np, it is 2.36 d.

Not all isotopes can be obtained in neutron capture reactions, and to obtain others, nuclear reactions with charged particles are used when the target from a suitable nuclide is irradiated by accelerated ions. For example, $^{238}$Pu is produced by reaction

$$^{238}_{92}\mathrm{U} + ^{2}_{1}\mathrm{D} \rightarrow ^{238}_{93}\mathrm{Np} + 2\mathrm{n}; ^{238}_{93}\mathrm{Np} \rightarrow ^{238}_{94}\mathrm{Pu}. \tag{17.2}$$

The half-life for beta decay $^{238}$Np is 2.1 d.

The last, heaviest nuclide that can be obtained by neutron capture on reactors is the fermium isotope $^{257}$Fm. The fact is that no known fermium isotope undergoes beta decay and, therefore, cannot turn into the next nuclide, i.e., Mendelevium. Fermium is the last element that can be accumulated in macroscopic quantities. Annual world production of fermium probably totals less than a millonth of a gram [3]. Further advance into the region of even heavier elements is possible only when bombarding targets from lighter transurans with accelerated ions. For example, the isotopes of lawrencium are obtained in reactions

$$^{252}_{98}\mathrm{Cf} + ^{11}_{5}\mathrm{B} \rightarrow ^{263}_{103}\mathrm{Lr} \rightarrow ^{258}_{103}\mathrm{Lr} + 5\mathrm{n} \tag{17.3}$$

or

$$^{243}_{95}\mathrm{Am} + ^{18}_{8}\mathrm{O} \rightarrow ^{261}_{103}\mathrm{Lr} \rightarrow ^{256}_{103}\mathrm{Lr} + 5\mathrm{n} \tag{17.4}$$

However, obtaining heavy elements in fusion reactions is complicated; the heavier the nuclide, the more the number of neutrons needed to increase the stability of the nucleus. And the lighter nuclei used for fusion do not have enough neutrons. Therefore, only relatively light, neutron-deficient isotopes can be obtained for the heaviest elements.

Thus, for example, for flerovium, whose isotope with a mass number of 298 is expected to be a very stable nucleus, up to now only isotopes with mass numbers from 284 to 290 are obtained. The $^{290}$Fl, the longest living one, has a half-life of 19 s.

Some transuranic elements are decayed predecessors of existing radioactive series. For example, Einsteinium $^{254}$Es as a result of a chain of radioactive decays turns into $^{238}$U, the founder of a uranium chain

$$^{254}_{99}\mathrm{Es} \rightarrow ^{254}_{100}\mathrm{Fm} \rightarrow ^{250}_{98}\mathrm{Cf} \rightarrow ^{246}_{96}\mathrm{Cm} \rightarrow ^{242}_{94}\mathrm{Pu} \rightarrow ^{238}_{92}\mathrm{U} \tag{17.5}$$

Another isotope of einsteinium $^{256}$Es in an even longer chain of beta and alpha decays passes into $^{232}$Th, the progenitor of a thorium chain.

The studies to find ever heavier elements and to synthesize new isotopes of already discovered elements continue. These activities are of great scientific interest. But if nuclides with convenient half-life periods are found in the zone of the island or archipelago of stability, they can prove to be extremely useful in a practical sense. Many already discovered transurans are widely used in various industries, medicine, and science.

### 17.4.2 Plutonium, $_{94}$Pu

The most famous and most widely used transuranic element is plutonium $_{94}$Pu. In total, 20 isotopes of plutonium with $A = 228-247$ are known. The most famous are $^{238}$Pu ($T_{1/2} = 87.74$ y) and $^{239}$Pu ($T_{1/2} = 2.41 \cdot 10^4$ y). The isotope with atomic number 239 has a large fission cross section due to thermal neutrons and a large number of fission neutrons. Therefore, it can be a base of an effective chain reaction, and it is used both in nuclear reactors and in atomic bombs.

The use of fissionable nuclides in nuclear power engineering and explosive devices is determined by the critical mass, the minimum mass of fissile material needed to initiate a self-sustaining fission chain reaction. The critical mass depends on the chemical composition of the sample, on the presence of a neutron moderator, and on the reflector surrounding the fissile material. Reflectors and moderators can significantly reduce the critical mass. The lowest critical mass is possessed by solutions of salts of pure fissile nuclides in water with a water neutron reflector. For $^{235}$U, the critical mass of such a solution is 0.8 kg, for $^{239}$Pu is 0.5 kg, and for some salts $^{251}$Cf is 10 g. And for pure metals of spherical forms, the critical mass is $^{235}$U $\sim$ 50 kg, $^{239}$Pu $\sim$ 10 kg, and $^{245}$Cm $\sim$ 6.8 kg.

The most widely used isotopes of plutonium are $^{238}$Pu and $^{239}$Pu. The isotope of $^{238}$Pu has $T_{1/2} = 87.74$ years. It is an alpha emitting nuclide with a very small fraction of gamma quanta and neutrons from spontaneous fission. It emits very significant energy, but weakly penetrating, from which it is easy to protect. The specific energy release of the isotope is about 0.57 W/g of thermal energy. For the use of energy generators based on $^{238}$Pu, see Chapter 28.

Other transuranic actinides also have useful properties as sources of ionizing radiation.

### 17.4.3 Americium, $_{95}$Am

There are known 19 isotopes of americium and 8 nuclear isomers. The most interesting isotopes is $^{241}$Am ($T_{1/2} = 432.2$ y) and $^{243}$Am ($T_{1/2} = 7370$ y). The isomer $^{242m1}$Am has a half-life of 141 years. As an alpha source, the isomer $^{241}$Am is used in smoke detectors, medicine, and radiological studies. The specific energy release of $^{241}$Am is 0.11 W/g.

### 17.4.4 Curium, $_{96}$Cm

20 isotopes of curium and 7 nuclear isomers with mass numbers of 233–252 are known. The most interesting isotopes are $^{242}$Cm ($T_{1/2} = 162$ days), $^{244}$Cm ($T_{1/2} = 18.1$ y), $^{245}$Cm ($T_{1/2} = 3320$ y), and $^{248}$Cm ($T_{1/2} = 3.48 \cdot 10^5$ y). The longest-lived isotope of curium is $^{247}$Cm ($T_{1/2} = 1.56 \cdot 10^7$ y). Curium-242, in the form of oxide, is used to produce compact and powerful radioisotope energy sources (energy release of about 120 W/g). The convenience of using this isotope is that it is practically a pure alpha emitter. On its basis, an alpha source is made for an X-ray fluorescence spectrometer that studies the composition and structure of the surface of the planets. Such spectrometers are installed on the Mars rovers "Sojourner," "Opportunity," and "Curiosity," as well as on the apparatus "Philae," fixed on the Churyumov–Gerasimenko comet.

### 17.4.5 Berkelium, $_{97}$Bk

There are about 20 isotopes of berkelium and 6 nuclear isomers with mass numbers of 235–254. Until now, berkelium isotopes have not found practical applications of sources, but they have been used as targets in the production of transuranium elements. In particular, the target of $^{249}$Bk was bombarded with $^{48}$Ca ions for 150 days during the synthesis of tennessine ($Z = 117$) in the G.N. Flerov laboratory in Dubna.

### 17.4.6 Californium, $_{98}$Cf

There are 17 isotopes of californium, the most stable of which are $^{251}$Cf ($T_{1/2} = 900$ y), $^{249}$Cf ($T_{1/2} = 351$ y), $^{250}$Cf ($T_{1/2} = 13.08$ y), and $^{252}$Cf ($T_{1/2} = 2.645$ y). The isotope $^{252}$Cf has found the greatest application. It is used as a powerful source of neutrons arising in the process of spontaneous fission, in neutron activation analysis, and in radiation therapy of tumors.

## 17.5 NUCLIDES—FISSION FRAGMENTS

One of the most important sources of radiation hazard is the fission products generated during the operation of nuclear reactors and during nuclear weapons tests, which burst into the environment during accidents at nuclear fuel reprocessing facilities.

The distribution of the fission fragments by mass in the fission of $^{235}U$ by thermal neutrons is described in Section 7.8 and is shown in Fig. 7.6.

It can be seen that during fission, mainly fragments of unequal mass are formed, both light and heavy. Fission into fragments with a mass ratio of 3/2, more precisely 1.46, is the most probable. The yield of such fragments reaches about 6%, whereas fragments with equal masses are about $10^{-2}$%. With increasing neutron energy, the probability of fission by equal masses increases and at a neutron energy of ~100 MeV the distribution curve turns out to be a symmetric bell with one maximum. The most probable fragments in fission by thermal neutrons have the following mass numbers: a light fragment ~94, a heavy fragment ~140, which is evident from the fission reaction

$$^{235}U + n \rightarrow {}^{236}U* \rightarrow {}^{140}Xe + {}^{94}Sr + 2n \tag{17.6}$$

The lightest of the fragments has a mass number of 72, the heaviest—161.

The resulting fission fragments contain an excess of neutrons relative to the equilibrium, so they undergo a series of radioactive transformations, all due to beta-minus decay. For example, the chain of decays of a heavy fragment $^{140}Xe$ has the form (the half-life in parentheses is indicated)

$$^{140}Xe\ (14s) \rightarrow {}^{140}Cs(64s) \rightarrow {}^{140}Ba(13d) \rightarrow {}^{140}La(40h) \rightarrow {}^{140}Ce(\text{stable}), \tag{17.7}$$

and of a light fragment $^{94}Sr$

$$^{94}Sr(75s) \rightarrow {}^{94}Y(19\text{min}) \rightarrow {}^{94}Zr(\text{stable}). \tag{17.8}$$

The yield of fission fragments is usually considered based on the number of fissile nuclei and not on the number of fragments, i.e., the sum of all divisions is 200%. The yield of the most probable fragments is given in Table 17.2 [4].

Among the fission products, there is a stable nuclide $^{149}Sm$ with a yield of 1.09%, and among nuclides with a yield of less than 1% not indicated in the table, it is worth noting $^{129}I$ ($T_{1/2} = 15.7 \cdot 106$ y, 0.9%) and $^{85}Kr$ ($T_{1/2} = 10.78$ y, 0.27%).

The most dangerous fission products, which determine the main threats to the health of population, are $^{131}I$, present in the environment in the first months, and $^{137}Cs$, present for decades. But such a widely known and widely used nuclide, such as $^{60}Co$, is not a product of fission.

## 17.6 COSMOGENIC RADIONUCLIDES [5–7]

It is believed that cosmic rays form in the atmosphere, hydrosphere, and lithosphere of the Earth up to two dozen radionuclides, called cosmogenic in this case. The main reactions of cosmogenic radionuclides are the interaction of cosmic ray protons and neutrons with nitrogen, oxygen, and argon atoms. Approximately 70% of cosmogenic radionuclides are formed in the upper atmosphere and only about 30% in the troposphere. The subsequent behavior of cosmogenic radionuclides is due to the processes of exchange between the stratosphere and the troposphere, the movement of air masses in the troposphere, and the exchange between the atmosphere and other geospheres. Cosmogenic radionuclides, with the exception of noble gases, are rapidly oxidized after their formation.

**TABLE 17.2 Yield of the Most Probable Fragments of Fission [4]**

| Group | Heavy Fragments | | | | | Light Fragments | | | |
|---|---|---|---|---|---|---|---|---|---|
| Fragment | $^{133}Cs$ | $^{135}I$ | $^{137}Cs$ | $^{131}I$ | $^{147}Pm$ | $^{93}Zr$ | $^{99}Mo$ | $^{99}Tc$ | $^{90}Sr$ |
| $T_{1/2}$ | 2.065 y | 6.57 h | 30.17 y | 8.02 d | 2.62 y | $1.53 \cdot 10^6$ y | 69.94 h | $211 \cdot 10^3$ y | 28.9 y |
| Yield, % | 6.79 | 6.33 | 6.09 | 2.83 | 2.27 | 6.3 | 6.1 | 6.05 | 5.75 |

### 17.6.1 Tritium, $^{3}H$

For tritium, $T_{1/2} = 12.32$ years, the energy of decay is 18.59 keV, and the average electron energy is 5.7 keV. Tritium is formed in the upper layers of the atmosphere as a result of the interaction of cosmic radiation, mainly with the nuclei N and O, in the testing of nuclear and, mainly thermonuclear weapons, and in the operation of nuclear power plants. One of the reactions of the formation of tritium is given below

$$n + {}^{14}N \rightarrow {}^{12}C + {}^{3}H \tag{17.9}$$

In the atmosphere, tritium is rapidly oxidized and appears in the composition of the superheavy water molecule HTO. According to modern estimates, the equilibrium activity of cosmogenic tritium in the external environment is $(1.11-1.30)\cdot 10^{9}$ GBq (3.0−3.5 kg). About 90% of natural tritium is contained in the hydrosphere. The explosion of a hydrogen bomb with a trotyl equivalent of 1 Mt leads to the emission of $(2.6-7.4)\cdot 10^{8}$ GBq of tritium (from 0.7 to 2 kg of tritium). Modern nuclear power plants annually allocate several dozens kilograms of tritium. Tritium is also present in the human body, where it enters with food, water, inhaled air, and through the skin.

Tritium is the isotope of hydrogen, and hydrogen is one of the main elements of which almost all molecules of the body are built. Therefore, tritium is distributed to tissues and organs, and in accordance with the proportion of hydrogen, it is involved in metabolic processes and is excreted from the body.

Tritium enters the body, mainly ($\sim$80%) with food and drinking water, but it can also be well absorbed with inhaled air and through intact skin and mucous membranes.

Tritium, accumulated in soft tissues and fat, has a biological half-life of about 11 days, and the half-life of tritum deposited in bones is much longer.

Tritium is a pure beta emitter, and the energy of its beta particles is relatively low. Beta particles of $^{3}H$ decay are completely absorbed in the body, thus the dose can be estimated either by calculation or by measuring the content of radionuclides in the liquid phase of the body's secretions: in the condensate of water vapor from the exhaled air and in the urine.

The equilibrium activity of tritium in the body is $\sim$7 Bq; on average, the human body contains about $5\cdot 10^{-12}$ g of tritium, which gives $\sim$1.3 μSv/y, i.e., a very small contribution to the total dose.

### 17.6.2 Isotopes of Beryllium, $^{7}Be$ and $^{10}Be$

Beryllium has 12 isotopes known, only one of them is stable, which is $^{9}Be$. The two most important and most interesting isotopes are $^{7}Be$ ($T_{1/2} = 53.22$ d, EC = 862 keV) and $^{10}Be$ ($T_{1/2} = 1.51\cdot 10^{6}$ y, $\beta^{-}$, $E_{max} = 556.2$ keV). In the remaining isotopes, the half-life equals a few or small fractions of a second.

The $^{10}Be$ isotope, which has a half-life of $\sim$1.5 million years, is of exceptional interest for geochemistry and nuclear meteorology. Born in the atmosphere, at an altitude of about 25 km, the $^{10}Be$ atoms together with the sediments enter the ocean and settle on its bottom. Knowing the $^{10}Be$ concentration in the sample taken from the bottom and the half-life of this isotope, one can calculate the age of any layer on the ocean floor. $^{10}Be$ is also accumulated in sea ooze and fossil bones (bones sorb beryllium from natural waters). In this connection an assumption was made about the possibility of determining the age of organic residues using $^{10}Be$. The fact is that a rather widely used radiocarbon method is not suitable for determining the age of the samples that is more than $10^{5}$ years. The isotope $^{10}Be$ just helps to solve this problem.

However, in the dose load on the population, both beryllium isotopes play a rather insignificant role [8].

### 17.6.3 Carbon-14, $^{14}C$

Carbon is the main element of all biological processes. Natural carbon consists predominantly of the stable isotope $^{12}C$. The isotopes $^{10}C$ and $^{11}C$ have half-lives, 19 s and 20.5 min, respectively, and half-life of $^{14}C$ is 5730 years. At its decay, $^{14}C$ emits only beta particles with the maximum energy of 154 keV. The isotope $^{14}C$ is widely used in radiocarbon dating.

Carbon-14 is generated in the atmosphere on interaction of cosmic rays with atmospheric nitrogen and is rapidly oxidized to a state of $^{14}CO_2$. As a result, an equilibrium concentration is established. In preindustrial period, the concentration ratio $^{14}C/^{12}C$ was equal to $1.2\cdot 10^{-12}$. This concentration ratio characterizes organisms that consume carbon dioxide during perspiration. When the organism dies, the carbon exchange stops, new portions of $^{14}C$ do not come, and it just decays. Subsequently, the concentration ratio falls. By measuring the residual concentration of $^{14}C$, one can calculate when the organism is dead.

Carbon is one of the main elements of which almost all body molecules are built. Therefore radionuclide is distributed to tissues and organs in accordance with the fraction of carbon; it participates in metabolic processes and is excreted from the body.

The major way by which $^{14}C$ enters the body is food of plant and animal origin, as radiocarbon accumulates in plants.

Radioactive carbon, accumulated in soft tissues and fat, has a biological half-life of approximately 12 days, which is markedly longer deposited in bones.

$^{14}C$ is a pure beta emitter. Beta decay particles are completely absorbed in the body, so the dose load can be estimated either by calculation or also as for tritium by measuring the radionuclide content in the liquid phase of the body's secretions, i.e., in the condensate of water vapor from the exhaled air and in the urine.

At present, a certain equilibrium concentration of radiocarbon in organic objects and in the human body, in particular, has been established. The average equilibrium activity of $^{14}C$ in the body is 3−4 kBq, which results in about 10 μSv/year.

Atmospheric nuclear weapon tests in the 1950s and 1960s led to a rapid increase in the concentration of $^{14}C$. In 1963, the concentration of atmospheric $^{14}C$ exceeded preatomic era by about twofold. After the ban of nuclear tests in the atmosphere, $^{14}C$ content began to decline and now it is approaching the preatomic time.

Impact of nuclear explosions on the content of $^{14}C$ is shown in Fig. 17.2 [9]. The levels of $^{14}C$ were obtained from measurements of atmospheric $CO_2$, tree rings, many organic objects, and ice layers.

The observed change in the content of $^{14}C$ in the atmosphere has found rather interesting criminological applications. Earlier, radiocarbon dating was used for time periods, the duration of which can be compared with a half-life, that is, from a few thousand to about 50,000 years. However, the discovery of a concentration jump associated with testing of nuclear weapons (bomb pulse) allows to date recent biological materials.

Hence, by measuring the concentration of $^{14}C$ in wine, one can determine if the wine is aged, that is, produced before 1950s, as the manufacturer insists, or it is falsified.

Many artificial nutritional supplements are prepared from petroleum-based materials. These materials do not contain radioactive carbon. A natural product contains in it concentrations typical for the time of production. Consequently, by analyzing the concentration of $^{14}C$, one can determine the proportion of artificial additives in a food product.

Against drug trafficking, this method was used to determine the age of the drug to make clear if it is a fresh production or somewhere there is a warehouse of drugs produced earlier. It is enough to have milligrams of a substance for analysis.

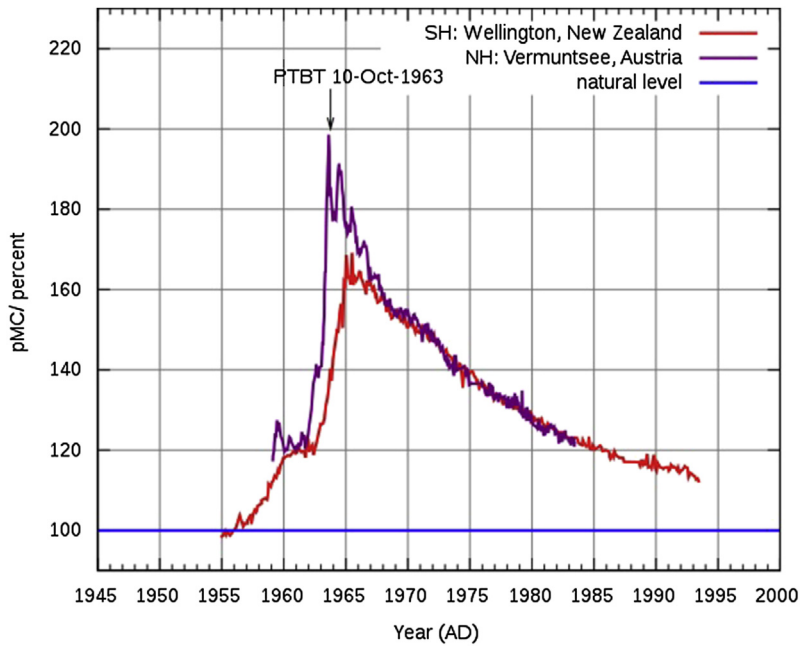


**FIGURE 17.2** The $^{14}C/^{12}C$ ratio relative to the natural level in the atmospheric $CO_2$ as a function of time in the second half of the 20th century. *Upper curve* is representative for the Northern Hemisphere, Austria, *lower curve* is representative for the Southern Hemisphere, New Zealand. *Straight line* along the level of 100% is the usual natural level of $^{14}C$. *Figure from Bomb Pulse, Wikipedia, Author of the fig: Hokanomono. https://en.wikipedia.org/wiki/Bomb_pulse#/media/File:Radiocarbon_bomb_spike.svg.*

$^{14}C$ dating allows to estimate how many of new grown nerve cells are in an adult human. The earth population at the time of the air testing of nuclear bombs took up more than usual of $^{14}C$ and incorporated it into the deoxyribonucleic acid (DNA) of their cells. Using accelerator mass spectroscopy to count $^{14}C$ atoms in the DNA from hippocampal nerve cells from the autopsied brains of 55 adults who were contemporaries of the tests, the team of scientists found out that about 35% of the nerve cells in the hippocampus were renewed in the course of their lives [10].

Currently, $^{14}C/^{12}C$ ratio decreases exponentially with a half-life of about 15 years. In a few years, seasonal variations exceeded deviations and performed like this, the dating of fresh biological materials was impossible.

### 17.6.4 Isotopes of Sodium, $^{22}Na$ and $^{24}Na$

In nature, there exist one stable isotope $^{23}Na$ and six radioactive isotopes of this element, two of which are of special interest, which are $^{22}Na$ and $^{24}Na$. $^{22}Na$ ($T_{1/2} = 2.58$ y) is $\beta^+$-active, and $^{24}Na$ ($T_{1/2} = 15.06$ h) is $\beta^-$-active. $^{22}Na$ is used as a source of positrons, and $^{24}Na$ is used in medicine for diagnostics and for the treatment of certain forms of leukemia.

Both isotopes of sodium appear in the atmosphere under the action of cosmic rays in the reactions of spallation of argon atoms. The annual intake of $^{22}Na$ is 50 Bq/y, and the annual effective dose for a person is 0.15 μSv/y.

In medicine and biology, $^{24}Na$ is of primary interest. Introduced into the flow of blood, $^{24}Na$ is distributed throughout the body and can be registered with special radiometric equipment. With the help of $^{24}Na$, the blood flow velocity is determined in various parts of the large and small circle of blood circulation, and the metabolic processes between the blood and tissues are examined. To investigate blood flow in a large circle of blood circulation, the patient is intravenously injected with 70 μCi of $^{24}Na$ in 0.2 mL of isotonic sodium chloride solution, and the rate of passage of radioactive blood through any of the studied segments of the vascular system is recorded.

## 17.7 RADIOACTIVE TRACERS

The method of radioactive tracers uses the chemical affinity of radioactive and stable isotopes of the same element. At the same time, a radioactive isotope can easily be identified by its radiation. Adding a radioactive isotope to the element under investigation and recording its radiation in time, one can trace the path of this element within the body, in a chemical reaction, in the melting of a metal, etc.

At present, about 100 artificially produced radioactive isotopes are used in the radiotracer method. We indicate here some of them.

Tritium, $^{3}H$: This is a pure beta emitter, and its characteristics are given in Section 17.6.1. Introduced into some organic matter, it replaces hydrogen in it and, together with hydrogen, undergoes all chemical transformations. As the energy of the beta particles is rather low, after all transformations the final preparation is dissolved in a liquid scintillator and the resulted activity is measured.

Phosphorus, $^{32}P$: One of the most important elements in the composition of nucleic acids, proteins, and bones is phosphorus. In nature, phosphorus exists only in the form of $^{31}P$. It has a biologically important isotope $^{32}P$, with a half-life of 14.3 days and a maximum beta-particle energy of 1.7 MeV. Radioactive atoms of the $^{32}P$ isotope were used to study the rate of synthesis of DNA. In mucosis of the small intestine, up to 15% of DNA reappears within 1 day. In embryonic and cancerous tissues, the cells of which multiply rapidly, the rate of restoration (or synthesizing anew) of DNA is even higher.

Iodine, $^{131}I$: Iodine significantly affects the functioning of the thyroid gland and the entire hormonal apparatus of the body. In nature, iodine consists mainly of the isotope $^{127}I$. Radioactive isotopes of iodine are $^{128}I$ ($T_{1/2} = 25$ min), $^{129}I$ ($T_{1/2} = 107$ y), 130I ($T_{1/2} = 12$ h), and $^{131}I$ ($T_{1/2} = 8$ d). $^{131}I$ has the most convenient half-life for most applications.

## 17.8 SOME SPECIFIC RADIONUCLIDES

### 17.8.1 Krypton-85, $^{85}Kr$

This is the isotope of an inert gas that has a relatively long half-life, i.e., $T_{1/2} = 10.8$ years. $^{85}Kr$ is practically a pure beta emitter, its energy of decay is equal to 687 keV, and the average electron energy is 251 keV.

The main sources of $^{85}Kr$ in the atmosphere are nuclear weapon tests, nuclear power plants, and accidents on nuclear enterprises. During the period of nuclear tests in the atmosphere (1945–62), approximately $190 \cdot 10^{15}$ Bq ~5 MCi has been injected into it. The accident at the Three Mile Island nuclear power plant in 1979 injected approximately $1.9 \cdot 10^{15}$ Bq and the Chernobyl accident injected 10 times more. The maximum concentration of $^{85}Kr$ in the atmosphere has been achieved in the 1970s (about 0.4 Bq/m$^3$) and has since decreased.

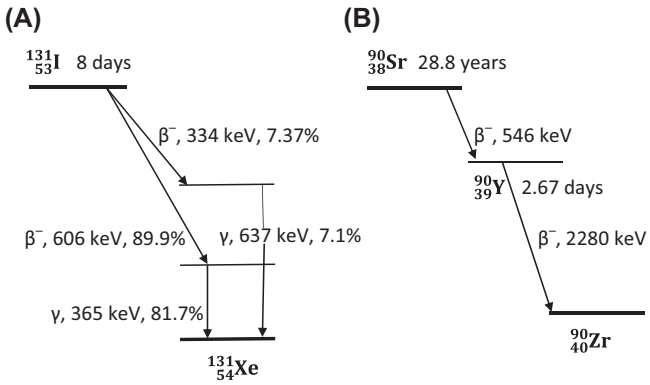


**FIGURE 17.3** Simplified scheme of the decay of $^{131}$I—left, scheme of the chain of decays $^{90}$Sr → $^{90}$Y → $^{90}$Zr—right.

A large operating nuclear power plant annually produces about $1 \cdot 10^{16}$ Bq $^{85}$Kr, which is basically stored, mainly, in the rods of the fuel elements, but yet a certain part of it leaks out. Additional intake of $^{85}$Kr in the atmosphere occurs during the processing of nuclear fuel.

## 17.8.2 Iodine-131, $^{131}$I

Natural iodine has one stable isotope $^{127}$I and a large number of radioactive isotopes (37) and even more nuclides because many isotopes have isomers. Of particular interest are the two radioactive isotopes $^{129}$I ($T_{1/2} = 1.57 \cdot 10^7$ y) and $^{131}$I ($T_{1/2} =$ 8.02 d). Both nuclides are gaseous fission products, highly volatile, and they can escape into the atmosphere both during the operation of nuclear reactors and, especially, in reprocessing nuclear fuel. Getting into the human body, iodine rapidly accumulates in the thyroid gland and is one of the most dangerous radioactive nuclides. The decay scheme for $^{131}$I is shown in Fig. 17.3A.

## 17.8.3 Strontium-90, $^{90}$Sr, and Isotopes of Cesium, $^{137}$Cs and $^{134}$Cs

All three nuclides are the products of uranium fission. $^{137}$Cs and $^{90}$Sr have practically identical half-lives: $^{137}$Cs—$T_{1/2} =$ 30.2 y and $^{90}$Sr—$T_{1/2} = 28.8$ y. The decay scheme for $^{137}$Cs is shown in Fig. 17.1D and $^{90}$Sr in Fig. 17.3B. As can be seen from the decay schemes, $^{90}$Sr is a pure beta emitter, whereas $^{137}$Cs emits gamma quanta, a well-known 662 keV line.

The main mode of decay of $^{134}$Cs is beta decay into excited levels of $^{134}$Ba (5 beta lines) and further occurs a series of transitions with gamma-ray emission (a total of 12 lines). The maximum probability of 70.2% has a beta transition with $E_{max} = 658.4$ keV and $E_{av} = 210.3$ keV. The average energy of all beta transitions is estimated at 157 keV. For gamma transitions, a line of 604.7 keV is emitted with a probability of 98.2%, and a line of 795.9 keV is emitted with a probability of 85.7%. The maximum energy has a line of 1365.2 keV with a probability of 3%. On average, 2.23 gamma rays are emitted per decay of the nucleus.

Cesium is a chemical analog of sodium and potassium and can participate in metabolic processes on a par with these abundantly present in the body nuclides. It is essential that cesium isotopes can be excreted from the body with other salts through urine and sweat. The average time for the biological half-life of cesium in the body is approximately 70 days.

Strontium is a chemical analog of calcium that can accumulate in the bones, remaining in the body for a long time.

The isotopes of cesium and strontium are the most dangerous fission products.

## 17.8.4 Potassium-40, $^{40}$K

The decay scheme of $^{40}$K is shown in Fig. 17.1B. 89.28% of $^{40}$K decays into $^{40}$Ca with the emission of a beta particle with a maximum energy of 1.31 MeV and an average energy of 0.44 MeV. 10.72% of $^{40}$K undergo electronic capture and turn into $^{40}$Ar in an excited state. On transition to the ground state, gamma quanta with an energy of 1.461 MeV are emitted. The half-life of $^{40}$K is $1.248 \cdot 10^9$ y. In a natural mixture of isotopes, $^{40}$K is contained in a concentration of 0.0117%.

A man weighing 70 kg contains 0.2% of potassium, i.e., 140 g. Consequently, the number of radioactive $^{40}$K nuclei is $2.5 \cdot 10^{20}$ nuclei. It is believed that in an adult body weighing 70 kg, about 4400 nuclei of $^{40}$K decay every second or $1.35 \cdot 10^{11}$ y$^{-1}$. It corresponds to activity $4.17 \cdot 10^3$ Bq ~0.1 μCi. Entering the body, potassium is involved in metabolic

transformations and is excreted with feces and urine. The total content of potassium in the body is subject to strict homeostatic regulation, the amount of potassium excreted is related to intake. It was found that the biological half-life of $^{40}K$ is approximately 30 days.

Beta particles emitted during the decay of $^{40}K$ are almost completely absorbed in tissues, but gamma quanta can escape from the body. Therefore, the dose loading from $^{40}K$ is less than all the energy released during decay. Calculations show that every year this isotope produces a dose of about 180 μSv in soft tissues and about 140 μSv in bones.

It is significant that due to the output of $^{40}K$ gamma radiation from the body, the dose rate created by it can be reliably measured by external dosimeters.

## 17.9 NATURAL RADIATION BACKGROUND

### 17.9.1 General Cosiderations

All life on Earth is immersed in the ocean of ionizing radiation. Life came into existence in the irradiation conditions, probably more intense than in the current era, developing under the conditions of exposure and reaching the modern state under irradiation, and it continues to exist, still immersed in this ocean. These radiations fall on the surface of the Earth from space and come from the radioactive substances in the Earth's crust, and they can come from the buildings around us and can be found in the food, water, air, and even in our body. All radiation sources can be divided in several groups:

1. The sources of natural origin (85%) and resulting from human activities including nuclear medicine (15% on average); in developed countries and especially in the United States, the situation is quite different;
2. The sources of the earth origin (92%) and cosmic (8%);
3. The sources of external (35%) and internal (65%) irradiation.

The approximate ratio of the contributions of different sources to the total average annual dose is shown in Table 17.3 [11–13].

For selected individuals and groups of population, different sources of background radiation can vary significantly depending on the place of residence and type of activity. For example, the annual dose due to terrestrial sources for Louisiana residents is 0.15 mSv, whereas for Colorado residents, it is 1.4 mSv. In Europe, the average natural background exposure by country ranges from under 2 mSv annually in the United Kingdom to more than 7 mSv annually in Finland.

**TABLE 17.3 Approximate Relation of Contributions of Various Sources Into Total Annual Dose**

| | USA | | Russia | |
|---|---|---|---|---|
| **Source** | **Dose, mSv/y** | **%** | **Dose, mSv/y** | **%** |
| **Natural Sources:** | | | | |
| Radon (internal, only lungs and bronchi) | 2.3 | 37 | 1.7 | 43.1 |
| Cosmic (space, external) | 0.31 | 5 | 0.3 | 7.6 |
| Terrestrial (soil, external) | 0.19 | 3 | 0.35 | 8.9 |
| Internal (food and water, mainly $^{40}K$ and $^{14}C$) | 0.3 | 5 | 0.38 | 9.6 |
| Total natural sources | 3.1 | 50 | 2.73 | 69.2 |
| **Artificial Sources:** | | | | |
| Medicine | 3.0 | 48 | 1.2 | 30.5 |
| Others | 0.1 | 2 | 0.01 | 0.3 |
| Total external irradiation | 0.6 | | 0.66 | 30.8 |
| Total | 6.2 | 100 | 3.94 | 100 |

Remarks to the Table 1.4. Medicine includes computed tomography (24%), nuclear medicine (12%), interventional fluoroscopy (7%), conventional radiography/fluoroscopy (5%). Source called "others" include coal-fired power plants, nuclear power plants, fertilizers, consumer products, atmospheric nuclear testing, nuclear accidents, and nuclear fuel cycle.
On the basis of **Source**s of Irradiation of Russia Population (in Russian). http://www.ibrae.ru/russian/chernobyl-3d/man/1.htm; U.S. Environmental Protection Agency, Radiation Protection. http://www.epa.gov/radiation/understand/perspective.html; United States Nuclear Regulatory Commission, Fact Sheet on Biological Effects of Radiation. http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/bio-effects-radiation.html.


**FIGURE 17.4** Radiation background in the center of Moscow, Russia, on November 22, 2016. Photo taken by the author. On the photo, units are in Russian (мкЗв/ч = μSv/h).

The contribution of medical applications of nuclear techniques is continuously growing for the population of the United States. In July 2014, this medical component reaches an average of 3 mSv per year across the US population (global average = 0.6 mSv/y).

Typical average normal background radiation in the open countryside, expressed in units of absorbed dose rate, is ~1 mGy/y = 0.1 rad/y. Often radiation dosimeters show radiation background in mR per hour. For rough estimates, one can take 1 mGy/y to 10 mR/h. This background includes only external irradiation and does not include internal exposure due to radon and radioactive nuclides that enter the body with food.

The radiation background on the territory of Russia can be found on the website of Rosatom [14] in the section "Radiation Map," in which one can find the readings of dosimeters installed at various locations within nuclear power plants and in plants for fabrication and processing of nuclear fuel.

The typical radiation background in Moscow, Russia, on November 22, 2016, is shown in Fig. 17.4.

Let us analyze some of the sources of background radiation.

## 17.9.2 Cosmic Radiation

Detailed description of the cosmic radiation is given in Section 48.1. There the main attention is paid to the radiation situation at the altitudes of the aircraft flights. of the orbital space flights and interplanet cosmic flights. Here we only point out that at the sea level, the average dose rate due to cosmic radiation is 0.03 μSv/h (~0.26 μSv/y).

The dose rate due to the cosmic radiation increases with height. Concerning that the Earth population is distributed by height and some dependence of the dose rate on longitude, average dose rate is slightly higher, and it is equal to 0.053 mSv/h = 0.46 mSv/y.

## 17.9.3 Terrestrial Radiation

In the time since the formation of the Earth, all the short-lived nuclides are decayed and only long-lived nuclides with half-lives of the order of billions of years left in the rocks. They include two isotopes of uranium $^{235}$U and $^{238}$U, one isotope of thorium $^{232}$Th, and radioactive isotope of potassium $^{40}$K.

Natural radioactive substances, uranium, thorium, and potassium-40, are contained in many objects that surround humans, particularly in seawater, soil, stones, etc., as well as in building materials, and determine a natural radioactive background. The concentration of radioactive nuclides in some objects is given in Table 17.4.

It is interesting to point out that relatively high amount of $^{40}$K is present in banana. So, one banana with mass 150 g has an activity of about 20 Bq.

**TABLE 17.4 Content of Uranium, Thorium, and Potassium-40 in Some Natural Objects**

| | U | Th | $^{40}$K |
|---|---|---|---|
| Granite, ppm | 3–4 | 14 | 4 |
| Upper layers of soil, ppm | 3–4 | 8–10 | Strongly depends on fertilizer |
| Ocean water, g/L | $(2–3)\cdot10^{-6}$ | $1\cdot10^{-8}$ | $4.5\cdot10^{-5}$ |
| Organism of an adult man with mass 70 kg | $7\cdot10^{-4}$ g (~10 Bq) | $7\cdot10^{-5}$ g (<1 Bq) | $3\cdot10^{-3}$ g (4–5 kBq) |

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