Chapter 2
Short Refresher of Radiobiology

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2.1 Atoms and Isotopes

The atoms are built up of a nucleus, containing positive (protons) and neutral (neutrons) particles, surrounded by negative particles (electrons), circulating around the "atomic orbit". The number of the protons in the nucleus is giving the atomic number of the element (usually labelled as "Z"), and the sum of the neutrons and protons in the nucleus is giving the atomic or mass number of the element (usually labelled as "A"). The number in the electrons in the atomic orbit is always equal to the number of protons in the nucleus. However, as the mass of the electrons is almost equal to zero, they do not influence the whole atomic mass.

The atomic number and the mass number are defining the properties of the atoms. The oxygen, for example, has eight protons and eight neutrons in the nucleus. If oxygen would have seven protons and seven neutrons, it would be nitrogen. The description of the atomic and mass numbers for atoms or isotopes in the periodic system is expressed by convention as shown in Fig. 2.1.

Some of the atoms have the same number of protons but different number of neutrons. Accordingly, their atomic number will be the same, but the mass number will be greater for the difference in the number of neutrons. These atoms are called **isotopes**. Isotopes, by their nature, can be stable (they do not decay) or, more often, unstable. A schematic example of the hydrogen isotopes deuterium and tritium is given in Fig. 2.2.

An example of the difference between atoms and their respective isotopes is shown in Table 2.1.

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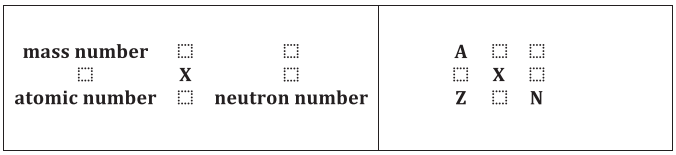

Fig. 2.1 The mass number (A) is the sum of protons and neutrons in the nucleus of the atom, the atomic number (Z) is the number of protons in the nucleus and the neutron number is labelled as N. From practical reasons, atoms and isotopes are labelled only with A and Z numbers. The N number can be calculated as difference between A and Z (N = A−Z)

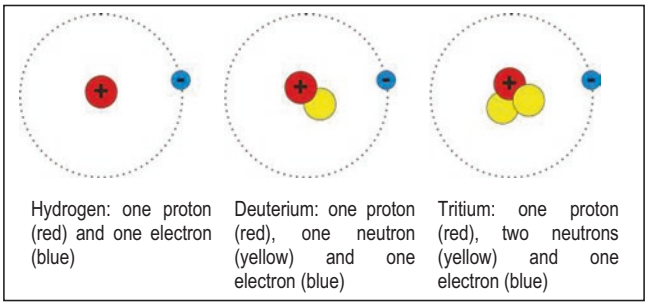

Fig. 2.2 Schematic example of the hydrogen isotopes deuterium and tritium. (Adapted from IAEA 2004)

Table 2.1 Difference between atoms and isotopes

Number of:	Atoms				Isotopes *			
	$^{1}_{1}H$	$^{12}_{6}C$	$^{14}_{7}N$	$^{16}_{8}O$	$^{2}_{1}H$	$^{13}_{6}C$	$^{15}_{7}N$	$^{18}_{8}O$
Protons (Z)	1	6	7	8	1	6	7	8
Neutrons (N)	**0**	**6**	**7**	**8**	**1**	**7**	**8**	**10**
Mass number (A)	**1**	**12**	**14**	**16**	**2**	**13**	**15**	**18**

*Note the different number of neutrons in the atoms (blue font) and their respective stable isotopes (red font)

2.2 Definition of Radiation

Radiation in its wider definition refers to the energy emitted from various sources of the whole electromagnetic spectrum, such as heat, ultraviolet and visible light, microwaves, radio waves, x-rays, low-frequency radiation (such as used in alternate electric transmission, ultrasound thermal radiation) and ionizing radiation.

The ionizing radiation is the energy emitted from the atomic or subatomic structures in a form of waves (γ rays) or particles (α or ß), as a result of the instability of the isotopes. With the increase of the atomic and mass number, the neutron-to-proton ratio increases, leading to formation of unstable isotopes or so-called

"excited" state of the nucleus. Such isotopes tend to reach the "ground" state through the release of α, ß, or γ ionizing radiation (IAEA/WHO 2002).

2.3 Types of Ionizing Radiation

Alpha (α) particles (α decay, α radioactivity) are produced when two neutrons and two protons (i.e. the nucleus of helium) are released from an excited nucleus of the isotopes with higher mass numbers (Z > 83, such as uranium, thorium and radium), as shown schematically in Fig. 2.3.

Therefore, the consequence of the α decay is decreased in the atomic number of the resulting decay (daughter) isotope by 2 and decrease in the mass number by 4 (Fig. 2.4).

The alpha particles are positively charged and because of their large mass (4), they cannot penetrate deep in the body. They can reach a distance of few centimetres through open air and cannot penetrate a sheet of paper. However, once entered in the body, usually by inhalation (lungs) or ingestion GI tract, they may cause short range but devastating consequences for the cell's structures (IAEA 2004). An example of alpha decay is shown in Fig. 2.5.

Beta (ß) particles (ß decay, ß radioactivity) are generated when the nucleus of an isotope has too many protons or neutrons (neutron or proton deficiency, respectively) and are the result of the tendency of the nucleus to rearrange itself to a more stable configuration. Consequently, there are two types of ß decay, the $ß^-$ and $ß^+$ decay.

2.3.1 ß⁻ Decay

In case when the nucleus has too many neutrons (it is proton deficient), the neutrons (n) are converted to protons (p) by releasing an electron ($ß^-$ particle), under high speed (approximately the speed of light) and a particle without mass and charge, called anti-neutrino ($\bar{\upsilon}$). The changes during $ß^-$ decay may be described as follows:

$n \rightarrow p + ß^- + \bar{\upsilon}$ (Fig. 2.6)

Thus, during $ß^-$ decay, the atomic number of the resulting decay (daughter) isotope increases for 1, while the mass number remains the same (Fig. 2.7).

An example of $ß^-$ decay is shown in Fig. 2.8.

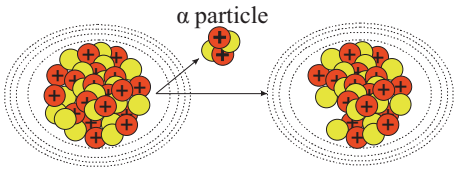

Fig. 2.3 Schematic example of α decay. (Adapted from IAEA/WHO 2002)

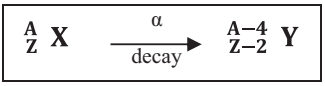

Fig. 2.4 General pattern of the changes in the atomic and the mass number of the resulting decay product (Y) from the source isotope (X) during α decay

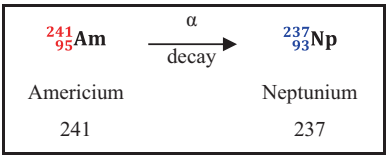

Fig. 2.5 Examples of an α decay are shown in following examples. *Note: the decrease in the atomic and the mass number of the resulting daughter isotopes (blue font) compared to the respective numbers of the decaying parent isotope (red fonts)

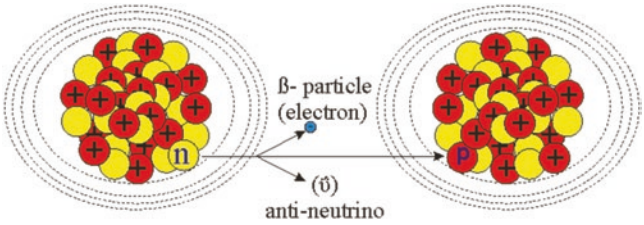

Fig. 2.6 Schematic example of ß⁻decay. Note the change of the yellow-filled neutron (n) to a red-filled proton (p), following the long arrow. (Adapted from IAEA/WHO 2002)

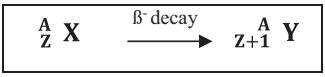

Fig. 2.7 General pattern of the changes in the atomic number of the resulting daughter product (Y) from the source parent isotope (X) during ß⁻ decay

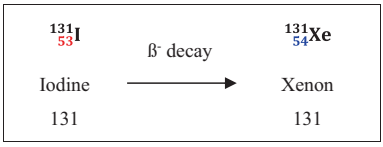

Fig. 2.8 Example of a ß⁻ decay of ^{131}I to ^{131}Xe. *Note the increase of the atomic number by maintaining the same mass number of the resulting daughter isotope (blue font) compared to the respective numbers of the decaying parent isotope (red fonts)

2.3.2 ß+ Decay

In case when the nucleus has too many protons (it is neutron deficient), the protons (p) are converted to neutrons (n) by releasing a positron (positively charged electron, ß+ particle), under high speed (approximately the speed of light) and a particle without mass and charge, called neutrino (υ). The changes during ß+ decay may be described as follows:

$p \rightarrow n + ß^+ + \upsilon$ (Fig. 2.9)

Thus, during ß+ decay, the atomic number of the resulting decay (daughter) isotope decreases for 1, while the mass number remains the same (Fig. 2.10).

An example of ß+ decay is shown in Fig. 2.11.

2.3.3 Electron Capture

In case when the nucleus has protons in excess (situation similar to the ß+ decay), the protons (p) may be converted to neutrons (n) by the phenomenon called electron capture. In such cases, the orbital electrons are captured by the protons which convert to neutrons by emitting a neutrino (υ).

The changes during electron capture may be described as follows:

$p + e \rightarrow n + \upsilon$ (Fig. 2.12)

Thus, during the electron capture (similar as during the ß+ decay), the atomic number of the resulting decay (daughter) isotope decreases for 1, while the mass number remains the same (Fig. 2.13). An example of electron capture is shown in Fig. 2.14.

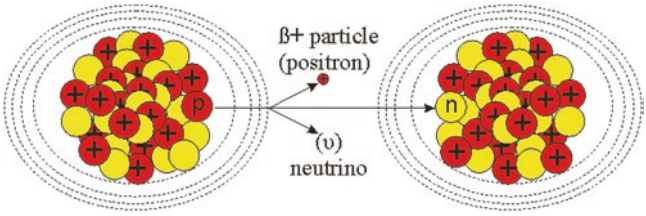

Fig. 2.9 Schematic example of ß+ decay. Note the change of the red-filled proton (p) to a yellow-filled neutron (n), following the long arrow. (Adapted from IAEA/WHO 2002)

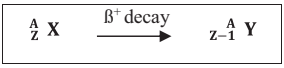

Fig. 2.10 General pattern of the changes in the atomic number of the resulting decay product (Y) from the source isotope (X) during ß+ decay

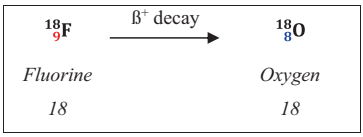

Fig. 2.11 Example of a ß+ decay of ^{18}F to ^{18}O. *Note the decrease of the atomic number by maintaining the same mass number of the resulting daughter isotope (blue font) compared to the respective numbers of the decaying parent isotope (red fonts)

Fig. 2.12 Schematic example of the electron capture. Note the orbital electron is captured by the proton from the nucleus. (From IAEA/WHO 2002)

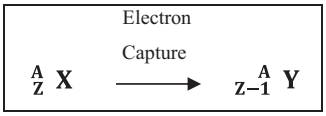

Fig. 2.13 General pattern of the changes in the atomic number of the resulting decay product (Y) from the source isotope (X) during electron capture

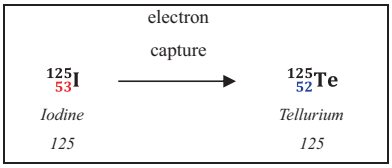

Fig. 2.14 Example of an electron capture of the ^{125}I to ^{125}Te. *Note: the decrease of the atomic number by maintaining the same mass number of the resulting daughter isotope (blue font) compared to the respective numbers of the decaying parent isotope (red fonts). (From IAEA/WHO 2002)

During the electron capture, specific x-rays are emitted, and, in some cases, where an excess of energy remains, γ rays are also emitted (IAEA/WHO 2002).

Gamma (γ) rays (γ radioactivity) are high-energy electromagnetic rays (similar to x-rays) which are produced in the atomic nucleus. They have no electrical charge and an extremely high frequency (over 10^{19} Hz) and energy (over 100 keV). For this reason, they have highly penetrating potential. Their release may be induced through excitation of the atomic nucleus by other decay processes, such as α or ß decay (Fig. 2.15).

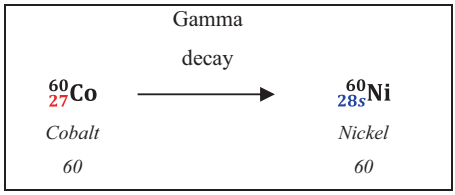

Fig. 2.15 Example of gamma decay of the ^{60}Co to ^{60}Ni

2.4 Physical Half-Life of Radioactive Isotopes

Each radioactive isotope, by emission of certain particles and/or rays, expends the energy (radioactivity) and tends towards stabilization. The time required to expend half of the radioactivity is called physical half-life of the radioactive isotope and is most commonly labelled as $T_{1/2}$. Each isotope has specific physical half-life; thus the calculation of $T_{1/2}$ is based on the isotope constant, as follows:

$$T_{1/2} = \mathrm{Ln}\,2 / \lambda$$

where λ is a radioactive constant specific for the isotope.

Very often, it is necessary to predict the activity of certain isotope, after a certain time (A). This can be also calculated, based on the initial radioactivity (A_0), the isotope constant (λ) and the elapsed period (t), as follows:

$$A = A_0 + e^{(-\lambda t)},$$

where the "e" is the natural logarithm and has the value of 271,828.

A list of the most important isotopes, the ionizing particles/rays are emitting, and the physical half-lives are shown in Table 2.2. The schematic overview of the radioactive decay of isotopes with short (^{131}I, 8 days), long (^{137}Cs, 30 years) and very long (^{239}Pu, 24,390 years) half-life is shown in Fig. 2.16.

2.5 Biological Half-Life of the Radioactive Isotopes

Once entered into the body of animals, via the intestines or inhalation, a part of the ingested radionuclides is absorbed into the blood stream, and the rest is excreted via the faeces or exhaled. The amount entered into the blood stream is distributed among the different tissues. The distribution pathways vary for different isotopes. Some isotopes are distributed throughout the body, and some are incorporated into certain organs. Absorbed radionuclides can be excreted in urine or endogenously excreted in the faeces. The time required for a radioactive isotope to lose half of its activity in the body is called the biological half-life ($T^b_{1/2}$) which depends on the metabolic characteristics of each isotope and is not related to the physical half-life of the isotope ($T^p_{1/2}$). Some of the isotopes may have short $T_{1/2}$ and long $T^b_{1/2}$, and the opposite also occurs.

Table 2.2 List of most important radioisotopes, occurring after a NRE, their mass number, type of decay and the physical half-life

Radioactive element	Atomic number	Atomic mass number	Decay type	Half-life
Cesium (Cs)	**55**	**134**	**(β-), γ**	**2 years**
Cesium (Cs)	55	135	(β-), γ	2 million years
Cesium (Cs)	**55**	**137**	**(β-), γ**	**30 years**
Iodine (I)	53	129	(β-), γ	17.2×10^6 years
Iodine (I)	**53**	**131**	**(β-), γ**	**8 days**
Iodine (I)	53	134	(β-), γ	52 min
Plutonium (Pu)	94	236	α	285 years
Plutonium (Pu)	94	238	α	86 years
Plutonium (Pu)	**94**	**239**	**α**	**24,390 years**
Plutonium (Pu)	94	240	α	6580 years
Plutonium (Pu)	94	241	(β-), α	13 years
Plutonium (Pu)	94	242	α	379,000 years
Plutonium (Pu)	94	243	α	5 years
Plutonium (Pu)	94	244	α	76×10^6 years
Strontium (Sr)	**38**	**89**	**(β-)**	**53 days**
Strontium (Sr)	**38**	**90**	**(β-)**	**28 years**

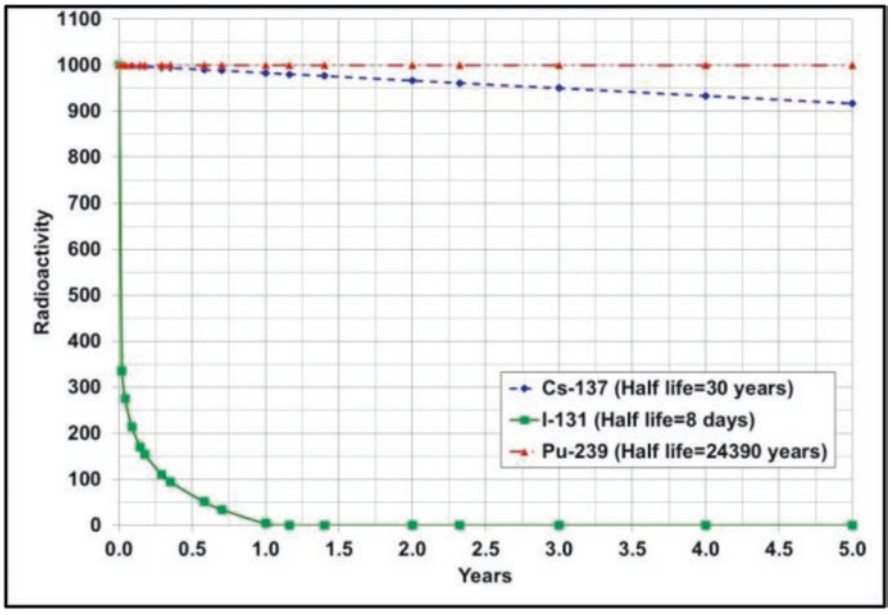

Fig. 2.16 Schematic overview of the radioactive decay of three isotopes with different half-life (simulation of a 5-year period)

2.6 Effective Half-Life of the Radioactive Isotopes in the Body of Animals

The effective half-life ($T_{1/2}^{\text{eff}}$) is the time required to lose half of the overall activity in the body and is a result of the interrelation between the $T_{1/2}^{p}$ and $T_{1/2}^{b}$. The $T_{1/2}^{\text{eff}}$ can be calculated according to the following equation:

$$T_{1/2}^{\text{eff}} = \left(T_{1/2}^{p} \times T_{1/2}^{b}\right) / \left(T_{1/2}^{p} + T_{1/2}^{b}\right)$$

Example: Iodine-131 has a $T_{1/2}^{p}$ of 8 days and a $T_{1/2}^{b}$ of 138 days. The $T_{1/2}^{\text{eff}}$ can be calculated as:

$$T_{1/2}^{\text{eff}} = \left(8 \times 138\right) / \left(8 + 138\right) = 1104 / 146 = 7.6\,\text{days}.$$

2.7 Decay Chains and Ingrowth

The radioactive isotopes undergo radioactive decay through numerous transformations. Until the last decay, with each transformation, these radionuclides emit particles (energy) and become another isotope (Fig. 2.17). This stepwise decay ends with formation of a stable atom or isotope and is called decay chain of the specific isotope.

The result of the decay chain is a dynamic change of the concentration of different between-products (isotopes); unit of the final stable product is formed. Through this process, the concentration of the source nucleotide continuously decreases, and the concentration of between products increases, until the final, stable element achieves the maximal concentration. This process is called ingrowth (Fig. 2.18).

Information and knowledge related to the decay chain and the ingrowth are of utmost importance for the waste management or post-accident mitigation strategies, even though some of these processes may continue over thousands of years!

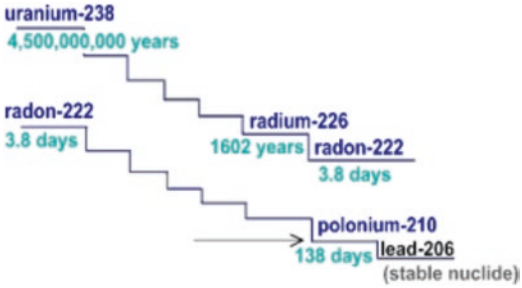

Fig. 2.17 Example of a decay chain for unstable (radioactive) ^{238}U to stable lead (EPA 2015a)

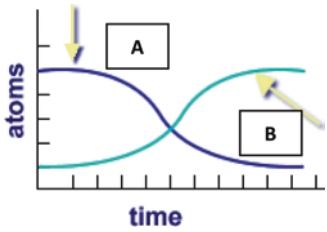

Fig. 2.18 As decay progresses, the concentration of original radionuclide is decreasing (A), while the concentration of the stable decay product is increasing! (EPA 2015b)

There are three natural (uranium, thorium and actinium) and one artificial (americium) decay series, for which detailed information on the type of radiation, energy and half-lives of parent and daughter isotopes are calculated (US Department of Energy 1997). Detailed calculation of the decay and growth of individual parent and daughter isotopes, respectively, is given in IAEA/UNESCO (2000).

2.8 Units of Radioactivity

The radioactivity of the isotopes represents decays per time unit. According to the SI system, the measure for radioactivity is Becquerel (Bq) and represents one disintegration per second. The conventional unit, Curie (Ci), has been defined as activity of 1 g of ^{226}Ra (IAEA 2004) and equals 37×10^9 disintegrations per second. Accordingly, 1 Ci = 3.7×10^{10} Bq or 1 Ci = 3.7 GBq and 1 Bq = 2.703×10^{-11} Ci.

2.9 Specific Radioactivity

Specific radioactivity is the radioactivity per mass or volume of certain material. It is expressed as Bq/kg (mass) or Bq/m^3 (volume). The legislation limits for animal products are based on the specific radioactivity.

2.10 Radiation Dose

The radiation dose is the amount of radiation energy (amount of radiation exposures) absorbed by the body and is defined by two variables:

The absorbed dose (physical dose) is the amount of energy deposited in a unit of mass in the tissue or other media. The SI unit for absorbed dose is Gray (Gy) and represents an energy of 1 Joule/kg mass. In older literature, Rad is used, which is 100 times smaller dose than Gray (1 Gray = 100 Rad).

The dose equivalent (biological dose) takes into consideration the total energy deposited and the amount of energy lost from the particles (rays) per unit dis-

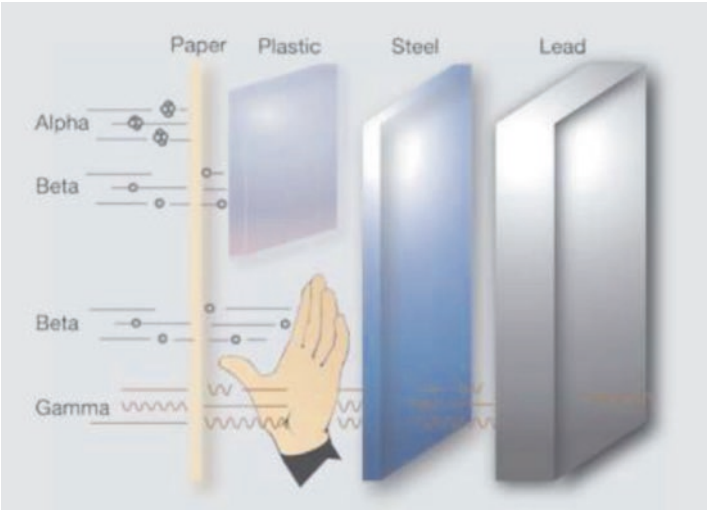

Fig. 2.19 A schematic example of the capacity for penetration of α and β particles and γ rays through different materials (IAEA 2004)

tance (linear energy transfer or LET). The LET depends on the size of the particles, their charge and their energy. Larger and charged particles (α and β) have higher LET compared to γ rays. Schematic example of the capacity for penetration of the ionizing radiation through different substances is shown in Fig. 2.19.

The biological effect of different radiation particles/rays is measured by the quality factor (Q). The Q factor is a correction for different types of radiation particles/rays, used to correct for the biological effect caused by these particles. For electrons, x-rays and gamma rays, the Q is taken to be 1; for alpha particles it is 20 and for neutrons varies from 5 to 20, depending on neutron energy (Table 2.3). The biological impact is specified by the dose equivalent (H), which is the product of the absorbed dose D and the quality factor (Radiation weighting factors) Q (H = QxD). Consequently, if an organism has absorbed a dose of 1 Gy of gamma rays, the dose equivalent would be 1 Sv, whereas for the same absorbed dose of alpha particles, the dose equivalent would be 20 Sv. In older literature, instead of Sievert, the Rem unit is used, which is a product of Rads × Q. The Sievert is 100 times higher than the Rem (1 Sv = 100 Rem).

2.11 Effective Dose Equivalent

Even if same biological dose is absorbed by different organs or biological systems, the overall risk may vary depending on the organ/biological system affected. The effective dose equivalent is therefore discounted for the appropriate weighting factor, in order to reflect the overall risk. Estimated weighting factors for some parts of the body are shown in Table 2.4.

Table 2.3 The quality factors (Q) of different types of ionizing (Gusev et al. 2001)

Body part	Quality factors
Protons (all energies)	1
Electrons (all energies)	1
Neutrons (<10 keV)	5
(<10–100 keV)	10
(100 keV–2 MeV)	20
(2–20 MeV)	10
(>20 MeV)	5
Protons (>2 MeV)	5
Alpha particles, fission fragments, heavy nuclei	20

Table 2.4 The estimated weighting factors for selected organs of the human body (ICRP 2012)

Body part	Weighting factor
Whole body	1 (100%)
Ovaria, testis	0.25 (25%)
Bone marrow	0.12 (12%)
Bone surface	0.03 (3%)
Thyroid gland	0.03 (3%)
Chest	0.15 (15%)
Lungs	0.12 (12%)
Other tissues	0.3 (30%)

2.12 Lethal Dose

The effective dose equivalent that will cause death in 50% of the exposed individuals is called 50% lethal dose (LD_{50}), and it is different for different species.

LD50 in different animal species is shown in Table 2.5.

A simplified way for interpretation of the units of radiation mentioned above is shown in Table 2.6.

2.13 Interaction of the Ionizing Radiation with the Matter

Based on their mass and the energy of the ionizing radiation, different sources have different capacities of penetration through the matter. They have also different biological action when entered into the body of humans and animals.

During penetration, the ionizing particles are causing electrical interactions with the matter, either by interactions with the electrons (α, β and γ) or interactions with the atomic nuclei (neutrons). The energy that is lost during the penetration of the ionizing radiation causes vibrations of the atomic and molecular structures, which results in short heat production in biological tissues. Ionization and the consequent

Table 2.5 LD 50% for different animal species (Gy) (Yarmonenko 1988)

Species	Dose (Gy)	Species	Dose (Gy)
Sheep	1.5–2.5	Birds	8.0–20.0
Donkey	2.0–3.8	Fishes	8.0–20.0
Dog	2.5–3.0	Rabbit	9.0–10.0
Monkeys (different species)	2.5–6.0	Hamster	9.0–10.0
Mice (different lines)	6.0–15.0	Snake	80.0–200.0
		Plants	10.0–1500.0

Table 2.6 Illustration of simplified ways of interpretation of different units for measuring radiation exposure (Gusev et al. 2001)

Amount of radioactivity	Quantity	Unit
How much radioactivity is in the observed matrix (sample)	Specific radioactivity	Bq/kg
How much radioactivity (energy) has been deposited (for human population only)	Absorbed dose	Gy
Deposited energy (absorbed dose) corrected for the quality factor of the radiation type (alpha, beta, gamma)	Equivalent (biological) dose	Sv
Effective dose, corrected for the weighting factor of the organ (tissue) affected	Effective dose equivalent	Sv

chemical changes are actually the reason for the harmful biological effects of the ionizing radiation (IAEA 2004).

2.14 The Sources of Man-Made Environmental Contamination

Continuous nuclear tests (UNSCEAR 1977), radiation accidents and large-scale nuclear disasters (Dyachenko 2008) have led to the omnipresent pollution of the biosphere by radioactive hazardous substances such as ^{137}Cs and ^{90}Sr. Nowadays, the typical density of land contamination caused by these radionuclides makes up a few tens of kBq/m^2.

Four hundred twenty-three nuclear explosions were conducted in the atmosphere during the period of nuclear testing in 1945–1980. Altogether, they discharged around 5.9×19^{17} Bq of ^{90}Sr and approximately 9.5×10^{17} Bq of ^{137}Cs. The present-time deposition density of these radionuclides in the mid-latitudes of the Northern Hemisphere, from both nuclear testing and global fallouts, makes up 1.1 and 1.8 kBq/m^2, respectively.

The radiation accident of 27 September 1957 that had occurred at "Mayak" reprocessing nuclear facility in Chelyabinsk region, USSR, involved the explosion of 70–80 tons of high-activity nuclear wastes with a total activity of around 7.4×10^{17} Bq, of which approximately 7.4×10^{16} Bq was released into the

environment. The contribution of ^{90}Sr and ^{137}Cs in the total discharged activity was 2×10^{15} and 3×10^{13} Bq, respectively. The extensive radioactive trace with a total area over 1000 km^2 and ^{90}Sr contamination level of 74 kBq/m^2 had spread over USSR's Chelyabinsk, Sverdlovsk and Tyumen regions (Aleksakhin 2006; Avramenko et al. 1997).

On 26 April 1986, the radiation disaster at the Chernobyl NPP was accompanied by powerful releases of radioactive materials into the atmosphere. The total activity of radioactive materials released from the nuclear core in the accident was $(1–2) \times 10^{18}$ Bq, with a share of ^{137}Cs equalling to 3.6×10^{16} Bq and that of ^{90}Sr equalling to 8.0×10^{15} Bq (IAEA 2008).

Two hundred sixty-five thousand hectares of the agricultural lands in Belarus are contaminated by either ^{137}Cs or and ^{90}Sr with the deposition densities of above 1480 kBq/m^2 and 111 kBq/m^2, respectively (CMRB 1997). A particular challenge for the country has been the production of foods in compliance with the regulation values in the areas where land contamination by cesium-137 is 5–40 Ci/km^2. The total area of such lands in the republic is 415.6 thousand hectares, of which 35.7 thousand hectares is simultaneously contaminated by ^{90}Sr with a density of 1–3 Ci/km^2 (Annenkov and Averin 2003).

The most important and equally complicated task of the regional development strategy is about overcoming the consequences of the Chernobyl disaster. The strategy of sustainable development of the areas affected by radioactive contamination should be built with taking into account the need to improve the living standards and the overall wellbeing of the residents on the basis of environmentally radiological and socio-economic recovery of such areas. The following efforts are planned to help to reach this objective:

- Reduction of poverty and unemployment, increased profits, enhancement of social protection of affected populations based on revival of economic activities in affected areas, intensification of investment projects, creation of favourable conditions for the development of farming, small and medium businesses
- Improvement of living conditions, social and cultural environments of the residents of affected areas, particularly in the countryside

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