Quantities and Units

Previous chapter: 5.2.1 *The Fundamental Law of Radioactive Decay*

Basic units

For the purpose of determining the effect of ionizing radiation on biological subjects we need to first define the units and quantities characterising the extent of this effect.

In the area of radioactivity and ionizing radiation there are three specific and unique main quantities with specific names:

- The unit of (radio) **activity,** called **becquerel (Bq)**,
- the unit of **absorbed dose**, called **gray (Gy)**,
- and the unit of **equivalent dose**, called **sievert (Sv)**.

The quantity characterising the amount of radionuclide was previously called activity. **Activity is based on the frequency of radioactive transformations occurred in the radionuclide**. Activity of a radioactive sample is described as t**he amount of radioactive nuclei transformed (decayed) per second**. The activity of a sample decreases exponentially with time. **The unit of activity is 1 s^{-1}**. However, this unit was too general in its description, and lead to the decision made in May 1975, which stated that the unit of activity (1 s-1) should be called Becquerel.

A radioactive sample is characterised by the activity of 1 Bq if 1 radioactive nucleus decays per 1 second. In some cases it is also possible to use a unit of activity associated with a unit of mass (activity per unit of mass - Bq.kg-1), volume (activity per unit of volume – Bq.m-3), and surface area (activity per unit of surface area – Bq.m-2) etc.

Activity of a radionuclide is closely connected with a quantity called **decay constant λ (s-1**), which is followed by **mean lifetime $\tau = 1 .\lambda^{-1}$ (s)**.

A source of ionizing radiation is generally characterised according to the amount of emitted radiation by a quantity called **source emission.** This is defined as **mean amount of particles emitted by the source per unit of time**. Radiation sources can be found in the form of a radionuclide, an X-ray tube or a particle accelerator. The resulting particles can then originate via the radioactive transformation itself, through the process of acceleration in the accelerator, or via nuclear interactions (secondary particles). T**he unit of source emission is a reciprocal second (s^{-1}**). The unit of energy of radioactive particles, gamma radiation, or X-radiation is characterised as 1 eV.

Generally, **the probability of interaction between particles is expressed via the concept of a cross section σ**. This expresses the likelihood of a certain interaction for one target entity (atom, electron, nucleon) per unit fluency (density) of particles passing through a medium. The unit of cross section is a square meter (m2).

The **linear attenuation coefficient** describes the fraction of a particle stream density which has been removed from the stream during its passing through a layer of a defined medium with unit thickness.

Exposure is the most commonly used parameter to describe X-radiation and gamma radiation. The exposure is defined by the effects ionizing radiation has in a certain environment.The standard environment used to measure exposure is air. **Exposure describes the absolute value of the total electrical charge of ions produced by ionizing radiation in the air** (which originated during the deceleration of all the electrons and positrons liberated by photons), **divided by the mass of the air sample, where the electrons were released.** The unit of radiation exposure is **coulomb per kilogram** ($C.kg^{-1}$).

Exposure rate, X´, is defined as an increase of the exposure ΔX in a unit of mass per a unit of time Δt, $X´= \Delta X/\Delta t$. The unit of exposure rate is $A .kg^{-1}$.

Specific absorption rate, D´, is defined as a measure of the rate ΔD at which the energy is absorbed by a unit of mass per a unit of time Δt, $D´= \Delta D/\Delta t$. The unit of this quantity is W.kg-1.

The extent of the effects of ionizing radiation on a substance is defined by the absorbed dose. **The absorbed dose is the amount of energy deposited by the ionising radiation in a unit of mass**. The unit of absorbed dose is **$1 Gy = 1 J.kg^{-1}$.**

The biological effects of radiation depend on radiation dose and on type of radiation (i. e. linear energy transfer and spatial distribution of the radiation dose). For these reasons there was a new quantity established. The new quantity reflects these conditions and respect different biological effectiveness of different types of ionizing radiation on humans. This biophysical quantity represents a better connection between the extent and probability of biological effects of ionizing radiation. It is called equivalent dose (H). **The equivalent dose is the product of dose (D) and respective dimensionless modifying factors (Q, N): H = D .Q . N.**

Quality factor, Q, describes different quality of the radiation with regards to the biological effects it causes. Q applies only to humans and its significance lies mainly in radiation protection. The specific values of quality factor are specified by the quantities of internal radiation. The term describes radiation produced by radionuclides located

within the body of the irradiated person, usually as a result of a radionuclide intake via ingestion or inspiration. In order to limit the internal radiation through radionuclides and their intake, there are several parameters that can be considered:

- Effective dose E
- Dose equivalent HT (Sv) (which is a time integral of the effective dose input)
- Dose equivalent for the time duration of 50 years from the radionuclide intake (in adults) and time duration up to 70 years of age for the radionuclide intake in children.

Dose equivalent, HT, is the product of radiation weighting factor and mean absorbed dose. The weighting factor is 1 for photons and electrons, 5-10 for neutrons (based on their energy), 5 for protons, and 20 for α-particles and heavy nuclei. Effective dose E is the sum of the products of tissue weighting factors and the dose equivalent, HT, in the irradiated tissues or organs. The weighting factor for gonads is 0.2, for red bone marrow, lungs, large intestine and stomach the weighting factor is 0.12, and for urinary bladder, liver and thyroid gland it is 0,05 etc.

Physical, biological and effective half-life

Physical half-life of a radioactive transformation (T_f) is **the average time required for the decay of exactly half the atoms in a given amount of a radioactive isotope.** The quantity is mainly used to characterise the speed of the nuclear radioactive transformation. The mathematical dimension of half-life is time and depends on the type of the isotope. The resulting values of physical half-life are arranged in tables in appropriate time units (seconds, minutes, hours, days, years). It is important to realize that the value of physical half-life varies significantly in different radionuclides. If we consider the same nuclide, the physical half-life of its radioactive transformation is always constant.

Biological half-life (T_b) is t**he time in which a living organism eliminates half of a given amount of a radionuclide**. This definition assumes that the isotope has been evenly spread throughout the organism and there is no additional intake of it. The unit of **dose equivalent** is Sievert (Sv), and this quantity holds the same unit as radiation dose (J.kg-1).

Effective half-life is the half-life of a radionuclide in a biologic organism resulting from the **combination of biologic elimination and radioactive deca**y. If the radionuclide were not a subject to biologic elimination (in the form of stool, urine etc.) the effective half-life would equal to the physical half-life. In real conditions, the effective half-life is always shorter than the physical half-life. The effective half-life that is the most significant when determining the radiation dose received by a living organism.

Isotopes, isobars, isotones, isomers, nuclides

As it is evident from the first chapter of this textbook, the nuclei of all atoms are composed of nucleons, which are protons and neutrons combined together. The atomic number (also known as the proton number; Z) is the number of protons found in the nucleus and defines the position of the element in the periodic table. The neutron number (N) is the number of neutrons. The nucleon number, also known as the mass number (A), is the total number of nucleons found in the nucleus (A = Z + N). The isotopic number (I) is the difference between the amount of neutrons and protons in the nucleus (I = A – Z).

Atomic nuclei with different composition very often differ drastically in their physical properties. These nuclei can, however, share the same values of some of the numbers that characterise them. Based on this congruence there are some relationships between atoms, which are described by the following definitions:

Isotopes are elements having the same number of protons but different number of neutrons (same Z, different A). For example while the nucleus is stable, nucleus is radioactive. From the chemical point of view, both of these atoms act as phosphorus – they are therefore called phosphorus isotopes. They share the same chemical properties, and can be distinguished or separated only with the use of physical methods. Following the discovery of artificial radioactivity, isotopes of almost all the chemical elements have been obtained, and the number of isotopes is still rising.

Isobars are elements with the same number of nucleons (meaning they have the same nucleon number) but different number of protons (i.e. different charge – different Z, same A). Because of this they represent different chemical elements. Examples of isobars are 83Li, 84Be, 85B, or , , , etc.

Isotones are elements having the same number of neutrons. Their neutron number is therefore the same (N = A – Z). Isotones are for example nuclei of - - - - - - all of these elements have exactly 14 neutrons. The first and the last two elements are radioactive. To characterise the atomic nucleus,we need to know more than the proton and nucleon (mass) number. Nuclei with the same Z and A can differ in some other important properties, such as the energy content, inner structure, spin, radioactive properties etc.

Isomers are atoms that share the same number of protons (same charge) and the same number of nucleons (same Z, same A). However, they differ in their energy state (for a certain duration of time [> 10-9 s] they display elevated levels of energy), and in their radioactive properties. Nuclear isomerism was first discovered in 1921, and considering that naturally radioactive elements it can only be found in one single element – protactinium . The nuclear isomerism phenomenon is characteristic for artificial radionuclides, and is very common for these radionuclides. During the nuclear reaction the maternal nucleus can produce a radioactive element in either ground state or in an energetically excited state. The energetically excited state is a form that is characterized by a measurable life length and physical half-time. Today there are several hundred known cases of nuclear isomerism.

A collection of atoms sharing the same number of protons and the same number of neutrons (same Z, same A), all existing for at least a fraction of a second, is called nuclide. This term is used to describe an atomically individual kind of elements. Nuclides consisting of atoms with nuclei displaying higher levels of energy than those of stable nuclides are called radionuclide.

Nuclei existing in an energetically excited state undergo a spontaneous radioactive decay and give rise to more stable nuclides. Absolutely stable nuclides are characterized by zero activity, which means its physical half-life is infinitely long. Absolutely stable nuclides are impossible due to the energetic reasons. Practically stable nuclides are defined as nuclides, including the ones actually being radioactive, with such a long half-life time that the activity cannot be detected by current detection methods (for example Tf for is 4,51 x 109 years).

Natural and artificial radioactivity

Spontaneously transforming atomic nuclei that are found in nature, are called naturally radioactive. Natural radioactivity was first discovered only a couple of months after the discovery of X-radiation. In 1896 Antoine Henri Becquerel presented the results of his experiments, in which he was examining whether or not certain fluorescent materials (uranium compounds) could act as a source of X-radiation. During this research he discovered a new kind of radiation, which was spontaneously emitted, not only by metallic uranium, but also by non-fluorescent compounds.

Natural radioactivity

Naturally radioactive elements can be divided into 3 groups:

Radio nuclides with high proton number, giving origin to decay chains

The process of creating decay chains is described as a reaction in which a parent nuclide transforms into a daughter nuclide. The daughter atom is characterised by a different energy state, and may also be radioactive. Over time, the new atom can transform and give rise to another radioactive atom. After a number of transformations, the decay chain ends with a stable lead isotope. Each chain therefore begins as an unstable paternal nuclide and ends in a stable nuclide.

Heavy radioactive elements produce 3 main decay chains:

1. **Radium** (also known as uranium) series (beginning with uranium and ending with lead)
2. **Actinium series** (beginning with actinouranium and ending with lead)
3. **Thorium series** (beginning with thorium and ending with lead)

Natural radionuclides with lower proton number

Following the discovery of a large number of radioactive nuclides among the heavy elements, there was an intensive search for the signs of natural radioactivity among lighter elements as well. Very soon it was shown that some of these indeed do have the ability of a radioactive transformation, mainly type β-. Through their radioactive decay are produced stable nuclei. The most important biological effect possesses potassium isotope with physical half-life of 1,3 x 109 years: (+ ↑β- → , 89%), or (+ electron capture → , 11%).

Light natural radionuclides

The scientific research, dating back to the second half of the 1930’s, lead to the discovery that there is a minute amount of other nuclides in the natural environment. These where previously only known as products of artificial reactions. The main examples are tritium 3T (Tf= 12,26 years, β-) and carbon 14C (Tf = 5730 years, β-), which are created by the neutron component of cosmic radiation affecting the nitrogen in atmosphere {reaction 14N (n, 3α) → 3T; 14N (n, p) → 14C}. These nuclides are therefore a minute, but stable part of Earth’s atmosphere and biosphere.

The knowledge gained during the research of natural radioactivity lead to the unequivocal conclusion that a radioactive nuclide can produce a new nuclide. This happens through the process of transmutation, which is accompanied by an emission of a certain type of radiation. This new nuclide can then undergo the process of transformation again, and eventually create a stable product. A reversed process, in which a non-radioactive nuclide would give origin to a radioactive one, has long been thought impossible. Such a radical interference with the atomic nucleus would be powerful enough to cause a nuclear reaction. Before the discovery of the neutron, this was thought to only be possible with the use of extremely high energy – higher by million orders of magnitude than the ones classic physics were familiar with. The instruments able to generate such amounts of energy are

1. targeting with particles/irradiating with photons γ with the energy level > 106 eV, and/or
2. using high temperatures (>107 K).

When the atom approaches a state of total ionization, the thermal motion of ions reaches extreme high levels of energy. During these energy states, atom collisions cause an increased probability of a particle exceeding the nuclear potential barrier, thereby making thermonuclear reactions possible.

Artificial radioactivity

Radioactive nuclei produced by a nuclear reaction in particle accelerators or nuclear reactors, are called artificially radioactive. Artificial radioactivity was discovered in 1934. The married couple Frederic and Irene Joliot-Curie observed, while irradiation aluminium with a-particles in their laboratory, that during some nuclear reactions they created a radioactive isotope (+ 42α → + 10n; → + 0 + 1β+). In order to carry out nuclear reactions it is necessary to transport the particles close to each other. The nuclei have to be in such close proximity that the nuclear binding energy could affect them. The probability of a nuclear reaction is derived from the cross-section of a given isotope. The electron and the nucleus are attracted to each other due to opposite charges; however the electron is not effective enough. For the nuclear reaction to take place the electron would have to first overcome the nuclear potential barrier. Then it would have to, because of the low mass, enter the nucleus with a sufficient enough speed. All particles carrying a positive charge, and having substantial mass this reaction, would also have to be supported by significant kinetic energy. The kinetic energy in the nuclear proximity, with positively charged particles, is necessary to overcome the repulsive Coulomb forces. Neutrons, on the other hand, have a mass high enough and can approach the nucleus without the supportive high speed. This is because neutrons are not subject to any repulsive forces. The probability of a nuclear reaction involving neutrons differs from case to case and depends on the energy of neutrons. In some cases the lower the speed of neutrons, the higher the probability of a nuclear reaction. This is because small neutrons possess larger cross section.

The artificial reactions give origin to radioactive elements that are not normally found in nature. The radioactive decay follows the same laws and principles as the decay of naturally radioactive elements.

In conclusion, the process of transmutation (a reaction producing a new nucleus with both proton and nucleon numbers being no more than only a couple of units different from the proton and nucleon numbers of the original nucleus) can be currently conducted with any particles or photons. Preferably these particles should be accelerated. The progress in creating artificial radionuclides has reached such levels that it is currently possible to produce practically any isotope. Targeting elements with protons can produce mostly reactions (p, α), (p, γ), (p, n), (p, d).

Targeting elements with deuterons (nuclei of hydrogen 21H = d) gives origin to similar type of reactions (d, α), (d, n), (d, p). Deuterons are positively charged and therefore can be accelerated. Targeting elements with accelerated particles α most commonly produces one proton or one neutron (α, p), (α, n).

With the use of particle accelerators, it is even possible to transmute nuclei by targeting them with accelerated electrons or ions.

Very impressive effects were also displayed by neutrons, which can sometimes be absorbed by the target nucleus without liberating any other particles. They therefore give origin to an isotope of the targeted element. This isotope is usually radioactive. In 1933 the Italian physicist Fermi observed that it is possible to transform almost all of the known elements into radioisotopes through the process of targeting with slow neutrons.

The result of a radioactive decay of artificial radionuclides is usually stable daughter nuclides. However, even in the area of artificial radioactivity there were cases when the newly produced daughter nucleus remained unstable and acted as a paternal nucleus of another daughter nuclide. This means that there can be a certain „genetic link“ found between several nuclides forming decay chains.

Radioactive equilibrium

In most cases, the radionuclides transform into stable nuclides. In some cases, as described above, the process of transformation starts with an already decayed daughter radionuclide. Radioactive equilibrium then describes the state when, within the decay chain, the same number of paternal and daughter radionuclides‘ nuclei are being transformed per a unit of time (Fig. 5.2.). A stable radioactive equilibrium can only occur when the physical half-life of the paternal nuclide transformation (T1) is significantly longer than the physical half-life of the daughter nuclide transformation (T2): T1 >> T2 (for example 226Ra with Tf = 1622 years transforms into 222Rn with Tf= 3,8 days). In such cases the activity of a daughter radionuclide approaches and then remains constantly equal to the activity of the paternal radionuclide. The ratio between the number of paternal and daughter nuclides remains the same. Under these conditions the decrease in the number of daughter nuclides per unit time (due to their own transformation) is compensated by the production of new daughter nuclides via the transformation of paternal nuclides.

If T1> T2, a temporary radioactive equilibrium is possible. In this case there is a decrease in the number of atoms (activity) of the paternal nuclides.

If T1< T2, it is impossible to reach radioactive equilibrium.

Generator systems using the nuclides with a very long half-life of the paternal (enables long-term usage) and short half-life of the daughter nuclide, (low radiation exposure for the patient), represent the main tool used in the nuclear medicine practise.

Links

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