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Radioactivity, Radiation Detection, and Definition of Dose

1. The nucleus of the atom

1.1 The structure of the nucleus

Atoms consist of very small nuclei of about 10^{-15} m diameter (that is 1/100,000 of the diameter of the whole atom) and the electrons of the shell. The elements of the nucleus (nucleons) consist of neutrons and protons which were considered to be indivisible for a long time after their detection. The proton has a positive charge and the neutron is uncharged. The masses of the proton and the neutron are nearly equal. There is a strong attractive force nucleons between the nucleons. Because the number of protons in the nucleus equals the number of electrons in the shell, the atom as a whole is electrically neutral. The nucleus is completely characterised if the number of protons and neutrons is known.

The number of the nucleons M – the ´mass number` - equals the sum of protons and neutrons. The number of the protons is designated Z. It equals the electron number in the shell. The amount of neutrons N is the difference of mass number and atomic number (N = M-Z).

Commonly, the mass number M is written above and the atomic number below and both before the symbol of the element. Accordingly, $^{238}_{92}$U contains 92 protons and 146 neutrons in the nucleus, 92 electrons in the atomic shell and represents the element uranium in the periodic system of elements. If only the mass number is of interest to characterise the isotope one may also write U-238.

1.2 Isotopes

Many of the natural chemical elements are mixtures of atoms of the same atomic number but of different mass numbers. The element potassium e.g. consists of 93.1 % of $^{39}_{19}$K, 6.88 % of $^{41}_{19}$K, and 0.02 % of $^{40}_{19}$K.

Isotopes are atoms with the same number of protons but different number of the neutrons. But they are the same chemical element.

The isotopes of hydrogen ^{1}H, ^{2}H, and ^{3}H have special names: ^{2}H is called deuterium – often written as D. Its nucleus consists of 1 proton and 1 neutron. Deuterium is a natural substance; one in 6000 hydrogen atoms is a deuterium atom. ^{3}H has a nucleus consisting of 1 proton and 2 neutrons. It is called ´tritium (T)`and is radioactive.

Because part of the nucleons have a positive charge while the others are uncharged, there must exist strong attractive forces to compensate for the electrostatic repulsion: the nuclear forces. Their range of interaction is only about 10^{-15} m and therefore the interaction is limited to the neutrons and protons inside the nucleus.

2. Radioactivity

2.1 Unstable nuclei

Not every combination of protons and neutrons is possible in a stable nucleus. In stable nuclei the ratio between neutrons and protons is about 1 for light elements. With increasing mass number this ratio increases and reaches values up to 1.6 in heavy nuclei. If the ratio deviates from this value, the nuclei tend to alter the neutron/proton ratio by spontaneous processes.

In nature, there are nuclei such as ^{238}U or ^{226}Ra with atomic mass greater than 210 or with a high neutron to proton ratio. They are unstable and reach more stable configurations by emitting charged particles, thereby changing their composition. These nuclei are radioactive. Their instability leads to different kinds of radioactive decay.

The decay of an unstable nucleus occurs spontaneously, without energy input. It is therefore a kind of exothermic process. The energy of the emitted radiation is gained by the so-called ´mass defect`, i.e. a conversion of mass to energy.

2.2 Types of decay

The radiation emitted with a nuclear conversion consists of charged particles, usually accompanied by electromagnetic waves. Radiation energy is characteristic for, and defines every radionuclide.

The energy unit used in the context of atomic and nuclear processes is the electron volt (eV). Charged particles are accelerated in electric fields and thereby acquire kinetic energy. 1 eV is the kinetic energy gain of an electron (the elementary negative charge) which passes a voltage difference of 1 V.

Conversion factor of eV to Joule (J):
$1\ eV = 1.609\ 10^{-19}\ J$
$1\ keV = 1.000\ eV = 1.609\ 10^{-16}\ J$
$1\ MeV = 1.000\ keV = 10^{6}\ eV = 1.609\ 10^{-13}\ J$

Alpha-decay

Disintegration of the nucleus occurs in heavy elements by emitting a charged particle consisting of 2 protons and 2 neutrons. This is the nucleus of the helium isotope $^{4}_{2}He$ and is called alpha-particle (α) in this context. The process increases the proportion of neutrons in the remaining nucleus.
The emitted α-particle has a discrete kinetic energy in the range 1-10 MeV depending on the specific initial nucleus.

Beta-decay

In the case of neutron excess, the nucleus may emit an electron. This electron is generated by the disintegration of a neutron to a proton and an electron. The electron leaves the nucleus while the proton remains. This kind of electron is called a β-particle. The β-energy can vary between 0 and a maximum energy which depends on the isotope. The energy difference between the maximum energy and the β-energy leaves the nucleus in the form of an uncharged particle called neutrino which accompanies each β-decay.
The maximum β-energies range from 10 keV to a few MeV.

Gamma-radiation

Most of the decaying nuclei emit one or more accompanying γ-rays which are electromagnetic waves. This process corresponds to the emission of electromagnetic waves by an excited atom as visible light. Similarly, after an α- or β-decay the nucleus changes from a higher energy level to the ground state.
The energy of the emitted rays is discrete (´γ-lines`). The energies of the γ-radiation range from x-ray energies up to several MeV.

Nuclear fission

Heavy nuclei may also break spontaneously into two parts which are bigger than the α-package. This process is accompanied by the emission of 2-3 neutrons. The resulting excess energy yield of the conversion is about 200 MeV. The artificially induced fission of the isotope ^{235}U by neutron bombardment produces for example the nuclei ^{137}Cs and ^{98}Rb (fission products). This is the basic process of the energy production in nuclear fission bombs and in nuclear power reactors. The fission products are radioactive.

2.3 The law of radioactive decay

The precise moment of decay of an individual unstable nucleus is not predictable. It is, however, possible to predict the average number of decays per unit of time for a large number of identical nuclei. The larger the number of nuclei and the shorter their half-life the more decays per unit of time will occur.

For a large number of identical unstable nuclei the following observations are made:

The number of decaying nuclei of a radioactive substance per second (dN/dt) is proportional to the number of remaining intact nuclei N:

$$-dN/dt = \lambda\, N(t)$$

The integration of this equation leads to the law of decay for radioactive elements. The number of nuclei of a radioactive substance reduces exponentially with time:

$$\boldsymbol{N(t) = N_0 \exp(-\lambda \cdot t)}$$

where N_0 is the initial number of nuclei, and λ is called the decay-constant.

The decay-constant λ is a characteristic quantity of the nucleus. The following relations are valid because of the exponential decay:

The half-life $T_{1/2}$ denotes the time it takes until 50% of the initial nuclei are disintegrated. The half-life is inversely proportional to the decay-constant:

$$T_{1/2} = \ln 2/\lambda = 0.693/\lambda$$

The average life time τ of an unstable nucleus is equivalent to the time until the number of intact nuclei is reduced to 1/e of the initial number. These quantities are shown in Fig.1.

The ´activity` A of a radioactive sample denotes the amount of decays per unit of time which occur in the sample. It equals the quantity dN/dt introduced above:

$A = -dN/dt = \lambda\, N(t)$ measured in Becquerel (Bq) $1\ \text{Bq} = 1\ \text{s}^{-1}$ (1 decay per second)

It follows from this equation that the **activity** of a specific substance is a measure for the **amount** of the substance because λ of the substance is known. The activity of a homogenous radioactive substance is also given by an exponential dependency:

$A(t) = A0 \exp(-\lambda \cdot t)$

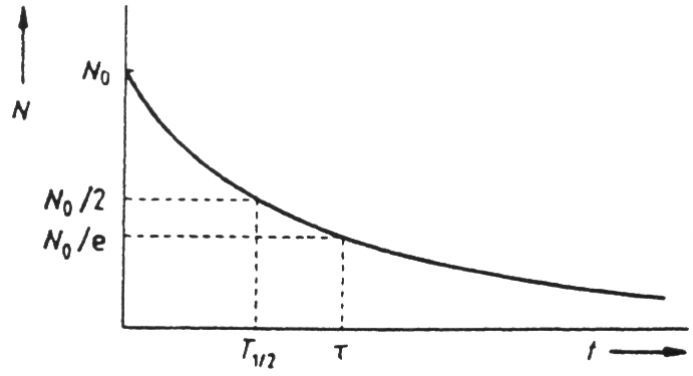

Fig.1: The course of the radioactive decay

From the equation between activity A and the number of nuclei *N*(t) we can derive the following dependency between mass m of a radioactive substance m and activity:

$$m = N(t)\, m_a = A/\lambda\, m_a$$

where m_a is the atomic weight in kg.

The relation A/m is called the specific activity. Data for uranium isotopes and plutonium-239 are given in table 1.

Table 1: Activity of 1 mg of specified substances

1 mg U-238	1 mg U-236	1 mg U-235	1 mg U-234	1 mg Pu-239
12.4 Bq	2,400 Bq	80 Bq	231,000 Bq	2,300,000 Bq

2.4 Natural and man-made radioactivity

The earth´s crust and the atmosphere contain several elements with unstable, i.e. radioactive, isotopes. The most common isotope of the element uranium is ^{238}U, an α-emitter. The decay products of this nucleus are also unstable. They decay by emitting an α- or ß-particle and end up as a stable isotope of lead. The decay chain of ^{238}U is given in the scheme of Fig. 2 where the changes of the atomic number Z and the number of neutrons in the daughter nuclei are shown. The first descendant of ^{238}U is the isotope ^{234}Th of the element thorium which is a β-emitter. The uranium isotope ^{234}U is a further descendant of this chain.

The other natural decay chains start with Ac (Actinium), Np (Neptunium), and Th (Thorium) and also end up as stable isotopes of lead.

Tritium and radioactive isotopes of carbon (^{14}C), potassium (^{40}K), and rubidium (^{87}Rb) are present in the natural environment. ^{3}H, ^{14}C, ^{40}K are therefore also found in living organisms.

These natural radionuclides in the earth and the atmosphere as well as the cosmic radiation are the source of the natural background exposure.

Numerous man-made radionuclides are produced for applications in medicine and scientific research. The main technique of production of arificial radionuclides is neutron activation. Stable nuclei are bombarded by neutrons. The neutron is absorbed and a new isotope is created which is radioactive.

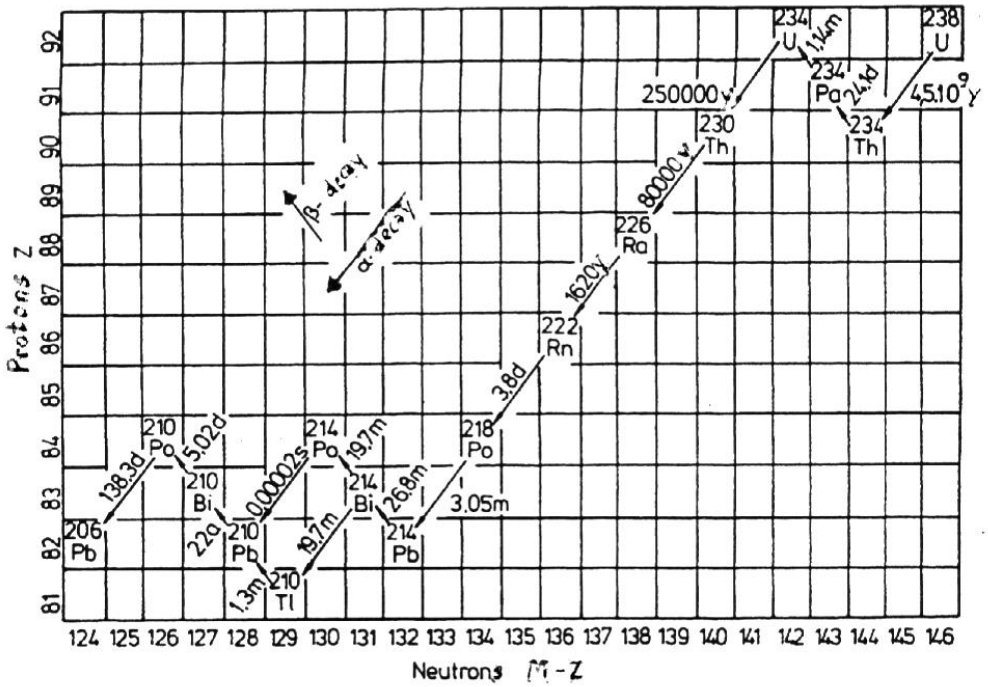

Fig.2: Natural decay chain of ^{238}U with half-lives of the descendants (d days; m minutes; s seconds; y years)

3. Interaction of radiation with matter

The main processes of interaction between α- and β-particles with matter are
a), elastic collisions in which only kinetic energy is transmitted to the atoms of the material, and b), excitation and ionisation of atoms.
In these processes, electrons of the atomic shell are either excited to higher energy levels or completely removed from the atom (ionised). The ionising energy ranges from about 4 to 14 eV. Because α- and β-rays have energies of about 1 MeV=10^6 eV they are able to produce about 10^5 ion pairs.

The range of the radioactive particle is the distance through which it passes in matter. The higher the energy of the particle, and the lower the density of the material, the greater is the range. Examples for the range in air and water (tissue) are given in Table 2.

Straight pathways, several cm long, of α-rays in air can be made visible in cloud chambers. The ions which are generated along the track generate condensation centres for water in the air of the chamber and the track is shown by tiny drops (see Fig.3).

Neutrons are uncharged and react very rarely with matter, which means that their pathways are long. Their energy is transmitted in elastic collisions with nuclei, or the neutron is absorbed by a nucleus.

Gamma rays are electromagnetic waves just as x-rays. Their absorption follows the rules known for x-rays.

Materials of high density, like metals and especially lead, are suitable for an effective absorption of ionising radiation and for protection purposes.

Table 2: Range of β- and α-particles in matter

Energy [MeV]	Range in air [cm]		Range in water or soft tissue [mm]	
	β	α	β	α
0.1	12	0.12	0.14	0.0014
0.2	33	0.18	0.40	0.0022
0.5	140	0.32	1.7	0.0039
1.0	330	0.50	4.0	0.0061
2.0	790	1.0	9.5	0.012
5.0	2100	3.2	25	0.039
10	4150	9.5	50	0.12

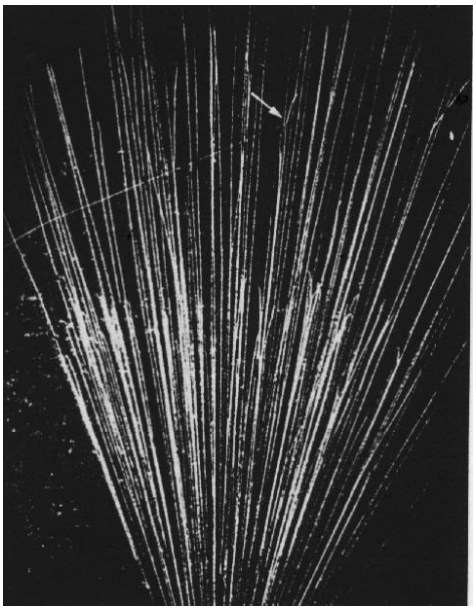

Fig.3
Tracks of α-particles emitted by a radium-sample shown in a cloud chamber. The isotope ^{226}Ra emits an α-energy of 4.8 MeV. The longer tracks originate from the descendants ^{218}Po (6.1 MeV), ^{218}At (6.8 MeV), and ^{214}Po (7.8 MeV).
The arrow shows the location of a nuclear collision. A $^{14}_{7}$N-nucleus absorbs an α-particle, the generated nucleus $^{18}_{9}$F decays immediately to $^{17}_{8}$O (short thick track) and a proton (long fine track).

4. Detection and measurement of ionising radiation

Ionising radiation includes α-, ß-, γ-, and x-rays. The generation of ions is used for detection or the excitation of atoms. Intensity and energy of the radiation can be measured.

Ion chambers, proportional and Geiger counters contain a volume of gas in which ions are produced by the entering radiation rays in an electrical condenser field. The migration of the ions in the electric field is measured (in proportional and Geiger counters) as an electric current after enhancement by collision ionisation.

Semiconductor detectors are suitable for registration of single particles and rays and for energy measurement. They are used in high resolution γ-spectrometry which identifies radionuclides by their characterictic γ-energies.

Scintillation counters are highly sensitive for γ-radiation but have a smaller energy resolution than semiconductor detectors. They consist of a crystal which emits a light flash after absorption of a γ-ray. This light is transferred and amplified by photomultipliers and generates an electrical signal which is proportional to the amount of absorbed energy.

Because radioactive particles darken **photographic emulsions**, this effect can be used for detection, mainly to show local distributions (autoradiography).

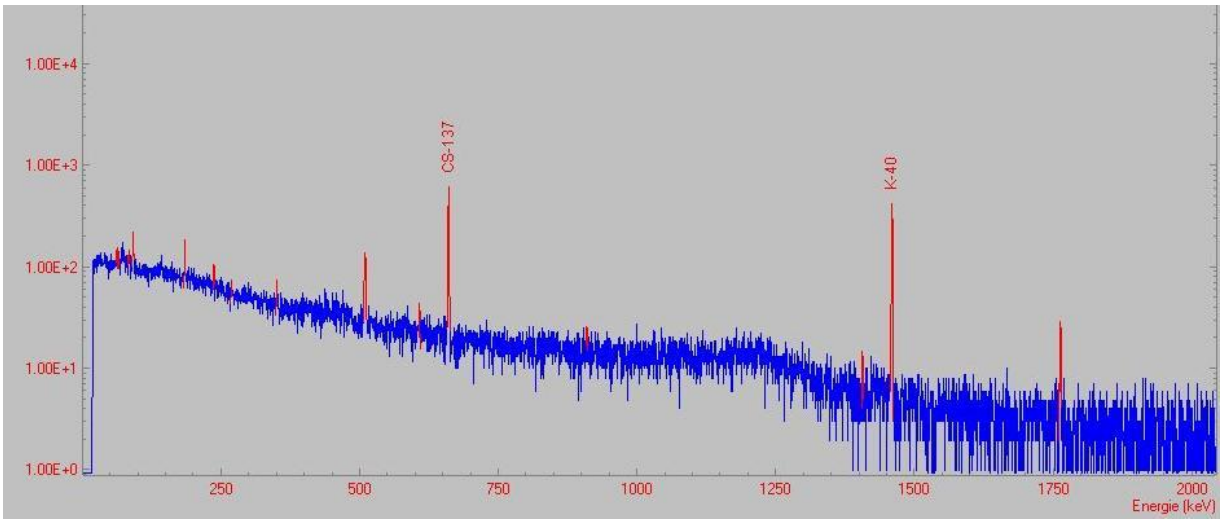

Fig.4: Typical γ-spectrum of a mushroom sample contaminated with Cs-137

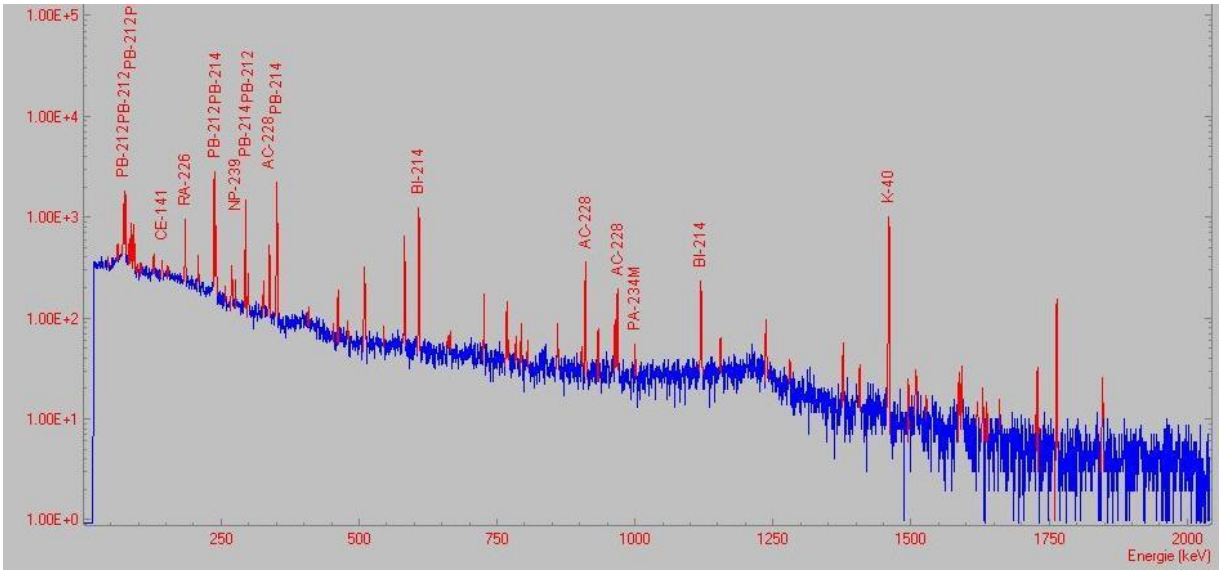

Fig.5: γ-spectrum of construction material containing natural uranium

5. Dosimetry

The dose as measure for biological effects is based on a physical quantity, the absorbed dose:

The **absorbed dose** D_T to a tissue volume is defined as the absorbed energy dW of the radiation, divided by the mass of the volume:

$$D_T = \frac{energy}{mass} = \frac{dW}{dm} \quad \text{measured in SI-units} \quad 1\,\frac{J}{kg} = 1 \text{ Gray} = 1 \text{ Gy}$$

Because the radiation effects in tissue depend not only on the absorbed dose but also on the type and energy of radiation, the dose is weighted with a factor that expresses the relative biological effectiveness. This factor is called the ´radiation weighting factor` w_R.

The **equivalent dose** to a tissue volume is defined as the product

$H_T = w_R D_T$ measured in the unit Sievert (Sv) which also has the dimension $\frac{J}{kg}$

The weighting factor for ß-, γ-, and x-rays is defined as $w_R = 1$, for α-rays it is i $w_R = 20$

The weighting factor was derived as a simple constant for protection purposes. The science of radiation biology has defined the Relative Biological Effectiveness (RBE) for comparing the different kinds of radiation of the same energy dose. The RBE depends on many factors as, e.g., energy of the radiation, energy dose and dose-rate (dose per time), and the investigated biological endpoint.

The definition of dose does not include information about the irradiated part of the body. It is used as the dose to an organ, tissue or whole body. In order to have a comparable dose quantity for different radiated parts of the body, the International Commission on Radiological Protection (ICRP) has introduced the quantity ´effective` dose. It accounts for the different sensitivity of organs and tissues to develop cancer.

The **effective dose** E is defined as the sum of all equivalent doses in all tissues and organs of the body, each weighted by a tissue weighting factor w_T:

$$E = \sum_T w_T H_T$$

Table 3 shows the tissue weighting factors assumed by the ICRP.

Table 3 Tissue weighting factors

Tissue or organ	Tissue weighting factor w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05

Because of $\sum_T w_T = 1$, the effective dose for a homogenous whole body irradiation is equal to the whole body dose equivalent.

Dose limits and exposures in rules and official regulations are given as effective dose. Table 4 contains dose values for practical survey.

Table 4: Exposure by natural and technical radiation sources

Source	Dose	Remarks
Natural background	ca. 1 mSv/y	Whole body dose
Increase cosmic radiation by 1500 m	0.3 mSv/y	Whole body dose
Radon in houses	5-50 mSv	Bronchial dose
X-ray film usually	‹ several mSv	Mean tissue dose
CT-scan	10-100 mSv	Mean tissue dose
Radiation therapy	several 10 Sv	Mean tissue dose
Dose limit for workers	20 mSv/y	Effective dose
Dose limit population	1 mSv/y	Effective dose

When estimating the accumulated dose for the case of a continuous irradiation by external or internal sources, one needs to consider the dose-rate. The dose-rate from incorporated radio-nuclides in a tissue volume V of density ρ is given by:

$$dD/dt = e_{eff}\, A/\rho V$$

where e_{eff} is the effective particle energy, i.e., the part of the energy which is absorbed in the volume after decay, and A the activity of the radionuclide in volume V.

For particles of short range in tissue, like α-particles and often also for β-radiation when the tissue volume is greater than the particle range, e_{eff} equals the total energy of the particle.

In order to calculate the dose one has to consider that the activity A decreases over time as a consequence of radioactive decay and biological elimination processes. Starting with an initial activity A_0 - i.e., after a single uptake - the total dose D(t) at time t is:

$$D(t) = (A_0 \cdot e_{eff}/\rho V) \cdot \int \exp(-\lambda_{eff} \cdot t)dt = (A_0 \cdot e_{eff}/\rho V \lambda_{eff}) \cdot (1 - \exp(-\lambda_{eff} \cdot t).$$

The decay constant λ_{eff} accounts for the physical decay and the biological elimination which can be expressed by a ´biological` decay constant λ_B if it can also be described by a single exponential.) . With $\lambda_{eff} = \lambda_{ph} + \lambda_B$, where λ_{ph} represents the physical decay constant, the **effective half-life** T_{eff} is

$$T_{eff} = \ln(2)/(\lambda_B + \lambda_{ph})$$

The quantity $\ln 2/\lambda_B = T_B$ is called the **biological half-life** of the radioactive substance.