Determining the mass related activity of radionuclides

ÄQUIVAL/MASSAKT

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Determining the mass related activity of radionuclides

The activity of a radionuclide is defined as the number of transformations (decays) per unit of time. Due to the radioactive decay, the activity decreases in the course of time. There are questions, when the activity per mass of a radionuclide is of interest. The mass of the radionuclide is calculated from the number of atoms. The activity is directly proportional to the number of atoms of the radionuclide at any time, whereby the decay constant of the radionuclide is the proportional factor. With the help of this fundamental relation, the mass m_r of a radionuclide r can be calculated from the activity A and, thus, the mass related activity $a_{\mathrm{m,r}}$ of the radionuclide. This mass related activity is usually expressed in Bq per gram of radionuclide.

Note 1:

In contrast, when defining the specific activity of a radioactive substance $a = A/m$, the quantity m denotes the mass of the entire radioactive substance including all non-radioactive constituents [1].

Note 2:

Previously, however, only the activity $a_{m,\mathrm{r}}$ related to the mass of the radionuclide r was called specific activity.

The mass related activity is calculated according to Equation (1) which is derived in Annex A.

$$a_{m,\mathrm{r}} = \frac{A_\mathrm{r}}{m_\mathrm{r}} = \frac{\ln 2 \cdot N_\mathrm{A}}{t_\mathrm{r} \cdot M_\mathrm{r}} = \frac{4{,}1742 \cdot 10^{23}}{t_\mathrm{r} \cdot M_\mathrm{r}} \tag{1}$$

Herein are:

$a_{m,\mathrm{r}}$	activity related to the mass of a radionuclide r, in Bq·g^{-1};
A_r	activity of the radionuclide r, in Bq;
m_r	mass of the radionuclide r, in g;
N_A	Avogadro constant (Loschmidt constant): 6,02214076·10^{23} mol^{-1};
t_r	half-life of the radionuclide r, in s;
M_r	mass of the radionuclide r related to the amount of substance, in g·mol^{-1} (the numerical value for M corresponds to the mass number of the radionuclide).

Table 1 lists the mass related activities for selected artificial radionuclides, Table 2 for selected natural radionuclides, as they result from Equation (1).

In Table 3, the massic concentrations for selected radionuclides are given. They correspond to an activity concentration of 1 Bq·l^{-1}, in each case.

Tab. 1: Mass related activity of selected artificial radionuclides

Radionuclide	**Half-life# t_r in s**	**Mass related activity# $a_{m,\mathrm{r}}$ in Bq·g^{-1}**
P-32	$1{,}23 \cdot 10^{6}$	$1{,}06 \cdot 10^{16}$
Cr-51	$2{,}39 \cdot 10^{6}$	$3{,}42 \cdot 10^{15}$
Mn-54	$2{,}70 \cdot 10^{7}$	$2{,}87 \cdot 10^{14}$
Co-58	$6{,}12 \cdot 10^{6}$	$1{,}18 \cdot 10^{15}$
Co-60	$1{,}66 \cdot 10^{8}$	$4{,}18 \cdot 10^{13}$
Fe-55	$8{,}67 \cdot 10^{7}$	$8{,}76 \cdot 10^{13}$
Fe-59	$3{,}84 \cdot 10^{6}$	$1{,}84 \cdot 10^{15}$
Ni-63	$3{,}11 \cdot 10^{9}$	$2{,}13 \cdot 10^{12}$
Zn-65	$2{,}11 \cdot 10^{-7}$	$3{,}05 \cdot 10^{14}$
Sr-90	$9{,}09 \cdot 10^{8}$	$5{,}10 \cdot 10^{12}$
Tc-99m	$2{,}16 \cdot 10^{4}$	$1{,}95 \cdot 10^{17}$
I-125	$5{,}13 \cdot 10^{6}$	$6{,}51 \cdot 10^{14}$
I-131	$6{,}93 \cdot 10^{5}$	$4{,}60 \cdot 10^{15}$
Cs-134	$6{,}51 \cdot 10^{7}$	$4{,}78 \cdot 10^{13}$
Cs-137	$9{,}48 \cdot 10^{8}$	$3{,}21 \cdot 10^{12}$
Tl-201	$2{,}63 \cdot 10^{5}$	$7{,}90 \cdot 10^{15}$
Pu-238	$2{,}77 \cdot 10^{9}$	$6{,}33 \cdot 10^{11}$
Pu-239	$7{,}61 \cdot 10^{11}$	$2{,}30 \cdot 10^{9}$
Pu-240	$2{,}07 \cdot 10^{11}$	$8{,}40 \cdot 10^{9}$
Pu-241	$4{,}52 \cdot 10^{8}$	$3{,}83 \cdot 10^{12}$
Am-241	$1{,}37 \cdot 10^{10}$	$1{,}27 \cdot 10^{11}$
Cm-242	$1{,}41 \cdot 10^{7}$	$1{,}23 \cdot 10^{14}$
Cm-244	$5{,}72 \cdot 10^{8}$	$2{,}99 \cdot 10^{12}$

Source: Laboratoire National Henri Becquerel (see General Chapter „KERNDATEN“ of this Procedures Manual)

Tab. 2: Mass related activity of selected natural radionuclides

Radionuclide	**Half-life# t_r in s**	**Mass related activity# $a_{m,r}$ in Bq·g^{-1}**
U-238	$1{,}41 \cdot 10^{17}$	$1{,}24 \cdot 10^{4}$
U-235	$2{,}22 \cdot 10^{16}$	$8{,}00 \cdot 10^{4}$
U-234	$7{,}48 \cdot 10^{12}$	$2{,}30 \cdot 10^{8}$
Th-232	$4{,}42 \cdot 10^{17}$	$4{,}07 \cdot 10^{3}$
Th-230	$2{,}38 \cdot 10^{12}$	$7{,}63 \cdot 10^{8}$
Th-228	$6{,}04 \cdot 10^{7}$	$3{,}03 \cdot 10^{13}$
Ra-228	$1{,}82 \cdot 10^{8}$	$1{,}01 \cdot 10^{10}$
Ra-226	$5{,}05 \cdot 10^{10}$	$3{,}66 \cdot 10^{10}$
Ra-224	$3{,}14 \cdot 10^{5}$	$5{,}94 \cdot 10^{15}$
Po-210	$1{,}20 \cdot 10^{7}$	$1{,}66 \cdot 10^{14}$
Pb-210	$7{,}02 \cdot 10^{8}$	$2{,}83 \cdot 10^{12}$
U_{nat} [1)]		$2{,}53 \cdot 10^{4}$
Th_{nat} [2)]		$8{,}14 \cdot 10^{3}$

\# Source: Laboratoire National Henri Becquerel (see General Chapter „KERNDATEN" of this Procedures Manual)

1) Natural uranium U_{nat} is composed of the uranium isotopes U-238, U-235 and U-234 which are in a defined ratio to each other. Therefore, the specific activity of U_{nat} is determined as follows:

$$a_{m,\mathrm{U_{nat}}} = 0{,}992745\ a_{m,\mathrm{U-238}} + 0{,}0072\ a_{m,\mathrm{U-235}} + 0{,}000055\ a_{m,\mathrm{U-234}}$$

2) The term natural thorium Th_{nat} used here only refers to the thorium isotopes Th-232 and Th-228 which occur in the thorium decay chain with a defined ratio [2]. The specific activity of Th_{nat} is calculated for an untreated sample that is more than 60 years old via the sum of each specific activity weighted with the relative mass contributions:

$$a_{m,\mathrm{Th_{nat}}} = a_{m,\mathrm{Th-232}} + \left(\frac{a_{m,\mathrm{Th-232}}}{a_{m,\mathrm{Th-228}}}\right) \cdot a_{m,\mathrm{Th-228}} = 2 \cdot a_{m,\mathrm{Th-232}}$$

The weighting factor in brackets is calculated from the inverse values of the specific activities $(a_{m,\text{Th-228}})^{-1}/(a_{m,\text{Th-232}})^{-1}$.

Note:

In former versions of this General Chapter, the same mass fractions were supposed to both thorium isotopes which led to a specific activity of $1{,}52 \cdot 10^{13}$ Bq·g^{-1} for Th_{nat}, although Th-228 practically doesn't contribute to the mass due to its relative short half time compared to Th-232.

Tab. 3: Mass concentrations of selected radionuclides at an activity concentration of 1 Bq·l^{-1}

Radionuclide	**Mass concentration in µg·l^{-1}**
Co-60	$2{,}4 \cdot 10^{-8}$
Ra-226	$2{,}7 \cdot 10^{-5}$
Th-232	246
U-235	13
U-238	81
Pu-240	$1{,}2 \cdot 10^{-4}$

Note:
In practice, due to their relatively high mass concentrations, the detection of Th-232, U-235 and U-238 compared to other radionuclides, e. g. in water, can be achieved more sensitively by means of inductively coupled plasma mass spectrometry (ICP-MS) than by means of alpha spectrometry, which is commonly used in radioactivity measurement technology.

References

[1] DIN 6814-4:2006 *Begriffe in der radiologischen Technik – Teil 4: Radioaktivität*.

[2] Walz, K. F., Schötzig, U.: *Natürlich radioaktive Substanzen als Aktivitätsnormale*. PTB-Ra-23. Braunschweig: Physikalisch-Technische Bundesanstalt, 1989. ISBN 3-88314-966-7

Annex A
Derivation of the mass related activity

This Annex shows the procedure for calculating the mass related activity of a radionuclide.

A.1 The radioactive decay

The radioactive decay is defined according to Equation (A1)

$$-\frac{\mathrm{d}N}{\mathrm{d}t} = \lambda_{\mathrm{r}} \cdot N \tag{A1}$$

with

$$N = N_0 \cdot \mathrm{e}^{-\lambda_{\mathrm{r}} \cdot t} \tag{A2}$$

Herein are:

N number of atoms of the radionuclide r;

N_0 number of atoms of the radionuclide r at time $t = t_0$;

λ_{r} decay constant of the radionuclide r, in s^{-1};

t duration, in s.

A.2 Activity of a radionuclide

The activity of a radionuclide A_{r} is calculated according the Equations (A3) and (A4):

$$A_{\mathrm{r}} = \lambda_{\mathrm{r}} \cdot N \tag{A3}$$

with

$$\lambda_{\mathrm{r}} = \frac{\ln 2}{t_{\mathrm{r}}} \tag{A4}$$

Herein are:

A_{r} activity of the radionuclide r, in Bq;

t_{r} half-life of the radionuclide r, in s.

A.3 Mass related to the amount of substance

The mass related to the amount of substance M is defined in Equation (A5) as:

$$M = \frac{m}{n} \tag{A5}$$

Herein are:

M mass related to the amount of substance, in g·mol^{-1};

m mass of the substance, in g;

n amount of substance, in mol.

The mass m of a system of N atoms is calculated according Equation (A6):

$$m = N \cdot m_\mathrm{a} \tag{A6}$$

where m_a is the mass of an atom or a molecule in g.

Equation (A7) follows from the Equations (A5) and (A6):

$$M = \frac{m}{n} = \frac{N}{n} \cdot m_\mathrm{a} = N_\mathrm{A} \cdot m_\mathrm{a} \tag{A7}$$

with the Avogadro constant $N_\mathrm{A} = N/n$, i. e. N_A is equal to the number N of the atoms or molecules in one mole of the amount of substance.

Thus, Equation (A8) is obtained to:

$$m_\mathrm{a} = \frac{M}{N_\mathrm{A}} \tag{A8}$$

Note:

m_a can be expressed in the unit u (atomic mass unit). That means that the numerical value of M in g·mol^{-1} is equal to the numerical value of the particle mass in u (mass number of the isotope).

A.4 Mass related activity of a radionuclide

The activity of a radionuclide with the mass m_r is calculated according to Equation (A9) derived from the Equations (A3), (A6) and (A8):

$$A_\mathrm{r} = \lambda_\mathrm{r} \cdot \frac{m_\mathrm{r} \cdot N_\mathrm{A}}{M} \tag{A9}$$

For the mass m_r of one gram, i. e. for the mass related activity $a_{m,\mathrm{r}}$ of a radionuclide, Equation (A10) will be used taking Equation (A4) into account:

$$a_{m,\mathrm{r}} = \frac{4{,}1742 \cdot 10^{23}}{t_\mathrm{r} \cdot M_\mathrm{r}} \tag{A10}$$