

# EVALUATION OF RADIOACTIVE EQUILIBRIUM STATES OF RADIONUCLIDES IN THE URANIUM DECAY CHAIN

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## Abstract

This article investigates the factors that cause disturbances in radioactive equilibrium within the uranium decay chain. Numerous nuclear-physical factors influence the violation of radioactive equilibrium, the most significant of which is the heat energy released by the multiple radioisotopes formed from the parent ore. Additionally, relationships among atomic mass number, half-life, decay energy, radioactive equilibrium coefficient and nuclear decay constants of radionuclides in the uranium decay chain are analyzed.

**Keywords:** Uranium radionuclide chain, radioactive equilibrium, half-life, radioactive equilibrium coefficient, nuclear decay constants.

## Introduction

Currently, with the increasing global demand for electricity, an energy crisis is emerging. Therefore, various methods are being developed to solve this problem. One of the most widely used approaches for generating electricity is the use of atomic energy. The solution to utilizing atomic energy lies in the construction of nuclear power plants and the processing of uranium or other naturally occurring chain metals. Uranium serves as the primary fuel for nuclear energy worldwide. This is because the energy released from the fission of 1 kg of uranium-235 ( $^{235}\text{U}$ ) is equivalent to the energy produced by burning 2800 tons of coal – a fact proven both theoretically and experimentally. Natural uranium consists of  $^{238}\text{U}$  - 99.28%,  $^{235}\text{U}$  - 0.72%, and  $^{234}\text{U}$  - 0.0054%. Their specific activities are, respectively,  $1,25 \cdot 10^4$  Bq/g,  $4,9 \cdot 10^4$  Bq/g,  $2,3 \cdot 10^8$  Bq/g [1-3].

Recent research results have shown that the radionuclides in natural uranium -  $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{234}\text{U}$  are not always in perfect radioactive equilibrium. As is known, the activity of a radioactive substance can be calculated using the following equation [4]:

$$A = \lambda N \quad (1)$$

Where,  $\lambda$ - is the decay constant,  $N$ - is the number of decaying atoms. If we consider (1) – formula then substituting these into the first equation, the activity formula becomes:

$$\lambda = \frac{\ln 2}{T_{1/2}} \quad (2)$$

where  $N$ - we write the formula for the number of atoms,

$$N = \frac{m}{M} N_A \quad (3)$$



And quoting the (2)- and (3)- expressions to the (1)-formula gives rise to the activity formula of radionuclides:

$$A = \frac{\ln 2}{T_{\frac{1}{2}}} \cdot \frac{m}{M} N_A \quad (4)$$

where,  $m$ - is the mass of the given amount of radionuclide,  $M$  - is the molar mass of the radionuclide whose activity is being determined, and  $T_{\frac{1}{2}}$  is the half-life of the radionuclide.

Using formula 4, we can calculate the specific activities of the radionuclides of the uranium decay chain. We place the obtained values in the table below [5]:

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**Nuclear-physical characteristics of radionuclides of the uranium decay chain**

№	Radionuclides	T1/2 (half-life)	Specific activity of a radionuclide (Bq/g)	The amount of mass in equilibrium (g)
1	U-238	4,468·10 <sup>9</sup> y.	1,24·10 <sup>4</sup>	1.000
2	Th-234	24,10 d.	8,21·10 <sup>13</sup>	3.58·10 <sup>-11</sup>
3	Pa-234m	1,17 min	2,54·10 <sup>19</sup>	4,9·10 <sup>-16</sup>
4	U-234	2,45·10 <sup>5</sup> y.	2,30·10 <sup>8</sup>	53,41·10 <sup>-6</sup>
5	Th-230	7,54·10 <sup>4</sup> y.	8,21·10 <sup>7</sup>	1,69·10 <sup>-5</sup>
6	Ra-226	1600 y.	3,7·10 <sup>10</sup>	0,34·10 <sup>-6</sup>
7	Rn-222	3,83 d.	5.73·10 <sup>15</sup>	7,40·10 <sup>-12</sup>
8	Po-218	3.097 min.	8,43·10 <sup>18</sup>	4·10 <sup>-15</sup>
9	Pb-214	27.06 min.	9,60·10 <sup>17</sup>	3.59·10 <sup>-14</sup>
10	Bi-214	19.9 min.	1,29·10 <sup>18</sup>	2.66·10 <sup>-14</sup>
11	Po-214	163.5·10 <sup>-6</sup> s	3,53·10 <sup>23</sup>	3.76·10 <sup>-23</sup>
12	Pb-210	22.2 y.	2,30·10 <sup>12</sup>	4.99·10 <sup>-9</sup>
13	Bi-210	5.012 d.	3,82·10 <sup>14</sup>	3.09·10 <sup>-12</sup>
14	Po-210	138.376 d.	1.665·10 <sup>15</sup>	8.49·10 <sup>-11</sup>
15	Pb-206	stable	stable	stable

Column 1 of the table lists the designation of radionuclides and atomic mass numbers. Column 2 lists the half-decay periods of decay chain radionuclides. Column 3 lists the specific activity of radionuclides. Column 4 of the table lists the mass quantities in radioactive equilibrium with radionuclide <sup>238</sup>U of radionuclides calculated using the formula below. To determine the radioactive equilibrium between radionuclides in the uranium decay chain, we use the following formula::

$$K_{re} = \frac{A_{U-234}}{A_{U-238}}$$

If  $A_{U-238}$  va  $A_{U-234}$  are in equilibrium,  $K=1$ . It follows that,  $m_{U-238} = 1t$  uranium ore must contain  $m_{U-234} = 53.41g$ . From the results obtained, it follows that the radionuclide <sup>234</sup>U must be at a concentration of 53,41 g/t in equilibrium with <sup>238</sup>U. These radioactive equilibrium disturbances between radionuclides are mainly observed in groundwater.

The radioactive equilibrium between the <sup>234</sup>U/<sup>238</sup>U radionuclides involved in the uranium decay chain is well maintained in solids ( $k<1$ ). If a solid uranium-containing substance is dissolved in water, especially in groundwater and subsurface waters,  $k>1$  is observed, resulting in an increase in the amount of <sup>234</sup>U.



**Conditions resulting from imbalance:**

1. High concentrations of U-234 in groundwater and carbonaceous layers
2. Over time, radioactive balance is restored in sedimentary rocks, which allows geochronological assessments to be conducted.
3. Mining and leaching processes in uranium ores also disrupt the balance.

The radioactive imbalance between  $^{234}\text{U}$  and  $^{238}\text{U}$  is a natural geochemical process caused by the radioactive decay chain and the energy released by it.

This phenomenon is important in hydrogeological studies, in the assessment of uranium ore reserves and the age of uranium samples. At the same time, it is important in assessing the migration of radionuclides by studying the radioactive imbalance between radionuclides in the uranium decay chain and in assessing the radioecological state of the area according to the radioactive equilibrium value.

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