Factors increase in background radiation at uranium production facilities

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Abstract. This article presents the results of a study of the relationship between the increase in the radiation background in uranium production facilities and the coefficient of radioactive equilibrium between the radionuclides of the uranium decay chain. A theoretical calculation formula for the mixing of daughter radionuclides is given and, based on this formula; the mixing distance between daughter radionuclides in the uranium decay chain is calculated. It has been established that the reason for the increase in the radiation background in uranium production facilities is the violation of the radioactive equilibrium between radionuclides.

1 Introduction

In the objects of uranium production, the values of the radiation background are higher than in natural objects. The reason for this is the presence of radioactive elements in these objects.

It is known from the literature data [1-2] that natural uranium consists of three natural radionuclides - ^{238}U, ^{235}U and ^{234}U. Their quantitative ratio is ^{238}U-99.27%, ^{235}U-0.72%, ^{234}U-0.0053%, and the specific activity of these radionuclides in mutual radioactive equilibrium is – $1.23 \bullet 10^4$ Bq/g, $4.9 \bullet 10^4$ Bq/g and $2.3 \bullet 10^8$ Bq/g accordingly [3-6]. And research conducted in recent years shows [7-9] that there are violations of the radioactive equilibrium between these radionuclides in the uranium decay chain, negatively affecting the quality of finished uranium products and creating an additional gamma background of ionizing radiation. There are many nuclear-physical factors that are the causes of violations of the radioactive equilibrium between these radionuclides, such as the age of minerals, migration coefficients of radionuclides, geochemical factors, recoil energies, geotechnology conditions of leaching, etc. [10-16].

The purpose of this study is to study the relationship of the increase in the radiation background in uranium production facilities with the coefficient of radioactive equilibrium between the radionuclides of the uranium decay chain.

To achieve this goal, a number of urgent tasks of nuclear physics, radioecology and analytical chemistry have been solved to study the relationship between the increase in the radiation background in uranium production facilities and the coefficient of radioactive equilibrium between the radionuclides of the uranium decay chain.

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2 Materials and methods

An analysis of the literature of foreign and domestic researchers shows that the factors of violation of the radioactive equilibrium between daughter radionuclides in the uranium decay chain are poorly studied. In the literature, only some reasons for the violation of the coefficient of radioactive equilibrium between the radionuclides of the uranium decay chain are given. Having studied the nuclear-physical properties of chemical elements in a more diverse way, having investigated the mechanism of recoil energy, the properties of daughter radionuclides and so on, factors can determine the main one of them. Radionuclides in a closed homogeneous system are in a state of radioactive equilibrium with each other. Over time, nuclear transformations on the basis of α – and β - decay occur in the nuclei of radioactive elements. The mother core ^{238}U stable ^{206}Pb is converted to the base of 8 α – decay and 6 β – decay.

It is known that the specific activity of each radionuclide has different values, that is, the activity of 1 g of ^{238}U is 12.500 Bq, and the activity of 1 g of ^{226}Ra is 3.70 10^{10} Bq, etc. [13-14].

In addition to the above, there is information in foreign and domestic literature that violations of the radioactive equilibrium between radionuclides may be associated with the age of minerals and may cause an increase in the radiation background [15, 16].

As is known, during α-decay, the daughter radionuclides of the uranium chain receive recoil energies.This reaction can be written as follows:

$$M_\alpha E_\alpha = \mathrm{M}_{return}\mathrm{E}_{return} \quad (1)$$

where M_α and E_α are the mass and energy of the alpha particle, respectively, and M_{Return} and E_{Return} are the mass and energy of the radionuclide that has undergone decay. In order for alpha decay to be energetically possible, the following inequality must be satisfied:

$$M(A,Z) > M(A-4, Z-2) + M(^4_2He) \quad (2)$$

that is, the mass (energy) of the mother nucleus must be greater than the sum of the masses (energies) of the formed nucleus and the α-particle. The excess energy of the parent nucleus during α-decay is released in the form of kinetic energies of particles:

$$E_{full} = [\mathrm{M(A,Z)} - \mathrm{M(A-4,Z-2)} - \mathrm{M}(^4_2He)]c^2 = \mathrm{E}_\alpha + \mathrm{E}_{return.nuc} \quad (3)$$

here is the E_{Return}. is the kinetic energy of the pulsed nucleus, E_α is the binding energy of the α-particle.

If the decaying nucleus is in a relatively stable state, then their pulses will be

$$P_\alpha = P_{\mathrm{Return}.nuc.} \quad (4)$$

Then the kinetic energy of the formed daughter nucleus from the momentum equation (4) is expressed as follows:

$$\mathrm{E}_{\mathrm{Return}.nuc} = \frac{\mathrm{E}_\alpha M_\alpha}{M_{\mathrm{Return}.nuc}} \quad (5)$$

in accordance with (3)

$$E_{full} = \left(1 + \frac{M_\alpha}{\mathrm{M}_{return.nuc}}\right)\mathrm{E}_\alpha \quad (6)$$

$$\mathrm{E}_\alpha = \left(\frac{M_{return.nuc.}}{M_\alpha + M_{return.nuc.}}\right)E_{full} \quad (7)$$

It is here: E - the pulsed mass of the nucleus.

In the alpha decay of a radionuclide, the energy of the alpha particle released from the mother nucleus causes a change in its position. Because an alpha particle is one of the heaviest elementary particles having an electric charge equal to 2, and an atomic mass number equal to 4. Since alpha particles have the largest mass of particles in nature, when they fly out of the nucleus, they force daughter radionuclides to move a certain distance from their original location. To find the distance to which the daughter radionuclide has moved due to alpha decay, the following formula is used [6].

$$\delta = \frac{(M_\alpha + M_U)*((M_\alpha * E_k^U * N_A)*(Z_U^{\frac{2}{3}} + Z_\alpha^{\frac{2}{3}})}{(M_U * Z_U * Z_\alpha * \rho)} \quad (8)$$

Here $M_\alpha and\ M_U$ - are the mass of the alpha particle and the uranium nucleus (the parent nucleus), E_k^U - is the reaction energy of the radionuclide, Z_u and Z_α - are the number of charge in the uranium nucleus and the number of charge of the alpha particle, respectively, p is the density of the nucleus.

3 Results

Using formula (8), it is calculated how far radionuclides have shifted as a result of the recoil energy of alpha decay. The nuclear-physical characteristics of the alpha decay of radionuclides in the uranium decay chain and their calculated displacement distances are given in Table 1.

Table 1. Nuclear-physical characteristics of alpha decay of radionuclides in the uranium decay chain and their calculated displacement distance.

Radionuclide	E_α - alpha decay energy, MeV	E_{OT} - recoil energy, MeV	Z	δ - the calculated distance is the displacement of the radionuclide. (nm)
1	2	3	4	5
^{238}U	4.196	0.0700	92	17.10
^{234}U	4.777	0.0816	92	19.81
^{230}Th	4.688	0.0813	90	19.99
^{226}Ra	4.785	0.0846	88	21.02
^{222}Rn	5.490	0.0989	86	24.81
^{218}Po	6.002	0.1100	84	27.87
^{214}Po	7.692	0.1438	84	36.44

As can be seen from the results given in Table 1 the calculated displacement distance of the daughter radionuclides in column 5 is related to the radius and atomic mass number of the radionuclide. That is, the greater the atomic mass number of the radionuclide, the smaller its displacement distance, namely for - ^{238}U – 17.1 nm, ^{234}U – 19.81 nm, ^{230}Th - 19.99 nm, ^{214}Po – 36.44 nm. etc.

Knowing about the relationship of the atomic mass number of a radionuclide with its displacement distance, it is possible to find out how far the radionuclide is displaced within 1 second, since the half-life - $T_{1/2}$ of each radionuclide has its constant value.

Table 2. Nuclear-physical constants of radionuclides and their interrelated characteristics.

Radionuclide	Weight in 1 g	Half life, $T_{1/2}$	Specific activity of a radionuclide	Number of particles used in 1 s, pcs	PH displacement distance in one act of decay, δ (nm)	Offset distance PH behind 1 s, mkm
1	2	3	4	5	6	7
^{238}U	1.00	$4.5 \cdot 10^9$ years	12500	12500	17.10	213.75
^{234}U	$53.41 \cdot 10^{-6}$	$2.5 \cdot 10^5$ years	$230.22 \cdot 10^6$	12300	19.81	243.66

^{230}Th	$173\cdot10^{-10}$	$8.0\cdot10^{4}$ years	$7.2\cdot10^{7}$	12460	19.99	249.08
^{226}Ra	$0.34\cdot10^{-9}$	1602 years	$3.7\cdot10^{10}$	12580	21.02	264.43
^{222}Rn	$0.22\cdot10^{-14}$	3.8 days	$5.7\cdot10^{15}$	12540	24.81	311.12
^{218}Po	$12\cdot10^{-16}$	3.1 min	10^{19}	12000	27.87	334.44
^{214}Po	10^{-20}	$1.6\cdot10^{-4}$ s	$1.22\cdot10^{25}$	12750	36.44	464.61

From the Table 2. it can be seen that in columns 1-2, 3 and 4 of the Table the nuclear-physical constants of radionuclides are given, and columns 5, 6 and 7 show the number of particles emitted in 1 s (5), the distance of their displacement in one act of decay (6) and the distance of displacement in 1 sec (7). As can be seen from the results given in column (5) tab. 2. The number of particles emitted in 1 s for radionuclides - ^{238}U is 8900 pcs., ^{234}U is 8700 pcs., ^{230}Th is 8920 pcs., ^{226}Ra is 8918 pcs., ^{222}Rn is 8970 pcs., ^{218}Po is 8870 pcs., ^{214}Po is 8750 pcs. The number of particles emitted in 1 s for radionuclides varies from 8700 pcs. to 9100 pcs. and in the average 8860 pcs. This fact shows that, at radioactive equilibrium, the number of particles emitted during the same time is the same numbers.

Based on the law of conservation of body momentum, the greater the mass of the radionuclide, the smaller its displacement distance obtained during alpha decay, that is, the displacement distance of radionuclides in 1 s. - ^{238}U is - 152.2 microns., ^{234}U is - 172.3 microns., ^{230}Th is - 178.4 microns, ^{226}Ra is - 187.4 microns., ^{222}Rn is - 225.8 microns., ^{218}Po is - 247.2 microns., ^{214}Po is - 318.9 microns. This fact, in turn, confirms that the fundamental law of physics - the law of conservation of momentum is fulfilled even with radioactive decay.

In addition to the above studies, the coefficients of radioactive equilibrium between radionuclides ^{226}Ra/^{238}U and the values of the effective dose rate in uranium production facilities Table 3.

Table 3. Results on the determination of the coefficient of radioactive equilibrium between radionuclides ^{226}Ra/^{238}U and the values of the effective dose rate in uranium production facilities.

Sample number	Specific activity - ^{226}Ra, (Bq/g)	Specific activity - ^{238}U, (Bq/g)	The coefficient of radioactive equilibrium – $K_{rad.eq}$	Effective dose rate - EDR, (μZv/hour)
Calculation	$3.70\cdot10^{10}$	12500	1.0	0.15-0.20
1	$4.17\cdot10^{10}$	12000	1.16	0.18-0.24
2	$5.32\cdot10^{10}$	14500	1.22	0.20-0.28
3	$6.12\cdot10^{10}$	15000	1.36	0.23-0.31
4	$7.16\cdot10^{10}$	16500	1.45	0.25-0.34
5	$7.74\cdot10^{10}$	16000	1.61	0.27-0.42
6	$8.13\cdot10^{10}$	15000	1.81	0.32-0.58
7	$8.71\cdot10^{10}$	13400	2.16	0.38-0.67
8	$8.98\cdot10^{10}$	12800	2.34	0.45-0.82

As can be seen from the Table 3. The results obtained with an increase in the coefficient of radioactive equilibrium - $K_{rad.eq}$ in the range from 1.16 to 2.34 between radionuclides ^{226}Ra/^{238}U and increase the values of the effective dose rate in the range from (min=0.18; max= 0.24) to (min=0.45; max=0.82).

Thus, it has been studied that during alpha decay, the daughter radionuclide receives recoil energies and is displaced by a certain distance from the parent nucleus. Based on these facts, it can be concluded that the daughter radionuclides of the uranium decay chain, formed during alpha decays, are displaced by a certain distance from the mother nucleus due to the recoil energy and there is a violation of the radioactive equilibrium between the radionuclides in this object.

4 Conclusion

As a result of theoretical calculations and existing nuclear-physical constants of the uranium decay chain, the number of alpha particles emitted in 1 second, their displacement distance in one act of decay and displacement distance in 1 second are found. From the results obtained, it became clear that the number of particles emitted in 1 s for radionuclides of the uranium decay chain varies from 1200 pcs to 12750 pcs. and in the average 12500 pcs. The fact has been established that at radioactive equilibrium in objects, the number of particles emitted during the same time is equal to the same numbers. And based on the law of conservation of momentum of the body, the greater the mass of the radionuclide, the smaller its displacement distance. The data confirms that the fundamental law of physics, the law of conservation of momentum, is fulfilled even with radioactive decay.

Based on the graphical relationship with the atomic mass number of the radionuclide with its displacement distance, it is established that the radionuclides of the uranium decay chain - ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{222}Rn, ^{218}Po and ^{214}Po are shifted by different distances in one act of decay, with different amounts of alpha particles, these radionuclides are shifted by different distances.

In addition to the above studies, the interrelationships of an increase in the radiation background with the coefficients of radioactive equilibrium between radionuclides $^{226}Ra/^{238}U$ were studied, in which, with a change in the coefficient of radioactive equilibrium - $K_{rad.eq}$ in the range from 1.16 to 2.34, the effective dose rate values vary from (min=0.18; max=0.24) till (min=0.45; max=0.82).

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