ATOMIC PHYSICS

Practical 11

STUDY OF DECOMPOSITION OF RADIOACTIVE RADON

1. INTRODUCTION

I. People usually receive radiation mainly from natural sources. About one-third of the natural radiation is related with cosmic rays. The main radioactive isotopes, found in the rocks of the Earth, are potassium-40, rubidium-87, as well as members of two radioactive families originating from uranium – 238 and thorium – 232, long-lived isotopes formed at the time of the birth of the Earth. The radon (Rn) is the most significant from all natural sources of radiation. It is an invisible heavy (7.5 times heavier than air) gas that has no taste or smell. Radon, along with its decay products, is responsible for approximately 3/5 of the annual equivalent radiation dose received by people from terrestrial sources of radiation.

In nature, radon exists in two forms: in the form of Rn – 222, an element of the radioactive series formed by the decay products U^{238}:

$$_{92}\mathbf{U}^{238} \xrightarrow{\alpha} {}_{90}\mathbf{Th}^{234} \xrightarrow{\beta} {}_{91}\mathbf{Pa}^{234} \xrightarrow{\alpha} {}_{92}\mathbf{U}^{234} \xrightarrow{\alpha} {}_{90}\mathbf{Th}^{230} \xrightarrow{\alpha} {}_{88}\mathbf{Ra}^{226}\mathbf{(Ra)} \xrightarrow{\alpha}$$

$4{,}46\cdot10^{9}$ years 24,1 day 1,17 min $2{,}45\cdot10^{5}$ years $7{,}52\cdot10^{4}$ years 1620 years

$$\xrightarrow{} {}_{86}\mathbf{Rn}^{222}\mathbf{(Rn)} \xrightarrow{\alpha} {}_{84}\mathbf{Po}^{218}\mathbf{(RaA)} \xrightarrow{\alpha} {}_{82}\mathbf{Pb}^{214}\mathbf{(RaB)} \xrightarrow{\beta} {}_{83}\mathbf{Bi}^{214}\mathbf{(RaC)} \xrightarrow{\beta}$$

3,82 day 3,11 min 26,8 min 19,9 min

$$\xrightarrow{} {}_{84}\mathbf{Po}^{214}\mathbf{(RaC')} \xrightarrow{\alpha} {}_{82}\mathbf{Pb}^{210}\mathbf{(RaD)} \xrightarrow{\beta} {}_{83}\mathbf{Bi}^{210}\mathbf{(RaE)} \xrightarrow{\beta} {}_{84}\mathbf{Po}^{210}\mathbf{(RaF)} \xrightarrow{\alpha}$$

$\downarrow 1{,}63\cdot10^{-4}$ s 21,8 years 5,013 dayт 138,37 day

$$\xrightarrow{\alpha} {}_{82}\mathbf{Pb}^{206}\ \textit{(stable)}$$

in the form of Rn^{220}, an element of the radioactive series of Th^{232}:

$$_{90}\mathbf{Th}^{232} \xrightarrow{\alpha} {}_{88}\mathbf{Ra}^{228}\mathbf{(ThI)} \xrightarrow{\beta} {}_{89}\mathbf{As}^{228}\mathbf{(ThII)} \xrightarrow{\beta} {}_{90}\mathbf{Th}^{228} \xrightarrow{\alpha} {}_{88}\mathbf{Ra}^{224} \xrightarrow{\alpha}$$

$1{,}4\cdot10^{10}$ years 5,75 years 6,1 hour 1,913 years 3,66 day

$$\xrightarrow{} {}_{86}\mathbf{Rn}^{220}\mathbf{(Th)} \xrightarrow{\alpha} {}_{84}\mathbf{Po}^{216}\mathbf{(ThA)} \xrightarrow{\alpha} {}_{82}\mathbf{Pb}^{212}\mathbf{(ThB)} \xrightarrow{\beta} {}_{83}\mathbf{Bi}^{212}\mathbf{(ThC)} \xrightarrow{\alpha}$$

55,61 s 0,145 s 10,64 hour 60,55 min

$$\xrightarrow{} {}_{81}\mathbf{Th}^{208}\mathbf{(ThC)} \xrightarrow{\beta} {}_{82}\mathbf{Pb}^{208}\ \textit{(stable)}$$

3,055 min

According to the contribution to the total radiation, Rn_{222} is about 20 times more potent than Rn_{220} (Toron), however both isotopes are usually considered together and are called radon. Moreover, most of the radiation comes from the decay products of the radon rather than the radon itself. Radon is an element universally released from the earth. The specific activity of radon in atmospheric air, depending on the place and time of observation, ranges from 10^{-15} to $5 \cdot 10^{-13}$ Ci/l. Once, inside the body along with inhaled air partially deposited in the lungs, α- and β-radioactive isotopes of the radon chain can lead to localized sources of radiation. The effective equivalent dose of radiation from radon and its decay products is about 1.3 mSv/year, that is more than half of the whole annual dose received by people from all natural sources of radiation.

A person usually receives the radiation dose from radon while he/she is in a closed room without appropriate ventilation. In zones with a temperate climate, the concentration of radon in enclosed spaces is about 8 times higher than in the outdoor air. Radon is concentrated in indoor air when they are sufficiently isolated from the external environment. As a result, a relatively high level of radiation can occur in the room, especially if the house is built on the ground with a high content of radionuclides, or if materials with increased radioactivity were used during its construction. The most common building materials, wood, brick, and concrete, release relatively little radon. However, the main source of radon in enclosed spaces is ground. Therefore, as a rule, the radon concentration in the upper floors of multi-storey buildings is lower than on the first floor. Sealing the premises with the aim of warming them only aggravates the situation, since the release of radioactive gas from the room is even more difficult. An effective means of reducing the amount of radon seeping through the slots in the floor are ventilating installations in basements. When facing walls with plastic materials, after covering the walls with a layer of epoxy-based paint or three layers of oil paint, radon emission from them is reduced by about 10 times. Airing of the rooms also leads to a significant decrease radon concentration. A less important source of radon in the living room is water. The concentration of radon in water is usually low, but water from deep wells and artesian wells contains a lot of radon. Water with a high content of radon in the lungs along with inhaled air, which occurs most often in the bathroom, is a great danger. Radon also penetrates into natural gas underground, so its concentration in the rooms can increase substantially if the gas-heating devices are not equipped with an extractor hood.

II. Natural radioactivity is a spontaneous process, in which the decay of each individual nucleus is a random event with a certain probability. The number of nuclei that decayed over a period of time *dt*, is proportional to *dt* and number of non-decayed nucleus *N*:

$$dN = -\lambda N dt \qquad (1)$$

The “minus” sign appears due to the fact that the number of non-decaying nuclei decreases in the process of decay. Constant decay λ is the relative decrease in the number of nuclei per unit time. Integrating equation (1) with the initial condition $N = N_0$ at $t = t_0$, we get the law of radioactive decay:

$$N = N_0 e^{-\lambda t}. \qquad (2)$$

Introducing the concept of a sample activity:

$$A = \left|\frac{dN}{dt}\right| = / N\left(c^{-1}\right), \qquad (3)$$

obtain:

$$A = A_0 t^{-\lambda t}. \qquad (4)$$

From equations (2) or (4) we obtain a relation between the decay constant and the half-life period:

$$T = \frac{ln\,2}{\lambda} = \frac{0{,}693}{\lambda}. \qquad (5)$$

A graphic representation of the law of radioactive decay is shown in Fig. 11.1. and 11.2.

To determine the decay constant, you need to use the experimentally obtained curves and the formula:

$$\lambda = \frac{ln\,A_0 - ln\,A_i}{t_i - t_0}. \qquad (6)$$

If the nuclei N_2, resulting from the radioactive decay of the nuclei N_1, are radioactive, then to describe the process of these two successive transformations, instead of equation (2), you need to write a system of two differential equations:

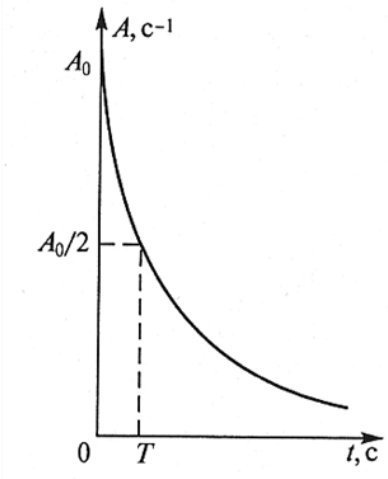

Рис. 11.1

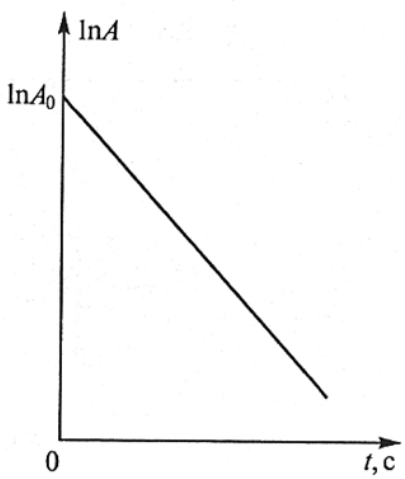

Рис. 11.2

$$\frac{dN_1}{dt} = -\lambda_1 N_1(t), \qquad (7)$$

$$\frac{dN_2}{dt} = \lambda_1 N_1(t) - \lambda_2 N_2(t), \qquad (7a)$$

where λ_1 и λ_2 are constant of decay of the nuclei N_1 and N_2. The first equation describes the decay process of the primary (maternal) isotope. The second equation determines the total change in the number of nuclei of the secondary (subsidiary) isotope and contains two terms. The first term gives an increment of radioactive nuclei of the secondary isotope due to the decay of the primary isotope and therefore is exactly equal to $\lambda_1 N_1(t)$, that is, the number of decayed nuclei of the primary isotope. The second term is equal to the number of decaying nuclei of the secondary isotope. The solution of the system of equations (7) is:

$$N_1(t) = N_1(0) \cdot e^{-\lambda_1 t} \qquad (8)$$

$$N_2(t) = N_2(0) \cdot e^{-\lambda_2 t} + \frac{\lambda_1 N_1(0)}{\lambda_2 - \lambda_1}\left[e^{-\lambda_1 t} - e^{-\lambda_2 t}\right], \qquad (8a)$$

where $N_1(t)$ and $N_2(t)$ are the number of non-decaying nucleis of the primary and secondary isotope by the time t; $N_1(0)$ and $N_2(0)$ are number of nucleis at $t = 0$.

If at the moment $t = 0$ there was only the parent isotope, then in this case $N_2(0)=0$. The nature of the dependence of the number of nuclei of the daughter isotope $N_2(t)$ is determined by the ratio of constants λ_1 and λ_2. If the nuclei of the parent isotope decay much faster than the daughter ($\lambda_1 >> \lambda_2$), then $N_2(t)$ firstly it grows rapidly, reaches a maximum, and then decreases exponentially (Fig.11.3.), that is determined by a constant λ_2.

Similarly, one can consider consistent decay of three, four, etc. isotopes.

III. In this practical, a comparative analysis of the levels of natural radioactivity of air in an open area and in a room is carried out, as well as an experimental test of the law of radioactive decay using short-lived decay products of radon.

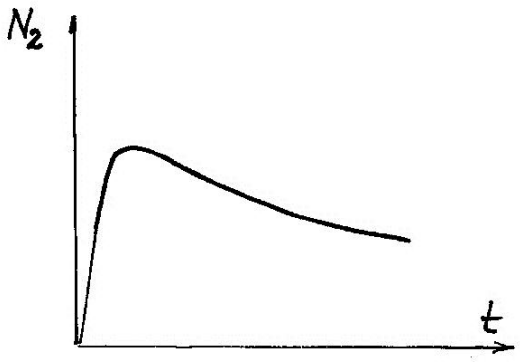

Fig. 11.3

Since all members of the radioactive family of uranium beyond radon are metals, they cannot remain in the atmosphere in the free state for a long time. When meeting with solid particles of smoke, dust (with a radius from 10^{-6} to 10^{-7} cm) or droplets of fog, which are always present in atmospheric air, metal atoms are deposited on their surface.

In assessing the level of natural radioactivity in atmospheric air, the decay of such isotopes, such as ${}_{84}Po^{218}$, ${}_{82}Pb^{214}$, ${}_{83}Bi^{214}$, ${}_{84}Po^{214}$. Further decomposition products of radon by the radioactive series can be disregarded, since they have long half-lives periods and, therefore, they are precipitated or washed out of the atmosphere, not reaching equilibrium concentrations.

Since the volume activity of the air is very small (from 0.04 to 20 Bq/m^3) and cannot be directly measured, it is necessary to concentrate the solid decay products of radon contained inside to detect and study the natural radioactivity of air under laboratory conditions. To do this, use the filtering method, the essence of which is that a large amount of air is pumped through paper or layered fiber filters that trap solid particles. As a result, radioactive isotopes of metals contained in the investigated volume of air are deposited on the filter. Subsequent measurement of the specific α– or β – activity of the filter can be carried out using scintillation or gas-discharge counters.

This practical uses a β-particle counter, so the filter activity determined by isotopes ${}_{82}Pb^{214}$ и ${}_{83}Bi^{214}$ will be measured. The parent nuclei of this chain are the nuclei of a short-lived isotope ${}_{84}Po^{218}$.

If at the time of termination of pumping air through the filter $t = 0$ the activity of the substance collected by the filter was equal A_0, then the change in filter activity over time will be described by the following formula:

$$A_\beta(t) = A_0 \cdot e^{-\lambda_{eff} t}, \qquad (9)$$

where $A_\beta(t) = A_1(t) + A_2(t)$, considering the decay of the argon-222, and λ_{eff} is an effective constant decay of the mixture of isotopes located on the filter.

Since the number of particles trapped in the counter is proportional to the β – activity of the filter under study,

$$n_\beta(t) = n_\beta(0) \cdot e^{-\lambda_{eff} t}. \qquad (10)$$

Thus, plotting the graph of the dependence of the number of β-particles trapped in the counter, over time, it is possible by using formula (5) to determine the effective half-life period T_{eff} of a mixture of radionuclides deposited on the filter.

2. DESCRIPTION OF EXPERIMENTAL SETUP

The block diagram of the laboratory setup is shown in the figure 11.4, and the general view is in the figure 11.5. The laboratory setup consists of an ionizing radiation detector - a Geiger counter located in measuring unit 1, a stabilized power source 2, a counting device 3, and a set of filters 4 made of special fiber. To collect the radioactive aerosol, a vacuum cleaner 5, an evacuation pipe 6 for sampling from the street, a fixing device 7 on the vacuum cleaner hose for sampling the room and a filter cartridge 8 are used. The signals from the counter are recorded by a counting device and recorded at a predetermined time interval on the electronic scoreboard.

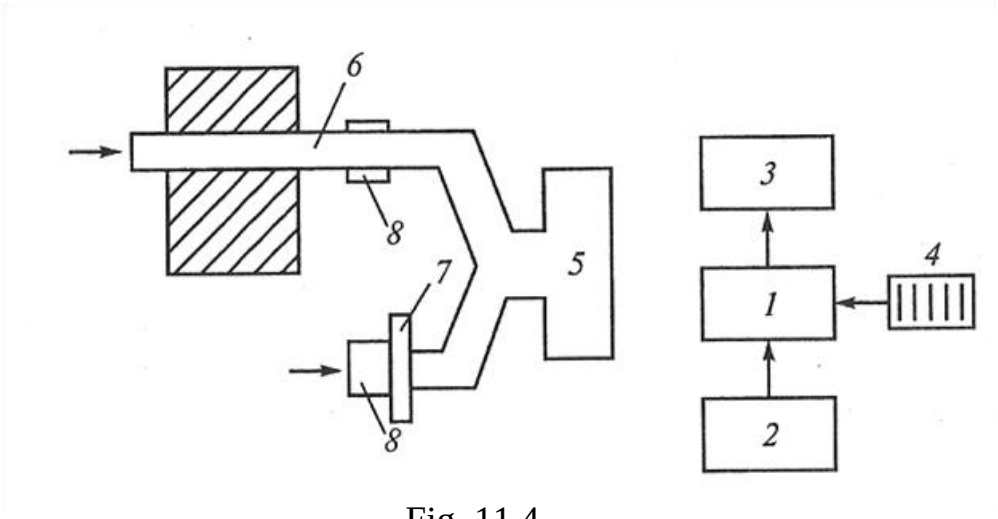

Fig. 11.4

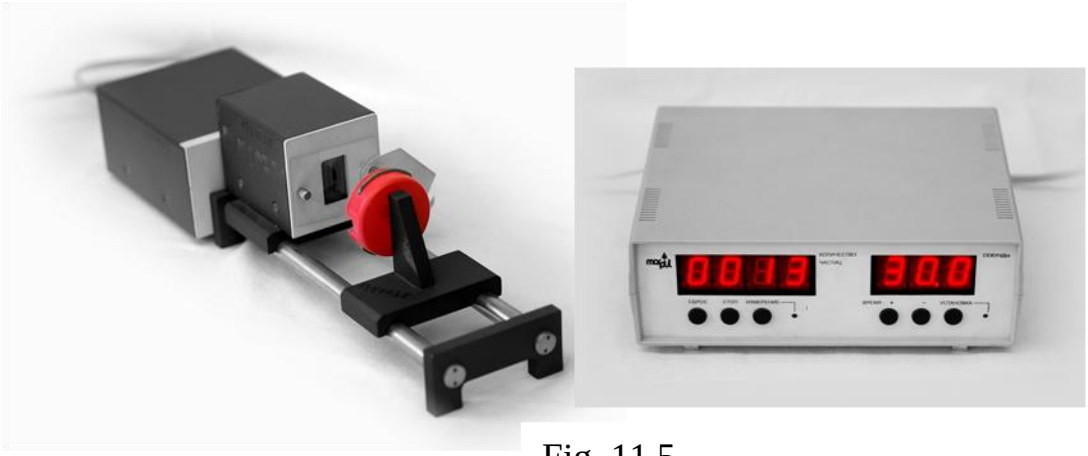

Fig. 11.5

3. MEASUREMENT AND DATA PROCESSING

Task 1. Determination of the relative content of radon and its decay products in indoor air and in the open air.

1. Turn on the counting device. Prepare him for the measurement, using the passport of the laboratory installation. Allow the appliance to warm up for 15 minutes.

2. Measure the level of natural radioactive background in the laboratory n_f (cpm). The recommended time for one measurement is 5 minutes. Repeat the measurements at least 5 times and calculate the average value of n_b. (cpm).

3. Collect radioactive aerosol outdoors. To do this, fix the cartridge with filter No. 1 in the exhaust pipe going outside, which you then connect to the vacuum cleaner and pump air through the filter for 15 minutes.

4. After completion of pumping, install the test filter in front of the particle counter and determine the counting rate from it by conducting successively 5 measurements (the recommended time for one measurement is 100 s). Calculate the average value of n_1 (cpm).

5. Determine the activity A_1 of the investigated filter by using an expression:

$$A_1 \cong n_1 - n_b.$$

6. Write down the results of measurements and calculations in Table 1.

7. Collect radioactive aerosol from laboratory air. To do this, install the cartridge with filter number 2 in the mounting device. Put the fixing device on the vacuum cleaner hose and conduct air pumping through the filter in the laboratory for 15 minutes.

8. After completion of pumping, place the filter in front of the particle counter. Determine the counting rate of the pulses from the filter under study by conducting successively 5 measurements (the time of each measurement is 100 s) and calculate the average n_2 (cpm).

9. Determine the activity A_2 of the investigated filter by using an expression:

$$A_2 \cong n_2 - n_b.$$

10. Write down the results of measurements and calculations in Table 1.

11. Compare the activity of filters A_1 and A_2 and make conclusions.

Table 1

Background			Ooutdoor				Indoor				$\frac{A_2}{A_1}$
t, s	n_b, count	$n_{b\ av}$, cpm	t, s	n_1, count	$n_{1\ av}$, cpm	$A_{1\ av}$, cpm	t,	n_2, count	$n_{2\ av}$, cpm	$A_{2\ av}$, cpm	
300	1.		100	1.			100	1.			
…	….		….	….			….	…..			
300	5.		100	5.			100	5.			

Task 2. **Estimation of the effective half-life period of the isotope mixture**

1. With the filter number 2, measure the dependence of the filter activity on time. To do this, carry out sequentially (in the continuous mode of operation of the counting device) ~ 40 measurements (the duration of each measurement is 100 s).
2. Write down the results of measurements and calculations in Table 2.
3. At the end of the measurement, turn off the counting device.
4. Plot the graphs $A = f(t)$ and $\ln A = f(t)$ (plotting the graphs, also use the measurement results obtained in task №1(8)). Explain the observed dependences.
5. Using formulas (4), (5) and (6), estimate the magnitude of the decay constant and the effective half-life period of the studied isotope mixture. Calculate λ and $T_{1/2}$ for t > 1000s (measure the time t from the moment of the beginning of task 1 (8)).

Table 2

№	t, s	n_2, count	n_2, cpm	$n_{b\,av}$, cpm	$A_{\text{filter №2}}$, cpm	$\ln A$	λ, s^{-1}	$T_{1/2}$, min
1.	0– 100							
…	100-200							
…	…….							
40.	…4000							

QUESTIONS

1. What is the physical meaning of the decay constant? What is the half-life period?
2. What is the origin of α– and β – particles arising during radioactive transformations?
3. What is a radioactive family called? What radioactive families are found in nature?
4. What is the condition of the transition equilibrium in the radioactive chain?
5. What isotope is obtained from $_{86}Rn^{222}$ after two α- and two β-decays?
6. How many α– and β – decays does U^{238} undergo, eventually turning into a stable Pb^{206} isotope?
7. What are the two main forms of radon in nature?
8. What are the main sources of radon indoor.
9. Why is radon and its decay products especially dangerous for internal exposure of the body?
10. What measures are taken to reduce the radon concentration in the premises?
11. What is the filtering method? What radioactive isotopes are deposited on the filter?
12. Why it is necessary to take radioactive background into account when calculating the activity of a drug?
13. Why it is recommended to calculate λ and $T_{1/2}$ according to the graphs for t > 1000 s?