Practical 12

STUDY OF LONG-LIVED POTASSIUM ISOTOPE

A i m : Experimental determination of the half-life of $_{19}\mathrm{K}^{40}$; estimate of β– activity of the DUT and a human being.

E q u i p m e n t a n d a c c e s s o r i e s : the indicator of ionizing particles (Geiger counter), a counting device, a stabilized power supply unit ВУП-2М, the source under study is salt *KCl*.

INTRODUCTION

In this practical, the object of study is one of the most common natural long-lived radioactive isotopes of our planet. – $_{19}\mathrm{K}^{40}$, the half-life of which is comparable to the lifetime of the solar system. Natural potassium includes: $_{19}\mathrm{K}^{39}$ (≈93.1%), $_{19}\mathrm{K}^{40}$ (≈0.012%), and $_{19}\mathrm{K}^{41}$ (≈6.88%) isotopes, with the $_{19}\mathrm{K}^{40}$ being radioactive only. Potassium is found in a fairly large number not only in the rocks of the Earth and in the soil, but also forms part of the tissues of plants and animals. The relative weight content of potassium in the human body is approximately 0.12-0.35%. $_{19}\mathrm{K}^{40}$ – the only isotope that, when injected through the gastrointestinal tract, makes a significant contribution to the person's internal exposure throughout his life. [read about *Banana equivalent dose*].

Decay schematic of $_{19}\mathrm{K}^{40}$ is given in Fig. 12.1.

In 89 % cases, potassium isotope $_{19}\mathrm{K}^{40}$ undergoes a β^--decay (transition of a nucleon from the neutron state to the proton state) with the formation of $_{20}\mathrm{Ca}^{40}$ isotope in the ground state (the maximum kinetic energy of the β-particles E_{max}=1.33 MeV):

$$_{19}K^{40} \rightarrow {}_{20}Ca^{40} + {}_{-1}e^{0} + {}_{0}\tilde{\nu}_{e}^{\,0} \quad . \qquad (1)$$

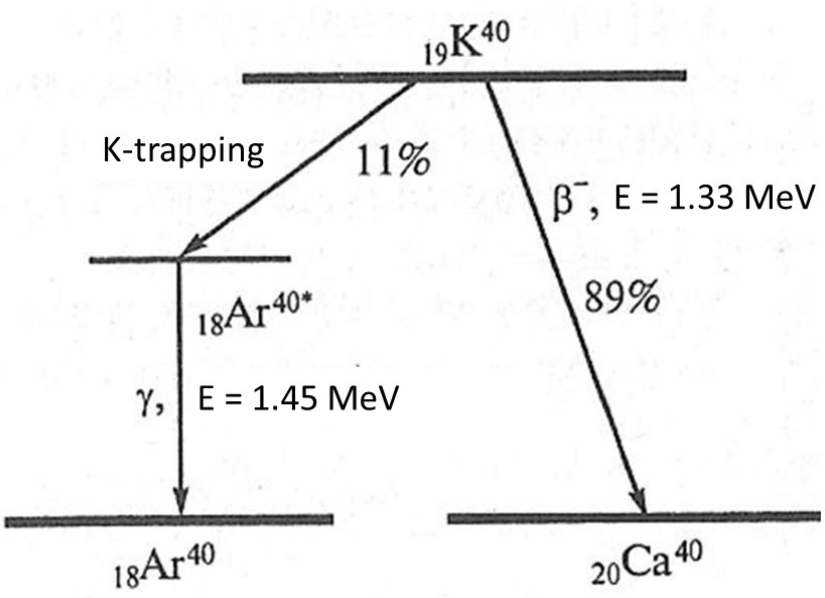

Fig. 12.1

In 11 % cases the $_{19}K^{40}$ decays via orbital electron trapping (K-trapping, transition of a nucleon from a proton to a neutron state) with the formation of an argon isotope in an excited state). Nuclei $_{18}Ar^{40*}$ relaxes to the ground state $_{18}Ar^{40}$ via γ–quantum escape with the energy Eγ =1.45 MeV:

$$_{19}K^{40} + _{-1}e^{0} \rightarrow _{18}Ar^{40*} + _{0}\nu_{e}^{0} \rightarrow _{18}Ar^{40} + \gamma . \qquad (2)$$

Thus, the $_{19}K^{40}$-isotope decay is accompanied by the emission of β–particles with a continuous spectrum with a maximum energy of 1.33 MeV, and monoenergetic γ – radiation with an energy of 1.45 MeV.

A person is exposed to radiation in two ways. Radioactive substances can be outside the body and irradiate it outside; in this case they talk about external exposure. In another case, they can be in the air, food or water and get inside the body. This method of exposure is called internal.

On average, about 2/3 of the effective equivalent dose of radiation that a person receives from natural sources of radiation comes from radioactive substances trapped in the body with food, water or air. A very small part of this dose falls on radioactive isotopes such as carbon-14 or tritium, which are formed under the influence of cosmic radiation. Everything else comes from sources of terrestrial origin. A person receives a sufficiently large dose of internal exposure from the nuclides of the radioactive series of uranium-238 and thorium-232 (radon and its daughter products). However isotope $_{19}K^{40}$ also makes a significant contribution to the internal exposure of living organisms. Potassium can be found in all tissues of the body, although its bulk is concentrated in the muscles. In the same way, the radioactive

form of potassium introduced into the body will be distributed. β-particles formed during decay of ${}_{19}\mathrm{K}^{40}$ have a free-patch in biological tissues of about 0.7 cm, and γ-radiation freely passes through the tissues of a living body. Since the half-life of ${}_{19}\mathrm{K}^{40}$ is long enough, and its reserves in the body are constantly replenished by food sources, this long-lived radioactive isotope is one of the main natural sources of radiation, causing permanent internal β- и γ-radiation. During a year, on average, a person receives a radiation dose of 0.3 mSv (12.5% of the effective equivalent radiation dose from natural sources) due to this radioactive isotope absorbed by the body along with non-radioactive potassium isotopes necessary for the body's vital activity (table salt, grains and legumes, brewer's yeast , dairy products, etc.).

For long-lived isotopes, the usual method of determining the half-life by decreasing the activity of a DUT with time (the exponential law) is not suitable, since during the course of the experiment the activity of the DUT remains practically unchanged. To determine the half-life of such isotopes, it is necessary to know the full activity A (that is, taking into account all types of decays, the) of the DUT and the number N of radioactive atoms in it:

$$A = \lambda N = \frac{ln\ 2}{T} N = \frac{ln\ 2}{T} N_0 V\ , \qquad (3)$$

where λ– is the decay constant; N_0 – number of the radioactive atoms per unit volume; V – actual volume of the DUT; T – half-live period.

The DUT, which is a cuvette with the thickness **a** with salt KCl, is placed in front of the window of the β–particles counter (see Fig. 12.2.). We can assume that only those particles that have flown from a source whose base area is equal to the counter window area fall into the counter window with area: $S = d \cdot l$.

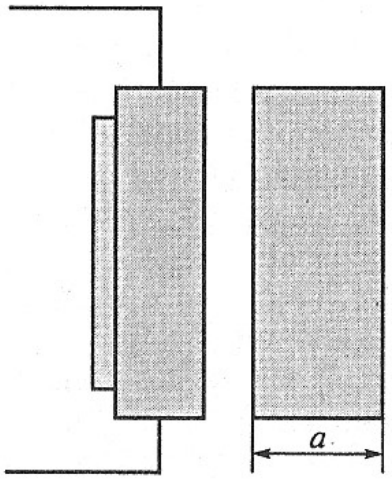

Fig. 12.2

From the layer of the thickness dx, placed at a distance x apart from the counter window, during 1 sec dn electrons will be emitted towards the window:

$$dn = \frac{1}{2} \cdot \frac{ln\ 2}{T} N_0 S dx\, \varepsilon\ , \qquad (4)$$

where ε – % of ${}_{19}K^{40}$ decays, going on through the β–decay.

When passing through a layer of thickness x, the particle density decreases according to the law: $J = J_0 e^{-\alpha x}$, with α – linear absorption coefficient. Thus, β-particles are partially absorbed by the KCl crystals and only $e^{-\alpha x} \cdot dn$ particles will reach the counter window. Assuming that the thickness **a** is much larger than the distance ($a \sim \infty$) and integrating $e^{-\alpha x} \cdot dn$ over the DUT thickness, we get:

$$N^* = \int_0^\infty e^{-\alpha x} dn = \frac{ln\, 2 N_0 S \varepsilon}{2T\alpha}, \qquad (5)$$

with N^* – number of β–particles, due to decay of ${}_{19}K^{40}$, which reaches the counter window within 1 sec.

Now, account for the counter efficiency φ: we get φN^*. However, the counter registers not only the particles emitted by the DUT but also that from the background. Background-limited count rate N_b is caused not only by cosmic radiation and environmental radioactivity, but also by γ-quanta emitted by the DUT. Therefore, the total number of particles recorded by the counter per unit of time is determined by the following expression:

$$N^{**} = \varphi N^* + N_\Phi = \varphi \cdot \frac{\ln 2 N_0 S \varepsilon}{2T\alpha} + N_b . \qquad (6)$$

The number of radioactive atoms per unit volume:

$$N_0 = \frac{N_A}{\mu_K} \cdot \frac{m^o}{V}, \qquad (7)$$

where μ_K – molar mass of ${}_{19}K^{40}$; m^o – the mass of the isotope ${}_{19}K^{40}$ in the DUT; V –volume of the DUT, N_A – Avogadro number.

If f – partition of ${}_{19}K^{40}$ ($f = 1{,}19 \cdot 10^{-4}$) included in the natural potassium of mass M_K, then

$$m^o = f \cdot M_K = f \frac{M_{KCl}}{\mu_{KCl}} \mu_K , \qquad (8)$$

with M_{KCl} being the DUT mass of KCl, and μ_{KCl} – molar mass of KCl.

Taking into account (7) and (8), we have using (6):

$$T = \frac{\varphi \ln 2 \cdot N_A f M_{KCl} \varepsilon S}{2\left(N^{**} - N_\Phi\right)\mu_{KCl} V \alpha} . \qquad (9)$$

Linear absorption coefficient α (cm^{-1}) is associated with the thickness of the half attenuation layer $\Delta\rho_{1/2}$:

$$\alpha = \frac{ln\,2}{\Delta\rho_{1/2}} \qquad (10)$$

Since the linear absorption coefficient depends on the density ρ of the absorbing substance: $\alpha=\alpha^*\rho$, with α^* being the mass absorption coefficient, then the half attenuation (or absorption) layer (taking into account the material of the absorber $\Delta\rho^*_{1/2}$ (expressed in g/cm^2)):

$$\Delta\rho^*_{1/2} = \frac{ln\,2}{\alpha^*} = \frac{\rho\,ln\,2}{\alpha} = \rho\Delta\rho_{1/2}\,. \qquad (11)$$

Finally, the formula for calculating the half-life period of a long-lived isotope of ${}_{19}K^{40}$:

$$T = \frac{\varphi\ N_A f\varepsilon\ S\Delta\rho^*_{1/2}}{2\left(N^{**} - N_\Phi\right)\mu_{KCl}}\,. \qquad (12)$$

Knowing the half-life period T, it is possible by the formula (3) to estimate the activity A of the source. For a source of mass M activity (dec / s) is equal to:

$$A = \frac{ln\,2}{T}\cdot\frac{m^o N_A}{\mu_K}\,. \qquad (13)$$

Then β–activity (dec/s) is:

$$A_\beta = A\varepsilon\,. \qquad (14)$$

The unit of radioactivity in the SI is Becquerel (Bq): 1 Bq = 1 dec / s.
The radioactivity is also expressed in Curie units: 1 Ci = 3.7*10^{10} Bq.

EXPERIMENTAL SETUP

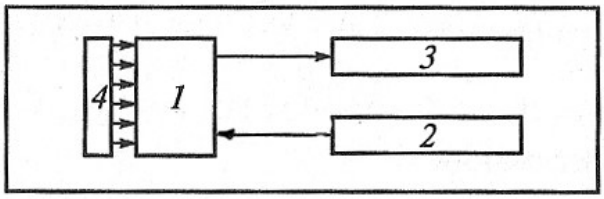

Fig. 12.3

The block diagram of the experimental setup is shown in Fig. 12.3, and a general view of the setup is shown in Fig. 12.4. The installation consists of an ionizing particle indicator — a Geiger counter (1), which is powered by a stabilized power source (2). The signal from the counter enters the input of the counting device PSO-2 (3), where it accumulates for a specified time and is fixed on the liquid crystal board. The work uses an environmentally safe radioactive source (4) - pure salt KCl, pressed into a cuvette.

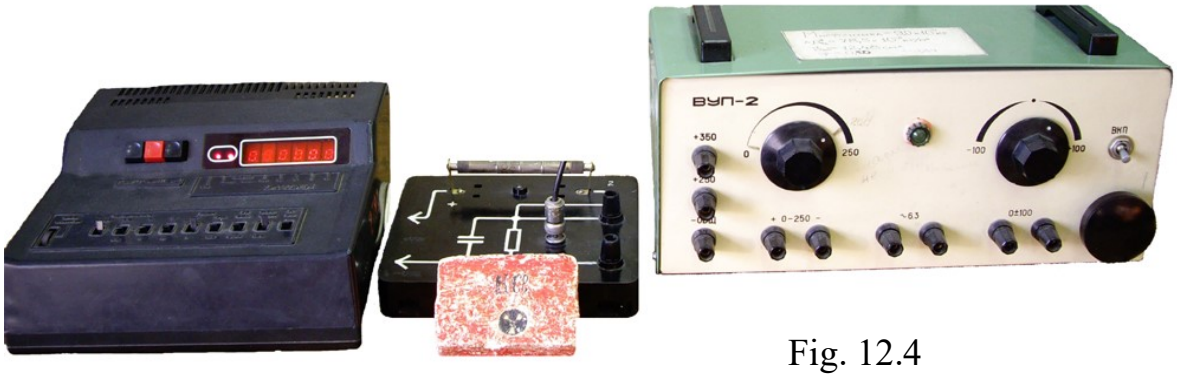

Fig. 12.4

MEASUREMENTS AND DATA PROCESSING

T a s k 1 . **Experimental determination of the half-life of the isotope $_{19}K^{40}$.**

1. Turn on a counter (ПСО-2) using a button **ВКЛ** at the rear panel. Let it to warm up for ~20 min.

2. Set up the counter:

1) make sure that the following regime is set up (Fig. 12.5):

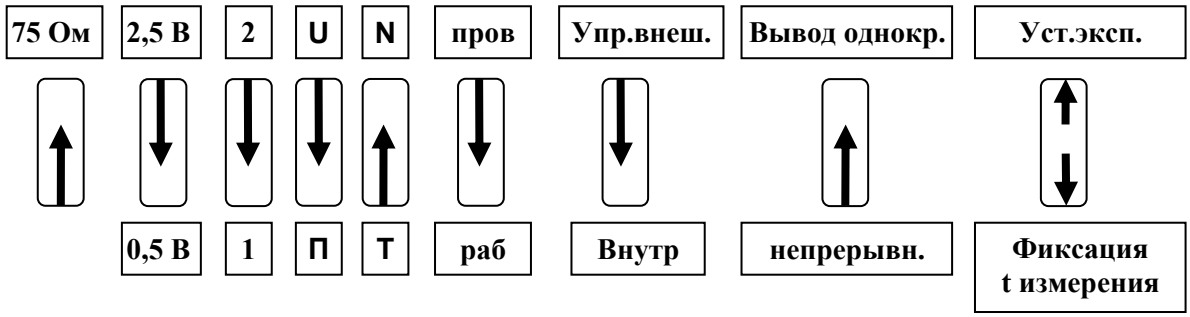

Fig. 12.5

- Set the exposure time (using “**Уст**.**эксп**.”) to 300 sec.

To do this, move the switch to the top position and wait until the time count indicator (the red mark on the digital scoreboard) is set above the “**100**” on the indicator board and at the same time the indication is **on** above the “X3”. After that, turn the “ **Уст**.**эксп**.” switch to the lower position.

3. Determine the number of counts triggered by the radioactive background.

- remove the block with the DUT KCl away from the counter window. Measure the number of pulses recorded by the counter within 5 minutes.

- To count the pulses, press the "**ПУСК**" button. During the preset counting period a red indicator (above the button) should be on. After the counting is completed, the indicator should be automatically switched off and the counted number should be registered on the display.

- Before each subsequent measurement, first press the " **СБРОС** " button and then the "**ПУСК**" button.

- Repeat the background measurement 5 times, compute the averaged value $<N_b>$ *(pulses/min).*

4. Install the unit with the reference source KCl opposite the counter window. Measure the total number of particles *N**,* registered by the counter within 5 minutes. Repeat the measurement 5 times and compute the averaged value *<N**> (pulses/min).*

5. Using formula (12), compute the half-life of the isotoope $_{19}\mathrm{K}^{40}$. Assume the following parameters: $\Delta\rho^{*}_{1/2} = 78.5\cdot10^{-2}$ kg/m^2; $\mu_{KCl} = 74.55$ g/mol.

Other parameters needed are written on the setup.

6. Tabulate the measurement results:

Table 1

№	t, min	N_b, pulses/min	$<N_b>$, pulses/min	N**, pulses/min	<N**>, pulses/min	$T_{1/2}$, s	$T_{1/2}$, years
1							
…							
5							

7. Turn off the counter.

Task 2. **Evaluation of the β–activity of the studied source and the human body**

1) Using the formula (14), calculate *β–activity* of the DUT. Express the activity of the study drug in Bq and Ci.

2) Estimate *β–activity* of $_{19}K^{40}$ isotope in a human body, assuming that amount of potassium in a human is ~ 0.2% of the mass.

3) Often, the concept of specific source activity is used as one of the characteristics of a radioactive source. The specific activity of the source A_m is the ratio of the activity of the DUT to its mass: $A_m = A / m$ [Ci / kg]. Knowing the mass of the DUT (specified in the installation passport), evaluate its specific activity.

4) Estimate specific *β–activity* (caused by decay of the $_{19}K^{40}$) in a human body.

5)* Estimate the absorbed dose rate due to the β – activity of the isotope contained in the tissues of the human body. The average energy of the emitted β–particles is equal to 0.6 MeV.

6)* Estimate the average expected effective equivalent dose of radiation that you receive for 1 year of life due to the presence in the body of a radioactive isotope $_{19}K^{40}$. Compare the obtained value with the radiation dose that a person receives on average for 1 year of life from all natural sources of radiation (about 2 mSv).

QUESTIONS

1. Write down the law of radioactive decay. Explain the physical meaning of the constant decay and half-life.
2. What is called the activity of a radioactive drug? List the units of activity known to you.
3. Write down the reaction equations for the decay of nuclei according to the scheme of β^+ и β^--decays, and K–trapping.
4. What peculiarities of β-decay confirms that a neutrino is involved in this process?
5 What natural radioactive isotopes are responsible for the constant internal irradiation of the human body?
6. What contribution to human internal exposure is given by $_{19}K^{40}$ isotope?
7. What factors need to be considered when evaluating the body's internal exposure?
8. Determine the concentration of $_{19}K^{40}$ in the cow’s milk if 1 liter of milk includes 1.4 g of natural potassium and the $_{19}K^{40}$ percentage is 0.0119%.