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ANALYSIS OF THE PRODUCTION OF RARE-EARTH ISOTOPES AT THE WWR-K RESEARCH REACTOR: PROMISING THERAPEUTIC RADIONUCLIDES

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Rare Earth Elements (REE) are a group of seventeen chemical elements in the periodic table, including lanthanides and scandium and yttrium. These elements have unique physical and chemical properties that make them valuable in various industries, including electronics, magnets, and catalysts. However, radioactive isotopes of rare earth elements also possess effective nuclear physical properties that make them promising for the development of new radiopharmaceuticals for therapeutic purposes. These radioactive isotopes have unstable atoms with excess nuclear energy, and they undergo radioactive decay, which can be utilized for medical applications.

The nuclear physical properties of radioactive isotopes of rare earth elements make them suitable for therapeutic purposes in medicine. For example, technetium-99m, a radioactive isotope of technetium, is widely used in diagnostic nuclear medicine due to its outstanding physical-chemical characteristics. Other radioactive isotopes of rare earth elements, such as holmium-166, have been established for a broad spectrum of medical applications. These isotopes can be used in targeted radiation therapy to treat various diseases, including cancer. The unique properties of these radioactive isotopes allow for precise targeting and delivery of radiation to specific tissues or cells, minimizing damage to healthy tissues.

The potential of radioactive isotopes of rare earth elements for therapeutic purposes extends beyond the current applications. Ongoing research and innovations in the field of radiopharmaceuticals continue to explore the use of underutilized lanthanoid radionuclides for theranostic purposes. For example, astatine, a rare and highly radioactive element, exhibits multiple isotopes that can be potentially utilized in targeted therapy. The development of new radiopharmaceuticals using radioactive isotopes of rare earth elements holds promise for advancing medical treatments and improving patient outcomes. With further research and advancements, these isotopes may play a crucial role in the future of therapeutic medicine.

This research work makes it possible to evaluate the possibility of obtaining REE such radioisotopes as: ^{90}Y, ^{141}Ce, ^{147}Nd, ^{153}Sm, ^{165}Dy, ^{166}Ho, ^{169}Tm, ^{175}Yb, ^{177}Yb, ^{177}Lu by reaction (n, γ) at the WWR-K reactor.

Keywords: *rare-earth isotopes, WWR-K research reactor, neutron irradiation, specific activity, direct nuclear reaction.*

1. INTRODUCTION

The main goal of radiotherapy is to ensure the specificity of RP delivery to a malignant cell at a low dose of radiation to healthy tissues [1]. Therefore, when developing new radiopharmaceuticals, special attention should be paid to both the nuclear and physical properties of the radioactive isotopes included in the composition and the chemical and (or) biological component labeled with one or another radioactive isotope. The suitability of RP with one or another chemical or biological component is evaluated to reflect the function of the cell or the whole organism as fully as possible.

The criteria for choosing a radionuclide for radionuclide therapy are: type of decay – radionuclides emitting corpuscular radiation are used for therapeutic procedures: α and β-emitters, as well as emitters of Auger electrons and X-rays. Moreover, the emitted radiation should have a suitable linear energy transfer coefficient and «mileage» (absorption) in the tissues of the body: from fractions to several millimeters, and the daughter decay products should be short-lived or stable. The presence of additional gamma radiation in the range from 70 to 250 keV is a positive factor that allows determining the exact location of the radiopharmaceutical after its administration and monitoring the treatment process.

β-particles have variable energy (0.1−2.2 MeV) and relatively low penetrating power, which is usually in the range of 0.2 keV/μm. Although beta-emitters are the most developed class of radiotherapeutic agents, it is known that their low resolution leads to a high attenuation range (0.5−10 mm; 50–1000 cell diameters), which often goes beyond the diameter of target tumors. This can lead to the death of healthy cells and is the main deterrent to beta therapy. Currently, low-energy β-emitters (for example, ^{177}Lu) are being actively investigated due to their lower radiation energy compared to high-energy β-emitters (for example, ^{90}Y); radiation energy – isotopes with low, medium and high maximum particle energy are used for radiotherapy, depending on the volume of tissue or organ, in need of treatment; half-life – preference is given to radionuclides with a half-life of 6 hours to 7 days [2].

The selection of an isotope with a suitable half-life is carried out taking into account the pharmacokinetics of the transport molecule, which is designed to deliver the radionuclide to the zone of interest [3]. Radiopharmaceuticals with a therapeutic effect should be in the focus of cancer formation for a sufficient time so that radiation has time to destroy cancer cells [4]. Definitely, in the case of using an isotope with a too short half-life, the activity

of the isotope will decrease before the transport molecule penetrates into the oncological neoplasm and settles in it. The worst thing is that the therapeutic effect will not be achieved, and the radiation dose of healthy and radiation-sensitive tissues will take place. On the other hand, a long half-life will provide a therapeutic effect of oncological diseases, since long-lived nuclides are quite tolerant to the bone marrow. Moreover, a very long half-life does not always have a positive effect, since an excessively long half-life increases the amount of radiopharmaceutical that needs to be moved to an oncological neoplasm to obtain a therapeutic effect, taking into account decay and excretion [4].

The main criteria for choosing the half-life of an isotope are based on data on the molecular weight, size and topological characteristics of the transport molecule, as well as on the size of tumor formations [1]. If the RP is aimed at scattered cells, then the half-life should preferably be selected in the range from several hours to several days. Significantly longer half-lives of the isotope (more than a week) are necessary to achieve a therapeutic effect on large tumors [5, 6].

Also an important factor in the quality and safety of drugs is the absence of toxic impurities or radioactive substances, as a result of the radioactive decay of which long-lived radionuclide impurities form [7, 8].

To determine the list of the most promising REE for irradiation at the WWR-K reactor, an analysis of their nuclear physical characteristics was carried out according to the literature data.

Research reactor WWR-K, rated power of 6 MW with a maximum density of thermal neutron flux of $2 \cdot 10^{14}$ n·cm^{-2}·s^{-1}. The duration of the standard irradiation cycle of the reactor is 21 days.

Table 1 presents data on the natural composition of REE and the nuclear physical properties of radioactive isotopes formed by irradiation with thermal neutrons, as well as criteria for the selection of isotopes.

Radioactive isotopes were taken into consideration, the half-life of which lies in the range from 1 hour to 700 days, which is associated with the possibility of their further use for radionuclide therapy or brachytherapy. The table does not provide data on the element promethium, since this element occurs on Earth only in trace amounts as a product of spontaneous fission of uranium – ^{235}U and ^{238}U and has no stable isotopes.

^{90}Y – Natural yttrium oxide Y_2O_3 will be used to carry out the ^{89}Y(n, γ)^{90}Y reaction, with an activation cross section σ = 1.26±0.08 barns. This isotope has a beta decay mode $T_{1/2}$ = 64 hours, with a 100% probability, decaying at ^{90}Zr. It has a low-intensity gamma radiation energy equal to 2186.24 keV, as well as X-ray radiation energies of 15.775 keV and 15.691 keV [9].

^{141}Ce – The reaction ^{140}Ce(n, γ)^{141}Ce has an activation cross section of 0.58 barns. This isotope has a beta decay mode $T_{1/2}$ = 32.511 days, with 100% probability, decaying in ^{141}Pr. It has a gamma-ray energy equal to 145.4433 keV, with a radiation intensity of ε_γ = 48.4%, as well as X-ray energies of 36.027 keV and 35.551 keV [9].

^{147}Nd – The reaction ^{146}Nd(n, γ)^{147}Nd has an activation cross section of 1.41 barns. This isotope has a beta decay mode $T_{1/2}$ = 11.03 days, with 100% probability, decaying at ^{147}Pm. It has gamma radiation energies equal to 91.1050 keV, with a radiation intensity of ε_γ = 28.9% and 531.012 keV, with a radiation intensity of ε_γ = 13.11%, as well as X-ray radiation energies of 38.724 keV and 38.171 keV [9].

^{153}Sm – The reaction ^{152}Sm(n, γ)^{153}Sm has an activation cross section of 206 barns. This isotope has a beta decay mode $T_{1/2}$ = 45.284 hours, with 100% probability, decaying in ^{153}Eu. It has gamma radiation energies equal to 103.180 keV, with a radiation intensity of ε_γ = 29.14%, 69.673 keV, with a radiation intensity of ε_γ = 4.67%, 97.431 keV, with a radiation intensity of ε_γ = 0.763%, as well as X-ray energies of 41.541 keV and 40.901 keV[9].

^{165}Dy – The reaction ^{164}Dy(n, γ)^{165}Dy has an activation cross section of 2650 barns. This isotope has a beta decay mode $T_{1/2}$ = 2.332 hours, with 100% probability, decaying in ^{165}Ho. It has a gamma radiation energy equal to 94.700 keV, with a radiation intensity of ε_γ = 3.8% as well as X-ray energy of 47.547 keV and 46.700 keV [9].

^{166}Ho – The reaction ^{165}Ho(n, γ)^{166}Ho has an activation cross section of 64.7 barns. This isotope has a beta decay mode $T_{1/2}$ = 26.824 hours, with 100% probability, decaying in ^{166}Dy.It has a gamma radiation energy equal to 80.576 keV, with a radiation intensity of ε_γ = 6.56%, 1379.437 keV, with a radiation intensity of ε_γ = 0.922%, 1581.834 keV, with a radiation intensity of ε_γ = 0.182%, 1662.439 keV, with a radiation intensity of ε_γ = 0.1191%, as well as X-ray energies of 49.128 keV and 48.222 keV [9].

^{170}Tm – The reaction ^{169}Tm (n, γ)^{170}Tm has an activation cross section of 105 barns. This isotope has a beta decay mode $T_{1/2}$ = 128.6 days, with a 99.869% probability, decaying in ^{170}Yb and with a probability of 0.131% in ^{170}Er. It has a gamma radiation energy equal to 84.255 keV, with a radiation intensity of ε_γ = 2.48%, as well as X-ray radiation energies of 6.545–10.459 keV and 52.389 keV[9].

^{175}Yb – The reaction ^{174}Yb(n, γ)^{175}Yb has an activation cross section of 63.2 barns. This isotope has a beta decay mode $T_{1/2}$ = 4.185 days, with 100% probability, decaying at ^{175}Lu. It has gamma radiation energies equal to 396.329 keV, with a radiation intensity of ε_γ = 13.2%, 282.522 keV, with a radiation intensity of ε_γ = 6.13%, 113.805 keV, with a radiation intensity of ε_γ = 3.87%, as well as X-ray energies of 54.070 keV and 52.965 keV [9].

Table 1. Isotopic abundance of natural rare-earth isotopes and activation products [9]

Isotope	% Natural abundance	σ (b) for (n, γ) reaction	Product RN and its characteristics, probability >0.1%
^{45}Sc	100	27.2	^{46}Sc (β⁻, 83.9 d)
^{89}Y	**100**	**1.28**	**^{90}Y (β⁻, 64.0 h)**
^{159}Tb	100	23.3	^{160}Tb (β⁻, 72.1 d)
^{136}Ce	0.19	6.5	^{137}Ce (β⁺, 8.9 h)
^{138}Ce	0.25	1.02	^{139}Ce (EC, 137.6 d)
^{140}Ce	**88.45**	**0.58**	**^{141}Ce (β⁻, 32.5 d)**
^{142}Ce	11.11	0.97	^{143}Ce (α, $5\cdot10^{16}$ y)
^{141}Pr	100	11.5	^{142}Pr (β⁻, 19.1 h)
^{142}Nd	27.2	18.7	^{143}Nd (stable)
^{143}Nd	12.2	325.15	^{144}Nd (stable)
^{144}Nd	23.8	3.59	^{145}Nd (stable)
^{145}Nd	8.3	49.83	^{146}Nd (stable)
^{146}Nd	**17.2**	**1.41**	**^{147}Nd (β⁻, 10.98 d)**
^{148}Nd	5.7	2.58	^{149}Nd (β⁻, 1.73 h)
^{150}Nd	5.6	1.03	^{151}Nd (β⁻, 12.44 m)
^{144}Sm	3.07	1.64	^{145}Sm (EC, 340.3 d)
^{147}Sm	14.99	57	^{148}Sm (α, $6.98\cdot10^{15}$ y)
^{148}Sm	11.24	2.39	^{149}Sm (stable)
^{149}Sm	13.82	40.54 kb	^{150}Sm (stable)
^{150}Sm	7.38	100	^{151}Sm (β⁻, 88.8 y)
^{152}Sm	**26.75**	**206**	**^{153}Sm (β⁻, 1.93 d)**
^{154}Sm	22.75	8.3	^{155}Sm (β⁻, 22.3 m)
^{151}Eu	47.81	9200	^{152}Eu (72.1% β⁺, 27.9% β⁻, 13.5 y)
^{153}Eu	52.19	312	^{154}Eu (β⁻, 8.59 y)
^{152}Gd	0.2	735	^{153}Gd (EC, 240.4 d)
^{154}Gd	2.18	85.01	^{155}Gd (stable)
^{155}Gd	14.8	60.74 kb	^{156}Gd (stable)
^{156}Gd	20.47	2.19	^{157}Gd (stable)
^{157}Gd	15.65	253.7 kb	^{158}Gd (stable)
^{158}Gd	24.84	2.50	^{159}Gd (β⁻, 18.5 h)
^{160}Gd	21.86	2.2	^{161}Gd (β⁻, 3.66 m)
^{159}Tb	100	23.3	^{160}Tb (β⁻, 72.3 d)
^{156}Dy	0.06	33	^{157}Dy (β⁺, 8.1 h)
^{158}Dy	0.1	43	^{159}Dy (EC, 144.4 d)
^{160}Dy	2.34	56.65	^{161}Dy (stable)
^{161}Dy	18.91	600.1	^{162}Dy (stable)
^{162}Dy	25.51	193.9	^{163}Dy (stable)
^{163}Dy	24.9	124.2	^{164}Dy (stable)
^{164}Dy	**28.18**	**2650**	**^{165}Dy (β⁻, 2.33 h)**
^{165}Ho	**100**	**64.7**	**^{166}Ho (β⁻, 1.12 d)**
^{162}Er	0.14	13	^{163}Er (β⁺, 1.25 h)
^{164}Er	1.60	12.88	^{165}Er (EC, 10.4 h)
^{166}Er	35.5	16.75	^{167}Er (stable)
^{167}Er	22.9	644.2	^{168}Er (stable)
^{168}Er	26.98	2.74	^{169}Er (β⁻, 9.375 d)
^{170}Er	14.91	8.85	^{171}Er (β⁻, 17.52 h)
^{169}Tm	**100**	**105**	**^{170}Tm (β⁻, 128.6 d)**
^{168}Yb	0.13	2300	^{169}Yb (EC, 32 d)
^{170}Yb	3.04	10	^{171}Yb (stable)
^{171}Yb	14.28	53	^{172}Yb (stable)
^{172}Yb	21.83	1	^{173}Yb (stable)
^{173}Yb	16.13	17	^{174}Yb (stable)
^{174}Yb	**31.83**	**63.2**	**^{175}Yb (β⁻, 4.2 d)**
^{176}Yb	**12.76**	**2.85**	**^{177}Yb (β⁻, 1.9 h)**
^{175}Lu	97.41	23.1	^{176}Lu (stable)
^{176}Lu	**2.59**	**2090**	**^{177}Lu (β⁻, 6.65 d)**

^{177}Yb – The reaction ^{176}Yb(n, γ)^{177}Yb has an activation cross section of 2.85 barns. This isotope has a beta decay mode $T_{1/2}$ = 1.911 hours, with 100% probability, decaying at ^{177}Lu. It has gamma radiation energies equal to 150.399 keV, with a radiation intensity of ε_γ = 18.0%, 1080.204 keV, with a radiation intensity of ε_γ = 5.1%, 1241.8 keV, with a radiation intensity of ε_γ = 3.07%, 121.621 keV, with a radiation intensity of ε_γ = 3.05%, as well as X-ray energies of 54.070 keV and 52.965 keV [9].

^{177}Lu – The reaction ^{176}Lu(n, γ)^{177}Lu has an activation cross section of 2090 barns. This isotope has a beta decay mode $T_{1/2}$ = 6.6443 days, with 100% probability, decaying in ^{177}Hf. It has gamma-ray energies equal to 208.3662 keV, with a radiation intensity of ε_γ = 10.41%, 112.9498 keV, with a radiation intensity of ε_γ = 6.23%, as well as X-ray energies of 54.070 keV and 52.965 keV [9].

2. EXPERIMENTAL

2.1. Materials and measurements

Scandium oxide Sc_2O_3, Yttrium nitrate $Y(NO_3)_3$, Dysprosium nitrate $Dy(NO_3)_3$, Erbium nitrate $Er(NO_3)_3$, Cerium chloride $CeCl_3$, Neodymium chloride $NdCl_3$, Samarium chloride $SmCl_3$, Holmium chloride $HoCl_3$, Ytterbium chloride $YbCl_3$, Lutetium chloride $LuCl_3$, Thulium oxide $_{Tm2O3}$: natural composition of AR class, were purchased from well-known manufacturers of chemical reagents. All chemical reagents and solvents used corresponded to the CP class (chemically pure)

The activity and radionuclide purity of the obtained isotopes ^{90}Y, ^{141}Ce, ^{147}Nd, ^{153}Sm, ^{165}Dy, ^{166}Ho, ^{169}Tm, ^{175}Yb, ^{177}Yb, ^{177}Lu were determined using a high-resolution gamma-spectrometric analysis method using an HPGe detector (ORTEC) connected to a multichannel analyzer DSP^{EK}50^{TM}.

Measurements by atomic emission spectrometry were carried out on an inductively coupled plasma SpectroGenesis optical spectrometer.

The irradiation was carried out on a research reactor WWR-K in a peripheral channel with a thermal neutron flux of $8.09\cdot10^{13}$ n·cm^{-2}·s^{-1}.

2.2. Target preparation

To prepare REE samples for irradiation, a preparation technology consisting of several stages was developed:

Preparation of solutions of rare earth elements with a concentration of 1.0 mg/mL.

A sample of scandium oxide Sc_2O_3 in the amount of 153.4 mg and thulium oxide Tm_2O_3 in the amount of 114.2 mg was placed in a 100 mL chemical heat-resistant glass, moistened with 1–2 drops of purified water and 20 mL of 4M hydrochloric acid was added. After complete dissolution of the oxide during heating, the solution was cooled, quantitatively transferred to a 100 mL volumetric flask and brought to the mark with purified water. The concentrations of scandium and thulium in solutions were 1 mg/mL.

Samples of yttrium nitrate $Y(NO_3)_3$ in the amount of 309.2 mg; dysprosium nitrate $Dy(NO_3)_3$ in the amount of 214.5 mg; erbium nitrate $Er(NO_3)_3$ in the amount of 211.2 mg were placed separately in chemical heat-resistant glasses per 100 mL and added to each glass 10–20 mL of purified water, after complete dissolution the suspended solutions were evaporated in a water bath dry and until the vapor release was completely stopped, the dry residues were dissolved in 20 mL of 4M hydrochloric acid, the solution was cooled, quantitatively transferred to 100 mL volumetric flasks and brought to the mark with purified water. The concentration of yttrium, dysprosium and erbium in the corresponding solutions was 1 mg/mL.

Preparation of solutions of cerium, neodymium, samarium, gadolinium, holmium, erbium, ytterbium and lutetium chlorides from metal chlorides.

Samples of cerium chloride $CeCl_3$ in the amount of 176.0 mg; neodymium chloride $NdCl_3$ in the amount of 173.8 mg; samarium chloride $SmCl_3 \cdot 6H_2O$ in the amount of 242.7 mg; gadolinium chloride $GdCl_3$ in the amount of 167.7 mg; holmium chloride $HoCl_3$ in the amount of 164.6 mg; ytterbium chloride $YbCl_3$ in the amount of 161.6 mg; lutetium chloride $SmCl_3 \cdot 6H_2O$ in the amount of 222.6 mg they were placed separately in 100 mL chemical heat-resistant glasses and 20–30 mL of purified water was added to each glass, after complete dissolution of the attachments, the solutions were quantitatively transferred to 100 mL volumetric flasks and brought to the mark with purified water. The concentration of metals in the corresponding solutions was 1 mg/mL.

2.3. Production of rare-earth isotopes by (n,γ) activation

Isotopes ^{90}Y, ^{141}Ce, ^{147}Nd, ^{153}Sm, ^{165}Dy, ^{166}Ho, ^{169}Tm, ^{175}Yb, ^{177}Yb, ^{177}Lu were obtained by bombardment with thermal neutrons from naturally occurring targets at the WWR-K reactor with a neutron flux of $8.09 \cdot 10^{13}$ n·cm^{-2}·s^{-1}. Irradiation was carried out for 2 hours. At the end of the irradiation, the target was cooled for 3 hours.

2.4. Preparation of radioactive solution

For dissolve the irradiated target, 1 mL of 0.1 M hydrochloric acid was fed into the ampoule by a peristaltic pump. The peristaltic pump is connected to a timer that automatically turns off the pump after feeding 1 mL of hydrochloric acid solution. After the acid entered the ampoule, the REE solution was pumped into a 10 mL vial. The dissolution operation was repeated three times for the complete transfer of the dissolved REE into the vial for synthesis.

To carry out irradiation at the WWR-K reactor of the selected group of sample elements weighing from 50 to 200 micrograms, standard sealing was used by the sealing method.

After welding, each ampoule was checked for tightness by the bubble method: immersed in a container heated to 80 °C and were kept for 10 minutes. The absence of air bubbles on the surface of the ampoule testified to its tightness. A sealed ampoule is loaded into a standard pencil case, a standard pencil case for irradiation at the reactor. Figure 1 shows a photo of an ampoule for irradiation.

Figure 1. Ampoule for irradiation

2.5. Radionuclidic purity

Radionuclide purity was determined by the g-spectrum using an HPGe detector. All spectra were recorded at regular intervals in time.

Energy and efficiency calibration in a certain geometry was performed using a standard ^{152}Eu source. The samples were measured for 1 hour.

3. Results and Discussion

Results of measurements of concentrations of dissolved salts of samarium(^{153}Sm), holmium (^{166}Ho), lutetium (^{177}Lu), erbium (^{169}Er), gadolinium (^{153}Gd), neodymium (^{147}Nd) and cerium (^{141}Ce), yttrium (^{90}Y), ytterbium (^{175}Yb) and dysprosium (^{157}Dy) as well as the presence of impurities of other rare earths the elements showed the presence of only the main elements. Impurities of other REES were in quantities below the detection limit, which range from 1 to 10 ng/mL.

For the most promising isotopes, such as: ^{90}Y, ^{141}Ce, ^{147}Nd, ^{153}Sm, ^{165}Dy, ^{166}Ho, ^{169}Tm, ^{175}Yb, ^{177}Yb, ^{177}Lu, the accumulated activity during irradiation in the peripheral channel (thermal neutron flux $8.1 \cdot 10^{13}$ n·cm^{-2}·s^{-1}) was calculated. The formula 1 was used for the calculation:

$$A = \sigma \cdot \Phi \cdot N\left(1 - e^{-\lambda \cdot t}\right), \quad (1)$$

where: A – accumulated activity, Bq; σ – activation cross section, barn; Φ – neutron flux, n·cm^{-2}·s^{-1}; N – number of atoms; λ – decay constant; t – irradiation time.

Calculations have shown that when irradiating samples in the central channel of a reactor with a thermal neutron flux of $2 \cdot 10^{14}$ n·cm^{-2}·s^{-1}, that irradiation for 3–5 days is the optimal time for REE irradiation, since an increase in the irradiation time does not lead to a significant increase in the accumulated activity, while for lutetium it is advisable to carry out irradiation for 21 days, throughout the entire irradiation campaign.

The activity of all promising radioisotopes obtained by irradiating targets of natural composition with a stream of thermal neutrons 24 hours after EOB is shown in Table 2. Calculations were also performed to predict the accumulated activity of various radioisotopes formed by irradiation with thermal neutrons at the WWR-K reactor, which were compared with theoretically calculated values.

Table 2. Activity of various radioisotopes obtained as a result of irradiation with thermal neutrons at the WWR-K reactor

Isotope	Activity	
	A, MBq (Theor.)	A, MBq (Experiment)
^{153}Sm	96431.2	52980.0
^{166}Ho	79666.4	104500.0
^{175}Yb	10486.3	6990.0
^{147}Nd	48.2	39.9
^{177}Lu	25279.4	38400.0
^{46}Sc	3827.9	4530.0
^{141}Ce	31.8	33.9

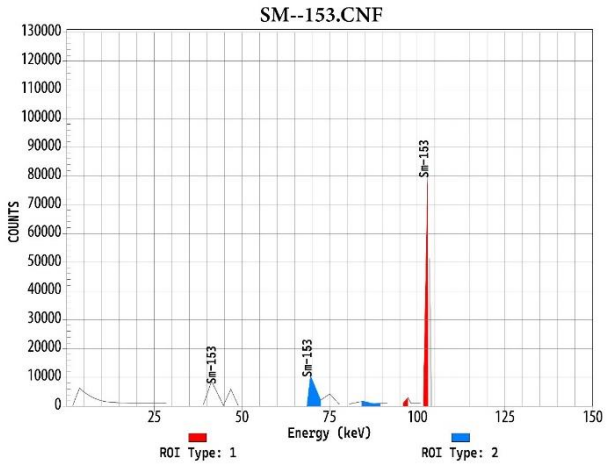

Figure 2. Typical gamma-ray spectra of ^{153}Sm

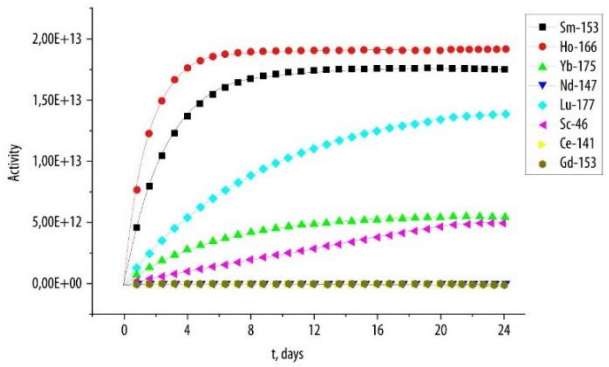

Figure 3. REE operating time schedule

These values were obtained by analyzing the gamma-ray spectra of irradiated samples. Typical gamma-ray spectra are shown in Figure 2. By analyzing all the spectra regularly recorded over a long period of time, it was found that the gamma lines correspond only to ^{153}Sm.

The ^{176}Lu core has a high value of the capture cross-section of both thermal neutrons (2090 barons) and resonant ones (the resonance integral is 1087 barons). This leads to the rapid achievement of a relatively high specific activity of ^{177}Lu. However, as a result of intensive burnout of the nuclei of the starting material during irradiation, the values of the specific activity and the yield (maximum activity) of the reaction product do not coincide.

Figure 3 shows the graphs of isotope production in the peripheral channel of the WWR-K reactor under irradiation of 1 g of each REE element.

Currently, commercially available substances enriched in isotopic composition, including REE compounds, have become available. The transition from compounds of natural isotopic composition to enriched ones makes it possible to develop activities exceeding the capabilities of compounds of the drive composition by several orders of magnitude higher. Table 3 shows the calculated data on the irradiation of some REE compounds of natural and enriched compositions, with a neutron flux of $8.09 \cdot 10^{13}$ n·cm^{-2}·s^{-1}, for 2 hours.

Table 3. Example of possibilities production some of REE isotope at the WWR-K reactor

Isotope (target enrichment)	Specific activity, Bq/g
^{153}Sm (natural)	521.25
^{153}Sm (98,7%)	1923.26
^{175}Yb (natural)	77.22
^{175}Yb (99,3%)	240.90
^{147}Nd (natural)	0.42
^{147}Nd (98,8%)	2.44
^{177}Lu (natural)	133.75
^{177}Lu (88,4%)	4565.18
^{141}Ce (natural)	0.32
^{141}Ce (99,88%)	0.36

4. CONCLUSION

The present study shows the possibility of developing promising isotopes of rare earth elements (^{90}Y, ^{141}Ce, ^{147}Nd, ^{153}Sm, ^{165}Dy, ^{166}Ho, ^{169}Tm, ^{175}Yb, ^{177}Yb, ^{177}Lu) at the WWR-K reactor with an average neutron flux to obtain a high specific activity of the radioisotopes of interest. The paper shows data on the irradiation of REE of natural composition and compared with calculations for enriched targets.

Obtaining REE solutions by dissolving in simple mineral acids makes it possible to obtain a radiochemically pure product.

However, the radionuclide purity will be in the range of 95–96%. Our laboratory is already working on the development of compounds labeled with promising REE isotopes for various therapeutic applications.

The analysis showed that irradiation for 3–5 days is the optimal irradiation time for samarium, holmium and erbium, since an increase in the irradiation time does not lead to a significant increase in the accumulated activity, while for lutetium it is advisable to irradiate for 21 days, throughout the entire campaign.

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ССР-К ЗЕРТТЕУ РЕАКТОРЫНДА СИРЕК ЖЕР ИЗОТОПТАРЫН АЛУДЫ ТАЛДАУ: ПЕРСПЕКТИВАЛЫ ТЕРАПЕВТІК РАДИОНУКЛИДТЕР

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Сирек жер элементтері – лантаноидтар, скандий және иттрий сияқты периодтық жүйенің он жеті химиялық элементтерінің тобы. Бұл элементтер электроника, магниттер және катализаторларды қоса алғанда, әртүрлі салаларда құнды ететін бірегей физикалық және химиялық қасиеттерге ие. Дегенмен, сирек жер элементтерінің радиоактивті изотоптары да тиімді ядролық-физикалық қасиеттерге ие, бұл оларды терапевтік мақсаттағы жаңа радиофармацевтикалық препараттарды әзірлеуге перспективалы етеді. Бұл радиоактивті изотоптардың құрамында артық атом энергиясы бар тұрақсыз атомдар бар және олар медициналық мақсатта пайдаланылуы мүмкін радиоактивті ыдырауға ұшырайды.

Сирек жер элементтерінің радиоактивті изотоптарының ядролық-физикалық қасиеттері оларды медицинада емдік мақсаттарға жарамды етеді. Мысалы, технеций-99м, технецийдің радиоактивті изотопы, өзінің керемет физика-химиялық сипаттамаларына байланысты диагностикалық ядролық медицинада кеңінен қолданылады. Сирек жер элементтерінің басқа радиоактивті изотоптары, мысалы, гольмий-166, медициналық қолданудың кең ауқымы үшін жасалған. Бұл изотоптарды әртүрлі ауруларды, соның ішінде онкологиялық ауруларды емдеу үшін мақсатты сәулелік терапияда қолдануға болады. Бұл радиоактивті изотоптардың бірегей қасиеттері сәулеленуді белгілі бір тіндерге немесе жасушаларға дәл бағыттауға және жеткізуге мүмкіндік береді, сау тіндердің зақымдануын азайтады.

Сирек жер элементтерінің радиоактивті изотоптарының терапевтік мақсаттағы әлеуеті қолданыстағы қолданудан асып түседі. Радиофармацевтика саласындағы қазіргі зерттеулер мен инновациялар лантаноидты радионуклидтерді тераностикалық мақсатта қолдануды зерттеуді жалғастыруда. Мысалы, сирек кездесетін және радиоактивті элемент болып табылатын астатта адрестік терапияда қолданылуы мүмкін көптеген изотоптар бар. Сирек жер элементтерінің радиоактивті изотоптарын пайдалана отырып, жаңа радиофармацевтикалық препараттарды әзірлеу емдеу әдістерін жетілдіруге және пациенттердің нәтижелерін жақсартуға уәде береді. Қосымша зерттеулер мен жетістіктермен бұл изотоптар терапевтік медицинаның болашағында шешуші рөл атқаруы мүмкін.

Бұл зерттеу жұмысы ССР-К реакторында реакция (n, γ) арқылы ^{90}Y, ^{141}Ce, ^{147}Nd, ^{153}Sm, ^{165}Dy, ^{166}Ho, ^{169}Tm, ^{175}Yb, ^{177}Yb, ^{177}Lu сияқты радиоизотоптарды алу мүмкіндігін бағалауға мүмкіндік береді.

Түйін сөздер: *сирек жер изотоптары; ССР-К зерттеу реакторы; нейтрондық сәулелену; меншікті белсенділік; тікелей ядролық реакция.*

АНАЛИЗ ПОЛУЧЕНИЯ РЕДКОЗЕМЕЛЬНЫХ ИЗОТОПОВ НА ИССЛЕДОВАТЕЛЬСКОМ РЕАКТОРЕ ВВР-К: ПЕРСПЕКТИВНЫЕ ТЕРАПЕВТИЧЕСКИЕ РАДИОНУКЛИДЫ

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Редкоземельные элементы (РЗЭ) – это группа из семнадцати химических элементов периодической таблицы Менделеева, включая лантаноиды, скандий и иттрий. Эти элементы обладают уникальными физическими и химическими свойствами, которые делают их ценными в различных отраслях промышленности, включая электронику, магниты и катализаторы. Однако радиоактивные изотопы редкоземельных элементов также обладают эффективными ядерно-физическими свойствами, которые делают их перспективными для разработки новых радиофармпрепаратов терапевтического назначения. Эти радиоактивные изотопы содержат нестабильные атомы с избыточной ядерной энергией, и они подвергаются радиоактивному распаду, который может быть использован в медицинских целях.

Ядерно-физические свойства радиоактивных изотопов редкоземельных элементов делают их пригодными для терапевтических целей в медицине. Например, технеций-99m, радиоактивный изотоп технеция, широко используется в диагностической ядерной медицине благодаря своим выдающимся физико-химическим характеристикам. Другие радиоактивные изотопы редкоземельных элементов, такие как гольмий-166, были созданы для широкого спектра медицинских применений. Эти изотопы могут быть использованы в адресной лучевой терапии для лечения различных заболеваний, включая онкологические. Уникальные свойства этих радиоактивных изотопов позволяют точно нацеливать и доставлять излучение к определенным тканям или клеткам, сводя к минимуму повреждение здоровых тканей.

Потенциал радиоактивных изотопов редкоземельных элементов в терапевтических целях выходит за рамки существующих применений. Текущие исследования и инновации в области радиофармпрепаратов продолжают изучать использование недоиспользуемых радионуклидов лантаноидов в тераностических целях. Например, астат, редкий и высокорадиоактивный элемент, содержит множество изотопов, которые потенциально могут быть использованы в адресной терапии. Разработка новых радиофармпрепаратов с использованием радиоактивных изотопов редкоземельных элементов обещает усовершенствовать методы лечения и улучшить результаты лечения пациентов. При дальнейших исследованиях и достижениях эти изотопы могут сыграть решающую роль в будущем терапевтической медицины.

Данная исследовательская работа позволяет оценить возможность получения таких радиоизотопов, как: ^{90}Y, ^{141}Ce, ^{147}Nd, ^{153}Sm, ^{165}Dy, ^{166}Ho, ^{169}Tm, ^{175}Yb, ^{177}Yb, ^{177}Lu путем реакции (n, γ) на реакторе ВВР-К.

Ключевые слова: *редкоземельные изотопы; исследовательский реактор ВВР-К; нейтронное облучение; удельная активность; прямая ядерная реакция.*