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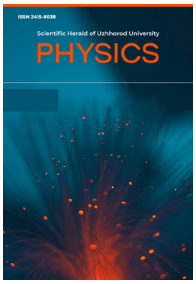

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Research of spallation reaction on plutonium target irradiated by protons with energy of 660 MeV

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Abstract

Relevance. This paper describes the measurement of the cross sections of the fission and fragmentation reactions of a plutonium target irradiated with a series of protons characterized by an energy of 660 MeV at the Phazotron accelerator of the Joint Institute for Nuclear Research.

Purpose. The experiment focuses on the determination of short-lived radionuclides.

Methods. The experimental sample was measured in offline mode using gamma spectrometry with HPGe detector. The reaction rates of the formed residual nuclei were studied. The products of spallation reaction were determined with the help of the direct kinematics method. The DEIMOS32 software was used to process γ-spectra.

Results. As a result of the interaction of nuclear elements with protons, nuclei were formed in the ^{239}Pu sample. Those nuclei were identified using the TJ02000321–V3 software. The reaction products were identified based on gamma energies, intensity and half-life after the measurement set. During the study of the gamma spectra determined for the irradiated plutonium target, it was possible to establish 50 gamma lines and reveal 31 nuclides by energy and half-life cycles from 14.4 m to 3.19 h. The measured nuclear reaction cross-sections can serve as reference data for theoretical simulations of the interaction of protons with ^{239}Pu and they can be a supplement to the nuclear databases.

Conclusions. The obtained experimental result is compared with the simulation on MCNP 6.1. The data overall correspond to the expected range, but it still needs more evaluation. The next logical step is to search for primary products (mother nuclei) and compare the obtained experimental data with the results of computer simulations

Keywords: Phasotron accelerator, TJ02000321–V3 software, gamma spectra, radionuclides, γ-spectroscopy, accelerator-driven systems

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Introduction

Given the large number of nuclear power plants around the world and plans to build new ones, it is safe to say that nuclear power continues to play an important role in the industry. At the same time, one of the biggest problems facing nuclear energy is still highly radioactive material produced during energy production.

An extremely important place in the policy of the world's leading states is occupied by the environmental vector, namely processing and working with waste generated during the operation of nuclear power plants. The issue of processing or domestic sale of weapons of plutonium and highly enriched uranium is urgent among the international community. This is especially true of countries that possess nuclear weapons, which brings about constant updating of approaches to the regulation of this sphere. Such programs will be developed in Europe, North America, Japan and russia [1-3]. According to the IAEA, in 2018 the volume of all exploited nuclear fuel in the world has reached 330.000 tons [4].

The composition of exploited energy resources includes uranium (≈96%), plutonium (≈1%) and high-level radioactive waste (≈3%). Uranium with a fission of less than 1% ^{235}U and plutonium can be reused. The products formed as a result of the exploitation of energy resources and their processing should be classified depending on their chemical composition into uranium, plutonium, and high-level waste.

Plutonium is the only transuranic element that is released and used on a large scale. Plutonium is better as a fuel for energy production because the fission reaction of one nucleus usually forms 3 new neutrons. Plutonium can be used in nuclear reactors from two sources: as a fission product in reactors of ^{238}U isotope; or excess plutonium created for atomic bombs [5]. By solving the problems and issues that arise in nuclear policy, with the help of nuclear fission energy, it is possible to provide permanent electric resources with a base load.

Accelerator-driven nuclear cross-section (ADS) data obtained by the subcritical system will help future researchers in the field of nuclear technology [6]. As for solving the issue of transmutation of highly active nuclear products, it is advisable to implement this process based on the approach using accelerators (ADS). These systems have a higher margin of safety due to their ability to stop the chain reaction by stopping the supply of protons.

Materials and Methods

In this experiment, direct kinematics method [7; 8] was used for determining spallation products. In this method, relativistic light projectile hits a heavy target. Using γ-spectroscopy and mass spectrometry, the cleavage products are detected and stopped at the target. Gamma-ray spectrometry is used to identify radionuclides and to measure their activity. Gamma-ray spectra were obtained from experimental results and prepared using the DEIMOS program. The spectrum is the main part of determining the experimental rates of the reaction products.

As a result of the implementation of the intranuclear cycle, as well as differentiation, fragmentation, evaporation of light nuclei and nucleons, the nuclei of the operated object are formed in connection with protons located in the target nucleus. The general form for this process is:

$$ {}^{A_T}_{Z_T}T(p,x){}^{A}_{Z}N \tag{1}$$

where, (p, x) expresses the type of nuclear reaction, T and N are the chemical objects of the target nucleus and the element, AT and ZT are the mass number and charge of the target nuclide, A and Z are the mass number and charge of the nuclide resulting from the nuclear reaction. The yields of radioactive products nuclear reaction are determining:

$$R = \sigma(E) \cdot \Phi(E) \tag{2}$$

where σ(E) – cross sections of a nuclide production and Φ(E) is the proton flux density.

The number of formed residual nuclei Q (Ar, Zr) per atom in the sample N_A and one incident deuteron per second N_D form the reaction rate, which is determined by the equation (Fig. 1).

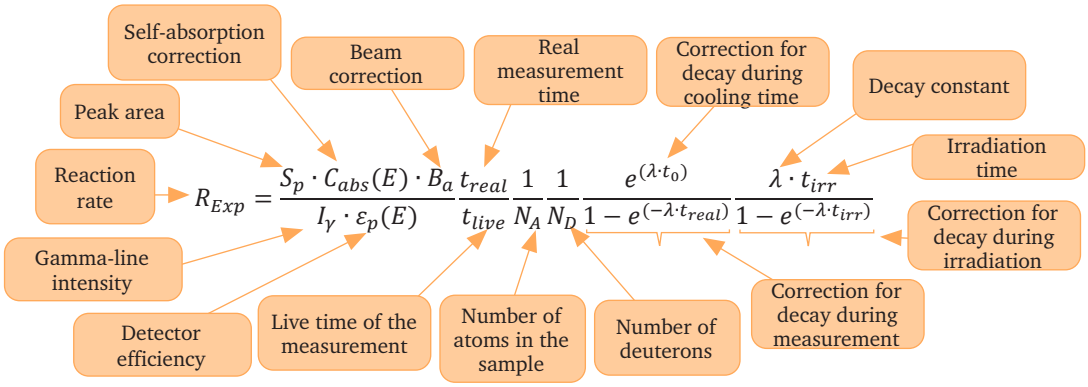

Figure 1. Reaction rate formula

Source: [9]

The effective cross-section of the reaction σ expresses the probability of this transformation in 1 s when the nucleus is bombarded with a flux density of 1 particle in 1 s per 1 cm^2. If N nuclei are contained in the target and the flux of I particles per 1 cm^2 per s falls on it, then σ*NI* of nuclear transformations per 1 s occurs. The total effective cross section is the sum of the cross sections of the processes on all channels:

$$\sigma = \sigma_b + \sigma_c + \cdots \quad (3)$$

The reaction depends on the effective heat cross section of the incident particle, which is important:

$$\sigma = f(E) \quad (4)$$

In real physical experiments, it is not always possible to directly measure the effective cross section. The directly measured value is the yield of the reaction. The output of the nuclear reaction B at a given energy of the falling particles is the ratio of the number of acts of reaction that occurred to the number of particles that fell on the target, provided that all target nuclei fall the same stream of bombarding particles. The yield can be calculated if the known effective cross section of the process σ:

$$B = \frac{I_0 - I}{I_0} = \frac{I_0(1-e^{-\sigma n})}{I_0} = 1 - e^{-\sigma n} \approx \sigma n \quad (5)$$

For targets of complex isotopic composition and targets in which the studied isotope is part of a chemical compound, there is the following formula for calculating the cross section:

$$\sigma_a\left(E_\gamma(j)\right) = \frac{S_\gamma(E_\gamma(j))\lambda_a x \frac{t_{r,i}}{t_{l,i}}}{N_p N_{targ}\varepsilon_\gamma I_\gamma\left(E_\gamma(j)\right)(1-e^{-\lambda_a\tau_1})e^{-\lambda_p t_{2,i}}(1-e^{-\lambda_a t_{r,i}})}, \quad (6)$$

$\lambda_a[c^{-1}]$ – is the decay constant for the nucleus a; $\varepsilon_\gamma(E_\gamma(j))$ absolute efficiency of registration of γ-quanta with energy $E_\gamma(j)$; $I_\gamma\left(E_\gamma(j)\right)$ – intensity of gamma ray decay with energy $E_\gamma(j)$;τ_1, t_2, $t_{r,i}$, $t_{l,i}$ – exposure time, delay, real and real measurement time, respectively.

The ratio between the cross sections of the daughter product and the main maternal product σ_a [10]:

$$S_\gamma(E_{\gamma,i}) = \{Ae^{-\lambda_a t_2(i)}\left(1-e^{-\lambda_a t_{3,r}(i)}\right) + Be^{-\lambda_b t_2(i)}\left(1-e^{-\lambda_b t_{3,r}(i)}\right)\}\frac{t_{3(l,i)}}{t_{3(r,i)}} \quad (7)$$

Experimental setup

The experiment was carried out at the Phasotron at the Joint Institute for Nuclear Research (JINR) in Dubna. The experiment is to irradiate a thin target composed of a mixture of PuO_2 with Al. Irradiation of the plutonium target occurred on the external proton beam with an energy of 660 MeV. The target was made according to the sandwich geometry of plutonium and aluminium product. The size of the object is Ø21x1.5 mm, it consists of ^{239}Pu foil, and its mass is 446 mg. At the same time, the thickness of the foil is about 58.1 microns. Three aluminium foils served as a monitor for the incident proton beam, and one as a collector of plutonium target fragmentation nuclides (Fig. 2).

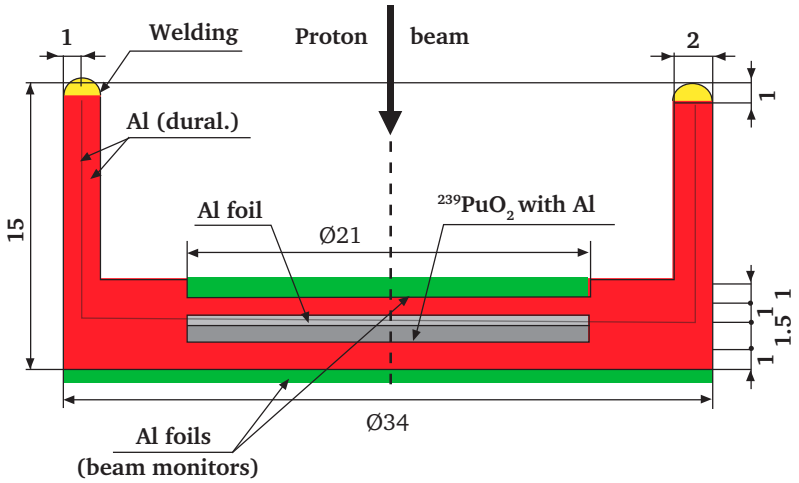

Figure 2. Arrangement and description of the plutonium target

Using Phasotron, the experimental samples were irradiated [11]. This device is a cyclic accelerator of heavy charged protons, which allows elements to carry out motor activity in a constant and uniform magnetic field, as well as to accelerate in a high-frequency electric field, which decreases in frequency. An accelerated series of protons provided an energy of 660 MeV. During the irradiation cycle, the tray with the sample sandwich inside was taped to the centre of a 50x50 mm, 0.1 mm thick aluminium plate placed on the fixture perpendicular to the protons. This position prevents the accumulation of ^{24}Na, ^{22}Na and ^{7}Be appearing on the Al monitor. All control over the intensity of the proton beam is provided by the monitor. Table 1 shows the exposure indicators of ^{239}Pu.

Table 1. Indicators of ^{239}Pu target irradiation

Energy, (MeV)	Mass of sample, (g)	Irradiation time, (min)	Integrated proton flux, p/(cm^2·s)x 10^{13}	Output beam current, mA
660	446	5.25	4.9 ± 0.1	2.02

Irradiation lasted 5.25 min; the experiment was performed after 12 minutes of experiment with Uranium. The integral flow of protons was (4.9 ± 0.1) 1013 as a result of starting a current of 2.02 mA in the output beam. The beam parameters are especially important for determination of the decay of short-lived nuclei during irradiation.

As a result of the irradiation, the objects were removed from the phasotron camera and placed on the spectroscopic mechanism of the YaSNPP-2. After that, the characteristic gamma radiation spectra of the released residual nuclei in the target were measured, in particular along the 1332 keV vector with a power of 19% and 1.78 keV of the CANBERRA HPGe detector. Due to the high activity of the sample, the irradiation was carried out at a great distance from the detector.

The transfer time of the plate to the detectors was not more than 10 minutes. The measuring position was chosen so that the dead time of the detector did not exceed 20%, and in the case of active samples did not reach much below 10%. As for actinides, which often have their own low-energy gamma particle, this use of the filter is very advantageous. Filters made of lead sheets provide the absorption of higher energies of gamma quanta. It is advisable to supplement them with filters with a smaller number of nucleons (Cd, Cu), which absorb X-rays excited in lead.

The study calculated the average proton flux density. With the help of activated aluminium films, the verification and control of the proton beam was implemented for the reactions ^{27}Al (p, 3pn) ^{24}Na, ^{27}Al (p, 3p3n+) ^{22}Na, ^{27}Al (p, 10p11n+)^{7}Be. A monitoring reaction was used for this purpose ^{27}Al (p, 3pn) ^{24}Na. Insights into the effective cross section on the Al plate reaction and their small energy dependence at high energies were used to monitor the number of protons trapped of the p + Al.

However, ^{27}Al (p, 3pn) ^{24}Na reaction is usually affected by the parasitic neutron reaction ^{27}Al (n, α) ^{24}Na. The effect depends on the distance of the aluminium foil from the system, and with a reasonable choice it is effect is in the order of units or tenths of a percent. Control can be carried out by reactions of ^{27}Al (p, 3p3n) ^{22}Na and ^{27}Al (p, 10p11n) ^{7}Be. When placing the film directly on the target, it can give these reactions 30% less proton integral (Table 2).

Table 2. The neutron- and proton-induced yields are calculated in the ratio of ^{24}Na, ^{22}Na and ^{7}Be formed in ^{27}Al+p

Degrader	Nuclide	$\overline{\sigma_n}$(mb)	σ_p (mb)	$\frac{N_n}{N_p}$	R (%)
Al	24Na	31.1	11.4	0.0301	8.21
	22Na	12.8	18.1		2.13
	7Be	0.0143	0.99		0.043

Source: [12]

Data calculation and evaluation

During the experiment, DEIMOS32 software was used for processing γ-spectra. DEIMOS32 software was developed at the Institute of Nuclear Physics in the Czech Republic (Rzezh) and at the Joint Institute for Nuclear Research in Dubna, was used to process γ-spectra [12]. Thanks to this software, it was possible to analyse and evaluate the peaks, their size and other indicators. In addition, an examination and detection of short-lived radionuclides formed in ^{239}Pu samples as a result of nuclear interaction with protons was carried out. The last process was implemented on the basis of a number of scripts belonging to the Ruby programming language (TimeConst, AttCor, EffCor, MidLit5, NonLin64, PureGam, SepDepe, SigmaJ7). The output files of each program in the package are input files for the next, and they must be in the root folder of the corresponding program, so the output files must be copied to the root of the program for which this file is input.

The study used the program EFEKT8.EXE, which determined the effectiveness of the HPGe detector. At high gamma radiation energy, annihilation radiation can leak out. After creating a positron-electron pair, the positron annihilates and creates two annihilation photons 511 keV. In germanium detectors, there is a high probability that one of the peaks of destruction will escape. If one of the photons escapes, one output peak (SEP) will appear in the measured spectrum. If both photons escape, a double output peak (DEP) will result.

The peak area of SEP or DEP can be determined according to the area of peak E at full energy:

$$S(E_{SEP}) = S(E_\gamma) * \epsilon_{SEP}(E_\gamma) \quad (8)$$

$$S(E_{DEP}) = S(E_\gamma) * \epsilon_{DEP}(E_\gamma) \quad (9)$$

ϵ_{SEP},ϵ_{DEP} are single and double-peak coefficients determined experimentally. These coefficients are independent of the distance of the target to the detector. The dependence of ϵ_{EP} on the peak energy is shown in the Figure 3.

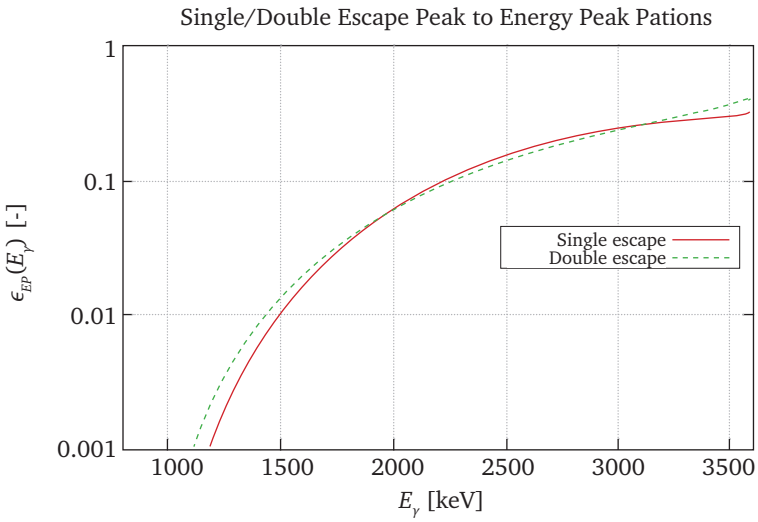

Figure 3. Experimentally determined dependency of SEP/DEP and full-peak area ratios on full-peak energy E_γ

Source: [13]

The parameters set by the program EFFEKT8 are given in the Table 3. The experimentally measured points were determined by formula:

$$\epsilon_{EP}(E_\gamma) = \exp\left(s_0 + s_1 * \ln(E_\gamma) + s_2 \ln(E_\gamma)^2 + s_3 \ln(E_\gamma)^3\right) \quad (10)$$

Table 3. Experimentally determined parameters $\epsilon_{EP}(E_\gamma)$ of the function

	SEP		DEP	
i	Si [-]	ΔSi [-]	Si [-]	ΔSi [-]
0	-2.0866027851	0.2860230743	-1.3273140355	0.1814312750
1	13.8832738535	1.1099975243	12.8053750577	0.8383854495
2	-8.2291578426	1.3992857931	-8.9129115117	1.1473203273
3	1.7178618884	0.5675750337	2.6470549618	0.4847393276

Source: [14]

The program that is responsible for correcting the efficiency of the detector. This amendment (η_e (E_γ)) is defined by the formula:

$$\eta_e(E_\gamma) = \exp(a_0 + \sum_{i=1}^{np} a_i ln^i(E_\gamma)) \quad (11)$$

a_i – parameters of the efficiency curve, estimated using the program EFFEKT8.EXE after a series of measurements calibration standards and E – gamma peak energy.

In the study AD4HEL – Activation Detectors for High Energy Lasers [15] program was used. This is a special program for the analysis of the spectrum of neutrons generated by the laser. Software developed on the basis of the Brno University of Technology, located in the Czech Republic. Only “prn” format is supported. This program gives possibility to calculate production/reaction rate: unit of production rate is the number of reactions in sample per 1 second and reaction rate is number of reactions normalised per one incident particle and one atom of foil (need integral flux). Some values and results are saved in the “.xlsx” file in the “out” folder.

Based on the energies of γ-rays Co-57, Eu-152, Co-60, Ra-226, Cd-109 and Ba-133, which have the required energy range, the quality (ε) of the structure of the HPGe detector was revealed. In parallel, the efficiency calibration can be performed in order to obtain not only the range of energy value but in the future also the values of the activity of the sample and radionuclide impurities. The change in the efficiency index with the heat of γ-radiation is not characterized by the location of the detector, although its absolute value is correlated with this feature.

Efficiency calibration: mathematical fitting 43 experimental values (points) in the 121-to-2614 keV range (Fig. 4). Fitting coefficients were determined for each position, which used to further calculate the result (Table 4).

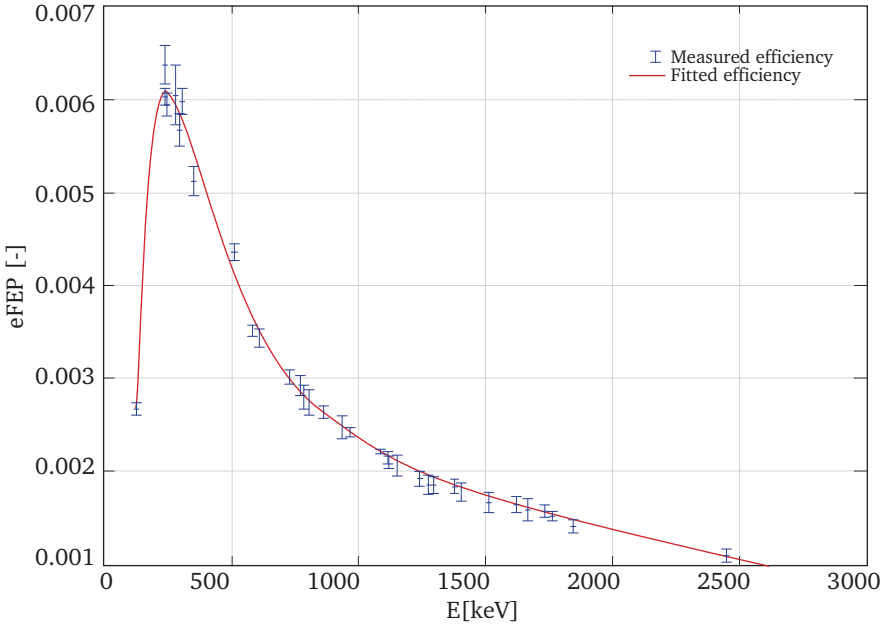

Figure 4. Efficiency calibration obtained with help of the Python scripts

Table 4. Efficiency fit coefficients of the HPGe-detector for example Position 2

a0	6.43425653
a1	-0.78928838
a2	0.09669678
a3	-0.20612789
a4	-0.440179361
a5	0.08561548
a6	0.25554557
a7	0.08057409

Results and Discussion

50 gamma lines and 31 nuclides (see Figs. 5, 6) were established as a result of the examination of 21 gamma spectra described for the irradiated plutonium target. During this process, the energy and half-life ranged from 14.4 m to 3.19 h. The investigated nuclides are characterized by indicators from 41-239 with gaps in indicators 41-149 and 197-239.A sample of ^{239}Pu was subjected to fragmentation during neutron irradiation. The latter was formed in an aluminium target. Quantitative materials for 31 nuclides were described with a wide range of plutonium fission elements:^{92}Sr, ^{89}Rb, ^{98m}Nb, ^{101}Mo, ^{95}Ru, ^{135m}Cs, ^{118m}Sb, ^{134}Te, ^{134}I, ^{130}La, ^{201}Bi and other. The results of isomers are shown in Table 5. All obtained nuclides are shown Figure 5-6. Also, ^{24}Na was obtained which formed in the aluminium foils.

Table 5. List of isomers with their cross-section

Isotope	E, keV	Iγ, %	RR, s^{-1}	dRR, s^{-1}	∑σ, b	dσ, b	$T_{1/2table,}$ h	$T_{1/2exp,}$ h
^{98m}Nb	722	73.8	2.63E-29	1.47E-30	2.33E-05	1.23E-06	0.85	1.56
	787	93	3.08E-29	1.64E-30			0.85	0.8
	1169	17.8	4.96E-30	3.25E-31			0.85	1.26
^{91m}Y	555	95	1.48E-29	1.34E-30	5.12E-05	2.36E-06	0.83	1.3
^{90m}Y	479		7.27E-30	3.67E-31	2.52E-05	9.79E-07	3.19	3.49
^{116m}In	1293	84.44	5.31E-29	2.79E-30	2.74E-05	7.31E-07	0.9	0.93
	1097	56.2	8.52E-30	4.50E-31			0.9	0.91
	2112	15.5	6.48E-30	4.33E-31			0.9	1.62
^{116m}Sb	843	11.2	1.08E-29	2.24E-30	4.15E-05	1.79E-06	1	0.16

Table 5, Continued

Isotope	E, keV	Iγ, %	RR, s^{-1}	dRR, s^{-1}	∑σ, b	dσ, b	$T_{1/2table,}$ h	$T_{1/2exp,}$ h
	1293	100	1.02E-28	1.27E-29			1	0.94
^{135m}Cs	846	95.9	3.37E-30	4.79E-31	1.79E-05	4.79E-07	0.88	0.67
	786	100	4.58E-30	1.83E-30			0.88	0.89
^{201m}Bi	846.833	5	1.77E-28	1.21E-29	9.87E-05	4.45E-06	0.98	1.33

Note: $\sum \sigma, b$ – *the sum of cross-section of all γ-lines for one isomer (b-barn)*

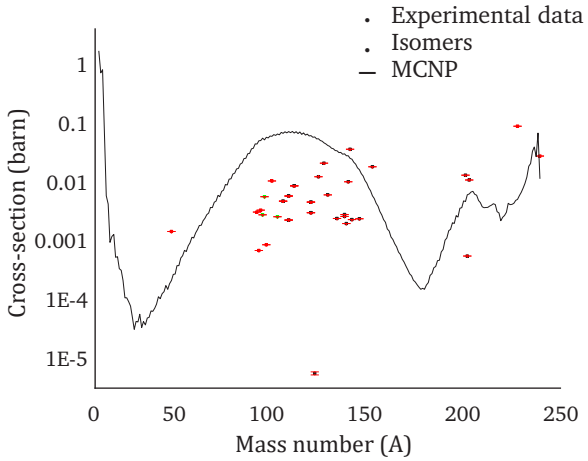

Figure 5. Calculated and experimental cross-sections of created isotopes in irradiated ^{239}Pu target

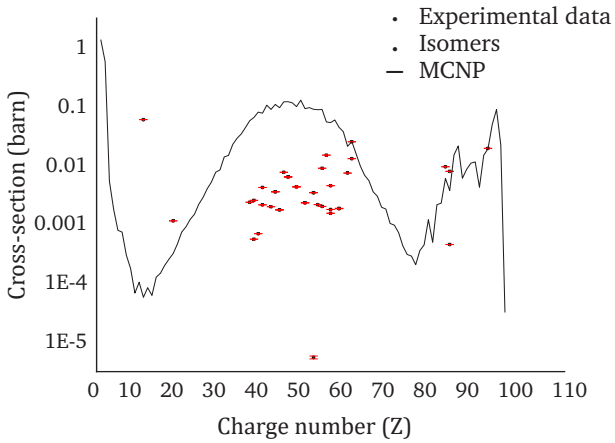

Figure 6. Calculated and experimental cross-sections of created isotopes in irradiated ^{239}Pu target

In Figures 5-6 the red points are experimental data, and the green points are obtained isomers. The figures reveal the researched and developed cross-sections of short-lived radionuclides that were identified in the ^{239}Pu target. The latter, in turn, was irradiated with a beam of 660 MeV protons.

As it was mentioned before, plutonium is widely used in the nuclear industry as a component for nuclear weapon, fuel for nuclear reactors, as well as an energy source for space devices. Therefore, the need for experimentation for the plutonium study, its behaviour in reaction time, such as nuclear fission, is increased.

Most of the heavier elements, such as plutonium, uranium and others, fission under the influence of protons, if the proton energy is high enough to overcome the nucleus Coulomb repulsion. In the work carried out, the plutonium target was bombarded with a number of protons characterized by an energy of 660 MeV. As a result of the conducted research, it was possible to establish 50 gamma-lines and reveal 31 nuclides, the obtained results are confirmed by the data presented in the previous section.

In order to compare the obtained research results, their confirmation or refutation, an analysis of works in this field by other authors over the last few years of publication was carried out. Since the reaction of nuclear fission belongs to multifaceted cycles, which are affected by a number of indicators, therefore a rather small number of works have been covered in this area.

In their study, J. Adam et al. [16] studied the transmutation of ^{238}Pu and ^{239}Pu and other radioactive chemical elements such as ^{129}I, ^{237}Np, and ^{241}Am. During the work, the "Energy and Transmutation" target was irradiated with a number of protons. In turn, the latter were formed from the Nuclotron accelerator. The research was conducted in russia, namely at the High Energy Physics Laboratory of the Joint Institute for Nuclear Research in Dubna. In the neutron field, outside the blanket, and the outputs of transmutation reactions (the outputs of the formation of residual nuclei) were determined using γ-spectroscopy, it was possible to irradiate samples of radioactive iodine, neptunium, plutonium, and americium. An examination of the energy distribution of the neutron field was carried out, based on a number of threshold detectors. According to the authors, the results of this scientific work are among the primary indicators of plutonium transmutation in the "Energy and Transmutation" target-blanket system. According to the work results, ^{238}Pu has a smaller fission cross-section than ^{239}Pu in the energy region below 0.5 MeV. Five ^{238}Pu fission products and 19 ^{239}Pu fission products are observed.

Another work by J.-S. Wang et al. [17] was aimed at researching transmutation. In this work, the transmutation of ^{239}Pu and similar differentiated elements ^{91}Sr, ^{92}Sr, ^{97}Zr, ^{99}Mo, ^{103}Ru, ^{105}Ru, ^{129}Sb, ^{132}Te, ^{133}I, ^{135}I and ^{143}Ce was investigated. The research was conducted on the basis of the Joint Institute for Nuclear Research in Dubna. For a beam of protons, the

energy of which corresponds to 1.0 GeV, the differentiation dynamics of ^{239}Pu was 0.0032 atoms per proton in plutonium samples weighing 1 g; for a proton with an energy of 0.53 GeV is about 0.0022. The studied error can reach 15%. Surveys are analysed and evaluated based on the numerical data of a pair of theoretical models with negligible efficiency with the implementation of the Duben Cascade Model (CEM) and the LAHET code.

A. Al-Adili et al. [18] in their work studied the effect of corrections for prompt neutrons on the final fission fragments distributions. According to the authors, the multiplicity of fast neutrons also depends on the weight of the fragment and the kinetic energy of fragmentation. These indicators are characteristic of a small number of fission reactions under the influence of thermal neutrons. As a result of their study, the authors concluded that establishing an approach to neutron operations played an important role in the context of the nature and planning of the differentiation reaction. In this way, it affects the formation of new surveys that concern the calculations of fission fragments, which are more similar to fission neutrons. In addition, the qualitative analysis of the output of post-neutron fragments affects the correct assessment of the processing of nuclear surplus products and the effective selection of methods for the output of precursors of late neutrons.

J.P. Lestone [19] developed the interpolation method between and/or extrapolation from two fission product yield curves to the first chance neutron emission of mass-asymmetric fission. Measured spontaneous fission of ^{240}Pu, as well as thermal neutron fission of ^{239}Pu fission element excesses (FPY) are determined to establish the probable energy interaction and n + ^{239}Pu FPY for incident neutron characteristics from 0 to 16 MeV. As a result, the inclusion of innovations related to mass-symmetric differentiation, neutron emission, and multi-hour fission revealed by the FPY model are described with the data and estimate of ENDF/B-VII.1. In addition, the model is provided with the ability to reproduce the energy dependence of the ENDF/B-VII.1 estimate, indicating that the weight classification of differentiated plutonium is not fixed on the plane of the fission barrier, but is characterized by heat and surface nuclear potential energy, especially during significant changes.

Research by D. Neudecker et al. [20] was aimed at evaluating the energy spectra of neutrons emitted instantaneously as a result of the differentiation of ^{235}U and ^{239}Pu. Neutron energy spectra were reanalysed for ENDF/B-VIII.0. Complementing the considered data, which is published and characteristic of ENDF/B-VII.1, relevant surveys are disclosed in the context of experimental specific indicators or concerning a number of properties of incident energy, materials on deformed measurements that reveal differences. In addition, the factors affecting the size and distribution of the total kinetic energy from the energy tasks of the incident neutron were determined. The considered and proven numerical materials and covariances fully correspond to the studied amount of information that affects the conduct of the survey and the establishment of the assessment.

M. Alrwashdeh [21] analyzed ^{239}Pu based on the SAMMY code for neutron operations in the resonance plane up to 2.5 keV. In state 8.0.0 of the SAMMY code, the handling of wide covariance matrices of opposite parameters was developed. The value of this article lies in the analysis of the investigated information using the specially formed fitting code of the studied nuclear materials FITWR and their analysis using the SAMMY code, as well as the evaluation of indicators with the Bayesian approach. The output of these methods is based on the SAMMY code, in order to reveal the opposite parameters of the covariance matrix within the range of energies from 0 to 2.5 keV. Thus, the experiments conducted within this paper were conducted at the IMAN1 facility, the Jordan National Supercomputing Centre (IMAN1).

As it can be seen from the literature analysis, most of the work was aimed at studying the transmutation of ^{239}Pu, while in the carried out experimental work the main vector was aimed at studying the reaction of fragmentation and fission of the ^{239}Pu nucleus at an energy of 660 MeV. Nuclear fission, fragmentation and transmutation are interrelated processes. The key difference between these concepts is that fission is the process of nuclear fission, fragmentation is the process of ions dissociation from molecules, and transmutation is the process of transformation of one nucleus into another, as a result of nuclear reactions. The study of the radioactive element behaviour in induced processes is a very important part of the experiments.

In comparison with previous studies, it can be emphasised that this work confirms the results obtained earlier. It can also be noted that this work complements the previous study and is exclusive in its kind.

The next logical step in conducting experimental work is the search for primary products (mother cores) and the evaluation of the received information in accordance with computer modelling materials. Also, it will be very important to conduct a study on the study of plutonium fission under the influence of deuterons, or under the action of slow neutrons.

Conclusions

In this experiment, the reactions of fragmentation and fission of the ^{239}Pu nucleus at the energy of 660 MeV were investigated. The experiment focuses on the determination of short-lived radionuclides. Irradiation of the sample took place on a direct proton beam by means of activation gamma spectrometry and so-called direct kinematics. This measurement method has been used for a long time for very accurate and complete measurement of the effective cross sections

of nuclear reaction nuclei under special conditions, namely high heat. When measuring the qualitative distribution of the exploitation of protons with ^{239}Pu nuclei by γ-spectroscopy and mass spectrometry methods, the arrival of protons into the plutonium target is detected, after which residual products are formed that stop in the target.

In total, 85 spectra were measured as a result of the experiment. The survey and calculations were carried out on different planes based on two HPGe detectors from CANBERRA and ORTEC, the efficiency of which is from 19% to 33%, and the resolution is from 1.78 keV to 1.86 keV along the 1332 keV line. The calculations were divided into two parts (1-5 positions by CANBERRA detector, 6-9 positions by ORTEC detector) to avoid overlap of energy lines, accurate identification of radionuclides, and due to different characteristics of the used detectors (efficiency, nonlinearity, etc.). For a complete picture of the formed radionuclides, it is necessary to calculate the results separately.

Therefore, as a result of the examination of 21 gamma spectra calculated by the Canberra detector, during the study of the plutonium target that was irradiated, 31 nuclides were identified, for which the reaction rate and effective cross sections were determined. Figure 5-6 shows the results of effective cross-sections of the spallation products of the plutonium target. These data can serve as input data for theoretical simulations of the interaction of protons with ^{239}Pu, and they can be a supplement to the nuclear database. The study is useful for future applications of accelerated nuclear waste transmutation and energy enhancement (subcritical type reactor). The obtained experimental result is compared with the simulation on MCNP 6.1 (Fig. 5-6). The data overall correspond to the expected range but for a complete result needs to be evaluated other spectres. The logical next step is to search for primary products (mother nuclei) and compare the obtained experimental data with the results of computer simulations (Geant4, MCNP or other).

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Дослідження реакції спаляції на плутонієвій мішені, опроміненої протонами з енергією 660 МеВ

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Анотація

Актуальність. У статті описано вимірювання перерізів реакцій поділу та відколу плутонієвої мішені, опроміненої протонним пучком з енергією 660 МеВ на прискорювачі Фазотрон Об'єднаного інституту ядерних досліджень.

Мета. Експеримент спрямований на визначення короткоживучих радіонуклідів.

Методологія. Експериментальний зразок вимірювали в автономному режимі за допомогою гамма-спектрометрії з HPGe детектором. Досліджено швидкості реакцій утворених залишкових ядер. За допомогою методу прямої кінематики визначали продукти реакції відколу. Для обробки γ-спектрів використовували програмне забезпечення DEIMOS32. За допомогою програмного забезпечення TJ02000321–V3 було ідентифіковано ядра, що утворилися в зразку ^{239}Pu в результаті ядерних реакцій з протонами. Продукти реакції були ідентифіковані на основі гамма-енергій, інтенсивності та періоду напіврозпаду після вимірювання.

Результати. У результаті обробки гамма-спектрів, виміряних для опроміненої плутонієвої мішені, було виявлено 50 гамма-ліній, а 31 нукліди ідентифіковані за енергією та періодами напіврозпаду від 14,4 м до 3,19 год. Виміряні перерізи ядерних реакцій можуть слугувати опорними даними для теоретичного моделювання взаємодії протонів з ^{239}Pu і можуть бути доповненням до ядерних баз даних.

Висновки. Отриманий результат експерименту порівнюється з моделюванням на MCNP 6.1. Загалом отримані дані відповідають очікуваному діапазону, але дані все ще потребують додаткової оцінки. Наступним логічним кроком є пошук первинних продуктів (материнських ядер) та порівняння отриманих експериментальних даних з результатами комп'ютерного моделювання

Ключові слова: фазотронний прискорювач, програмне забезпечення TJ02000321–V3, гамма-спектри, радіонукліди, γ-спектроскопія, системи з прискорювачем