Cross-Sections of Nuclear Isomers in the Interaction of Protons on Thin Thorium Target

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Abstract - **The paper shows the results of experimental gamma spectra obtained from thorium ^{232}Th target, and an aluminum collector irradiated with protons at JINR Synchrocyclotron at energies of 100 and 660 MeV. For ^{232}Th, identified 258 and 222 gamma lines that belong to 45 and 55 nuclides. For Al - 238, 330 lines and 81, 119 nuclides respectively. The cross sections of fragmentation of the ^{232}Th and Al nuclei under the interaction of protons 100 and 660 MeV was determined. A comparison of the obtained cross sections of the reaction with theoretical calculations was made.**

Keywords: thorium, transmutation, gamma spectrum, semiconductor spectrometer, protons.

I. Introduction

Relevance – the interest of the world scientific community in research of this kind is primarily associated with the problem of transmutation of long-lived radioactive waste and the creation of subcritical nuclear power plants with a uranium-thorium cycle controlled by Accelerator Driven Subcritical Systems, (ADS). These installations may also partially take on the function of radioactive waste disposal. Also of great interest is the ability to use ^{238}U and ^{232}Th as nuclear fuel, since these isotopes are more common in nature than ^{235}U.

The purpose is to study the process of separation of ^{232}Th protons.

The task - processing experimental γ-spectrum experiment performed on Synchrocyclotron JINR (Dubna).

The object of the study is the nucleus of ^{232}Th.

The subject of research is the reaction of fission and fragmentation of the ^{232}Th nucleus under the interaction of protons.

The research methods are γ-spectroscopy of the irradiated target and the collector of the fragments. For theoretical calculations - the monte-carlo method, with the CEM model was used.

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II. Study of Transmutations and Reactors on Accelerators

A. JINR

In Russia, a number of studies on the irradiation of small targets on direct proton beams are made in ITEF. Experiments with long-lived fragmentation fragments and transuranium targets, both in direct beams and in the streams of evaporating neutrons, were carried out only in the JINR, which is the leader here. These works on the study of transmutation of long-lived waste, primarily ^{129}I and younger actinides ^{237}Kr, ^{238}U, ^{239}Pu, ^{241}Am, have been conducted within the framework of a broad international collaborative work on the subcritical installation "Energy plus transmutation" on the cyclotron beam LFBE [1], [2].

B. MYRRHA

A multipurpose hybrid research reactor for application in the field of high technology - it's an installation of fast neutrons with lead-bismuth coolant and heat capacity of 50-100 MW. It is designed as a system using an accelerator to operate in subcritical and critical modes. The reactor is scheduled to be commissioned in 2023. MYRRHA will contribute the development of technologies in the field of energy, as well as in the field of nuclear medicine, industry and renewable energy. Investments of 960 million euro will be required to create the MYRRHA installation. The version of the MYRRHA reactor with smaller power is already in operation in Mol [3].

C. Installation of neutron generation in KIPT

The US government supports the development, construction, and operation of an ADS system (neutron source research facility, KHPTI) at the Kharkiv Institute of Physics and Technology (KPI) of Ukraine under the Russian Research Reactor Fuel Return (RRRFR) program of the United States Department of Energy.

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The purpose of the installation is:

- demonstration of the functioning of the accelerator system and monitoring methods,
- Providing opportunities for fundamental and applied research using neutrons,
- the implementation of physical and material experiments inside the subcritical device and neutron experiments, including cold neutrons outside the subcritical device,
- production of medical isotopes and provision of neutron source for neutron therapy procedures

This device consists of a sub-critical accelerator system that uses low-enriched uranium oxide with a cooling fluid (water) and a beryllium-carbon reflector. An electron accelerator is used to create a neutron source used by a subcritical device to function. The target of this installation is in the middle of a tungsten plate or natural uranium to create neutrons that cool water. Tungsten or uranium is the target material for generating neutrons. Water, like the coolant and the aluminum alloy structure, are used for the target. The target configuration is designed to place a beam square profile and hexagonal fuel geometry. The power of the accelerator beam is 100 kW from 100 MeV electrons [4].

III. Experiment

The samples, using a special device, were placed in an accelerator chamber at a radius corresponding to the energy of protons 100 MeV at a current of 0.3 μA. The dimensions of the beam in the cross-section were $\Delta X=2.5$ cm and $\Delta Y=2.6$ cm. As a result, for each of the irradiations, an integral proton flow on samples was determined, which was $7.64 \cdot 10^{12}$.

At the irradiation, foils of ^{232}Th were used with a thickness of 100 microns and a weight of 149.5 mg. The foil area was 1.5 cm2. To determine the integral flow of protons falling on ^{232}Th samples, an activation method of ^{27}Al with ^{24}Na was used. To do this, two sides of the ^{232}Th were placed close to the foil (50μm) ^{27}Al.

After irradiation, the samples were removed from the chamber of the Synchrocyclotron and moved to the spectroscopic complex YSNAPP-2, which separately measured the spectra of γ-radiation of the foil ^{232}Th and ^{27}Al using the HPGe-detector of the CANBERRA company with an efficiency of 18% and a resolution of 1.9 keV in the line 1332 keV ^{60}Co [5].

IV. Processing of Gamma Spectra

The processing of the gamma spectra was carried out using the DEIMOS32 program used to find positions of peaks, their areas, and other parameters. Identification of the nuclei formed in ^{232}Th samples as a result of nuclear reactions with protons was carried out using a set of scripts based on the Ruby programming language (AttCor , EffCor, MidLit5, NonLin64, PureGam, SepDepe, SigmaJ7, TimeConst, TrueConic, TransCs9). After that, the cross sections of the obtained isotopes were compared with data from the Los Alamos National Laboratory under the program MCNP6 1.0 (database of theoretically calculated sections of isotopes CEM100.asc) [6], [7].

V. Results

A. ^{232}Th

For 100 MeV protons 45 nuclides were identified. The identified nuclides have a mass number in the range of 71-224 with spaces in the range of values 100-110, and 150-223. In fig.1 shows the dependence of the cross section for fragmentation of nuclei on the mass number A. The intervals of the mass number of nuclides correspond to the intervals of the ordinal number Z 44, 45 (Ru, Rh) and 61-88 (from Pm to Ra).

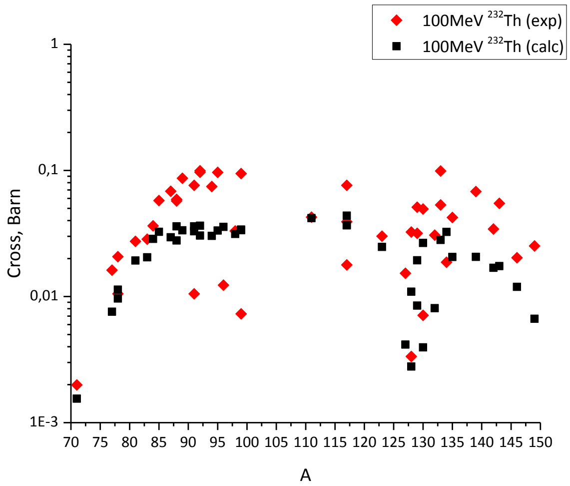

Fig.1 Graph of the cross-section of atomic mass of isotopes

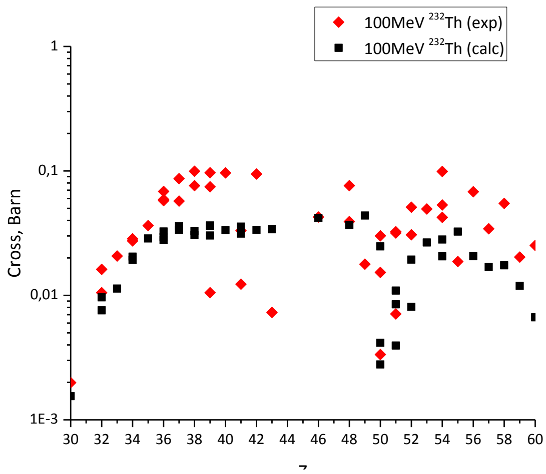

Fig.2 Graph of the cross-section's dependence on the number of the elements

As a result of processing of gamma spectra measured for irradiated thorium target with protons of 660 MeV energy, we identified 222 gamma lines. Comparison of the obtained data with literary sources allowed identification of 55 nuclides by energy and half-life. The identified nuclides have a mass number in the range 68-211 with spaces in the range of values 134-142 and 143-186. The spacing of the mass number of nuclides corresponds to spaces of the serial number Z 54-57 and 58-77. The sections of fragmentation of the ^{232}Th nucleus under the action of 660 MeV of protons were determined, respectively.

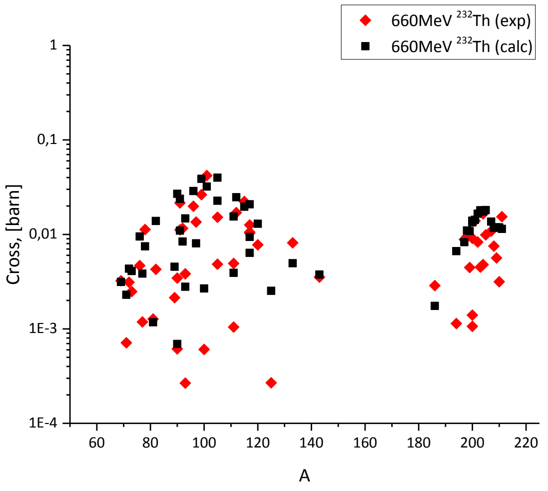

Fig.3 Graph of the cross-section of atomic mass of isotopes

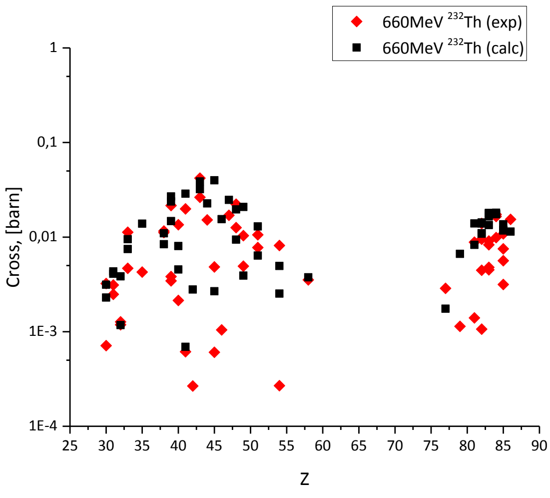

Fig.4 Graph of the cross-section's dependence on the number of the elements

B. Aluminum

For aluminum irradiated with 100MeV protons, 81 nuclides were identified. The identified nuclides have a mass number in the range of 24-233 with spaces in the range of values 63-71, and 150-171 Z and A, respectively. In fig. 5 shows the dependence of the fragmentation cross section of nuclei on the mass number A. In Fig. 6 shows the dependence of the fragmentation cross section of nuclei from serial number Z.

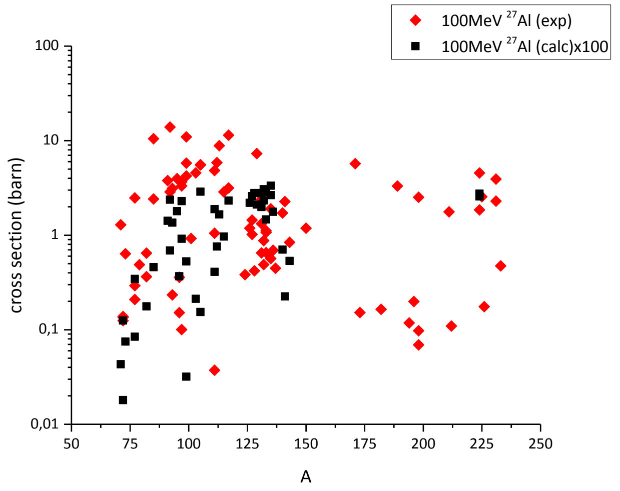

Fig. 5 Dependence of the experimental cross-section on the atomic mass of isomers

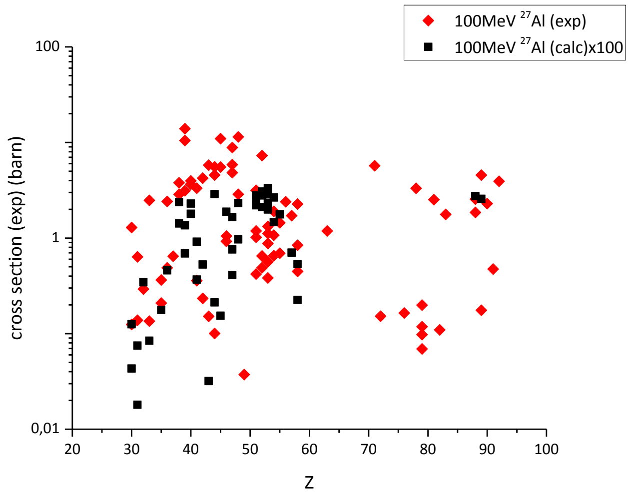

Fig. 6 Dependence of the experimental cross-section on the charge of isomers

For aluminum irradiated with 100MeV protons 119 nuclides were identified. The identified nuclides have a mass number in the range 7-237 with spaces in the range of values 58-69, and

143-167 Z and A, respectively. Figure 7 shows the dependence of the fragmentation cross section of nuclei on the mass number A. In Fig. 8 shows the dependence of the fragmentation cross section of nuclei from the serial number Z.

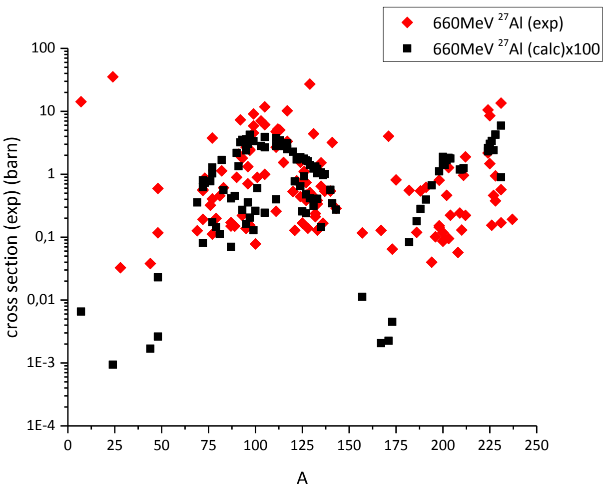

Fig. 7 Dependence of the experimental cross-section on the atomic mass of isomers

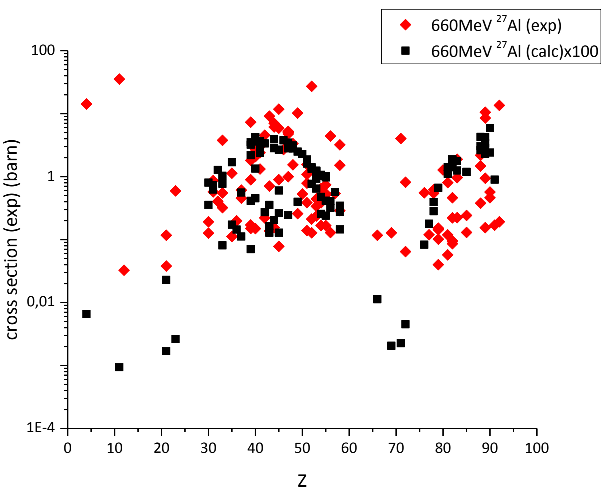

Fig. 8 Dependence of the experimental cross-section on the charge of isomers

VI. CONCLUSION

The processing of experimental data on the fragmentation of the ^{232}Th nucleus under the influence of protons in the energy of 100 and 660 MeV has been processed. The experiment is executed on the Synchrocyclotron of JINR of Dubna. The cross-sections of fragmentation of the ^{232}Th nucleus have been obtained, depending on the charge and mass number of the reaction fragments. For 100 MeV proton beam there were identified for 258 gamma lines that belong to 45 nuclides and identified 222 gamma lines that belong to 55 nuclides in the case of 660 MeV proton beam. For the Al collector 238 gamma lines belonging to 81 nuclides in the case of 100 MeV protons and 330 lines for 119 nuclides in the case of 660 MeV.

The incommensurability of the number of lines for the target and the collector can be explained by the different distribution of fragments by kinetic energy. In the mass and charge spectra there are clearly separated fission and spallation reactions.

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