Experimental and simulated data at fragment productions in 100 MeV proton-induced reaction on ^{232}Th

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***Abstract* - This paper shows the results from the experiment that was done in JINR (Joint Institute for Nuclear Research) Dubna. Thorium foil between two aluminum foils was irradiated inside Phasotron with 100 MeV protons. As a result – gamma spectra was obtained from the Th and aluminum foils and residual nuclei cross-sections were evaluated from the reaction. Also there was made a simulation analysis of the beam distribution inside the Th foil and particle escape from the target. The experimental cross-sections were compared with calculations made in Monte-Carlo simulation (MCNP 6.1).**

Keywords - thorium; transmutation; gamma spectrum; protons; monte-carlo;

I. Introduction

In recent years, a lot of attention has been paid to alternative energy sources in the world society. This is due to the worldwide consent of rapid climate change after the industrial era. There may also be a shortage of natural resources in the future, such as coal and oil, which in the most cases are used for electricity and heating. Nuclear power is also considered as an alternative to thermal power plants. Although this is a fairly old technology, they only have just 10% of the total energy production in the world [1]. The main problems of the NPP are the risk of accidents and the problem of radioactive waste, which has not yet been resolved. This has been partially addressed by III+ generation reactors, which are an improvement on generation II reactors and are more economical and safer.

But in order to finally solve these two problems, we need reactors based on other principles and technologies. These include IV. generation reactors. One of those generation IV reactors are Accelerator-Driven Systems (ADS).

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II. Study of ADS

A. MYRRHA

The MYRRHA (**M**ulti-purpose h**Y**brid **R**esearch **R**eactor for **H**igh-tech **A**pplications) reactor is being built to replace the BR2 reactor currently operating at SCK-CEN, which is close to the end of its service life. The main tasks of the new reactor will be: experimental development of technologies for transmutation of long-lived isotopes in radioactive waste and production of radioisotopes for medical purposes. Also, the new reactor will carry out scientific research in the field of nuclear physics and materials science. MYRRHA it's a reactor of fast neutrons that uses linac with 600MeV 4mA proton beam. Having lead-bismuth coolant the reactor will have heat capacity of 50-100 MW. The ADS is scheduled to be commissioned in 2033 and require 960 million euro of investments[2].

B. The European Spallation Source

The European Spallation Source (ESS) project has the mission to design, build and commission a powerful spallation source for neutron scattering research. It is currently under construction in Lund, Sweden. The facility for ESS consist of a linac in which protons are accelerated to 2 GeV 62.5 mA and collide with a rotating, helium-cooled tungsten target. All of these components need auxiliary support services like electrical power, water cooling and air conditioning, cryogenics, active cells for manipulation of activated components, sample preparation laboratories for experiments, logistics[3].

C. Joint Institute for Nuclear Research

The main research in Russia on ADS have been performed in ITEF (Institute of Theoretical and Experimental Physics). The aim of this research is the transmutation of the long-lived waste, mainly ^{129}I and younger actinides ^{237}Kr, ^{238}U, ^{239}Pu, ^{241}Am. For this purpose three subcritical installation where build: "Energy plus Transmutation", "QUINTA" and

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"BURAN". As a particle source the Phasotron accelerator on LHEP (Laboratory of High Energy Physics) was used [4].

D. KIPT (Kharkov Institute of Physics and Technology)

Since February 2012 ADS Subcritical Assembly Neutron Source has been under construction in NSC KIPT, Kharkov, Ukraine. In 2016 the construction, assembling and installation of the main technological systems of the Neutron source were completed and commissioning of the systems were started and ready for the fuel load [5]. The electron linear accelerator, driver of the subcritical assembly, was designed and manufactured in Institute of High Energy Physics (IHEP), Beijing, China. Now the accelerator assembled in NSC KIPT and is under beam commissioning and tests. The subcritical assembly core is a set of fuel elements of WWR-M2 type by the TVEL corporation production (Russia) of low enriched uranium (19,7% ^{235}U). The fuel is finely dispersed uranium dioxide UO2 that is uniformly distributed in aluminum matrix. The main fissions of actinides are produced with thermal neutrons [6].

III. EXPERIMENT

The experiment was performed on the Phasotron in DLNP (Dzhelepov Laboratory of Nuclear Problems), JINR (fig. 1). The main parameters of the Phasotron are:

1. Energy of accelerated protons – T_r = (659.6) MeV.
2. Energy dispersion - T_e = (3.1 ± 0.8) MeV.
3. Frequency of proton acceleration cycles (modulation frequency) - 250 Hz.

Emittance at the boundary of the scattered magnetic field of the Phasotron:

1. Horizontal e_x = (5,1 ± 2,3) cm*mrad.
2. Vertical e_y = (3.4 ± 1.4) cm*mrad.
3. Intensity of the extracted proton beam mode fast output (pulse duration 30 µs) (2-2,5) µA.
4. Intensity of the extracted proton beam in the slow output mode (beam extended in time for 85% of the modulation period (4 ms)) (1.6-2.0) µA.
5. Extracted proton beam has a microstructure - bunches of particles with a duration of about 10 ns follow with an interval of about 70 ns.[7]

The target was thorium foil with thickness of 100 µm placed between two aluminum foils 50 µm thick. The area of the target was 1.5cm^2 and the mass of Th – 149.5 mg. To determine the integral flow of protons falling on ^{232}Th samples, an activation method of ^{27}Al with ^{24}Na was used. The samples where placed inside the Phasotron and the orbit that corresponds for 100 MeV by special device parallel to the proton beam how it shown on fig. 2 and fig. 3.

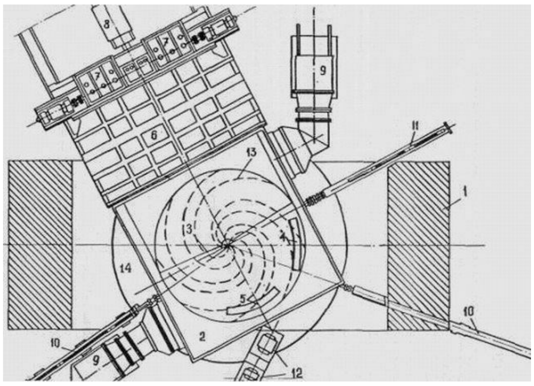

Fig. 1. Schema of the Phasotron in DLNP, JINR
1 - magnet housing; 2 - vacuum chamber; 3 - duant; 4 - output channel; 5 - SI-electrode for beam stretching; 6 - intermediate chamber; 7 - variator; 8 - HF generator; 9 - vacuum pumps; 10 - samplers; 11 - ion source rod; 12 - the first magnetic elements of the proton path; 13 - spiral shimmy for the spatial variation of the magnetic field; 14 - magnet excitation winding [7].

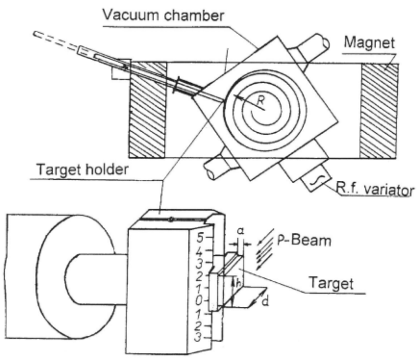

Fig. 2. Placement scheme of the target on the inner beam of the phasotron [8].

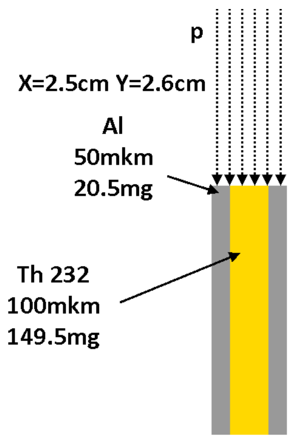

Fig. 3. Scheme of the target irradiation.

After target irradiation, foils where removed from the device and moved to YSNAPP-2 complex where was separately measured the spectra of radiation from the Th and Al foils by HPGe detectors of the CANBERRA company with efficiency 18% and resolution of 1.9 keV in the line 1332 keV

^{60}Co. The measurement time of the foils was 1 m, 2 m, 4 m, 8 m, 16 m, 30 m, 1h, 2 h, 4 h, 6 h, 12 h, 1d, 2d [9].

IV. Simulation and Calculation Methods

A. Data evaluation

For the data evaluation was used software developed at the Nuclear Physics Institute in Rez Czech Republic and the Joint Institute for Nuclear Research in Dubna Russia.

The processing of the gamma spectra where carried out using the DEIMOS32 program to find positions of peaks, their areas and other parameters [10]. The 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, ECor, MidLit5, NonLin64, PureGam, SepDepe, SigmaJ7, TimeConst, TrueConic, TransCs9) [11].

B. Monte Carlo simulation

For modeling of the experiment MCNP 6.1 was used. MCNP (Monte Carlo N-Particle Transport Code) Monte Carlo N-Particle Transport Code is a family of programs for modeling the process of transfer of ionizing radiation (neutrons, photons, electrons, etc.) in material systems using Monte Carlo methods [12]. The program is under development at the Los Alamos National Laboratory in the USA in the programming languages ANSI C and FORTRAN (90 and 95).The program simulates the interaction of particles (neutrons, photons and electrons) with the substance of the system. The reactions of scattering and capture, as well as fission of nuclei by neutrons, are considered. It generates a source of secondary particles formed in nuclear reactions (fission neutrons, photons, electrons, and spallation) or during electron-electron interaction. It is used to solve problems in the field of nuclear reactor physics, radiation protection, and radiation medicine [13]. In this program a simplified model of the irradiation was created. The main purpose was to simulate creation of parent residual nuclei during proton irradiation, their distribution and escaping from the Th foil and calculate the cross-section of the residual nuclei.

V. Results

As a result there where evaluated spectra from thorium foils and aluminum collectors irradiated under 100 and 600 MeV proton beams. The results for cross-sections of residual nuclei for Th under 600 MeV and aluminum under 100 and 600 MeV proton beam can be found in previous papers [9, 14].

For the case of Thorium foils irradiated by 100 MeV proton beam was made comparison of the experimentally obtained cross-sections of residual nuclei and calculation in the Monte-Carlo simulation. For 100 MeV protons 45 nuclides were identified. The identified nuclides have mass numbers within the range of 71-224 [9]. Figure 4 shows the dependence of the cross section for fragmentation of nuclei on the charge and comparison with cross-sections obtained from the Monte-Carlo simulation.

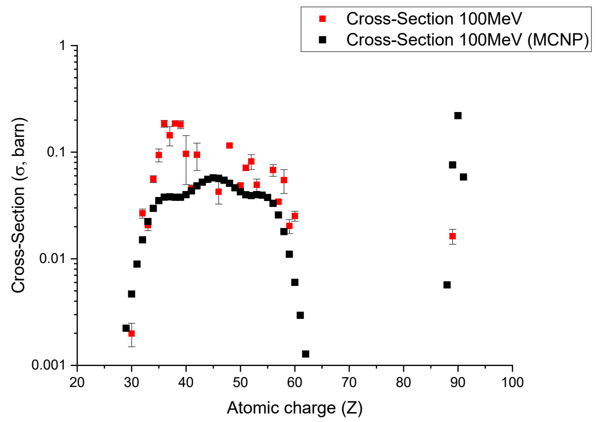

Fig. 4. Graph of the cross sections for thorium irradiated by 100 MeV protons and comparison with the simulation.

On fig. 5 there is shown the proton tracks inside the Thorium foil made with The Visual Editor for MCNP (Vised). For this case simulation was running with 100000 protons. As it's visible on the simulation, protons with energy of 100MeV rarely penetrate the target more than half of its length and almost didn't reach the end of the foil.

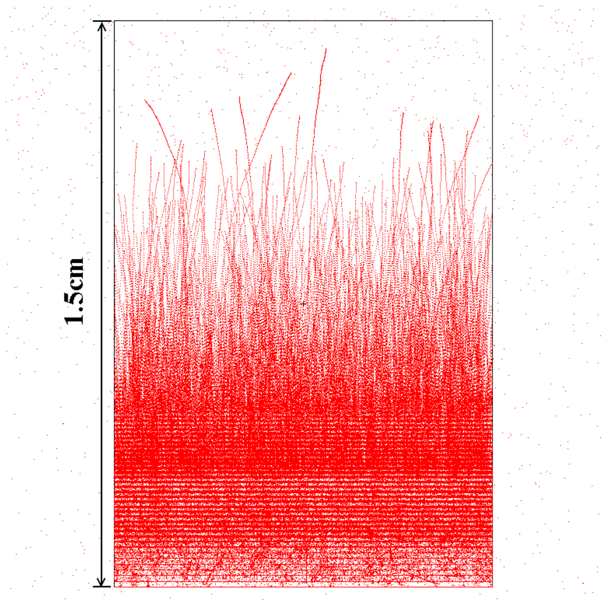

Fig. 5. Proton beam penetration depth in the foil.

On fig. 6 there is depicted distribution of neutrons, alpha particles, and heavy particles that were created inside the thorium foil under irradiation with protons. The run was made with 100000 protons.

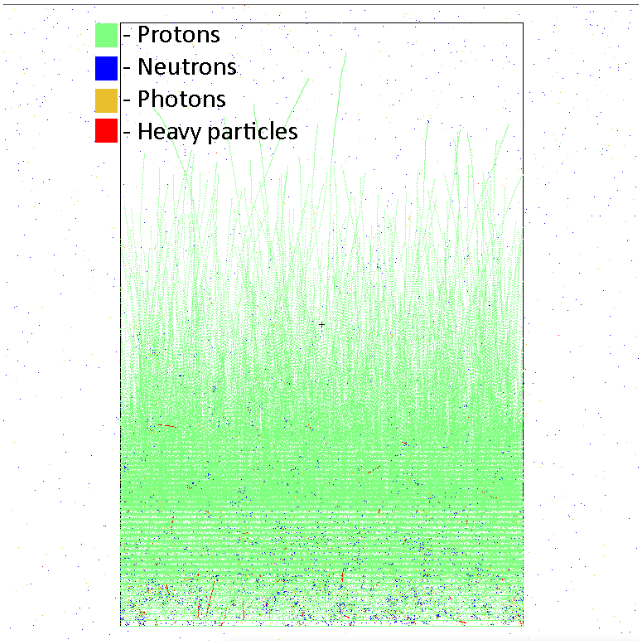

Fig. 6. Particle distribution on the Th foil.

Fig. 7 is depicting particle tracks in the side projection. It was also running with 100000 protons. As it is seen here, the proton beam is noticeably scattered by the foil and substantial amount of neutrons and photons escaping in wide range of angles. Heavy particles are also scattering in wide range but the amount is lower than neutrons and not so noticeable on the simulation.

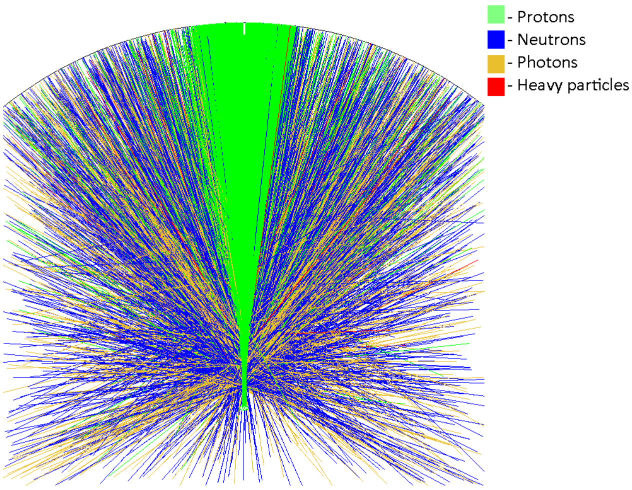

Fig. 7. Proton beam scattering and particle scattering.

VI. Conclusion

The experimental data on the fragmentation of ^{232}Th nucleus under the interaction of protons with energy of 100 have been processed in the previous paper [14]. This experiment was performed at the Phasotron in JINR, Dubna in 2014. The cross-sections of fragmentation of the ^{232}Th nucleus have been obtained depending on the charge number of the reaction fragments. For 100 MeV proton beam there were identified for 258 gamma lines that belong to 45 nuclides. Also a simulation using Mote-Carlo calculations (MCNP) was performed. Cross-sections of residual nuclei, particle distribution in the foil, particle scattering and beam penetration was obtained from the model. The simulation shows that the majority of protons that have energy 100 MeV from the accelerator brake in the first half of the thorium foil and the creation of heavy particles with neutrons occur respectively to it. The majority of scattered particles are protons, neutrons and photons, where neutrons and photons are scattered in much wider angle than protons. Heavy particles were just a fraction of the total particles that was escaping from the foil. A comparison between experimentally obtained cross-sections and cross-sections from the simulation was made. The experimental data mostly correspond to the simulation but there significant divergence.

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