INVESTIGATION OF THE SPATIAL AND ENERGY DISTRIBUTIONS OF NEUTRONS IN THE MASSIVE URANIUM TARGET IRRADIATED BY DEUTERONS WITH ENERGY OF 1…8 GeV

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The paper presents the results of investigations of nuclear-physical characteristics of neutron fields generated in a massive uranium target irradiated by deuterons with an energy of 1, 4, 8 GeV. The research was performed within the framework of the scientific program "Research of the deeply subcritical accelerator-driven systems and possibilities of their use for energy production and transmutation of radioactive waste" – project “Energy and Transmutation RAW”, JINR, Dubna, Russia.

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INTRODUCTION

Today, nuclear power plants account for about 15% of global electricity production [1]. There are two main reasons that prevent a wider spread of nuclear energy:

1. the remaining challenge of disposal of spent nuclear fuel in the framework of the modern concept of nuclear energy;
2. the problem of utilization of stocks of depleted uranium (^{238}U) and thorium in energy production.

Fast and thermal reactors that form the basis of the world accepted concept of nuclear energy development, work on the controlled chain fission reaction with average energy of neutrons near or substantially below 0.2 MeV. This energy is determined by the fission neutron spectrum (average energy of fission neutrons is about ~ 2 MeV) and the structure of the reactor core.

Subcritical multiplying systems initiated by accelerators (electronuclear systems or Accelerator-Driven Systems - ADS) can technically work on a much more harder neutron spectrum. However, the classical ADS designs (an accelerator with energy of 1 GeV + a neutron producing lead target + a subcritical core with the criticality k_{eff} ~ 0.97…0.98) utilize the same "reactor" neutron spectrum. Analysis of different areas of nuclear power development shows the principal limitations of the capacity of the traditional reactor and classical accelerator driven (ADS) systems utilizing the neutron fission spectrum to solve the global energy challenges.

Today, the use of neutron spectrum that is harder than that of fission seems to a most viable option in solving of the modern nuclear power problems. With the purpose of practical implementation of this approach we developed a brand new scheme of electronuclear method that is based on the nuclear relativistic technologies (NRT). The NRT scheme is aimed at the formation of the hardest possible neutron spectrum in deeply subcritical, quasi-infinite (with minimal leakage of neutrons) reactor core due to, in particular, the use of accelerated particles with energies of up to 10 GeV. It is expected that such spectrum will allow cost- and environmentally effective disposal of spent fuel assemblies (FA) containing spent nuclear fuel (SNF) with simultaneous energy production as well as to "burn" waste uranium and thorium for energy production. [2 - 4].

It should be noted that the suggestion to use the NRT in the electronuclear method is based, among other things, on the experiments of the V.I. Yurevich – R.M. Yakovlev [5] that were performed on the "classic" electronuclear lead target with the diameter of 20 cm and the length of 60 cm, at the energies of protons and deuterons in the range of about 1 GeV up to ~ 3.7 GeV. It was found that with the increase of the beam energy a significant increase in the average energy of leakage neutron, the kinetic energy of the leakage neutron and the share of the primary proton energy going into kinetic energy of the leakage neutron is observed.

This work was performed in the framework of the international collaboration "Energy and Transmutation of RAW" and is dedicated to research of neutron production processes in the massive uranium target. The main purposes of the collaboration were: determination of optimum energy and type of accelerated particles; the study of the processes of the neutron formation and the spatial distribution of neutron spectra; determination of dependence of the beam power amplification on energy of the incident particles; the study of the effectiveness of transmutation of a number of isotopes of spent nuclear fuel; obtaining a set of experimental data for modifying existing models and transport codes.

The main purposes of this work were:

- to obtain spatial distributions of density of radiative capture reactions (the number of accumulating ^{239}Pu nuclei) and density of ^{238}U fissions in the volume of the uranium target of the QUINTA assembly;
- to obtain spatial distribution of spectral indices;
- to determine the total number of ^{238}U fissions and total amount of ^{239}Pu, accumulated in the volume of the uranium target of the QUINTA assembly;
- to compare obtained experimental results as a function of the energy of deuteron beam.

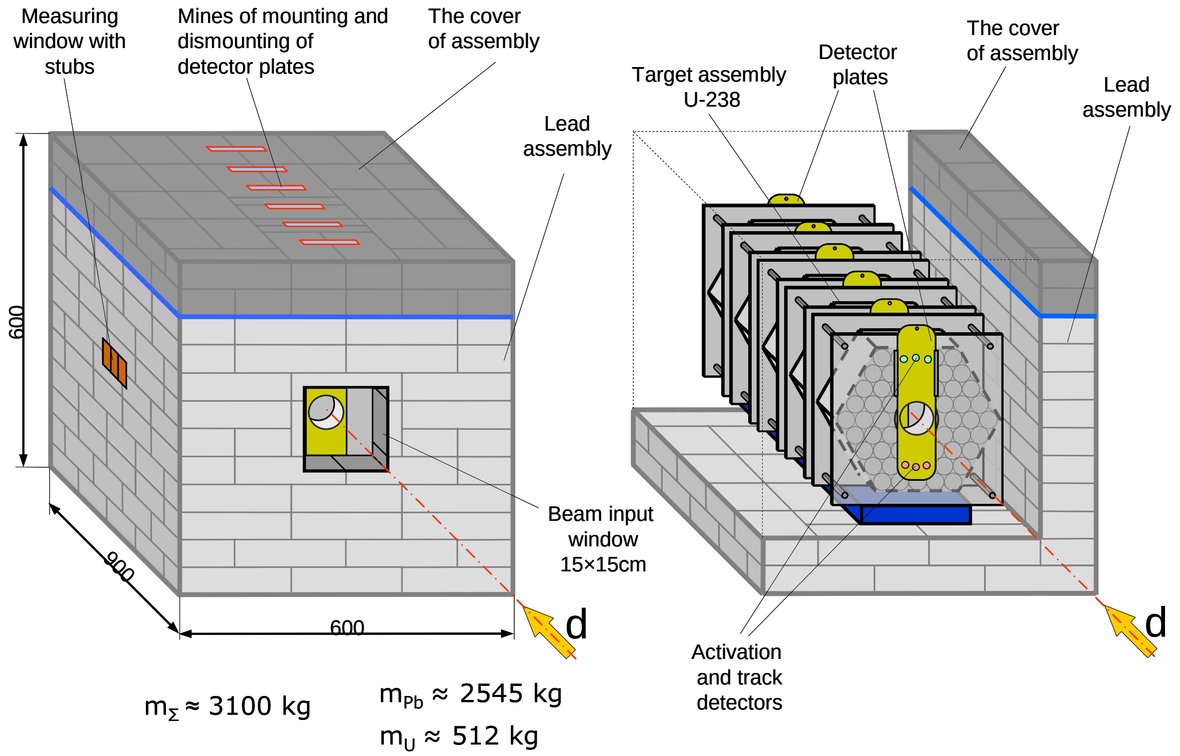

Fig. 1. The uranium target with the lead blanket of the "QUINTA" assembly

1. DESCRIPTION OF EXPERIMENT

The uranium target of the QUINTA assembly surrounded by a lead blanket was irradiated by deuterons with the energy of 1, 4, 8 GeV in the Nuclotron accelerator. The target (Fig. 1) consists of 5 sections that were made in the form of hexahedron filled by cylindrical rods of natural metal uranium. Section No. 1 contains 54 uranium rods and has a central through-hole Ø 80 mm for the beam input to the target. This was made to reduce the leakage of neutrons from the target. Sections No.'s 2…5 are structurally identical and contain 61 uranium rods each. The total weight of uranium in 5 sections of the target is ≈ 512 kg. The uranium target is placed inside a lead reflector with a thickness of 10 cm. Accelerated deuteron beam falls to the wall of section No. 2 of the target through a square hole in the lead reflector with the dimensions 15×15 cm and the input window of section No. 1 and generates neutrons and other particles, which in turn are the source of various nuclear reactions with the formation of secondary radiation. In order to obtain the spatial distribution of the neutron flux and reactions caused by them in the volume of uranium target different detectors that are placed on 6 removable detector plates are used. The detector plates are installed in the gaps between the sections of the uranium target, as well as on the front and on the end face of the target (Z = 0, 123, 254, 385, 516, 647 mm). The spatial distributions of density of reactions (n, f) and (n, γ) were studied using activation of foils (29 pieces) of natural uranium (Ø 8 mm, thickness 1 mm) that were positioned on each detector plate in the positions of R = -80, 0, 40, 80, 120 mm from the beam axis.

Monitoring of the total intensity of deuteron beams was carried out using standard method of activation of aluminum foil by reaction $^{27}Al(d,x)^{24}Na$. The cross sections of the reaction for the deuteron energies used were determined using the method described in work [6] and were: 16.8 *mb* (1 GeV), 14.6 *mb* (4 GeV), 14.0 *mb* (8 GeV). Using these cross sections the following values of the total intensity of deuterons were obtained: $1.8(0.2)\cdot10^{13}$ (1 GeV), $2.7(0.3)\cdot10^{13}$ (4 GeV), $3.7(0.3)\cdot10^{13}$ (8 GeV).

For comparison of the results that were obtained at different deuteron energies it is necessary to recalculate the coordinates for each irradiated uranium foil relative to the real axis of the beam. For such recalculation it is necessary to know the beam profile as well as its position when it hits the target. Determination of the profile and position of the beam was performed using the technique of solid-state track detectors [7, 8]. The target sandwiches (size 40×40 mm) consisting of artificial mica + lead foil radiator were installed at the beam input. This type of track detector has high efficiency of detection of fission fragments and eliminates the background from the recoil nuclei when it is exposed to neutron fields with a hard spectrum.

After the end of irradiation the γ-spectra of irradiated Al beam monitors and uranium foils were measured by the high-purity germanium detectors γ-spectrometers. The number of nuclei of different radioactive nuclides produced throughout the time of irradiation was determined considering the following correction factors: the factor associated with the accelerator stops and changes in the beam intensity during irradiation; the factor that takes into account self-absorption of γ-radiation detected in the sample, the factor that takes into account changes of the geometry during the measurements; the factor that takes into account the geometrical dimensions of the sample, the factor that takes into account the coincidences during γ-line registration.

The number of radioactive capture reactions of ^{238}U corresponds to the number ^{239}Pu, that is formed as a result of the ^{239}U β-decay chain:

$$^{238}\mathrm{U}(n,\gamma)^{239}\mathrm{U}\ (23.54\ \mathrm{min})\ \beta^- \rightarrow$$
$$^{239}\mathrm{Np}\ (2.36\ \mathrm{d})\ \beta^- \rightarrow {}^{239}\mathrm{Pu}.$$

Measurement of gamma-ray spectra of irradiated foils was performed in 4 hours after the end of irradiation (more than 10 half-lives of ^{239}U) on the yield of γ-line with energy of 277.6 keV (there are no contribution from the γ-lines of other radionuclides) accompanying the decay of ^{239}Np.

The γ-lines of different fission fragments were identified in the measured γ-ray spectra of irradiated uranium foils. Those fission products with yields per fission by neutrons close in a wide energy range (from fission spectrum neutrons up to 22 MeV neutrons [9, 10]) were used for determination of the number of ^{238}U fission reactions. The number of nuclear fissions was determined by averaging the results for the following fragments (the yield per fission is given in parentheses): ^{97}Zr (5.7%), ^{131}I (3.6%), ^{133}I (6.3%), ^{143}Ce (4.3%).

2. RESULTS AND DISCUSSION

Fig. 2 shows the radial distributions of density of numbers of ^{nat}U(n, γ)-reactions, ^{nat}U(n, f)-reactions (per 1 deuteron and 1 GeV of energy) over the volume of the target and spectral indices for deuteron energies of 1, 4 and 8 GeV for three detector plates (Z = 0, 254, 647 mm).

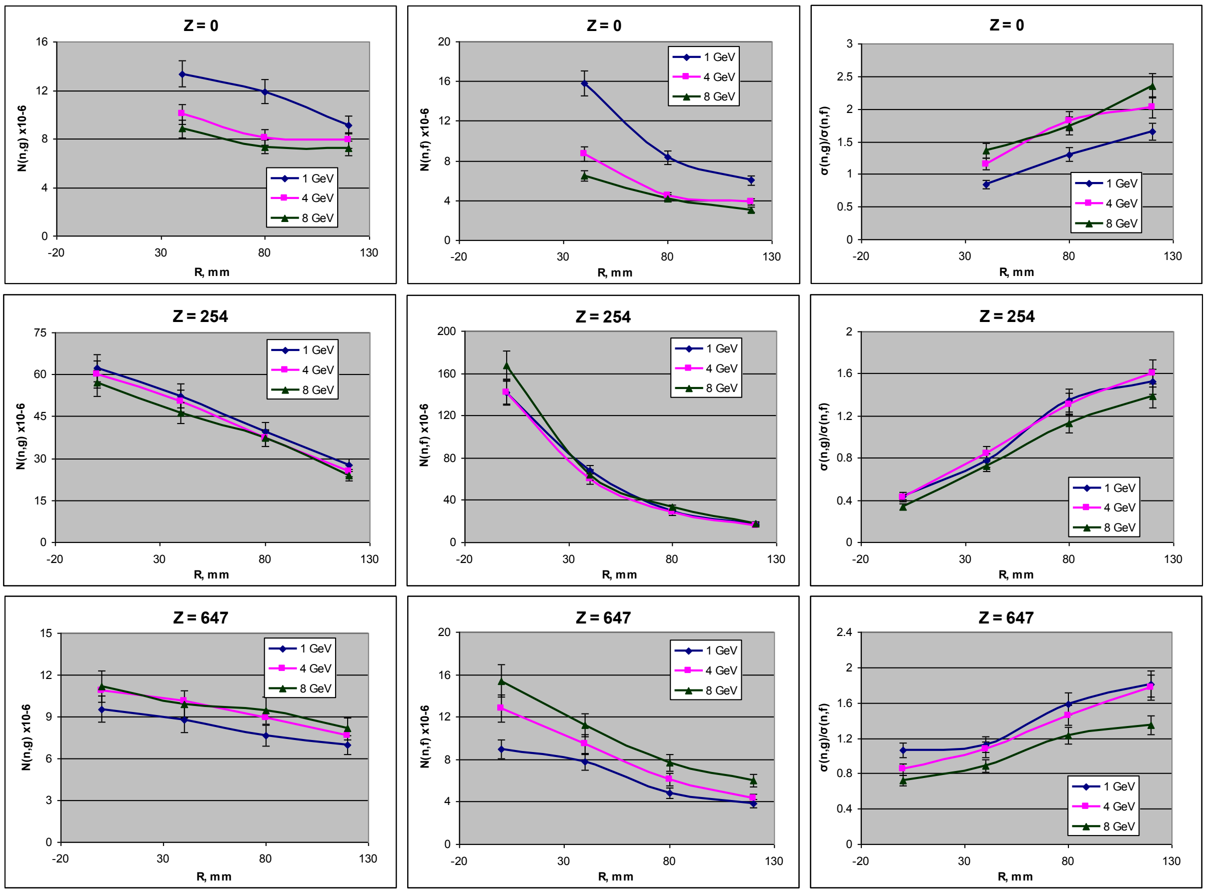

Fig. 2. Radial distributions of density of numbers of ^{nat}U(n, γ)-reactions, ^{nat}U(n, f)-reactions (per 1 deuteron and 1 GeV of energy) over the volume of the target and spectral indices for deuteron energies of 1, 4 and 8 GeV

It should be noted that the type of the spatial distributions of the number density of the uranium fission reactions and the number of produced ^{239}Pu nuclei per unit of deuteron primary beam depends on the deuteron energy: with the increase of primary deuteron energy the density of number of uranium fission and number of produced ^{239}Pu nuclei is reduced in the near field to the deuteron beam input at the target and at the same time there is an increase in the number of uranium fission and number of produced ^{239}Pu to the periphery of the target. Spectral index (the ratio between the average cross sections of neutron capture and uranium fission) is most suitable for comparison with the results of calculations as it does not contain errors of deuteron flux definition. The spectral indices change from the axis of the deuteron beam to the periphery of the uranium target from about 0.4 to 2, indicating a softening of the neutron spectrum, and do not depend on the energy of the beam in the range of 1…8 GeV.

Figs. 3-4 shows the dependencies of values of numbers of uranium fissions and produced ^{239}Pu, integrated to a given radius R for each of the 5 sections (on the left) and in the whole QUINTA target assembly (on the right).

Each point on the left part shows the total number of fissions or the number of (n, γ) reactions in a cylindrical volume of the corresponding radius R of this section, calculated under the assumption of axial symmetry of the considered spatial distributions relative to the axis of the deuteron beam, and the right part shows the result of the sum on 5 sections.

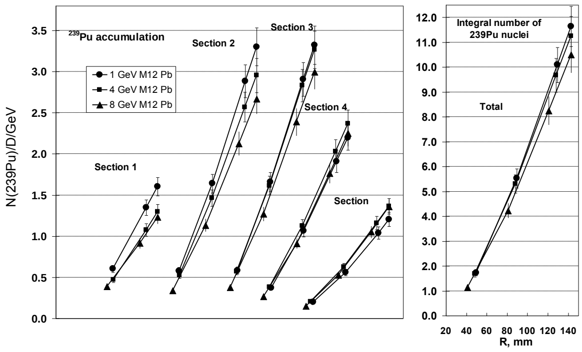

Fig. 3. Dependence of number of produced plutonium nuclei on radius R (on the left) and in the whole of the target (on the right) for deuterons 1, 4 and 8 GeV

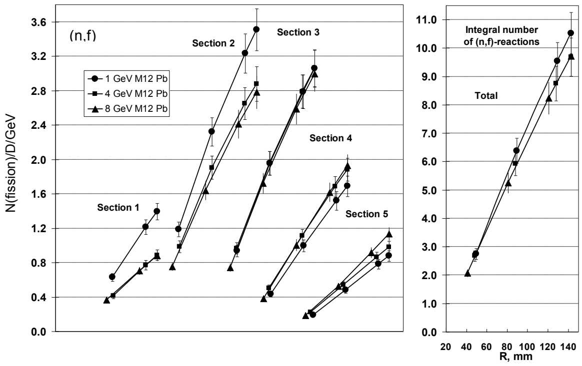

Fig. 4. Dependence of number of fissions on radius R (on the left) and in the whole of the target (on the right) for deuterons 1, 4 and 8 GeV (relative to the axis of the deuteron beam)

One should note almost linear radial dependence of the values of number of plutonium production and fission. It should be noted that such behavior indicated in Figs. 3-4, with the growth of the transverse size of the uranium target, should go to the plateau. This condition corresponds to the condition of quasi-infinite target. However, the existing size of the uranium target of the QUINTA assembly is not enough for the quasi-infinite target and it is impossible to estimate experimentally what size is required for this. In addition, the behavior of the curves in Figs. 3-4 indicates that a significant part of neutrons escapes the the QUINTA target assembly. Also based on the obtained data we can conclude that for given sizes of uranium target of the QUINTA assembly, for deuteron energies exceeding 1 GeV, it is impossible to experimentally estimate (at least using the activation technique) the required size of the uranium target, satisfying the condition of its quasi-infinity and, therefore, it is impossible to estimate the total number of fissions and accumulated ^{239}Pu nuclei for quasi-infinite target. This requires the measurement of uranium targets of larger mass.

Table summarizes the integral numbers of ^{239}Pu production and ^{nat}U fission in the volume of the uranium target of the QUINTA assembly per one deuteron and 1 GeV of initial energy, that were obtained by different methods: the activation method, the method of solid-state track detectors, as well as the calculated values obtained using the MCNPX 2.7e program [11].

Integral numbers of ^{239}Pu production and ^{nat}U fission in the volume of the uranium target of the QUINTA assembly

E_d	1 GeV	4 GeV	8 GeV
Total number of ^{nat}U fission in QUINTA N_f(tot)			
SSTD	8.9±1.5	8.1±1.5	9.2±1.6
Activation detector	(10.2±0.5) ±1.1	(9.6±0.4) ±1.0	(9.4±0.5) ±1.0
Calculation	9.5	8.3	7.3
Total number of produced ^{239}Pu nuclei			
Activation detector	(11.3±0.6) ±1.2	(11.0±0.5) ±1.1	(10.2±0.5) ±1.1
Calculation	12	11.6	9.2

The table gives the results with two errors: statistical (~5%) and systematic (~11%). The systematic error is mainly due to an error in the cross section of aluminum monitor reaction. The total number of neutron captures and ^{238}U fissions (per 1 deuteron and 1 GeV of initial deuteron energy) in the volume of the uranium target of the QUINTA assembly that were defined by different methods, remains approximately constant within the statistical errors for deuteron energies of 1…8 GeV.

CONCLUSIONS

The research of the spatial and energy distributions of neutrons in the system "uranium target+lead blanket" irradiated by deuterons with energy of 1, 4 and 8 GeV was performed. The measured distributions of plutonium production and number of fission reactions of uranium allowed to obtain the total amount of these values, which increase proportionally to the deuteron energy. A similar result was obtained by calculation using the MCNPX 2.7e program and methods of solid-state track detectors for the number of fissions. Starting from 2014 JINR is planning to launch experiments on target of depleted uranium with the weight of 21 tons. The uranium target of the QUINTA assembly to a limited extent simulates the central part of the new target. The developed methods and the obtained results will be used in future experiments.

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ИССЛЕДОВАНИЕ ПРОСТРАНСТВЕННО-ЭНЕРГЕТИЧЕСКИХ РАСПРЕДЕЛЕНИЙ НЕЙТРОНОВ В МАССИВНОЙ УРАНОВОЙ МИШЕНИ ПРИ ОБЛУЧЕНИИ ДЕЙТРОНАМИ С ЭНЕРГИЕЙ 1…8 ГэВ

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Представлены результаты исследований ядерно-физических характеристик нейтронных полей, генерируемых в массивной урановой мишени, при облучении дейтронами с энергией 1, 4, 8 ГэВ. Работа выполнена в рамках научной программы «Исследование глубокоподкритических электроядерных систем и возможностей их применения для производства энергии и трансмутации РАО» – проект «Энергия и Трансмутация РАО», ОИЯИ, г. Дубна, Россия.

ДОСЛІДЖЕННЯ ПРОСТОРОВО-ЕНЕРГЕТИЧНИХ РОЗПОДІЛІВ НЕЙТРОНІВ У МАСИВНІЙ УРАНОВІЙ МІШЕНІ ПРИ ОПРОМІНЕННІ ДЕЙТРОНАМИ З ЕНЕРГІЄЮ 1…8 ГеВ

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Представлено результати досліджень ядерно-фізичних характеристик нейтронних полів, що генеруються в масивній урановій мішені, при опроміненні дейтронами з енергією 1, 4, 8 ГеВ. Робота виконана в рамках наукової програми «Дослідження глибокопідкритичних електроядерних систем і можливостей їх застосування для виробництва енергії і трансмутації РАО» – проект «Енергія і Трансмутація РАО», ОІЯД, м. Дубна, Росія.