MEASURING PARAMETERS OF THE DEUTERON BEAMS IN EXPERIMENTS WITH THE TARGET ASSEMBLY QUINTA USING SOLID-STATE TRACK DETECTORS

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The results of measurements of the deuteron beams parameters with energies of 1, 4 and 8 GeV at the irradiation of the uranium subcritical assembly "QUINTA" are presented. The data obtained on the incident beam position relative to the axis of the target and on the real geometric parameters of the beam allow one to analyze correctly the spatial distribution of reaction rates within the target assembly and compare these measured in different irradiation runs as well as to simulate experiments by such codes as MCNPX, GEANT4, FLUKA et al. The investigation has been performed at the V.I. Veksler and A.M. Baldin Laboratory of High Energy Physics, JINR.

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The experience of nuclear power reactors operation with uranium and plutonium isotope fuel fissioned by neutrons has shown that future extensive nuclear power usage is impossible without solutions of some scientific, technological and ecological problems. One possible solution to these problems is to create ADS [1, 2]. It is a combination of a subcritical reactor coupled with an external accelerator. The basic principle consists in production of a large number of neutrons in the spallation process induced by relativistic ions impacting on a heavy metal target, and their multiplication in a subcritical blanket, resulting in a dense neutron field which can be used for transmutation of long-lived nuclear waste to short-lived radioisotopes.

INTRODUCTION TO THE "E&T RAW" PROJECT

There is a long tradition of spallation and high energy neutron studies in the JINR. During the 1980 s and 1990 s, wide range of spallation targets was irradiated and the neutron production was studied with the respect to the target shape, dimensions, material and to the surrounding volumes. This aim culminated at the end of 1990 s in the Energy plus Transmutation (E+T) project. The leader of this project was for almost last two decades M. I. Krivopustov, who established a big international team with interest in transmutation studies. Target systems Gamma-2, Energy plus Transmutation and Gamma-MD were developed and irradiated with protons and deuterons from the Nuclotron accelerator.

Since 2009, M. Kadykov has been a new leader of the collaboration. The collaboration was renamed to Energy and Transmutation of Radioactive Waste (E&T RAW) and got a better position in the JINR structure, so a further development is foreseen. Collaboration is still growing and has nowadays approximately 85 members from 15 countries (Armenia, Australia, Bulgaria, Czech Republic, Poland, Germany, Russian federation, Bela-

rus, Ukraine, Mongolia, Serbia, Kazakhstan, Greece, India, and Moldova). Two new target systems are developed, the first setup called QUINTA was already tested in experiment, the Large Uranium Target setup is in the phase of technical design.

The JINR project "E&T RAW" is based on so called Relativistic Nuclear Technology (RNT) proposed recently [3] by one of the institutions (CPTP «Atomenergomash», Moscow) participating in "E&T RAW" collaboration.

About all RNT engineering problems including creation of appropriate accelerator can be discussed only after detailed study and verification of basic physics ideas of the proposed approach. This is the aims of JINR project "E&T RAW" adopted for realization during 2011-2013 on the basis of deuteron and proton beams of Nuclotron in incident energy range from 1 to 10 GeV and natural (or depleted) massive uranium targets available at JINR.

1. EXPERIMENTAL INSTALLATIONS

1.1. NUCLOTRON ACCELERATOR

The Nuclotron is a superconducting strong focusing accelerator of relativistic nuclei. The Nuclotron lattice is typical for strong-focusing synchrotrons with separated functions. It contains 8 super periods and 8 straight sections, one of which is "warm". The magnets are fastened to a vacuum shell of the cryostat Ø 540 mm by 8 suspension parts of stainless steel. A nitrogen shield Ø 490 mm covered with 20 layers of super insulation is placed in the vacuum space between the magnet and the vacuum shell. The dipole magnet has a window-frame type iron yoke with the sizes of window of 110×55 mm. The quadrupole lens has the iron yoke with hyperbolic poles. The SC-cable was manufactured of a 5 mm in diameter copper-nickel tube with a wall thickness of 0.5 mm and 31 in parallel connected multifilament strands of 0.5 mm in diameter covering an outer surface

of the tube. The strand consist of 1045 NbTi filaments 10 μm in diameter stabilized by copper [4].

The design parameters of the dipoles are: B=2.2 T and dB/dt=2…4 T/s. Nominal current amplitudes are: up to 6.3 kA and 6 kA for the dipoles and quadrupoles respectively. There are 96 dipoles, 64 quadrupole, and 32 correcting SC-magnets in the Nuclotron ring with circumference of 251.5 m.

All the magnets are connected in parallel with supply and return helium headers. The cooling of the magnets is performed by two-phase helium flow. The Nuclotron operational temperature is 4.5…4.7 K. The cryogenic supply system is based on three industrial helium refrigerator/liquefiers with a total capacity of 4.8 kW at 4.5 K.

1.2. TARGET ASSEMBLY DESCRIPTION

The target assembly "QUINTA" (Fig. 1) consists of five identical sections of hexagonal aluminum containers with an inner diameter of 284 mm, each of which is filled with 61 cylindrical metallic natural uranium blocks of 36 mm diameter and a length of 104 mm aluminum cover. One block weight is 1.72 kg and the total mass of uranium in one section is 104.92 kg. The front section has the cylindrical input beam channel of 8 cm in diameter. The total mass of uranium in the target assembly is about 500 kg.

In front of the target and between the sections as well as behind it, there are 6 experimental plates for detectors and samples. To prevent the free passage of some part of an incident beam through the horizontal empty space between the tightly packed uranium cylinders, an axis of the target assembly is shifted by 2 degrees with respect to the beam axis.

The lead blanket with thickness of 10 cm with the input beam window (150×150 mm) surrounds "QUINTA". In the top cover of the blanket there are special slots for quick removal of the detector's plates.
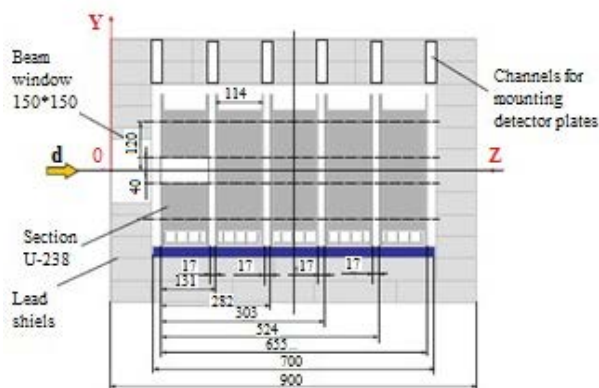

Fig. 1. The target assembly "QUINTA" equipped by lead blanket

The main objectives of the experiments with the target assembly "QUINTA" were:

- Testing methods to measure the basic characteristics of nuclear processes occurring in the active core under the influence of relativistic particles. It is necessary for the further experiments at quasi-infinite uranium target (mass ~ 21 t) available at JINR.
- Basic and applied studies of the interactions of relativistic particles with massive multiplying target.

It is important to note that basic aim of all measurements with this target is to prepare and to test the experimental technique for realization of main research program with Large Uranium Target (LUT) (19.5 t, diameter 120 cm, length 100 cm) setup. Of course, the results obtained in experiments with QUINTA and presented below have independent meaning for understanding and modeling the processes occurring in the central zone of LUT setup.

The design of LUT setup is shown in Fig. 2. It has a steel case, the replaceable central zone diameter of 20 cm and many axial detector channels are shown in red. The frame provides a precise positioning of the target In general Large Uranium target setup is well suited for realization of extended research program adopted in the "E&T RAW" project for 2013-2014.
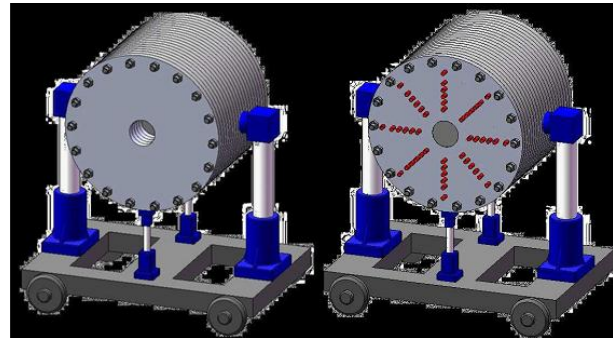

Fig. 2. Front and rear view of target setup Large Uranium Target (left and right pictures respectively)

1.3. EXPERIMENT DETAILS

Irradiation of the "QUINTA" setup was carried out with 2, 4 and 8 GeV deuteron beams.

The axis of the setup was aligned with beam axis with the help of the adjustable stand under the whole setup. The alignment of the beam center with the center of the setup was achieved by examining polaroid films placed in front of the target and exposed to a couple of deuterons pulses prior to the installation of the sample plates and the start of the main irradiation.

Deuteron beams shape and position on the target were obtained from track density distributions on the irradiated track detectors. Sensors made of ^{nat}Pb foils and artificial mica as SSNTD were used for registration of ^{nat}Pb(d,f) reaction. Sensors were placed (Fig. 3) directly onto the beam input window in the lead blanket surrounding the uranium target and at the first experimental plate (Plata 0). The sensors had the size 3×4 cm.

Fig. 3. The location of the sensors to measurement the beam parameters

2. EXPERIMENTAL TECHNIQUE

In our experiments we used a SSNTD method to determine the beam parameters such as beam shape and size, beam center position on the target, total beam intensity.

SSNTD technique is based on correlation between the track density on a track detector and a flux density of the investigated beam.

Sensors made of track detectors placed in contact with a fission foil are irradiated by the beam (Fig. 4). Fission fragments produced in spallation reactions in fission foils form tracks on the track detectors surface.
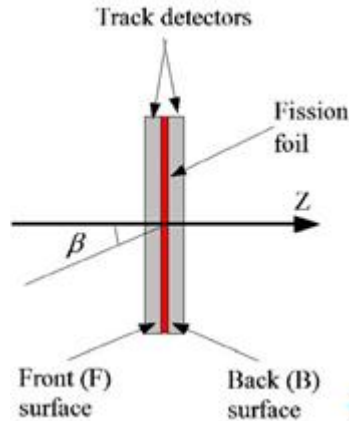
Fig. 4. The schematic drawing of the foil-detector assembly that was used in the calculations and in the experiments

After the exposure the detectors are etched in appropriate chemical reagents (depending on the detector type) to make tracks "visible" in an optical microscope (Fig. 5). To obtain an accurate measure of the track densities the tedious method of manual track counting is chosen. We count tracks in many photomicrographs produced for each detector using an optical microscope. The distributions of the track density along the X- and Y-axis are used to obtain the beam intensity distribution on the target.
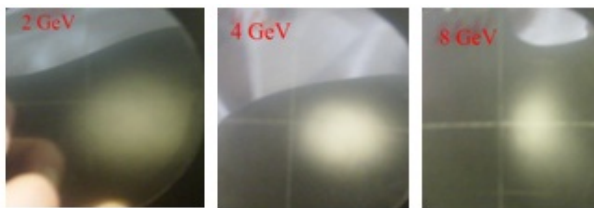
Fig. 5. SSNTD after etching, RUN DECEMBER 2012

The most common formula for the relationship between the tracks density and the flux density is determined as:

$$N^i = A^i \mu^i \varepsilon \, d \, \rho \, t_{\exp} \int_0^\infty \sigma_f^i(E) \varphi^t(E) dE ,$$

where A^i – number of charged particles produced in the fission reaction of i-nuclides; μ^i – the fraction of charged particles reaching the detector in the fission reaction of i-nuclides; ε – detection efficiency of the charged particle track detectors; d – i-layer thickness of nuclides in the radiator, cm; ρ – nuclear density of i-nuclides in the radiator, nuclei/cm^3; $t_{\exp}$ – duration of

sensors the exposure, s; $\sigma_f^i(E)$ – differential microscopic fission cross section of i-nuclides with deuterons, cm^2.

The technique was developed by I. Zhuk and A. Malikhin [5, 6]. It was applied for fission reactions rates measurements in reactor systems. The presented technique has a resolution of 1 mm.

In this work thick radiators were used. In the context of SSNTD technique "thick" radiator means that the radiator thickness is exceeded significantly the mean free path of fission fragments in the radiator material. This circumstance allows to reject an uncertainty caused by radiator thickness determination (as for thin foils) and to increase the total number of fission fragments. At the same time, due to the radiator thickness, we can register the only one fission fragment from the binary fission process and cannot distinguish it by using two correlated tracks. So, the fission process cannot be discriminated from the other high energy processes (such as spallation, multifragmentation and strong asymmetric fission) in which heavy and medium mass particles can be generated. FLUKA, intranuclear cascade model and the model of the nucleon-nucleon interactions RQMD-2.4 were applied to study this effect. The overall contribution of this effect into the relative variation of the sensitivity of the sensor is ~ 0.5% and was taken into account when analyzing the results.

In addition, the influence of the kinematics of ^{nat}Pb fission process on the track density on the track detectors has to be taking into account for the whole deuterons energy range. Pulse transfer effect for ^{nat}Pb can be compensated by the "sandwich-like" composition of sensors, which allows to register tracks in 4π geometry [7].

3. EXPERIMENTAL RESULTS

The experimental tracks density distributions of fission fragments of ^{nat}Pb, which characterize the spatial distribution of the incident deuteron beams at the front end of a uranium target, are shown in Fig. 6. These distributions are well approximated by a three-dimensional Gaussian function. Calculated from the experimental data the beam position parameters of the Gaussian distributions are shown in Tables 1 and 2.

Table 1

Primary Beam Parameters (at the Beam Input Window in the Lead Blanket

Deuterons energy, GeV	Beam centre coordinates, cm		FWHM of distribution, cm	
	X	Y	FWHM$_X$	FWHM$_Y$
2	2.0±0.2	0.0±0.1	2.2±0.3	1.5±0.3
4	2.1±0.1	-0.3±0.2	1.4±0.2	0.9±0.1
8	1.0±0.2	-0.1±0.1	0.9±0.1	1.0±0.1

Table 2

Primary Beam Parameters (at the Plata 0)

Deuterons energy, GeV	Beam centre coordinates, cm		FWHM of distribution, cm	
	X	Y	FWHM$_X$	FWHM$_Y$
2	1.5±0.2	0.1±0.1	2.0±0.1	1.7±0.2
4	1.8±0.1	-0.3±0.1	1.5±0.2	1.1±0.1
8	0.9±0.1	0.1±0.1	1.0±0.1	1.3±0.1

Total deuteron beam intensity in 46th Nuclotron Run (December 2012) measured with SSNTD is presented in the Table 3. Full width at half-maximum (FWHM) of a Gaussian distribution is expressed in terms of its standard deviation σ as $FWHM = 2\sigma\sqrt{2\ln 2}$.
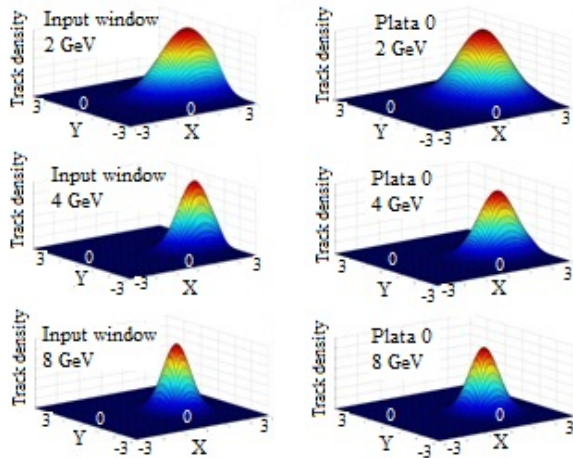

Fig. 6. The spatial distributions of the beam at the target

<div align="right">***Table 3***</div>

Total Deuteron Beam Intensity in 46-th Nuclotron Run (December 2012) Measured with SSNTD

Deuterons energy, GeV	Total deuteron intensity, number of deuterons
2	$(3.0\pm0.3)\cdot10^{13}$
4	$(3.1\pm0.3)\cdot10^{13}$
8	$(8.6\pm0.9)\cdot10^{12}$

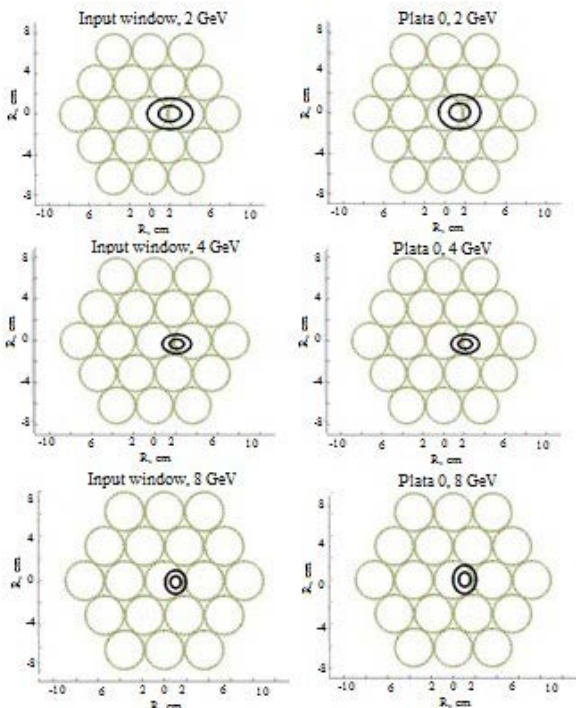The Fig. 7 shows the position of the deuteron beams at the central uranium rods of the target.

Fig. 7. 2D projections of the tree-dimensional distributions of the deuteron beam intensity on the target

At the figure the 2D projections of the tree-dimensional distributions of the deuteron beam intensity on the input surface and the first plate of the "QUINTA"

assembly are presented. Dotted lines show the uranium rods cross-sections. The ellipse semi-major and semi-minor axes (thick lines on the figure) correspond to the 1σ and 2σ parameters of the Gauss distribution. Integration over the surface of the minor and major ellipses gives respectively 68 and 95% of the total number of primary deuterons hitting the target.

From the Fig. 7 it is obvious that in all experiments the beam center was shifted from the assembly central point. This has to be taking into the account for analyzing the experimental data on nuclear reactions inside the setup.

CONCLUSIONS

Beam position measurements, as well as beam size and beam shape, on a massive target irradiated by relativistic particles, allow to determine the analysis correctness of spatial distributions of nuclear reactions measured inside the target. In our case, it is number of fission of ^{238}U and the rate of production of ^{239}Pu, recorded by different detectors located inside and on the surface of the assembly. In addition, the experimental results of the beam parameters determination using the presented SSNTD technique can be used for the correct modeling of the experiments using by different program codes (such as MCNPX, GEANT4, FLUKA) and testing them by comparison with measurements.

REFERENCES

1. C. Rubbia, J.A. Rubio, S Buono, et al. Conceptual Design of a Fast Operated High Power Energy Amplifier // *CERN/AT/95-44 (ET)*, Geneva, 1995.

2. A.S. Gerasimov, G.V Kiselev. Science and Technology Problems of the Electronuclear Devices for Transmutation and Energy Production (Russian experience) // *Fizika Elementarnych Chastits I Atomnogo Yadra*. 2001, v. 32, iss. 1, p. 143-188 (in Russian).

3. V.V. Chilap et al. The problems of development of worldwide nuclear power an the relativistic nuclear technologies (RNT) (in Russian), http://www.cftp-aem.ru/Data/RADS02.pdf.

4. A.D. Kovalenko. Nuclotron: first beams and experiments at the superconducting synchrotron in Dubna, http://nucloserv.jinr.ru/text/2004/nuclotron_overview.html

5. I.V. Zhuk. *The spatial and energy distribution of neutrons and functional in critical systems modeling composition of active zones temperature gas-cooled reactor fuel matrix:* dis. candidate. tehn. sciences. Minsk, 1989.

6. A.P. Malikhin. *Experimental study of integral parameters of critical systems with different neutron spectrum by solid track detectors:* dis. candidate. tehn. sciences. Minsk. 1979.

7. K.V. Husak, A.S. Patapenka, A.A. Safronova, I.V. Zhuk. Experimental determination of value of linear momentum transfer by deuterons to fission fragments of lead (in Russian) / Scientific publication "Youth in Science" // *Proc. of the International Conf. of Young Scientists (Minsk, 17-20 April 2012)*, p. 291-298.

ИЗМЕРЕНИЕ ПАРАМЕТРОВ ПУЧКА ДЕЙТРОНОВ В ЭКСПЕРИМЕНТАХ С МИШЕННОЙ СБОРКОЙ «КВИНТА» ТРЕКОВЫМИ ТВЁРДОТЕЛЬНЫМИ ДЕТЕКТОРАМИ

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Представлены результаты измерений параметров пучка на мишени при облучении подкритической урановой сборки «КВИНТА» дейтронами с энергиями 1, 4 и 8 ГэВ. Информация о положении пучка падающих частиц относительно оси сборки и о его реальных геометрических параметрах позволяет корректно анализировать данные о пространственных распределениях скоростей реакций внутри мишенной сборки и сравнивать их для различных сеансов облучения, а также моделировать эксперименты программами типа MCNPX, GEANT4, FLUKA и другими.

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ВИМІР ПАРАМЕТРІВ ПУЧКА ДЕЙТРОНІВ В ЕКСПЕРИМЕНТАХ З МІШЕНЕВОЮ ЗБІРКОЮ «КВІНТА» ТРЕКОВИМИ ТВЕРДОТІЛЬНИМИ ДЕТЕКТОРАМИ

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Представлено результати вимірювань параметрів пучка на мішені при опроміненні підкритичної уранової збірки «КВІНТА» дейтронами з енергіями 1, 4 та 8 ГеВ. Інформація про положення пучка падаючих частинок щодо осі збірки та про його реальні геометричні параметри дозволяє коректно аналізувати дані про просторові розподіли швидкостей реакцій усередині мішеневої збірки та порівняти їх для різних сеансів опромінення, а також моделювати експерименти програмами типу MCNPX, GEANT4, FLUKA та іншими.

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