INVESTIGATION OF NEUTRON FIELDS ON THE SURFACE OF THE MASSIVE LEAD TARGET UNDER IRRADIATIONTS WITH PROTONS AT ENERGIES OF 1.5 AND 5.0 GEV USING SYNCHROPHASOTRON (JINR, DUBNA)

M.K. Kievets[1], I.V. Zhuk[1], A.N. Sosnin[2], M.I. Krivopustov[2], V.M. D'yachenko[2]

[1]*Joint Institute of Power and Nuclear Research - NASB, Sosny, Krasin str., 99, 220109 Minsk, Belarus, e-mail: kievets@sosny.bas-net.by*
[2]*Joint Institute of Nuclear Research, 141980 Dubna, Russia*

Collaboration **"Energy plus Transmutation"**

Abstract

Some spatial and energy characteristics of neutron fields formed on the surface of a massive lead target (50×50×80 cm^3) under irradiation with protons at energies of 1.5 and 5.0 GeV have been investigated. The irradiations were carried out at the Syncrophasotron of the Laboratory of High Energies, JINR (Dubna, Russia) [1].

Distributions of fission rates of threshold nuclides ^{232}Th and ^{209}Bi on the outer surface of the lead target in two directions (transverse and longitudinal) were measured. Fission rates of nuclides ^{235}U (with and without a cadmium filter), ^{234}U, ^{236}U, ^{237}Np, ^{238}U were measured on the surface of the target; corresponding spectral indices $\overline{\sigma}_f^{\,i}/\overline{\sigma}_f^{\,235U}$ and cadmium ratio for ^{235}U were obtained.

Obtained experimental values for two energies of protons are intercompared as well as comparison with the results of the calculations by means of Monte-Carlo modelling using the computer code *DCM/CEM* is performed [2].

Keywords: Spectral index, fission rate, spallation reaction, Synchrophasotron, lead target, ADS, protons, secondary neutrons, track detectors.

1. Introduction

The progress of accelerator engineering caused promotion of scientific ideas to create and use intensive neutron sources developed in accelerator driven systems (ADS), which operation is based on spallation reaction. These systems are envisaged to solve in perspective such applied problems as safe generation of nuclear energy, transmutation of radioactive waste, research of material properties etc. At the present stage of research of ADS experimental investigations of their characteristics are of special importance. Such investigations allow one to receive integral nuclear data necessary to test and improve computer codes used for calculation of parameters of ADS.

It's been proposed to use the system which is a rectangular lead target with dimensions of 50×50×80 cm^3 (massive lead target) irradiated with protons at energies in the range from 1.5 and 5 GeV performed at the Synchrophasotron of the Laboratory of High Energies (JINR, Dubna, Russia). The target specified has a quite simple configuration, which is convenient for calculations and interpretation. At the beginning of 90th of the last century the target has been investigated by the group of Prof. K.D. Tolstov within the framework of the project "Lead block" intended to study physical aspects of secondary neutron generation [3]. Experiments with a target assembly of similar configuration but with larger dimensions were carried out at CERN in the frame of the "TARC" experiment [4]. Description and results of other investigations within the scope of the same experiment are presented in [1]. Present investigation is carried out within the framework of the project "Energy plus Transmutation" and its aim is as follows:

- investigation of spatial distribution of fast neutrons over a lateral surface of the massive lead target, bombarded by protons at energies 1.5 and 5 GeV;
- obtaining of the integral nuclear data on fission rates of a number of fissile nuclides and correspondent spectral indices in the system under investigation;
- intercomparison of experimental data obtained at two energies of protons, as well as their comparison to the calculated results.

The method of solid state nuclear track detectors is chosen as an experimental technique.

2. Experiment

2.1 Target

The target is a rectangular lead block made in with dimensions of $50\times50\times80$ cm^3 assembled from lead bricks with the dimensions $5\times10\times20$ cm^3. There was the recess hole with the dimensions of $10\times10\times20$ cm^3 along the longitudinal axis of the target to introduce the proton beam. Layout of the target is shown in Fig. 1.

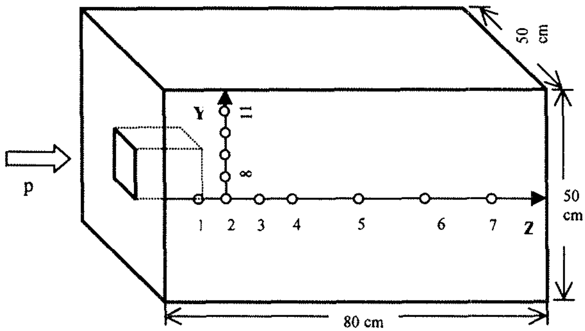

Fig. 1 Layout of the massive Pb-target

The target was irradiated with protons at energies of 1.5 and 5 GeV provided from the slow extraction line of the Synchrophasotron of Laboratory of High Energies (JINR, Dubna). Cross section of the proton beam is in a shape of the ellipse with axes 2.5 and 3 cm.

2.1. Measuring positions and detectors used in the experiment

Measuring positions (points) are distributed over the side surfaces of the target along the two axes – Z and Y. Z axis is parallel to the trajectory of the proton beam; Y axis is perpendicular to it. The beginning of the Z axis coincides with a front end surface of the target, and the beginning of the Y axis corresponds to the point 2 of the Z axis. Seven measuring positions are located along the Z axis, and five – along the Y axis. The chart of their locations is presented in Fig. 1. Experimental detectors consisting of a radiator, which is a source of fission fragments, and a track detector are located in each measuring position. These detectors are supplied with radiators made of ^{232}Th (Th) and ^{209}Bi (Bi). Th- radiators consist of foils with a diameter of 7 mm and thickness of 0.1 mm and are manufactured from metal ^{232}Th.

They are considered to be "thick" radiators which is determined by the identical yield of fission fragments. The latter fact appears to be convenient because it excludes the necessity of individual calibration for each detector. Bi -radiators are manufactured with a diameter of 10 mm and they are composed of layers of ^{209}Bi metal foils with thickness of about 1 mg/cm^2 put on top of Al- substrate. Detectors with radiators containing ^{234}U, ^{236}U, ^{237}Np and ^{238}U nuclides, as well as ^{235}U (with and without Cd-cover with thickness of 1 mm) were placed in the detector position 2. All these radiators appear to be made as a thin layer *(d*=0.12–1.14 mg/cm^2) with a diameter of 7 mm containing corresponding fissile material applied over the Al- substrate. All materials used for radiators are pure with the content of the isotope of interest exceeding 99%. Individual calibration of each radiator is required. Lavsan (analog of lexan) is used as a track detector. All sensors are allocated in the measuring points in the 2π - geometry. All sensors, except for sensors with Bi-radiator, were calibrated in a standard thermal and fast (with *En*=14.7 MeV) neutron fields.

Fission rate Q_f^i of one fissile nucleus is equal to an activation integral (or fission integral). It is determined in the ADS under investigation in compliance with the following formula:

$$Q_f^i = \int_0^\infty \sigma_f^i(E)\varphi^P(E)dE = \frac{N_q^i}{k_q^{sens}P}, \tag{1}$$

where $\varphi^P(E)$ – differential energy density of the neutron flux; $\sigma_f^i(E)$ – differential microscopic fission cross-section of the *i*-th nuclide when fission is induced by neutrons; N_q^i – track density registered in the track detector, exposed to the neutron flux in contact with the *q*-th radiator, containing *i*-th nuclide; k_q^{sens} – sensitivity coefficient of a sensor; *P* - number of incident particles striking the target. Spectral index *(SI)* $\overline{\sigma}_f^i/\overline{\sigma}_f^{235U}$ is equal to the ratio of fission rates of *i*- th nuclide and ^{235}U nuclide; it is determined in the ADS under investigation in compliance with the following formula:

$$\frac{\overline{\sigma}_f^i}{\overline{\sigma}_f^{235U}} = \frac{\int_0^\infty \sigma_f^i(E)\varphi(E)dE}{\int_0^\infty \sigma_f^{235U}(E)\varphi(E)dE} = \left(\frac{N_q^i}{N_j^{235U}}\right)_{inv}\left(\frac{N_j^{235U}}{N_q^i}\right)_{st}\left(\frac{\overline{\sigma}_f^i}{\overline{\sigma}_f^{235U}}\right)_{st}, \tag{2}$$

where indices *st* and *inv* relate to the values obtained for standard and the investigated neutrons fields [5].

3. Calculation

Calculation of neutron spectra at the measuring positions is performed by means of Monte-Carlo simulation using the computer code *DCM/CEM* (Dubna cascade-evaporation model [2]. Neutron cross sections for the above mentioned nuclides are well known in the range up to 20 MeV. There are also experimental data available up to energies 400 MeV. It allows one to carry out comparison of experimental and calculated results for these fissile nuclides. Group neutron sections from the libraries ABBN-78 and IRDF-90 and experimental data obtained by P. Lisowski and others at the LANL for energies of neutrons exceeding 20 MeV [6,7] were used to determine the values of fission rates and spectral indices. Two types of calculation were implemented:

- the first type is the calculation for the "bare" target (calculation 1);
- the second type is the calculation for the target surrounded with a concrete reflector having rectangular shape with thickness 1m and placed at a distance of 2.0 m which simulates the reflection of neutrons from the walls of the experimental hall (calculation 2). Calculated neutron spectra for both cases are presented in fig. 2.

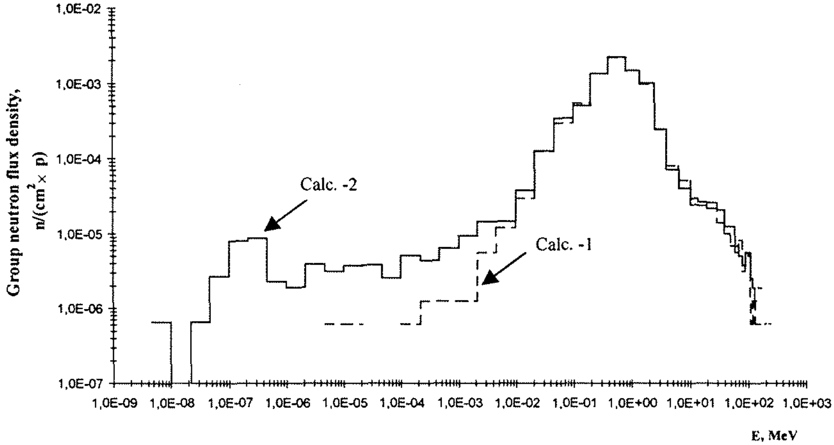

Fig. 2. Calculated (DCM/CEM) neutron spectra at point 2 on the side surface of the massive Pb-target with the concrete reflector surrounded the target (Calc.-2) and without it (Calc. -1)

4. Results and discussion

Distribution of ^{232}Th fission rate characterizes spatial distribution of fast neutrons in a system with energy exceeding or equal to the energy of its fission threshold (1.4 MeV). During the carried research the distributions of ^{232}Th fission rate along the axes Z (Z-distribution) and Y (Y- distribution) for both proton energies are measured. Experimental and calculated distributions of ^{232}Th fission rate on both axes for kinetic energy 1.5 GeV protons are shown in fig. 3.

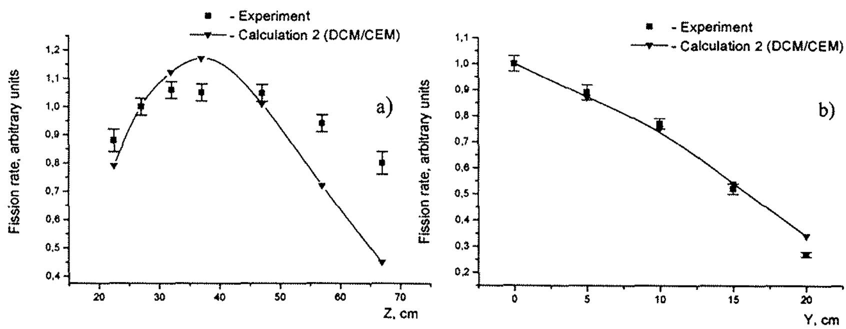

Fig. 3. Experimental and calculated Z- (a) and Y -(b) distributions of ^{232}Th fission rate on the side surface of Pb-target at *Ep*=1.5 GeV (solid lines are drawn to guide the eyes)

As it is seen from this figure the shapes of the two distributions for the Z axis differ, and the shapes of distributions for the Y axis practically coincide (within the limits of experimental errors) in case of calculation and experiment. The shape of the experimental distribution is not as sharp as the calculated one (maximal decrease of fission rate is ~20% in case of experiment and ~55 % in case of calculation). Experimental distributions of fission rate for ^{232}Th along both axes for both kinetic energies of the proton beam (1.5 and 5 GeV) are shown in fig. 4 for comparison.

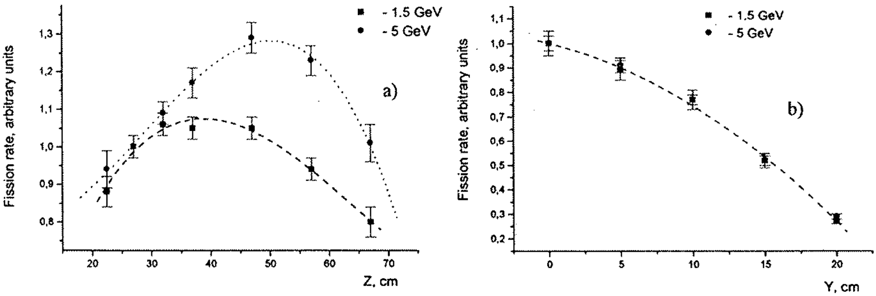

Fig. 4. Experimental Z-(a) and Y - (b) distributions of ^{232}Th fission rate on the side surface of the Pb-target at *Ep*=1.5 and 5 GeV (dashed lines are drawn to guide the eyes)

As it is seen from the given figure the shapes of the Y-distributions coincide (within the limits of an experimental errors) and the shape of the Z-distribution differ for both energies of protons. The maxima of distributions of ^{232}Th fission rate on the Z axis for both energies are at the distances of 32 and 47 cm from the front end surface of the target for proton energies 1.5 and 5 GeV, respectively. Maximum decrease of the fission rate, as it has been already discussed, is ~20 % at energy 1.5 GeV and ~30% at energy 5 GeV. Distributions of fission rate for ^{232}Th could be approximated rather well by 2 and 3 order polynomial fits for Y and Z axes, respectively. According to calculations the absolute values of fission rate for ^{232}Th at the measuring point 2 are 2.78×10^{-28} and 7.76×10^{-28} fissions /(proton× nucleus) for proton energies 1.5 and 5 GeV, respectively.

^{209}Bi has a neutron fission threshold at about 30 MeV, therefore distribution of fission rate for ^{209}Bi characterizes spatial distribution of ultrafast neutrons with energy exceeding or equal to 30 MeV. Unfortunately, the events of fission for ^{209}Bi could be registered only for proton energy of 5 GeV. Experimental distributions of ^{209}Bi fission rate along both axes for the given energy are shown in fig. 5.

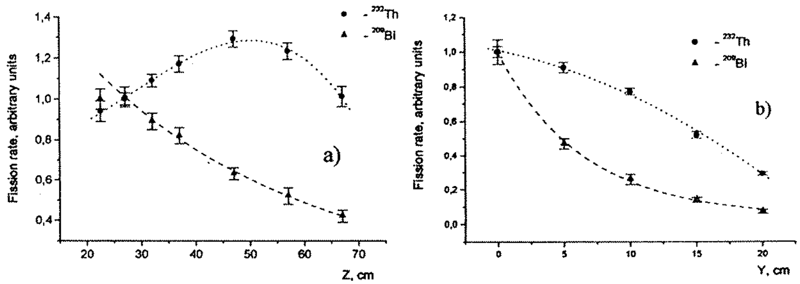

Fig. 5. Experimental Z-(a) and Y(b) - distributions of fission rates of ^{209}Bi and ^{232}Th on the side surface of Pb-target at *Ep*=5 GeV (dashed lines are drawn to guide the eyes)

Experimental distributions of fission rate for ^{232}Th are shown in the same figure for comparison. As it is seen from this figure the distributions of fission rates for ^{209}Bi and ^{232}Th differ considerably. The distribution of ^{209}Bi fission rate is characterized by the decrease which is close to exponential and is equal to the factor of ~2.4 and 14 for axes Z and Y, respectively.

There is a threshold in the fission cross section of ^{234}U, ^{236}U, ^{237}Np, ^{238}U as well as ^{232}Th (fission thresholds are in the interval from 0.5 to 1.4 MeV). The nuclide ^{235}U is fissile over the whole range of the neutron spectrum, and it's fission threshold is ~0.5 eV in the case when it is covered with cadmium sheets with thickness 1 mm. Threshold *SI* $\overline{\sigma}_f^{i}/\overline{\sigma}_f^{235U}$ and cadmium ratio for ^{235}U characterize energy distribution of neutrons in the system under investigation. Measured and calculated values for *SI* $\overline{\sigma}_f^{i}/\overline{\sigma}_f^{235U}$ (*i*- ^{232}Th, ^{234}U, ^{236}U, ^{237}Np, ^{238}U), as well as $R_{Cd}(^{235}U)$ at the measuring point 2 are presented for both proton energies in table 1.

Table 1. Values of spectral indices $\overline{\sigma}_f^{i}/\overline{\sigma}_f^{235U}$ at the measuring point 2 on the side surface of the Pb-target

i- nuclide	$\overline{\sigma}_f^{i}/\overline{\sigma}_f^{235U}$		
	Experiment	Calc.-1	Calc.-2
		1.5 GeV	
Th-232	0.0105±0.0009	0.0270	0.0172
U-234	0.185±0.016	0.60	0.37
U-236	0.076±0.006	0.211	0.130
Np-237	0.193±0.015	0.66	0.41
U-238	0.034±0.003	0.097	0.061
R_{Cd} (U-235)	1.34±0.09	1.00	1.48
		5 GeV	
Th-232	0.0106±0.0009	0.0294	0.0172
U-234	0.178±0.015	0.61	0.36
U-236	0.071±0.006	0.217	0.127
Np-237	0.199±0.015	0.67	0.39
U-238	0.034±0.003	0.102	0.059
R_{Cd} (U-235)	1.40±0.10	1.02	1.55

As it is seen from this table the values of all the threshold *SI* $\overline{\sigma}_f^{i}/\overline{\sigma}_f^{235U}$ (*i*- ^{232}Th, ^{234}U, ^{236}U, ^{237}Np, ^{238}U), as well as $R_{Cd}(^{235}U)$ at the measuring point 2 on the side surface of the lead target coincide (within the limits of an experimental error) for proton energies of 1.5 and 5 GeV. Comparison of the experimental and calculated data for *SI* $\overline{\sigma}_f^{i}/\overline{\sigma}_f^{235U}$ and $R_{Cd}(^{235}U)$ has shown their significant difference. The calculated values (calculation 1) exceed experimental by a factor of 2.8–3.5 for *SI*, and by a factor of 1.5 for $R_{Cd}(^{235}U)$. The given fact indicates that the calculated spectrum is harder in comparison with the experimental one. The account of reflection effect of neutrons from the walls of the experimental hall allows one to reduce this difference down to 1.7–2.2 for *SI*, and allows one to receive good agreement for $R_{Cd}(^{235}U)$.

Experimental and calculated values for ratios of fission rate for the *i*-th nuclide to the fission rate of ^{232}Th $Q_f^i/Q_f^{232\,Th}$ (*i*- ^{234}U, ^{235}U, ^{236}U, ^{237}Np, ^{238}U, $(^{235}U)_{Cd}$) at the measuring point 2 for both investigated proton energies are shown in table 2. As it is seen from this table good and satisfactory agreement between the experimental and calculated values for this parameter is observed (within the limits of 8–30%), with the exception of ^{235}U and ^{235}U in Cd-cover. The deviations of values for these cases are somewhat larger and come up to 60 and 40% for ^{235}U and ~45 % for ^{235}U in Cd-cover for calculations 1 and 2, respectively.

Table 2. Values of ratio of fission rates $Q_f^i/Q_f^{232\,Th}$ at the measuring point 2 on the side surface of the Pb-target

i- nuclide	$Q_f^i/Q_f^{232\,Th}$		
	Experiment	Calc.-1	Calc.-2
		1.5 GeV	
U-234	17.6±1.4	22.2	21.3
U-235	95±8	37	58
U-236	7.3±0.6	7.8	7.6
Np-237	18.3±1.4	24.6	23.5
U-238	3.3±0.3	3.6	3.5
$(U\text{-}235)_{Cd}$	71±5	37	39
		5 GeV	
U-234	16.9±1.4	20.7	20.8
U-235	94±8	34	58
U-236	6.8±0.6	7.4	7.4
Np-237	19.0±1.5	22.9	23.0
U-238	3.2±0.3	3.5	3.5
$(U\text{-}235)_{Cd}$	68±5	35	38

Values of fission rates for ^{232}Th and ^{237}Np, measured by track detectors inside the experimental channels of the massive lead target (3.3×3.3×3 м^3), irradiated with protons at kinetic energy 2.75 GeV are given in the report of the group from CERN which was carried out the "TARC" experiment. The values of fission rates for ^{232}Th and ^{237}Np at the measuring point located at a distance 12–14 cm from the entrance point of the proton beam in the target and at a distance of 15 cm from the longitudinal axes of the target, are equal to 3.0×10^{-27} and 1.3×10^{-25} fissions/(protonxnucleus), respectively. It follows from these data that the fission rate ratio for these nuclides is equal 43.3. This figure exceeds the value obtained in the present work (19.0) by a factor of 2.3. Our value agrees satisfactorily (within the limits of 30–35%) with the calculated data.

5.Conclusions

- Spatial and energy distribution of neutrons is experimentally determined on the side surface of the massive lead target irradiated with protons at energies 1.5 and 5 GeV.

- Distributions of fission rates for ^{232}Th and ^{209}Bi over the surface of the target are obtained as a result of the carried experimental research.
- Values of the spectral indices $\overline{\sigma}_f^{i}/\overline{\sigma}_f^{235U}$ (*i*- ^{232}Th, ^{234}U, ^{236}U, ^{237}Np, ^{238}U), as well as the cadmium ratio for ^{235}U are measured on the surface of the target.
- The calculation of these parameters by means of Monte-Carlo simulation using the computer code *DCM/CEM* with the account and without the account of neutrons reflected from the walls of the experimental hall is carried out.
- The distributions of fission rate for ^{232}Th, as well as the behaviour of fast neutrons (with $En \geq 1.4$ MeV), in the direction of the Z axis, which is parallel to the proton beam, differ considerably for proton energies of 1.5 and 5 GeV, as well as the calculated and measured distributions at the same energy.
- Distributions of ^{232}Th fission rate in the transverse direction agree (within the limits of an experimental error) for proton energies of 1.5 and 5 GeV, and also for calculated and measured data for the same energy.
- Distributions of fission rates for ^{232}Th and ^{209}Bi, as well as the behaviour of fast (with $En \geq 1.4$ MeV) and ultrafast neutrons (with $En \geq 30$ MeV), differ considerably in the investigated system for proton energies 1.5 and 5 GeV both in longitudinal and transverse directions to the proton beam.
- The values of *SI* $\overline{\sigma}_f^{i}/\overline{\sigma}_f^{235U}$ (*i*–^{232}Th, ^{234}U, ^{236}U, ^{237}Np, ^{238}U) and cadmium ratio for ^{235}U are independent (within the limits of an experimental error) on energy of protons, irradiating on the target.
- The calculated values of *SI* $\overline{\sigma}_f^{i}/\overline{\sigma}_f^{235U}$ exceed significantly (by a factor of 1.73–3.5) the experimental ones, which indicates that the calculated neutron spectrum is harder.
- Good and satisfactory agreement (in limits 8–38 %) of the calculated and experimental values of the ratio of fission rates Q_f^{i}/Q_f^{232Th} (*i*–^{234}U, ^{236}U, ^{237}Np, ^{238}U) is observed.

Authors thank the crew of the Synchrophasotron of Laboratory for High Energies (JINR) for their excellent work during the irradiations and Professor A.I. Malachov and Professor A.D. Kovalenko for their continuous support of this work.

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VIII.

POLARIZATION PHENOMENA AND SPIN PHYSICS