Определение накопления 239Pu в подкритической сборке, управляемой ускорителем

Presenter: Igor Zhuk *zhuk@sosny.bas-net.by*

Joint Institute for Power and Nuclear Research,

220109, Minsk, Belarus

OUTLINE

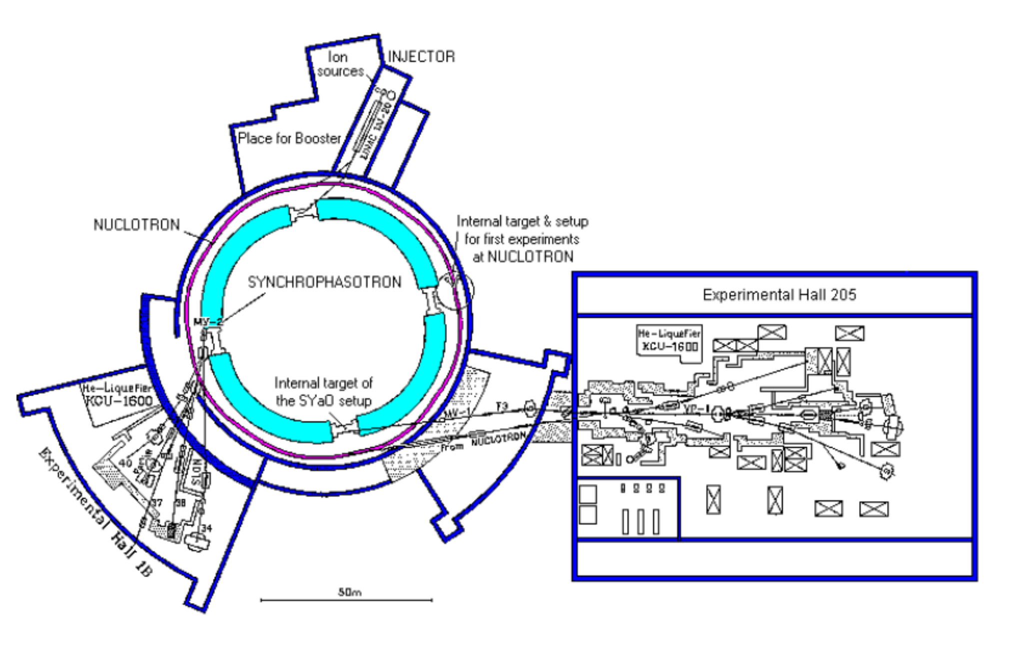
- **Collaboration "Energy plus Transmutation"**
    - *Membership*
    - *project "Energy plus Transmutation"*
- **Experiment**
    - *Experimental instruments*
        - accelerator "Nuclotron"
        - experimental subcritical setup
    - *Results*
        - *experimental results*
        - *Monte Carlo simulations*
        - *simulations vs. experiment*

COLLABORATION

Collaboration “Energy plus Transmutation”

Collaboration exists in Joint Institute for Nuclear Research (in Dubna, Russian Federation) since 1997

LABORATORY
OF HIGH ENERGY
PHYSICS,
Building of the accelerator
ring



Layout of the Accelerator Centre

C O L L A B O R A T I O N

Membership

At the moment, scientists from the following research institutes and countries are taking part in the collaboration:

1. ***Joint Institute for Nuclear Research, Dubna, Russia***
2. ***Aristotle University, Thessaloniki, Greece***
3. ***Institute of Nuclear Sciences,Vinca, Belgrad, Serbia***
4. ***Nuclear Physics Institute, Rez near Praha , Czech Republic***
5. ***Joint Institute of Power and Nuclear Research, Sosny, Minsk, Belarus***
6. ***University, Department of High Energy Physics, Sydney, Australia***
7. ***Stepanov Institute of Physics, Minsk, Belarus***
8. ***Philipps-Universität, Marburg, Germany***
9. ***Institute of Atomic Energy, Otwock-Swierk near Warzhawa, Poland***
10. ***Kharkov Institute of Physics and Technology, Kharkov, Ukraine***
11. ***Technical University, Darmstadt, Germany***
12. ***Czech Technical University in Prague, Czech Republic***
13. ***Institute of Physics and Technology NASK, Almaty, Republic Kazakhstan***
14. ***University of Rajasthan, Jaipur, India***
15. ***National University, Ulan-Bator, Mongolia***
16. ***Bhabha Atomic Research Centre, Mumbai, India***

C O L L A B O R A T I O N

“Background” of the Project “Energy plus Transmutation” in JINR

В 1963–69 гг. Р.Г. Васильков и др. из Московского радиотехнического института (МРТИ) исследовали размножение нейтронов в массивных мишенях из металлического урана, бомбардируемых протонами с кинетическими энергиями 300, 400, 500 и 660 МэВ

В 1965–68 гг. Р.Г. Васильков и др. в экспериментах [60] измеряли выходы вторичных нейтронов из толстых свинцовых мишеней (цилиндры с ∅=10–26 см и *l*=55 см) при кинетических энергиях протонов 400; 500 и 660 МэВ.

В 1979–1984 гг. Р.Г. Васильков и др. продолжили эксперименты по измерению полных выходов вторичных нейтронов из толстых свинцовых мишеней, бомбардируемых протонами с кинетическими энергиями 0,97–8,1 ГэВ

В 1987–92 гг. рамках проекта “Энергия” группа К.Д. Толстова из ОИЯИ проводила исследования процессов генерации и переноса в среде нейтронов, возникающих при бомбардировке протонами и другими заряженными частицами (дейтроны, α-частицы) массивной свинцовой мишени, представлявшей собой прямоугольный параллелепипед $50\times50\times80$ см^3

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Project "Energy plus Transmutation"

The project is included in the
TOPICAL PLAN
FOR JINR RESEARCH
AND INTERNATIONAL COOPERATION
IN 2009

C O L L A B O R A T I O N

Цели проекта:

В период с 1999-2007 проведена серия экспериментов по облучению установки с подкритическим бланкетом протонными пучками и дейтронными пучками в диапазоне энергий 0.7 - 2.0 GeV (протоны) и 0.80 – 1,26 GeV/nucleon (дейтроны).

Целью экспериментов являлось :

- ❑ Генерация и размножение нейтронов
- ❑ Определение спектра нейтронов (от тепловых до быстрых и сверхбыстрых)
- ❑ Образование вторичных изотопов в свинцовой мишени и урановом бланкете
- ❑ Генерация и распределения энергии
- ❑ Трансмутация под действием нейтронов :
  - долго-живущих актинидов (^{237}Np and ^{241}Am),
  - продуктов деления (^{129}I)
  - изотопов Плутония (^{238}Pu and ^{239}Pu).

[illegible] (stable)

$^{129}I(n,nx)$ and $^{129}I(n,xn)$ → stable and radioactive isotopes

[illegible] ($T_{1/2}$=87.74 y)

$^{238,239}Pu(n,f)$ → fission products

EXPERIMENT

Nuclotron: beam parameters

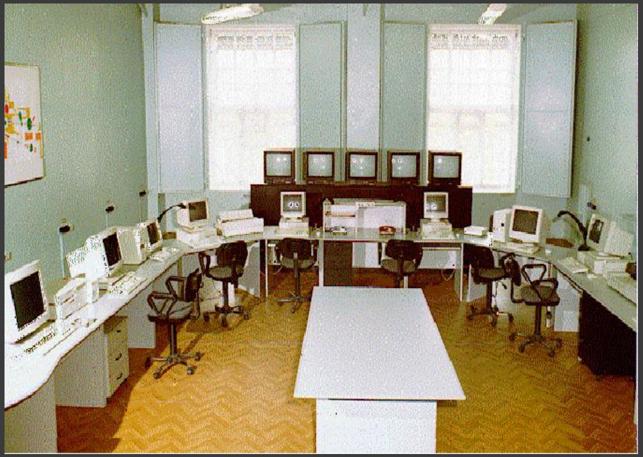
Parameter	Project	Real
Accelerated particle	$1<Z<92$	$1<Z<36$
Max. energy, GeV/nucleon	6 (A/Z=2)	4.2
Magnetic field, T	2.0	1.5
Vacuum, Tor	10^{-10}	10^{-10}
Frequency, hertz	0.5	0.2

Basic research proceedings at Nuclotron regards investigation in the fields of a pre-asymptotic manifestation of quark and gluon degrees of freedom in nuclei, the study of the spin structure of the lightest nuclei, the search for hypernuclei, the study of polarization phenomena using polarized deuteron beams. There is also a number of projects being implemented in the frame

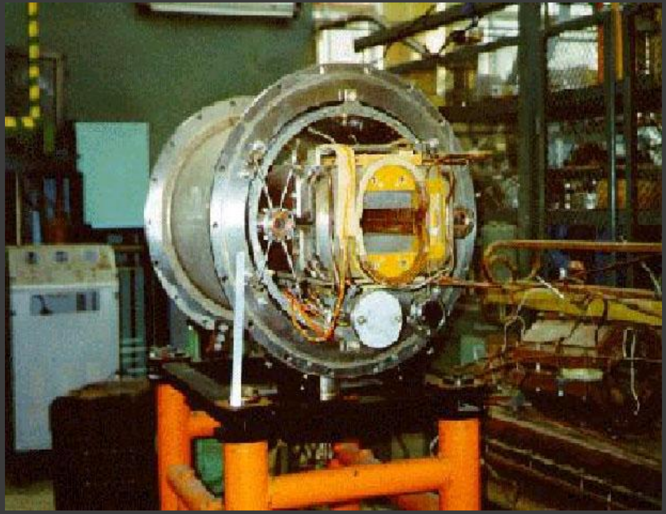
of an applied research - radiobiology and space biomedicine, the impact of nuclear beams on the microelectronic components, the use of a carbon beam in cancer therapy, and transmutation of radioactive waste associated with the electro-nuclear energy generation method.

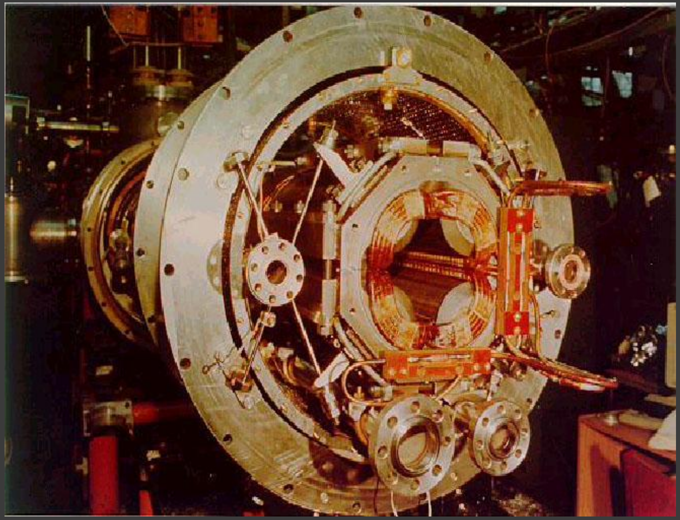
E X P E R I M E N T

Nuclotron: how it's looks



Nuclotron ring and operating console of the Nuclotron





Nuclotron superconducting magnets. Dipole magnet (left) is anchored in the vacuum shell of the cryostat by eight parts of a stainless steel (m = 500 kg, l = 1462 mm, B = 2 T). Quadrupole magnet (right), m = 200 kg, l = 450 mm, grad B = 33.4 T/m

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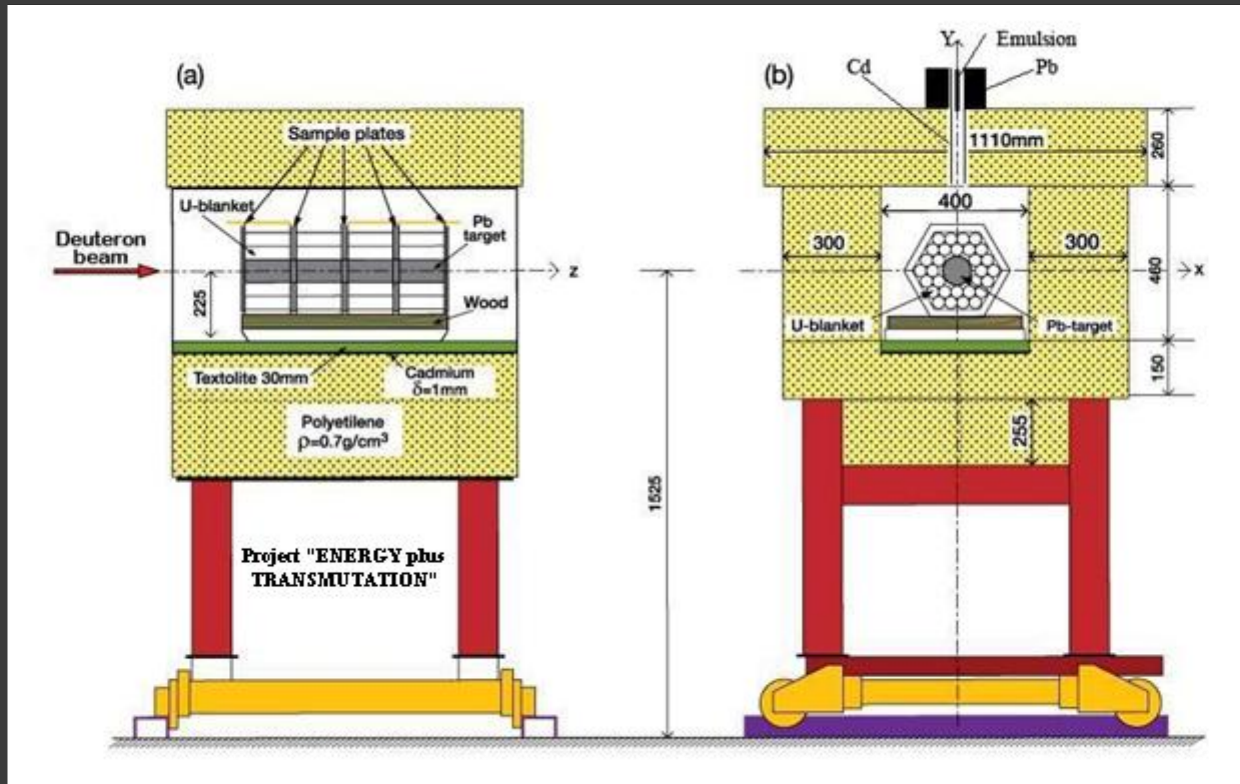
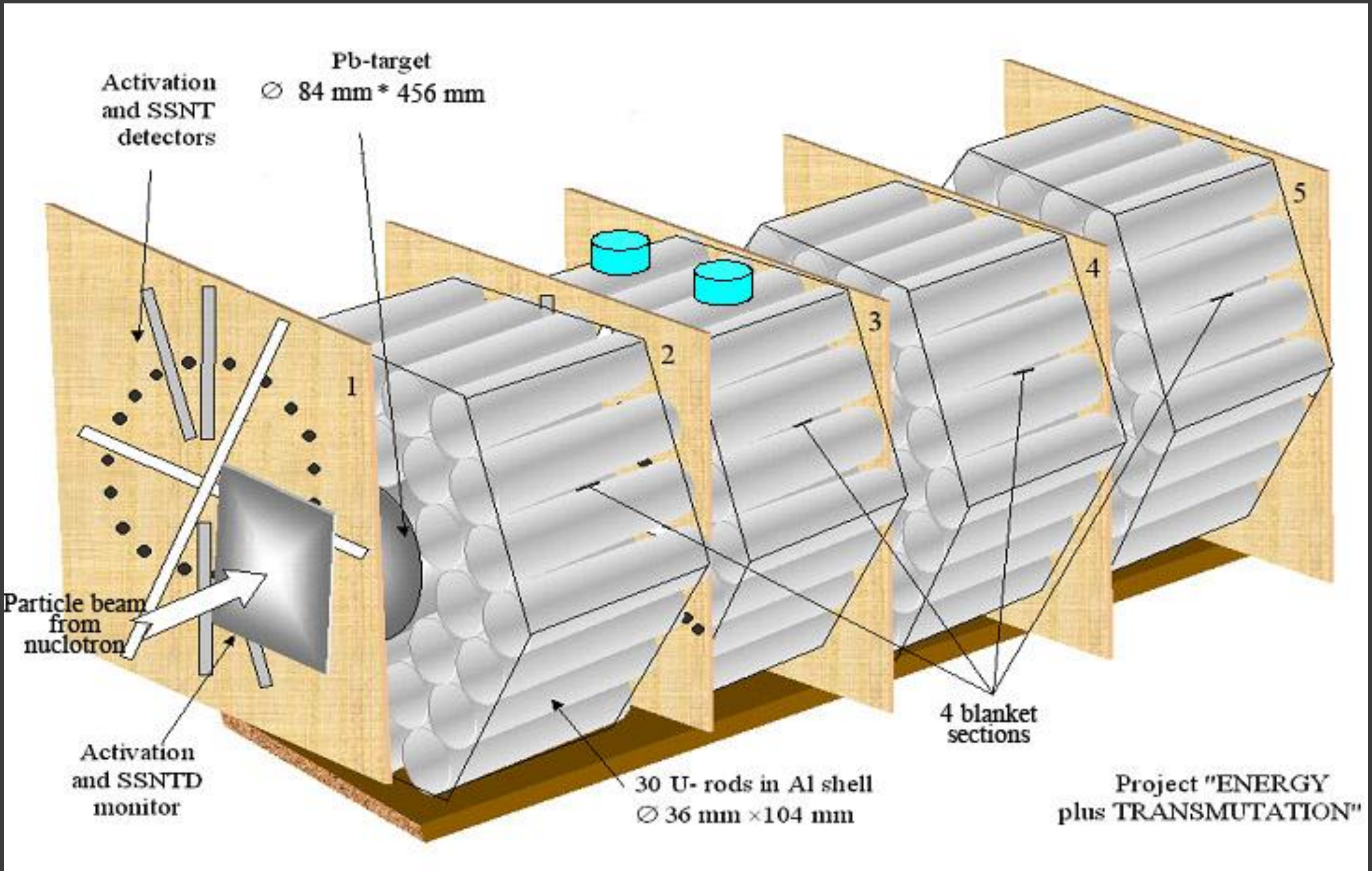
Experimental setup



1) Cylindrical lead targets with diameter 8.4 cm and length 45.6 cm.
2) A natural uranium blanket surrounds the target.
In the experiment these blanket sections were located one after another; the front of the first blanket section and the front face of the lead target were in the same plane. Blanket sections consist of uranium rods (metal natural uranium packed into aluminum cladding), with diameter 3.6 cm, length 10.4 cm and weight 1720g. Each blanket section contains 30 uranium rods with weight 51.6 kg. Thus the 4 blanket sections contain 120 uraniu rods with total weight 206.4 kg. There is a 0.8 cm gap between the blanket sections to be used for detectors.
3) The whole target-blanket system was placed within a wooden container filled with granulated polyethylene. The inner walls of the container were covered with a Cd foil of thickness 1 mm.

E X P E R I M E N T

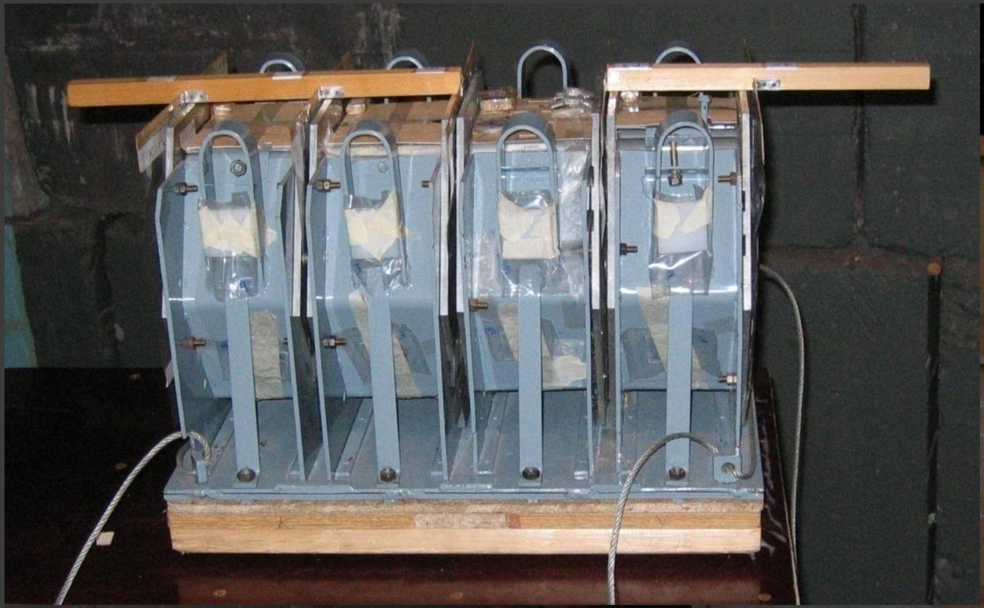
Target + blanket assembly



Scheme of the four-section “Energy plus Transmutation” setup with a massive lead target and uranium subcritical blanket. The placement of transmutation samples in presented at the surface of the second section of U-banket.

EXPERIMENT

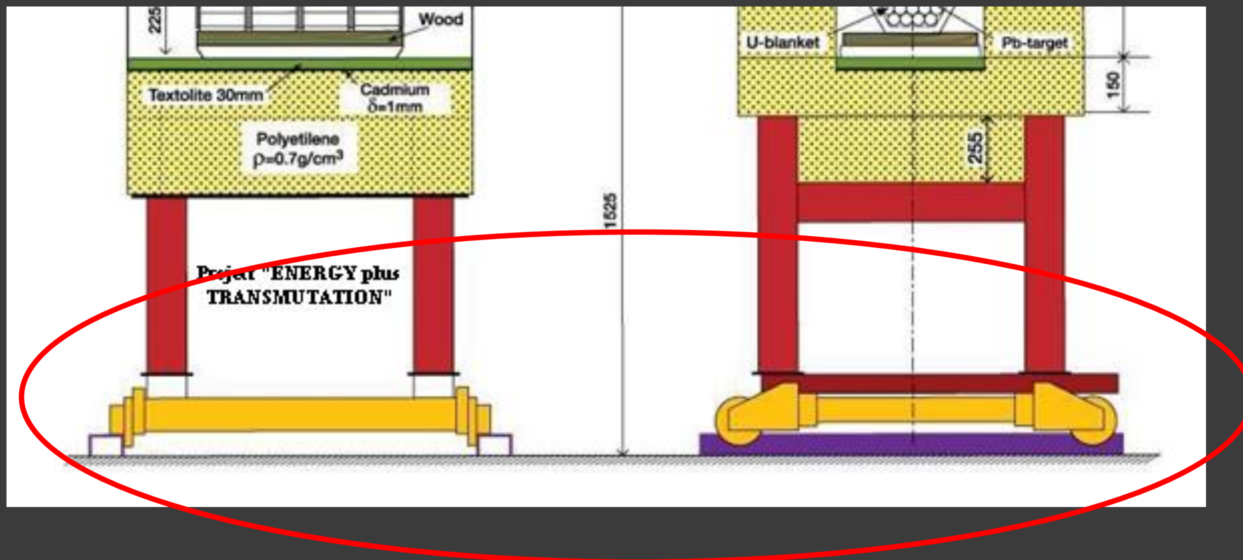
Haw it's looks



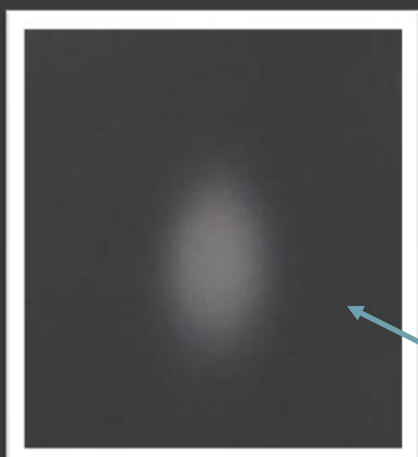
Subcritical assembly + biological shieldi

EXPERIMENT

Юстировка пучка на мишени



Установка может быть перемещена к месту облучения (фокус ФЗН – экспериментального зала) по системе рельсов



Перед облучением установка юстировалась с помощью поляроидных пленок. (т.е. ось мишени совмещалась с осью пучка «Нуклотрона»)

«Фотография» дейтронного импульса (~109 частиц) полученная с помощью поляроидной пленки, перед свинцовой мишенью

E X P E R I M E N T

Techniques

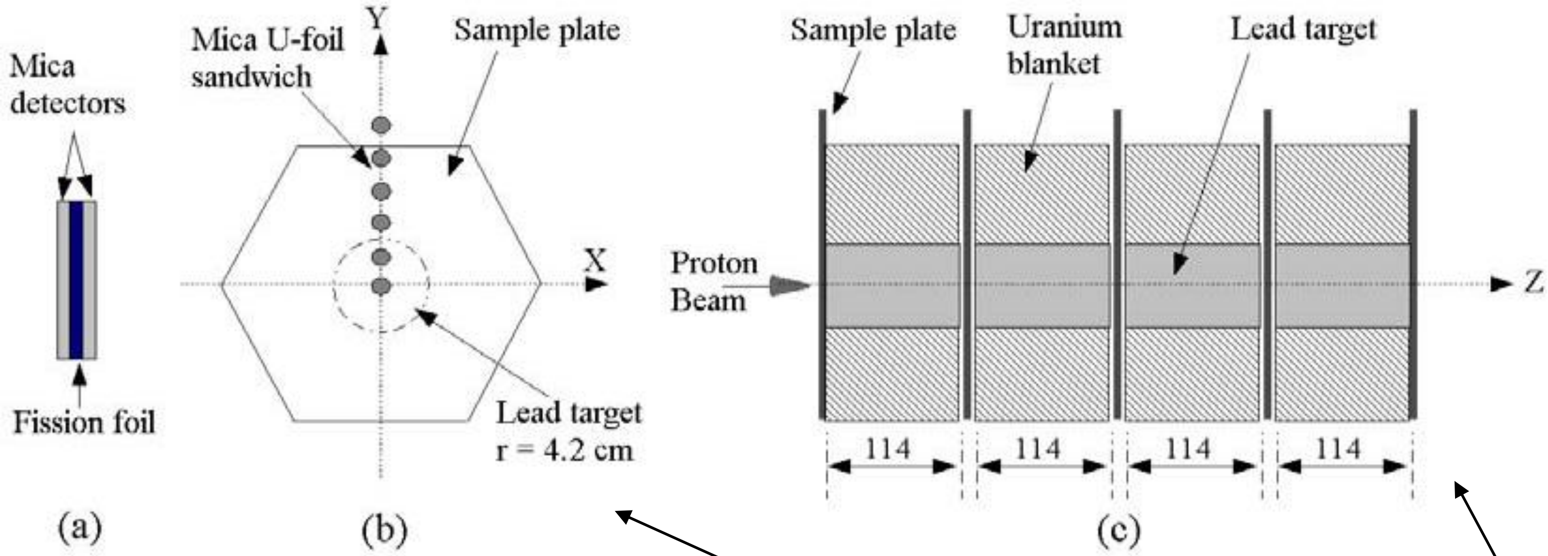
Measured value: reaction rates

- **total fission [$^{nat}U(n,f)$, $^{nat}U(p,f)$, $^{nat}U(d,f)$, $^{nat}U(\gamma,f)$]**
- **capture [$^{238}U(n,\gamma)$]**

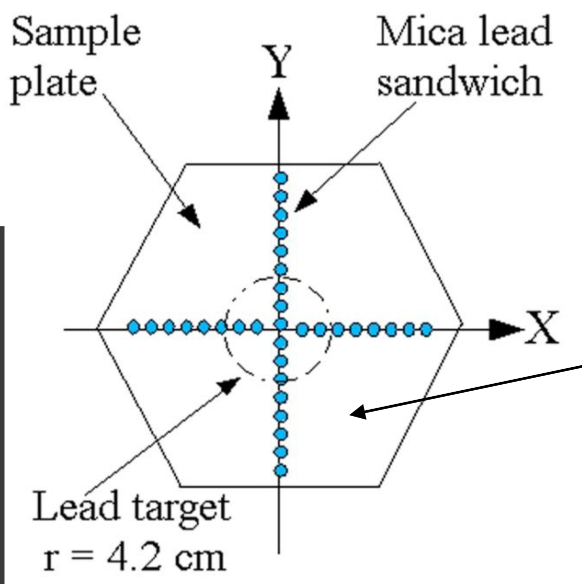
Experimental techniques

- **Solid nuclear track detectors (SSNTD)**
  (total fission reaction rates measurement)
- **Standard activation method (γ-spectrometry)**
  (neutron induced fission reaction rates measuremen
  capture reaction rates measurement)

Расположение сенсоров



сенсор (ТТДя+радиатор)
экспериментальная пластина
бланкет

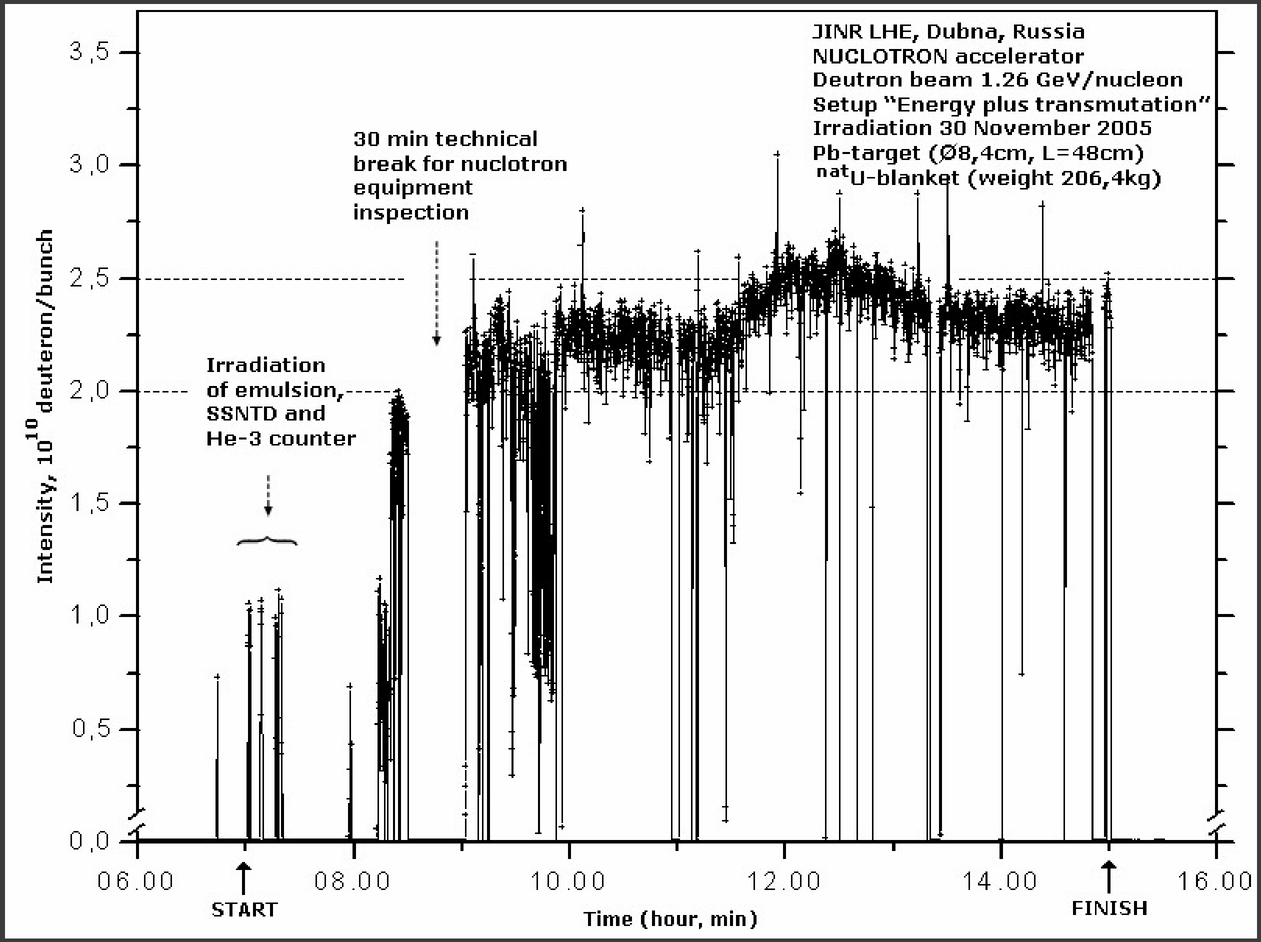


Первая экспериментальная пластина - образцы со свинцовыми радиаторами – определение параметров первичного пучка

Секции имеют длину 114 мм и разделены экспериментальным зазором 8 мм

EXPERIMENT

Beam parameters: intensity



The intensity profile of the irradiation of the Pb-target with U-blanket at 2.52 GeV deuteron beam, as delivered by the Nuclotron.

E X P E R I M E N T

Параметры дейтронных пучков

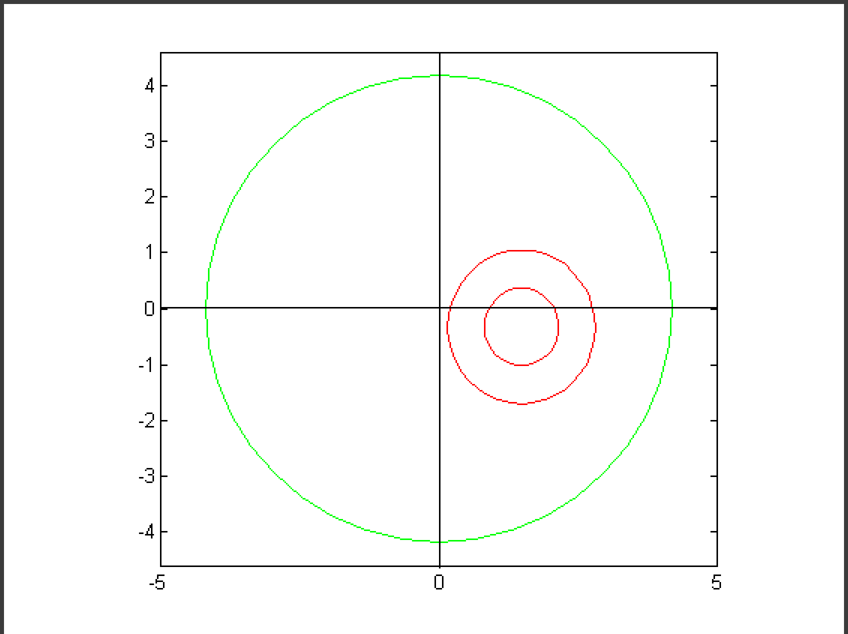
The beam profiles obtained using ^{Nat}Pb(*p, f)* reaction and mica track detector.
The proton beam fluence was determined using ^{27}Al(d, 3p2n)^{24}Na reaction.

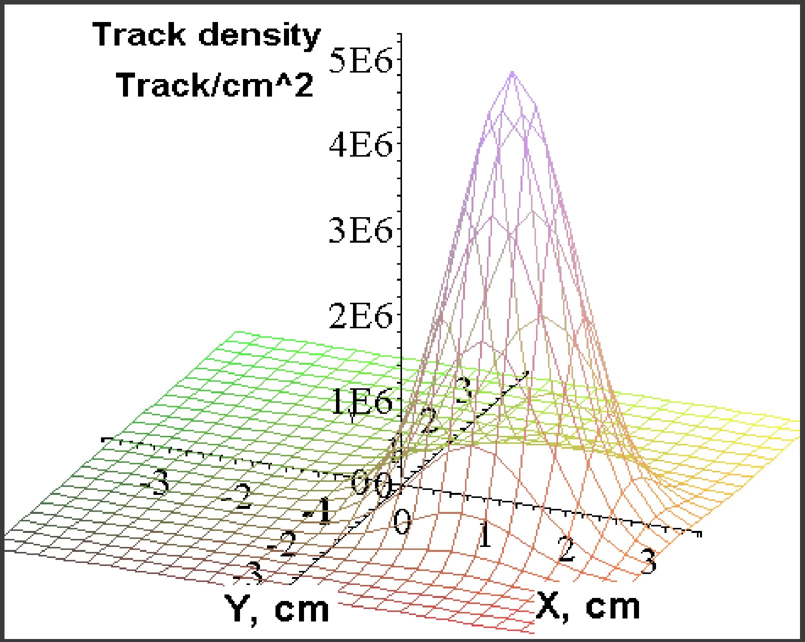
Энергия дейтронов	FWHM (cm)		Координата центра (cm)		Полный интеграл пучка
	X	Y	Xc	Yc	
2.52	1.5±0.1	1.6±0.1	1.5±0.1	-0.3±0.1	5.9×10^12
1.60	2.8±0.1	1.9±0.1	-0.6±0.1	-0.4±0.1	2.1*10^13

EXPERIMENT

Beam parameters: profile

The parameters of the deuteron beam were determined using the ^{Nat}Pb-mica samples in the sample plate that was placed in front of the lead target. On this plate 37 samples were placed along the X- and Y-axes in the interval of -13.5 to 13.5 cm in both cases.





The structure (profile) of the 1.26 GeV/nucleon deuteron beam.

1. (left) The large circle shows the lead target area. The small ellipse and large ellipses show the areas within which 68% and 95% of the incident deuterons strike the target.
2. (right) 3D track density distribution of the deuteron induced fission in natural lead in the XY (target surface).

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Experiment: ^{238}U fission rate

1. The fission rate - $R_f^{U238} = \int_{1.5}^{\infty} \sigma_f^{U238}(E)\varphi(E)dE$ describes fast part of neutron spectra (with the energy higher fission threshold of 238-U 1.5 MeV) in the experimental setup.

2. The fission rate was measured using two methods: Activation and SSNTD technique

3. All data are in very good agreement (except region near the axis of the setup)

EXPERIMENT

Эксперимент: скорость радиационного захвата нейтронов ядрами ^{238}U (накопление ^{239}Pu)

Число реакций радиационного захвата 238U соответствует количеству ^{239}Pu, образующемуся в результате цепочки β-распадов

$$^{238}U(n,\gamma)^{239}U^{*} \xrightarrow{\beta^{-};T_{1/2}=23,4\,\mathrm{min}} {}^{239}Np^{*} \xrightarrow{\beta^{-};T_{1/2}=2,36d} {}^{239}Pu^{*} \xrightarrow{\alpha;T_{1/2}=2,41.10^{4}\,y}$$

Перед измерением урановые фольги выдерживались в течение более 4 часов (больше 10 периодов полураспада 239U) для достижения 99.9% распада 239U. Скорость захвата 238U нейтронов определялась путем измерения наведенной в экспонировавшихся образцах активности нуклида 239Np по γ -линии с энергией 277.6 кэВ (период полураспада 2.36 дня). В измерениях использовался полупроводниковый спектрометр с детектором из особо чистого германия.

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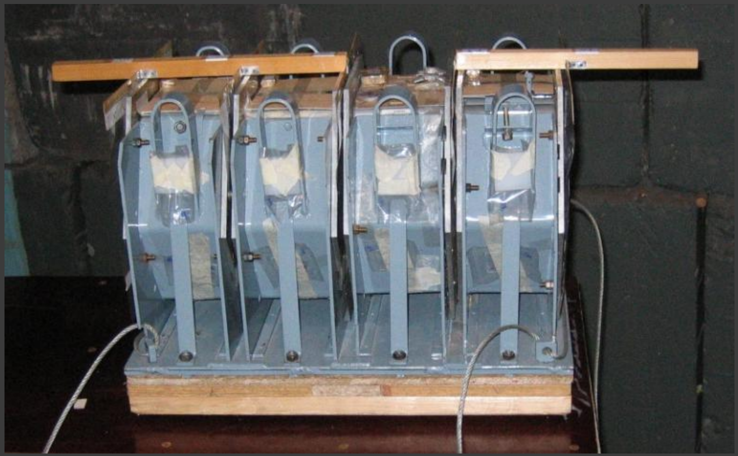
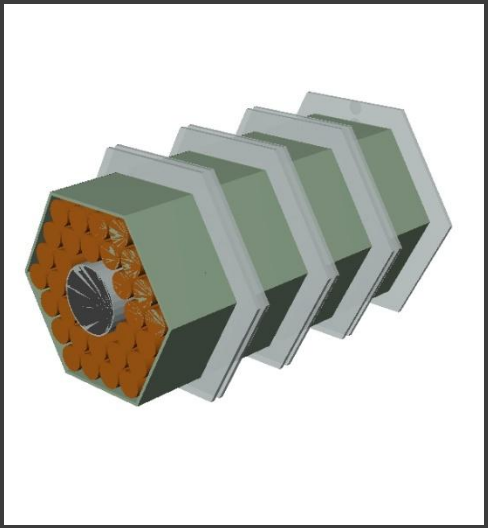
Simulations: codes

Codes : MCNPX 2.6 C
FLUKA 2006.3

From the real view …to the geometrical module for Monte Carlo codes





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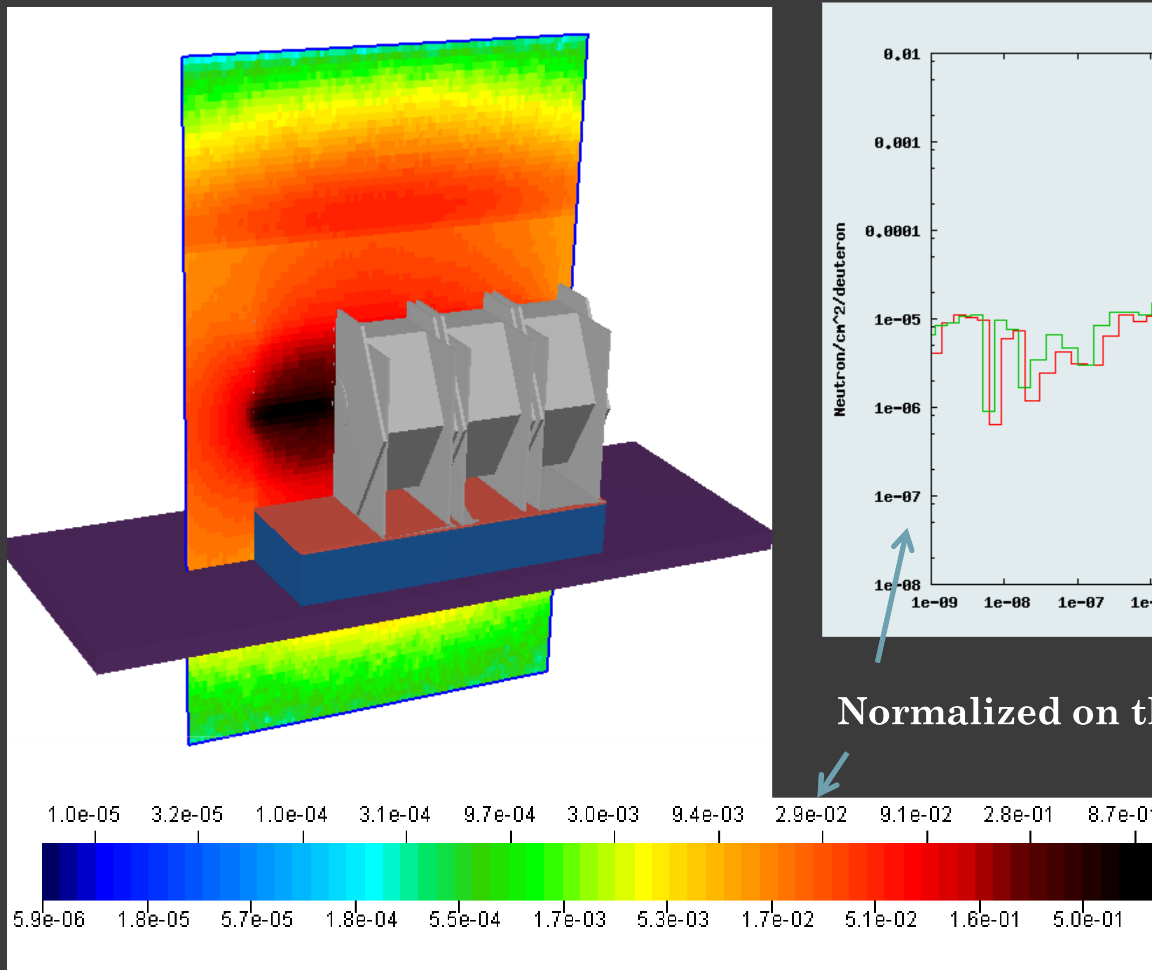
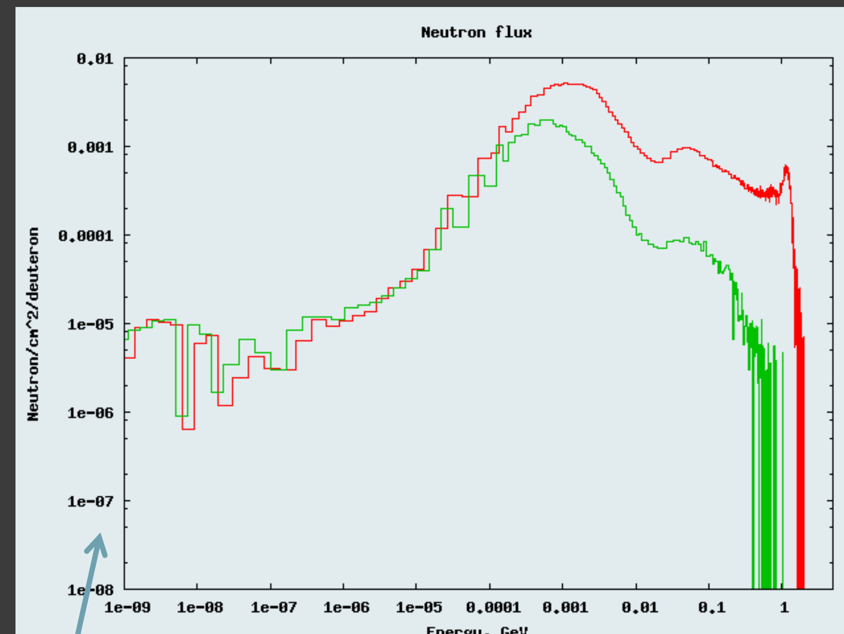
Simulations: FLUKA results

Neutron spatial distribution: slice yz (the first section and shielding were removed for the best view)



Neutron spectrum for points:
Z=118 mm, R=0 mm (red line)
Z=118 mm, R=85 mm (green line)



Normalized on the primary particles

EXPERIMENT

Накопление ^{239}Pu

Экспериментальные данные

Энергия дейтронов, GeV	Количество дейтронов	^{239}Pu накопление в бланкете, г	^{239}Pu накопление в бланкете, г/дейтрон·ГэВ
1.60	$2.1 \; 10^{13}$	$(4.2\pm0.4)\cdot10^{-8}$	$(1.2\pm0.1)\cdot10^{-21}$
2.52	$5.9 \; 10^{12}$	$(1.6\pm0.2)\cdot10^{-8}$	$(1.1\pm0.1)\cdot10^{-21}$

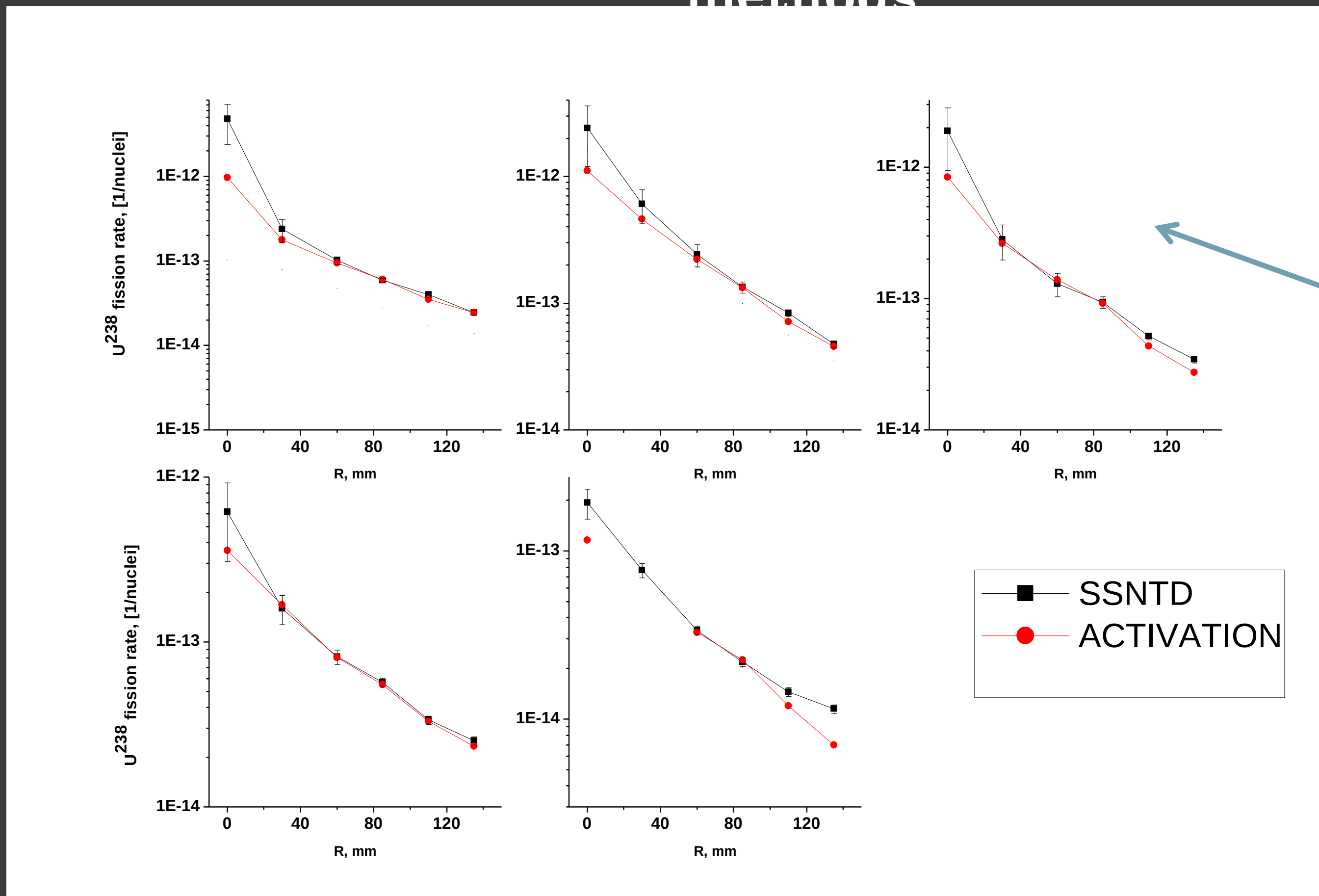
спектр нейтронов в бланкете не зависит от энергии первичных частиц

Эксперимент и расчетные значения

Энергия дейтронов, GeV	^{239}Pu накопление в бланкете, г		
	ЭКСПЕРИМЕНТ	MCNPX - расчет	FLUKA -расчет
1.60	$(4.2\pm0.4)\cdot10^{-8}$	-	$(4.96\pm0.25)\cdot10^{-8}$
2.52	$(1.6\pm0.2)\cdot10^{-8}$	$(1.43\pm0.07)\cdot10^{-8}$	$(1.71\pm0.10)\cdot10^{-8}$

EXPERIMENT

Experiment: two independent experimental methods

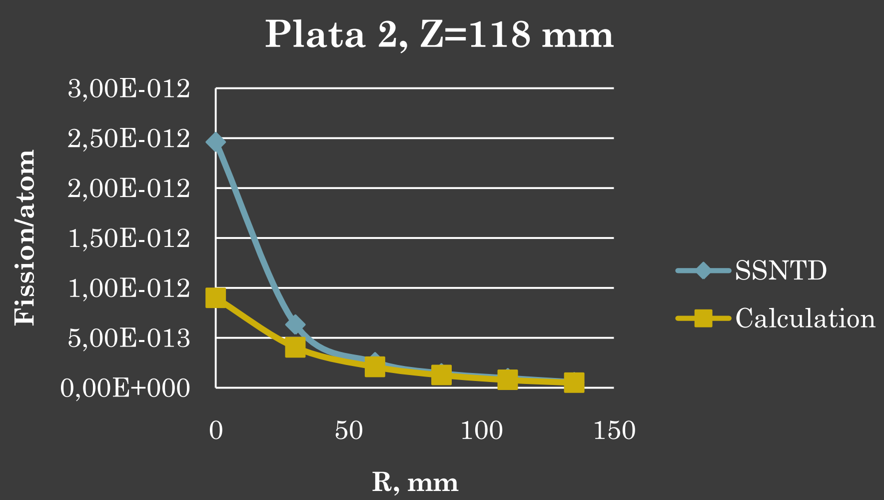


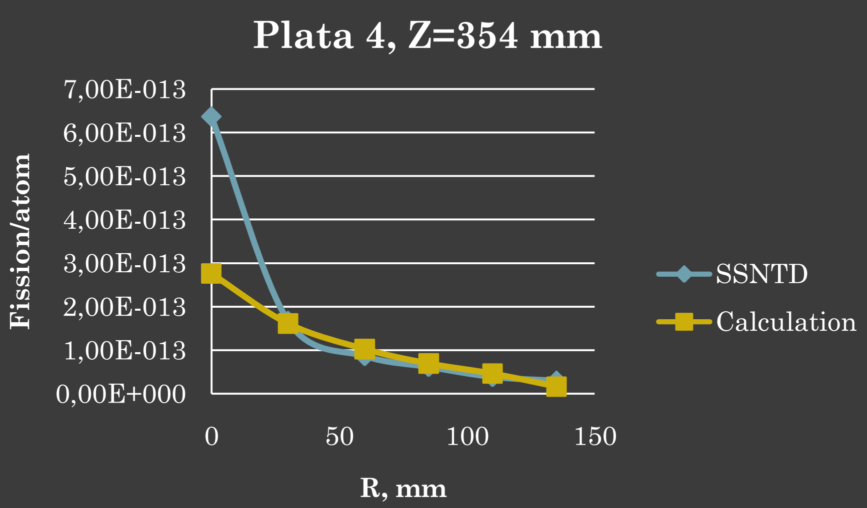
Note that the vertical scale ranges are not the same for all plots. Maximum is Situated on the third plata

Radial distributions of ^{238}U fission rates inside the Pb-target and U-blanket for the five detector plates. R is the radial distance from the axis of the lead target. Lines are drawn to guide the eyes.

S I M U L A T I O N S

Simulations: comparison FLUKA and SSNTD data





Natural Uranium fission rates: Experimental and calculated results

Radial distributions for Experimental plates No 2 and 4

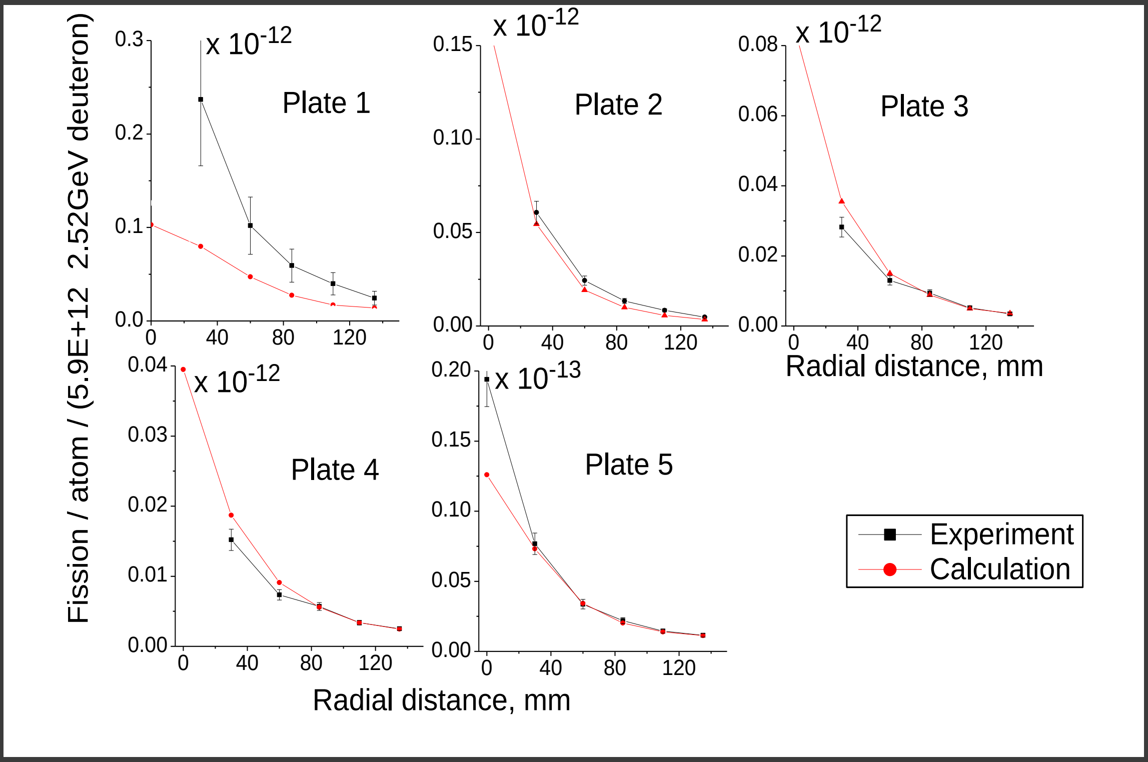
Experimental results are in very good agreement with calculation in the "blanket region" (radial distances R>4.2 cm)
of the setup. It can be explained by overwhelming contribution of neutron induced fission reaction in the total uranium fission process

Note that the calculation Includes only neutron induced fission

S I M U L A T I O N S

Simulations: comparison MCNPX and SSNTD data

Natural Uranium fission rates: Experimental and calculated results



Experimental results are in very good agreement (within the experimental error interval) with calculation in the “blanket region” (radial distances R>4.2 cm) of the setup.

Radial distributions of ^{238}U fission rates inside the Pb-target and U-blanket for the five detector plates. R is the radial distance from the axis of the lead target. Lines are drawn to guide the eyes.

Simulations are in progress

C O N C L U S I O N

1. The structure primary deuterons beam was investigated using SSNTD technique.
2. Experimental radial and axial distributions of fission rates natural Uranium were measured by two independent methods
3. Comparison of experimental data with the calculation results obtained with using of computer codes MCNPX 2.6 and FLUKA were carried out.
4. The developed technique allows to determine ^{239}**Pu** accumulation in the blanket of U/Pb-assembly.
5. It is shown that proton, pion, photon and deuteron induced fissions contribute significantly to the total fission-rate in the samples within the target volume and its immediate vicinity.

A K N O W L A D G E M E N T S

We would like to thank

Veksler and Baldin Laboratory of High Energies (VBLHE), Joint Institute for Nuclear Research (JINR), Dubna, Russia and staff of the Nuclotron accelerator for providing us the research facilities used in these experiments.

JINR for the hospitality during their stay in Dubna.

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THANK YOU