ISHEPP XX Relativistic Nuclear Physics & Quantum Chromodynamics, 4-9 October 2010, Dubna

METHODS AND RESULTS OF THE ^{nat}Pb(d,f), ^{209}Bi(d,f) AND ^{209}Bi(d,xnyp) REACTIONS CROSS SECTIONS MEASUREMENTS AT 1.6 AND 4 GeV DEUTERON BEAMS

A.S. Patapenka, A.A. Safronava, I.V. Zhuk, V.A. Voronko, V.V. Sotnikov, P.A. Martynenko, Ju.T. Petrusenko

Joint Institute for Power and Nuclear Research – "Sosny", NAS of Belarus

National Science Center "Kharkov Institute of Physics and Technology", NAS of Ukraine

Presenter: Patapenka Andrei
a.potapenko@tut.by

Outline

- **Experimental technique:**

  SSNTD technique for fission cross-section measurement

  Technique for direct reaction cross-section measurement

- **Experimental results**

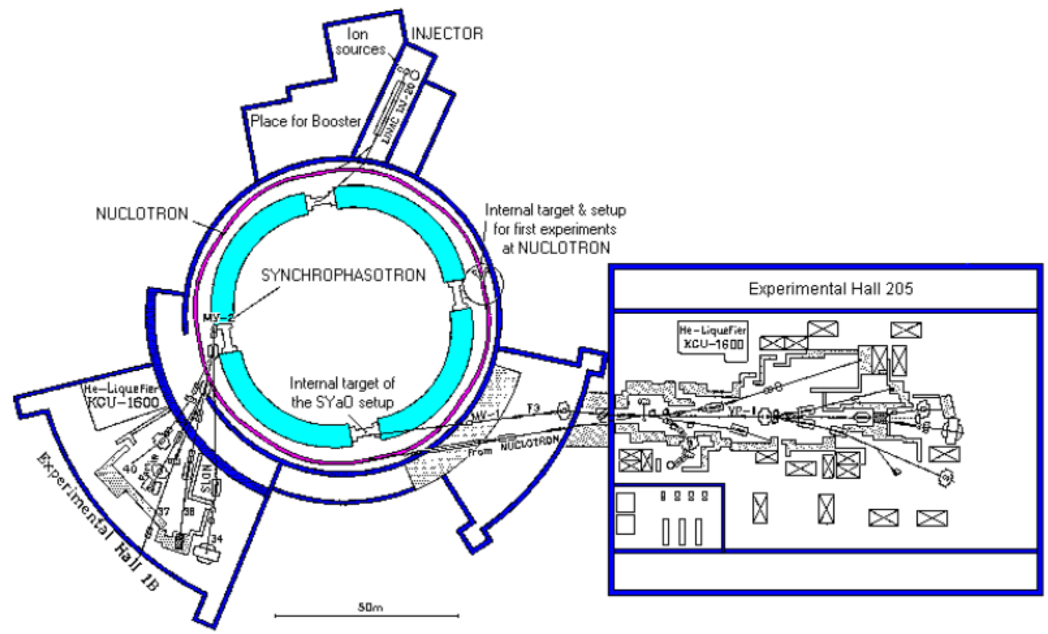
Experimental

Collaboration “Energy plus Transmutation”

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

Accelerator building (Laboratory of High Energy Physics, JINR)

Layout of accelerator complex and experimental hall



E
X
P
E
R
I
M
E
N
T
A
L

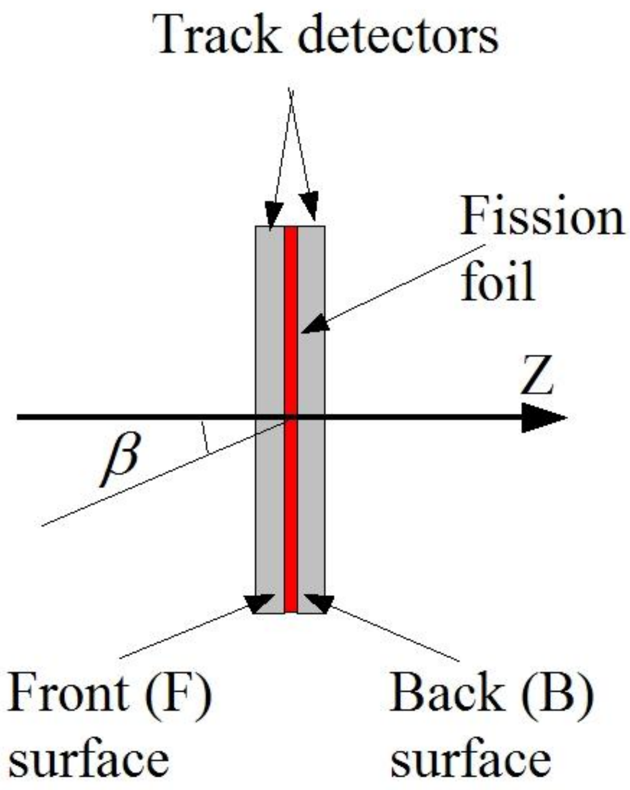
EXPERIMENTAL

Experimental technique for fission reaction rate measurements at high energies

Experimental technique for (*d, xn*) and (*d, pxn*) reaction rate measurements

E X P E R I M E N T A L S S N T D

SSNTD for fission rate measurement : concept



The basis of fission reaction rates measurement using **solid nuclear track detectors** (SSNTD) is the parity between a density of tracks formed on the surface of the detector, (irradiated at close contact to a radiator which is a source of fission fragments), and investigated neutron flux.

Reaction rate is proportional to the track density on the detector.

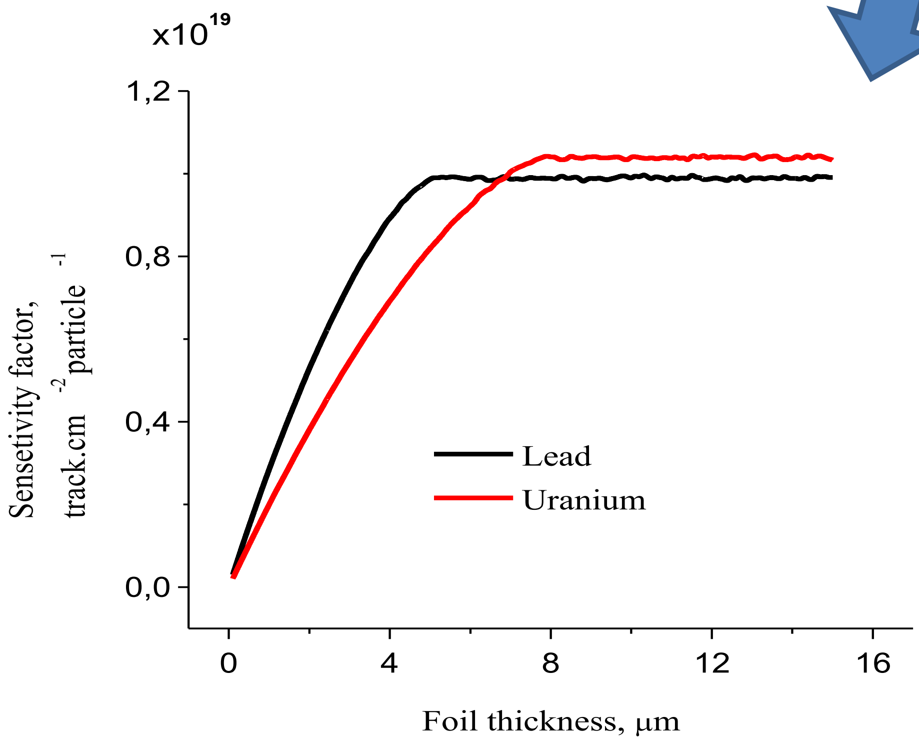
$$N_q^i = A^i \mu^i \varepsilon_q d_q \rho_q P \int_0^\infty \sigma_f^i(E) \varphi^P(E) dE$$

E X P E R I M E N T A L S S N T D

SSNTD for fission rate measurement : concept (2)

The yield of fission fragment μ accounts for different foil thicknesses as:

$$\mu = \begin{cases} \frac{1}{2}\left(1 - \frac{d}{2R}\right) & For \quad d < R \\ \frac{1}{4} & For \quad d = R \\ \frac{1}{4}\frac{R}{d} & For \quad d > R \end{cases}$$



Sensitivity factor does not depend on radiator thickness if it exceeds fission fragments range in radiator material

EXPERIMENTAL SSNTD

SSNTD for fission rate measurement : concept (3)

This definition of the *k* implies that if fission track density *N,* is measured in a sample, then the ratio of *N / k* represents the number of fissions per atom of the fissionable nuclei in the foil during the irradiation.

depend on radiator's parameters

$$k_q^{sens} = A^i \mu^i \varepsilon_q d_q \rho_q$$

depends on ion type (Z-number)

depend on fission processes

For "thick" foil

E X P E R I M E N T A L S S N T D

SSNTD for fission rate measurement : concept (3)

Sensitivity factor depends on:

1. Linear momentum transfer from projectile to the target nuclei - calculation were performed with analytical model (for fission fragments distributions) + TRIM code

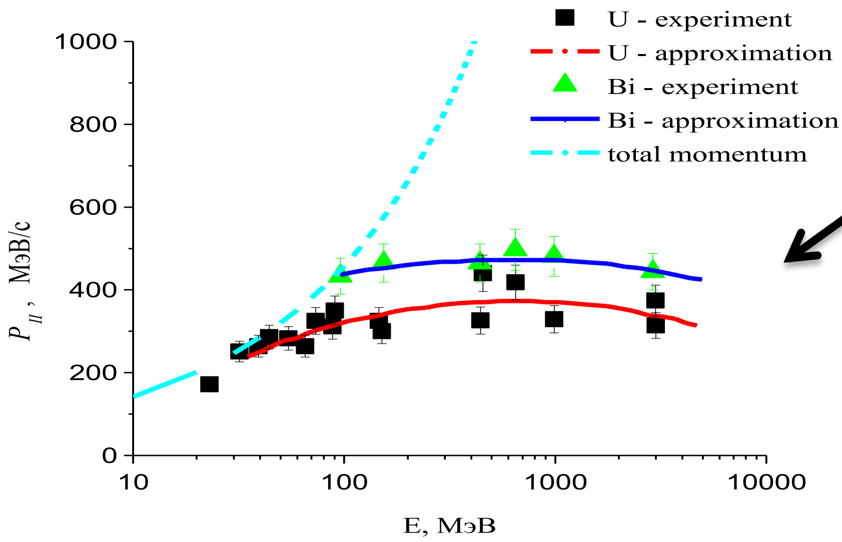
2. Fission anisotropy (in c.m.s.) - calculation were performed with analytical model (for fission fragments distributions) + TRIM code

3. Multifragmentation (at the projectile energy > 500 MeV) - calculation were performed with FLUKA (RQMD and DPMJET models) + TRIM code

SSNTD for fission rate measurement : momentum transfer

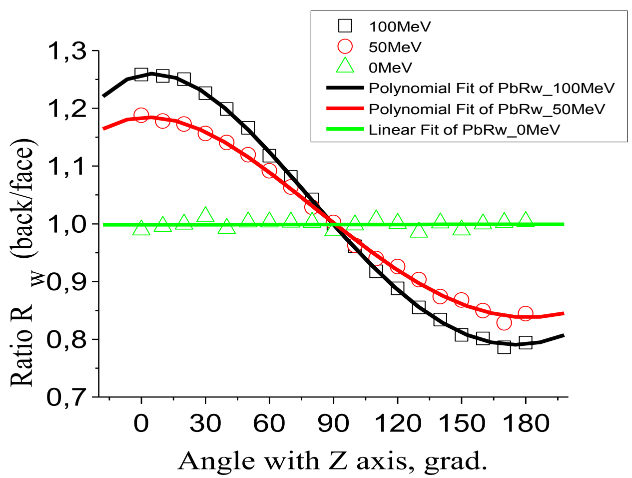
EXPERIMENTAL SSNTD

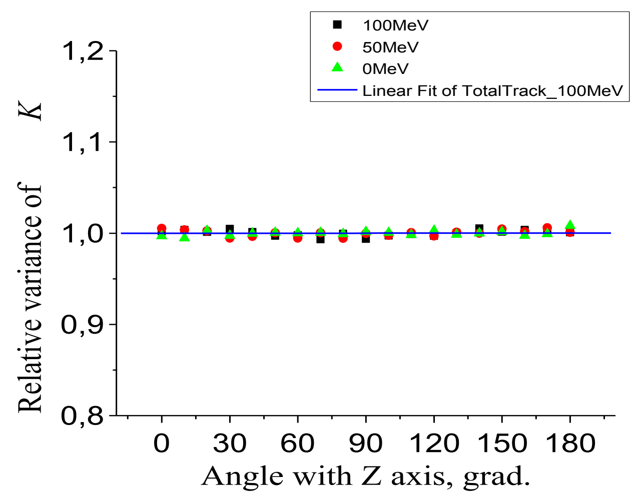
Data from Обухов и др. ЭЧАЯ 32/2. 2001



Fission fragment registration in 4π - geometry

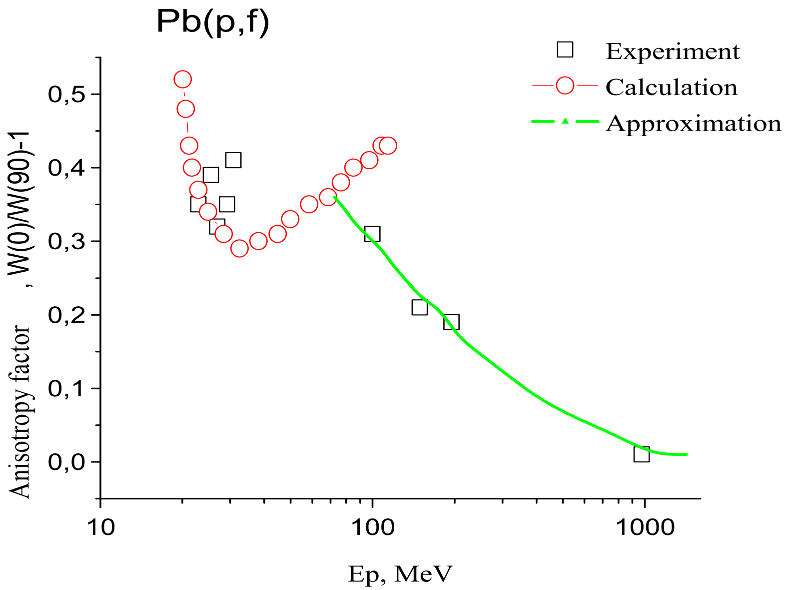
results





EXPERIMENTAL SSNTD

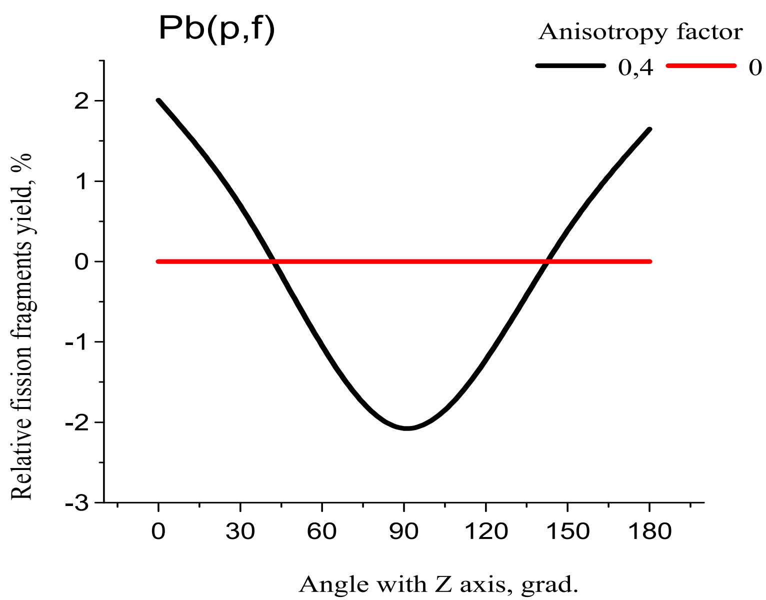
SSNTD for fission rate measurement: fission anisotropy



$$W(\vartheta) = \frac{k_{norm}}{2\pi}(1 + B\cos^2\vartheta)$$

where *B is the angular anisotropy factor;*
k_{norm} is a normalization constant;
ϑ is angular coordinate.

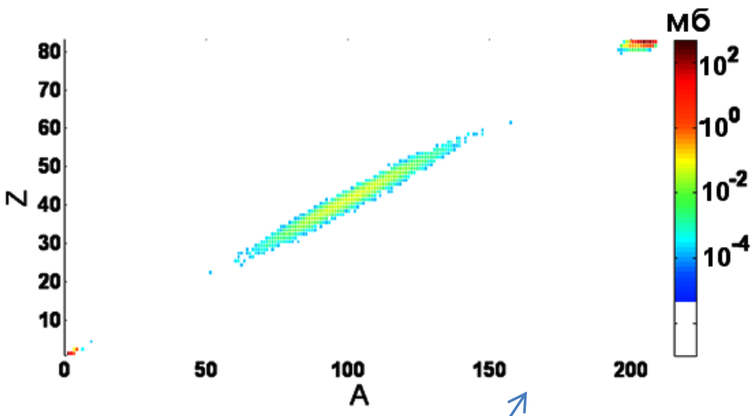
(Data and formula are taken from
А. И. Обухов и др. ЭЧАЯ 32/2. 2001 and
I. V. Ryzhov *et al., J. Nucl. Sci. Techn., Suppl. 2, 295-298 (2002)*)



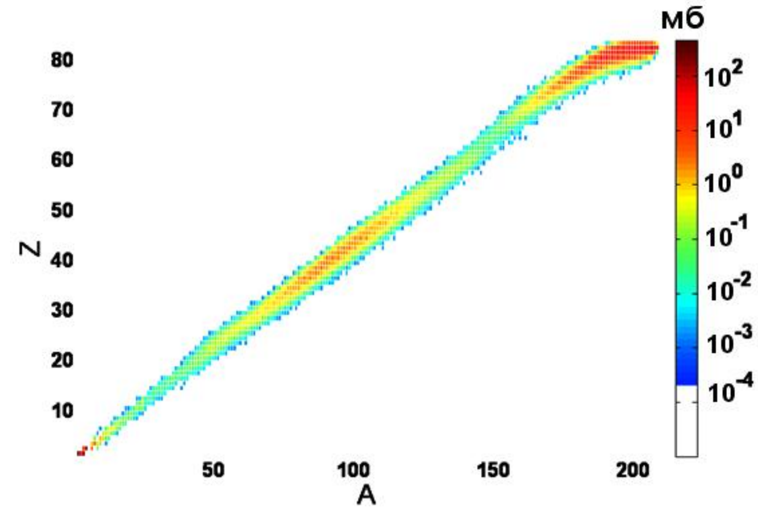
results

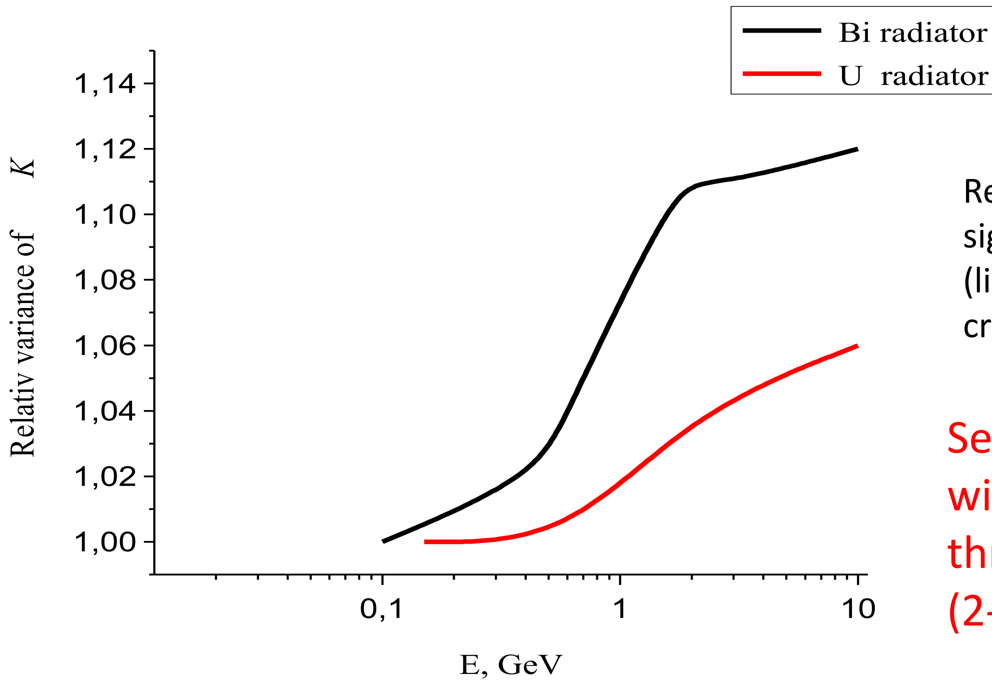
1. Effect is negligible at the energy > 1 GeV
2. Correction factor don't exceed 2-3 %

SSNTD for fission rate measurement: non-fissionable background



Residual nuclei after $^{nat}Pb(p,f)$ Ep=60 and 600 MeV





results

Residual nuclei distributions are changing significantly with projectile energy increasing (light fragments (which has a LET value enough to create track on detector) appears)

Sensitivity coefficient slowly increases with energy after multifragmentation threshold
(2-3 MeV/nucleon for heavy nuclei)

E X P E R I M E N T A L S S N T D

SSNTD for fission rate measurement : sensitivity factor

Calculated values

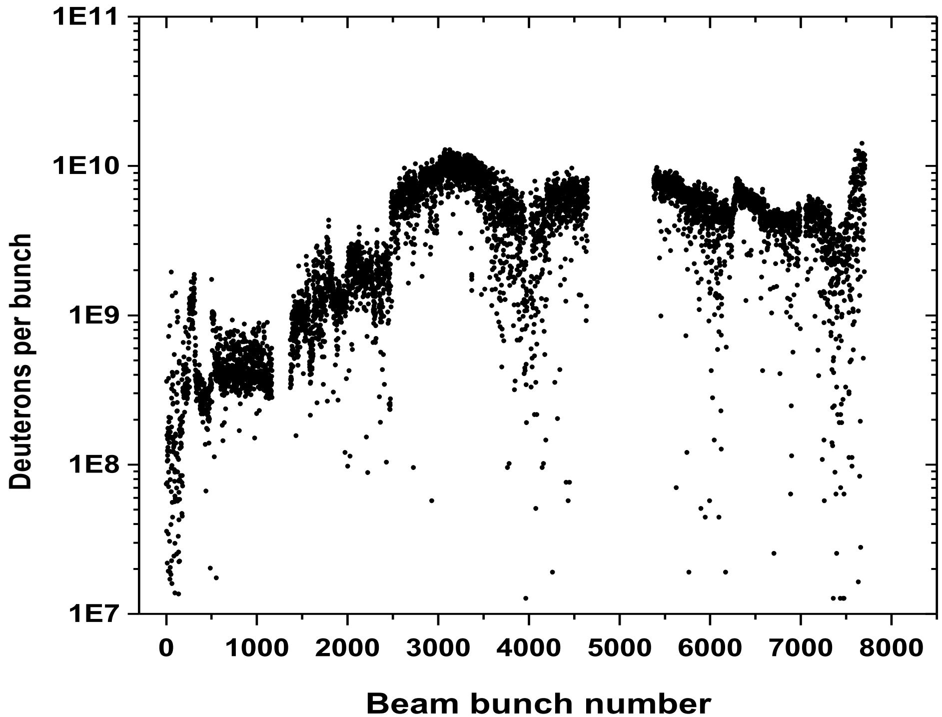
Metallic radiator	U	Bi	Pb	Au	W	Ta
Sensitivity factor *w*, $\times 10^{19}$, track$\times$cm$^{-2}\times$ deuteron^{-1}	0,95	0,92	1,05	1,03	0,95	0,79

Experimental values for

1. U radiator – (0,96±0,02) $\times 10^{19}$
2. Pb radiator – (1,03±0,11) $\times 10^{19}$

E X P E R I M E N T A L A C T I V A T I O N

Activation method for (d, xn) and (d, pxn) reactions rates measurements



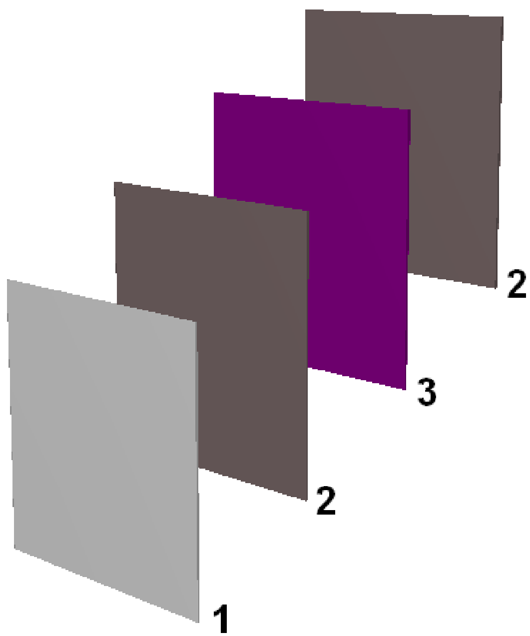
Corrections

1. decay during cooling, measurement, irradiation (intensity data from Nuclotron)
2. unequable irradiation (intensity data from Nuclotron)
3. coincidences (MCNP)
4. non point-like emittors (MCNP)
5. detector deadtime
6. detector efficiency

R
S
U
L
T
S

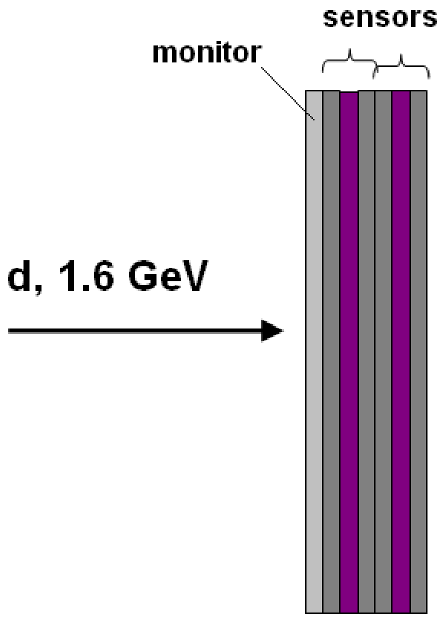
S
S
N
T
D

SSNTD for fission rate measurement : scheme of sandwiches



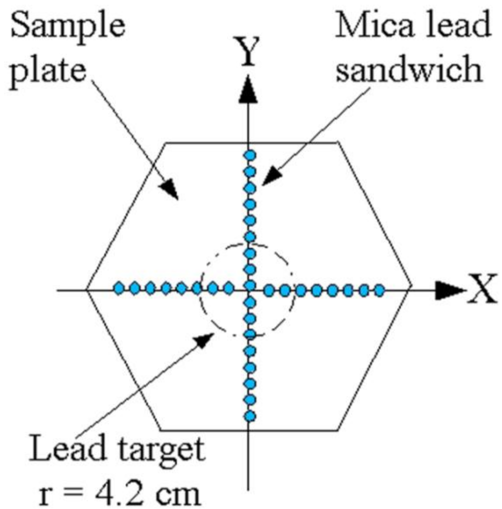
1. Al foil (flux monitor)
2. SSNTD (mica)
3. Radiators (^{nat}U, ^{209}Bi, ^{nat}Pb)

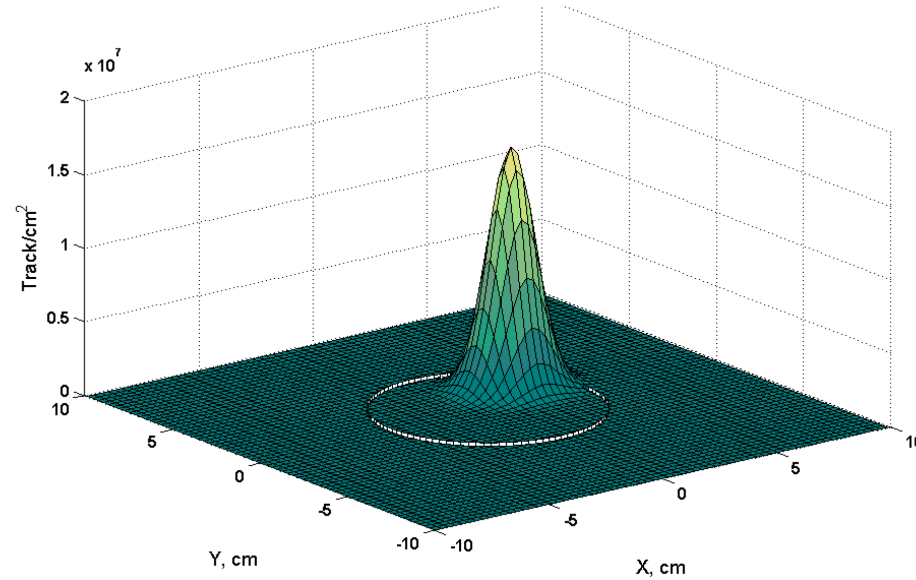
(Size of Al foils: 12 x 12 x 0,1 mm)



RSULTS SSNTD

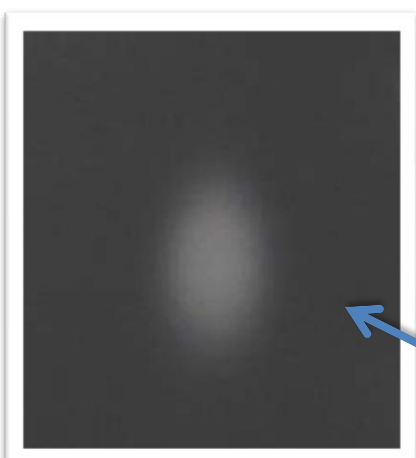
Deuteron beams profiles and sensors location





Gaussian approximation of experimental data from SSNTD sensors / Pb(d,f) reaction /

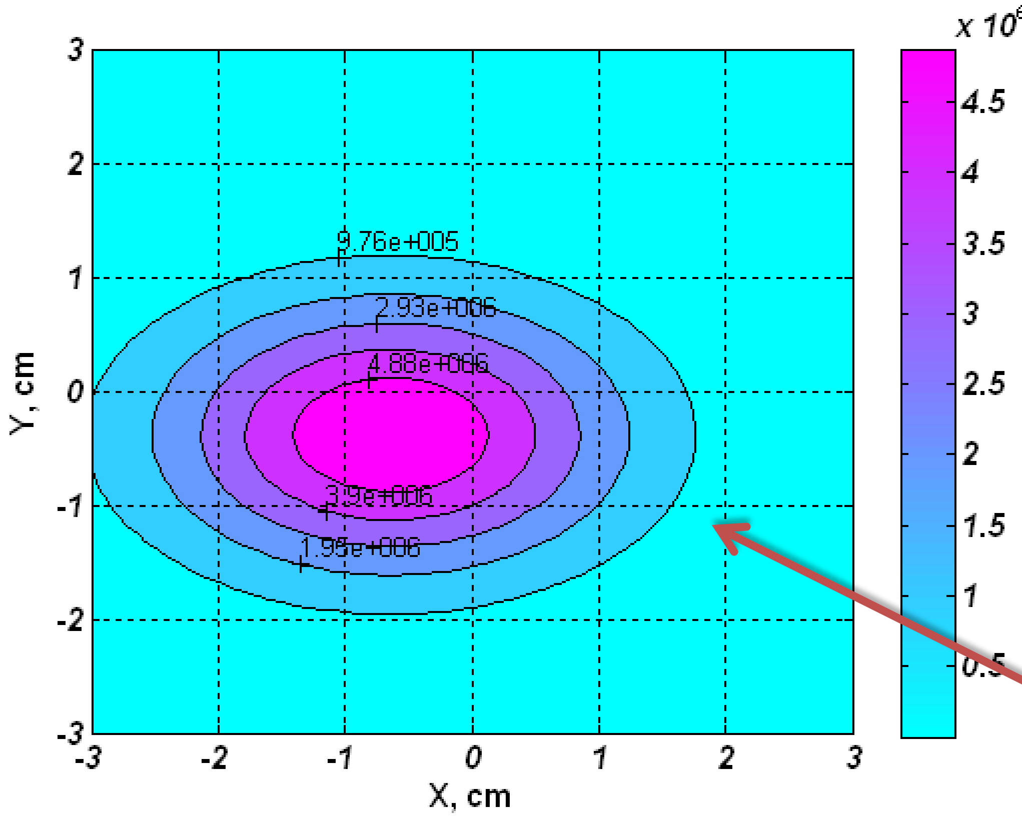
Track densities on the top of the assembly is proportional to spatial distribution of primaries particles.



The traces of one bunch of beam particles on polaroid film placed in front of the target

RSULTS SSNTD

Deuteron beams profiles and sensors location



Sensor location on the direct beam at deuteron energy 1.6 and 4.0 GeV:

1. **(x=0cm, y=0cm)**
2. **(x=-2cm, y=0cm)**

Total deuteron fluxes on the samples were $10^{11} – 10^{12}$

A structure (profile) of deuteron beam for Energy 1.6 GeV

Energy	FWHM (cm)		Center position (cm)	
	X	Y	Xc	Yc
4.0	2.10±0.1	1.80±0.1	2.40±0.1	1.70±0.1
1.6	2.8±0.1	1.9±0.1	-0.6±0.1	-0.4±0.1

R
S
U
L
T
S

S
S
N
T
D

Results of experimental measurements of fission cross-section for deuteron energy 1.6 and 4.0 GeV (SSNTD method)

Samples	Fission cross-section for deuteron energy 1.6GeV **(experiment, present work) mb**	Fission cross-section for deuteron energy 2.1GeV **(experiment, EXFOR library) mb**	Fission cross-section for deuteron energy 4.0GeV **(experiment, present work) mb**
U-nat	**1700 ±300**	**1654 ± 340**	**-**
Pb-nat	**200 ± 50**	**182 ± 40**	**170 ± 40**
Bi-209	**220 ±80**	**323 ± 60**	**310 ± 60**

SIMULATION

Calculated fission cross-section at 1.6 GeV deuterons for U-nat using MCNPX 2.6C

U-nat σexp = 1.7±0.3b, Present work

Calculations were performed with MCNPX 2.6c (S.R. Hashemi-Nezhad).

Calculation model	Fission cross section, b	$(\sigma_{exp} - \sigma_{cal}) / \sigma_{exp}$ (%)
Bertini + RAL	1.31 (0.4)	25.31
Bertini + ABLA	1.51 (0.4)	13.94
CEM03 + RAL	1.31 (0.4)	25.31
CEM03 + ABLA	1.51 (0.4)	13.89
INCL4 + RAL	1.47 (0.4)	16.17
INCL4 + ABLA	2.02 (0.3)	-15.43

RSULTS ACTIVATION

Experimental independent (ind) and/or cumulative(cum) cross-sections of $^{209}Bi(d,pxn)^{A}Bi$ reactions; (x=210-A).

A	T1/2	E_{γ}, keV	Cross-sections, mb			
			E_d=1,6 GeV		E_d=4 GeV	
				cum		cum
206	6,24 d	516; 803	58± 6	78 ± 6	42 ± 4	56 ± 5
205	15,3 d	703,5; 1764	65 ± 7	75 ± 7	-	52 ± 5
204	11,2 h	899; 374	m2+m1+g 35 ± 3	48 ± 4	m2+m1+g 25 ± 4	33 ± 4
203	11,8 h	820; 1847	m+g 33 ± 3	37,5 ± 3	-	28 ± 3
201	103 m	629; 936,2; 1014	-	17 ± 2	-	-
200	36,4 m	1026; 462,3	g 12 ± 2	g 12 ± 2	-	-

R S U L T S A C T I V A T I O N

Experimental independet cross-sections of $^{209}Bi(d,xn)^{A}Po$ reactions; (x=211-A).

A	T1/2	E_γ , keV	Cross-sections, mb	
			E_d =1,6 GeV	E_d =4 GeV
207	5,8 h	992,3	m+g 12 ± 2	m+g 9 ± 1,5
206	8,8 d	1032,3	20 ± 4	14 ± 2.5
205	1,74h	872,4; 836,8; 849,8; 1001,2	m+g 10 ± 2	-
204	3,53 h	1016,3; 534,9	13±2	8 ± 4
203	36,7 m	908,6	m+g 4,5±1,4	-

Conclusions

- ✓ SSNTD technique was adjusted for high energy fission measurements.
- ✓ New experimental values of fission cross sections of ^{nat}U (d,f), ^{nat}Pb (d,f), ^{209}Bi (d,f) reactions were obtained.
- ✓ New experimental values of ^{209}Bi (d,pxn) and ^{209}Bi(d, xn) cross sections were obtained.

AKNOWLADGEMENTS

We would like to thank

- Laboratory of High Energy Physics, 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 our stay in Dubna

- NASB for supporting of this work

THANK YOU

Andrei Patapenka

a.potapenko@tut.by