DETERMINATION OF HEAVY METAL SPALLATION REACTIONS CROSS SECTIONS AT 2, 2.94, 3.5 GEV DEUTERON BEAMS

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OUTLINE

- Motivation
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- Uncertainties calculation
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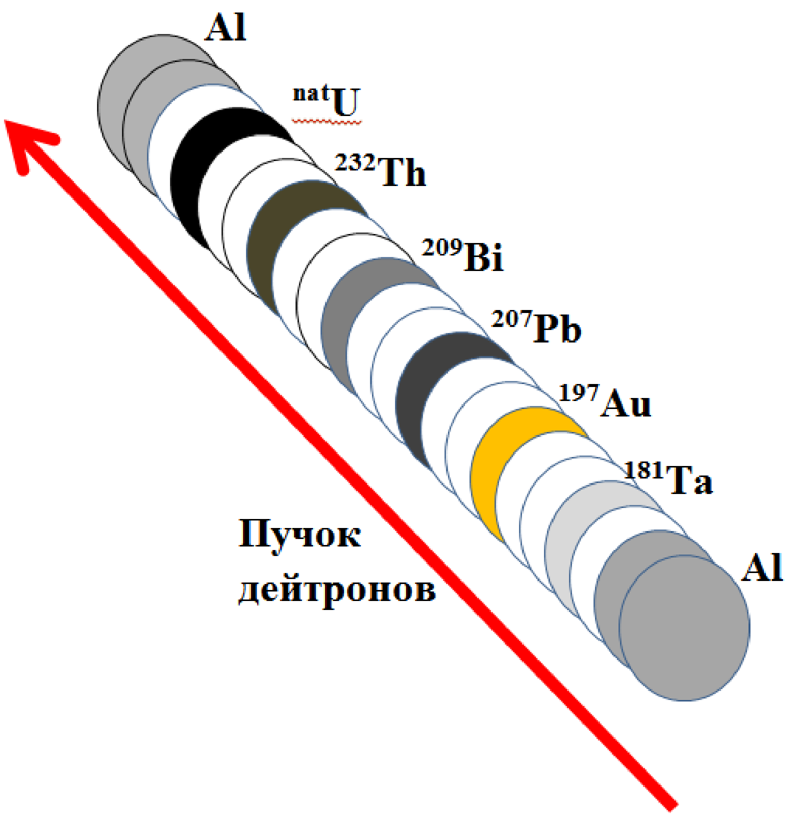
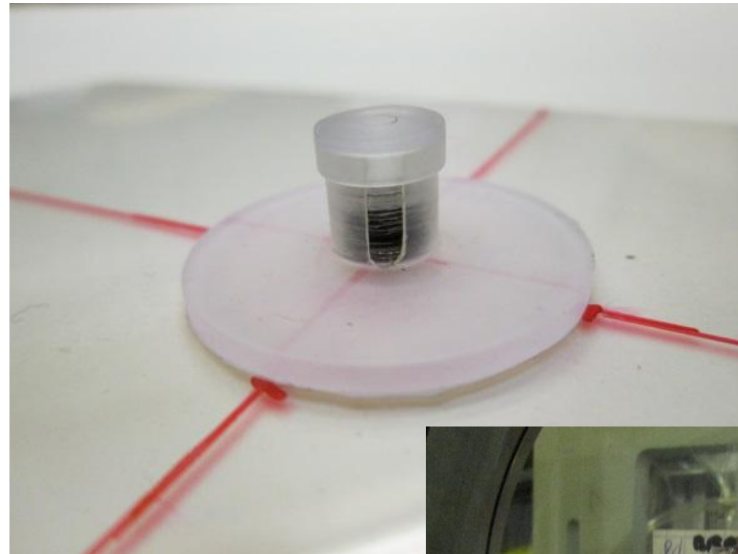
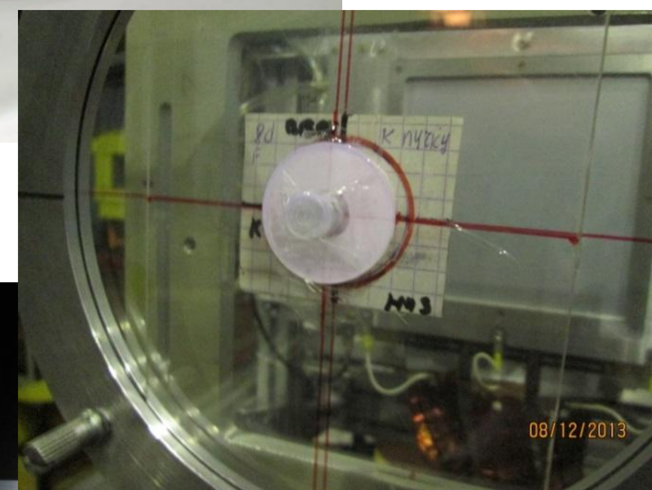
Motivation

- Deuteron experimental data on nuclear reaction cross section with the energy of bombarding particles above 500 MeV are still very limited (see EXFOR library)
- Target and constructional materials (could be made of such material as beryllium, tantalum, tungsten, uranium, plutonium or thorium) is important criteria for ADS
- Lack of nuclear date makes difficult to perform some model calculations of ADS assemblies

Experiment description



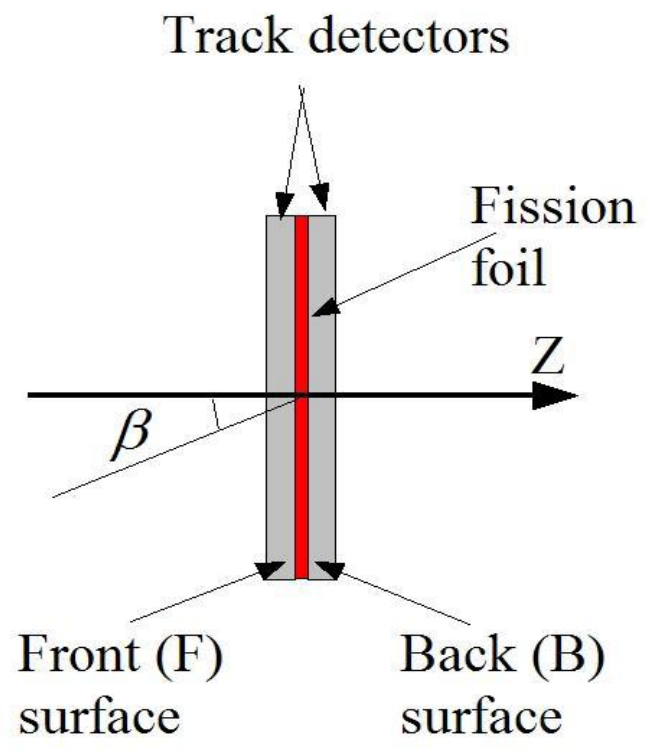




Experiment description

Used material dimensions:

- Diameter of all foils - 6.5 mm
- Thickness:
- Al – 1 mm
- Mica – 0.030 mm
- ^{238}U - 0.030 mm
- ^{232}Th - 0.060 – 0.080 mm
- ^{209}Bi - 0.025 mm
- ^{207}Pb - 0.5 mm
- ^{197}Au - 0.030 mm
- ^{181}Ta - 0.030 – 0.050 mm



Experiment description

- “Telescope” setup was irradiated by deuterons beams extracted from Nuclotron accelerator, Joint Institute for Nuclear Research
- Energy: 2 , 2.94, 3.5 GeV/nucleon
- Date: February 2014

Physical basis of the SSNTD method

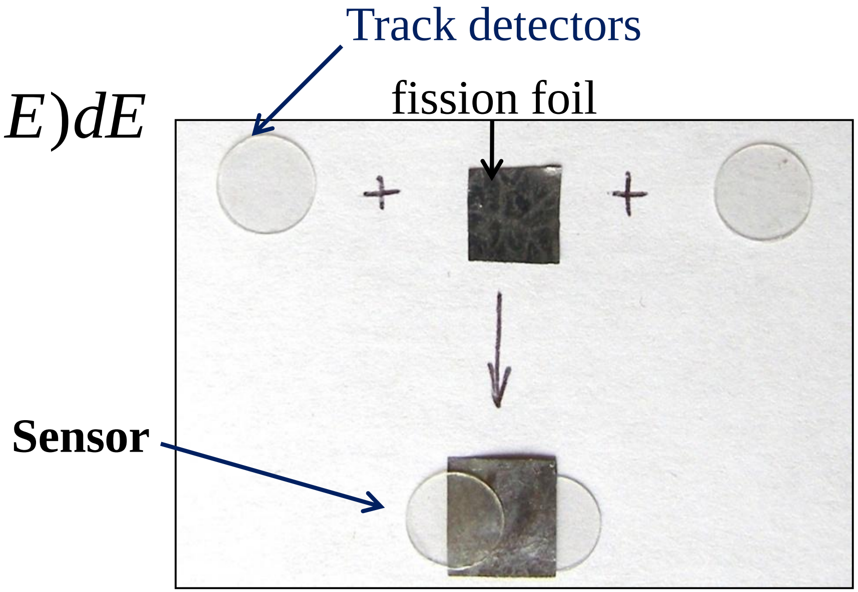
SSNTD technique is based on relation of tracks density and flux density of investigated neutron field

Track detector with fission foil (source of fission fragment) is irradiated in neutron field. After this the tracks are formed on the track detector surface

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

Sensor calibration factor :

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

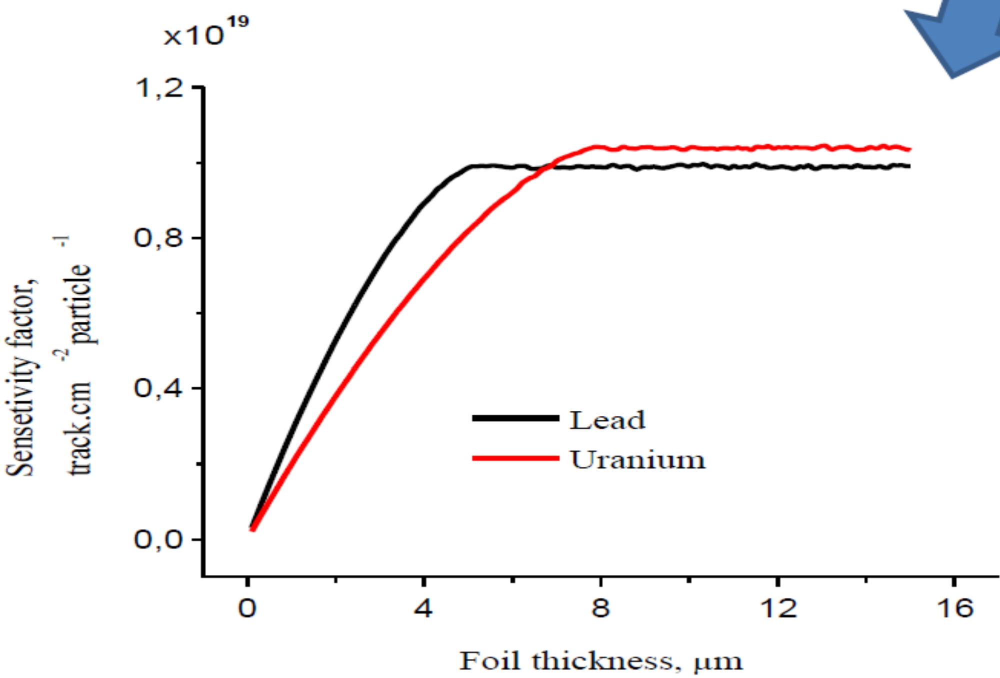


The technique was developed by I. Zhuk and A. Malikhin
was applied in fission reactions rate measurements in reactor systems

Physical basis of the SSNTD method

- μ - is a fraction of charged fragments reached the detector and depends on foil thicknesses

$$\mu^{i} = \begin{cases} \frac{1}{2}\left(1 - \frac{d_q}{2\overline{R_0}}\right) & \text{for} \quad d_q < \overline{R_0} \\ \frac{1}{4} & \text{for} \quad d_q = \overline{R_0} \\ \frac{1}{4}\frac{\overline{R_0}}{d_q} & \text{for} \quad d_q > \overline{R_0} \end{cases}$$



- d - is a thickness of foil
- R – is the range of fission fragments

Physical basis of the SSNTD method

Calibration factor is a unique characteristic for specific pair “fissionable foil - detector”

Calibration factor does not depend on the field of exposure

Depend on fissionable foil

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

depends on ion type (Z-number)

depend on fission processes

For “thick” foil

Calibration factor calculation

For Monte Carlo calculation SCILAB program code was used and:

- Consist of three modules:

  - module of sensor geometry (geometry of SSNTD and fissionable foil);

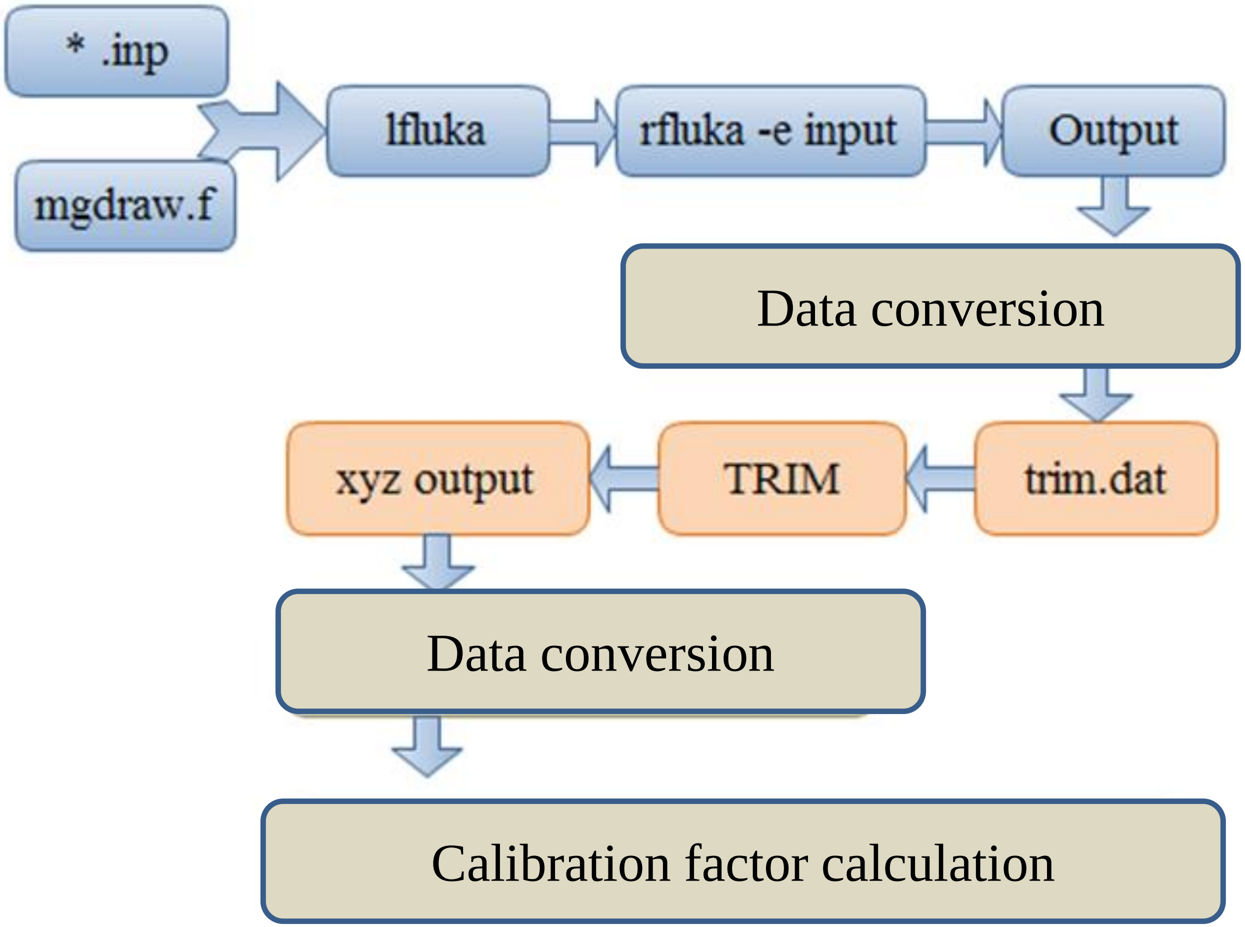
  - module of fission fragment parameters (kinematic characteristic: momentum and fission fragment distribution, here average fission fragment's range in the detector and foil is calculated ;

  - calculated module (here the spatial distribution of fission fragments after penetrating of fission foil and detector, parameter of ion trajectory in detector are calculated).

Patapenka A.S. (2011).Neutron –physical characteristics of the subcritical setup with natural uranium blanket, driven by accelerator. PhD Thesis, JINPR-Sosny NAS Belarus

Calibration factor calculation

For determination of dependence of calibration factor on fission fragments mass distribution and kinetic energy the FKUKA code was used.
(*Intra nuclear cascade INK* model *nucleon-nucleon interaction model RQMD-2.4*.)
General scheme of calculation is presented below



Calibration factor used in the cross section calculation

Нуклид	w, calibration factor, track × cm-2 × deuteron-1	w, calibration factor, track × barn-1 × deuteron-1
Ta-181	7,90E+18	7,90E-06
Au-197	1,03E+19	1,03E-05
Pb-207	1,05E+19	1,05E-05
Bi-209	9,20E+18	9,20E-06
Th-232	9,70E+18	9,70E-06
U-nat	9,50E+18	9,50E-06

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH

Calibration factors for determination of relativistic particle induced fission rates in ^{nat}U, ^{235}U, ^{232}Th, ^{nat}Pb and ^{197}Au foils

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Hashemi-Nezhad S.R., Zhuk I., Potapenko A.S., Krivopustov M.I. Calibration of track detectors for fission rate determination: an experimental and theoretical study // Nucl. Instr. and Meth. - 2006. - Vol. A568. - P. 816 - 825.
Patapenka A.S. (2011).Neutron –physical characteristics of the subcritical setup with natural uranium blanket, driven by accelerator. PhD Thesis, JINPR-Sosny NAS Belarus

Physical basis of the SSNTD method

In terms of SSNTD the cross section can be found as:

$$\sigma_f^i = N_q^i / (k_q^{sens} P)$$

N_q^i - is a track densities, [track/cm^2]

k_q^{sens} - calibration factor for the sensor, [track·cm^{-2}·deutron]

P - is the number of primaries, [deuteron]

Data used for spallation-reaction cross section determination

Deuteron 2 GeV/nucleon (February 2014)

Nuclide	Track density BACK, track/cm^2	Track density FACE, track/cm^2	BACK/ FACE	Average track density, track/cm^2	Deuteron flux, d/cm^2
^{181}Ta	1,25E+05	6,86E+04	1,83±0,08	9,68E+04	4,91E+10
^{197}Au	1,49E+05	9,23E+04	1,61±0,07	1,21E+05	
^{207}Pb	1,74E+05	1,07E+05	1,63±0,07	1,41E+05	
^{209}Bi	2,26E+05	1,42E+05	1,59±0,07	1,84E+05	
^{232}Th	5,97E+05	4,80E+05	1,24±0,05	5,39E+05	
^{nat}U	7,68E+05	6,23E+05	1,23±0,05	6,96E+05	

Deuteron 2.94 GeV/nucleon (February 2014)

Nuclide	Track density BACK, track/cm^2	Track density FACE, track/cm^2	BACK/ FACE	Average track density, track/cm^2	Deuteron flux, d/cm^2
^{181}Ta	1,18E+5	6,21E+4	1,90±0,08	9,01E+04	5,0E+10
^{197}Au	1,49E+5	8,39E+4	1,78±0,08	1,16E+05	
^{207}Pb	1,76E+5	1,05E+5	1,68±0,07	1,41E+05	
^{209}Bi	2,20E+5	1,43E+5	1,54±0,07	1,82E+05	
^{232}Th	5,38E+5	4,18E+5	1,29±0,06	4,78E+05	
^{nat}U	6,67E+5	5,46E+5	1,22±0,05	6,07E+05	

Data used for spallation-reaction cross section determination

Deuteron 3.5 GeV/nucleon (February 2014), irradiation time – 16 hours

Nuclide	Track density BACK, track/cm²	Track density FACE, track/cm²	BACK/ FACE	Average track density, track/cm²	Deuteron flux, d/cm²
^{181}Ta	0,983E+6	0,515E+6	1,91±0,08	7,49E+05	3,8E+11
^{197}Au	1,21E+6	0,722E+6	1,68±0,07	9,66E+05	
^{207}Pb	1,41E+6	0,894E+6	1,58±0,07	1,15E+06	
^{209}Bi	1,68E+6	1,087E+6	1,55±0,07	1,38E+06	
^{232}Th	≥3E+6	≥3E+6	-	-	
^{nat}U	≥3E+6	≥3E+6	-	-	

Deuteron 3.5 GeV/nucleon (February 2014) , irradiation time – 2.5 hours

Nuclide	Track density BACK, track/cm²	Track density FACE, track/cm²	BACK/ FACE	Average track density, track/cm²	Deuteron flux, d/cm²
^{181}Ta	2,16E+5	1,12E+5	1,93±0,08	1,64E+05	9,3E+10
^{197}Au	2,72E+5	1,73E+5	1,57±0,07	2,23E+05	
^{207}Pb	3,11E+5	1,94E+5	1,60±0,07	2,53E+05	
^{209}Bi	3,78E+5	2,63E+5	1,44±0,06	3,21E+05	
^{232}Th	1,05E+6	0,84E+6	1,25±0,05	9,45E+05	
^{nat}U	1,20E+6	1,00E+6	1,20±0,05	1,10E+06	

Uncertainties estimation

Heavy metal spallation-reaction cross section:

$$\sigma_f = (N/P \times K_{sen}) \times k_f \times k_{ss} \times k_n \times k_{impur}$$

N – average track density of fission fragments in the center of foil

P - average deuteron density fallen on the full detector's surface

K_{sen} – calculated calibration factor

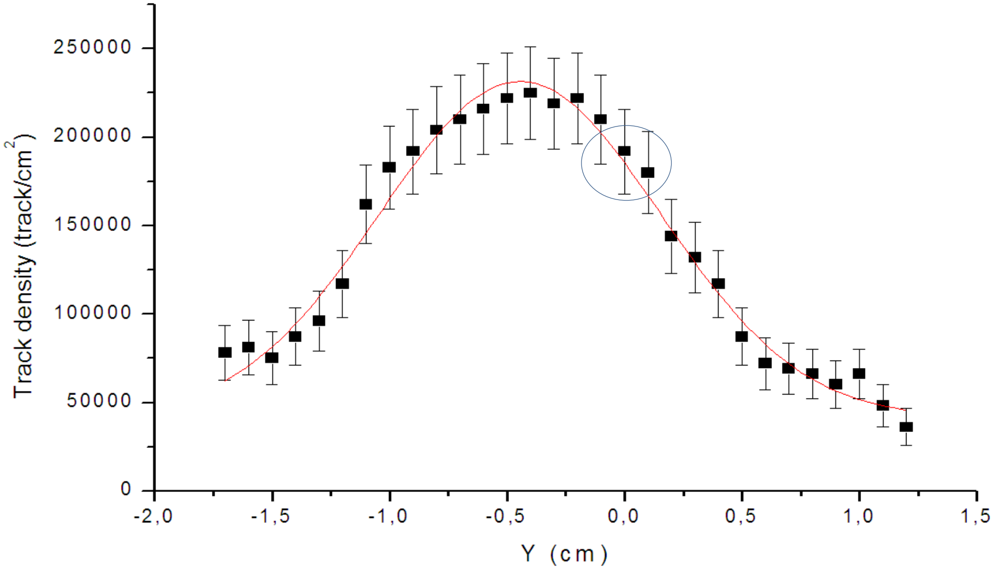
K_f – correction for average track density on the full detector surface

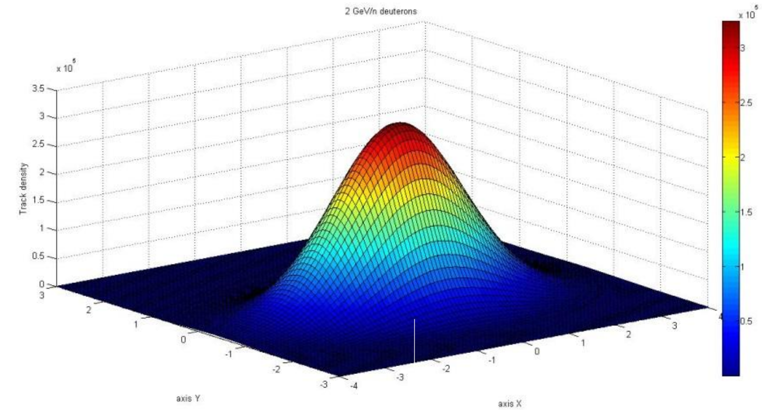
K_{ss} – correction for projectiles self-shielding

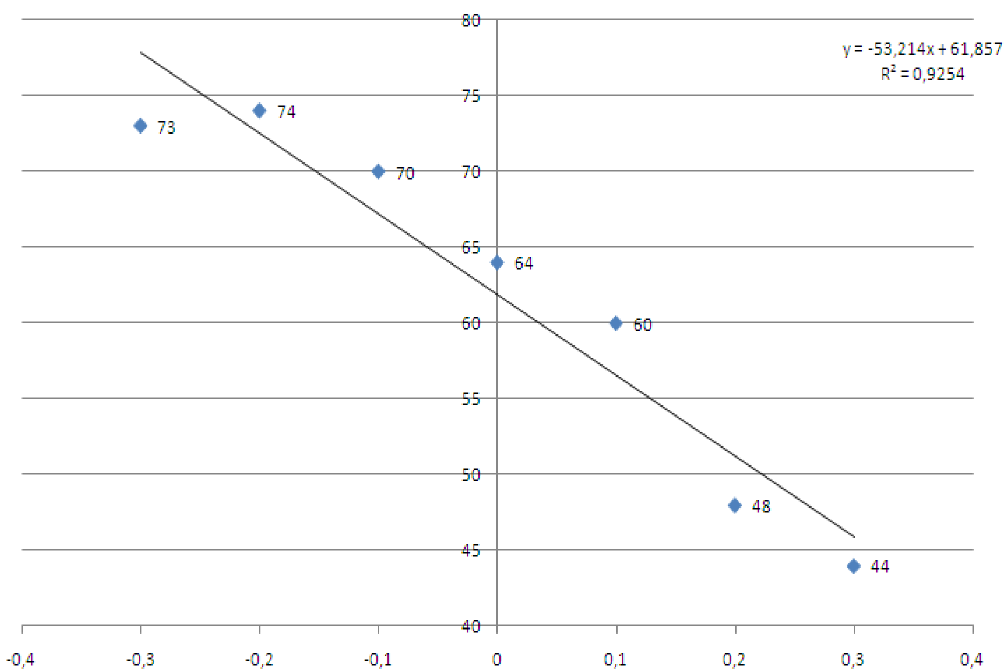
K_n – correction for fission non-connected with the deuterons (high energy neutrons as the result of projectiles with the surrounding things interaction)

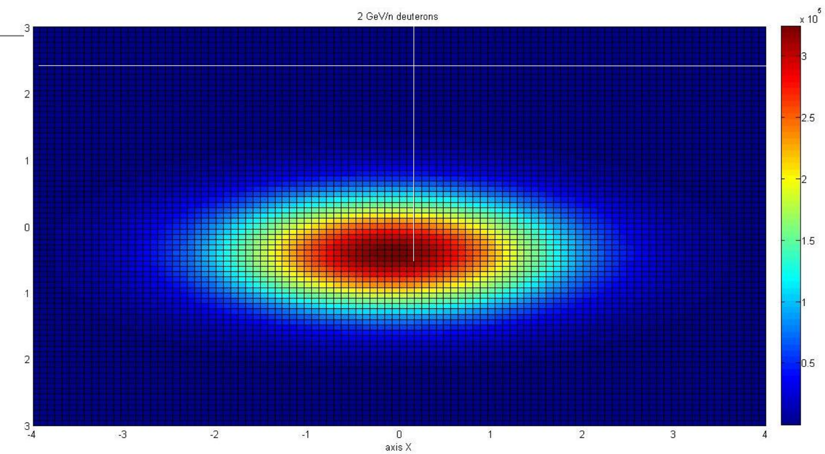
K_{impur} – correction for impurity atoms in the fissionable foils

Correction for average track density on the full detector surface



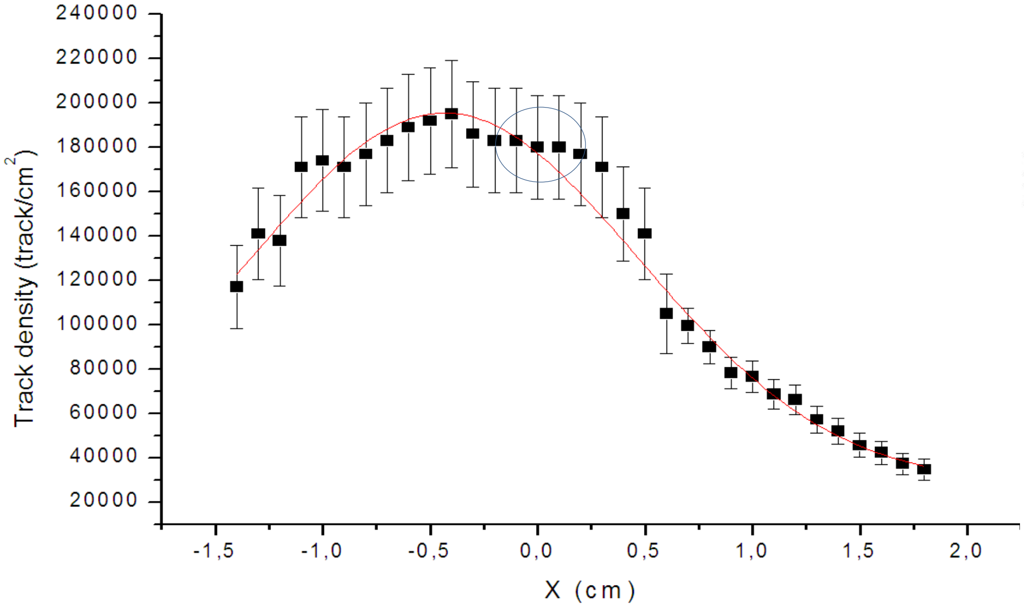


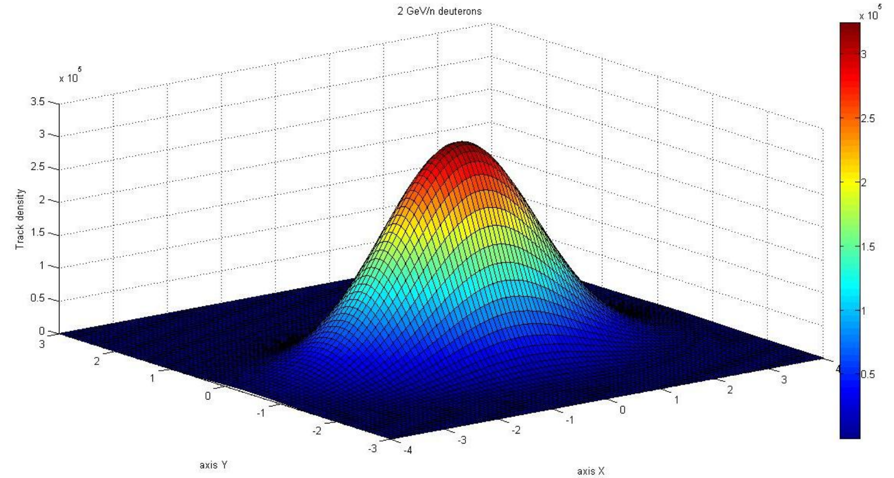


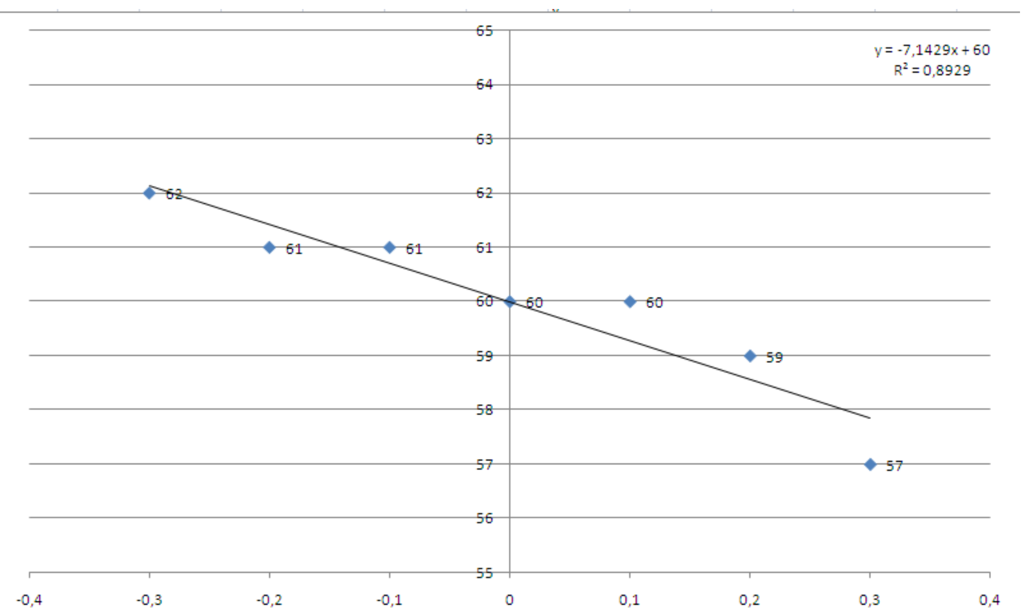


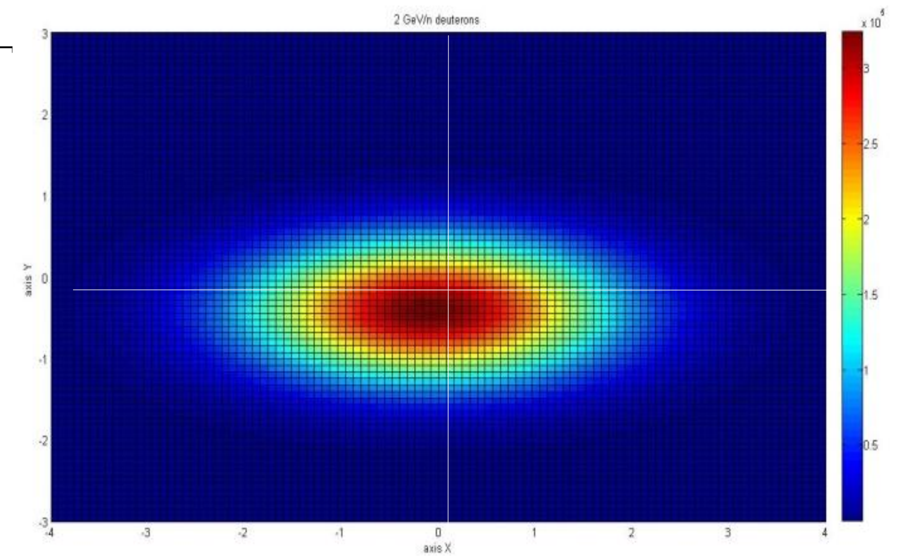
Deuteron 2 GeV/nucleon
Y axis

Correction for average track density on the full detector surface









Deuteron 2 GeV/nucleon
X axis

Input value K_f

(Correction for average track density on the full detector surface)

- Type of uncertainty – B
- Type of distribution – rectangular
- Interval of possible values - ± 7.5 %
- Relative standard uncertainty – 4.3 %

According to the result of measurement of deuteron flux density in the area of samples location , density is approximated by linear function with the error of 1.3 % along the Y axis and 7.4% along the X axis. The maximal error of correction for transition of track density from the detector's center to the full surface is 7,5%.
Relative standard uncertainty is equal to 7.5%/√3 = 4.3%

Uncertainty budget

Value X_i	Estimation x_i	Relative standard uncertainty $u(X_i)$, % /percentage contribution	Type of uncer-tainty	Type of probability distribution
N, average track density in the center of foil	$0{,}97 \cdot 10^5$ track/cm^2	3,6 / 14,2	A	normal
P , average deuteron flux density	$4{,}91 \cdot 10^{10}$ d/cm^2	12,7 / 50,2	B	rectangular
K_{sen}, calculated calibration factor	$0{,}98 \cdot 10^{-5}$ track/d·barn	2,9 / 11,4	B	rectangular
K_f, correction for average track density on the full detector surface	1,00	4,3 / 17,0	B	rectangular
K_{ss} – correction for projectiles self-shielding	1,00	0,6 / 2,4	B	rectangular
K_n – correction for fission non-connected with the d	1,00	0,6 / 2,4	B	rectangular
K_{impur} – correction for impurity atoms	1,00	0,6 / 2,4	B	rectangular

Relative standard uncertainty calculation

$$u(\sigma_f) = \sqrt{3,6^2 + 12,7^2 + 2,9^2 + 4,3^2 + 3 * 0,6^2} = 14\ \%$$

Relative extended uncertainty calculation

It is suppose that the probability coverage is equal to P = 95 %.

$$U(\sigma_f) = k \cdot u(\sigma_f) = 2 \cdot 14 = 28\ \%$$

Extended uncertainty :

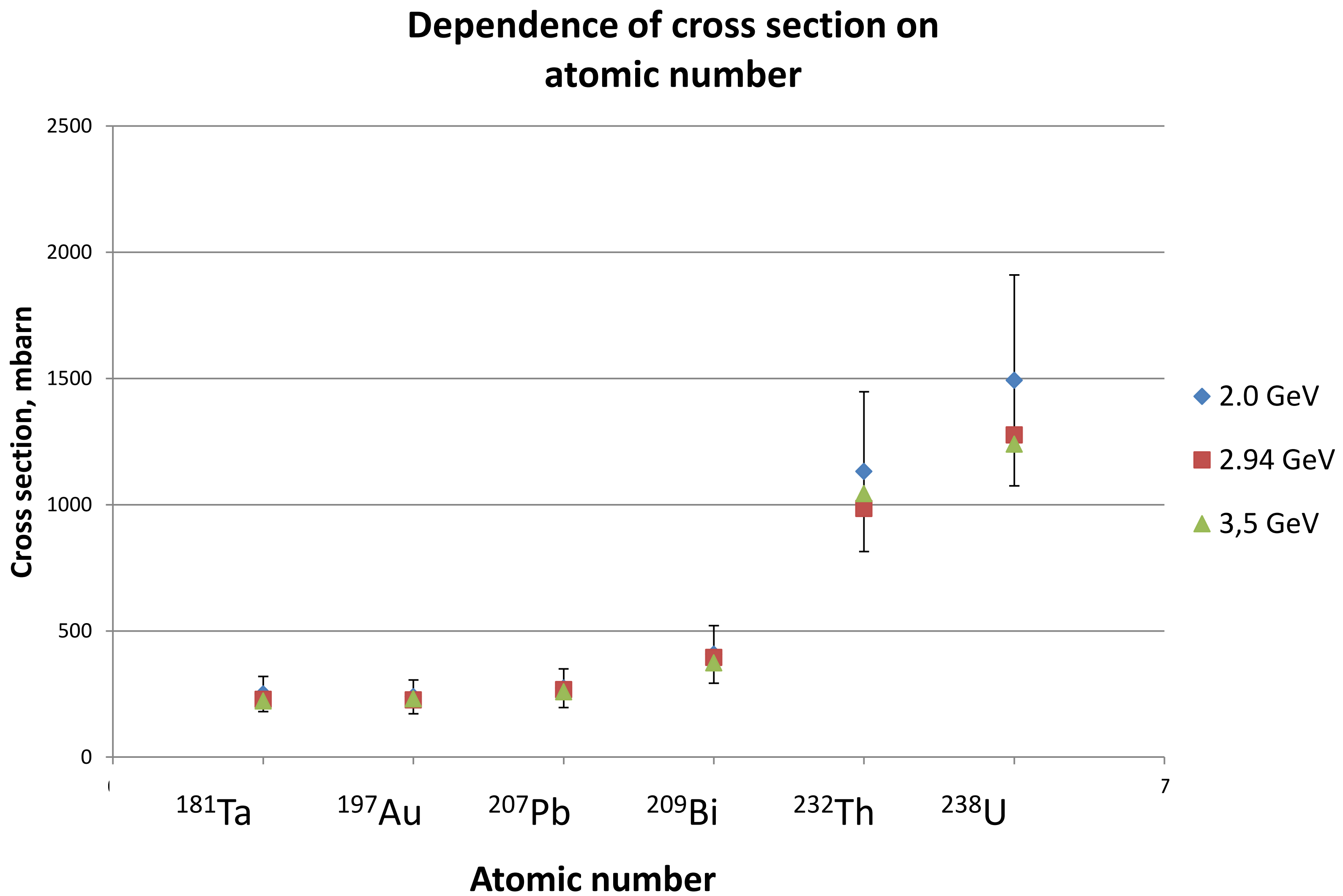
$$U(\sigma_f) = 1,13 \cdot 28/100 = 0,32\ \text{barn}$$

The uncertainty is estimate in accordance with ISO/IEC 17025:1999, ISO/IEC 17025:2001

Experimental results of heavy metal spallation-reaction cross sections measured with the help of SSNTD

Nuclide	Cross section, mbarn 2 GeV/nucleon	Cross section, mbarn 2,94 GeV/nucleon	Cross section, mbarn 3,5 GeV/nucleon
^{181}Ta	250 ± 70	228 ± 64	222 ± 62
^{197}Au	239 ± 67	226 ± 63	231 ± 65
^{207}Pb	273 ± 76	267 ± 75	258 ± 72
^{209}Bi	407 ± 114	394 ± 110	373 ± 104
^{232}Th	1131 ± 317	985 ± 276	1044 ± 292
^{nat}U	1492 ± 418	1276 ± 357	1240 ± 347

Experimental results



Comparison of results

Nuclide	Cross section, barn					
	1,6 GeV	2,5 GeV	4 GeV	4 GeV	5,88 GeV	7 GeV
^{181}Ta				250±70	228±64	222±62
^{197}Au			92±23	239±67	226±63	231±65
^{207}Pb	200±50*		173±40*	273±76	267±75	258±72
^{209}Bi	320±50*		306±40* 206±46	407±114	394±110	373±104
^{232}Th	1277±216	1232±207	1153±198	1131±317	985±276	1044±292
^{nat}U			1453±350	1492±418	1276±357	1240±347

*V.V.Sotnikov et al. "Experimental determination of the natPb(d,f), 209Bi(d,f), 209Bi(d,xnyp) nuclear reactions cross section at 1.6 GeV and 4 GeV deuteron beams; Int. Conf.Cur.Prob.in.Nucl.Phys.Atom .Ene. Kyiv,2010

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High-energy fission cross sections induced by deuterons on ^{232}Th and protons on ^{nat}Pb targets

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Nuclear fission cross sections induced by deuterons of 4 GeV

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Conclusions

- Spallation reaction cross sections of heavy metal ^{181}Ta, ^{197}Au, ^{207}Pb, ^{209}Bi, ^{232}Th, ^{238}U at energy 2, 2.94, 3 GeV/nucleon deuterons beam have determined
- Heavy metal spallation-reactions cross section strongly dependent on atomic number
- Cross sections changed slightly in the investigated range on energy
- There is absolutely new data which need to be added in the Experimental Nuclear Reaction Database (EXFOR)

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Thank you
for your attention!

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