Current research on ADS at the Joint Instute for Nuclear Research

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Outline

- Collaboration
- Spallation targets in Dubna
- Current research on ADS in Dubna
- Experiments in Dubna
- Conclusion

Energy and Transmutation- RAW

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Motivation

- **Experimental research on transmutation of spent nuclear fuel**
- **Validation of nuclear data important for ADS research**
- **Benchmarking of nuclear models of radiation transport codes (MCNPX, FLUKA, MARS15)**

Spallation targets in JINR

USED in PAST TIME:

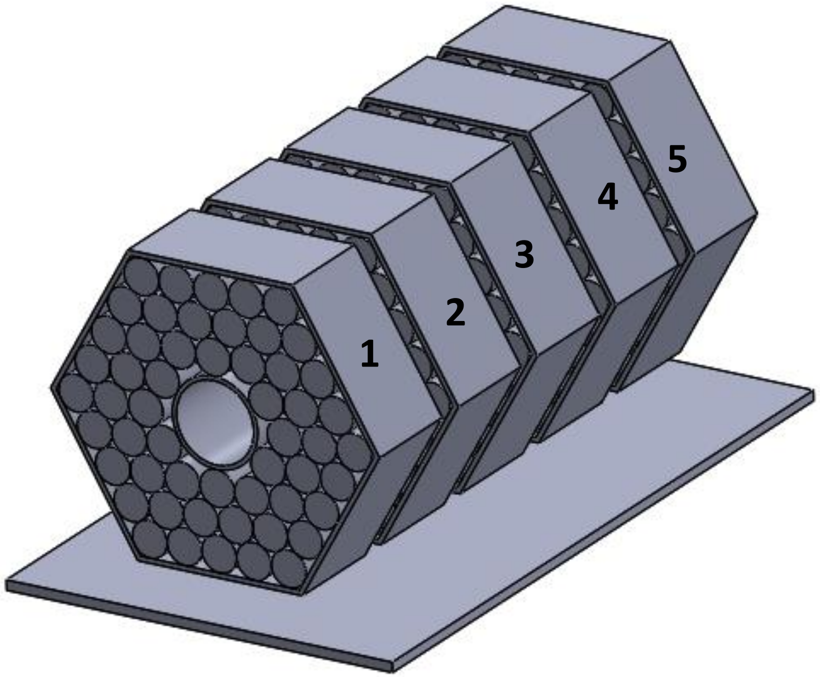
- **1995 – GAMMA 2**
- **2000 – GAMMA 3**
- **2005 – Energy and Transmutation**

USED in PRESENT:

- **2010 – QUINTA**

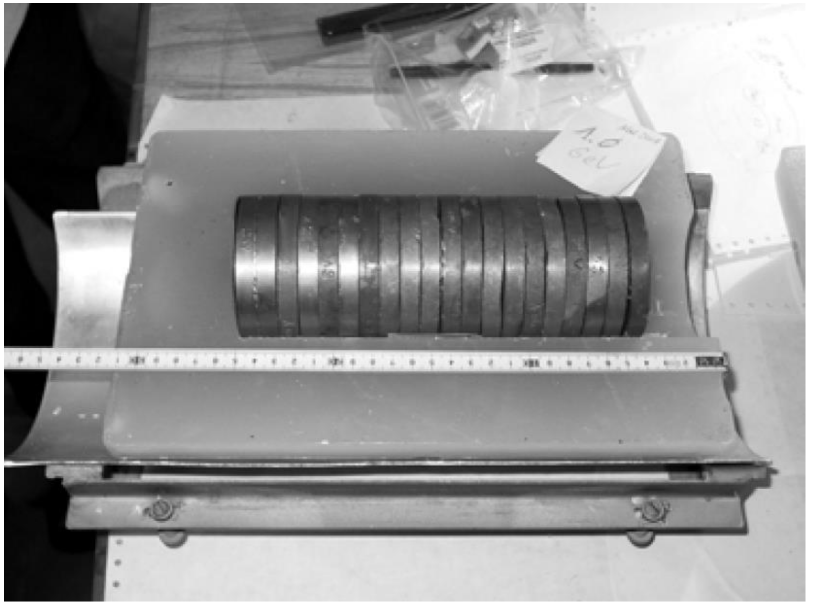
FUTURE PLAN:

- **2016 – BURAN**



GAMMA 2

- **Lead target+ paraffin blanket**
- **Lead: 80 mm in diameter, 200 mm in length**
- **Paraffin: 60 mm**
- **Irradiated at the Nuclotron (Synchrotron-proton up to 7.4 GeV) accelerator**

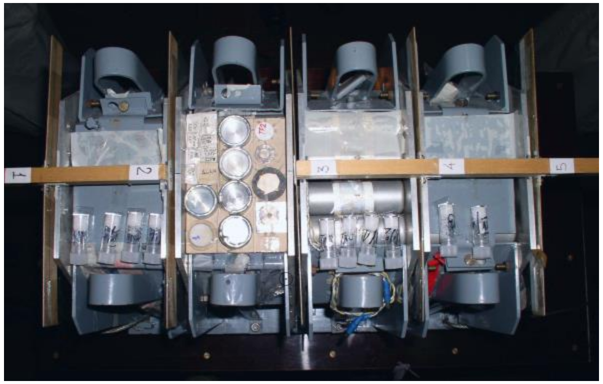


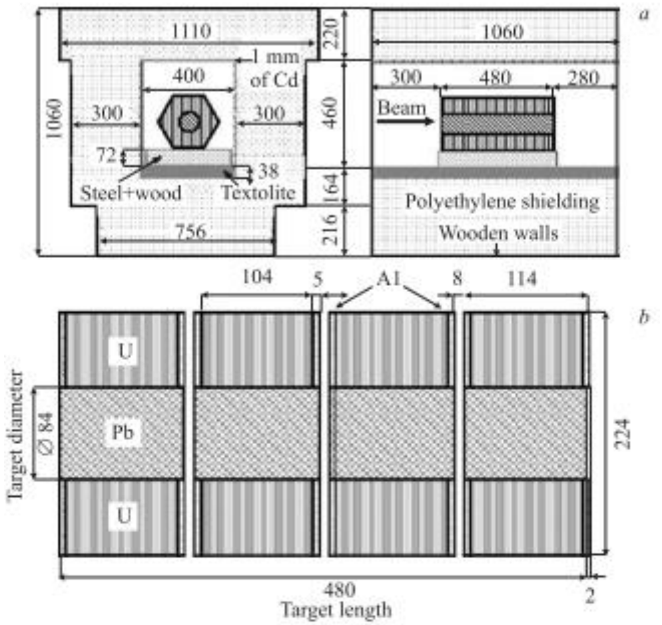
GAMMA 3

- **Lead target+ graphite**
- **Lead: 80 mm in diameter, 600 mm in lenght**
- **Graphite: 1100 x 1100 x 600 mm^3 (25 blocks)**
- **Irradiated at the Nuclotron accelerator**

Energy and Transmutation

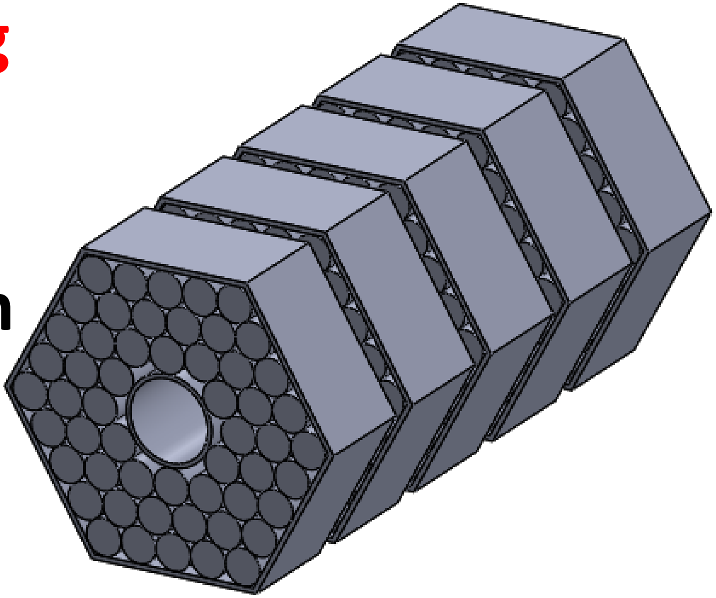
- **Lead target + uranium blanket (204 kg of natural metallic uranium)**
- **Target: 84 mm in diameter (43 kg)**
- **1000 x 1110 x 1125 mm^3**
- **4 sections**
- **Irradiated at the Nuclotron accelerator**

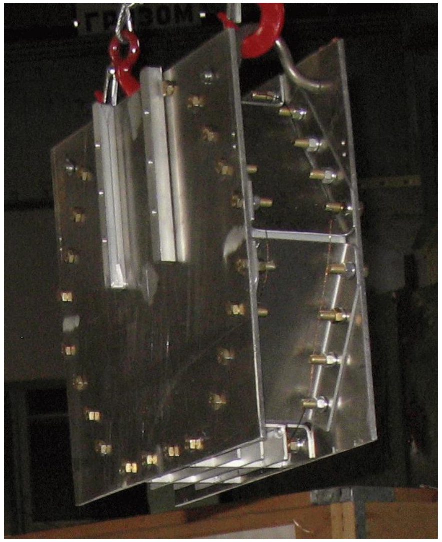




QUINTA

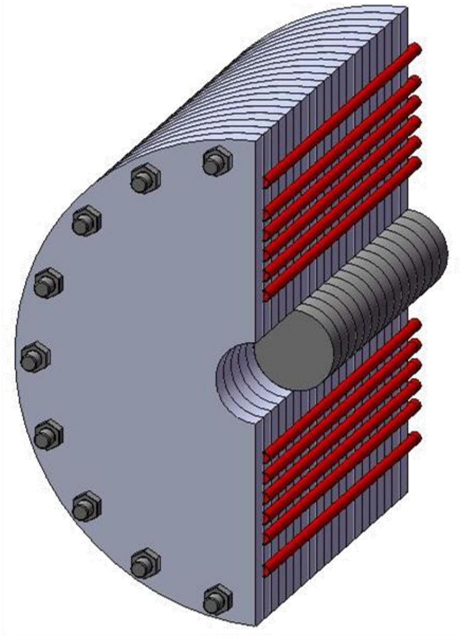
- **Natural metallic uranium - 512 kg**
- **350 x 350 x 700 mm^3**
- **5 sections**
- **Surrounded – lead bricks 100 mm**
- **Irradiated at the Nuclotron and Phasotron (Synchrocyclotron- protons with energy 660 MeV) accelerators**

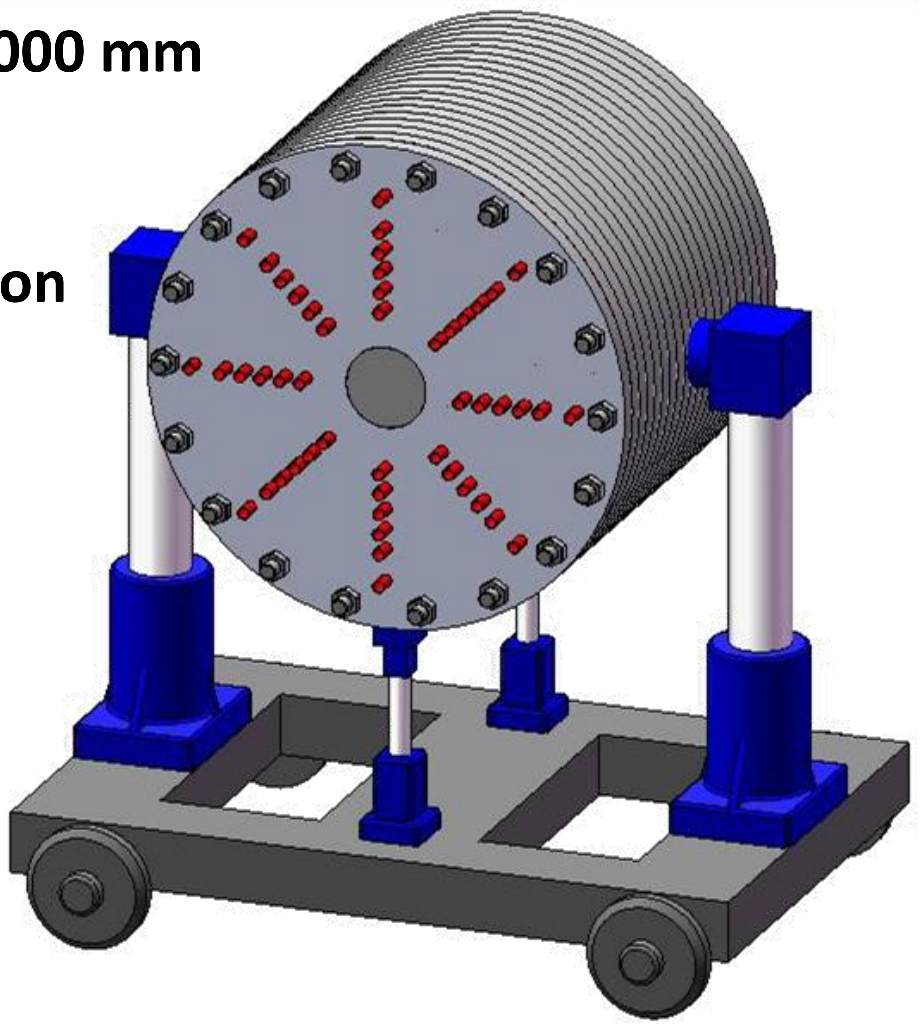




Buran

- **Depleted uranium - 20 t**
- **1200 mm in diameter, 1000 mm in length**
- **72 measurement canals**
- **Irradiated at the Phasotron accelerator**





Currnent research on ADS in JINR

- **Investigation of neutron production in a concept of Relativistic Nuclear Technology for nuclear energy production and transmutation of spent nuclear fuel (SNF) in a maximally hard neutron spectrum**

- **Since 2010, the research has been conducted at the massive natural uranium spallation target QUINTA that represents a central region of a true quasi-infinite spallation target for ADS purposes**

- **Estimation of cross sections in thorium and uranium samples irradiated by different particles and their energies**

Experiments with QUINTA target

Experimental Program:

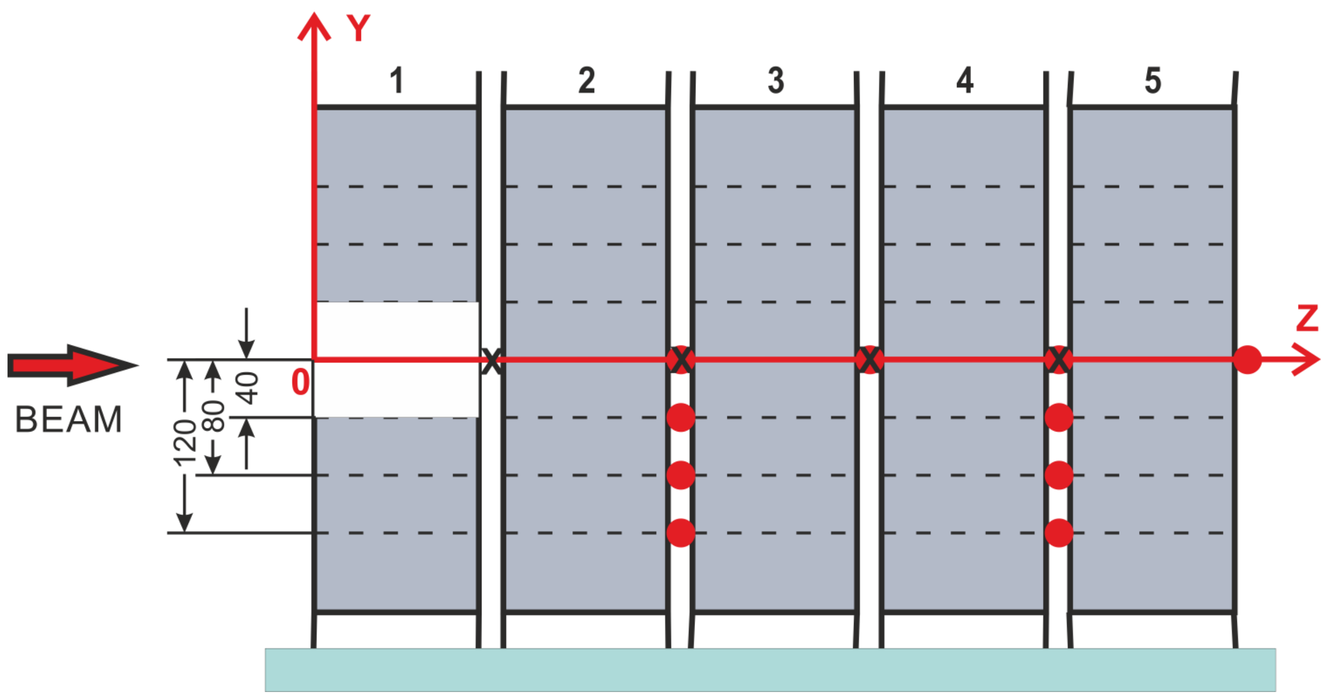
- **Spectral characteristics of neutron flux based on results of threshold activation detectors (Al, Au, Bi, Co, Mn, In)**
- **Determination of a total number of fissions as well as production of ^{239}Pu**
- **Total leakage of neutrons from the surface of the target**
- **Transmutation of actinides (^{237}Np, $^{238, 239}Pu$, ^{241}Am) and long-lived fission products (^{129}I)**

Steps of experiments

- **Activation measurement technique**
- **Gamma-ray spectroscopy with the use of both planar and coaxial, P- and N-type HPGe detectors Canberra and ORTEC of up to 35% relative efficiency**
- **Calibrated with standard point gamma-ray sources from 5 keV to 3 MeV**
- **Efficiency compared with MC simulation, which is used for performing corrections for volume emitters**

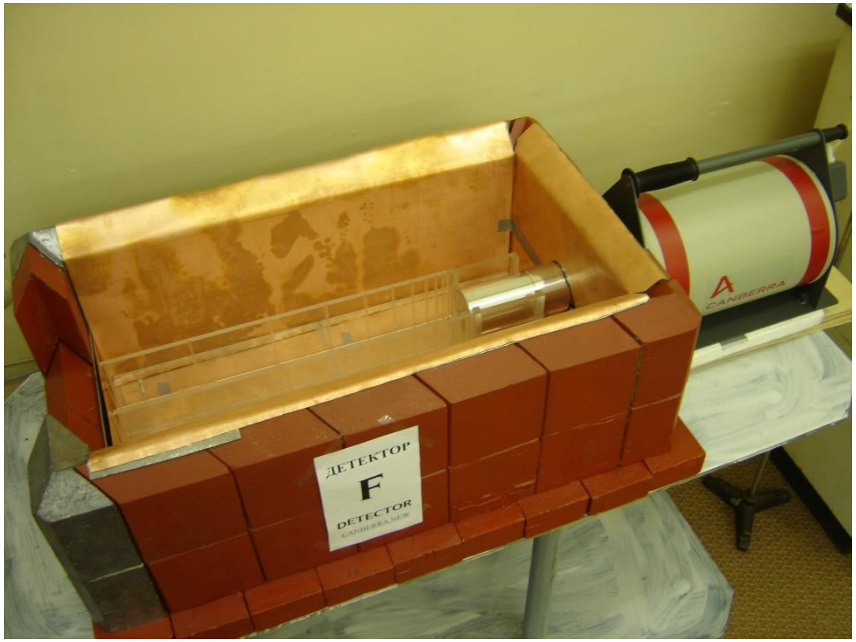
Nuclotron experiments

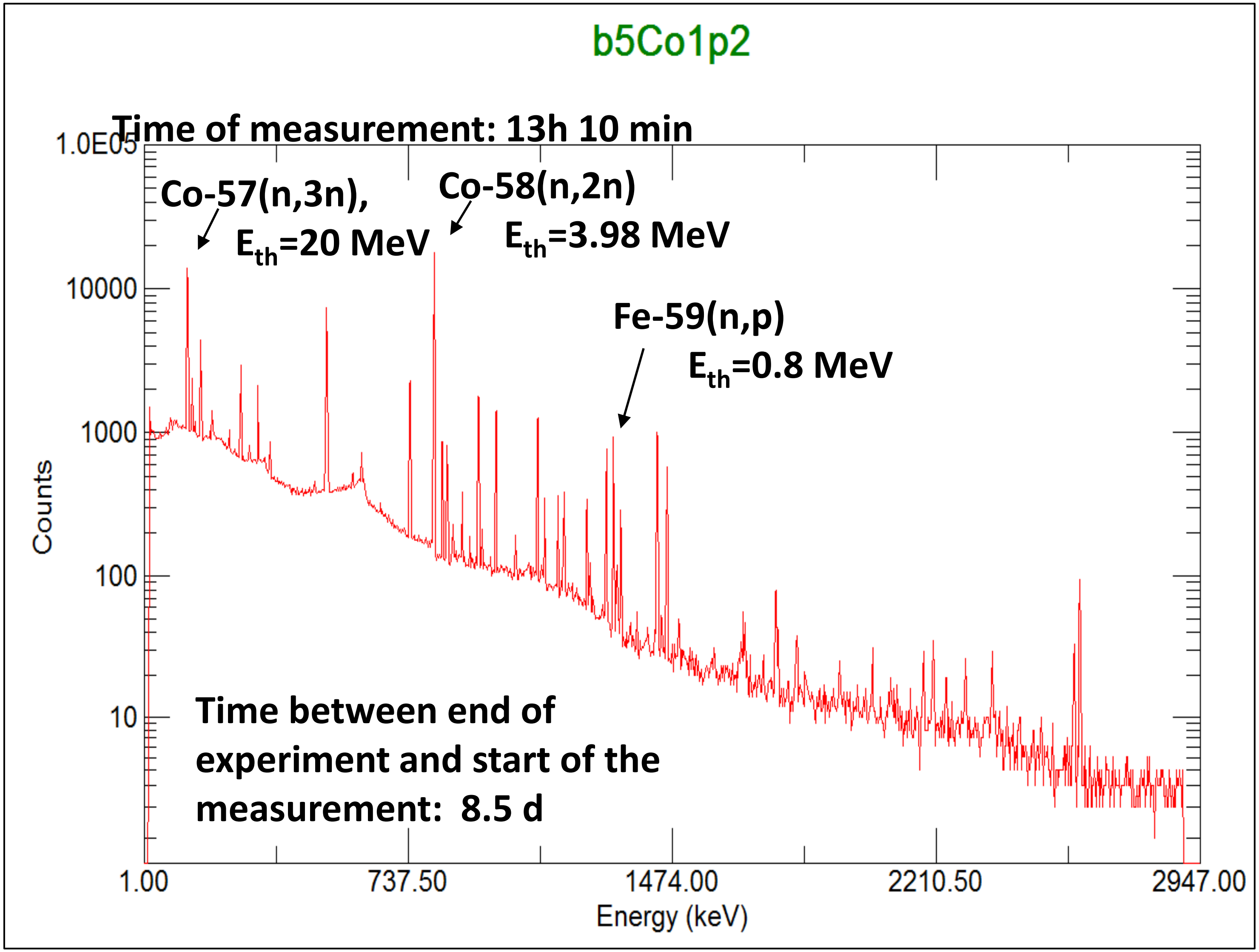
	Type of particles	Energy of particles	Number of particles	Time of irradiation
^{59}Co	Deuteron	4 AGeV	(6.11±0.08)E12	27 h and 18 min
^{59}Co	C12	2 AGeV	(2.14±0.15)E12	30 h and 18 min
Th	Deuteron	3 AGeV	(1.93±0.02)E13	16 h and 15 min

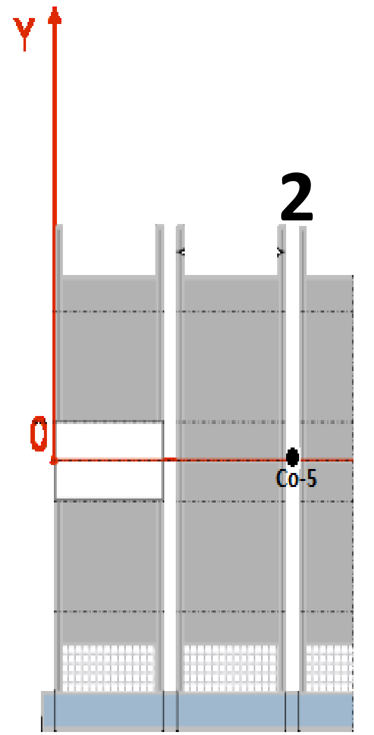


After irradiation, the experimental samples were transported to the YaSNAPP spectroscopy laboratory and measured with the use of high purity germanium semiconductor detectors.

Detector relative efficiency: 28-35 %







An example of γ-ray spectrum in the sample ^{59}Co.

Beam correction

Real measurement time

Correction for decay during cooling time

Decay constant

Self-absorption correction

Irradiation time

Peak area

Coincidence summing

Reaction rate

$$R_{Exp} = \frac{S_p \cdot C_{abs}(E) \cdot B_a}{I_\gamma \cdot \varepsilon_p(E)} \frac{t_{real}}{t_{live}} \frac{1}{N_A} \frac{1}{N_D} \frac{e^{(\lambda \cdot t_0)}}{1 - e^{(-\lambda \cdot t_{real})}} \frac{\lambda \cdot t_{irr}}{1 - e^{(-\lambda \cdot t_{irr})}} \cdot C_{coisum}$$

Gamma-line intensity

Correction for decay during irradiation

Detector efficiency

Live time of the measurement

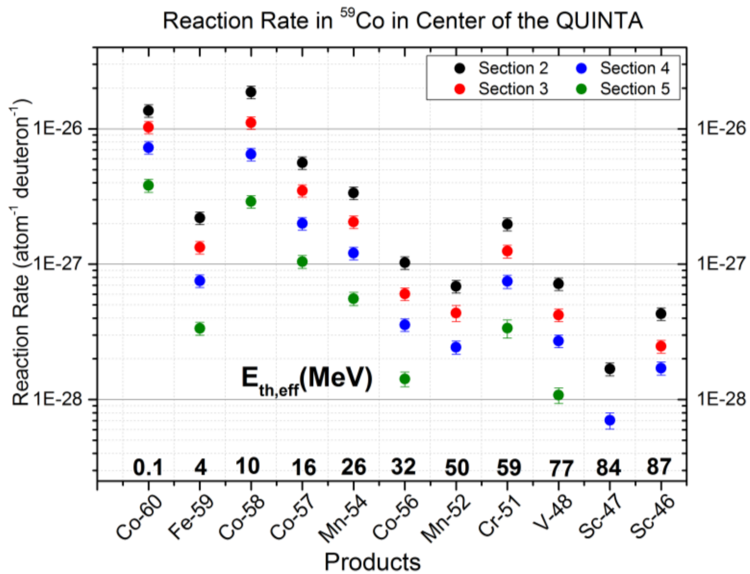
Number of atoms in the sample

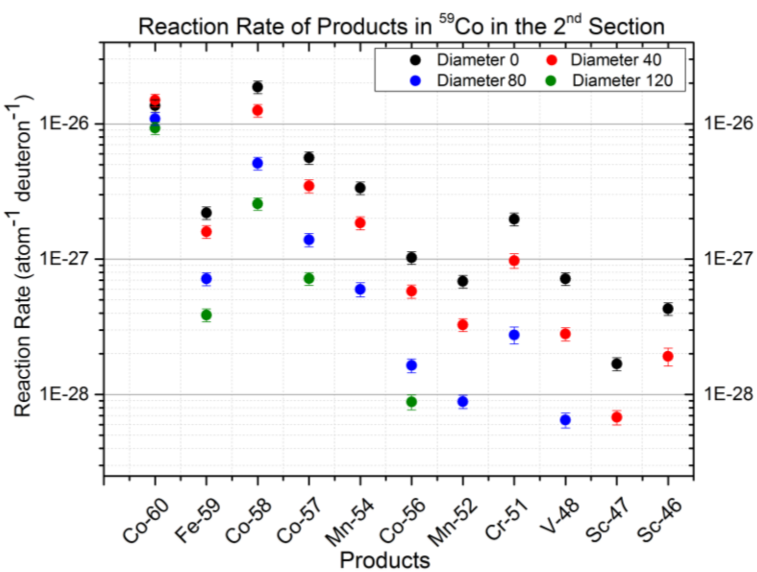
Number of deuterons

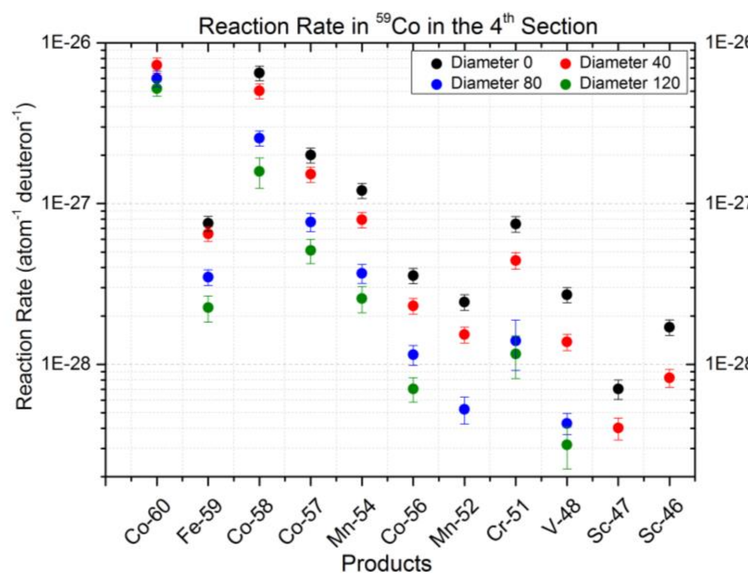
Correction for decay during measurement

Reaction rate - is defined as the number of produced residual nuclei *Q*(A$_r$, Z$_r$) per one atom in the sample N_t and one incident deuteron N_d according to the following equation.

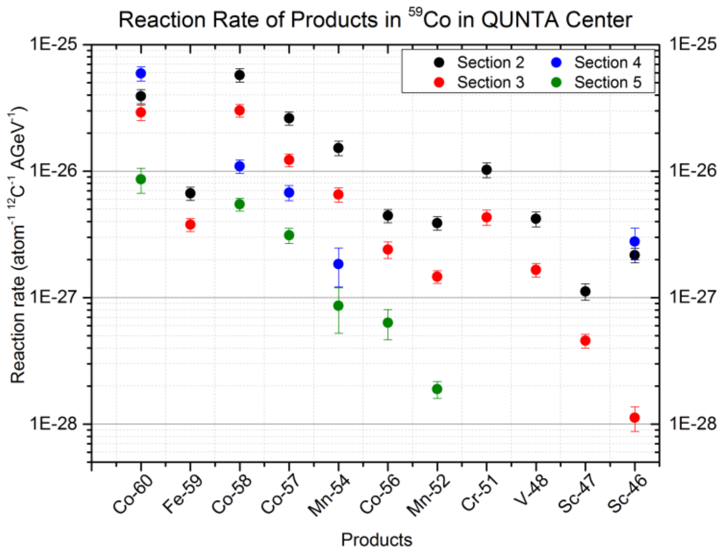
Experimental reaction rates - deuteron beam

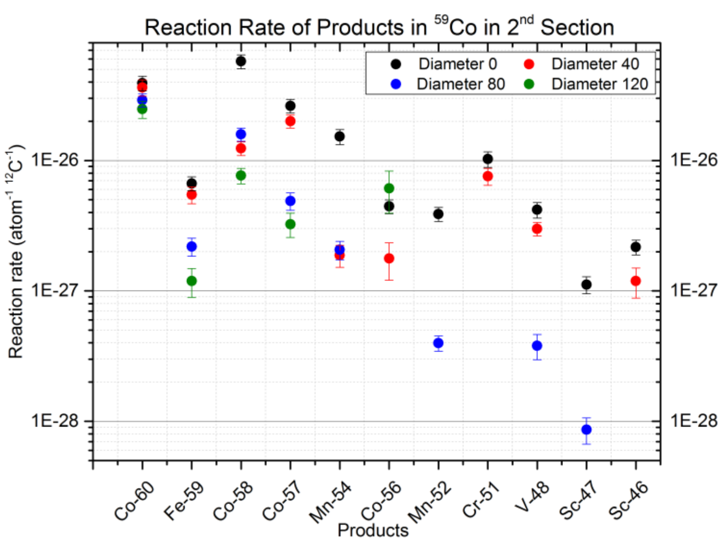


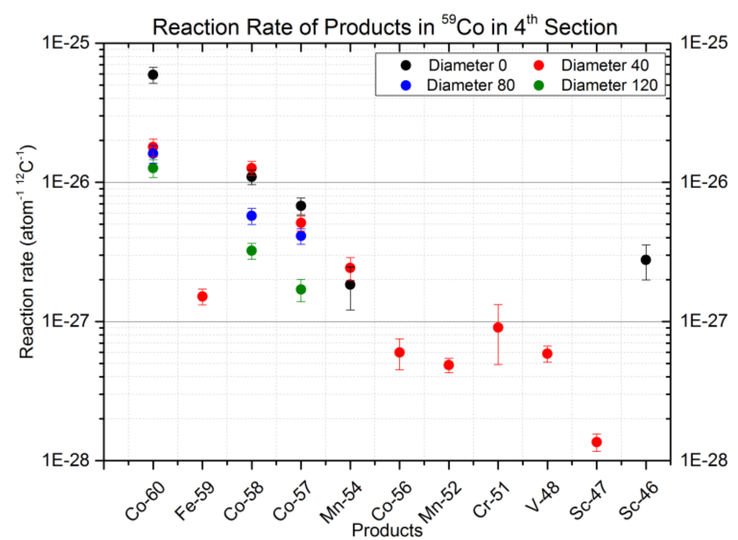




Experimental reaction rates – ^{12}C beam







Determination of the neutron flux

$$R_{exp} = \int_{E_{th}}^{\infty} \sigma(E) \cdot \phi(E) \cdot dE$$

Reaction	E_{theff} (MeV)	$T_{1/2}$
$^{59}Co(n,\gamma)^{60}Co$	0.1	5.27 y
$^{59}Co(n,p)^{59}Fe$	3.9	44.5 d
$^{59}Co(n,2n)^{58}Co$	10.4	271.8 d
$^{59}Co(n,3n)^{57}Co$	16.5	312.3 d
$^{59}Co(n,4n)^{56}Co$	31.9	77.3 d

$$R_5 = \phi(5) \int_{E_{theff}(n,4n)}^{E_{max}} \sigma_5(E) \cdot dE$$

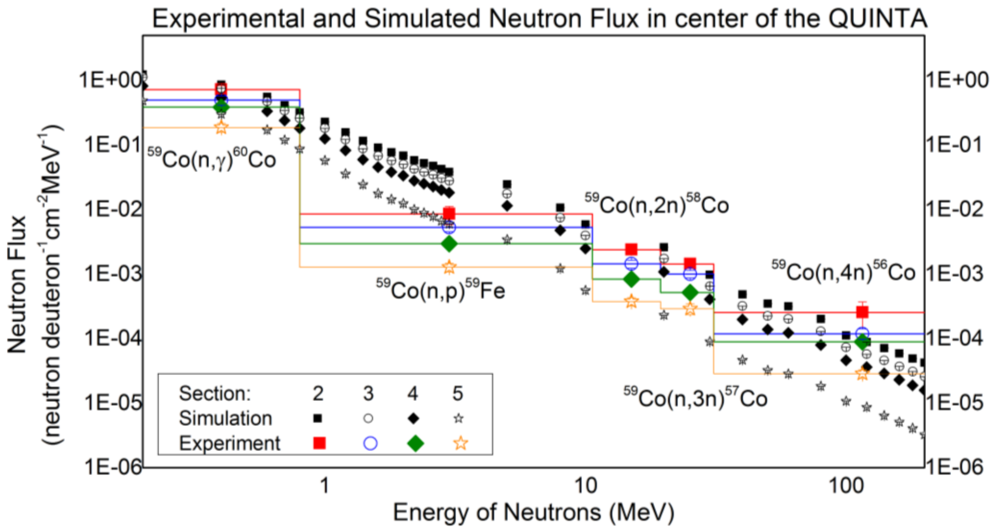
$$\Longrightarrow \phi(5) = \frac{R_5}{\int_{E_{theff}(n,4n)}^{E_{max}} \sigma_5(E) \cdot dE}$$

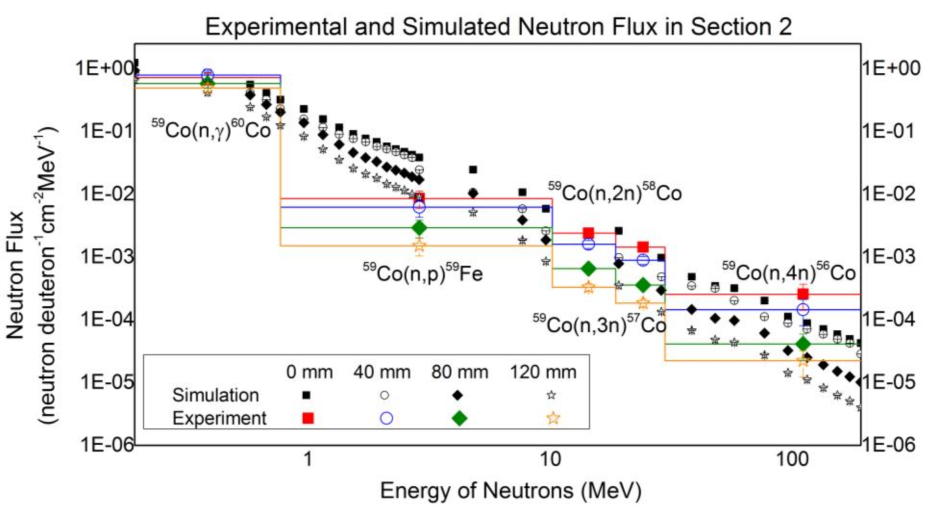
$$R_4 = \phi(4) \int_{E_{theff}(n,3n)}^{E_{theff}(n,4n)} \sigma_4(E) \cdot dE + \phi(5) \int_{E_{theff}(n,4n)}^{E_{max}} \sigma_4(E) \cdot dE$$

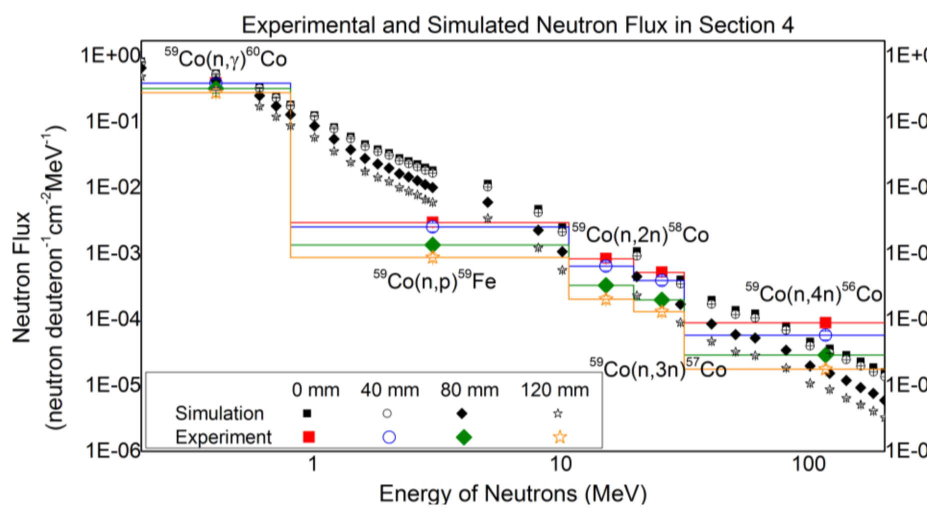
$$\Longrightarrow \phi(4) = \frac{R_4}{\int_{E_{theff}(n,3n)}^{E_{theff}(n,4n)} \sigma_4(E) \cdot dE + \int_{E_{theff}(n,4n)}^{E_{max}} \sigma_4(E) \cdot dE}$$

- **Cross section calculated in TALYS 1.6**
- **Simulation performed in MCNPX 2.7 (INCL4/ABLA)**

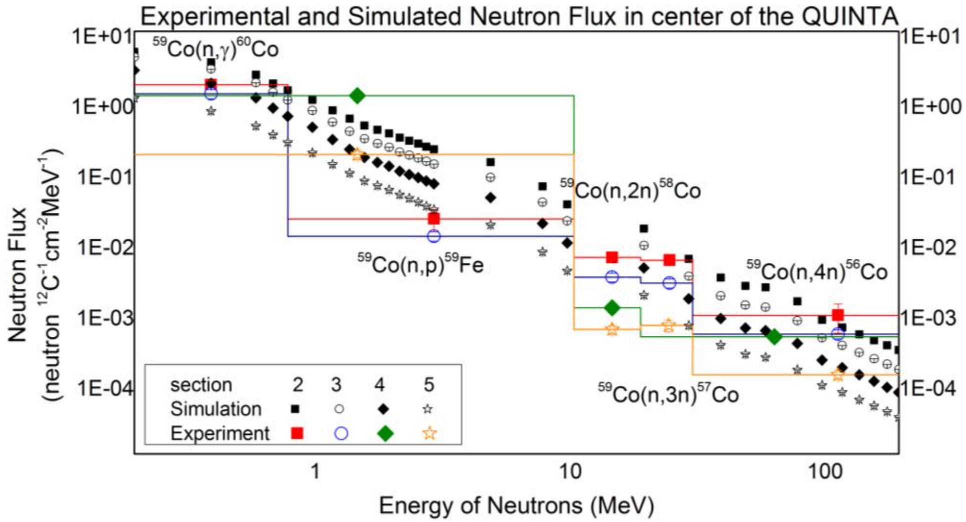
Determination of neutron flux – deuteron beam

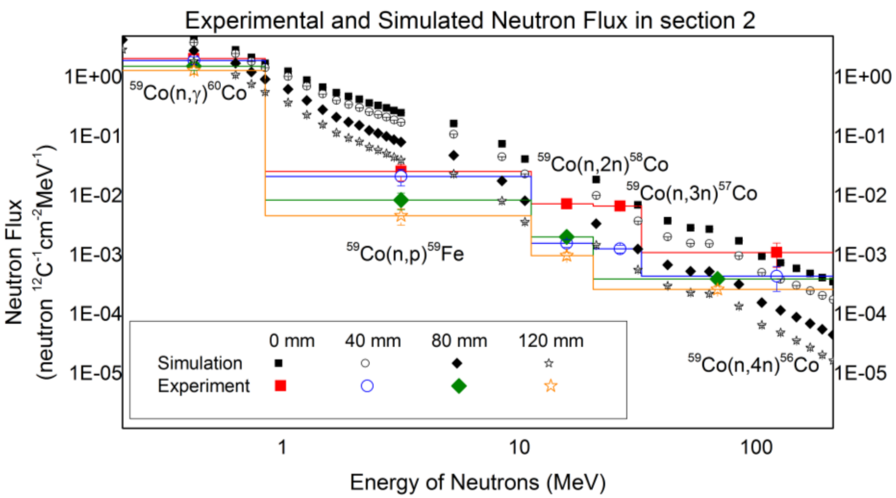


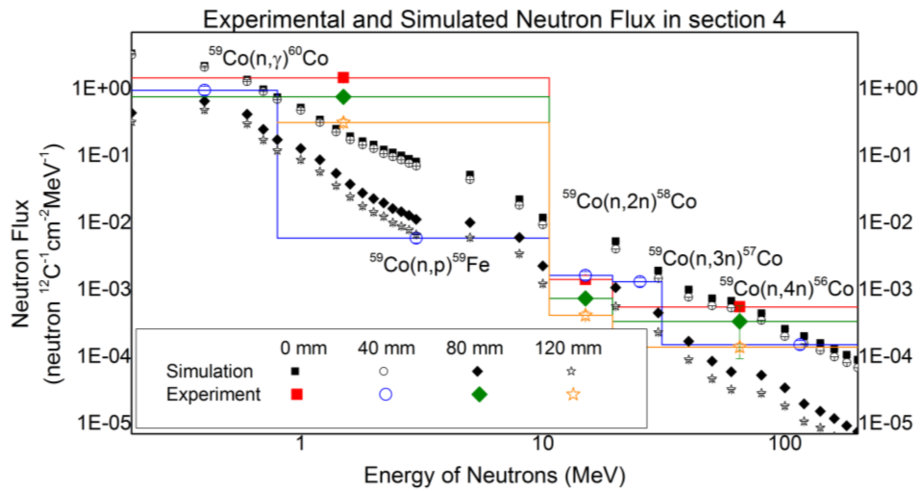




Determination of neutron flux –C^{12} beam







Comparison of neutron fluxes

Beam center

Section	$\varphi_{Carbon}/\varphi_{Deuteron}$
S2	(2.873±1.045)
S3	(2.835±1.043)
S4	(3.748±1.167)
S5	(1.039±0.809)

Second section

Position	$\varphi_{Carbon}/\varphi_{Deuteron}$
40	(2.445±1.094)
80	(2.665±0.993)
120	(2.658±1.256)

Fourth section

Position	$\varphi_{Carbon}/\varphi_{Deuteron}$
40	(2.463±1.277)
80	(1.231±0.456)
120	(1.120±0.537)

Experimental results and comparisons with Monte Carlo simulations by FLUKA code

Section	**1**	**2**	**3**	**4**
Nuclear reactions	Reaction rate (atom^{-1} deuteron^{-1})			
^{232}Th(n,γ)	7.22(23)E-26	18.2(5)E-26	12.4(4)E-26	7.66(23)E-26
^{232}Th(n,fission)	5.57(80)E-26	9.8(11)E-26	6.91(73)E-26	3.50(39)E-26
^{232}Th(n,2n)	3.73(42)E-26	7.04(26)E-26	4.85(29)E-26	2.91(21)E-26
	Ratio of the experimental and calculated reaction rates			
^{232}Th(n,γ)	1.64(5)	1.75(5)	1.70(5)	1.78(5)
^{232}Th(n,fission)	2.69(39)	1.29(15)	1.78(19)	1.87(21)
^{232}Th(n,2n)	1.68(19)	1.95(7)	2.32(14)	2.50(18)

Fission reaction rates R(n,f) from the experimental data were defined by the average values of the fission product R/Y ratios for the following nuclei: ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{91}Sr, ^{92}Y, ^{92}Sr, ^{93}Y, ^{95}Zr, ^{96}Nb, ^{97}Zr, ^{129}Sb, ^{131}I, ^{132}Te, ^{132}I, ^{132}Cs, ^{133}I, ^{134}I, ^{135}I, ^{135}Xe, ^{140}Ba, ^{141}Ce, ^{142}La and ^{143}Ce. Cumulative yields Y of the fission products of ^{232}Th at a neutron energy of 14 MeV were taken from the TENDL-2011 library.

Production cross sections

- **Spallation reactions play an important role in neutron production for Accelerator Driven Systems (ADS), are responsible for intensive production of radioactive beams using Isotope Separation On-Line (ISOL) technique, serve as a potential source of a-emitting radioisotopes for medical radiotherapy (^{225}Ac, ^{223}Ra)**
- **Measurement of cross sections of reaction residues implementing methods of inverse kinematics at GSI Darmstadt (max. 1 AGeV ^{197}Au, ^{208}Pb, ^{238}U + p/d target)**

or

- **using methods of direct kinematics at JINR Dubna (this experiments) to obtain new experimental data and validate nuclear physics models at the beams of relativistic energies - deuterons up to 3.5 AGeV and proton beam up to 660 MeV**

Cross section determination

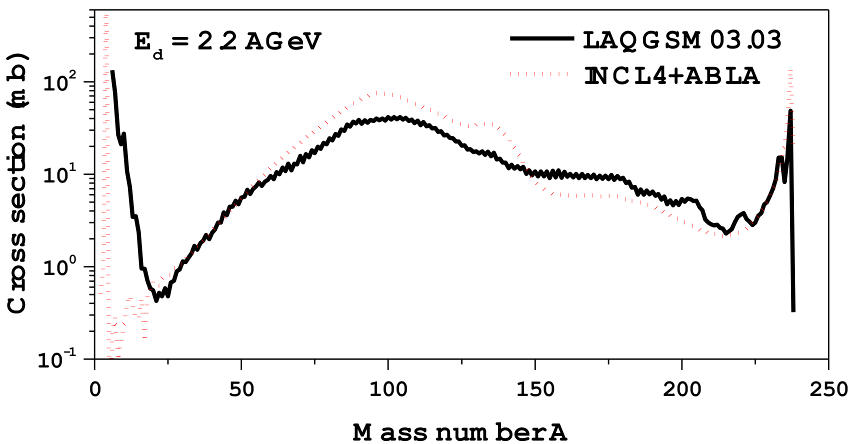
- **Thin spallation targets made of natural, enriched, and depleted uranium irradiated with 2.2 AGeV and 3.5 AGeV deuteron beams at JINR Nuclotron. Thorium samples irradiated with 200 MeV and 400 MeV proton beams at JINR Phasotron**
- **Time of irradiation: 23 and 40 hours; 2 and 30 min**
- **Beam integral: 4×10^{9} – 6×10^{11} deuterons; 3×10^{12} – 2×10^{13} protons**
- **At least 13 measurements at JINR YaSNAPP gamma-ray spectrometry complex with HPGe detectors**
- **Important spectroscopy correction factors considered in careful data analysis**
- **Cross sections calculated from measured activity of the uranium and thorium samples**

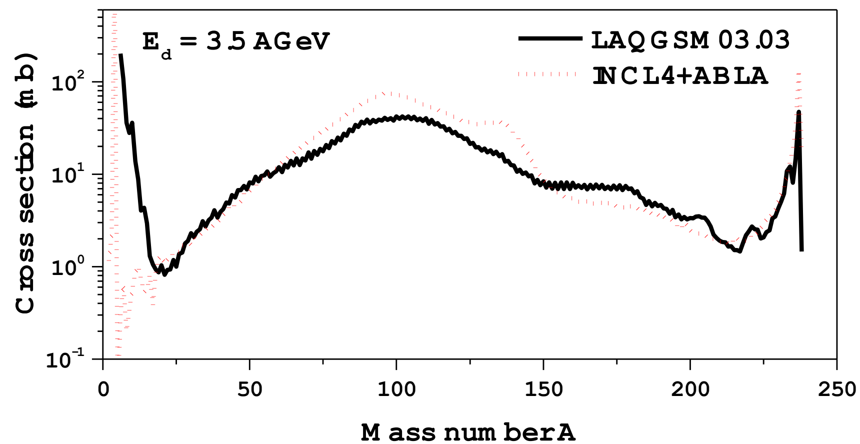
Cross section determination

- **Cross sections obtained for a large number of neutron-rich nuclei, including some metastable states of produced residues, as well as some neutron-deficit nuclei and products of quasi-elastic reactions**
- **New experimental data compared to the results of simulations employing physics models available in MCNP6 v 1.0: INCL4/ABLA and LAQGSM03.03, Bertini/RAL**
- **Independent residual nuclei cross sections and mass distributions calculated using GENXS option at TROPT card**

Cross section determination

- **Cross sections in ^{nat}U using INCL4/ABLA and LAQGSM03.03 in MCNP6 v 1.0**

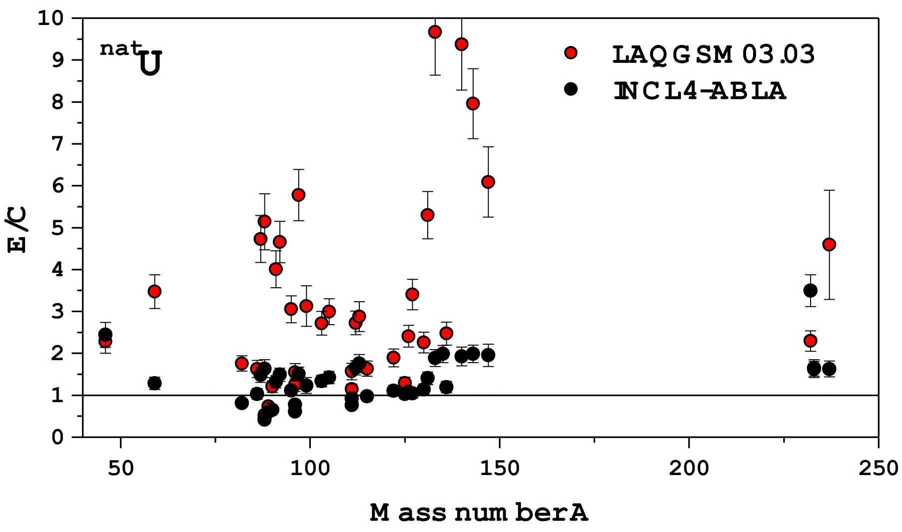




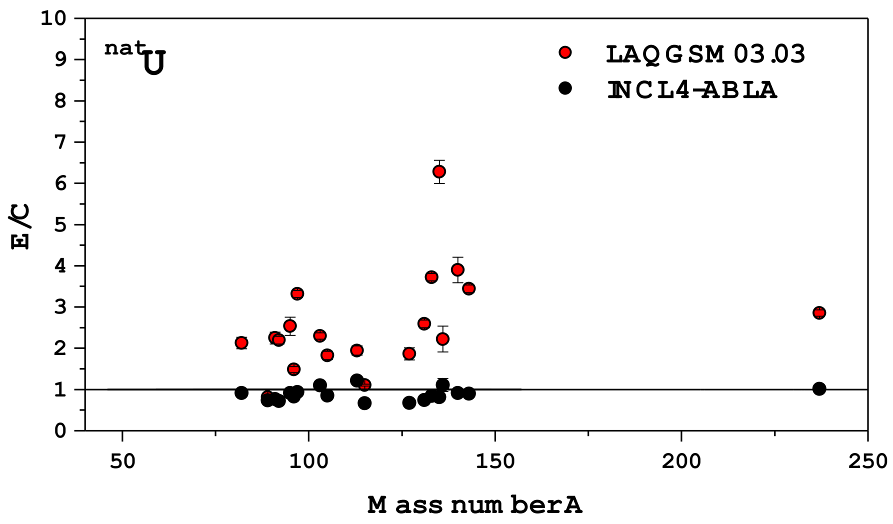
Cross section determination

- **Comparison between experiment and simulation employing INCL4/ABLA and LAQGSM03.03**

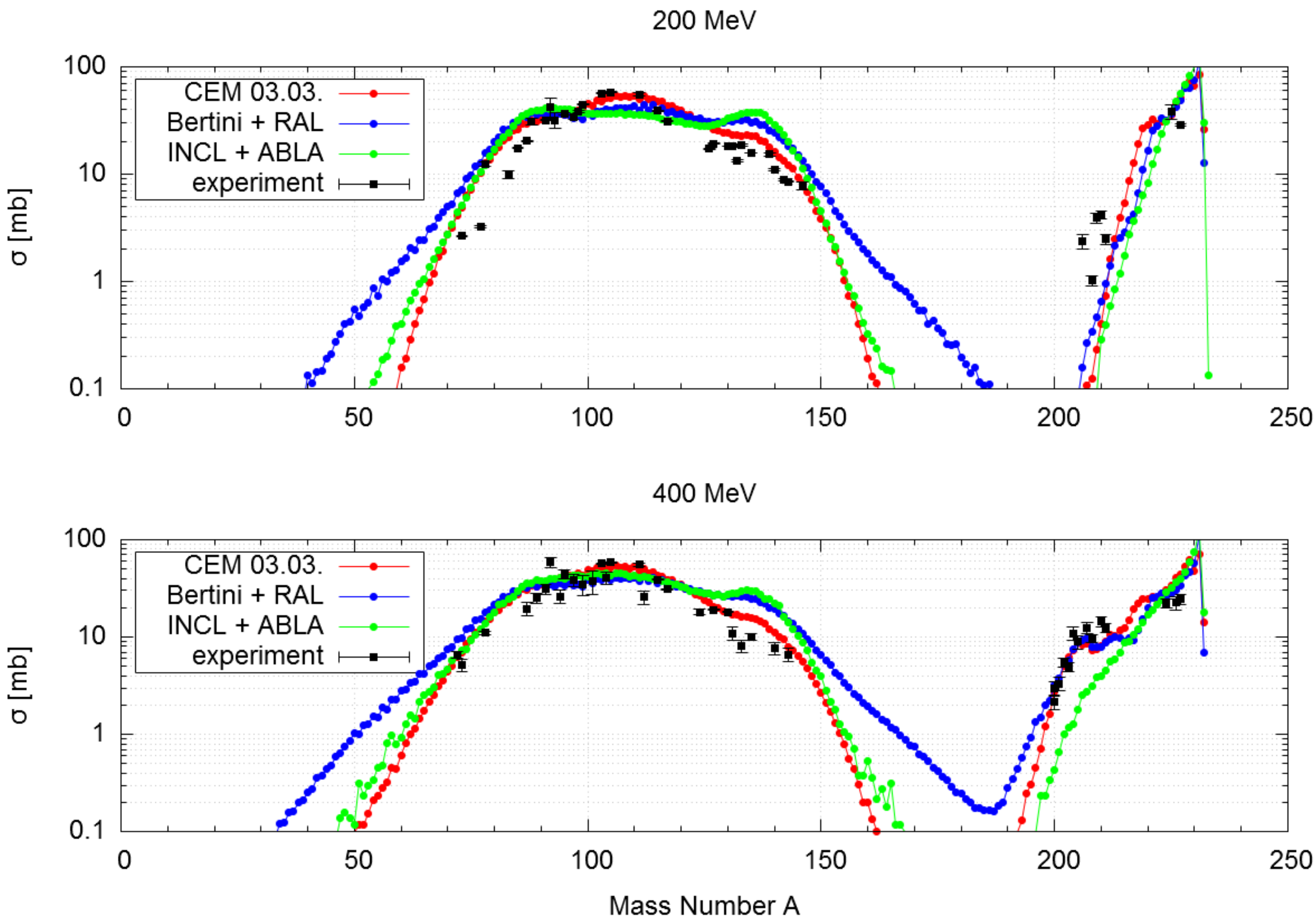
2.2 AGeV deuteron beam



3.5 AGeV deuteron beam

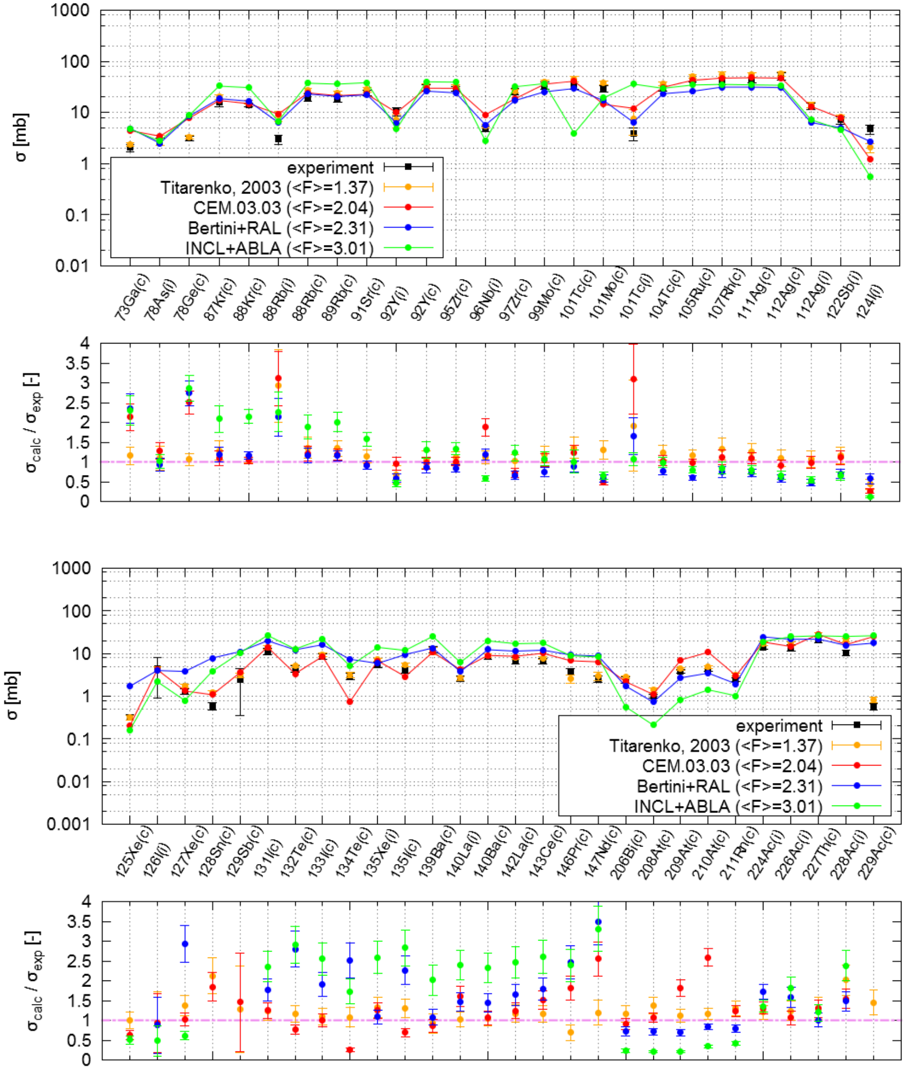


Comparison of different MCNP6 generators, thorium samples

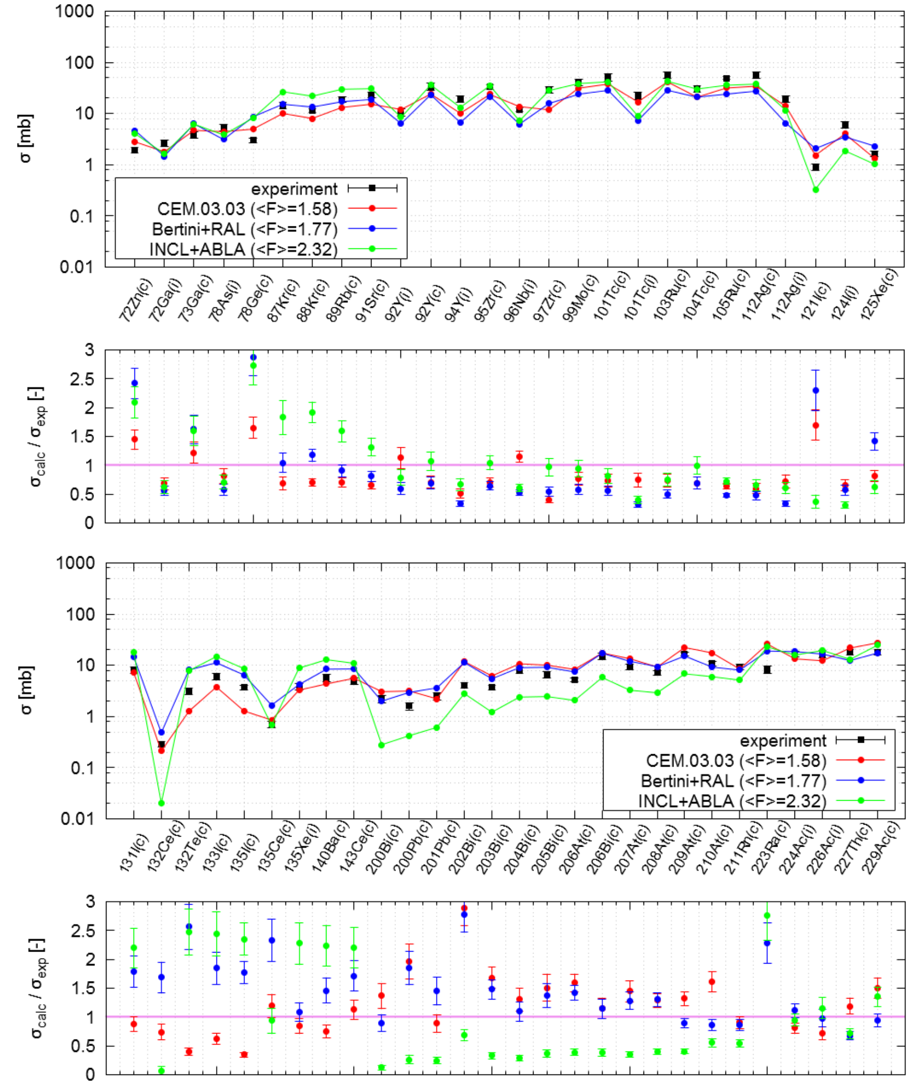


Comparison of experimental and predicted values

200 MeV proton beam



400 MeV proton beam



Conclusion

- **Experimental neutron flux was calculated for experimetns with deuteron and carbon beam and compared with simulation by MCNPX 2.7(INCL4/ALBA)**
- **The experiemtnal neutron flux was higher at experiment with carbon beam more than 2.5 times. The neutron flux was decreasing with increasing distance**
- **The reaction rates of products from natural thorium were compared with calculated values by FLUKA code. By comparison experimental and calculated data found agreements for residual nuclei ^{233}Pa, ^{231}Th and for several products of fission reactions and for other products of fission reactions ratio of the experimental and calculated cumulative reaction rates is above than 3.**

Conclusion

- **Experimental samples made of natural uranium and thorium were irradiated by a deuteron beam of 2.2 AGeV and 3.5 AGeV and proton beam of energy 200 MeV and 400 MeV**
- **More than 100 independent and cumulative cross-sections including metastable states were determined for all energies**
- **The results were compared with the predictions of CEM03.03,Bertini, and INCL+ABLA event generators of MCNP6**

Future plans:

- **Set of experiments with spallation target Buran - simple geometry, minimal leakage of neutrons**
- **High accuracy measurement of a temperature inside QUINTA and comparison with the neutron flux**

Thank you for your attention