

# Study of secondary neutron interactions with $^{232}\text{Th}$ , $^{129}\text{I}$ , and $^{127}\text{I}$ nuclei with the uranium assembly “QUINTA” at 2, 4, and 8 GeV deuteron beams of the JINR Nuclotron accelerator

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## Outline

Motivations

Experimental process

Cross sections from EXFOR data

Experimental results and comparison with the calculations  
with MARS-15 and MCNPX-2.7

Simulations by FLUKA for definition efficiency of HPGe planar detector

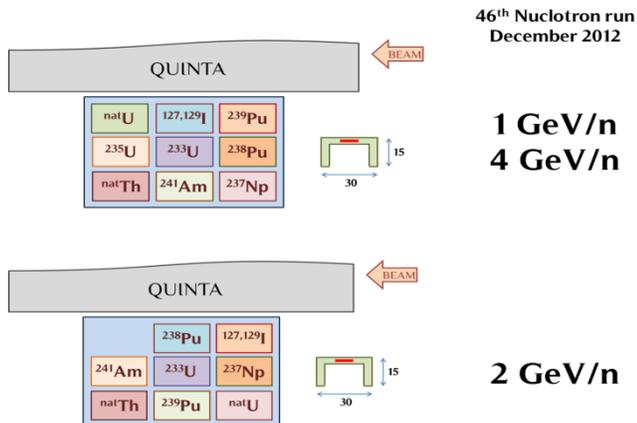
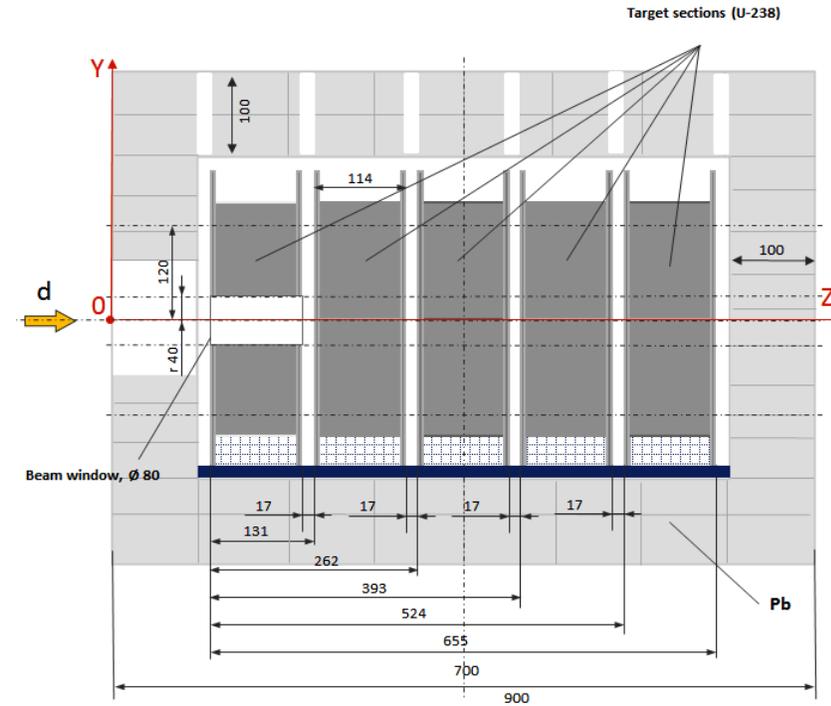
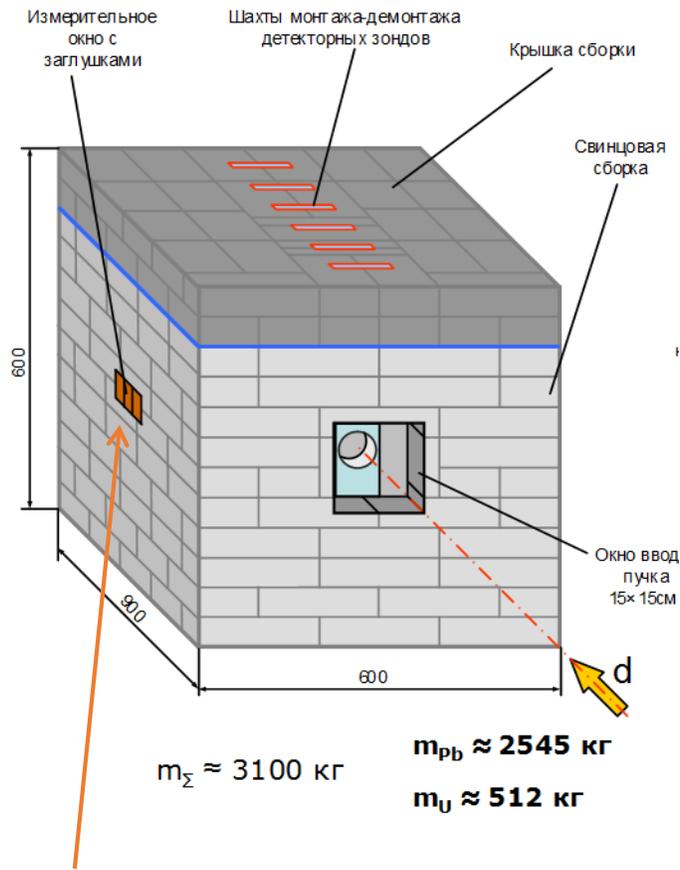
Simulations by FLUKA for experiments on the setup “QUINTA”

Summary

## Motivations

The ADS-related research has long been attracting attention of the international scientific community primarily due to societal concerns with the problem of the long-lived radioactive waste storage and the proposals of subcritical nuclear power plant concepts based on the uranium-thorium cycle, and controlled by high-energy particle accelerators (Accelerator Driven Subcritical systems)

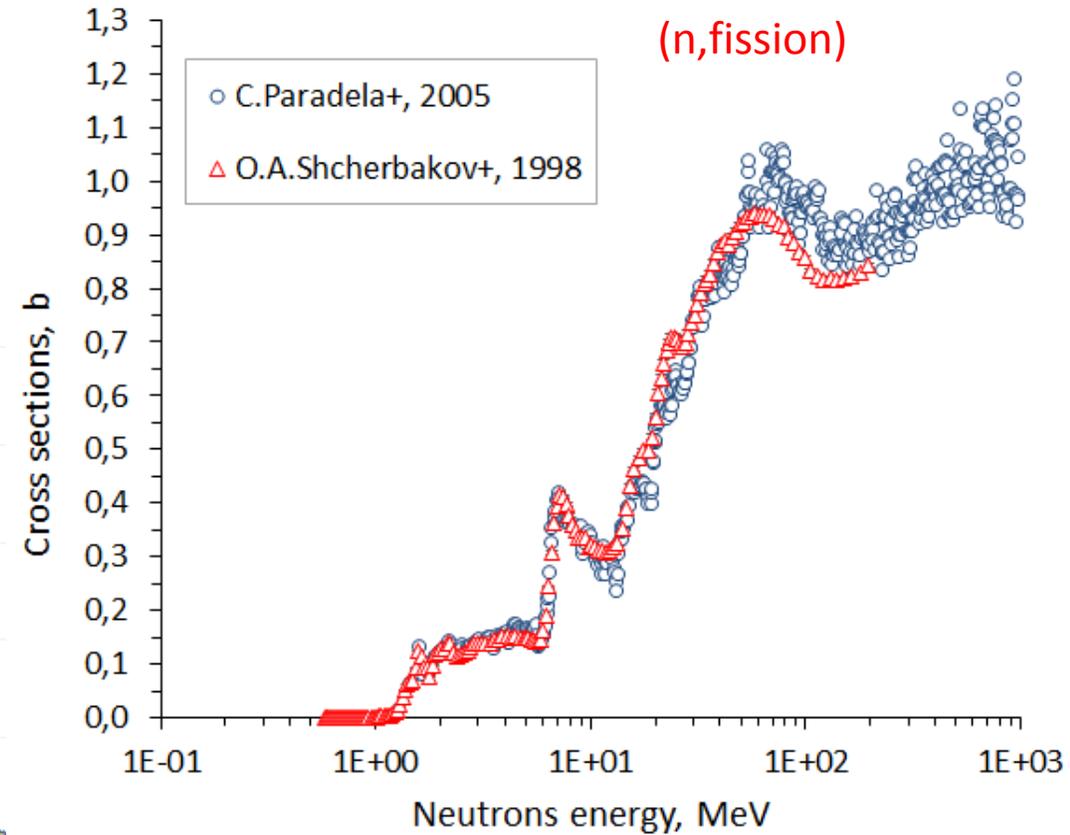
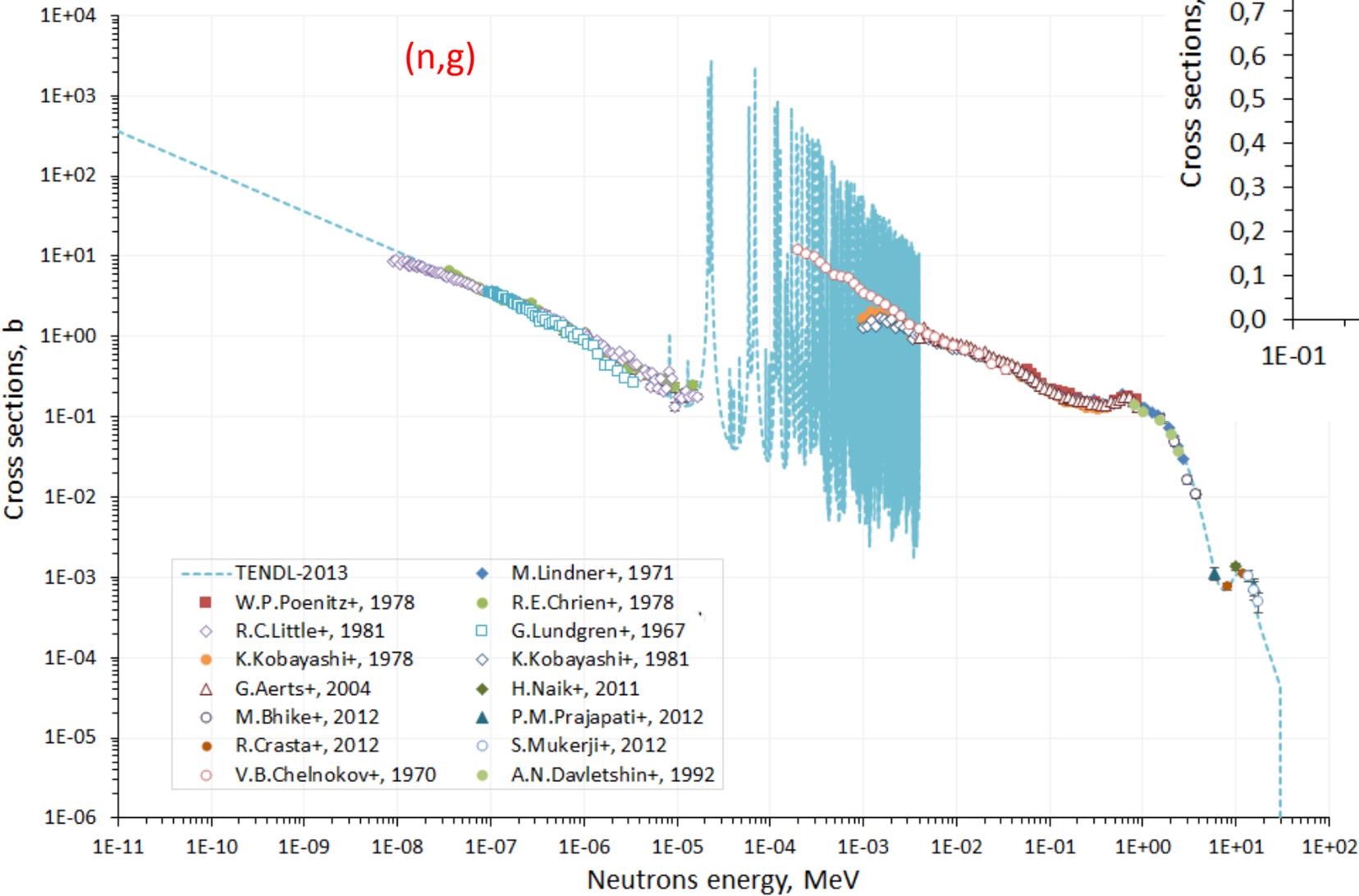
# Experimental setup «Quinta»



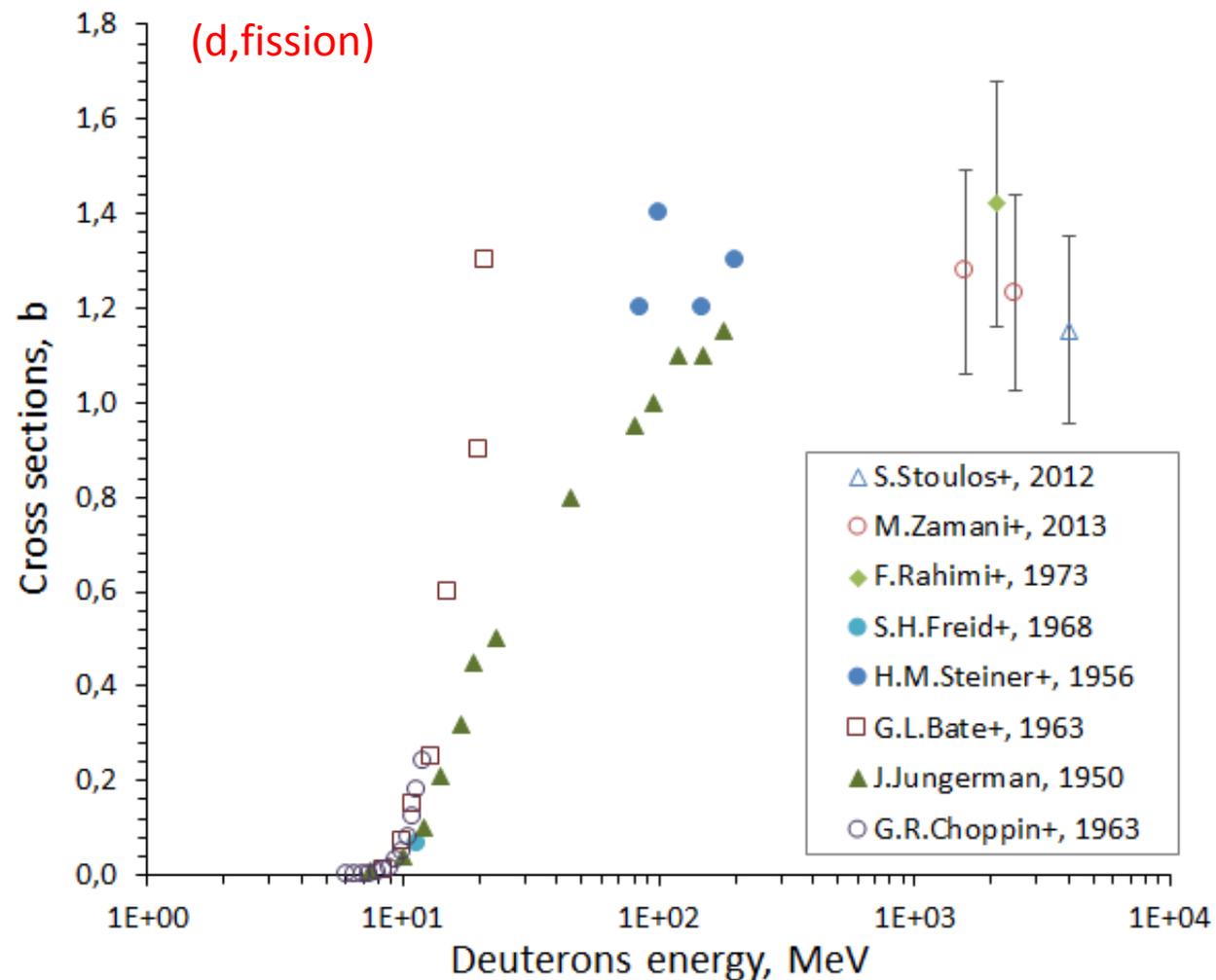
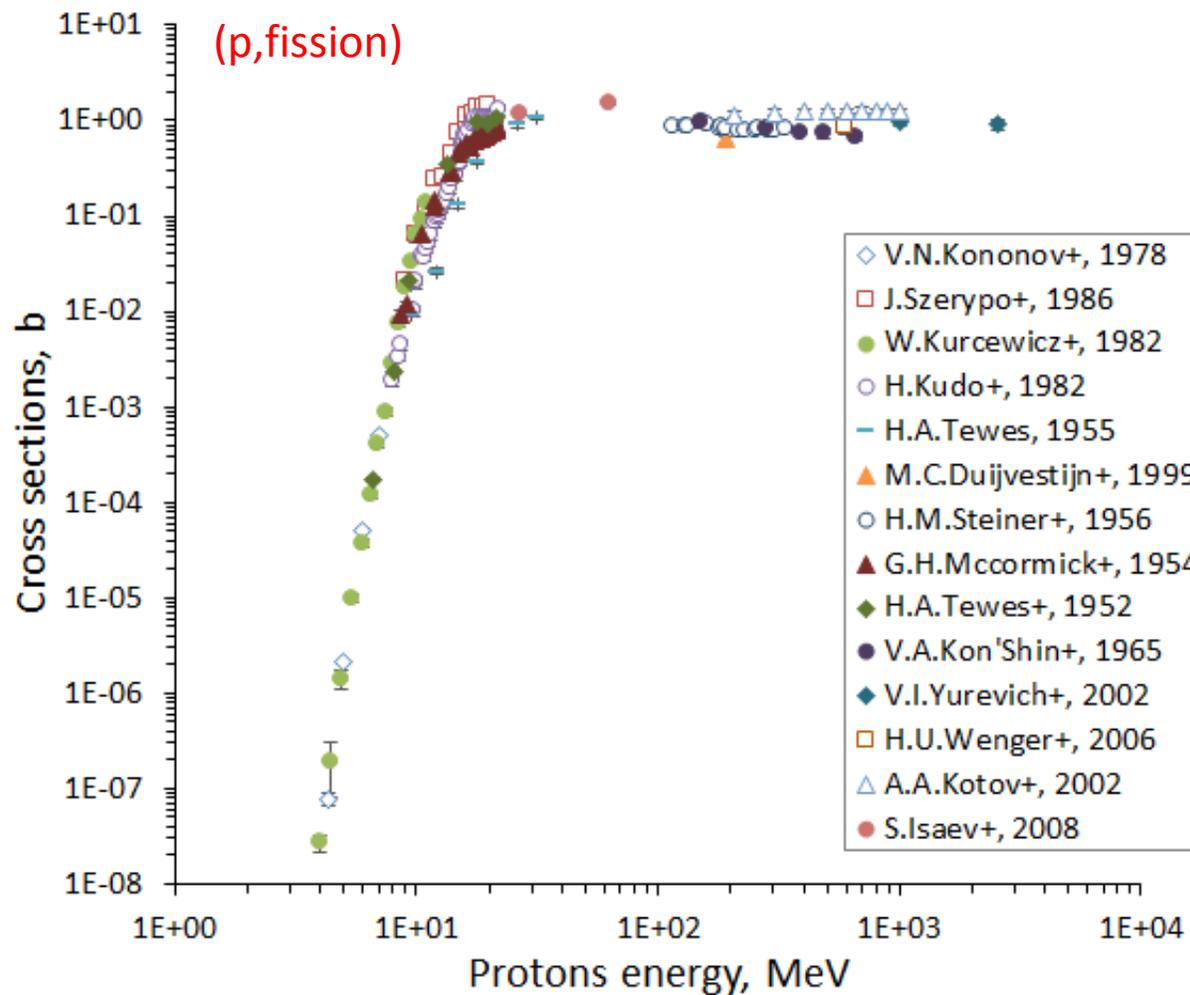
## Data on the irradiation conditions and characteristics of the samples Th-232

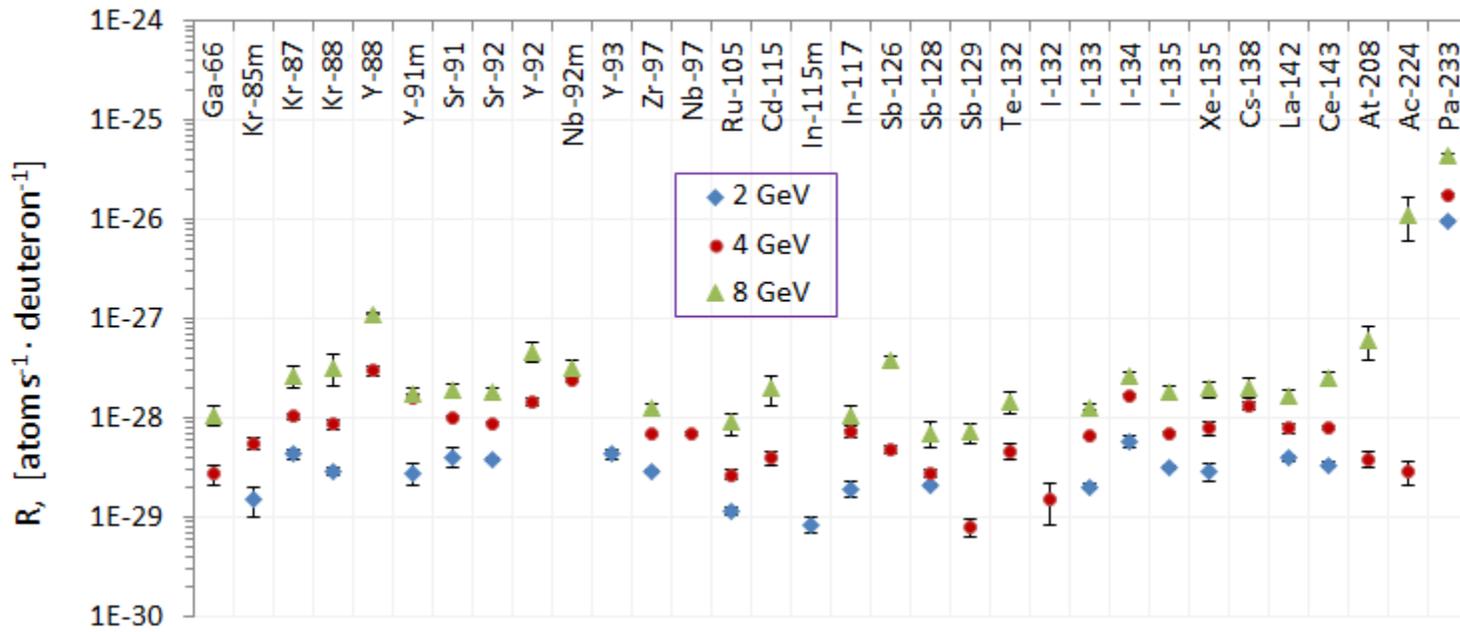
Energy of deuterons, GeV	2	4	8
Irradiation time, min.	376	561	970
Integral flux of deuterons	3.02(10)E+13	2.73(10)E+13	9.10(40)E+12
Samples	Th-232	Th-232	Th-232
Mass, g.	0.975	1.000	0.249
Diameter of samples, sm	1.3	1.3	1.3

Cross sections for  $^{232}\text{Th}(n,g)$  and  $^{232}\text{Th}(n,\text{fission})$  reactions from EXFOR data



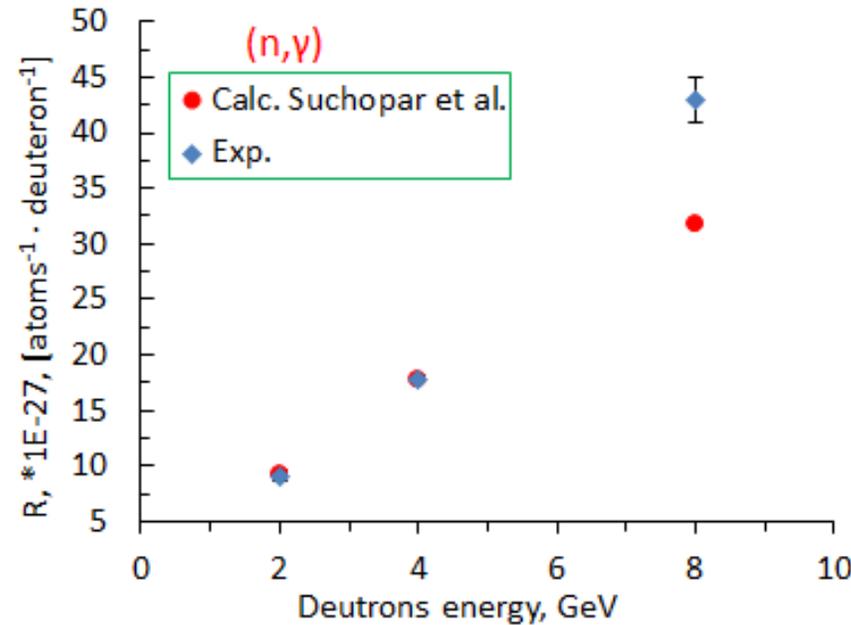
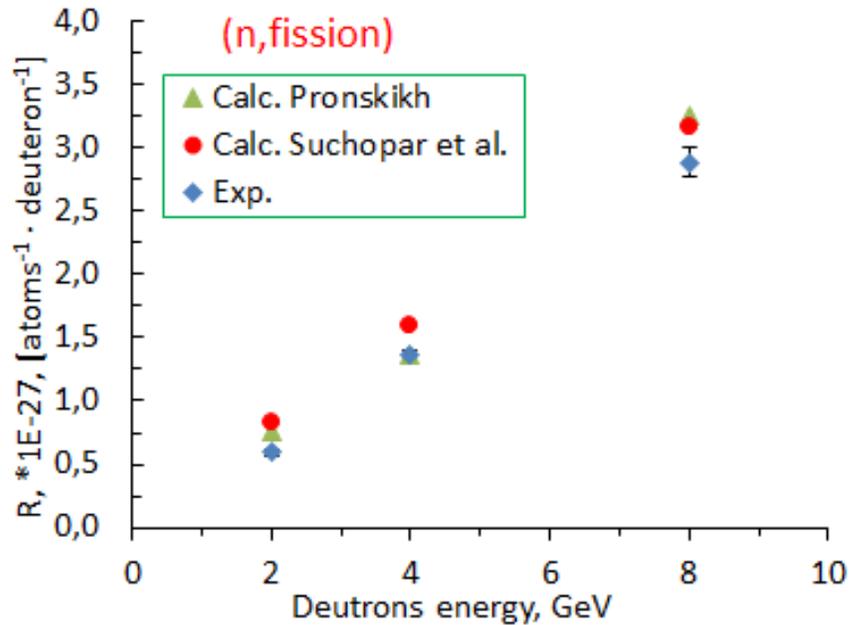
# Cross sections for $^{232}\text{Th}(p,\text{fission})$ and $^{232}\text{Th}(d,\text{fission})$ reactions from EXFOR data





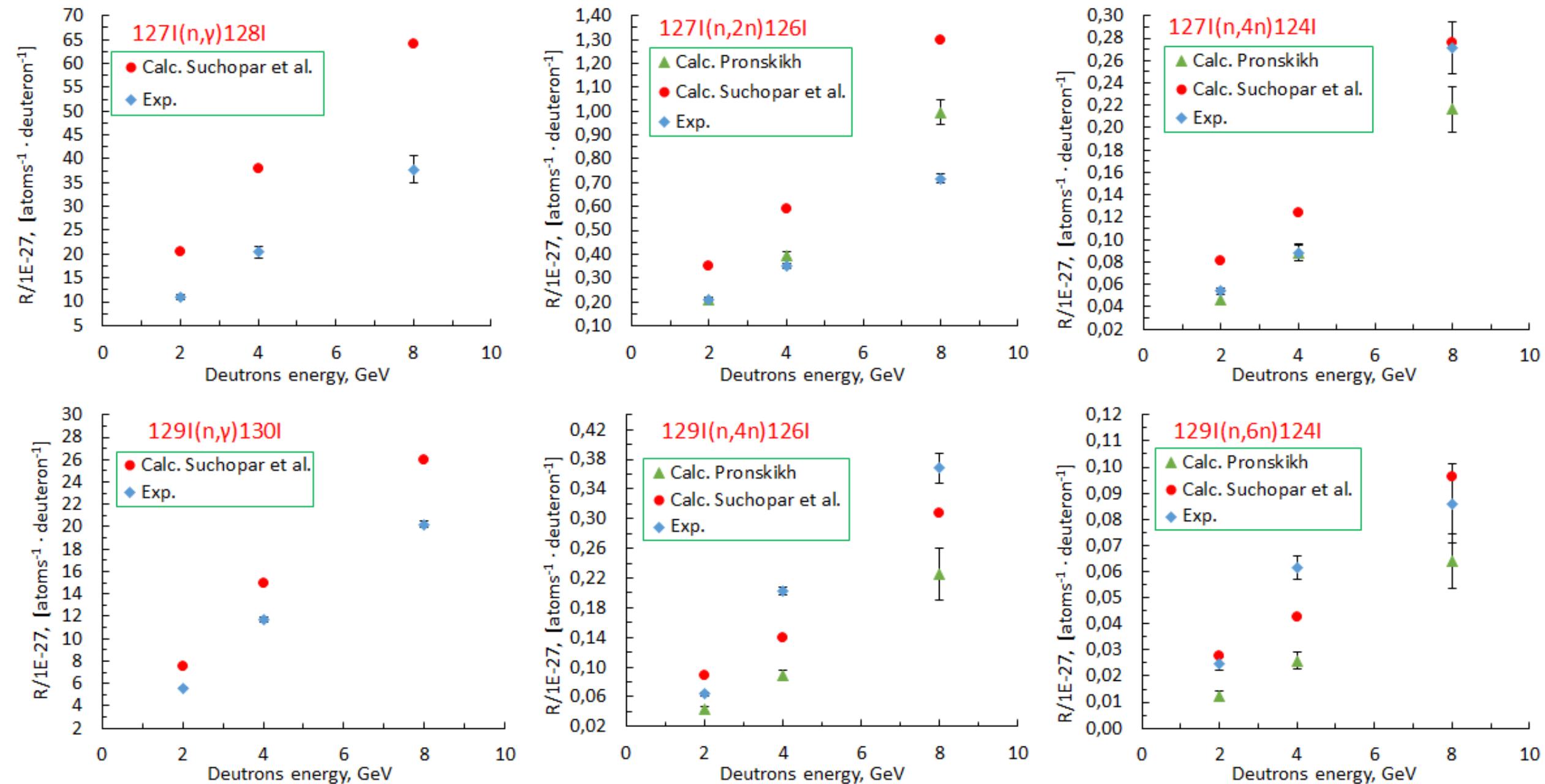
Reaction rates for residual nuclei of  $^{232}\text{Th}$  from experiments  $E_d = 2, 4, 8$  GeV, December, 2012. ("QUINTA" with Pb shields)

Dependence of reaction rates on the deuteron energy for  $^{232}\text{Th}(n, \text{fission})$  and  $^{232}\text{Th}(n, \gamma)$  reactions



Calc. Pronskikh is calculated by MARS-15,  
Calc. Suchopar is calculated by MCNPX-2.7 + TENDL(TALYS)

## Dependence of the $(n,\gamma)$ , $(n,xn)$ reactions rate of the energy deuterons in the samples $^{127}\text{I}$ and $^{129}\text{I}$

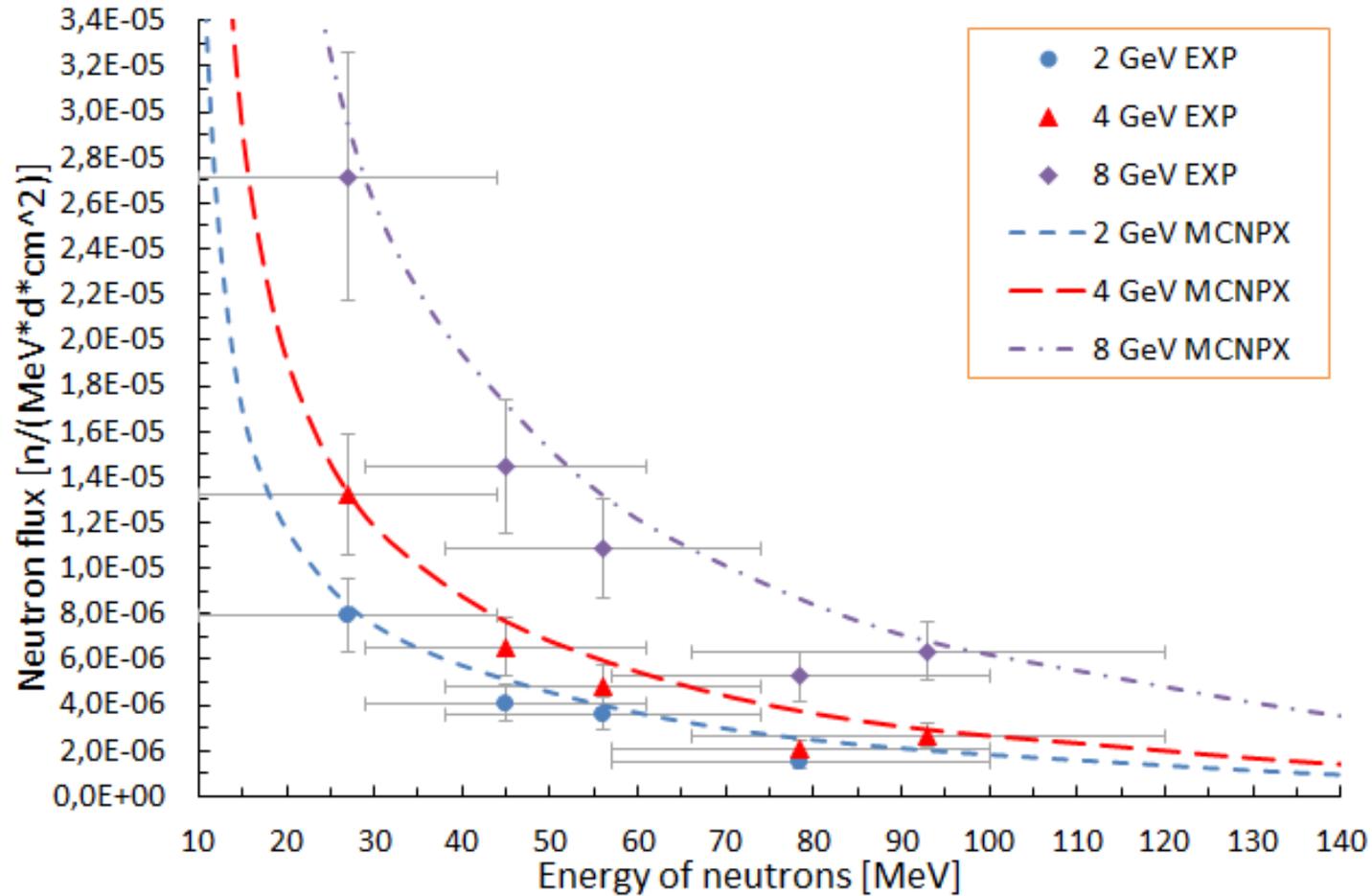


## Definition of neutron fluence using $^{127}\text{I}(n,xn)$ reactions

0.8R – 80% of reaction rate R(exp.) (by Calc.2. neutrons in energy interval dE adding 80(5)% contribution to the reaction rate),

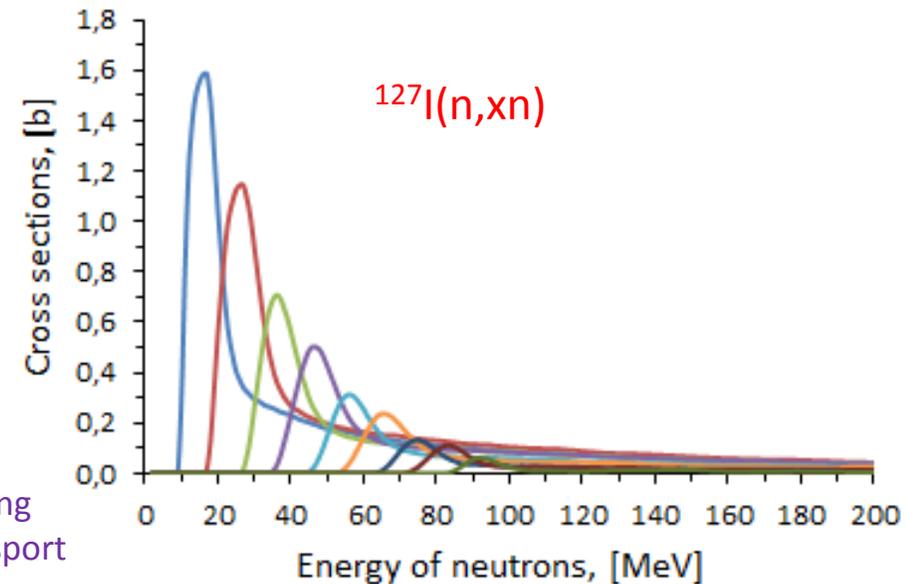
$\sigma$  – averaged values of reaction cross sections for energy interval dE,

F – fluence of neutrons ( $\text{n}/\text{MeV}\cdot\text{d}\cdot\text{cm}^2$ ).



! We couldn't define neutron fluence using  $^{129}\text{I}(n,xn)$  reactions because we have uncertainties depending on the mass of  $^{129}\text{I}$  in the samples I129b(4GeV) and I129c(8GeV), according to our estimates on the passport of the sample I129c(8GeV) mass of  $^{129}\text{I}$  showed to 30(5)% less.

Nuclear reactions	2 GeV			
	0.8R	dE (MeV)	$\sigma$ (b)	F
$^{127}\text{I}(n,8n)^{120}\text{I}$				
$^{127}\text{I}(n,7n)^{121}\text{I}$	7.15(29)E-30	57 – 100	0.110	1.51(30)E-6
$^{127}\text{I}(n,5n)^{123}\text{I}$	3.16(13)E-29	38 – 73	0.249	3.63(73)E-6
$^{127}\text{I}(n,4n)^{124}\text{I}$	4.40(18)E-29	29 – 61	0.337	4.08(82)E-6
$^{127}\text{I}(n,2n)^{126}\text{I}$	1.68(6)E-28	10 – 44	0.621	8.0(16)E-6
4 GeV				
$^{127}\text{I}(n,8n)^{120}\text{I}$	7.20(64)E-30	66 – 120	0.050	2.65(53)E-6
$^{127}\text{I}(n,7n)^{121}\text{I}$	9.84(48)E-30	57 – 100	0.110	2.07(41)E-6
$^{127}\text{I}(n,5n)^{123}\text{I}$	4.18(22)E-29	38 – 73	0.249	4.80(96)E-6
$^{127}\text{I}(n,4n)^{124}\text{I}$	7.07(57)E-29	29 – 61	0.337	6.6(13)E-6
$^{127}\text{I}(n,2n)^{126}\text{I}$	2.80(7)E-28	10 – 44	0.621	1.33(26)E-5
8 GeV				
$^{127}\text{I}(n,8n)^{120}\text{I}$	1.73(14)E-29	66 – 120	0.050	6.4(13)E-6
$^{127}\text{I}(n,7n)^{121}\text{I}$	2.49(16)E-29	57 – 100	0.110	5.2(10)E-6
$^{127}\text{I}(n,5n)^{123}\text{I}$	9.44(56)E-29	38 – 73	0.249	1.08(22)E-5
$^{127}\text{I}(n,4n)^{124}\text{I}$	1.56(8)E-28	29 – 61	0.337	1.45(29)E-5
$^{127}\text{I}(n,2n)^{126}\text{I}$	5.74(16)E-28	10 – 44	0.621	2.72(54)E-5



# Geometry of HPGe planar detector for FLUKA

The screenshot displays the Geometry Builder interface for the FLUKA simulation. The main workspace is divided into four views: Front, Top, Left, and Back. The geometry is composed of several nested rectangular regions and a central detector component.

**Geometry Tree (Left Panel):**

Type	Name
SPH	bikbody
SPH	void
RPP	Cu1
RPP	Cu2
RPP	PLEX1
RPP	PLEX2
RPP	PLEXIG3
RPP	PLEXIG4
RPP	PLEXIG5
RCC	PLASTIC
RCC	ENDCAP1
RCC	ENDCAP2
TRC	ENDCAP3
TRC	ENDCAP4
RCC	BERYLLIU
RCC	SHROUD1
RCC	SHROUD2
RCC	SHROUD3
RCC	MYLAR
RCC	COLLIMA1
RCC	COLLIMA2
RCC	COLLIMA3
RCC	COLLIMA4
RCC	COLLIMA5

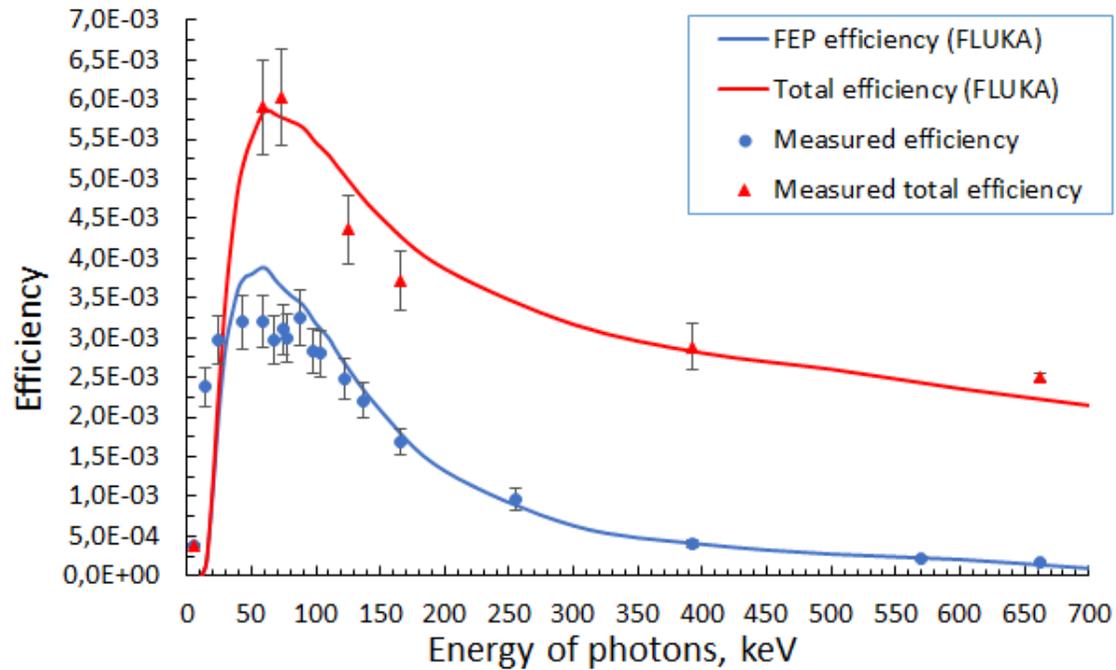
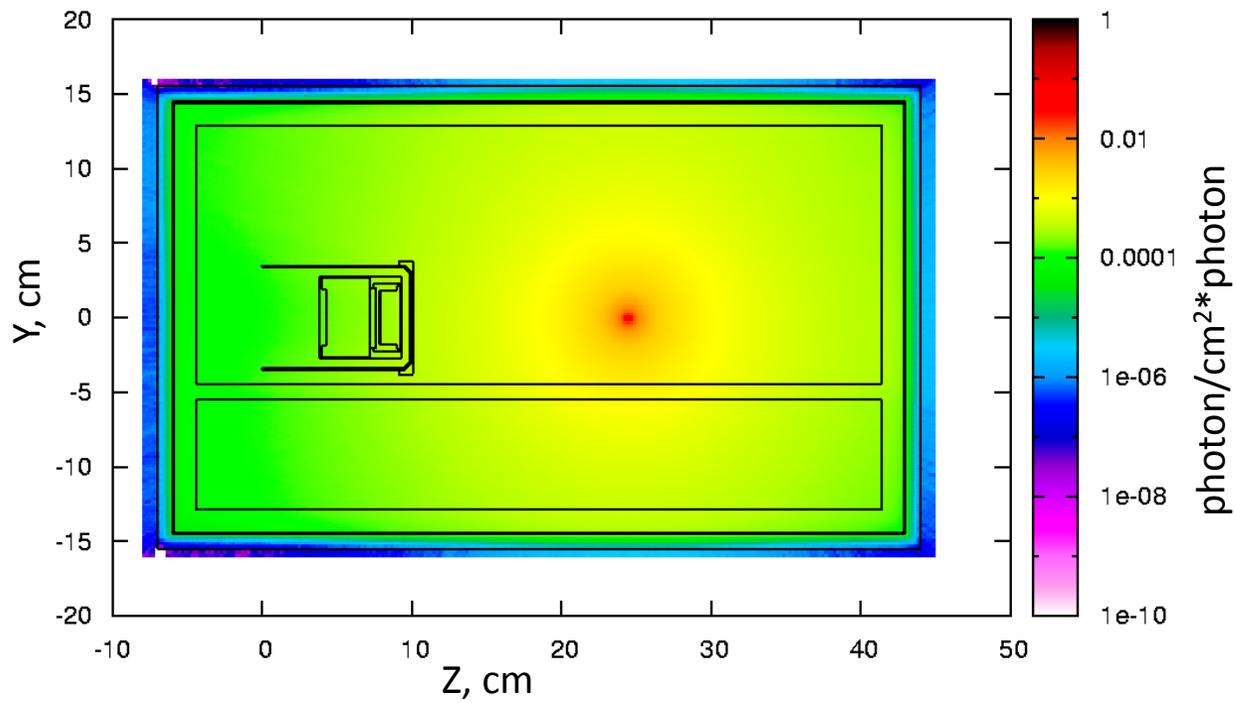
**View Details:**

- Front View:** Shows a large rectangular frame (PLEX) with a central vertical structure (VOID).
- Top View:** Shows the frame (PLEX) with a central horizontal structure (VOID) and a small rectangular component (AIR).
- Left View:** Shows the detector assembly (AIR, VACUUM, GERMANI, VACUUM, COLLIMA) within the frame (PLEX).
- Back View:** Shows the frame (PLEX) with a central vertical structure (VOID) and a circular component (AIR).

**Coordinate System:** The bottom status bar shows the current coordinates:  $x: 6.433519559$ ,  $y: -5.966825945$ ,  $z: 0$ .

## Efficiency of HPGe planar detector

Simulation of 100 keV gamma rays with FLUKA



Total efficiency (exp.) is measured, using <sup>55</sup>Fe, <sup>241</sup>Am, <sup>44</sup>Ti, <sup>57</sup>Co, <sup>139</sup>Ce, <sup>113</sup>Sn and <sup>137</sup>Cs sources.

# Geometry of setup "QUINTA" for FLUKA

Geometry

Media

Left

Back

Front

Properties

Attributes

Type	Name
SPH	bikbody
SPH	void
RCC	U231
RCC	U331
RCC	U431
RCC	U531
RCC	U232
RCC	U332
RCC	U432
RCC	U532
RCC	U133
RCC	U233
RCC	U333
RCC	U433
RCC	U533
RCC	U134
RCC	U234
RCC	U334
RCC	U434
RCC	U534
RCC	U135
RCC	U235
RCC	U335
RCC	U435

Geometry of setup "QUINTA" for FLUKA. The image displays four views of the simulation geometry: Left, Back, and Front views, along with a Properties/Attributes panel. The geometry consists of various components labeled Pb1 through Pb6e and U105 through U535. The components are arranged in a complex structure, with Pb1 being the top layer, Pb2 the bottom layer, and Pb3-Pb6e forming the sides and internal structures. The U components are arranged in a grid pattern within the central region. The Properties/Attributes panel lists the components and their types (SPH, RCC).

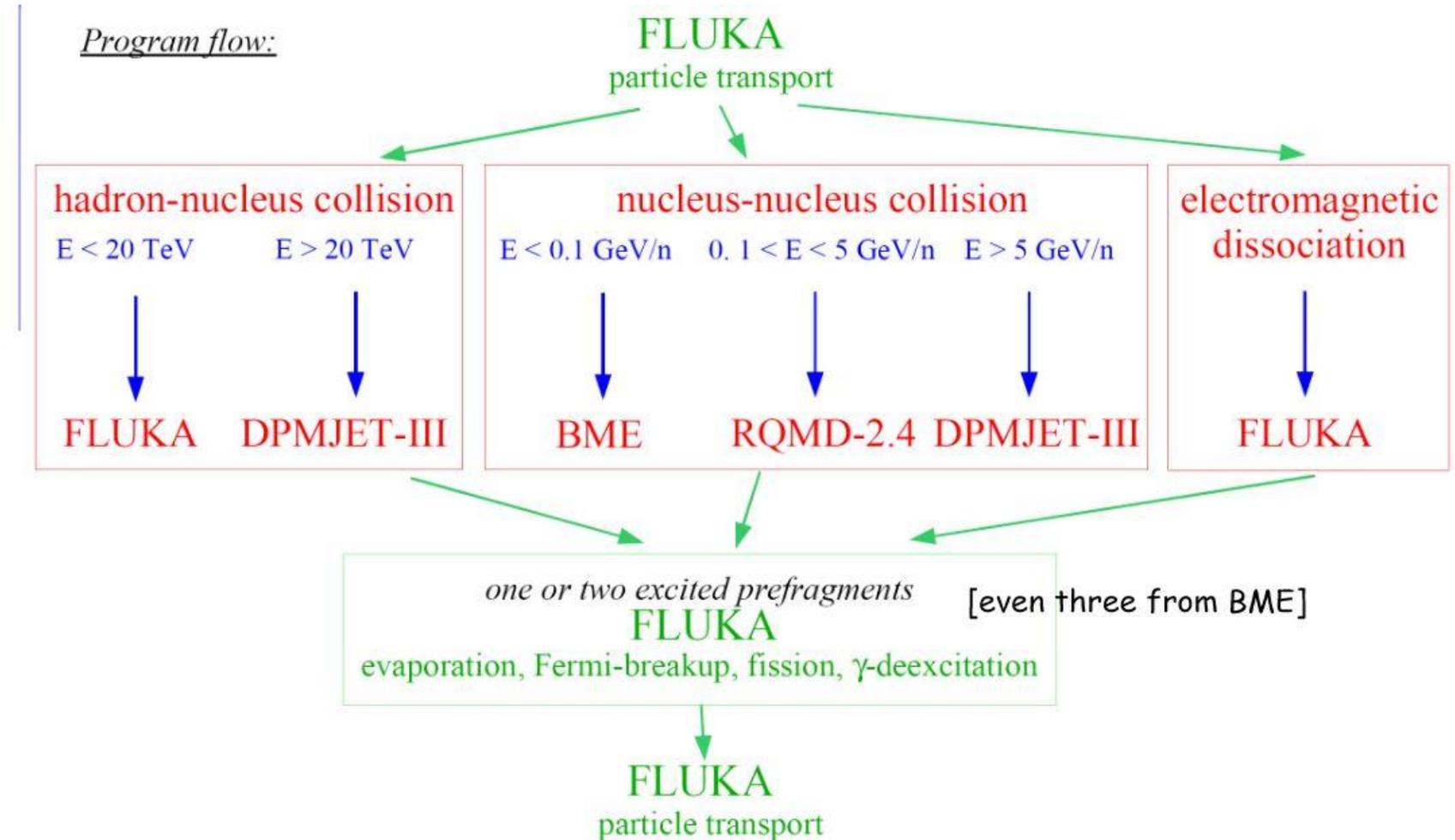
Coordinates: x: 7.4408, y: -21.15682859, z: 65.68110427

## Nuclear interaction models in FLUKA

Dual Parton Model (DPM) –  $E > 5 \text{ GeV/n}$

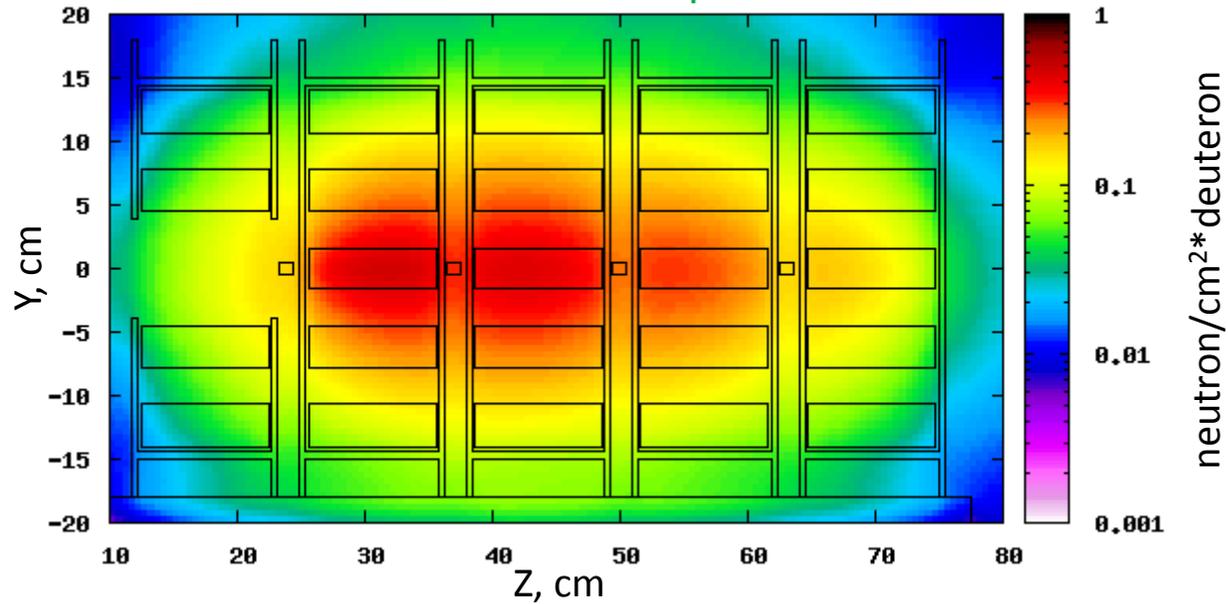
Relativistic Quantum Molecular Dynamics Model (RQMD) –  $0.1 \text{ GeV/n} < E < 5 \text{ GeV/n}$

Boltzmann Master Equation (BME) theory –  $E < 0.1 \text{ GeV/n}$

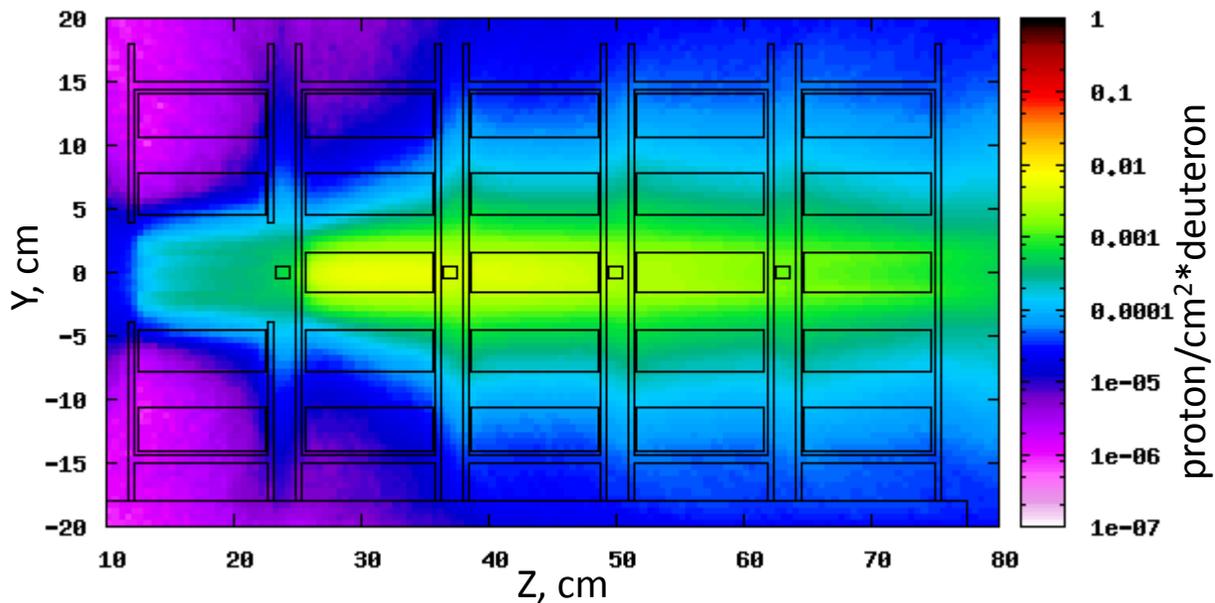


Some results of simulations for experiment  $E_d = 6$  GeV, March, 2011.  
("QUINTA" without Pb shields)

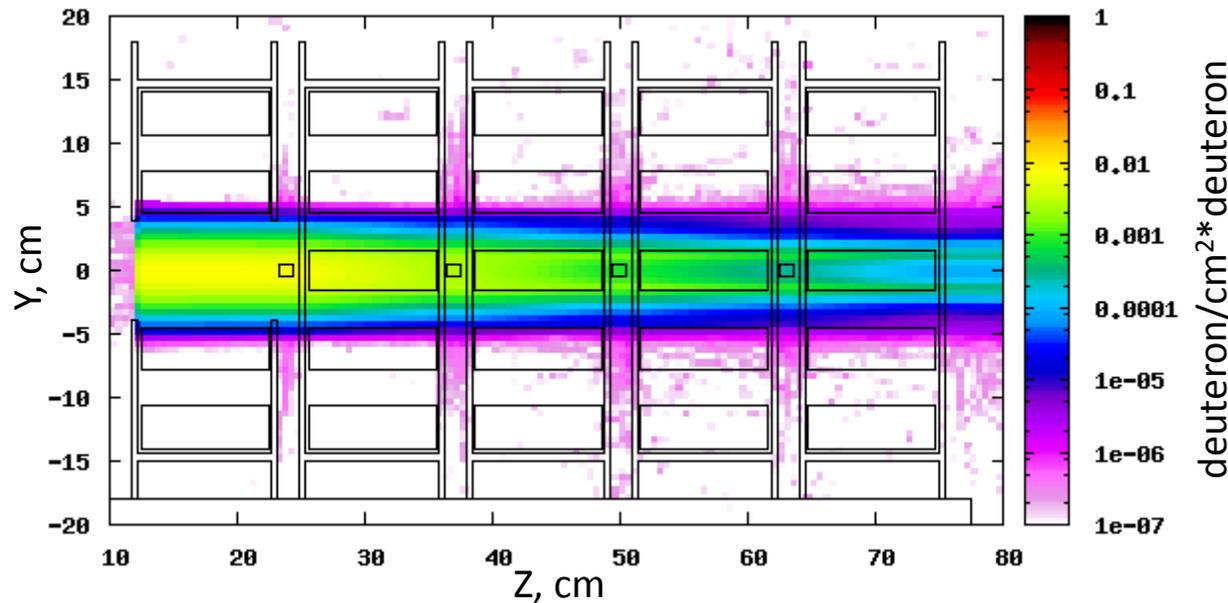
Neutrons on the setup "QUINTA"



Protons on the setup "QUINTA"



Deuterons on the setup "QUINTA"



# Dependence of calculated reaction rates on the mass of residual nuclei in the samples $^{232}\text{Th}$

$E_d = 6 \text{ GeV}$ , March, 2011.

("QUINTA" without Pb shields)

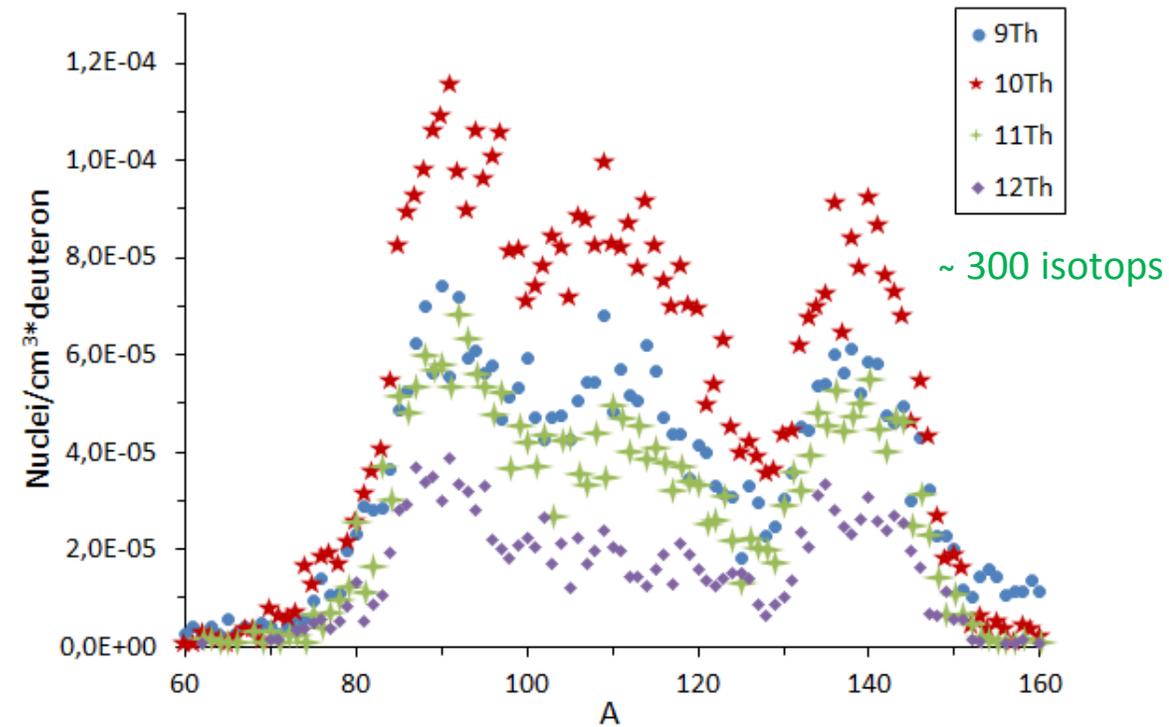
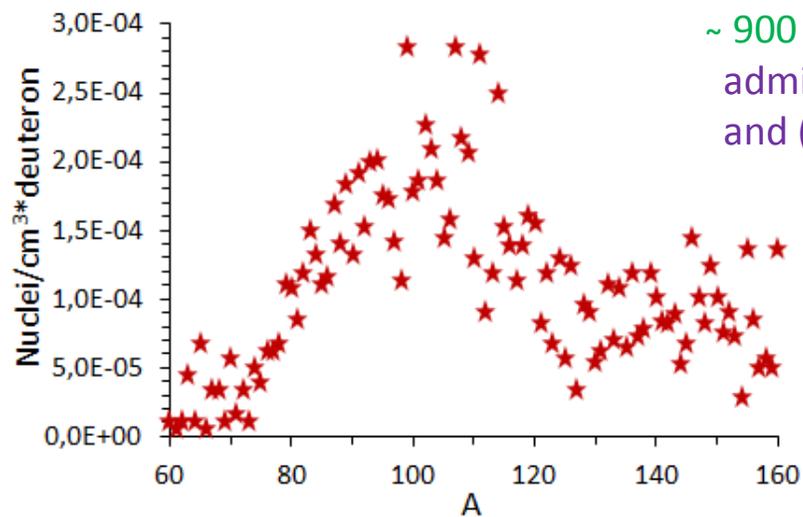
9Th – was placed between the first and second sections

10Th – was placed between the second and third sections

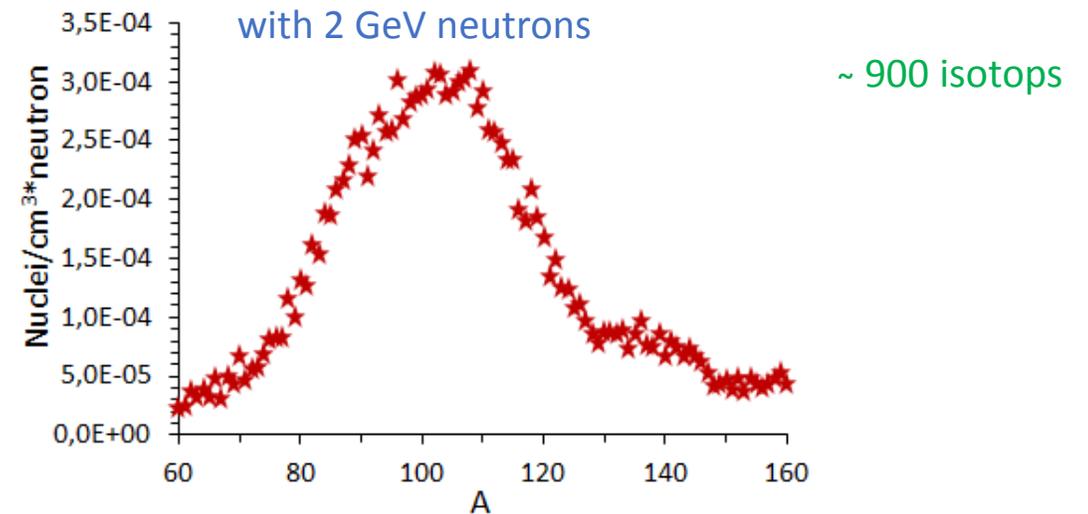
11Th – was placed between the third and fourth sections

12Th – was placed between the fourth and fifth sections

Calculated fission reaction rates for  $^{232}\text{Th}$  with 4 GeV deuterons



Calculated fission reaction rates for  $^{232}\text{Th}$  with 2 GeV neutrons



# Dependence of calculated reaction rates on the charge of residual nuclei in the samples $^{232}\text{Th}$

$E_d = 6 \text{ GeV}$ , March, 2011.

("QUINTA" without Pb shields)

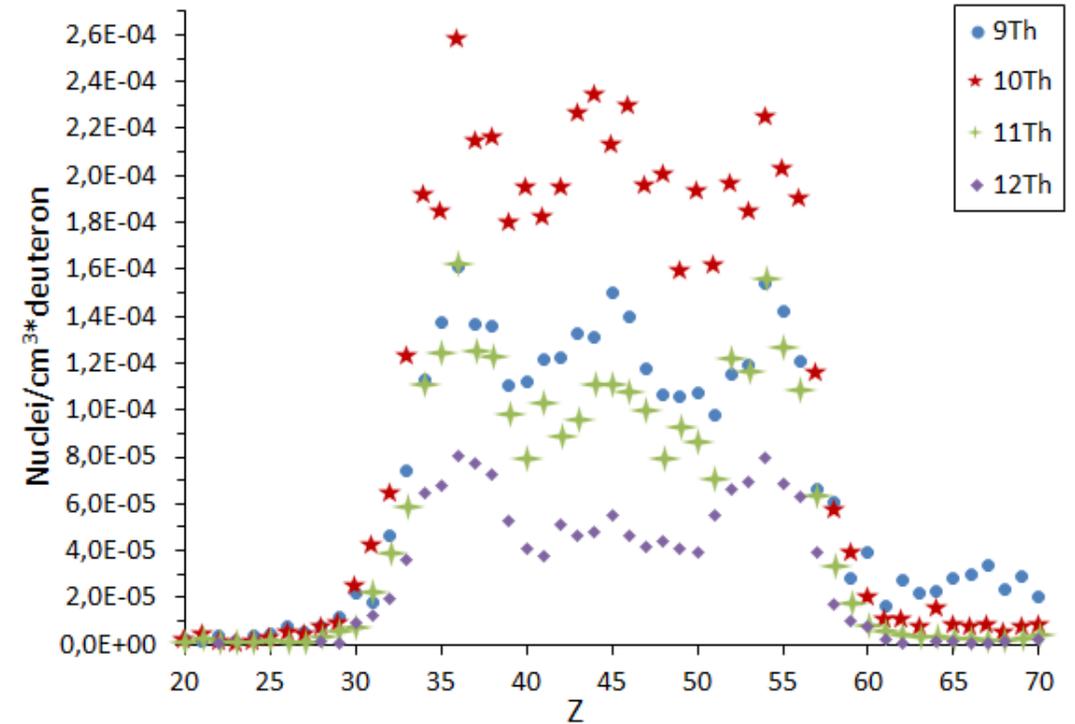
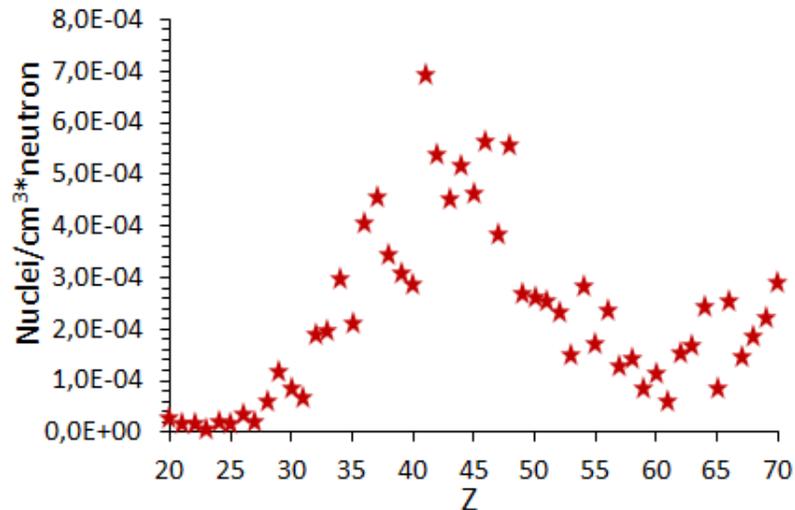
9Th – was placed between the first and second sections

10Th – was placed between the second and third sections

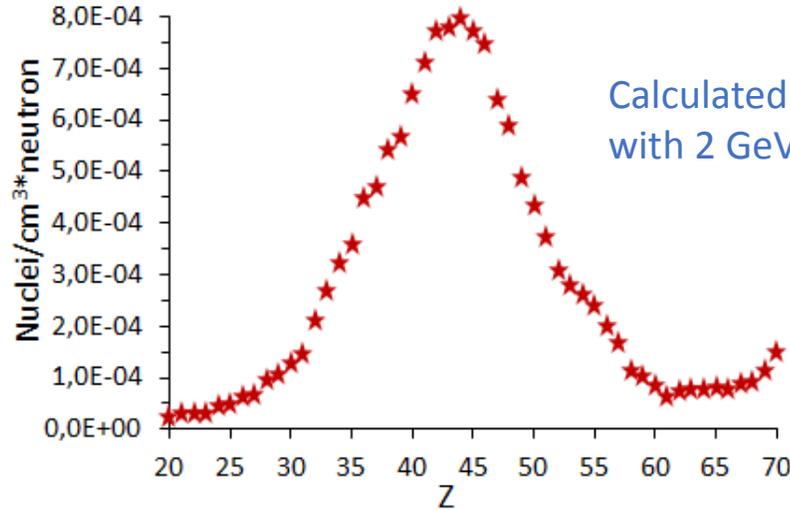
11Th – was placed between the third and fourth sections

12Th – was placed between the fourth and fifth sections

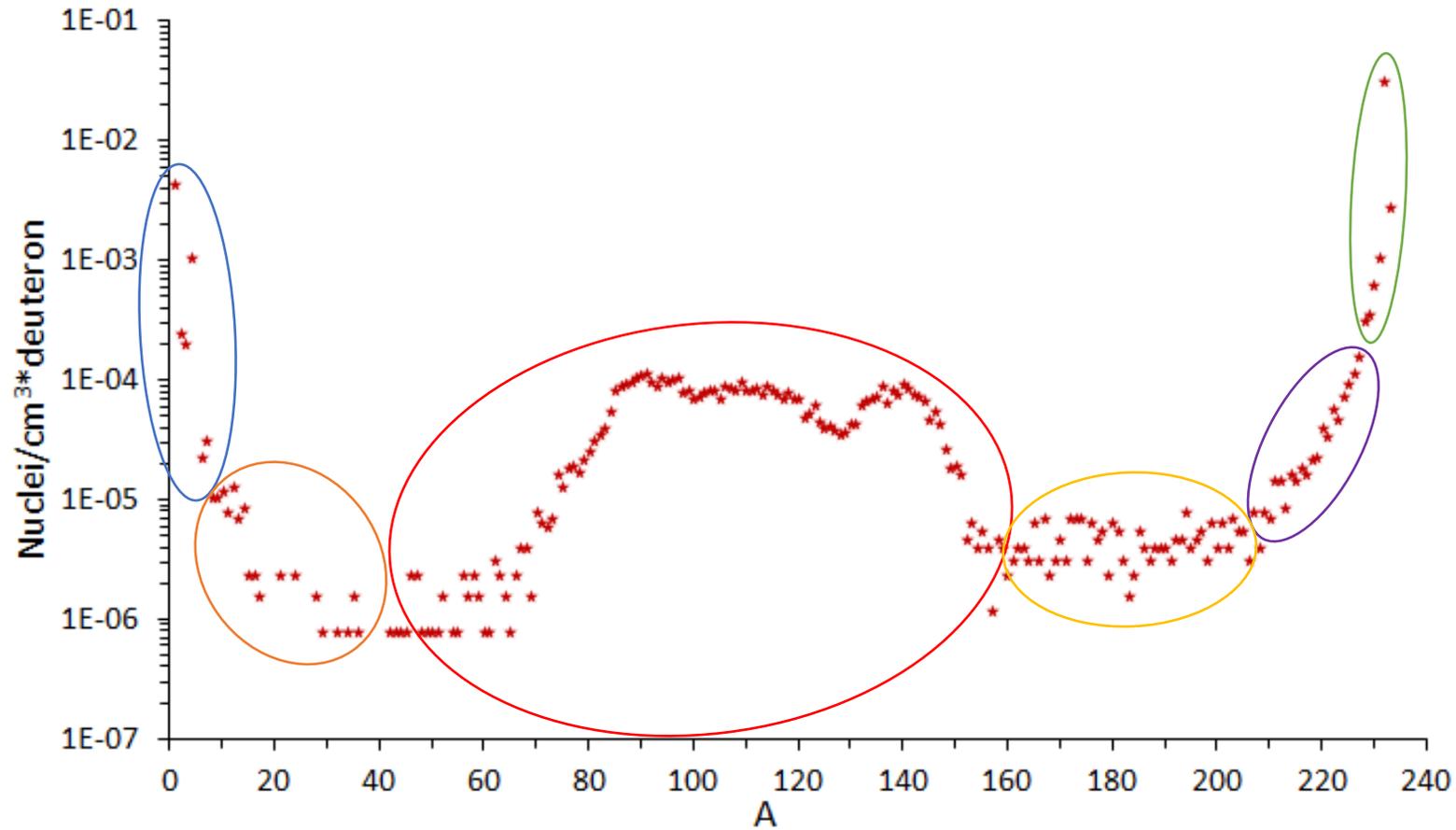
Calculated fission reaction rates for  $^{232}\text{Th}$  with 4 GeV deuterons



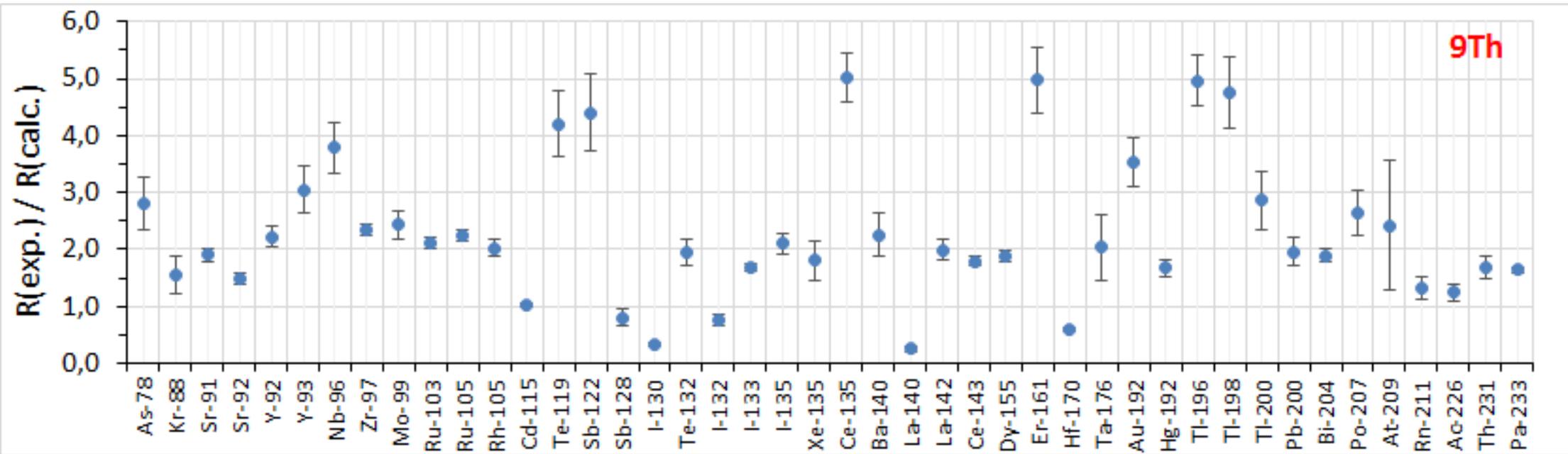
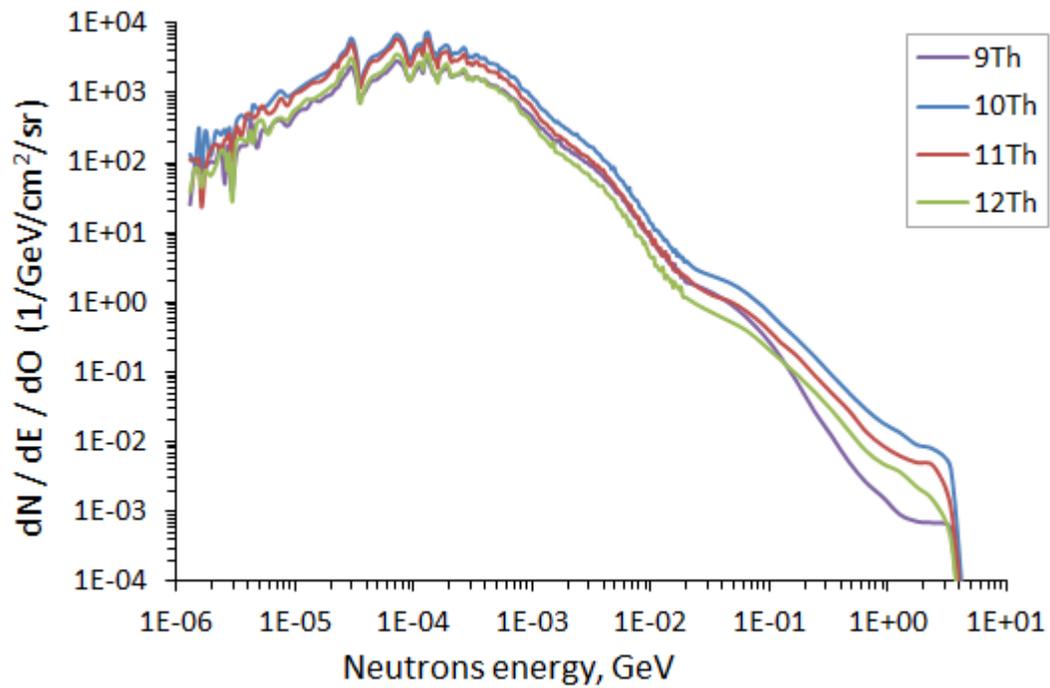
Calculated fission reaction rates for  $^{232}\text{Th}$  with 2 GeV neutrons

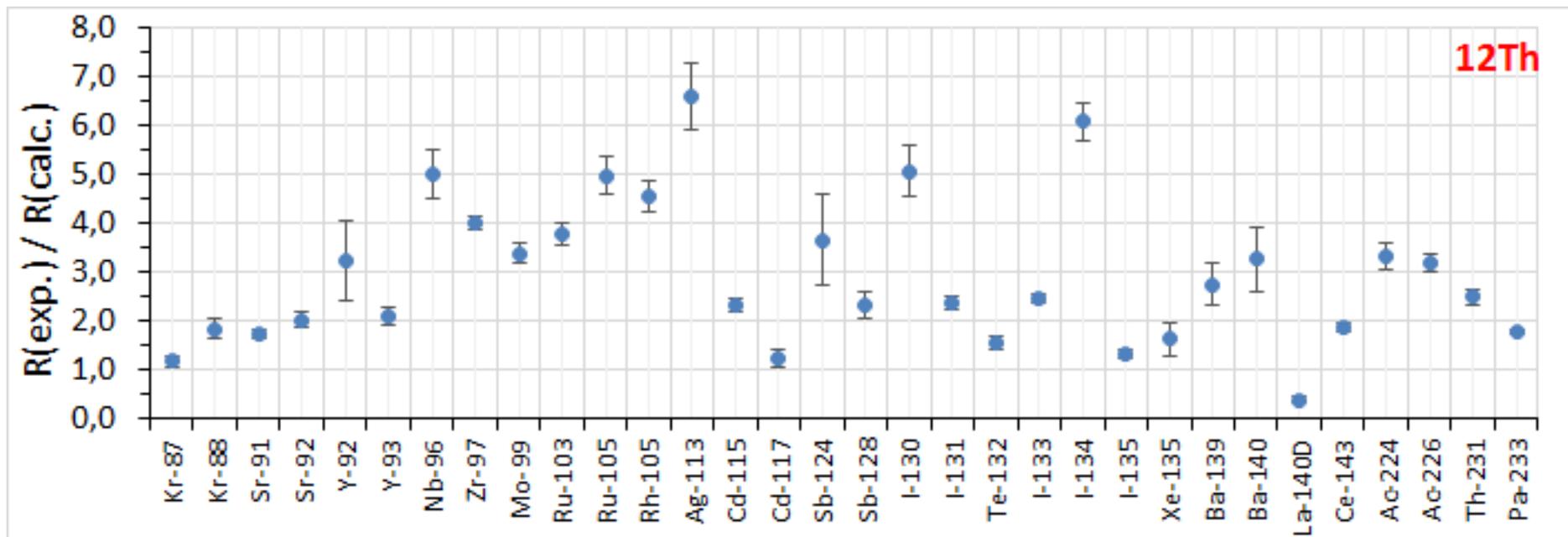
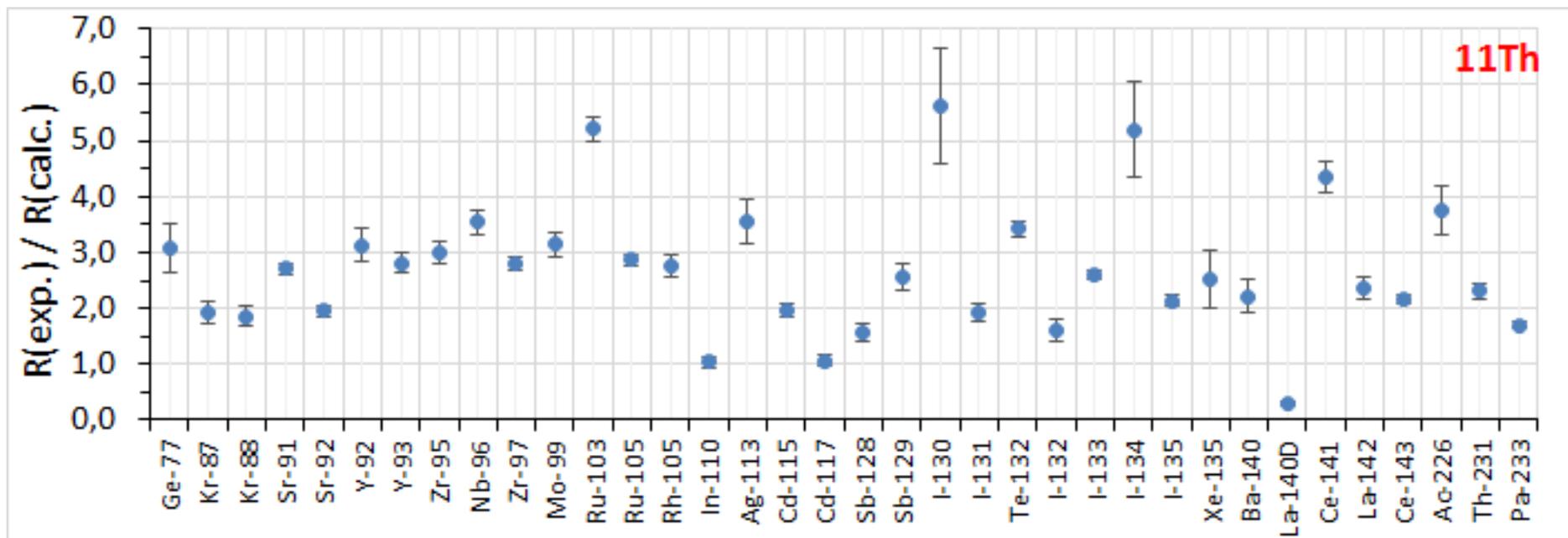


# Dependence of calculated reaction rates on the mass of residual nuclei in the sample $^{232}\text{Th}$ (10Th)



- Evaporation products
- Fragmentation products
- Low and high energy fission products
- Deep spallation products
- Spallation products
- Quasi-elastic products





## Summary

- The experimental data obtained in the study of the interaction of secondary neutrons with  $^{232}\text{Th}$ ,  $^{129}\text{I}$ ,  $^{127}\text{I}$  nuclei at the "QUINTA" show a proportional increase in the values of reaction rate with increasing energy of deuterons, for almost all produced nuclei.
- The experimental results were compared with Monte Carlo simulations performed with the MCNPX2.7 and MARS15 code. Ratios of experimental and calculated rates of (n, $\gamma$ ), (n,xn) and (n,fission) reactions are in the range 0.5 – 2.4.
- Ratios of experimental and calculated with FLUKA reaction rates for residual nuclei of  $^{232}\text{Th}$  samples (irradiated on the central axes of "QUINTA", P1, P3 and P4) are in the range 0.3 – 6.6.
- Defined fluence of neutrons (10 – 120 MeV) by  $^{127}\text{I}(n,xn)$  reactions in good agreement with calculated by MCNPX 2.7.

Thanks for your attention