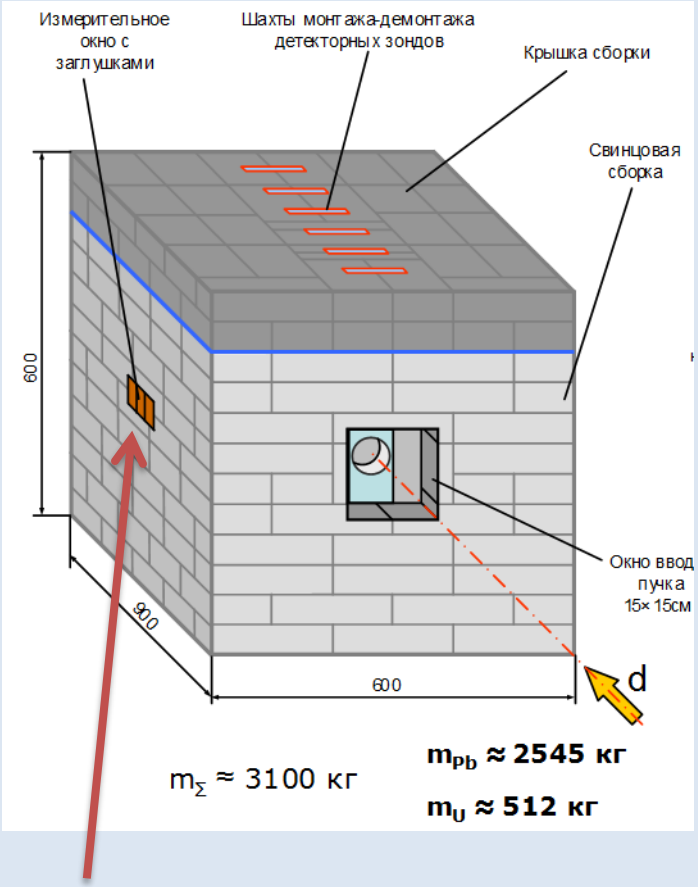
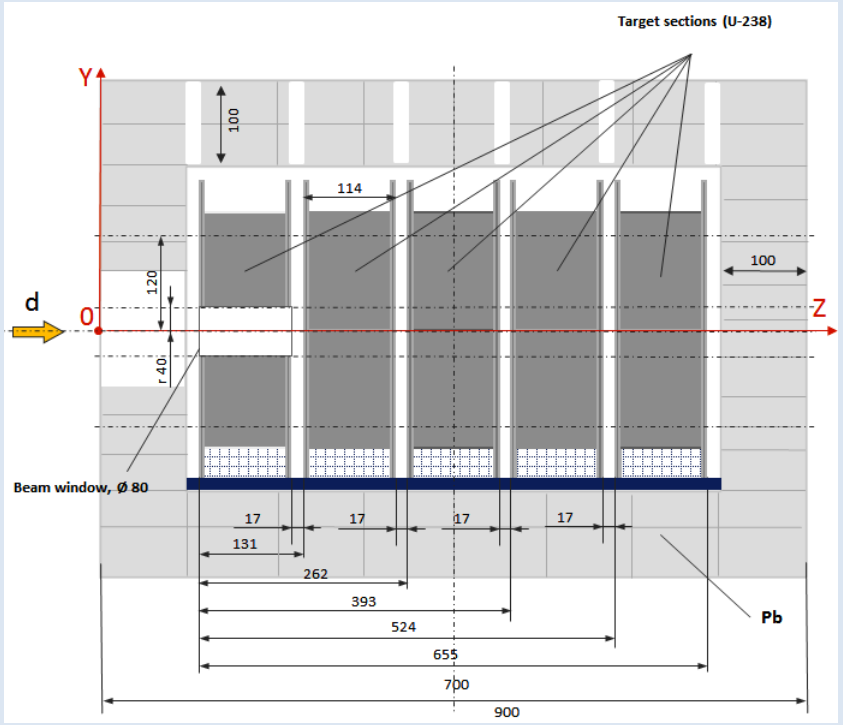
STUDY THE INTERACTION OF SECONDARY NEUTRONS WITH NUCLEI ^{232}Th, ^{129}I, ^{127}I ON THE URANIUM ASSEMBLY "QUINTA" NUCLOTRON JINR ON DEUTRONS BEAM WITH ENERGY 2, 4, 8 GeV

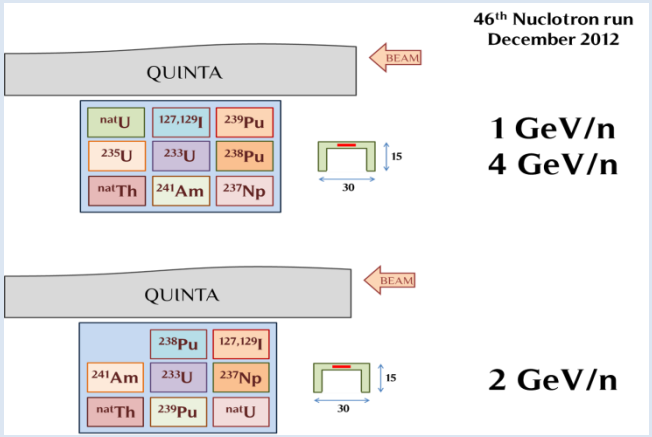
J. Adam[1,2], V.V. Chilap[3], V.I. Furman[1], J. Khushvaktov[1], V.S. Pronskikh[1], A.A. Solnyshkin[1], V.I. Stegailov[1], M. Suchopar[2], V.M. Tsoupko-Sitnikov[1], S.I. Tyutyunnikov[1], J. Vrzalova[1], V. Wagner[2], L. Zavorka[1]

[1]Joint Institute for Nuclear Research, Dubna, Russia.
[2]Nuclear Physics Institute ASCR PRI, Czech Republic.
[3]Center of Physical and Technical Projects "Atomenergomash", Moscow, Russia.

Experimental setup «Quinta»

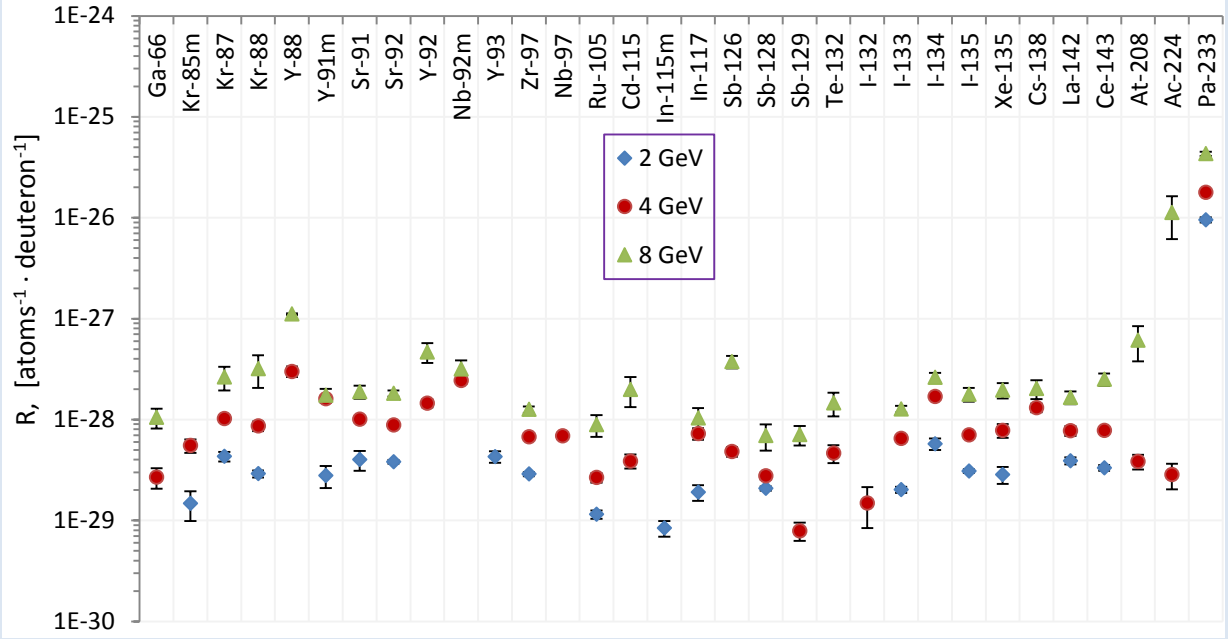






Data on the irradiation conditions and characteristics of the samples Th-232			
Energy of deuterons, GeV	2	4	8
Irradiation time, min.	376	561	970
Integral flux of deuterons	3.02(10)E+13	2.73(10)E+13	9.10(40)E+12
Samples	Th-232	Th-232	Th-232
Mass, g.	0.975	1.000	0.249
Diameter of samples, sm	1.3	1.3	1.3

Results of Th-232 for E(d) = 2, 4, 8 GeV



$$R(A_r, Z_r) = \frac{Q(A_r, Z_r)}{N_t N_d}$$

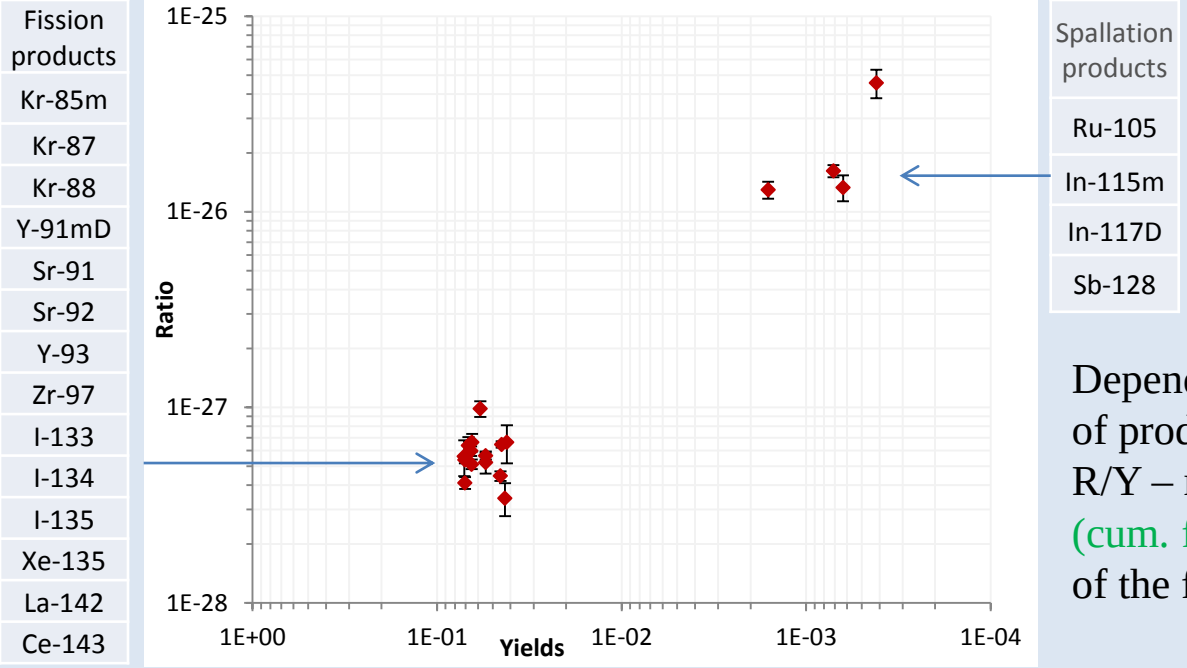
$Q(A_r, Z_r)$ – number of produced radionuclides (r)
N_t – number of atoms in the sample
N_d - number of incident deuterons on the target

	R(4 GeV)/R(2 GeV)	R(8 GeV)/R(2 GeV)
(n,fission)	2.89(31)	6.04(86)
(n,γ)	1.86(7)	4.50(23)

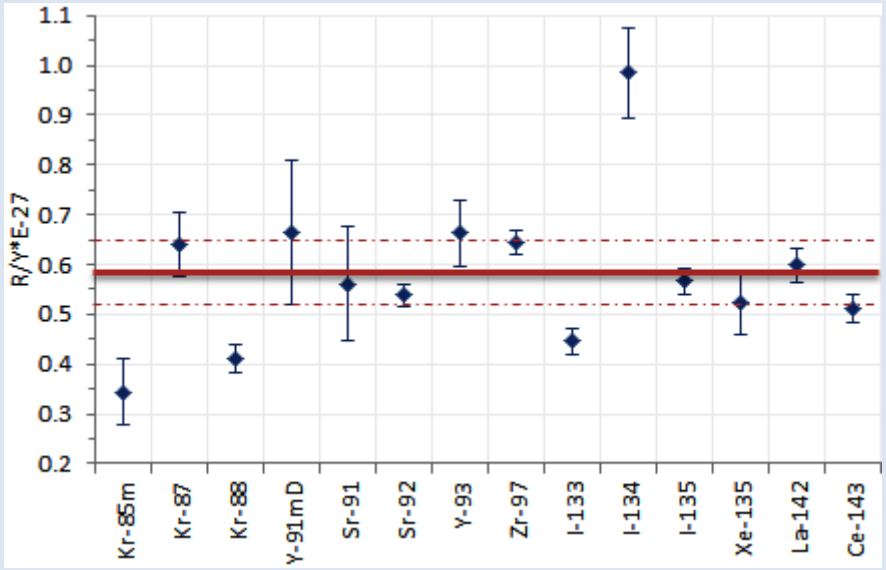
^{228}Th(n,t2n)^{224}Ac (E_{thr} = 16.56 MeV)

^{232}Th(n,γ)^{233}Th ---β$^-$ ($T_{1/2}$=22.3 m)---> ^{233}Pa ---β$^-$ ($T_{1/2}$=26,97 d)---> ^{233}U ($T_{1/2}$=1.59*10^5 y)

Results of Th-232 for E(d) = 2 GeV



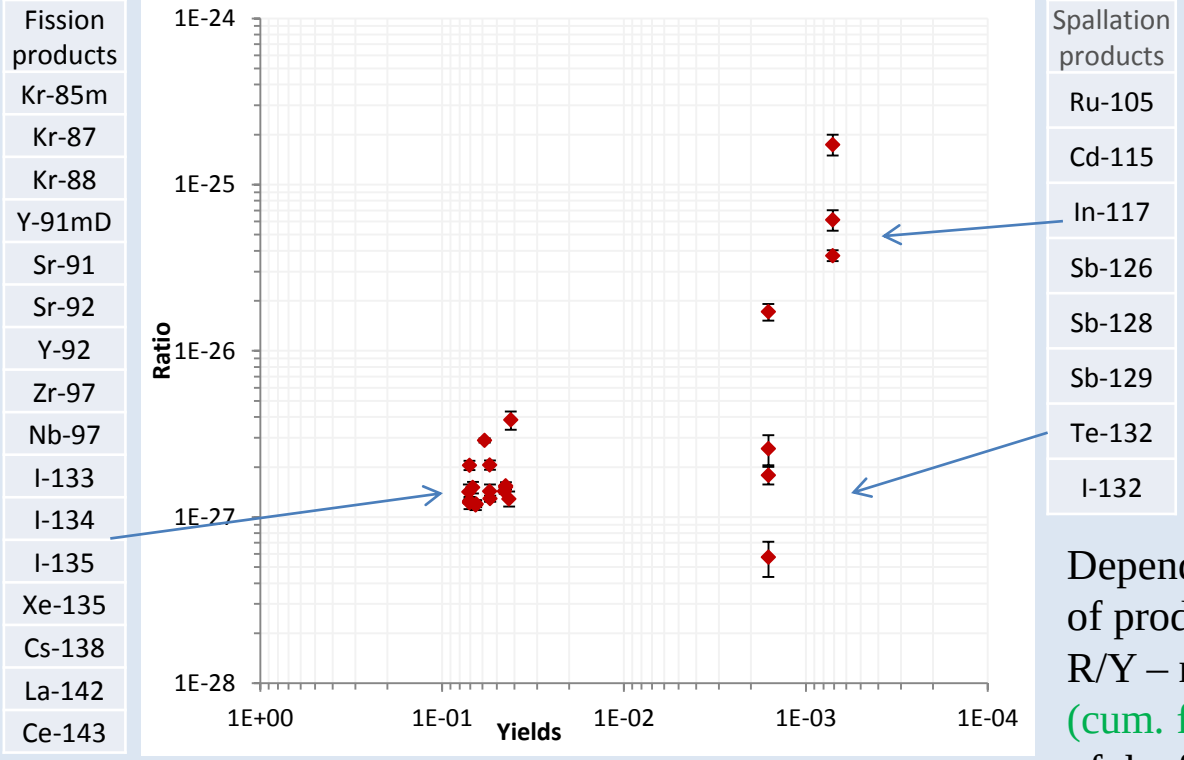
Dependence of the ratio R/Y from yields of product nuclei
R/Y – ratio of reaction rates to the yield (cum. from JEEF 3.1, E(n)=0.4 MeV) of the fission product nuclei thorium



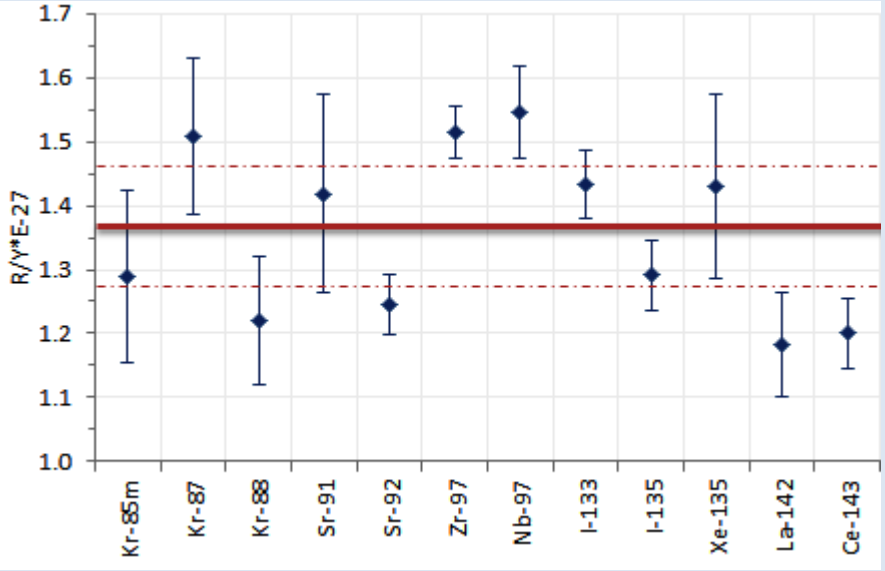
Average value of the ratio R/Y for fission product nuclei thorium

<R/y> = 0.58(6)E-27 --> R(n,fission)

Results of Th-232 for E(d) = 4 GeV



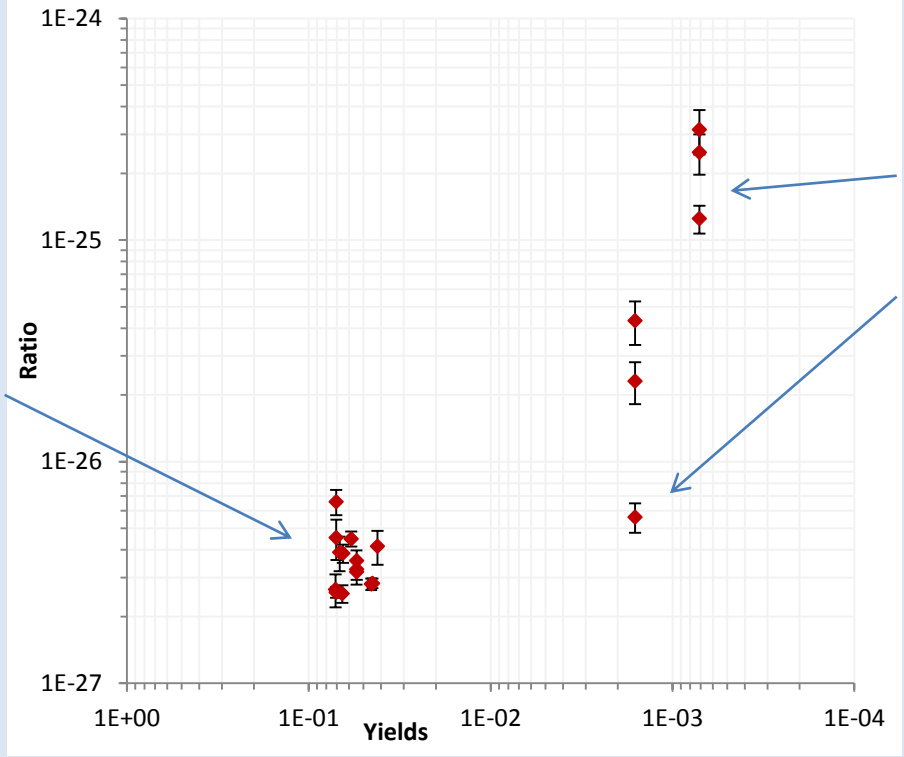
Dependence of the ratio R/Y from yields of product nuclei
R/Y – ratio of reaction rates to the yield (cum. from JEEF 3.1, E(n)=0.4 MeV) of the fission product nuclei thorium



Average value of the ratio R/Y for fission product nuclei thorium

<R/Y> = 1.36(9)E-27 --> R(n,fission)

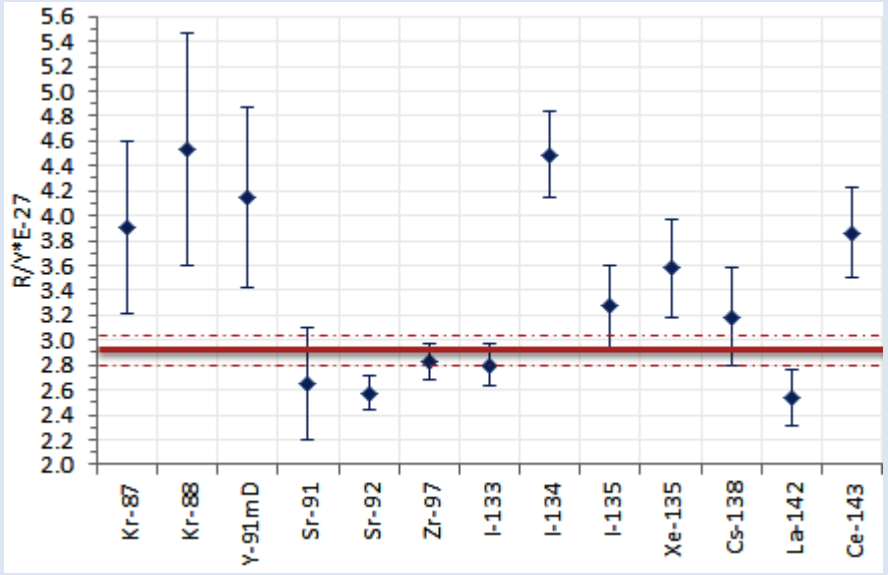
Fission products
Kr-87
Kr-88
Y-91mD
Sr-91
Sr-92
Y-92
Zr-97
I-133
I-134
I-135
Xe-135
Cs-138
La-142
Ce-143



Spallation products
Ru-105
Cd-115
In-117
Sb-128
Sb-129
Te-132

Results of Th-232 for E(d) = 8 GeV

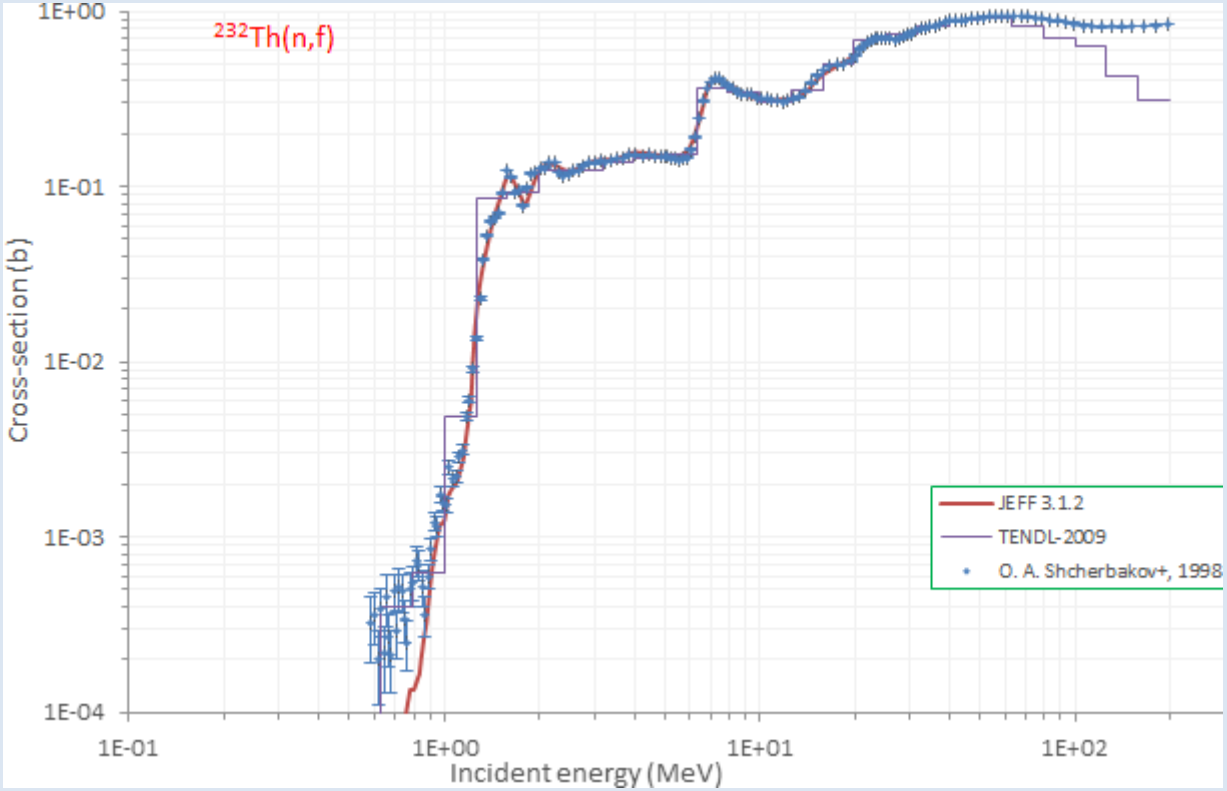
Dependence of the ratio R/Y from yields of product nuclei
R/Y – ratio of reaction rates to the yield (cum. from JEEF 3.1, E(n)=0.4 MeV) of the fission product nuclei thorium



Average value of the ratio R/Y for fission product nuclei thorium

<R/Y> = 2.92(14)E-27 --> R(n,fission)

Fission cross sections for Th-232.



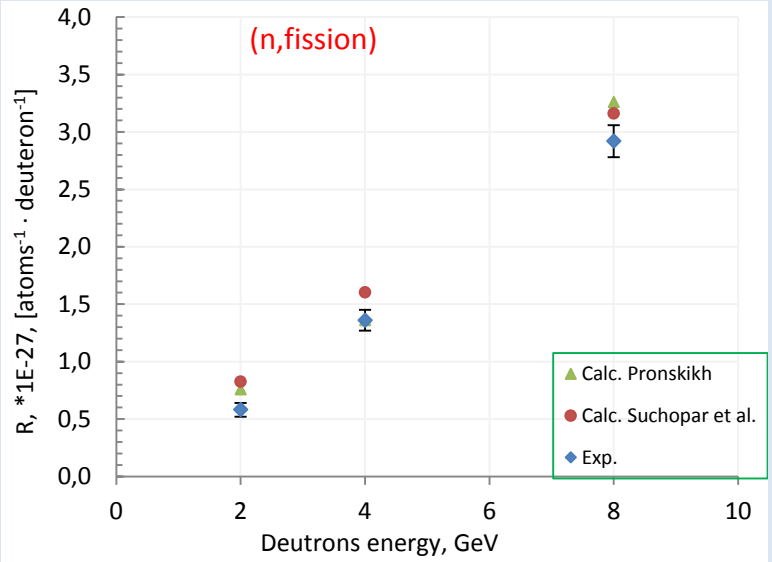
To calculate reaction rates used the following formula:

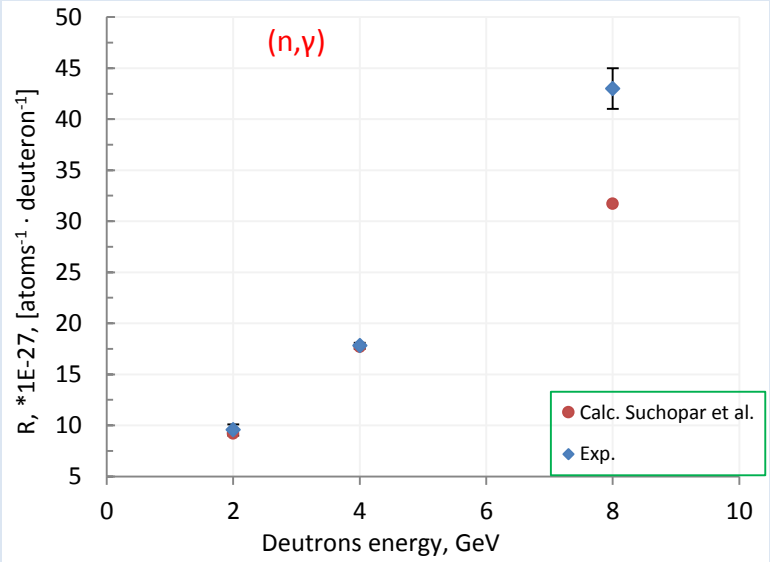
$$R(A_r, Z_r) = \int_{E_{thr}(A_r,Z_r)}^{\infty} \sigma(A_r, Z_r, E_n)\varphi(E_n)dE_n$$

where, $\sigma(A_r, Z_r, E_n)$ – reaction cross section, $\varphi(E_n)$ – neutron fluence.

In calculating of reaction rates (Calc.2): Neutron fluence was calculated using the program MCNPX. Values of the reaction cross sections for (n,γ) reactions were calculated by the program TALYS1.4 and for (n,fission) reactions are taken from the TENDL-2009.

Dependence of reaction rates on the deuteron energy for (n,fission) and (n,γ) reactions





Calc.1
2 GeV, E/C = 0.77(8)
4 GeV, E/C = 1.00(7)
8 GeV, E/C = 0.90(4)

Calc.2
E/C = 0.71(7)
E/C = 0.85(6)
E/C = 0.93(5)

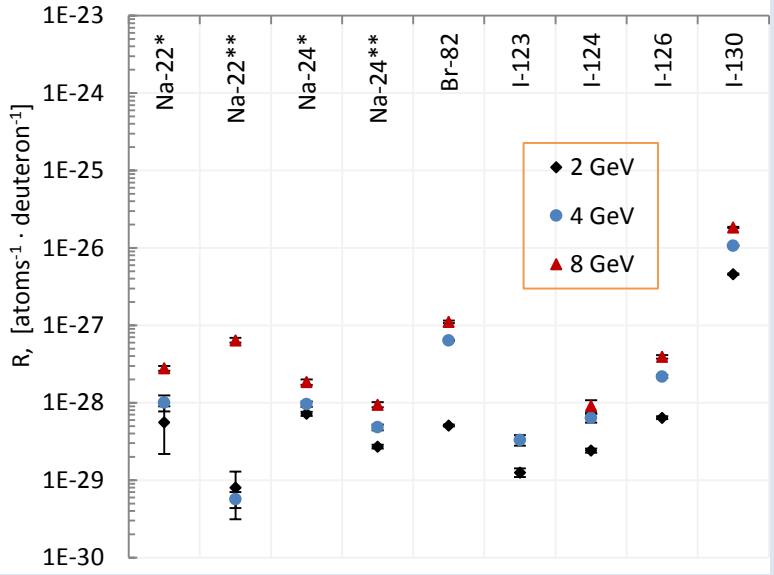
Calc.2
2 GeV, E/C = 1.04(6)
4 GeV, E/C = 1.00(2)
8 GeV, E/C = 1.36(7)

Results of I-129 and I-127

Data for samples I-129 and I-127						
Samples	I-129a	I-127a	I-129b	I-127b	I-129c	I-127c
Mass (I-129), g.	0.591	-	0.339	-	0.218	-
Mass (I-127), g.	0.129	1.550	0.074	1.270	0.048	1.980
Mass (Na-23), g.	0.118	0.290	0.067	0.230	0.043	0.360
Mass (Al-27), g.	17.6	-	17.6	-	17.6	-
Diameter of samples, sm	2.1	2.0	2.1	2.0	2.1	2.0

Samples 129I were coated aluminum weighing 17.6 g
Samples 127I were in the shell made of plexiglass weighing 2.53 g

In calculating of reaction rates (Calc.2):
Values of the reaction cross sections for I-127 are calculated with TALYS1.4
Values of the reaction cross sections for I-129 to 40 Mev neutron energy are taken from the TENDL-2011 and above 40 to 200 MeV were calculated with TALYS1.4



Reaction rates for the product nuclei in the samples I-129

Na-22* - $^{23}Na(n,2n)^{22}Na$

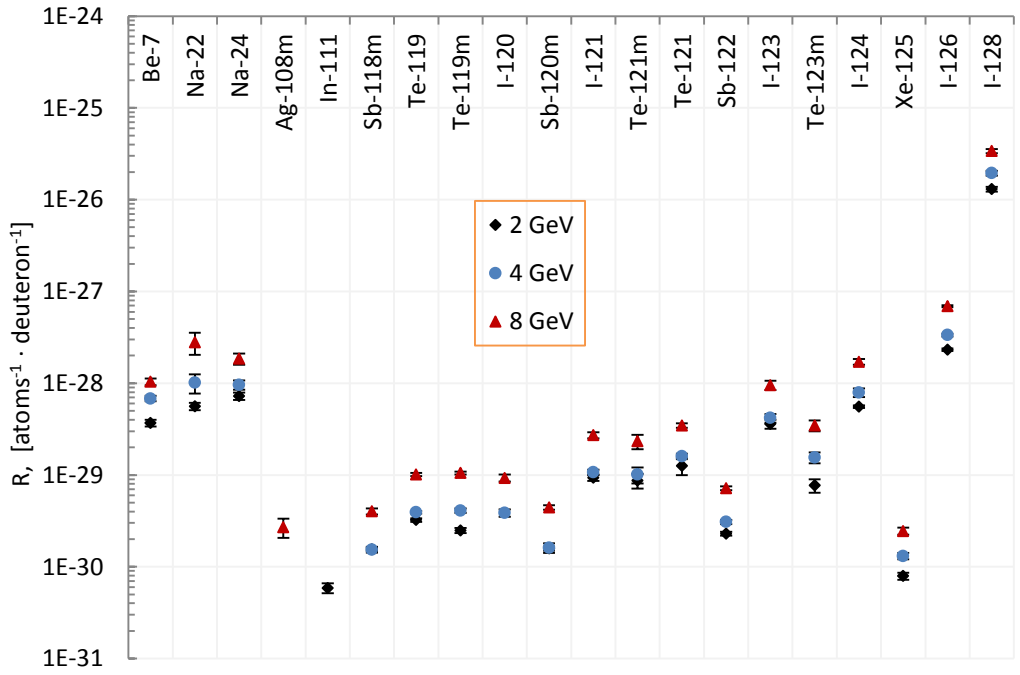
Na-22** - $^{27}Al(n,\alpha 2n)^{22}Na$

Na-24* - $^{23}Na(n,\gamma)^{24}Na$

Na-24** - $^{27}Al(n,\alpha)^{24}Na$

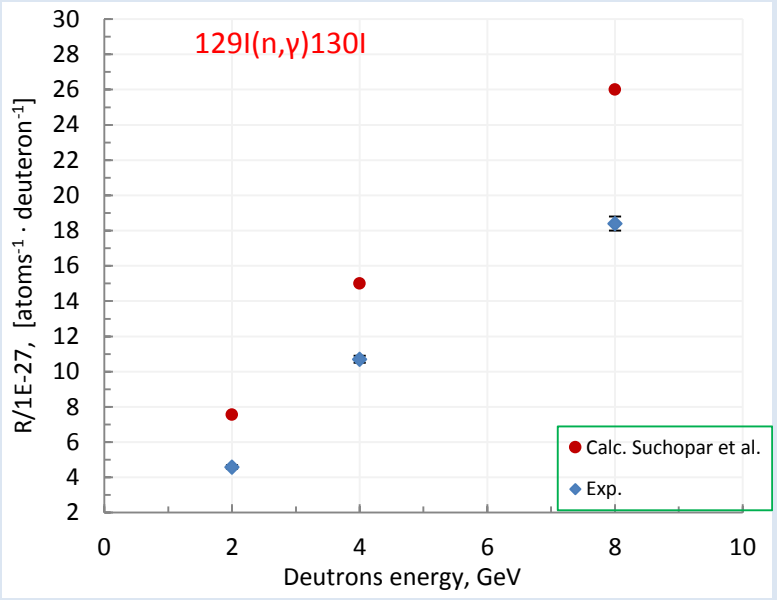
$^{81}Br(n,\gamma)^{82}Br$

Admixture of ^{81}Br by our estimates (Calc.2) no more than 1.5(5)%



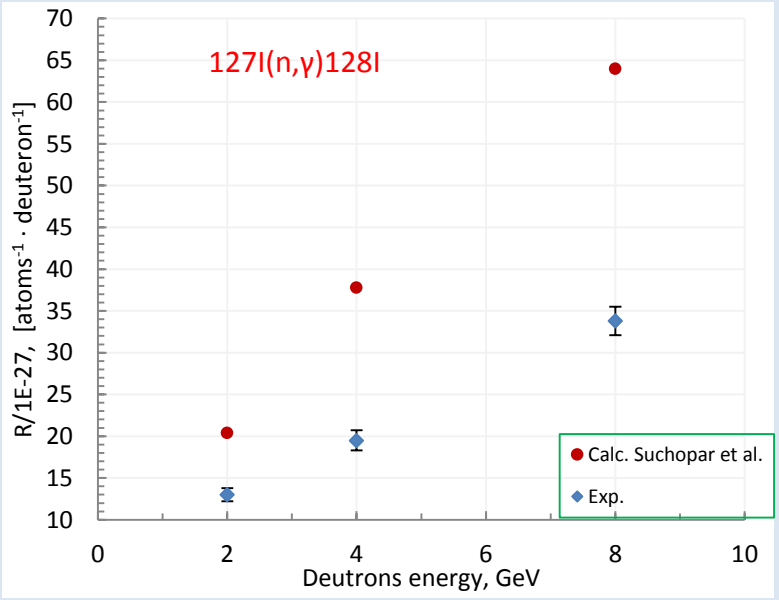
Reaction rates for the product nuclei in the samples I-127

Residual nuclei	Nuclear reactions	Threshold energy, MeV
I-126	(n,2n)	9.2
I-124	(n,4n)	26.0
I-123	(n,5n)	33.6
I-121	(n,7n)	51.5
I-120	(n,8n)	62.2
Te-123m	(n,t2n)	23.0
Te-121	(n,t4n)	39.9
Te-119	(n,t6n)	57.6
Sb-122	(n,α2n)	11.2
Sb-120m	(n,α4n)	27.4
Sb-118m	(n,α6n)	44.1



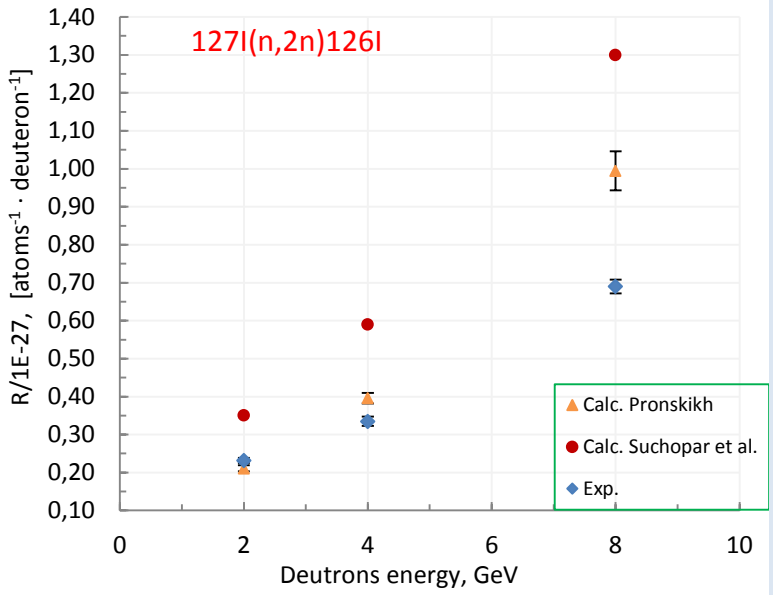
Dependence of the (n,γ) reaction rates of the energy deuterons in the samples I-129

Calc.2
2 GeV, E/C = 0.61(1)
4 GeV, E/C = 0.71(1)
8 GeV, E/C = 0.71(1)



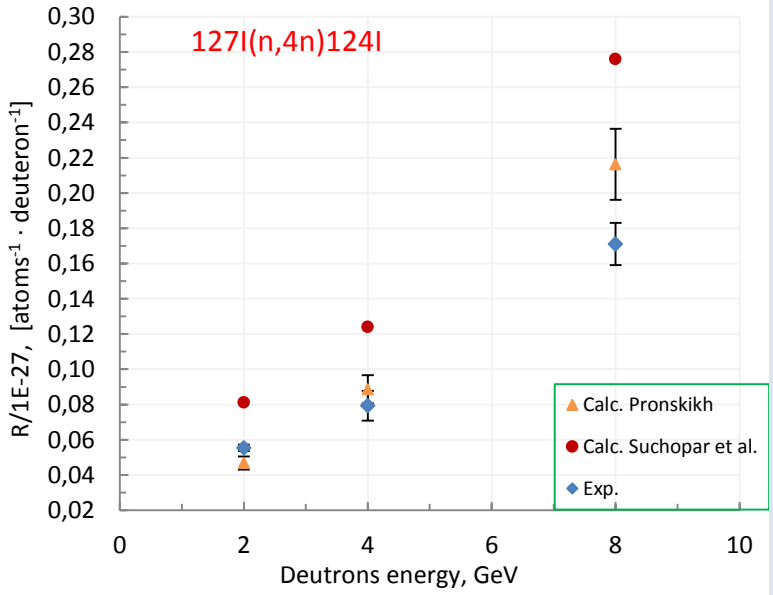
Dependence of the (n,γ) reaction rates of the energy deuterons in the samples I-127

Calc.2
2 GeV, E/C = 0.64(4)
4 GeV, E/C = 0.52(3)
8 GeV, E/C = 0.53(3)



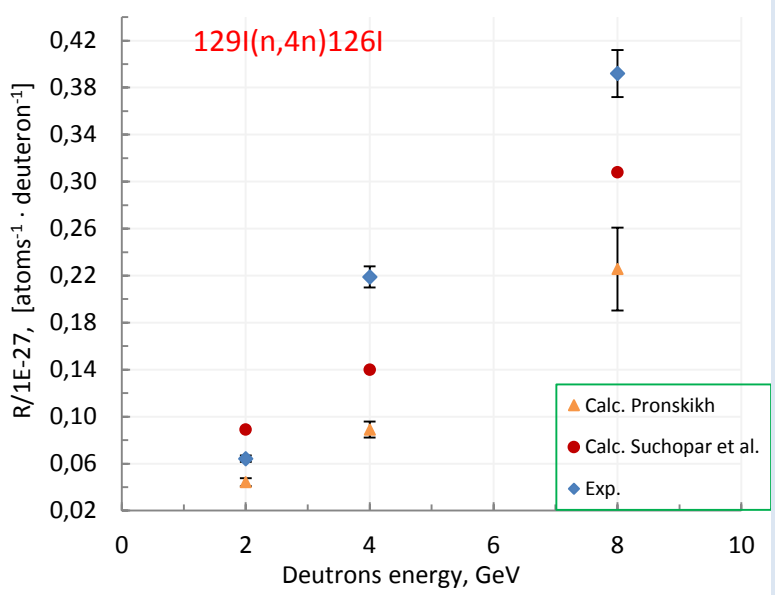
Dependence of the (n,2n) reaction rates of the energy deuterons in the samples I-127

	Cal.1.	Cal.2.
2 GeV,	E/C = 1.10(4)	E/C = 0.66(2)
4 GeV,	E/C = 0.85(3)	E/C = 0.57(2)
8 GeV,	E/C = 0.69(3)	E/C = 0.53(1)



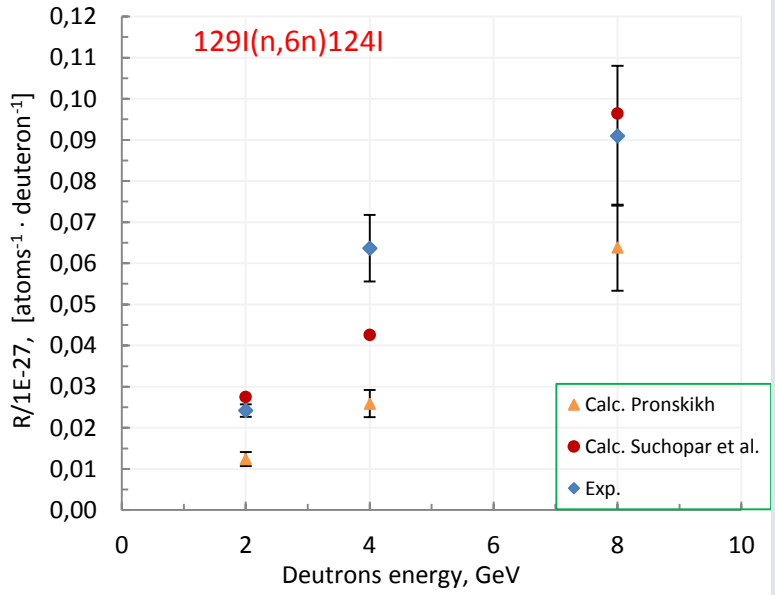
Dependence of the (n,4n) reaction rates of the energy deuterons in the samples I-127

	Cal.1.	Cal.2.
2 GeV,	E/C = 1.18(9)	E/C = 0.68(2)
4 GeV,	E/C = 0.89(8)	E/C = 0.64(7)
8 GeV,	E/C = 0.79(7)	E/C = 0.62(4)



Dependence of the (n,4n) reaction rates of the energy deuterons in the samples I-129

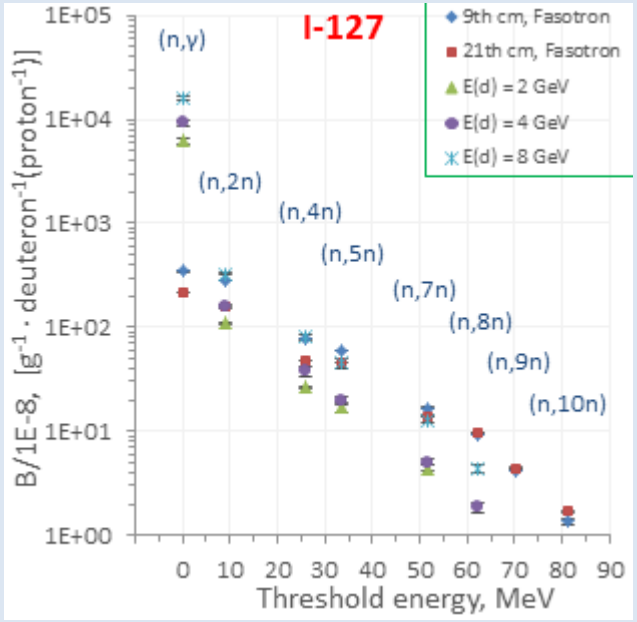
	Cal.1.	Cal.2.
2 GeV,	E/C = 1.45(12)	E/C = 0.72(3)
4 GeV,	E/C = 2.46(17)	E/C = 1.56(6)
8 GeV,	E/C = 1.74(27)	E/C = 1.27(6)

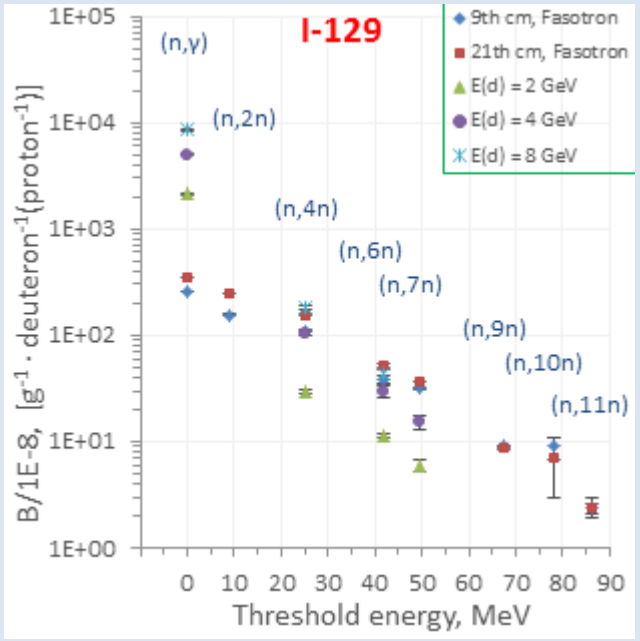


Dependence of the (n,6n) reaction rates of the energy deuterons in the samples I-129

	Cal.1.	Cal.2.
2 GeV,	E/C = 1.95(26)	E/C = 0.88(5)
4 GeV,	E/C = 2.49(32)	E/C = 1.49(19)
8 GeV,	E/C = 1.43(23)	E/C = 0.94(18)

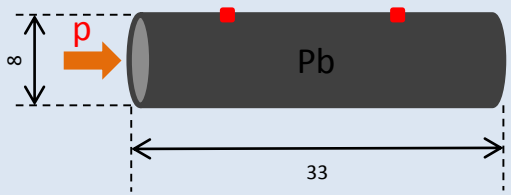
Comparison of the experimental results on ^{127}I and ^{129}I with previously measurement*





E(p) = 660 MeV, t(irr) = 10 min and integral number of protons ~ 1E+15

Four iodine samples were placed on top of the setup two samples at 9th cm and other two samples at 21st cm.



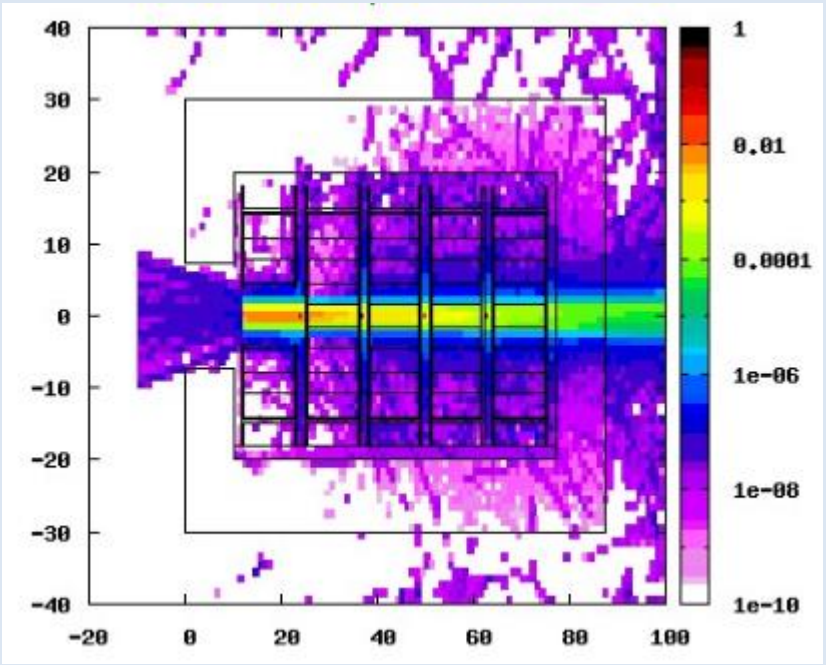
*M. Majerle et al. Spallation experiment on thick lead target: analysis of experimental data with Monte Carlo codes. Preprint JINR, E15-2008-94. Dubna, 2008, 20 p.

Preliminary results of a simulations by FLUKA to experiment E(d) = 8 GeV, December, 2012.

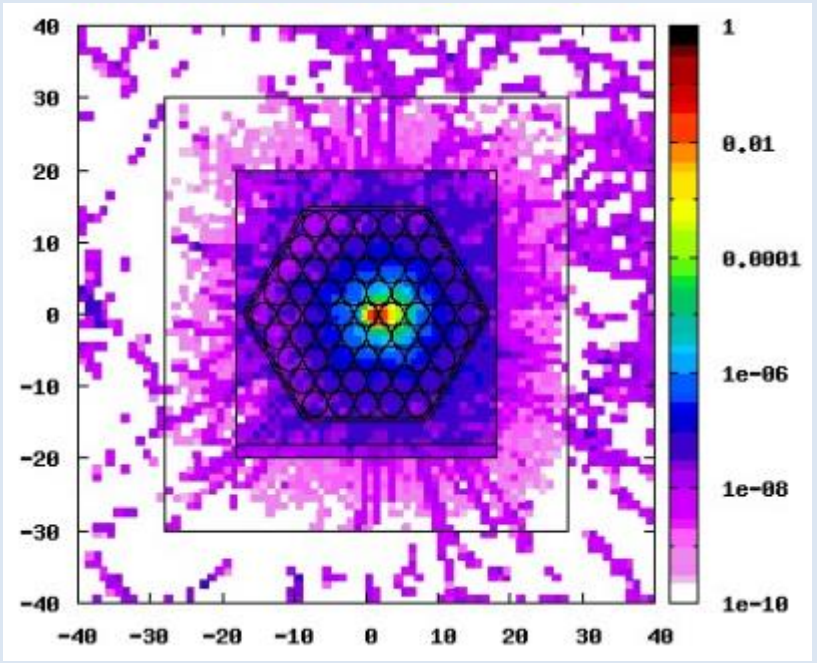
Number of primary particles – 300000 deuterons
Time of 5 cycle calculations – 4.5 d (Intel® Core™ i5-3470 CPU @ 3.20GHz)
Coordinates of the center of beam (plata0) Xc – 0.9(1), Yc – 0.1(1)
FWHMx – 1.0(1), FWHMy – 1.3(1)
Angle between the beam axis and z-axis – 2 degrees

Deuterons on setup "QUINTA"

(dimensions in cm, total fluence are normalized to particles/cm^2 per primary)



View from side



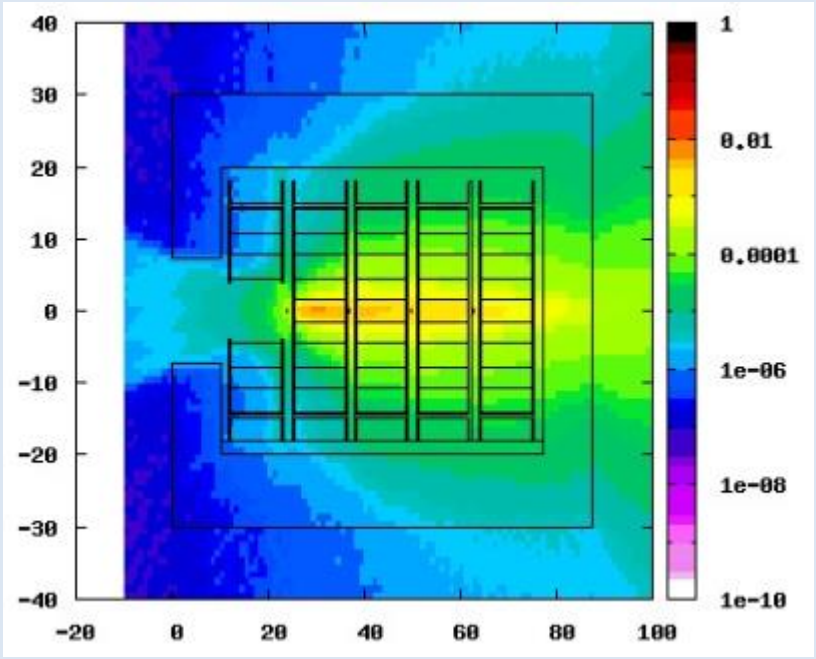
View from the front

Nuclear interaction models in FLUKA

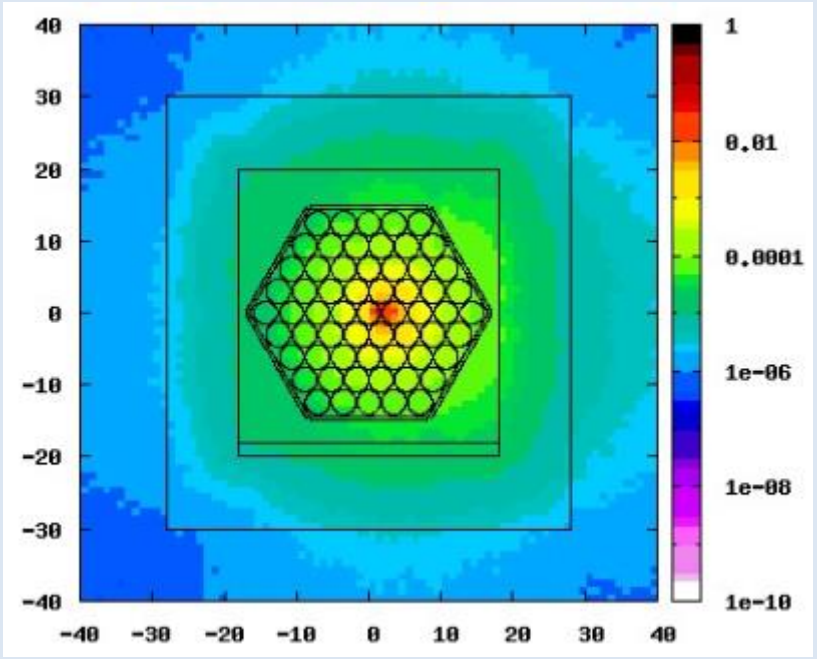
Dual Parton Model (DPM) – E > 5 GeV/n
Relativistic Quantum Molecular Dynamics Model (RQMD) – 0.1 GeV/n < E < 5 GeV/n
Boltzmann Master Equation (BME) theory – E < 0.1 GeV/n

Protons on setup "QUINTA"

(dimensions in cm, total fluence are normalized to particles/cm^2 per primary)



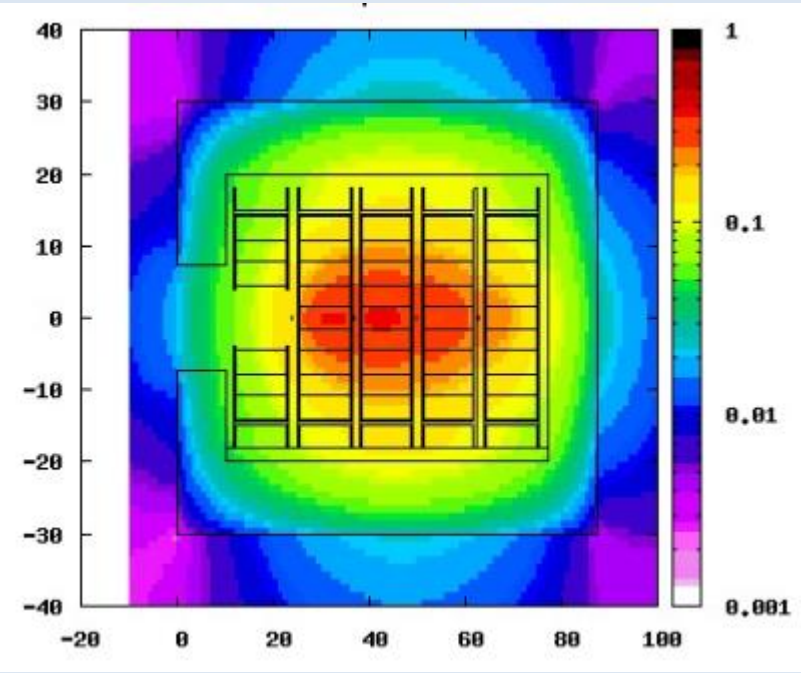
View from side



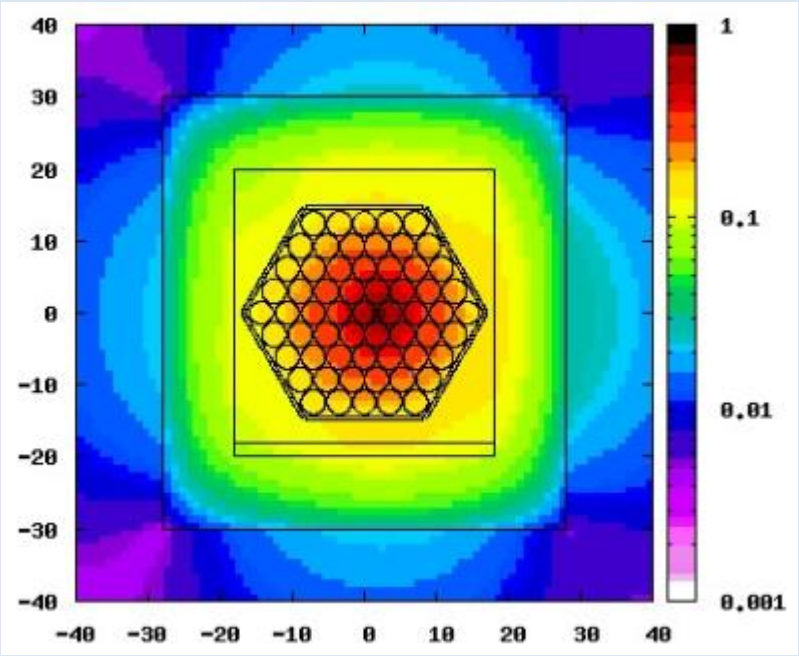
View from the front

Neutrons on setup “QUINTA”

(dimensions in cm, total fluence are normalized to particles/cm^2 per primary)



View from side



View from the front

THANKS
FOR
ATTENTION