

Neutron Physics and Radiation Materials Conference
Yerevan, Armenia
October 27-30, 2025

**Fundamental and applied research with
application of the Tagged neutron method in
FLNP JINR**



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On behalf of the TANGRA
collaboration

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The presented study is supported by the RSCF
grant No 23-12-00239

TANGRA collaboration

TAggered Neutrons & Gamma RAys

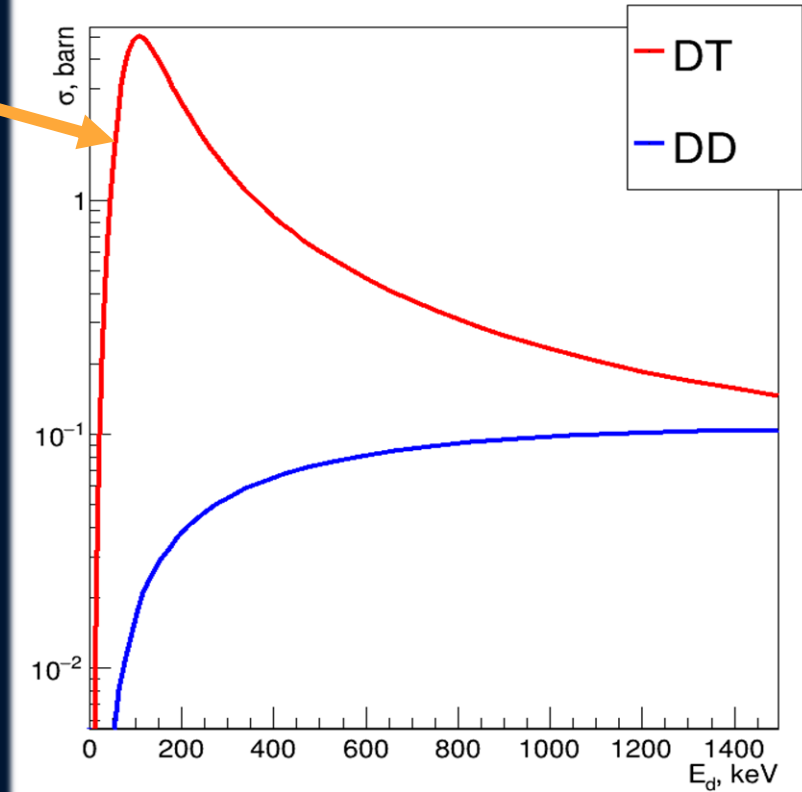
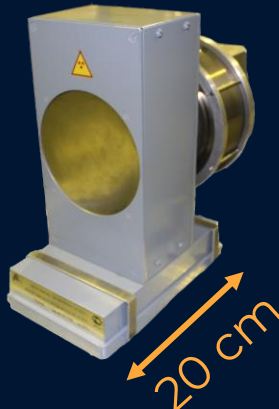
- An international collaboration 
- Main goals:
 - Nuclear reactions research using tagged neutron method (TNM): acquiring data for n and γ
 - Development of fast elemental analysis techniques
 - Theoretical description of processes under investigation
 - Software development for:
 - Data analysis
 - Nuclear database handling
 - Implementation of new theoretical approaches



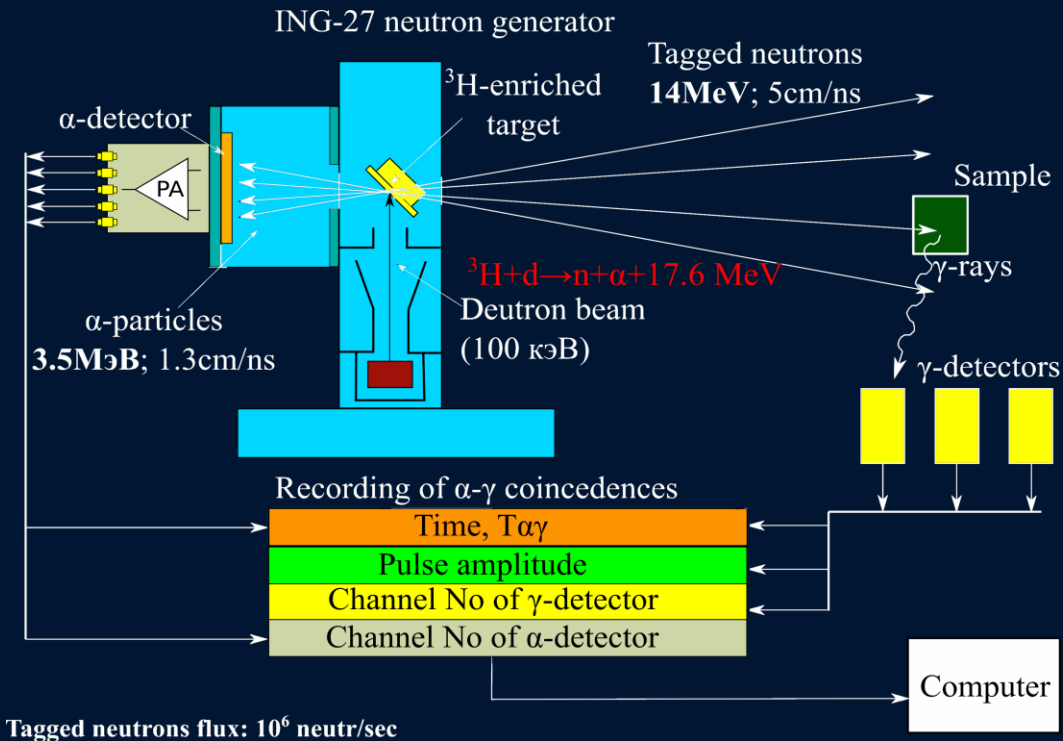


- **Features:**
- Low threshold
- High energy outcome
- Only two particles in products
- *Very suitable for neutron production*
- *Products move in opposite directions →*
- *Register one → determine direction for another!*

Portable neutron sources
with implementation of the
Tagged neutron method
(TNM)



Idea of the Tagged neutron method (TNM)

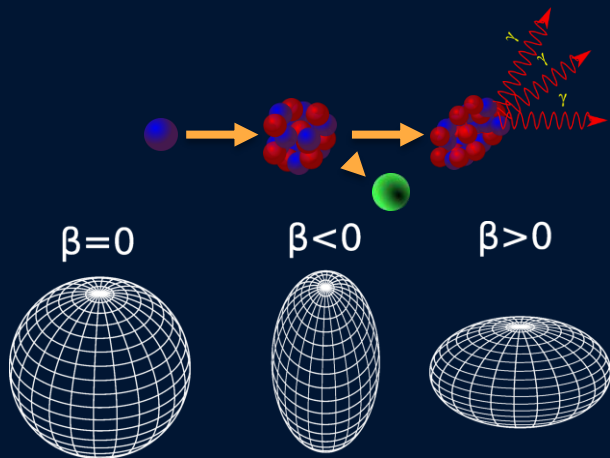


- + improves peak/background ratio
- + possible to determine all 3 spatial coordinates of reaction
- + NG is relatively cheap (~100 k\$)
- + Many neutron beams in one setup
- Limited lifetime
- Low tagged neutron flux

Interesting for nuclear reactions research:

- Angular distributions of n and γ
- Correlation between n and γ

Studying of neutron-induced reactions



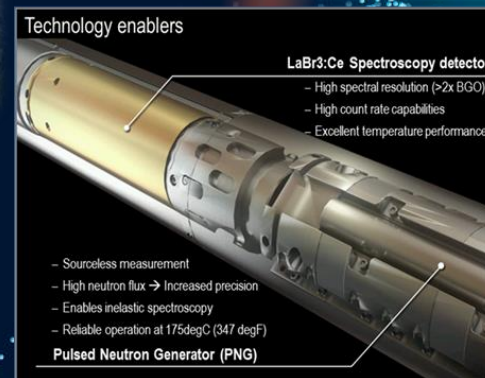
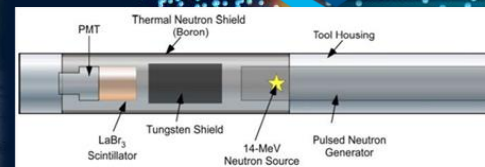
- (n,n') , $(n,2n)$, (n,p) and (n,α) reactions is a unique tool for nuclear structure and shape investigation
- Data needed to adjust parameters models for astrophysical calculations
- Acquiring more accurate data for applied research



- Prototype of soil analyzer

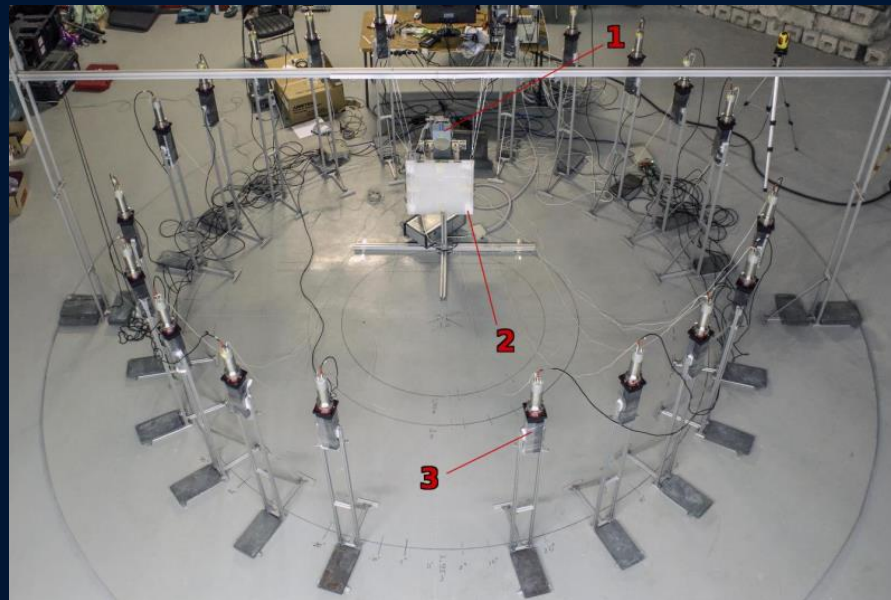


- Elemental analysis in space

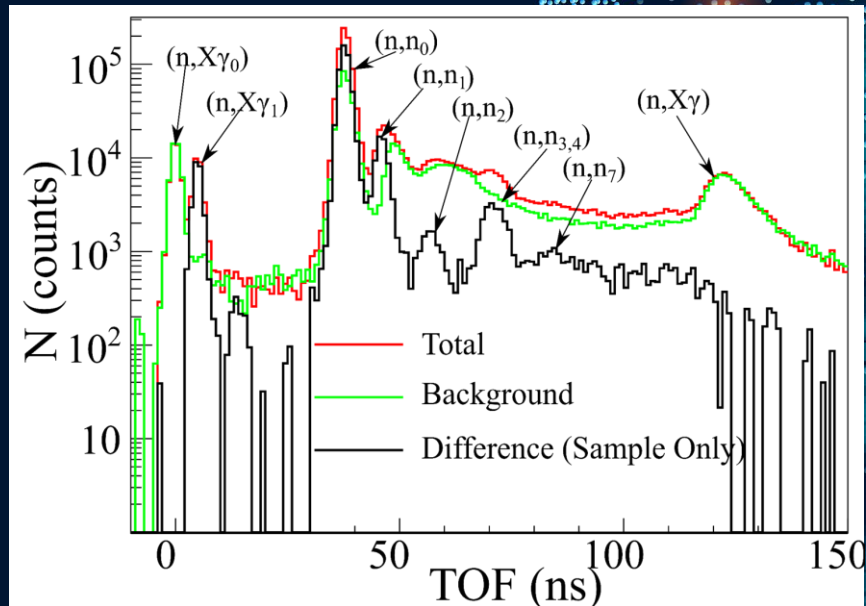


- Well logging

Measurements of the inelastic scattering cross-sections & angular distributions (Graphite sample)



- 1) NG-27 neutron generator
- 2) Graphite target
- 3) EJ200 n -detector



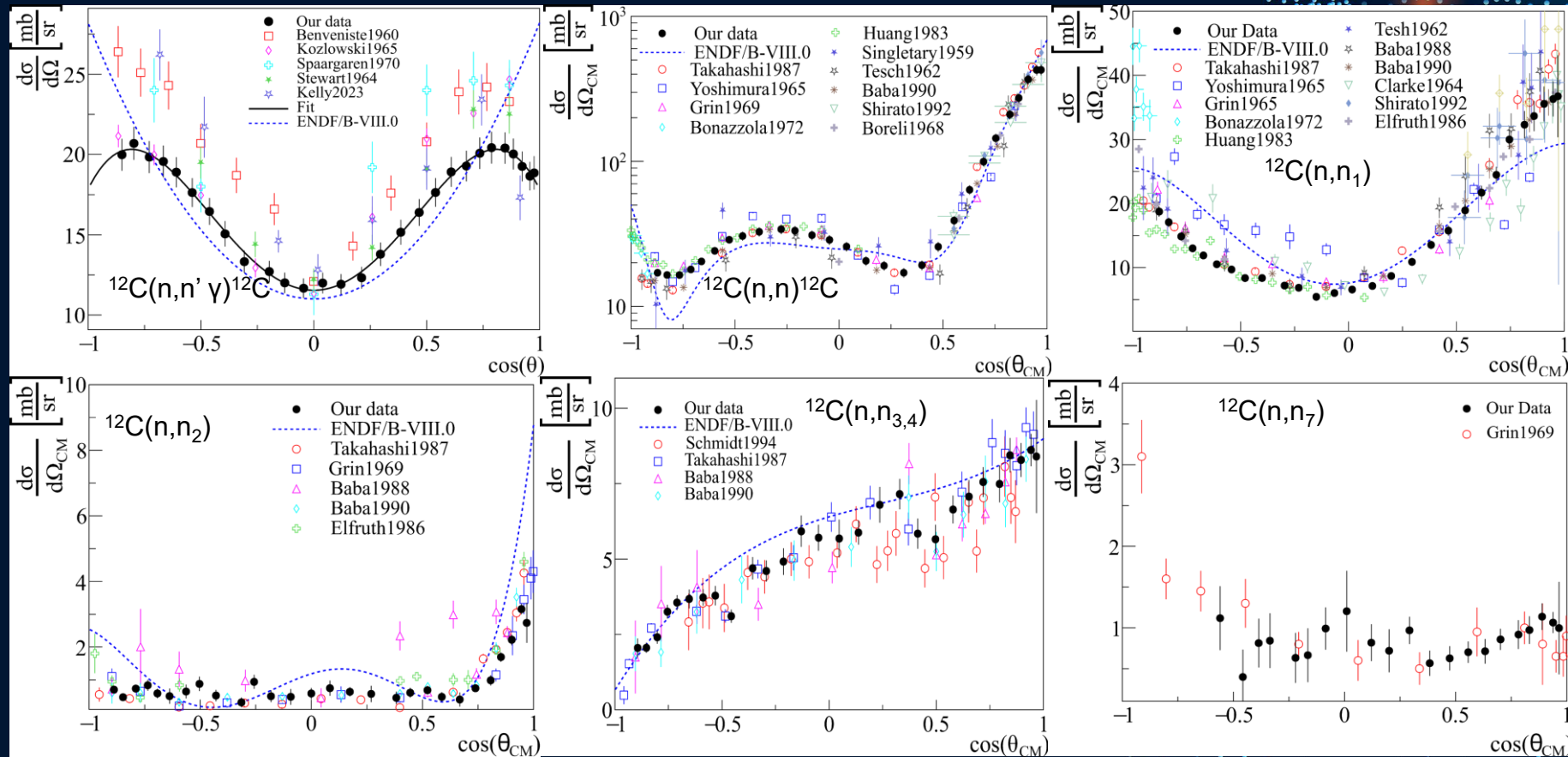
Spectrum components:

$(n, X\gamma_0)$, $(n, X\gamma_1)$ - γ -rays from (n, n') in ING and sample

(n, n_x) - elastic & inelastic scattering

$(n, X\gamma_1)$ - the wall of experimental hall

Measurements of the inelastic scattering cross-sections & angular distributions (Graphite sample)

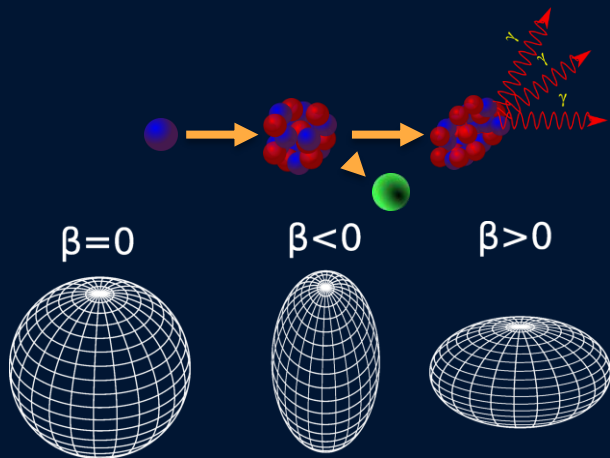


Measurements of the inelastic scattering cross-sections & angular distributions (Graphite sample)

References	Cross section (mb)							
	n_0	n_1	n_2	$n_{3,4}$	n_5	n_6	n_7	$(n,n')3\alpha$
This work	790 ± 6 1	192 ± 10 (n) 205 ± 11 (γ)	9.6 ± 0.7	66 ± 4	–	–	10.4 ± 0.7	86 ± 4 – $^{12}\text{C}(n, n_{2,3,4,7})$ this work; 55 ± 12 – $^{12}\text{C}(n, n_{5,6})$ from Grin*, 1969 141 ± 13 in total
ENDF/B-VIII.0	827	209	16	86	12	6.5	–	124
EAF-2010	–	–	–	–	–	–	–	270
FENDL-3.1b	801	182	0.9	12	2.7	3.1	3.3	22
JEFF-3.3	827	210	19.3	86	12	6.5	–	124.4
JENDL-4.0/HE	801	183	0.9	12	2.7	3.1	3.3	22

* G.A. Grin, B. Vaucher, J.C. Alder, C. Joseph, Helv. Phys. Acta 42, 990 (1969)

Studying of neutron-induced reactions



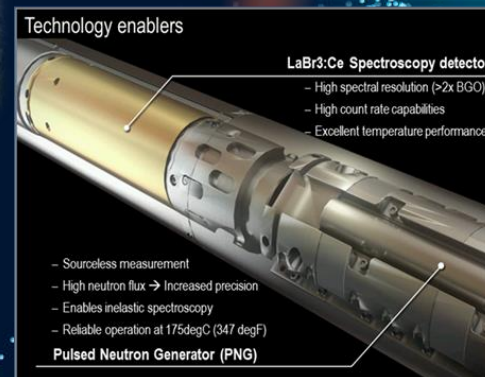
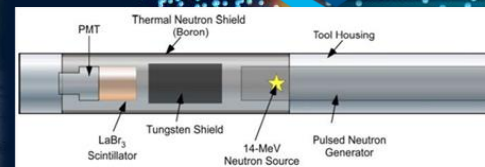
- (n,n') , $(n,2n)$, (n,p) and (n,α) reactions is a unique tool for nuclear structure and shape investigation
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- Prototype of soil analyzer



- Elemental analysis in space



- Well logging

What we know about (n,x γ)?



International Atomic Energy Agency

INDC(CCP)-413
Distr. G+RP



INDC

INTERNATIONAL NUCLEAR DATA COMMITTEE

STATUS OF EXPERIMENTAL AND EVALUATED DISCRETE γ -RAY PRODUCTION AT $E_n=14.5$ MeV

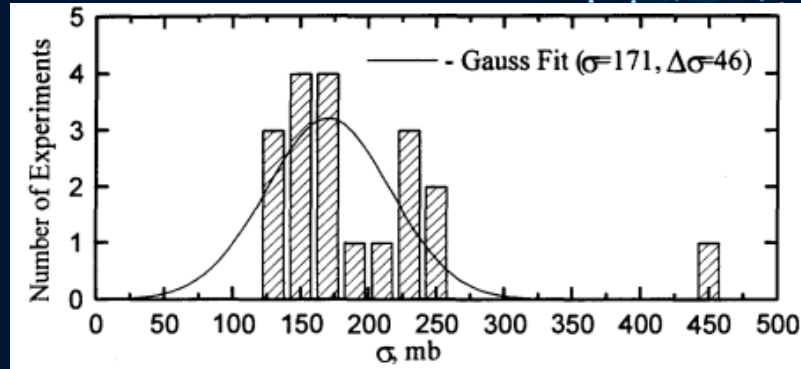
Final Report of Research Contract 7809/RB,
performed under the CRP on Measurement, Calculation
and Evaluation of Photon Production Data

S. P. Simakov¹, A. Pavlik², H. Vonach³, S. Hlaváč³

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²Institut für Radiumforschung und Kernphysik, University of Vienna, Austria

³Institute of Physics SAS, Bratislava, Slovakia



Discrepancy in two times!

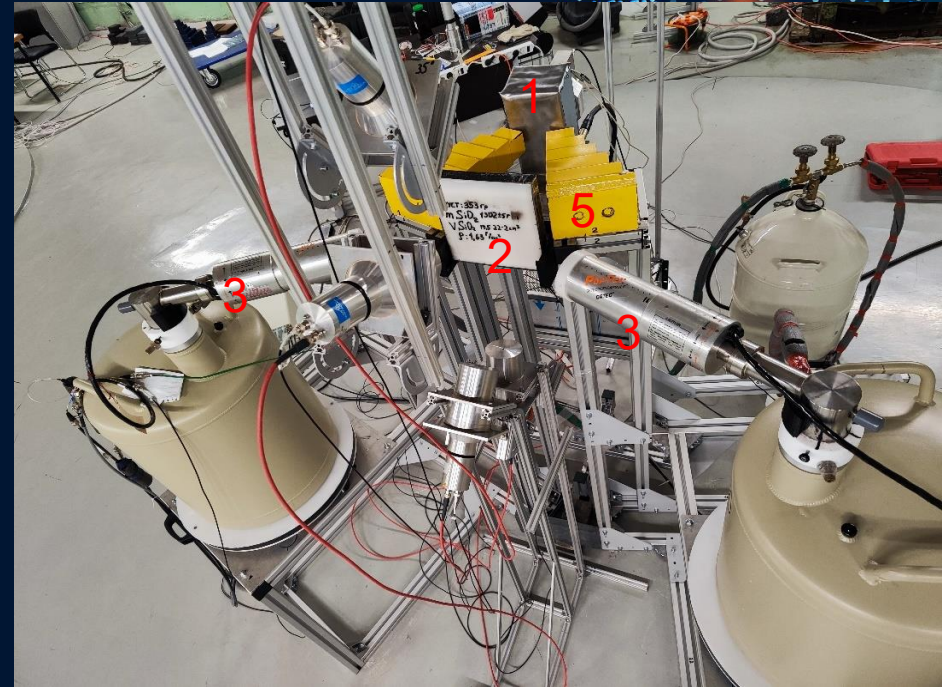
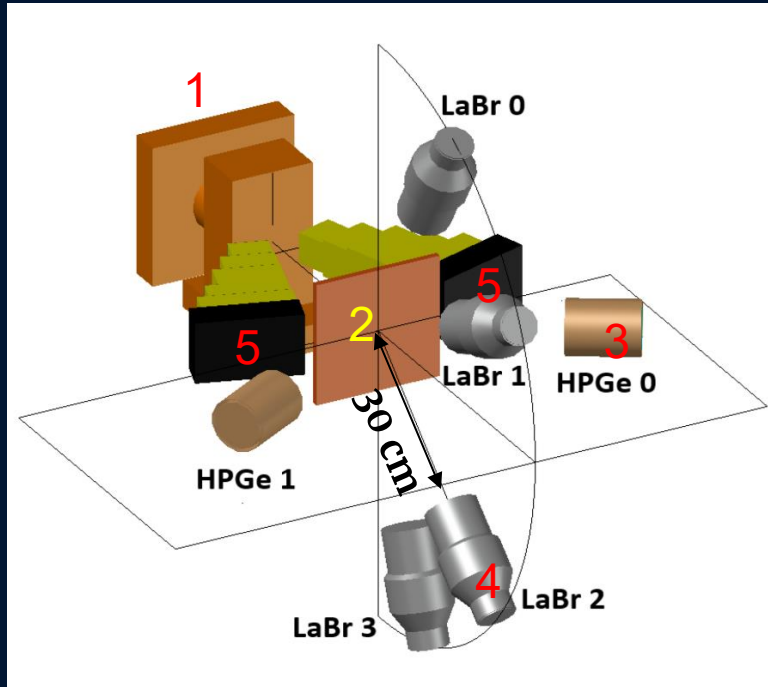
E γ	Reaction	Transition	E γ	Angle	Sample	Detect.	σ	Author	Publ	Correction	Corrected σ
4439	$^{12}\text{C}(n,n')^{12}\text{C}$	4439(2 $^+$) $\rightarrow$ 0(0 $^+$), p	14.1	30-150	$\varnothing 30\times\varnothing 26\times 70$, +/+	Ge	180 $\pm$ 7	Murata	1988	?	165 $\pm$ 7
			14.2	45-130	$\varnothing 44\times 6, \varnothing 31\times\varnothing 25\times 32$, +/+	Nal(Tl)	228 $\pm$ 30	Drake	1978	1.0	217 $\pm$ 30
			14.2	55	C: $\varnothing 30\times 40$, +/+	Ge(Li)	156 $\pm$ 28	Hino	1976	1.0	145 $\pm$ 28
			14	0-180	$\varnothing 60\times\varnothing 20$, +/-	Nal(Tl)	255 $\pm$ 26	Bezotosny	1976	1.0	237 $\pm$ 26
			14.2	125	C: $\varnothing 483\times\varnothing 279\times 25$, +/+	Ge(Li)	168 $\pm$ 20	Rogers	1975	1.0	157 $\pm$ 20
			14.2	45-125	No Information, +/+	Nal(Tl)	219 $\pm$ 29	Arthur	1975	1.0	208 $\pm$ 29
			14.1	90	C: $\varnothing 50\times 30$, +/+	Ge(Li)	121 $\pm$ 20	Clayeux	1969	1.0	115 $\pm$ 21
			14.2	0-180	Shell ??, +/+	Nalpair	163 $\pm$ 30	Maslov	1968	1.0	152 $\pm$ 30
			14	No Inf	C: $\varnothing 60\times 30$, +/+	Nal(Tl)	133 $\pm$ 17	Bezotosny	1966	1.0	115 $\pm$ 17
			14.1	30-160	C: $\varnothing 77\times 20$, +/+	Nal(Tl)	232 $\pm$ 18	Stewart	1964	1.0	217 $\pm$ 18
			=14	30-150	C: $\varnothing 165\times\varnothing 115\times 25$, +/+	Nal	249 $\pm$ 28	Benveniste	1960	1.0	230 $\pm$ 28

IAEA NUC

2

- The most complete set of (n,x γ) cross-sections
- Reason: something wrong in absolute CS estimation

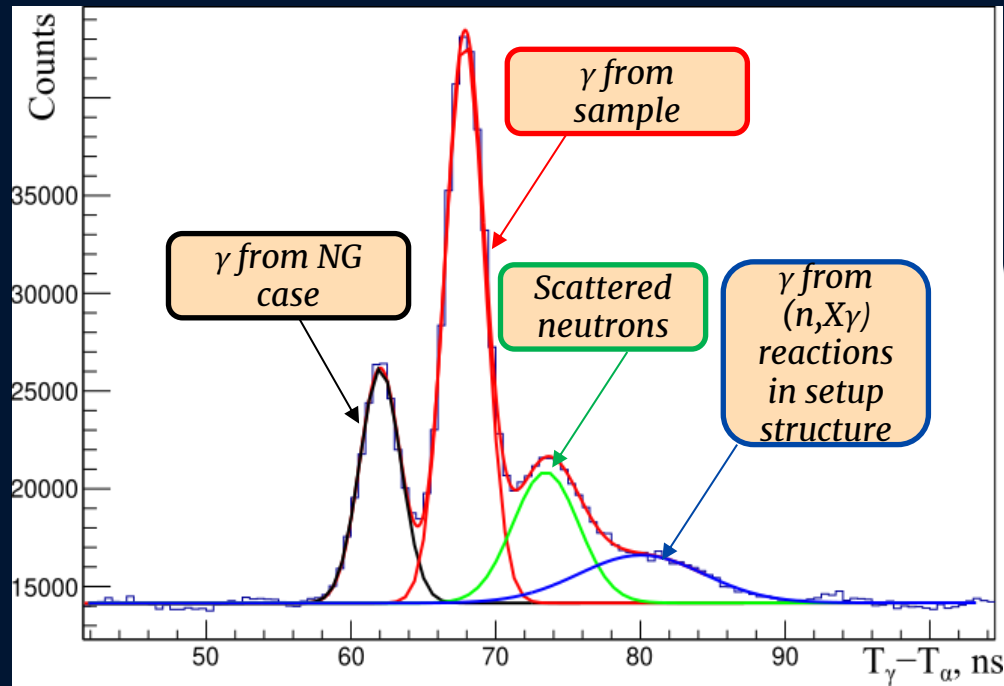
Measurements of the γ -quanta emission cross-sections & angular distributions



- 1) ING-27 neutron generator
- 2) sample 20×20×X cm
- 3) HPGe γ -detector (2 pcs, 60% eff)

- 4) LaBr₃ γ -detector (4 pcs)
+ Fast measurement
- Extreme detector load ($\sim 8 \times 10^4$ cps)

Data processing with TNM

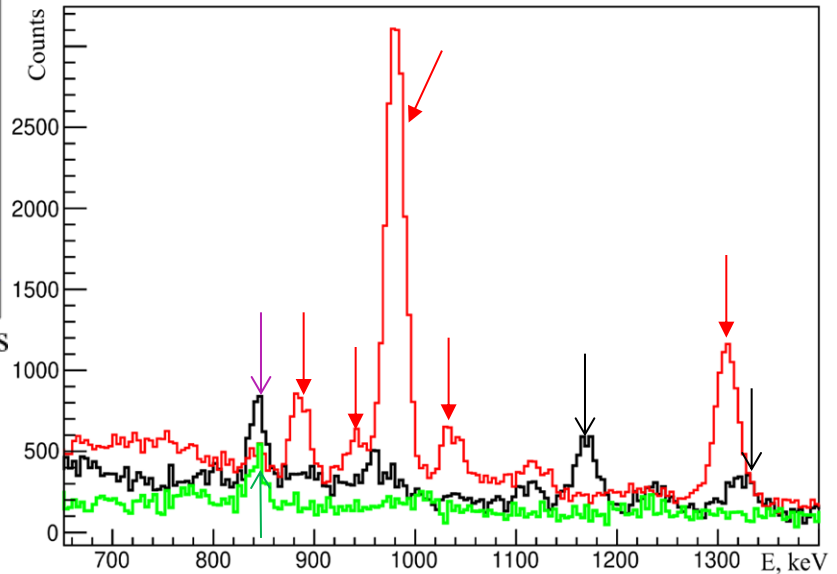


Main idea – separation of the background events by TOF

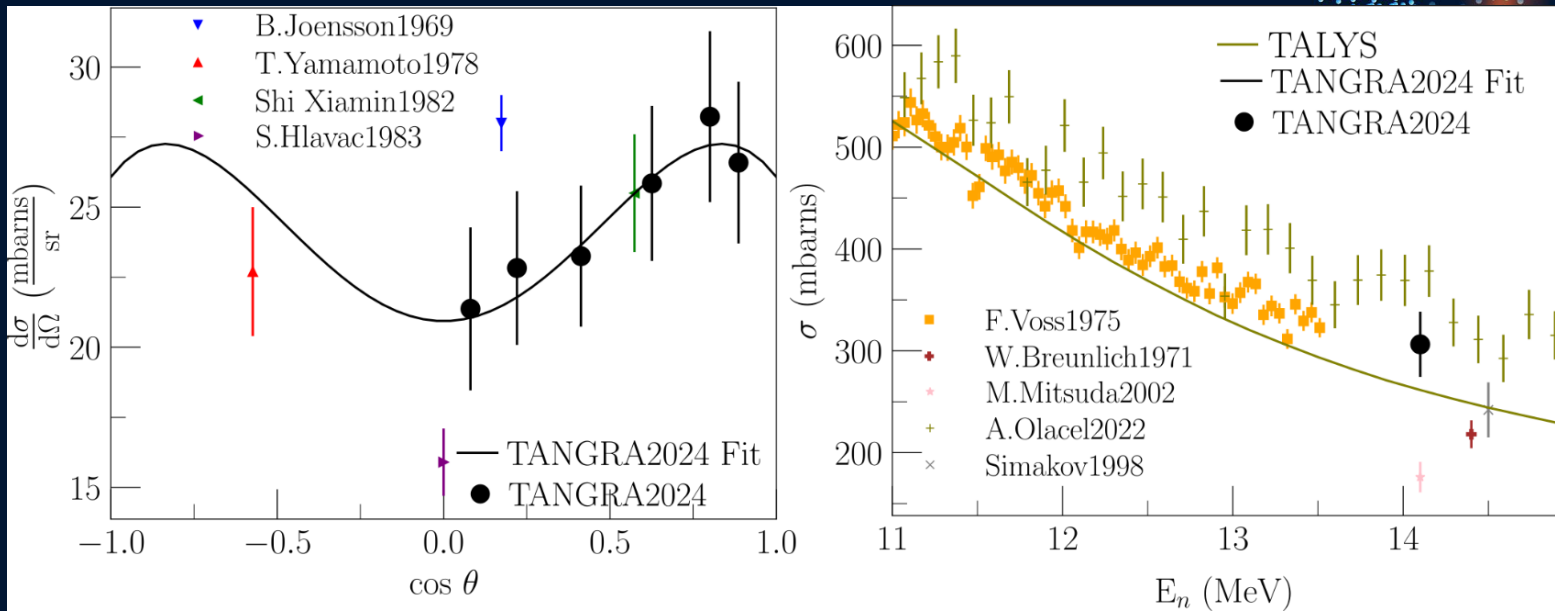
Spectrum below shows impact of different components to sum spectrum.

Peaks from sample marked with red arrows

Comparison of TOF components



Measurements of the γ -quanta emission cross-sections & angular distributions (Ni_2O_3 sample)



$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi} \sum_{l=0,2,4,\dots}^{2J} P_l(\cos(\theta))$$

E_γ , keV	Reaction	Reference	σ , mb	a_2	a_4
1454 keV	$^{58}\text{Ni}(n,n')$	Voss1975	323 ± 10	-	-
		Olcel 2022	378 ± 25	-	-
		TANGRA 2024	306 ± 32	0,19(2)	0,12(3)

Current status of measurements

ПЕРИОДЫ	ГРУППЫ																
	А I В	А II В	А III В	А IV В	А V В	А VI В	А VII В	А	VIII В								В
1	H 1,0079 1s ¹ Водород						H	He 4,00260 1s ² Гелий	Относительная атомная масса Порядковый (атомный) номер Символ Название Конфигурация валентных электронов Распределение электронов по уровням H 1,0079 1s¹ Водород								
2	Li 6,941 2s ¹ Литий	Be 9,01218 2s ² Бериллий	B 10,81 2s ² 2p ¹ Бор	C 12,011 2s ² 2p ² Углерод	N 14,007 2s ² 2p ³ Азот	O 15,9994 2s ² 2p ⁴ Кислород	F 18,9984 2s ² 2p ⁵ Фтор	Ne 20,179 2s ² 2p ⁶ Неон									
3	Na 22,9897 3s ¹ Натрий	Mg 24,305 3s ² Магний	Al 26,9815 3s ² 3p ¹ Алюминий	Si 28,086 3s ² 3p ² Кремний	P 30,9738 3s ² 3p ³ Фосфор	S 32,06 3s ² 3p ⁴ Сера	Cl 35,453 3s ² 3p ⁵ Хлор	Ar 39,948 3s ² 3p ⁶ Аргон									
4	K 39,0983 4s ¹ Калий	Ca 40,08 4s ² Кальций	Sc 44,956 3d ¹ 4s ² Скандий	Ti 47,88 3d ² 4s ² Титан	V 50,942 3d ³ 4s ² Ванадий	Cr 52,00 3d ⁵ 4s ¹ Хром	Mn 54,94 3d ⁵ 4s ² Марганец	Fe 55,845 3d ⁶ 4s ² Железо	Co 58,933 3d ⁷ 4s ² Кобальт	Ni 58,69 3d ⁸ 4s ² Никель							
	Cu 63,546 4s ¹ 3d ¹⁰ Медь	Zn 65,38 4s ² 3d ¹⁰ Цинк	Ga 69,72 4s ² 3d ¹⁰ 4p ¹ Галлий	Ge 72,63 4s ² 3d ¹⁰ 4p ² Германий	As 74,92 4s ² 3d ¹⁰ 4p ³ Мышьяк	Se 78,96 4s ² 3d ¹⁰ 4p ⁴ Селен	Br 79,904 4s ² 3d ¹⁰ 4p ⁵ Бром	Kr 83,80 4s ² 3d ¹⁰ 4p ⁶ Криптон									
5	Rb 85,4678 5s ¹ Рубидий	Sr 87,62 5s ² Стронций	Y 88,906 4d ¹ 5s ² Иттрий	Zr 91,224 4d ² 5s ² Цирконий	Nb 92,906 4d ⁴ 5s ¹ Ниобий	Mo 95,94 4d ⁵ 5s ¹ Молибден	Tc 98,906 4d ⁵ 5s ² Технеций	Ru 101,07 4d ⁷ 5s ¹ Рутений	Rh 102,905 4d ⁸ 5s ¹ Родий	Pd 106,42 4d ¹⁰ 5s ⁰ Палладий							
	Ag 107,868 5s ¹ 4d ¹⁰ Серебро	Cd 112,41 5s ² 4d ¹⁰ Кадмий	In 114,82 5s ² 4d ¹⁰ 5p ¹ Индий	Sn 118,71 5s ² 4d ¹⁰ 5p ² Олово	Sb 121,76 5s ² 4d ¹⁰ 5p ³ Сурьма	Te 127,60 5s ² 4d ¹⁰ 5p ⁴ Теллур	I 126,905 5s ² 4d ¹⁰ 5p ⁵ Йод	Xe 131,29 5s ² 4d ¹⁰ 5p ⁶ Ксенон									
6	Cs 132,905 6s ¹ Цезий	Ba 137,33 6s ² Барий	La 138,905 5d ¹ 6s ² Лантан	Ce 140,12 5d ¹ 6s ² Церий	Pr 140,908 5d ¹ 6s ² Прометий	Nd 144,24 5d ² 6s ² Неодим	Pm 144,913 5d ⁴ 6s ² Прометий	Sm 150,36 5d ⁶ 6s ² Самарий	Eu 151,96 5d ⁷ 6s ² Европий	Gd 157,25 5d ⁷ 6s ² Гадолиний	Tb 158,925 5d ⁹ 6s ² Тербий	Dy 162,50 5d ¹⁰ 6s ² Диспрозий	Ho 164,930 5d ¹⁰ 6s ² Гольмий	Er 167,26 5d ¹⁰ 6s ² Эрбий	Tm 168,934 5d ⁹ 6s ² Тулий	Yb 173,04 5d ¹⁰ 6s ² Иттербий	
	Au 196,967 5d ¹⁰ 6s ¹ Золото	Hg 200,59 5d ¹⁰ 6s ² Ртуть	Tl 204,383 6s ² 5d ¹⁰ 6p ¹ Таллий	Pb 207,2 6s ² 5d ¹⁰ 6p ² Свинец	Bi 208,98 6s ² 5d ¹⁰ 6p ³ Висмут	Po [209] 6s ² 5d ¹⁰ 6p ⁴ Полоний	At [210] 6s ² 5d ¹⁰ 6p ⁵ Астат	Rn [222] 6s ² 5d ¹⁰ 6p ⁶ Радон									
7	Fr [223] 7s ¹ Франций	Ra [226] 7s ² Радий	Ac [227] 6d ¹ 7s ² Актиний	Th [232] 6d ² 7s ² Торий	Pa [231] 5f ² 7s ² Протактиний	U [238] 5f ³ 7s ² Уран	Np [237] 5f ⁴ 7s ² Нептуний	Pu [244] 5f ⁶ 7s ² Плутоний	Am [243] 5f ⁷ 7s ² Америций	Cm [247] 5f ⁷ 7s ² Курций	Bk [247] 5f ⁹ 7s ² Берклий	Cf [251] 5f ¹⁰ 7s ² Калифорний	Es [252] 5f ¹¹ 7s ² Эйнштейний	Fm [257] 5f ¹² 7s ² Фермий	Md [288] 5f ¹³ 7s ² Менделевий	No [289] 5f ¹⁴ 7s ² Нобелий	
	Rg [280] Рентгений	Cn [285] Коперниций	Nh [286] Нихоний	Fl [289] Флеровий	Mc [288] Московский	Lv [293] Ливерморский	Ts [294] Теннессон	Og [294] Оганесон									

2024

2025

58 Ce 140,12 4f ¹ 6s ² Церий	59 Pr 140,908 4f ³ 6s ² Прометий	60 Nd 144,24 4f ⁴ 6s ² Неодим	61 Pm [145] 4f ⁵ 6s ² Прометий	62 Sm 150,36 4f ⁶ 6s ² Самарий	63 Eu 151,96 4f ⁷ 6s ² Европий	64 Gd 157,25 4f ⁷ 5d ¹ 6s ² Гадолиний	65 Tb 158,925 4f ⁹ 6s ² Тербий	66 Dy 162,50 4f ¹⁰ 6s ² Диспрозий	67 Ho 164,930 4f ¹¹ 6s ² Гольмий	68 Er 167,26 4f ¹² 6s ² Эрбий	69 Tm 168,934 4f ¹³ 6s ² Тулий	70 Yb 173,04 4f ¹⁴ 6s ² Иттербий	71 Lu 174,967 4f ¹⁴ 5d ¹ 6s ² Лютеций
90 Th 232,038 6d ² 7s ² Торий	91 Pa [231] 5f ² 6d ¹ 7s ² Протактиний	92 U [238] 5f ³ 6d ¹ 7s ² Уран	93 Np [237] 5f ⁴ 6d ¹ 7s ² Нептуний	94 Pu [244] 5f ⁶ 7s ² Плутоний	95 Am [243] 5f ⁷ 7s ² Америций	96 Cm [247] 5f ⁷ 6d ¹ 7s ² Курций	97 Bk [247] 5f ⁹ 6d ¹ 7s ² Берклий	98 Cf [251] 5f ¹⁰ 7s ² Калифорний	99 Es [252] 5f ¹¹ 7s ² Эйнштейний	100 Fm [257] 5f ¹² 7s ² Фермий	101 Md [288] 5f ¹³ 7s ² Менделевий	102 No [289] 5f ¹⁴ 7s ² Нобелий	103 Lr [262] 5f ¹⁴ 6d ¹ 7s ² Лоуренсий

Crucial advantage of TNM – direct count of neutrons

Conclusion

- 10 years of the TANGRA project operation demonstrate successful application of NG for fundamental & applied research
- There are still a lot of work: measure more nuclides, validate already available data (*and our data*), implement developed theoretical approaches
- There is a lot of challenges in developing applications of TNM in industry. Our data is helpful to estimate sensitivity of TNM-based approaches for different materials.

THANKS!



Backup

- Here the important materials about data processing are stored. They were not included in main presentation because of lack of time.
- Don't hesitate to ask me about that!

Cross section calculation

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{N_p \cos \xi}{4\pi N_\alpha n_{at} k} 10^{27} \left[\frac{\text{mbarns}}{\text{sr}} \right]$$

Area of γ -peak

Incident angle

Number of tagged neutrons

Surface density of atoms in the sample

$$\sigma = 2\pi \int_{-1}^1 \frac{d\sigma}{d\Omega}(\cos\theta) d\cos\theta$$

Total reaction cross section

- The features of the experimental approach are the close geometry and the quite large sample
- All corrections changed significantly depending on the target thickness
- We could not consider the various correction independently

$$k = \int_0^{x_0} \varepsilon(x) k_{ms}(x) k_{satt}(x) k_{iatt}(x) dx$$

Multiple inelastic scattering

Attenuation of incident neutron

Attenuation of γ -rays

Sample thickness

The total efficiency

Algorithm for determining the correction factor

There are two ways to calculate corrections:

- To calculate them independently in dependence on the sample thickness and take the integral
- **To simulate the total thickness-integrated correction in the GEANT4 using a separate ones as weighting factors**

Correction features:

- Multiple inelastic scattering overstates the number of emitted γ -rays
- Attenuation of incident neutrons and γ -rays understates the number of emitted γ -rays

Simulation features:

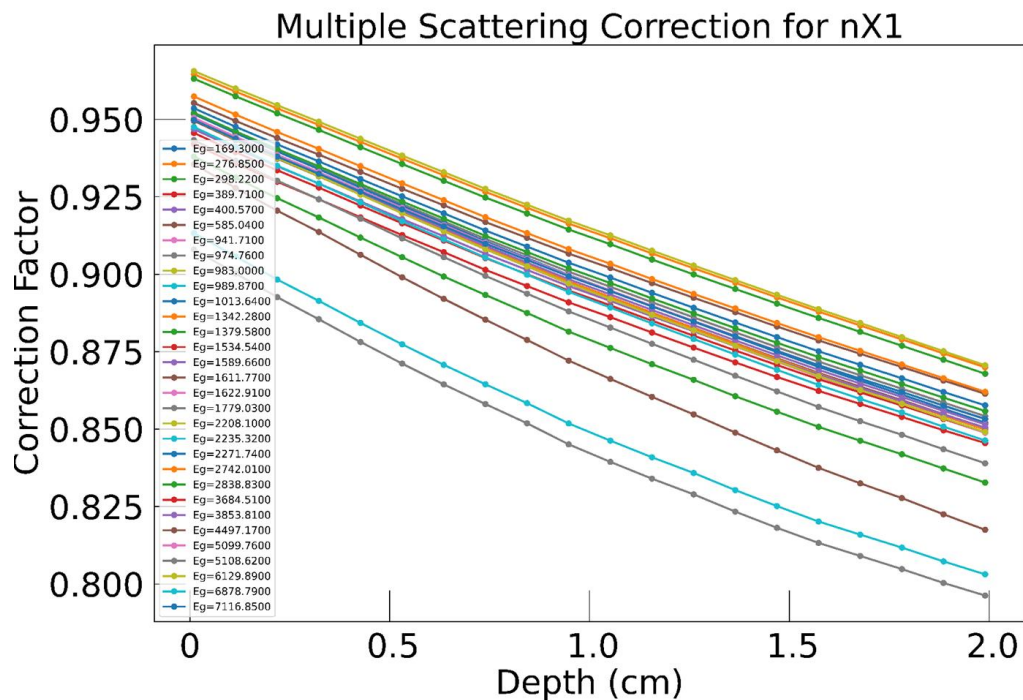
- 2 stage - neutron transport and γ -rays transport simulation
- The inelastic multiple scattering is used as a probability factor increasing the number of emitted γ -rays in comparison with its real number
- The inelastic multiple scattering correction calculates taking into account the energy dependence of emission cross section for specific γ -line taken from TALYS for each interaction point
- The correction factor resulted included thickness-integrated multiple scattering, absorption and efficiency coefficients

Simulation of the interaction point and neutron spectra depending on thickness

Calculation of the inelastic multiple scattering correction depending on the thickness

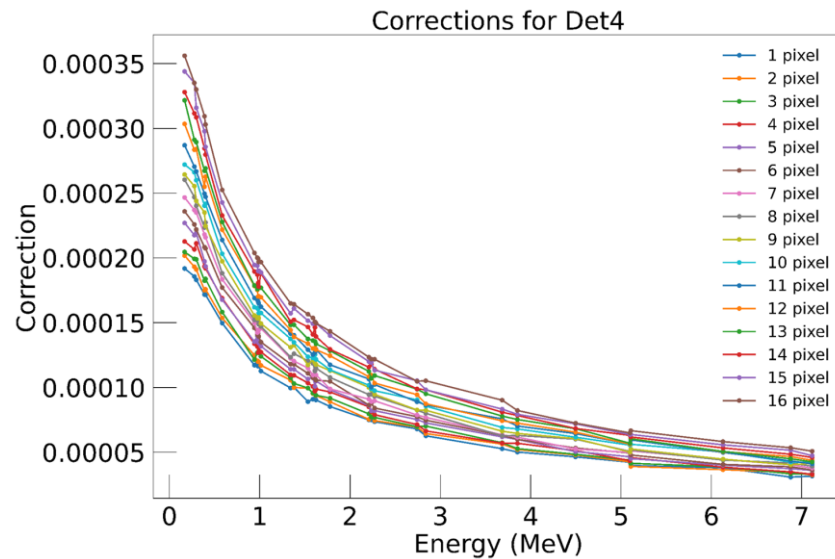
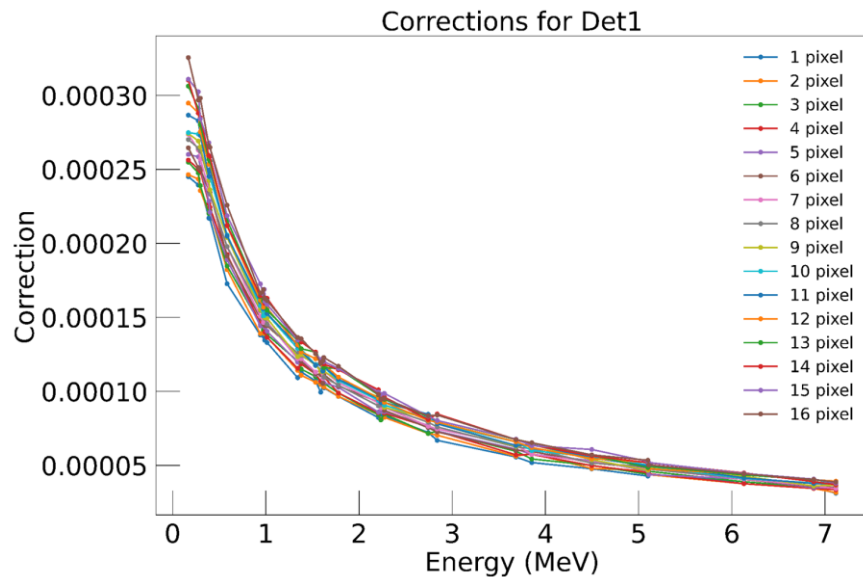
Simulation of γ -rays detection efficiency emitting them from the interaction points

Example of the multiple scattering correction



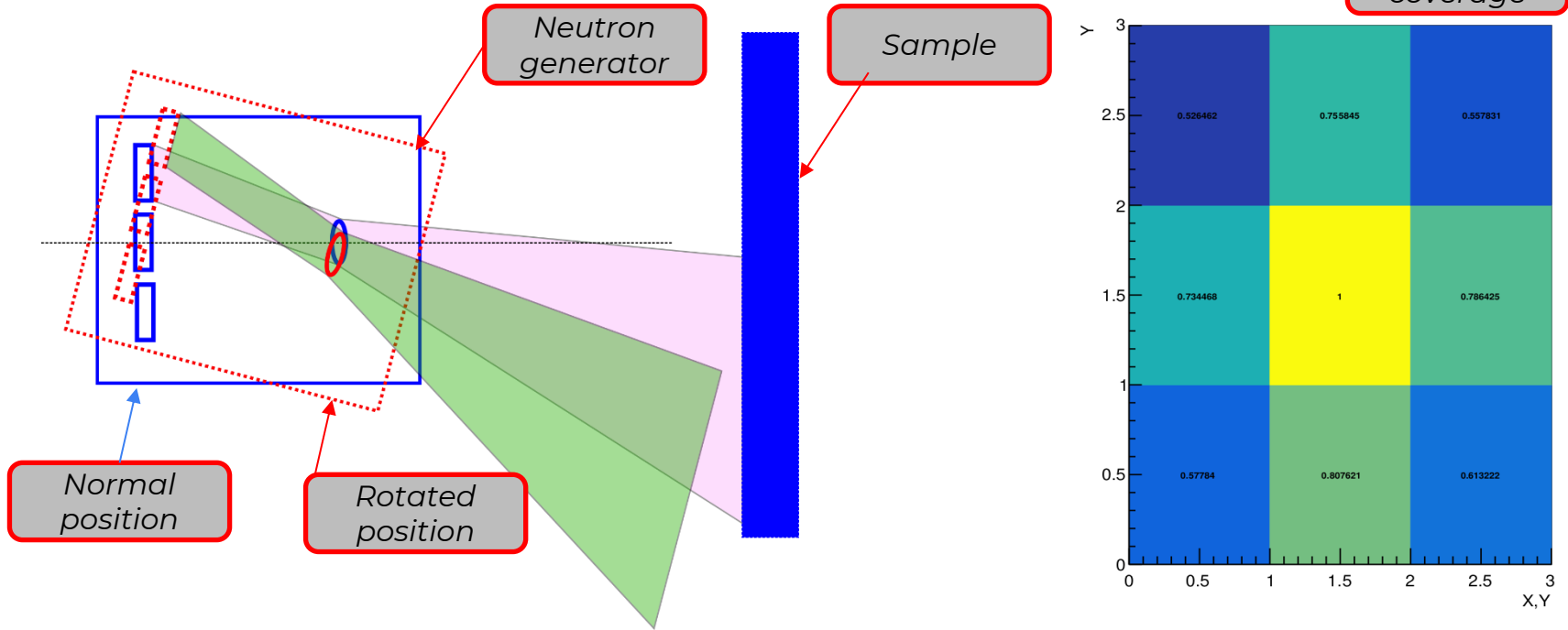
Multiple scattering correction factor depending on the sample thickness. The example corresponding to the SiO_2 sample and first vertical strip

Integrated correction factors using the example of the SiO_2 sample



The correction factors including the attenuation correction, total efficiency and multiple inelastic scattering corresponding to the various LaBr_3 detectors

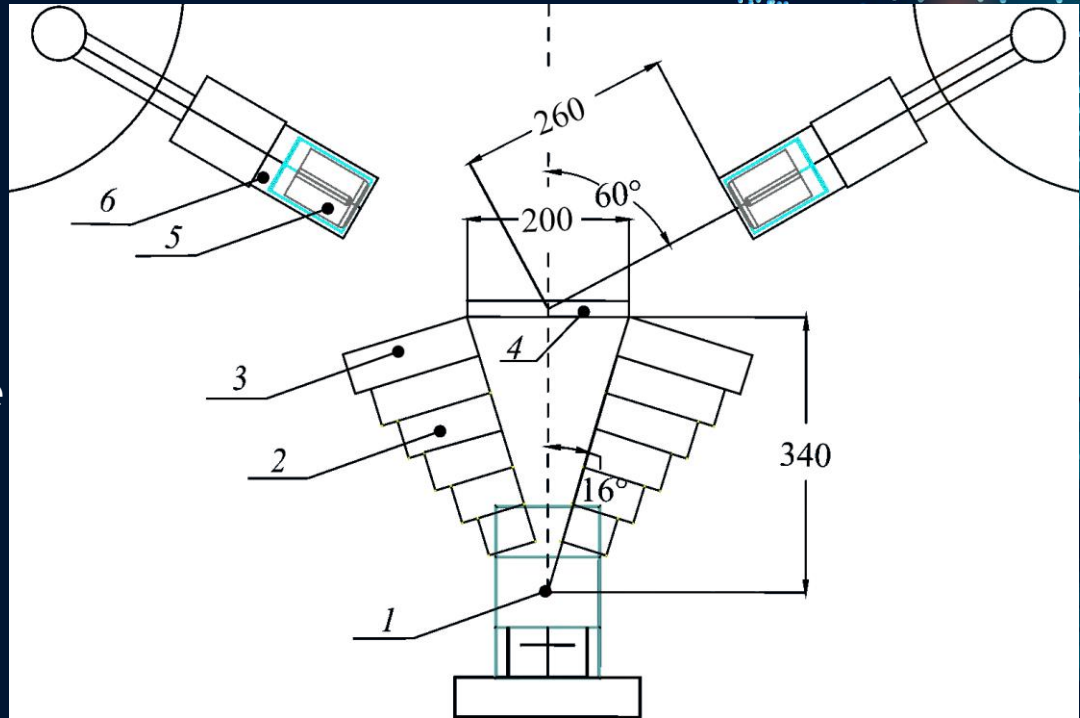
Main source of systematic uncertainties



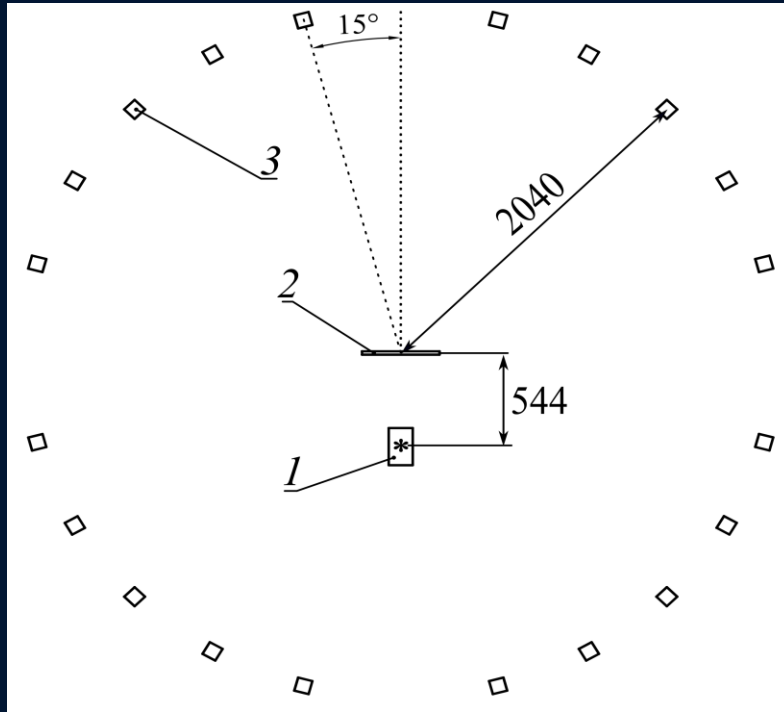
Small rotation of the NG could lead to dramatic change of target coverage. It could be corrected by relative calibration to central pixel and rotation angle could be adjusted to minimize CS difference between pix-det combinations with small difference in angle

Configuration for γ -quanta emission CS measurement

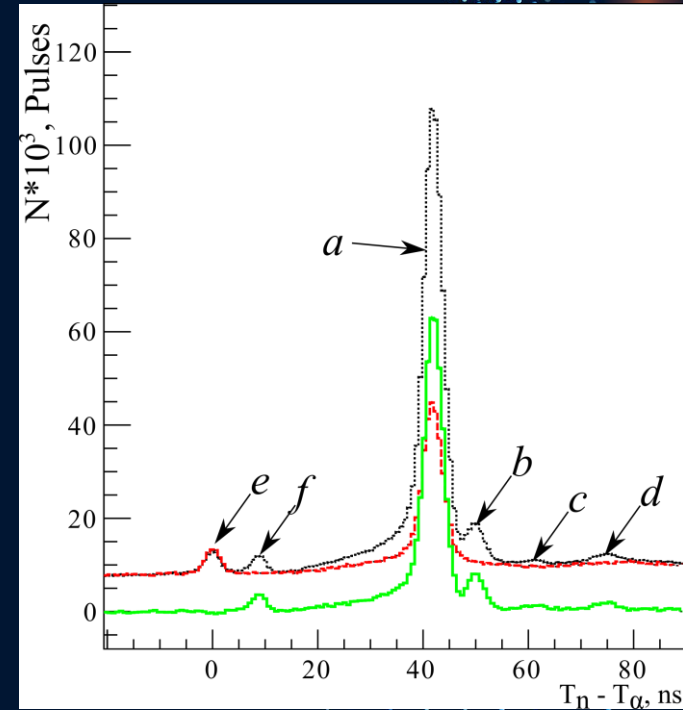
- 1-ING-27, 2-iron-, 3-lead parts of the collimator, 4-sample, 5-HPGe crystal, 6-case of the detector.
- Updated “HPGe” setup contains two ORTEC-made spectrometers with relative efficiency of 60%
- Set of LaBr detectors will be used to measure the γ -angular distribution



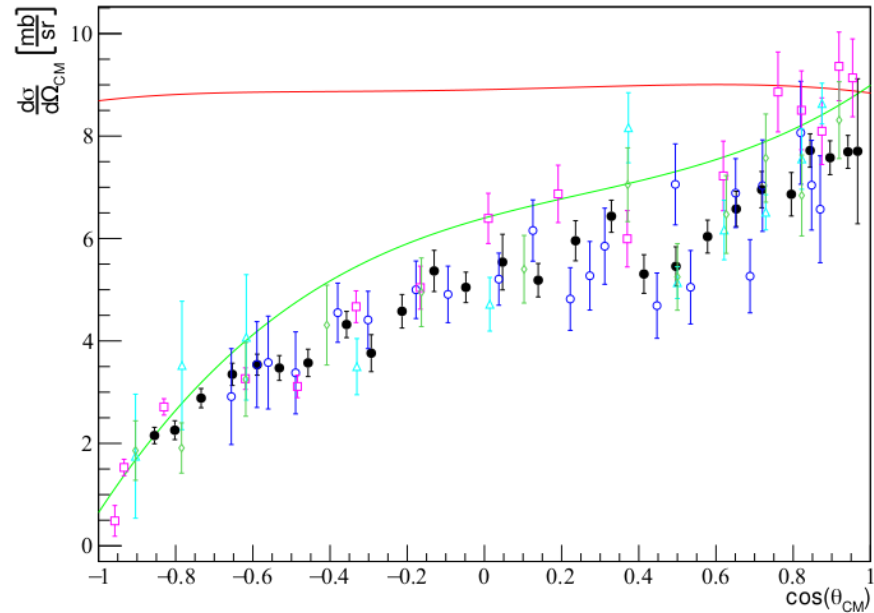
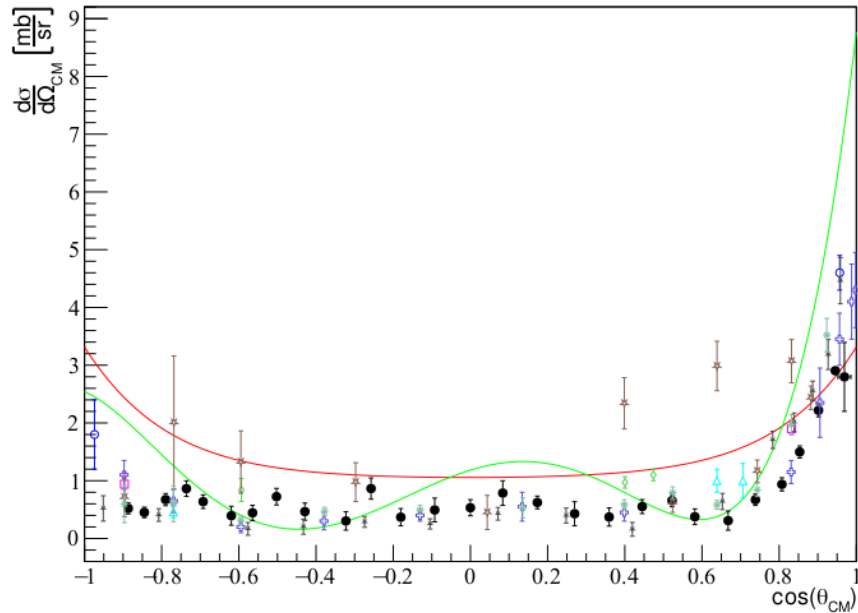
Measurement of n' angular distributions and n' γ correlations



- 1-ING-27 neutron generator, 2-sample, 3-PFT n-detector



a - direct and elastically scattered neutrons, *b* - 4.4 MeV, *c* - 7.6 MeV, *d* - 9.6 MeV excited states, *e* - γ -quanta emitted from case of the ING-27, *f* - γ from sample

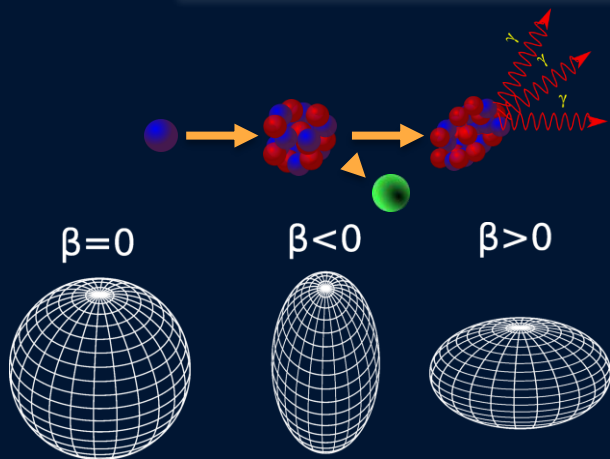


- 7.6 MeV state (Hoyle state)
- Green line – ENDF-B-VIII
- Red line - TALYS

- 9.6+9.8+9.9 MeV states

Studying of neutron-induced reactions

FLnP



- Optical model

$$U(r, E) = -\mathcal{V}_V(\mathbf{R}, r, E) - i\mathcal{W}_V(\mathbf{R}, r, E) - \\ -i\mathcal{W}_D(\mathbf{R}, r, E) + (\mathbf{R}, \vec{l} \cdot \vec{\sigma}) \times \\ \times (\mathcal{V}_{SO}(\mathbf{R}, r, E) + i\mathcal{W}_{SO}(\mathbf{R}, r, E))$$

$$R = R_{\kappa 0} \left(1 + \sum_{\lambda} \beta_{\lambda} Y_{\lambda}(\theta, \phi) \right), \quad R = R_{\kappa 0} \left(1 + \sum_{\lambda \mu} \alpha_{\lambda \mu} Y_{\lambda \mu}(\theta, \phi) \right),$$

Oscillator

Rotator

- (n, n') , $(n, 2n)$, (n, p) and (n, α) reactions is a unique tool for nuclear structure and shape investigation
- Data needed to adjust parameters models for astrophysical calculations
- Acquiring more accurate data for applied research

AZ
Levels at same
distance

AZ
Levels grows
as ΔE^2