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Progress in development of the γ -ray emission cross-section database for reactions with 14 MeV neutrons

FLNP

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On behalf of the TANGRA
collaboration

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TANGRA collaboration

TAggered Neutrons & Gamma RAys

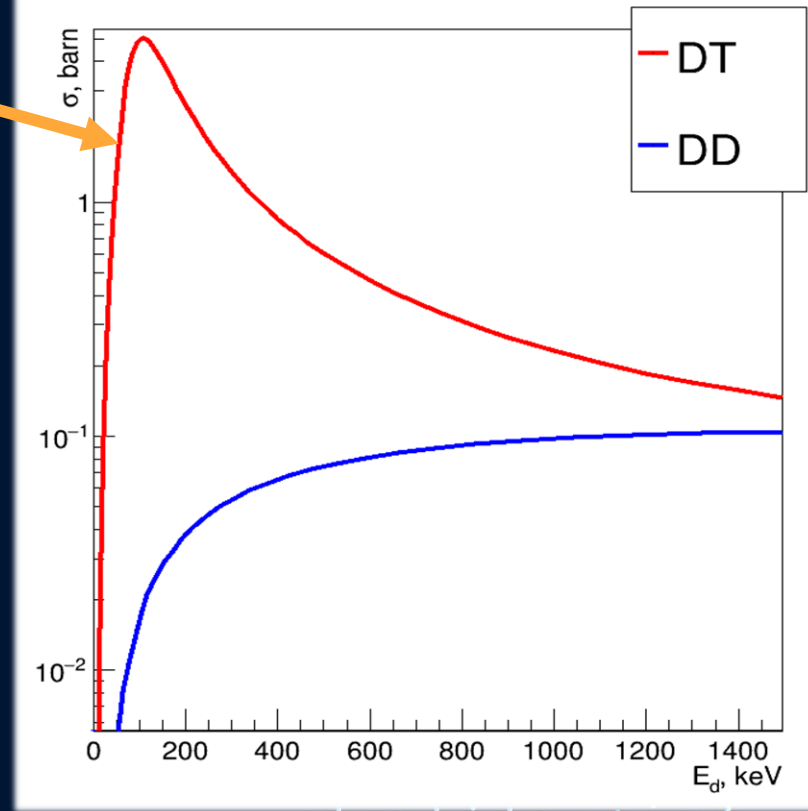
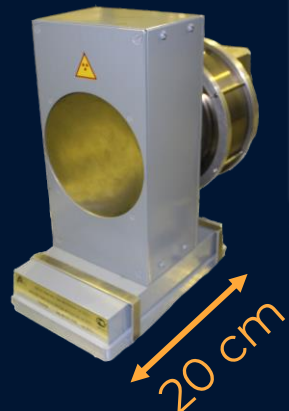
- An international collaboration   
- Main goals:
 - Nuclear reactions research using tagged neutron method (TNM): acquiring data for n and γ
 - Development of fast elemental analysis techniques
 - Theoretical description of processes under investigation
 - Software development for:
 - Data analysis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



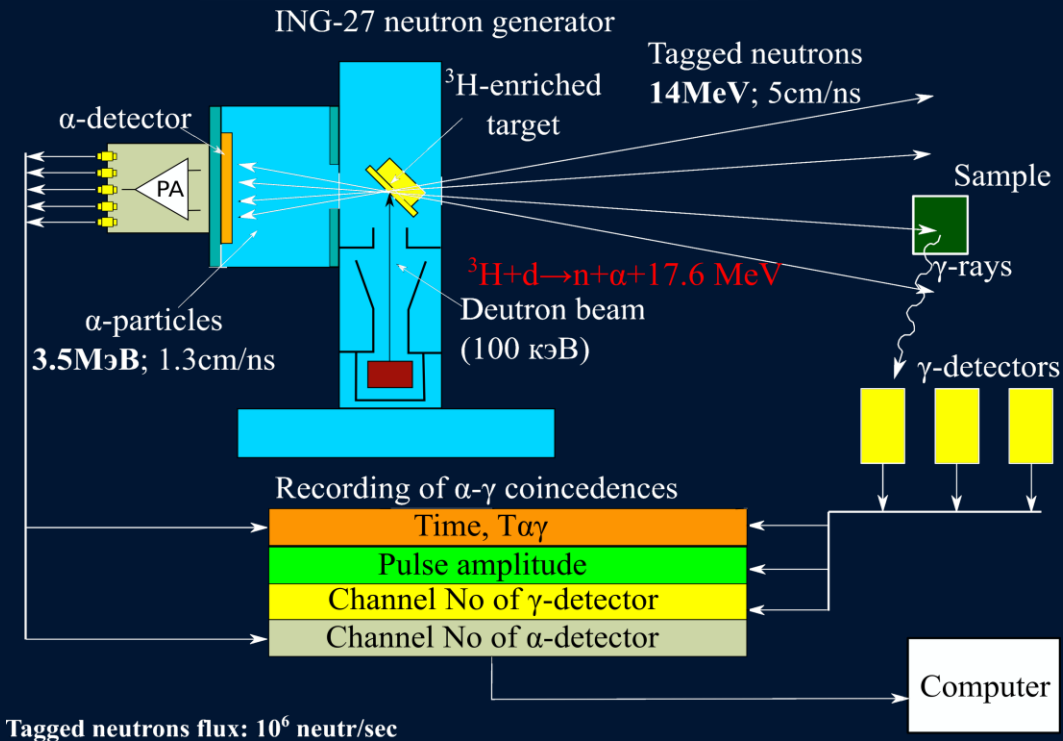


- **Features:**
- Low threshold
- High energy outcome
- Only two particles in products
- *Very suitable for neutron production*
- *Products move in opposite directions →*
- *Register one → determine direction for another!*

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

What we know about (n,xy) ?



International Atomic Energy Agency

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INDC

INTERNATIONAL NUCLEAR DATA COMMITTEE

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

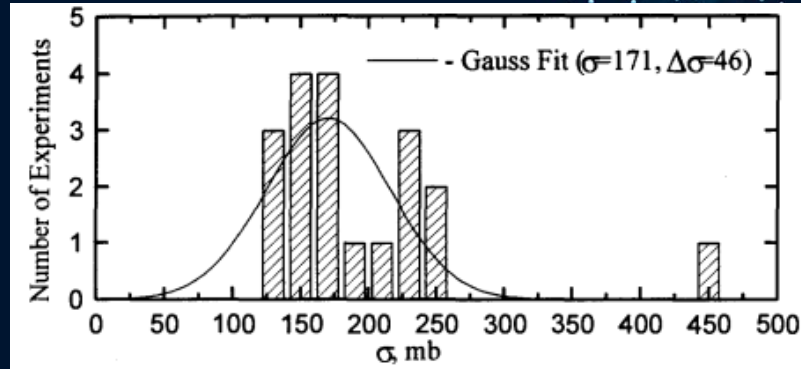
Final Report of Research Contract 7809/RB,
performed under the CRP on Measurement, Calculation
and Evaluation of Photon Production Data

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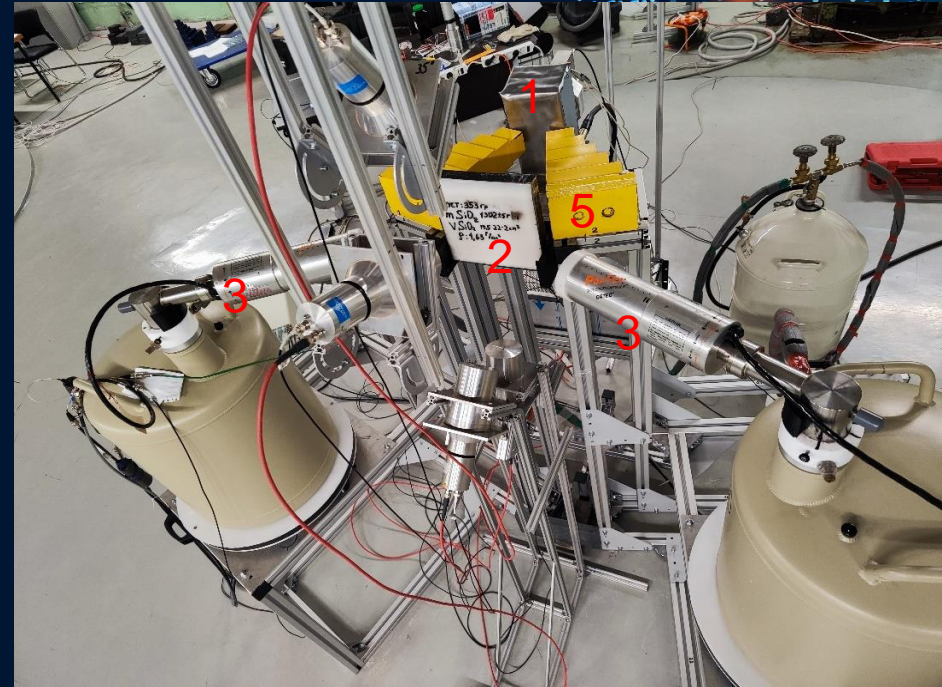
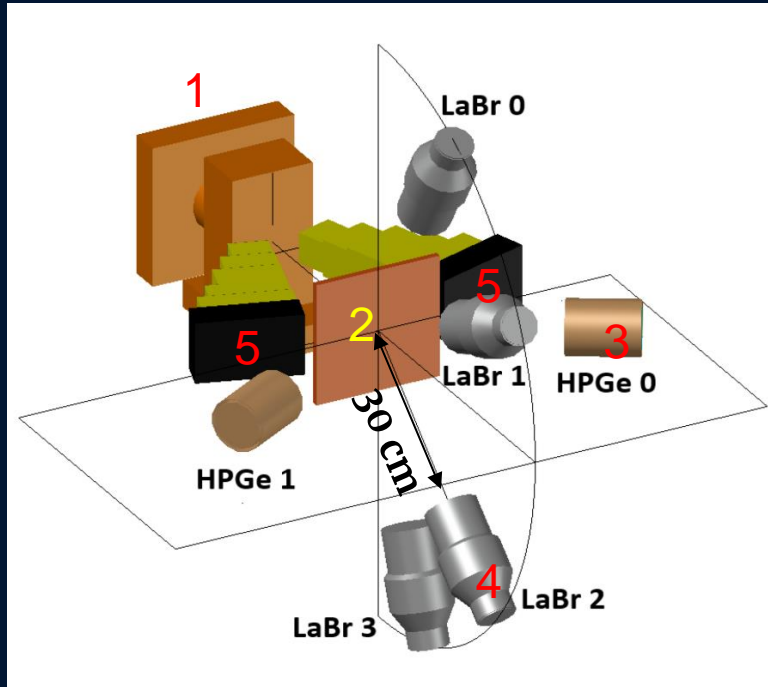
Discrepancy in two times!

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

The most complete set of (n,xy) cross-sections

Reason: something wrong in absolute CS estimation

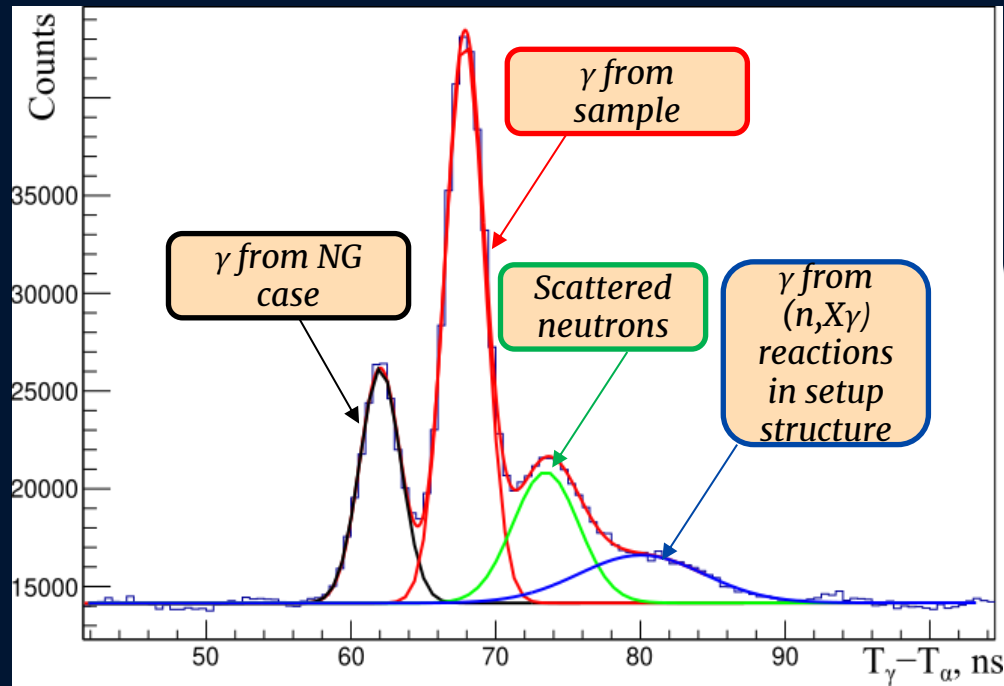
Measurements of the γ -quanta emission cross-sections & angular distributions



- 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

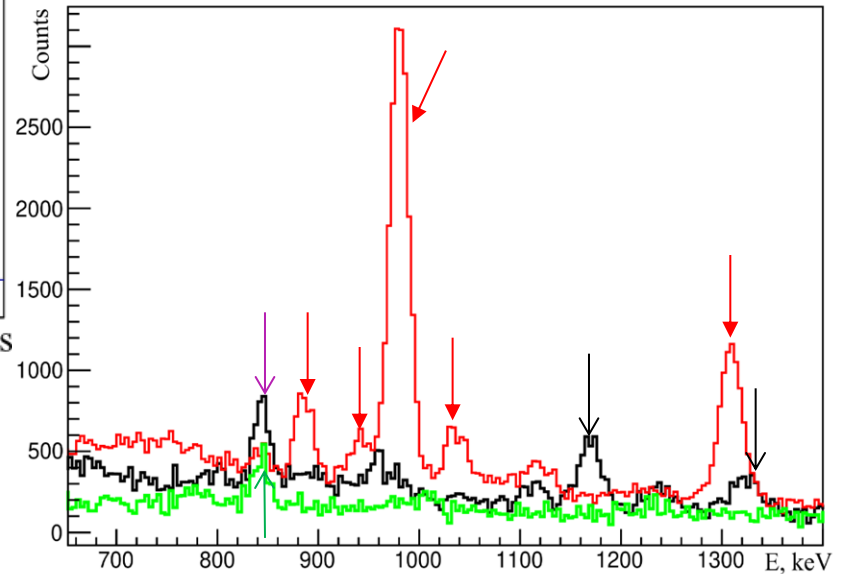


Main idea – separation of the background events by TOF

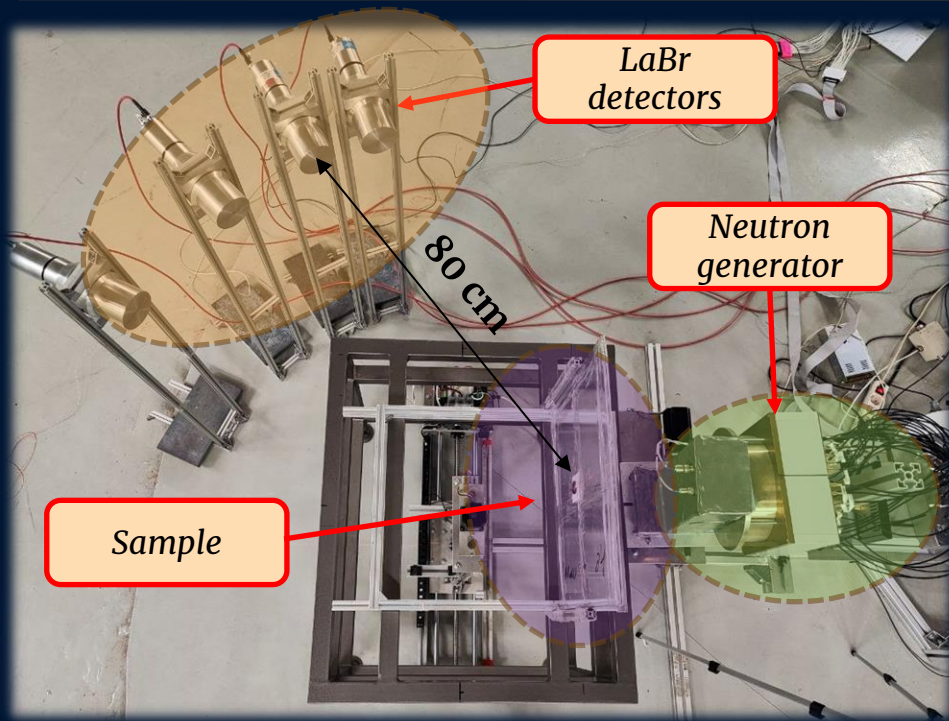
Spectrum below shows impact of different components to sum spectrum.

Peaks from sample marked with red arrows

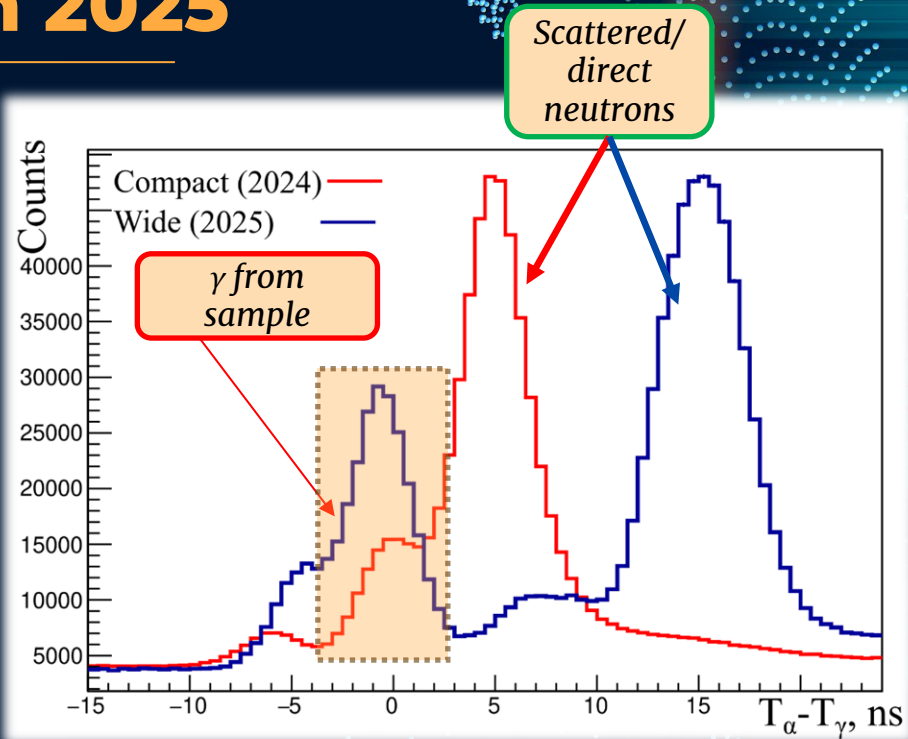
Comparison of TOF components



Verification campaign in 2025



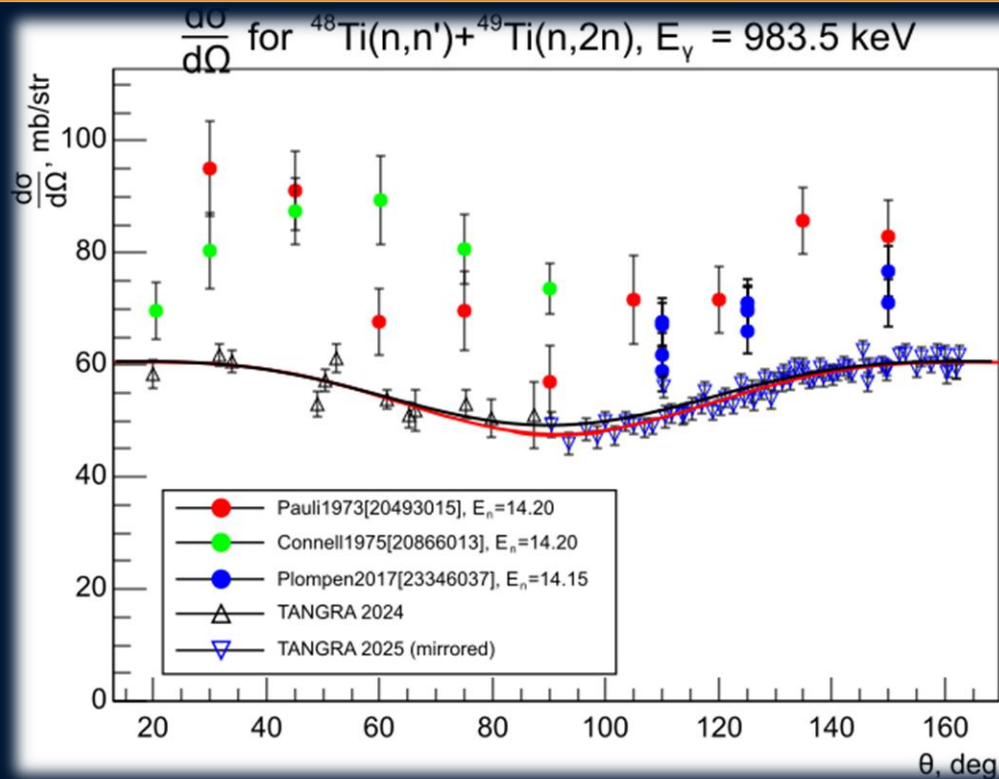
Data processing in compact version is very sophisticated



To verify obtained data another version of setup was created

$n - \gamma$ separation \rightarrow pbr ratio significantly improved

Measurements of the γ -quanta emission cross-sections & angular distributions (TiO_2 sample)



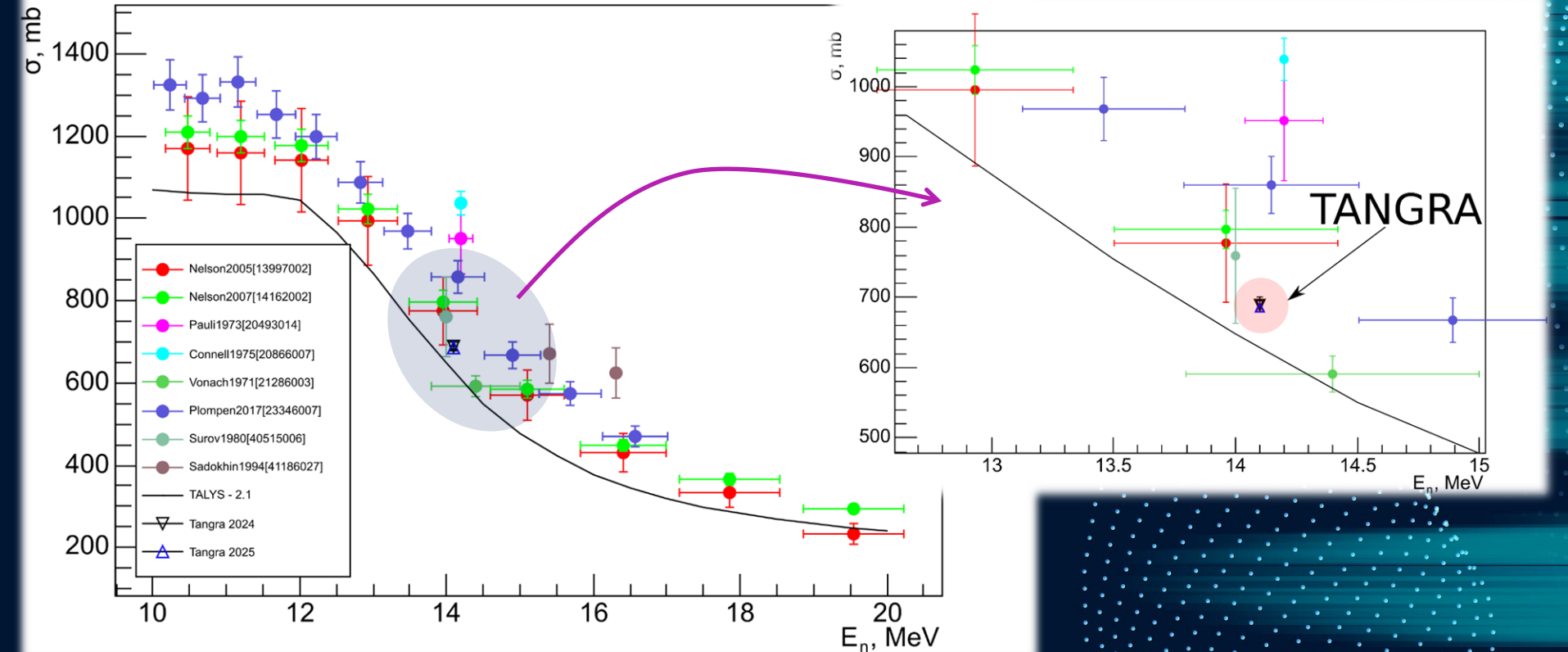
E_γ , keV	Reaction	Reference	σ , mb	a_2	a_4
983,5 keV	$^{48}\text{Ti}(n,n')$ $^{49}\text{Ti}(n,2n)$	Pauli 1973	940 (30)	0,31(8)	-0,1(1)
		Connell 1975	1020 (30)	-0,02(5)	-0.26(9)
		Plompen 2017	842 (15)	0,16(4)	-0,08(7)
		TANGRA 2024	690 (10)	0,16(3)	-0,05(4)
		TANGRA 2025	685 (3)	0,18(1)	-0.06(1)

• And 19 γ -lines more

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

Measurements of the γ -quanta emission cross-sections & angular distributions (TiO_2 sample)

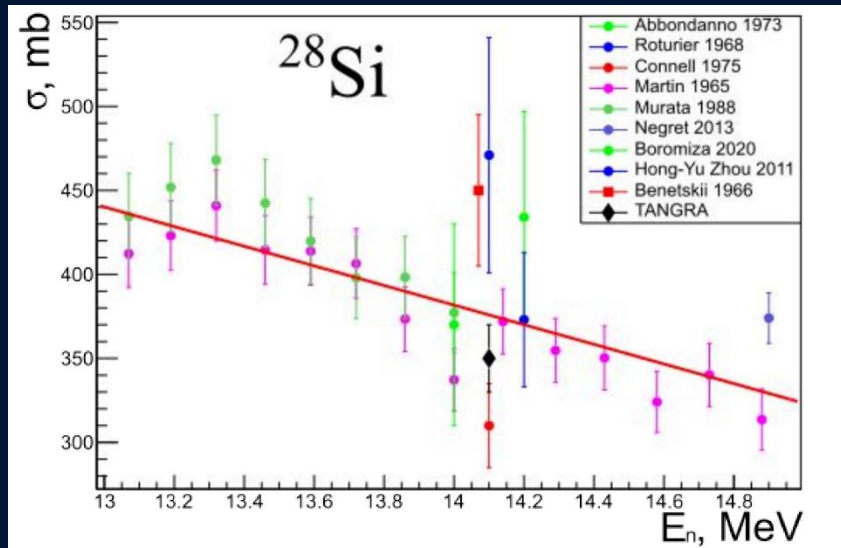
Cross-section of 983.5 keV γ -emission



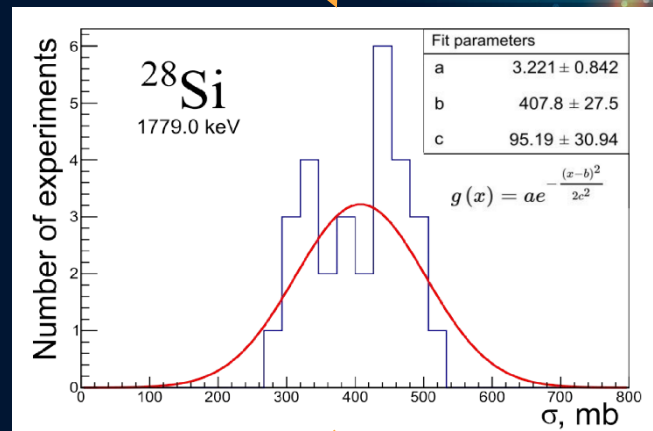
What is the purpose of this all?

Applied physics

- Cross-sections of γ -quanta emission are needed for **fast elemental analysis**, **but**



Correction on energy dependence



Estimated $\sigma = 408 \pm 28 \text{ mb}$

- We assume that main source of discrepancy – incorrect determination of neutron flux

*Data extracted from EXFOR using TalysLib

Crucial advantage of TNM – direct count of neutrons



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							
1	H 1,0079 1s ¹ Водород						H	He 4,00260 1s ² Гелий	<div>Относительная атомная масса</div> <div>Порядковый (атомный) номер</div> <div>Конфигурация валентных электронов</div> <div>Название</div>							
2	Li 6,941 2s ² Литий	Be 9,01218 2s ² Бериллий	B 10,81 2s ² 2p ¹ Бор	C 12,011 2s ² 2p ² Углерод	N 14,0067 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 22,98976928 3s ¹ Натрий	Mg 24,304 3s ² Магний	Al 26,9815386 3s ² 3p ¹ Алюминий	Si 28,0855836 3s ² 3p ² Кремний	P 30,973762 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 44,955912 3d ¹ 4s ² Скандий	Ti 47,88 3d ² 4s ² Титан	V 50,9415 3d ³ 4s ² Ванадий	Cr 51,9961 3d ⁵ 4s ¹ Хром	Mn 54,938 3d ⁵ 4s ² Марганец	Fe 55,845 3d ⁶ 4s ² Железо	Co 58,9332 3d ⁷ 4s ² Кобальт	Ni 58,6934 3d ⁸ 4s ² Никель						
5	Rb 85,4678 5s ¹ Рубидий	Sr 87,62 5s ² Стронций	Y 88,90584 4d ¹ 5s ² Иттрий	Zr 91,224 4d ² 5s ² Цирконий	Nb 92,90638 4d ⁴ 5s ¹ Никобий	Mo 95,94 4d ⁵ 5s ¹ Молибден	Tc 98 4d ⁵ 5s ² Технеций	Ru 101,07 4d ⁷ 5s ¹ Рутений	Rh 102,905 4d ⁸ 5s ¹ Родий	Pd 106,905 4d ¹⁰ Палладий						
6	Cs 132,905 6s ¹ Цезий	Ba 137,327 6s ² Барий	La* 138,9047 5d ¹ 6s ² Лантан	Hf 178,49 5d ² 6s ² Гафний	Ta 180,94788 5d ³ 6s ² Тантал	W 183,84 5d ⁴ 6s ² Вольфрам	Re 186,207 5d ⁵ 6s ² Рений	Os 190,2 5d ⁶ 6s ² Осмий	Ir 192,22 5d ⁷ 6s ² Иридий	Pt 195,08 5d ⁹ 6s ¹ Платина						
7	Fr [223] 7s ¹ Франций	Ra [226] 7s ² Радий	Ac** [227] 6d ¹ 7s ² Актиний	Rf [261] 6d ² 7s ² Резерфордий	Db [262] 6d ³ 7s ² Дубний	Sg [266] 6d ⁴ 7s ² Сибиргий	Bh [269] 6d ⁵ 7s ² Борий	Hs [271] 6d ⁶ 7s ² Гассий	Mt [270] 6d ⁷ 7s ² Мейтнерий	Ds [271] 6d ⁹ 7s ¹ Дармштадтий						
	Rg [280] Рентгеней	Cn [285] Коперниций	Nh [286] Нихоний	Fl [289] Флеровий	Mc [293] Московский	Lv [293] Ливерморий	Ts [294] Теннессин	Og [294] Оганесон								

2024

2025

58 Ce 140,12 4f ¹ 5d ¹ 6s ² Церий	59 Pr 140,908 4f ³ 6s ² Празеодим	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 Итербий	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 Кюрий	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 [258] 5f ¹³ 7s ² Менделевий	102 No [259] 5f ¹⁴ 7s ² Нобелий	103 Lr [260] 5f ¹⁴ 6d ¹ 7s ² Лоуренсий

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
- A lot of interesting things are still lied in the valley of stability. Let's investigate them!

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 $\rightarrow N_p \cos \xi$

Incident angle $\rightarrow \xi$

Number of tagged neutrons $\rightarrow N_\alpha$

Surface density of atoms in the sample $\rightarrow n_{at}$

k is defined by the integral below:

- 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

Total reaction cross section $\rightarrow \sigma$

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

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

Multiple inelastic scattering $\rightarrow k_{ms}(x)$

Attenuation of γ -rays $\rightarrow \varepsilon(x)$

Attenuation of incident neutron $\rightarrow k_{iatt}(x)$

Sample thickness $\rightarrow x_0$

The total efficiency \rightarrow (points to the integral expression)

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:

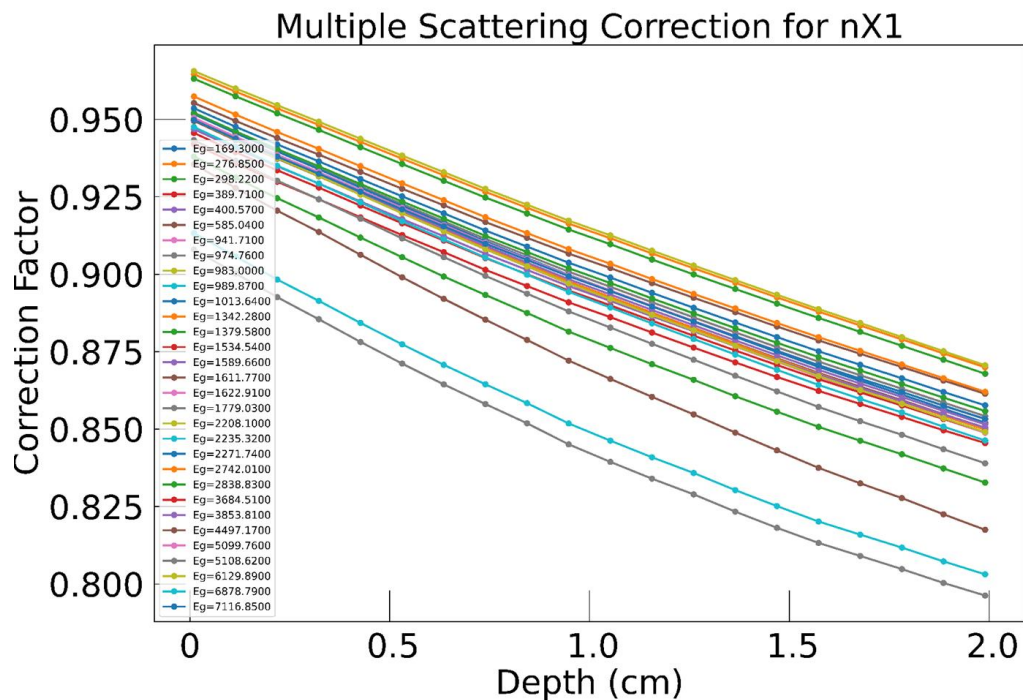
- 2 stage - neutron transport and γ -rays transport simulation
- The inelastic multiple scattering is used as a probability factor increasing the number of emitted γ -rays in comparison with its real number
- The inelastic multiple scattering correction calculates taking into account the energy dependence 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

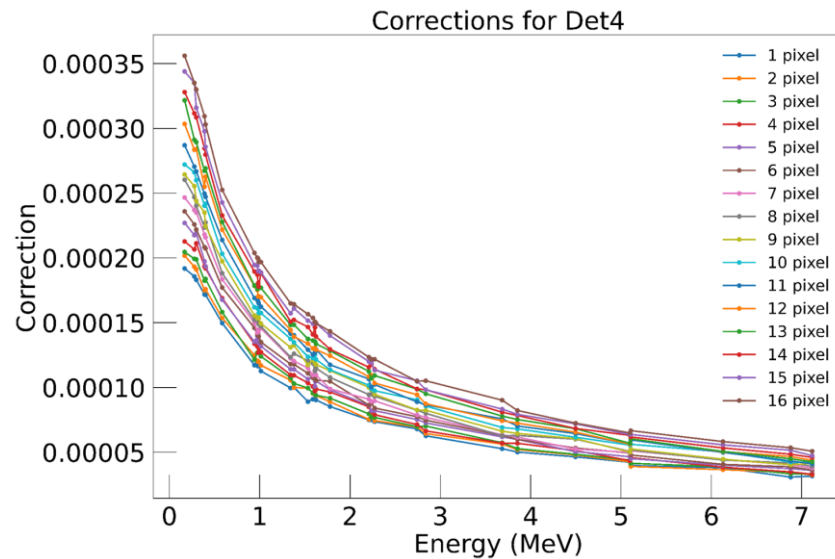
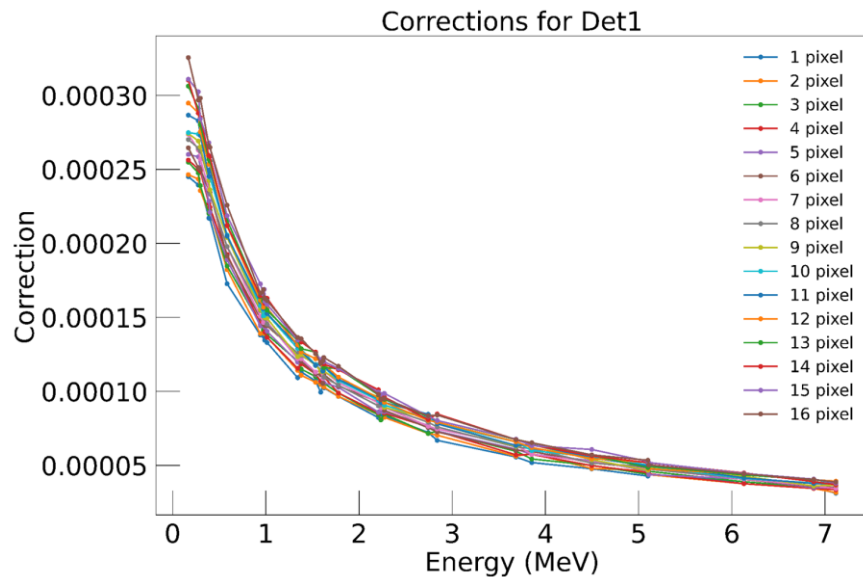
Simulation of γ -rays detection efficiency emitting them from the interaction points

Example of the multiple scattering correction



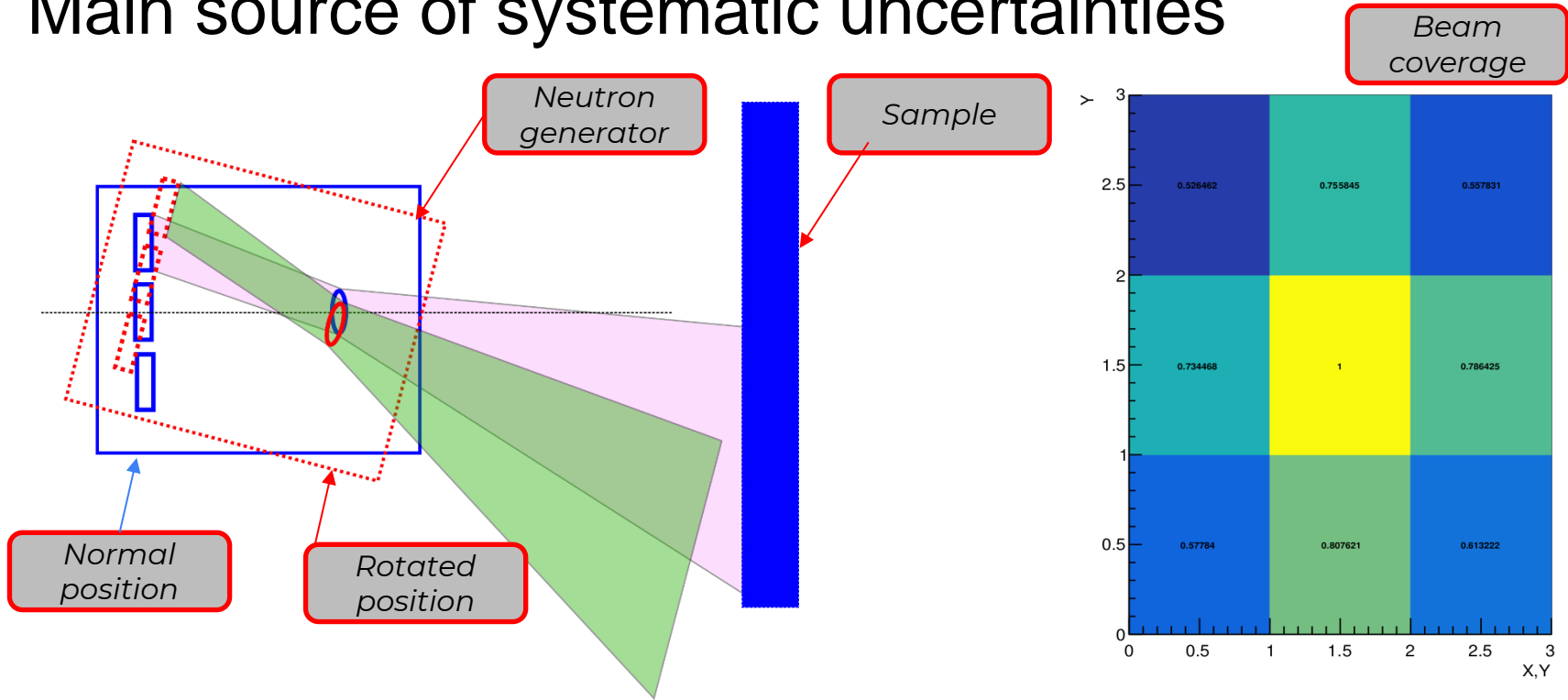
Multiple scattering correction factor depending on the sample thickness. The example corresponding to the SiO_2 sample and first vertical strip

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

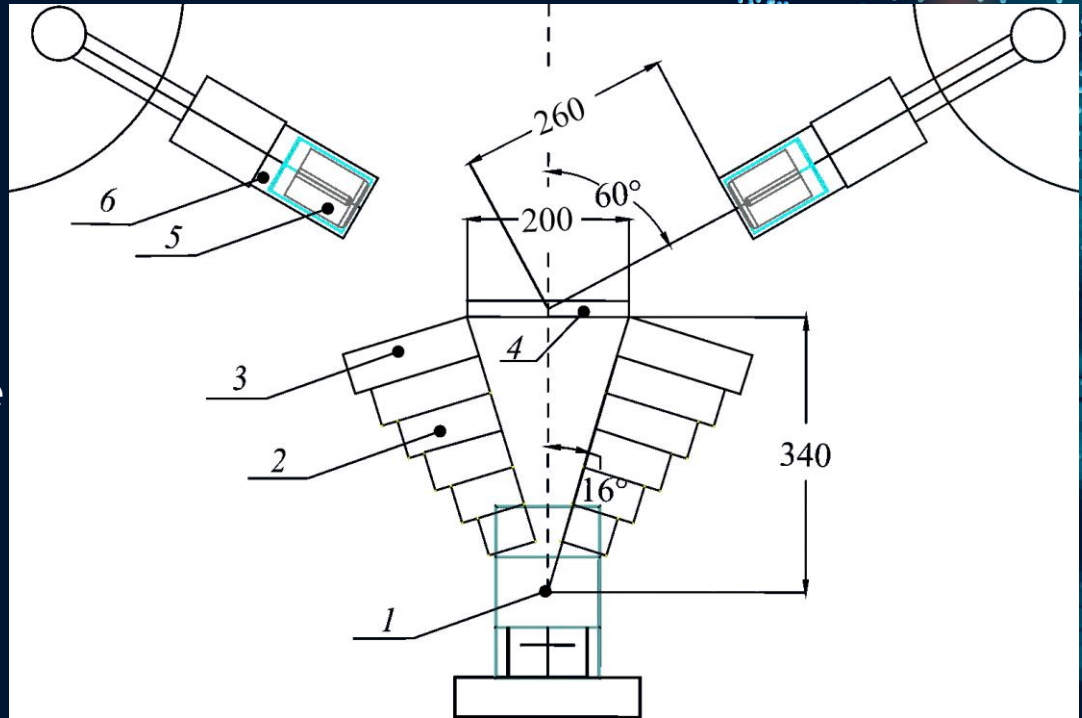
Main source of systematic uncertainties



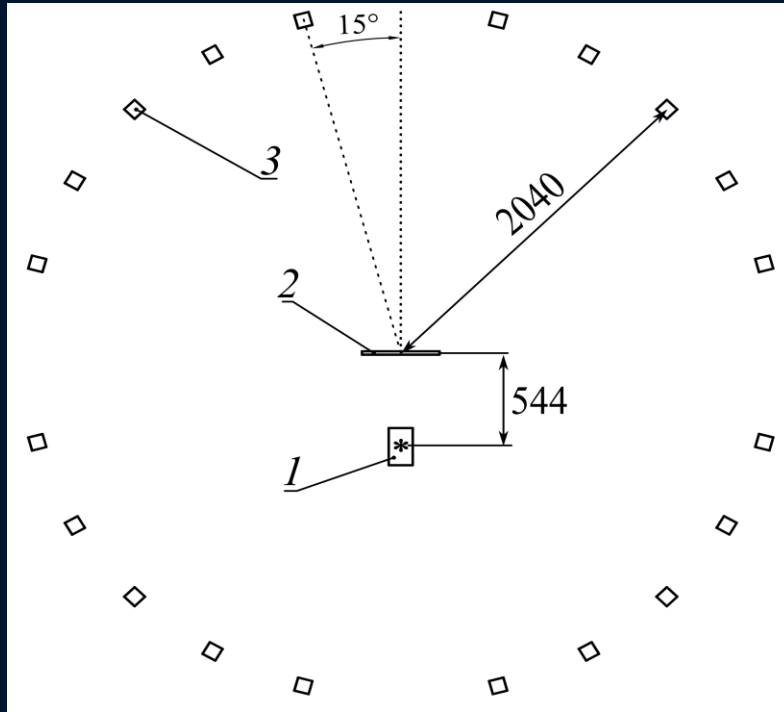
Small rotation of the NG could lead to dramatic change of target coverage. It could be corrected by relative calibration to central pixel and rotation angle could be adjusted to minimize CS difference between pix-det combinations with small difference in angle

Configuration for γ -quanta emission CS measurement

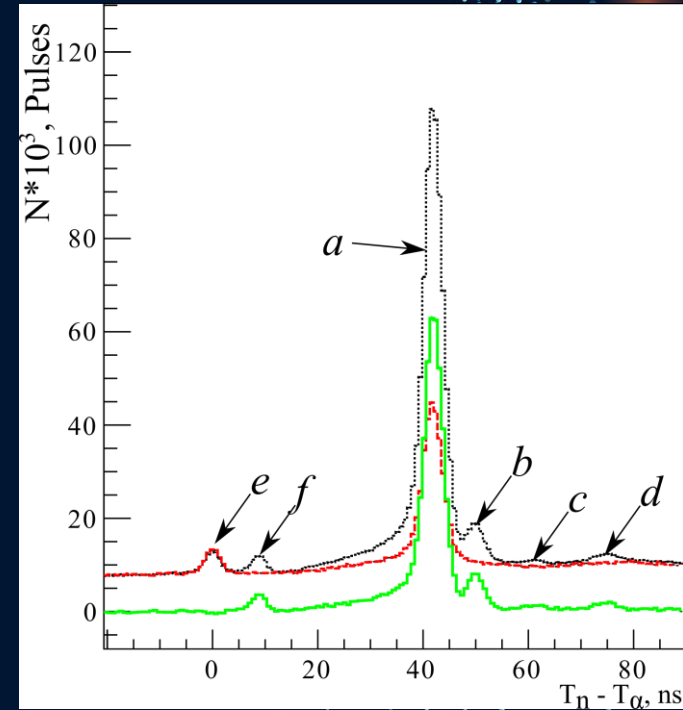
- 1-ING-27, 2-iron-, 3-lead parts of the collimator, 4-sample, 5-HPGe crystal, 6-case of the detector.
- Updated “HPGe” setup contains two ORTEC-made spectrometers with relative efficiency of 60%
- Set of LaBr detectors will be used to measure the γ -angular distribution



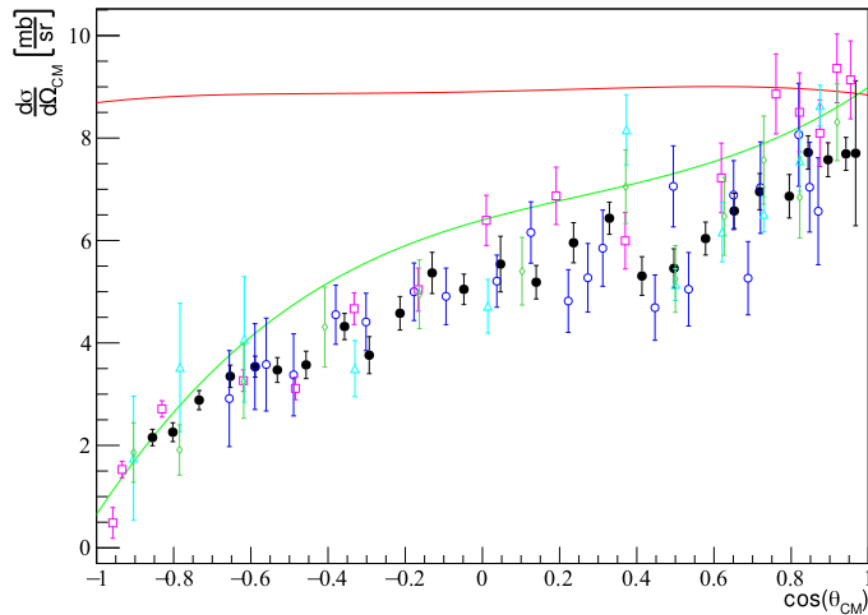
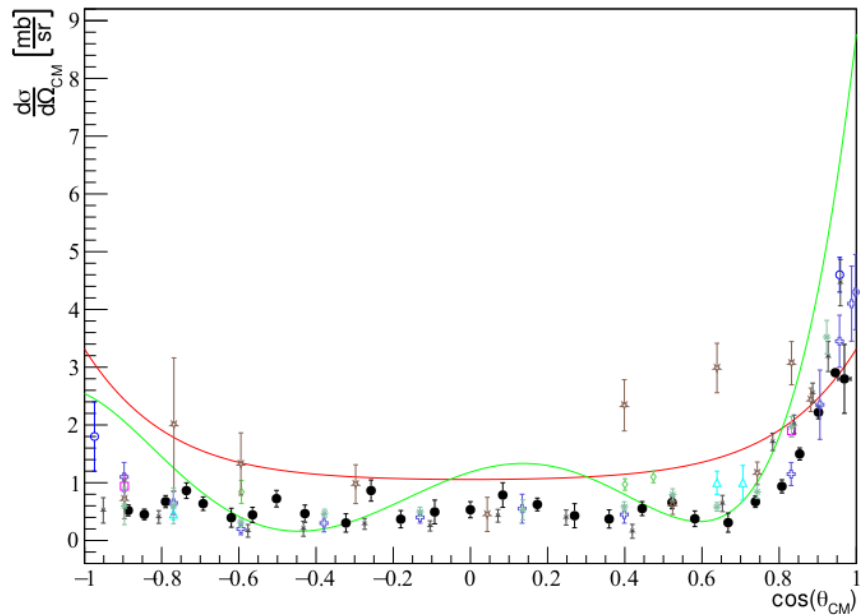
Measurement of n' angular distributions and $n' \gamma$ correlations



- 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