

# Response of LaBr<sub>3</sub> scintillation detector on 14.1 MeV neutrons irradiation



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collaboration

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# Motivation

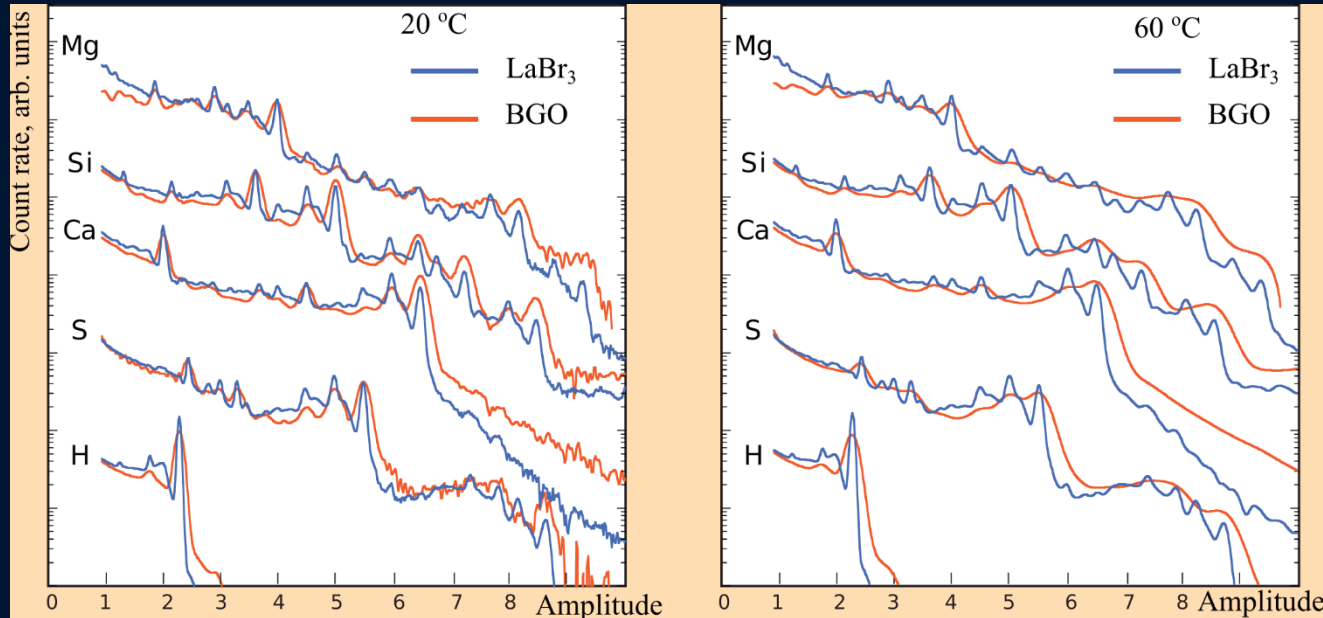
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- Lanthanum(III) bromide ( $\text{LaBr}_3$ ) – based detectors became more and more popular:
  - Best energetic resolution for scintillators (~14 keV FWHM for 662 keV)
  - Low light output drift on temperature



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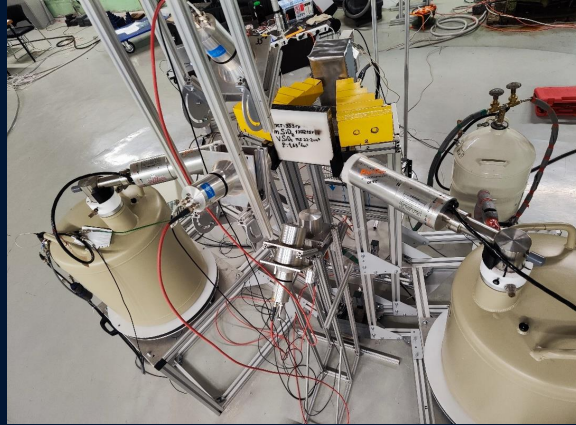


# Motivation

- Lanthanum(III) bromide ( $\text{LaBr}_3$ ) – based detectors became more and more popular:
  - Best energetic resolution for scintillators ( $\sim 14$  keV FWHM for 662 keV)
  - Low light output drift on temperature
- Used in many nuclear facilities/devices



OSCAR

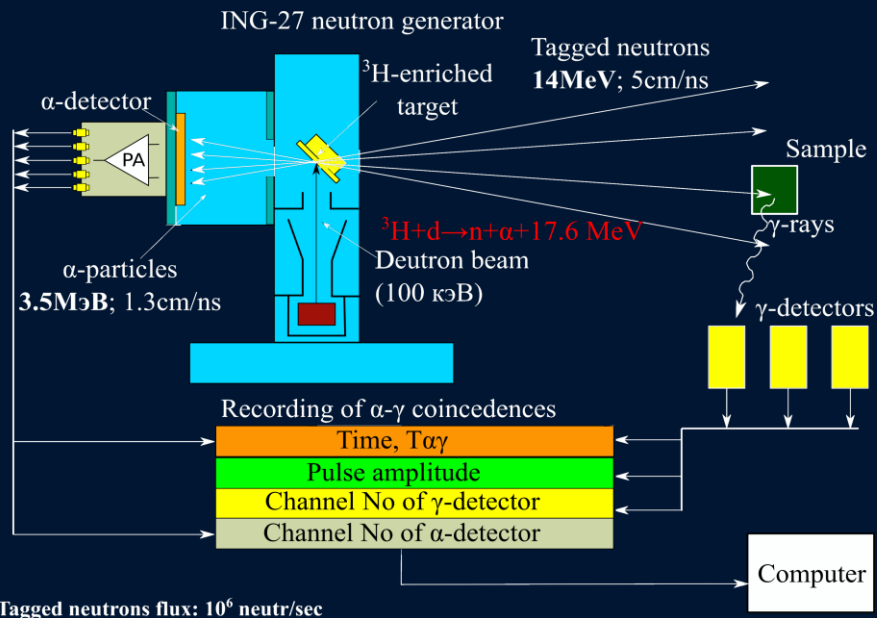


TANGRA



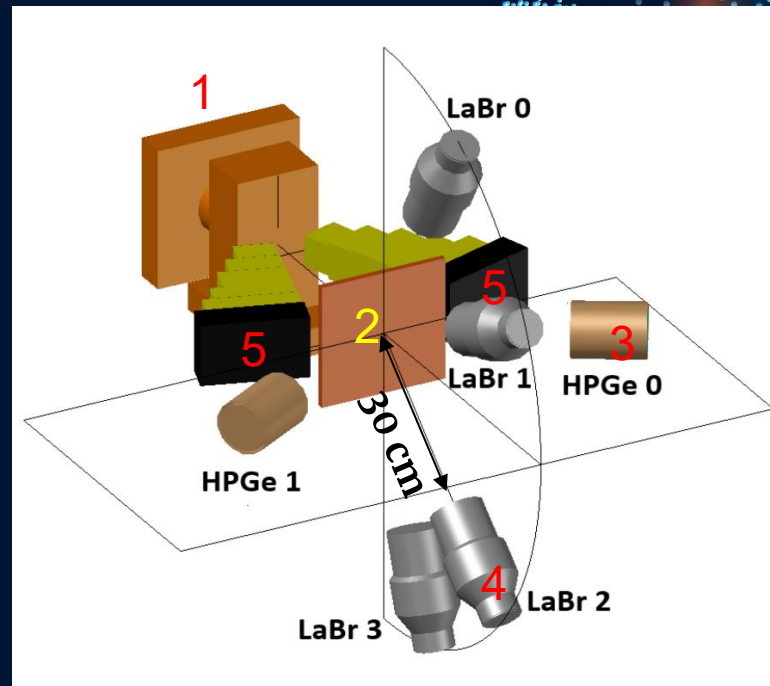
Litho Scanner  
([slb.com/lis](http://slb.com/lis))

# The tagged neutron method (TNM) & TANGRA setup



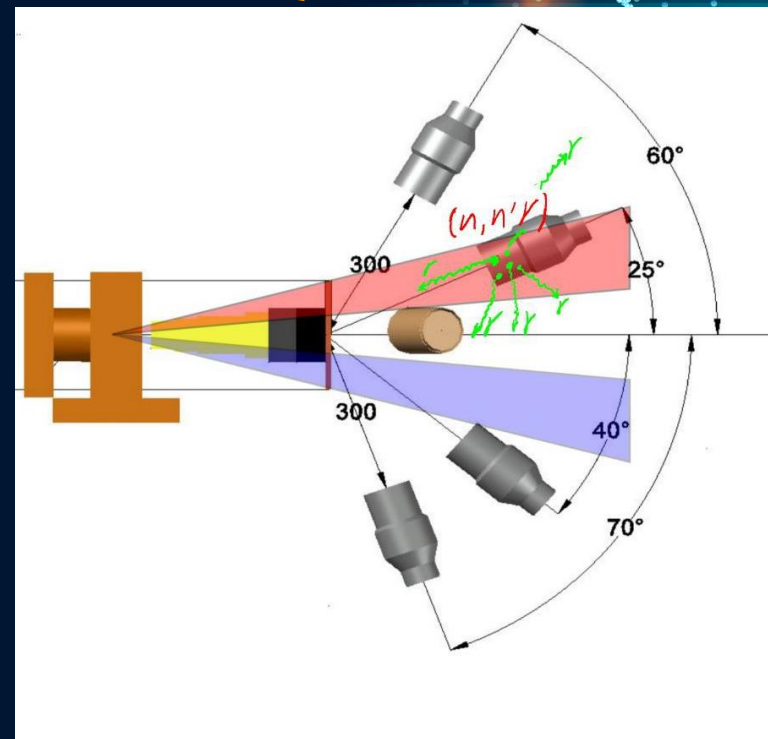
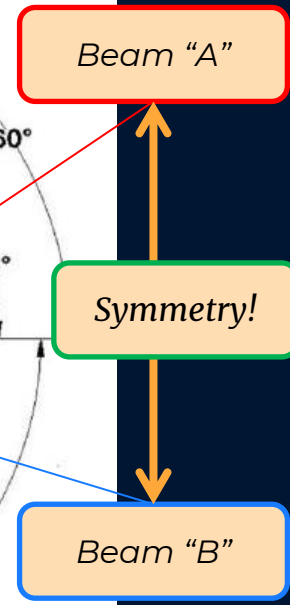
Interesting for nuclear reactions research:

- Angular distributions of  $n$  and  $\gamma$
- Correlation between  $n$  and  $\gamma$

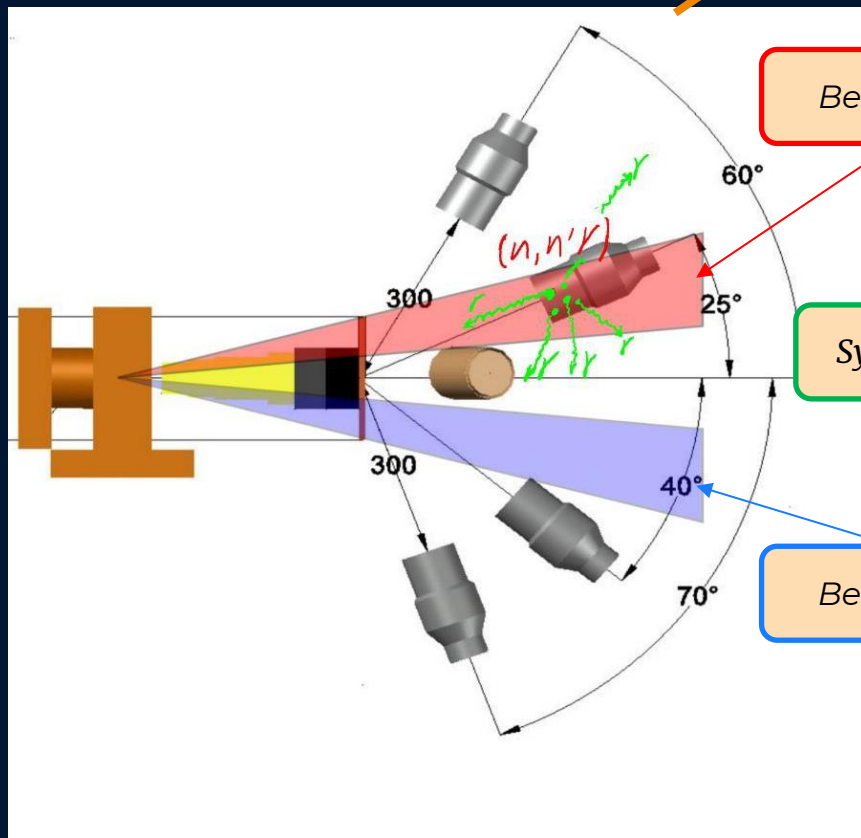


- 1) ING-27 neutron generator
- 2) sample 20x20xX cm
- 3) HPGe  $\gamma$ -detector (2 pcs, 60% eff)
- 4) LaBr<sub>3</sub> detector (4 pcs)

A diagram illustrating the relationship between two beams. A red box labeled "Beam 'A'" is connected by a curved orange arrow to a yellow box labeled "A-B". Another straight orange arrow points from the "A-B" box towards the bottom right.



# Idea of experiment

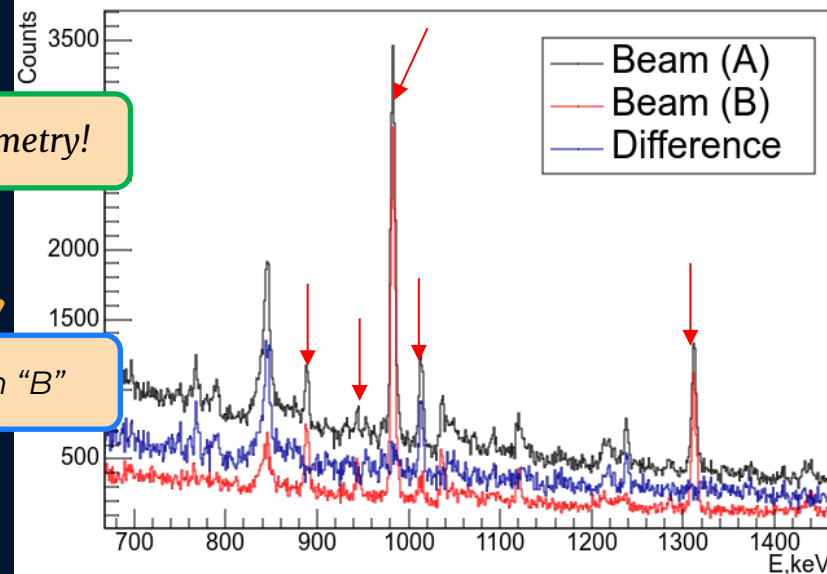


**A-B**

Beam "A"

Symmetry!

Beam "B"



$\gamma$  from sample marked with red arrows

# Results

$$Y_i = \frac{S_i \varepsilon_0}{S_0 \varepsilon_i}$$

- $S$  – area of full energy absorption peak
- $\varepsilon$  – correction coefficient (includes efficiency of the HPGe detector, solid angle and self-absorption in LaBr)
- $i$  – investigated peak
- $0$  – reference peak

Reference line marked with **red**  
Reactions leads to activation  
marked with **orange**

$E_\gamma$ , keV	Target	Reaction	Yield, %
88,7	<sup>139</sup> La	(n,2n)	161(11)
165,9	<sup>139</sup> La	(n,n')	34(7)
217,1	<sup>79</sup> Br	(n,n')	83(4)
230,4	<sup>139</sup> La	(n,2n)	42(3)
243,5	<sup>79</sup> Br	(n,2n)	87(2)
260,8	<sup>81</sup> Br	(n,n')	29(4)
276	<sup>81</sup> Br	(n,n')	100
291,4	<sup>139</sup> La	(n,n')	27(10)
306,5	<sup>79</sup> Br	(n,n')	34(17)
340,7	<sup>139</sup> La	(n,2n)	17(4)
381,5	<sup>79</sup> Br	(n,n')	27(2)
523,1	<sup>79</sup> Br	(n,n')	20(2)
562,4	<sup>81</sup> Br	(n,n')	20(3)
613,7	<sup>79</sup> Br	(n,np)	80(9)
640,6	<sup>81</sup> Br	(n,n')	19(2)
767	<sup>81</sup> Br	(n,n')	28(2)
789,4	<sup>81</sup> Br	(n,n')	22(4)
1043,1	<sup>139</sup> La	(n,n')	41(8)
1219	<sup>139</sup> La	(n,n')	41(10)
1237	<sup>81</sup> Br	(n,n)	26(2)

Identified 47  $\gamma$  – transitions in total



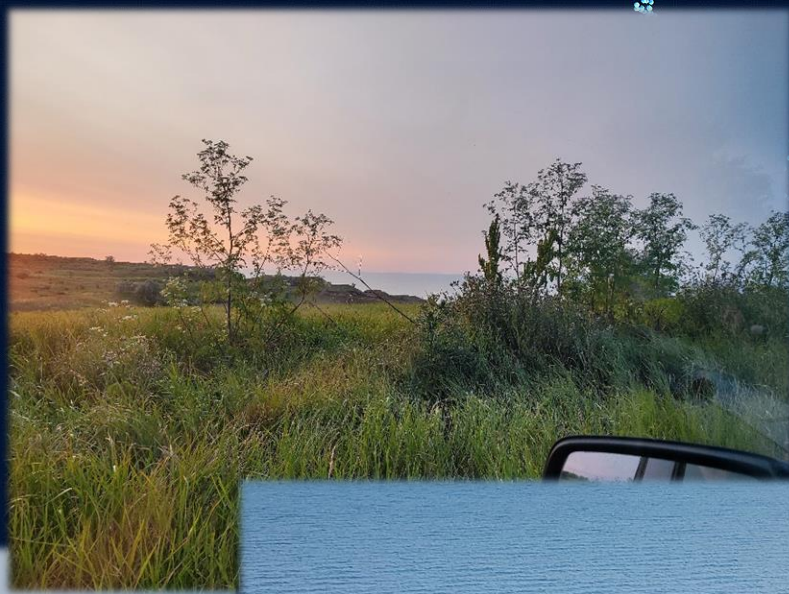
# Conclusion & TODO

- Applied technique allowed us to extract  $\gamma$  – yields for reactions in LaBr in “parasite” mode from data obtained in regular measurements
- There are no data for La and Br at 14MeV in EXFOR – probably this data obtained for the first time
- Identified 47  $\gamma$  – transitions in total

## TODO

- Perform regular measurement with La sample and Br-contained sample (planned in 2025) to extract angular distribution of  $\gamma$  – quanta and measure cross-sections
- Create a response function to use it for neutron background subtraction

# THANKS!



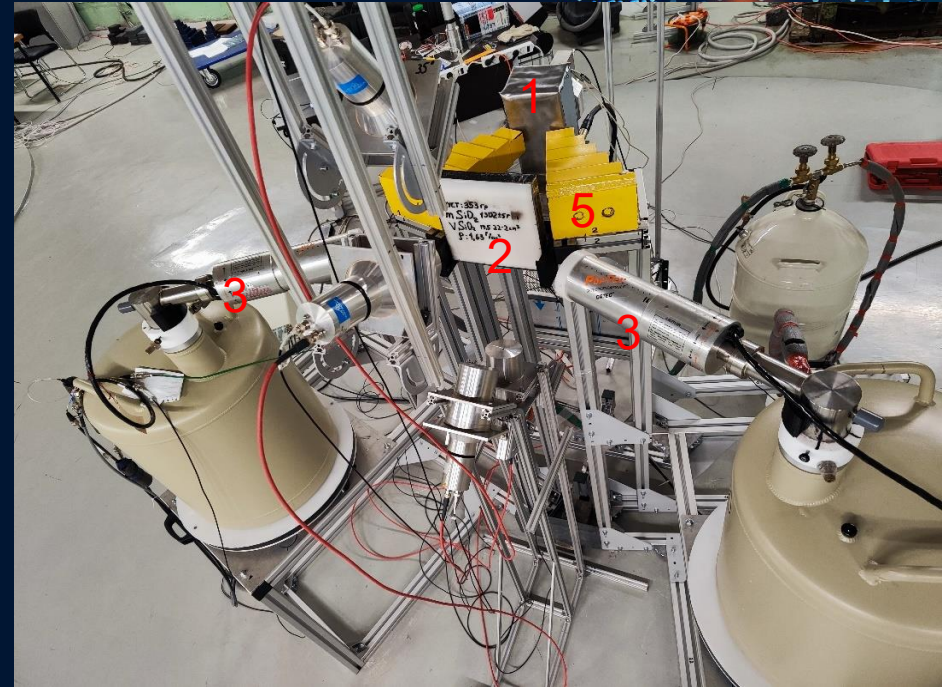
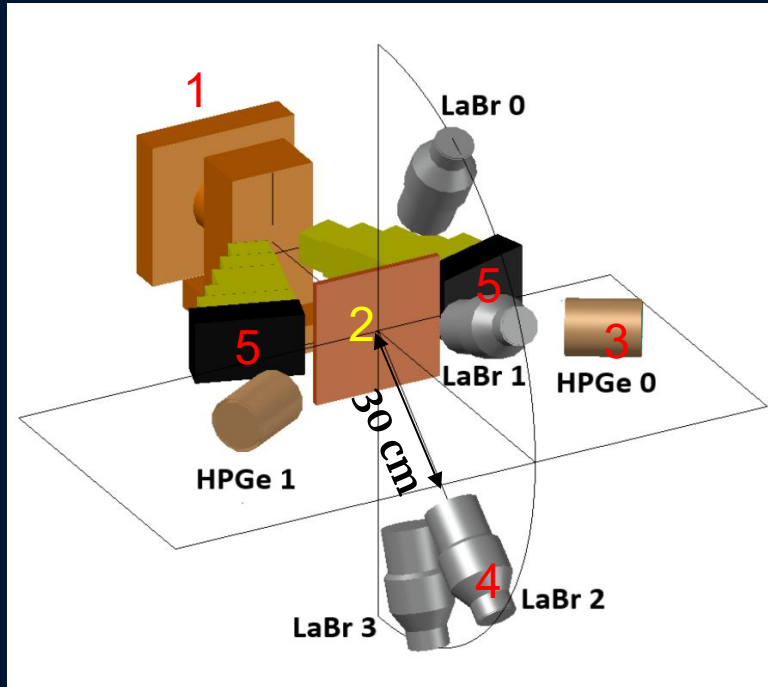
# Backup

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- 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!



# Measurements of the $\gamma$ -quanta emission cross-sections & angular distributions

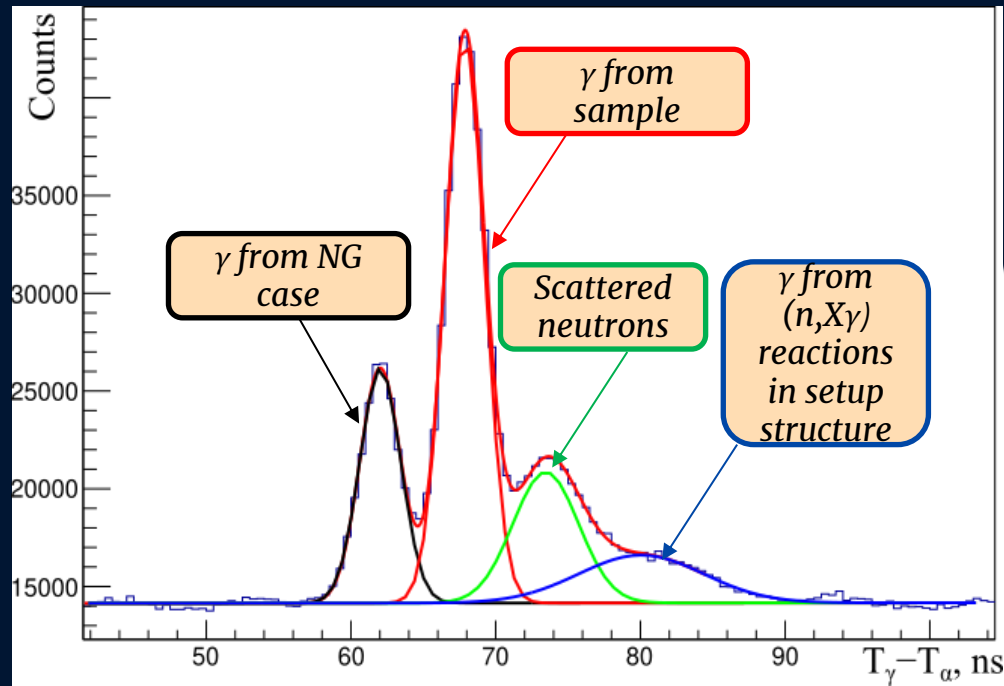


- 1) ING-27 neutron generator
- 2) sample 20×20×X cm
- 3) HPGe  $\gamma$ -detector (2 pcs, 60% eff)

- 4) LaBr<sub>3</sub>  $\gamma$ -detector (4 pcs)  
+ Fast measurement  
- Extreme detector load ( $\sim 8 \times 10^4$  cps)



# Data processing with TNM

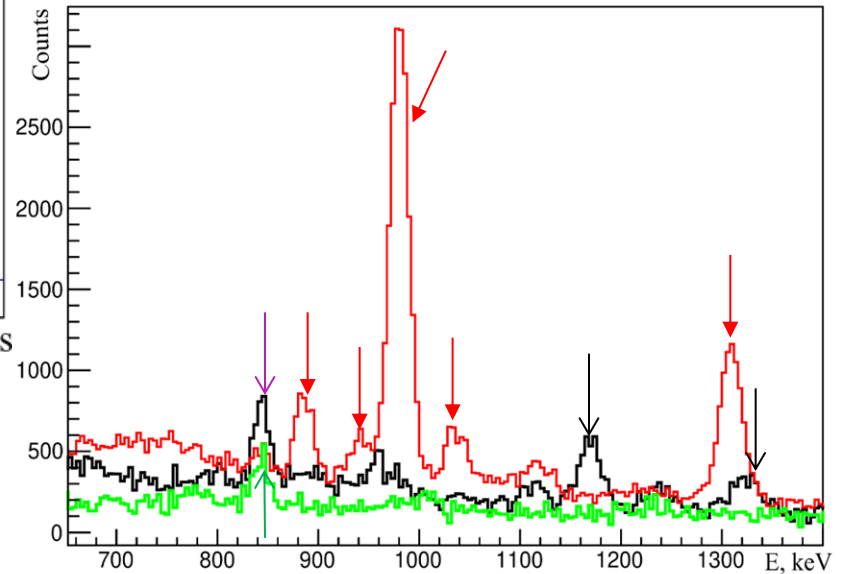


Main idea – separation of the background events by TOF

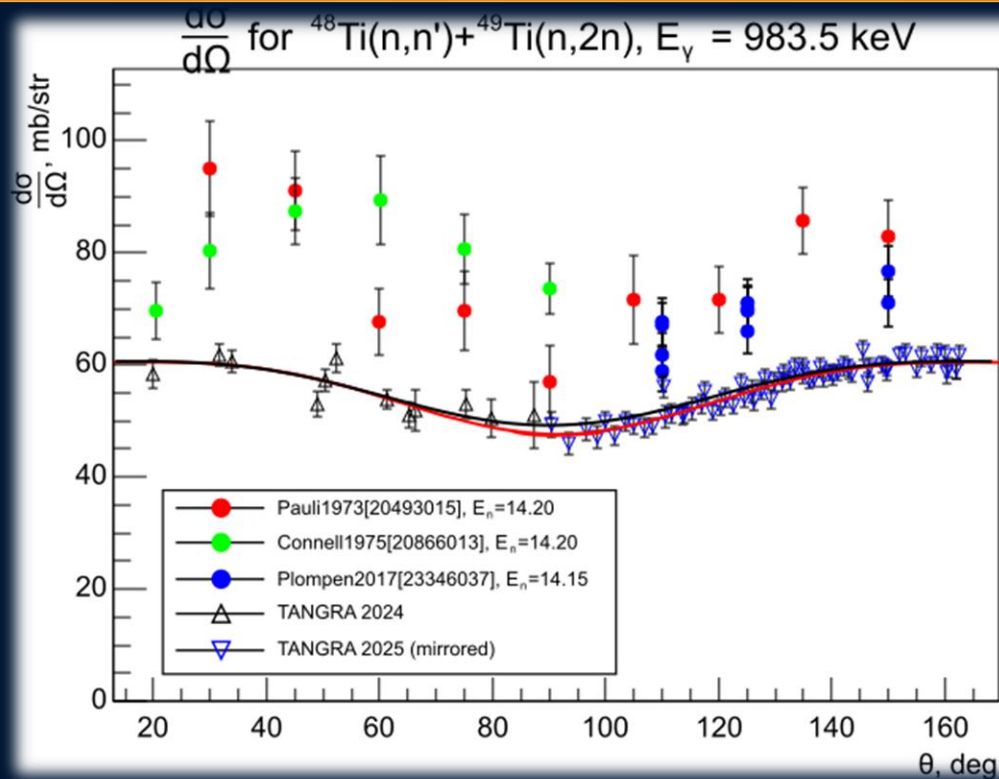
Spectrum below shows impact of different components to sum spectrum.

Peaks from sample marked with red arrows

Comparison of TOF components



# Measurements of the $\gamma$ -quanta emission cross-sections & angular distributions ( $\text{TiO}_2$ sample)



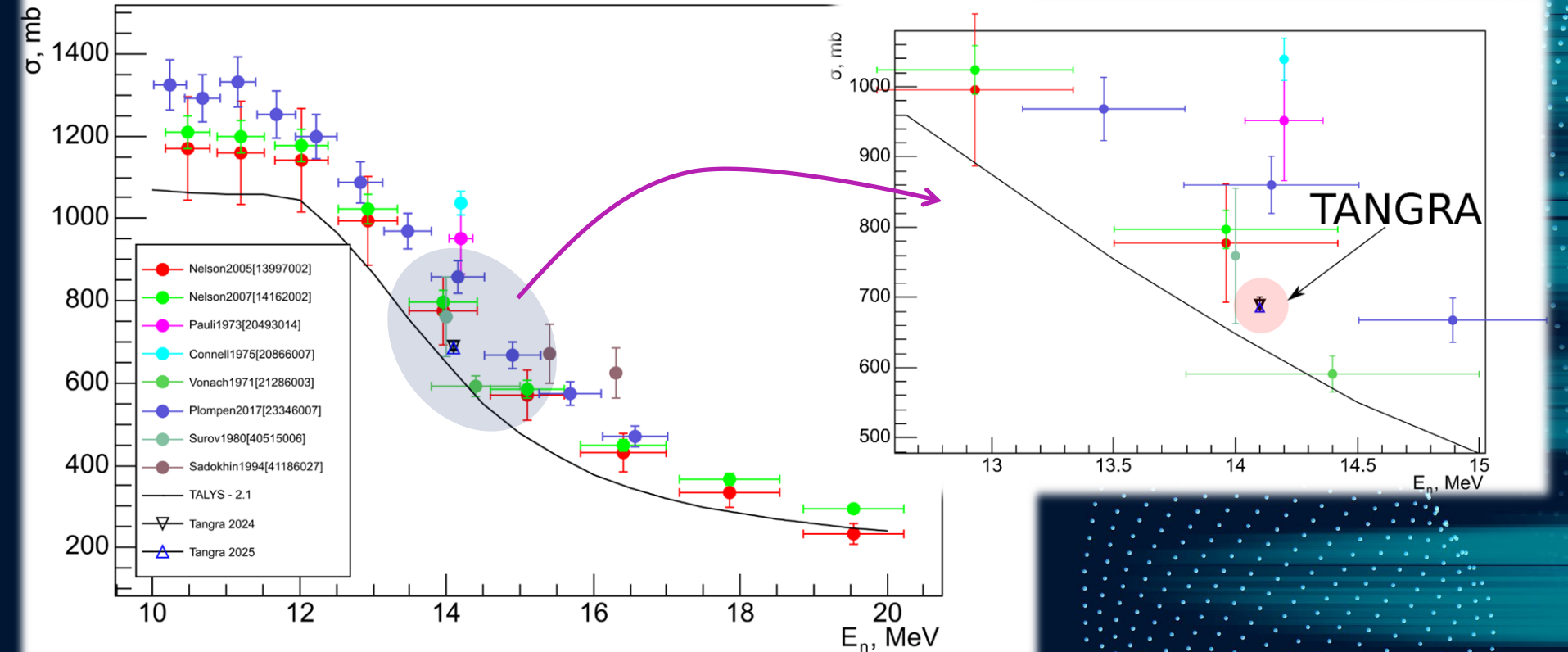
$E_\gamma$ , keV	Reaction	Reference	$\sigma$ , mb	$a_2$	$a_4$
983,5 keV	$^{48}\text{Ti}(n,n')$ $^{49}\text{Ti}(n,2n)$	Pauli 1973	940 (30)	0,31(8)	-0,1(1)
		Connell 1975	1020 (30)	-0,02(5)	-0.26(9)
		Plompen 2017	842 (15)	0,16(4)	-0,08(7)
		TANGRA 2024	690 (10)	0,16(3)	-0,05(4)
		TANGRA 2025	685 (3)	0,18(1)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

• And 19  $\gamma$ -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 $\gamma$ -quanta emission cross-sections & angular distributions ( $\text{TiO}_2$ sample)

Cross-section of 983.5 keV  $\gamma$ -emission



# 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	<b>H</b> 1,0079 1s <sup>1</sup> Водород							<b>H</b>	<b>He</b> 4,00260 1s <sup>2</sup> Гелий	<div>Относительная атомная масса</div> <div>Порядковый (атомный) номер</div> <div>Конфигурация валентных электронов</div> <div>Название</div> <div>Символ</div> <div>Водород</div>						
2	<b>Li</b> 6,941 2s <sup>2</sup> Литий	<b>Be</b> 9,01218 2s <sup>2</sup> Бериллий	<b>B</b> 10,81 2s <sup>2</sup> 2p <sup>1</sup> Бор	<b>C</b> 12,011 2s <sup>2</sup> 2p <sup>2</sup> Углерод	<b>N</b> 14,0067 2s <sup>2</sup> 2p <sup>3</sup> Азот	<b>O</b> 15,9994 2s <sup>2</sup> 2p <sup>4</sup> Кислород	<b>F</b> 18,9984 2s <sup>2</sup> 2p <sup>5</sup> Фтор	<b>Ne</b> 20,179 2s <sup>2</sup> 2p <sup>6</sup> Неон								
3	<b>Na</b> 22,98976928 3s <sup>1</sup> Натрий	<b>Mg</b> 24,304 3s <sup>2</sup> Магний	<b>Al</b> 26,9815386 3s <sup>2</sup> 3p <sup>1</sup> Алюминий	<b>Si</b> 28,0855836 3s <sup>2</sup> 3p <sup>2</sup> Кремний	<b>P</b> 30,973761998 3s <sup>2</sup> 3p <sup>3</sup> Фосфор	<b>S</b> 32,06 3s <sup>2</sup> 3p <sup>4</sup> Сера	<b>Cl</b> 35,453 3s <sup>2</sup> 3p <sup>5</sup> Хлор	<b>Ar</b> 39,948 3s <sup>2</sup> 3p <sup>6</sup> Аргон								
4	<b>K</b> 39,0983 4s <sup>1</sup> Калий	<b>Ca</b> 40,08 4s <sup>2</sup> Кальций	<b>Sc</b> 44,955912 3d <sup>1</sup> 4s <sup>2</sup> Скандий	<b>Ti</b> 47,88 3d <sup>2</sup> 4s <sup>2</sup> Титан	<b>V</b> 50,9415 3d <sup>3</sup> 4s <sup>2</sup> Ванадий	<b>Cr</b> 51,9961 3d <sup>5</sup> 4s <sup>1</sup> Хром	<b>Mn</b> 54,938044 3d <sup>5</sup> 4s <sup>2</sup> Марганец	<b>Fe</b> 55,845 3d <sup>6</sup> 4s <sup>2</sup> Железо	<b>Co</b> 58,933194 3d <sup>7</sup> 4s <sup>2</sup> Кобальт	<b>Ni</b> 58,6934 3d <sup>8</sup> 4s <sup>2</sup> Никель						
5	<b>Rb</b> 85,4678 5s <sup>1</sup> Рубидий	<b>Sr</b> 87,62 5s <sup>2</sup> Стронций	<b>Y</b> 88,90584 4d <sup>1</sup> 5s <sup>2</sup> Иттрий	<b>Zr</b> 91,224 4d <sup>2</sup> 5s <sup>2</sup> Цирконий	<b>Nb</b> 92,90638 4d <sup>4</sup> 5s <sup>1</sup> Нобий	<b>Mo</b> 95,94 4d <sup>5</sup> 5s <sup>1</sup> Молибден	<b>Tc</b> 98 4d <sup>5</sup> 5s <sup>2</sup> Технеций	<b>Ru</b> 101,07 4d <sup>7</sup> 5s <sup>1</sup> Рутений	<b>Rh</b> 102,905 4d <sup>8</sup> 5s <sup>1</sup> Родий	<b>Pd</b> 106,905 4d <sup>10</sup> Палладий						
6	<b>Cs</b> 132,905 6s <sup>1</sup> Цезий	<b>Ba</b> 137,327 6s <sup>2</sup> Барий	<b>La*</b> 138,9048 5d <sup>1</sup> 6s <sup>2</sup> Лантан	<b>Hf</b> 178,49 5d <sup>2</sup> 6s <sup>2</sup> Гафний	<b>Ta</b> 180,94788 5d <sup>3</sup> 6s <sup>2</sup> Тантал	<b>W</b> 183,84 5d <sup>4</sup> 6s <sup>2</sup> Вольфрам	<b>Re</b> 186,207 5d <sup>5</sup> 6s <sup>2</sup> Рений	<b>Os</b> 190,2 5d <sup>6</sup> 6s <sup>2</sup> Осмий	<b>Ir</b> 192,22 5d <sup>7</sup> 6s <sup>2</sup> Иридий	<b>Pt</b> 195,08 5d <sup>9</sup> 6s <sup>1</sup> Платина						
7	<b>Fr</b> [223] 7s <sup>1</sup> Франций	<b>Ra</b> [226] 7s <sup>2</sup> Радий	<b>Ac**</b> [227] 6d <sup>1</sup> 7s <sup>2</sup> Актиний	<b>Rf</b> [261] 6d <sup>2</sup> 7s <sup>2</sup> Резерфордий	<b>Db</b> [262] 6d <sup>3</sup> 7s <sup>2</sup> Дубний	<b>Sg</b> [266] 6d <sup>4</sup> 7s <sup>2</sup> Сибиргий	<b>Bh</b> [269] 6d <sup>5</sup> 7s <sup>2</sup> Борий	<b>Hs</b> [271] 6d <sup>6</sup> 7s <sup>2</sup> Гассий	<b>Mt</b> [272] 6d <sup>7</sup> 7s <sup>2</sup> Мейтнерий	<b>Ds</b> [277] 6d <sup>8</sup> 7s <sup>1</sup> Дармштадтий						
	<b>Rg</b> [280] Рентгеней	<b>Cn</b> [285] Коперниций	<b>Nh</b> [286] Нихоний	<b>Fl</b> [289] Флеровий	<b>Mc</b> [293] Московский	<b>Lv</b> [294] Ливерморий	<b>Ts</b> [294] Теннессин	<b>Og</b> [294] Оганесон								

2024

2025

58 <b>Ce</b> 140,12 4f <sup>1</sup> 5d <sup>1</sup> 6s <sup>2</sup> Церий	59 <b>Pr</b> 140,908 4f <sup>3</sup> 6s <sup>2</sup> Празеодим	60 <b>Nd</b> 144,24 4f <sup>4</sup> 6s <sup>2</sup> Неодим	61 <b>Pm</b> [145] 4f <sup>5</sup> 6s <sup>2</sup> Прометий	62 <b>Sm</b> 150,36 4f <sup>6</sup> 6s <sup>2</sup> Самарий	63 <b>Eu</b> 151,96 4f <sup>7</sup> 6s <sup>2</sup> Европий	64 <b>Gd</b> 157,25 4f <sup>7</sup> 5d <sup>1</sup> 6s <sup>2</sup> Гадолиний	65 <b>Tb</b> 158,925 4f <sup>9</sup> 6s <sup>2</sup> Тербий	66 <b>Dy</b> 162,50 4f <sup>10</sup> 6s <sup>2</sup> Диспрозий	67 <b>Ho</b> 164,930 4f <sup>11</sup> 6s <sup>2</sup> Гольмий	68 <b>Er</b> 167,26 4f <sup>12</sup> 6s <sup>2</sup> Эрбий	69 <b>Tm</b> 168,934 4f <sup>13</sup> 6s <sup>2</sup> Тулий	70 <b>Yb</b> 173,04 4f <sup>14</sup> 6s <sup>2</sup> Итербий	71 <b>Lu</b> 174,967 4f <sup>14</sup> 5d <sup>1</sup> 6s <sup>2</sup> Лютеций
90 <b>Th</b> 232,038 6d <sup>2</sup> 7s <sup>2</sup> Торий	91 <b>Pa</b> [231] 5f <sup>2</sup> 6d <sup>1</sup> 7s <sup>2</sup> Протактиний	92 <b>U</b> [238] 5f <sup>3</sup> 6d <sup>1</sup> 7s <sup>2</sup> Уран	93 <b>Np</b> [237] 5f <sup>4</sup> 6d <sup>1</sup> 7s <sup>2</sup> Нептуний	94 <b>Pu</b> [244] 5f <sup>6</sup> 7s <sup>2</sup> Плутоний	95 <b>Am</b> [243] 5f <sup>7</sup> 7s <sup>2</sup> Америций	96 <b>Cm</b> [247] 5f <sup>7</sup> 6d <sup>1</sup> 7s <sup>2</sup> Кюрий	97 <b>Bk</b> [247] 5f <sup>9</sup> 6d <sup>1</sup> 7s <sup>2</sup> Берклий	98 <b>Cf</b> [251] 5f <sup>10</sup> 7s <sup>2</sup> Калифорний	99 <b>Es</b> [252] 5f <sup>11</sup> 7s <sup>2</sup> Эйнштейний	100 <b>Fm</b> [257] 5f <sup>12</sup> 7s <sup>2</sup> Фермий	101 <b>Md</b> [258] 5f <sup>13</sup> 7s <sup>2</sup> Менделевий	102 <b>No</b> [259] 5f <sup>14</sup> 7s <sup>2</sup> Нобелий	103 <b>Lr</b> [260] 5f <sup>14</sup> 6d <sup>1</sup> 7s <sup>2</sup> Лоуренсий



# 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  $\gamma$ -peak

Incident angle

Number of tagged neutrons

Surface density of atoms in the sample

Total reaction cross section

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

- 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

Multiple inelastic scattering

Attenuation of incident neutron

Attenuation of  $\gamma$ -rays

Sample thickness

The total efficiency

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

# 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  $\gamma$ -rays
- Attenuation of incident neutrons and  $\gamma$ -rays understates the number of emitted  $\gamma$ -rays

Simulation features:

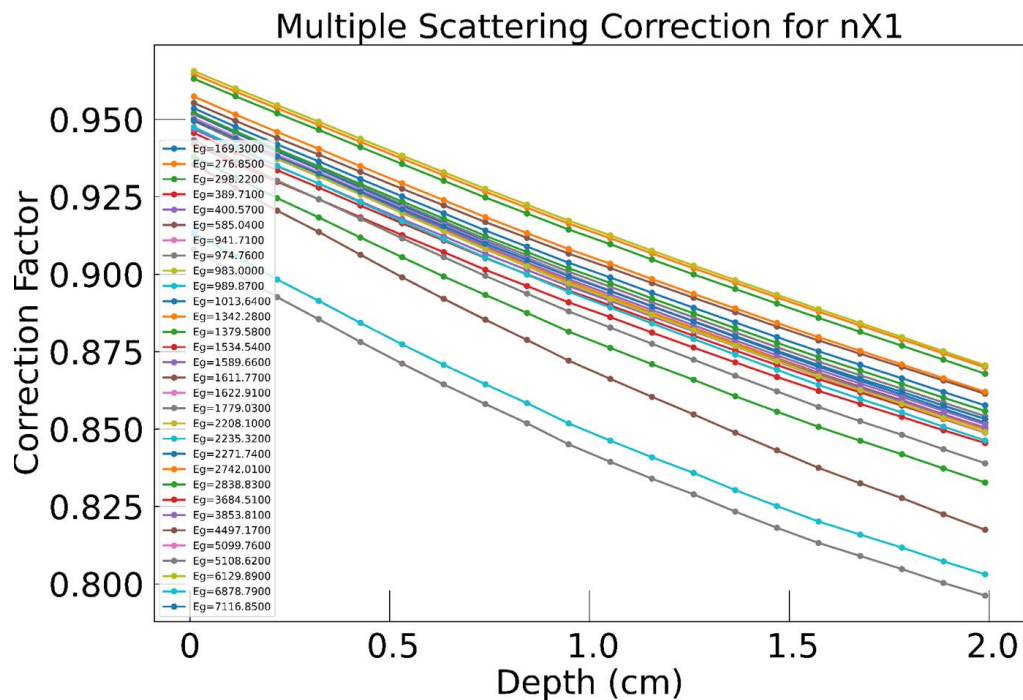
- 2 stage - neutron transport and  $\gamma$ -rays transport simulation
- The inelastic multiple scattering is used as a probability factor increasing the number of emitted  $\gamma$ -rays in comparison with its real number
- The inelastic multiple scattering correction calculates taking into account the energy dependence of emission cross section for specific  $\gamma$ -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

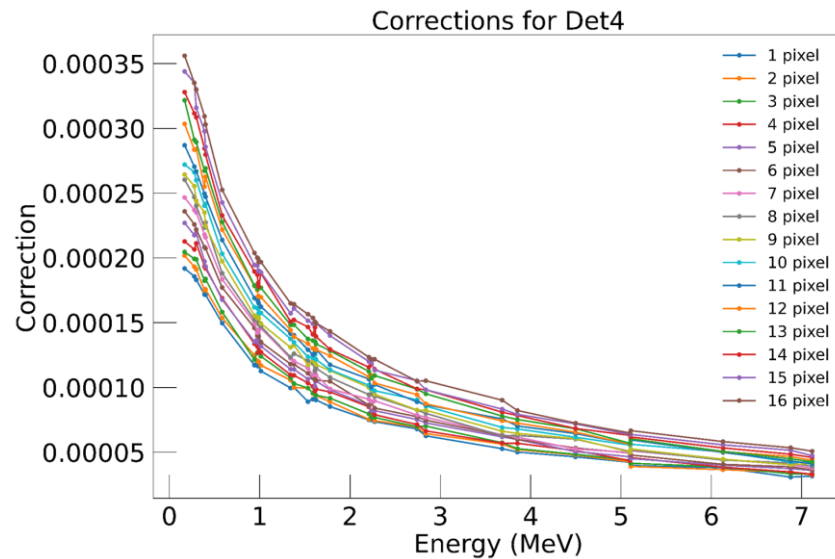
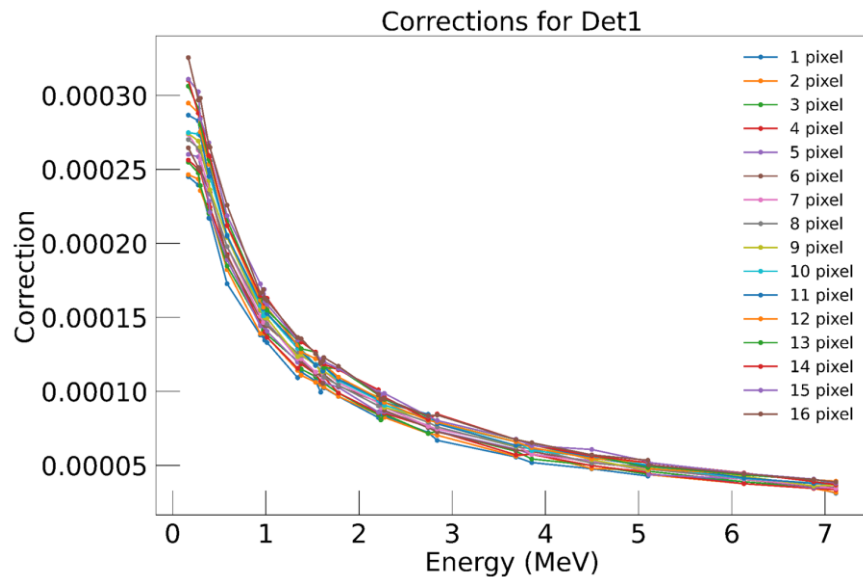
Simulation of  $\gamma$ -rays detection efficiency emitting them from the interaction points

# Example of the multiple scattering correction



Multiple scattering correction factor depending on the sample thickness. The example corresponding to the  $\text{SiO}_2$  sample and first vertical strip

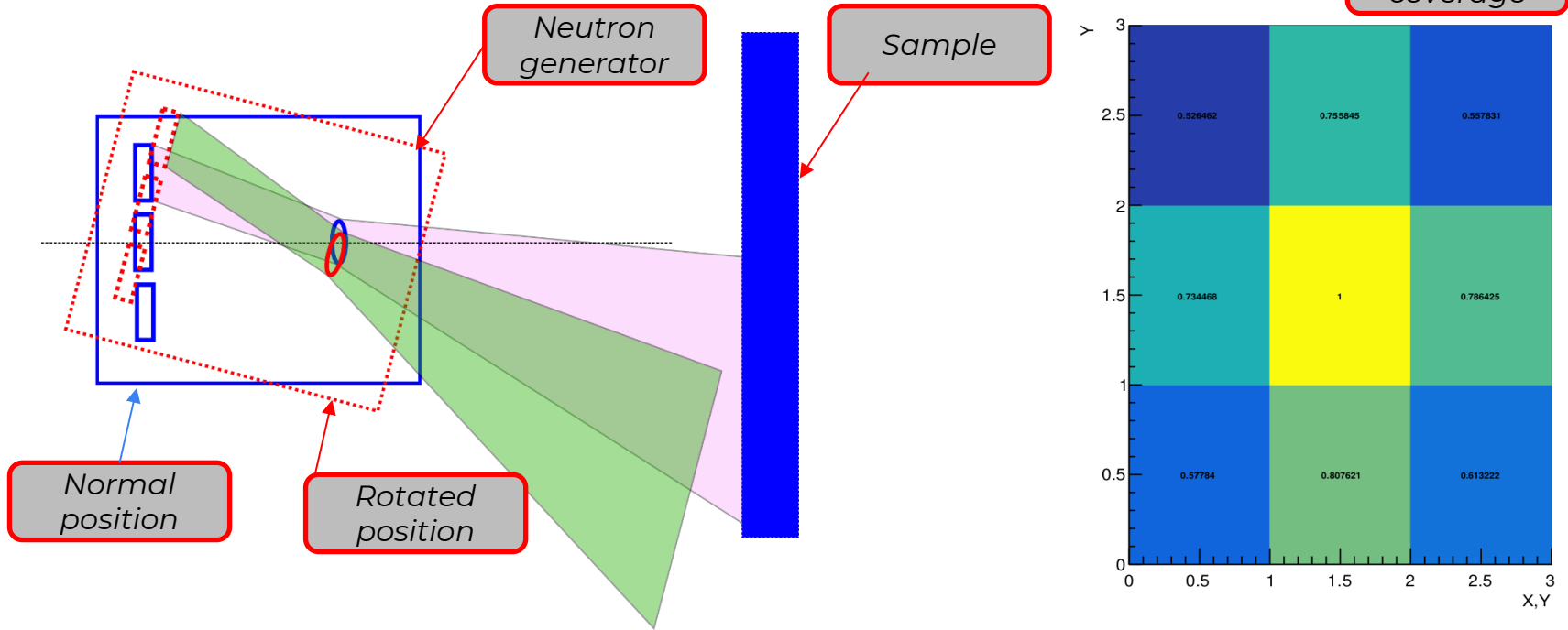
# Integrated correction factors using the example of the $\text{SiO}_2$ sample



The correction factors including the attenuation correction, total efficiency and multiple inelastic scattering corresponding to the various  $\text{LaBr}_3$  detectors



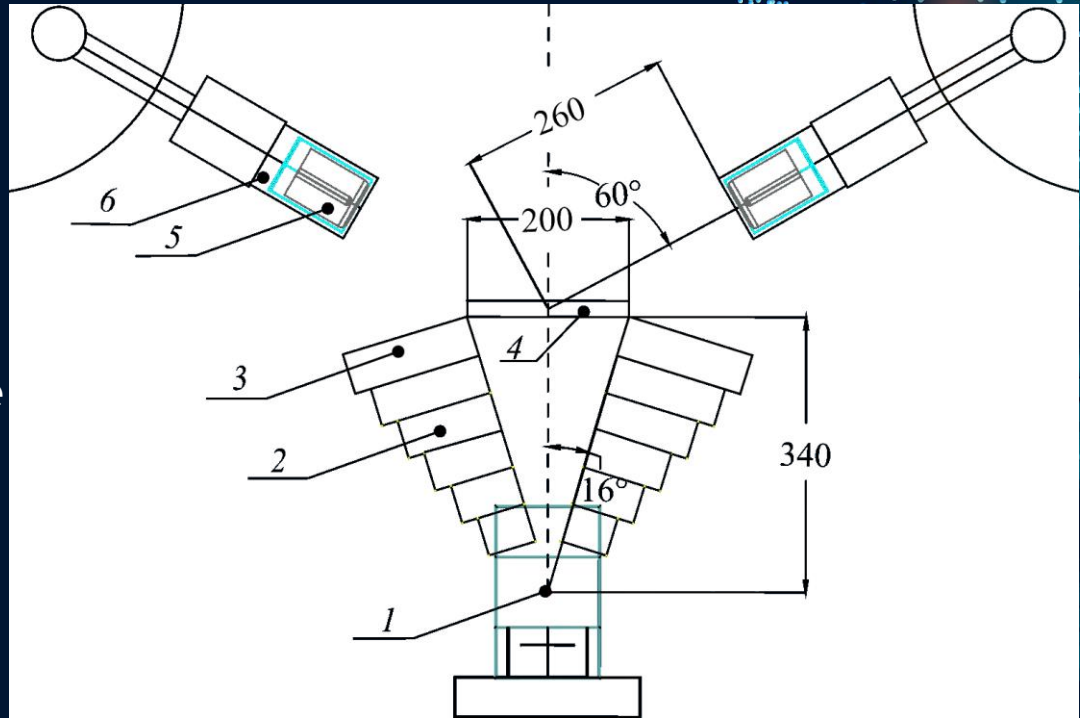
# Main source of systematic uncertainties



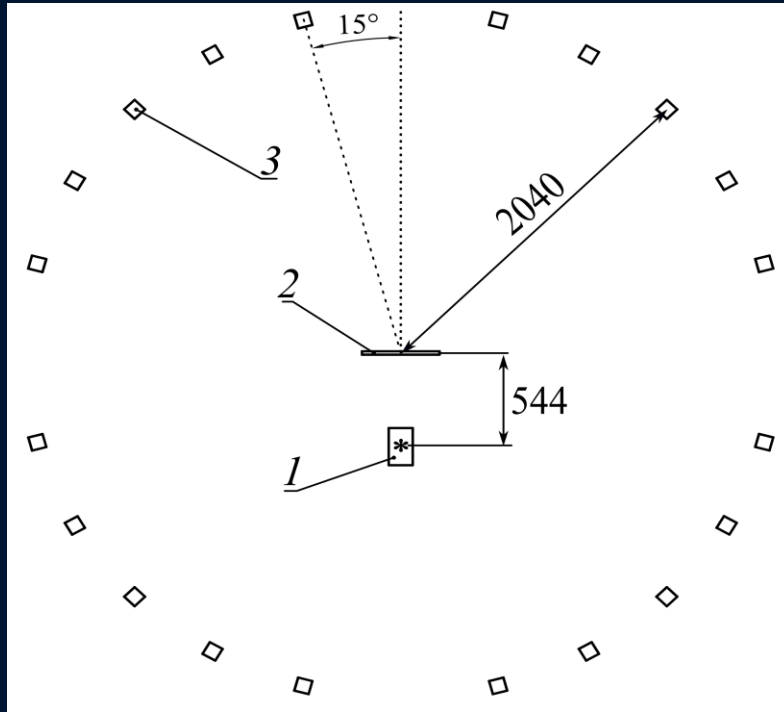
Small rotation of the NG could lead to dramatic change of target coverage. It could be corrected by relative calibration to central pixel and rotation angle could be adjusted to minimize CS difference between pix-det combinations with small difference in angle

# Configuration for $\gamma$ -quanta emission CS measurement

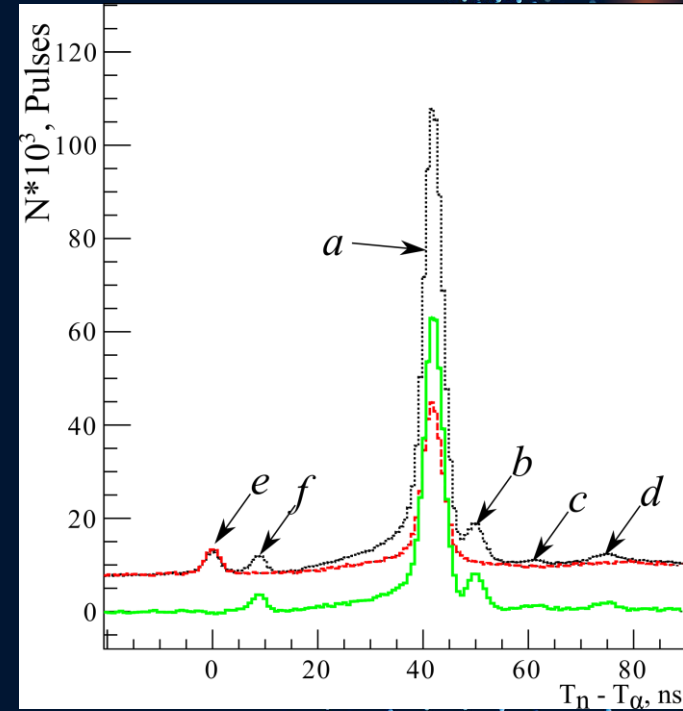
- 1-ING-27, 2-iron-, 3-lead parts of the collimator, 4-sample, 5-HPGe crystal, 6-case of the detector.
- Updated “HPGe” setup contains two ORTEC-made spectrometers with relative efficiency of 60%
- Set of LaBr detectors will be used to measure the  $\gamma$ -angular distribution



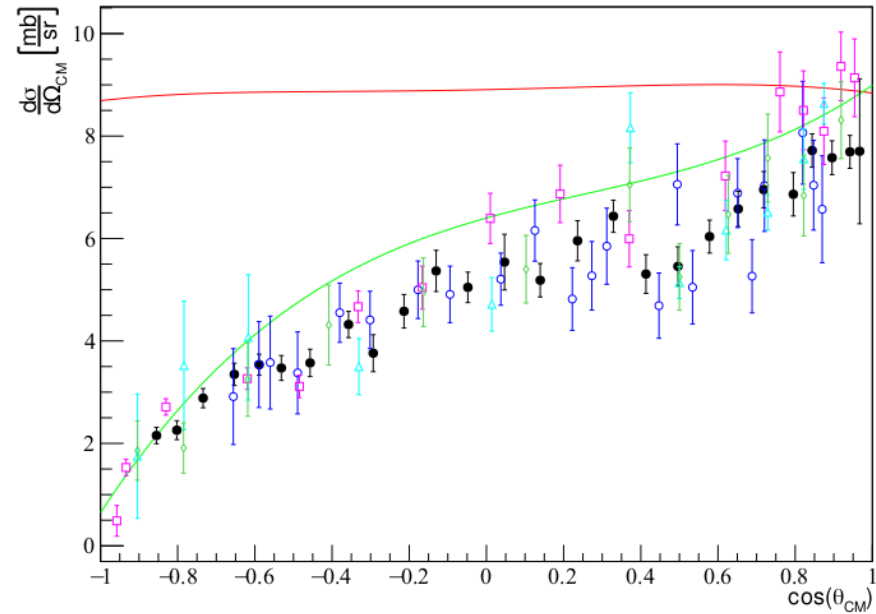
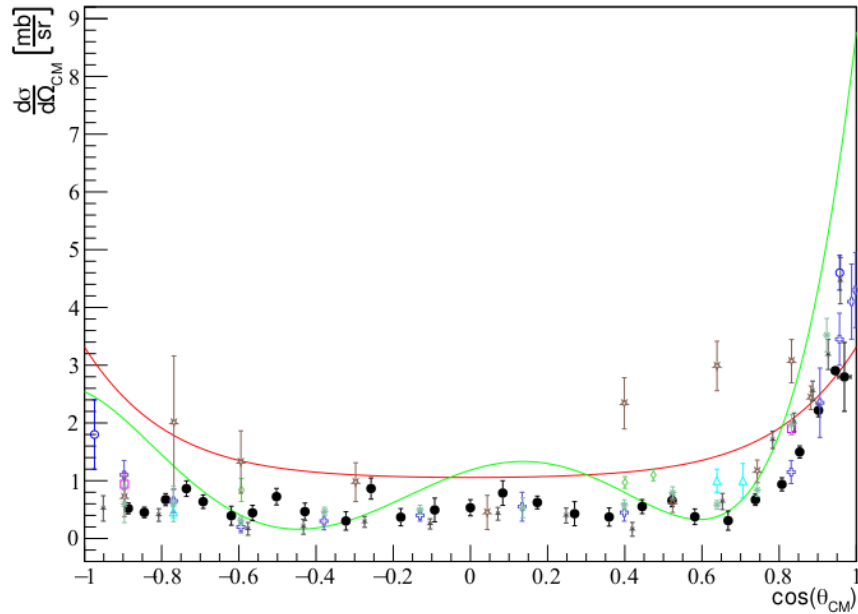
# Measurement of $n'$ angular distributions and $n'$ $\gamma$ correlations



- 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* -  $\gamma$ -quanta emitted from case of the ING-27, *f* -  $\gamma$  from sample



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

- 9.6+9.8+9.9 MeV states