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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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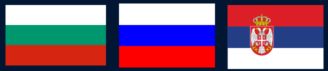
TANGRA collaboration

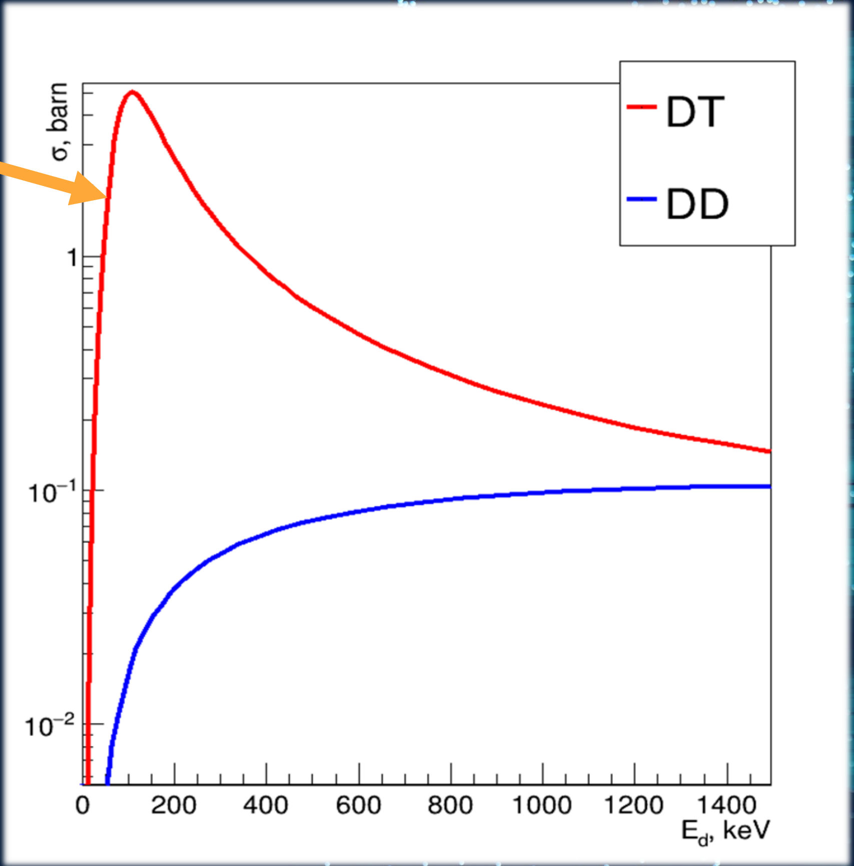
TAgged Neutrons & Gamma RAys

- 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

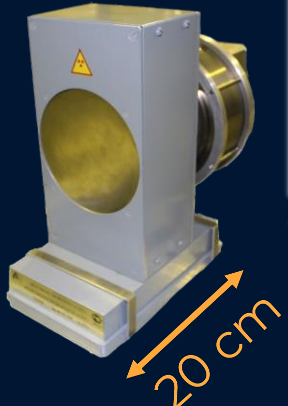
$$^{2}H + ^{2}H \rightarrow ^{3}He + n + 3.27\ MeV$$

$$^{2}H + ^{3}H \rightarrow ^{4}He + n + 17.6\ MeV$$

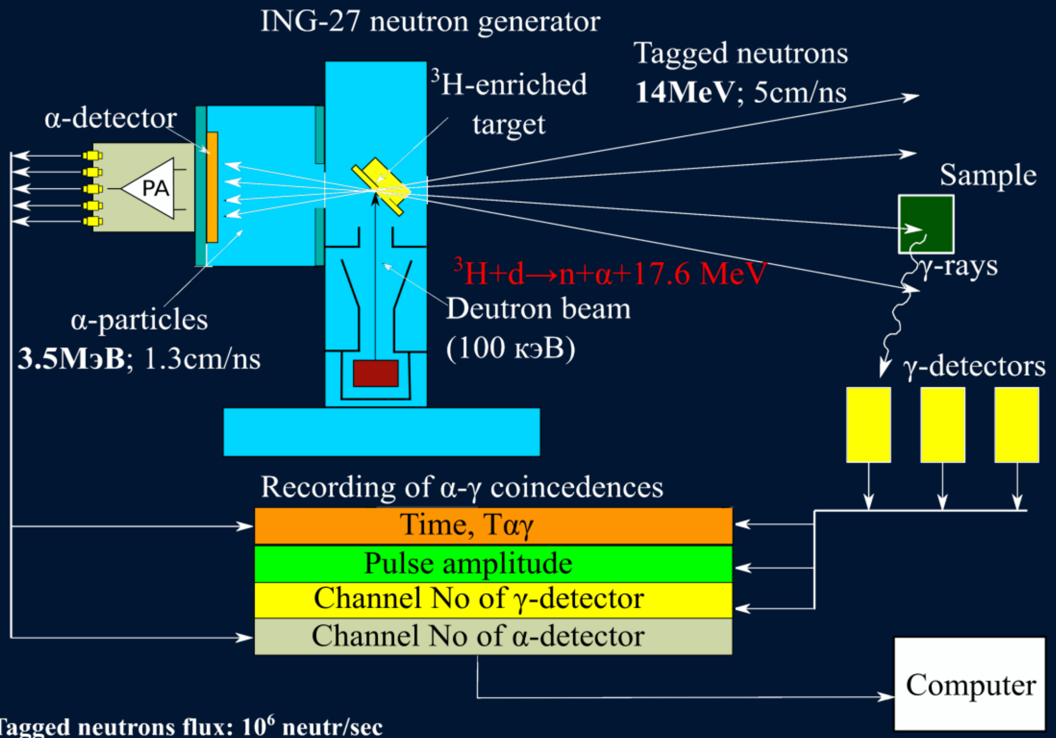
- Features:
- Low threshold
- High energy outcome
- Only two particles in products
- *Very suitable for neutron production*
- *Products move in opposite directions →*
- *Register one → determine direction for another!*



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



Idea of the Tagged neutron method (TNM)



Tagged neutrons flux: 10^6 neutr/sec

Interesting for nuclear reactions research:

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

\+ 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

What we know about (n,xγ)?

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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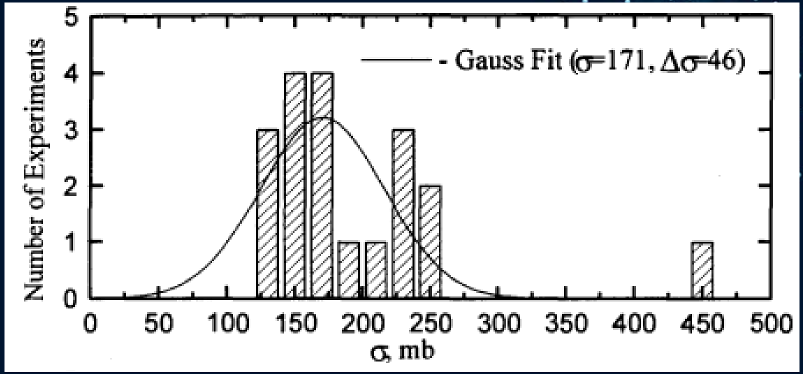
IAEA NUC

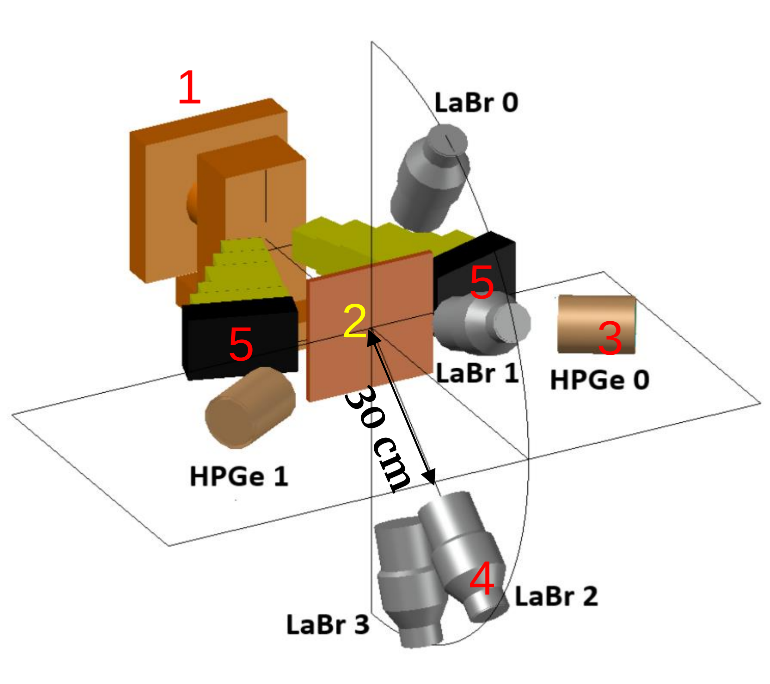


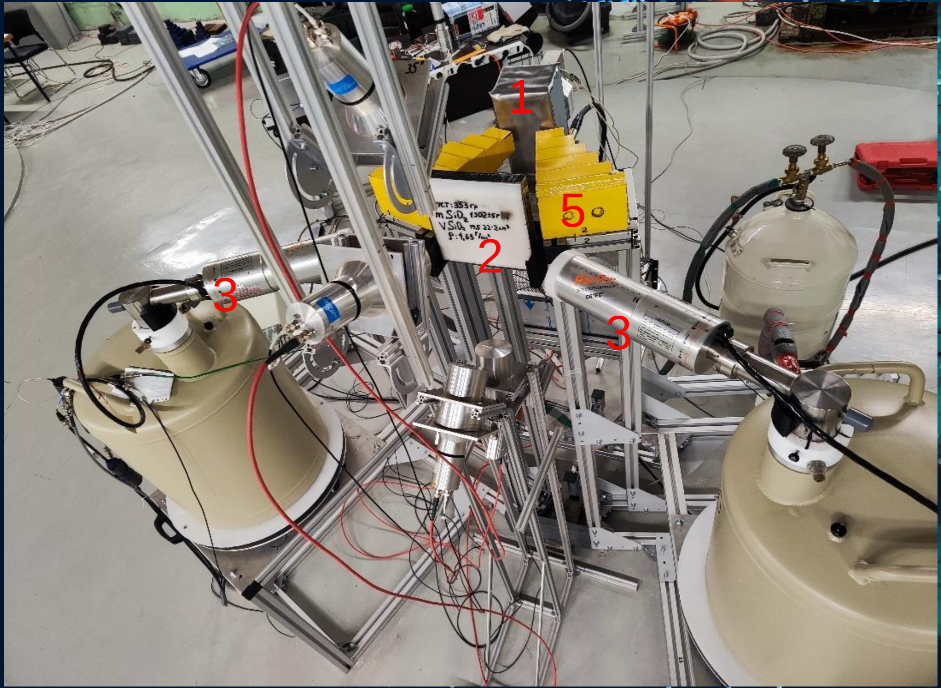
Discrepancy in two times!

Eγ,	Reaction	Transition	E,	Angle,	Sample	Detect.	σ,	Author	Publ	Correction			Corrected σ
4439	$^{12}C(n,n')^{12}C$	$4439(2^+)\to0(0^+)$, p	14.1	30-150	Ø30×Ø26×70, +/+	Ge	180±7	Murata	1988	?	1.0	-14.8	165±7
			14.2	45-130	Ø44×6,Ø31×Ø25×32,+/+	NaI(Tl)	228±30	Drake	1978	1.0	1.0	-11.1	217±30
			14.2	55	C:Ø30×40, +/+	Ge(Li)	156±28	Hino	1976	1.0	1.0	-11.1	145±28
			14	0-180	Ø60×Ø20, +/-	NaI(Tl)	255±26	Bezotosny	1976	1.0	1.0	-18.5	237±26
			14.2	125	C:Ø483×Ø279×25, +/+	Ge(Li)	168±20	Rogers	1975	1.0	1.0	-11.1	157±20
			14.2	45-125	No Information, +/+	NaI(Tl)	219±29	Arthur	1975	1.0	1.0	-11.1	208±29
			14.1	90	C:Ø50×30, +/+	Ge(Li)	121±20	Clayeux	1969	1.0	1.07	-14.8	115±21
			14.2	0-180	Shell ??, +/+	NaIpair	163±30	Maslov	1968	1.0	1.0	-11.1	152±30
			14	No Inf	C:Ø60×30, +/+	NaI(Tl)	133±17	Bezotosny	1966	1.0	?	-18.5	115±17
			14.1	30-160	C:Ø??×20, +/+	NaI(Tl)	232±18	Stewart	1964	1.0	1.0	-14.8	217±18
			=14	30-150	C:Ø165×Ø115×25, +/+	NaI	249±28	Benveniste	1960	1.0	1.0	-18.5	230±28

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

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



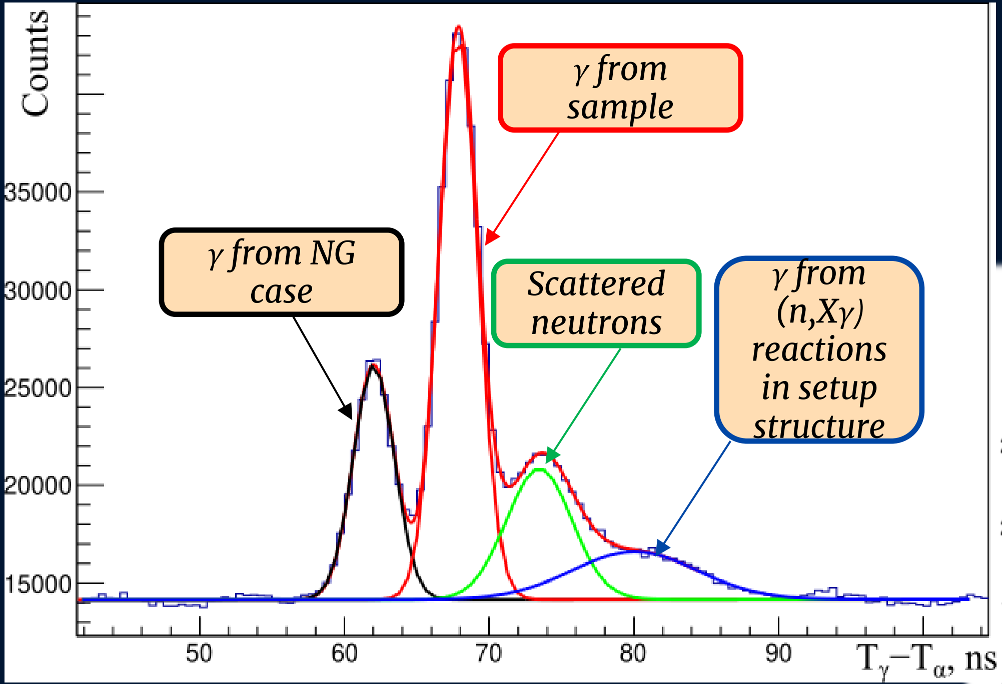


1) ING-27 neutron generator
2) sample 20×20×X cm
3) HPGe γ-detector (2 pcs, 60% eff)
4) $LaBr_3$ γ-detector (4 pcs)

\+ Fast measurement

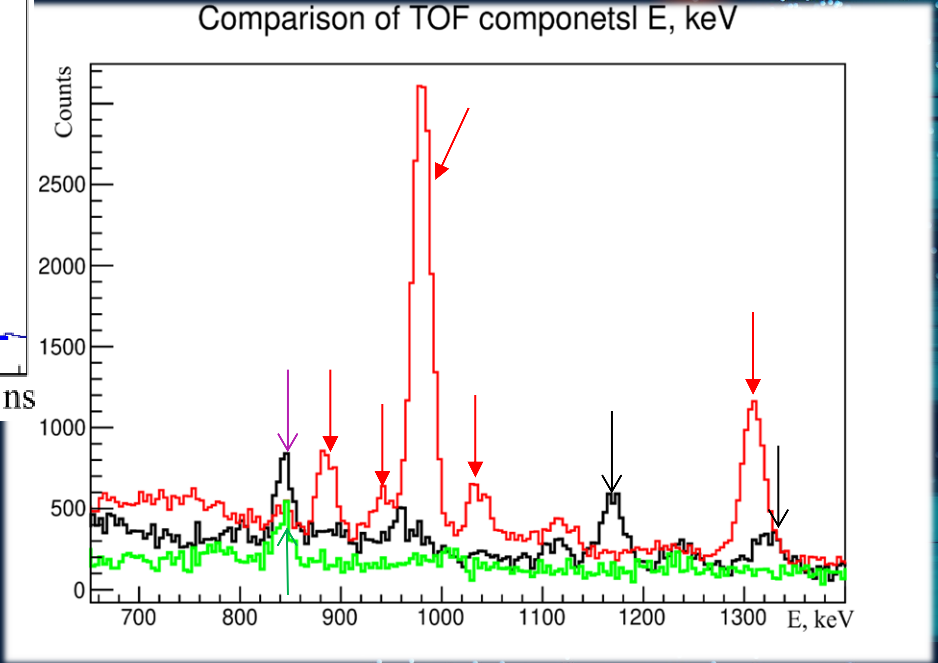
\- Extreme detector load (~8×10^4 cps)

Data processing with TNM



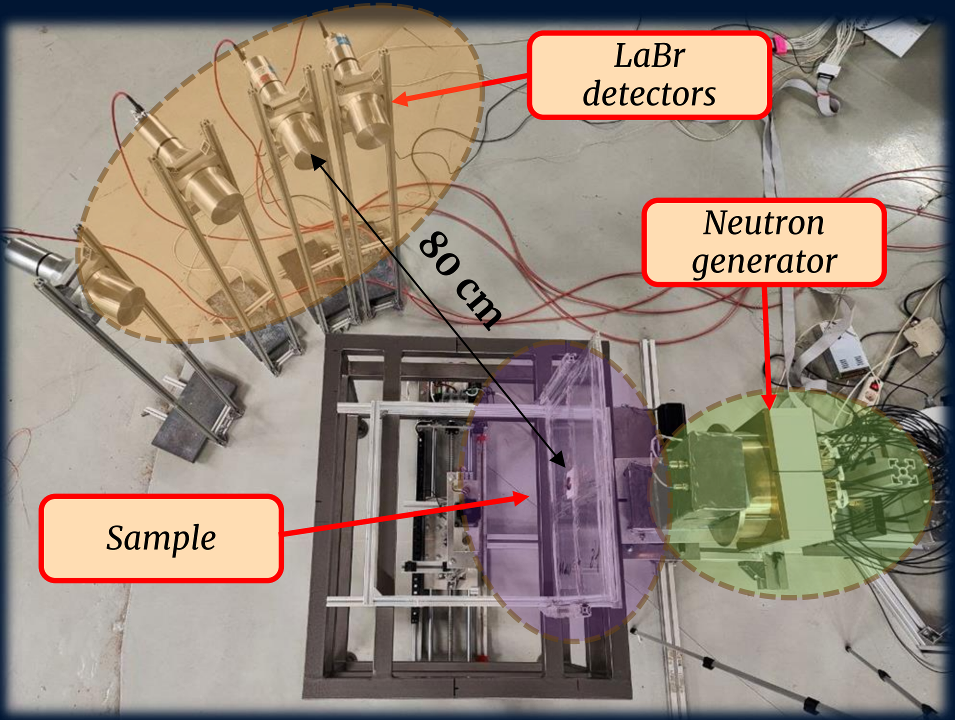
Spectrum below shows impact of different components to sum spectrum.

Peaks from sample marked with red arrows

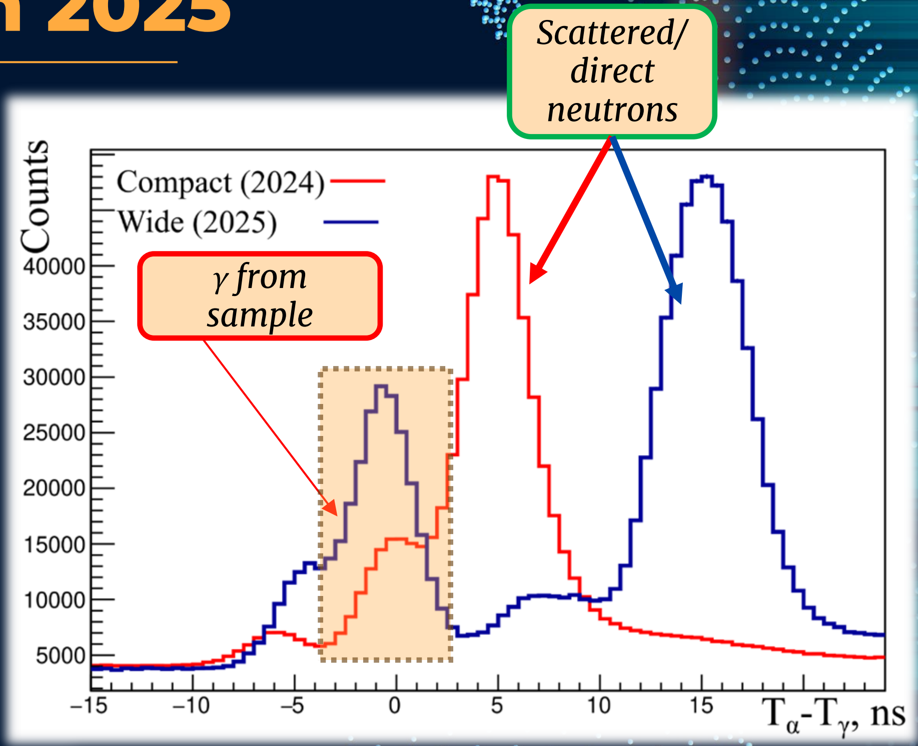


Main idea – separation of the background events by TOF

Verification campaign in 2025



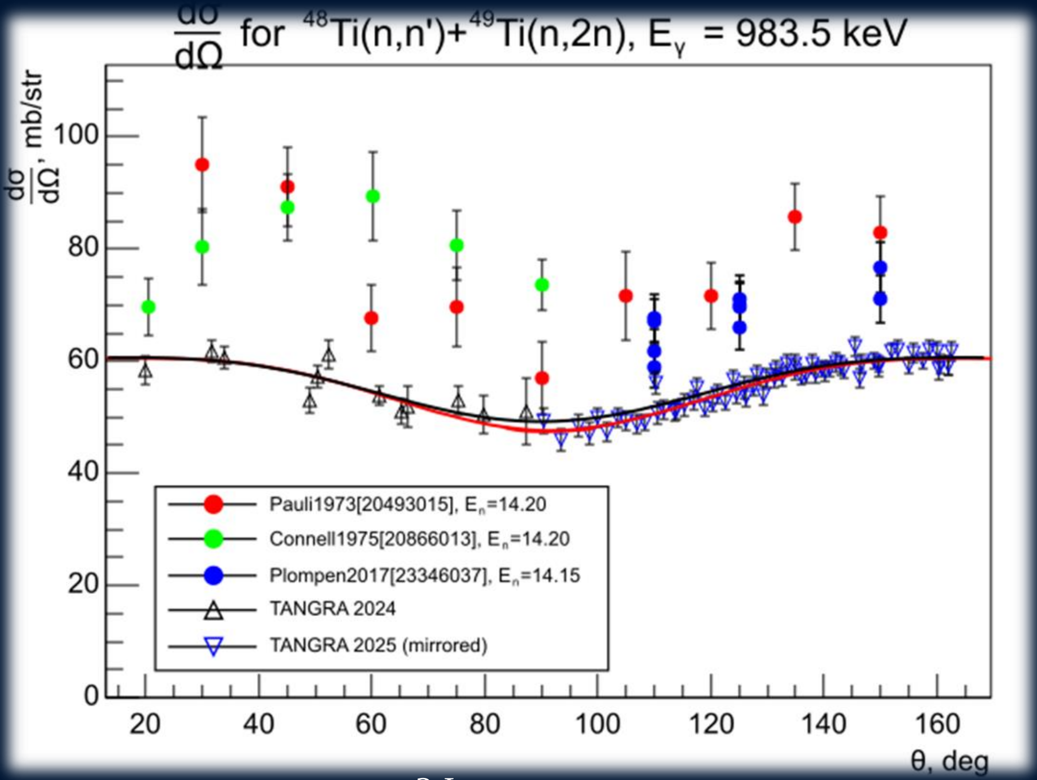
Data processing in compact version is *very sophisticated*



To verify obtained data another version of setup was created

n– γ separation –> pbr ratio significantly improved

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

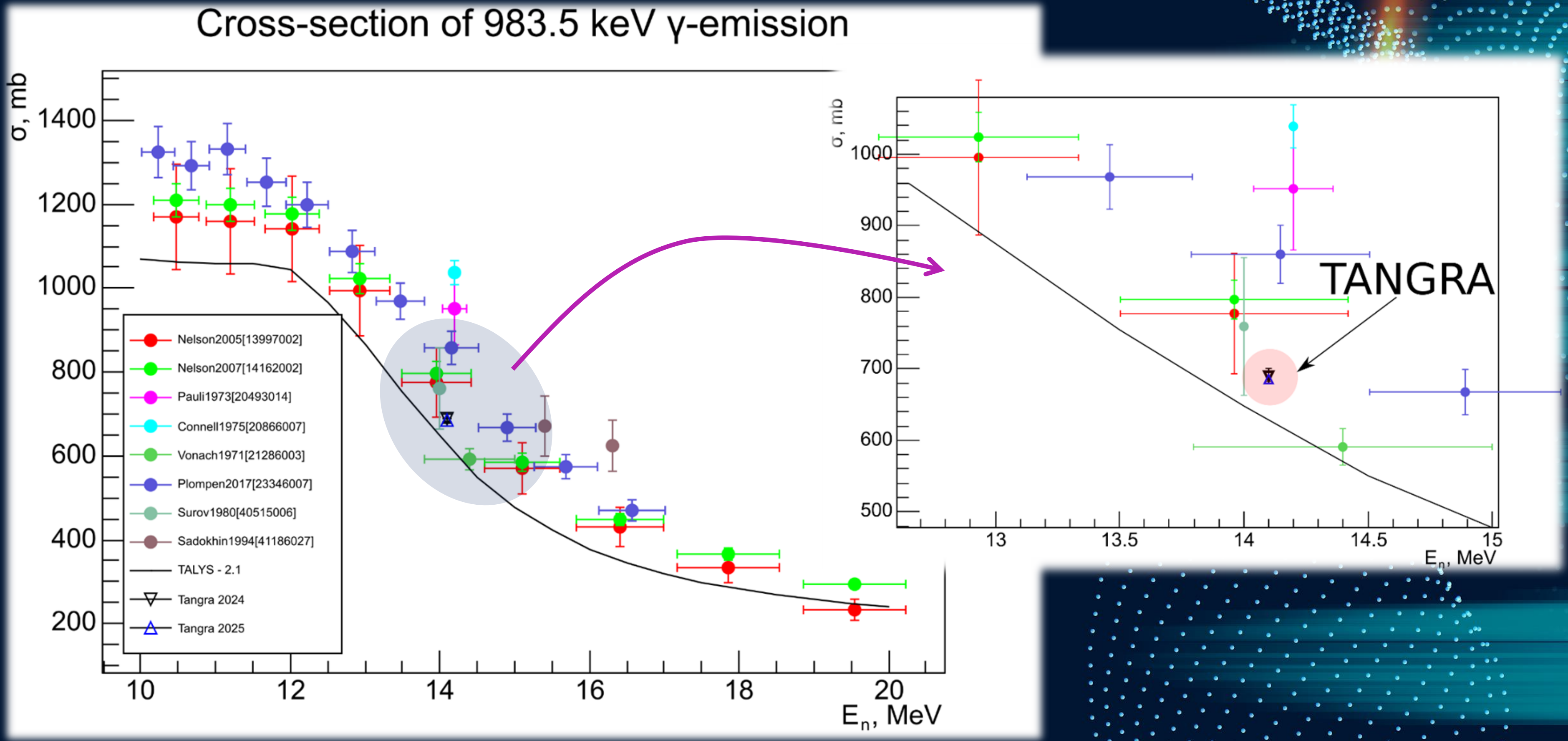


$$\frac{d\sigma}{d\Omega} = \frac{\sigma}{4\pi} \sum_{l=0,2,4...}^{2J} P_l(\cos(\theta))$$

Eγ, keV	Reaction	Reference	σ, mb	a_2	a_4
983,5 keV	^{48}Ti(n,n') ^{49}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)

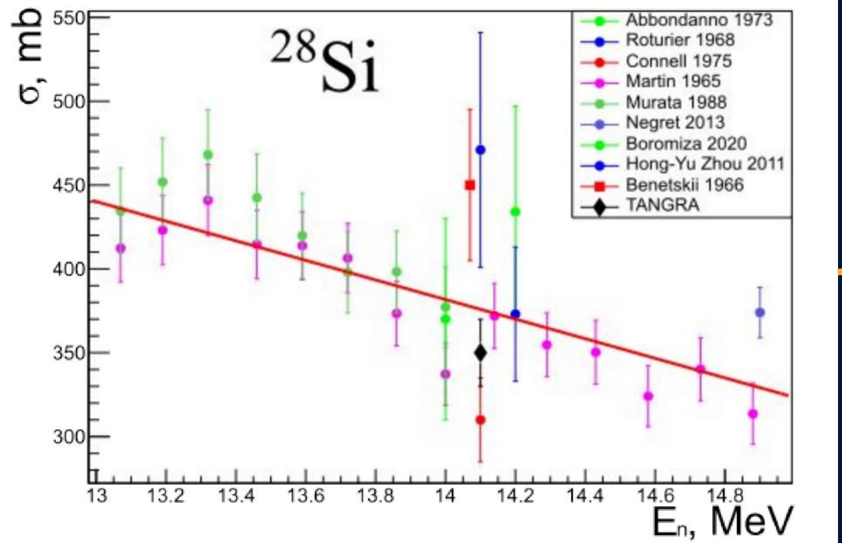
- And 19 γ-lines more

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



What is the purpose of this all?
Applied physics

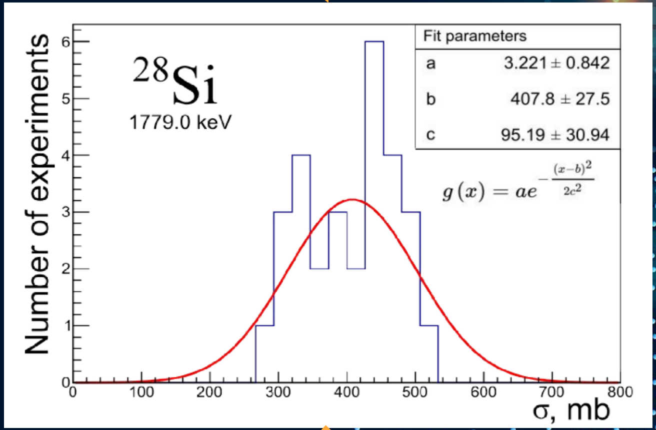
- Cross-sections of γ-quanta emission are needed for fast elemental analysis, **but**



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

*Data extracted from EXFOR using TalysLib

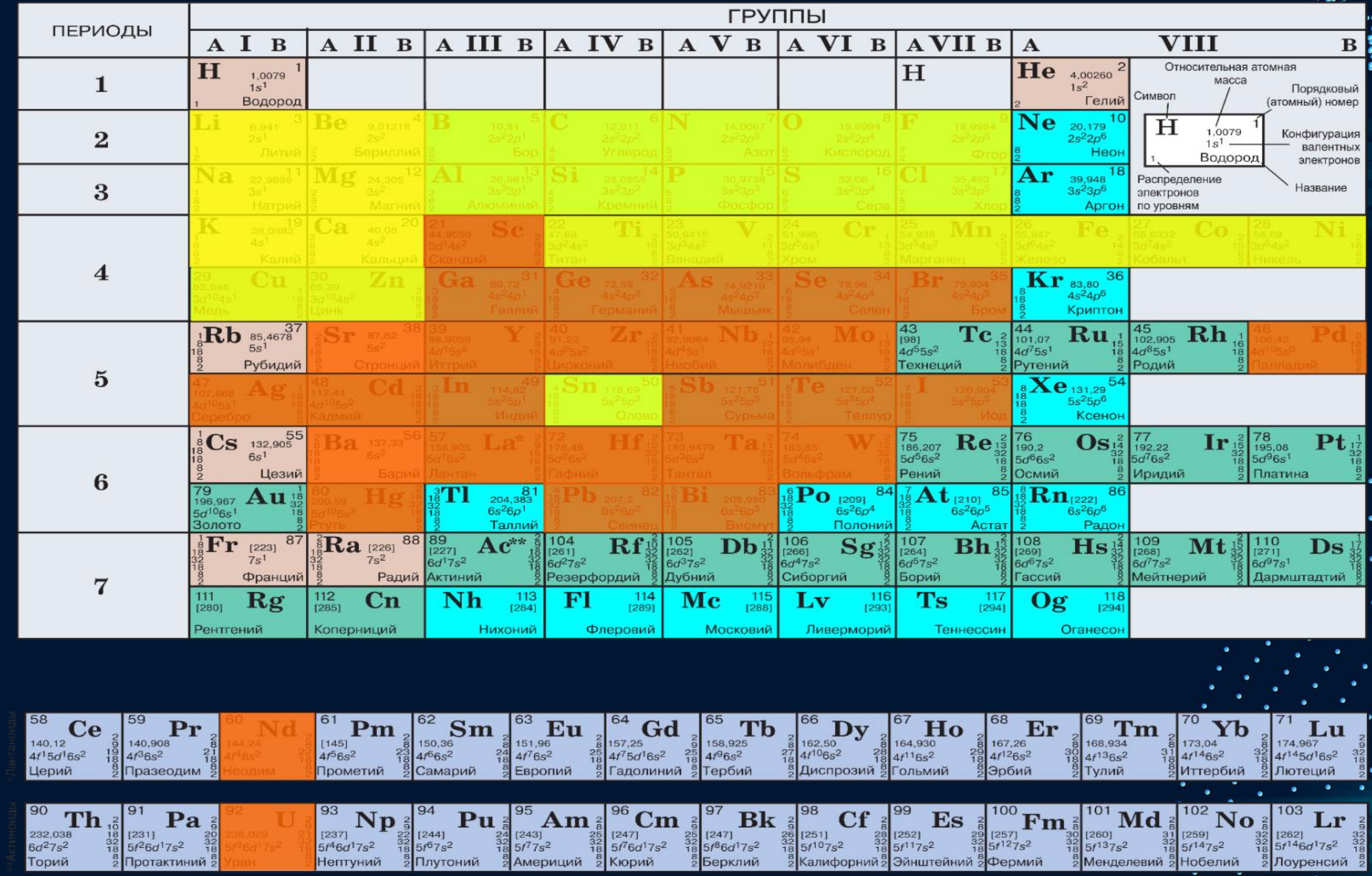
Correction on energy dependence



Estimated σ=408±28 mb

Crucial advantage of TNM – direct count of neutrons

Current status of measurements



2024

2025

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

Area of γ-peak

Incident angle

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

Number of tagged neutrons

Surface density of atoms in the sample

Total reaction cross section

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

Multiple inelastic scattering

Attenuation of incident neutron

Attenuation of γ-rays

Sample thickness

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

The total efficiency

- 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

Algorithm for determining the correction factor

There are two ways to calculate corrections:

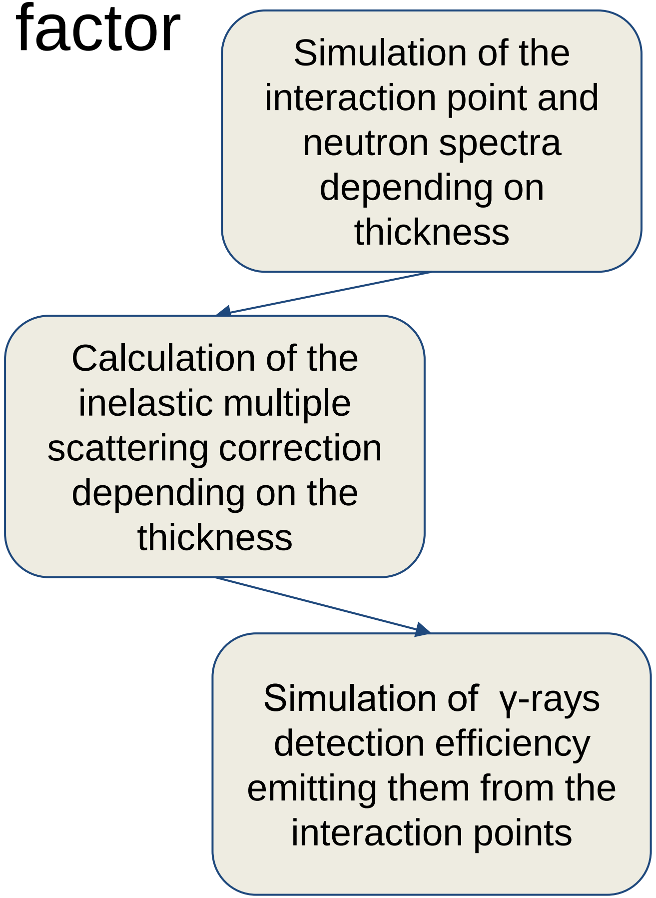
- To calculate them independently in dependence on the sample thickness and take the integral
- **To simulate the total thickness-integrated correction in the GEANT4 using a separate ones as weighting factors**

Correction features:

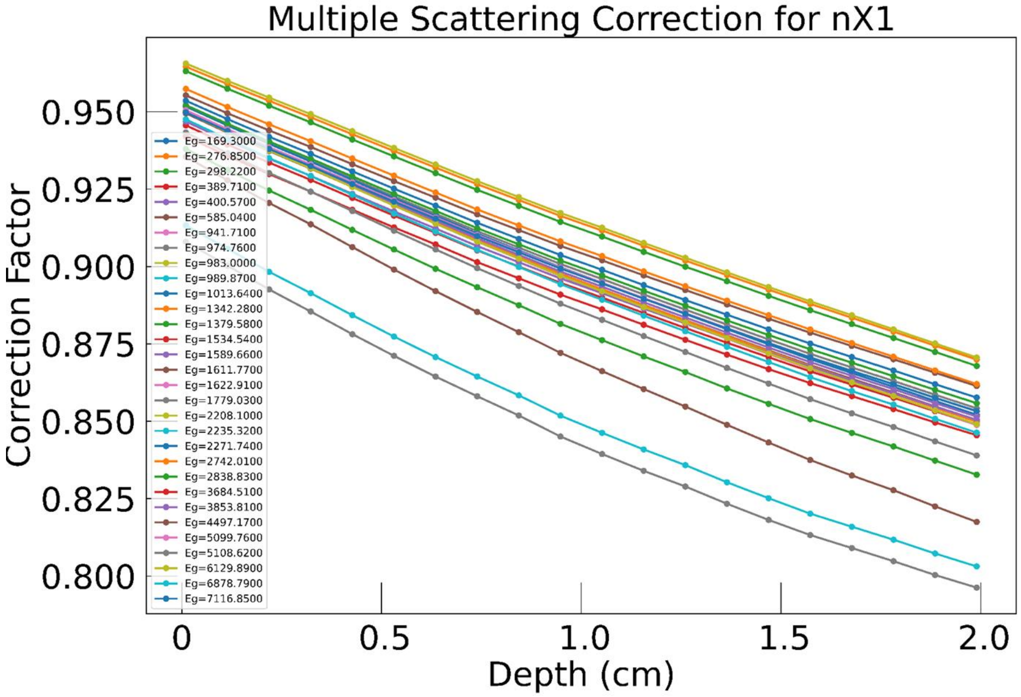
- Multiple inelastic scattering overstates the number of emitted γ-rays
- Attenuation of incident neutrons and γ-rays understates the number of emitted γ-rays

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

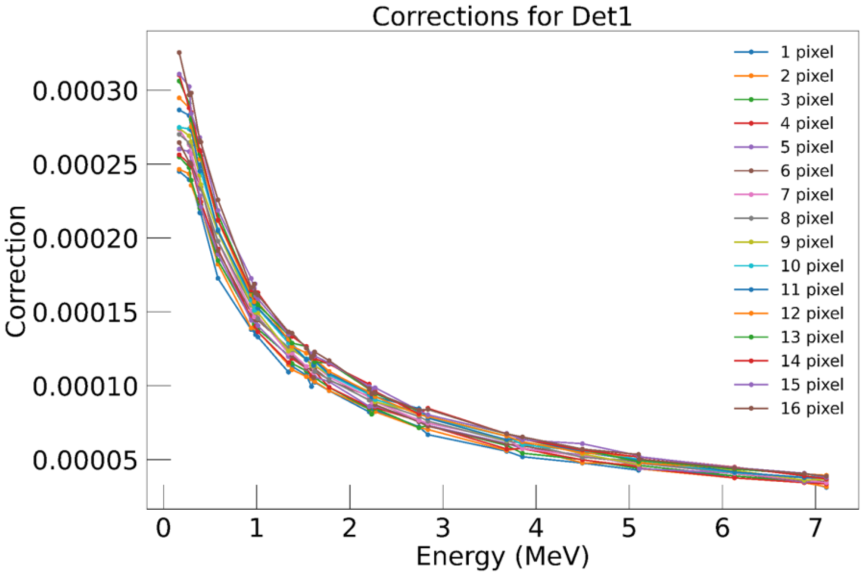


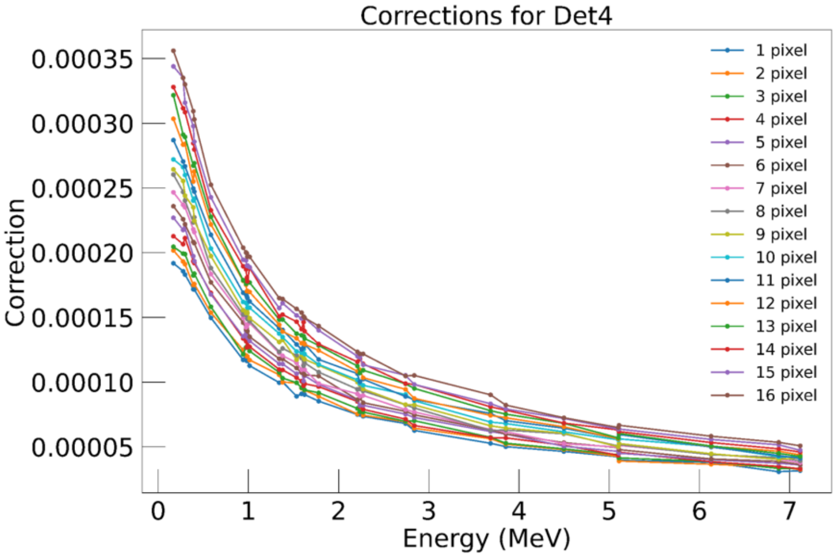
Example of the multiple scattering correction



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

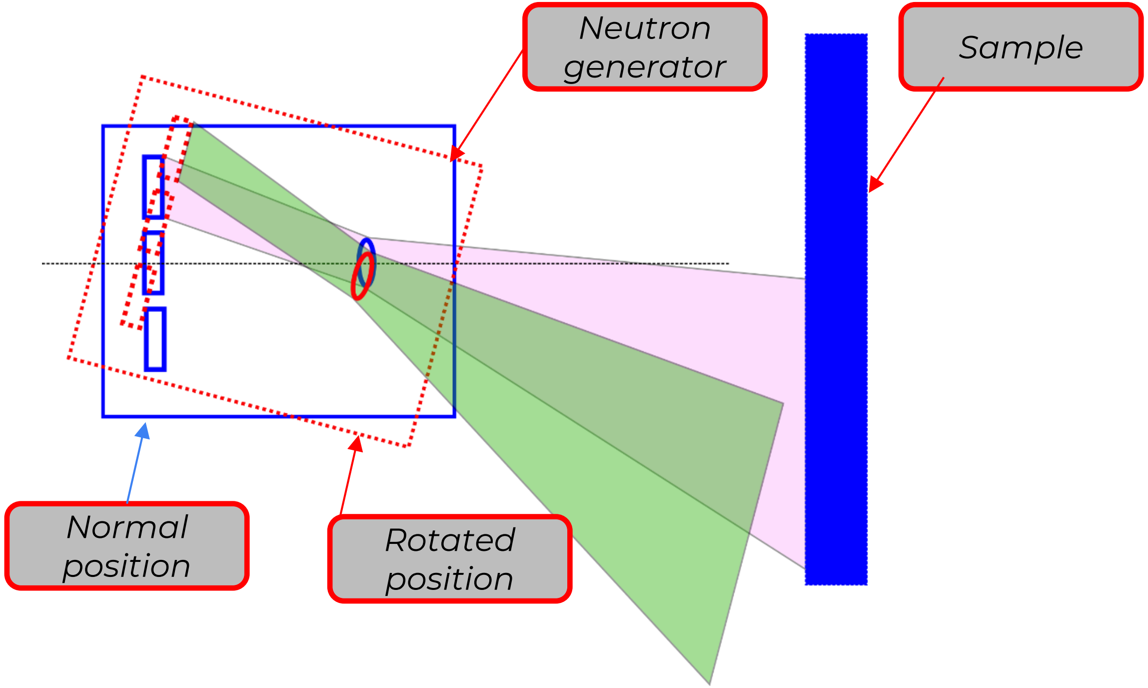
Integrated correction factors using the example of the SiO_2 sample

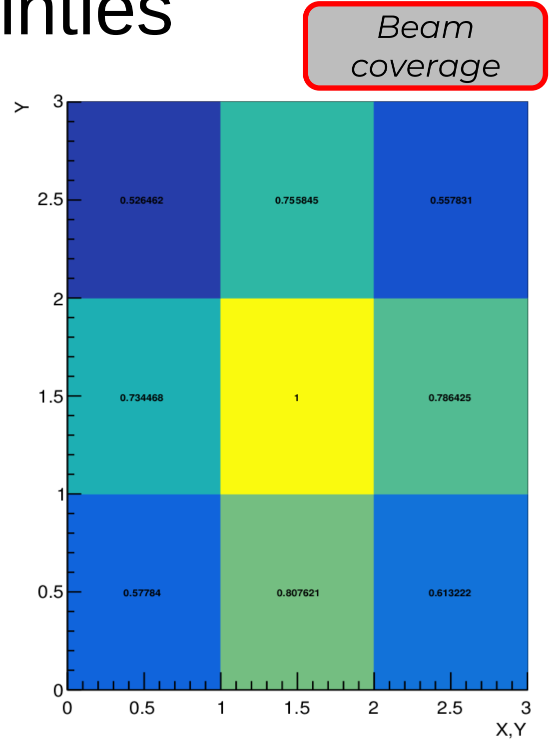




The correction factors including the attenuation correction, total efficiency and multiple inelastic scattering corresponding to the various $LaBr_3$ detectors

Main source of systematic uncertainties

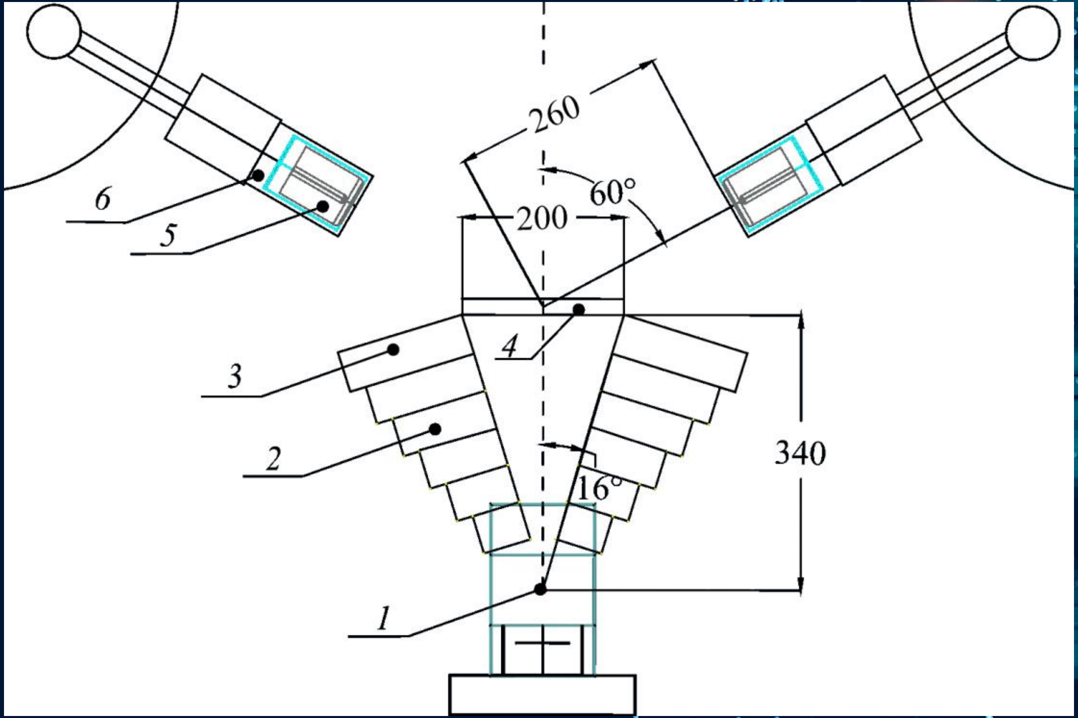




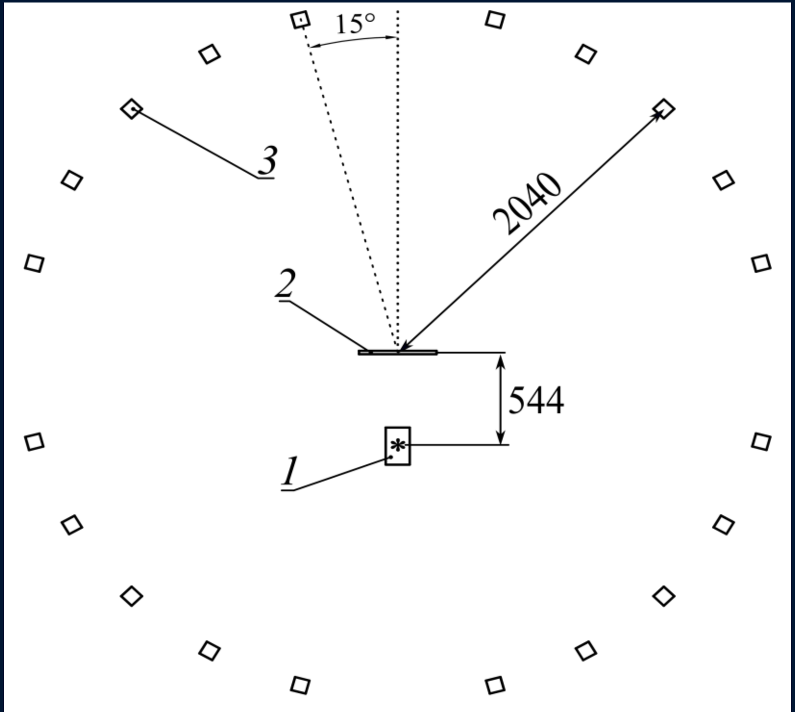
Small rotation of the NG could lead to dramatic change of target coverage. It could be corrected by relative calibration to central pixel and rotation angle could be adjusted to minimize CS difference between pix-det combinations with small difference in angle

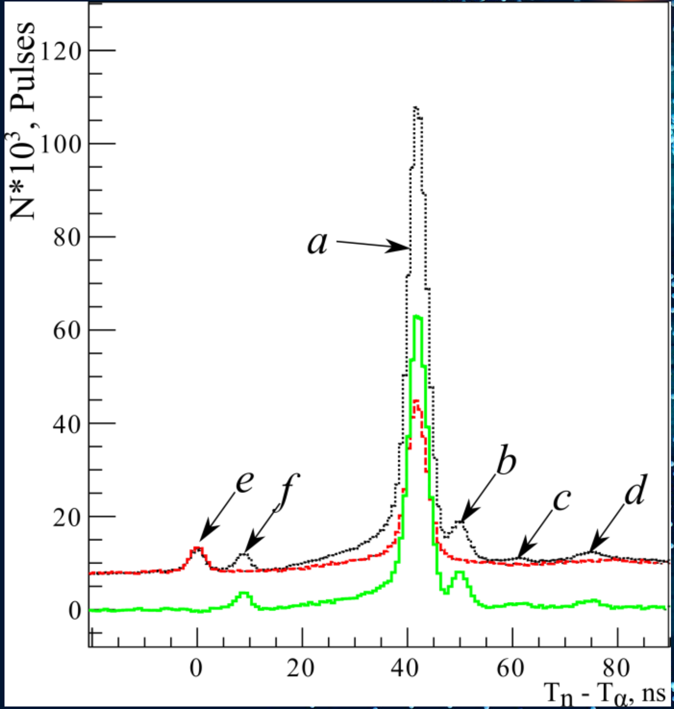
Configuration for γ-quanta emission CS measurement

- 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



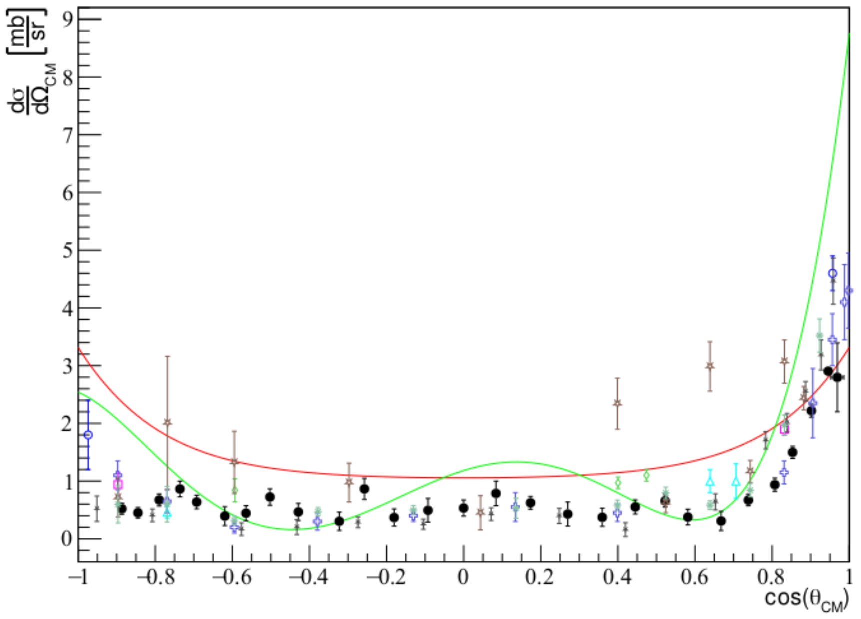
Measurement of *n'* angular distributions and n' γ correlations

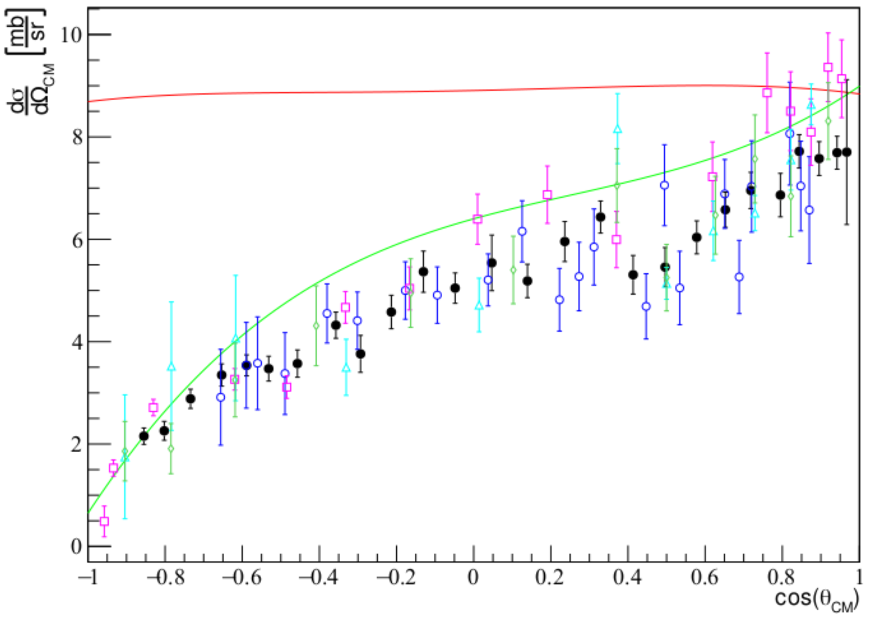




- 1-ING-27 neutron generator, 2-sample, 3-PFT n−detector

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