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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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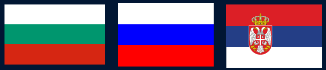
TANGRA collaboration

TAgged Neutrons & Gamma RAys

- An international collaboration 
- Main goals:

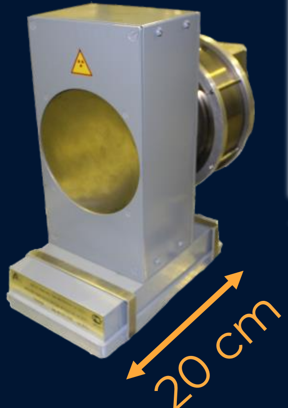
- Nuclear reactions research using tagged neutron method (TNM): acquiring data for n and γ
- Development of fast elemental analysis techniques
- Theoretical description of processes under investigation
- Software development for:
    - Data analysis
    - Nuclear database handling
    - Implementation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

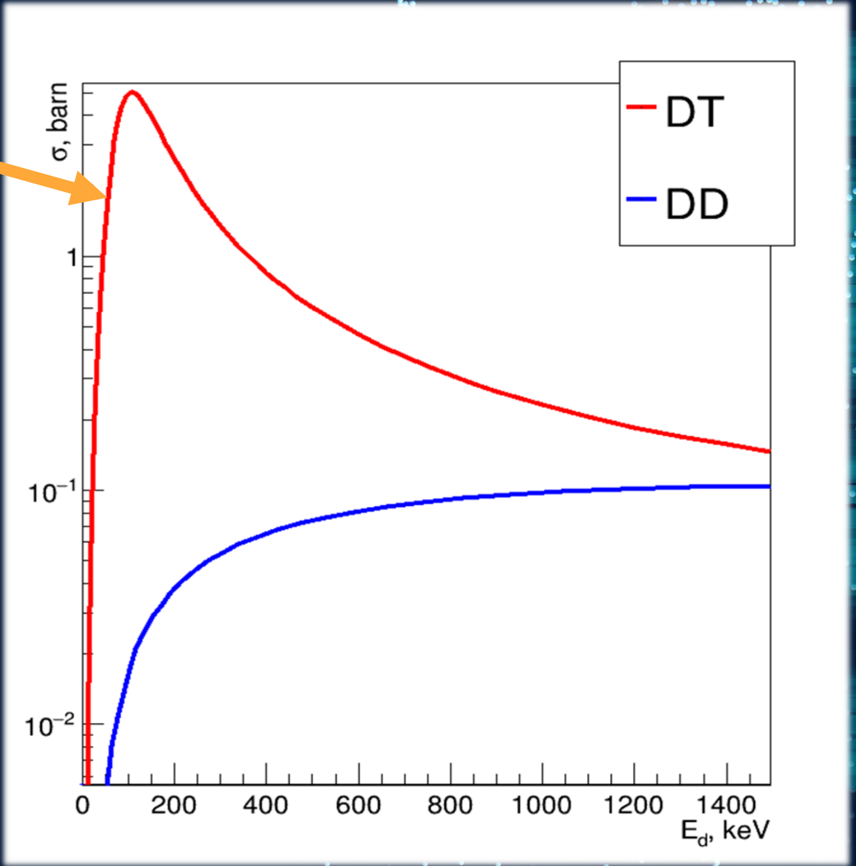
$$^{2}\mathrm{H} + ^{2}\mathrm{H} \rightarrow ^{3}\mathrm{He} + n + 3.27\ \mathrm{MeV}$$

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

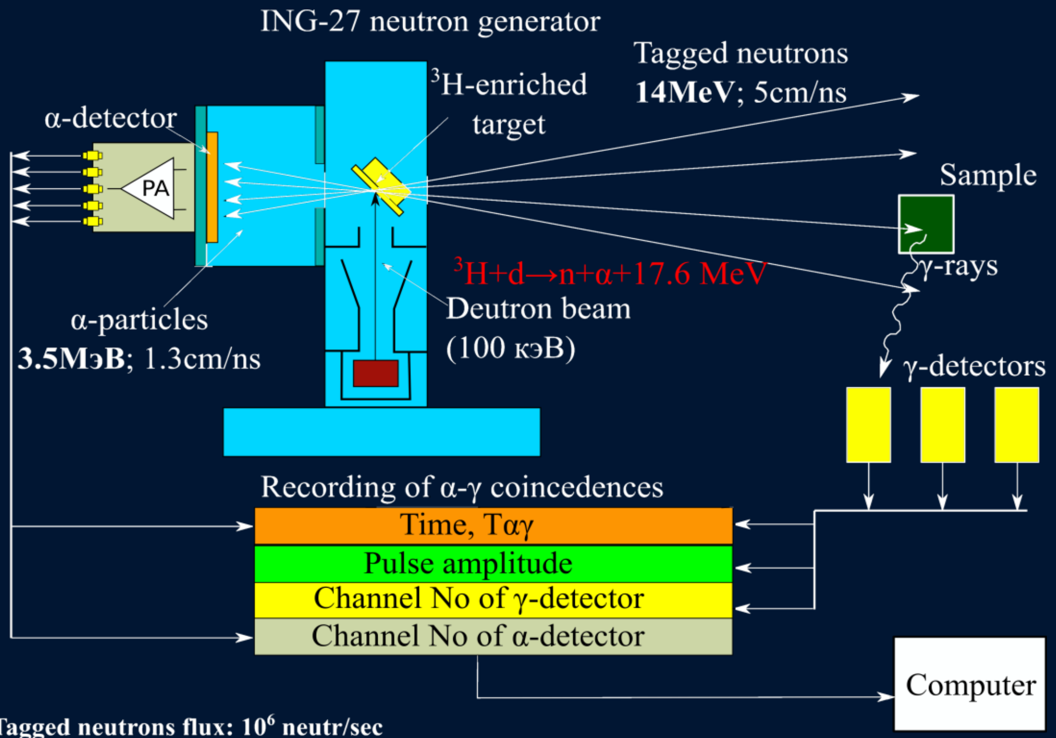
- Features:
- Low threshold
- High energy outcome
- Only two particles in products
- *Very suitable for neutron production*
- *Products move in opposite directions →*
- *Register one → determine direction for another!*

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

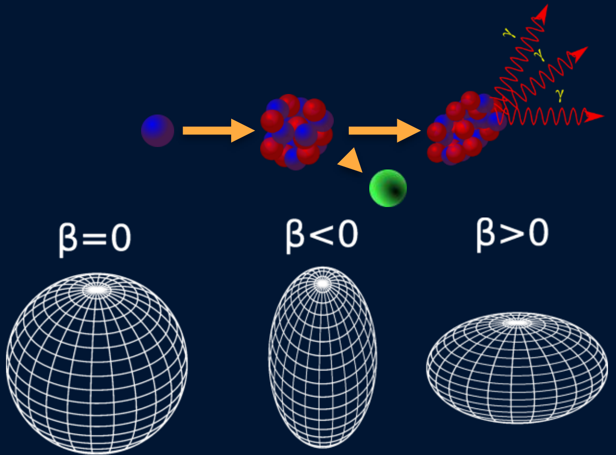
Interesting for nuclear reactions research:

- 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

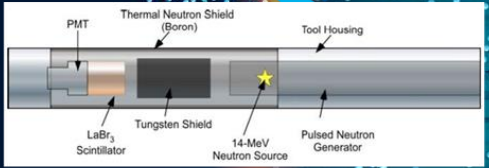
Studying of neutron-induced reactions

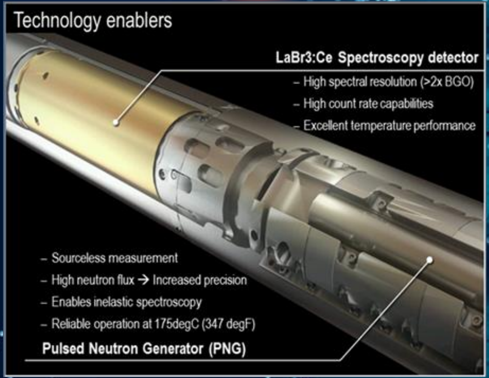


- (n,n’), (n,2n), (n,p) and (n,α) reactions is a unique tool for nuclear structure and shape investigation
- Data needed to adjust parameters models for astrophysical calculations
- Acquiring more accurate data for applied research

- Prototype of soil analyzer

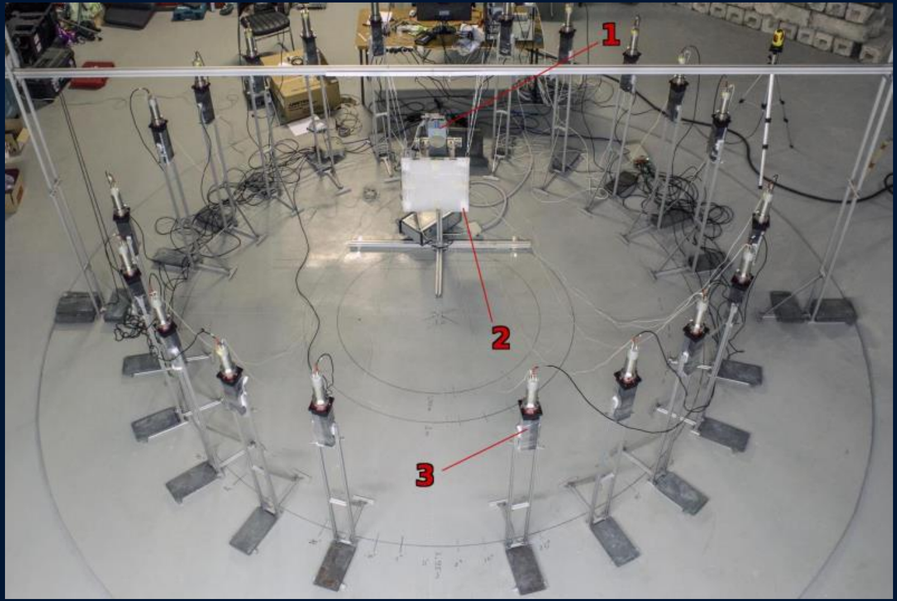
- Elemental analysis in space

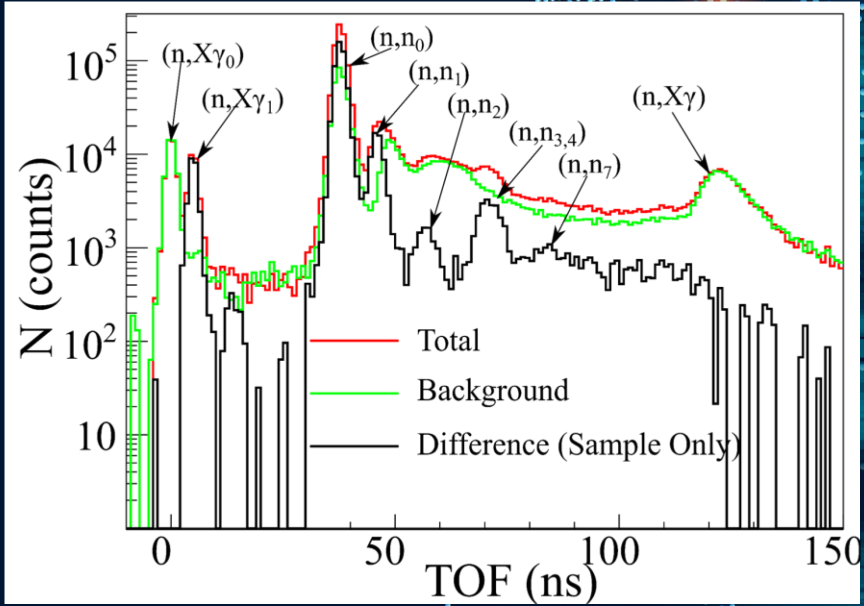




- Well logging

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





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

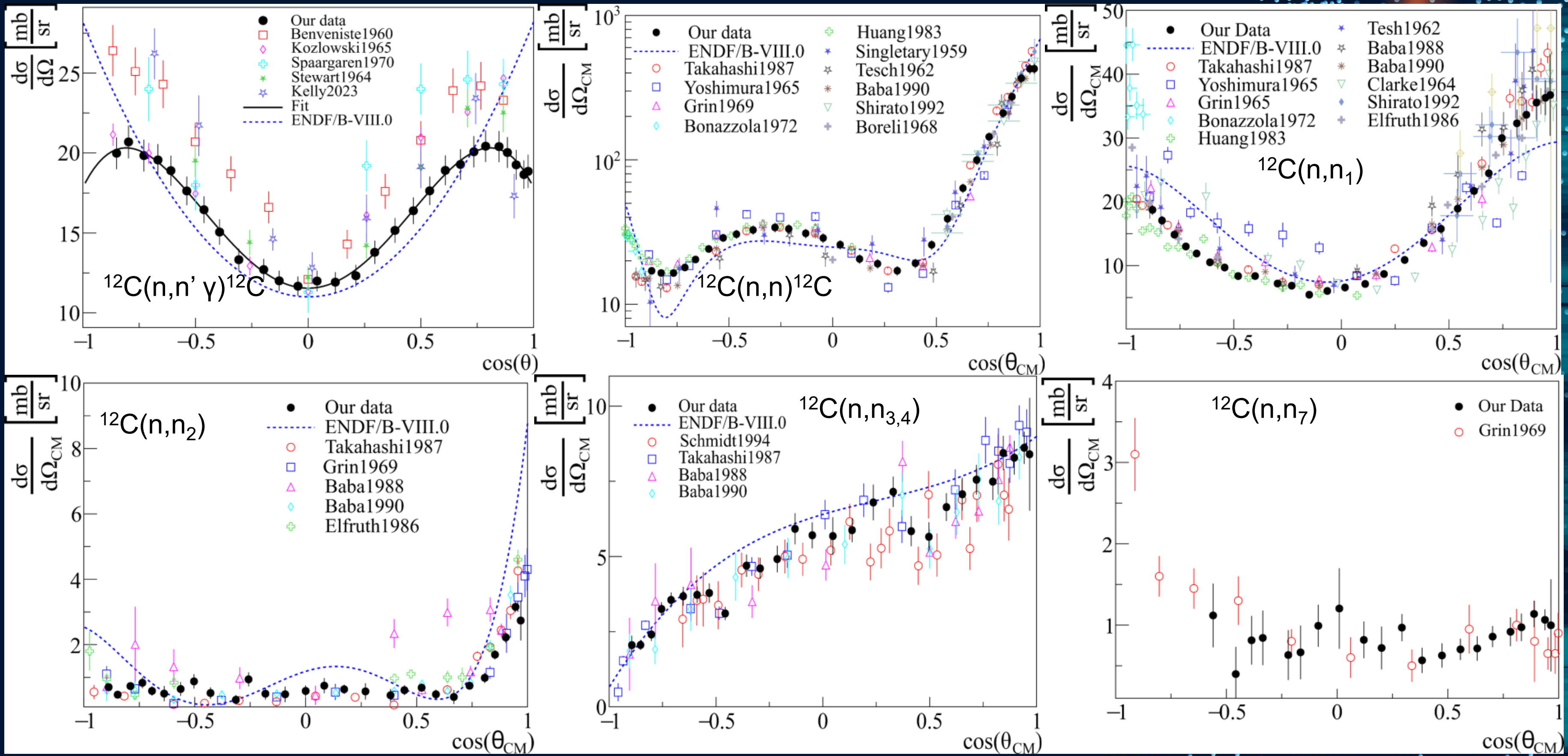
Spectrum components:

$(n,X\gamma_0)$, $(n,X\gamma_1)$ - 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)

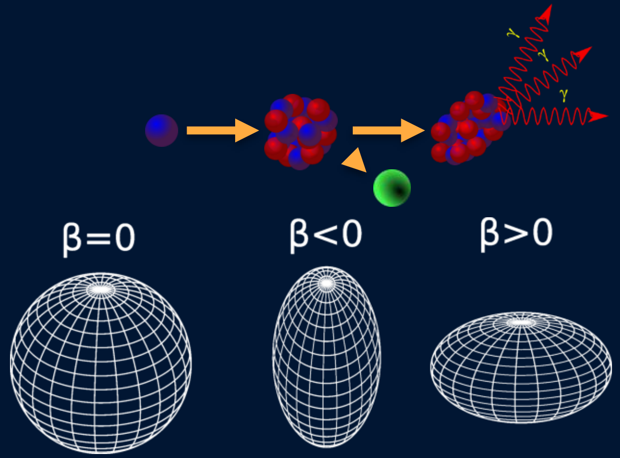


Measurements of the inelastic scattering cross-sections & angular distributions (Graphite sample)

References	Cross section (mb)							
	n_0	n_1	n_2	$n_{3,4}$	n_5	n_6	n_7	(n,n′)3α
This work	790±6 1	192±10 (n) 205±11 (γ)	9.6±0.7	66±4	–	–	10.4±0.7	86±4 – ^{12}C(n,$n_{2,3,4,7}$) this work; 55±12 – ^{12}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



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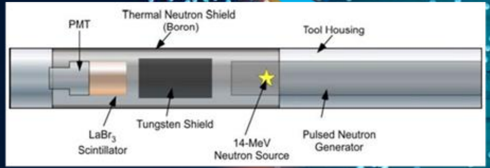
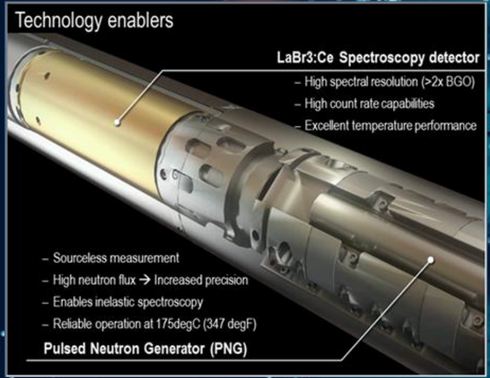
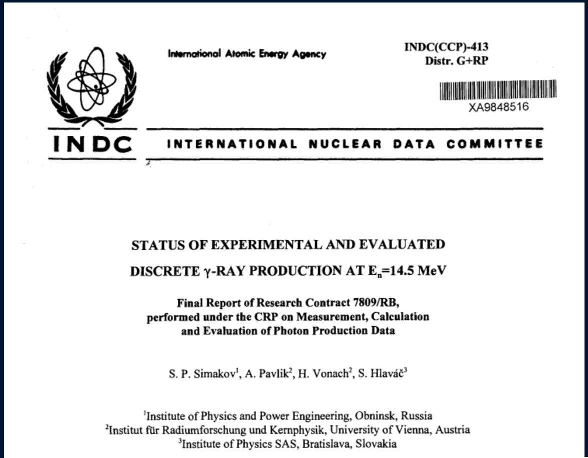




- Well logging

What we know about (n,xγ)?



International Atomic Energy Agency

INDC(CCP)-413
Distr. G+RP

XA9848516

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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[1]Institute of Physics and Power Engineering, Obninsk, Russia
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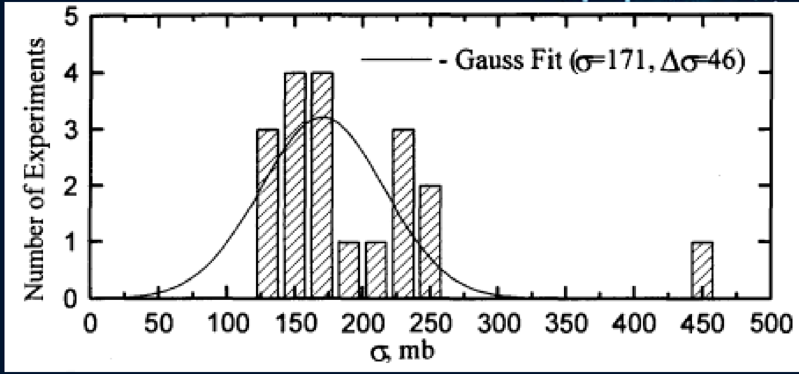
[3]Institute of Physics SAS, Bratislava, Slovakia

IAEA NUC

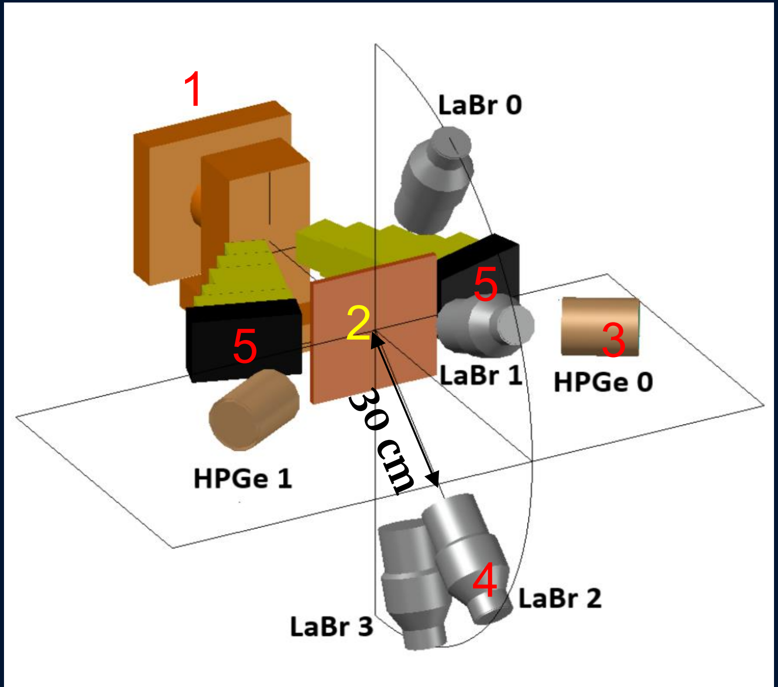


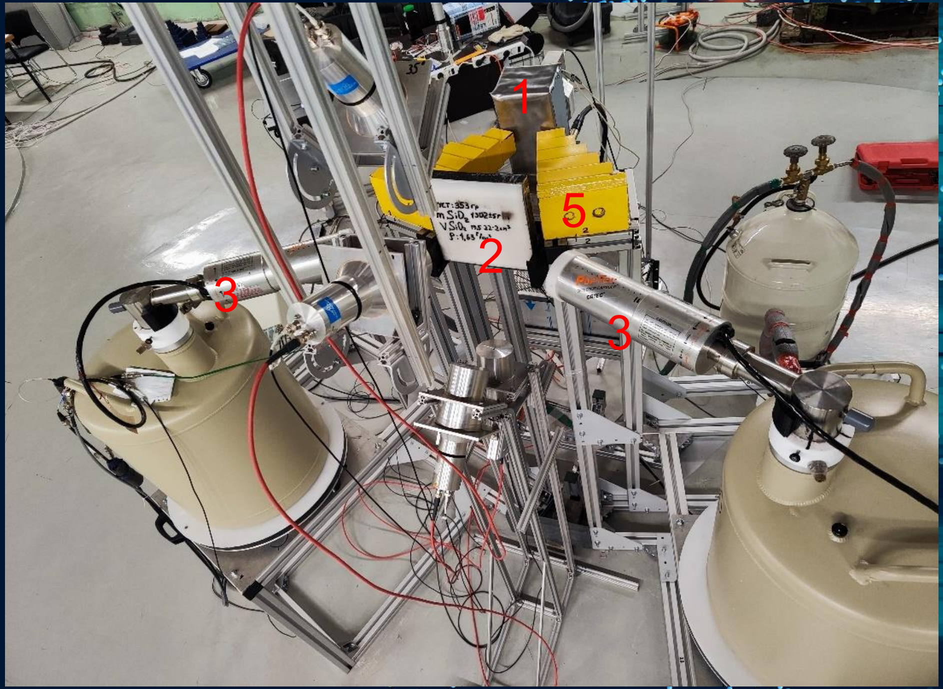
Discrepancy in two times!

Eγ,	Reaction	Transition	E,	Angle,	Sample	Detect.	σ,	Author	Publ	Correction			Corrected σ
4439	$^{12}C(n,n')^{12}C$	$4439(2^+)\to 0(0^+)$, 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

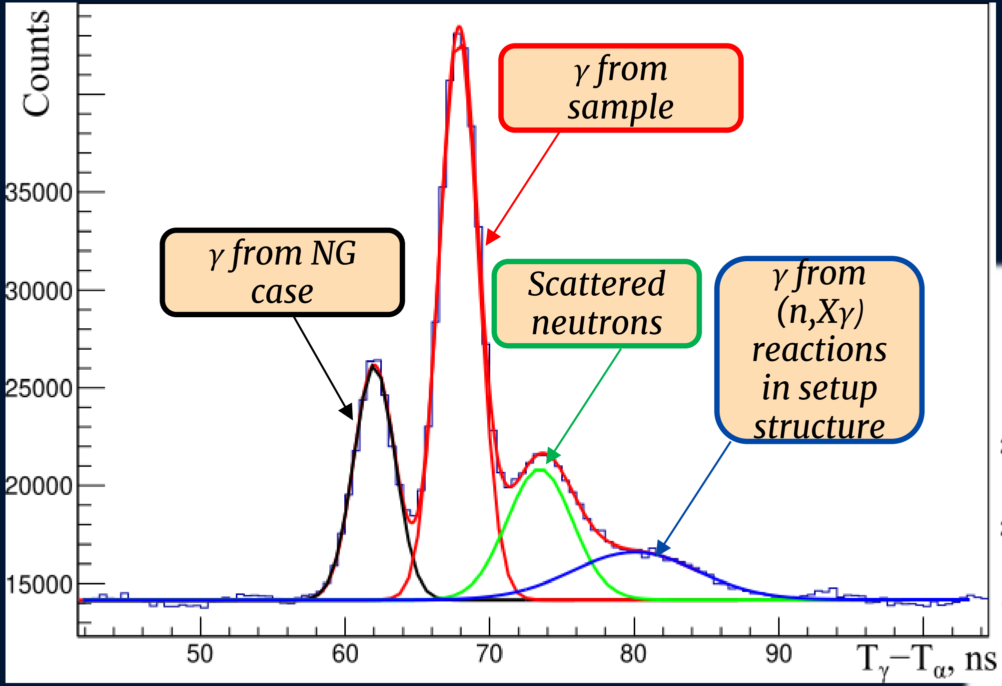
3) HPGe γ-detector (2 pcs, 60% eff)

4) $LaBr_3$ γ-detector (4 pcs)

+ Fast measurement

- Extreme detector load (~8×10^4 cps)

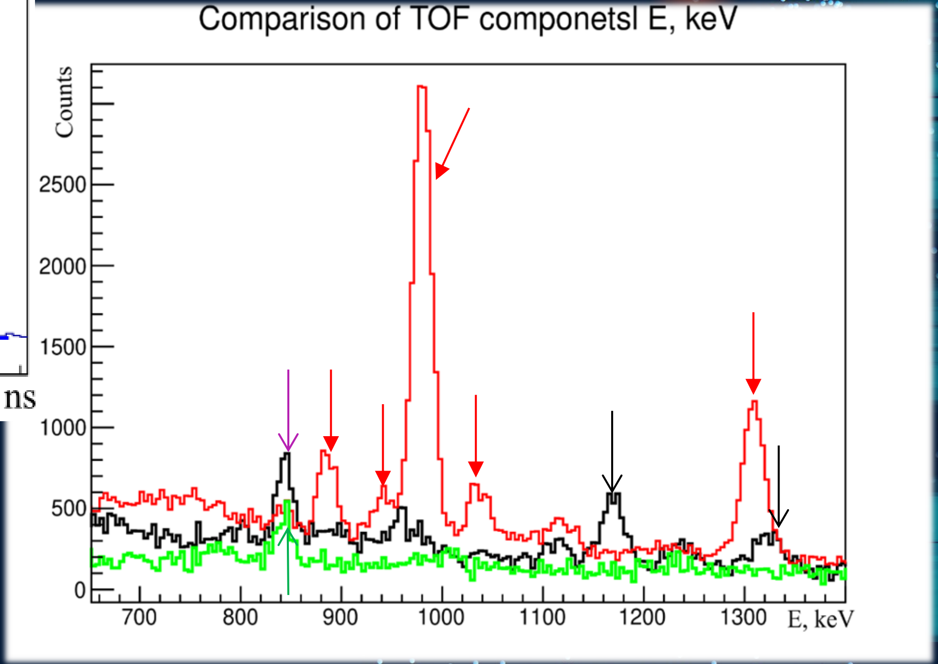
Data processing with TNM



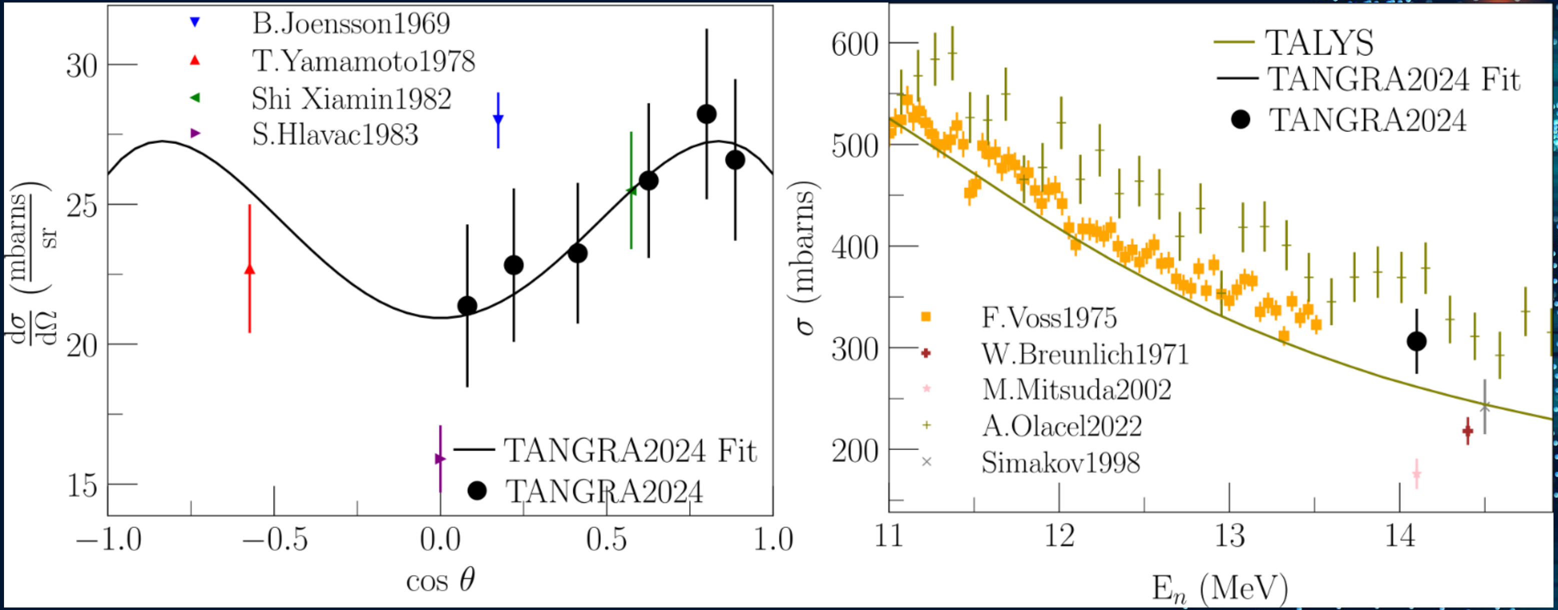
Main idea – separation of the background events by TOF

Spectrum below shows impact of different components to sum spectrum.

Peaks from sample marked with red arrows



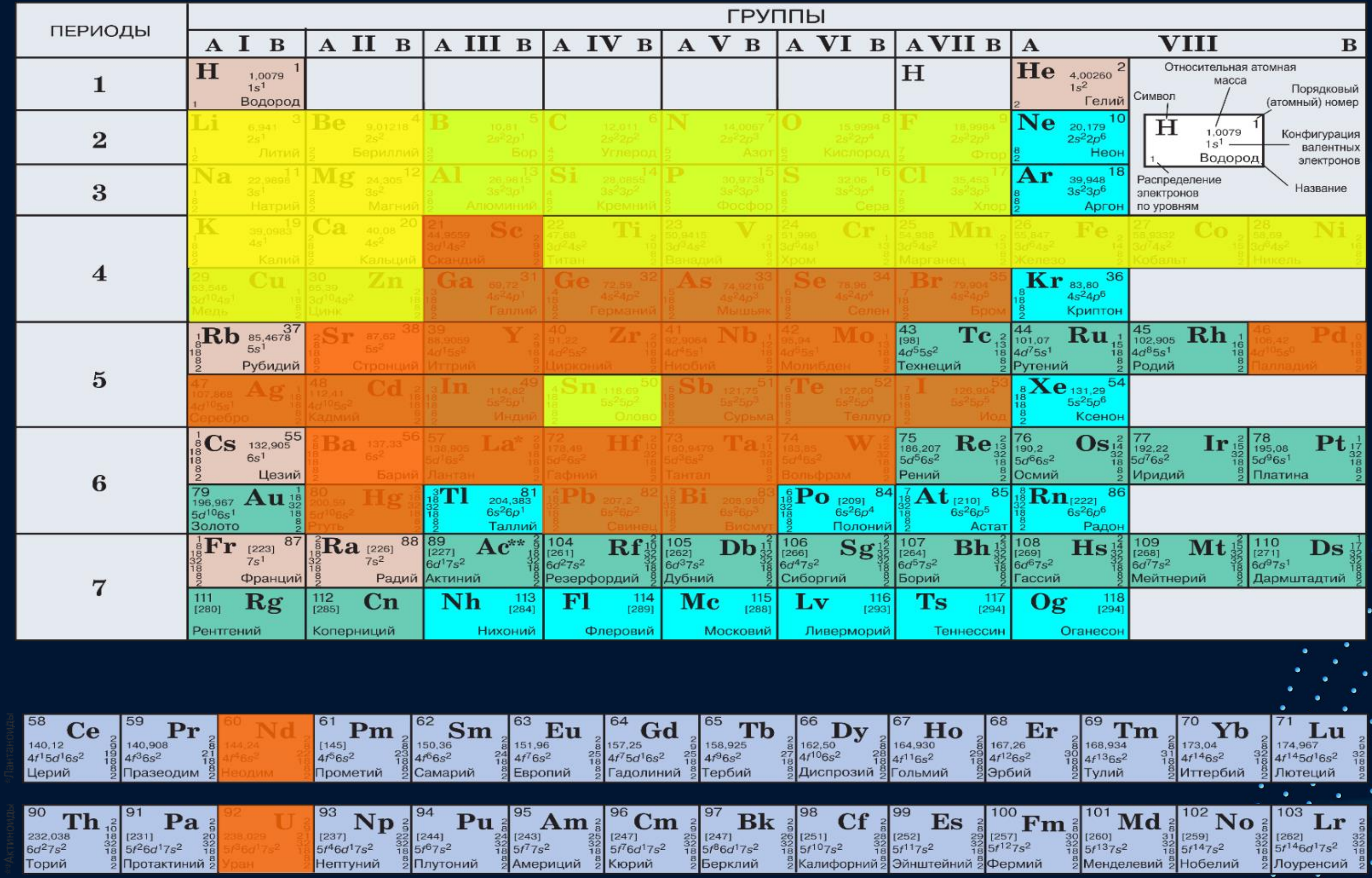
Measurements of the γ-quanta emission cross-sections & angular distributions (Ni_2O_3 sample)



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

Eγ, keV	Reaction	Reference	σ, mb	a_2	a_4
1454 keV	^{58}Ni(n,n’)	Voss1975	323±10	-	-
		Olacel 2022	378±25	-	-
		TANGRA 2024	306±32	0,19(2)	0,12(3)

Current status of measurements



2024

2025

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

Total reaction cross section

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

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

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:

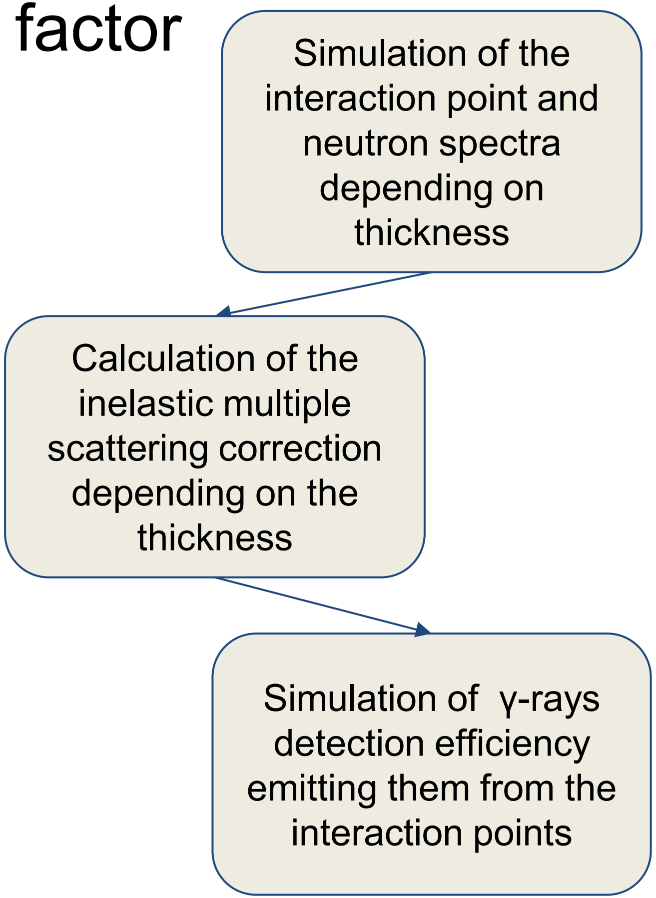
- To calculate them independently in dependence on the sample thickness and take the integral
- **To simulate the total thickness-integrated correction in the GEANT4 using a separate ones as weighting factors**

Correction features:

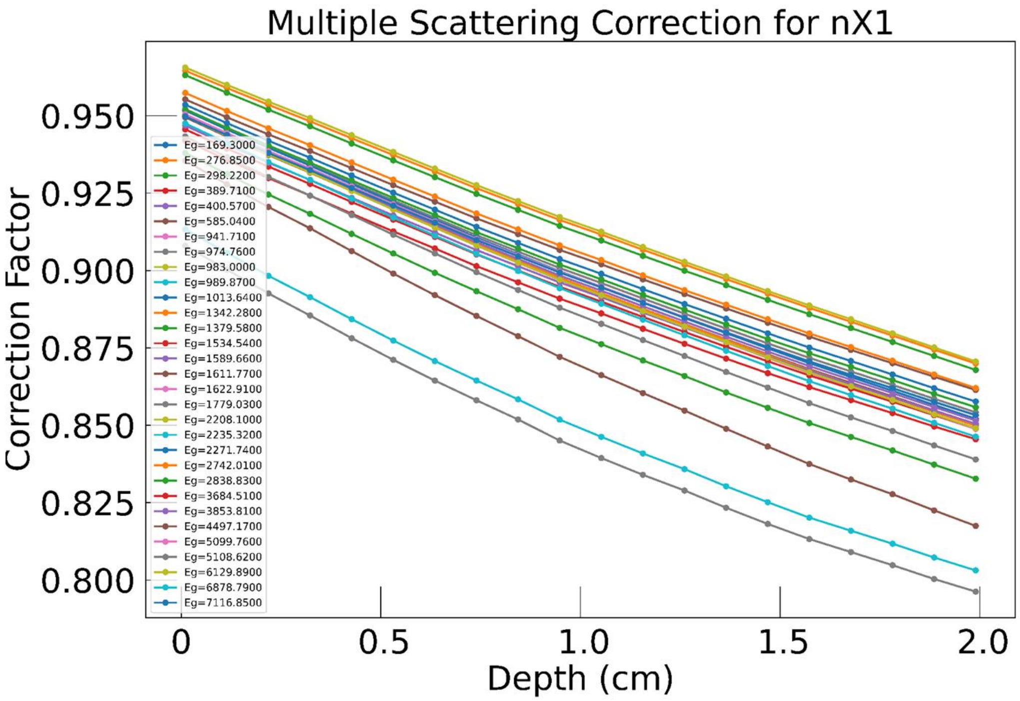
- Multiple inelastic scattering overstates the number of emitted γ-rays
- Attenuation of incident neutrons and γ-rays understates the number of emitted γ-rays

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

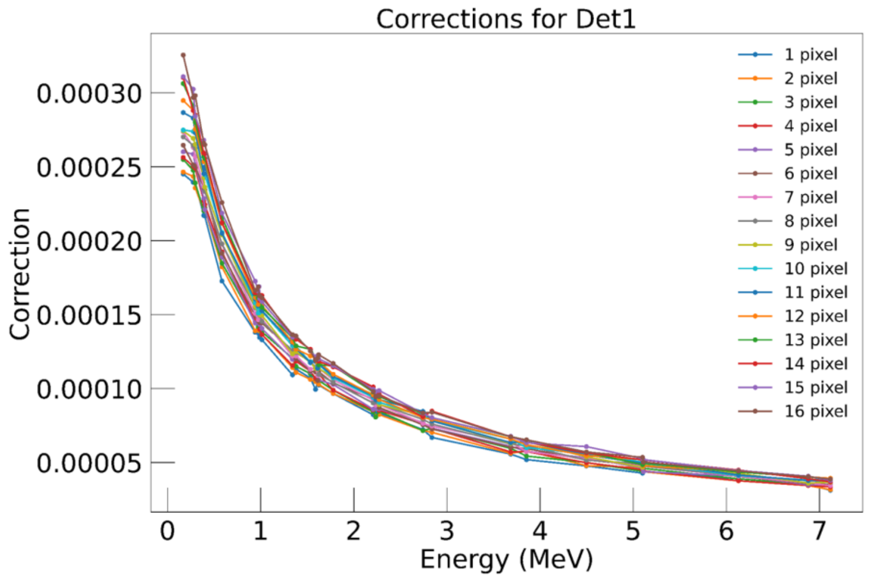


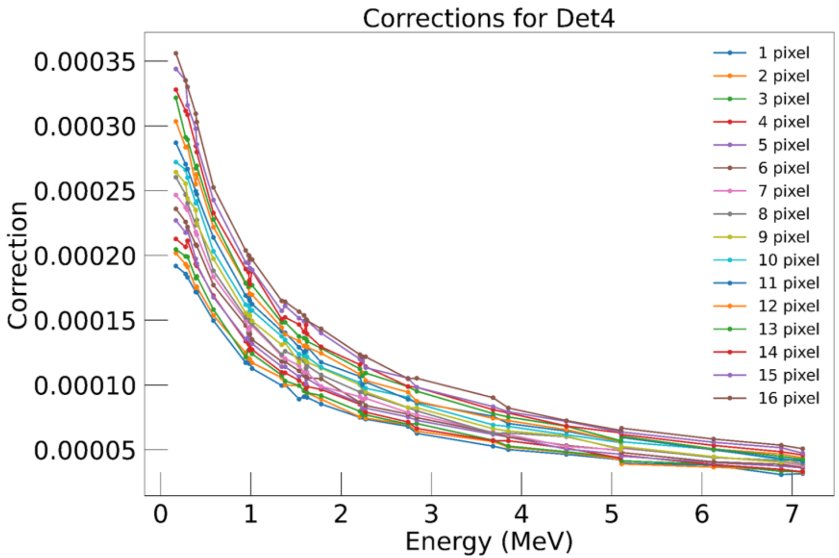
Example of the multiple scattering correction



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

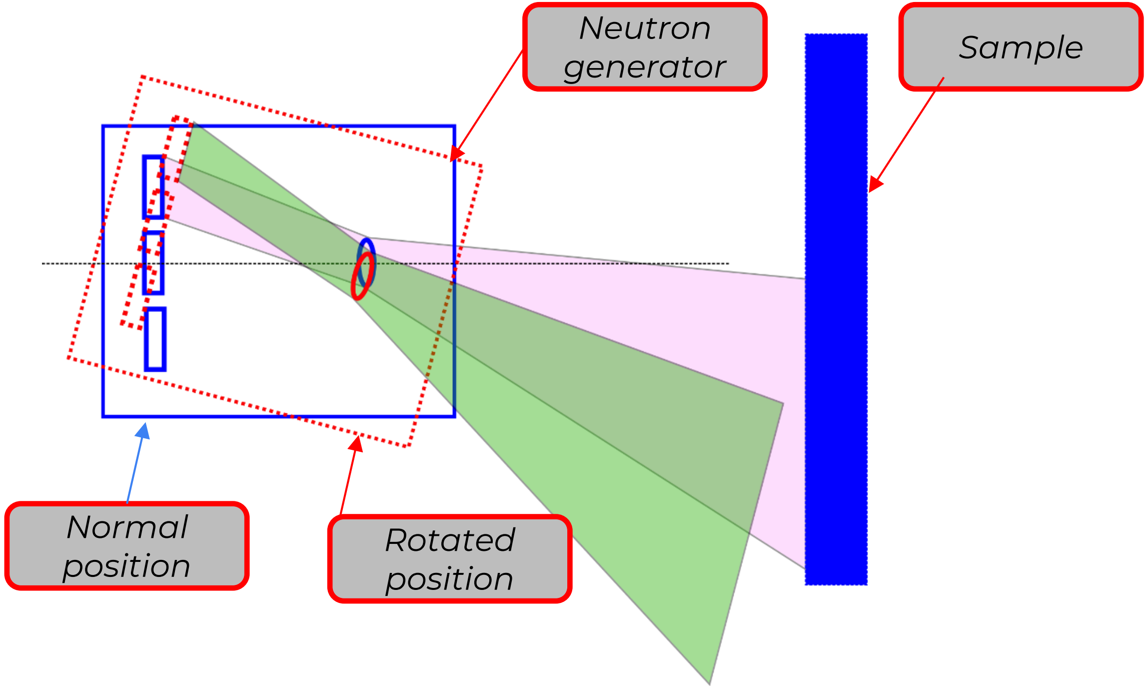
Integrated correction factors using the example of the SiO_2 sample

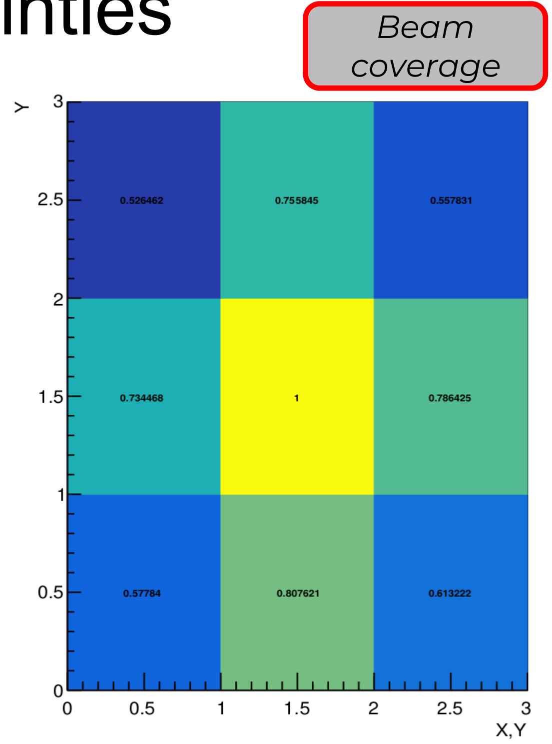




The correction factors including the attenuation correction, total efficiency and multiple inelastic scattering corresponding to the various $LaBr_3$ detectors

Main source of systematic uncertainties

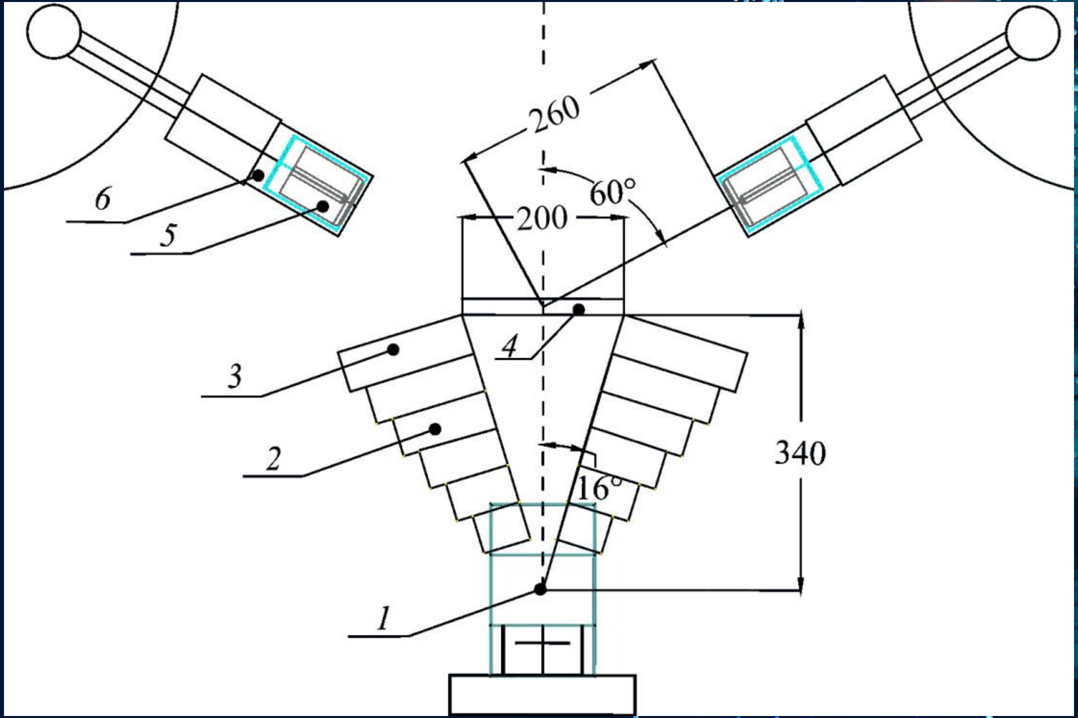




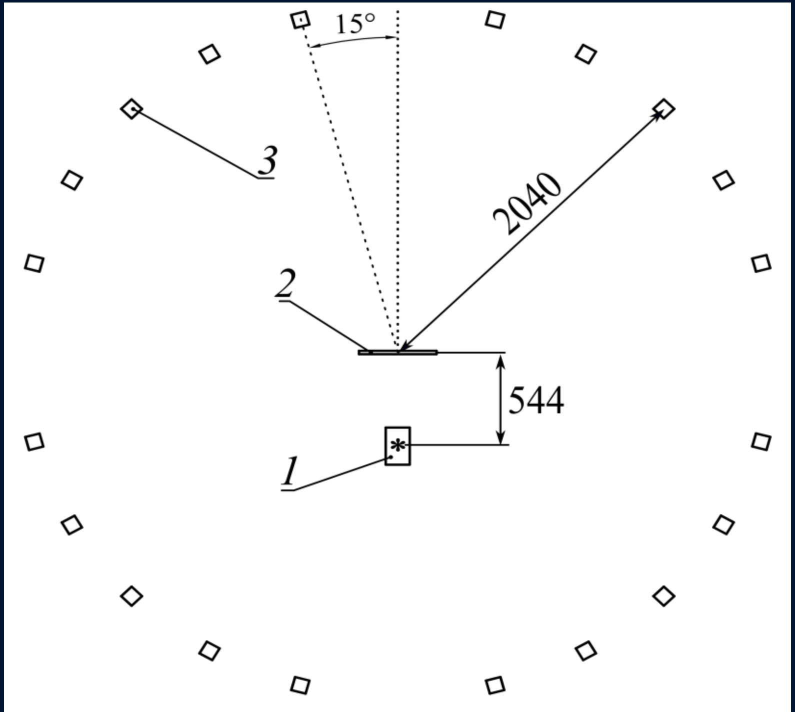
Small rotation of the NG could lead to dramatic change of target coverage. It could be corrected by relative calibration to central pixel and rotation angle could be adjusted to minimize CS difference between pix-det combinations with small difference in angle

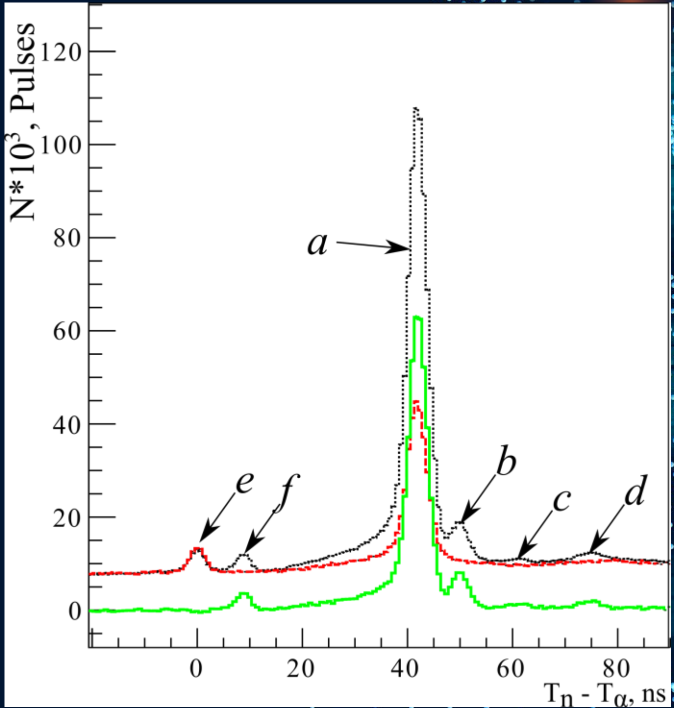
Configuration for γ-quanta emission CS measurement

- 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



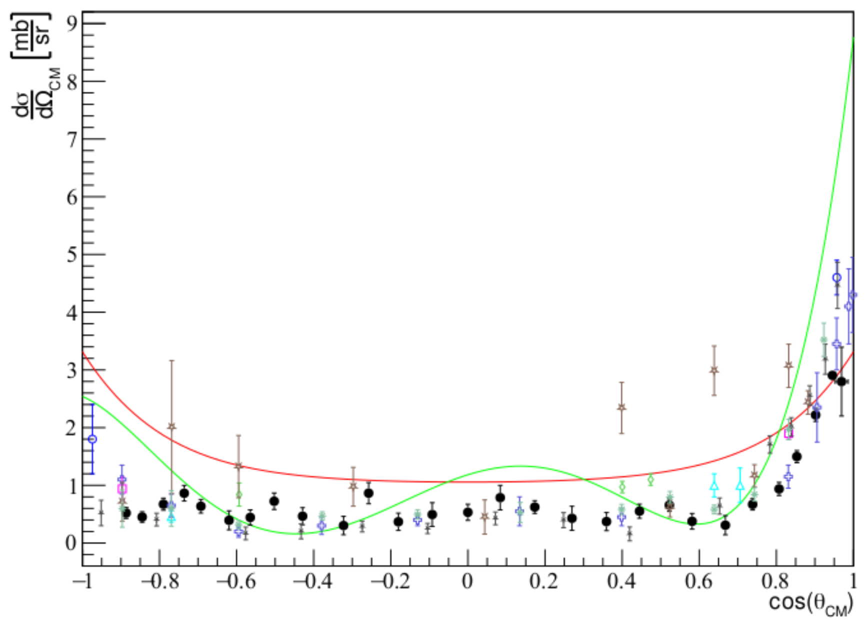
Measurement of *n'* angular distributions and n' γ correlations

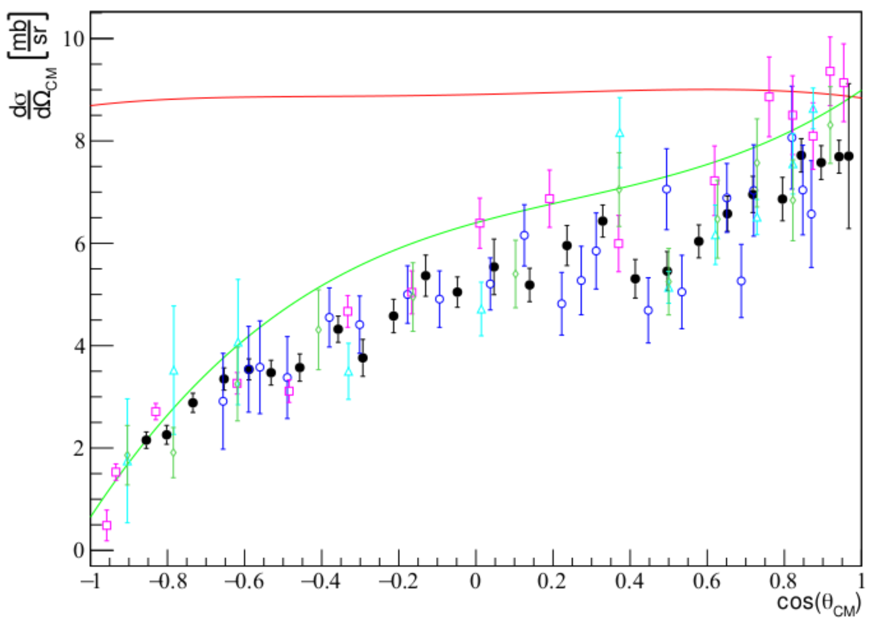




- 1-ING-27 neutron generator, 2-sample, 3-PFT n−detector

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

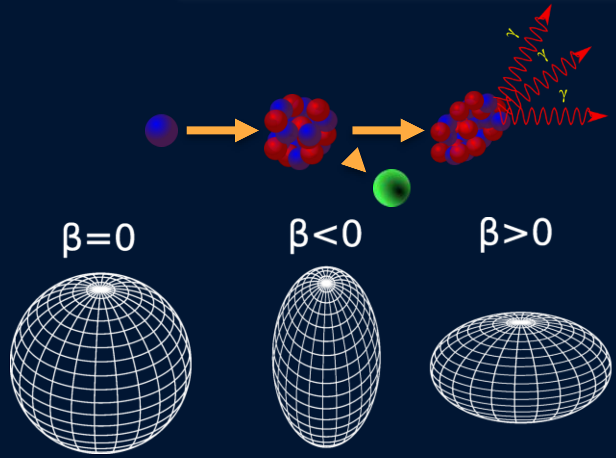




- 7.6 MeV state (Hoyle state)
- Green line – ENDF-B-VIII
- Red line - TALYS

- 9.6+9.8+9.9 MeV states

Studying of neutron-induced reactions



- Optical model

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

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

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Oscillator

^{A}Z
Levels at same distance

Rotator

^{A}Z
Levels grows as ΔE^2