MEASUREMENT OF ANGULAR DISTRIBUTIONS OF NEUTRONS AND GAMMA QUANTA FROM THE INTERACTION BETWEEN 14.1 MEV NEUTRONS AND CARBON NUCLEI

G.V. Pampushik on behalf of TANGRA collaboration
pampushik.g@gmail.com

This work was supported by a RSCF grant No.23-12-00239

TANGRA project

Project «**TANGRA**» (**TA**gged **N**eutron and **G**amma **RA**ys) at JINR-FLNP (Dubna) is aimed at studying nuclear reactions induced by fast neutrons. At a TANGRA setup, the sample under investigation is irradiated with 14-MeV neutrons, produced by the ING-27 neutron generator.

The main feature of the setup is the use of the **tagged neutron method (TNM)**.

Basically, the angular distributions of γ-rays and partial cross sections of detected γ-transitions were measured [1-3].

Recently, the angular distributions of scattered neutrons have been measured.

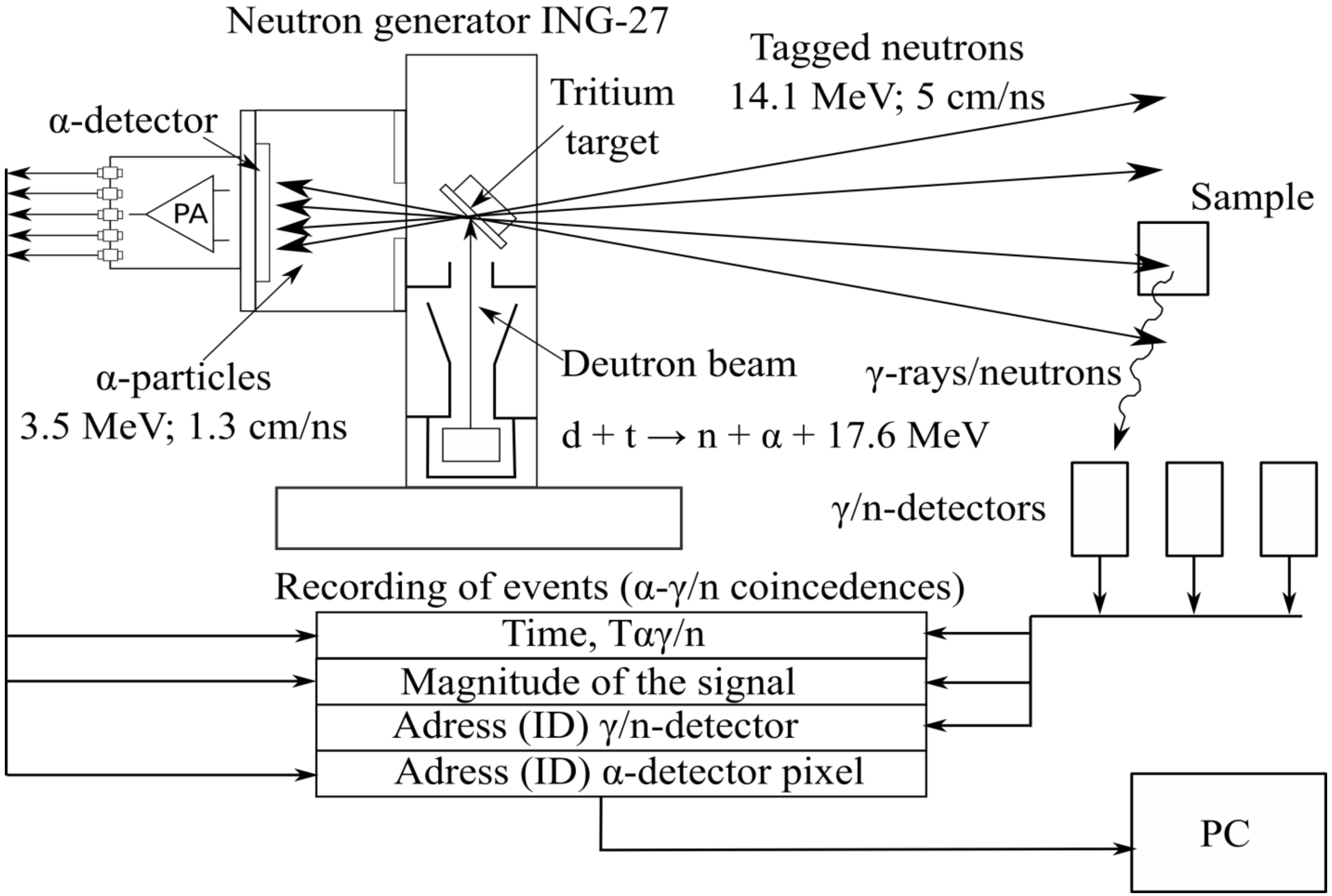


Fig. 1. Standard diagram of TANGRA experimental setups.

1. N.A. Fedorov *et al.* Bull. Russ. Acad. Sci.: Phys. **84** (2020) 367
2. D.N. Grozdanov *et al.* Phys. At. Nucl. **81** (2018) 588
3. D.N. Grozdanov *et al.* Phys. At. Nucl. **83** (2020) 384

Experimental setup

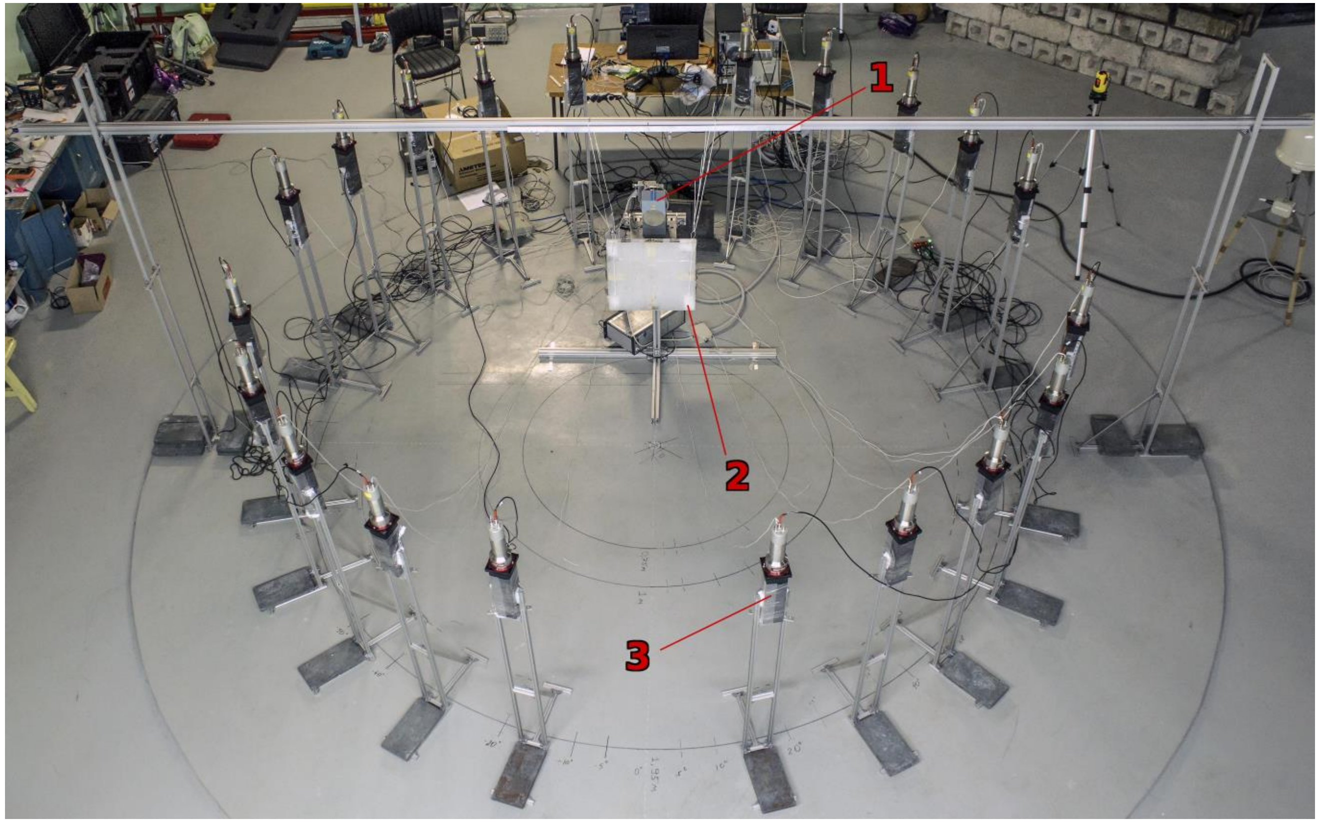


Fig. 2. Photo of the TANGRA setup with plastic detectors for measuring angular distributions of the scattered neutrons. *1* – ING-27 neutron generator, *2* – irradiated carbon sample, *3* – one of the 20 plastic detectors used in the registration system.

Neutron source: ING-27 generator

Sample: graphite block, 44 cm x 44 cm x 2 cm

Neutron detector: polyphenyltoluene detector ($Z \approx 5.5$)

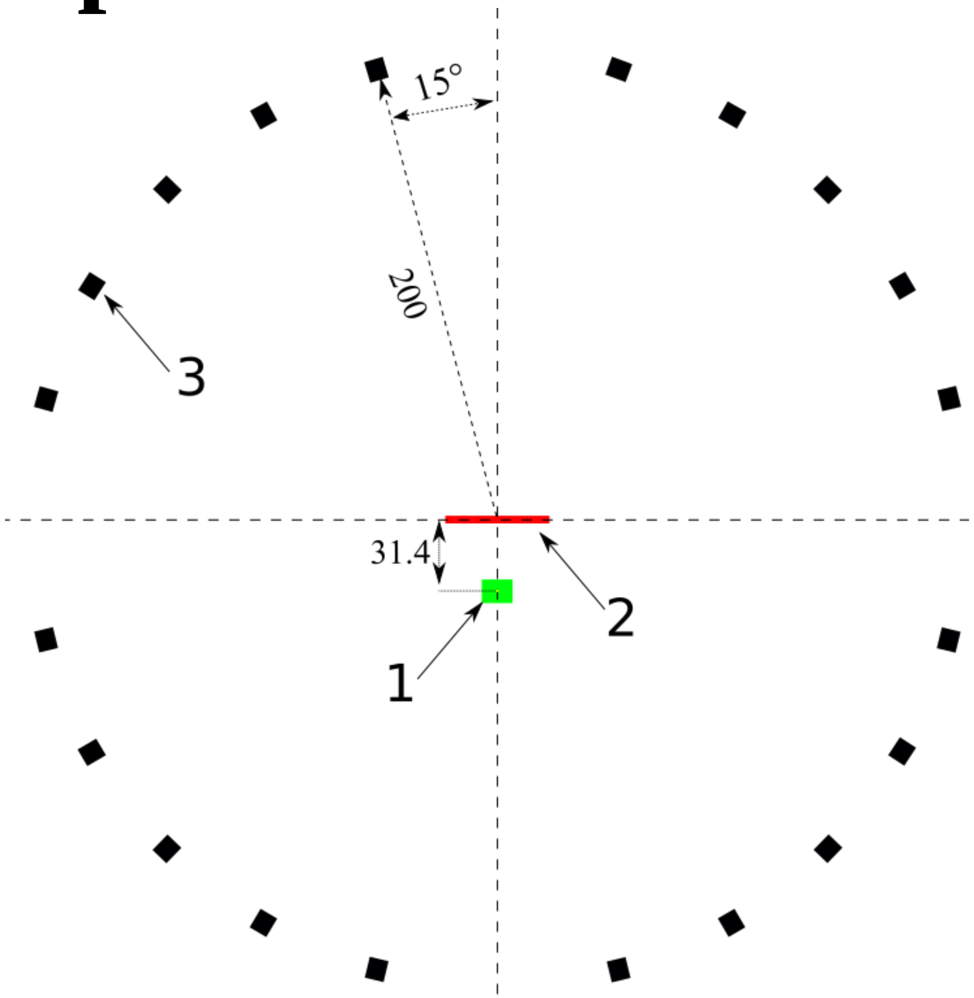


Fig. 3. Scheme of the TANGRA setup with plastic detectors for measuring angular distributions of the scattered neutrons. Designations as in Fig. 3. Dimensions are in cm.

Motivation and the object of research

Object of our research – ^{12}C nuclei.

- This is a light nucleus with a relatively high energy of the first excited state (4.44 MeV), which decays with the emission of n- and γ- radiation.
- The second and the third excited states are decaying through α-particle breakup.
- First excited states can be treated in the collective model [4, 5] using the rotational approach for a strongly oblate nucleus.

Table 1. Quadrupole deformation β_2 for ^{12}C state obtained from various sources using different methods.

$\beta_2(B(E2)\uparrow)$	$\beta_2(Q_{mom})$	β_2 (OM, CC)	β_2 (OM, CC)
0.592 ± 0.036 [6]	-0.411 ± 0.226 [7]	-0.62 [4]	-0.60 [5]

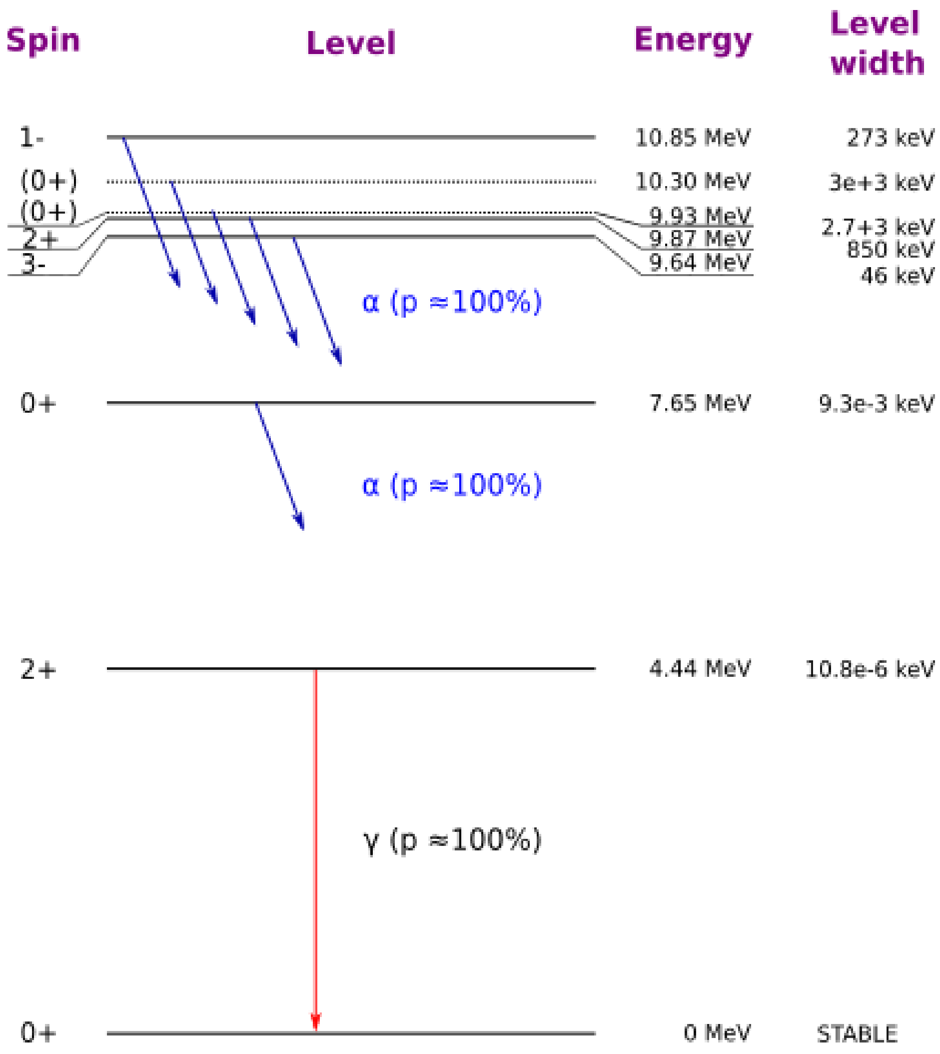
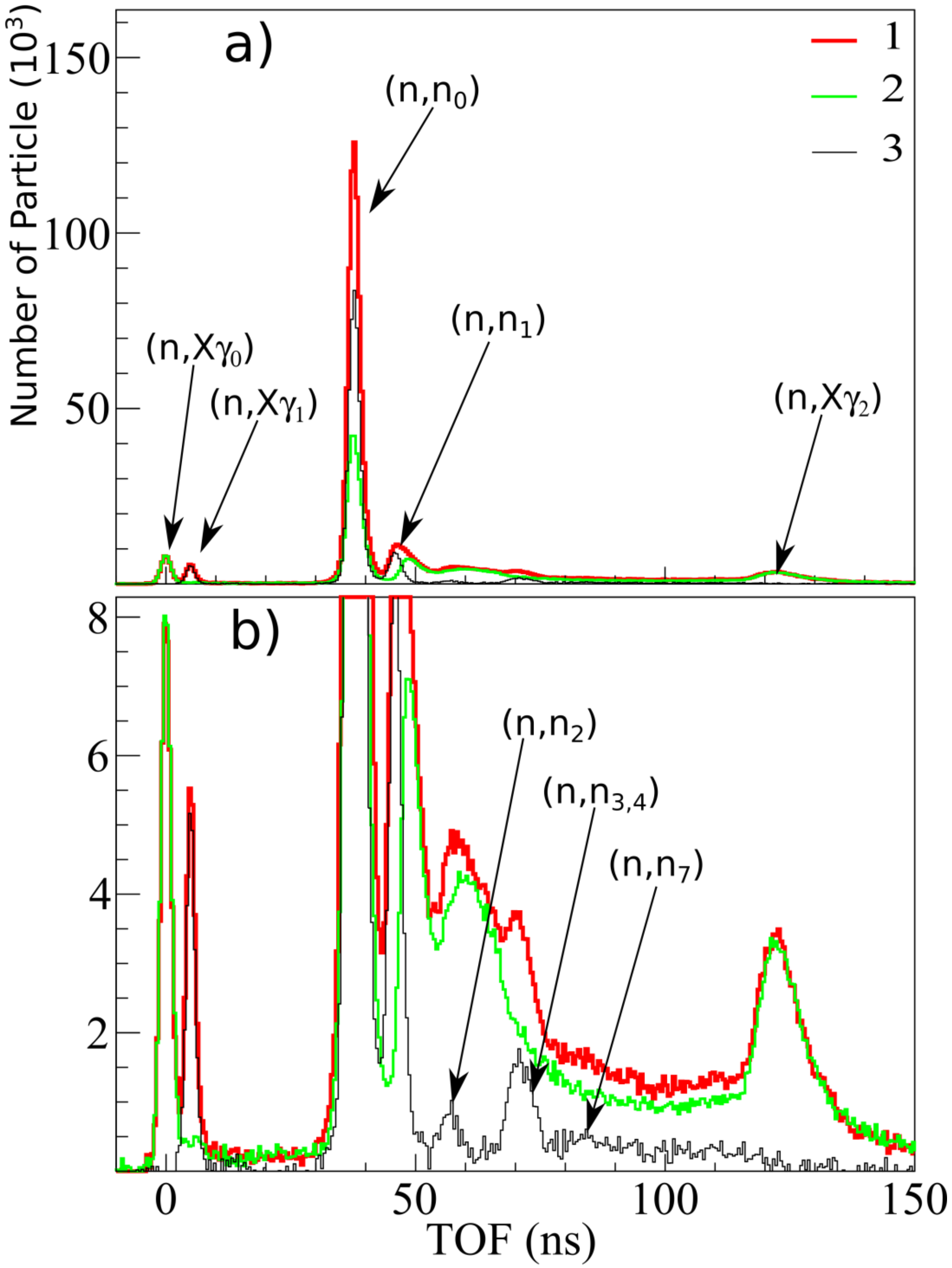


Fig. 6. Scheme for ^{12}C low-lying levels with the de-excitation processes probabilities *p*.
S_α stands for α-particle separation energy.

4. Z.M. Chen *et al.* J. Phys. G: Nucl. Part. Phys. **19** (1993) 877
5. G.A. Grin *et al.* Phys. Lett. **25B** (1967) 387
6. S. Raman *et al.* At. Data Nucl. Data Tables **78** (2001) 1
7. W.J. Vermeer *et al.* Phys.Lett. **122B** (1983) 23



Experimental data processing

Fig. 7. Examples of the time-of-flight spectra obtained. Peaks are labelled with source reaction, registered particle is painted red.

Where:

1 – is measurement with target (^{12}C), Time ~ 48h;

2 – is measurement without target (Background), Time ~ 28h,

3 – Net spectra (without background)

(n,Xγ_0) – γ from ING-27

(n,Xγ_1) – γ from target (^{12}C)

(n,Xγ_2) – γ from the opposite wall

(n,n$_0$) - elastic scattering

(n,n$_1$) - inelastic scattering to the 1 excited state of ^{12}C 4.44MeV

(n,n$_2$) - inelastic scattering to the 2 excited state of ^{12}C 7.65MeV

(n,n$_{3,4}$) - inelastic scattering to the 3 (9.64 MeV) and 4 (9.87 MeV)excited states of ^{12}C

(n,n$_7$) - inelastic scattering to the 7 excited state of ^{12}C 10.85MeV

Cross-section equation

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{N(\theta)}{N_a C_{\gamma,n} N_{nucl}} \cos(\varphi) \times 10^{27} \left[\frac{mb}{sr}\right]$$

Where:

θ - is the angle between the beam and the direction towards the detector from the point of interaction of the beam with the target

N(θ) - count of the neutron detector for the angle θ in coincidence with the X strip of the alpha detector

N_α - Neutron counting (alpha detector count without coincidence)

C - correction factor

ϵ - neutron detector intrinsic efficiency

$d\Omega$ - solid angle covered by a neutron detector [1/sr]

N_{nucl} - average number of nuclei

A - mass number of target atoms = 12 [g/mol]

ρ - target density = 1.6405 [g/cm^3]

N_a - Avogadro's number = 6.02 x 10^{23} [1/mol]

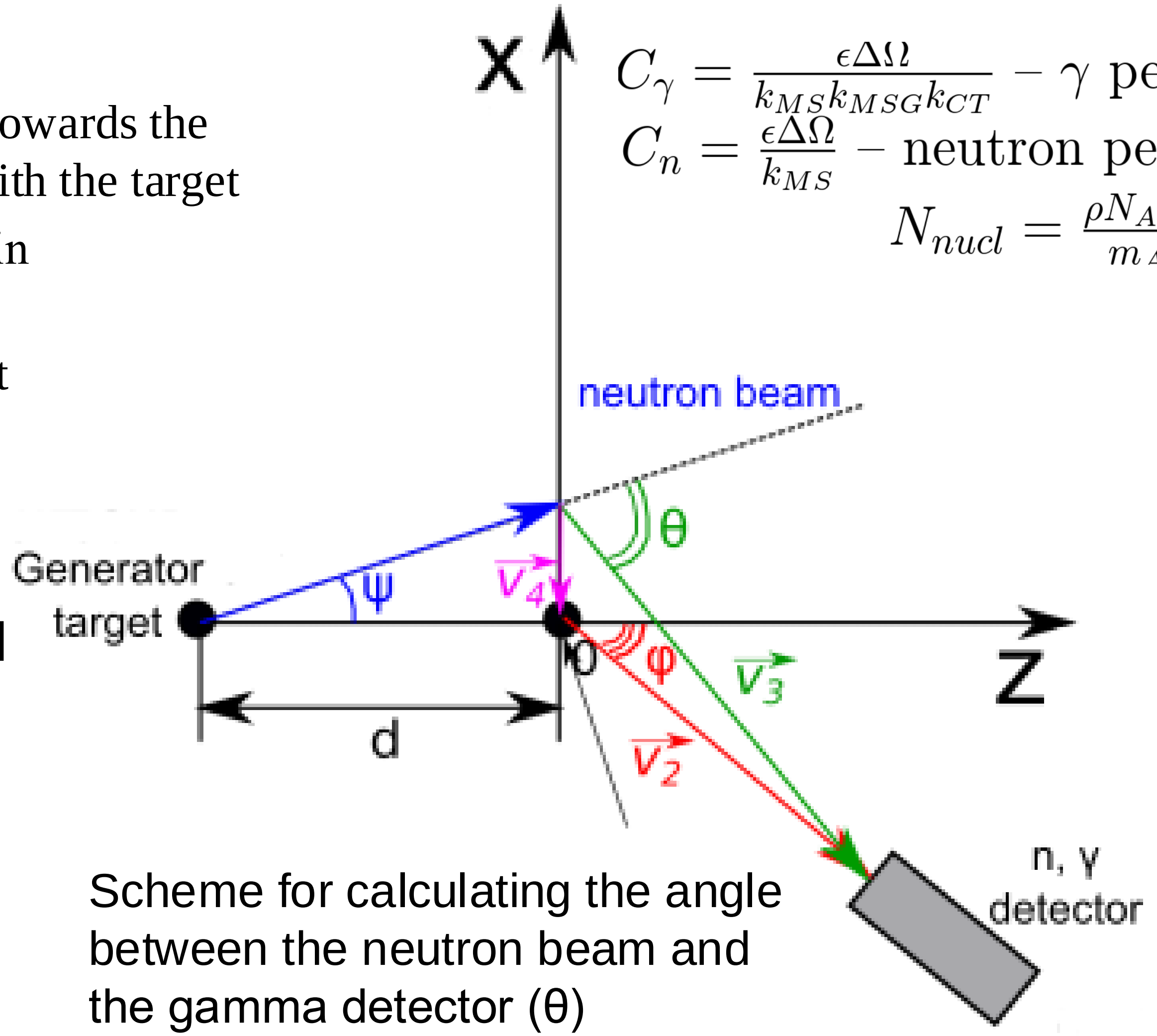
D - target thickness = 2 [cm]

$\cos(\psi)$ - angle between beam and axis of symmetry

$C_\gamma = \frac{\epsilon \Delta\Omega}{k_{MS} k_{MSG} k_{CT}}$ – γ peak correction

$C_n = \frac{\epsilon \Delta\Omega}{k_{MS}}$ – neutron peak correction

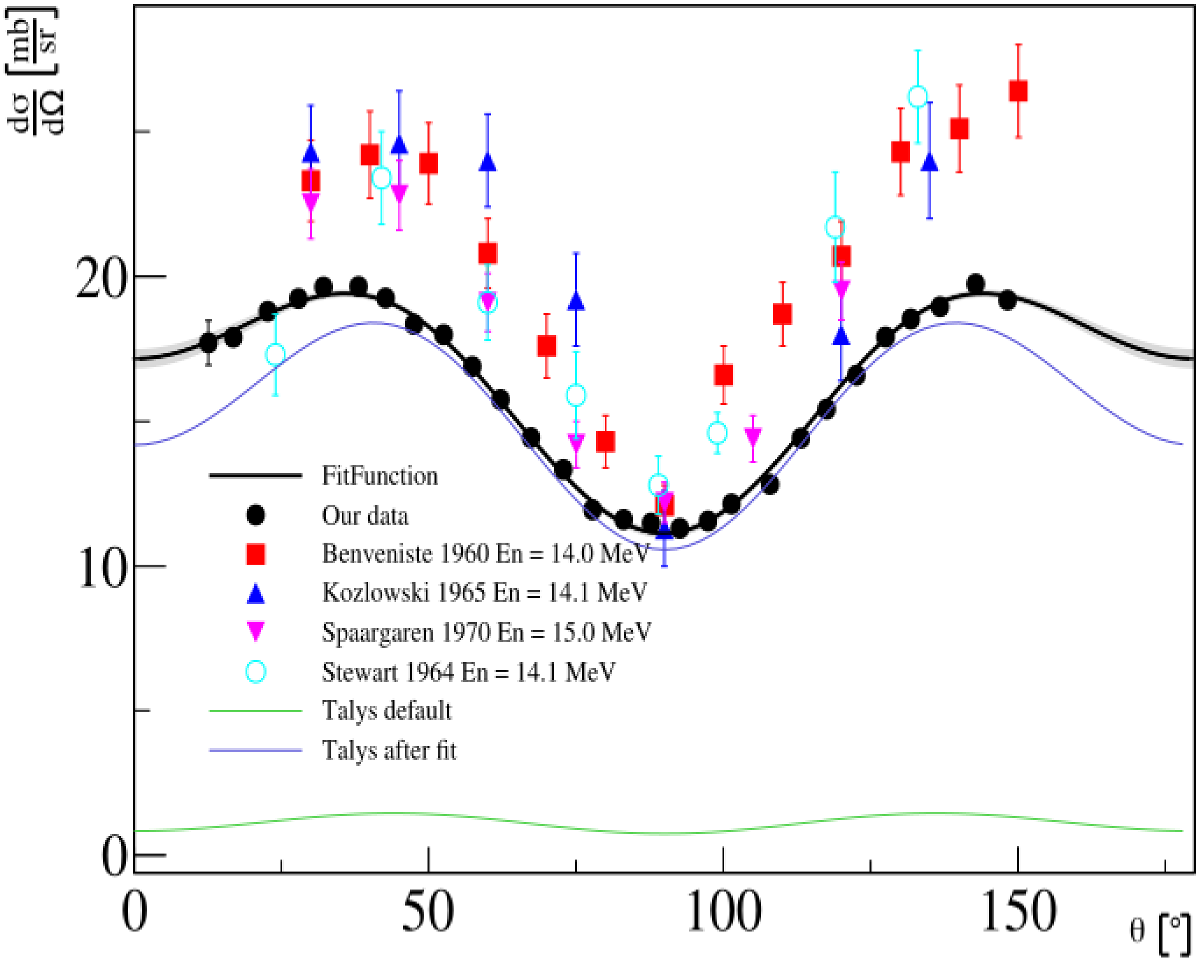
$N_{nucl} = \frac{\rho N_A D}{m_A}$



Scheme for calculating the angle between the neutron beam and the gamma detector (θ)

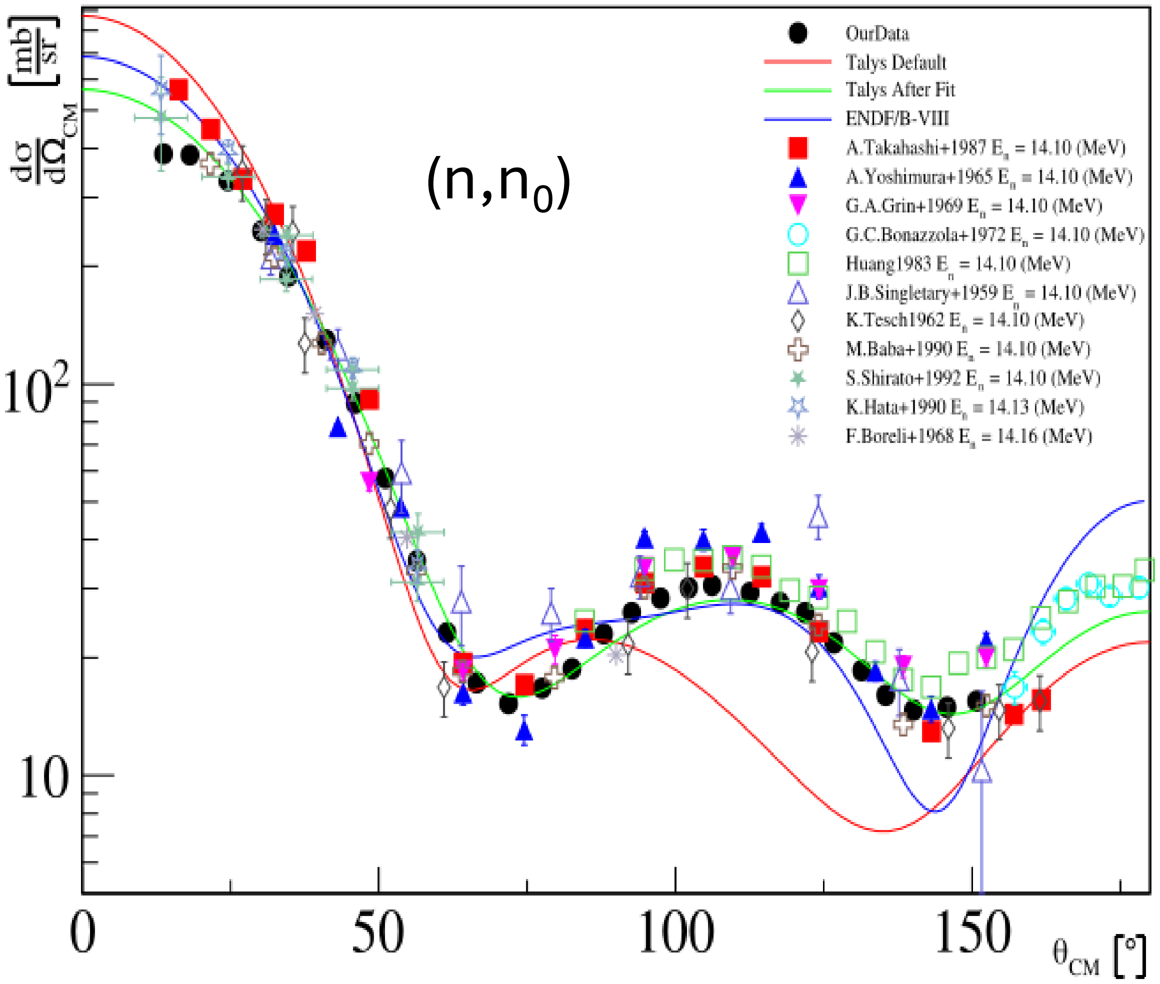
Angular anisotropy of 4.43-MeV γ-rays produced in inelastic scattering of 14.1-MeV neutrons by 12C nuclei.

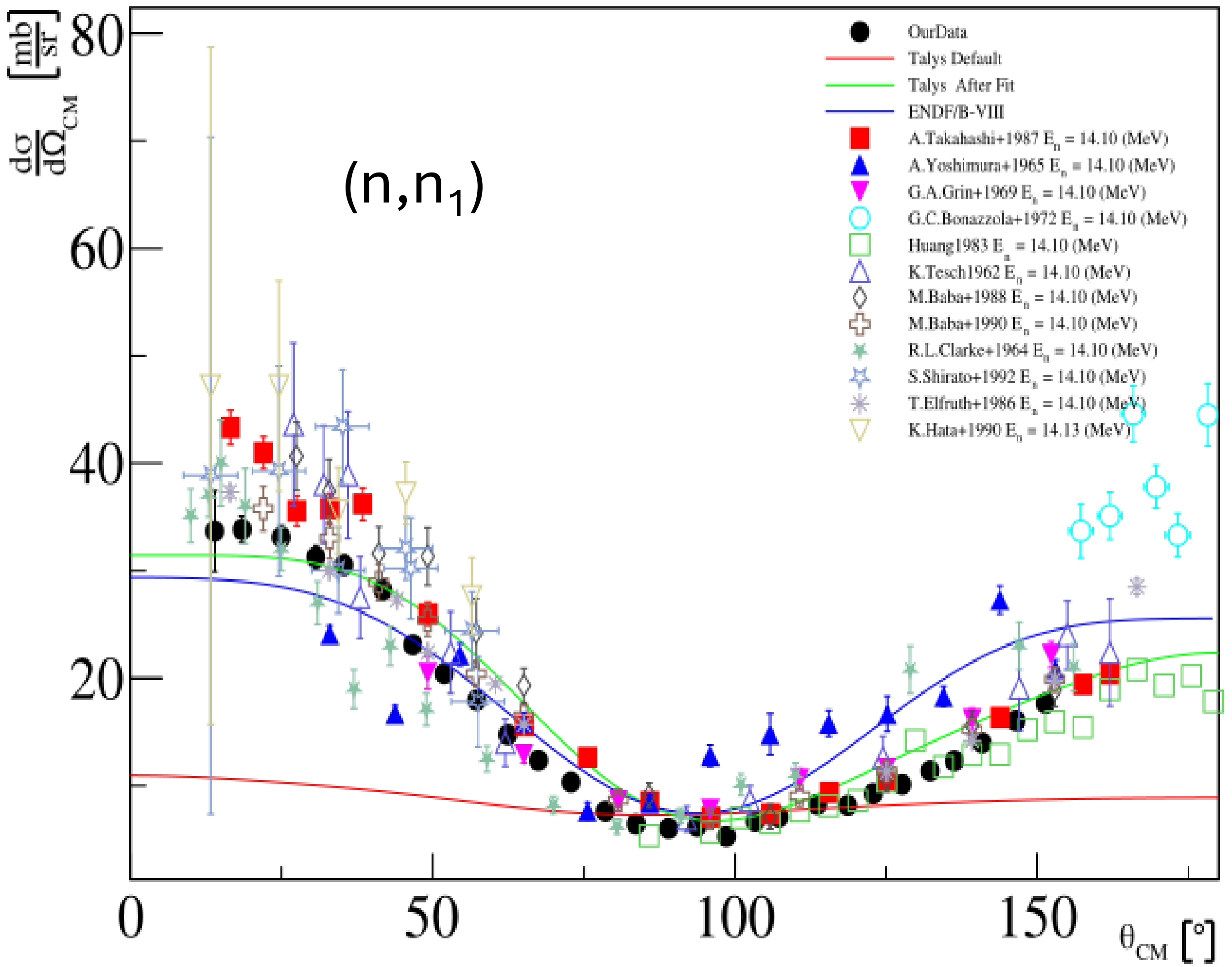
$$\sigma_\gamma(\theta) = \sigma_\gamma \left(1 + \sum_{l=2.4...}^{2J} a_l P_l(\cos(\theta))\right)$$



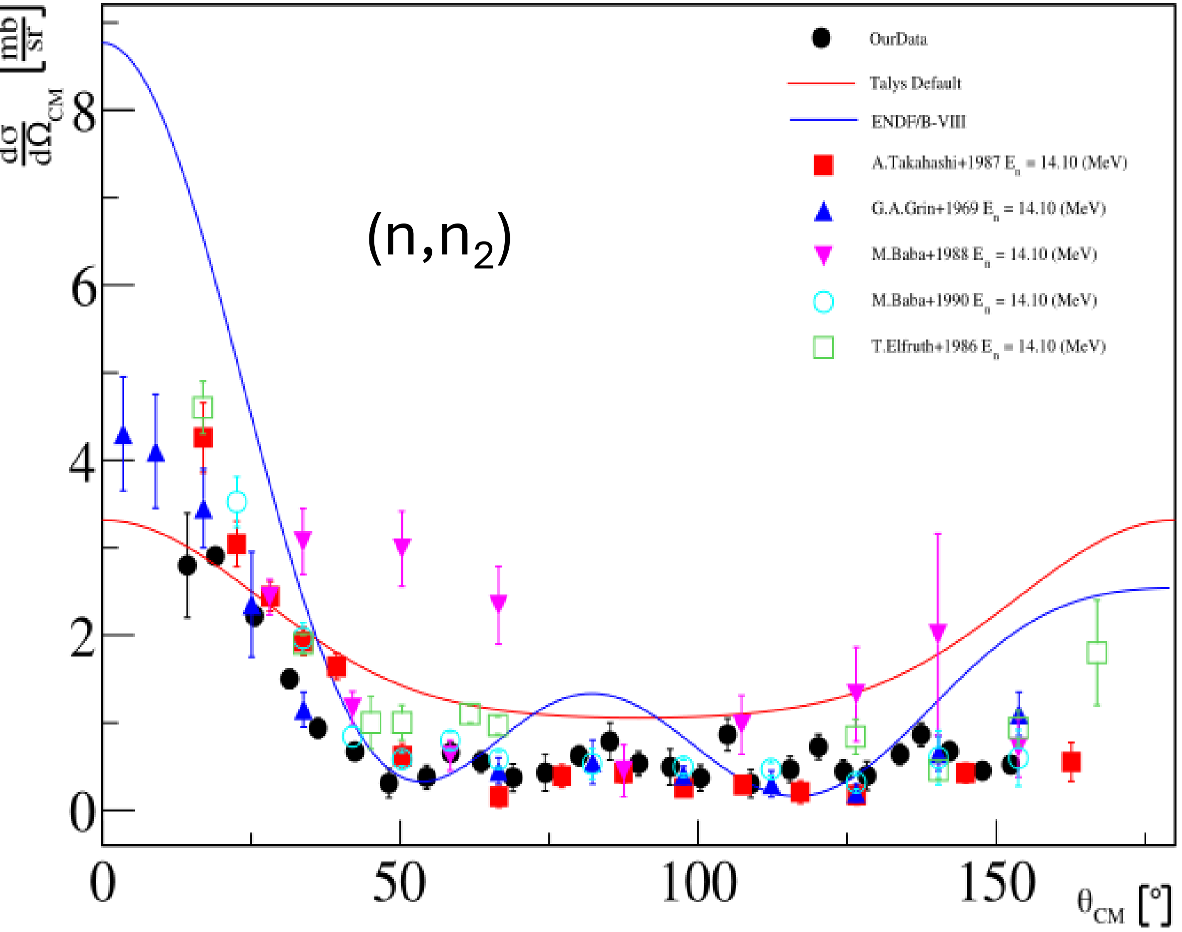
Source	σ_γ	a_2	a_4
Our data	197(1)	0.37(0.01)	-0.28(0.01)
Talys default	14	0.28	-0.53
Talys after fit (our data)	187	0.31	-0.36
Benveniste	250(5)	0.37 (0.06)	-0.39 (0.08)
Spaargen	229(1)	0.39 (0.01)	-0.37 (0.02)
Kozlowski	248(15)	0.36 (0.17)	-0.43 (0.24)
Stewart	234(7)	0.15 (0.07)	-0.58 (0.09)
Simakov	187(8)		
ENDF/B-VIII	210	0.68	0

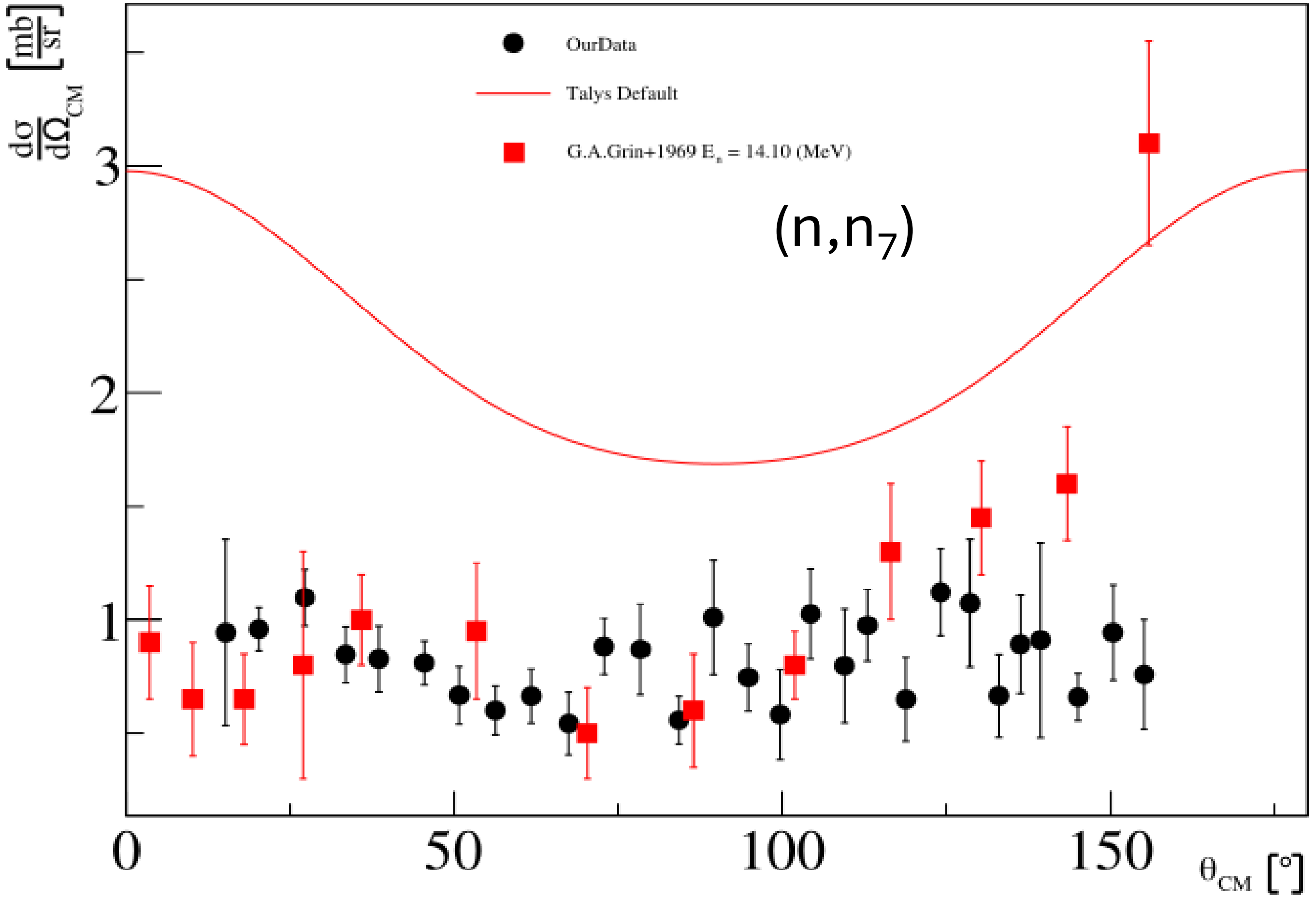
Angular distributions of scattered neutrons



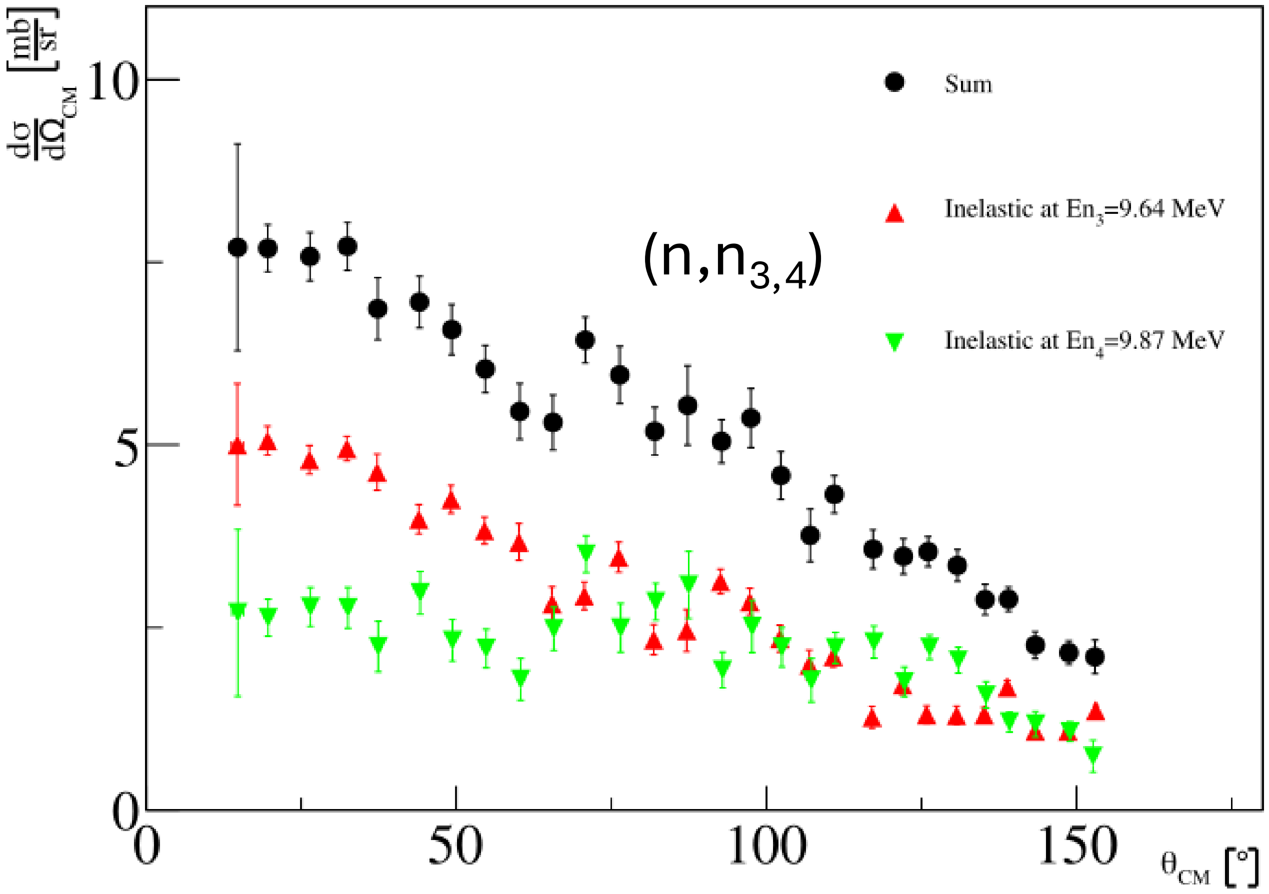


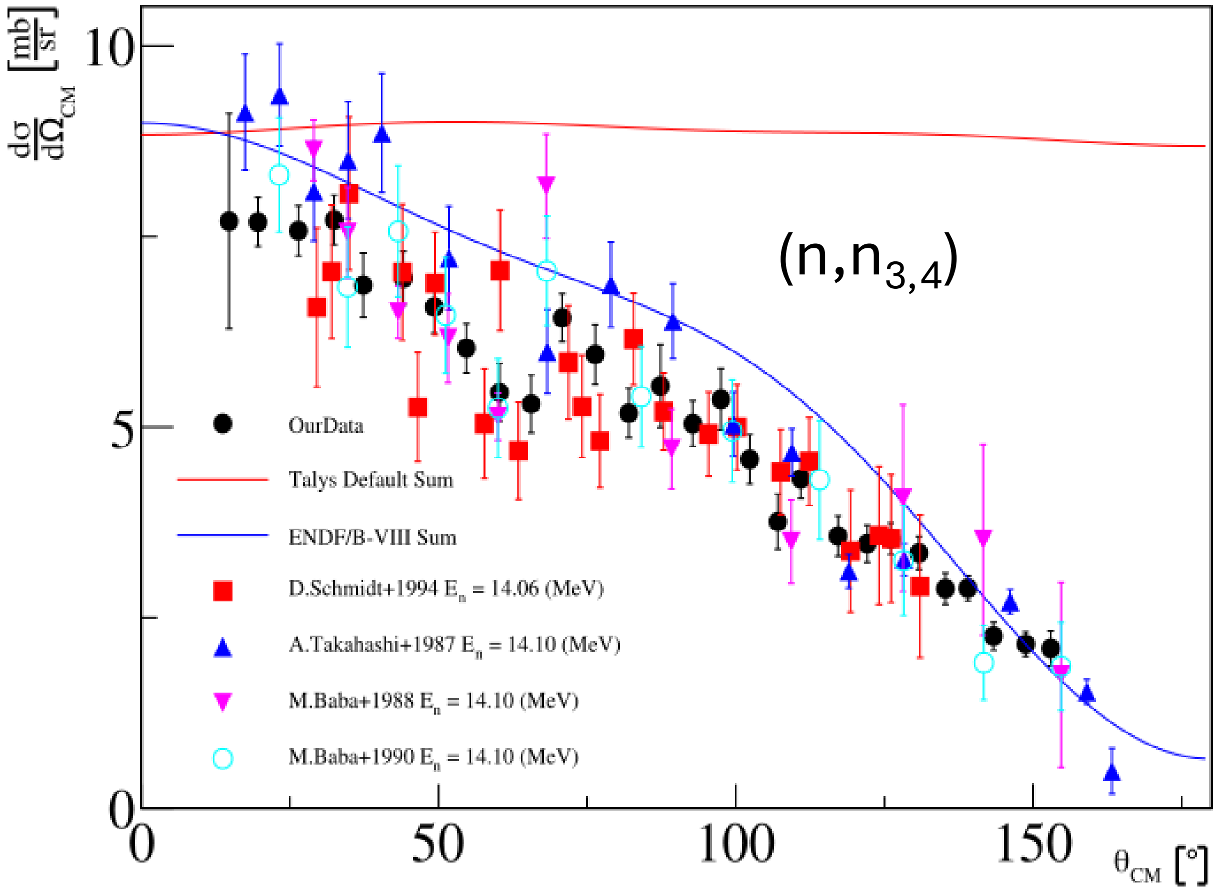
Angular distributions of scattered neutrons





Angular distributions of scattered neutrons





Optical model parameters for 14.1 MeV

Source	Approach	V_V MeV	W_V MeV	r_V fm	a_V fm	W_D MeV	r_D fm	a_D fm	V_{SO} MeV	W_{SO} MeV	r_{SO} fm	a_{SO} fm	β_2	χ^2/N
Default calc.	DWBA	49.07	1.26	1.13	0.68	7.65	1.31	0.54	5.39	-0.07	0.90	0.59	0.4	2621
Our data fit	CC rot.	43.68	0.50	1.18	0.28	1.42	1.05	0.73	9.44	0	0.82	0.34	-0.89	29.9

(*N* stands for number of experimental points used in the fit. The notations in the tables are the same as in the optical model parametrization of A.J. Koning and J.P. Delaroche [12].)

Comparison of integral cross sections of several processes taking place at 14.1 MeV

	σ_{el} mb	$\sigma(n,n_1)$ (4.44 MeV) mb	$\sigma(n,n_2)$ (7.65 MeV) mb	$\sigma(n,n_3)+\sigma(n,n_4)$ (9.64 MeV, 9.87 MeV) mb	$\sigma(n,n_7)$ (10.85 MeV) mb	$\sigma_\gamma(2^+\rightarrow 0^+_{g.s.})$ mb
Experiment	750.5±6.8	180.2±1.8	8.8±0.6	61.7±1.6	9.8±0.8	197.3±1.0
Default calc.	849.9	92.3				133.8
Our data fit	753.3	203.4				215.1

[12] A.J. Koning and J.P. Delaroche. Nucl.Phys.A **713** (2003) 231.

Conclusions

As a result of the work:

- Experiment of neutron scattering on carbon carried out by TANGRA setup showed us possibility to measure angular distributions of scattered neutrons and γ-quanta at the same time.
- In our experiment we managed to separate the angular distribution of neutrons from the third and fourth states, which was not done in the previous works.
- In the frame of symmetric rotator model of ^{12}C, new optical parameters and nucleus quadrupole deformation value, for ^{12}C interaction with 14.1 MeV neutrons, were obtained using Talys.
- We were able to get S-matrix from Talys code for the first exited state and calculate S-matrix coefficients. This allowed us to fit gamma angular distribution data together with an optical model for the elastic and first exited state.