*62nd meeting of the PAC for Nuclear Physics*

# Measurement of differential and total scattering cross sections of 14.1 MeV neutrons on carbon nuclei: methodological aspects and results

*P.S. Prusachenko on behalf of the TANGRA project*

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# Highlights

- The cross section of the $^{12}C(n,n)^{12}C$ reaction were measured at 14.1 MeV for several important channels
- New data were obtained on the characteristics of EJ-200 scintillators, in particular on the light output of secondary charged particles in a wide energy range.
- A new method for experimentally determining the detection efficiency of organic scintillation detectors for use in experiments with tagged neutron beams was developed and implemented.

# Motivation

Fundamental aspects:

- $^{12}C$ nucleus structure
- Data for improving theoretical models
- Hoyle's state and and more highly excited states

Applied aspects:

- The $^{12}C(n,n_1\gamma)^{12}C$ reaction is of interest to the elemental analysis
- Helium accumulation in potential fusion reactor materials due to the $^{12}C(n,n)3\alpha$ reaction[1]

The evaluated cross-sections from different libraries are extremely contradictory

1. C.G. Windsor et al., Nucl. Fusion 58(7), 076014 (2018). https://doi.org/10.1088/1741-4326/aabdb0

# Experimental setup and procedure

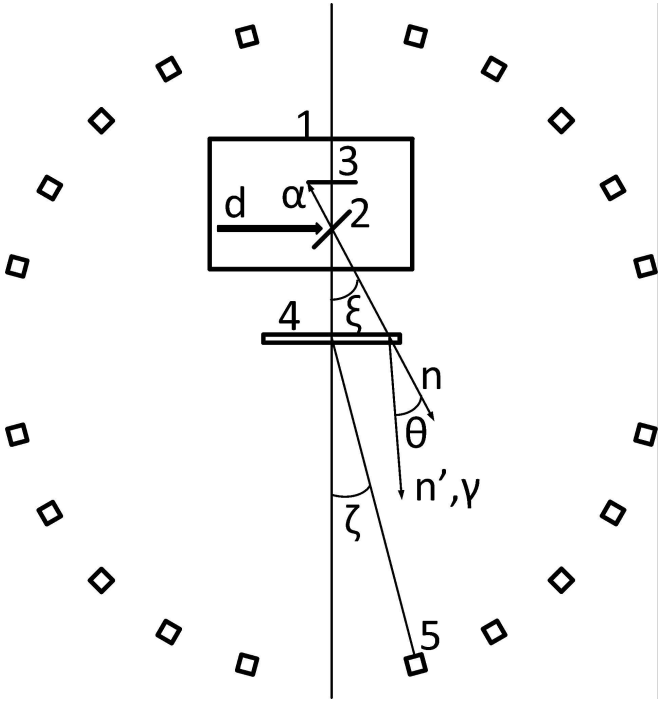



Fig. 1. Layout of experimental set-up (not to scale)
ξ - the incident neutron angle
θ - the scattering angle
ζ - the detector angle

**Experimental setup:**

- The ING-27 neuron generator (1) with tritium target (2)
- Position-sensitive silicon detector of α-particles (3)
- Sample (4) - chemical pure carbon
- 20 EJ-200 scintillators (5)

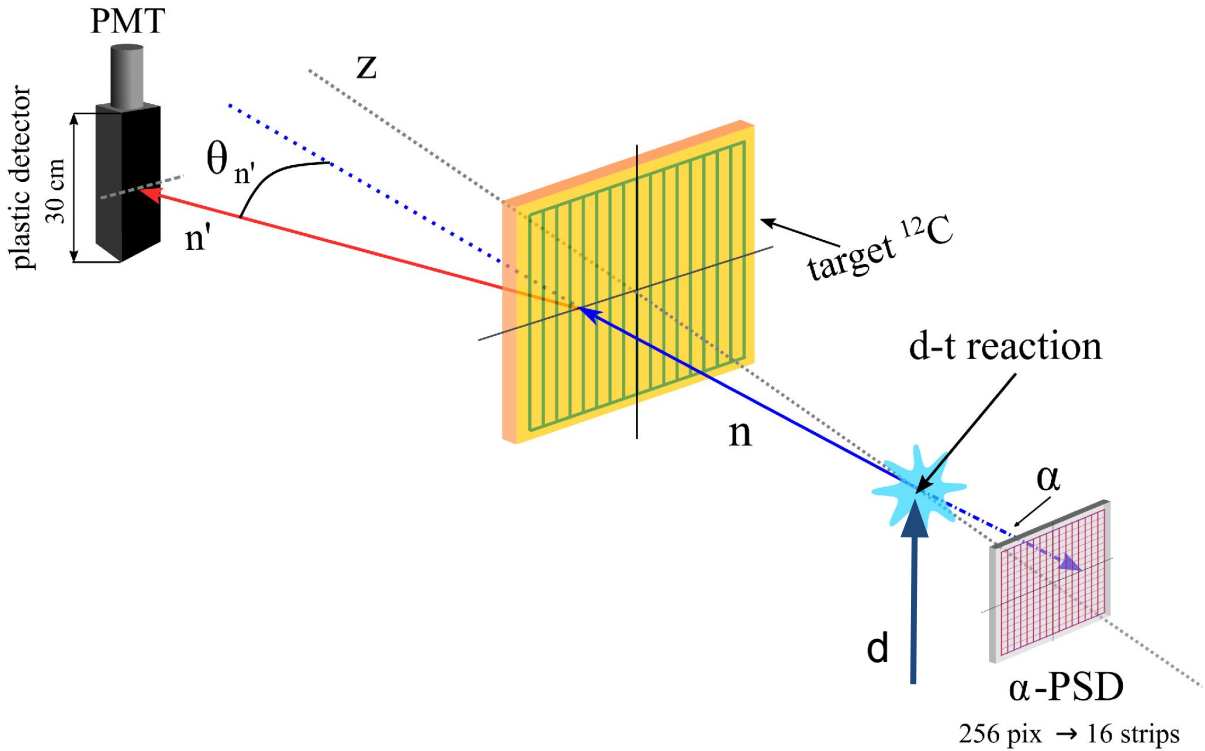
**Geometrical characteristics:**

- Sample-detector distance was 2040 mm
- Sample dimensions were 440x440x21 mm
- Detector dimensions were 80x80x300 mm

**Measurement procedure and data acquisition:**

- Waveform digitizer (100 MS/s, 16 bits)
- 25 hours - measurement time
- Background measurement

# Tagged neutron method




Demonstration of the principle of the tagged neutron method as applied to this experiment

# Data Analysis. Background Subtraction

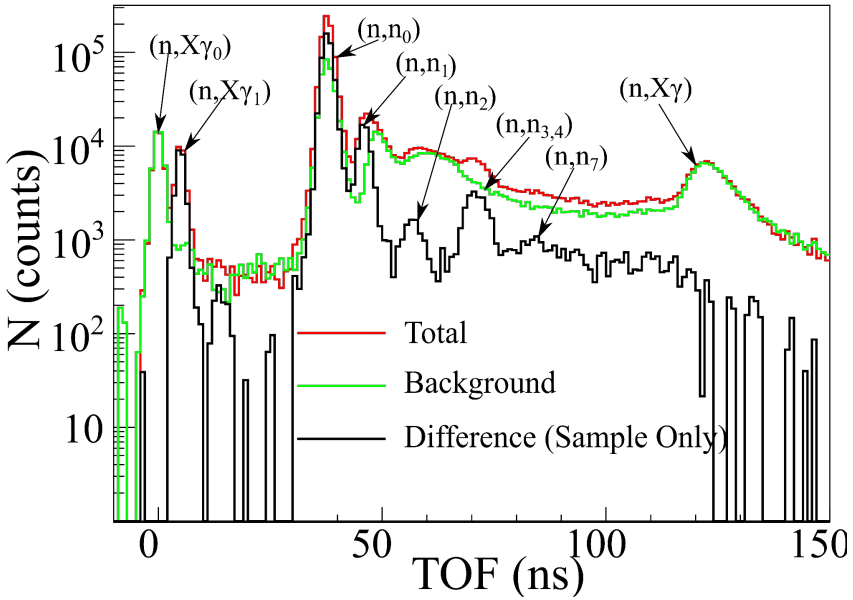



Fig. 2. The TOF spectra acquired with and without the carbon sample and their difference

- The background TOF spectra were subtracted from the corresponding spectra acquired in the presence of the sample after normalization to the number of α-particles (tagged neutrons)
- The attenuation of the background spectrum due to the attenuation of the tagged neutron beam in the sample was taken into account by GEANT4 simulation

**Spectrum components:**

$(n,X\gamma_0)$, $(n,X\gamma_1)$ - prompt γ-rays from inelastic scattering of neutrons in neutron generator and sample respectively

$(n,n_x)$ - neutrons elastically and inelastically scattered carbon and nuclei in the sample

$(n,X\gamma_1)$ - the wall of experimental hall

# Data Analysis. Cross Section Calculation

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{N_c k_{ms} k_{iatt} k_{ct} k_{satt} cos\xi}{N_\alpha n_{nucl} \varepsilon \Delta\Omega}$$

- $N_c$ is number of counts
- $k_{ms}$, $k_{iatt}$, $k_{satt}$ and $k_{ct}$ are the correction factors taking into account multiple scattering, attenuation of primary neutrons and secondary neutrons and gammas in the sample and cross-talk
- ξ is the incident neutrons angle
- $N_\alpha$ is the number of tagged neutrons
- $n_{nucl}$ is the surface density of carbon nuclei in the sample
- ε is the detector intrinsic efficiency
- ΔΩ is the solid angle

Total reaction cross section:

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

# Light output functions. Problems

- Response functions of the organic scintillators are formed by the products of the fast neutron induced reactions, mainly protons and alphas
- Light output for heavy charged particles depends nonlinearly on their dE/dx

**Problems:**

- Light output functions are extremely contradictory for protons
- There are no data for α-particles
- There is no working theoretical model for predicting light yield in scintillators[2]

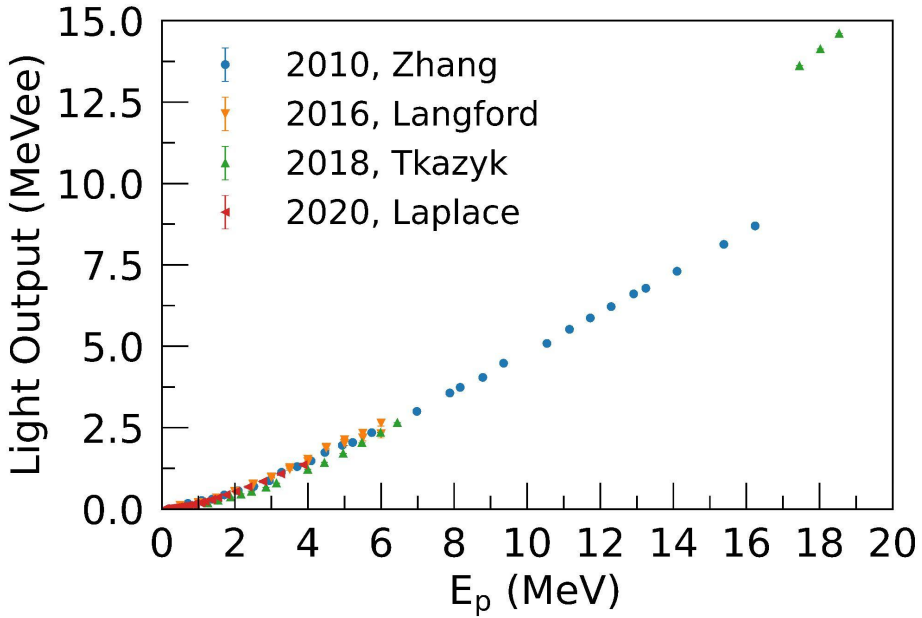



Fig. 3. The available experimental datasets on proton light output for the EJ-200 scintillator and its analogues

2. T.A. Laplace et al, Modeling ionization quenching in organic scintillators, Materials Advances 3 (2022) 5871, https://doi.org/10.1039/D2MA00388K.

# Light output functions. Two-dimensional spectrum

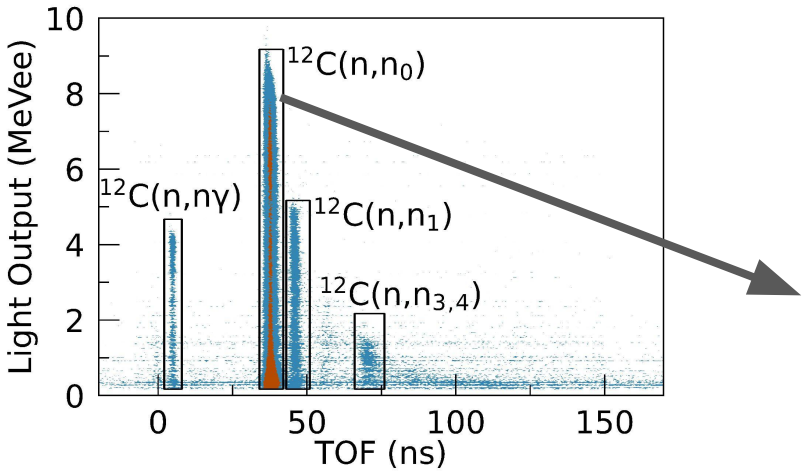



Fig. 4. The two-dimensional spectrum with axes Time-of-Flight - Light Output (pulse area) corresponding to the scattering angle of 13$^0$.

**Individual groups of events correspond to the detection of neutrons with a fixed energy from different scattering channels**

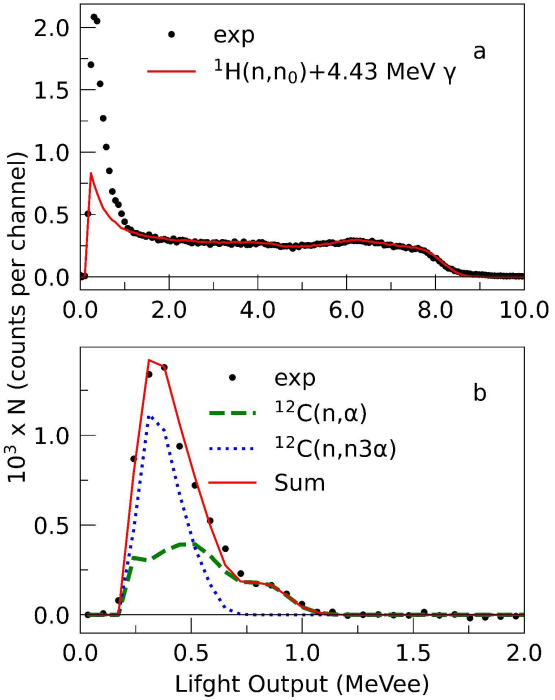



Fig. 5. The one-dimensional light output spectrum corresponding to the $^{12}$C(n,n$_0$)$^{12}$C reaction and scattering angle of 13 deg. (a) - total, (b) - alphas

**The right edge of each distribution corresponds to the detection of secondary particles with the highest possible energy.**

# Light output functions. Results

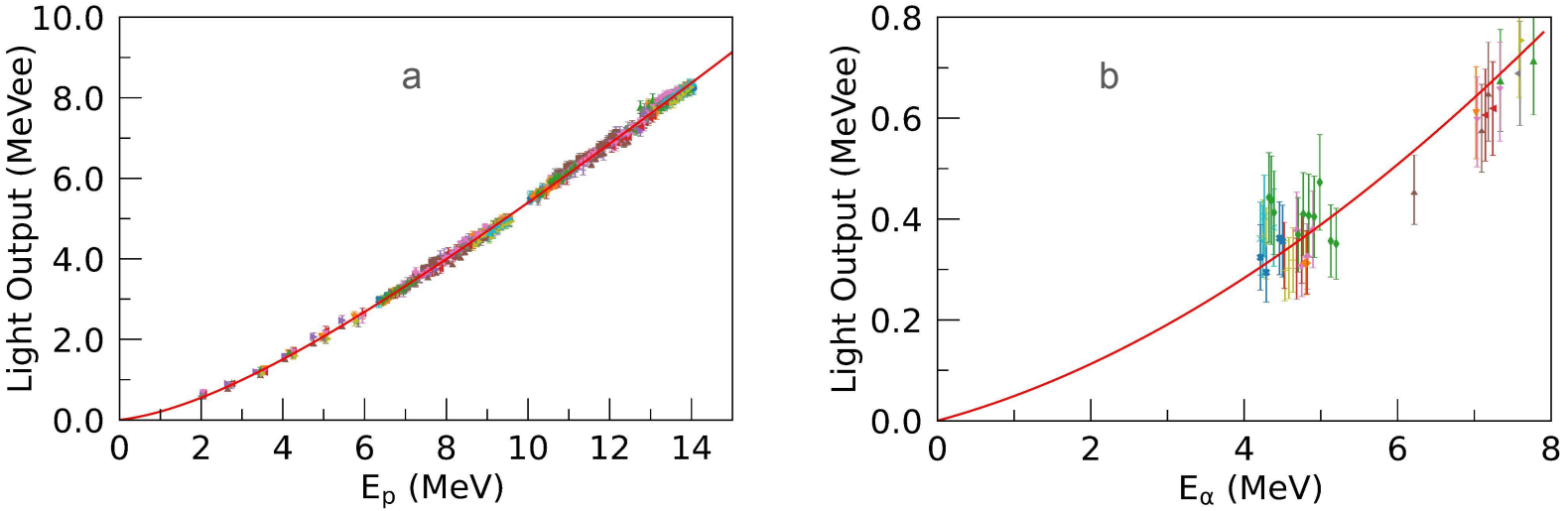



Fig. 6. Light output data measured in the work
(a) - data for protons
(b) - data for α-particles

# Detectors Efficiency. Approach

Problems:

- Large contribution (up to 30%) of $^{12}C(n,\alpha)^{9}Be$ and $^{12}C(n,n)3\alpha$ to the response function above 8 MeV
- There is no standard approach for measuring the neutron detection efficiency above 7-8 MeV
- The new experimental methods are needed to verify simulated efficiency curve

**Decision:**

- The $^{1}H(n,n_0)^{1}H$ reaction as a standard to determine the neutron detection efficiency

# Detectors Efficiency. Realization

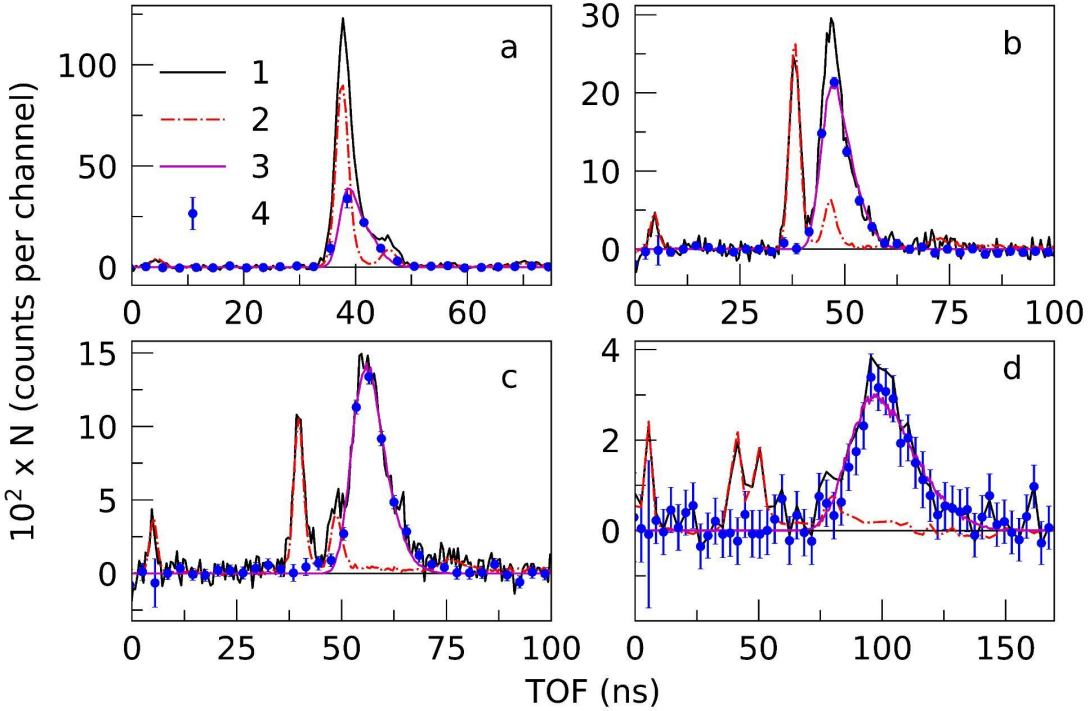



Fig. 7. TOF spectra measured with polyethylene sample (1), graphite sample (2, normalized), and its difference (4). 3 - the simulated TOF spectra corresponding to only scattering on hydrogen in polyethylene

# Detectors Efficiency. Results

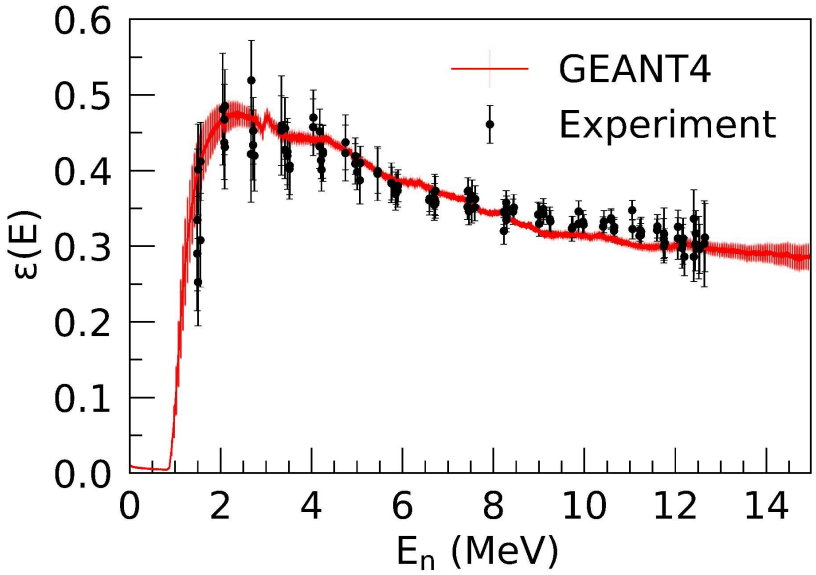



Fig. 8. The measured efficiency values vs the GEANT4 simulation

# Corrections

- The effects of multiple scattering, absorption and cross-talk were evaluated by GEANT4 simulation
- Cross-talk effect  was <<1%
- Absorption in the sample and multiple scattering of secondary neutrons effect varied from 5-10% (close to $0^0$ and $180^0$) to 35% (close to $90^0$)
- Contribution of the “additional” γ-rays from secondary inelastic scattering was about 10-12%

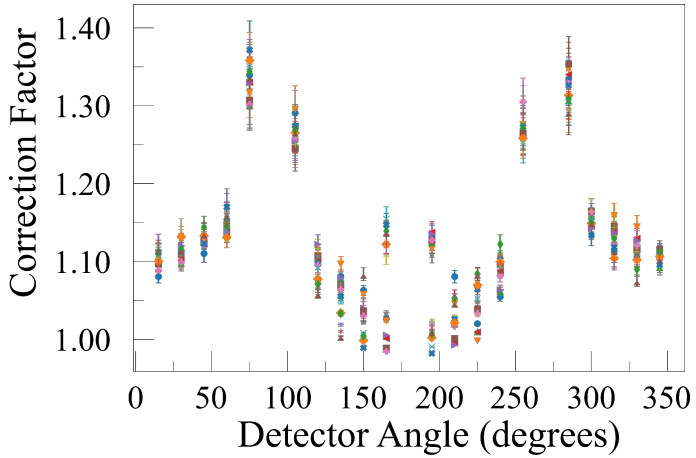
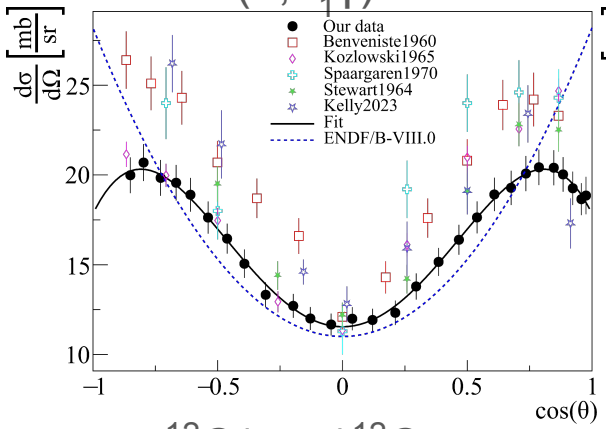


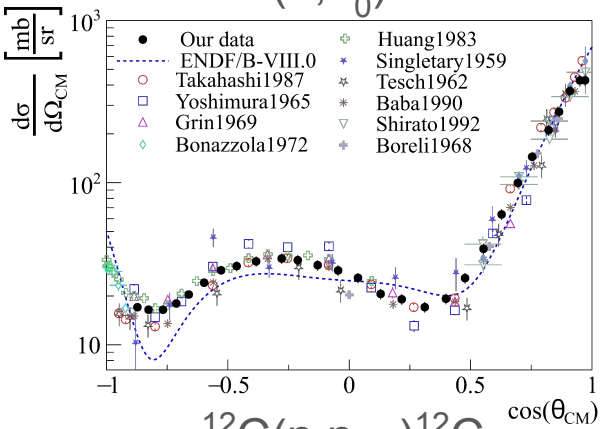

Fig. 9. Correction factor taking into account the absorption and multiple scattering. The elastic scattering case. Different symbols correspond to different vertical strips

# Differential Cross Sections

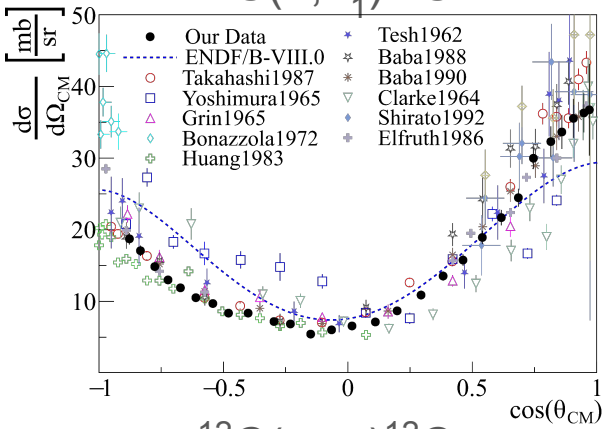
$^{12}C(n,n_1\gamma)^{12}C$



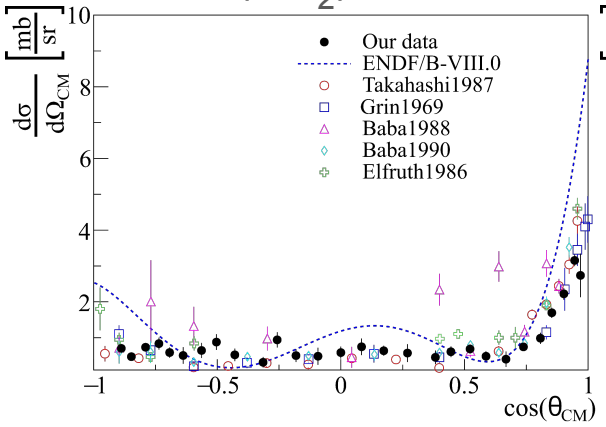

$^{12}C(n,n_0)^{12}C$



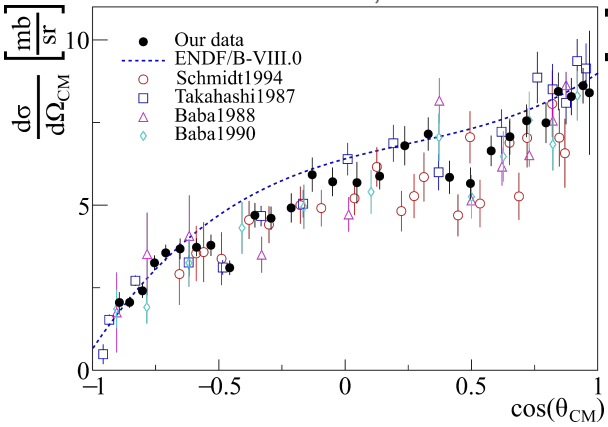

$^{12}C(n,n_1)^{12}C$



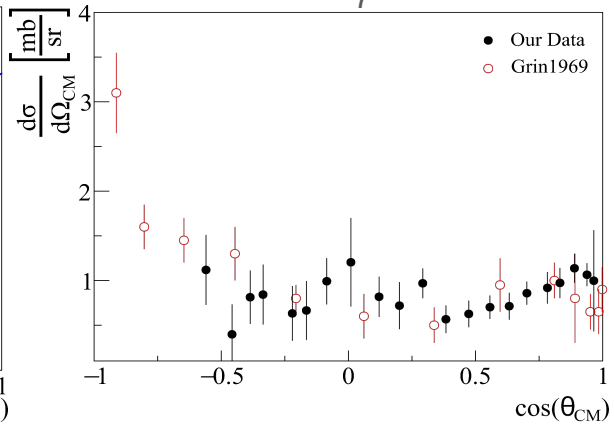

$^{12}C(n,n_2)^{12}C$




$^{12}C(n,n_{3,4})^{12}C$




$^{12}C(n,n_7)^{12}C$



# Total Cross Sections

| 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±61 | 192±10 (n)<br>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;<br>55±12 – $^{12}C(n,n_{5,6})$ from Grin[3], 1969<br>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 |

3. G.A. Grin, B. Vaucher, J.C. Alder, C. Joseph, Helv. Phys. Acta 42, 990 (1969)

# Summary

- New data on $^{12}C(n,n_{0,1,2,3,4,7})^{12}C$ reaction cross sections were presented
- The new data on proton and α-particle light outputs were obtained. This data are already available in the Organic Scintillator Library at the LBNL website (https://scintillator.lbl.gov/organic-scintillator-library/)
- The method for experimental determination of the detection efficiency for organic scintillators was implemented
- 2 papers

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Characterization of an EJ-200 plastic scintillator array for experiments with 14-MeV tagged neutrons using the carbon and polyethylene samples

P.S. Prusachenko [a,*], D.N. Grozdanov [a,b], N.A. Fedorov [a], Yu.N. Kopatch [a], V.R. Skoy [a], I.N. Ruskov [a,b], T.Yu. Tretyakova [a,c,d], P.I. Kharlamov [a,c], A.V. Andreev [a,d], G.V. Pampushik [a,d], C. Hramco [a], P.G. Filonchik [a,e], S. Dabylova [a], TANGRA collaboration

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Regular Article - Experimental Physics

**Measurement of differential and total cross sections for scattering of 14.1 MeV neutrons on $^{12}C$ nuclei**

D. N. Grozdanov[1,2,a], P. S. Prusachenko[1], N. A. Fedorov[1], Yu. N. Kopatch[1], T. Yu. Tretyakova[1,3,4], G. V. Pampushik[1,3], A. V. Andreev[1,3], V. R. Skoy[1], C. Hramco[1], P. G. Filonchik[1,5], P. I. Kharlamov[1,4], A. L. Barabanov[1,6], TANGRA collaboration

# Thank for your attention!

prusachenko@jinr.ru