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

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FOR NUCLEAR RESEARCH

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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 - the role of the $^{12}C(n,n)3\alpha$ reaction is poorly known
- Evaluated cross-sections from different libraries are extremely contradictory

Experiment and Data Analysis

Experimental setup and procedure

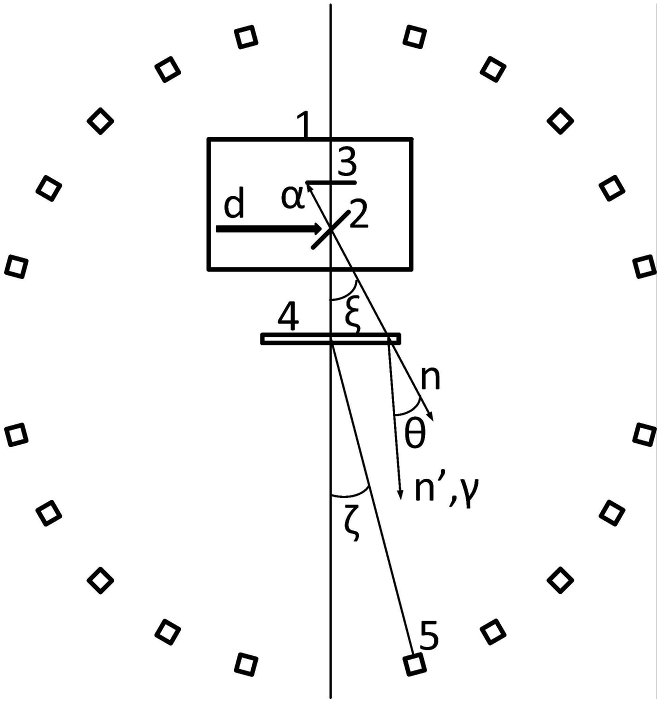


Fig. 1. Layout of experimental set-up (not to scale)
ξ - the incident neutron angle
θ - the scattering angle
ζ - the detector angle

Experimental setup:

- The ING-27 neuron generator (1) with tritium target (2)
- Position-sensitive silicon detector of α-particles (3) consisting on 16 vertical and 16 horizontal strips
- Sample (4) - chemical pure carbon or polyethylene
- 20 EJ-200 scintillators (5)

Geometrical characteristics:

- Sample-detector distance was 2040 mm
- Sample dimensions were 420x420x10 mm (polyethylene) and 440x440x21 mm (graphite)
- Detector dimensions were 80x80x300 mm

Measurement procedure and data acquisition:

- Waveform digitizer (100 MS/s, 16 bits)
- 8 hours - measurement with PE sample
- 25 hours - measurement with carbon sample
- Background measurement after each sample measurement

Data Analysis. Background Subtraction

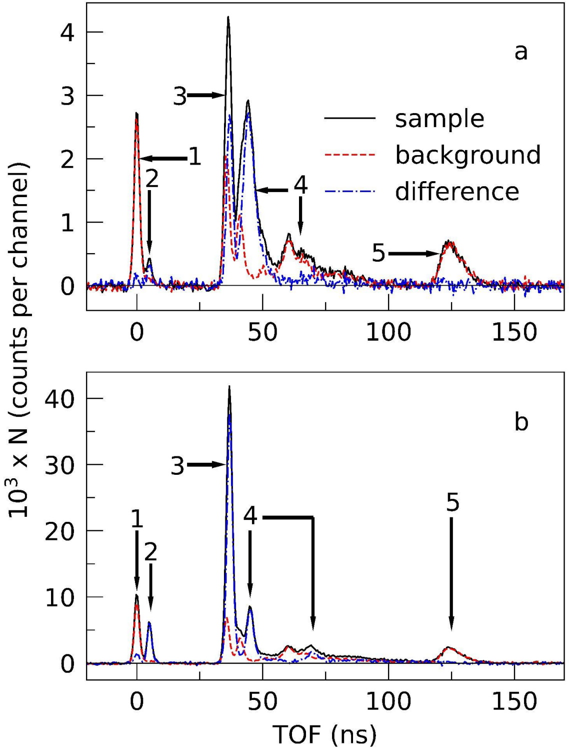


Fig. 2. The TOF spectra acquired with and without the sample. (a) is the measurement with the polyethylene sample and without it; (b) is the same only for carbon sample.

- 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:

1,2 - prompt γ-rays from inelastic scattering of neutrons in neutron generator and sample respectively

3,4 - neutrons elastically and inelastically scattered on the generator materials (background) or carbon and hydrogen nuclei in sample

5 - 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_α is the number of tagged neutrons
- n_{nucl} is the surface density of carbon nuclei in the sample
- ε is the detector intrinsic efficiency
- $\Delta\Omega$ is the solid angle

Total reaction cross section:

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

Methodological Aspects. Part I - Detectors Characterization

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

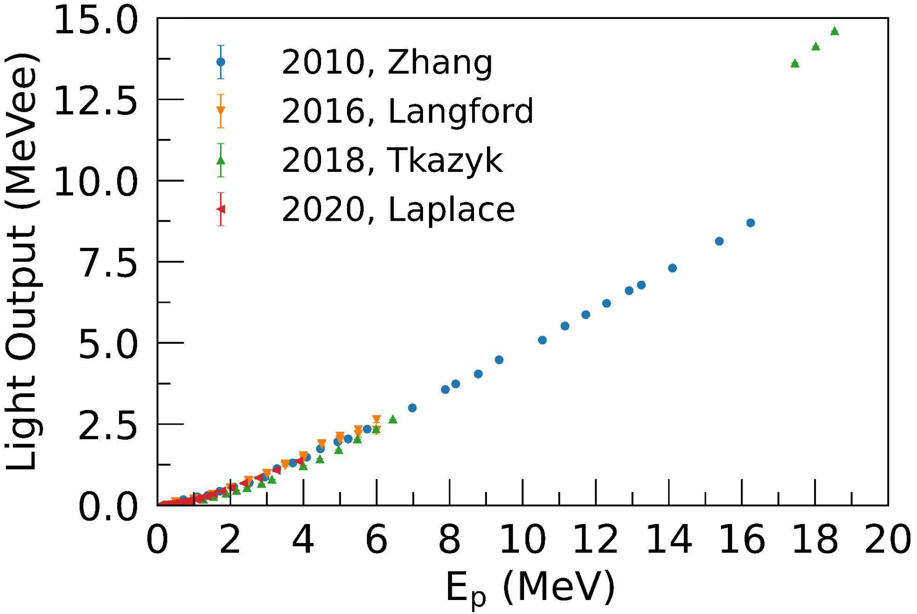


Fig. 3. The available experimental datasets on proton light output for the EJ-200 scintillator and its analogues

Light output functions. Decision

- Neutrons scattered at different angles have fixed energies (2.0-14.0 MeV)
- Light output value for fixed neutron energy can be extracted from the analysis of pulse-height

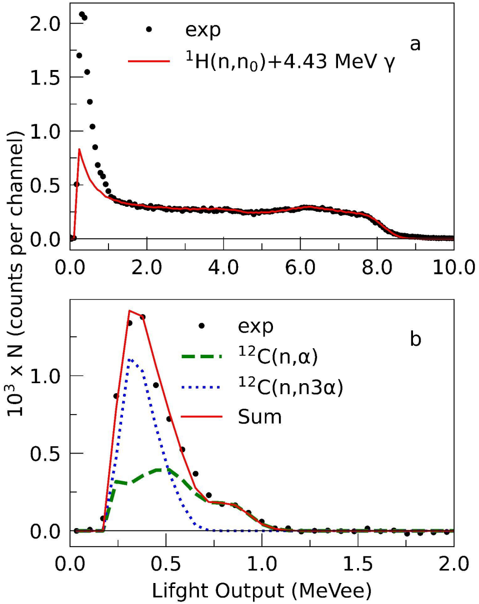


Fig. 4. The one-dimensional light output spectrum corresponding to the $^{12}C(n,n_0)^{12}C$ reaction and scattering angle of 13 deg. (a) - total, (b) - alphas

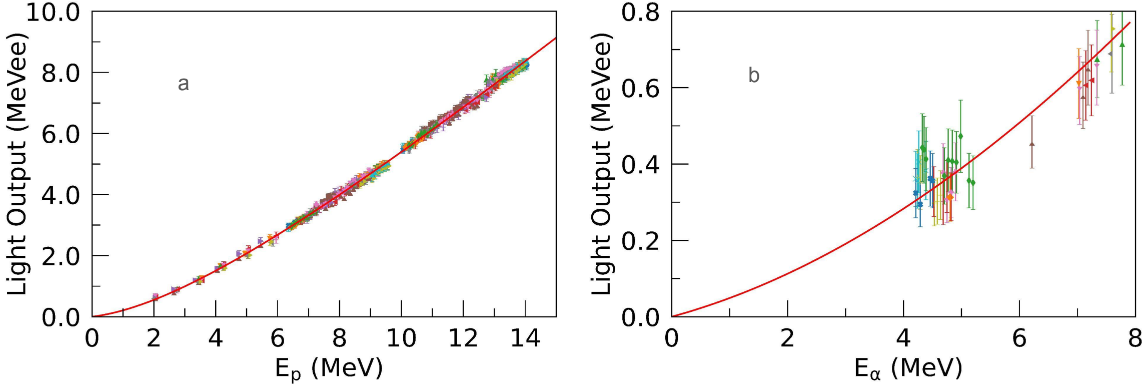


Fig. 5. Light output data measured in the work
(a) - data for protons
(b) - data for α-particles

Detectors Efficiency

Problems:

- Large contribution of $^{12}C(n,\alpha)^{9}Be$ and $^{12}C(n,n)3\alpha$ to the response function above 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

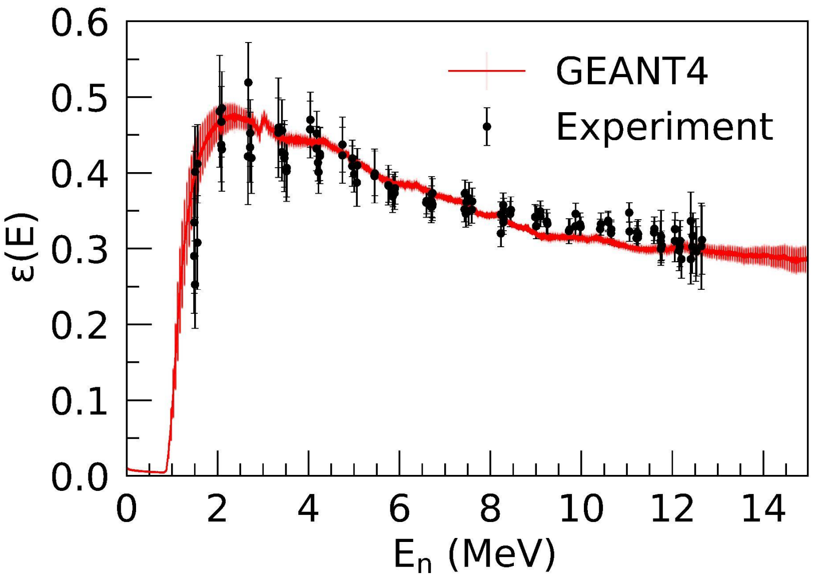


Fig. 6. The measured efficiency values vs the GEANT4 simulation

Methodological Aspects. Part II - Corrections and Uncertainties

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%

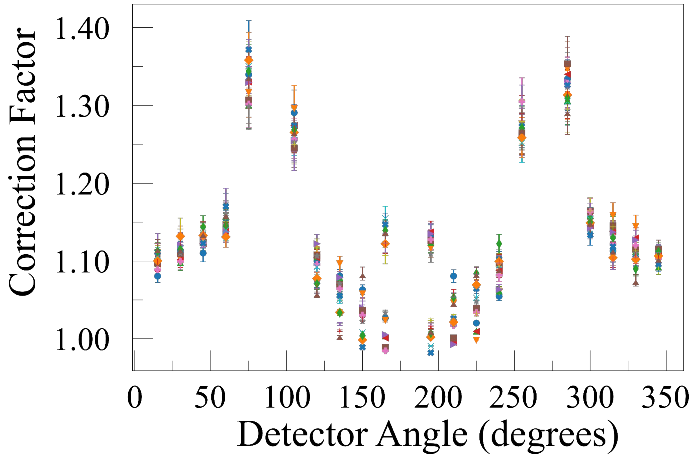


Fig. 7. Correction factor taking into account the absorption and multiple scattering. The elastic scattering case. Different symbols correspond to different vertical strips

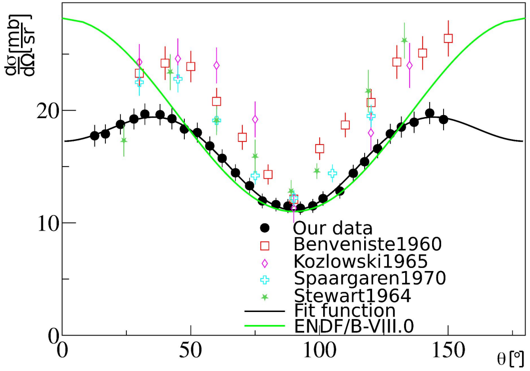
Uncertainties

- Statistic: 0.2 - 5.0% (total), 0.5-30.0% (differential)
- Efficiency: 4.0-7.0%
- Corrections: 1.0-3.0%
- Solid Angle: 1.0%
- Sample thickness: 0.7%

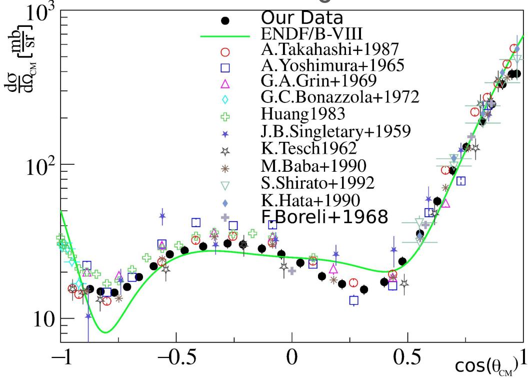
Results

Differential Cross Sections

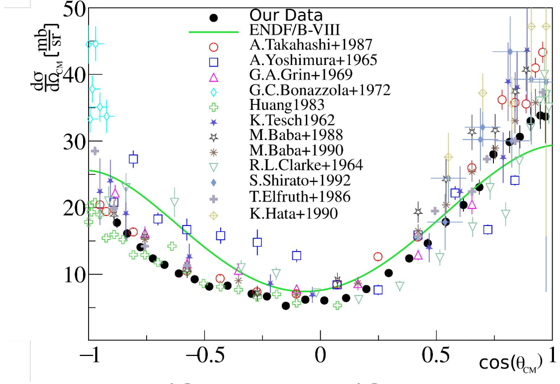
$^{12}C(n,n_1\gamma)^{12}C$



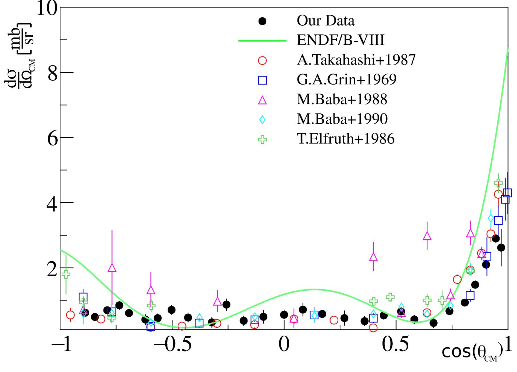
$^{12}C(n,n_0)^{12}C$



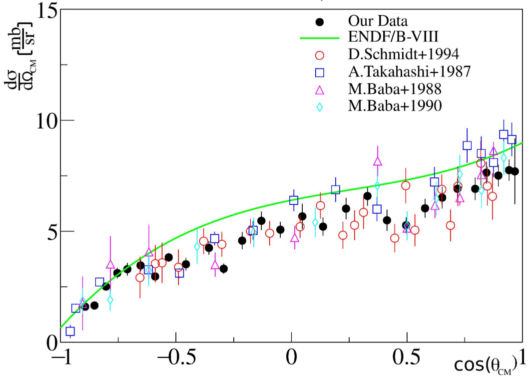
$^{12}C(n,n_1)^{12}C$



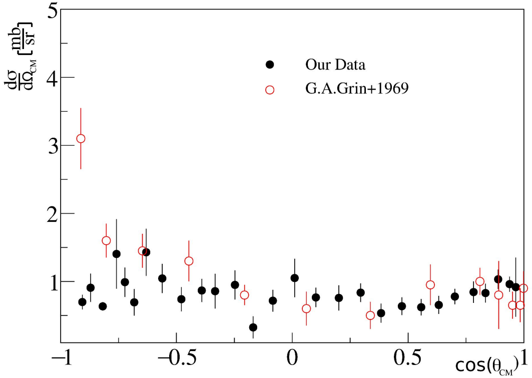
$^{12}C(n,n_2)^{12}C$



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



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



Total Cross Sections

References	Cross section (mb)								
	n_0	n_1	n_2	n_3	n_4	n_5	n_6	n_7	(n,n′)3α
This work	745±55	180±8	8.7±0.6	35±3	25±3	–	–	9.4±0.7	78±4 – $^{12}C(n,n_{2,3,4,7})$ this work; 55±12 – $^{12}C(n,n_{5,6})$ from Grin, 1969
ENDF/B-VIII.0	827	209	16	66.6	20	12	6.5	–	124
EAF-2010	–	–	–	–	–	–	–	–	270
FENDL-3.1b	801	182	0.9	9.9	2.1	2.7	3.1	3.3	22
JEFF-3.3	827	210	19.3	66.6	20.0	12	6.5	–	124.4
JENDL-4.0/HE	801	183	0.9	9.9	2.1	2.7	3.1	3.3	22

Publications

- **Prusachenko, P.S., Grozdanov, D.N., Fedorov, N.A. et al,** Characterization of an EJ-200 plastic scintillator array for experiments with 14-MeV tagged neutrons using the carbon and polyethylene samples, *Nuclear Instruments and Methods in Physics Research Section A 1072 (2025) 170143*. https://doi.org/10.1016/j.nima.2024.170143
- **Grozdanov, D.N., Prusachenko, P.S., Fedorov, N.A. et al,** Measurement of differential and total cross sections for scattering of 14.1 MeV neutrons on ^{12}C nuclei, *In Progress….*

Summary

- The differential cross-sections for scattering of 14.1 MeV neutrons on carbon nuclei were measured in the angular range of $13\text{-}150^0$
- The total cross-sections for each scattering channel were determined by integrating the angular distributions over entire solid angle range
- The neutron detector array used was characterized to obtain the initial data for simulating the response functions and efficiency. Simulated efficiency was experimentally verified using the $^{1}H(n,n_0)^{1}H$ reaction standard
- Corrections were taken into account for multiple scattering and attenuation of secondary neutrons and gammas, as well as crosstalk and attenuation of primary neutrons in the sample.
- The results obtained were compared with other experimental data and the evaluations. The data are generally in agreement with other experimental data but there is a large difference with the evaluated cross-sections from some libraries

Thank for your attention!

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