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Experimental Study of Thick Target Yield from the $^{13}C(\alpha,n_0)^{16}O$ Reaction

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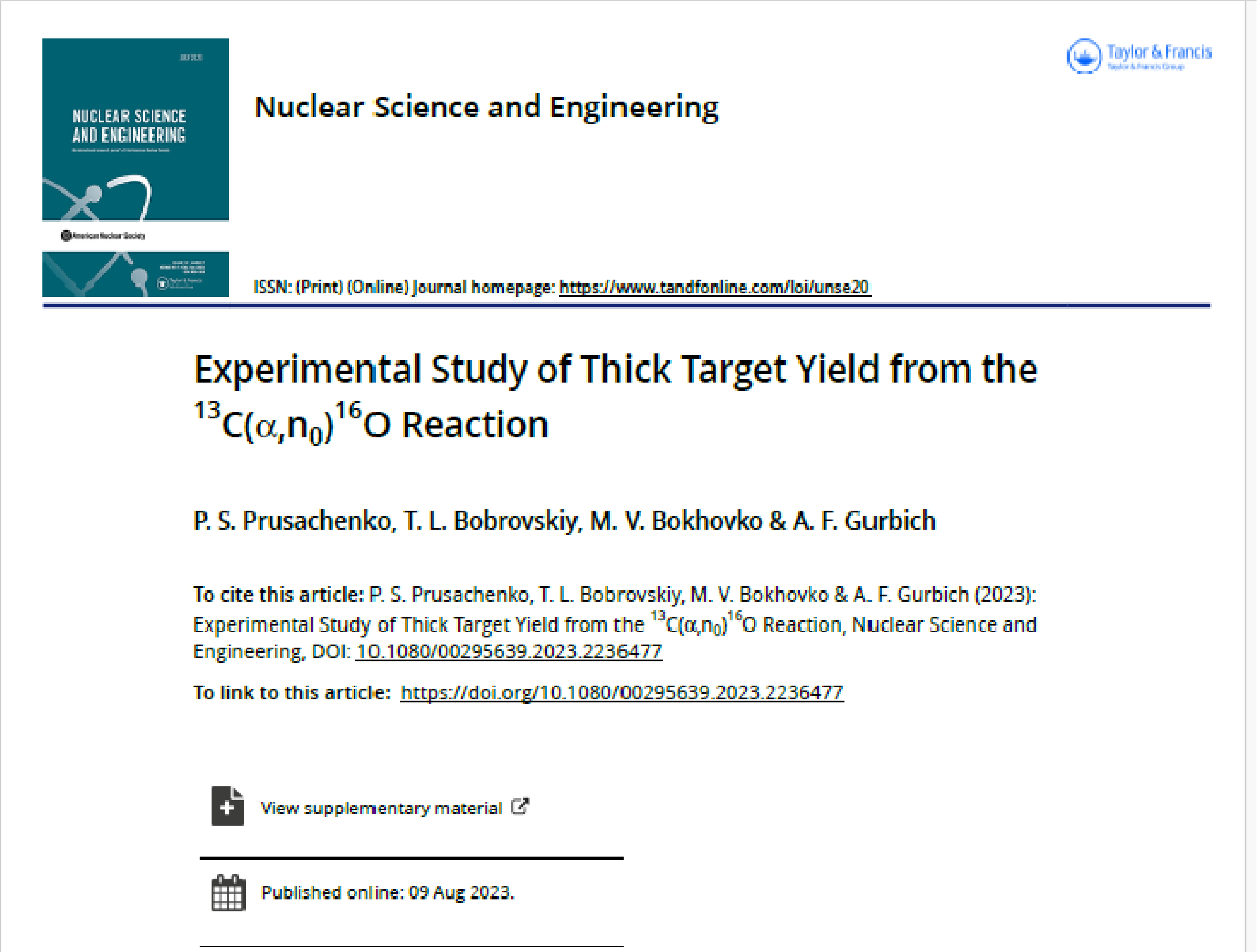

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Motivation

Needs:

- The data on the total thick target yield (TTY) from the $^{13}C(\alpha,n)^{16}O$ reaction are required to verify the evaluated cross-section of the $^{13}C(\alpha,n_0)^{16}O$ and $^{16}O(n,\alpha_0)^{13}C$ reactions
- The data on TTY from the $^{13}C(\alpha,n)^{16}O$ reaction are used to normalize the experimental data on the cross-section of the $^{13}C(\alpha,n_0)^{16}O$ reaction

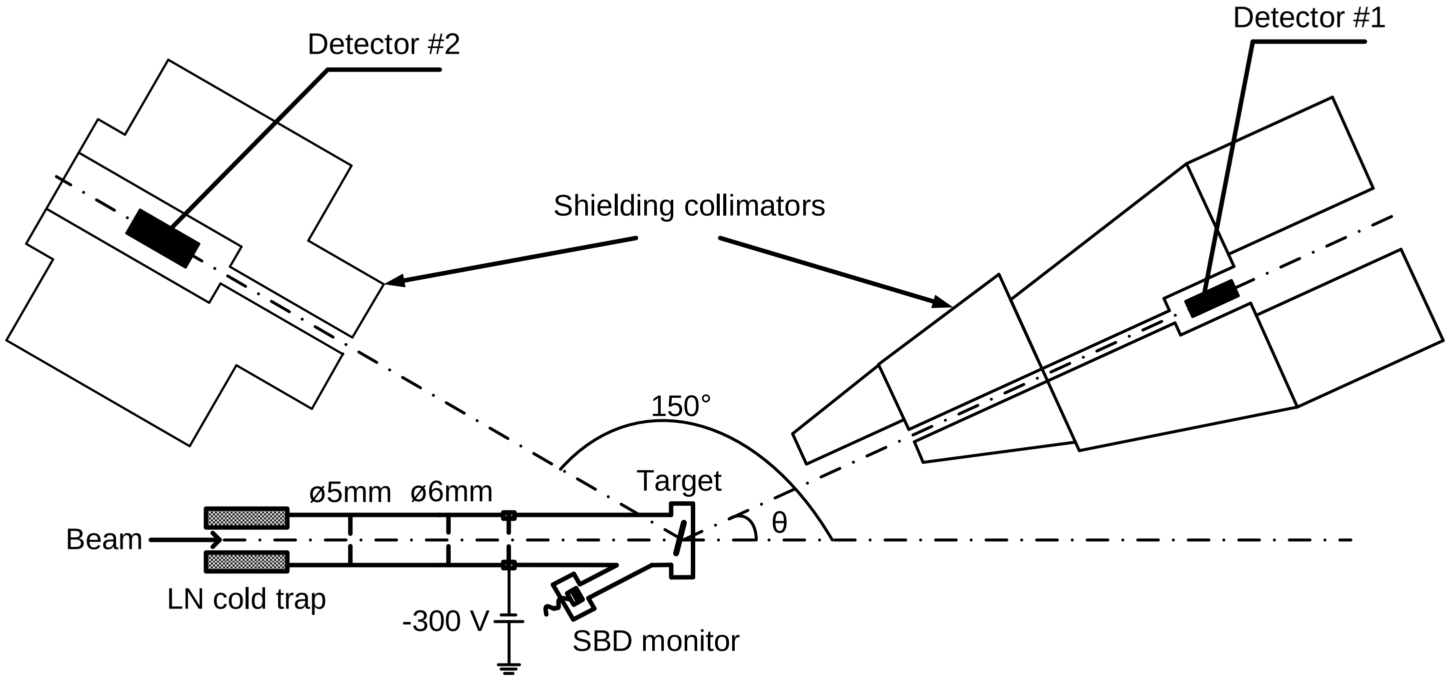
Current problems:

- The existing experimental data were measured with a large uncertainty
- ~10% - uncertainty of the ^{13}C contain in the natural carbon, 10-20% - the uncertainty of the 4π detectors efficiency
- The previously measured TTY data do not support the new ENDF-B/VIII.0 and JENDL-5.0 evaluations.

The aim of the work:

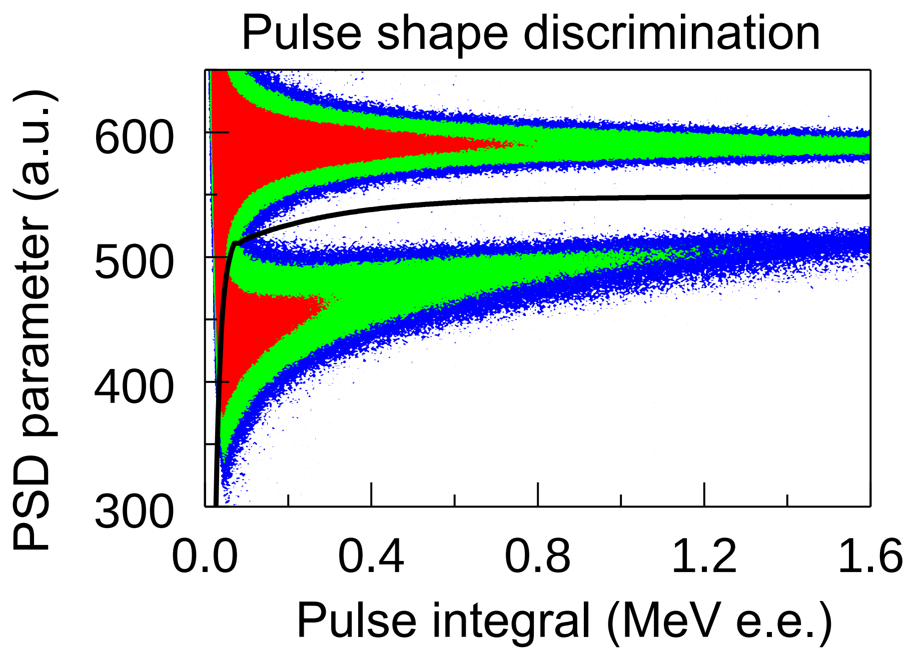
- To obtain new experimental data on TTY from the $^{13}C(\alpha,n_0)^{16}O$ reaction
- To decrease the data uncertainties

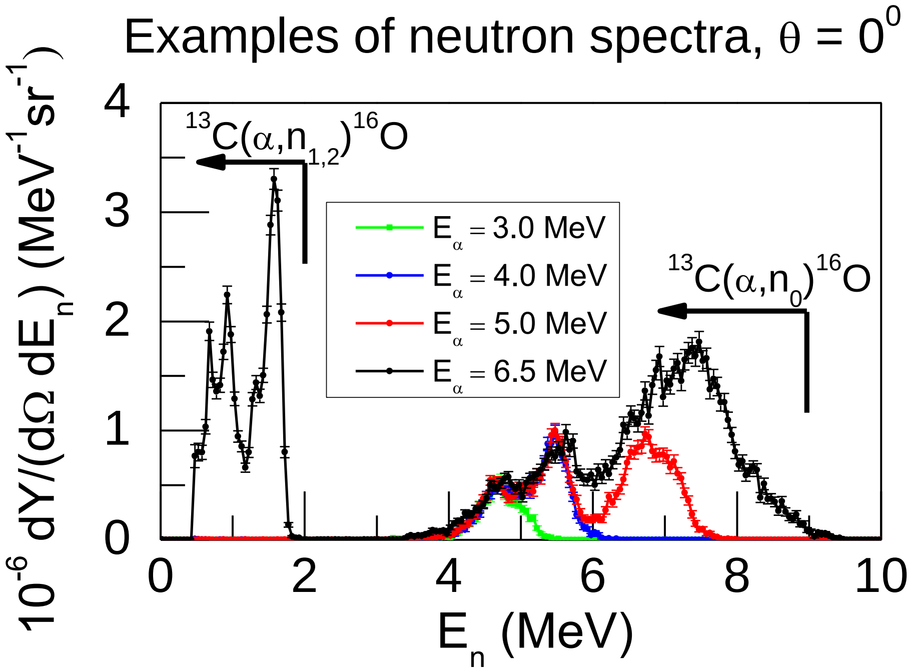
Experimental method



- Time-of-flight method
- Acquisition system based on a waveform digitizer
- Energy range – 3.0 – 6.5 MeV
- Angle range – 0 – 150°
- Detectors – p-terphenyl and stilbene
- Pulsed beam of He++
- Thick carbon target, 94% ^{13}C enrichment
- Surface barrier detector as beam monitor

Data analysis (I)





<u>Digital signal processing:</u>

- Pulse shape discrimination (PSD) – a cross-correlation based algorithm
- Timestamps – a constant fraction algorithm
- Pulse integral – numerical integration over 200 ns from the pulse start

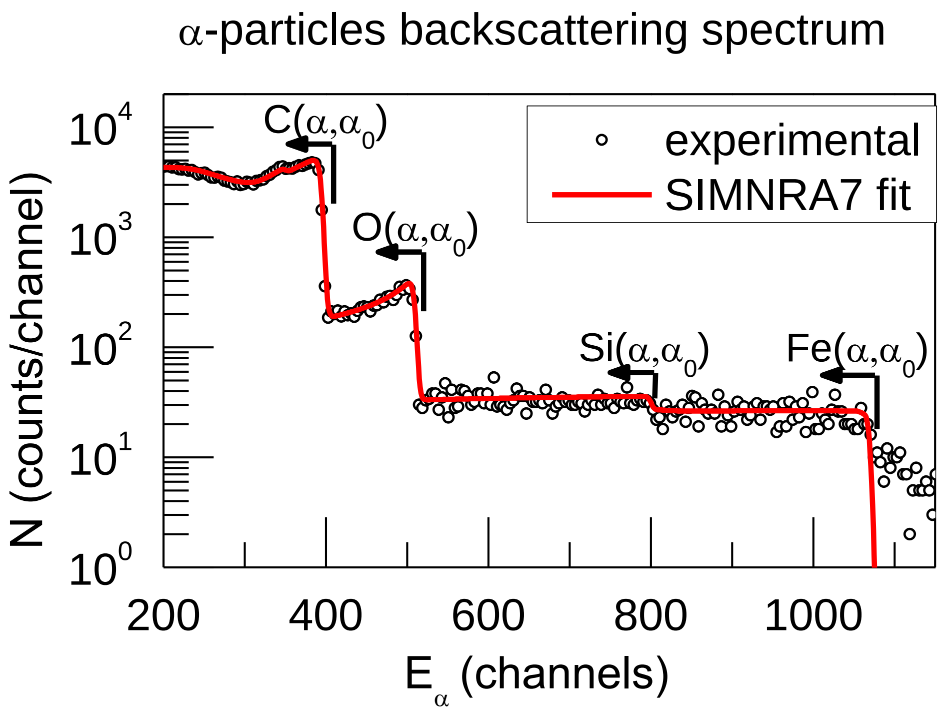
<u>1D neutron energy spectra were constructed after sorting the events on the PSD</u>

Data analysis (II)

$$\frac{dY^2(E_n,\theta)}{d\Omega\ dE_n} = \frac{N(E_n,E_n+\Delta E_n,\theta)}{\varepsilon(E_n)\eta\gamma(E_n,\theta)\rho\xi\Omega\ \Delta E_n}$$

- $N(E_n, E_n + \Delta E_n, \theta)$ – number of events corresponding to the neutron energy of E_n and the angle of θ
- $\varepsilon(E_n)$ – intrinsic efficiency of neutron detectors
- η – number of α-particles hitting the target
- $\gamma(E_n,\vartheta)$ – multiple neutron scattering correction factor
- ρ – content of ^{13}C in the target
- ξ – stopping power difference correction (the difference between SP of target used and the target from pure ^{13}C)
- Ω – solid angle of the detector
- ΔE_n – the spectrum bin width

Target composition. High Z impurities.



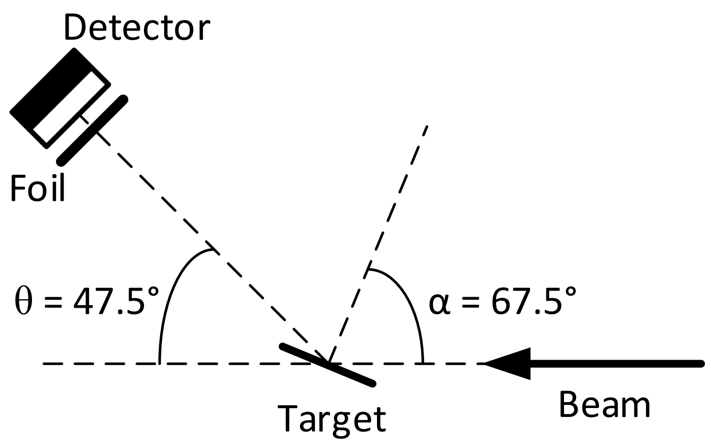
Spectrum of backscattered α-particles acquired at E_α = 6.5 MeV and θ = 165° from the target used and SIMNRA7 fit

- Contribution of high-Z impurities was determined by the analysis of backscattered α-particles spectra acquired during routine measurements
- Surface barrier silicon detector (SBD monitor)
- E_α = 6.5 MeV, θ = 165°
- Spectrum fitted by SIMNRA7[1] software
- Cross-section data:

- ^{13}C(α,α$_0$) - experimental dataset measured by Heil[2];
- ^{12}C(α,α$_0$), O(α,α$_0$), Si(α,α$_0$) – evaluations from SigmaCalc[3] software;
- Fe(α,α$_0$) – Rutherford;

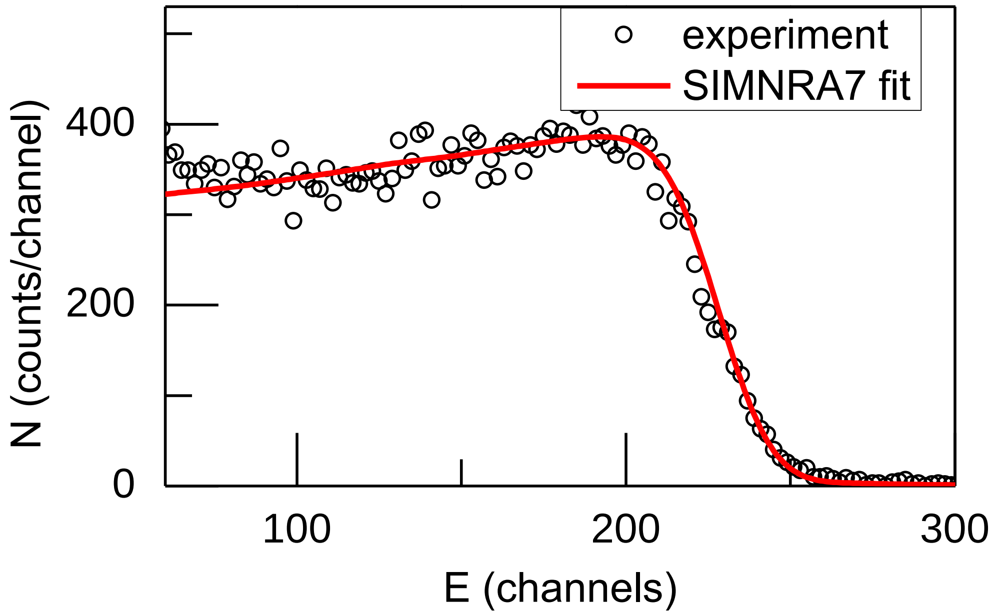
1. M. Mayer, Nuclear Instruments and Methods B, 332 (2014) 176.
2. M. Heil et al, Physical Review C, 78 (2008) 025803.
3. A. F. Gurbich, Nuclear Instruments and Methods B, 371 (2016) 27.

Target composition. Hydrogen content.



Layout of experiment on the determination of hydrogen atoms content

Recoil proton spectrum from $^{1}H(\alpha,p)^{4}He$

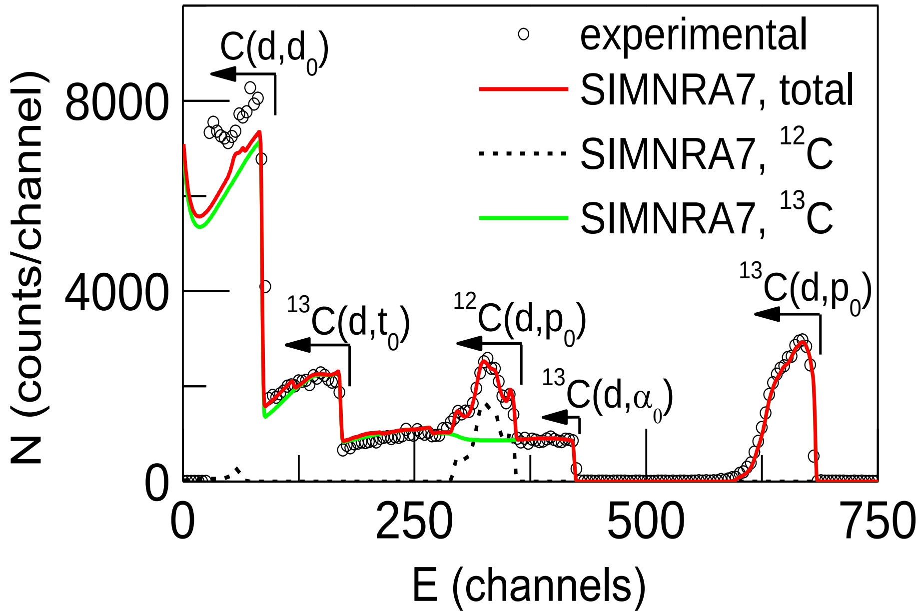


Spectrum of recoil protons acquired at E_α = 4.5 MeV and θ = 45° and SIMNRA7 fit

- The content of hydrogen was analyzed by elastic recoil detection analysis (ERDA) using the $^{1}H(\alpha,p)^{4}He$ reaction
- Detector – PIPS covered by a thin Al foil ($1.3\text{x}10^{20}$ at.·cm^{-2}) to filter the scattered α-particles.
- E_α = 4.5 MeV, θ = 47.5°
- Target tilt - 67.5°
- Spectrum fitted by SIMNRA7 software using SigmaCalc cross-section

Target composition. $^{13}C/^{12}C$ atoms ratio.

Charged particles spectrum from deutron induced reactions



Spectrum of charged particles from reaction induced in the target used by deuterons acquired at E_d = 1.5 MeV and θ = 150° and SIMNRA7 fit

- $^{13}C/^{12}C$ ratio was determined by NRA (nuclear reaction analysis)
- Reactions used - $^{12,13}C(d,p_0)^{13,14}C$, $^{13}C(d,\alpha_0)^{11}B$ and $^{13}C(d,t_0)^{11}B$
- Charged particle detector – PIPS
- E_d = 1.5 MeV, θ = 150°
- Spectrum fitted by SIMNRA7[1] software
- Cross-section data:

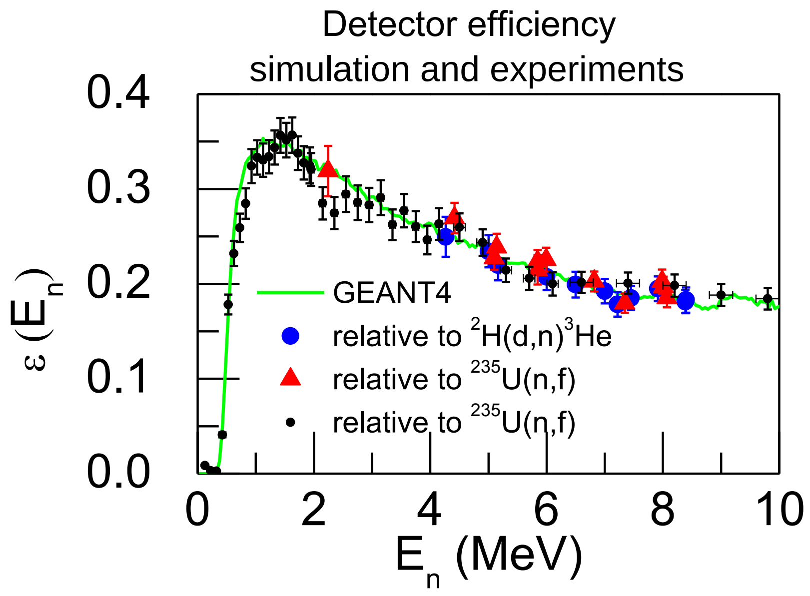
- $^{13}C(d,p_0)^{14}C$, $^{13}C(d,\alpha_0)^{11}B$, $^{13}C(d,t_0)^{11}B$ - experimental dataset measured by J. Colaux[2];
- $^{12}C(d,p_0)^{13}C$ – evaluation from SigmaCalc;

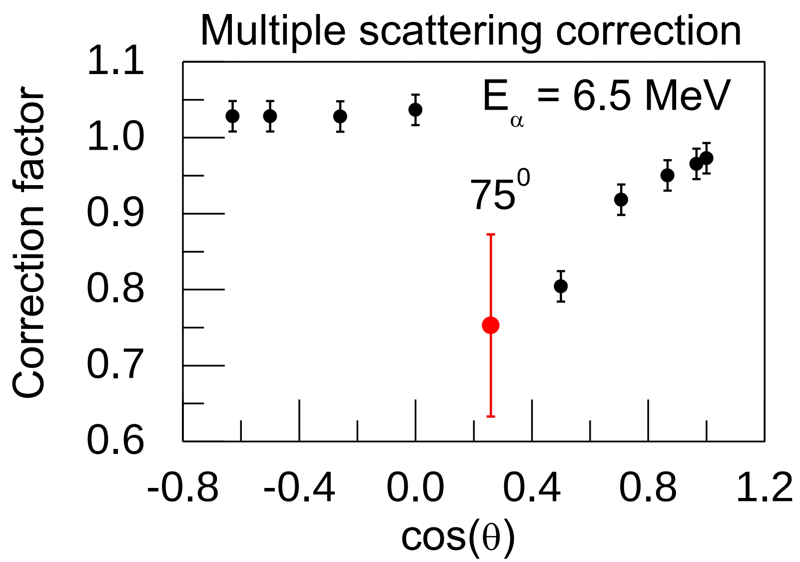
1. M. Mayer, Nuclear Instruments and Methods B, 332 (2014) 176.
2. J. L. Colaux, T. Thome, and G. Terwagne, Nuclear Instruments and Methods B, 254 (2007) 25.

Target composition

Element/Isotope	Concentration (%)	Uncertainty (%)
^{13}C	93.7	0.7
^{12}C	3.4	0.5
O	0.8	0.1
H	1.6	0.4
Si	0.3	0.2
Fe	0.2	0.1

Corrections

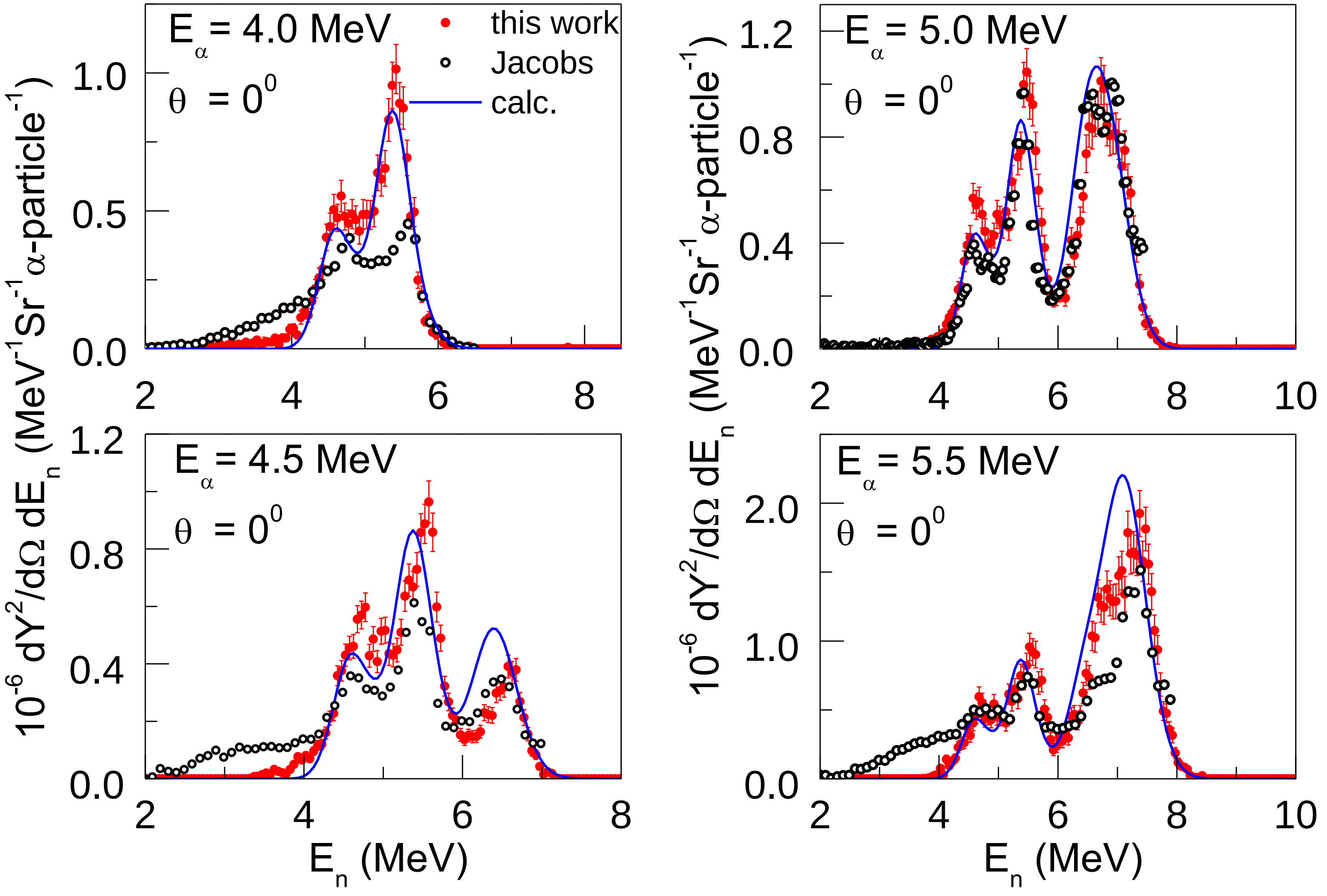




- The detectors efficiency was calculated using GEANT4 framework taking into account the NRESP7 model.
- The simulation results for the first detector were verified by three independent experiments
- The influence of the multiple scattering was negligible
- The efficiency of the second detector was verified relative to the first one.
- The efficiency uncertainties – 1.5% for the first detector, 4.0% for the second one

- Correction factor taking into account the multiple neutron scattering was determined by GEANT4 simulation
- The full geometry of the experiment was taken into account
- The attenuation of the neutron flux in the target made the main contribution to the correction
- The correction obtained for θ=75° had too large uncertainty, spectra at this angle were discarded in further analysis

Results. Neutron spectra

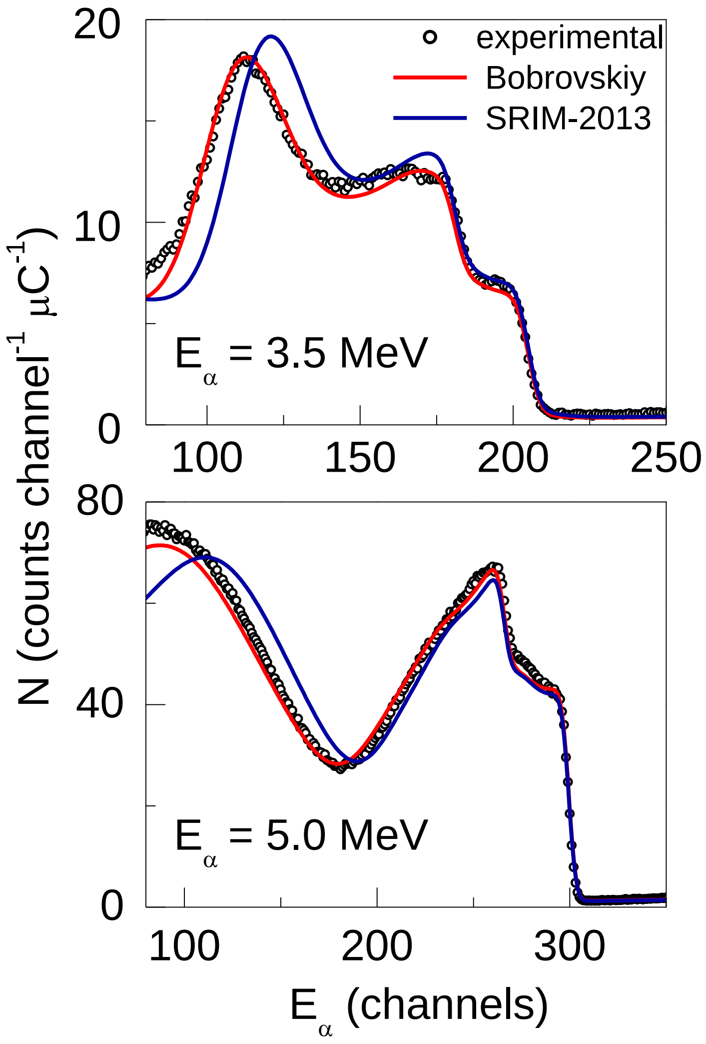


Measured and calculated neutron spectra from thick target from the $^{13}C(\alpha, n_0)^{16}O$ reaction

- The measured spectra were compared with the calculated ones and the data from paper of Jacobs and Liskien[1]
- Calculated spectra were obtained for $\theta=0^0$ using the cross-section presented in Barnes[2], Kerr[3], Prusachenko[4] papers
- There are significant discrepancies between data measured in this work and data presented by Jacobs

1. G.J.H. Jacobs and H. Liskien, Annals of Nuclear Energy 10 (1983) 541.
2. B. K. Barnes et al, Physical Review, 140 (1965) B616
3. G. W. Kerr, Nuclear Physics A, 110 (1968) 637
4. P. S. Prusachenko et al, Physical Review C, 105 (2022) 024612.

Stopping power



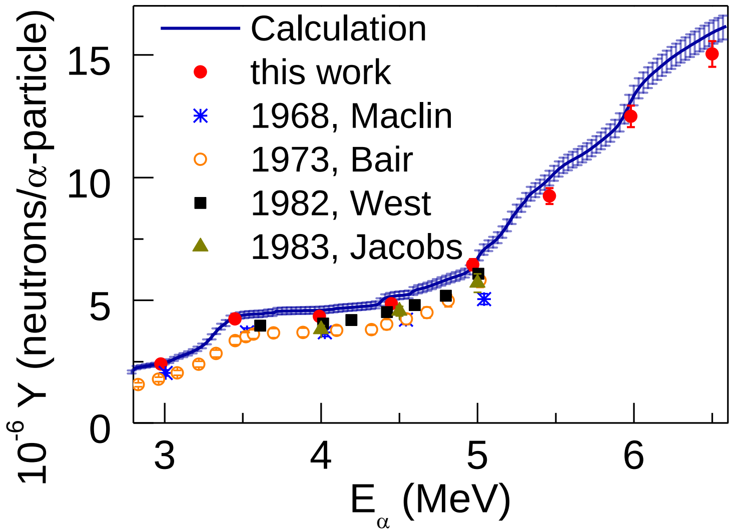
The spectra of a-particles backscattered from the ^{13}C target and SIMNRA7 fit with two different stopping powers models

- The stopping power of α-particles in carbon obtained by Bobrovskiy et al.[1] were used to calculate the TTY values based on the theoretical evaluations
- The stopping power obtained by Bobrovskiy et al.[1] reproduces the α-particle backscattered spectra acquired by the SBD monitor much better than other SP datasets such as SRIM-2013
- The influence of the allotropic effect was negligible[2]

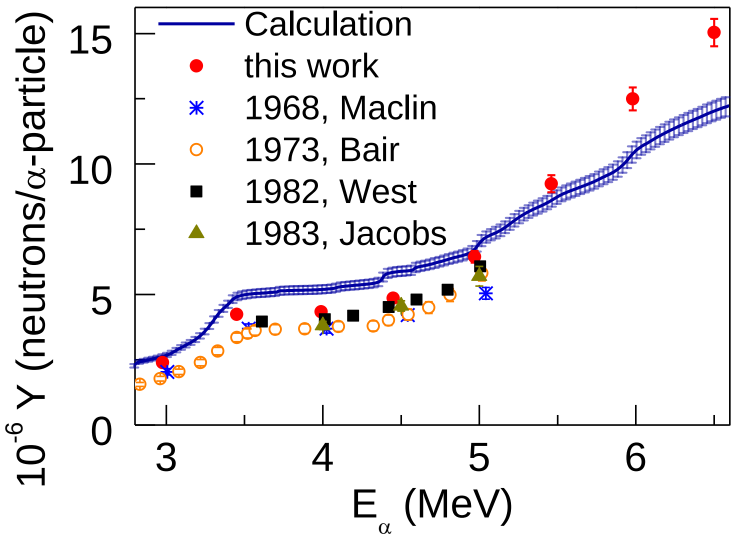
1. T. L. Bobrovskiy et al., *Nuclear Instruments and Methods in Physical Research B,* **543**, 165094 (2023).
2. Mitsuo Tosaki, Eero Rauhala, *Nuclear Instruments and Methods in Physical Research B,* **360**, 16 (2015)

Total thick target yields

Measured TTY vs ENDF-VIII.0 based calculation



Measured TTY vs JENDL-5.0 based calculation



- Measured TTY values were compared with calculations based on the ENDF-B/VIII.0 and JENDL-5.0 evaluations
- The average difference between the experimental results and ENDF/B-VIII.0 based calculation is ~3.8%
- The experimental data and the JENDL-5.0 based calculation differ significantly (17-19%)
- Total measurement uncertainty is ~3.5%, including:
  - efficiency (~2.0%),
  - current integration (~2.0%),
  - angle distribution integration (~1.5%)
  - etc.
- Calculation uncertainty is ~3.0%

Future plans in (α, n) nuclear data activity

- To finish analysis of the experimental data on the differential cross-sections of the $^{13}C(\alpha,\alpha_0)^{13}C$ reaction
- To obtain new data on the stopping power for alpha-particles in some actinide compounds (see T. Bobrovskiy's presentation)
- To measure and verify the differential and partial cross-sections of the α-induced reactions on the ^{19}F - (α, n), (α, α_0), (α, α'), (α, p)

Summary

- The double differential yields of neutrons from the $^{13}C(\alpha,n_0)^{16}O$ reaction were measured over the energy range of 3.0 - 6.5 MeV and over the angle range of 0-150°
- The total systematic uncertainty was 3.5%
- The total thick target yields were determined by integrating the double differential thick target yields both over the neutron energy and the solid angle
- The precision analysis of the elemental and isotope composition of the target was made using the α-particles backscattering spectrometry and the nuclear reaction analysis. The accuracy of the ^{13}C content determination is 0.7%
- The measured total thick target yields from $^{13}C(\alpha,n_0)^{16}O$ reaction support the ENDF-B/VIII.0 evaluation within the uncertainties of the experiment (3.5%) and the yield calculation (3.0%)

Thank for your attention!

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