29th International Seminar on Interaction of Neutrons with Nuclei: «Fundamental Interactions & Neutrons, Nuclear Structure, Ultracold Neutrons, Related Topics»

MEASUREMENT AND ANALYSIS OF THE TOTAL THICK TARGET YIELD FROM THE $^{13}C(\alpha,n_0)^{16}O$ REACTION

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Motivation

Needs:

- The data on the total thick target yield (TTY) from $^{13}C(\alpha,n)^{16}O$ 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 the 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

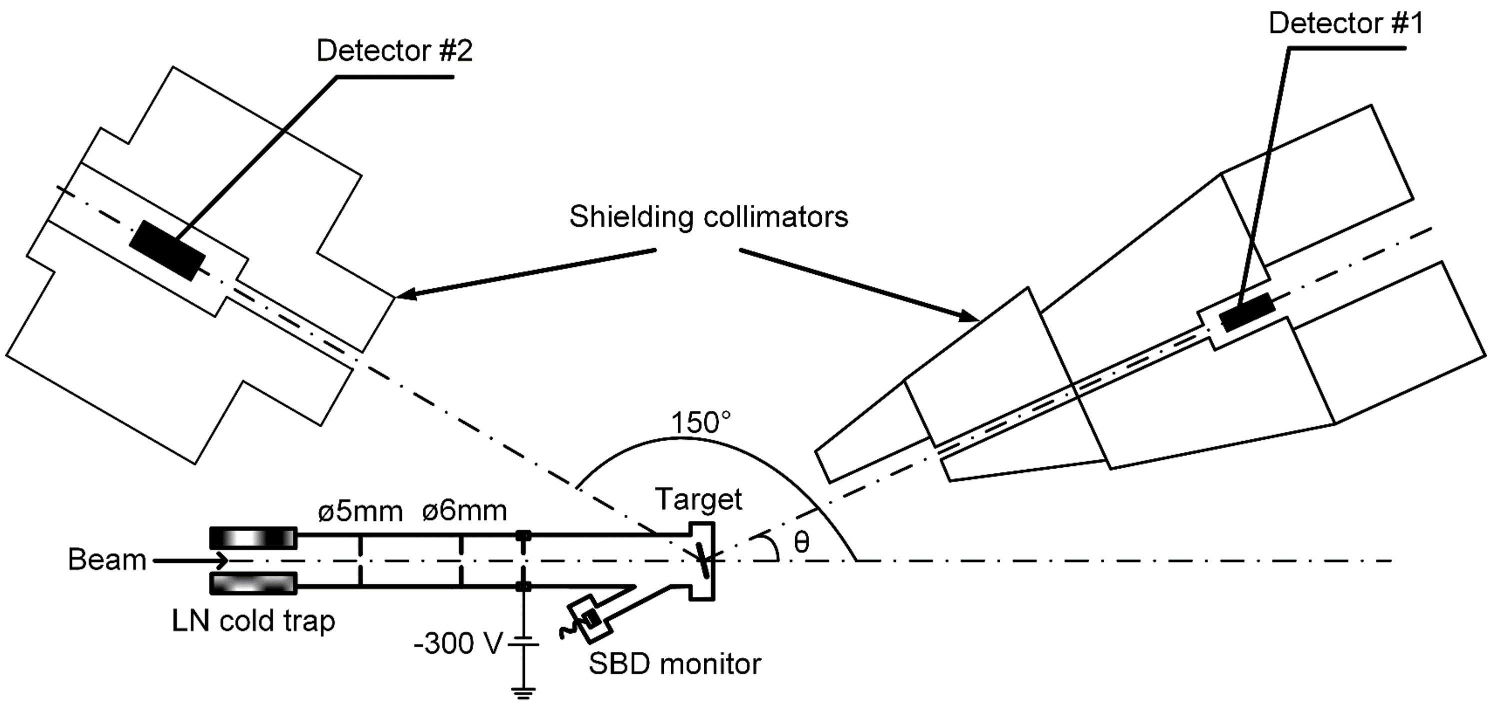
Current problems:

- 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 measured TTY data do not support the new ENDF-B/VIII,0 and JENDL-5.0 evaluations.

The aim of work:

- To obtain the new experimental data on the TTY from $^{13}C(\alpha,n0)^{16}O$ reaction
- To decrease the uncertainty influence

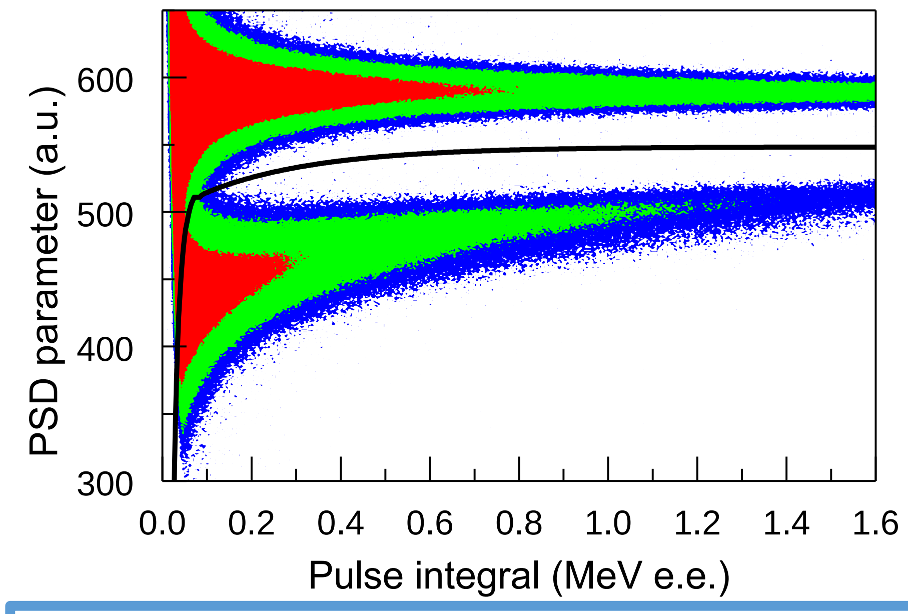
Experimental method



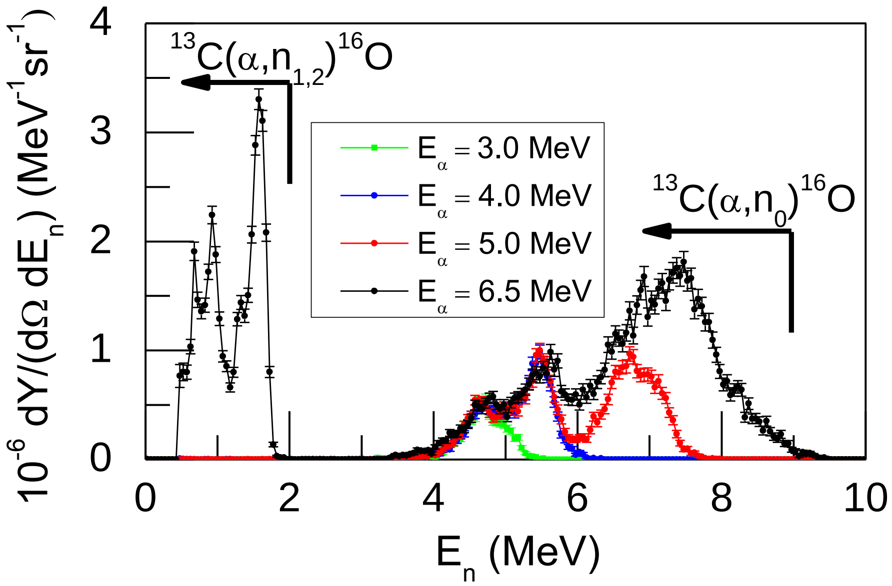
- Time-of-flight method
- Acquisition system based on waveform digitizer
- Energy range – 3.0 – 6.5 MeV
- Angle range – 0 – 150°
- Detectors – p-terphenyl and stilbene
- Pulsed beam of He++
- Thick carbon target, 90% ^{13}C enrichment
- Surface barrier detector as beam monitor

Data analysis (I)

Pulse shape discrimination



Examples of neutron spectra measured at $\theta = 0^0$



Digital signal processing:

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

1d neutron energy spectra were constructed after sorting the events on the PSD

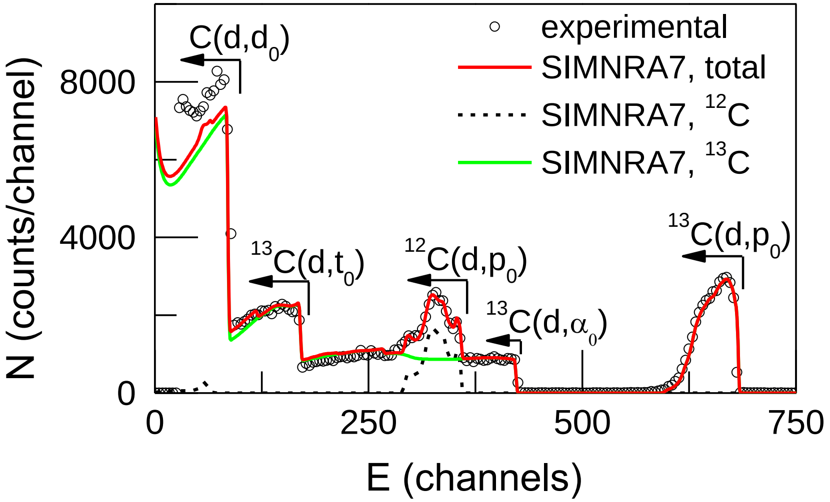
Data analysis (II)

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

- $N(E_n, E_n + \Delta E_n, \theta)$ – number of events corresponding to the neutron energy of E_n and the angle of θ
- $\varepsilon(E_n)$ – intrinsic efficiency of neutron detector
- η – number of α-particle 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
- Ω – solid angle of the detector
- ΔE_n – bin width in the spectrum

Target composition

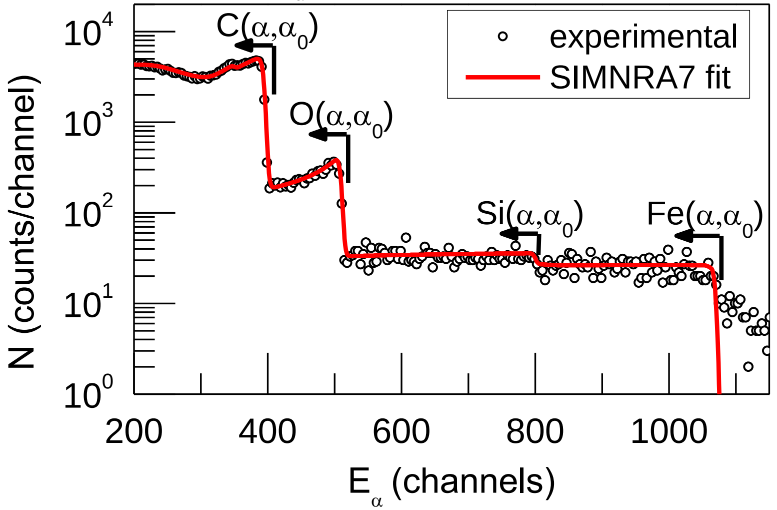
Charged particles spectrum from deutron induced reactions
E_d = 1.5 MeV, $\theta = 150^0$



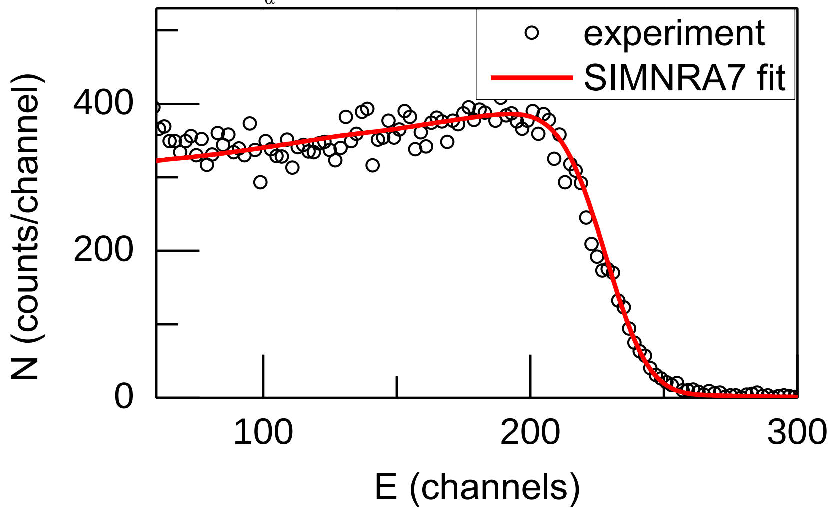
- $^{13}C/^{12}C$ ratio was determined by the nuclear reaction analysis using $^{12,13}C(d,p_0)^{13,14}C$, $^{13}C(d,\alpha_0)^{11}B$ and $^{13}C(d,t_0)^{11}B$ reactions.
- Contribution of high-Z impurities was determined by the analysis of backscattered α-particles spectrum
- The content of hydrogen was made by elastic recoil detection analysis using $^{1}H(\alpha,p)^{4}He$ reaction
- The spectra were fitted by SIMNRA7 program

Element/Isotope	Concentration
^{13}C	93.7±0.7
^{12}C	3.40±0.5
O	0.8±0.1
H	1.6±0.4
Si	0.3±0.2
Fe	0.2±0.1

α-particles backscattering spectrum
E_α = 6.5 MeV, $\theta = 165^0$

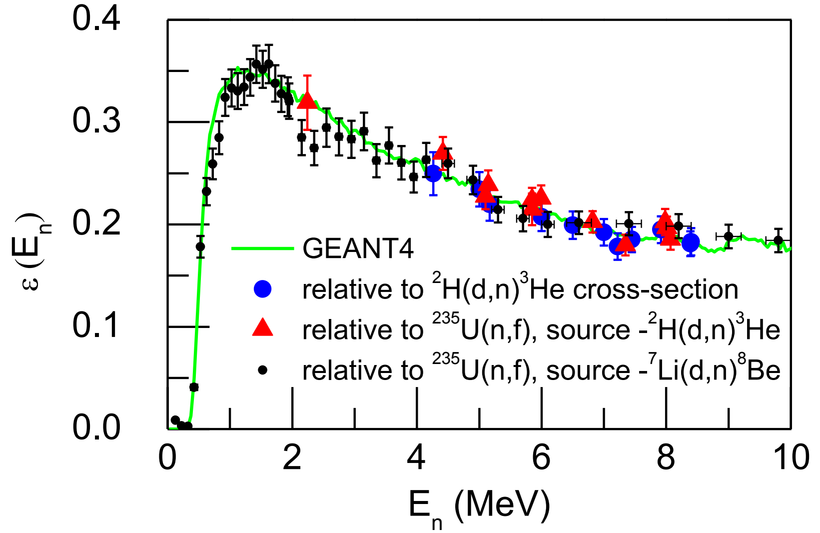


Recoil proton spectrum from $^{1}H(\alpha,p)^{4}He$ reaction
E_α = 4.5 MeV, $\theta = 47.5^0$, $\beta = 47.5^0$

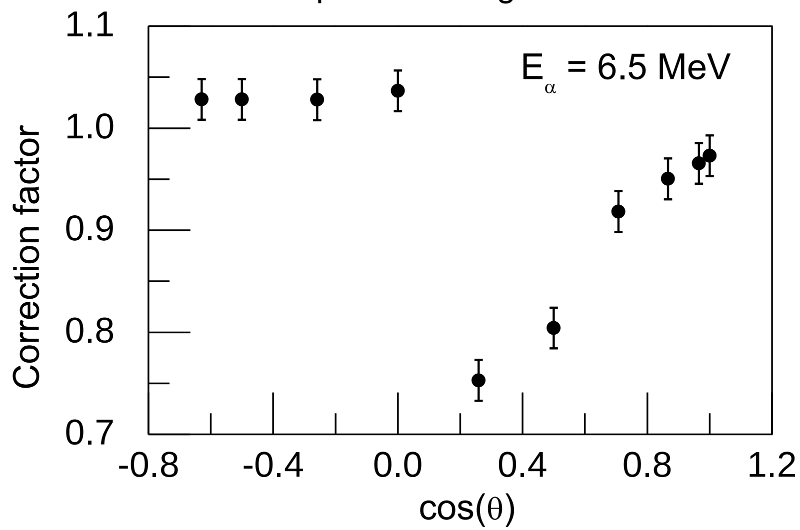


Corrections

Detector efficiency, the simulation and experiments



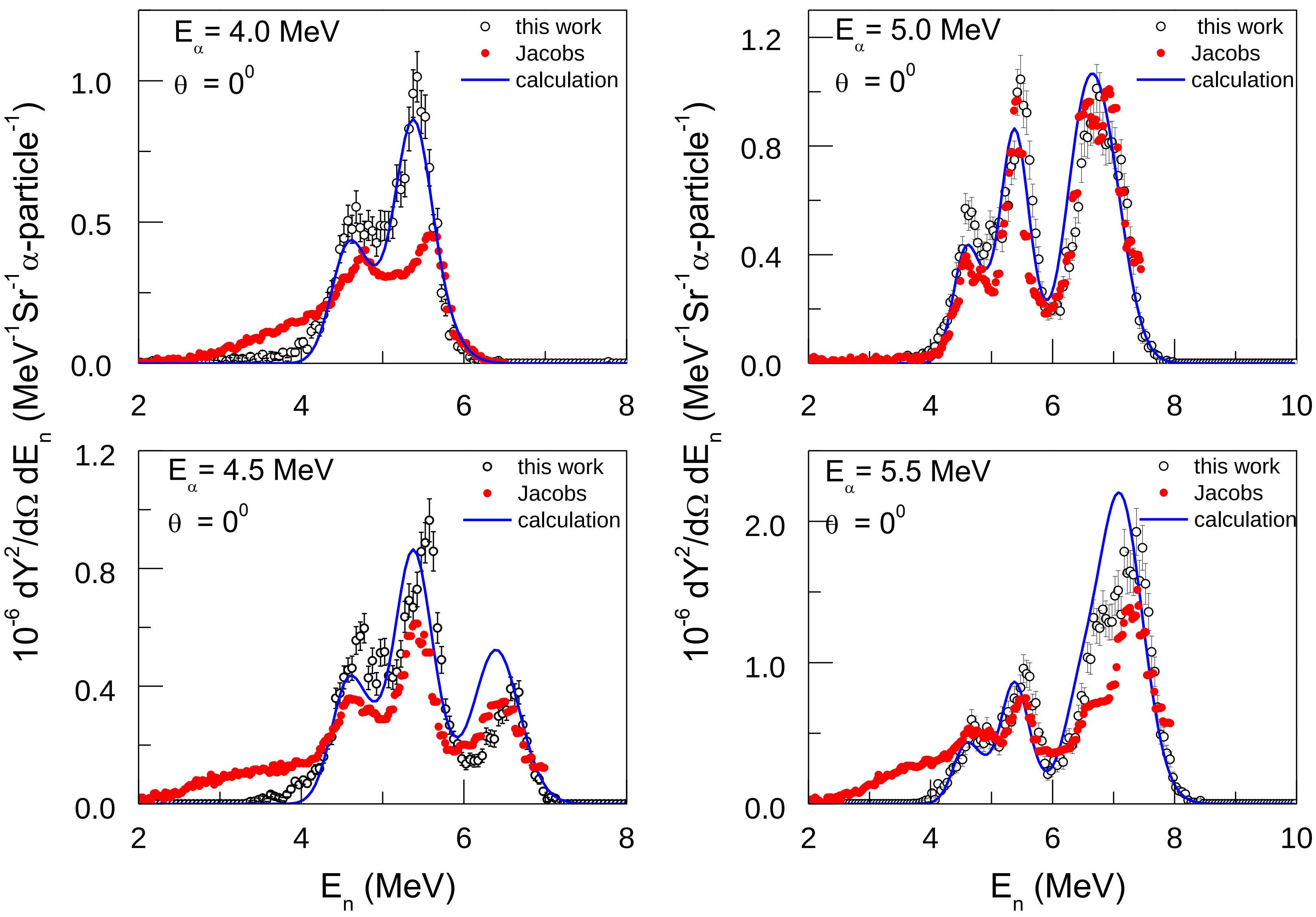
Multiple scattering correction



- The efficiency of detectors were calculated using GEANT4 framework taking into account the NRESP7 model.
- The simulation results were verified by the 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

- Multiple scattering correction was made based on the 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 the θ=75° had too large uncertainty, spectra at this angle did not taken into account in further analysis

Results. Neutron spectra

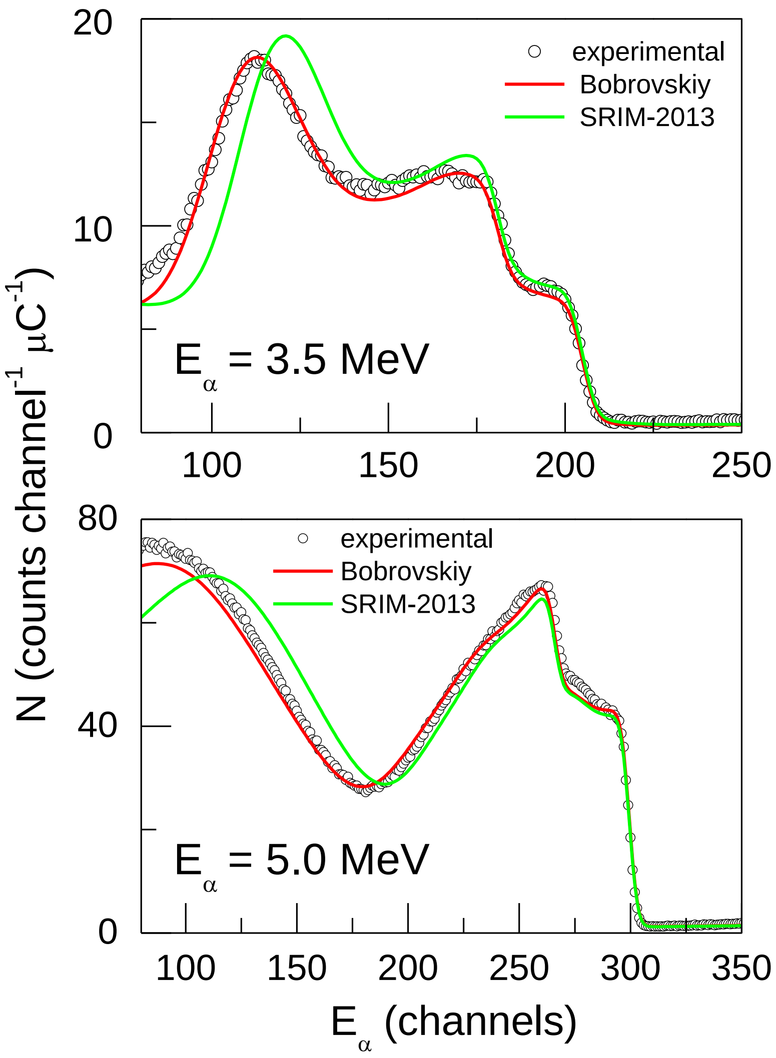


- The measured spectra were compared with the calculated ones and the data from paper of Jacobs and Liskien[1]
- Calculated spectra were obtained for $\theta=0^0$ using the cross-section presented in Barnes[2], Kerr[3], Prusachenko[4] papers
- There are significant discrepancies between data measured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

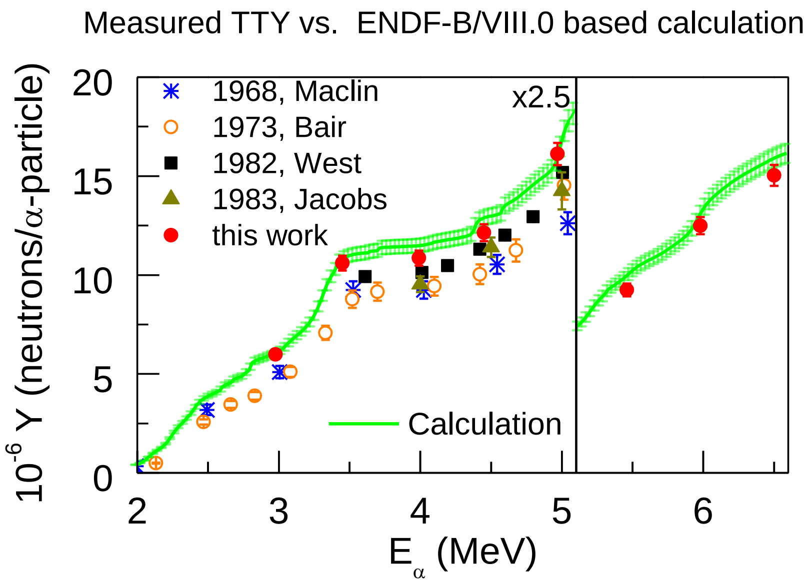
The spectra of α-particles backscattered from the ^{13}C target and SIMNRA7 fit with two different stopping powers models

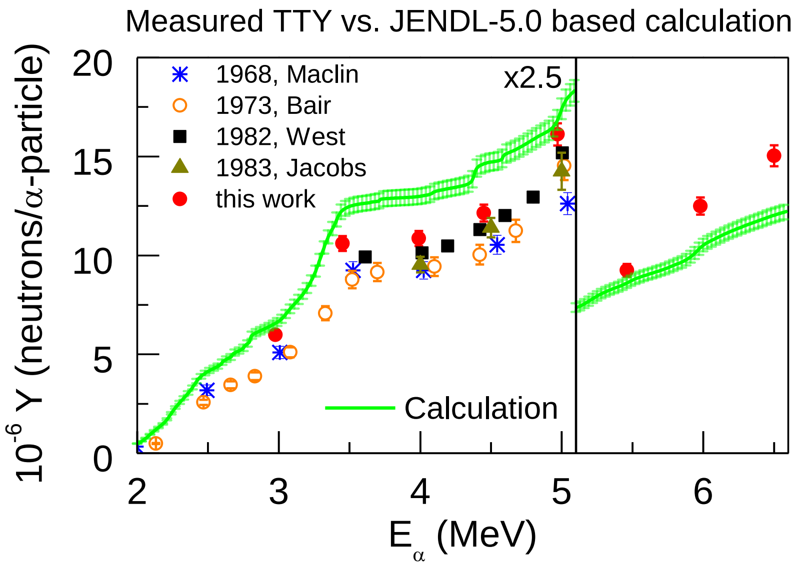


- The stopping powers of α-particles in carbon obtained by Bobrovskiy et al.[1] were used to calculate the TTY values based on the theoretical evaluations
- The stopping powers obtained by Bobrovskiy et al.[1] much better reproduce the α-particle backscattered spectra acquired by the SBD monitor than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

1. T. L. Bobrovskiy et al., “Determination of stopping power for light ions using resonance backscattering,” *Nuclear Instruments and Methods in Physical Research B* (submitted for publication).
2. Mitsuo Tosaki, Eero Rauhala, “Energy-loss of He ions in carbon allotropes studied by elastic resonance in backscattering spectra,” *Nuclear Instruments and Methods in Physical Research B,* **360**, 16 (2015)

Total thick target yields





- 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%), and angle distribution integration (~1.5%) uncertainties
- Calculation uncertainty is ~3.0%

Conclusions

- The double differential yields of neutrons from the $^{13}C(\alpha,n_0)^{16}O$ were measured over the energy interval of 3.0 - 6.5 MeV
- 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 are 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!