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The $^{13}C(\alpha,n_0)^{16}O$ reaction cross-section measurement and the $^{16}O(n,\alpha_0)^{13}C$ reaction cross-section determination

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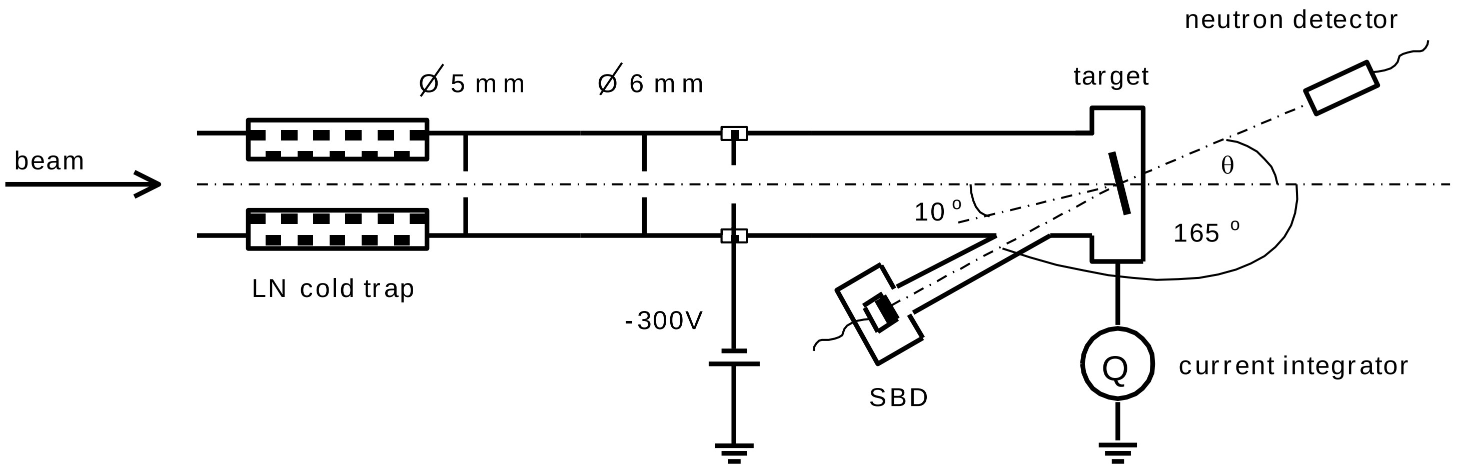
Motivation

- The $^{16}O(n,\alpha)^{13}C$ reaction cross-section is important for nuclear power engineering
- The $^{13}C(\alpha,n)^{16}O$ reaction is the background source at geo-neutrino measurements and the neutron source in the s-process in nuclear astrophysics
- The existing evaluations and experimental data sets differ significantly (20-80%)
- The new experimental data obtained after 2010 are quite few
- New experimental data are needed to clarify the reasons for the discrepancy between the experimental data sets and to refine the available cross sections for the $^{13}C(\alpha,n)^{16}O$ and $^{16}O(n,\alpha)^{13}C$ reactions in a wide energy range

Details of the measurements

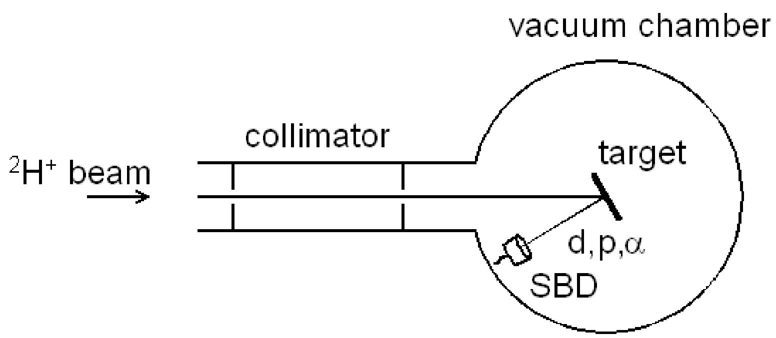
- Differential cross-sections of the $^{13}C(\alpha,n_0)^{16}O$ reaction were measured at the IPPE 3 MV tandem accelerator using the time-of-flight method to separate (α,n_0)- and $(\alpha,n_{1,2})$-reactions and reduce the scattered neutrons background
- Two experimental runs using different ^{13}C targets were made:
  - The fist run was made at 38 energy points in the 2.0–6.2 MeV energy range in the angle interval of 0–150° (15° step) with a thin target manufactured of amorphous ^{13}C deposited on a gold substrate
  - The second run aimed at verifying the results was performed at the same energy points as the first one at the angle of 0° with a target made of amorphous ^{13}C deposited on a molybdenum substrate

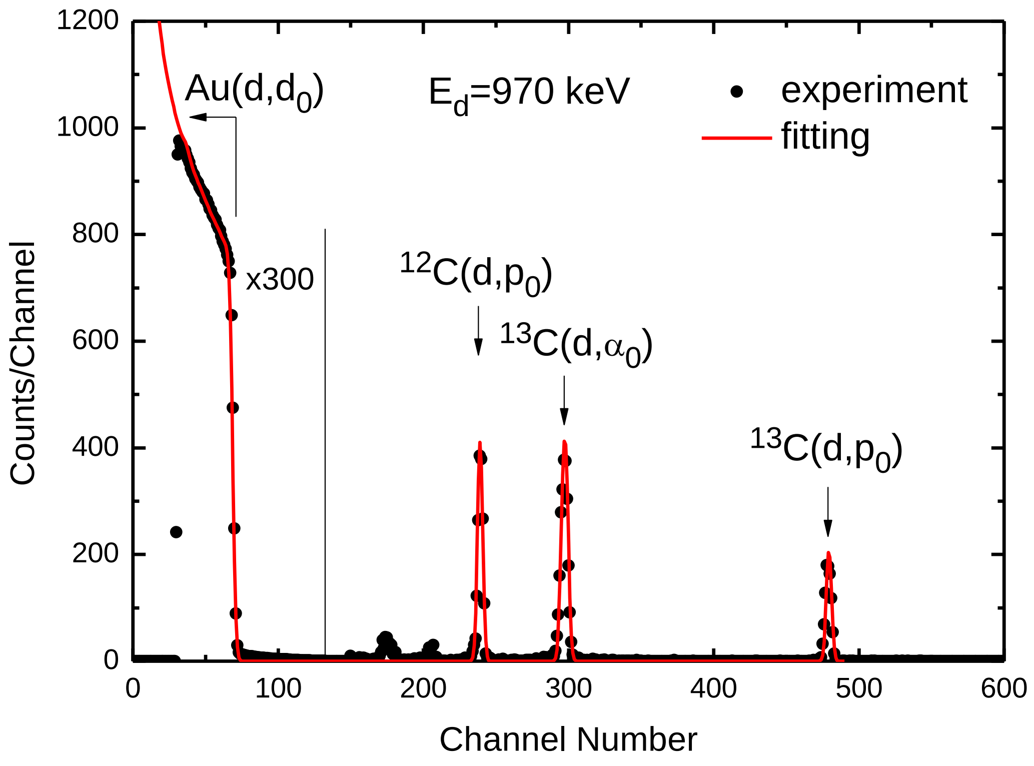
Experimental setup



- He^{++} pulsed beam with a repetition rate of 4 MHz
- Collimator – two apertures 5 and 6 mm in diameter located at the distance of 380 mm from each other
- The flight path between the target and the neutron detector – 71.3±0.4 cm for the first run and 65.2±0.4 cm for the second one
- Moveable neutron detector – based on a 40x40 mm p-terphenyl single crystal
- Neutron detector signals processing – a waveform digitizer with a sampling rate of 500 MHz and the ADC resolution of 14 bits with recording digitized signals in the list mode
- Target holder – used as a Faraday cup, the secondary electrons being suppressed by a guard electrode
- Silicon surface barrier detector (SBD) – served as an independent monitor of the number of the particles hitting the target and the monitor of the carbon buildup on the target during the measurements

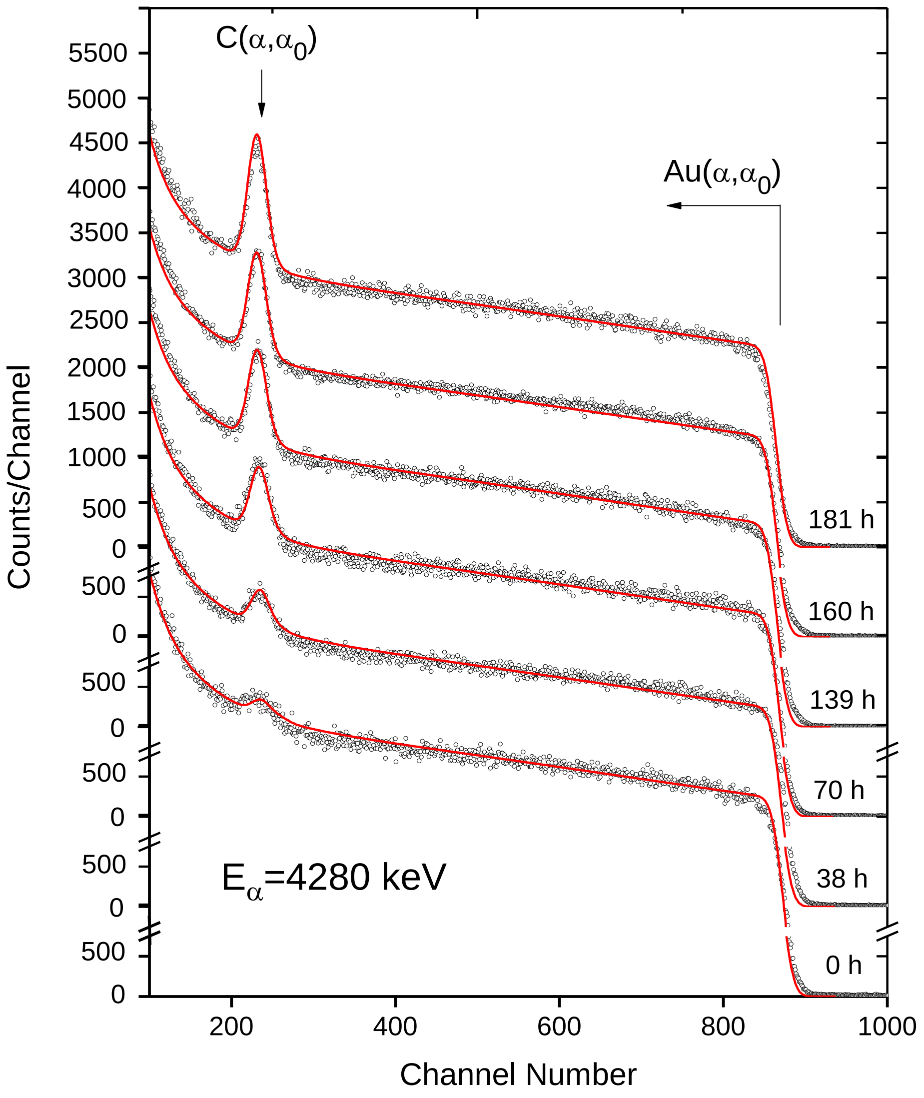
Determination of the target thickness





- The ^{13}C atoms surface density was measured in a separate experiment by nuclear reaction analysis using $^{13}C(d,p_0)^{14}C$ and $^{13}C(d,\alpha_0)^{11}B$ reactions
- The reaction cross-sections reported by J.L.Colaux et al. in *Nucl. Instrum. Methods in Physics Res. B, 254 (2007) 25* were used for spectra simulation by the SIMNRA program
- The ^{13}C atoms surface density in the targets was found to be $2.2\pm0.1\cdot10^{18}$ atoms/cm^2 for the target used in the run 1 and $2.1\pm0.1\cdot10^{18}$ atoms/cm^2 for the target used in the run 2
- Uncertainties: the total uncertainty ≈4% including the cross-section uncertainty from Colaux's paper and statistical uncertainty
- No deterioration of the targets was found in the comparison of the results obtained before and after the runs

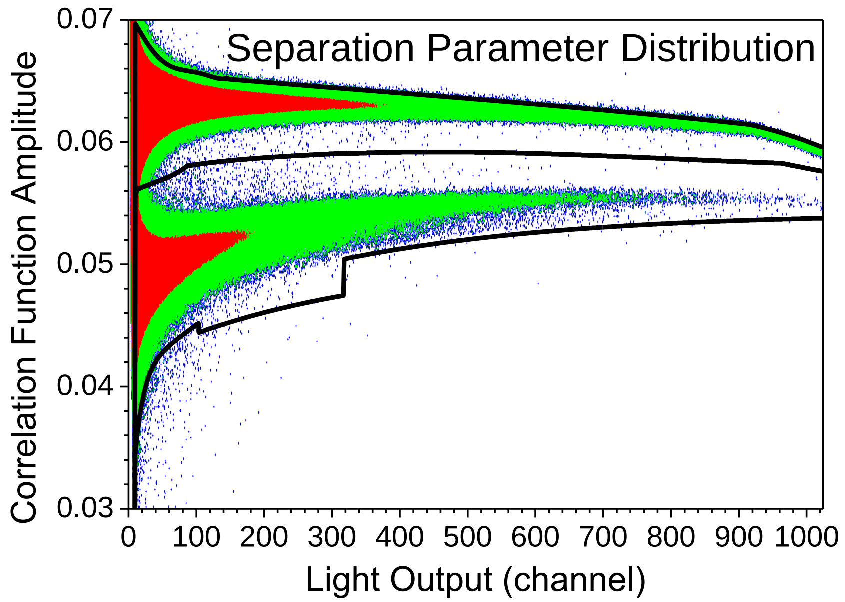
Monitoring ^{12}C build-up and number of α-particles impinged on the target

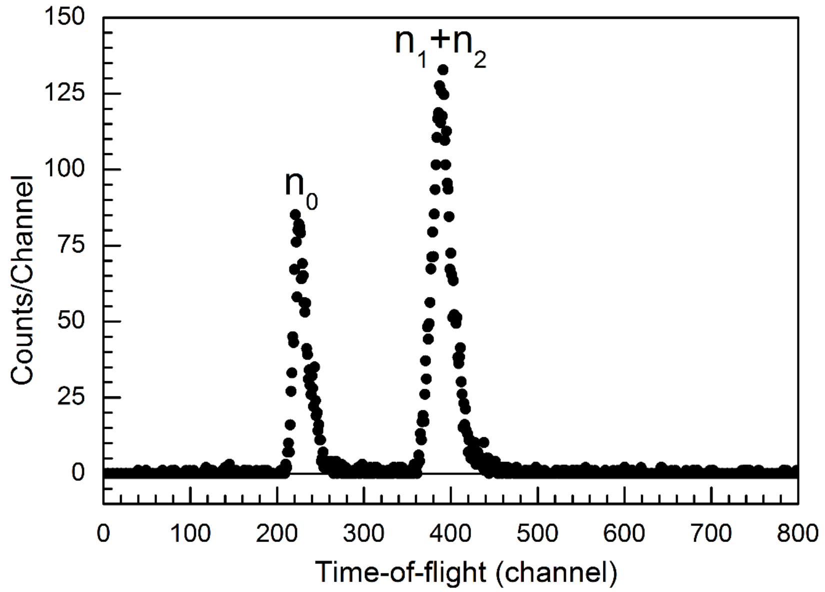


The ^{12}C deposit monitoring was carried out by periodical measurements of the α-particles backscattering spectra at the beam energy of 4280 keV slightly above a strong resonance in the elastic scattering of alphas from ^{12}C

The accumulated charge monitoring was made against Rutherford backscattering of α-particles on the target backing

Digital signal processing





The following parameters were determined for each event during digital signal processing:

1. Separation parameter and pulse area for the signals from the neutron detector
2. Time stamps for the signals from the neutron detector and pick-up electrode

The suppression of the γ-background and the construction of the timing distribution of neutron events were carried out in the course of the subsequent analysis

Cross-section calculation

Differential cross-section of the $^{13}C(\alpha,n_0)^{16}O$ reaction:

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{S_n(\theta)\gamma(\theta)}{N_\alpha \eta \varepsilon \Omega} 10^{24} \text{ (barns)}$$

$S_n(\theta)$ – neutron peak area,

$\gamma(\theta)$ – multiply scattering correction factor,

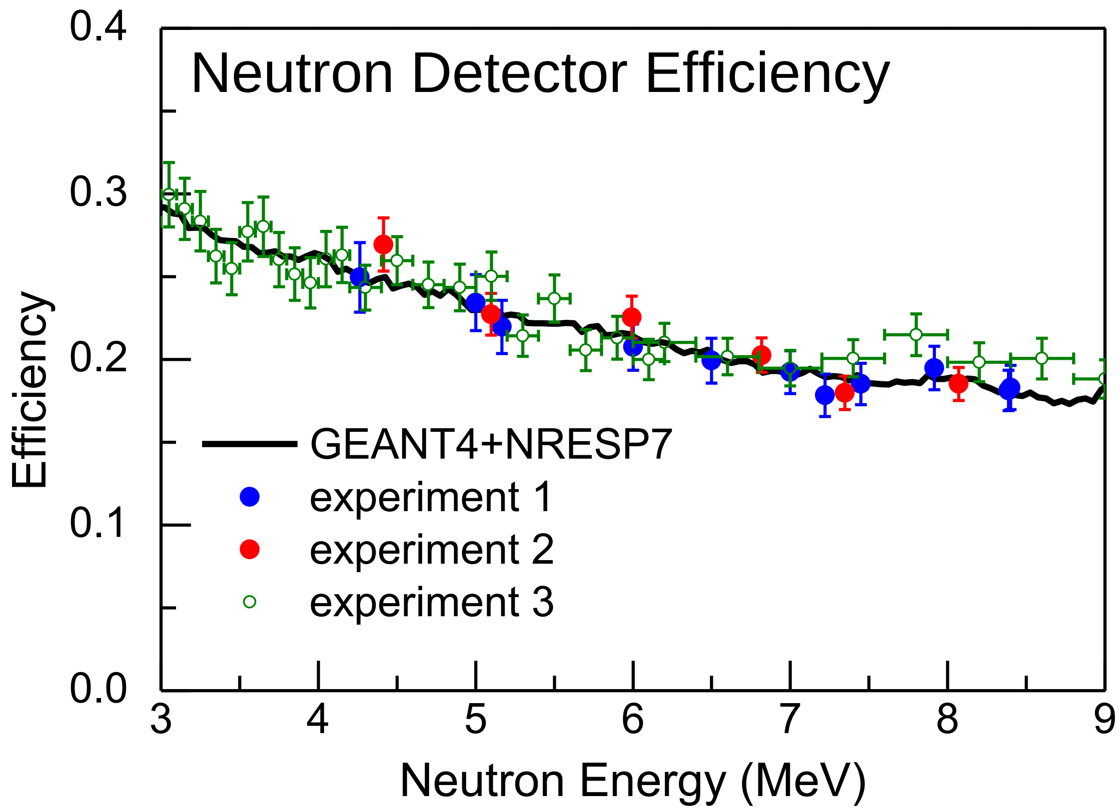
N_α – full number of α-particle,

η – surface density of ^{13}C atoms,

ε – neutron detector efficiency,

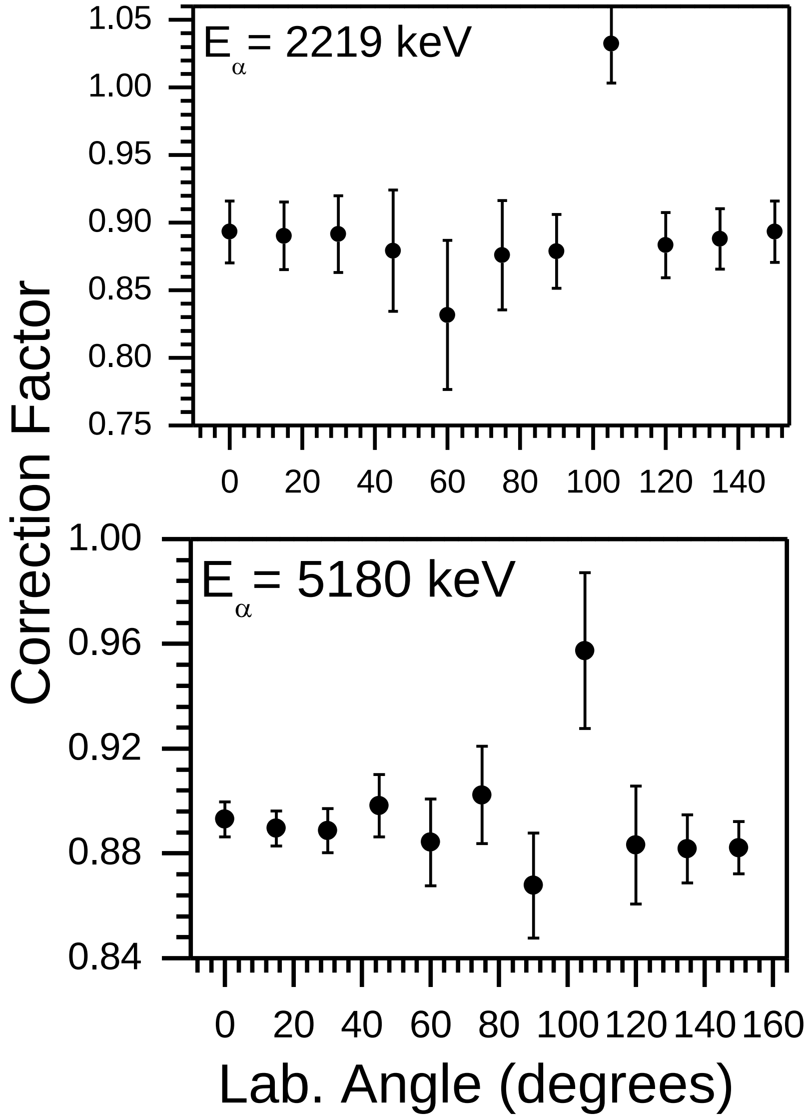
Ω – solid angle obtained from the geometrical parameters of the experimental setup

Neutron detector efficiency



- Intrinsic neutron detector efficiency was simulated using GEANT4 taking into account NRESP7 model.
- The simulated curve was verified by 3 different experiments:
  1. Measurements relatively to the well-known $^{2}H(d,n)^{3}He$ reaction differential cross-section;
  2. Measurements relatively to the ^{235}U(n,fission) cross-section standard with quasi-monoenergetic neutron source based on the $^{2}H(d,n)^{3}He$ reaction;
  3. Measurements relatively to the ^{235}U(n,fission) cross-section standard with a wide-spectrum neutron source based on the $^{7}Li(d,n)$ reaction.
- All measurements were carried out by the time-of-flight method. The neutron detector was placed inside a shielding collimator. The multiply scattering neutron influence did not exceed 1-2% in these experiments .
- The experimental results appeared to be in an agreement with simulated curve within 4%.

Multiply scattering neutron correction



The multiply scattered neutron influence was calculated by GEANT4 taking into account the experimental setup geometry, materials and timing characteristic of the beam pulse.

The correction factor was calculated as:

$$\gamma(E_\alpha, \theta) = \frac{S_{wm}}{S_{am}}$$

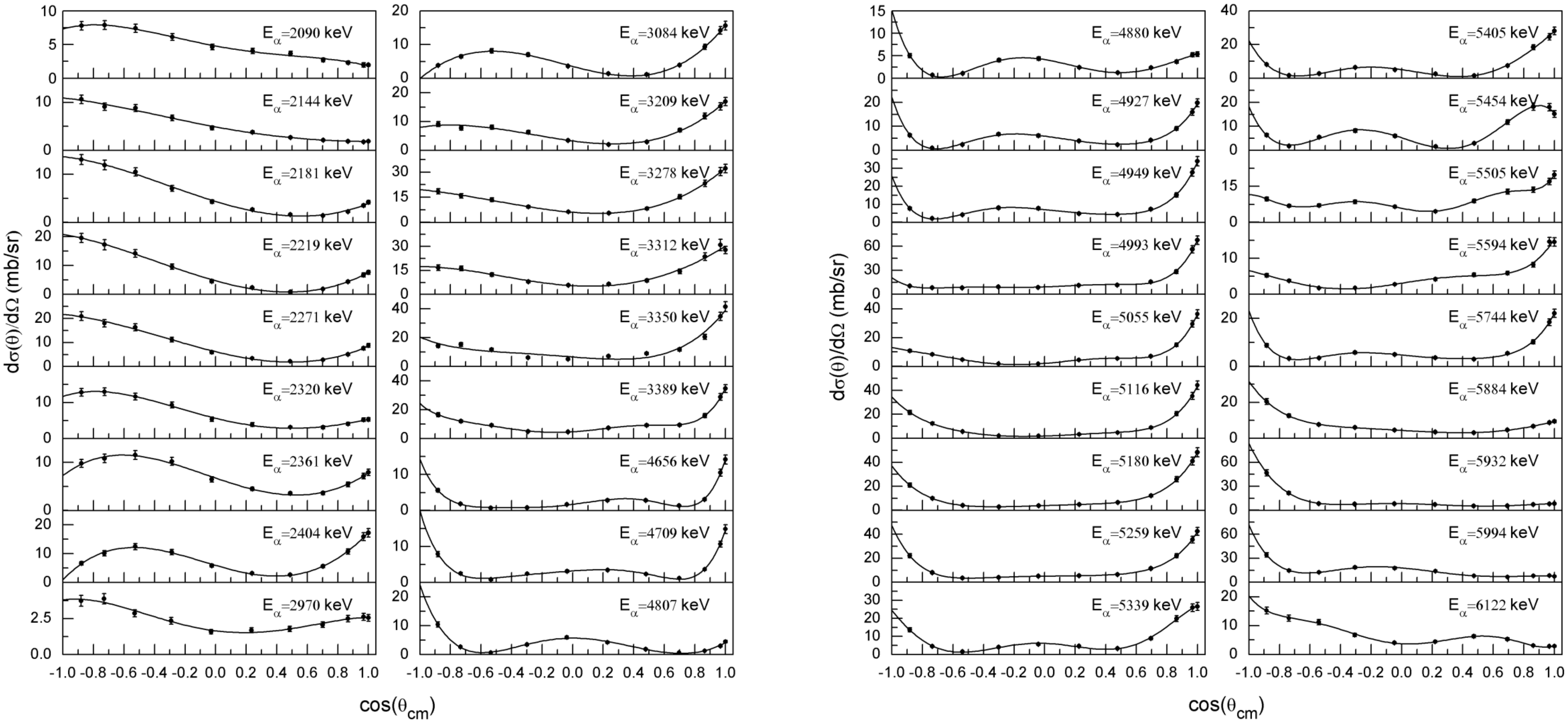
Where S_{wm} - neutron peak integral calculated for the case when all materials except detector were removed

S_{am} – the same but calculated for full experimental geometry

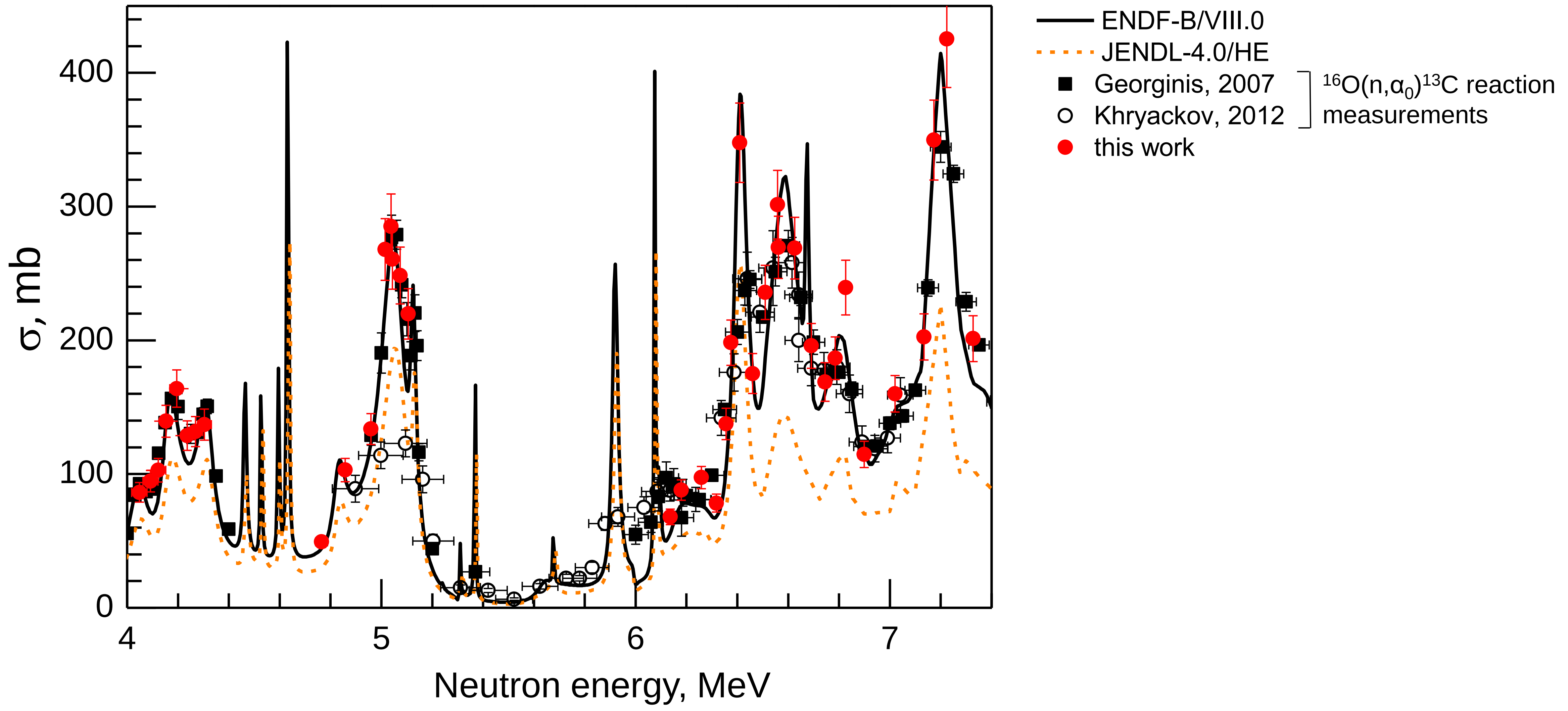
Uncertainty budget

Uncertainty source	Contribution, %
Statistics	0.5-1.5
Target thickness	4.0
Detector efficiency	4.0
Charge measurement	2.0
Solid Angle	2.5
Multiply scattering correction factor	2.0
Total	6.8-7.0

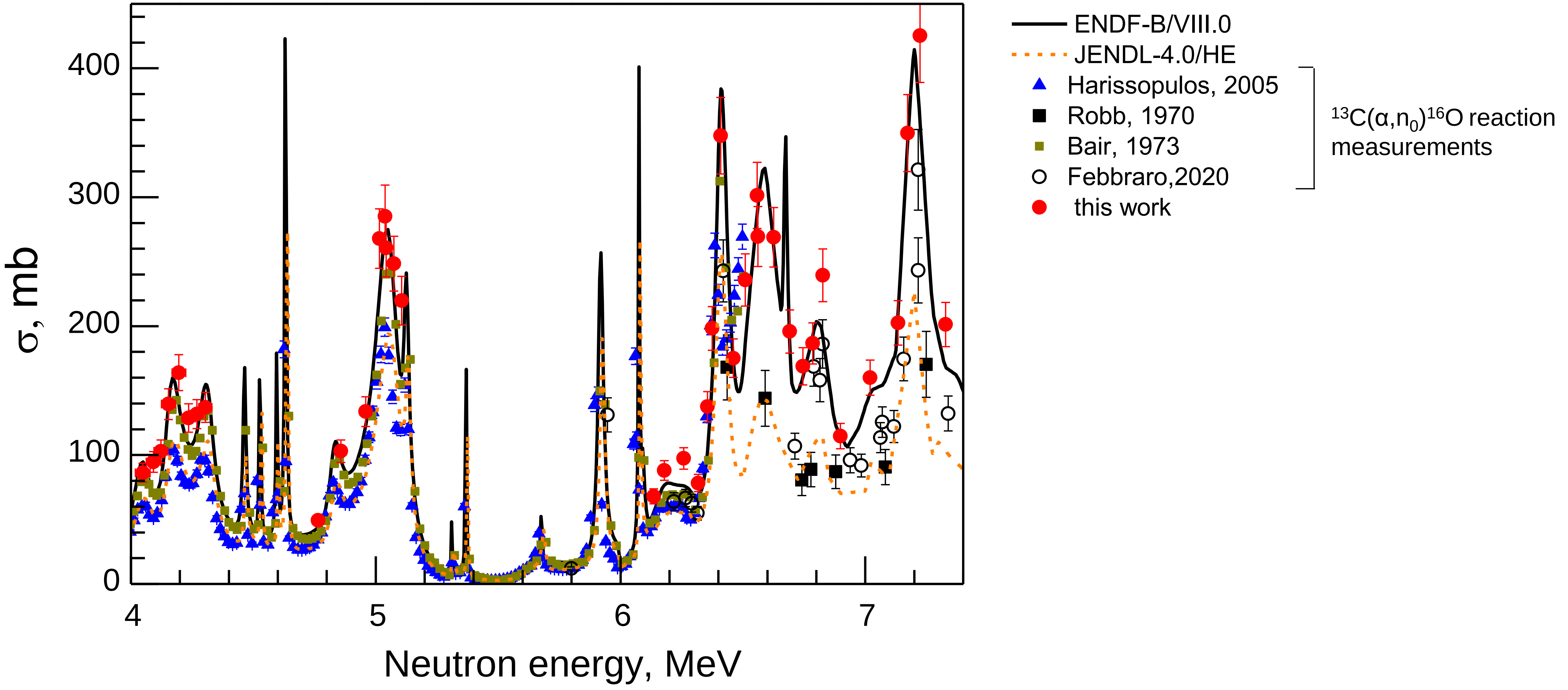
Measured angular distributions for the $^{13}C(\alpha,n_0)^{16}O$ reaction with approximation by Legendre polynomials



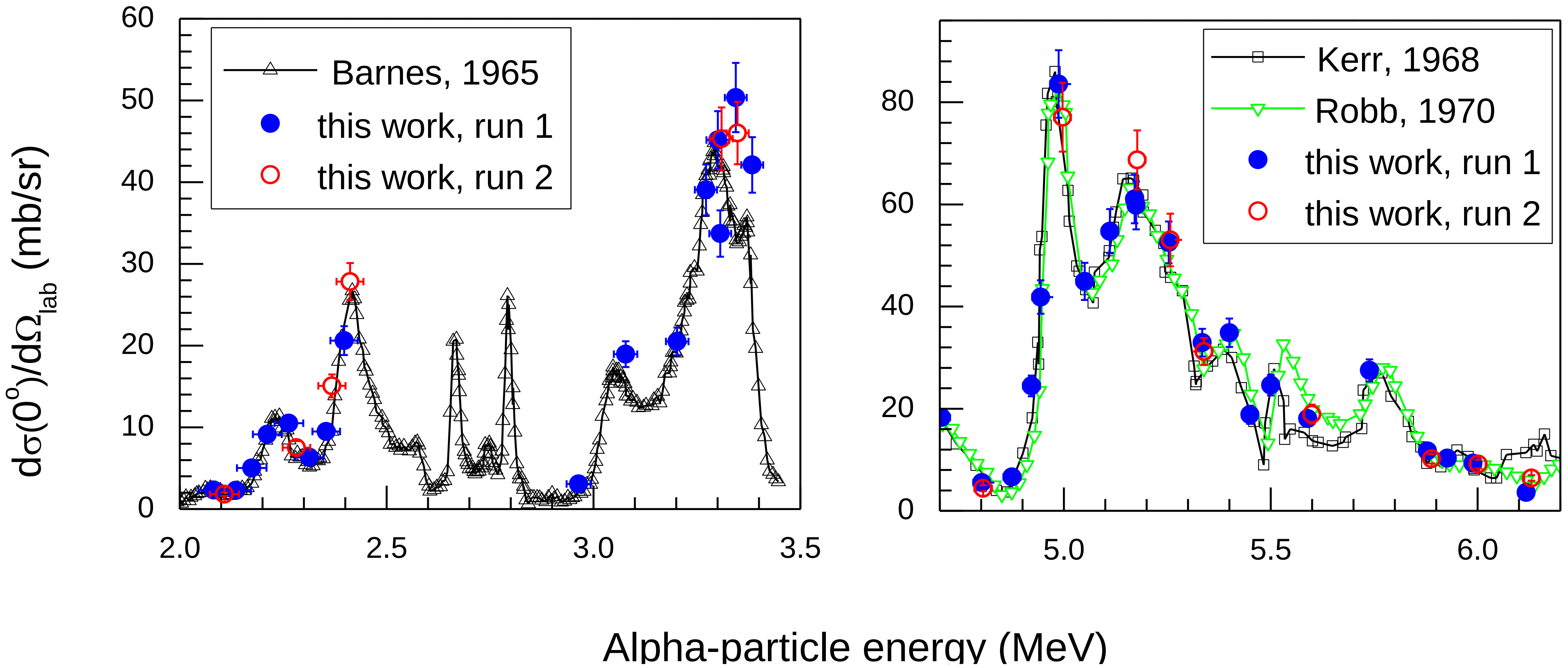
Results for the $^{16}O(n,\alpha_0)^{13}C$ cross-section (this work vs direct reaction measurements)



Results for the $^{16}O(n,\alpha_0)^{13}C$ cross-section (this work vs inverse reaction measurements)



Comparison of the results for the $^{13}C(\alpha,n_0)^{16}O$ differential cross-section at 0°



Conclusions

- The differential and integral cross-sections for the $^{13}C(\alpha,n_0)^{16}O$ reaction were acquired for the α-particle energy range of 2.0-6.2 MeV.
- The time-of-flight method in combination with the digital signal processing was used for suppressing the contribution of the neutrons from the first exited level of the residual nucleus.
- In order to minimize systematic errors the determination of the experimental parameters critical for normalizing the data was duplicated.
- The obtained angular distributions of the differential cross sections were fitted by Legendre polynomials to calculate the total reaction cross section.
- The $^{16}O(n,\alpha_0)^{13}C$ reaction cross-section was calculated using the reciprocity theorem.
- The obtained results support the ENDF-B/VIII.0 evaluation.
- Thick target yield measurements are currently being carried out with a ^{13}C enriched target to avoid ^{13}C abundance uncertainty specific to the available TTY data.

Thank you for your attention!