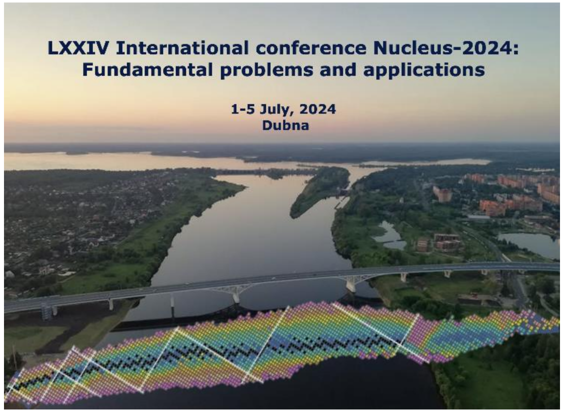
Measurement and analysis of the $^{13}C(\alpha, \alpha_0)^{13}C$ reaction cross-section in the energy range of 2.0 – 7.0 MeV

P.S. Prusachenko[1], A.F. Gurbich[2], M.V. Bokhovko[2]*

1 — Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research
2 — Leypunsky named Institute for Physics and Power Engineering

*email: prusachenko@jinr.ru



Outline

- Motivation
- Status of $^{13}C(\alpha, \alpha_0)^{13}C$ reaction cross-section data
- Experimental method and set-up
- Data analysis and correction
- Results
- Preliminary results of R-matrix analysis
- Conclusions

Our previous works

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Measurement of the cross section for the $^{13}C(\alpha, n)^{16}O$ reaction and determination of the cross section for the $^{16}O(n, \alpha)^{13}C$ reaction

P. S. Prusachenko,* T. L. Bobrovsky, I. P. Bondarenko, M. V. Bokhovko, A. F. Gurbich, and V. V. Ketlerov
Institute for Physics and Power Engineering, Bondarenko square 1, Obninsk 249033, Russian Federation

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The angular dependence of the differential cross sections for the $^{13}C(\alpha, n_0)^{16}O$ reaction was measured in the energy range 2.0–6.2 MeV using the time-of-flight method for separating neutrons corresponding to the ground state of the residual nucleus. The integrated total cross sections were derived from the measured data and the cross sections for the $^{16}O(n, \alpha_0)^{13}C$ reaction were determined using the reciprocity theorem. The cross sections obtained for the reaction $^{16}O(n, \alpha_0)^{13}C$ support the evaluation given in the ENDF/B-VIII.0 library.

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

P. S. Prusachenko, T. L. Bobrovskiy, M. V. Bokhovko & A. F. Gurbich

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Motivation

The $^{13}C(\alpha, \alpha_0)^{13}C$ reaction is one of the decay channel of ^{17}O compound nucleus so it is important for:

- To constrain the R-matrix evaluation of $^{13}C(\alpha, n)^{16}O$ reaction
- To evaluate J^π of ^{17}O compound nucleus

$^{13}C(\alpha, n)^{16}O$ reaction:

- Nuclear astrophysics – as a neutron source for s process
- Nuclear safety application
- Important source of background in rare events experiments (neutrino experiments, dark matter search etc.)

Current status of $^{13}C(\alpha, n)^{16}O$ reaction cross-section:

- Current theoretical evaluation of the $^{13}C(\alpha, n_0)^{16}O$ reaction cross-section presented in the ENDF-B/VIII.0 library covers a limited energy range (up to 5.7 MeV). There is only cross-section extrapolation for higher energies. The role of partial channels of $^{13}C(\alpha, n_{1,2})^{16}O$ poorly studied.
- The data on the $^{13}C(\alpha, n_{1,2})^{16}O$ reaction are extremely limited.
- New experimental data on $^{13}C(\alpha, n_0)^{16}O$ are very contradictory

Status of $^{13}C(\alpha, \alpha_0)^{13}C$ reaction data

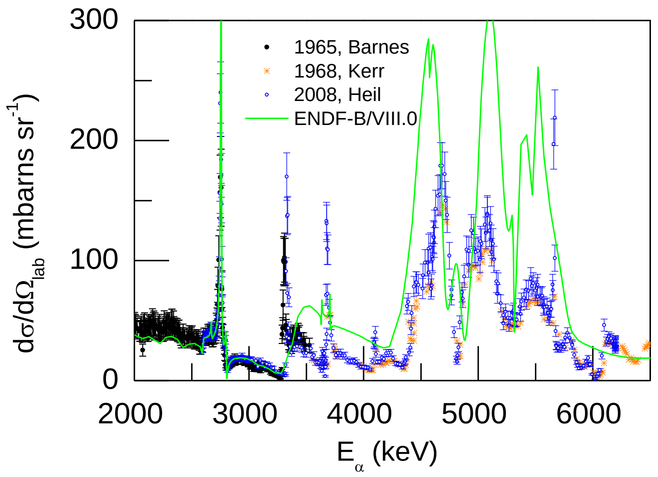

Fig.1. Experimental data and ENDF-B/VIII.0 evaluations of differential cross-section of $^{13}C(\alpha, \alpha_0)^{13}C$ reaction at the angle of 165°

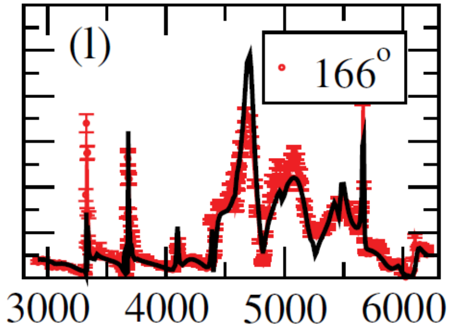

Fig. 2. Heil's data on $^{13}C(\alpha, \alpha_0)$ reaction at the angle of 166° vs his R-matrix evaluation

- Only three experimental datasets are available now for energies less than 10 MeV
- All data were measured with high uncertainty (>10%)
- The main sources of uncertainty are the target thickness and carbon build-up
- All data extremely contradict the R-matrix evaluation from ENDF-B/VIII.0
- The R-matrix evaluation performed by Heil reproduces his $^{13}C(\alpha, \alpha_0)$ data but does not reproduce the new experimental data on (α, n)

1. G.W. Kerr et al, Energy Levels of ^{17}O from $^{13}C(\alpha, \alpha_0)^{13}C$ and $^{13}C(\alpha, n)^{16}O$, Nuclear Physics A 110, 637–656 (1968); https://doi.org/10.1016/0375-9474(68)90378-3
2. B.K. Barnes et al, Level Assignments in ^{17}O from $^{13}C(\alpha, \alpha_0)^{13}C$ and $^{13}C(\alpha, n)^{16}O$, Phys. Rev. 140, B616-622 (1965); https://doi.org/10.1103/PhysRev.140.B616
3. M. Heil et al, The $^{13}C(\alpha, n)^{16}O$ reaction and its role as a neutron source for the s process, Phys. Rev. 78, 025803 (2008); https://doi.org/10.1103/PhysRevC.78.025803
4. (alpha, n) Nuclear Data Evaluations and Data Needs. Summary Report of the Technical Meeting 8-12 November 2021 (virtual event), INDC(NDS)-0836, March 2022

Experimental method and set-up

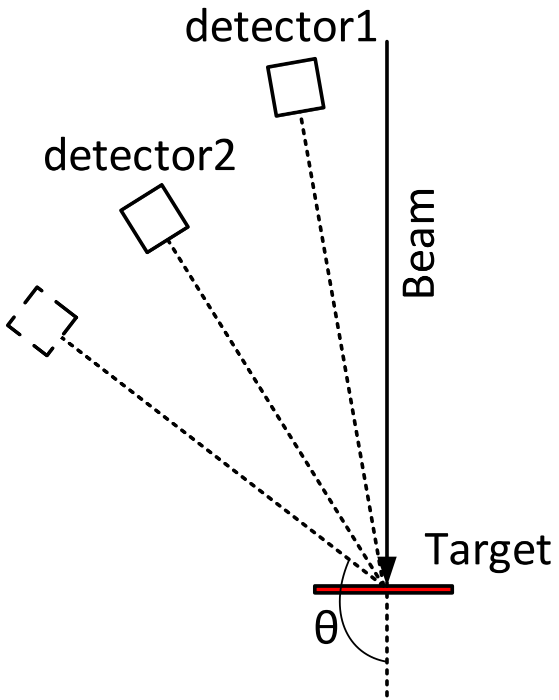

Fig. 3. Layout of experimental set-up (not to scale)

- Energy range: 2000 – 7000 keV
- Angles: 127.6°, 148°, 169.2°
- Laser evaporated thin film of amorphous carbon deposited on Be backing as a target
- ~92% enrichment at ^{13}C
- Two PIPS detectors – stationary detector at the angle of 169.2° and moveable one for the measurements at the angles of 127.6°, 148°
- Number of α-particles was determined by current integration
- I_α no more than 50 nA, Q/run no more than 5 uC
- $^{nat}Ni(\alpha,\alpha)$ as a inner standard for Q·Ω calibration

Data analysis

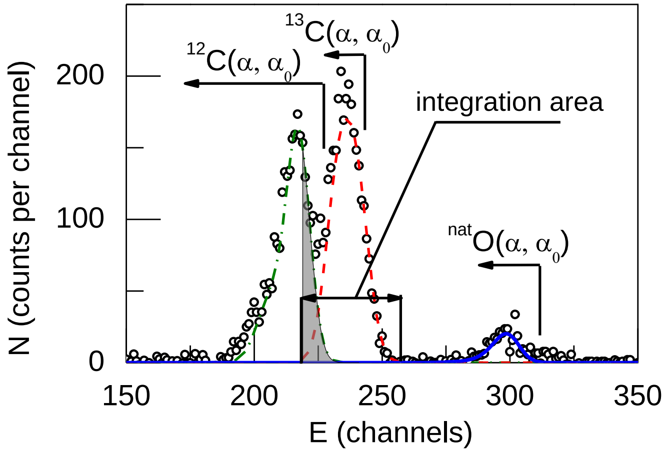

Fig. 4. Spectrum of scattered α-particles from the ^{13}C target, E_α=3888 keV and θ=148°
Points – the experimental data,
Lines – SIMNRA7 fit
Filled area – part of ^{12}C peak in the integration area

Differential cross-section of $^{13}C(\alpha, \alpha_0)^{13}C$ was determined by exp. (1):

$$\frac{d\sigma}{d\Omega}(E_\alpha,\theta) = \frac{N_{c13}e}{n_1 Q\Omega}10^{24}\frac{mb}{sr} \quad (1)$$

Where E_α - energy of α-particle; θ – scattering angle; N_{c13} – number of events, detected in $^{13}C(\alpha,\alpha_0)^{13}C$ peak; n_1 - the surface density of ^{13}C atoms; $Q\Omega$ – production of charge and solid angle.

Spectra analysis:

1. Spectra where there was not possibility to separate the contribution of $^{12}C(\alpha, \alpha_0)^{12}C$ and $^{13}C(\alpha, \alpha_0)^{13}C$ events - N_{c13} was determined taking into account previously measured surface densities of ^{12}C in target and carbon build-up

2. Spectra in which the contribution of $^{12}C(\alpha, \alpha_0)^{12}C$ and $^{13}C(\alpha, \alpha_0)^{13}C$ events were not separated clearly (see Fig. 3). In this case, the correction on $^{12}C(\alpha, \alpha_0)^{12}C$ events was simulated using SIMNRA7[1].

3. Spectra in which the $^{12}C(\alpha, \alpha_0)^{12}C$ and $^{13}C(\alpha, \alpha_0)^{13}C$ peaks were separated clearly – simple summation with background subtractions

Carbon build-up

- Thickness of carbon build-up was determined by analysis of the EBS spectra acquired during the routine measurements at the angle of 169.2°
- The thickness of build-up did not exceed $200\cdot10^{15}$ at.cm^{-2} ± 8-10%

1. M. Mayer, Improved Physics in SIMNRA7, Nucl. Instr. Meth. B 332, 176 (2016); https://doi.org/10.1016/j.nimb.2014.02.056

Target thickness and isotopic composition

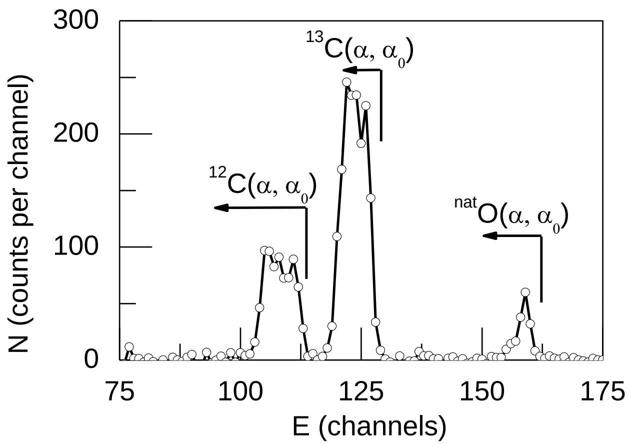

Fig. 5. EBS spectrum from ^{13}C measured at E_α=4006 keV and θ=169.2°

^{12}C content:

- Non-Rutherford Elastic Backscattered Spectrometry (EBS) was used
- E_α=4006 keV and θ=169.2° (see Fig. 5)
- The surface density of ^{12}C was 106±9·10^{15} at.cm^{-2}
- The SigmaCalc2.0 evaluation of the $^{12}C(\alpha,\alpha_0)^{12}C$ reaction cross-section was used

^{13}C content

- Rutherford Backscattering Spectrometry (RBS) and Nuclear Reaction Analysis (NRA) were independently used
- RBS spectrum - E_α=1793 keV and θ=169.2°. The surface density of ^{13}C atoms was 1194±32·10^{15} at.cm^{-2}
- The $^{13}C(d, p_0)^{14}C$ reaction in combination with differential cross-section measured by J. Colaux[2] was used for NRA analysis of the target. The surface density of ^{13}C atoms was 1217±55·10^{15} at.cm^{-2}

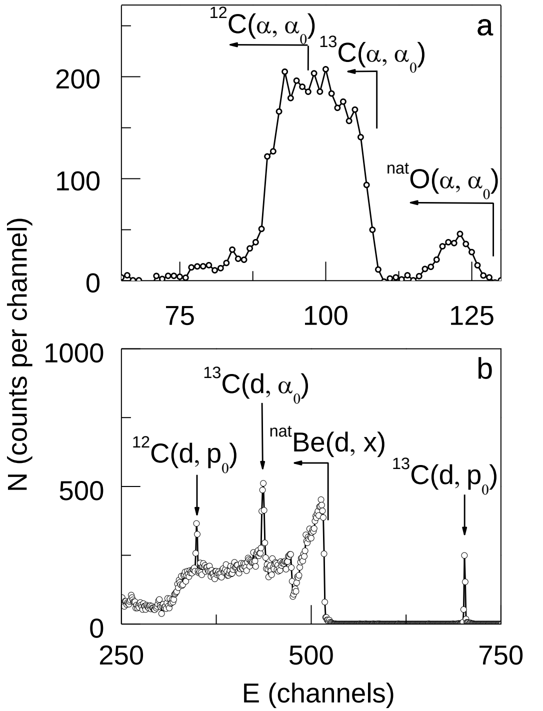

Fig. 6. a – RBS spectrum from ^{13}C target corresponding to E_α=1793 keV and θ=169.2°;
b – NRA spectrum from ^{13}C target obtained at the irradiation by deuterons with E_d=1000 keV at θ=148°

1. A.F. Gurbich, SigmaCalc resent development and present status of the evaluated cross-sections for IBA, Nucl. Instr. Meth. B 371, 27-32 (2016); https://doi.org/10.1016/j.nimb.2015.09.035

2. J.L. Colaux et al, Cross section measurements of the reactions induced by deuteron particles in ^{13}C, Nucl. Instr. Meth. B, 254 25-29 (2007); https://doi.org/10.1103/PhysRev.140.B616

Results of measurements

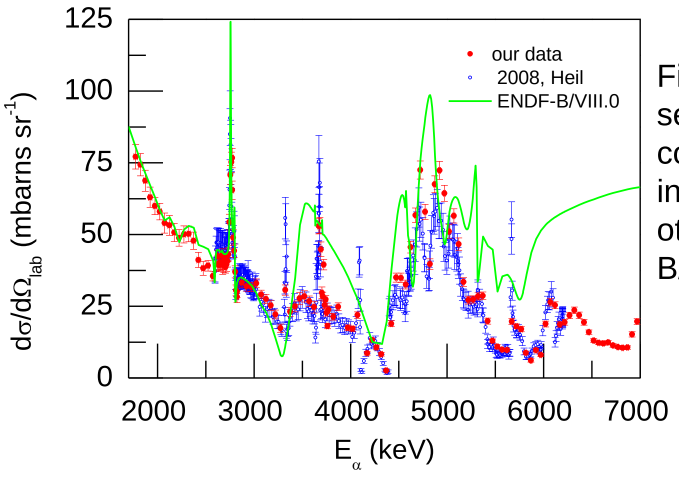

Fig. 7. The differential cross-section $^{13}C(\alpha, \alpha_0)^{13}C$ reaction corresponding to the θ=127.6° in comparison with data of other authors and ENDF-B/VIII.0 evaluation

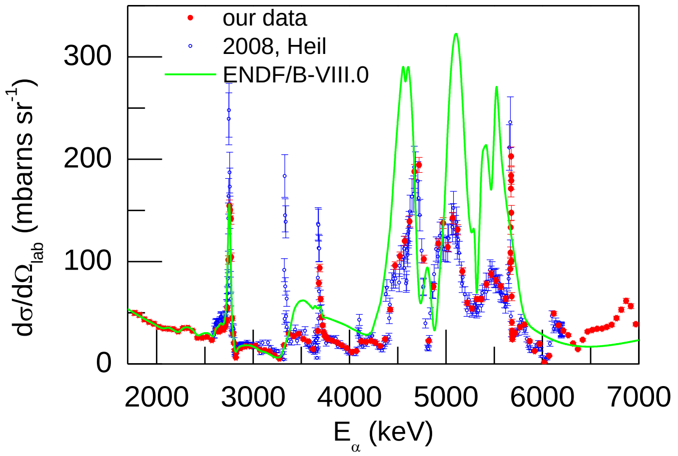

Fig. 9. The same as in Fig. 6 but for θ = 169.2°

- The data obtained in this work are in agreement with Heil's data within uncertainties
- The ENDF-B/VIII.0 evaluation extremely differ both from the our data and the Heil's data for the E_α>3500 keV
- The revision of current evaluation of ^{17}O compound nucleus system is needed

Uncertainty Source	Value (%)
Statistics of counts	3.0-4.0% in average
Background subtraction	2.0-3.0% in average
Thickness	2.9%
^{12}C events subtraction	0.0 – 0.8% in average Up to 10% in $^{12}C(\alpha, \alpha_0)$ resonances
Q·Ω	2.8%
Total	4.0-6.0%

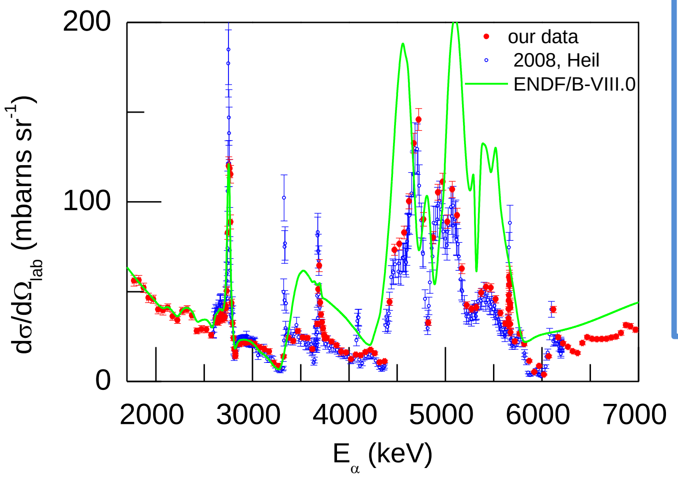

Fig. 8. The same as in Fig. 6 but for θ = 148°

Preliminary analysis

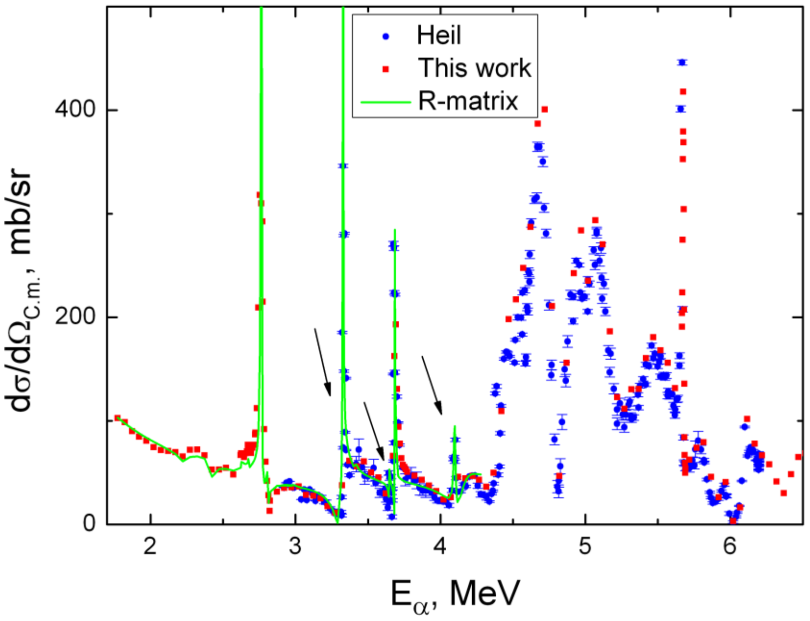

Fig. 10. The differential cross-section $^{13}C(\alpha, \alpha_0)^{13}C$ reaction corresponding to the θ=169.2° in comparison with Heil's data and our **preliminary** evaluation

- Our preliminary R-matrix evaluation are in agreement both with our data and Heil's data up to energy of 4.2 MeV
- There are problems with cross-section analysis at higher energies – significant modification of the level structure and resonance parameter of ^{17}O compound nucleus is required to reproduce the data
- The additional R-matrix analysis of other reaction in ^{17}O compound nucleus is needed

Summary

- The differential cross section of the $^{13}C(\alpha, \alpha_0)^{13}C$ reaction was measured in the energy range 2.0-7.0 MeV at the angles of 127.6°, 148.0° and 169.2°

- The total uncertainty was in average of 4.0 – 6.0%

- The data obtained are in agreement within uncertainty with experimental data previously measured by Heil

- Current evaluation of ^{17}O compound nucleus system needs to be revised for $E_\alpha > 3500$ keV

- Clarification of the level structure and resonance parameters of ^{17}O is needed

Thank you for your attention!

Pavel Prusachenko,

senior researcher of Frank Laboratory of Neutron Physics,
Joint Institute for Nuclear Research

prusachenko@jinr.ru