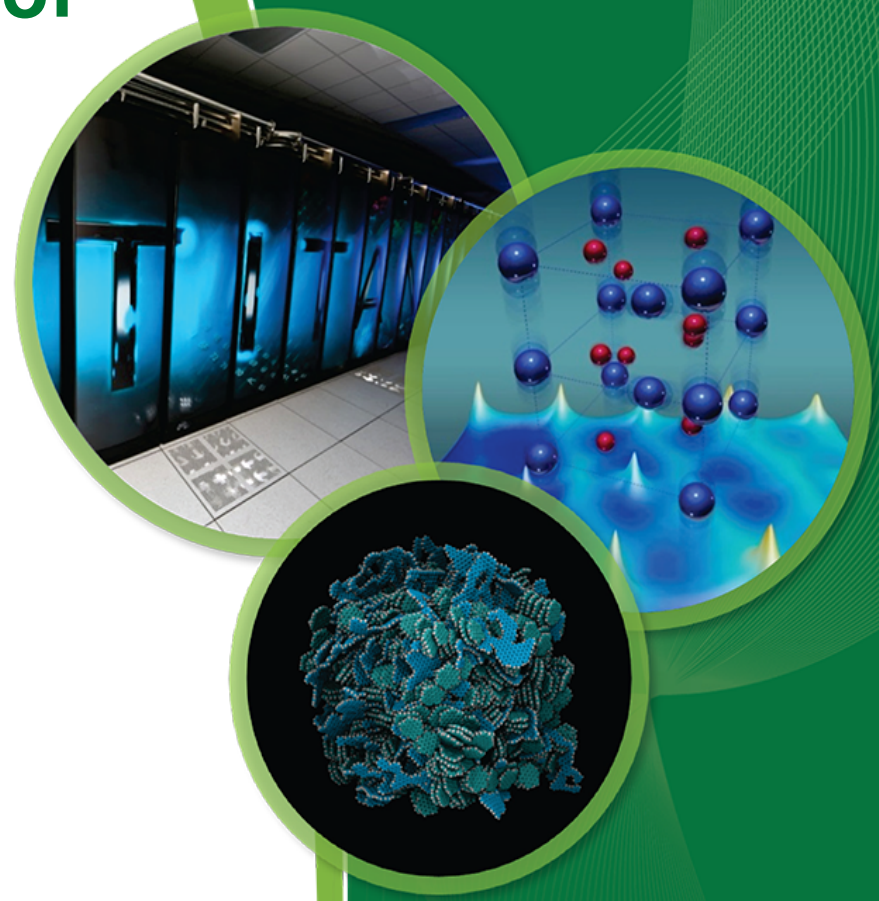
Notes on the consistency of ^{16}O(n,α) cross sections



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Background

- ORNL is working to provide resonance parameter evaluation able to describe n+^{16}O cross sections
- The evaluation work builds on a comprehensive resonance analysis performed by R.O. Sayer in 2000 (ORNL/TM-20000/212)
  - In Sayer's evaluation the Bair's (n,α) cross sections were normalized by -30%.
- Two major features of the present evaluation
  - The first one is the use of the B_c=-l boundary condition commonly used in the formal R-matrix theory but never used in SAMMY evaluation work. Default option is the energy-dependent boundary condition $B_c = S_c$
  - The second one is the study of the capture channel treated as in the Reich Moore approximation or as particle channels whose penetrability factor are set to be unitary in SAMMY input file. The aim of this study is to determine the accuracy of the Reich-Moore approximation compared to R-Matrix calculations specifically for n+^{16}O case
- Presentation was given at "The 2016 R-Matrix Workshop on Methods and Applications" June 27 July 1 2016, Santa Fe, NM, USA (see Reich-Moore R-matrix Parameters for n+^{16}O within CIELO Collaboration)
  - The evaluation work presented in June followed CIELO recommendations. Namely, -6% and +42% normalization factors for Bair's and Harissopulos' (n,α) cross sections.

Bair's and Harissopulos' data

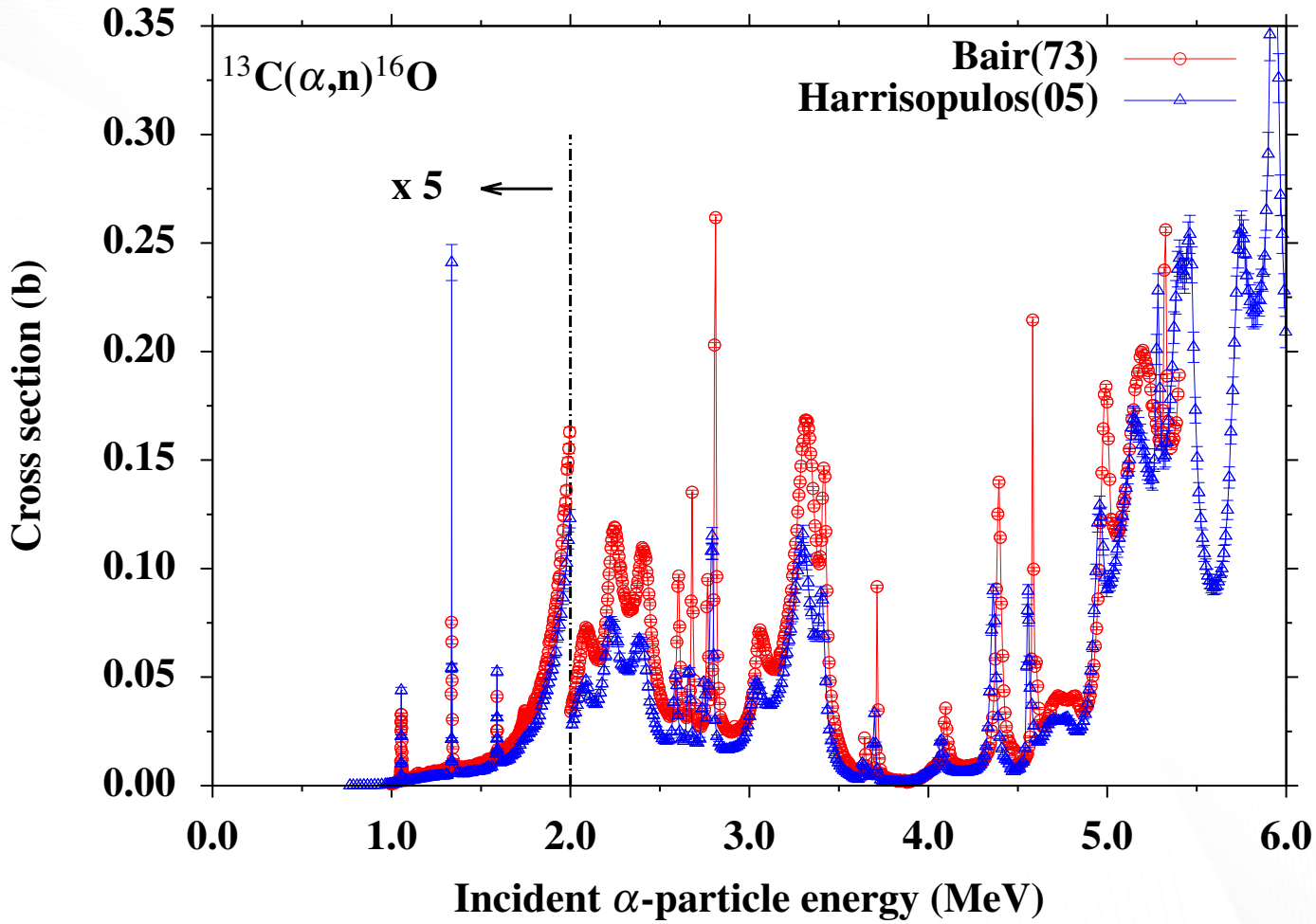

Figure 1: The plotted ^{13}C(α,n) cross sections and related uncertainties are taken from the EXFOR library, entry C0489 for Bair's cross sections published in Phys. Rev. C7, 1356 (received November 1972, published April 1973) in red and entry F0786 for Harissopulos' data published in Phys. Rev. C72, 062801 (2005) in blue. **Differences up to 30% between the two data sets**.

Bair's and Harissopulos' data

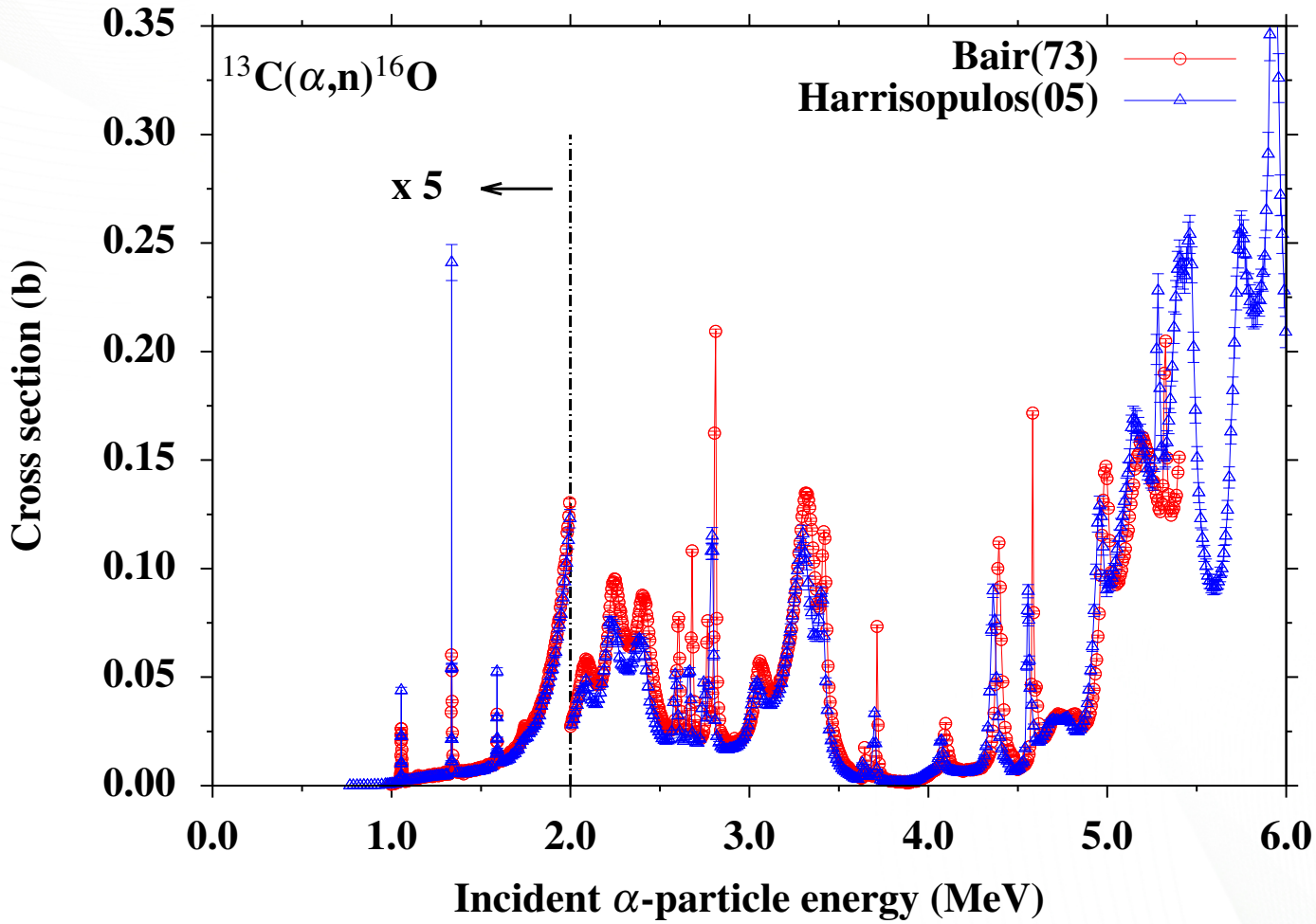

Figure 2: The plotted ^{13}C(α,n) cross sections and related uncertainties are taken from the EXFOR library, entry C0489 for Bair's cross sections published in Phys. Rev. C7, 1356 (received November 1972, published April 1973) in red and entry F0786 for Harissopulos' data published in Phys. Rev. C72, 062801 (2005) in blue. **Bair's data normalized by -20%**.

Bair's and Harissopulos' data

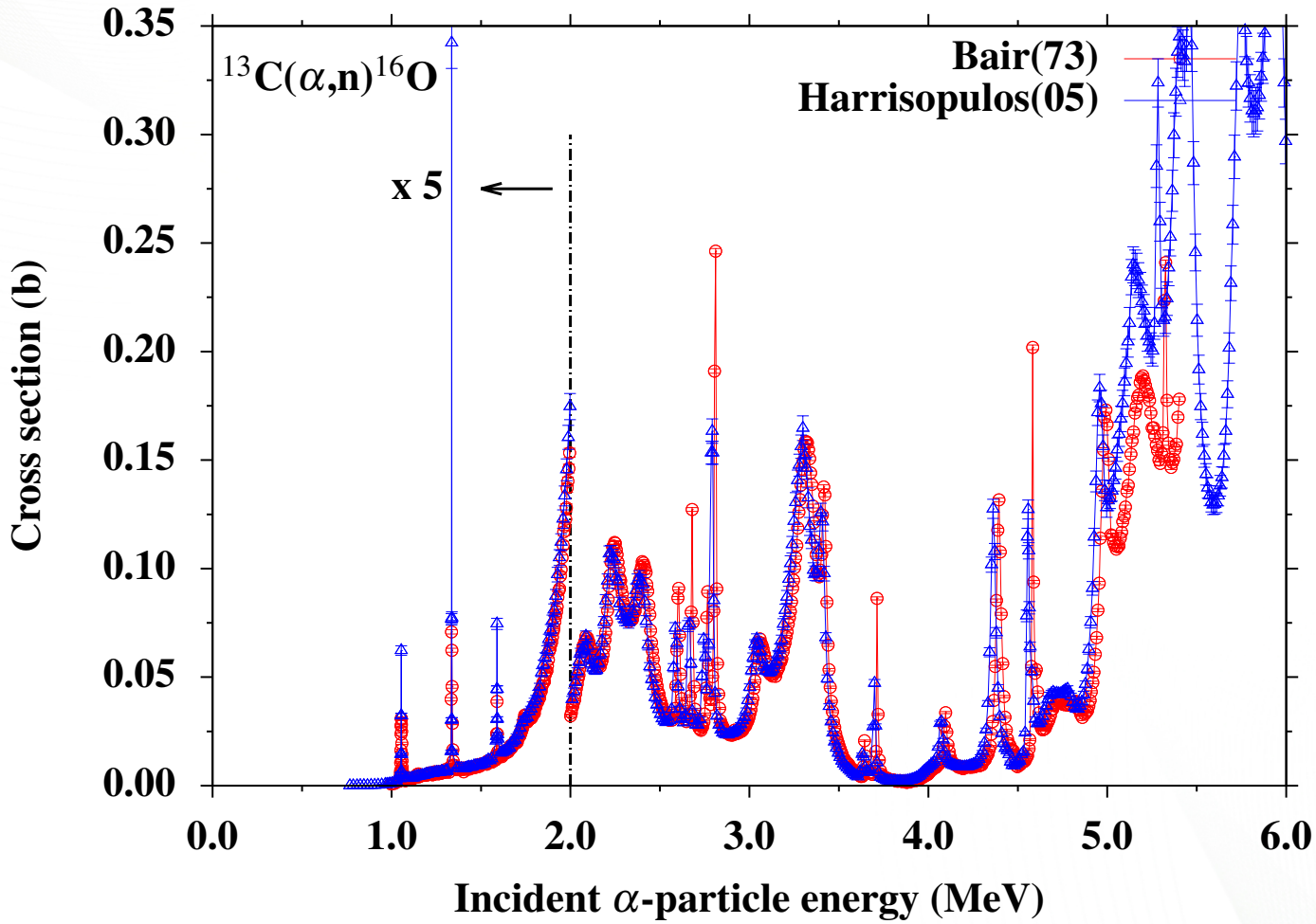

Figure 3: The plotted ^{13}C(α,n) cross sections and related uncertainties are taken from the EXFOR library, entry C0489 for Bair's cross sections published in Phys. Rev. C7, 1356 (received November 1972, published April 1973) in red and entry F0786 for Harissopulos' data published in Phys. Rev. C72, 062801 (2005) in blue. **Bair's data normalized by -6% and Harissopulos' by +42% as in CIELO**.

On Bair's recommendation

Ref. 1 In Phys. Rev. C7, 1356 (received November 1972, published April 1973), Bair's added proof states : "*Thick carbon target yields calculated from the thin target data give here must be reduced by 15% or 20% in order to match smoothly with recent thick target measurements made using α-particle. . . from 5.2 to 9.0 MeV energy.*"

Ref. 2,3 Bair's recent thick target measurements published in Nucl. Sci. Eng., 51, 83 (received December 1972, published May 1973) found a decimal point error in the figure of thick-target neutron yield published by R. L. Macklin in Nucl. Sci. Eng., 31, 343, (1968)

Ref. 4 Additional Bair's paper, Nucl. Sci. Eng., 71, 18 (1979) states : "*In the paper giving our $^{13}C(\alpha,n)$ thin-target cross section data (Ref. 1), we estimated our error as $\pm$20%,. . . we stated that the data must be reduced by 15 to 20% to match smoothly with our thick-target measurements (Ref. 2), which, at that time, had not yet been published. Ref. 2 again stated that thin-target data must be reduced by 15%.*"

On Bair's recommendation

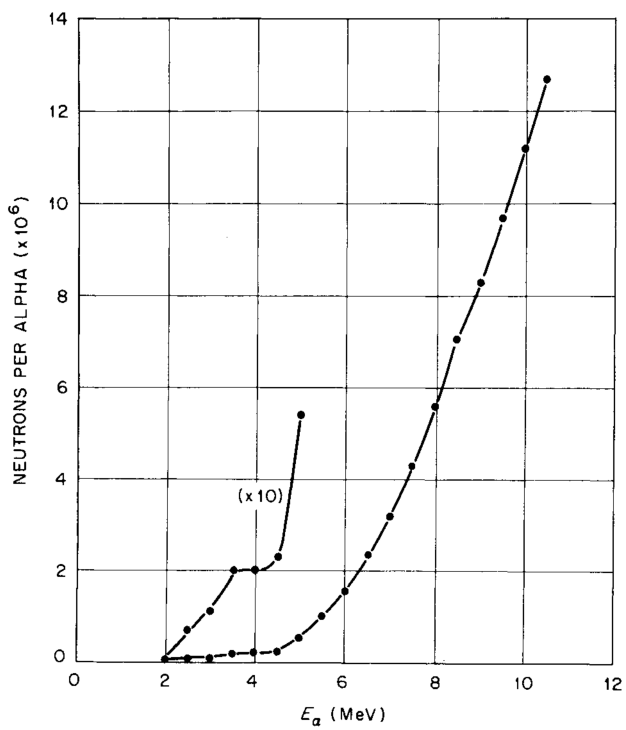

Fig. 1. Total neutron yield vs incident alpha particle energy for the C(α,n) reaction in a thick target.

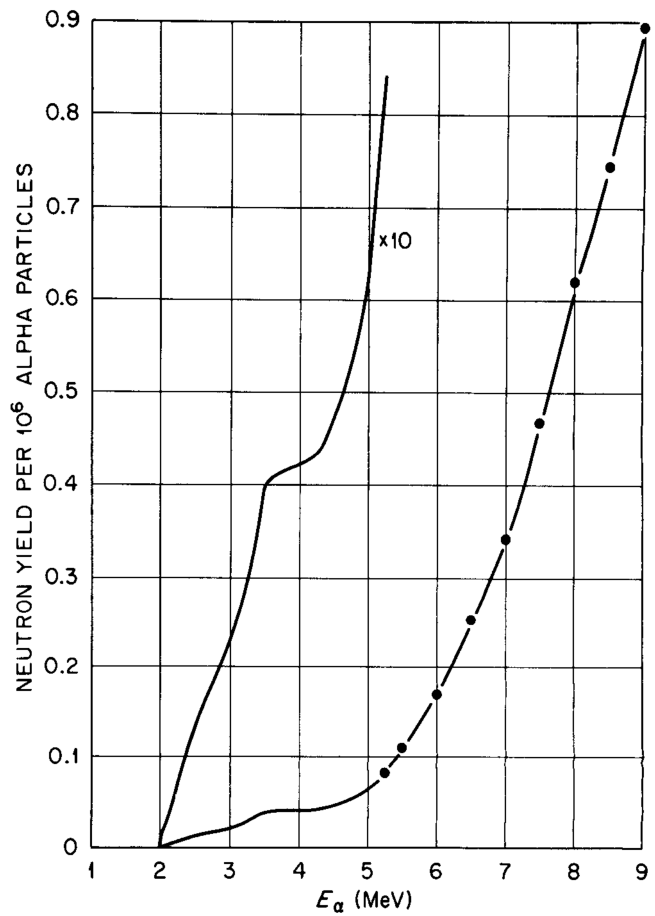

Fig. 1. Total neutron yield versus incident alpha-particle energy for the (α,n) reaction in a thick target of natural carbon.

Figure 4: (LEFT) Taken from Macklin et al. Nucl. Sci. Eng., 31, 343, (1968) showing a decimal point error. (RIGHT) Taken from Bair Nucl. Sci. Eng., 51, 83. Black dots represent measured data, solid line represents thick-target yields calculated from thin-target data.

On Bair's recommendation

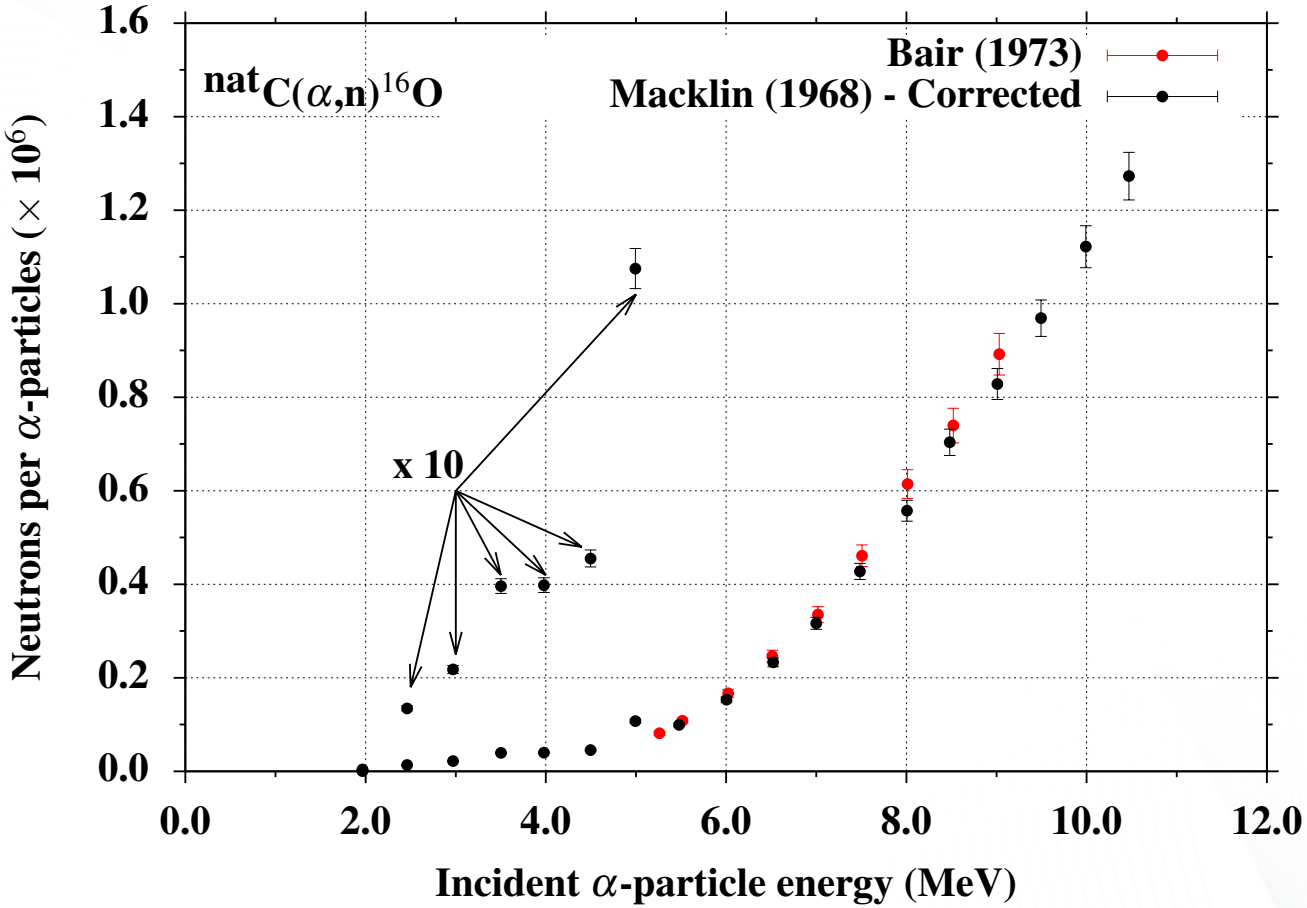

Figure 5: Total neutron yield vs incident α-particle energy from digitized data of Bair and Macklin. Macklin data (Nucl. Sci. Eng., 31, 343, 1968) were corrected by a factor of 10. Below 5 MeV an additional correction (factor of 2) included the change from singly charged helium (He^{+}) to doubly charged helium (He^{++}). From 4.5 to 5 MeV discrepancies are still visible.

Computation of thick-target yield from thin-target cross sections

- The thick-target neutron yield of ^{nat}C can be computed from the thin-target ^{13}C(α,n) cross sections $\sigma(E)$ and (e.g., amorphous) mass stopping power cross sections $L(E)$

$$Y_{\mathrm{nat}}(E) = \eta \cdot \int_0^E \sigma(E')[L(E')]^{-1} dE' , \tag{1}$$

where $\eta = N_{\mathrm{A}}\alpha_{\mathrm{nat}}/(\alpha_{13}A_{\mathrm{nat}})$ is the scaling factor from enriched ^{13}C yield to ^{nat}C yield.

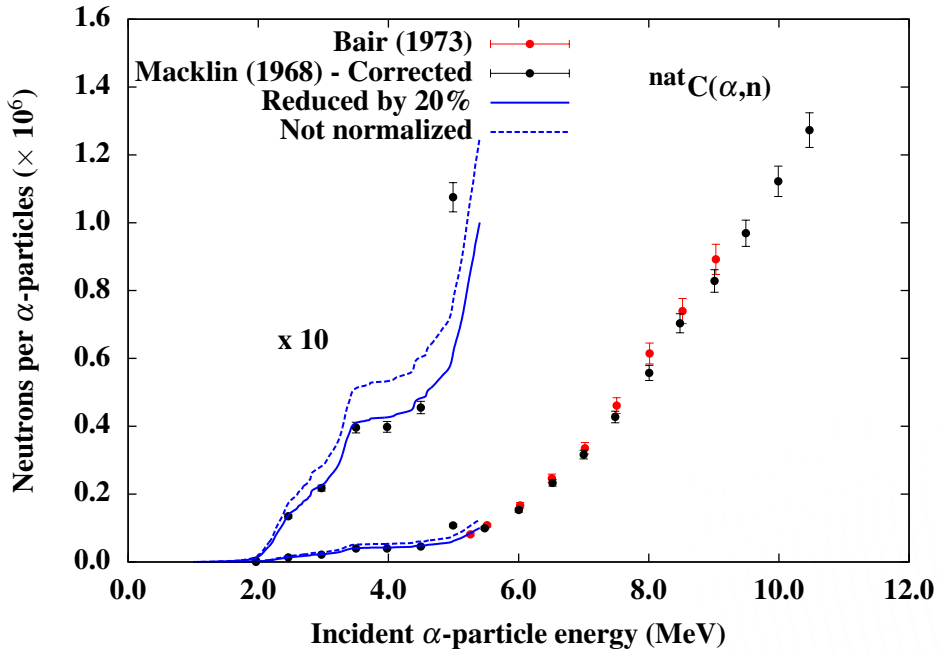

Figure 6: Total neutron yield vs incident α-particle energy (in blue) calculated from Eq.(1) using Bair's thin-target cross sections. ASTAR mass stopping power cross sections $L(E)$ were used. N_{A} is the Avogadro number, $\alpha_{13} = 1$ (fraction of ^{13}C in the enriched sample), $\alpha_{\mathrm{nat}} = 0.0107$ (fraction of ^{13}C in a natural sample), the ^{nat}C molar mass A_{nat}=12.0107359 g·mol^{-1}. Threshold of ^{12}C(α,n) reaction is about 11.4 MeV.

Comparison with West and Sherwood thick-target yield

- The thick-target neutron yield measured by Macklin and Bair used the same detector
- Is there any relatively recent measurement of natural carbon thick-target yield? Yes, West & Sherwood (1982).

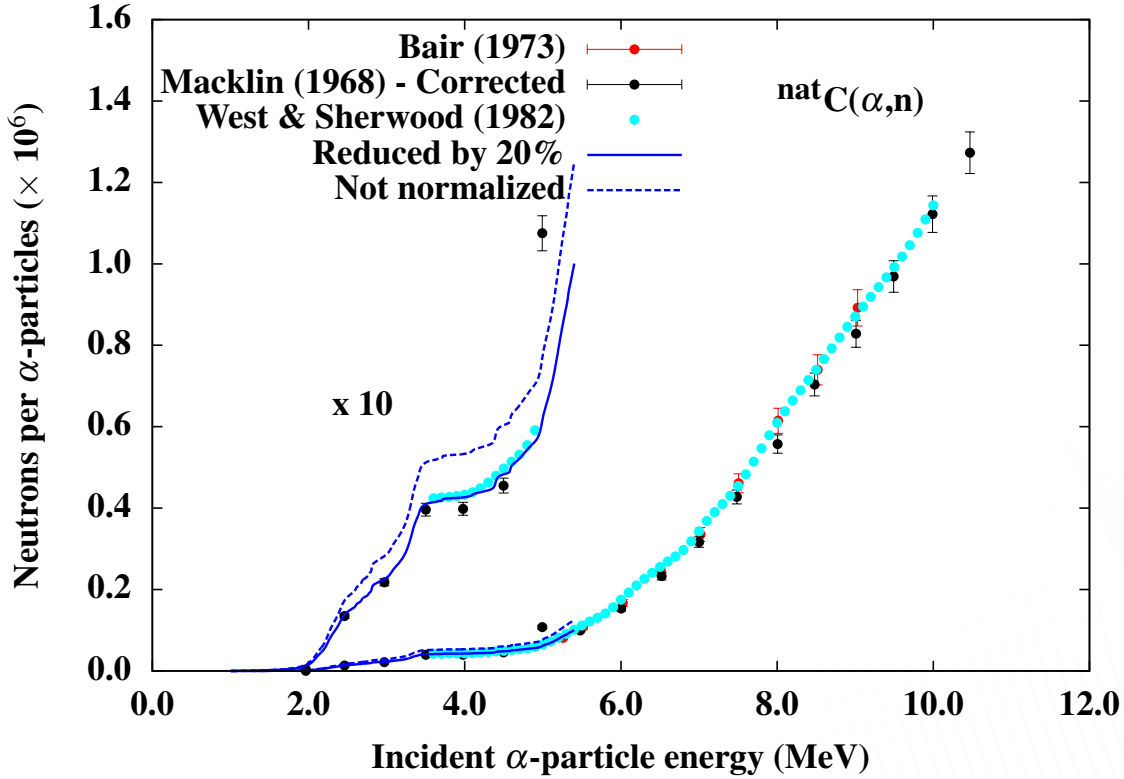

Figure 7: As Fig.6. Thick-target neutron yield measured by West and Sherwood (Ann. Nucl. Ene. 9, 551, 1982) is shown.

...including Harissopulos ...

- Harissopulos' thick target data computed from thin-target cross sections can match Macklin's thick target data by a normalization factor of +15%
- For energies above 5.5 MeV Harissopulos's thick target data deviates from other measurements : it is not clear how the efficiency was adjusted to the changing spectrum as E_α is changed.

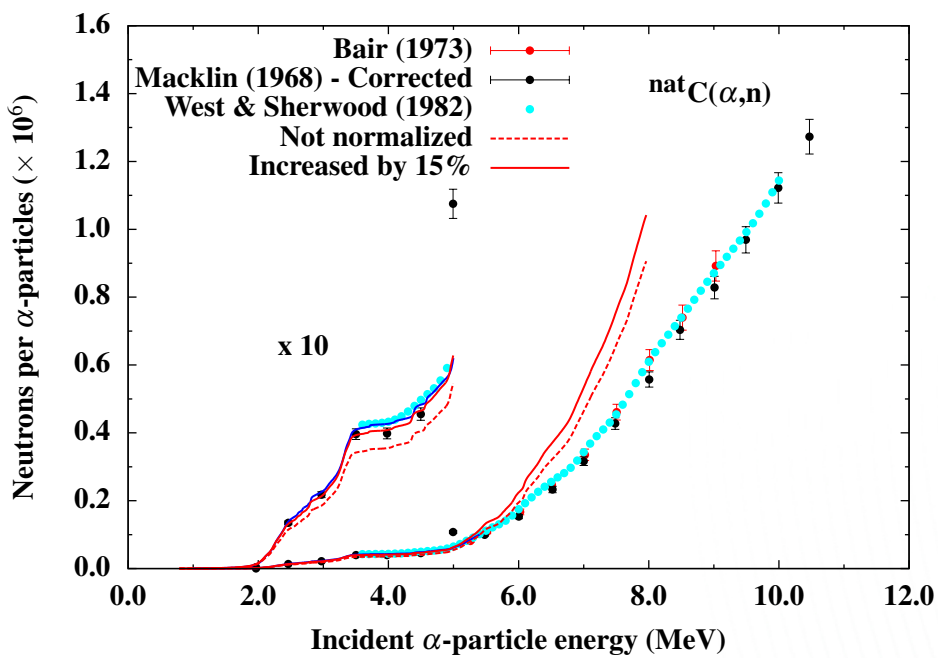

Figure 8: As Fig.7 including neutron yield computed on the basis of Harissopulos' data (in red dashed and solid lines). Threshold of $^{13}C(\alpha,n_1)$ reaction is above 5 MeV.

Neutron yield at E_α=1.056 MeV

- Using both Bair's (-20%) and Harissopulos' (+15%) thin-target cross sections and (amorphous and graphite) mass stopping power cross sections, one can compute from Eq.(2) the neutron yields

$$Y_{\rm enr} = \alpha_{13} N_A / A_{13} \cdot \int_{E_\alpha=1.050{\rm MeV}}^{E_\alpha=1.058{\rm MeV}} \sigma(E')[L(E')]^{-1} dE' \,, \tag{2}$$

- Using the resonance strength $\omega\gamma$=12$\pm$0.4 eV measured by Harissopulos one can compute the neutron yield from Eq.(3)

$$Y = \omega\gamma \left(\frac{\alpha_{13} \frac{N_A}{A_{13}}}{2L(E_\alpha)} \right) \frac{\lambda_\alpha^2}{2[E_\alpha/(m_\alpha c^2)]/(1+m_\alpha/m_{^{13}\rm C})^3} \,, \tag{3}$$

$Y_{\rm enr}$ (n/μC) for singly charged He$^+$		
	Amorphous	Graphite
Bair[a]	4760.1	4537.9
Harissopulos[a]	4762.1	4537.1
Bair[b]	4475$\pm$224	
Harissopulos[c]	4072.9	4277.2

[a] Computed from Eq.(2).
[b] Reported value in Phys. Rev. C7, 1356 (1973).
[c] Computed from Eq.(3) using measured $\omega\gamma$=12$\pm$0.4 eV reported in Phys. Rev. C72, 062801 (2005).

Summary and Conclusions

- Bair's recommendation on the normalization of his data is discussed in detail and confirmed to be accurate
- -20% normalization of thin-target cross sections recommended by Bair is consistent with his (1973) and Macklin's (1968) thick-target measurements but, most importantly, also with more recent measurements of West and Sherwood (1982).
- Thick-target yield calculated from Harissopulos' thin-target cross sections need to be normalized by +15% in order to agree with Macklin's measured thick-target data.
- Current CIELO recommendations (-6%) disagree with Bair's recommendation (-20%)
  - The huge normalization factor +42% for Harissopulos' data needs further investigation.
  - Need for a mathematical justification (unitary condition?) 1) for the strong normalization factor applied on Harissopulos' data and 2) for disregarding Bair's recommendation
- Recommendations from the present analysis are normalization factor of -20% for Bair's data and +15% for Harissopulos' data
  - An evaluation work based on -20% normalization for Bair's (n,α) data and +15% for Harissopulos' (n,α) data is almost ready for testing

Acknowledgments

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Thank you!