Neutron yield calculation for (α,n) reactions with SOURCES4

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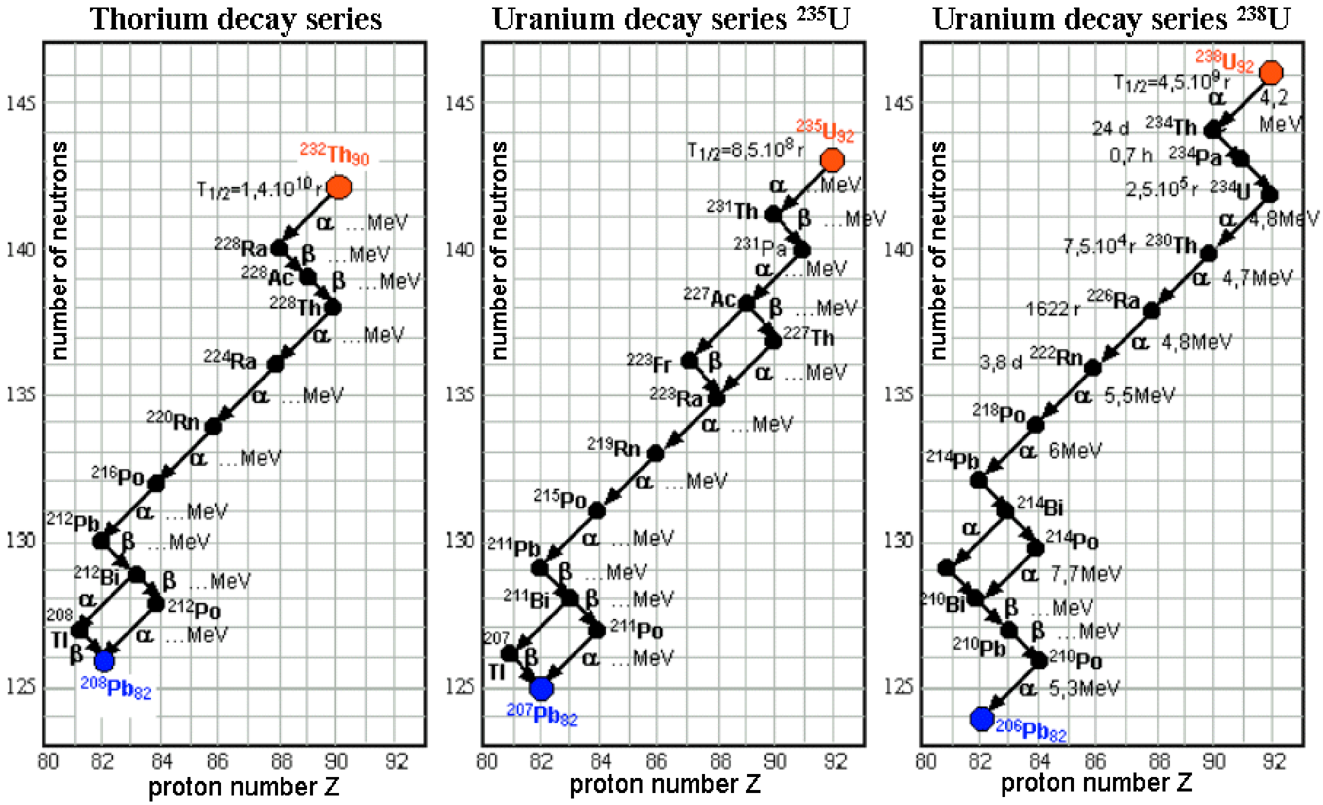
2nd Technical Meeting on (alpha,n) Reaction Nuclear Data Evaluations and Data Needs

Outline

- Why are neutrons “dangerous” is rare-event physics experiments?
- Neutron production in (α,n) reactions in SOURCES4
- Cross sections comparison
- Branching ratios calculations
- Neutron yields and neutron spectra
- Conclusions

The sensitivity of underground experiments searching for rare events such as dark matter or low-energy neutrino interactions is often limited by the background caused by neutrons from spontaneous fission and (α, n) reactions.

Potential alpha sources

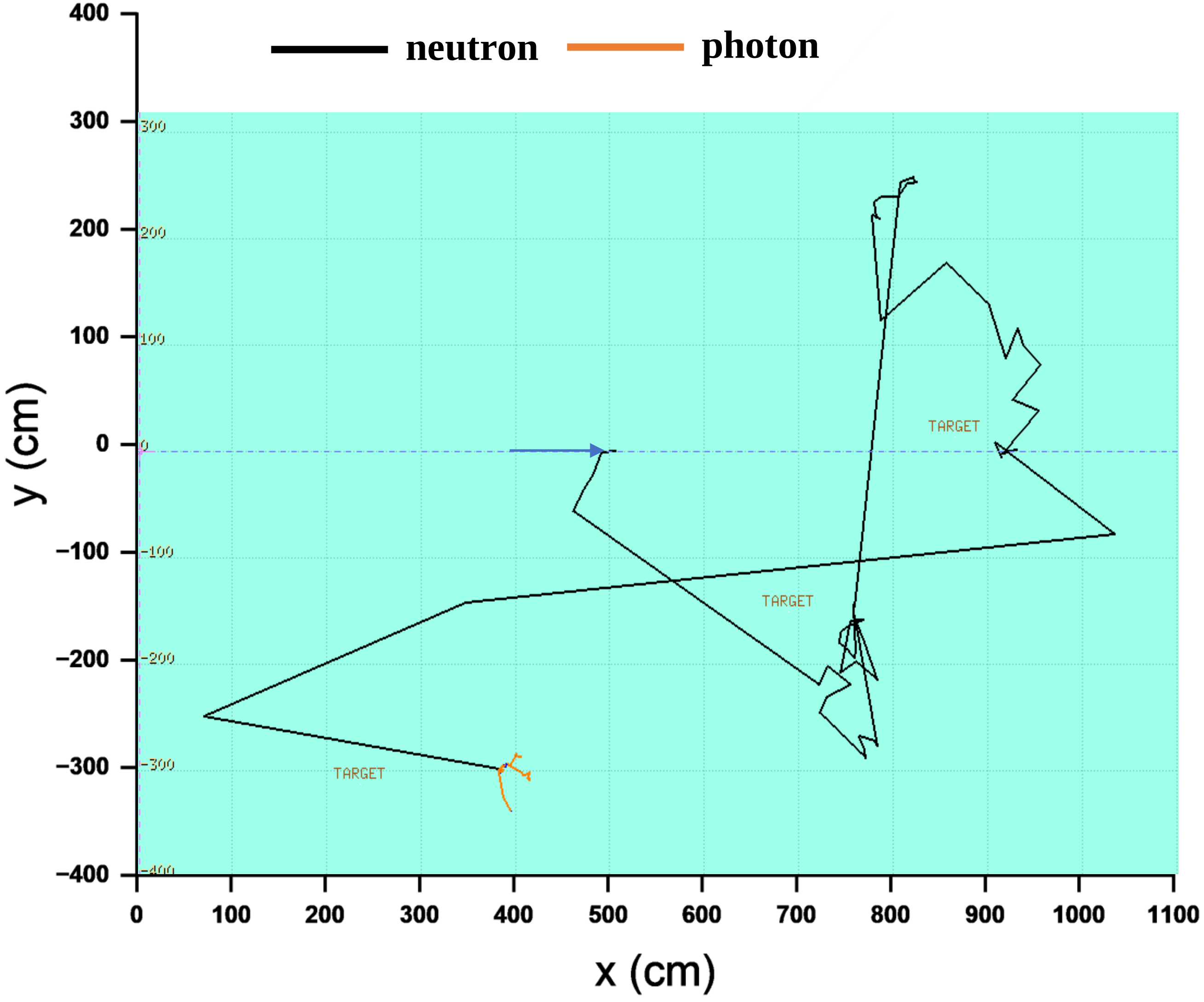


Alpha energies up to 9 MeV.

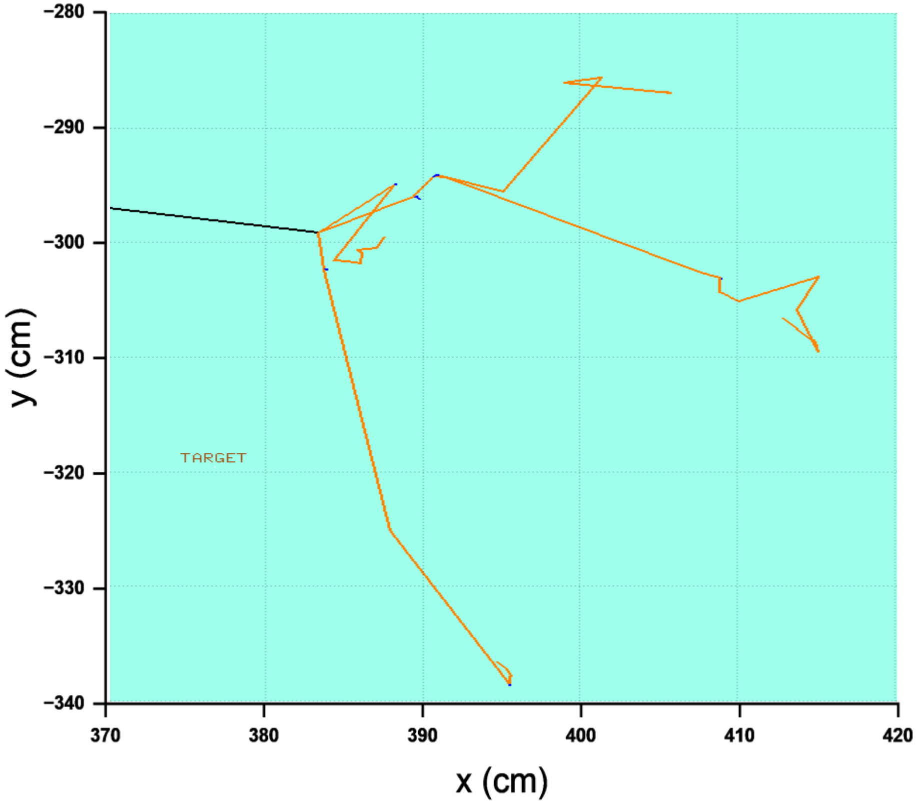
- U & Th inside cavern rocks
- U & Th chain decays in the target material
- U & Th chain decays in detector's structure
- Rn emanation
- ^{210}Po from Rn decay plating onto surfaces (accumulation over time, $T_{1/2}$(^{210}Pb)=138.376 d)

Simulation of a 1 MeV neutron in LAr using FLUKA

* PWXS treatment for neutron interaction has been enabled



- Long path of neutrons (up to a few metres)
- Multiple elastic scatterings in the target of an experiment
- Neutron capture resulting in a gamma cascade
- Complex event;
- Can mimic a low-energy signal in dark matter or neutrino experiment.



The target of interest for the low background neutrino experiments

- Carbon (^{13}C): component of liquid scintillators, plastics (such as acrylic, polyethylene, nylon, PTFE) which are often used close to the target volume, rock as many experiments are located in deep underground caverns;
- Oxygen (^{17}O and ^{18}O): component of water, plastics and rock;
- Nitrogen (^{14}N): components of plastics, wavelength shifters;
- Fluorine (^{19}F): component of PTFE that, thanks to the good reflectivity and high resistance is frequently used (enhance light collection, source containers);
- Aluminium (^{27}Al);
- Titanium, copper & stainless steel: used in cryostats, shielding, support structures, purification systems;
- Silicon: present in quartz, glass, light sensors;
- Beryllium (^{9}Be) present in wires and various neutron calibration sources;

Inspired from Valentina Lozza, IAEA Technical Meeting on (α,n) nuclear data evaluation and data needs Online, 8-13 November 2021

The SOURCES4 code to calculate neutron production (α, n) reactions

- The probability for an alpha particle to produce a neutron by interacting with a nuclide i (N_i is the number density of atoms of nuclide i):

$$P\left(E_\alpha\right) = \int_0^{E_\alpha} \frac{N_i \sigma_i\left(E\right)}{\left(-\frac{dE}{dx}\right)} dE$$

- Stopping power cross-sections from the tables compiled by Ziegler.

Ziegler, James F. "Helium: stopping powers and ranges in all elemental matter." (1977).

W.B. Wilson, et al., SOURCES4A: a code for calculating (α,n), spontaneous fission, and delayed neutron sourcesand spectra, Technical Report LA-13639-MS, Los Alamos, 1999;

J. Carson, et al., Neutron background in large-scale xenon detectors for dark matter searches, Astropart. Phys. 21 (2004) 667–687.

V. Tomasello, V. A. Kudryavtsev, M. Robinson, Calculation of neutron background for underground experiments, Nucl. Instrum. & Meth. in Phys. Res. A 595 (2) (2008), arXiv:0807.0851

The SOURCES4 code to calculate neutron production (α, n) reactions

Advantages

- Flexible libraries of cross-sections and branching ratios
- Fast calculation
- Total neutron spectra; spectra from interactions on individual isotopes and from the variety of radioisotopes in a single calculations
    - Spectra from the ground state
    - Spectra from excited states.

W.B. Wilson, et al., SOURCES4A: a code for calculating (α,n), spontaneous fission, and delayed neutron sourcesand spectra, Technical Report LA-13639-MS, Los Alamos, 1999;
J. Carson, et al., Neutron background in large-scale xenon detectors for dark matter searches, Astropart. Phys. 21 (2004) 667–687.
V. Tomasello, V. A. Kudryavtsev, M. Robinson, Calculation of neutron background for underground experiments, Nucl. Instrum. & Meth. in Phys. Res. A 595 (2) (2008), arXiv:0807.0851

The SOURCES4 code to calculate neutron production (α, n) reactions

- The original code SOURCES4A was **modified** to allow calculations of neutron production from alphas with **energies up to 10 MeV**.

- The **maximum number of discrete nuclear levels** for the product nuclides was increased from 100 to **500**.

- The **maximum number of target elements** was increased from 20 to **110**.

- The cross-sections and the branching ratios for (α, n) reactions in SOURCES4 have been taken from reliable experimental data (including some recent ones) where possible and complemented by the calculations with EMPIRE2.19/3.2.3, TALYS1.96 and JENDL-5 where the data were scarce or unavailable.

- Various sets of cross-sections are available in the library → we just recommend the most reliable.

W.B. Wilson, et al., Technical Report LA-13639-MS, Los Alamos, 1999;
J. Carson, et al., Astropart. Phys. 21 (2004) 667–687.
V. Tomasello, et al.,NIM A 595 (2) (2008)
V.A. Kudryavtsev et al., NIMA 972 (2020): 164095.
V.A. Kudryavtsevet al., SciPost Physics Proceedings 12 (2023): 018.
V.A. Kudryavtsev et al., AIP Conference Proceedings. Vol. 2908. No. 1 (2023)

The SOURCES4 code to calculate neutron production (α, n) reactions

- The first line of the cross-section from tape3 and tape4 are written in the output file (outp) so the user knows which set was used.

- The code was modified so the user **does not need to change the order of the cross-section** or **branching ratios** anymore, but only to indicate which one to use (the order that the cross-section appears in the library) → **data selection option in tape1**.

tape1 = user-defined input file
tape3 = total (α,n) cross section library
tape4 = target (α,n) product level branching library

The SOURCES4 code to calculate neutron production (α, n) reactions

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ZAID = (10000 Z) + (10 A) + state, where Z is the atomic number, A is the atomic mass, and the state is either 0 or 1 for ground or metastable, respectively.

^{54}Fe

the fraction of all atoms that are element j.

```
…
260540 0.15       # If there is nothing there, use whichever comes first.
260560 0.30 0 0   # This one means the same. Use whichever comes first.
260570 0.50 1 3   # Use second xs from tape3 and fourth branching from tape4.
260580 0.05 2     # Use third xs from tape3 and first branching from tape4.
…
```

First set of data for xs and BR

2nd set of data for xs
4th set of data for BR

3rd set of data for xs
1st set of data for BR

TALYS 1.96

- Currently, in the default version of the TALYS 1.96 nuclear reaction code, the maximum number of discrete levels that are considered in the Hauser-Feshbach model for the residual nuclei is set to 30.

- We have modified the code in order to increase the number of levels, therefore **all the possible excited states** for the final state nucleus that are available in RIPL-3 can be considered **for the calculation of the branching ratios**. In this way, we ensure that 100% of neutrons from the neutron energy spectrum are accounted for in the total neutron yield.

…/talys/source – talys.cmb – memorypar=2; numlev=260; numlev2=numlev
line 131 of the discreteout.f file: write(discfile(5:7),'(i3.3)') nex – in order to allow longer filenames

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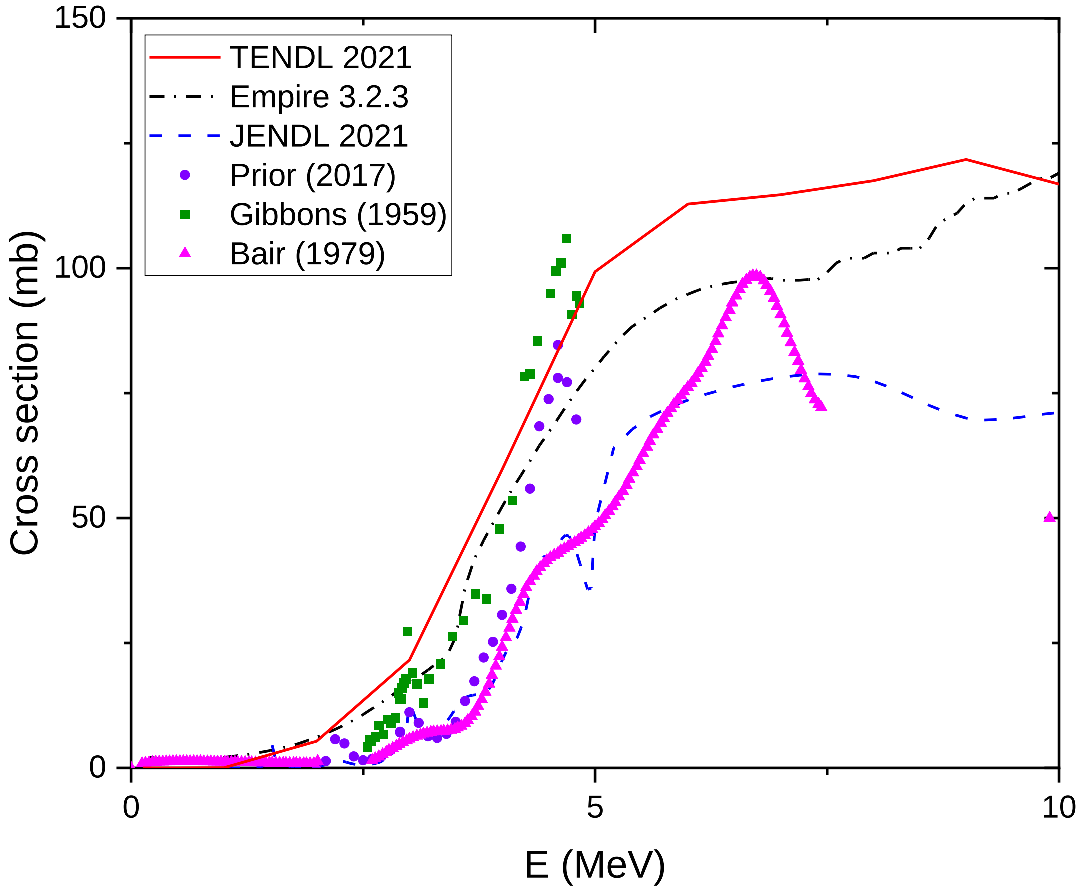
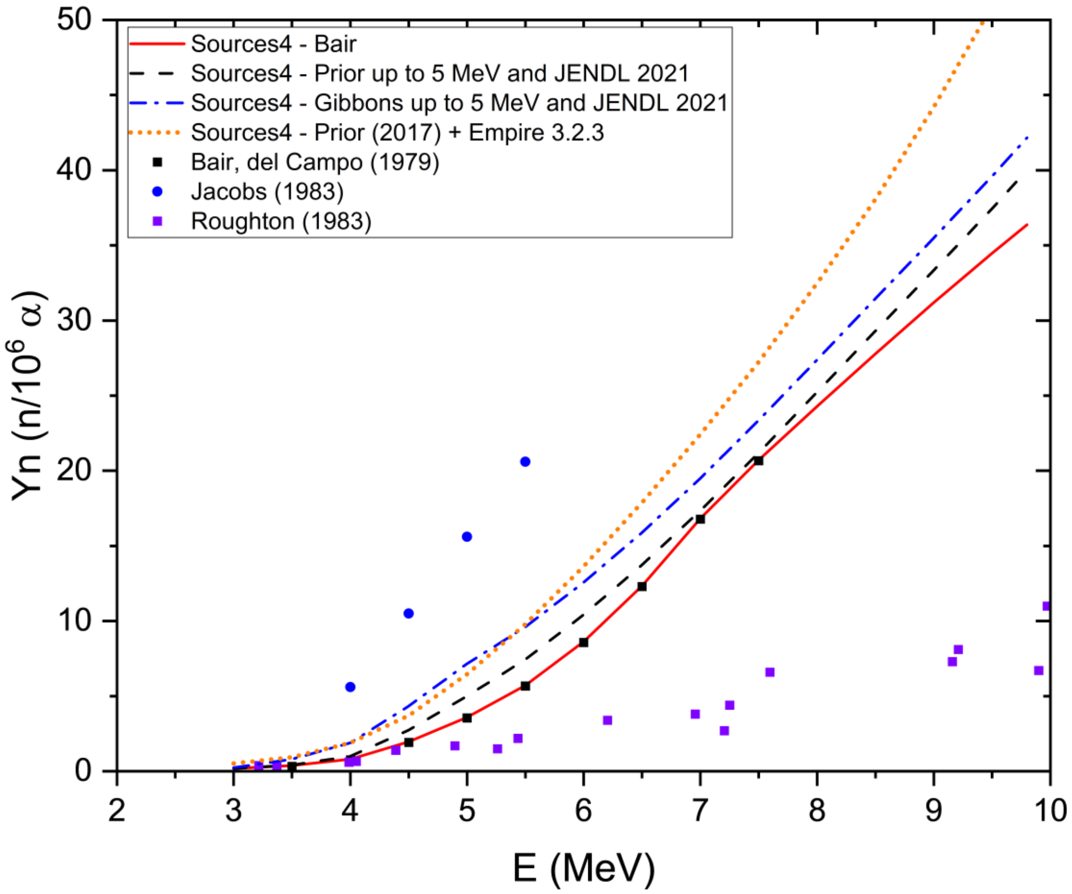
* Codes based on statistical models do not predict the resonance structure or the cross sections for light elements.

$^{10}B(\alpha,n)^{13}N$ (19.9%)

Prior + JENDL 2021 – default in SOURCES4



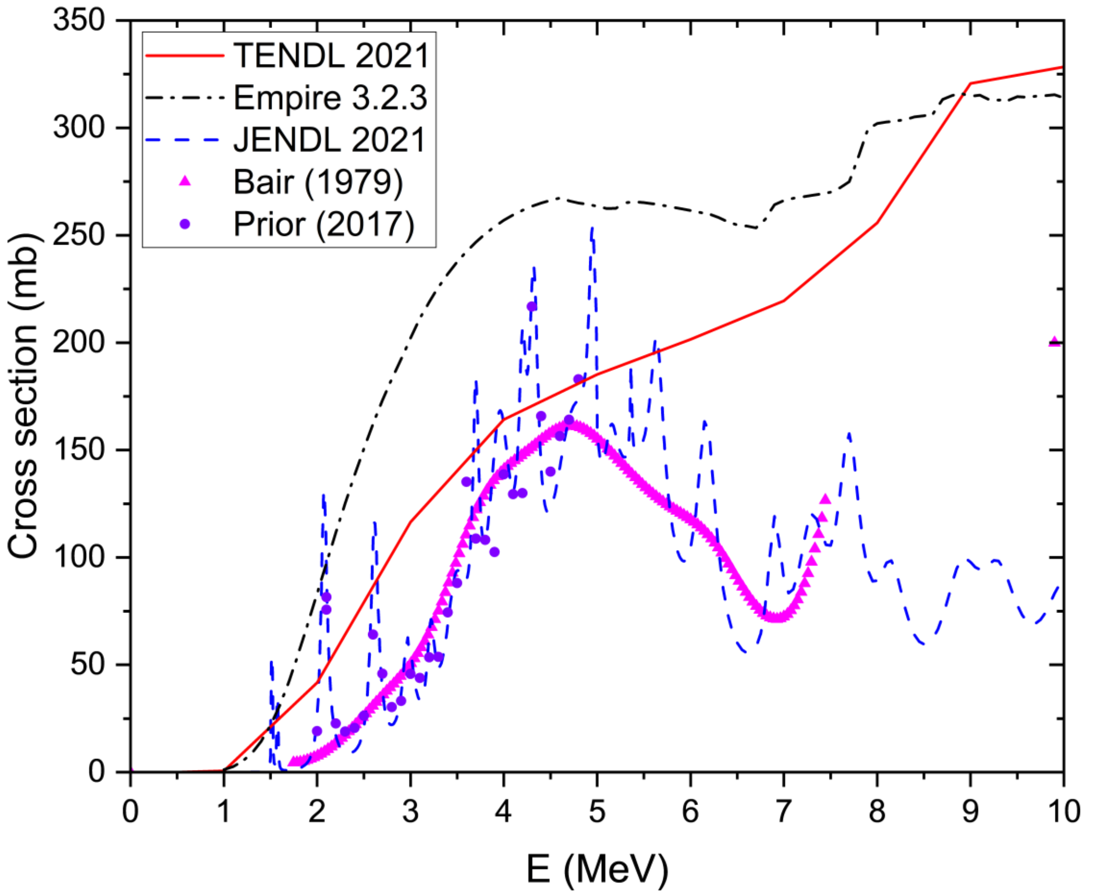


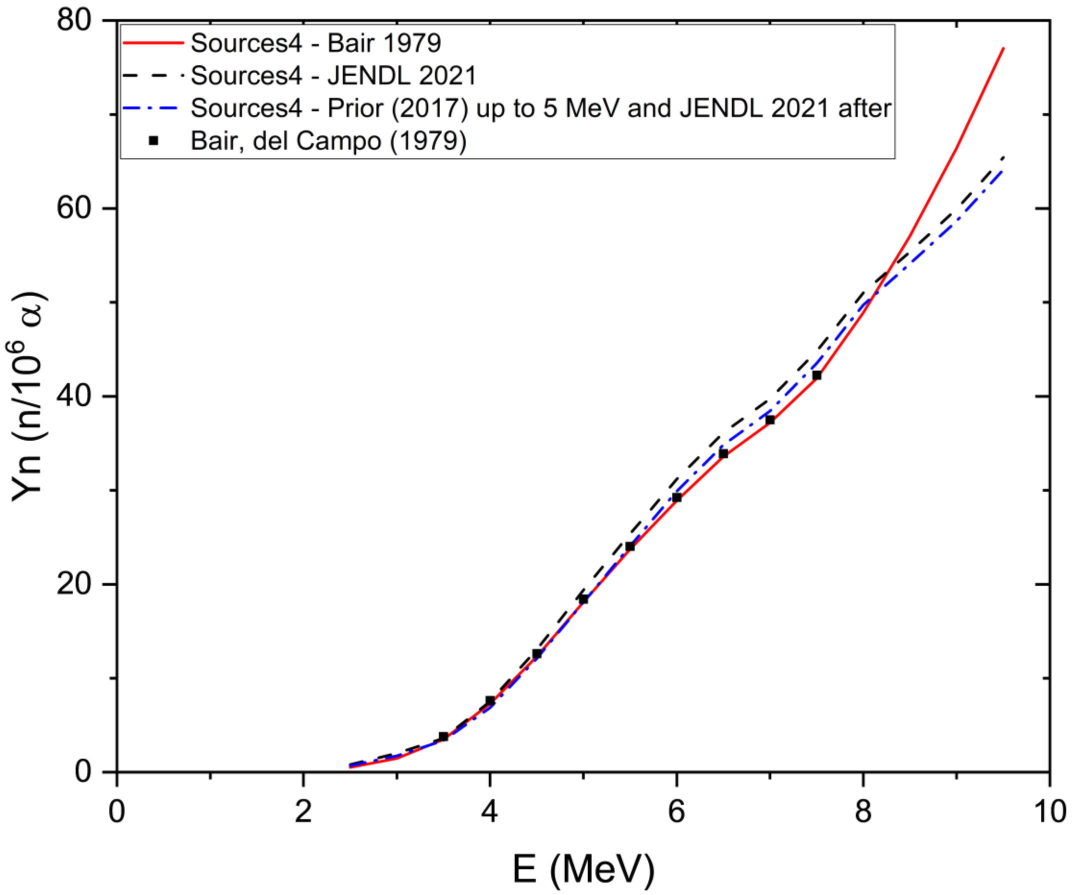
Typical example of multiple data sets not agreeing with each other.

J.H.Gibbons,R.L.Macklin:Phys.Rev.114,571(1959)
J.K.Bair,J.Gomez del Campo:Nucl.Sci.Eng.71,18(1979)
Prior, Prior, R. M., et al. "The total cross sections of the 11 B (α, n) 14 N and the 10 B (α, n) 13 N reactions between 2 and 6 MeV." Nuclear Science and Techniques 28 (2017): 1-6.

$^{11}B(\alpha,n)^{14}N$ (80.1%)

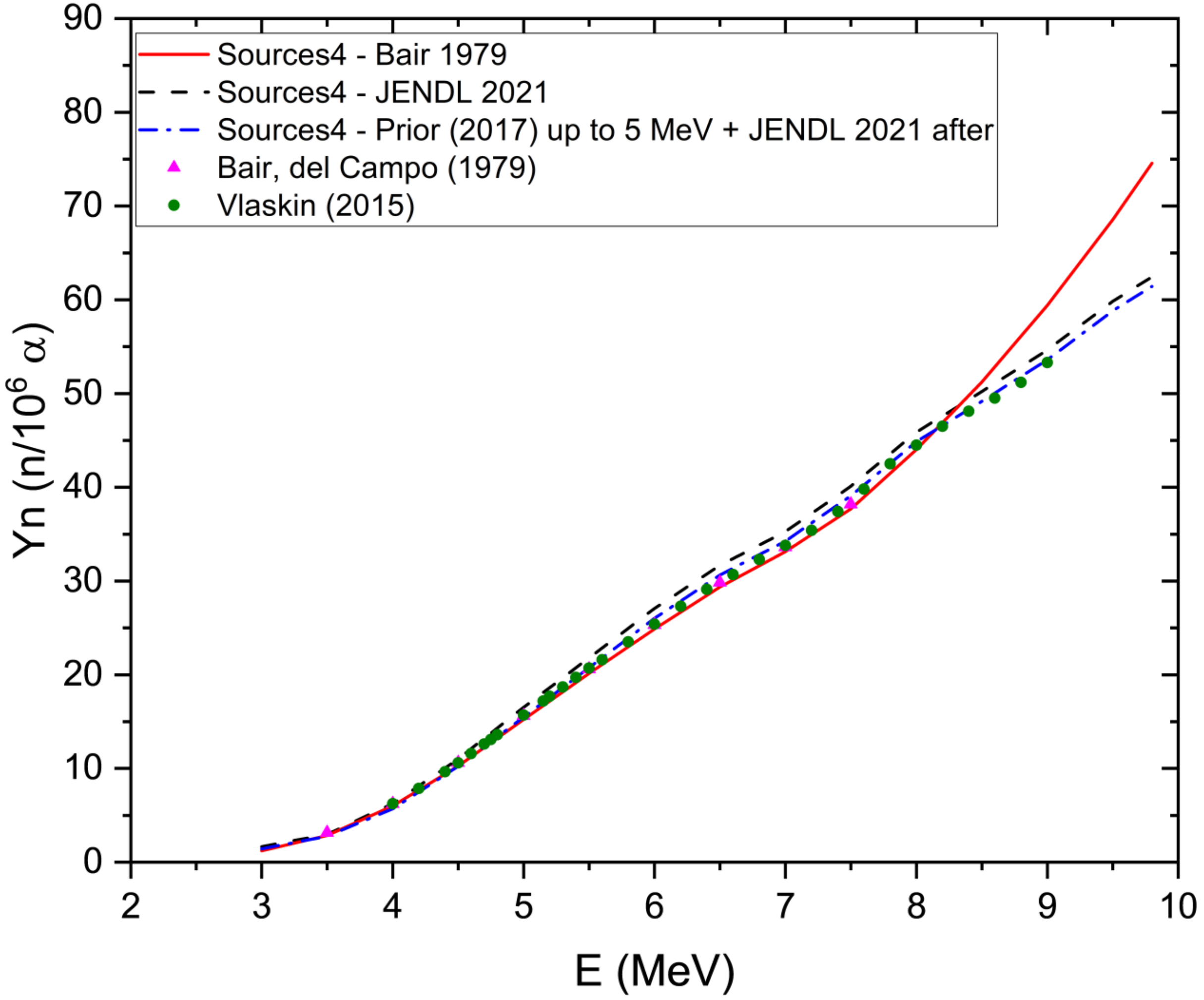
Prior + JENDL 2021 – default in SOURCES4





J.H.Gibbons,R.L.Macklin:Phys.Rev.114,571(1959)
J.K.Bair,J.Gomez del Campo:Nucl.Sci.Eng.71,18(1979)
Prior, Prior, R. M., et al. "The total cross sections of the 11 B (α, n) 14 N and the 10 B (α, n) 13 N reactions between 2 and 6 MeV." Nuclear Science and Techniques 28 (2017): 1-6.

$^{nat}B(\alpha,n)N$



B-11 has 80.1% abundance
→B-10 is not so critical.

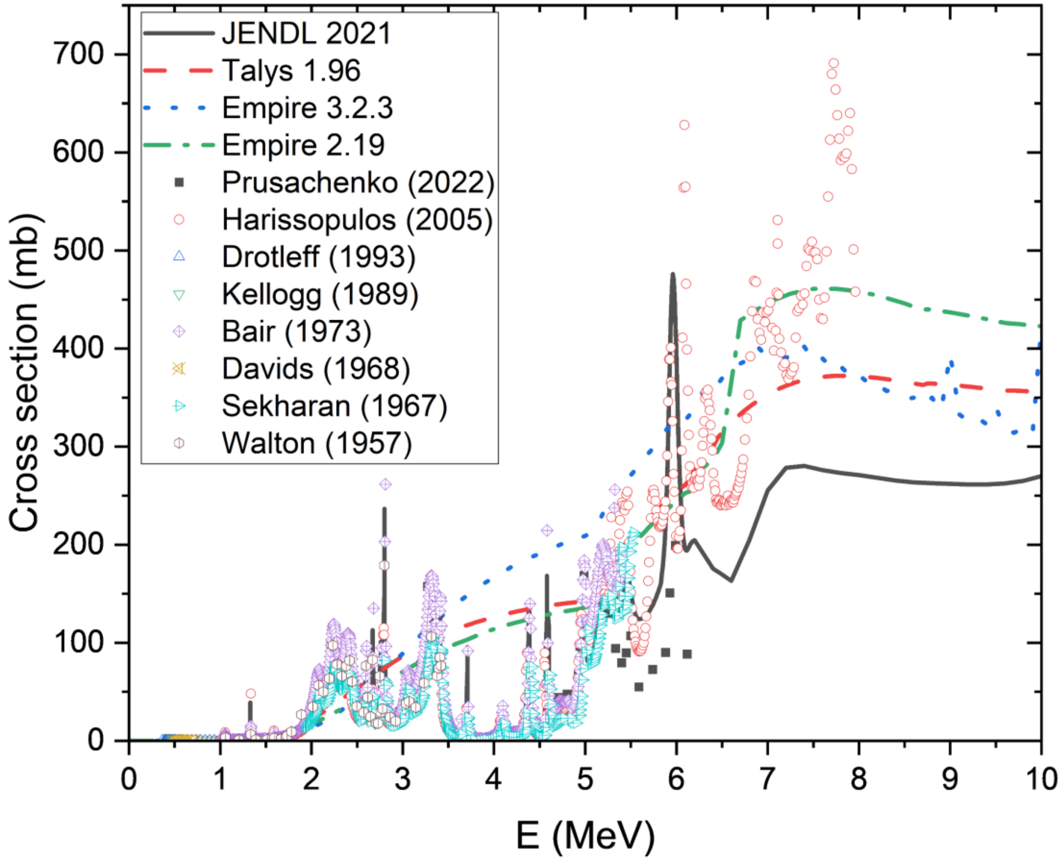
* Vlaskin points are **not** experimental data, but an analysis based on experimental data.

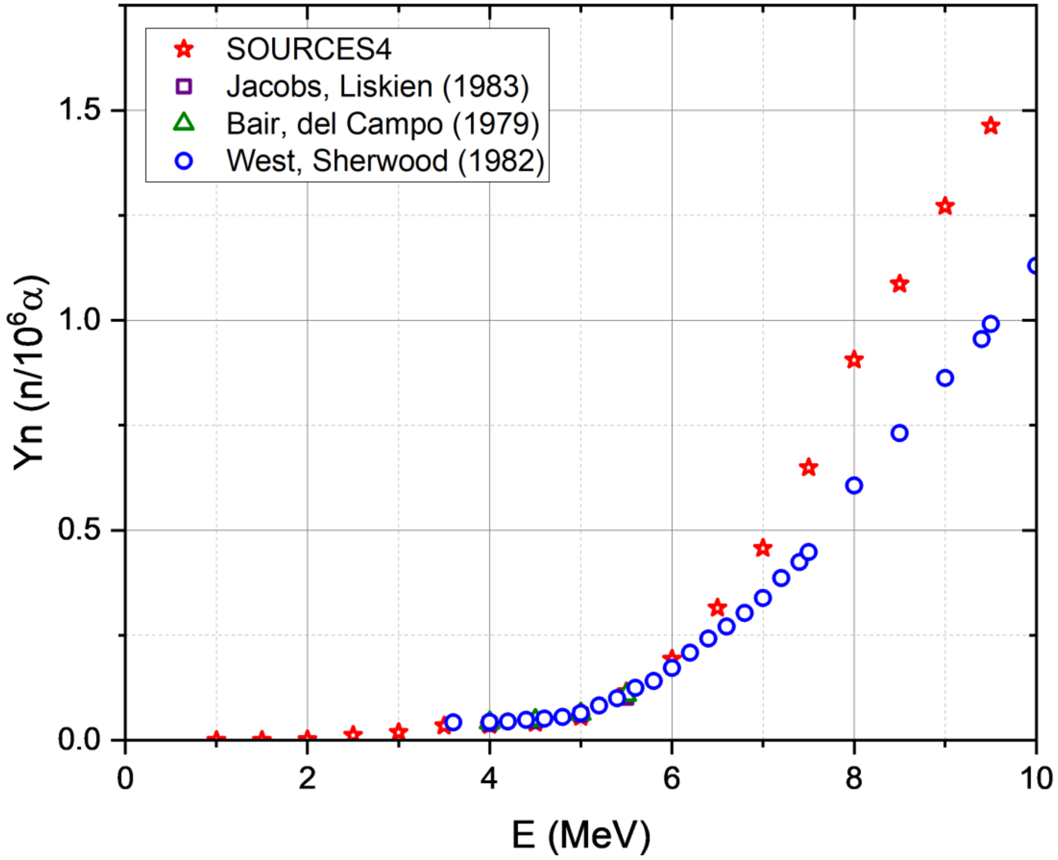
J.K.Bair,J.Gomez del Campo:Nucl.Sci.Eng.71,18(1979)
Vlaskin, G. N., Yu S. Khomyakov, and V. I. Bulanenko. "Neutron yield of the reaction (α, n) on thick targets comprised of light elements." Atomic Energy 117.5 (2015): 357-365.

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

$^{nat}C(\alpha,n)$ with 1.07% ^{13}C

Harissopulos 2005 + TALYS 1.96 calc. – default in SOURCES4





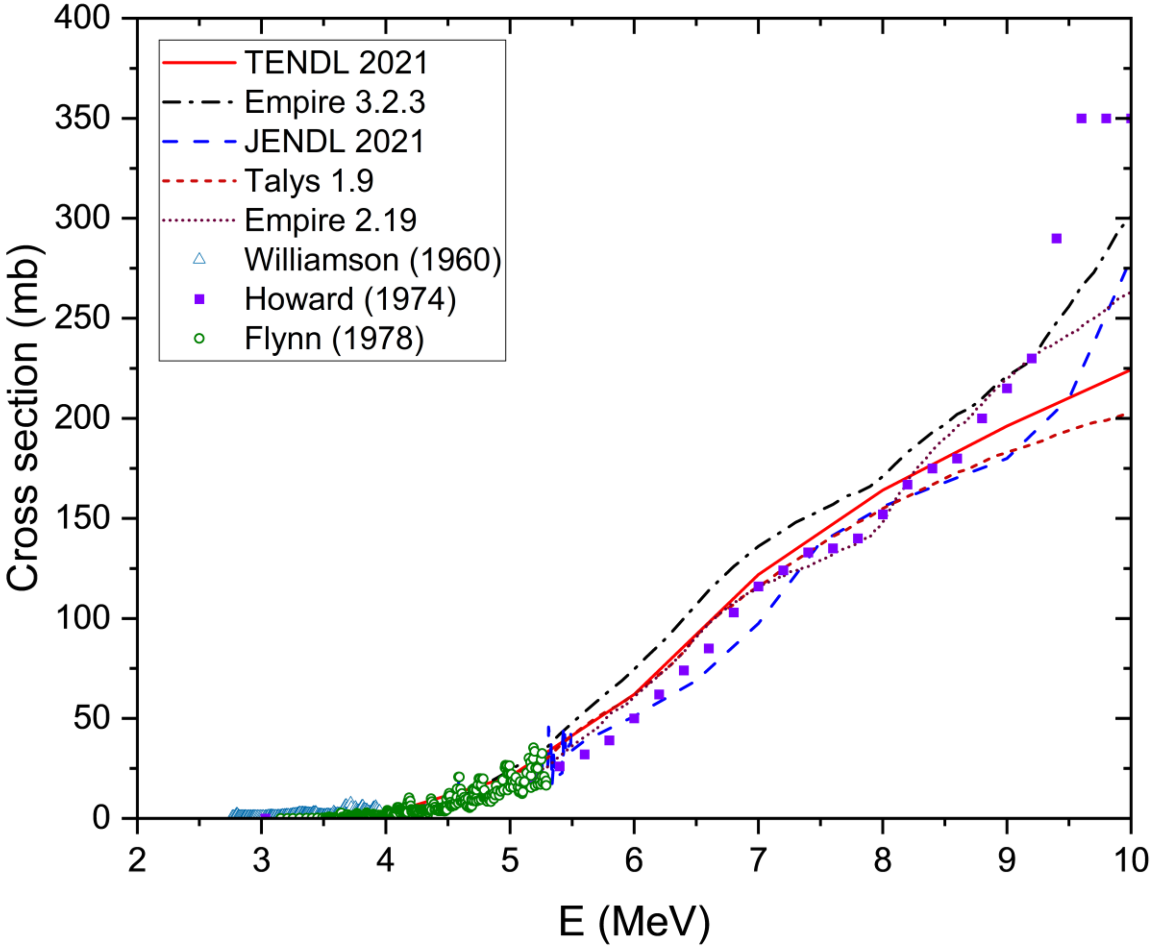
*Prusachenko data are for the ground state transition

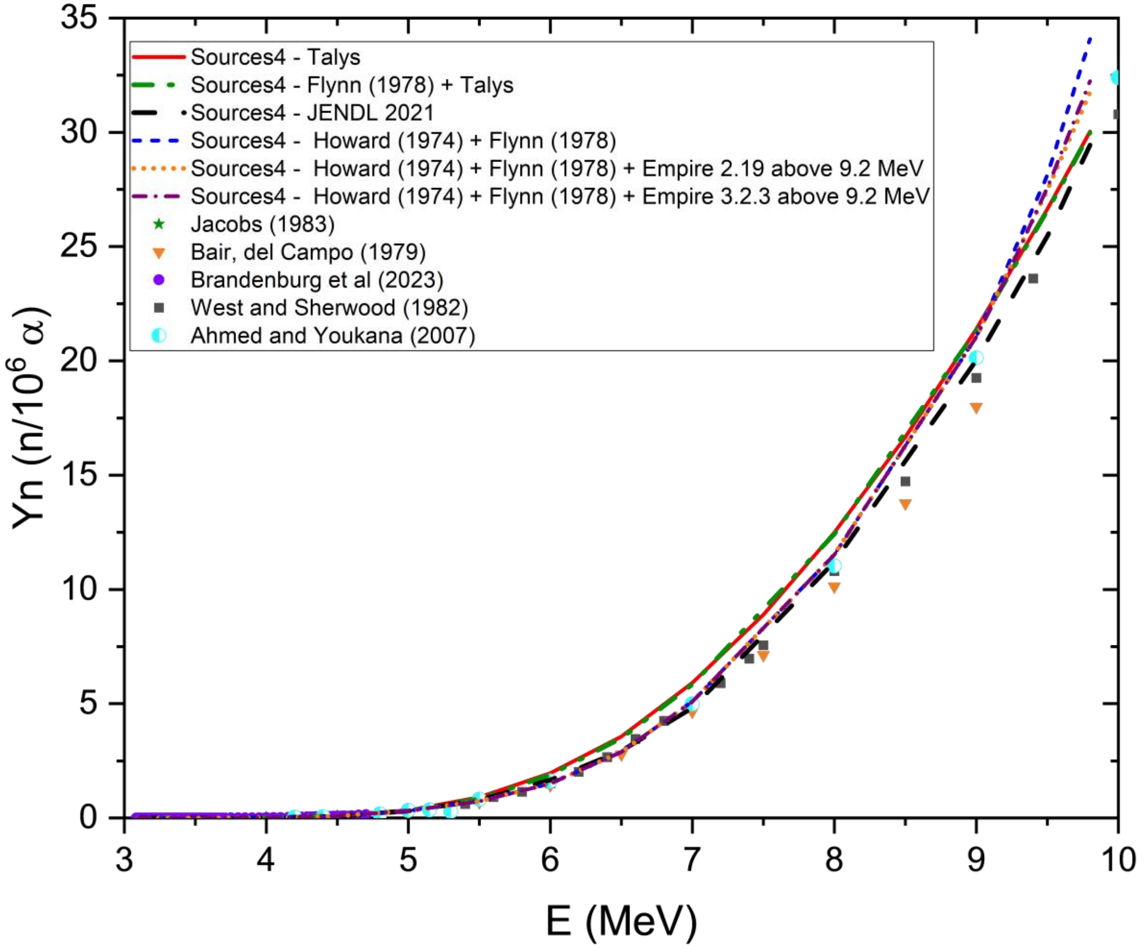
P. S. Prusachenko, T. L. Bobrovsky, I. P. Bondarenko, M. V. Bokhovko, A. F. Gurbich, and V. V. Ketlerov, Phys. Rev. C 105, 024612 (2022)
S. Harissopulos, H. W. Becker, J. W. Hammer, A. Lagoyannis, C. Rolfs, and F. Strieder, Phys. Rev. C 72, 062801(R) (2005)
H.W. Drotleff et al., Astrophysical Journal v.414, p.735 (1993)
Kellogg, S. E., R. B. Vogelaar, and R. W. Kavanagh. "13C (α, n) and 14C (p, n): Astrophysical neutron sources and sinks." Bulletin of the American Physical Society 34 (1989)
J. K. Bair and F. X. Haas, Phys. Rev. C 7, 1356 (1973)
Davids, Cary N. "A study of (α, n) reactions on 9Be and 13C at low energies." Nuclear Physics A 110.3 (1968)
K. K. Sekharan, A. S. Divatia, M. K. Mehta, S. S. Kerekatte, and K. B. Nambiar, Phys. Rev. 156, 1187 (1967)
R. B. Walton, J. D. Clement, and F. Boreli, Phys. Rev. 107, 1065 (1957)

- The cross-section is used from the recent data resulting in a higher neutron yield.
- Other cross-sections are available in the library.

West, D., and A. C. Sherwood. "Measurements of thick-target (α, n) yields from light elements." Annals of Nuclear Energy 9.11-12 (1982): 551-577.

$^{27}Al(\alpha,n)^{30}P$

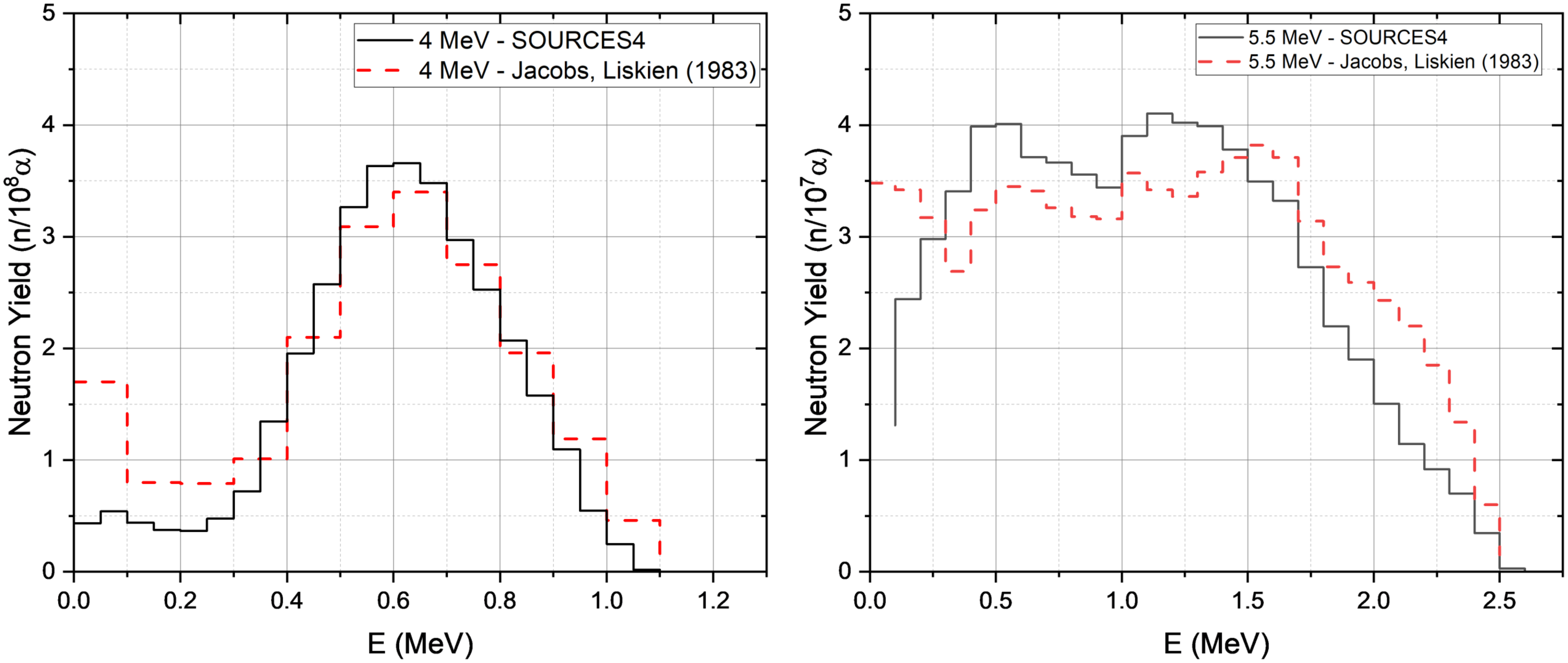




R. M. Williamson et al., Phys. Rev. **117**, 1325 (1960)
A Howard et al., The Astrophysical Journal 188 (1974)
D. S. Flynn et al., Phys. Rev. C **18**, 1566 (1978)
West, D., and A. C. Sherwood, Annals of Nuclear Energy 9.11-12 (1982): 551-577.
J.K.Bair,J.Gomez del Campo:Nucl.Sci.Eng.71,18(1979)
Jacobs, G. J. H., and Horst Liskien, Annals of Nuclear Energy 10.10 (1983): 541-552.
Brandenburg, K., et al. , Nuclear Science and Engineering 197.4 (2023): 510-516.
Ahmed, A. H., and H. M. Youhana, NIM A 582.2 (2007): 287-293.

The cross-sections measured by Flynn and Howard were used, and complemented with the ones calculated with EMPIRE 3.2.3 above 9.2 MeV.

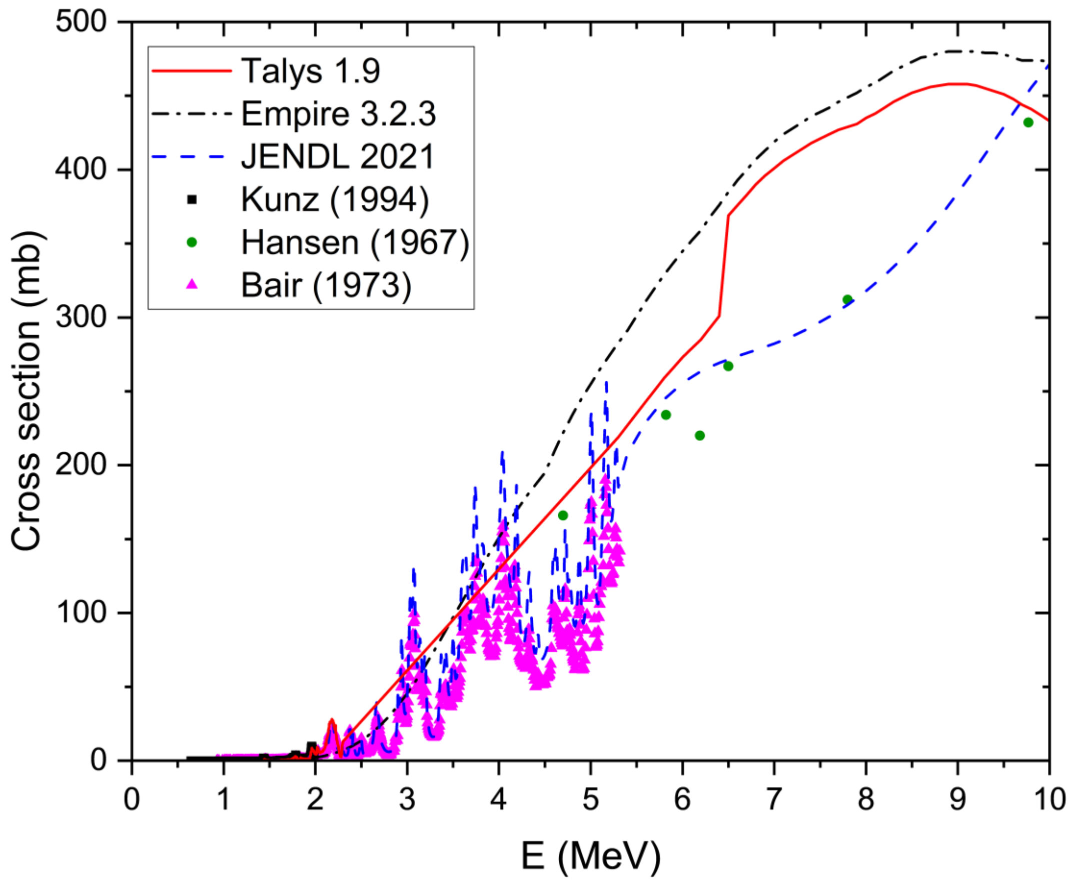
$^{27}Al(\alpha,n)^{30}P$ Neutron Spectra

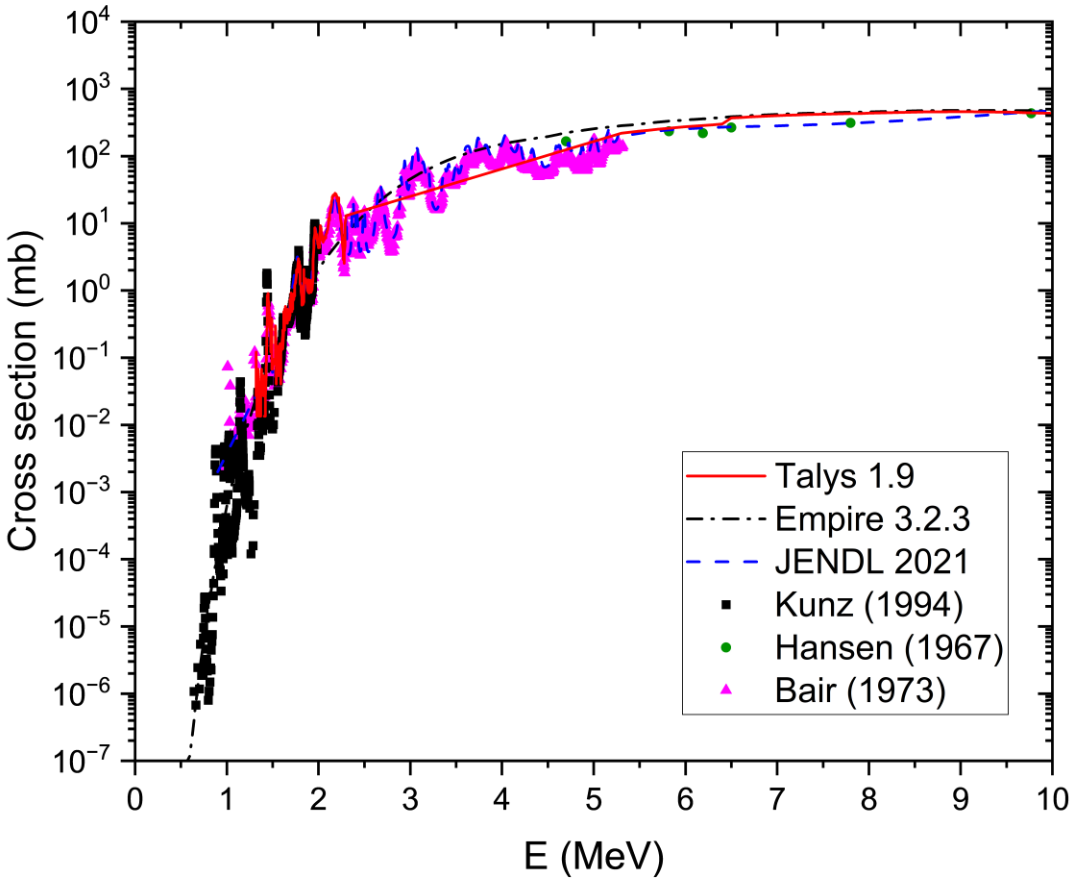


Jacobs, G. J. H., and Horst Liskien. "Energy spectra of neutrons produced by α-particles in thick targets of light elements." Annals of Nuclear Energy 10.10 (1983): 541-552.

$^{17}O(\alpha,n)^{20}Ne$

The cross-sections measured by Kunz and Bair were used, and replaced with the ones from JENDL-5 above ~5.2 MeV.

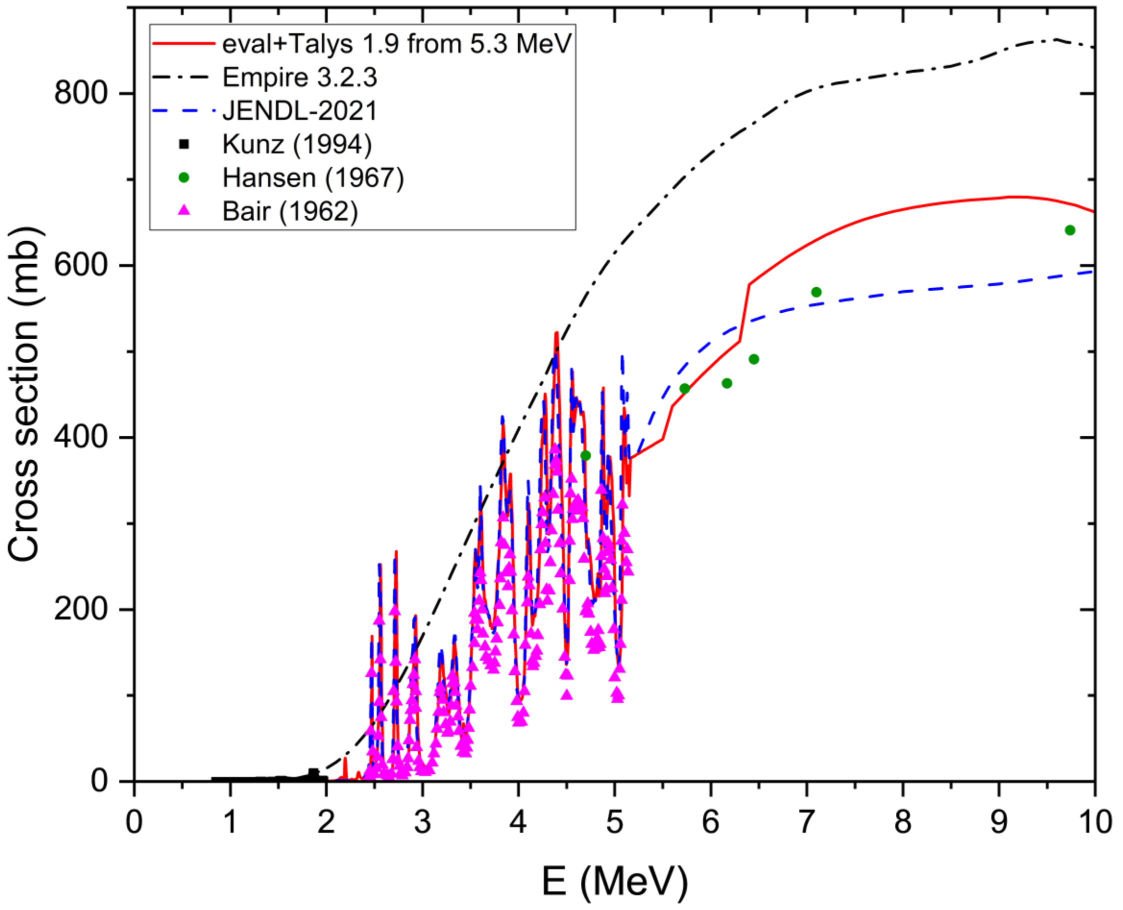


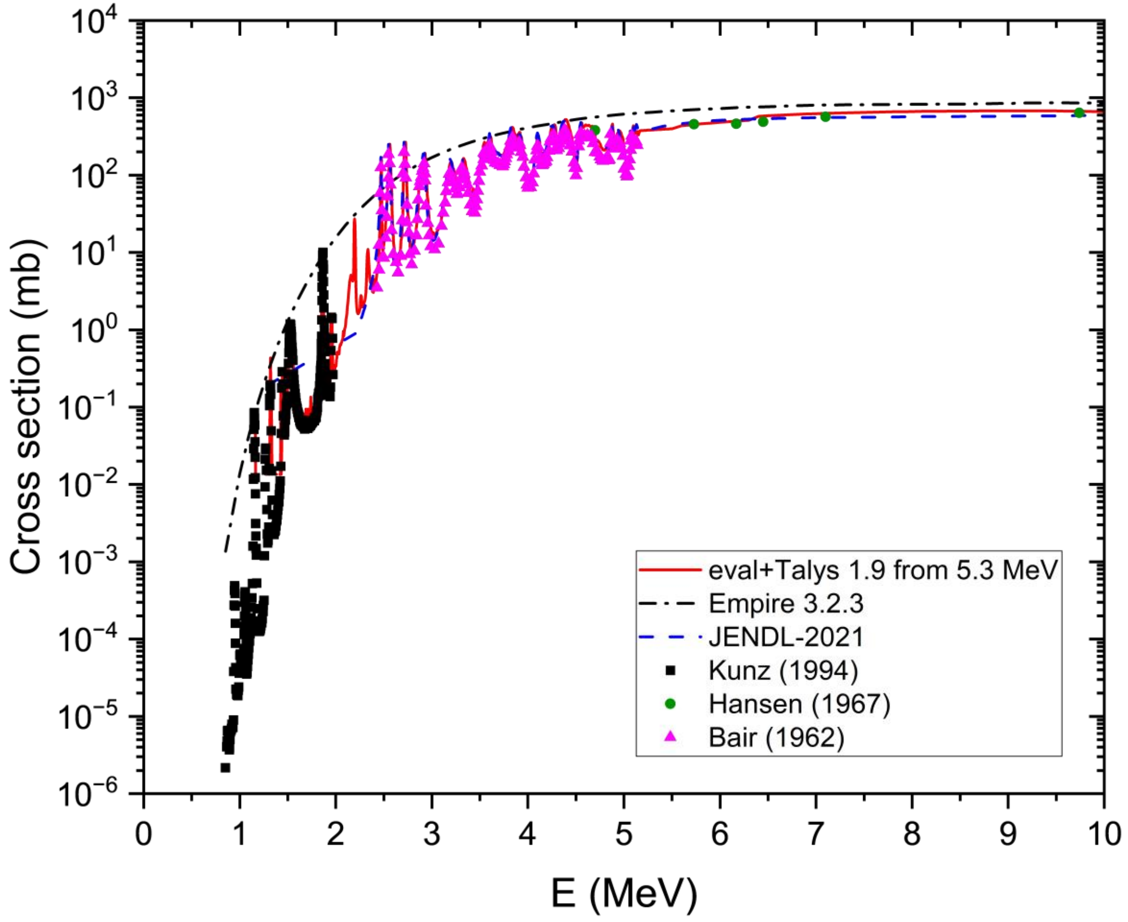


J.K.Bair,J.Gomez del Campo:Nucl.Sci.Eng.71,18(1979)
Kunz, Rino E., et al., International Conference on Neutrons and Their Applications. Vol. 2339. SPIE, 1995.
Hansen et al., Nuclear Physics A 98.1 (1967): 25-32.

$^{18}O(\alpha,n)^{21}Ne$

The cross-sections measured by Kunz and Bair were used, and replaced with the ones from JENDL-5 above ~5.2 MeV.





J.K.Bair,J.Gomez del Campo:Nucl.Sci.Eng.71,18(1979)

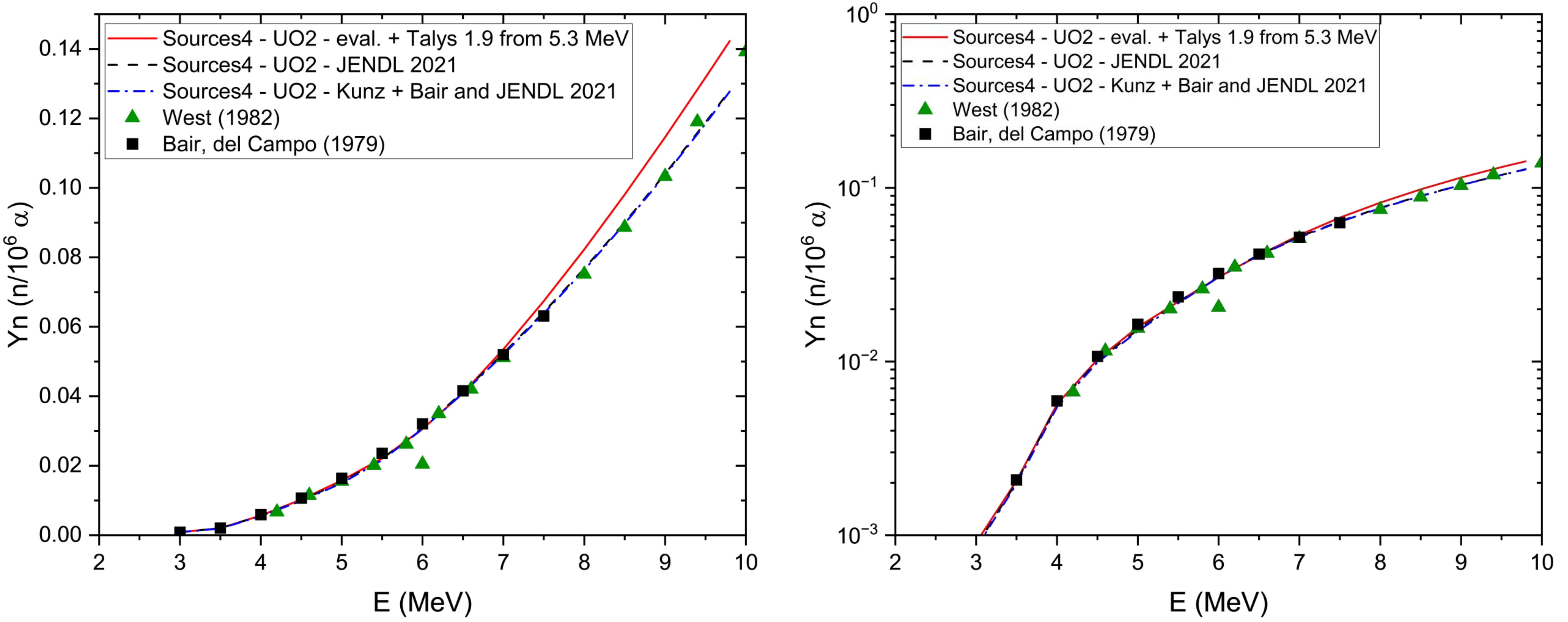
Kunz, Rino E., et al., International Conference on Neutrons and Their Applications. Vol. 2339. SPIE, 1995.

Hansen et al., Nuclear Physics A 98.1 (1967): 25-32.

UO2 neutron yield

The cross-sections measured by Kunz and Bair were used, and replaced with the ones from JENDL-5 above ~5.2 MeV.

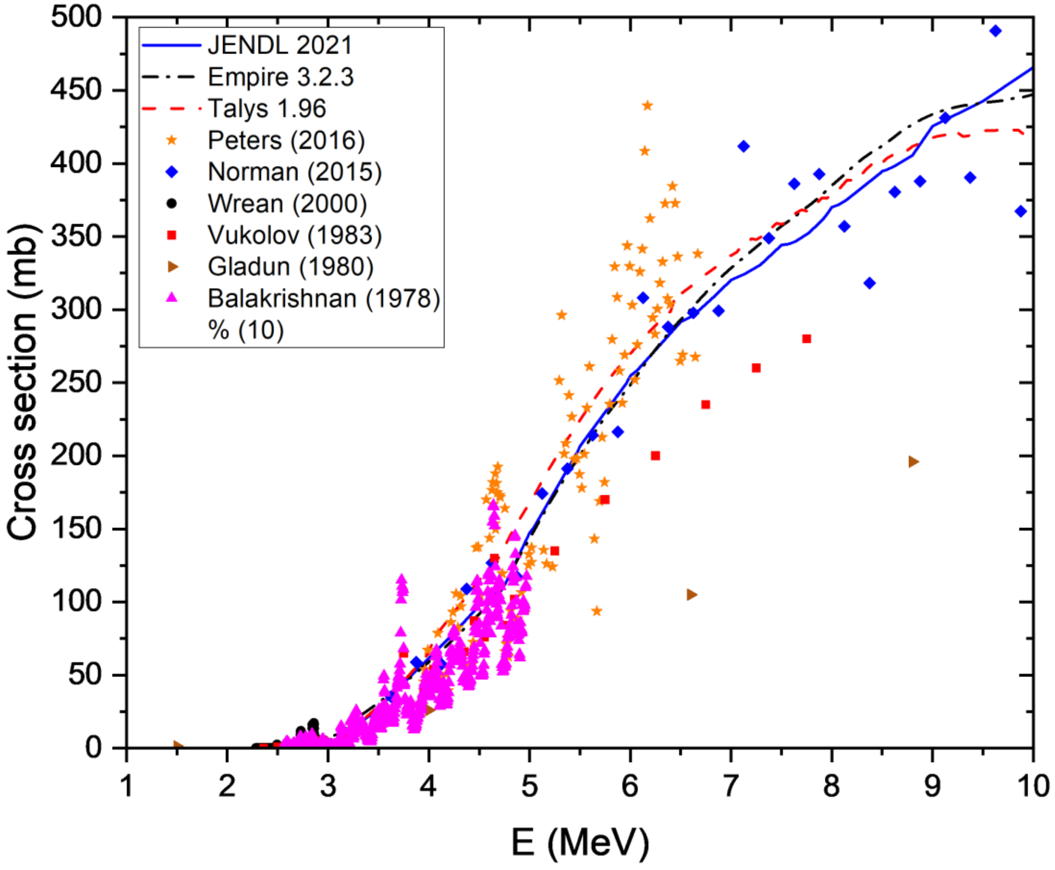
- very good agreement with the experimental data.

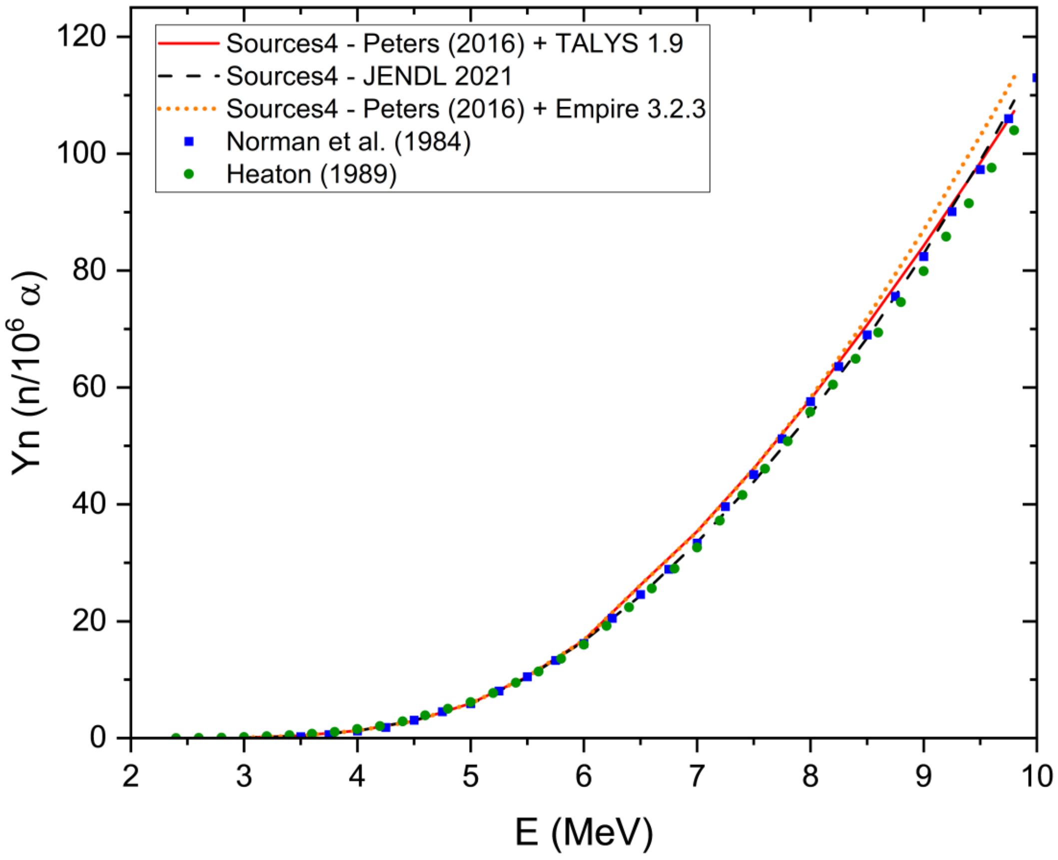


West, D., and A. C. Sherwood, Annals of Nuclear Energy 9.11-12 (1982): 551-577.
J.K.Bair,J.Gomez del Campo:Nucl.Sci.Eng.71,18(1979)

$^{19}F(\alpha,n)^{23}Na$

The cross-sections measured by Peters were used, and replaced with the ones from Talys above 7 MeV.

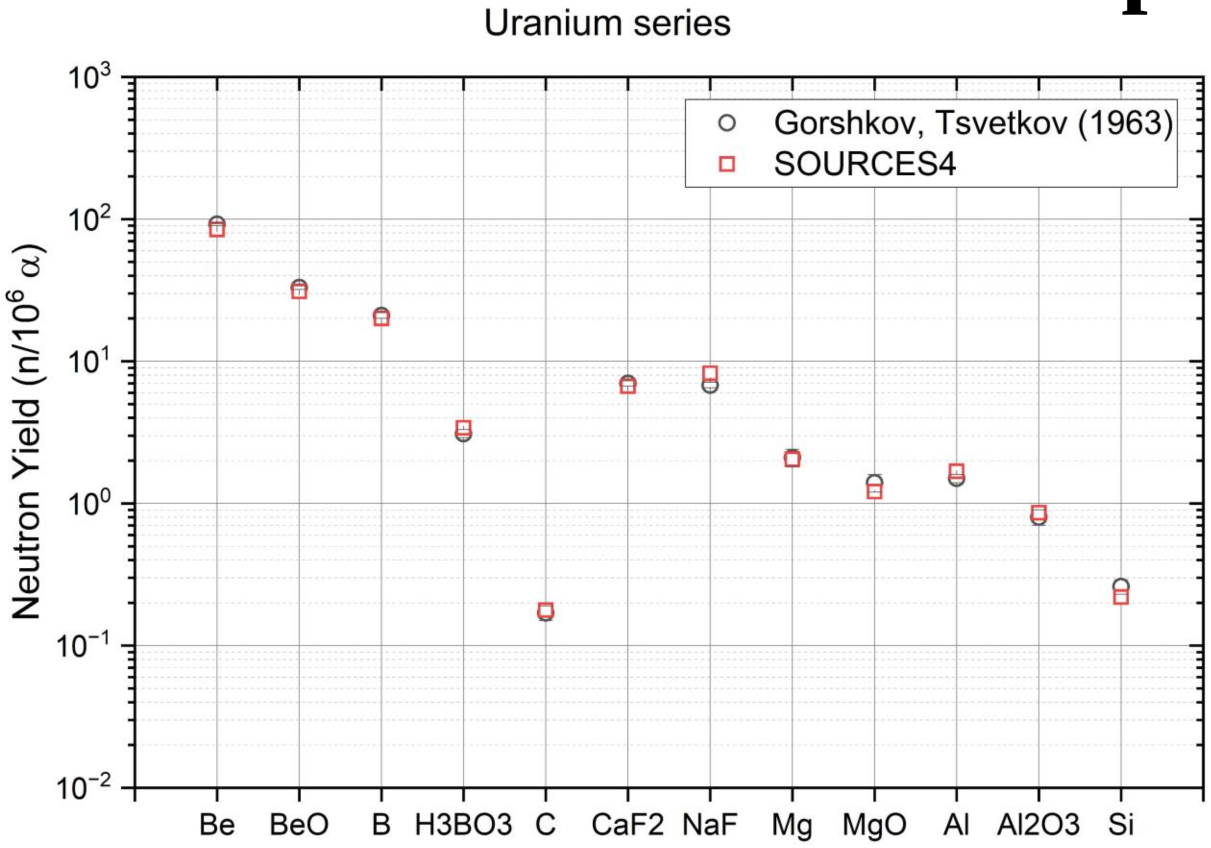


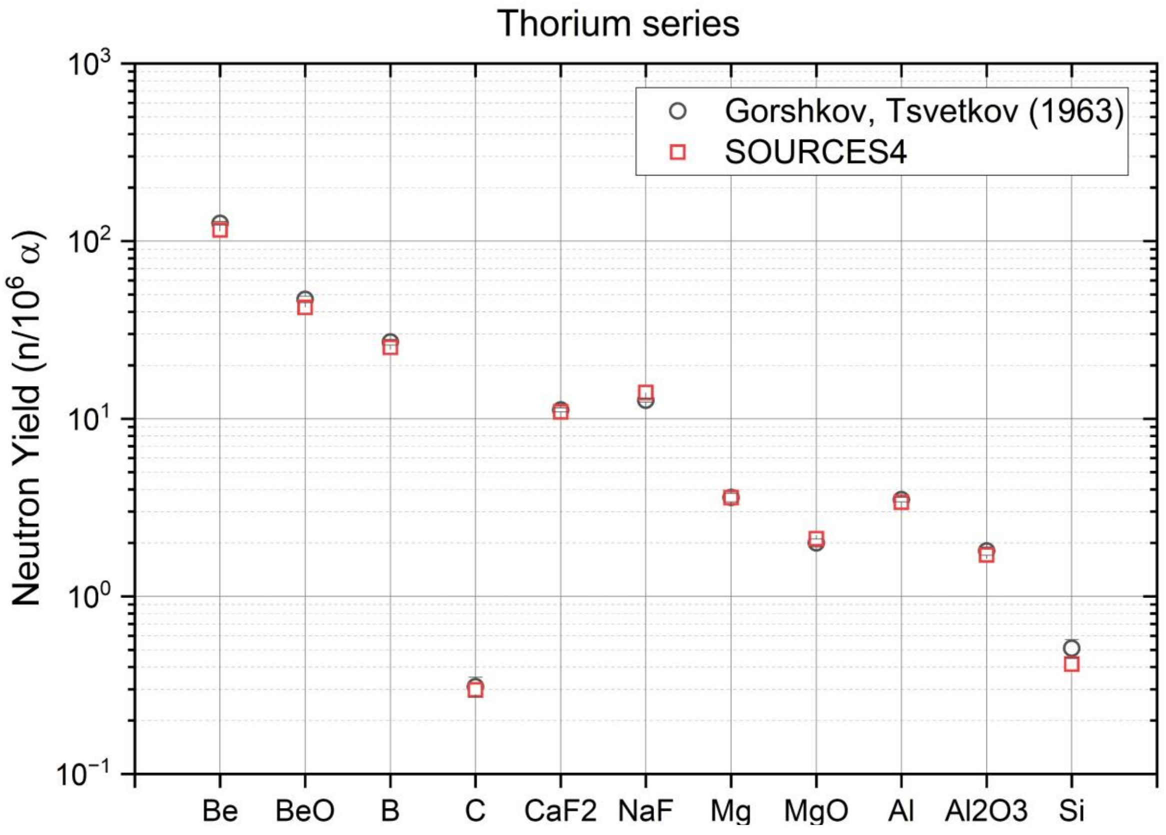


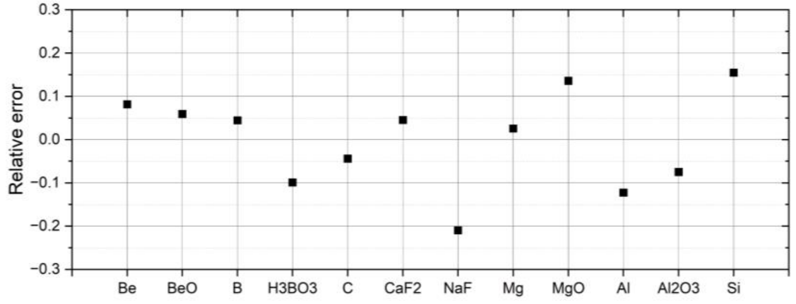
Heaton includes

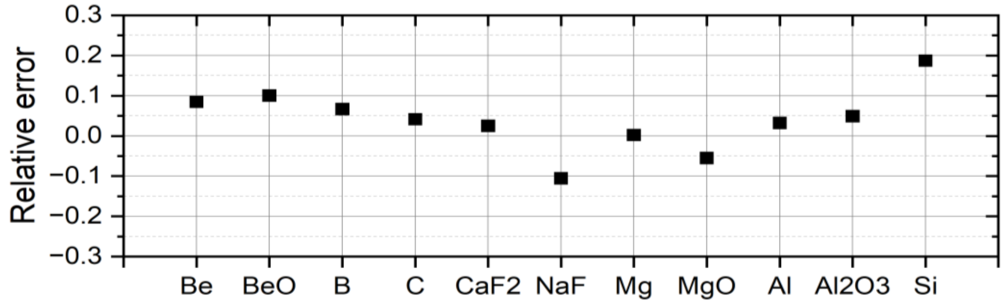
1. E.B. Norman, T.E. Chupp, K.T. Lesko, P.J. Grant andG.L. Woodruff, Phys. Rev. C30 (1984) 1339.
2. J.K. Bair and J. Gomez del Campo, Nucl. Sci. Eng. 71(1979) 18
3. G.J.H. Jacobs and H. Liskien, Ann. Nucl. Eng. 10 (1983)541
4. Y. Feige, B.G. Oltman and J. Kastner, J. Geophys. Res.73 (1968) 3135.

Neutron Yield with optimised SOURCES4 code





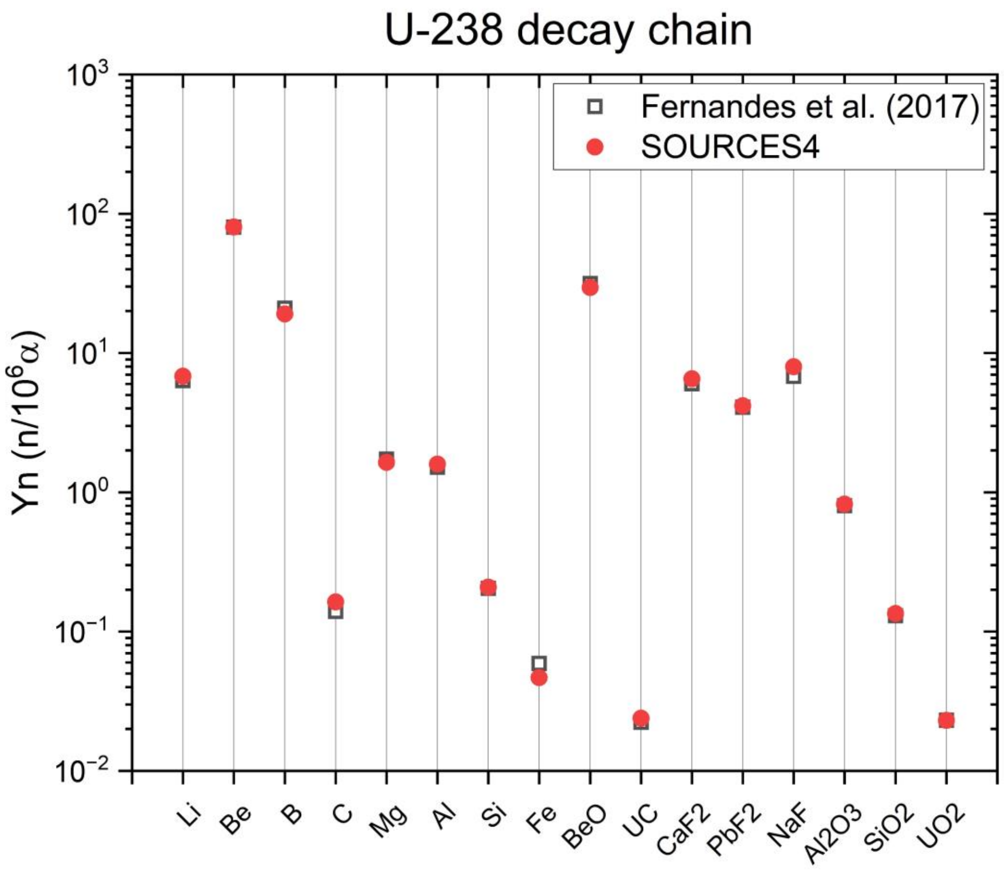


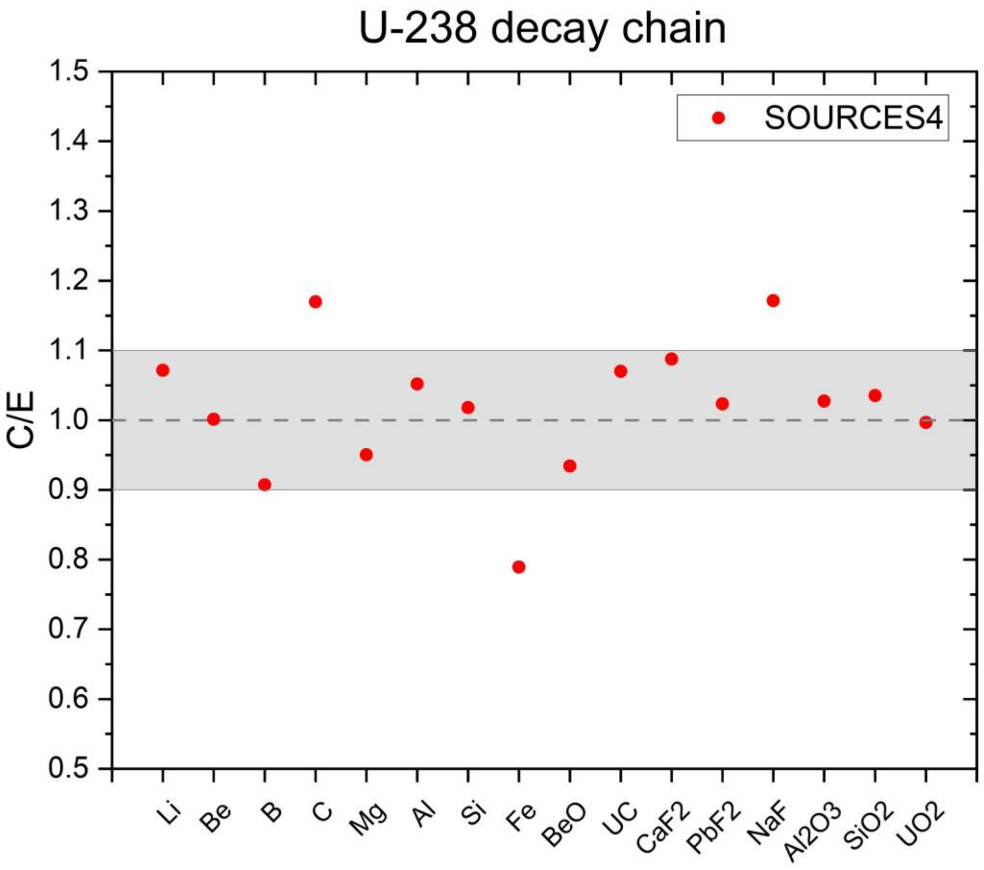


- Agreement within 10% for most isotopes and within 20% for almost all of them.

Gorshkov, G. V., and O. S. Tsvetkov. "Be, B, C, O, F, Na, Mg, Al and Si neutron yields from an (α, n) reaction under the effect of thorium and uranium α-particles and their decay products." Soviet Atomic Energy 14.6 (1964): 573-577.

Fernandes et al. ‘data’ are actually an evaluation of the neutron yields from alpha-beam measurements → not direct measurements;





Fernandes, Ana C., Andreas Kling, and Gennadiy N. Vlaskin. "Comparison of thick-target (alpha, n) yield calculation codes." EPJ Web of Conferences. Vol. 153. EDP Sciences, 2017.

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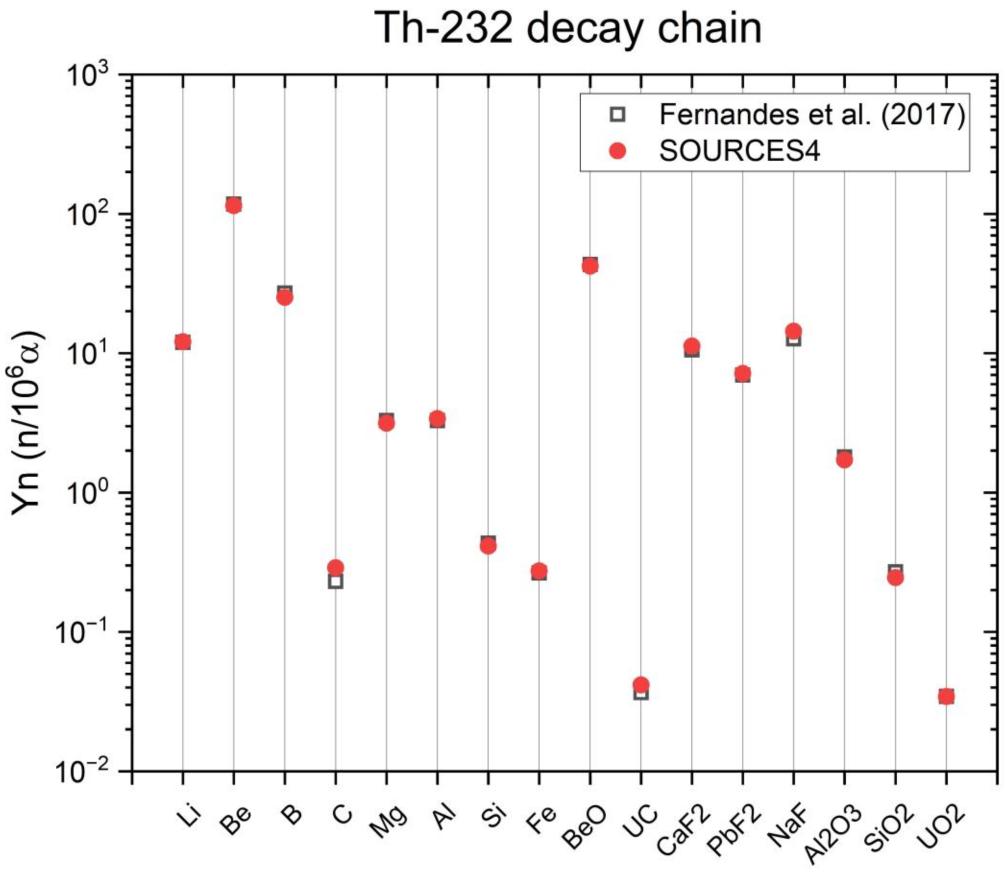
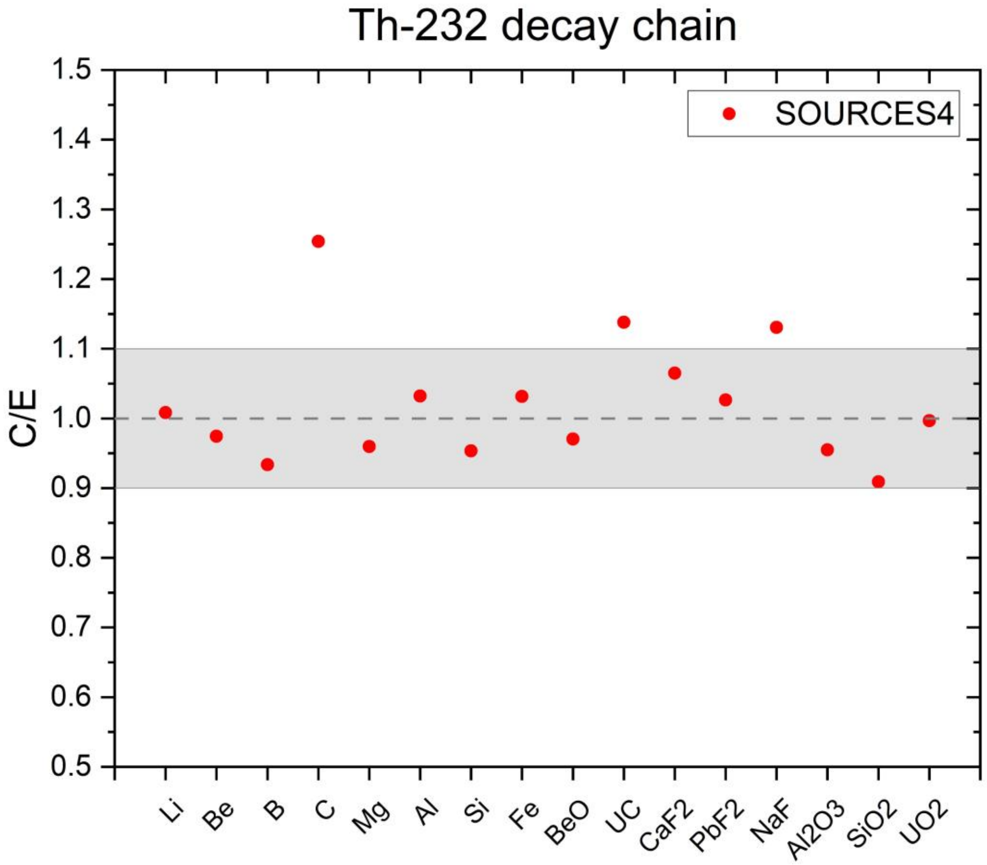
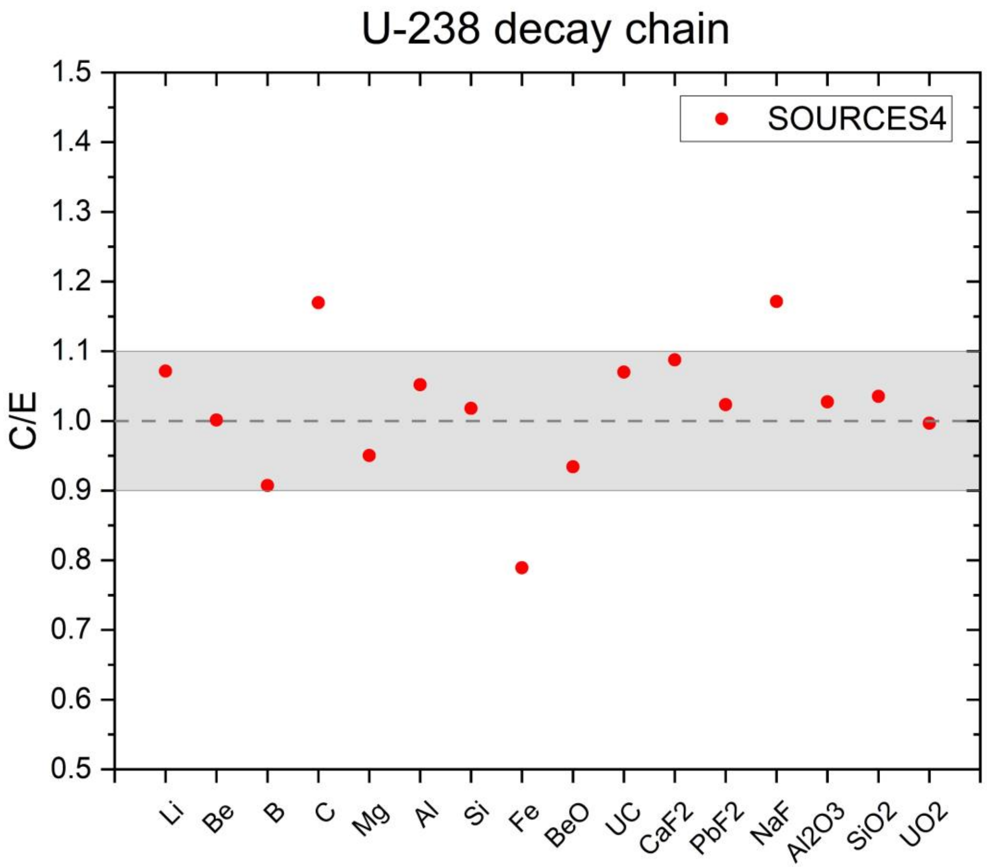
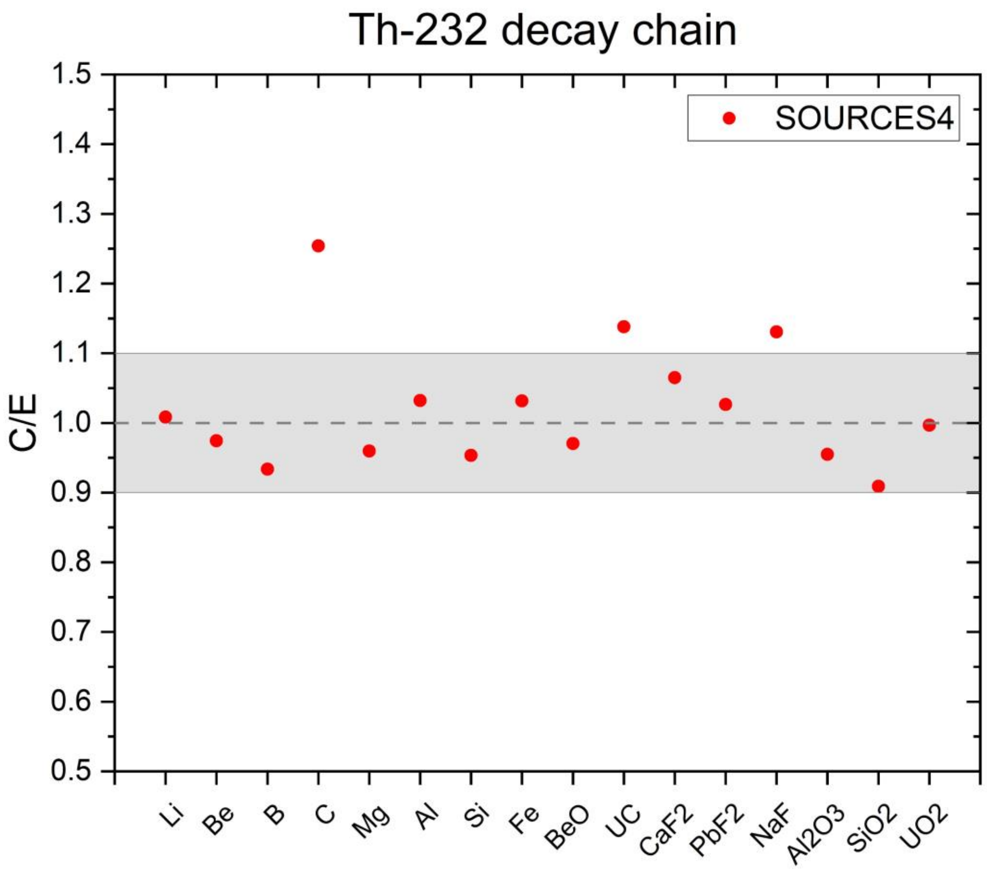




Fernandes, Ana C., Andreas Kling, and Gennadiy N. Vlaskin. "Comparison of thick-target (alpha, n) yield calculation codes." EPJ Web of Conferences. Vol. 153. EDP Sciences, 2017.

- The high Yn for C is because of the recent xs that we chose → this can be changed.
- In the case of Fe, the Yn for U-238 decay chain is much smaller, but in the case of Th-232 decay chain the results are closer to the evaluated ones. Is this due to different α energies or uncertainties? → needs further investigations.
- NaF should also be investigated in detail.





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Conclusions

- Data on cross-sections are not always sufficient to choose the best code/model or data set
- ‘Optimised' approach
  - Use reliable cross-section data where possible
  - If no data exist for an isotope, use a model (TALYS or EMPIRE) or JENDL database
  - Choose the model based on comparison with alpha beam data (when available)
- Neutron yields with the 'optimised' approach show a good agreement with data.

Thank you for your attention!