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Neutron production in (α,n) reactions: where we were and where we are now

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Outline

- Introduction: neutron production in (α,n) reactions.
- Comparing cross-sections and excitation functions from EMPIRE2.19/3.2.3, TALYS1.9 and experimental data.
- Neutron yields and spectra in different codes/models versus data.
- Conclusions.

Neutrons from radioactivity

- Neutron production: (α,n) reactions and spontaneous fission.
- Spontaneous fission is well understood although correlations between neutrons and gammas are not straightforward.
- (α,n) reactions - tricky: cross-sections, excitation functions and energy losses.
- 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):

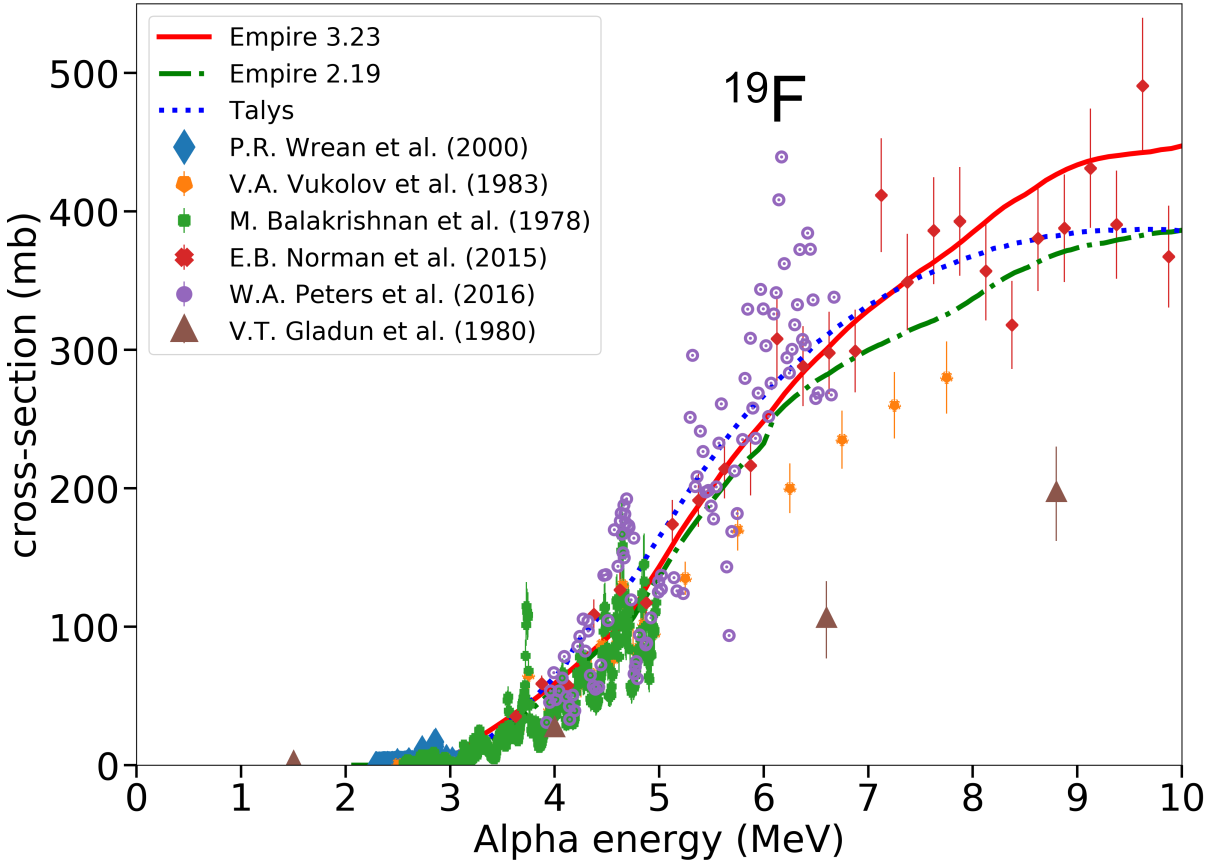
$$P(E_\alpha) = \int_0^{E_\alpha} \frac{N_i \sigma_i(E)}{\left(-\frac{dE}{dx}\right)} dE$$

- The final state nuclide can be in excited state so some energy is transferred to γs.
- Several codes exist to calculate neutron yields and spectra.
- Several collaborations are working with modified SOURCES4A/4C; W.B. Wilson, et al., SOURCES4A: a code for calculating (α,n), spontaneous fission, and delayed neutron sources and spectra, Technical Report LA-13639-MS, Los Alamos, 1999; modifications explained in Tomasello et al. NIMA, 595 (2008) 431.
- We claim an uncertainty of 20% (different cross-sections tested >10 years ago).

SOURCES4A and other tools

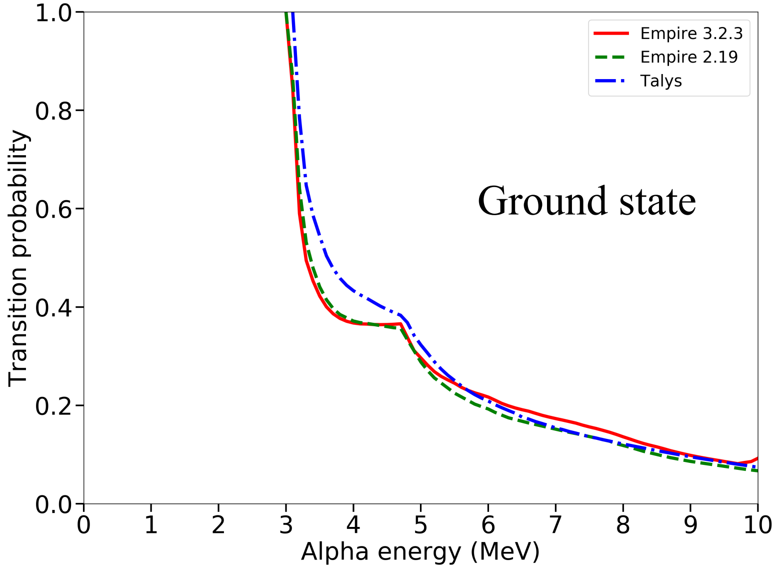
- SOURCES4A: cross-sections and excitation functions from EMPIRE2.19 or data (flexible). Approximation of thick target.
- USD web-based tool: http://neutronyield.usd.edu; Mei et al. NIMA 606 (2009) 651. Cross-sections from TENDL libraries (TALYS code).
- Comparison between SOURCES4A and USD based tool: J. Cooley et al. NIMA 888 (2018) 110-118, arXiv:1705.04736 [physics.ins-det]
- New code NeuCBOT: S. Westerdale and P.D. Meyers. Nuclear Instr. and Methods in Physics Research, A 875 (2017) 57–64. Neutron spectra are taken from TALYS code (TENDL libraries).
- Comparison of NeuCBOT and SOURCES4C: S. Westerdale and P.D. Meyers. Nucl. Instr. and Methods in Physics Research, A 875 (2017) 57–64.
- Results from USD tool and NeuCBOT are different from SOURCES4A. See also Kudryavtsev et al., Talk at IDM2018.
- New versions of TALYS1.9 and EMPIRE3.2.3 are available. Also new data on cross-sections.
- Next slides: comparison between EMPIRE3.2.3/2.19, TALYS1.9 and data.

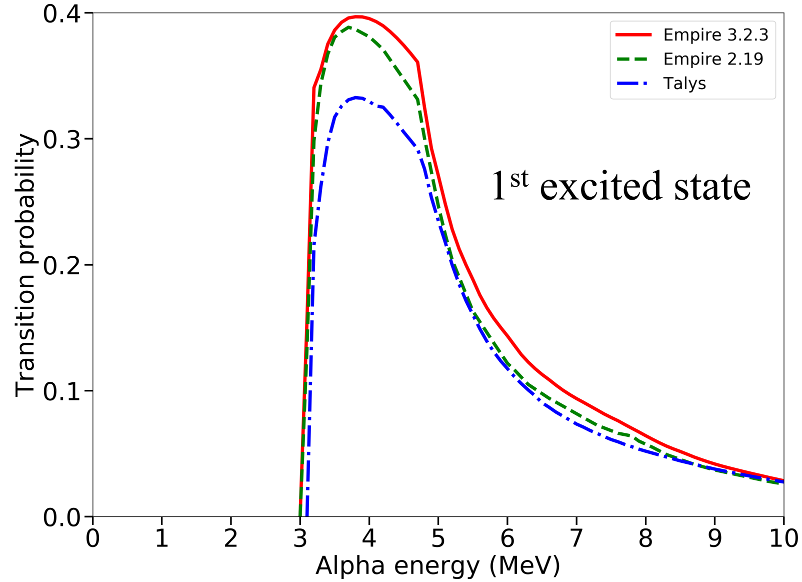
Cross-sections: EMPIRE2.19/3.2.3 vs TALYS1.9

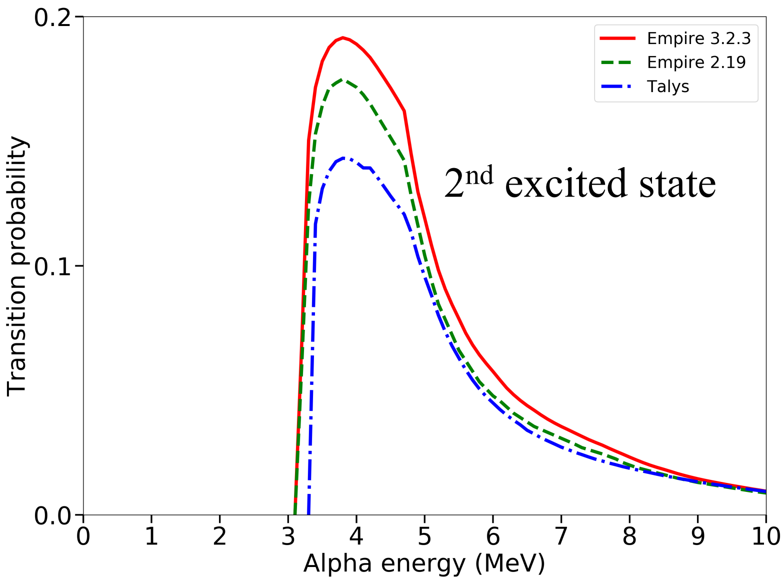


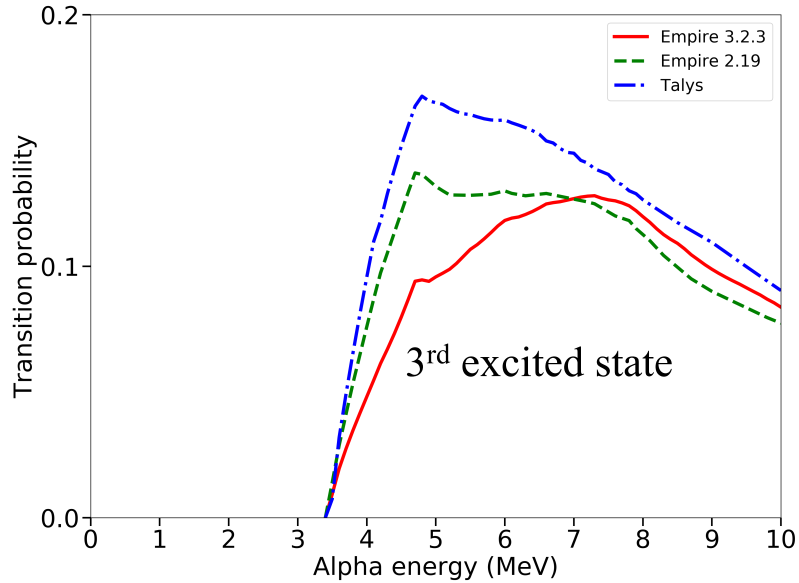
- Threshold is determined by the Q-value of the reaction and Coulomb barrier.
- Data do not allow us to choose an optimum model for ^{19}F.
- Data can be used in SOURCES4A (possibly in combination with another model). The results are quite different depending on a specific measurement.

Excitation functions for fluorine

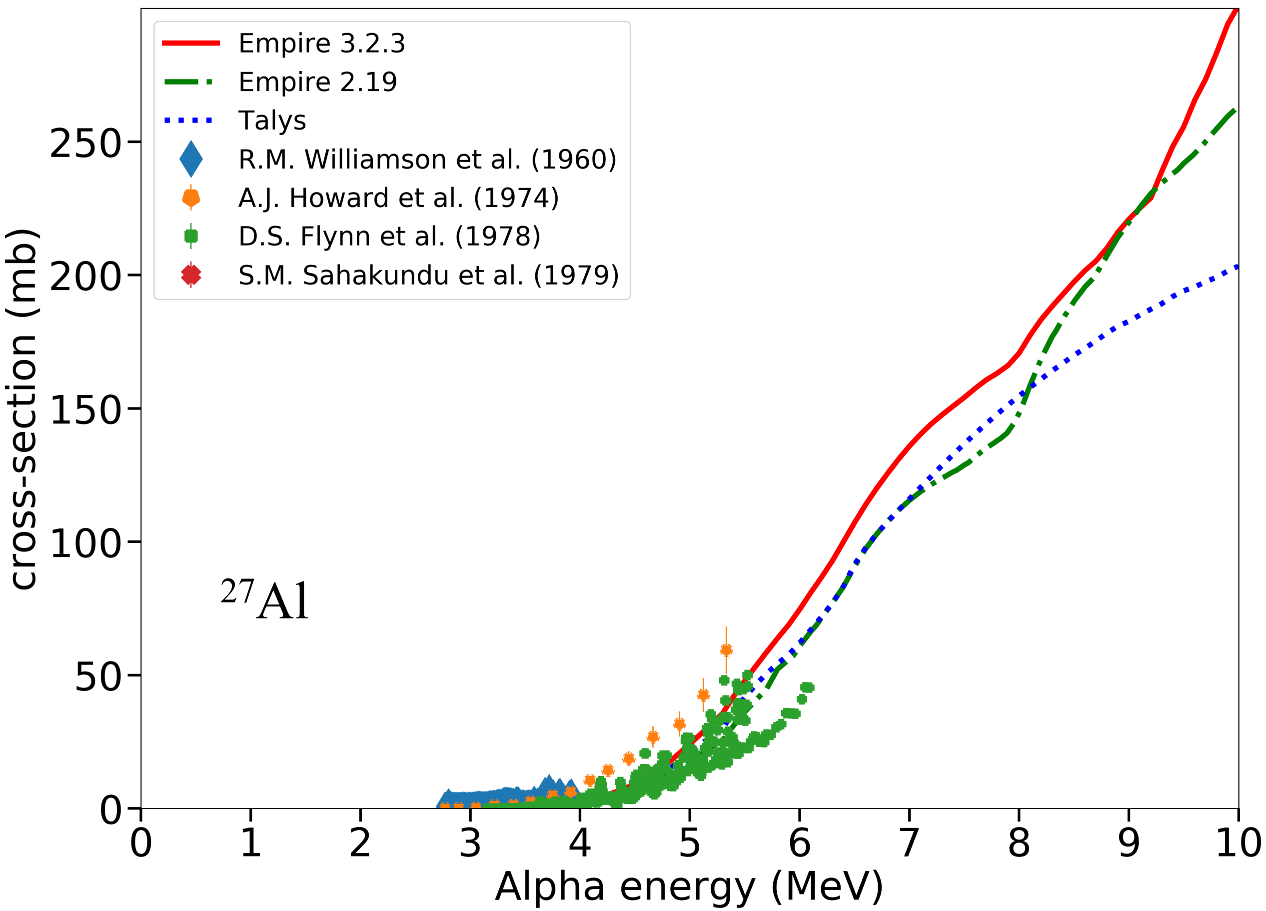






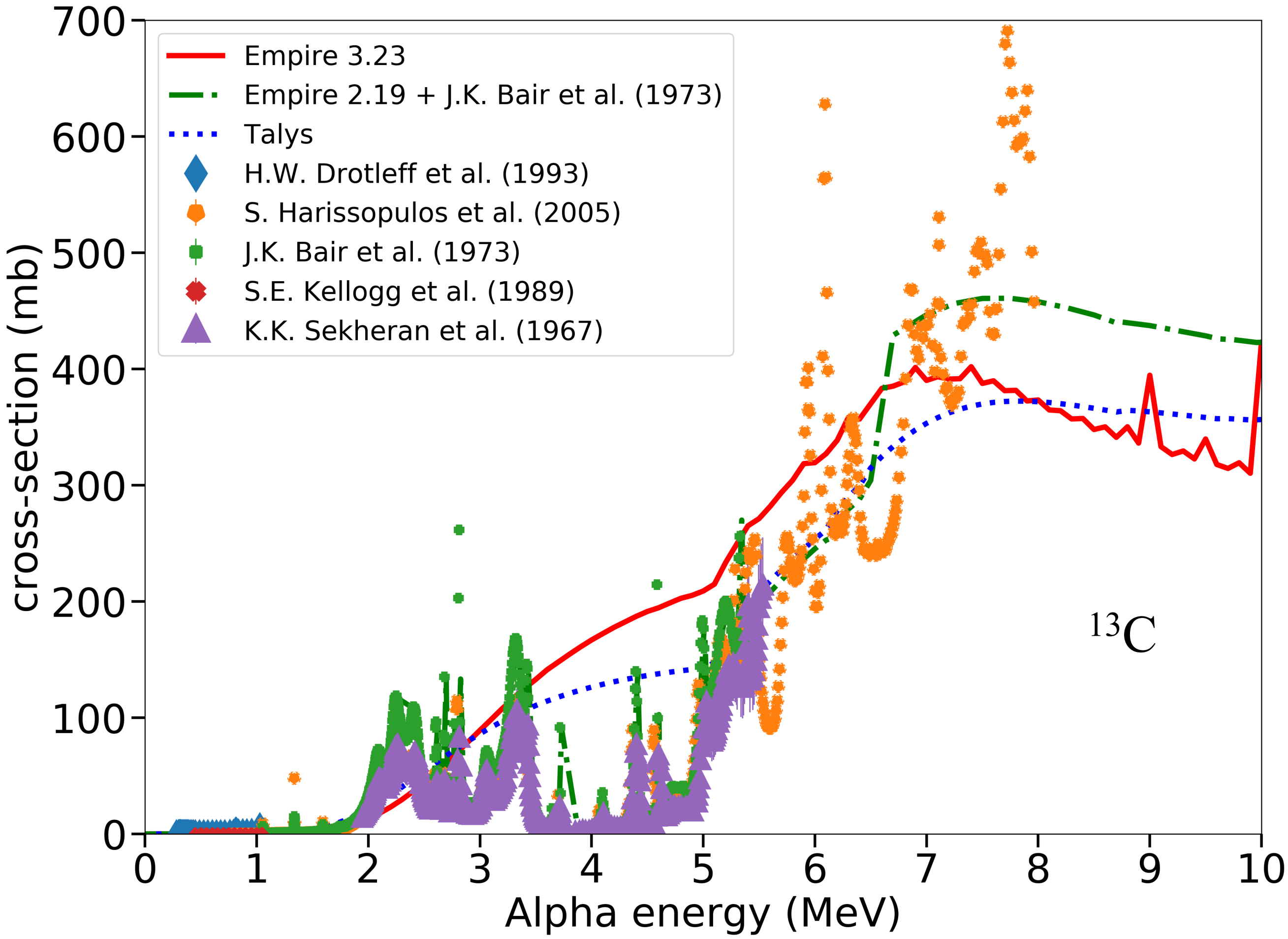


Cross-sections for aluminium



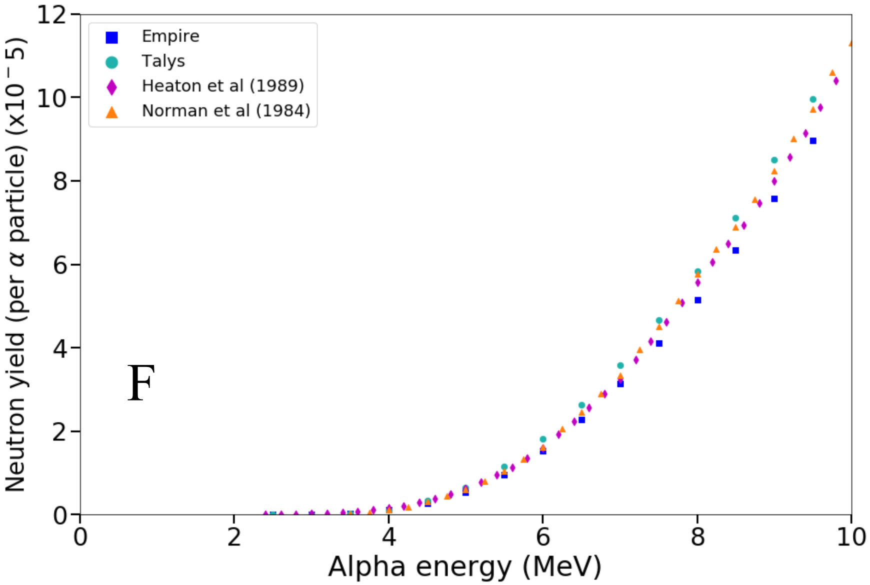
- Data are limited (quite old) and cannot help with the choice of the model. Using measured cross-sections leads to large variation in the neutron yield, depending on a specific measurements.

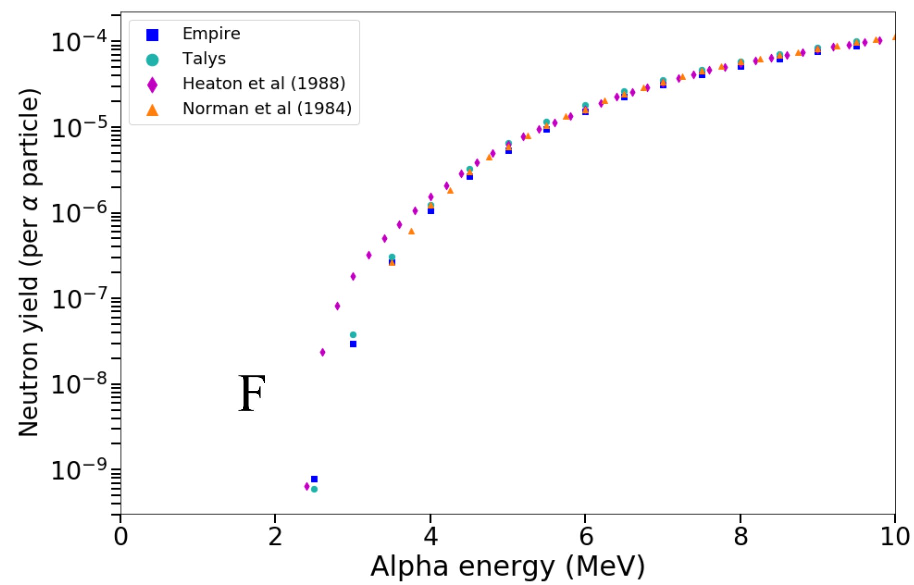
Cross-sections for carbon

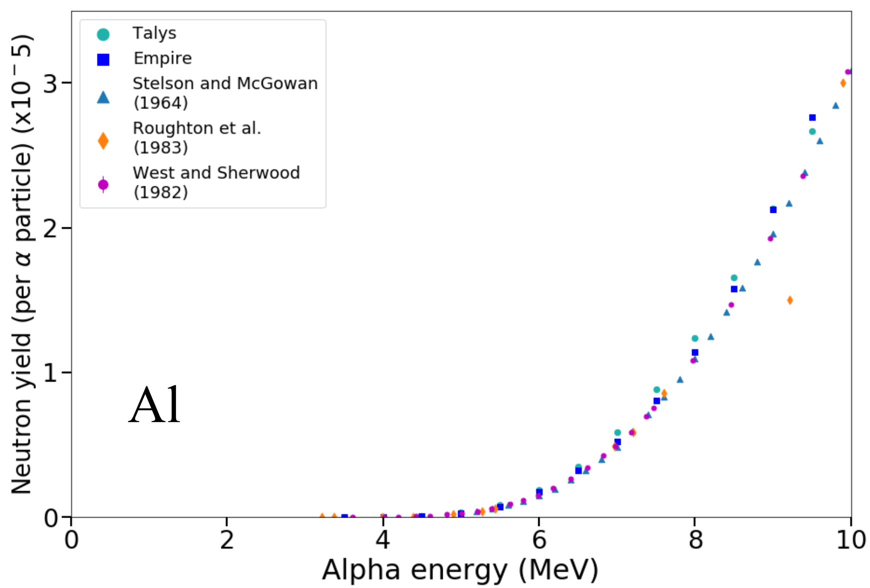


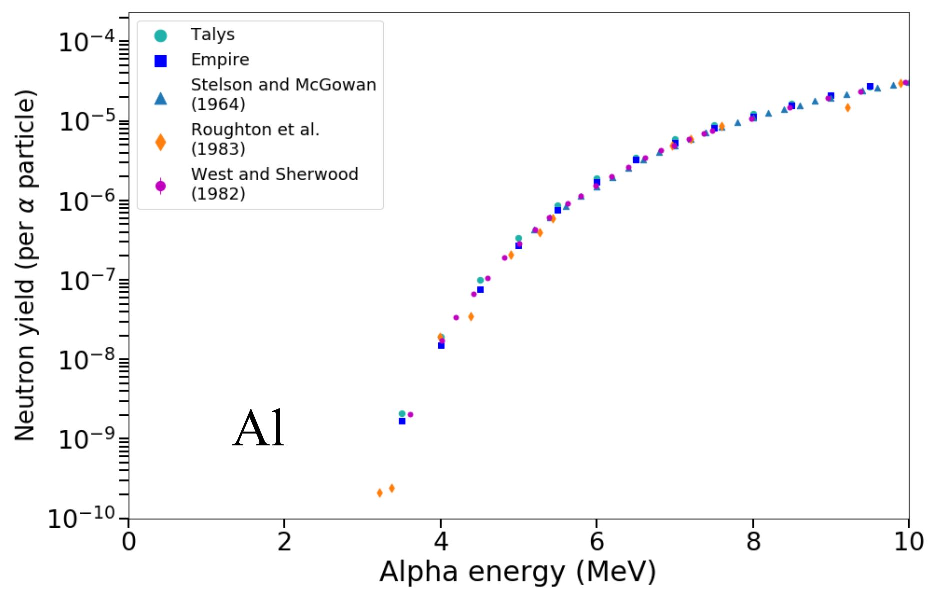
- ^{12}C does not contribute (high threshold). Only ^{13}C contributes to the neutron yield (but small abundance).

Neutron yield: TALYS1.9, EMPIRE2.19 and data

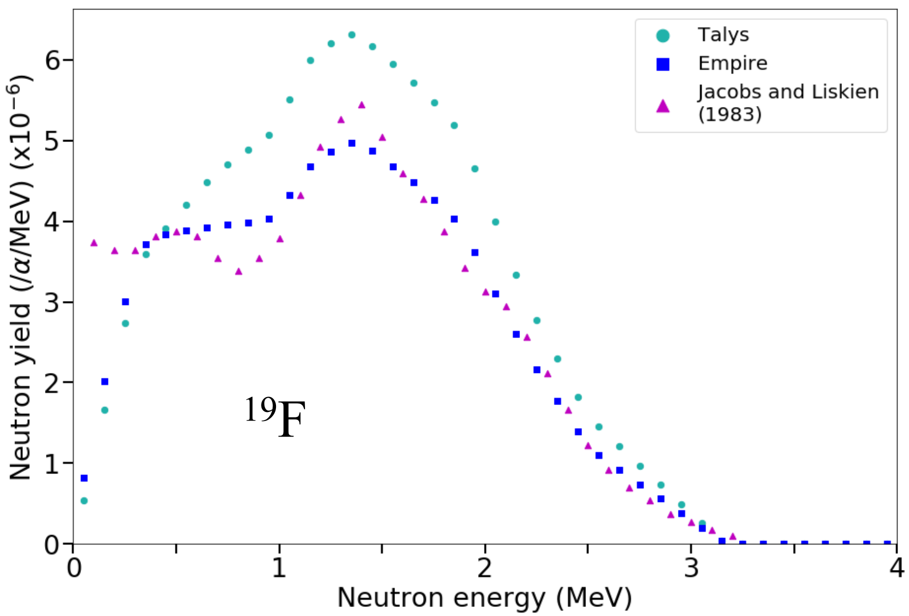


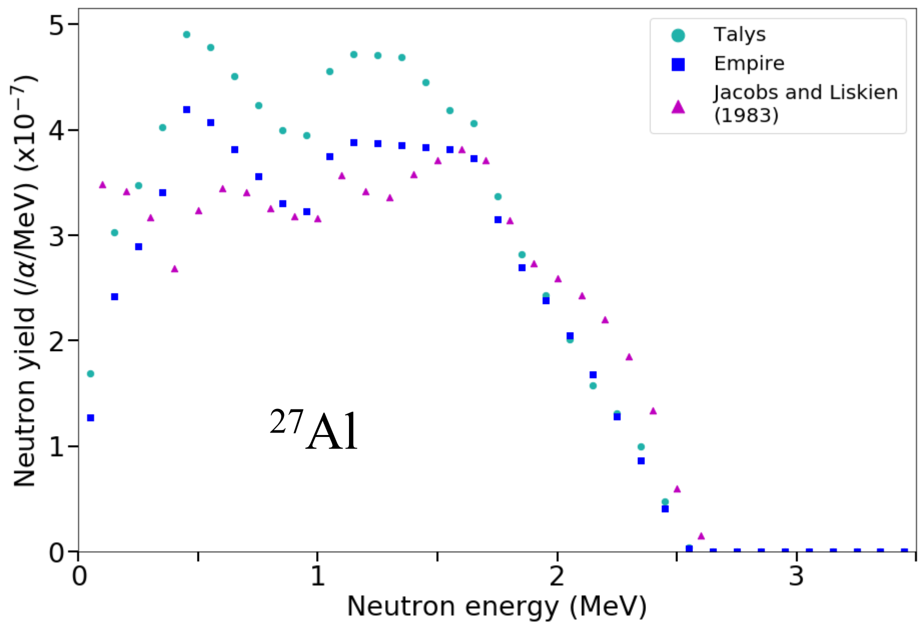






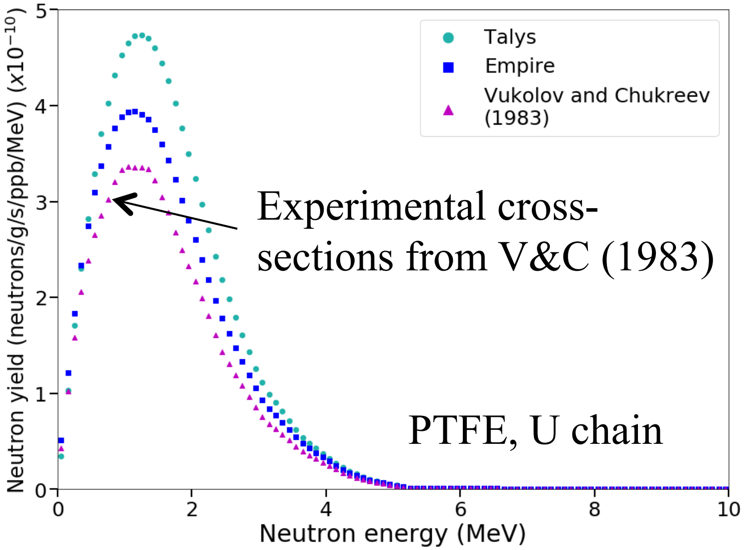
Neutron spectra: SOURCES4A vs measurements

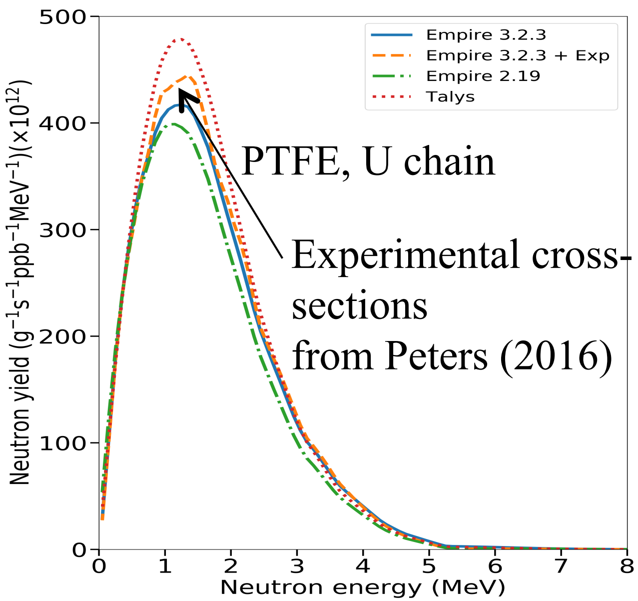




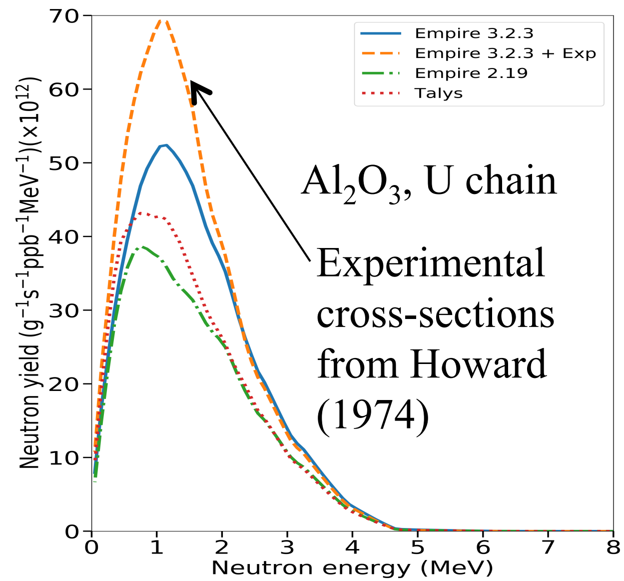
- Neutron spectra from 5.5 MeV alphas in fluorine and aluminium.
- SOURCES4A uses either EMPIRE2.19 or TALYS1.9 cross-sections.

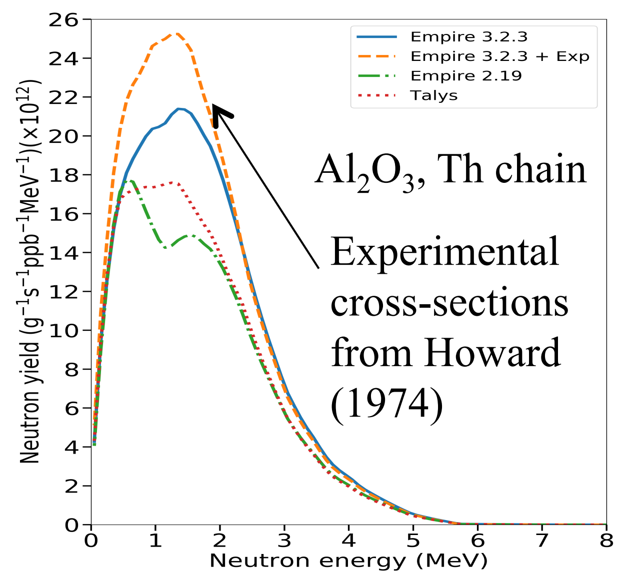
Neutron spectra: PTFE (C_2F_4) and Al_2O_3





Neutron spectra from U/Th decay chains in equilibrium using cross-sections from TALYS1.9, EMPIRE2.19/ 3.2.3 and measurements.





SOURCES4A: EMPIRE3.2.3/2.19 vs TALYS1.9

Material	Cross-section	$^{238}U + ^{235}U$	^{232}Th
Aluminium	TALYS1.9	1.86×10^{-10}	9.05×10^{-11}
	EMPIRE2.19	1.69×10^{-10}	8.59×10^{-11}
Al_2O_3	TALYS1.9	9.48×10^{-11}	4.56×10^{-11}
	EMPIRE2.19	8.59×10^{-11}	4.32×10^{-11}
	EMPIRE3.2.3	11.42×10^{-11}	5.45×10^{-11}
	EMPIRE3.2.3 +Experiment	13.55×10^{-11}	6.04×10^{-11}
PTFE	TALYS1.9	10.21×10^{-10}	4.03×10^{-10}
	EMPIRE2.19	8.72×10^{-10}	3.50×10^{-10}
	EMPIRE3.2.3	9.39×10^{-10}	3.78×10^{-10}
	EMPIRE3.2.3 +Experiment	9.68×10^{-10}	3.91×10^{-10}

Units: neutrons/g/s/ppb of the parent isotope. Only (α, n) reactions, no SF.

SOURCES4A: EMPIRE3.2.3/2.19 vs TALYS1.9

Material	Cross-section	$^{238}U + ^{235}U$	^{232}Th
SiO_2	TALYS1.9	1.54×10^{-11}	6.75×10^{-12}
	EMPIRE2.19	1.59×10^{-11}	7.03×10^{-12}
	EMPIRE3.2.3	2.07×10^{-11}	8.61×10^{-12}
	EMPIRE3.2.3 +Experiment	1.35×10^{-11}	6.21×10^{-12}
Ti	TALYS1.9	2.80×10^{-11}	2.33×10^{-11}
	EMPIRE2.19	2.55×10^{-11}	2.15×10^{-11}
	EMPIRE3.2.3	3.39×10^{-11}	2.48×10^{-11}
	EMPIRE3.2.3 +Experiment	3.39×10^{-11}	2.46×10^{-11}

Units: neutrons/g/s/ppb of the parent isotope. Only (α, n) reactions, no SF.

Conclusions

- All codes with recommended models (TALYS1.9 and EMPIRE2.19/3.2.3) give similar cross-sections (within 20%), at least for most critical isotopes.
- Data on cross-sections are not sufficient to make a choice of the code/model. Measured cross-sections have large variations. Using measured cross-sections makes the neutron yields bigger or smaller than using a model, depending on a specific measurement and the model.
- For most tested isotopes, EMPIRE3.2.3 and TALYS1.9 cross-sections give slightly higher neutron yields than EMPIRE2.19 but comparison with data does not allow us to select the best code/model.
- 20-25% difference between neutron yields obtained with SOURCES4A with cross-sections from 3 codes/models, has been found for Al_2O_3, PTFE, SiO_2, Ti. More materials are being tested.
- Bigger difference with NeuCBOT and USD tool even when the cross-sections from the same code/model (TALYS / TENDL libraries) are used.