BERKELEY LAB
Bringing Science Solutions to the World

U.S. DEPARTMENT OF ENERGY
Office of Science

Constraining i-process nucleosynthesis with quasi-continuum nuclear data

Mathis Wiedeking
Nuclear Science Division
mwiedeking@lbl.gov
https://nuclearscience.lbl.gov/

Supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contracts No. DE-AC02-05CH11231 and by the US Nuclear Data Program.

What are we trying to achieve?

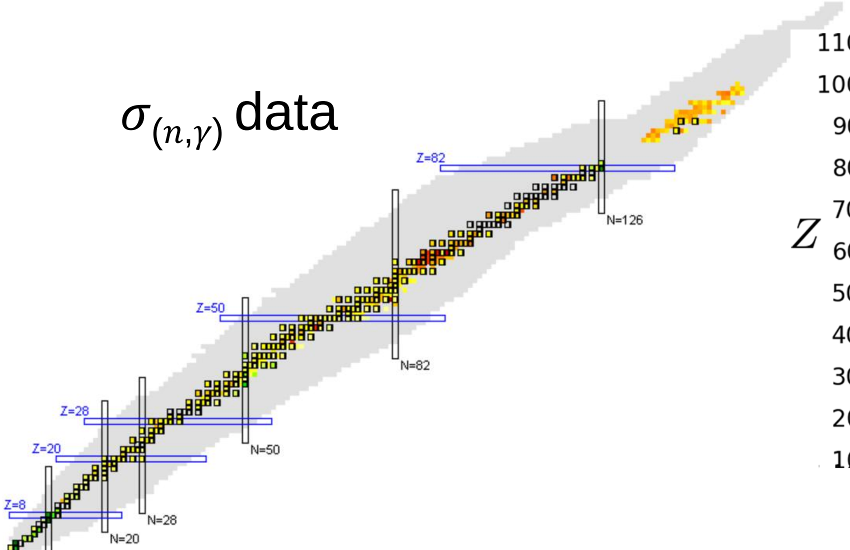
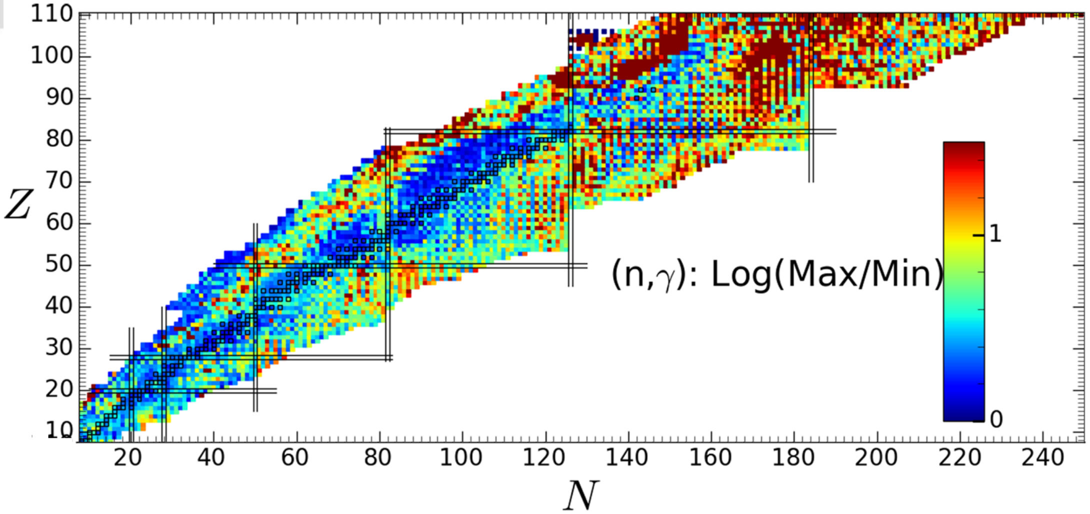


Figure from https://www.nndc.bnl.gov



Wiedeking & Goriely, Phil. Trans. R. Soc. A 382, 20230125 (2024).

Direct $\sigma(n,\gamma)$ measurements away from stability generally not possible.

Apply indirect techniques:

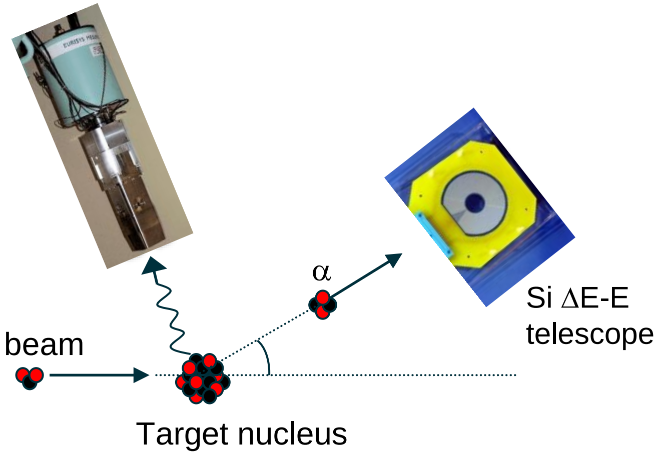
Surrogate Method

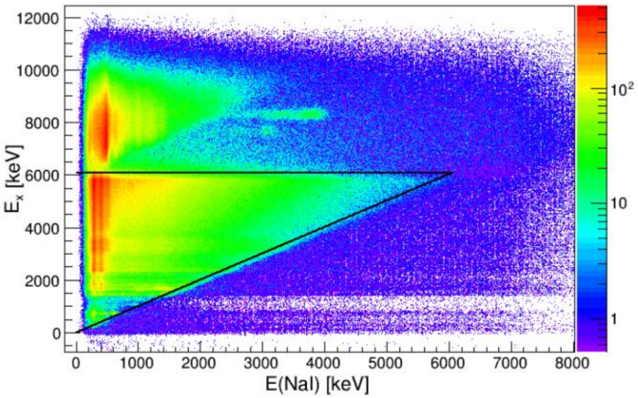
Quasi-continuum data (PSF/NLD), e.g. ^{66}Ni(n,γ)

Measuring the PSF and/or NLD

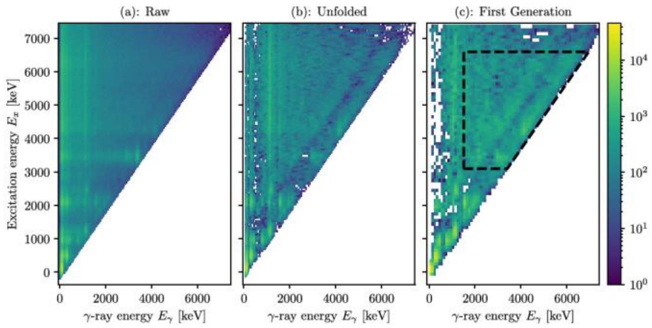
- Photonuclear Reactions ($>S_n$)
- Primaries from n-capture ($>S_n$)
- Nuclear Resonance Fluorescence ($<S_n$)
- Two-step cascade, n/p capture ($<S_n$)
- Inelastic p scattering with polarized beam ($<S_n$ and $>S_n$)

- Primaries from p-capture ($>S_p$ and $<S_n$)
- Primaries from charged particle reactions ($<S_n$)
  - Oslo, beta-Oslo, inverse Oslo Methods
  - Ratio/Shape Methods

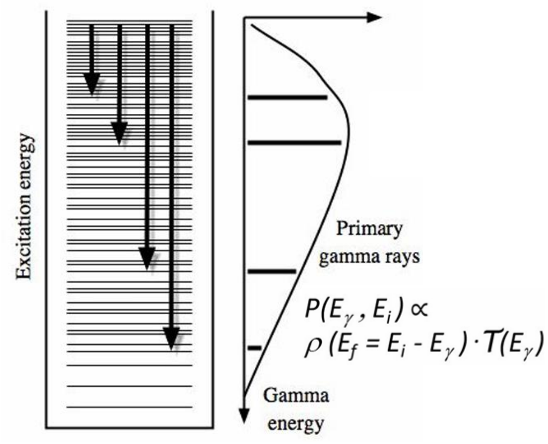




Oslo Methods



Ingeberg *et al.*, Phys. Rev. C 106 054315 (2022).



Beta-Oslo method

First for NLDs and PSFs to be measured away from stability.

PRL 113, 232502 (2014) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2014

Novel technique for Constraining r-Process (n, γ) Reaction Rates

A. Spyrou,[1,2,3,*] S. N. Liddick,[1,4,†] A. C. Larsen,[5,‡] M. Guttormsen,[5] K. Cooper,[1,4] A. C. Dombos,[1,2,3] D. J. Morrissey,[1,4] F. Naqvi,[1] G. Perdikakis,[6,1,3] S. J. Quinn,[1,7,3] T. Renstrøm,[5] J. A. Rodriguez,[1] A. Simon,[1,8] C. S. Sumithrarachchi,[1] and R. G. T. Zegers[1,7,3]

Picture from: https://groups.nscl.msu.edu /SuN/SuN_photos.php

Inverse-Oslo method

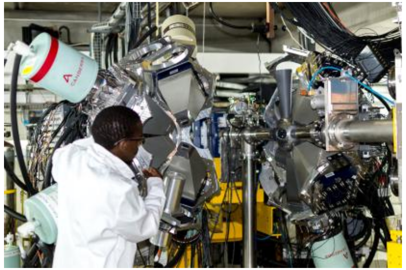
NLDs and PSFs from inverse-kinematic reactions. Applicable to stable and RIB facilities.

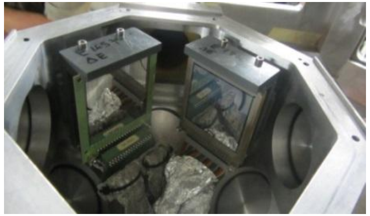
Eur. Phys. J. A (2020) 56:68
https://doi.org/10.1140/epja/s10050-020-00070-7
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Experimental Physics

First application of the Oslo method in inverse kinematics

Nuclear level densities and γ-ray strength functions of ^{87}Kr

V. W. Ingeberg[1,a], S. Siem[1], M. Wiedeking[2], K. Sieja[3,4], D. L. Bleuel[5], C. P. Brits[2,6], T. D. Bucher[2], T. S. Dinoko[2], J. L. Easton[2,7], A. Görgen[1], M. Guttormsen[1], P. Jones[2], B. V. Kheswa[2,8], N. A. Khumalo[2], A. C. Larsen[1], E. A. Lawrie[2], J. J. Lawrie[2], S. N. T. Majola[2,8,9], K. L. Malatji[2,6], L. Makhathini[2,6], B. Maqabuka[2,7], D. Negi[2], S. P. Noncolela[2,7], P. Papka[2,6], E. Sahin[1], R. Schwengner[10], G. M. Tveten[1], F. Zeiser[1], B. R. Zikhali[2,9]





PSF and NLD from Inverse Kinematics at CERN HIE-ISOLDE

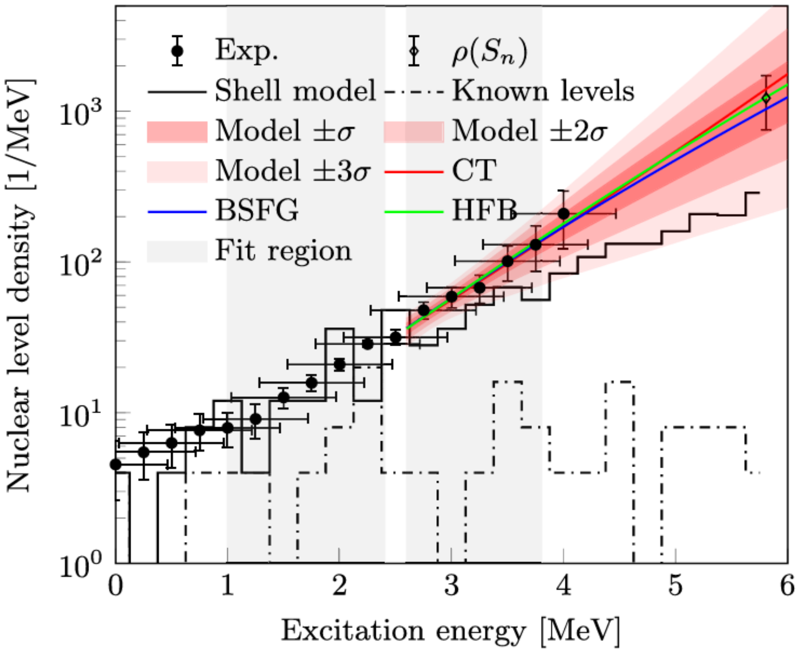
- d(^{66}Ni,p)^{67}Ni with 4.5 MeV/u
- CD target 0.7mg/cm^2
- 3.5x10^6 pps for 140 hours
- Miniball + LaBr + C-REX
- LaBr: ~320k p-γ, Miniball: ~1.1m p-γ

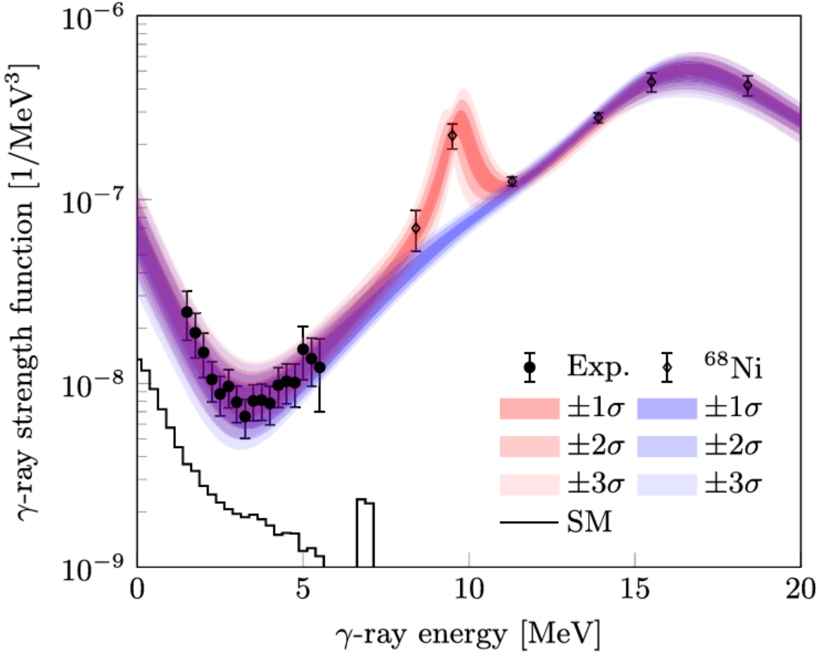
PHYSICAL REVIEW C **111**, 015803 (2025)

Nuclear level density and γ-ray strength function of ^{67}Ni and the impact on the *i* process

V. W. Ingeberg,[1,2,*] S. Siem,[1,2,†] M. Wiedeking,[3,4,5] A. Choplin,[6] S. Goriely,[6] L. Siess,[6] K. J. Abrahams,[7] K. Arnswald,[8] F. Bello Garrote,[1] D. L. Bleuel,[9] J. Cederkäll,[10,11] T. L. Christoffersen,[1] D. M. Cox,[12,13] H. De Witte,[14] L. P. Gaffney,[11,‡] A. Görgen,[1,2] C. Henrich,[15] A. Illana,[14,§] P. Jones,[4] B. V. Kheswa,[1,‖] T. Kröll,[15] S. N. T. Majola,[4,‖] K. L. Malatji,[4,16] J. Ojala,[12,13] J. Pakarinen,[12,13] G. Rainovski,[17] P. Reiter,[8] M. von Schmid,[15] M. Seidlitz,[8] G. M. Tveten,[1] N. Warr,[8] and F. Zeiser[1]
(The ISOLDE Collaboration)

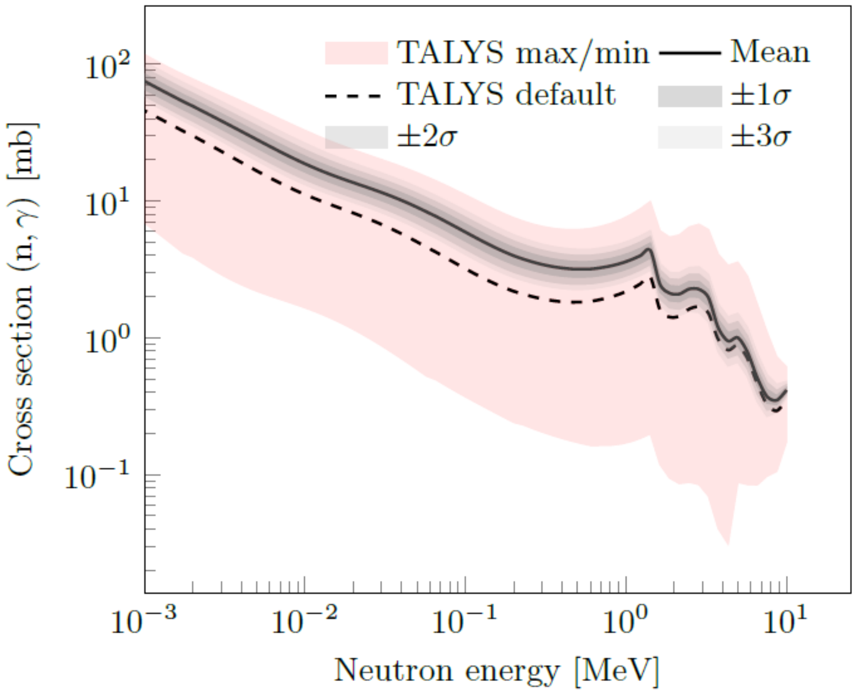
^{67}Ni: PSF and NLD

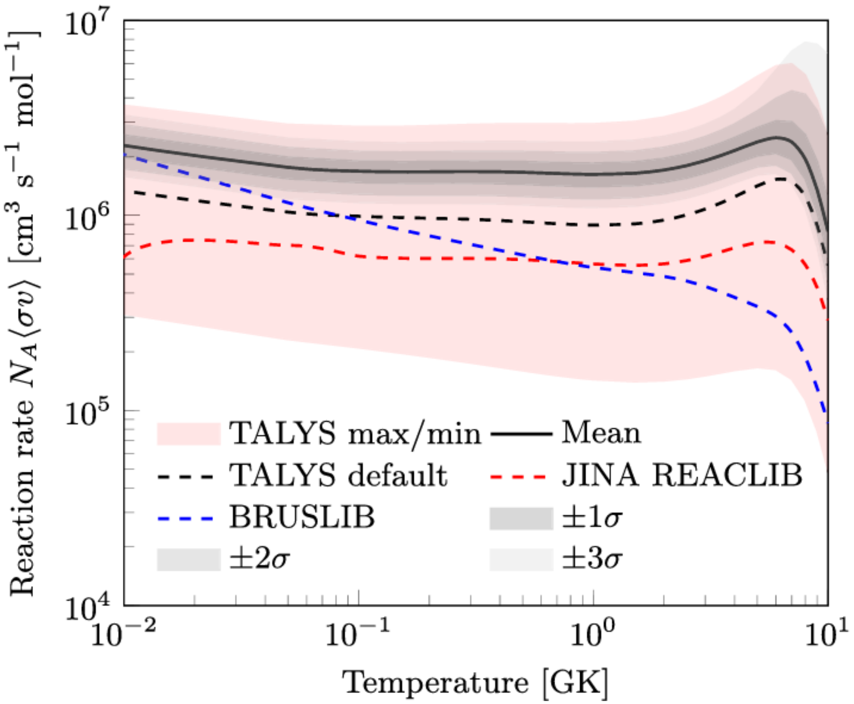




V. Ingeberg *et al,* Phys. Rev. C 111, 015803 (2025).

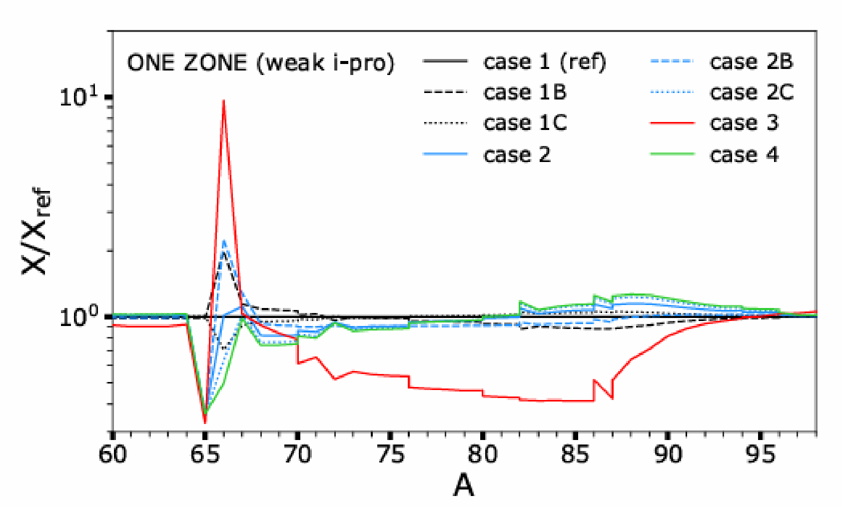
^{66}Ni(n,γ)

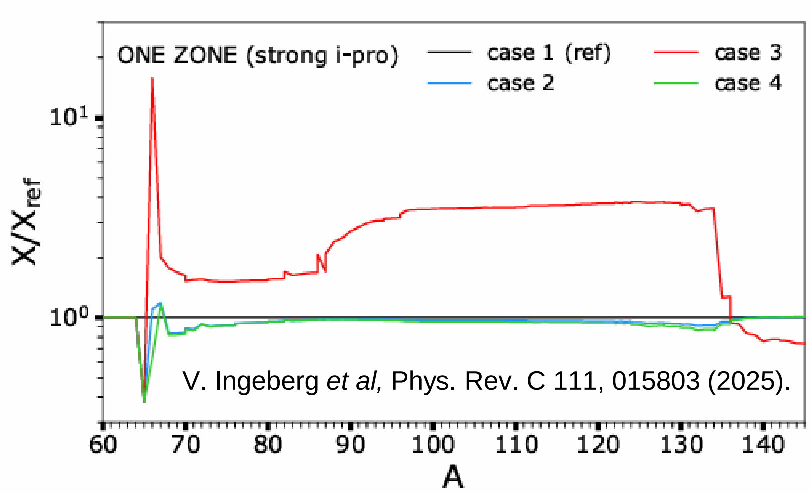




V. Ingeberg *et al,* Phys. Rev. C 111, 015803 (2025).

^{66}Ni(n,γ) i-process nucleosynthesis (one-zone)





V. Ingeberg *et al*, Phys. Rev. C 111, 015803 (2025).

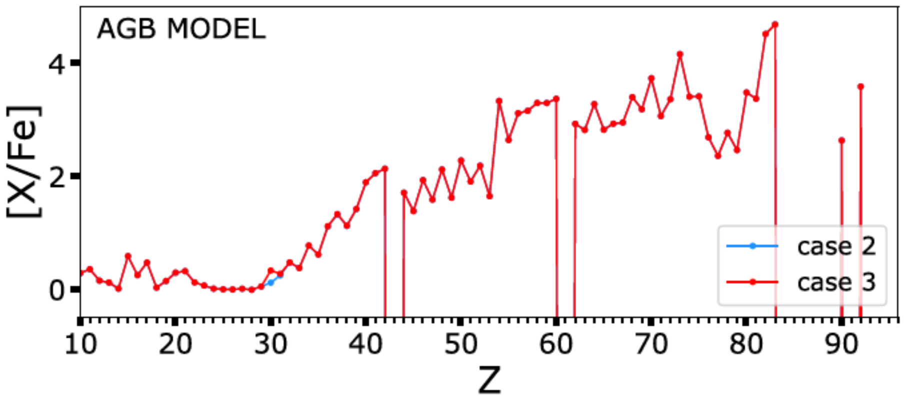
Low-metallicity, low-mass stars during the early thermally pulsating Asymptotic Giant Branch phase.

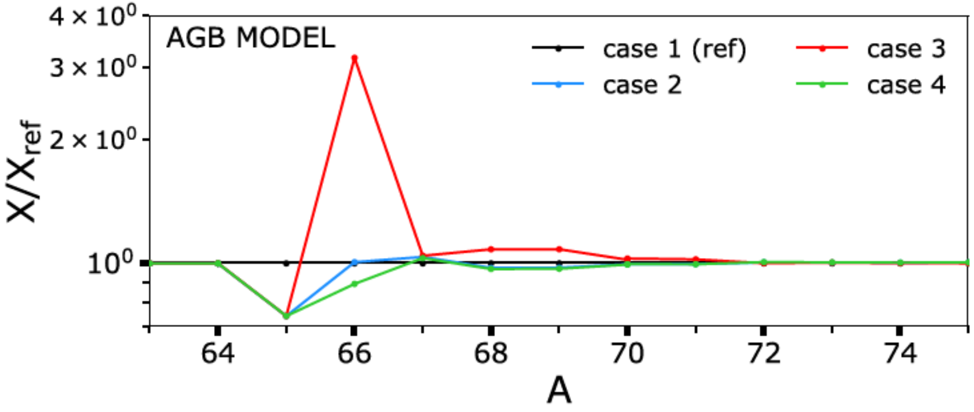
One zone model:

"The ^{66}Ni(n,γ) reaction is found to behave as a major bottleneck for the i-process nucleosynthesis."

McKay *et al*., MNRAS 491, 5179 (2020).

^{66}Ni(n,γ) i-process nucleosynthesis (multi-zone)





Low-metallicity, low-mass stars during the early thermally pulsating Asymptotic Giant Branch phase.

Impact is marginal in multi-zone low-mass, low-metallicity AGB stellar models experiencing i-process nucleosynthesis.

V. Ingeberg et al, Phys. Rev. C 111, 015803 (2025).

Summary

- Quasi-continuum Nuclear Data provide a tool to indirectly obtain (n,γ) cross sections away from stability.

- Majority of tools (experimental, analytical, detection) available

  - Many novel measurements now possible.

- i-process nucleosynthesis: (n,γ) cross sections for ^{66}Ni(n,γ)

  - Impact in one-zone calculations.
  - Negligible in multi-zone calculations.

Thank you!

Mathis Wiedeking
Nuclear Science Division
mwiedeking@lbl.gov
https://nuclearscience.lbl.gov/

Supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contracts No. DE-AC02-05CH11231 and by the US Nuclear Data Program.