CERN-INTC-2024-006 / INTC-P-689
10/01/2024

(proposal INFN + ENEA in APRENDE)

Study of **n + ^{63,65}Cu reactions** and their relevance for nuclear technologies and Astrophysics

M. Bacak[1], D. M. Castelluccio[2,3], S. Cristallo[4,3], P. Console Camprini[2,3], M. Diakaki[5]
G. Grasso[2], A. Guglielmelli[6], C. Massimi[7,3], M. Mastromarco[3,8], A. Mengoni[2,3],
A. Musumarra[9,3], M. P. Pellegriti[3], M. Pignatari[10], E. Pirovano[11], N. Terranova[2,3],
R. N. Sahoo[3], D. Vescovi[4,3], and the n_TOF Collaboration

[1] *CERN*
[2] *ENEA – Agency for New Technologies, Energy and Sustainable Economic Development, Italy*
[3] *INFN – National Institute for Nuclear Physics, Italy*
[4] *INAF– National Institute for Astrophysics, Italy*
[5] *NTUA– National Technical University of Athens, Greece*
[6] *European Commission, Joint Research Centre, Ispra, Italy*
[7] *Department of Physics and Astronomy, University of Bologna, Italy*
[8] *Department of Physics, University of Bari, Italy*
[9] *Department of Physics and Astronomy, University of Catania, Italy*
[10] *Konkoly Observatory, Research Centre for Astronomy and Earth Sciences, HUN-REN & CSFK, MTA Centre of Excellence, Budapest, Hungary*
[11] *PTB – National Metrology Institute, Germany*

Spokesperson: Cristian Massimi (massimi@bo.infn.it)
Technical coordinator: Olivier Aberle (oliver.aberle@cern.ch)

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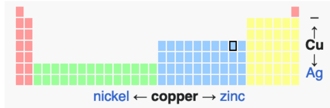
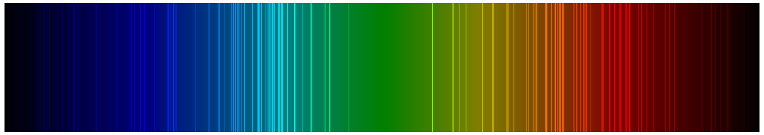
n + ^{63,65}Cu



Native_Copper_Macro_Digon3.jpg: "Jonathan Zander (Digon3)" derivative work: Materialscientist (talk) - Native_Copper_Macro_Digon3.jpg



- Introduction to scientific motivations
- Data in the literature
- Proposed measurements
- Conclusions

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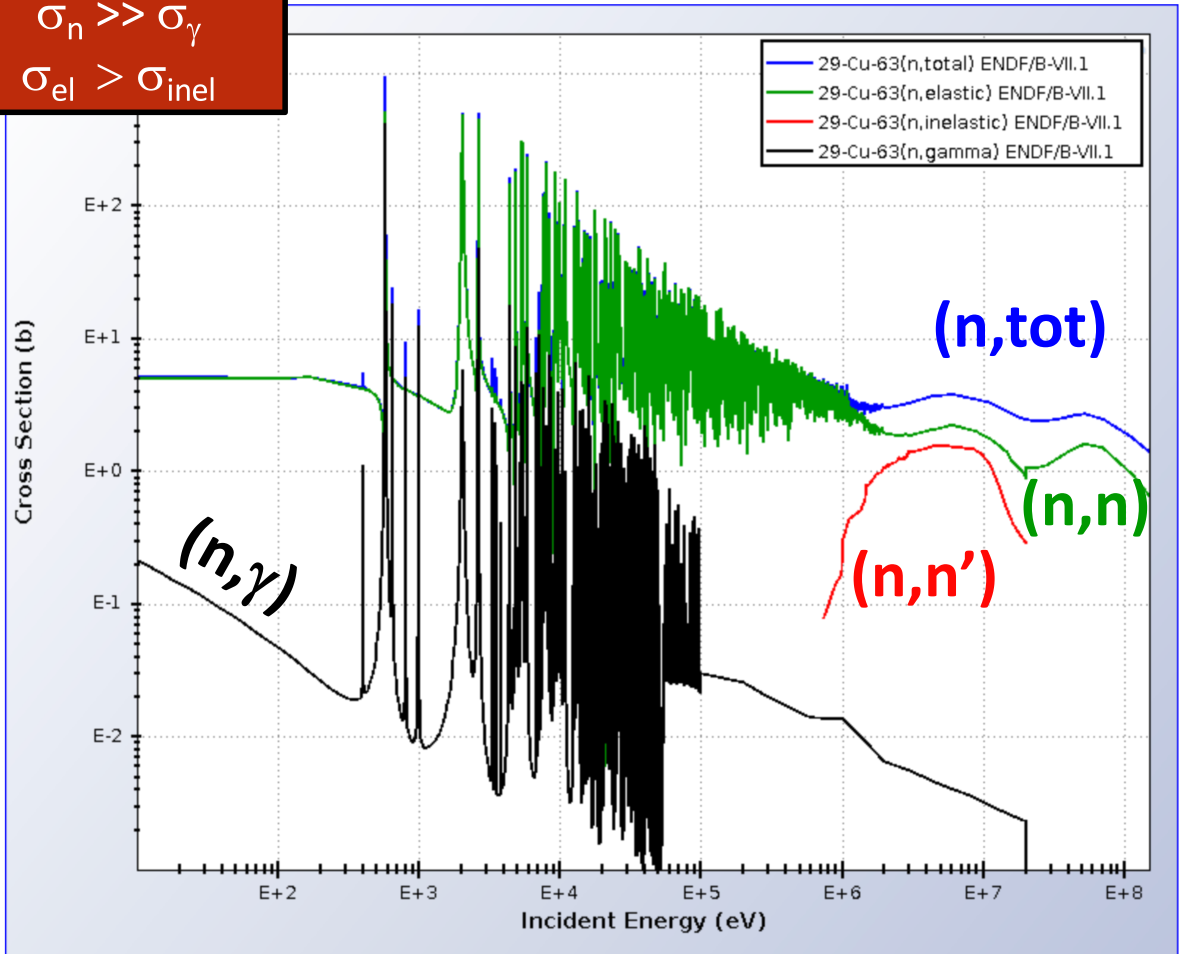
Why ^{63,65}Cu?

$\sigma_n >> \sigma_\gamma$
$\sigma_{el} > \sigma_{inel}$



Natural abundance:
^{63}Cu 69.2 %
^{65}Cu 30.8 %

Prodotti della reazione	*Q-valore* (keV)
$^{63}Cu + n$	0
$^{64}Cu + \gamma$	7915.9 ± 0.6
$^{60}Co + \alpha$	1717.0 ± 0.6
$^{63}Ni + p$	715.4 ± 0.6

Prodotti della reazione	*Q-valore* (keV)
$^{65}Cu + n$	0
$^{66}Cu + \gamma$	7065.9 ± 0.9
$^{62}Co + \alpha$	-193 ± 18
$^{65}Ni + p$	-1355.5 ± 0.8

Why ^{63,65}Cu?

- Nuclear Technology — Nucl. Techn.
- Nuclear Astrophysics — Nucl. Astro.

^{63}Cu and ^{65}Cu very **similar**
- ^{63}Cu presented here
- ^{65}Cu in backup slides

Why ^{63,65}Cu?

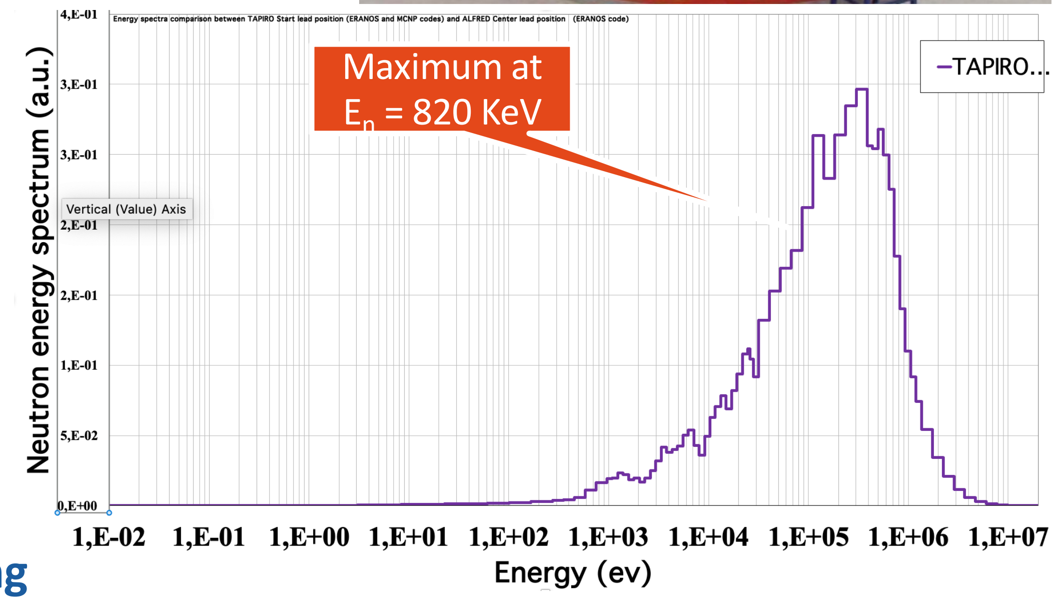
Nucl. Techn.

TAratura Pila Rapida Potenza ZerO (TAPIRO) research reactor:

- 5 kW power
- U-Mo fuel
- Core = 12 cm cylinder
- ^{235}U enrichment = 93.5%
- 4×10^{12} n/s

- **FAST SPECTRUM**

Evaluation benchmark   Material test

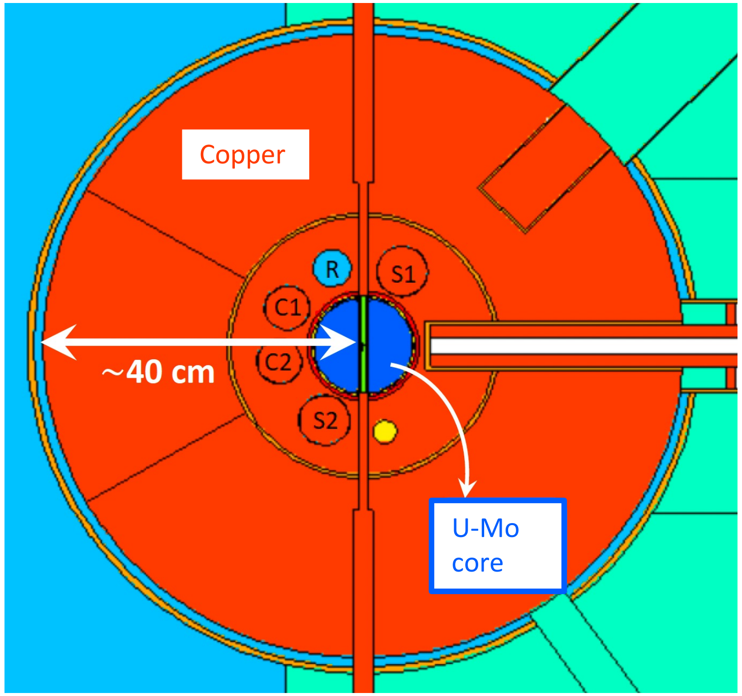


TAPIRO can play a **pivotal** role **in supporting** the development of **fast reactor projects**

Why ^{63,65}Cu?

Nucl. Techn.

TAPIRO: k_{eff} study by MCNP



ENDF/B-VIII.0 → k_{eff} = 1.00000

^{63}Cu

Evaluation	k_{eff}
JEFF3.3	1.00637 ± 0.00001
JENDL-5	1.00147 ± 0.00001
TENDL-2021	1.00102 ± 0.00001

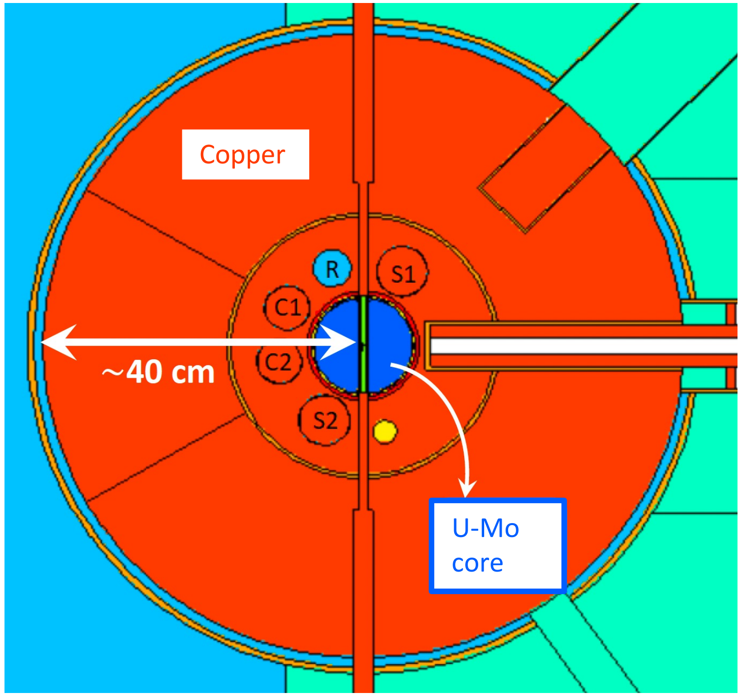
^{65}Cu

Evaluation	k_{eff}
JEFF3.3	0.99980 ± 0.00001
JENDL-5	0.99782 ± 0.00001
TENDL-2021	1.00017 ± 0.00001

Why ^{63,65}Cu?

Nucl. Techn.

TAPIRO: k_{eff} study by MCNP



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^{65}Cu

Evaluation	k_{eff}
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Library effect =
1.5 x regulation rod

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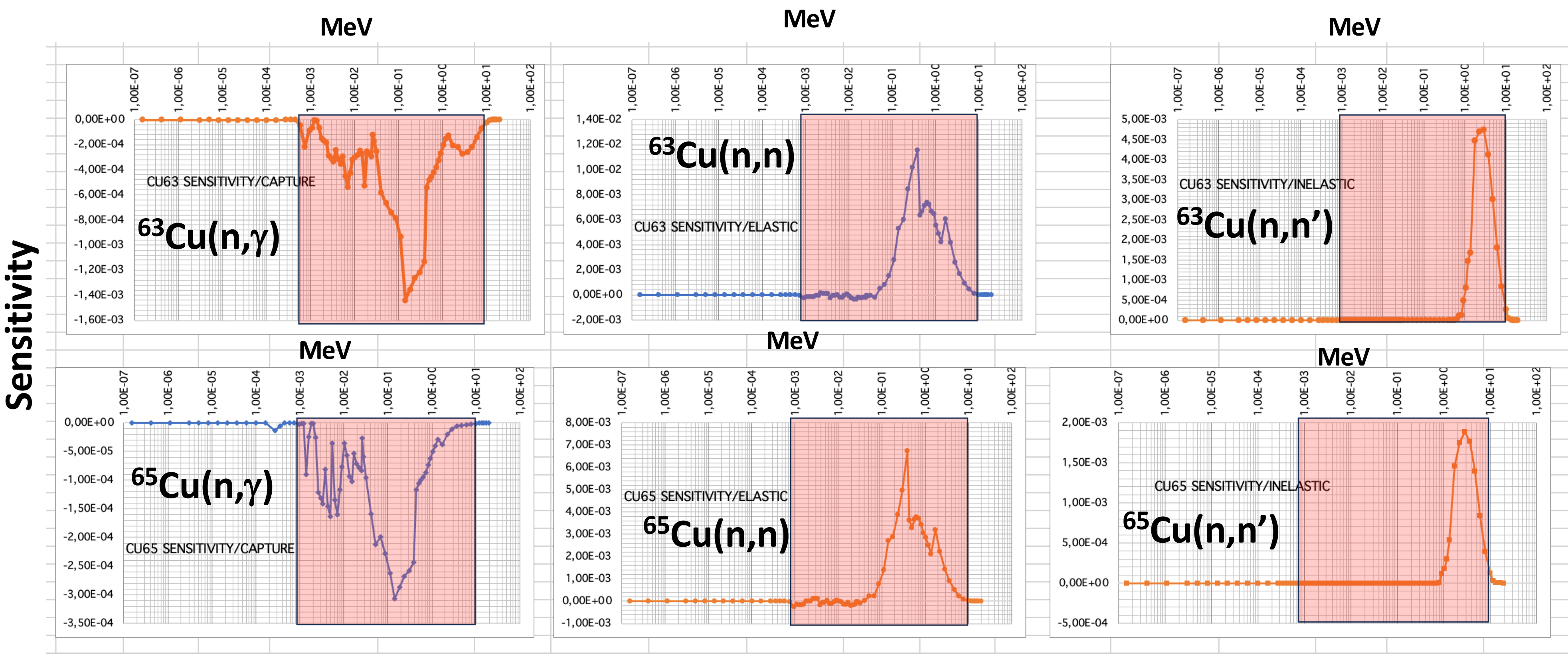
Why ^{63,65}Cu?

Nucl. Techn.

TAPIRO: spectral parameters sensitivity & uncertainty study by ERANOS 2.3



10 keV < E_n < 300 keV

50 keV < E_n < 5 MeV

1 MeV < E_n < 5 MeV

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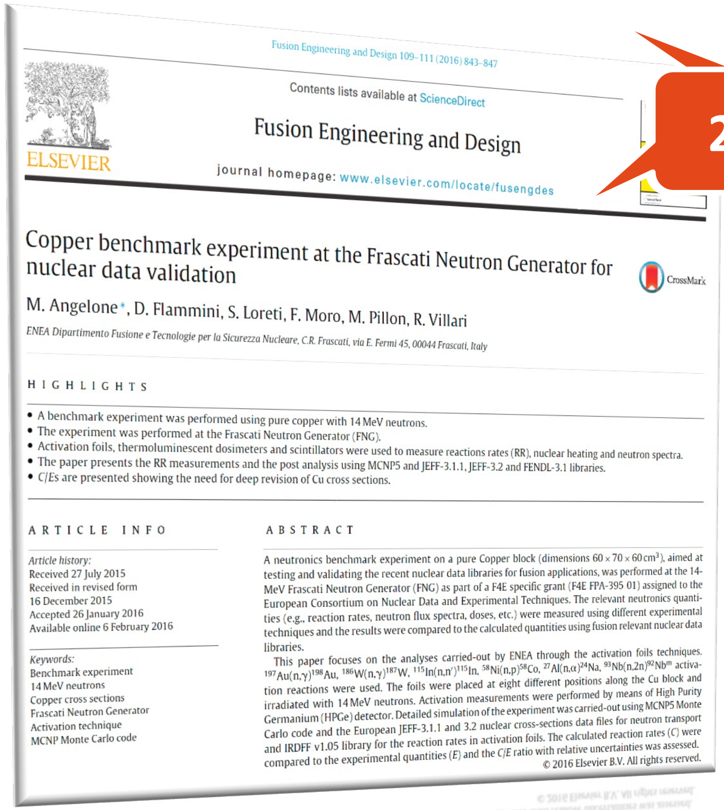
Why $^{63,65}Cu$?

Nucl. Techn.

Fusion – study at FNG

2016



Fusion Engineering and Design 109–111 (2016) 843–847

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journal homepage: www.elsevier.com/locate/fusengdes

ELSEVIER

Copper benchmark experiment at the Frascati Neutron Generator for nuclear data validation

M. Angelone*, D. Flammini, S. Loreti, F. Moro, M. Pillon, R. Villari

ENEA Dipartimento Fusione e Tecnologie per la Sicurezza Nucleare, C.R. Frascati, via E. Fermi 45, 00044 Frascati, Italy

HIGHLIGHTS

- A benchmark experiment was performed using pure copper with 14 MeV neutrons.
- The experiment was performed at the Frascati Neutron Generator (FNG).
- Activation foils, thermoluminescent dosimeters and scintillators were used to measure reactions rates (RR), nuclear heating and neutron spectra.
- The paper presents the RR measurements and the post analysis using MCNP5 and JEFF-3.1.1, JEFF-3.2 and FENDL-3.1 libraries.
- C/Es are presented showing the need for deep revision of Cu cross sections.

ARTICLE INFO

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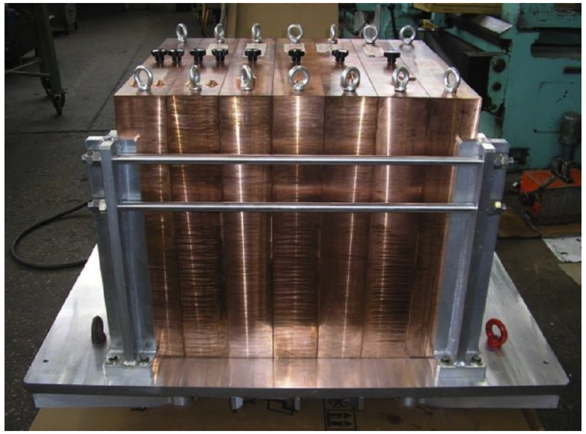
Frascati Neutron Generator
Activation technique
MCNP Monte Carlo code

ABSTRACT

A neutronics benchmark experiment on a pure Copper block (dimensions $60 \times 70 \times 60\,cm^3$), aimed at testing and validating the recent nuclear data libraries for fusion applications, was performed at the 14-MeV Frascati Neutron Generator (FNG) as part of a F4E specific grant (F4E FPA-395 01) assigned to the European Consortium on Nuclear Data and Experimental Techniques. The relevant neutronics quantities (e.g., reaction rates, neutron flux spectra, doses, etc.) were measured using different experimental techniques and the results were compared to the calculated quantities using fusion relevant nuclear data libraries.

This paper focuses on the analyses carried-out by ENEA through the activation foils techniques. $^{197}Au(n,\gamma)^{198}Au$, $^{186}W(n,\gamma)^{187}W$, $^{115}In(n,n')^{115}In$, $^{58}Ni(n,p)^{58}Co$, $^{27}Al(n,\alpha)^{24}Na$, $^{93}Nb(n,2n)^{92}Nb^m$ activation reactions were used. The foils were placed at eight different positions along the Cu block and irradiated with 14 MeV neutrons. Activation measurements were performed by means of High Purity Germanium (HPGe) detector. Detailed simulation of the experiment was carried-out using MCNP5 Monte Carlo code and the European JEFF-3.1.1 and 3.2 nuclear cross-sections data files for neutron transport and IRDFF v1.05 library for the reaction rates in activation foils. The calculated reaction rates (C) were compared to the experimental quantities (E) and the C/E ratio with relative uncertainties was assessed.



Conclusions

…

The present results call for a deep revision/re-evaluation of the copper cross sections. The new release JEFF-3.2 for Cu provided the highest disagreement in the C/E analysis and must be revised. To this end the results of the companion sensitivity/uncertainty post-analysis will help in identifying the main causes of uncertainty in the Cu cross sections. It worth to note that the largest discrepancy among the C/E values was observed for the thermal (capture) reactions suggesting problems and uncertainties in the $^{63,65}Cu$ capture and elastic cross sections at lower energy rather than at high energy.

Nucl. Astro.

n_TOF

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Why ^{63,65}Cu?

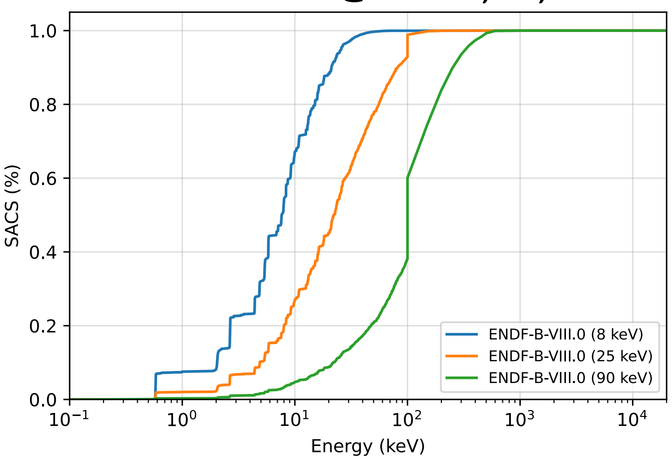
How copper was produced?

Not clear! Candidates:

1. **Weak *s* process (Massive stars)**
2. **Main *s* process (AGB)**
3. **SNe Ia**
4. **SNe II**

^{62}Ga 116.00 ms β^+	^{63}Ga 32.40 s β^+	^{64}Ga 2.63 m β^+	^{65}Ga 15.20 m β^+	^{66}Ga 9.49 h β^+	^{67}Ga 3.26 d β^+	^{68}Ga 1.13 h β^+
^{61}Zn 1.48 m β^+	^{62}Zn 9.19 h β^+	^{63}Zn 38.47 m β^+	^{64}Zn 48.63 59 mb	^{65}Zn 243.63 d 162 mb, β^+	^{66}Zn 27.9 35 mb	^{67}Zn 4.1 153 mb
^{60}Cu 23.70 m β^+	^{61}Cu 3.33 h β^+	^{62}Cu 9.67 m β^+	^{63}Cu 69.17 94 mb	^{64}Cu 12.70 h β^+	^{65}Cu 30.83 41 mb	^{66}Cu 5.12 m β^-
^{59}Ni 75.99 ka 87 mb, β^+	^{60}Ni 26.223 30 mb	^{61}Ni 1.14 82 mb	^{62}Ni 3.634 22.3 mb	^{63}Ni 100.11 a 31 mb, β^-	^{64}Ni 0.926 8.7 mb	^{65}Ni 2.52 h β^-
^{58}Co 70.86 d β^+	^{59}Co 100 38 mb	^{60}Co 5.27 a β^-	^{61}Co 1.65 h β^-	^{62}Co 1.50 m β^-	^{63}Co 27.40 s β^-	^{64}Co 300.00 ms β^-
^{57}Fe 2.119 40 mb	^{58}Fe 0.282 12.1 mb	^{59}Fe 44.50 d β^-	^{60}Fe 1.50 Ma β^-	^{61}Fe 5.98 m β^-	^{62}Fe 1.13 m β^-	^{63}Fe 6.01 s β^-

The *s* process requires
MACS @ kT= 8,25, 90 keV



With accurate determination of Cu MACS, it is possible to clarify what is the s-process contribution to Cu. Once this is done, it will be possible to constrain the Cu production by other nucleosynthesis processes, where stellar and nuclear uncertainties are much larger.

Why ^{63,65}Cu?

Nucl. Astro.

nTOF

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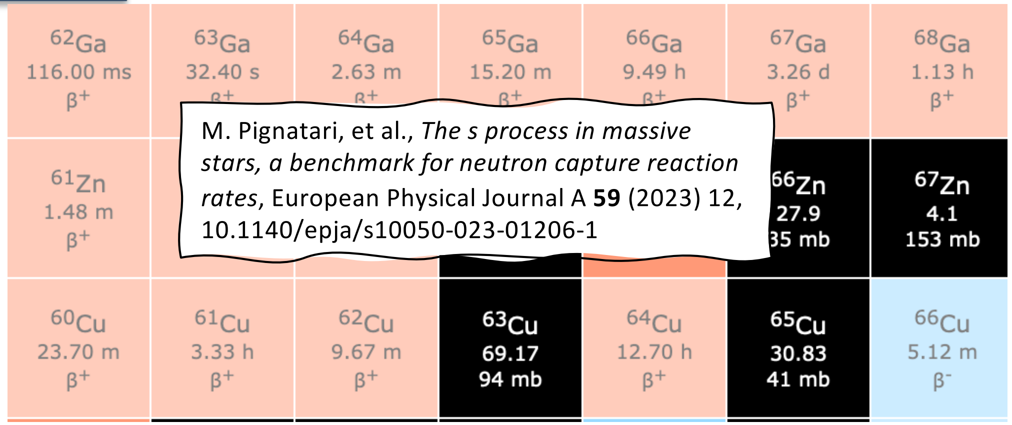
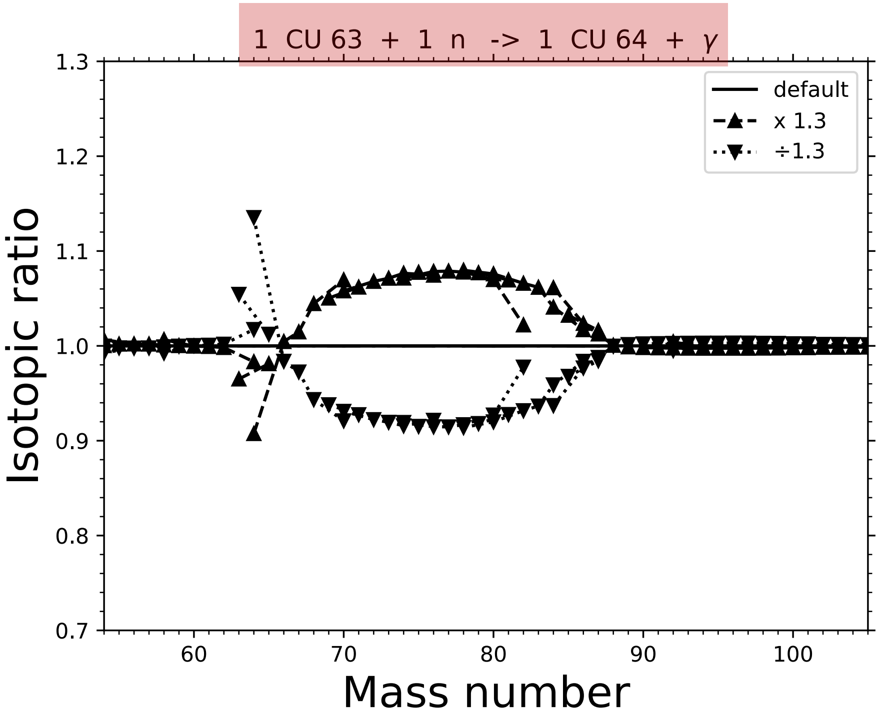
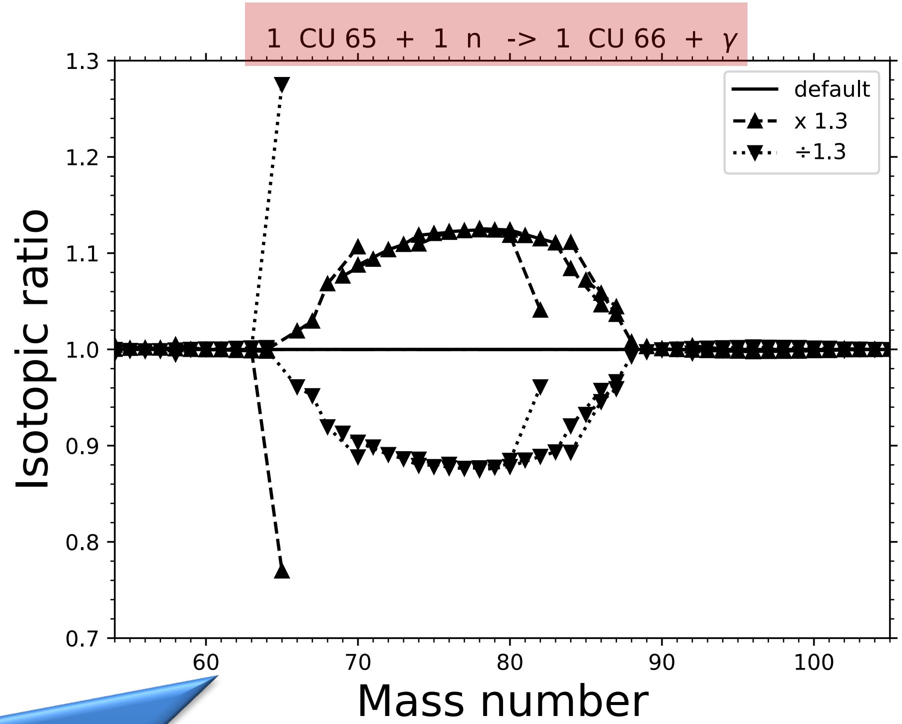


M. Pignatari, et al., *The s process in massive stars, a benchmark for neutron capture reaction rates*, European Physical Journal A **59** (2023) 12, 10.1140/epja/s10050-023-01206-1

Propagation effect in the **weak s-process** nucleosynthesis





Impact of ^{63,65}Cu(n,γ) cross sections on the efficiency for the production of elements heavier than Cu

Data in literature

View Maxwellian-Averaged (n,g) Cross Section

Isotope 63Cu Show

(Examples: Ba138, Ta180m, Se.)

Nucleosynthesis in Stars • Karlsruhe Astrophysical Database of Nucleosynthesis in Stars • KADoNiS

▼ Recommended MACS30 (Maxwellian Averaged Cross Section @ 30keV)

$$^{63}Cu\ (n,\gamma)^{64}Cu$$

Total MACS at 30keV: 60.1 ± 6.2 mb

Cross sections do not include stellar enhancement factors!

▼ History

Version	Total MACS [mb]	Partial to gs [mb]	Partial to isomer [mb]
1.0	60.1 ± 6.2	-	-
0.3	55.6 ± 2.2	-	-
0.0	94 ± 10	-	-

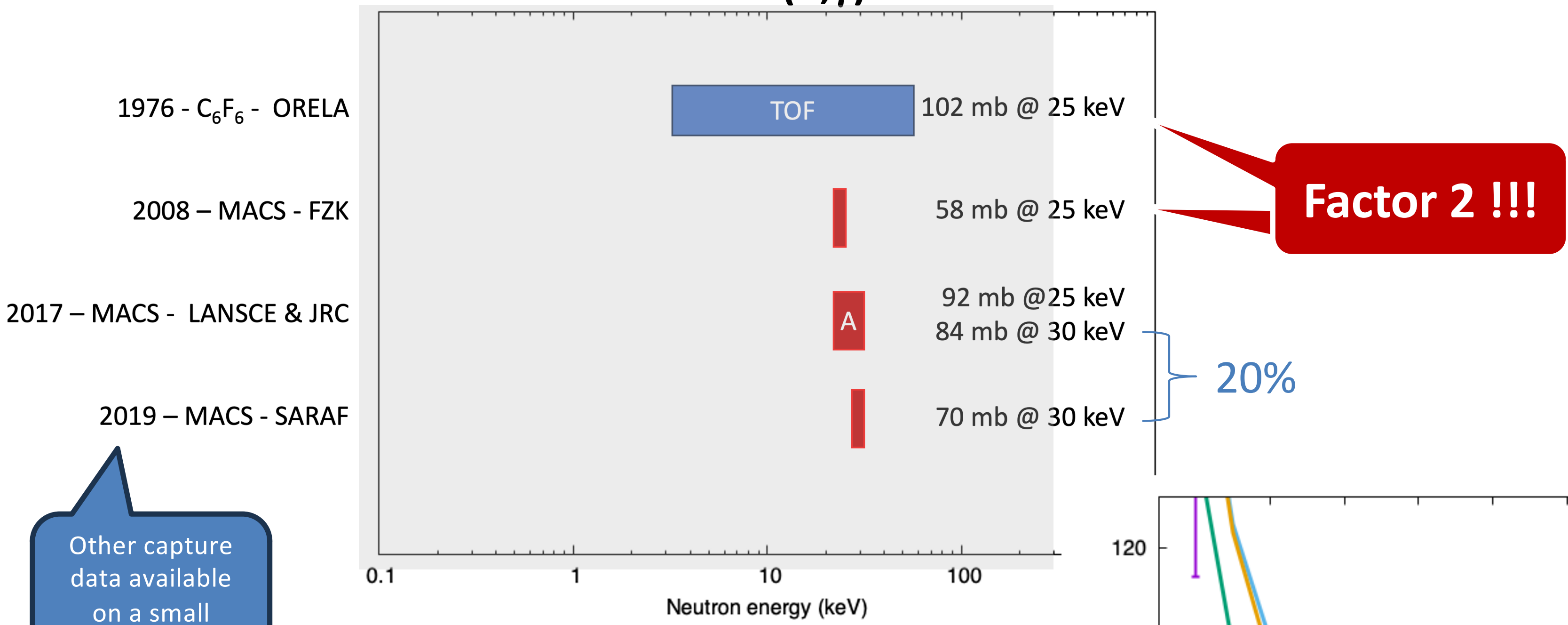
(Version 0.0 corresponds to Bao et al.)

▼ Comment

New rec. value is from HKU08, renormalized by 632 mb/586 mb = 1.0785, and recalculated with normalized energy dependencies of tendl15,endfb71,jendl40. Uncertainty is the deviation between different evaluations plus 4% exp. uncertainty from HKU08. **Note the large deviation between the activation measurement and the TOF measurements. More investigation needed!**
Last review: April 2017

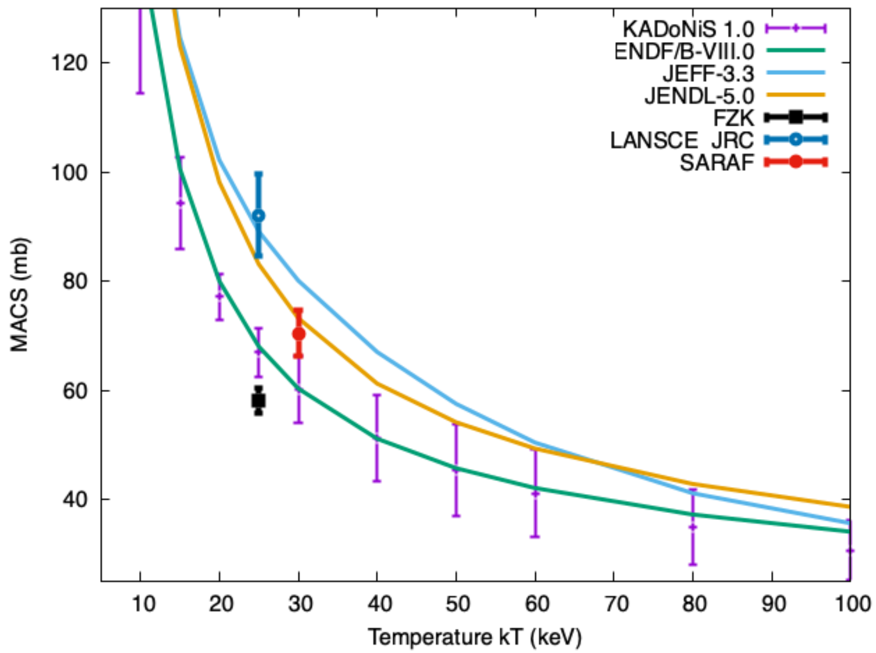
Data in literature

$^{63}Cu(n,\gamma)$



Other capture data available on a small energy range

- Time-of-flight data needed for E_n < 300 keV
- n_TOF can accurately cover this energy region



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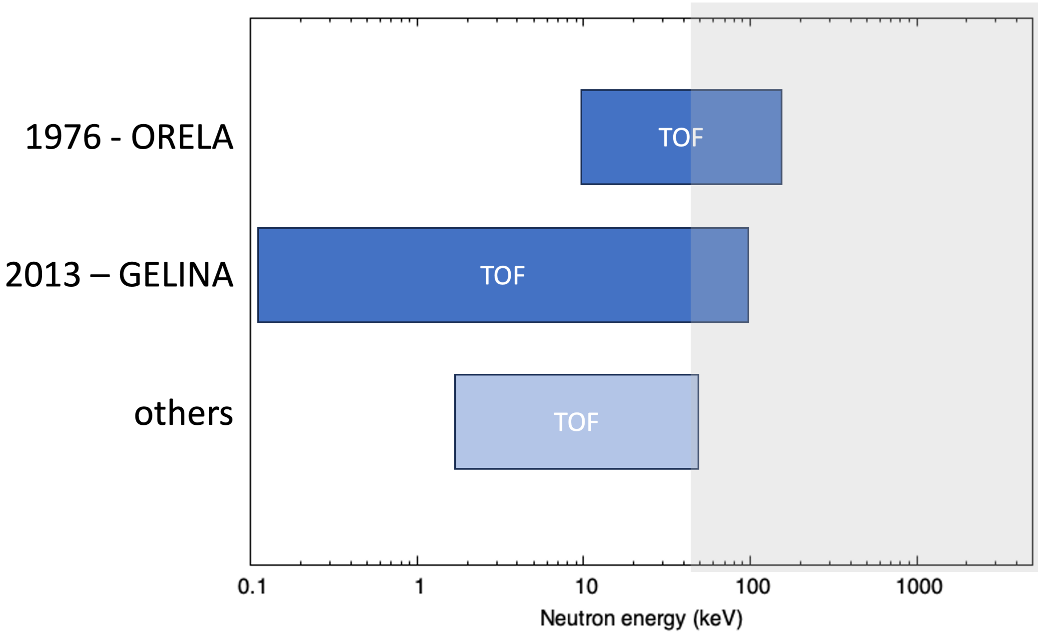
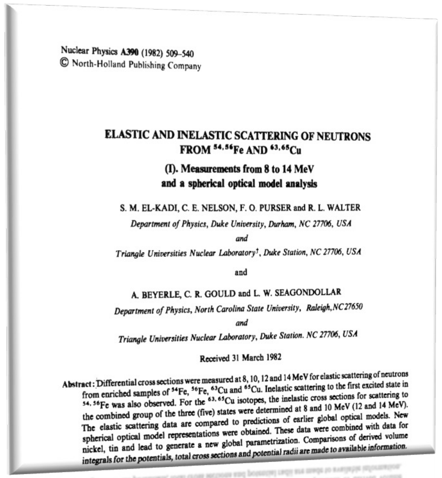
Data in literature

^{63}Cu(n, tot)



- Time-of-flight data needed for 50 KeV < E_n < 5 MeV
- n_TOF can accurately cover this energy region with a transmission experiment; $\sigma_{tot} = \sigma_n + \sigma_\gamma + \sigma_{n'}$
- $\sigma_{tot} \cong \sigma_n$ for E_n< 2 MeV

Link1
Link2
Link3



Nuclear Physics A390 (1982) 509–540
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ELASTIC AND INELASTIC SCATTERING OF NEUTRONS FROM ^{54,56}Fe AND ^{63,65}Cu

(I). Measurements from 8 to 14 MeV and a spherical optical model analysis

S. M. EL-KADI, C. E. NELSON, F. O. PURSER and R. L. WALTER
Department of Physics, Duke University, Durham, NC 27706, USA
and
Triangle Universities Nuclear Laboratory†, Duke Station, NC 27706, USA

and

A. BEYERLE, C. R. GOULD and L. W. SEAGONDOLLAR
Department of Physics, North Carolina State University, Raleigh, NC 27650
and
Triangle Universities Nuclear Laboratory, Duke Station. NC 27706, USA

Received 31 March 1982

Abstract: Differential cross sections were measured at 8, 10, 12 and 14 MeV for elastic scattering of neutrons from enriched samples of ^{54}Fe, ^{56}Fe, ^{63}Cu and ^{65}Cu. Inelastic scattering to the first excited state in ^{54,56}Fe was also observed. For the ^{63,65}Cu isotopes, the inelastic cross sections for scattering to the combined group of the three (five) states were determined at 8 and 10 MeV (12 and 14 MeV). The elastic scattering data are compared to predictions of earlier global optical models. New spherical optical model representations were obtained. These data were combined with data for nickel, tin and lead to generate a new global parametrization. Comparisons of derived volume integrals for the potentials, total cross sections and potential radii are made to available information.

^{63}Cu(n, n)

^{63}Cu(n, n')

Angular distribution

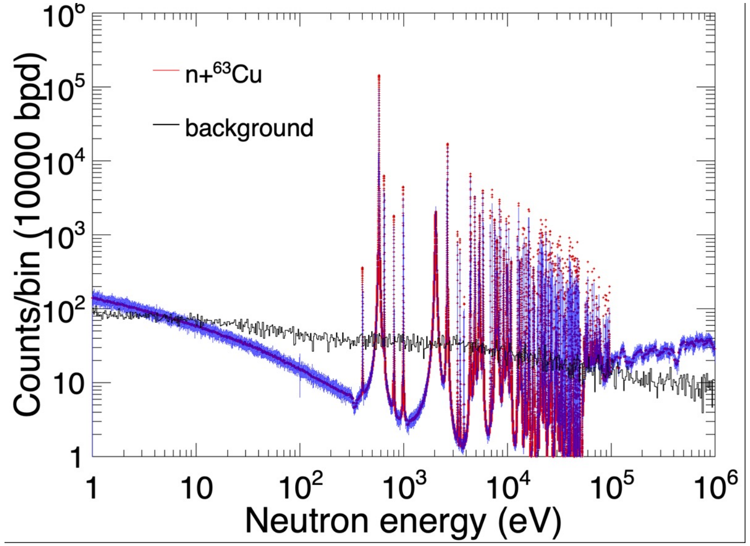
- Currently, detector R&D, to study these channels at n_TOF
- Possible synergy with JRC-Geel

Addendum in the future?

Proposed measurements

Consist of **capture** and **transmission** experiments at **EAR1** using highly enriched samples (**99.8%** in ^{63}**Cu** and **99.0%** in ^{65}**Cu**)

- Capture at EAR1 using 4 C_6D_6

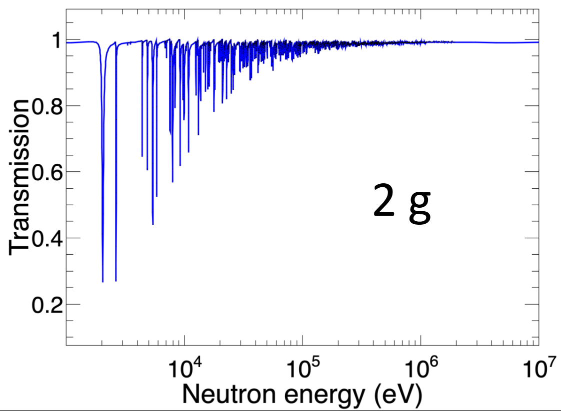


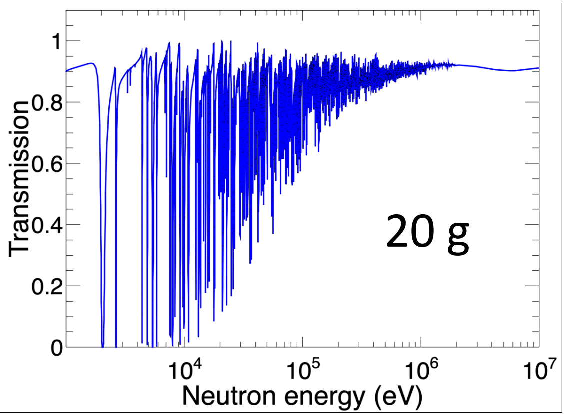
Example:

2 grams of ^{63}Cu and cylindrical sample of 1.5 cm radius (2.7×10^{-3} at/b)

2×10^{18} protons

- Transmission at EAR1 using ^{235}U fission chamber from PTB





Proposed measurements

Consist of **capture** and **transmission** experiments at **EAR1** using highly enriched samples (**99.8%** in **^{63}Cu** and **99.0%** in **^{65}Cu**)

Experiment	Sample	Protons	Comments
Capture	^{63}Cu	2.0×10^{18}	
Capture	^{65}Cu	2.0×10^{18}	
Capture	^{nat}Cu	0.3×10^{18}	EAR1 or EAR2
Capture	Empty-sample	0.2×10^{18}	background study
Capture	Pb	0.2×10^{18}	background study
Capture	C	0.2×10^{18}	background study
Capture	^{197}Au	0.1×10^{18}	normalization
Transmission	^{63}Cu	1.0×10^{18}	"Sample-in"
Transmission	^{65}Cu	1.0×10^{18}	"Sample-in"
Transmission	Empty-sample	1.0×10^{18}	"Sample-out"
		8.0×10^{18}	

Target:
- Observe resonances up to 50-200 keV
- σ_γ uncertainty below 3-5%

Target:
- σ_{tot} uncertainty below 5% for E_n > 100 keV with 100 bpd

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Conclusion

- n+^{63,65}Cu is an intriguing physics case! (new entry in HPRL?)

- Capture and transmission @ EAR1
  - 5x10^{18} Protons for ^{63}Cu(n,γ) and ^{65}Cu(n,γ)
  - 3x10^{18} Protons for ^{63}Cu(n,tot) and ^{65}Cu(n,tot)

Total: 8x10^{18} protons on target

- Proton request split into 2 runs over 2 years
  - e.g., (n,γ) in 2024 and (n,tot) in 2025

- Other reactions in future dedicated addendum (if feasible)

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Acknowledgement:

- ERANOS Sensitivity studies by **Donato Maurizio Castelluccio**
- MCNP calculations by **Patrizio Console Camprini**
- Massive stars sensitivity study by **Marco Pignatari**

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Cristian Massimi

Department of Physics and Astronomy

cristian.massimi@unibo.it

Why ^{63,65}Cu?

Natural abundance:
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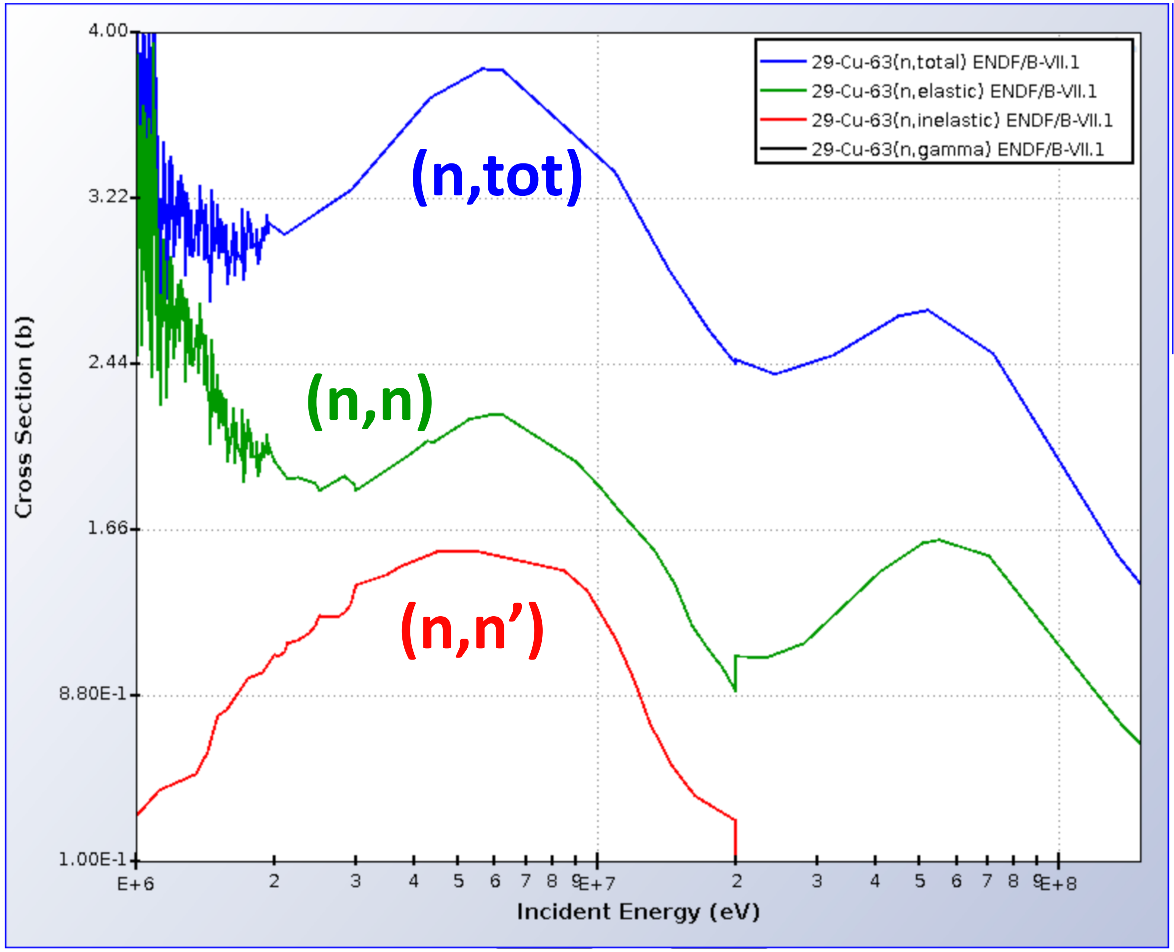

$\sigma_n >> \sigma_\gamma$
$\sigma_{el} > \sigma_{inel}$

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$^{63}Ni + p$	715.4 ± 0.6

Why $^{63,65}Cu$?

Nucl. Techn.

TAPIRO: **ERANOS** → S/U analysis

Sensitivity and Uncertainty (S/U) analysis was performed using the deterministic code ERANOS 2.3, for:

1. k_{eff} parameter — (n,n), (n,n'), (n,γ)
2. ratio of fission reaction rates U238/U235 — (n,n'), (n,n), (n,γ)
3. ratio of fission r.r. Np237/U235 — (n,n), (n,n'), (n,γ)

Relevant energy region

- **Elastic:** **50 keV < E_n < 5 MeV**
- **Inelastic** **1 MeV < E_n < 5 MeV**
- **Rad. capture:** **10 keV < E_n < 300 keV**

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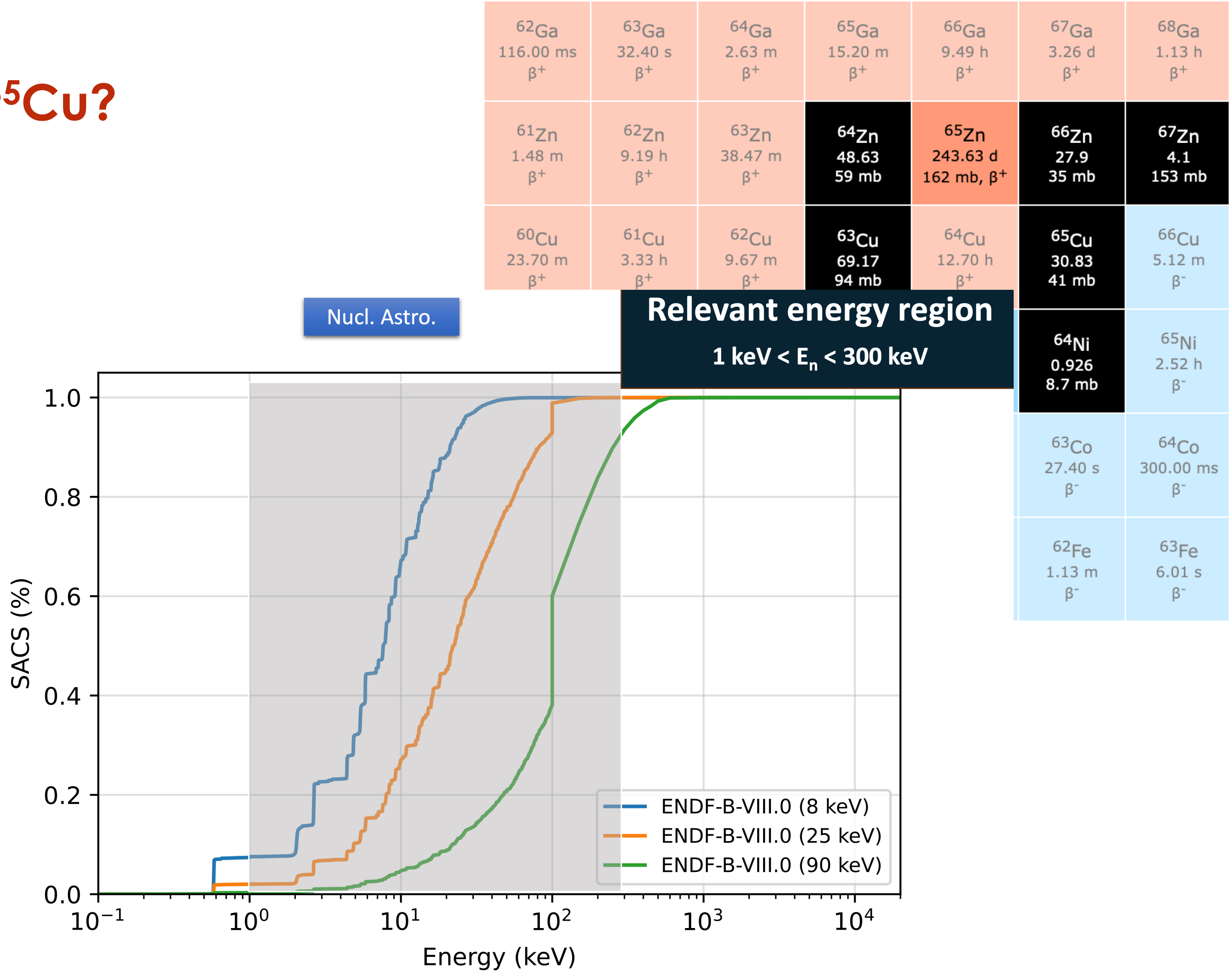
Why ^{63,65}Cu?

^{63}Cu(n,γ)

% MACS



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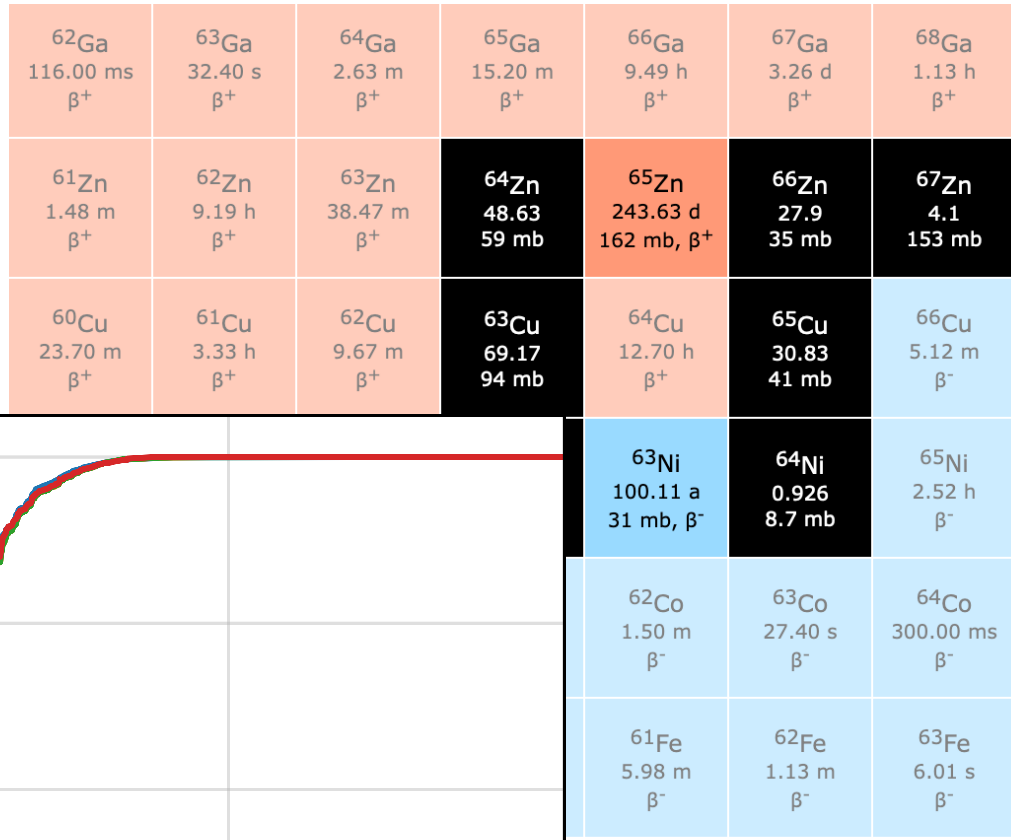
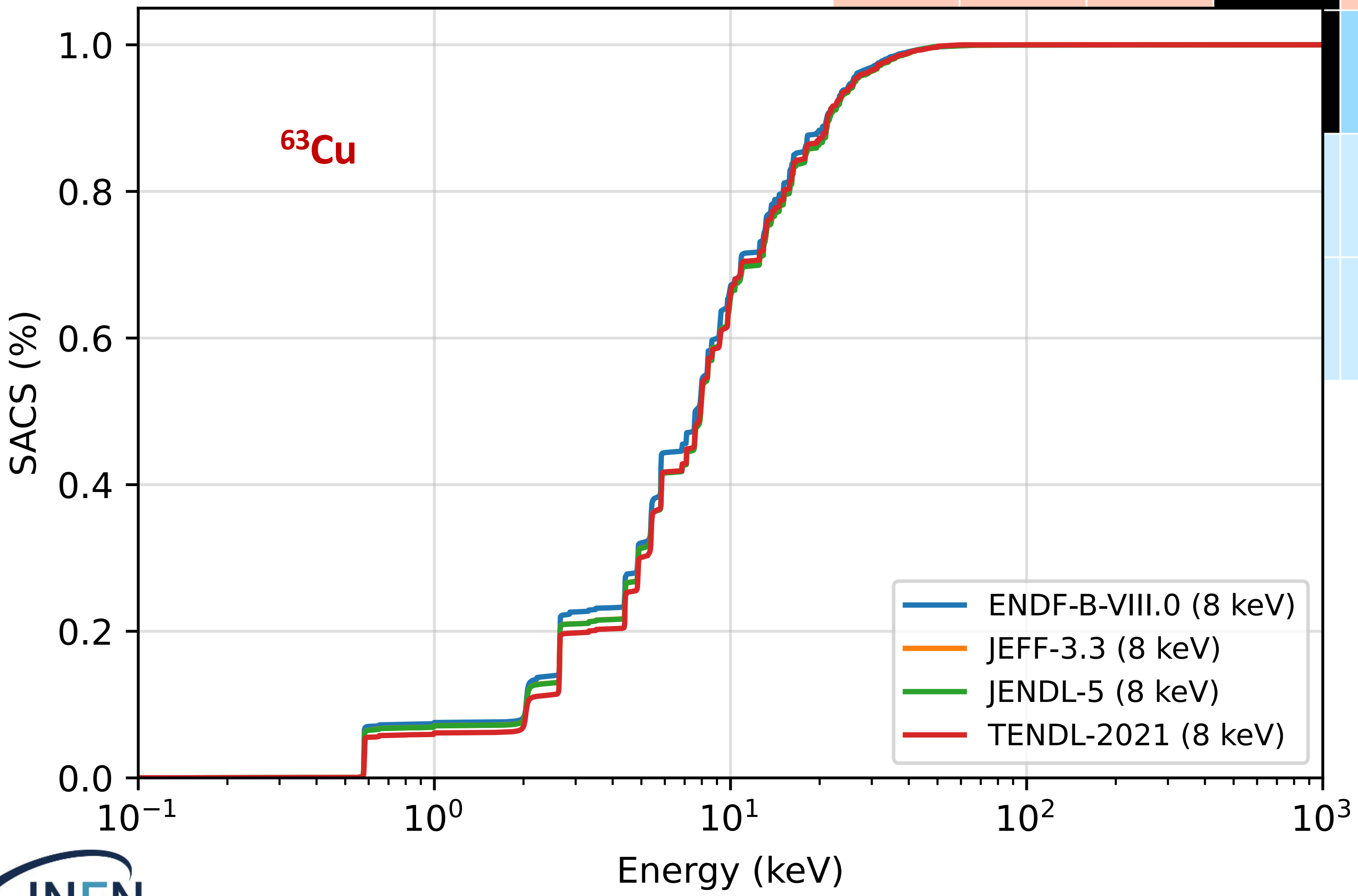
Why $^{63,65}Cu$?





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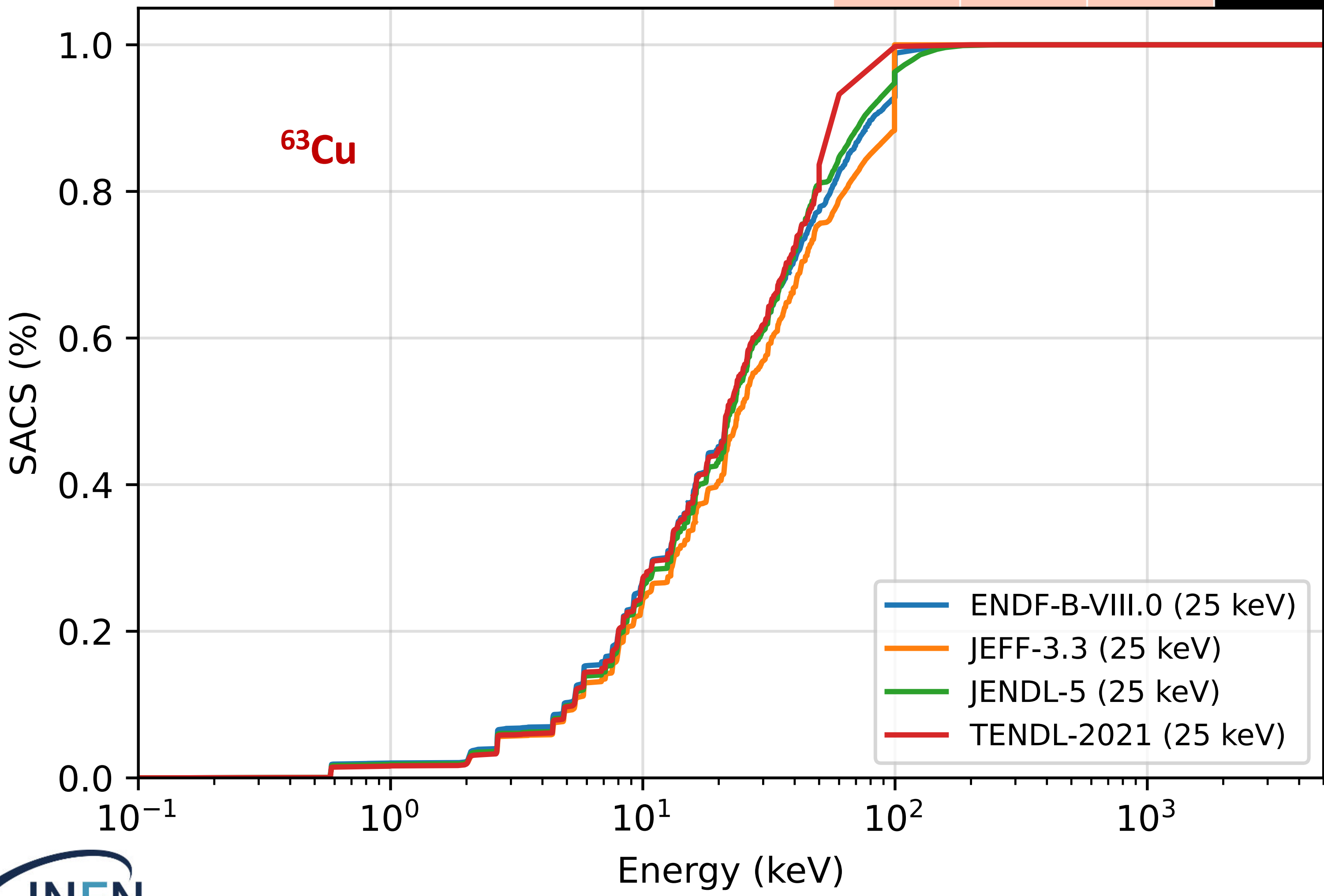
Why ^{63,65}Cu?

^{62}Ga 116.00 ms β+	^{63}Ga 32.40 s β+	^{64}Ga 2.63 m β+	^{65}Ga 15.20 m β+	^{66}Ga 9.49 h β+	^{67}Ga 3.26 d β+	^{68}Ga 1.13 h β+
^{61}Zn 1.48 m β+	^{62}Zn 9.19 h β+	^{63}Zn 38.47 m β+	^{64}Zn 48.63 59 mb	^{65}Zn 243.63 d 162 mb, β+	^{66}Zn 27.9 35 mb	^{67}Zn 4.1 153 mb
^{60}Cu 23.70 m β+	^{61}Cu 3.33 h β+	^{62}Cu 9.67 m β+	^{63}Cu 69.17 94 mb	^{64}Cu 12.70 h β+	^{65}Cu 30.83 41 mb	^{66}Cu 5.12 m β-
				^{63}Ni 100.11 a 31 mb, β-	^{64}Ni 0.926 8.7 mb	^{65}Ni 2.52 h β-
				^{62}Co 1.50 m β-	^{63}Co 27.40 s β-	^{64}Co 300.00 ms β-
				^{61}Fe 5.98 m β-	^{62}Fe 1.13 m β-	^{63}Fe 6.01 s β-



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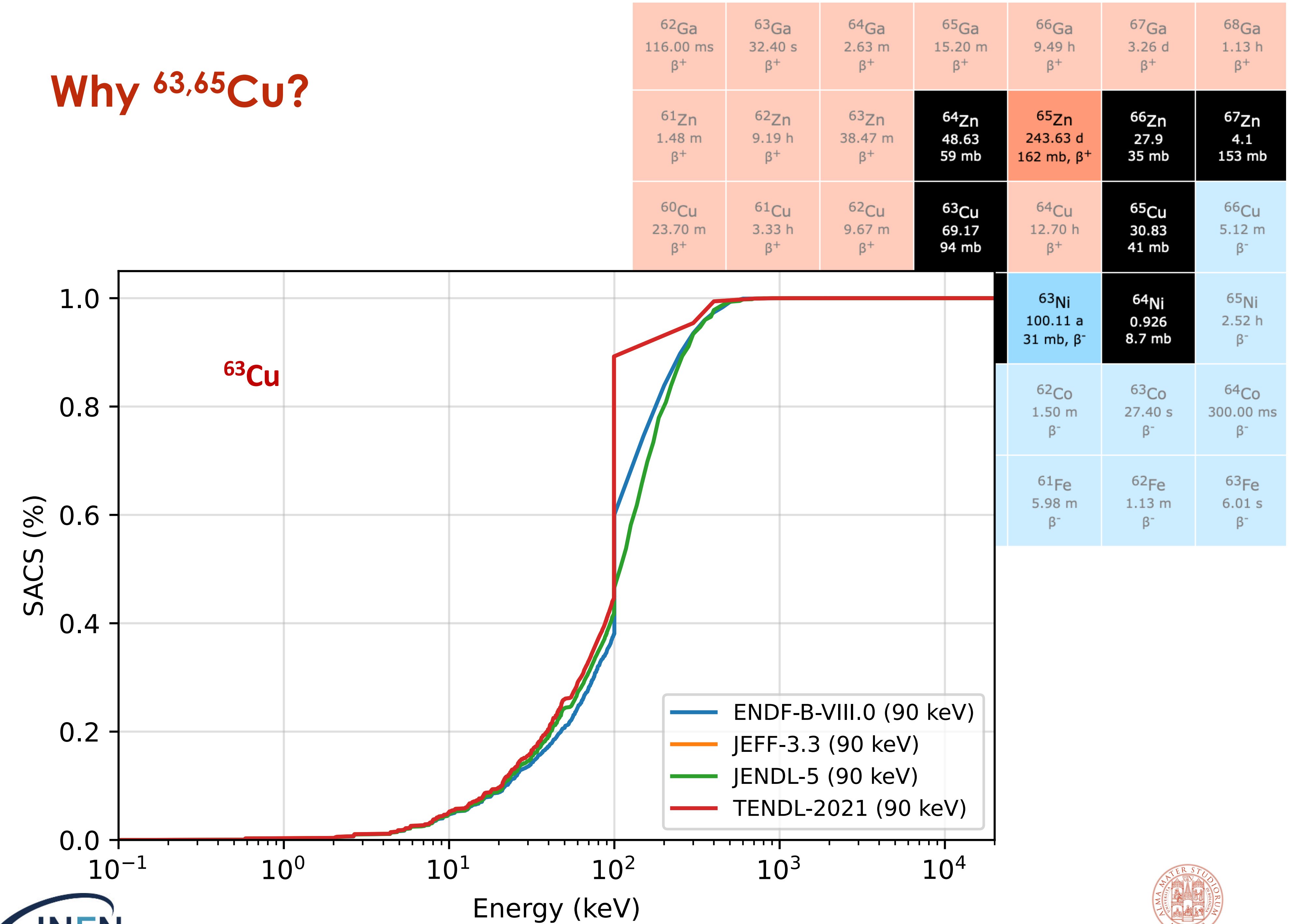
Why ^{63,65}Cu?



62Ga 116.00 ms β+
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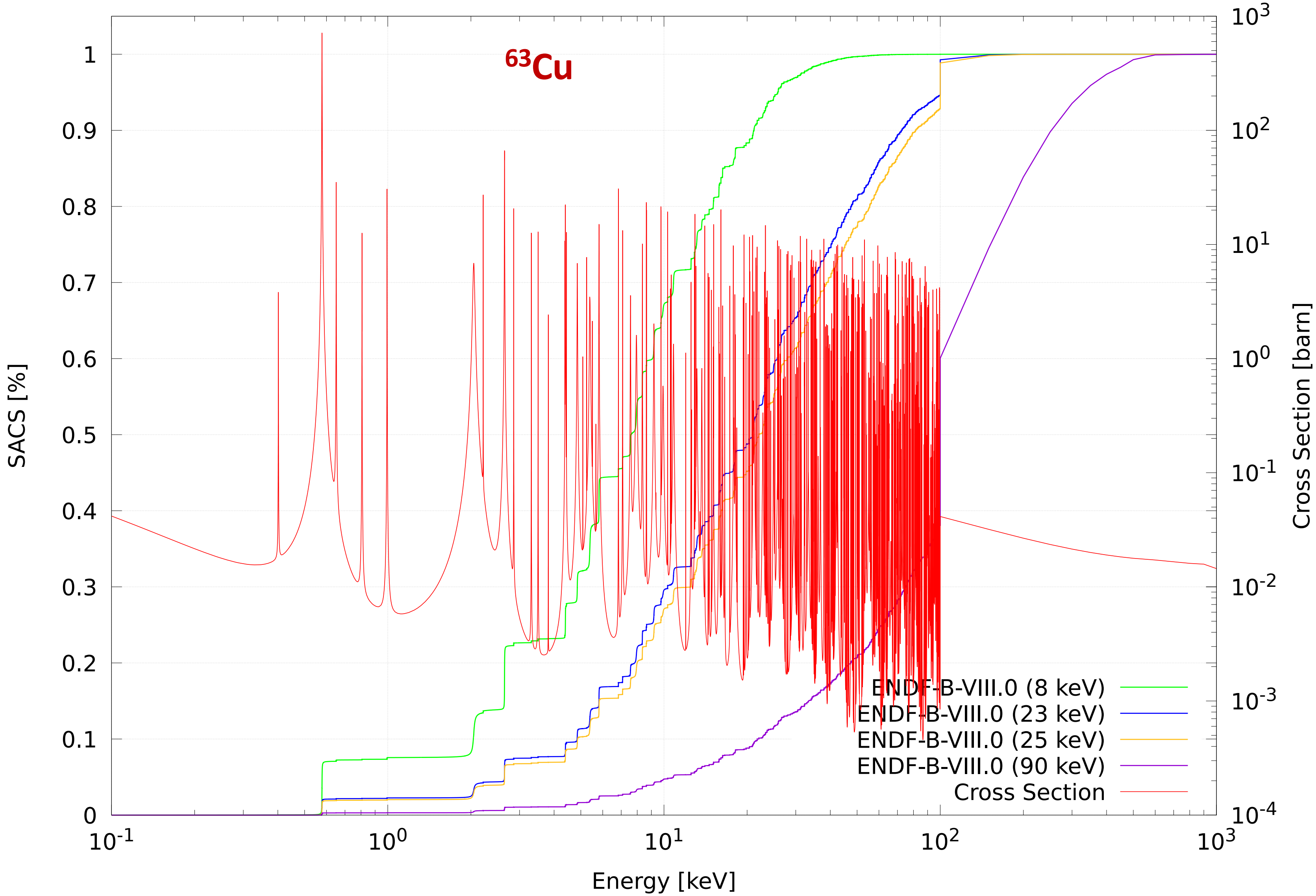
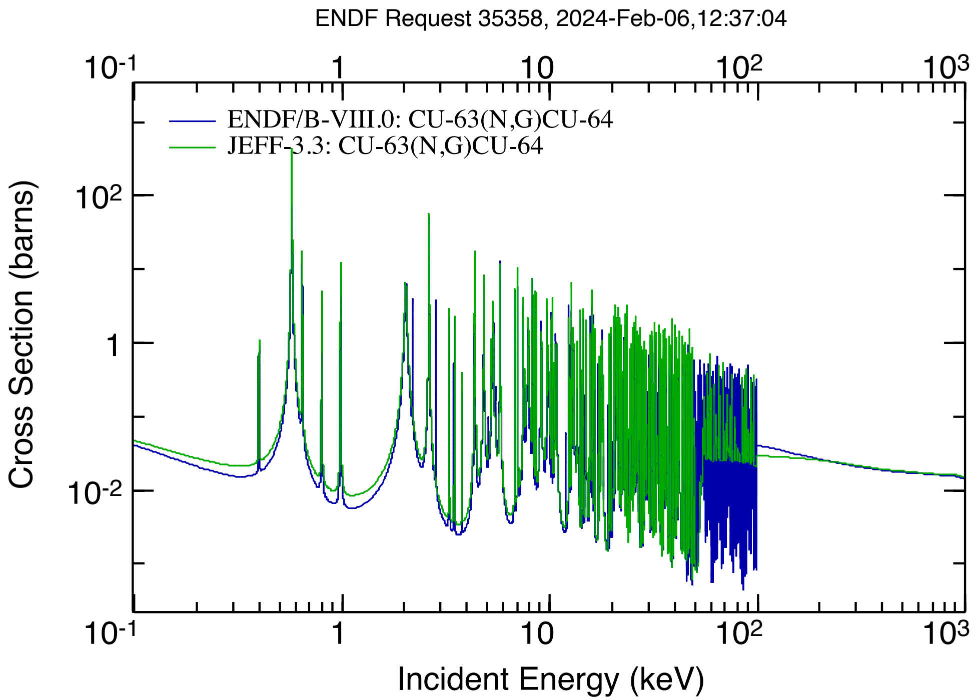
64Cu 12.70 h β+
65Cu 30.83 41 mb
66Cu 5.12 m β-
63Ni 100.11 a 31 mb, β-
64Ni 0.926 8.7 mb
65Ni 2.52 h β-
62Co 1.50 m β-
63Co 27.40 s β-
64Co 300.00 ms β-
61Fe 5.98 m β-
62Fe 1.13 m β-
63Fe 6.01 s β-
63Cu
SACS (%)
Energy (keV)
ENDF-B-VIII.0 (90 keV)
JEFF-3.3 (90 keV)
JENDL-5 (90 keV)
TENDL-2021 (90 keV)

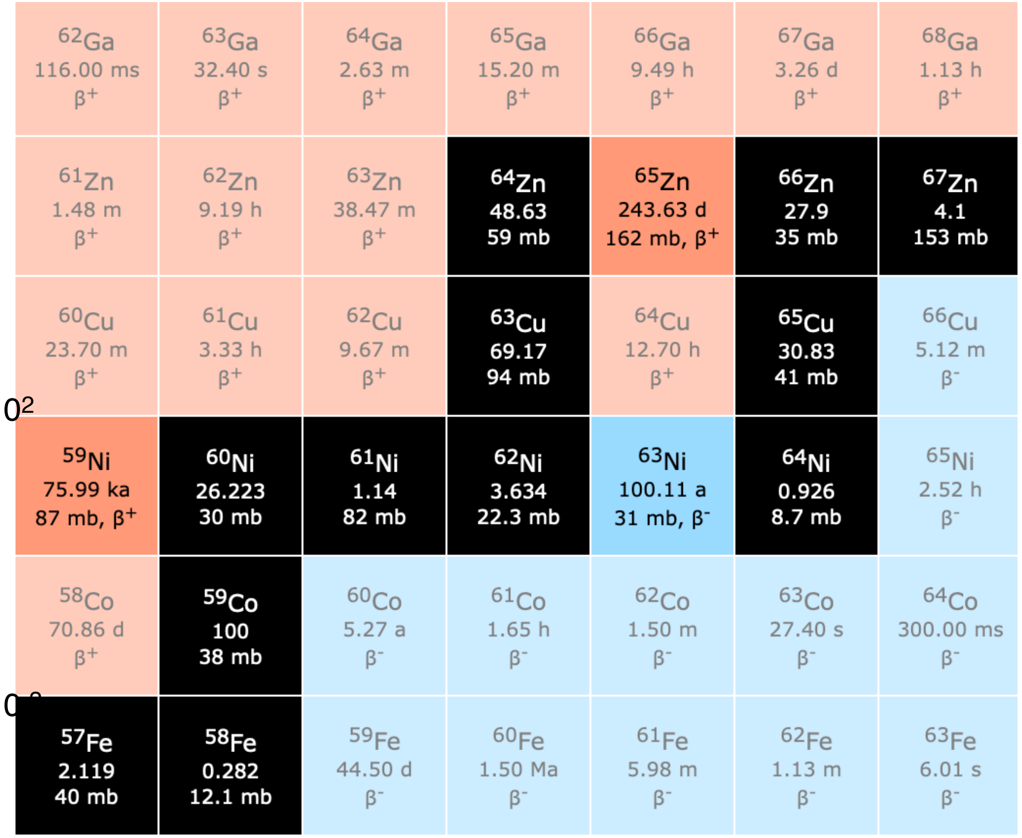
Why ^{63,65}Cu?

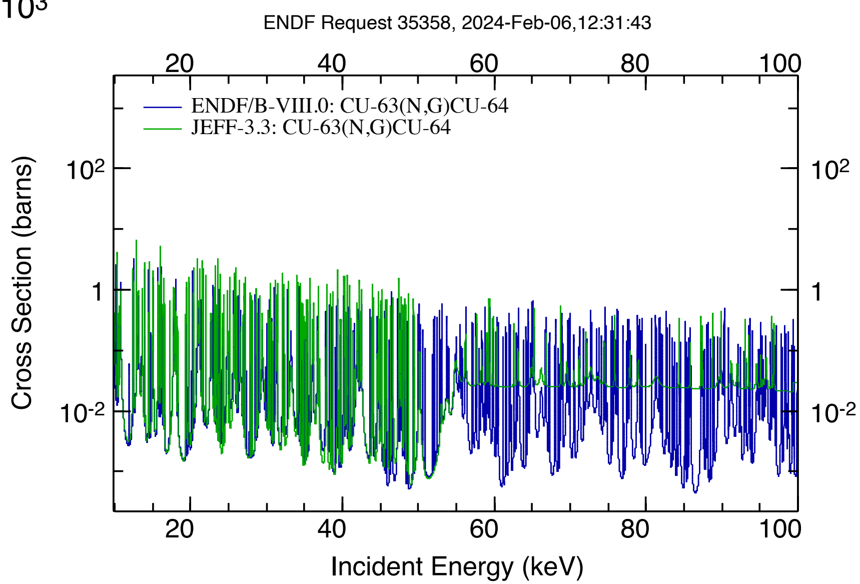


63Cu
SACS [%]
Cross Section [barn]
Energy [keV]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
10^-1
10^0
10^1
10^2
10^3
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
ENDF-B-VIII.0 (8 keV)
ENDF-B-VIII.0 (23 keV)
ENDF-B-VIII.0 (25 keV)
ENDF-B-VIII.0 (90 keV)
Cross Section

Why ^{63,65}Cu?







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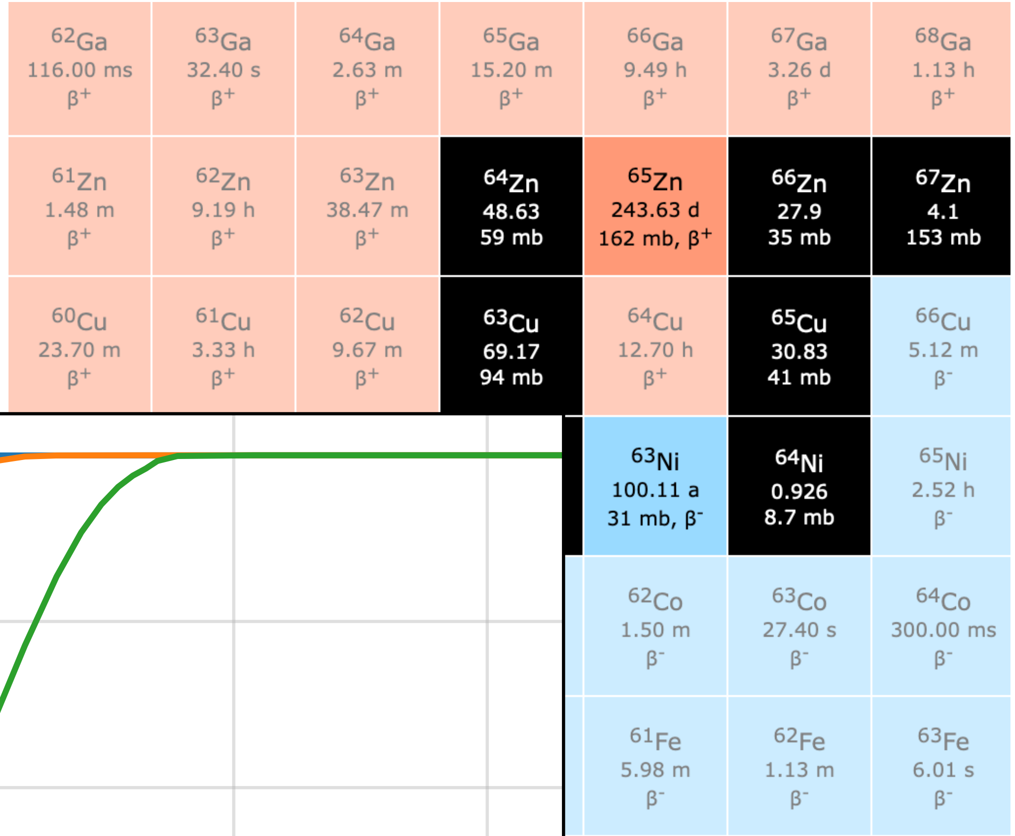
Why ^{63,65}Cu?



62Ga 116.00 ms β+
63Ga 32.40 s β+
64Ga 2.63 m β+
65Ga 15.20 m β+
66Ga 9.49 h β+
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66Cu 5.12 m β-
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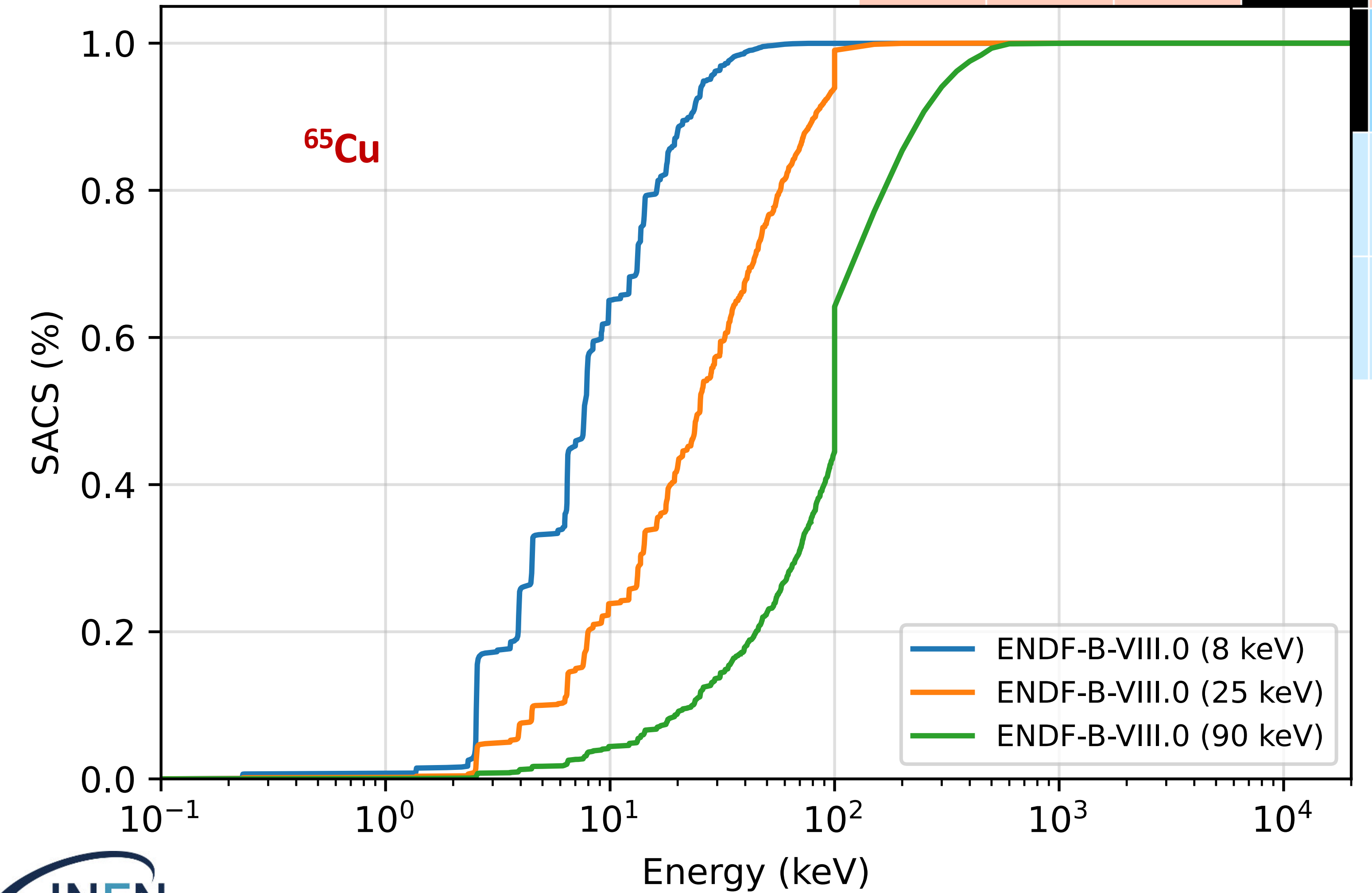
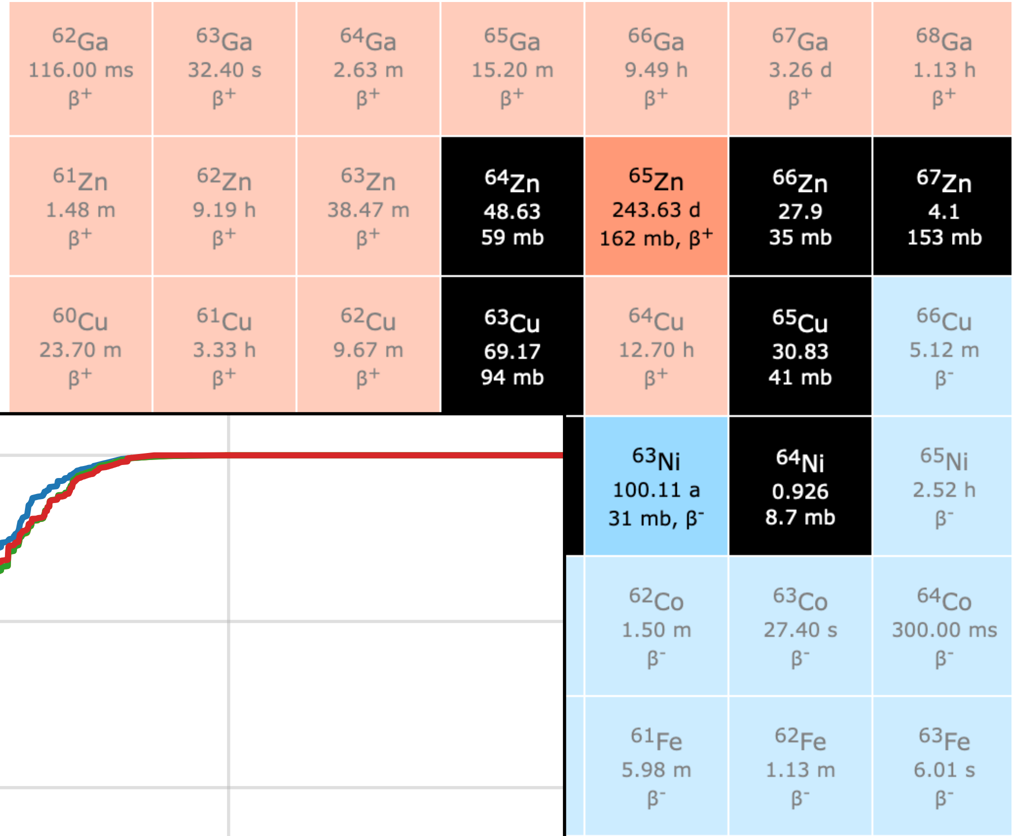
64Ni 0.926 8.7 mb
65Ni 2.52 h β-
62Co 1.50 m β-
63Co 27.40 s β-
64Co 300.00 ms β-
61Fe 5.98 m β-
62Fe 1.13 m β-
63Fe 6.01 s β-



65Cu
SACS (%)
Energy (keV)
ENDF-B-VIII.0 (8 keV)
ENDF-B-VIII.0 (25 keV)
ENDF-B-VIII.0 (90 keV)

Why $^{63,65}Cu$?



62Ga 116.00 ms β+
63Ga 32.40 s β+
64Ga 2.63 m β+
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63Ni 100.11 a 31 mb, β-
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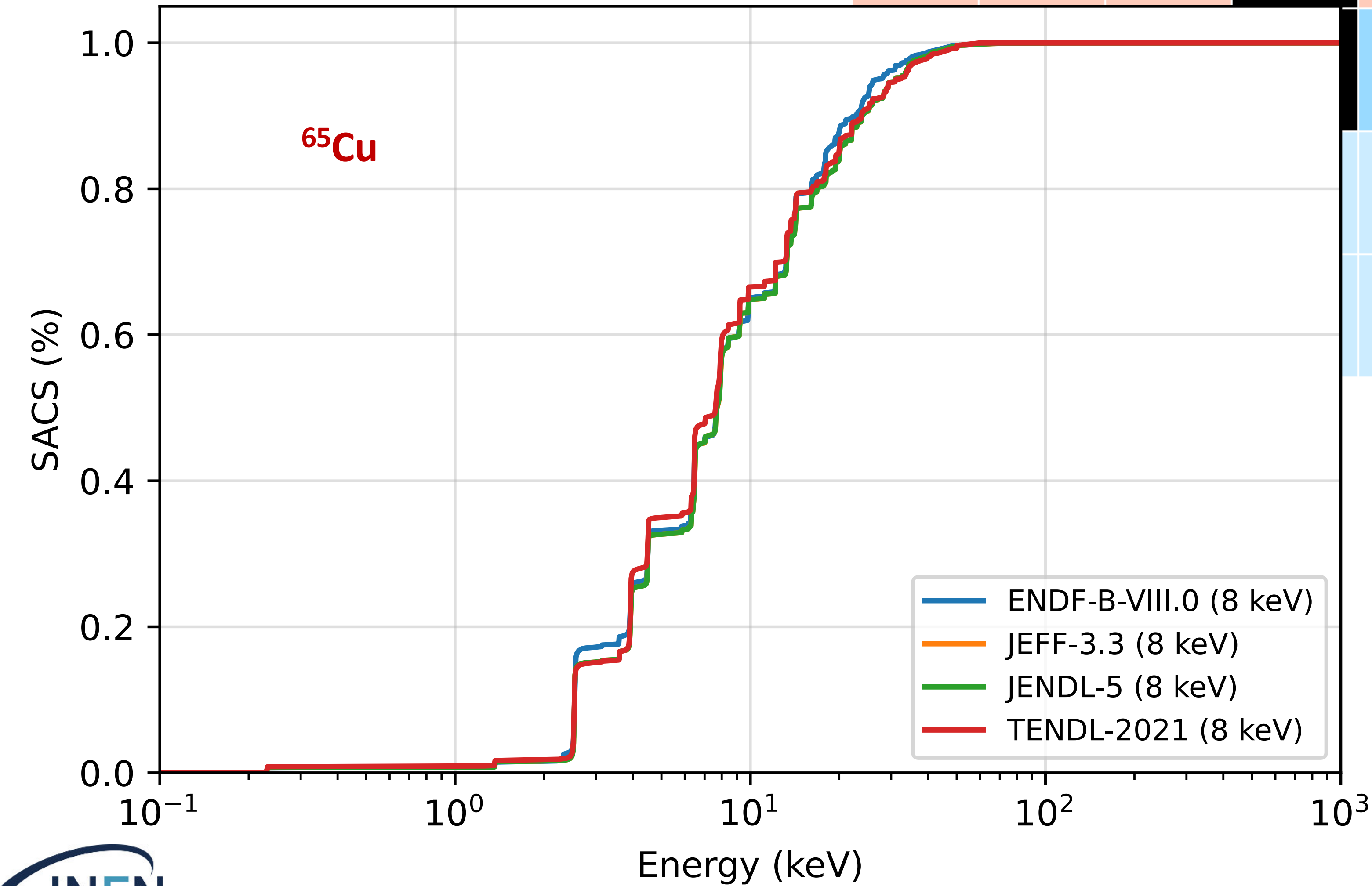
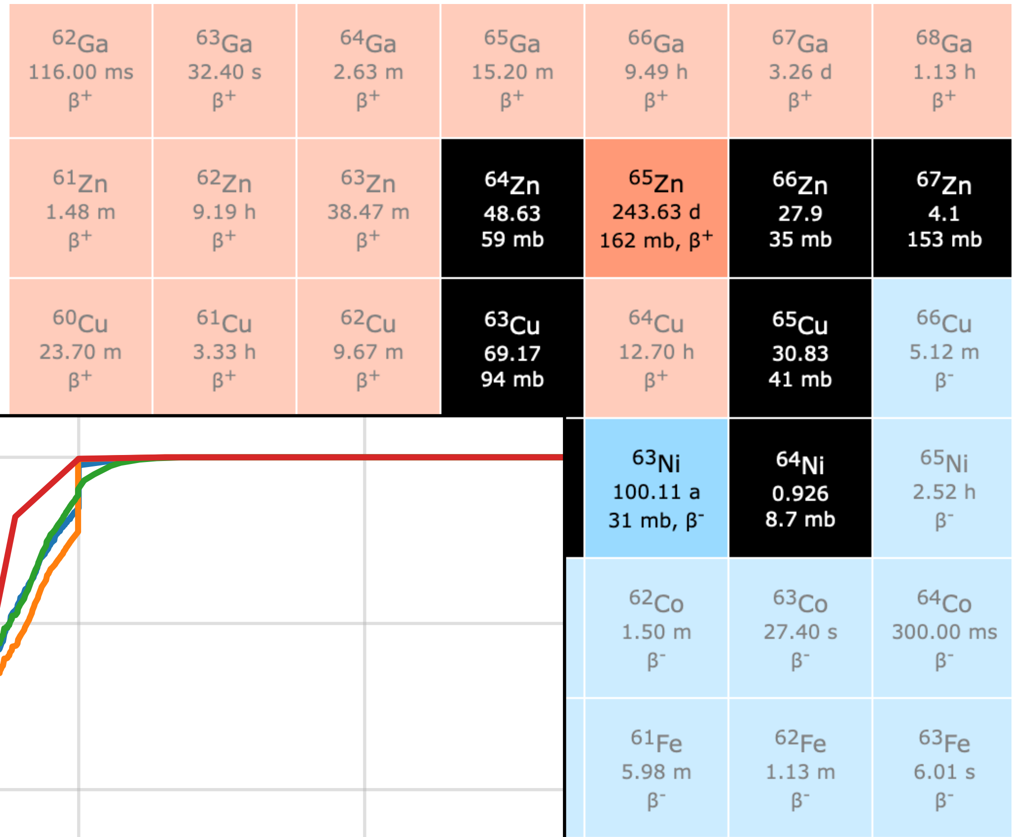
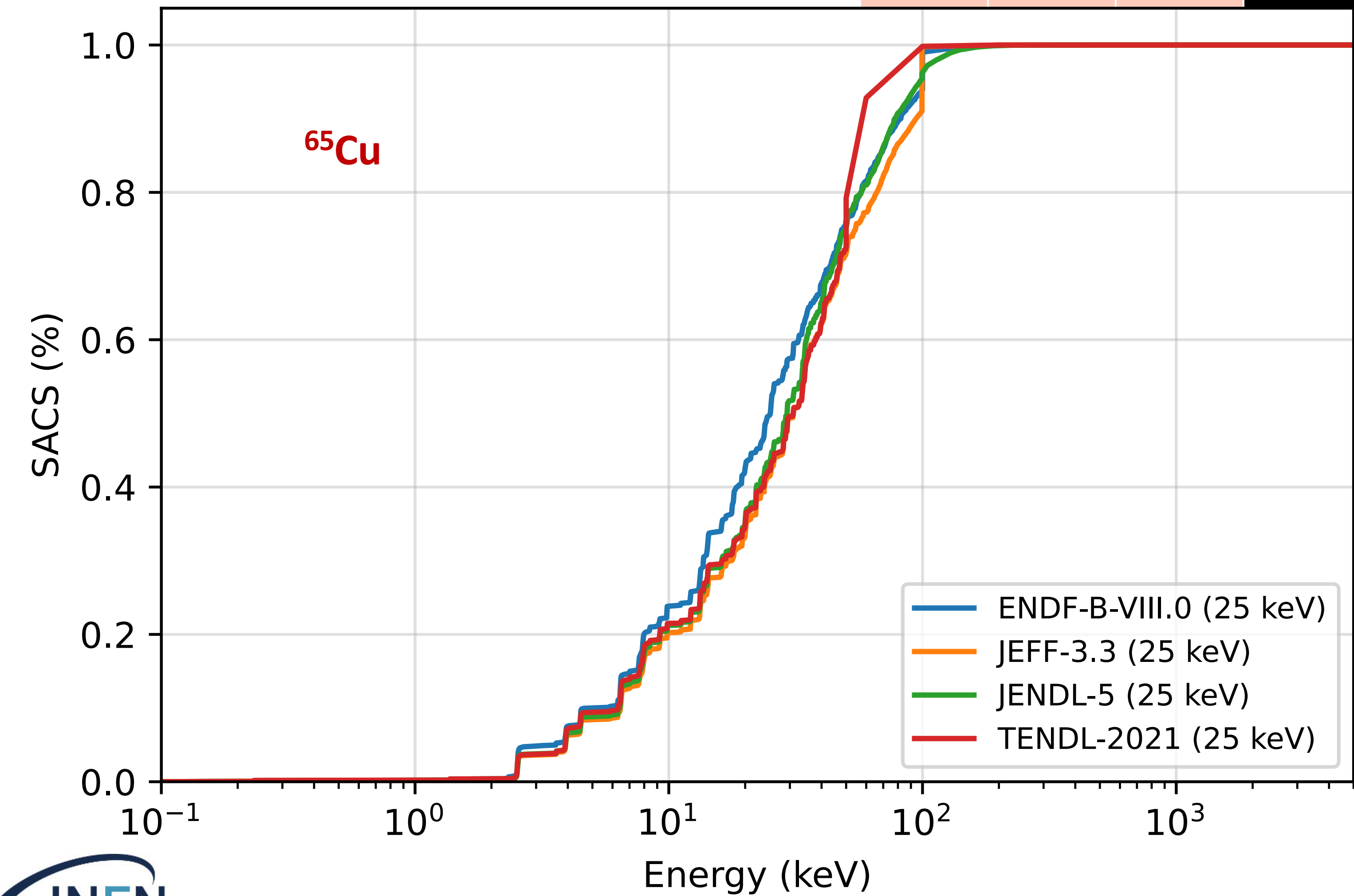


65Cu
SACS (%)
1.0
0.8
0.6
0.4
0.2
0.0
10−1
100
101
102
103
Energy (keV)
ENDF-B-VIII.0 (8 keV)
JEFF-3.3 (8 keV)
JENDL-5 (8 keV)
TENDL-2021 (8 keV)

Why $^{63,65}Cu$?





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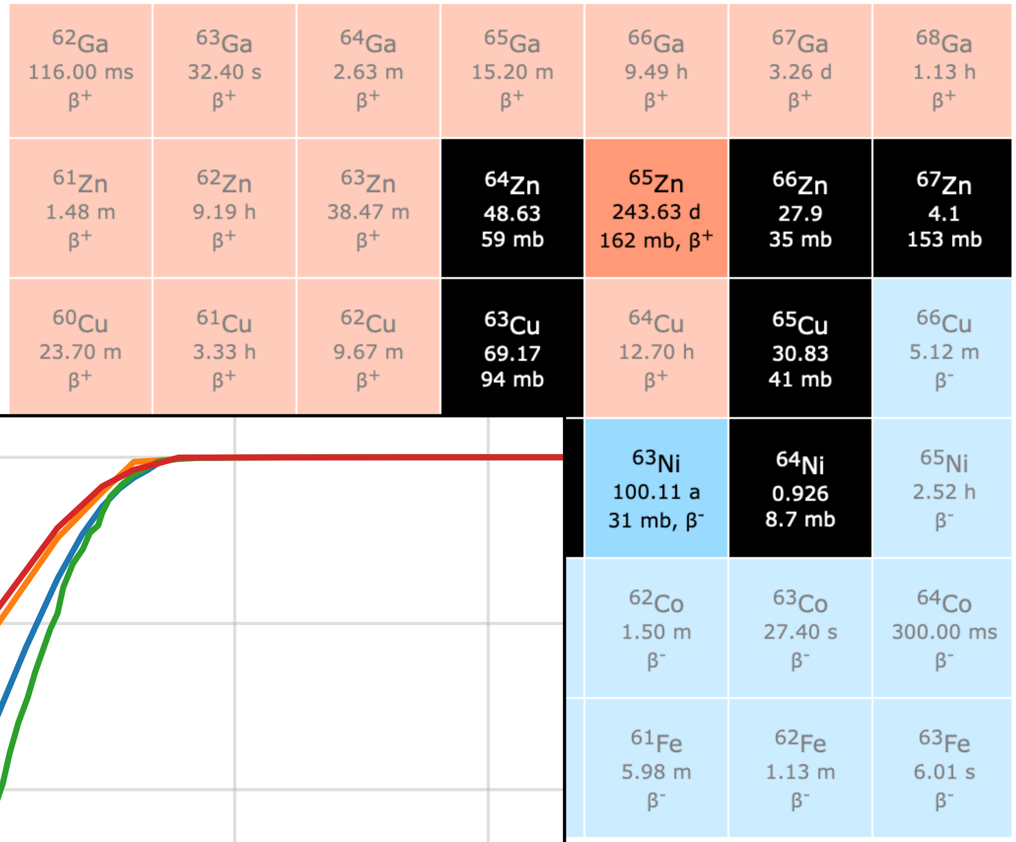
Why ^{63,65}Cu?



62Ga 116.00 ms β+
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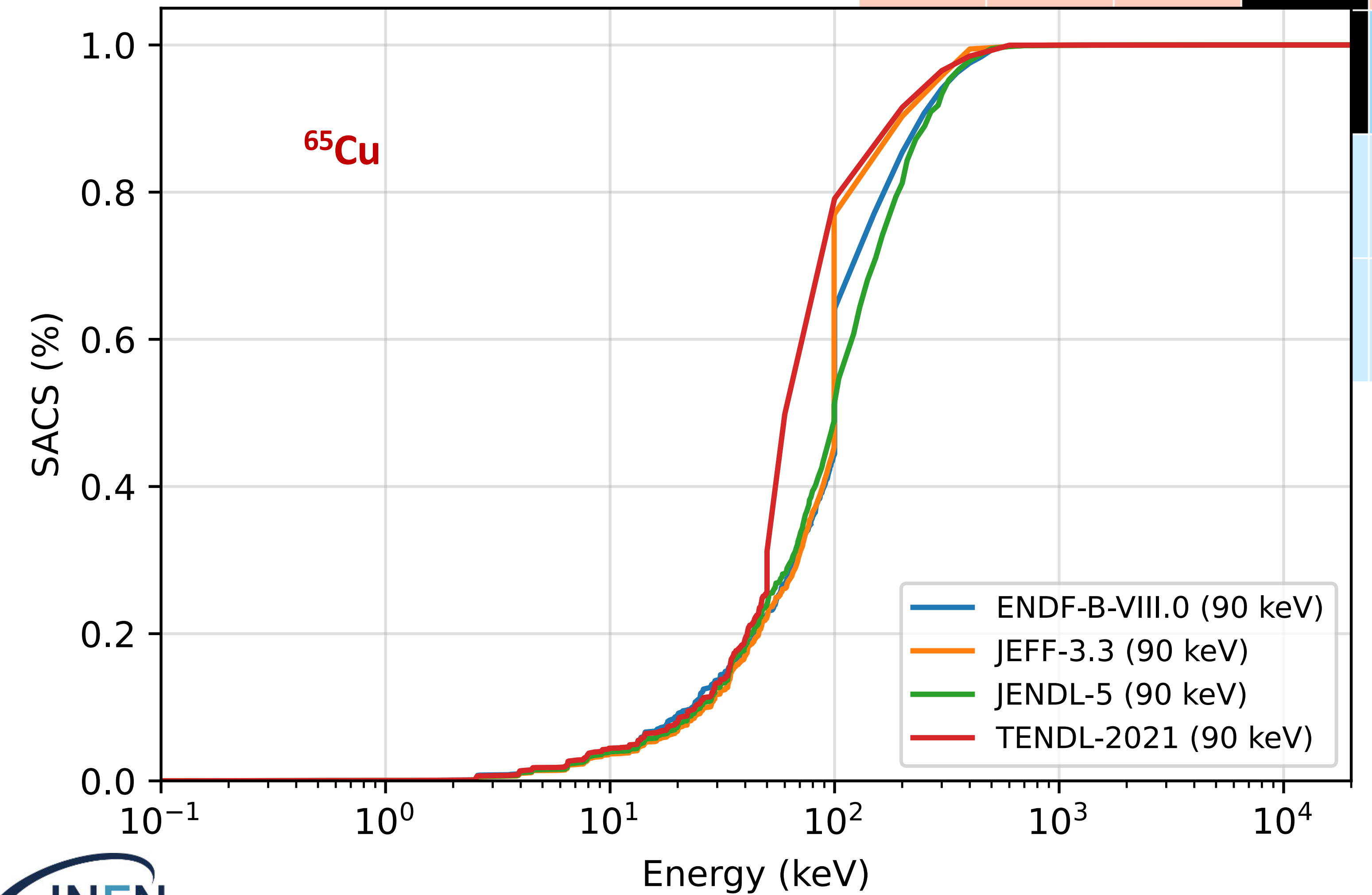


65Cu
SACS (%)
Energy (keV)
ENDF-B-VIII.0 (90 keV)
JEFF-3.3 (90 keV)
JENDL-5 (90 keV)
TENDL-2021 (90 keV)

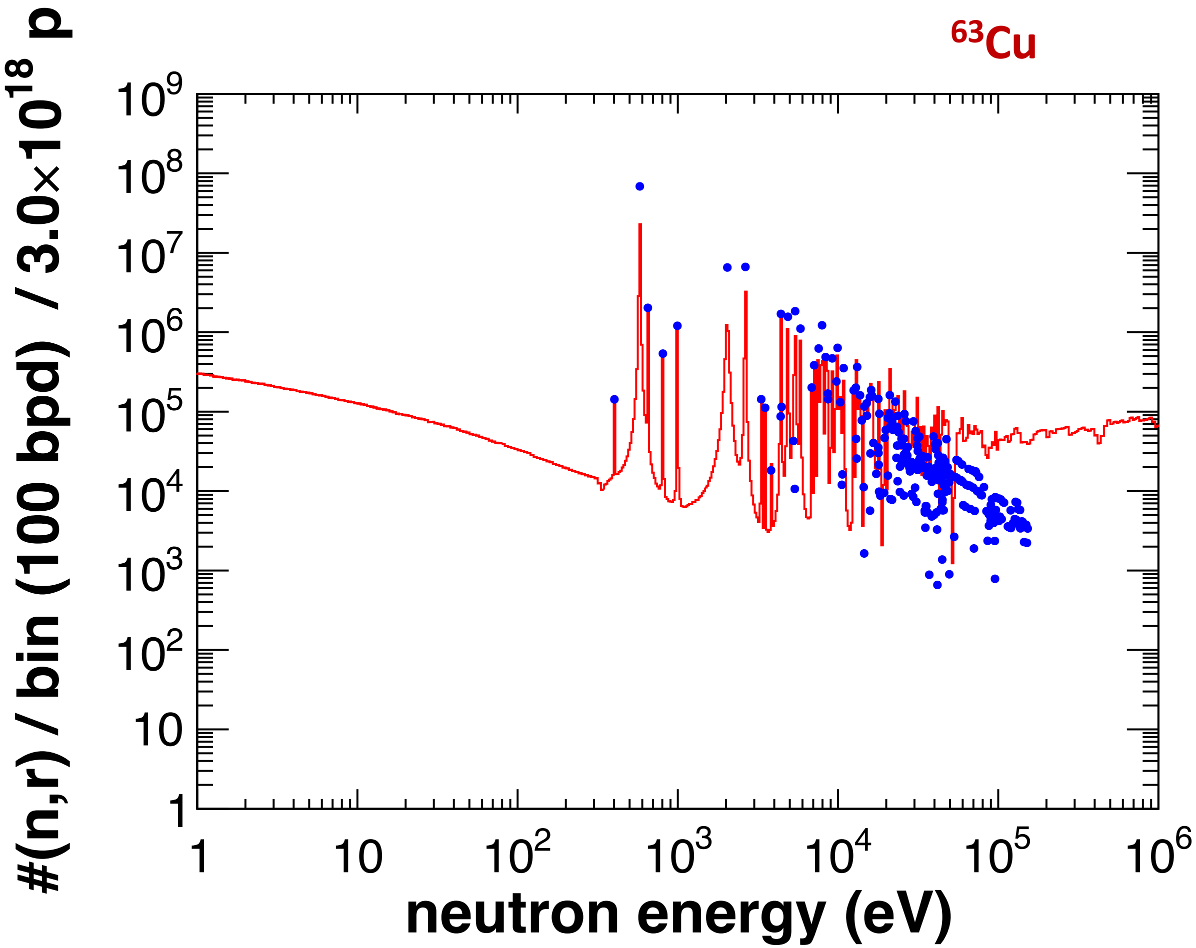
Uncertainties in a capture experiment

Mastromarco et al., Eur. Phys. J. A (2019) 55: 9

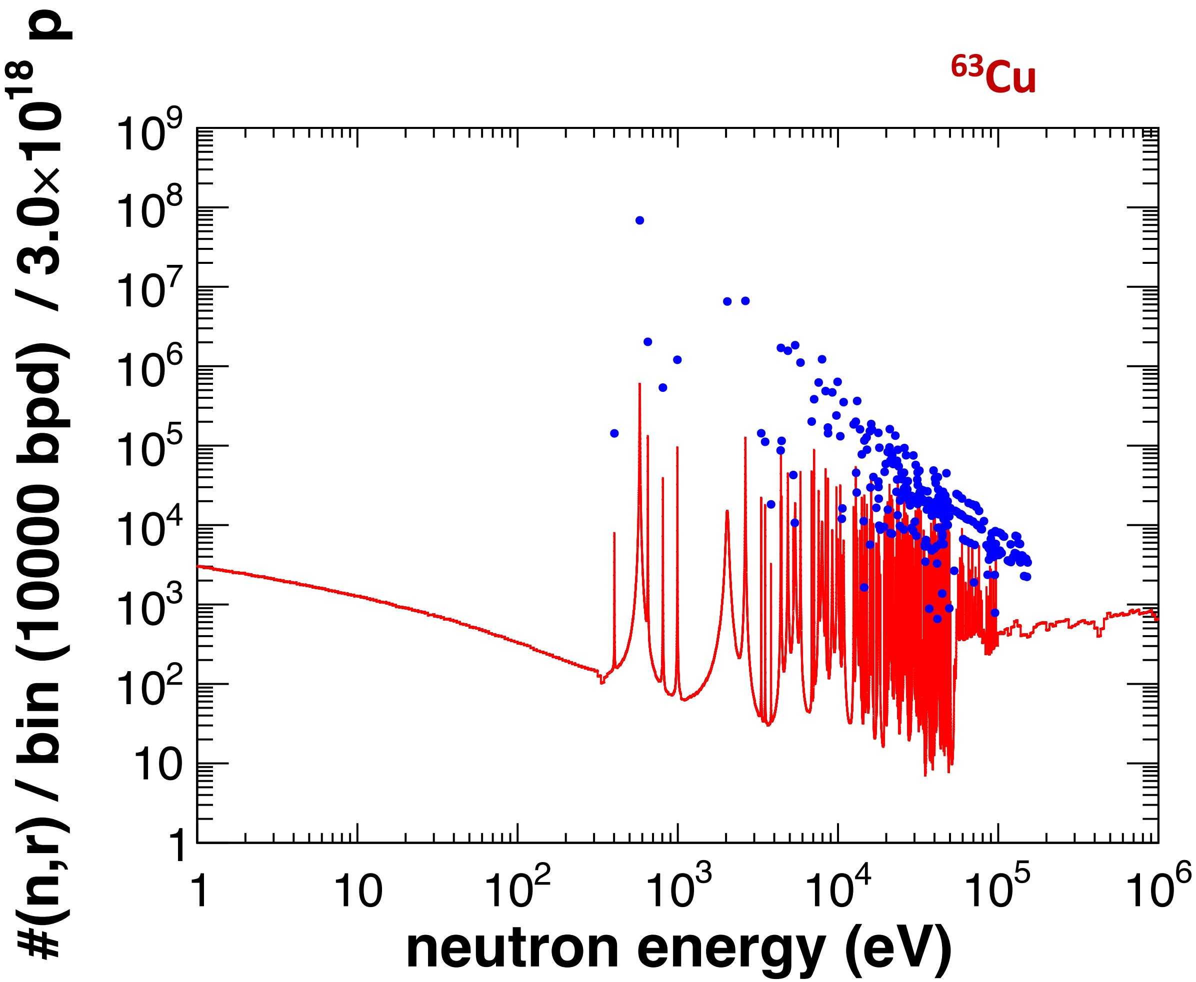
Table 3. Summary of the correlated uncertainties in the ^{155}Gd(n, γ) and ^{157}Gd(n, γ) cross section measurements.

Source of uncertainty	^{155}Gd(n, γ) near thermal	^{155}Gd(n, γ) resonance region	^{157}Gd(n, γ) near thermal	^{157}Gd(n, γ) resonance region
Normalization	1.2%	1.2%	1.2%	1.2%
PHWT	1.5%	1.5%	1.5%	1.5%
Background	1.4%	$\approx$ 1%	1.0%	$\approx$ 1%
BIF	1.5%		1.5%	
Flux	1.0%	1.0%	1.0%	1.0%
Sample mass	1.0%	$<$ 0.2%	2.1%	$<$ 0.2%
Temperature		1%		1%
Total	3.2%	2.6%	3.5%	2.6%

Count rate estimate

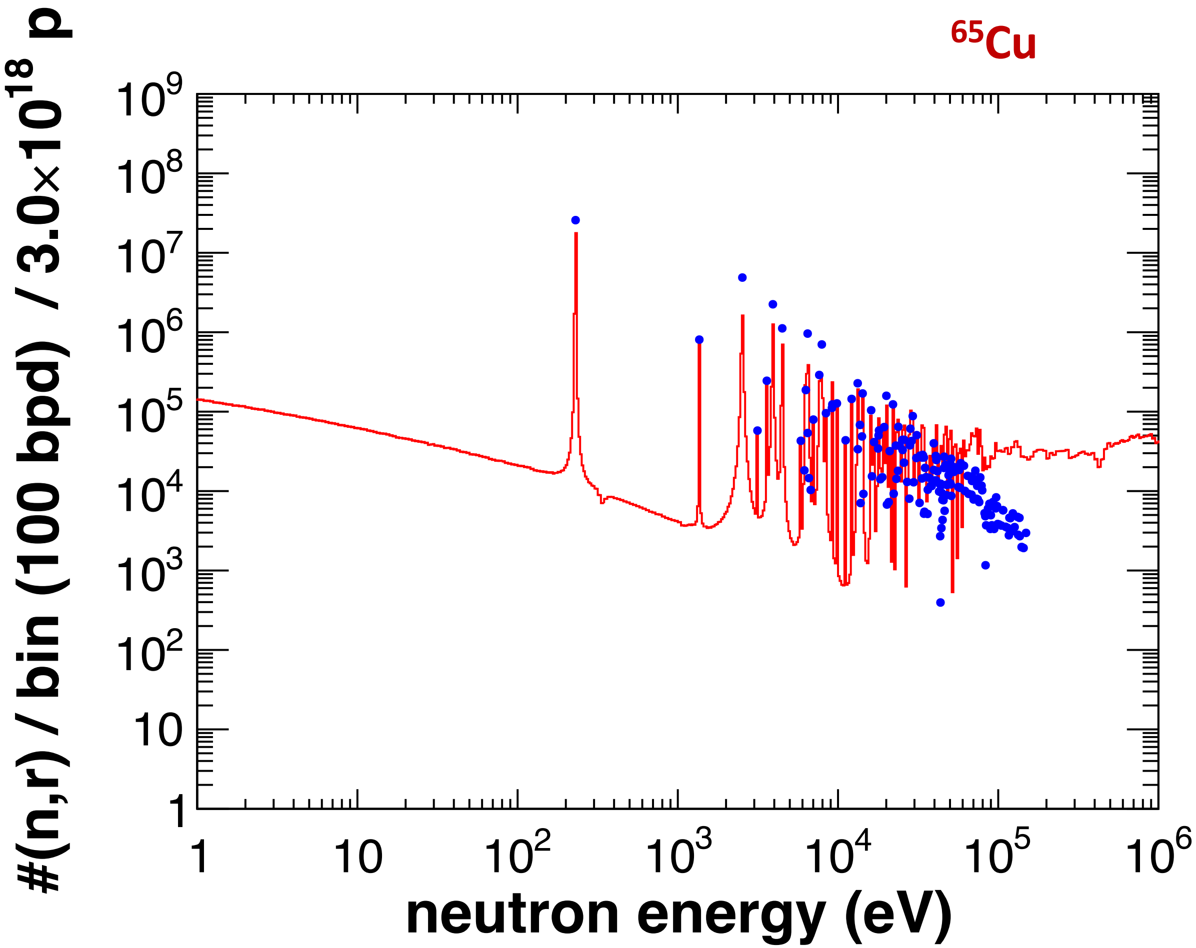


Countrate

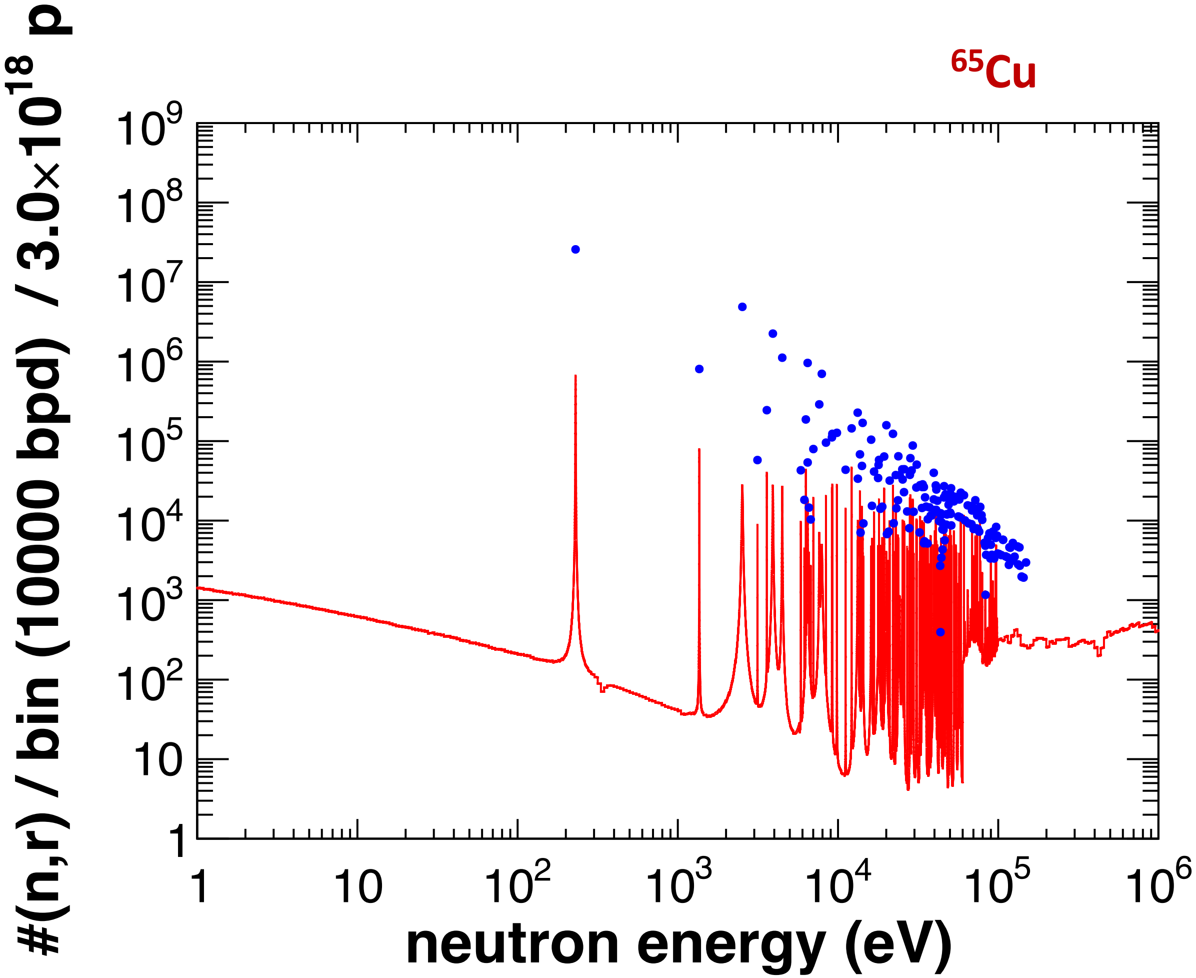


63Cu
#(n,r) / bin (10000 bpd) / 3.0×10^18 p
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
1
10
10^2
10^3
10^4
10^5
10^6
neutron energy (eV)

Count rate estimate

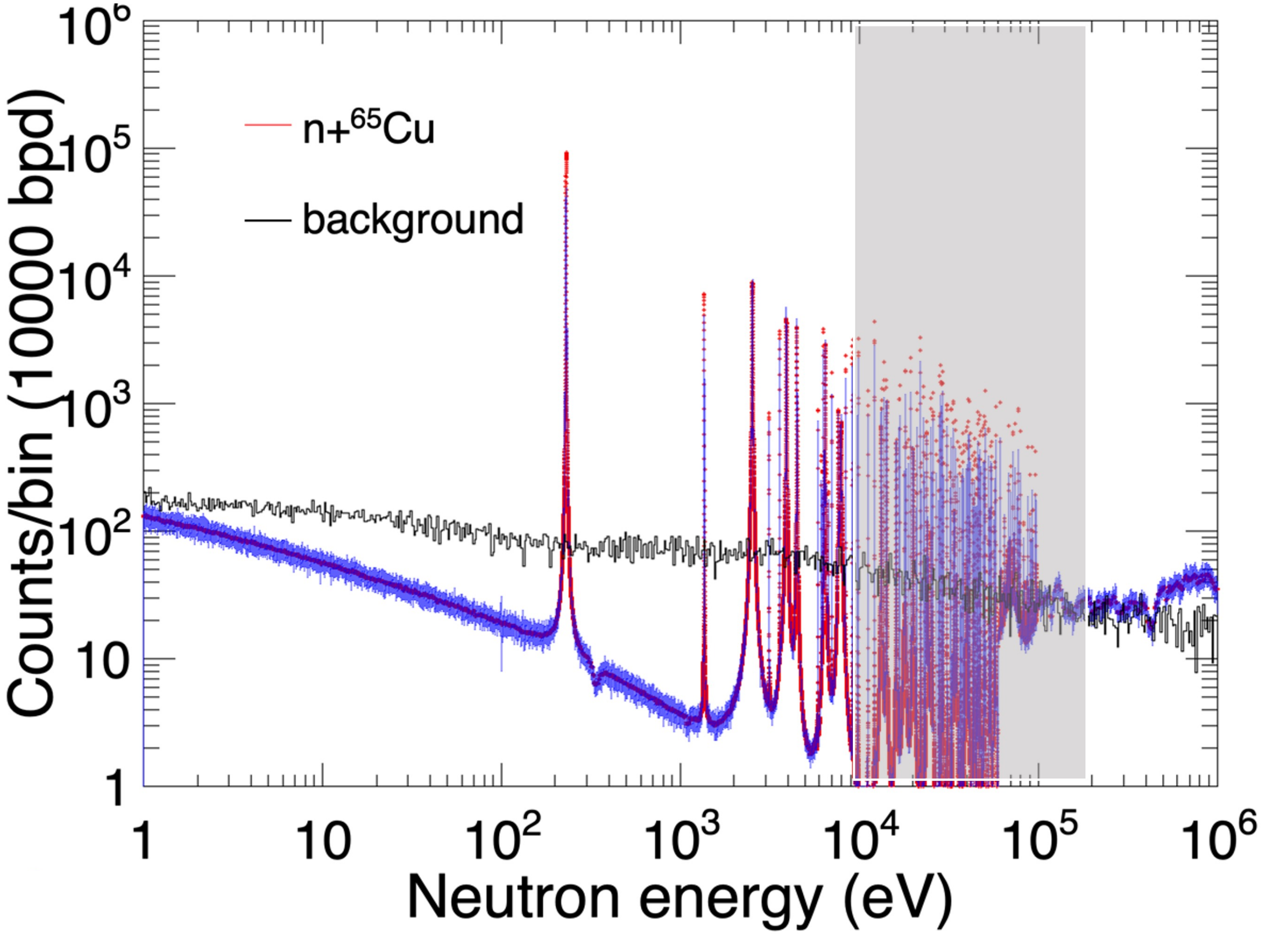


Count rate estimate

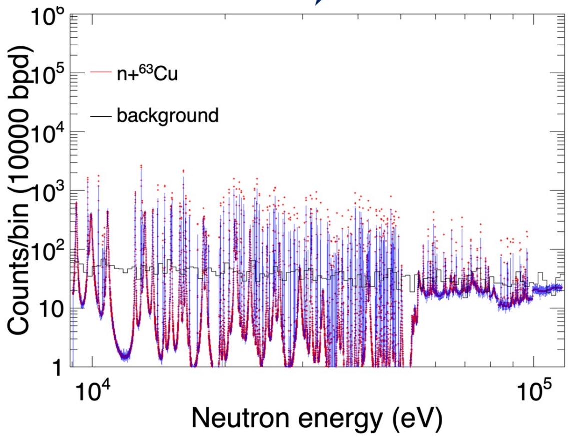


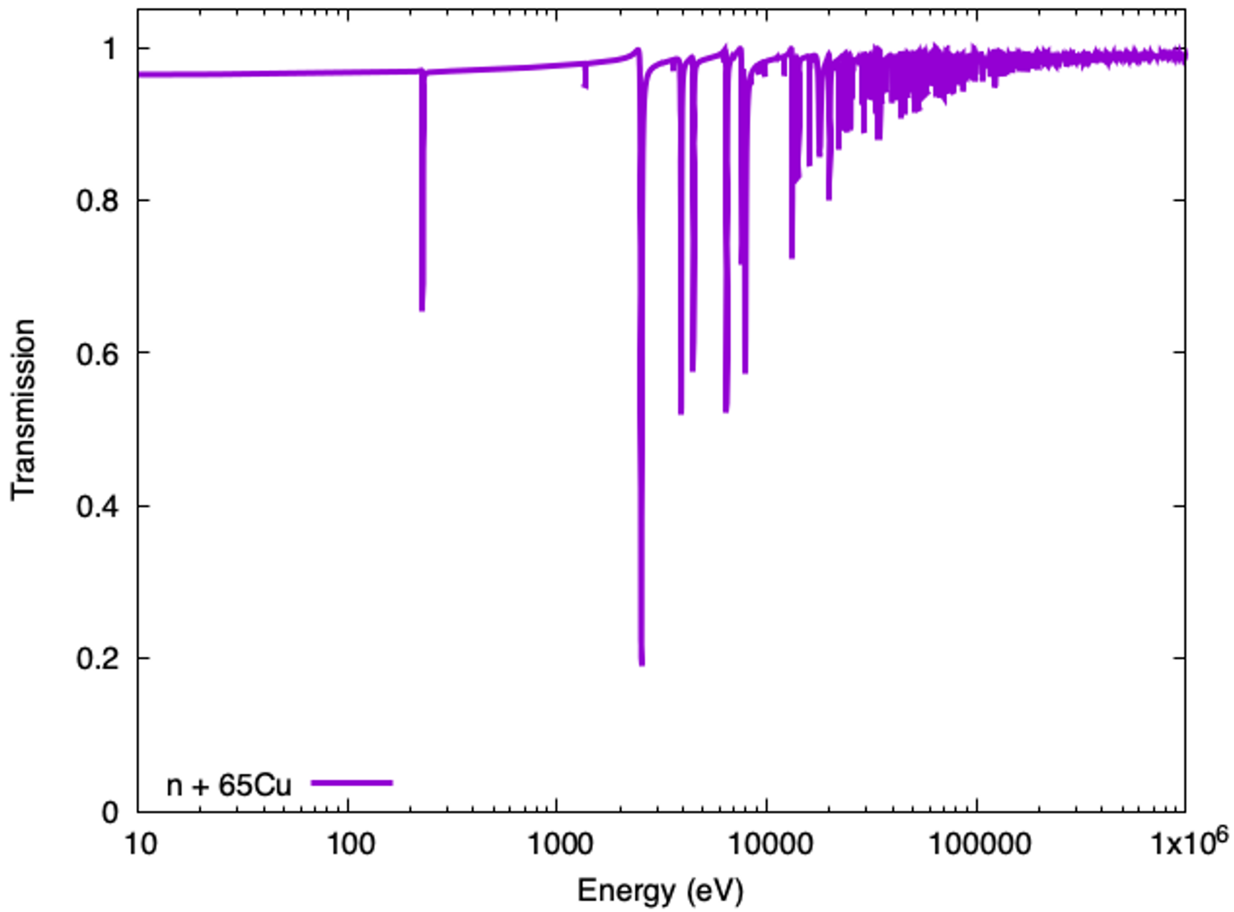
Count rate estimate

(n,γ) @ EAR 1, 4 C_6D_6, Ø = 3 cm, mass = 2 g



$2x10^{18}$ p





1
0.8
0.6
0.4
0.2
0
Transmission
n + 65Cu
10
100
1000
10000
100000
1x10^6
Energy (eV)

Transmission

	n	Display	Year	Author-1	Energy range,eV		Points	Reference	Subentry#P	NSR-Key	Info+
1)	29-CU-63(N,TOT),,SIG C4: MF=3 MT=1 Op=0										
	Quantity: [CS] Cross section										
	1	+ i X4 X4+± CSV+ T4 Cov	1977	M.S.Pandey+	5.00e1		1	+ J,PR/C,15,600,197702	10725002 [6]	1977PA04	
	2	+ i X4 X4+± CSV+ T4 Cov			3.83e3	1.12e6	12165		10725012 [5]	1977PA04	
	3	+ i X4 X4+± CSV+ T4 Cov			3.16e1	1.85e5	6208		10725014 [4]	1977PA04	
	4	+ i X4 X4+± CSV+ T4 Cov	1972	A.I.Dyumin+	1.42e7		1	+ J,IZV,36,852,1972	40149011 [6]	1972DY02	#2:1972dy02 #3:pdf
	5	+ i X4 X4+± CSV+ T4 Cov	1968	G.Rohr+	3.98e4	1.43e5	880	+ P,EANDC(E)-89,1,6802	20151002 [5]		
g*	6	+ i X4 X4+± CSV+ T4 Cov	1966	W.M.Good+	2.06e3	5.95e4	299	+ J,PR,151,912,1966	11626024 [5]	1966GO38	
	7	+ i X4 X4+± CSV+ T4 Cov	1957	H.Marshak+	1.10e3	9.72e4	164	+ J,PR,106,110,57	11640010 [4]	1957MA59	
2)	29-CU-63(N,TOT),,SIG,,AV C4: MF=3 MT=1 Op=0										
	Quantity: [CS] Cross section										
	8	+ i X4 X4+± CSV+ T4 Cov	1975	V.V.Filippov	5.00e4	9.50e5	11	[pdf]+ C,75KIEV,2,53,197505	41301002 [6]		
3)	29-CU-63(N,TOT),,SIG,,RES C4: MF=3 MT=1 Op=0										
	Quantity: [CS] Cross section at resonance										
	9	+ i X4 X4+± CSV+ T4 Cov	1958	R.E.Cote+	5.77e2	5.39e3	3	+ J,PR,111,288,58	116410182 [4]	1958CO69	
4)	29-CU-63(N,TOT),,TRN C4: MF=3 MT=? Op=0										
	Quantity: [CS] Transmission										
	10	+ i X4 X4+± CSV+ T4 Cov	2013	K.Kauwenberghs+	1.50e2	9.00e4	21528	+ R,EUR-26479,2013	23325002 [1]		
	11	+ i X4 X4+± CSV+ T4 Cov			1.50e2	9.00e4	21528		23325003 [1]		
	12	+ i X4 X4+± CSV+ T4 Cov			1.50e2	9.00e4	21528		23325004 [1]		
5)	29-CU-63(N,TOT),,WID C4: MF=402 MT=6010 Op=0										
	Quantity: [RP] Resonance width										
	13	+ i X4 X4+± CSV+ T4	1958	R.E.Cote+	5.77e2	5.39e3	3	+ J,PR,111,288,58	116410182 [4]	1958CO69	

List of

PHYSICAL REVIEW C VOLUME 15, NUMBER 2 FEBRUARY 1977

Neutron total cross sections and resonance parameters of $^{63}_{29}$Cu and $^{65}_{29}$Cu. I*

M. S. Pandey† and J. B. Garg‡
State University of New York at Albany, Albany, New York 12222

J. A. Harvey
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 8 April 1976)

High resolution neutron total cross sections of the isotopes of copper have been measured from about 10 to 150 keV using 5 nsec electron pulses and a flight path of 78.2 m. From the area and shape analysis of the transmission and total cross section data, precise values of the resonance parameters, such as E_0, Γ_n^0, Γ_n^1, J^π, etc., have been determined. For ^{63}Cu many s-wave resonances have been observed from 10 to 150 keV giving values of $\langle D\rangle_{J=1} = (2.7\pm0.3)$ keV, $\langle D\rangle_{J=2} = (4.0\pm0.5)$ keV, $\langle D\rangle_{J=1+2} = (1.63\pm0.13)$ keV, $S_{0\,J=1} = (3.0\pm0.6)\times10^{-4}$ eV$^{-1/2}$, $S_{0\,J=2} = (2.0\pm0.5)\times10^{-4}$ eV$^{-1/2}$, $S_{0\,J=1,2} = (2.5\pm0.4)\times10^{-4}$ eV$^{-1/2}$. For ^{65}Cu s-wave resonances were observed giving values of $\langle D\rangle_{J=1} = (3.6\pm0.4)$ keV, $\langle D\rangle_{J=2} = (5.0\pm0.7)$ keV, $\langle D\rangle_{J=1+2} = (2.12\pm0.19)$ keV, $S_{0\,J=1} = (2.9\pm0.6)\times10^{-4}$ eV$^{-1/2}$, $S_{0\,J=2} = (1.8\pm0.5)\times10^{-4}$ eV$^{-1/2}$, $S_{0\,J=1,2} = (2.3\pm0.4)\times10^{-4}$ eV$^{-1/2}$.

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