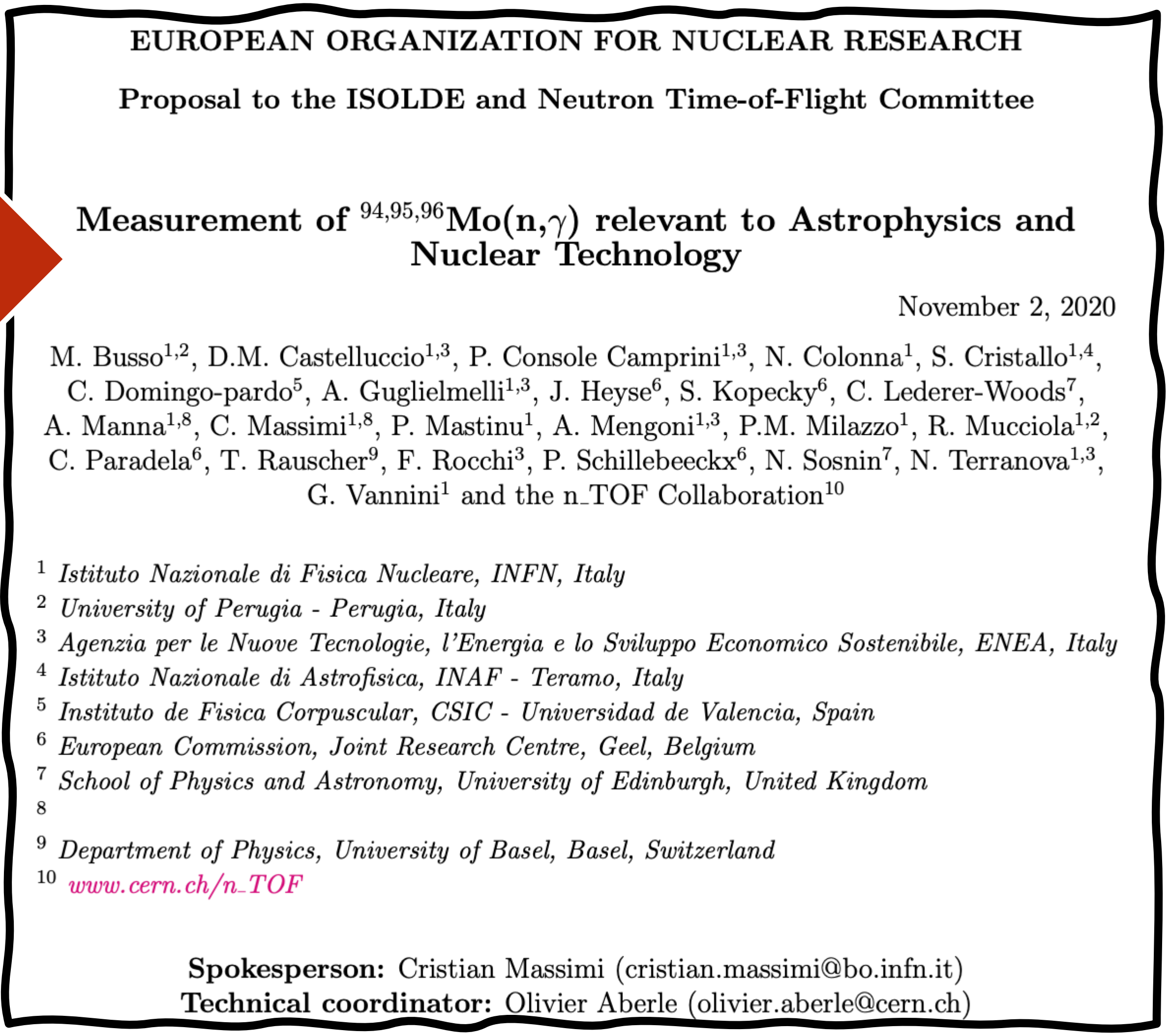
Proposal

^{94,95,96}Mo(n,γ)



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Measurement of ^{94,95,96}Mo(n,γ) relevant to Astrophysics and Nuclear Technology

November 2, 2020

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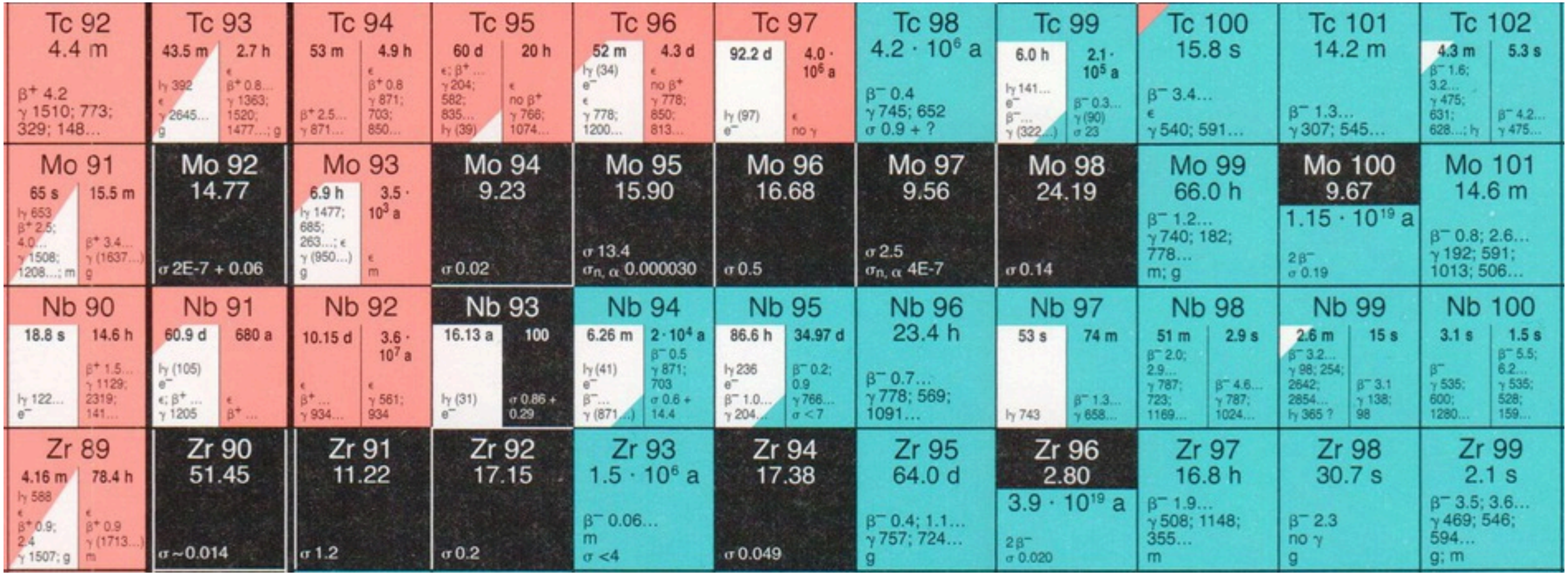
Technical coordinator: Olivier Aberle (olivier.aberle@cern.ch)

Outline

- Brief introduction to scientific motivations
- Data in the literature
- Proposed measurements
- Conclusions

Why ^{94,95,96}Mo?

- **Molybdenum** is relevant for **nuclear astrophysics** and **nuclear technology.**
- Presently ^{94,95,96}Mo(n,γ) cross sections are recommended in libraries **with large uncertainties**.



Tc 92 4.4 m β^+ 4.2 γ 1510; 773; 329; 148...	Tc 93 43.5 m Iγ 392 ϵ γ 2645... g 2.7 h ϵ β^+ 0.8... γ 1363; 1520; 1477...; g	Tc 94 53 m β^+ 2.5... γ 871... 4.9 h ϵ β^+ 0.8 γ 871; 703; 850...	Tc 95 60 d ϵ; β^+ ... γ 204; 582; 835... Iγ (39) 20 h ϵ no β^+ γ 766; 1074...	Tc 96 52 m Iγ (34) e^- ϵ γ 778; 1200... 4.3 d ϵ no β^+ γ 778; 850; 813...	Tc 97 92.2 d Iγ (97) e^- 4.0 · 10^6 a ϵ no γ	Tc 98 4.2 · 10^6 a β^- 0.4 γ 745; 652 σ 0.9 + ?	Tc 99 6.0 h Iγ 141... e^- β^-... γ (322...) 2.1 · 10^5 a β^- 0.3... γ (90) σ 23	Tc 100 15.8 s β^- 3.4... ϵ γ 540; 591...	Tc 101 14.2 m β^- 1.3... γ 307; 545...	Tc 102 4.3 m β^- 1.6; 3.2... γ 475; 631; 628...; Iγ 5.3 s β^- 4.2... γ 475...
Mo 91 65 s Iγ 653 β^+ 2.5; 4.0... γ 1508; 1208...; m 15.5 m β^+ 3.4... γ (1637...) g	Mo 92 14.77 σ 2E-7 + 0.06	Mo 93 6.9 h Iγ 1477; 685; 263...; ϵ γ (950...) g 3.5 · 10^3 a ϵ m	Mo 94 9.23 σ 0.02	Mo 95 15.90 σ 13.4 $\sigma_{n,\alpha}$ 0.000030	Mo 96 16.68 σ 0.5	Mo 97 9.56 σ 2.5 $\sigma_{n,\alpha}$ 4E-7	Mo 98 24.19 σ 0.14	Mo 99 66.0 h β^- 1.2... γ 740; 182; 778... m; g	Mo 100 9.67 1.15 · 10^{19} a 2β^- σ 0.19	Mo 101 14.6 m β^- 0.8; 2.6... γ 192; 591; 1013; 506...
Nb 90 18.8 s Iγ 122... e^- 14.6 h β^+ 1.5... γ 1129; 2319; 141...	Nb 91 60.9 d Iγ (105) e^- ϵ; β^+ ... γ 1205 680 a ϵ β^+ ...	Nb 92 10.15 d ϵ β^+ ... γ 934... 3.6 · 10^7 a ϵ γ 561; 934	Nb 93 16.13 a Iγ (31) e^- 100 σ 0.86 + 0.29	Nb 94 6.26 m Iγ (41) e^- β^-... γ (871...) 2 · 10^4 a β^- 0.5 γ 871; 703 σ 0.6 + 14.4	Nb 95 86.6 h Iγ 236 e^- β^- 1.0... γ 204... 34.97 d β^- 0.2; 0.9 γ 766... σ < 7	Nb 96 23.4 h β^- 0.7... γ 778; 569; 1091...	Nb 97 53 s Iγ 743 74 m β^- 1.3... γ 658...	Nb 98 51 m β^- 2.0; 2.9... γ 787; 723; 1169... 2.9 s β^- 4.6... γ 787; 1024...	Nb 99 2.6 m β^- 3.2... γ 98; 254; 2642; 2854... Iγ 365 ? 15 s β^- 3.1 γ 138; 98	Nb 100 3.1 s β^- γ 535; 600; 1280... 1.5 s β^- 5.5; 6.2... γ 535; 528; 159...
Zr 89 4.16 m Iγ 588 ϵ β^+ 0.9; 2.4 γ 1507; g 78.4 h ϵ β^+ 0.9 γ (1713...) m	Zr 90 51.45 σ ~0.014	Zr 91 11.22 σ 1.2	Zr 92 17.15 σ 0.2	Zr 93 1.5 · 10^6 a β^- 0.06... m σ <4	Zr 94 17.38 σ 0.049	Zr 95 64.0 d β^- 0.4; 1.1... γ 757; 724... g	Zr 96 2.80 3.9 · 10^{19} a 2β^- σ 0.020	Zr 97 16.8 h β^- 1.9... γ 508; 1148; 355... m	Zr 98 30.7 s β^- 2.3 no γ g	Zr 99 2.1 s β^- 3.5; 3.6... γ 469; 546; 594... g; m

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p process

s process & r process

s-only isotope

r-only isotope

Nuclear Astrophysics: the s process around Zr-Nb-Mo

Why ^{94,95,96}Mo?

^{94}Rh 25.80 s	^{95}Rh 5.02 m	^{96}Rh 9.90 m	^{97}Rh 30.70 m	^{98}Rh 8.72 m	^{99}Rh 16.10 d	^{100}Rh 20.80 h	^{101}Rh 3.30 a	^{102}Rh 206.94 d
^{93}Ru 59.70 s	^{94}Ru 51.80 m	^{95}Ru 1.64 h	^{96}Ru 5.54	^{97}Ru 2.79 d	^{98}Ru 1.87	^{99}Ru 12.76	^{100}Ru 12.6	^{101}Ru 17.06
^{92}Tc 4.25 m	^{93}Tc 2.75 h	^{94}Tc 4.88 h	^{95}Tc 20.00 h	^{96}Tc 4.28 d	^{97}Tc 4.21 Ma	^{98}Tc 4.20 Ma	^{99}Tc 211.11 ka	^{100}Tc 15.80 s
^{91}Mo 15.49 m	^{92}Mo 14.84	^{93}Mo 4.00 ka	^{94}Mo 9.25	^{95}Mo 15.92	^{96}Mo 16.68	^{97}Mo 9.55	^{98}Mo 24.13	^{99}Mo 2.75 d
^{90}Nb 14.60 h	^{91}Nb 680.04 a	^{92}Nb 34.70 Ma	^{93}Nb 100	^{94}Nb 20.30 ka	^{95}Nb 34.99 d	^{96}Nb 23.35 h	^{97}Nb 1.20 h	^{98}Nb 2.86 s
^{89}Zr 3.27 d	^{90}Zr 51.45	^{91}Zr 11.22	^{92}Zr 17.15	^{93}Zr 1.53 Ma	^{94}Zr 17.38	^{95}Zr 64.03 d	^{96}Zr 2.8	^{97}Zr 16.74 h
^{88}Y 106.62 d	^{89}Y 100	^{90}Y 2.67 d	^{91}Y 58.51 d	^{92}Y 3.54 h	^{93}Y 10.18 h	^{94}Y 18.70 m	^{95}Y 10.30 m	^{96}Y 5.34 s
^{87}Sr 7	^{88}Sr 82.58	^{89}Sr 50.57 d	^{90}Sr 28.90 a	^{91}Sr 9.63 h	^{92}Sr 2.66 h	^{93}Sr 7.42 m	^{94}Sr 1.25 m	^{95}Sr 23.90 s
^{86}Rb 18.64 d	^{87}Rb 49.69x10^{9} y	^{88}Rb 17.77 m	^{89}Rb 15.15 m	^{90}Rb 2.63 m	^{91}Rb 58.40 s	^{92}Rb 4.49 s	^{93}Rb 5.84 s	^{94}Rb 2.70 s

- **AGB stars** (during pulses and between pulses)
- **SiC pre-solar grains**

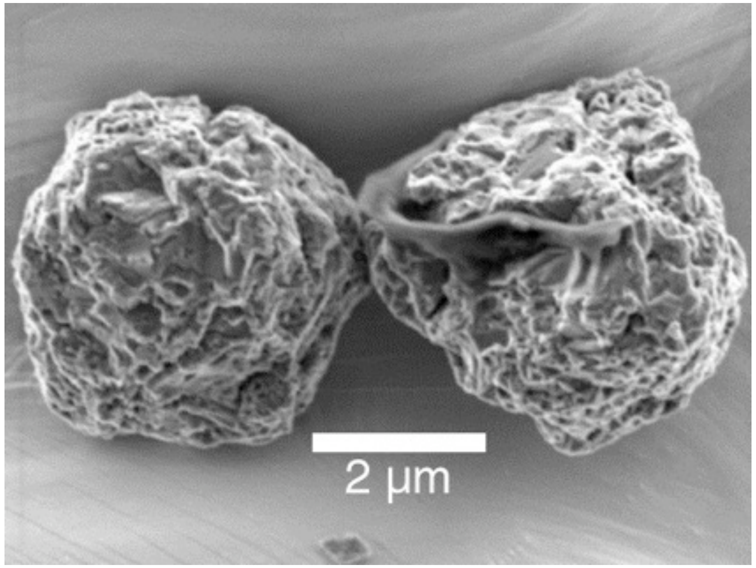
See for instance:

- Cescutti et al. MNRAS **478** (2018) 4101
- Liu et al. APJ **881** (2019) 28
- Battino et al. MNRAS **489** (2019)1082

Why ^{94,95,96}Mo?

Nuclear Astrophysics: the s process around Zr-Nb-Mo

Current stellar models cannot explain Mo isotopic ratios observed in pre-solar grains



- **AGB stars** (during pulses and between pulses)
- **SiC pre-solar grains**

^{94,95,96}Mo(n,γ) key uncertainties impacting Mo abundances

Nuclear uncertainties could explain discrepancies in Mo isotopic ratios between models & observation

Accurate predictions of Mo isotopic abundance allow to constrain stellar conditions in the s-process.

See for instance:
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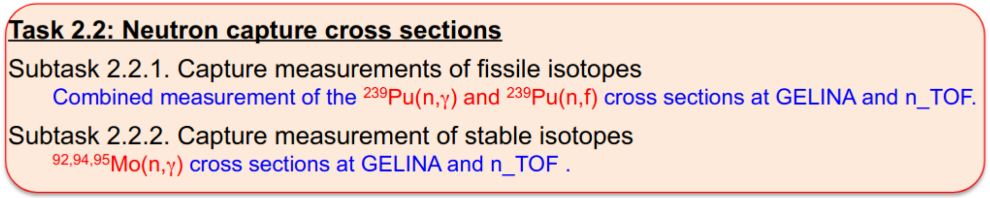
Why ^{94,95,96}Mo?

Nuclear technology

- **fission products** in nuclear reactors
- Related to **safety assessments of spent nuclear fuel** transport, storage and final disposal (**^{95}Mo(n,γ)** reaction cross section related to **criticality safety studies**, based on a **burnup credit)**
- **Mo-based alloys** used to produce **nuclear fuel for research, naval** and **space reactors** and **nuclear fuel cladding** considered in Accident Tolerant Fuel**.**
- ^{93}Mo ($T_{1/2}$ = 4000 yr) present in spent nuclear fuel (radiotoxicity)
- Improve/handling of spent nuclear fuel in **reprocessing** facilities

SANDA



Task 2.2: Neutron capture cross sections

Subtask 2.2.1. Capture measurements of fissile isotopes

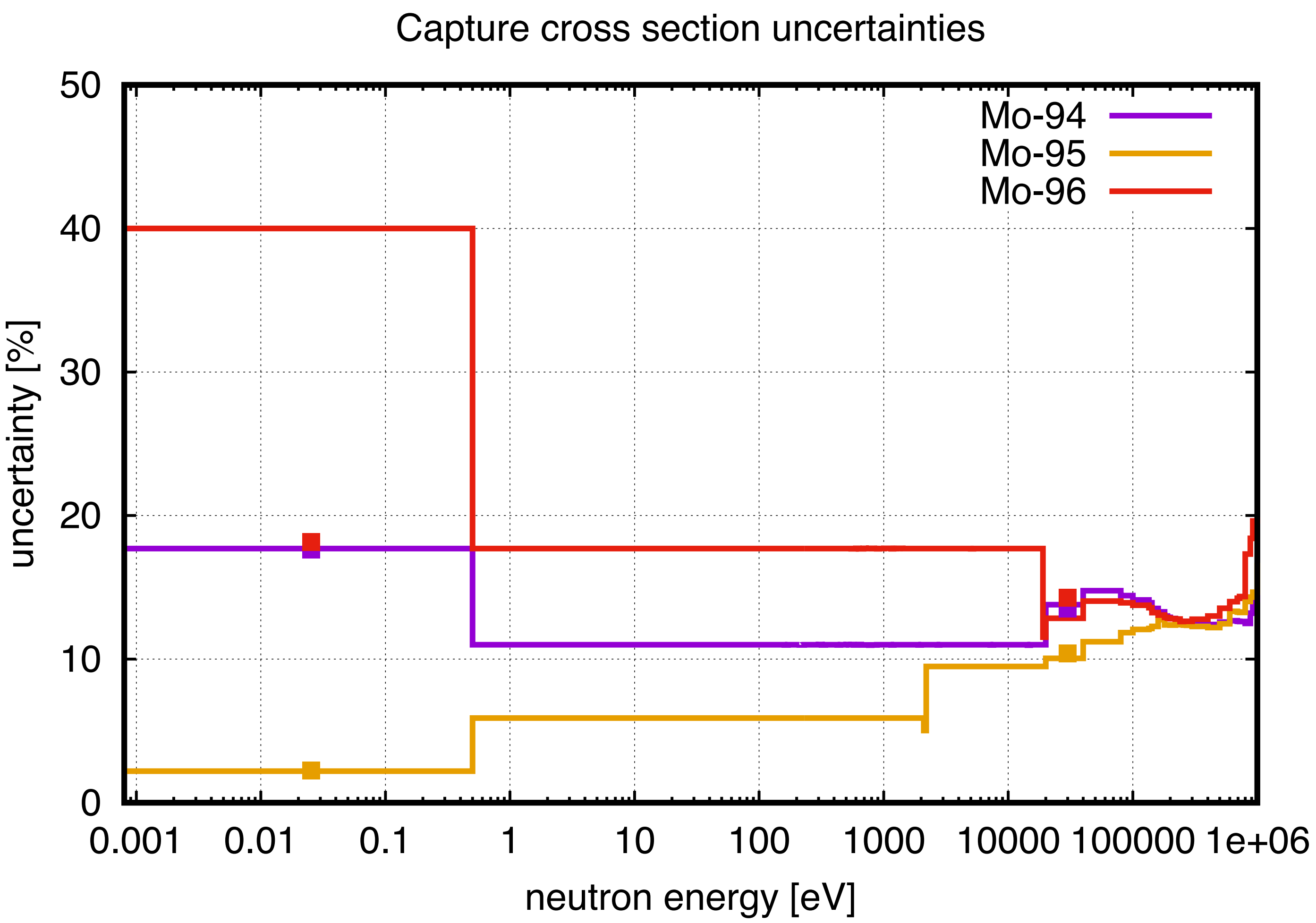
Combined measurement of the ^{239}Pu(n,γ) and ^{239}Pu(n,f) cross sections at GELINA and n_TOF.

Subtask 2.2.2. Capture measurement of stable isotopes

^{92,94,95}Mo(n,γ) cross sections at GELINA and n_TOF .

Why ^{94,95,96}Mo?

Scientific relevance, in addition to other constraints (uncertainty, sample material, …) led to this proposal, limited to the 3 isotopes.



Data in the literature

Capture data

1. Weigmann and Schmid. **10 eV – 1 keV (25 keV)** **@ GELINA** (30 m), total energy detection principle using a **Moxon-Rae detector** and **natural molybdenum** samples.
2. Musgrove et al. **3 – 90 keV** **@ ORELA** (40 m) **C_6F_6** liquid scintillators and **enriched samples**.
3. Leinweber et al. **10 eV – 600 eV** **@ RPI** using **natural samples** and the capture detection system was a **total absorption detector** based **NaI**.
4. …other data present, poor or absent description.

Transmission data

1. Leinweber et al. **10 eV – 2 keV** **@ RPI** using **natural samples.**

Spin and parity

1. Sheets et al. **@ Los Alamos** using **DANCE** for n+^{94,95}Mo.

Data in the literature

No capture data on enriched samples using C_6D_6

Capture data

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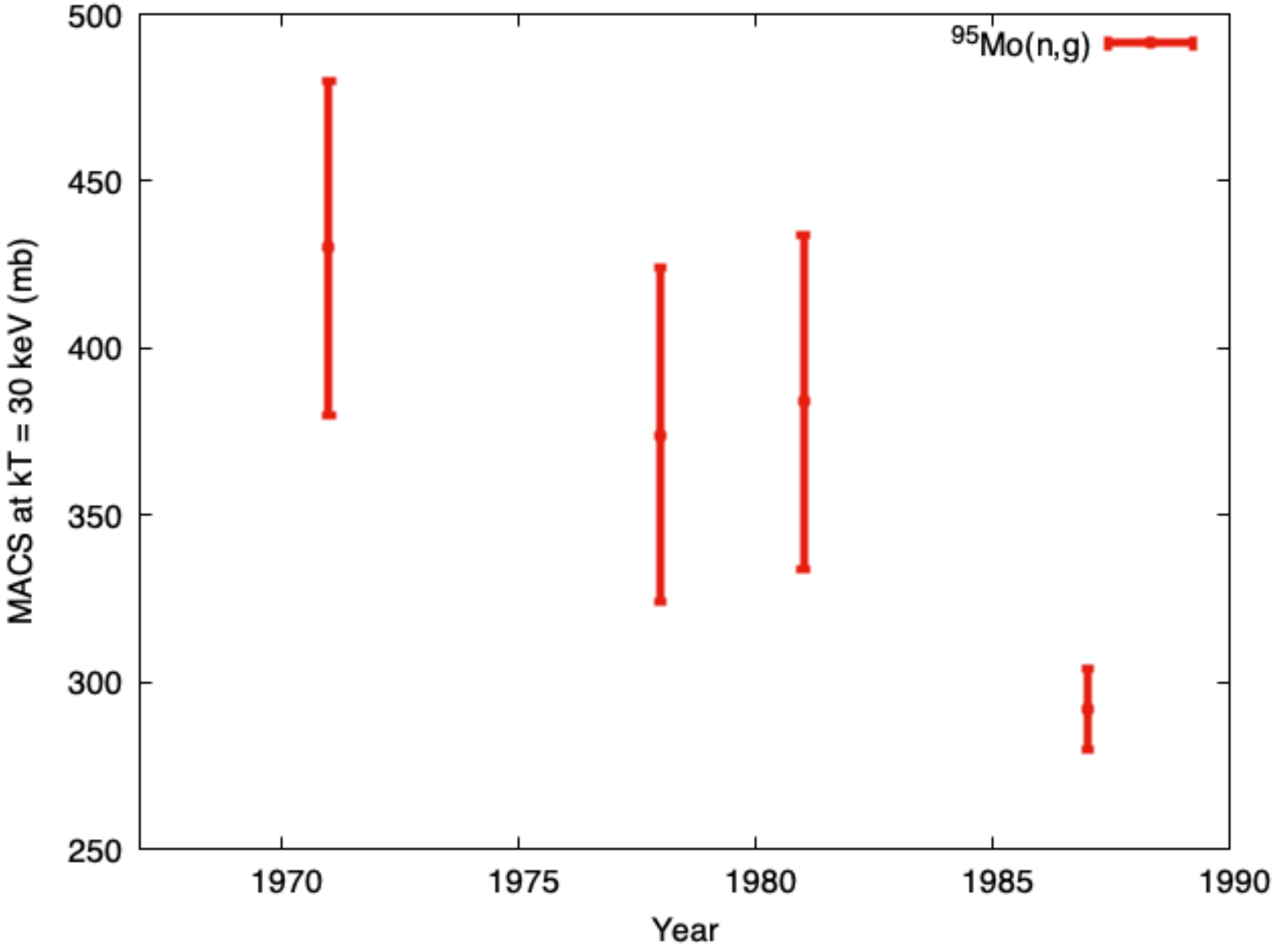
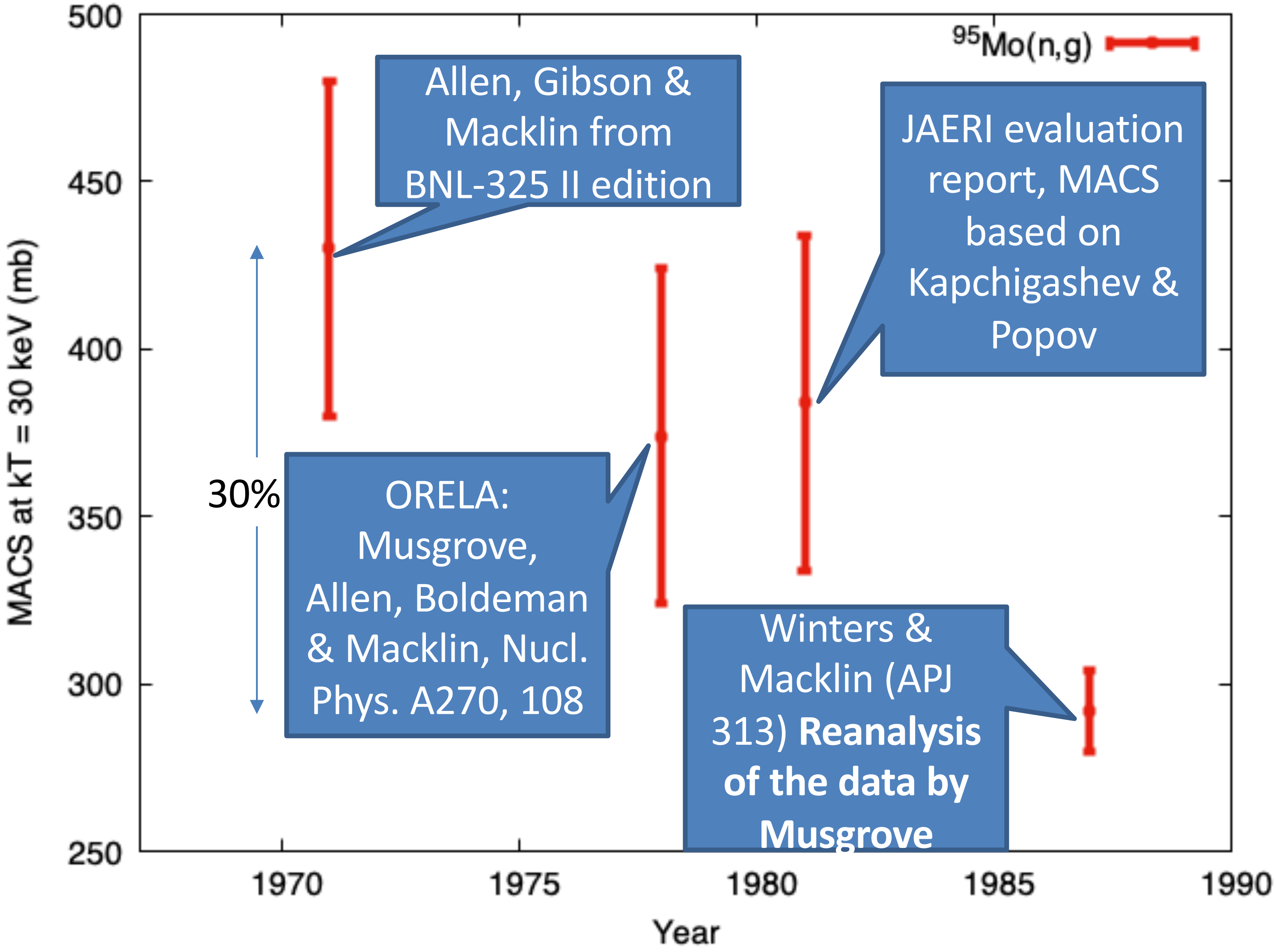
No transmission data on enriched samples

Data in the literature: MACS @ kT = 30 keV



from
KADoNiS

Data in the literature: MACS @ kT = 30 keV



Allen, Gibson & Macklin from BNL-325 II edition

JAERI evaluation report, MACS based on Kapchigashev & Popov

ORELA: Musgrove, Allen, Boldeman & Macklin, Nucl. Phys. A270, 108

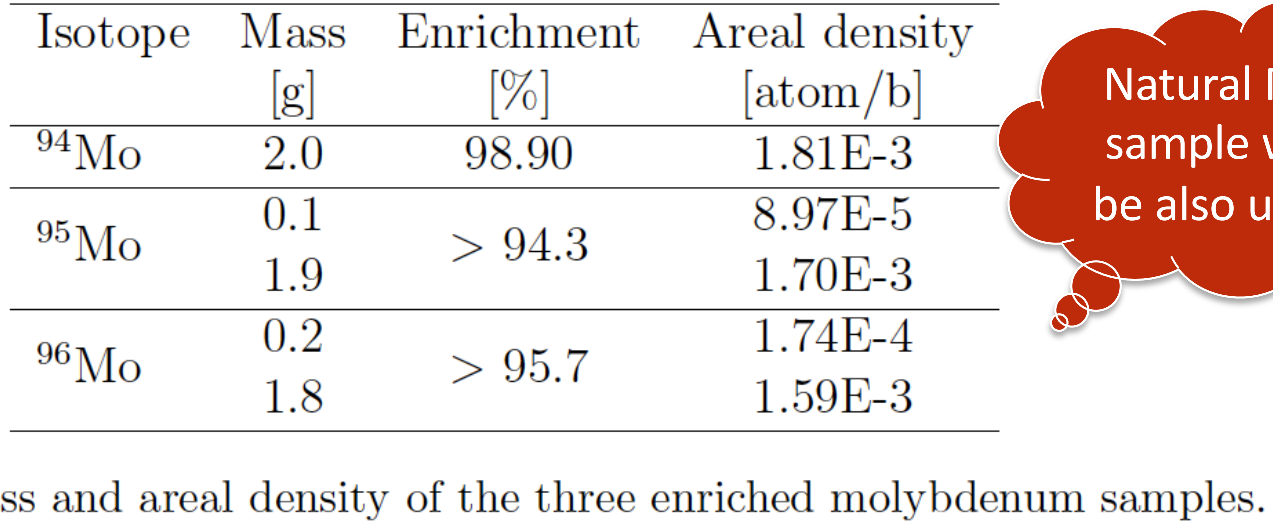
Winters & Macklin (APJ 313) **Reanalysis of the data by Musgrove**

from KADoNiS

Versions:
0.3 Musgrove
1.0 Macklin

Proposed measurements

The measurements are proposed at both **EAR1** and **EAR2** measuring stations in order to accurately estimate the neutron capture cross-section for neutron energies **between thermal energy (25.3 meV) and ~ 100 keV**.



Isotope	Mass [g]	Enrichment [%]	Areal density [atom/b]
^{94}Mo	2.0	98.90	1.81E-3
^{95}Mo	0.1	> 94.3	8.97E-5
	1.9		1.70E-3
^{96}Mo	0.2	> 95.7	1.74E-4
	1.8		1.59E-3

Table 1: Mass and areal density of the three enriched molybdenum samples.

Natural Mo sample will be also used

Metallic discs with a 30 mm diameter.

The Molybdenum enriched samples have been already located.

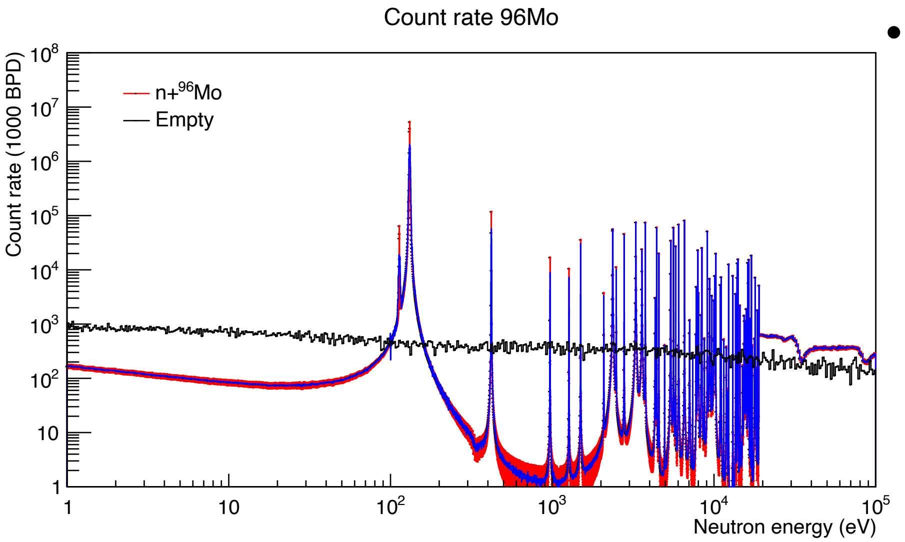
Proposed measurements

under similar conditions to previous successfully completed measurements:

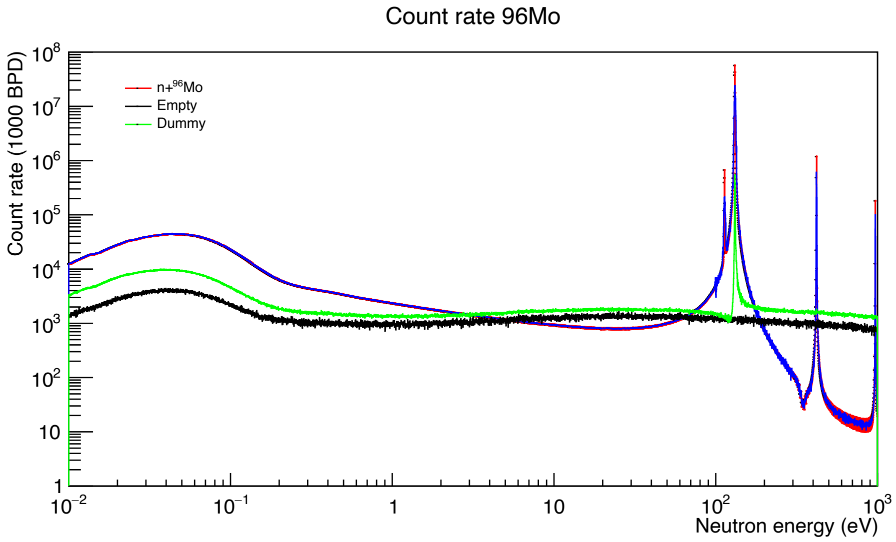
- Mazzone et al. PLB **804** (2020) 135405

Background:
$6x10^{17}$

Normalization:
$3x10^{17}$



Array of 4 C_6D_6
$20x10^{17}$ POT@ EAR1

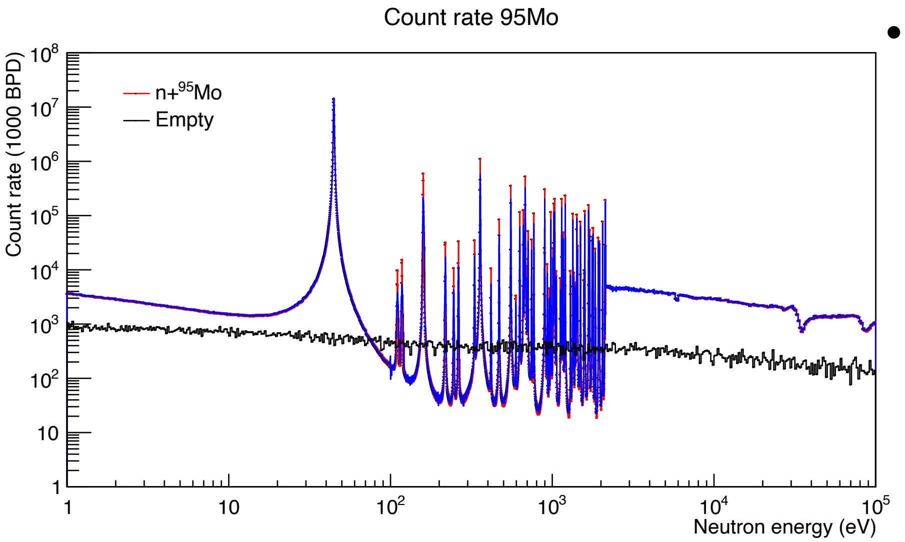


Array of 3 C_6D_6
$5x10^{17}$ POT@ EAR2

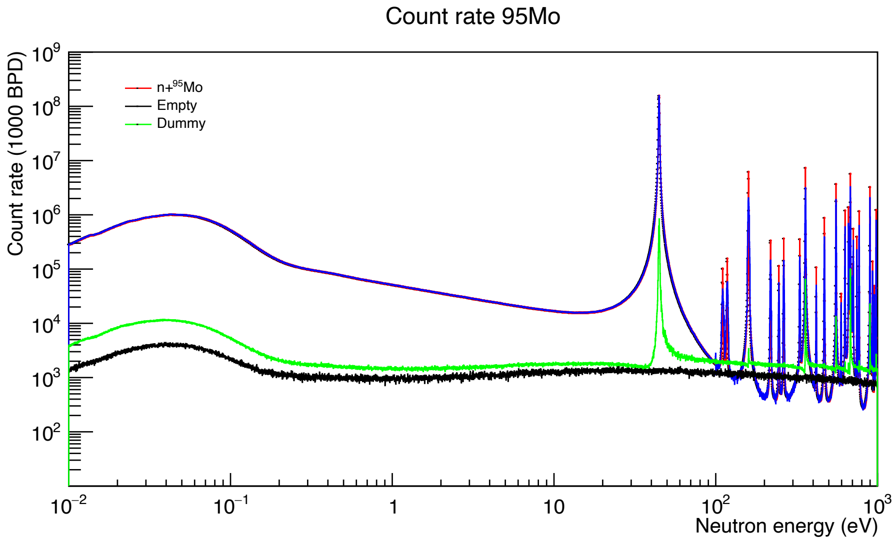
Proposed measurements

under similar conditions to previous successfully completed measurements:

- Mazzone et al. PLB **804** (2020) 135405



Array of 4 C_6D_6
20×10^{17} POT@ EAR1



Array of 3 C_6D_6
5×10^{17} POT@ EAR2

Proposed measurements

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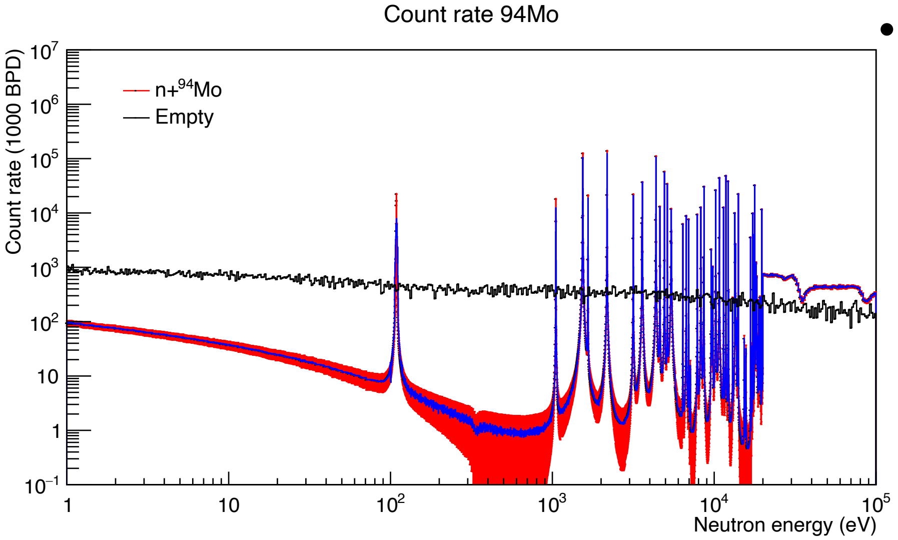
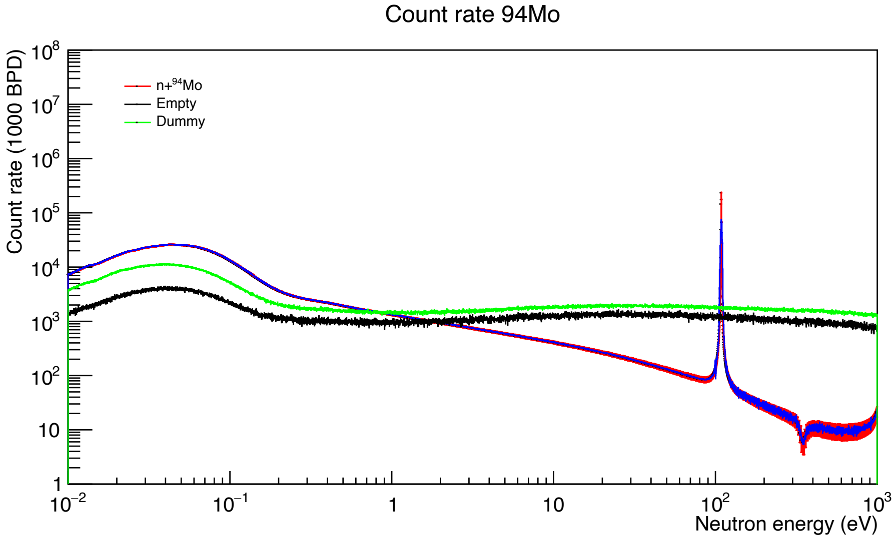


Array of 4 C_6D_6
20×10^{17} POT@ EAR1



Array of 3 C_6D_6
5×10^{17} POT@ EAR2

Conclusions

To improve the status of evaluated data libraries for Mo isotopes and in particular **to improve the quality of the recommended capture cross sections**, a **collaborative effort** has been planned as part of the **SANDA project** supported within the EU Horizon 2020 framework programme:

- capture measurements at n_TOF
- Transmission measurements GELINA

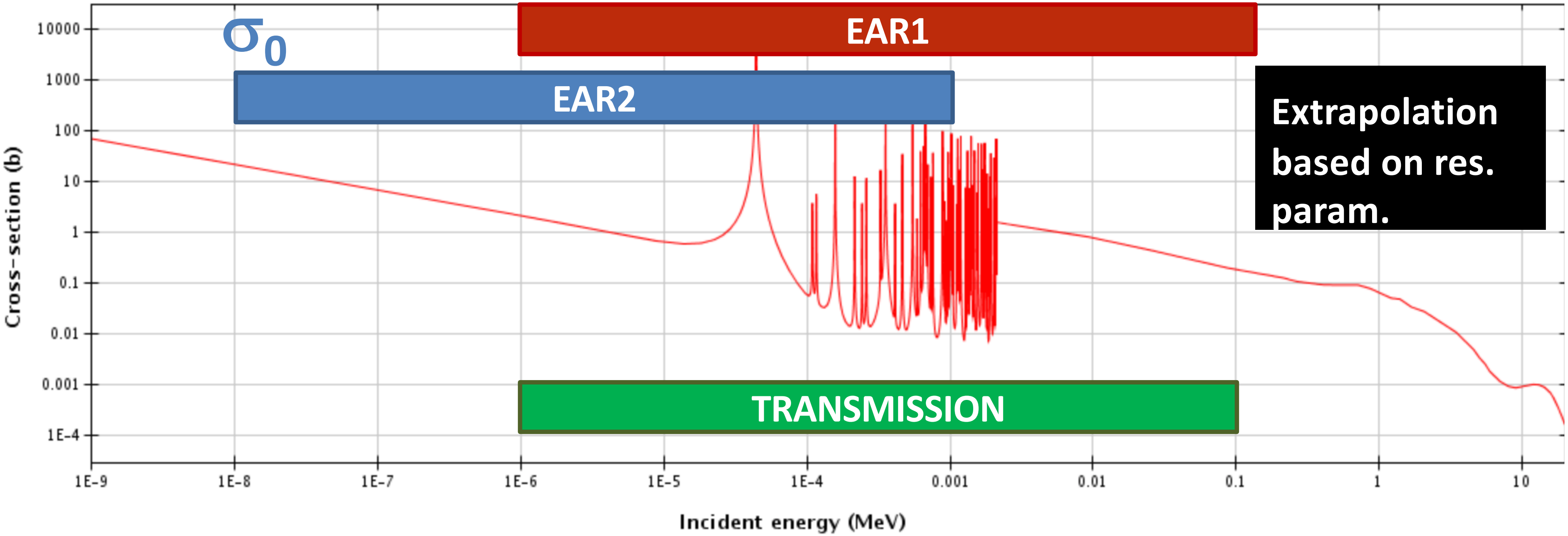
using isotopically enriched Mo metallic samples.

Requested protons: 8×10^{18} protons on target
Experimental Area: EAR1 and EAR2

Conclusions

n_TOF

Resonance parameters (RRR & URR)



σ_0

EAR1

EAR2

TRANSMISSION

Extrapolation based on res. param.

JANIS Web

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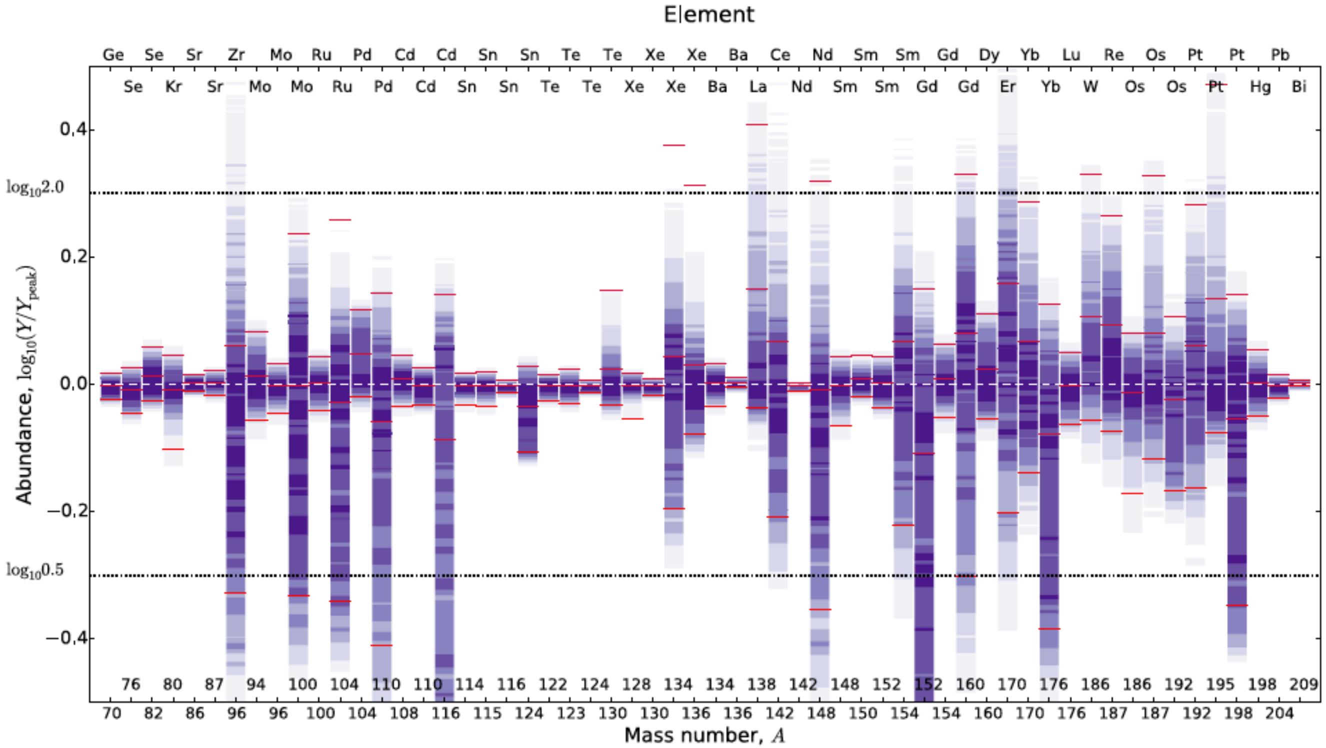
Why ^{94,95,96}Mo?

Nuclear Astrophysics: the s process around Zr-Nb-Mo



- **AGB stars** (during pulses and between pulses)

See for instance:

- Cescutti et al. MNRAS **478** (2018) 4101

Monte Carlo reaction rate variation study for all s-process reactions: simultaneously varied all reaction rates within their current uncertainties and determined correlations and key reactions for uncertainties in final abundances of nuclides both for the s-process in the ^{13}C-pocket and in the thermal pulse of an AGB star.

^{95,96}Mo(n,γ) appear as **strong key reactions** in all of the investigated models of s-processing in the **^{13}C-pocket of massive AGB stars.**

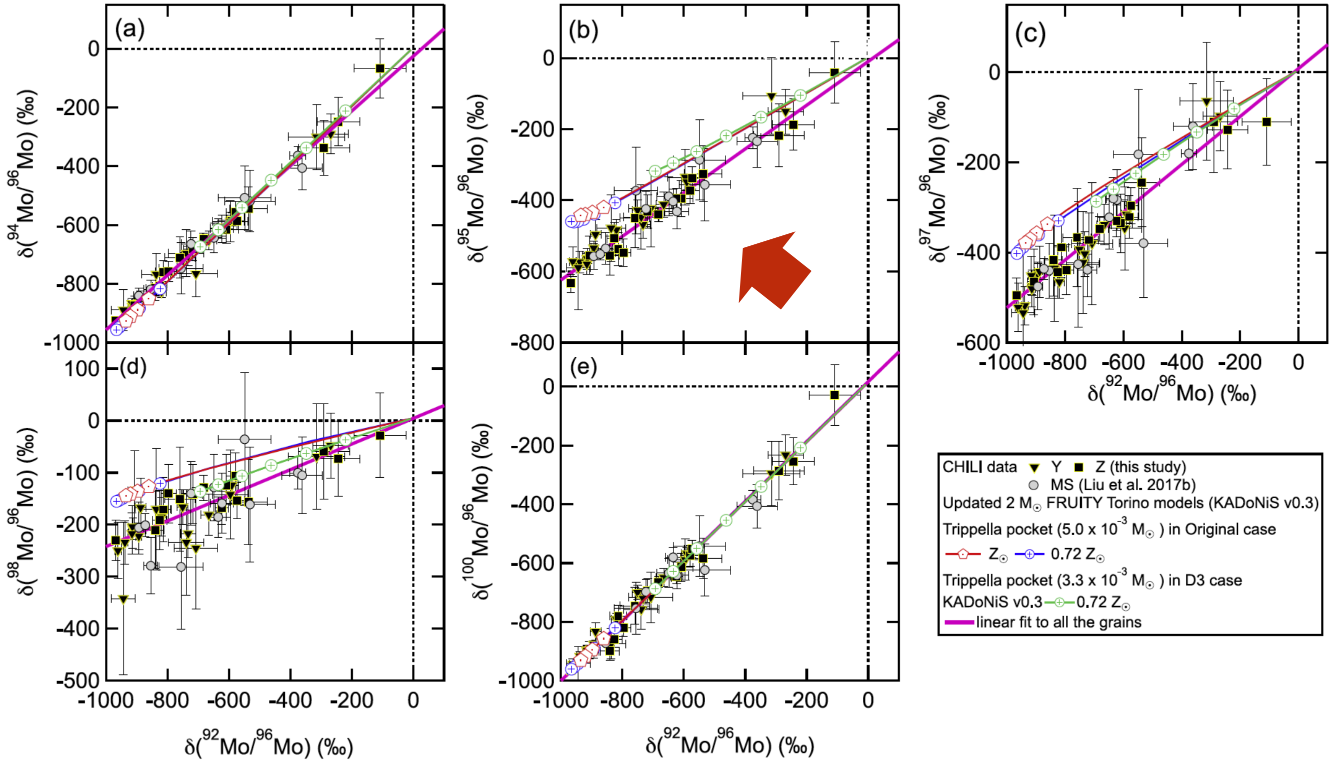
^{94,96}Mo(n,γ) appears as **strong key reaction** also in the **thermal pulse** processing of the AGB star

^{94,95,96}(n,γ) appear in all models

Why ^{94,95,96}Mo?

Nuclear Astrophysics:
the s process around Zr-Nb-Mo

Isotopic abundance ratios measured for several trace elements discovered in presolar SiC grains recovered from primitive meteorites represent stringent tests for s-process models



- **SiC pre-solar grains**

See for instance:

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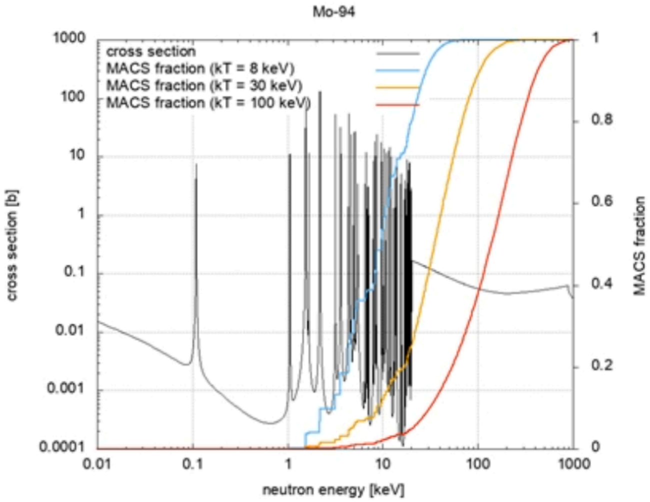
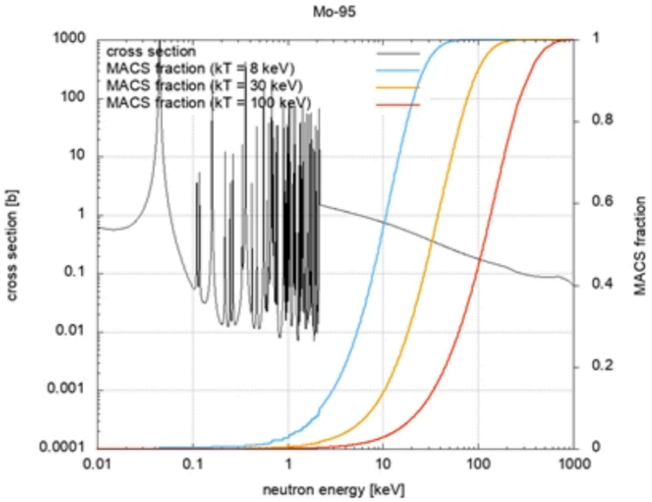
Pre-solar SiC grains with different metallicity have indistinguishable Mo isotopic composition.
Mo constrains the maximum stellar temperatures during thermal pulses in AGB stars.

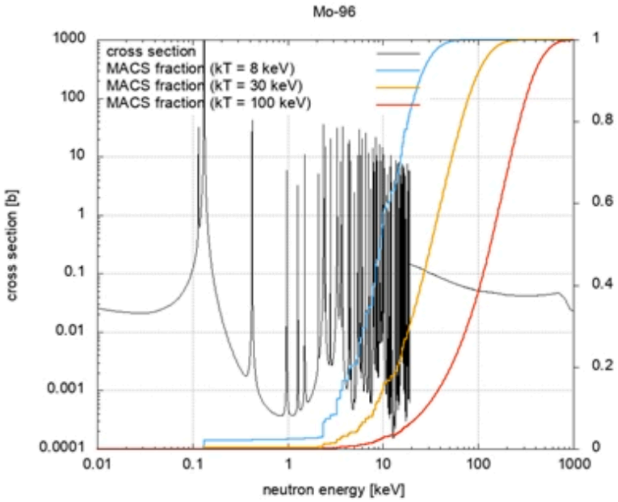
^{96}Mo is the reference,
95/96 ratio inconsistent

backup

Energy regions: contribution to the MACS.

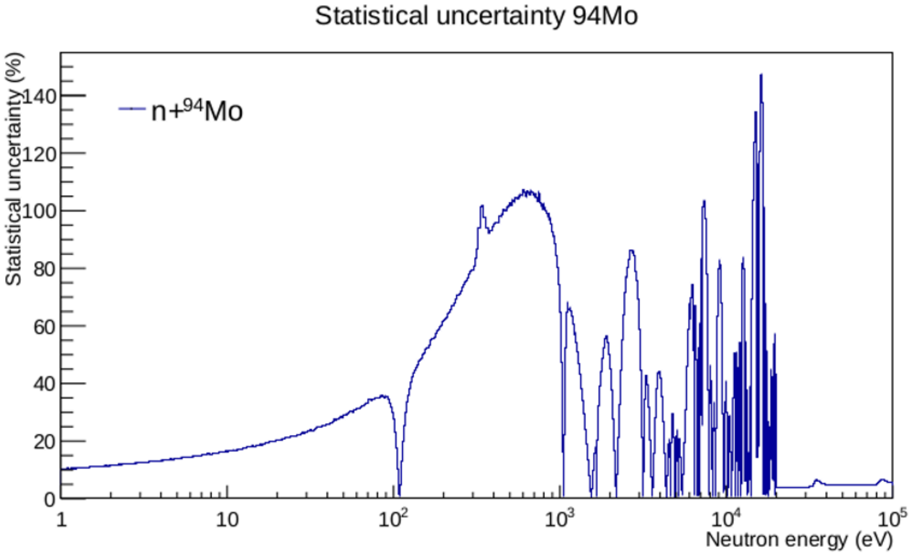


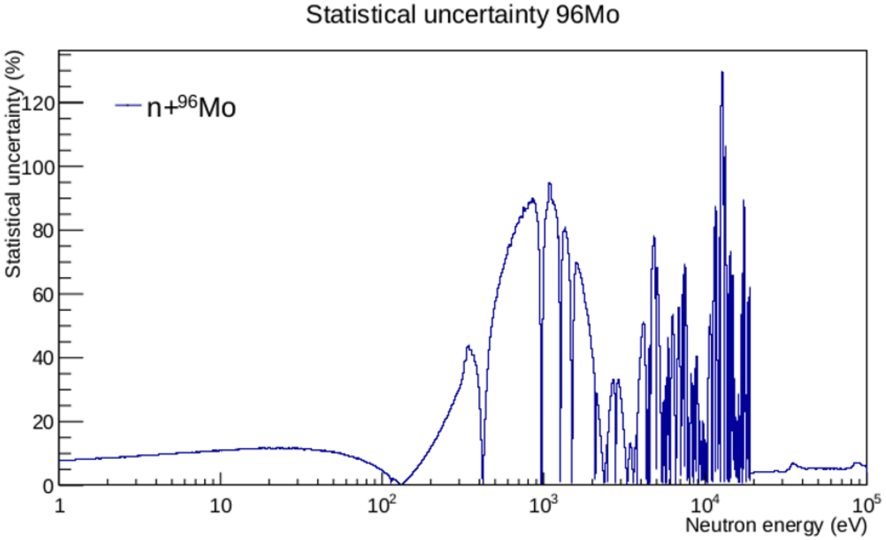


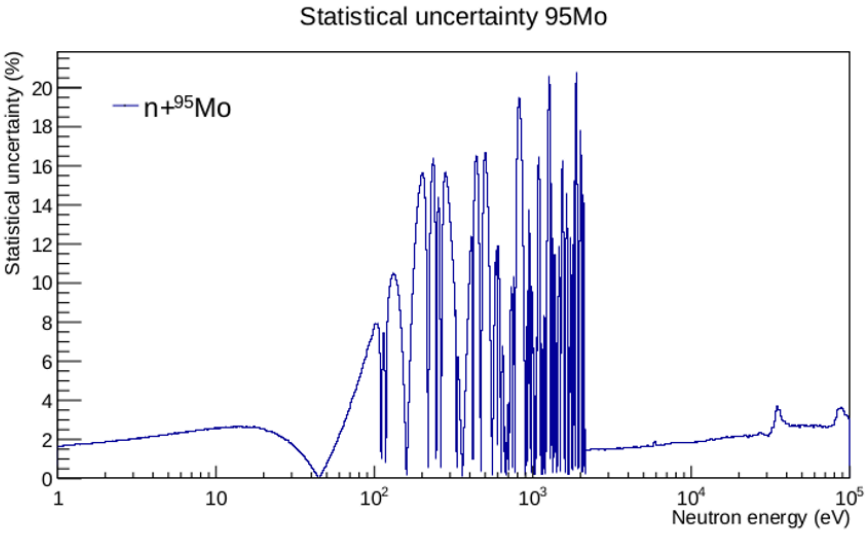


backup

Measurements: counting statistics.







backup

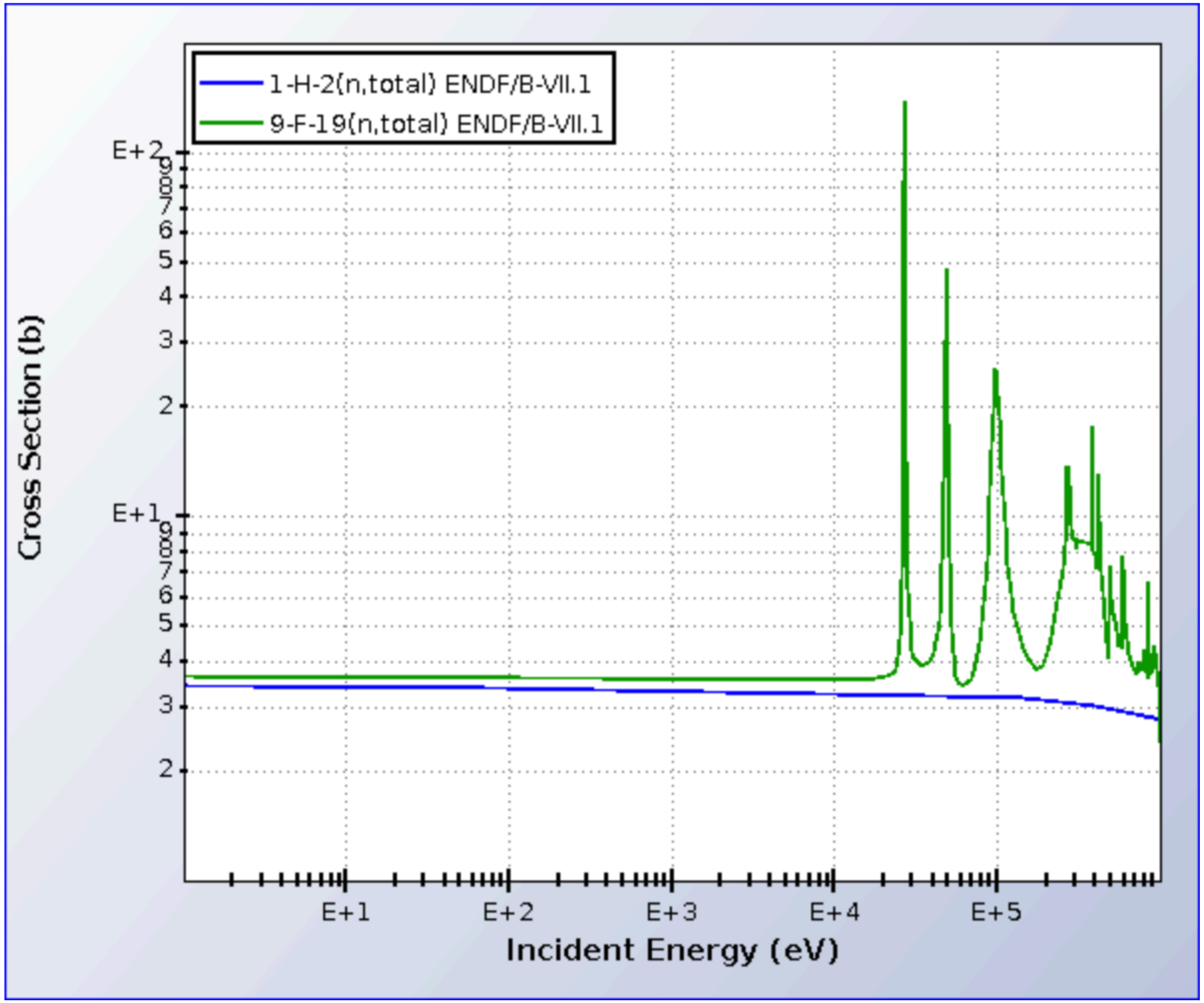
Protons

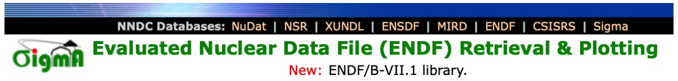
Measurement	EAR1	EAR2
n + ^{94}Mo	20 x 10^{17}	5 x 10^{17}
n + ^{95}Mo	10 x 10^{17}	3 x 10^{17}
n + ^{96}Mo	18 x 10^{17}	5 x 10^{17}
Normalization	3 x 10^{17}	1 x 10^{17}
Background	9 x 10^{17}	6 x 10^{17}
TOTAL	**60 x 10^{17}**	**20 x 10^{17}**

backup

C_6F_6

C_6D_6





NNDC Databases: NuDat | NSR | XUNDL | ENSDF | MIRD | ENDF | CSISRS | Sigma

Sigma Evaluated Nuclear Data File (ENDF) Retrieval & Plotting

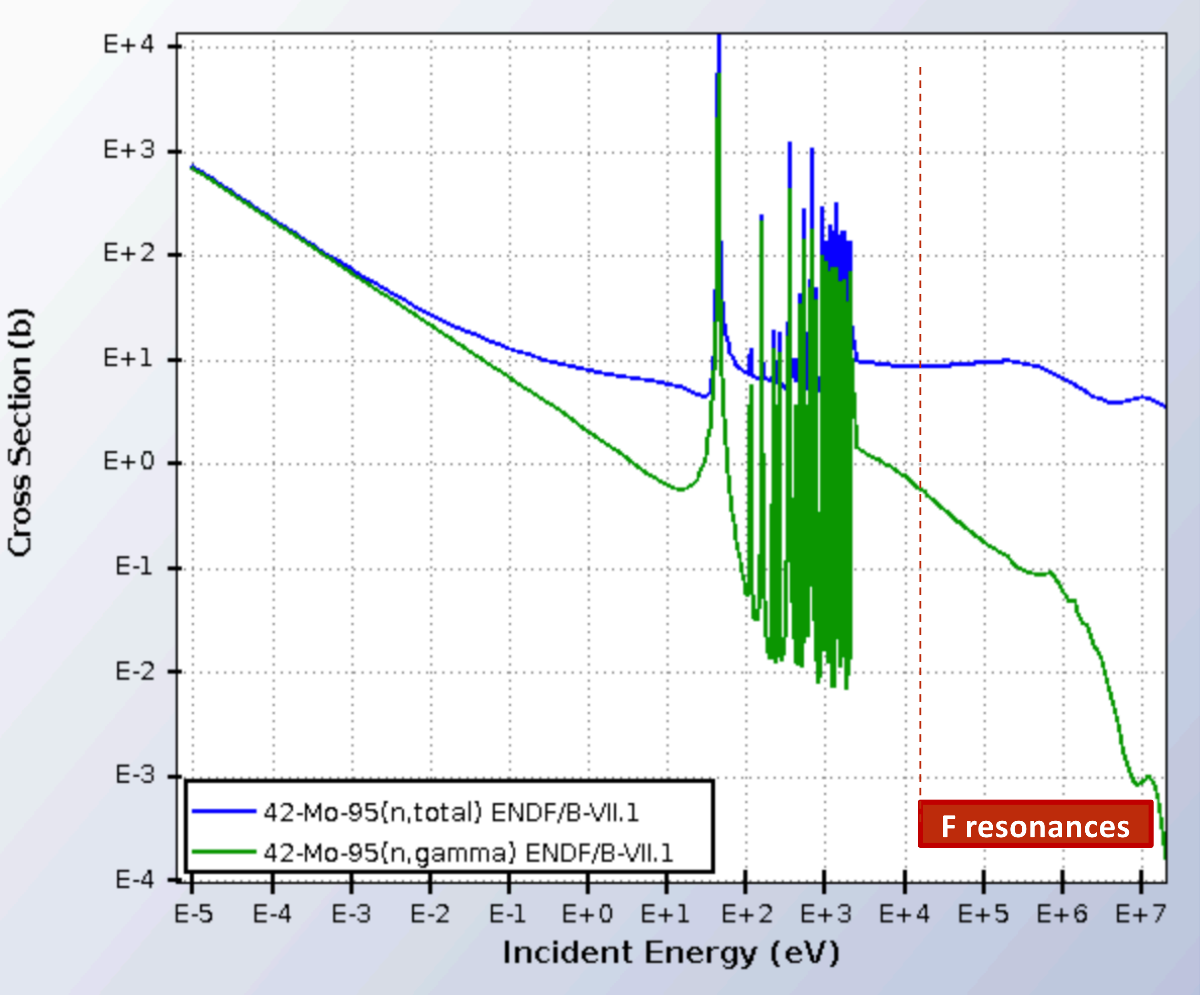
New: ENDF/B-VII.1 library.

backup

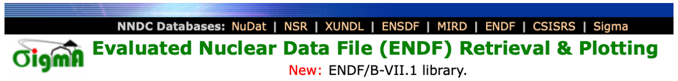
(n,γ) / (n,n)

C_6F_6

C_6D_6



F resonances



NNDC Databases: NuDat | NSR | XUNDL | ENSDF | MIRD | ENDF | CSISRS | Sigma

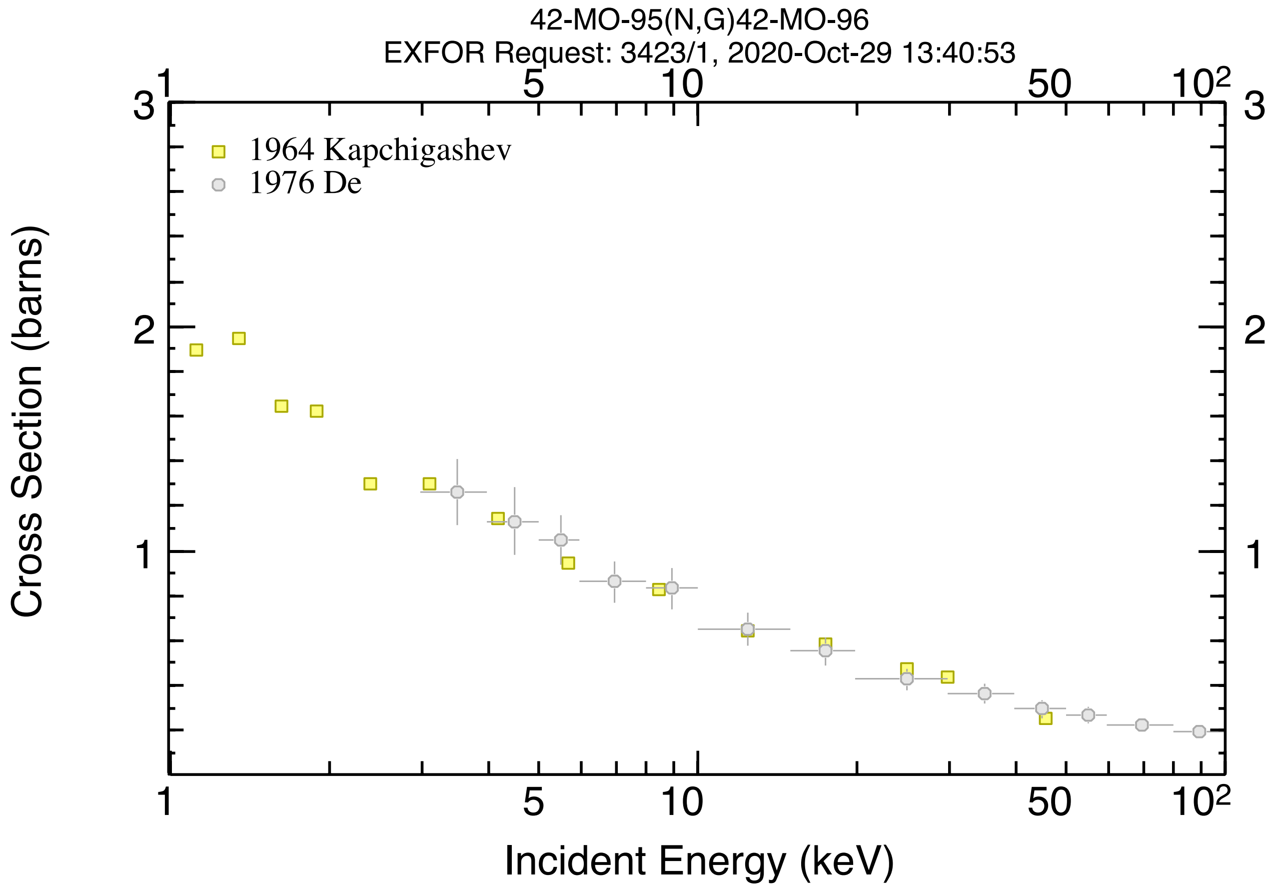
Evaluated Nuclear Data File (ENDF) Retrieval & Plotting

New: ENDF/B-VII.1 library.

backup

(n,γ) Kapchigashev data Vs Musgrove data

n+^{95}Mo

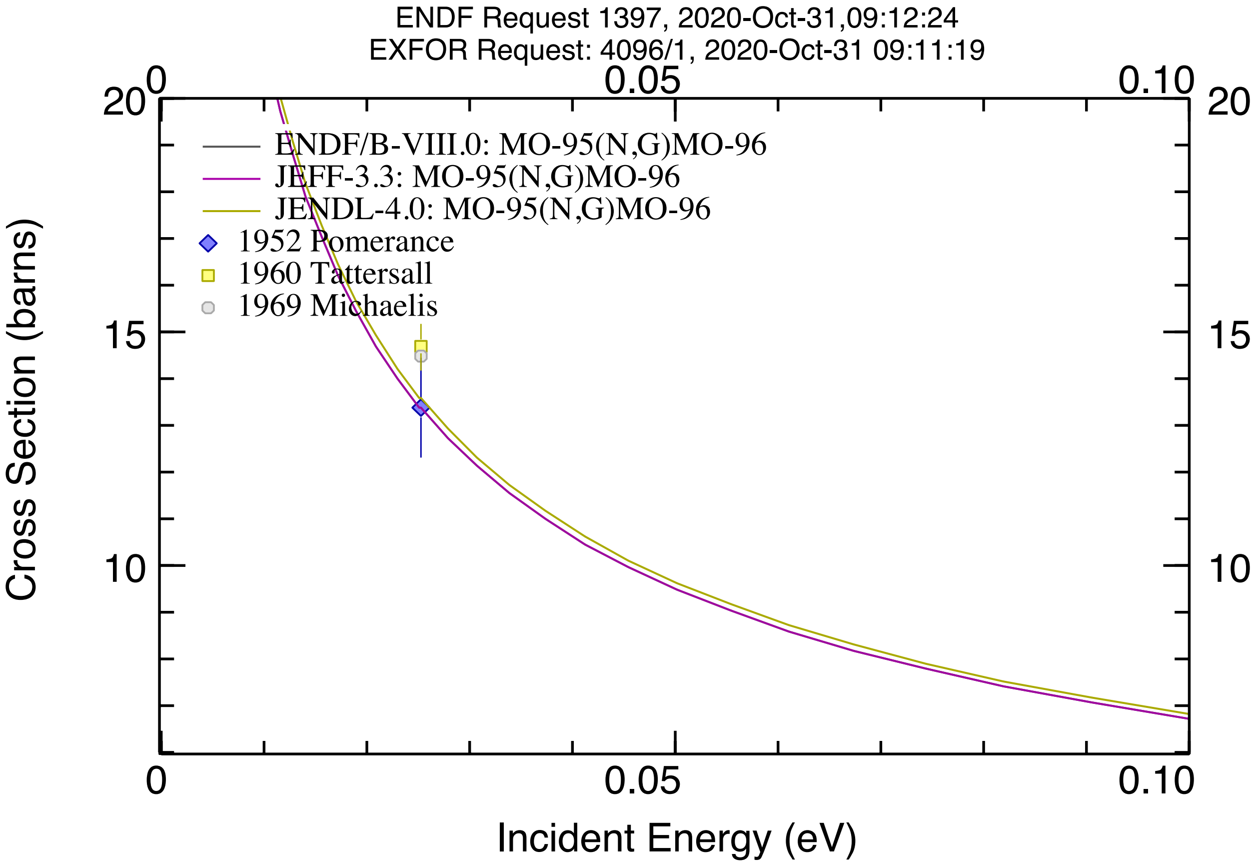


Koehler unpublished data: MACS ~ 350 mb

backup

(n,γ) data at E_n = 0.0253 eV

n+^{95}Mo



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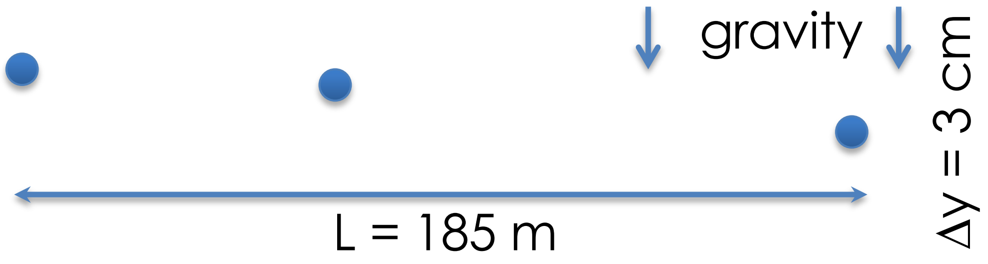
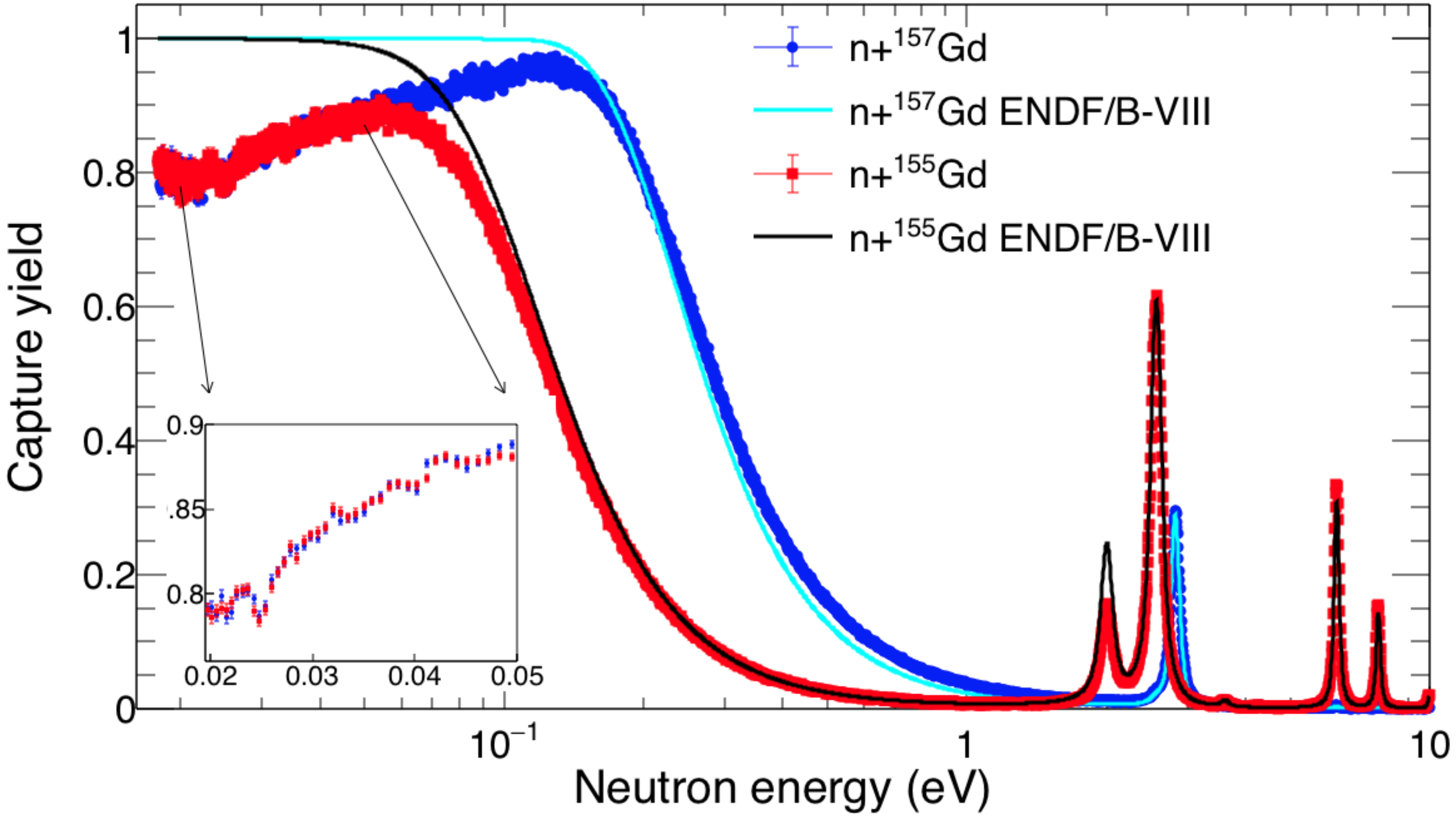
Beam Interception factor





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Uncertainties in a capture experiment

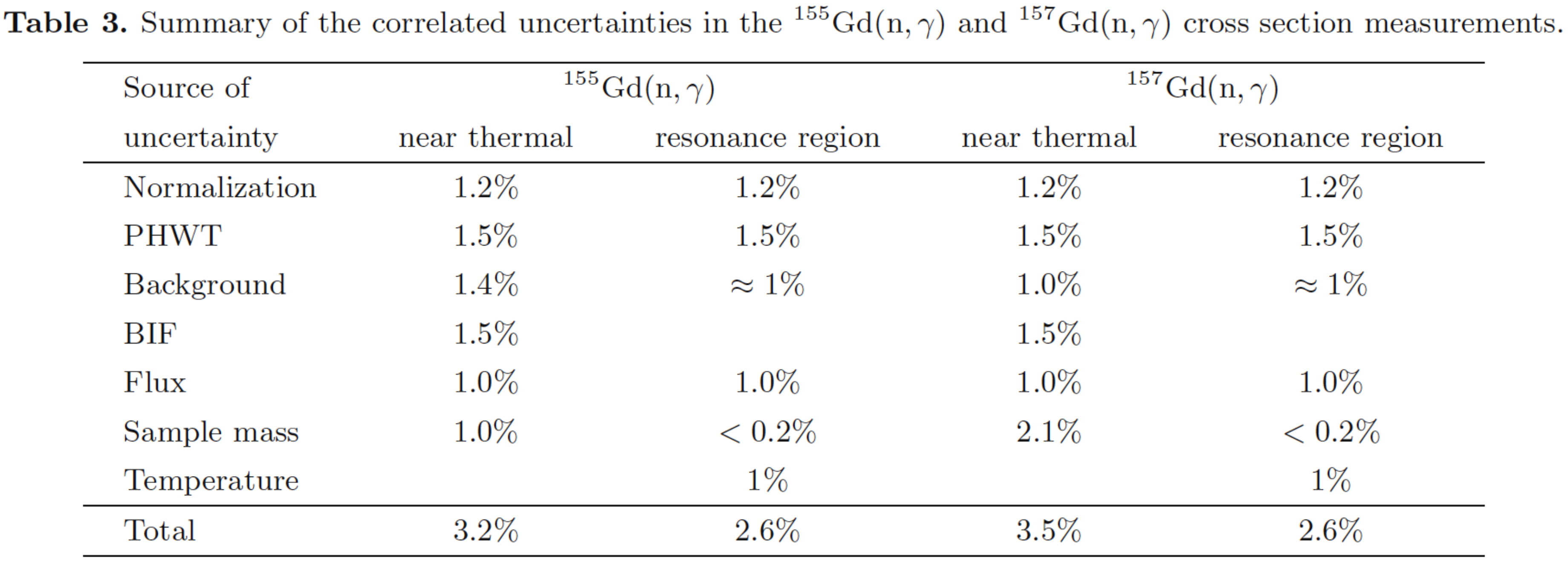

Table 3. Summary of the correlated uncertainties in the ^{155}Gd(n, γ) and ^{157}Gd(n, γ) cross section measurements.

Source of	^{155}Gd(n, γ)		^{157}Gd(n, γ)	
uncertainty	near thermal	resonance region	near thermal	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%

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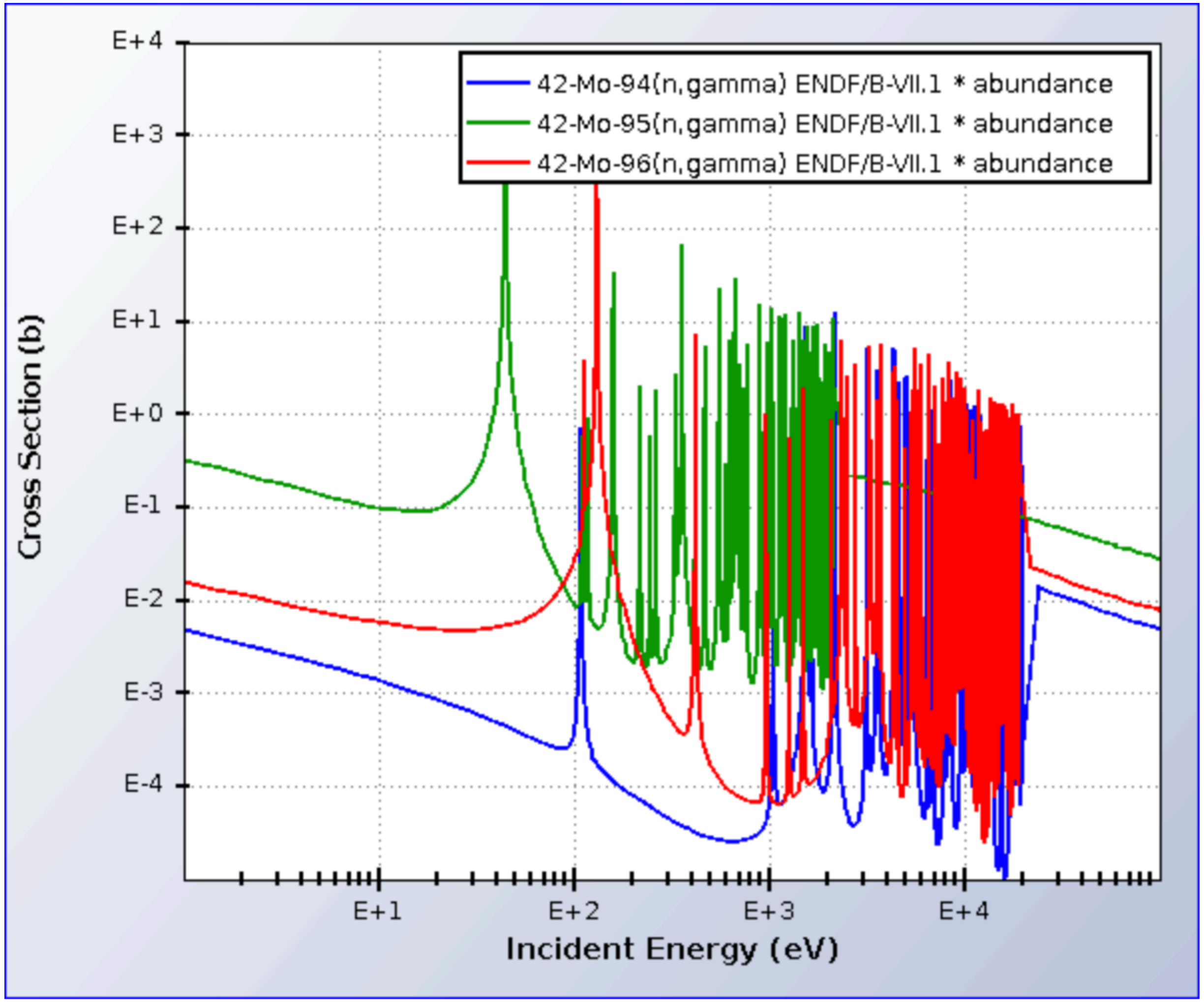
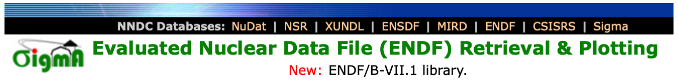
Natural molybdenum sample



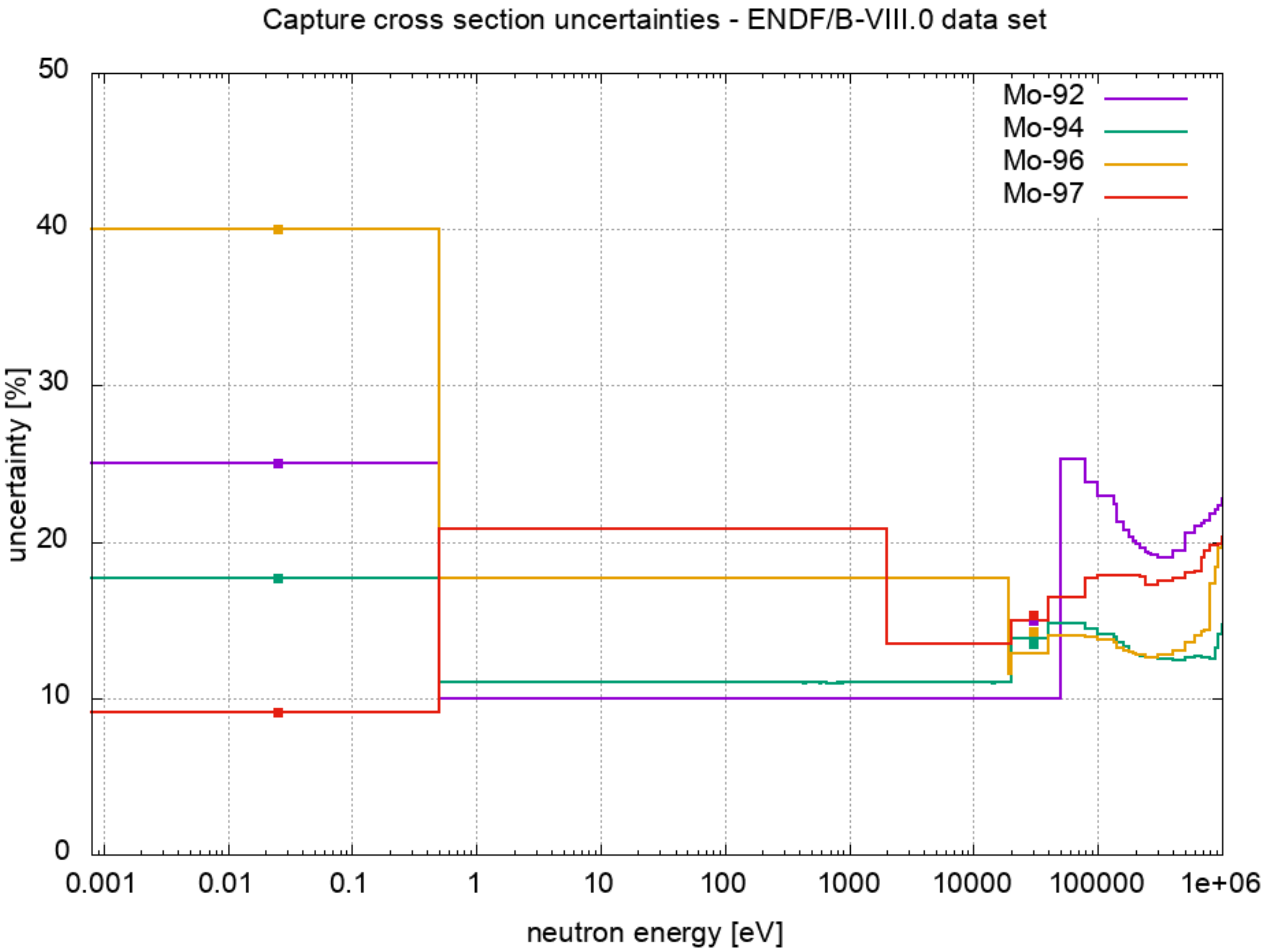

NNDC Databases: NuDat | NSR | XUNDL | ENSDF | MIRD | ENDF | CSISRS | Sigma

Evaluated Nuclear Data File (ENDF) Retrieval & Plotting

New: ENDF/B-VII.1 library.

backup

Cross section: uncertainties.



backup

Cross section: uncertainties.