Measurement of ^{92,97,98,100}Mo(n,γ) relevant to Astrophysics and Nuclear Technology

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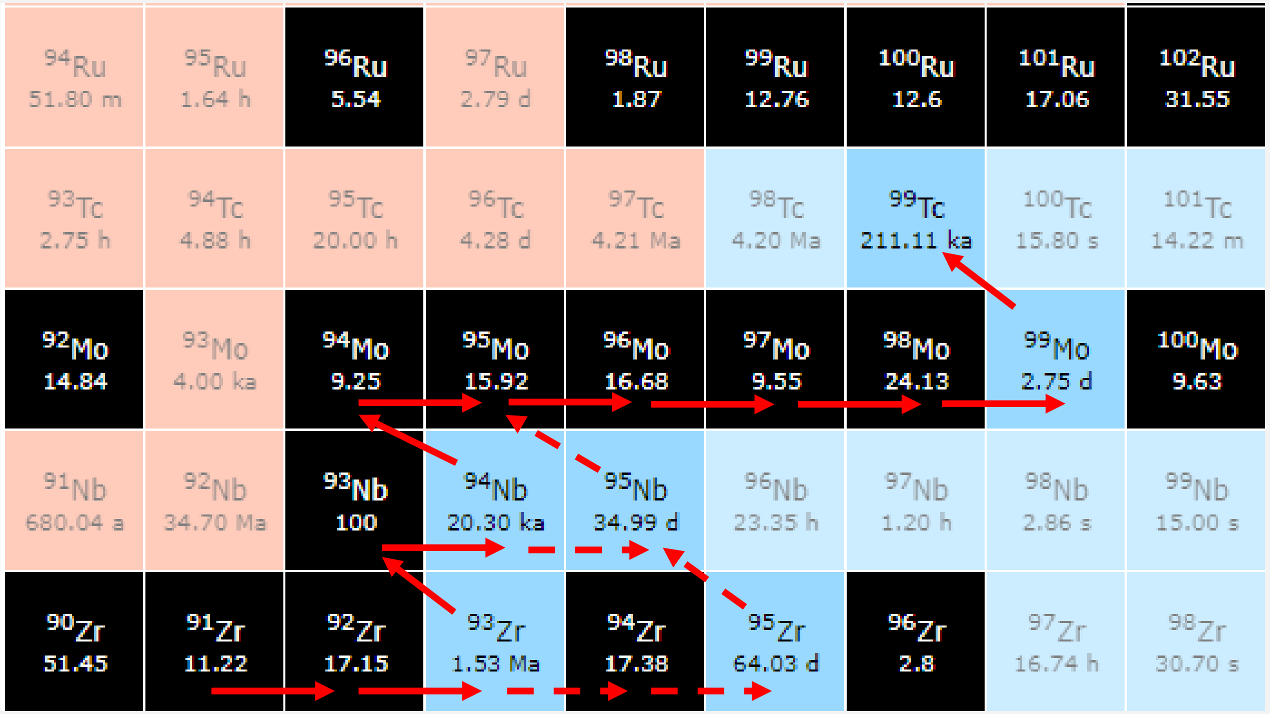
76th meeting of the INTC

Importance of molybdenum

- Stellar nucleosynthesis;
- Fission product in nuclear power plants;
- Transport casks, irradiated fuel storage;
- Research reactors and Accident Tolerant Fuels;
- Future fusion reactors;
- Production of ^{99m}Tc for nuclear medicine.

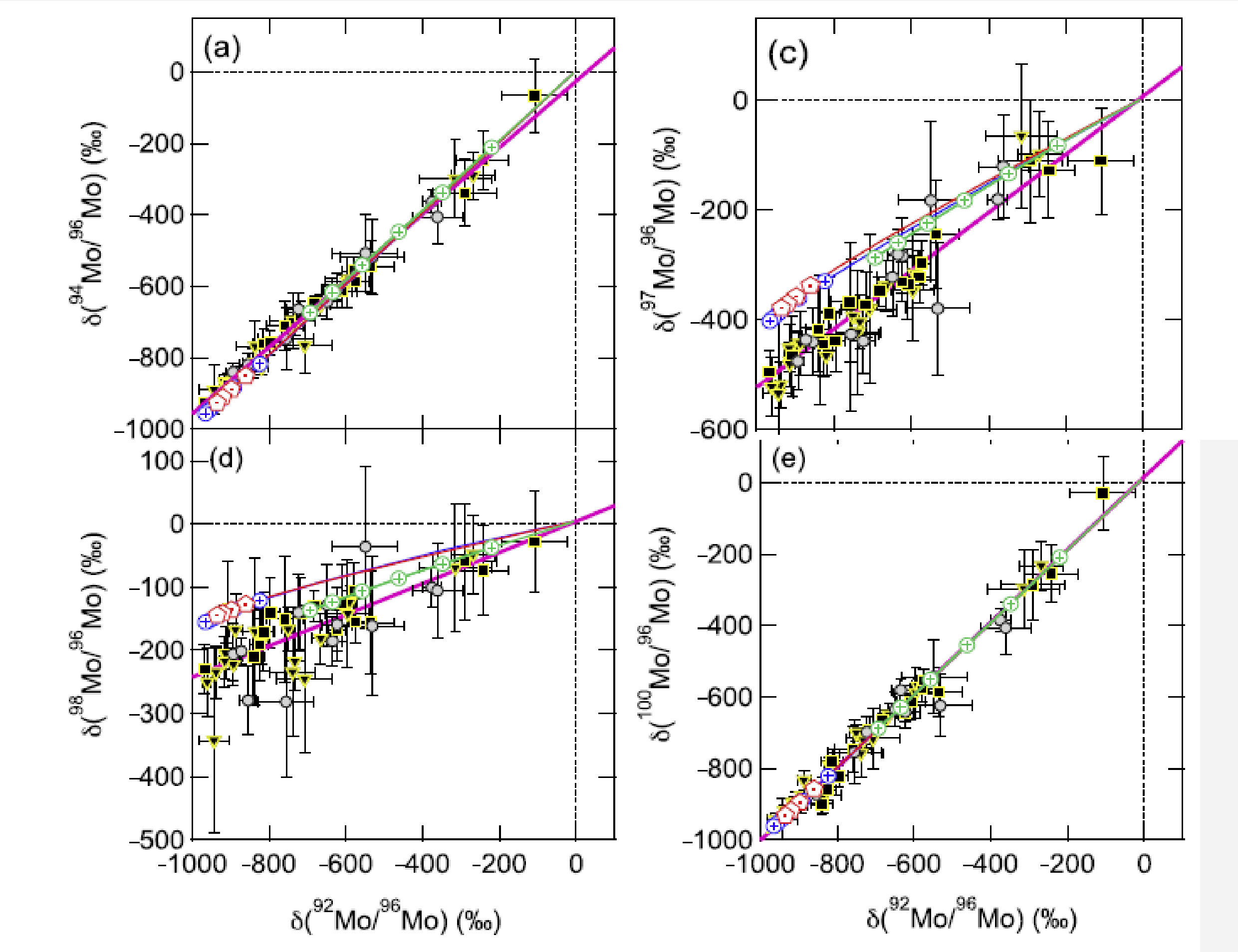
Stellar nucleosynthesis

- Four main nucleosynthesis processes for elements heavier than iron: s-process, r-process, i-process, and p-process;
- Some isotopes can be synthetized only by one process (e.g., ^{92}**Mo** p-only, ^{100}**Mo** r-only);
- Possible to set constraints on intensity of the processes.



s-process path around molybdenum

Presolar grain composition



- Comparison of SiC grains composition versus stellar model using delta notation:

$$\delta\left(\frac{^{95}Mo}{^{96}Mo}\right) = 10^3 \times \left[\left(\frac{^{95}Mo}{^{96}Mo}\right) \Big/ \left(\frac{^{95}Mo}{^{96}Mo}\right)_{\odot} - 1\right]$$

- MACS from **KADoNiS v0.3** database,
- Slight discrepancies between model and isotopic composition, especially for ^{97}**Mo** and ^{98}**Mo**,
- Possible overestimation of MACS in KADoNiS.

N. Liu et al., APJ 881 (2019)

Astrophysical motivations beyond s-process

^{92}Mo

- Produced via p-process;
- Main processes of production are (γ, n), (γ,p), (γ, α);
- For stars with temperature $T<3 \times 10^{9}$ K, the (γ,n) process is more relevant for this isotope.

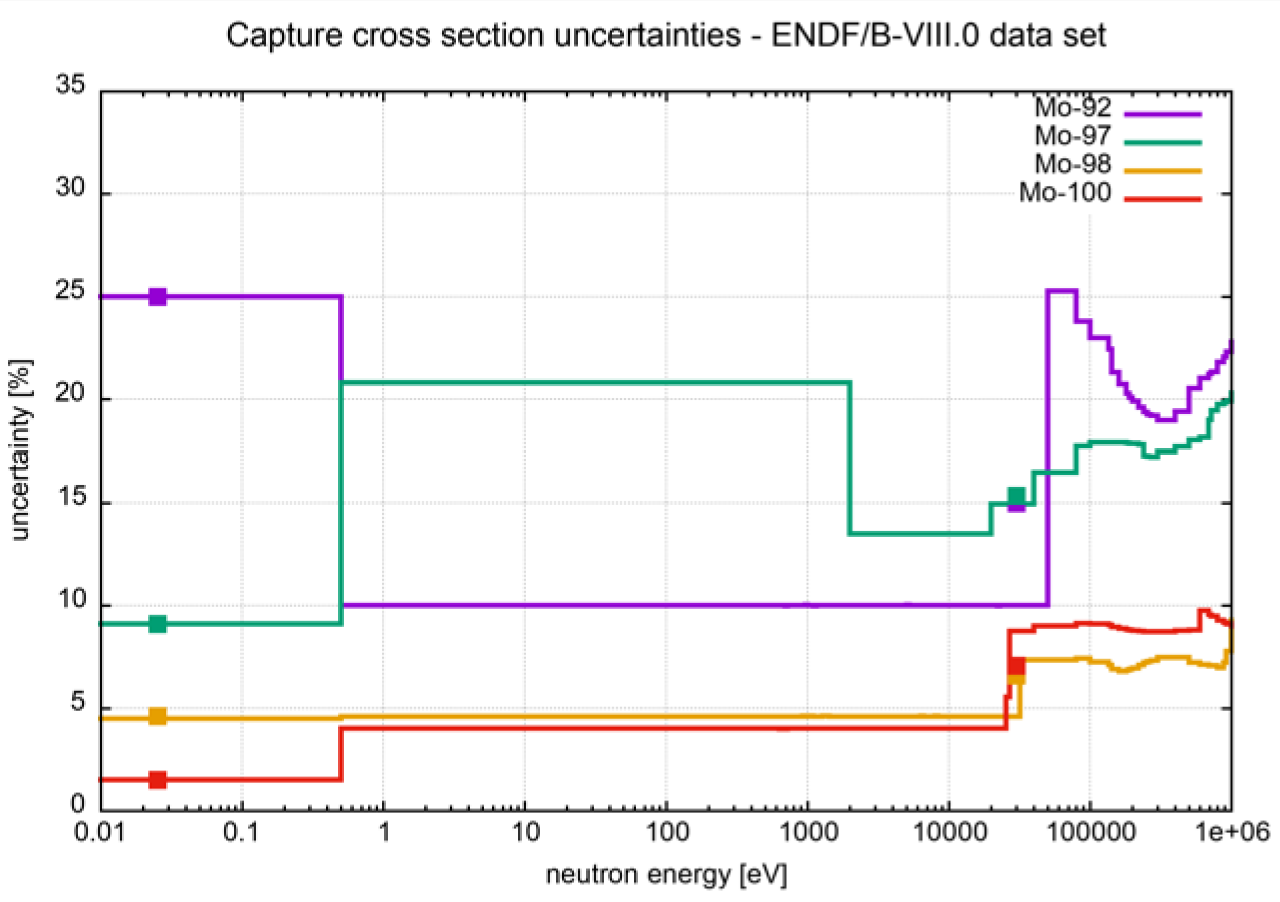
^{100}Mo

- Produced by r-process and n-process;
- In explosive He burning conditions in CCSN, neutron interactions are relevant for the creation and destruction of ^{100}Mo.

Production of ^{99m}Tc

- ^{99m}**Tc** is one of the most important radioisotope in nuclear medicine;
- Mainly produced in nuclear reactors;
- Production of ^{99m}Tc with in irradiation facilities with epithermal or fast neutrons can be useful for small domestic use;
- ^{98}**Mo(n,γ)** and ^{100}**Mo(n,2n)** are the main candidates to produce ^{99m}Tc with irradiation;
- Accurate knowledge of the neutron interaction cross sections is relevant to accurately predict the production rates in new facilities.

Cross section uncertainties in ENDF/B-VIII

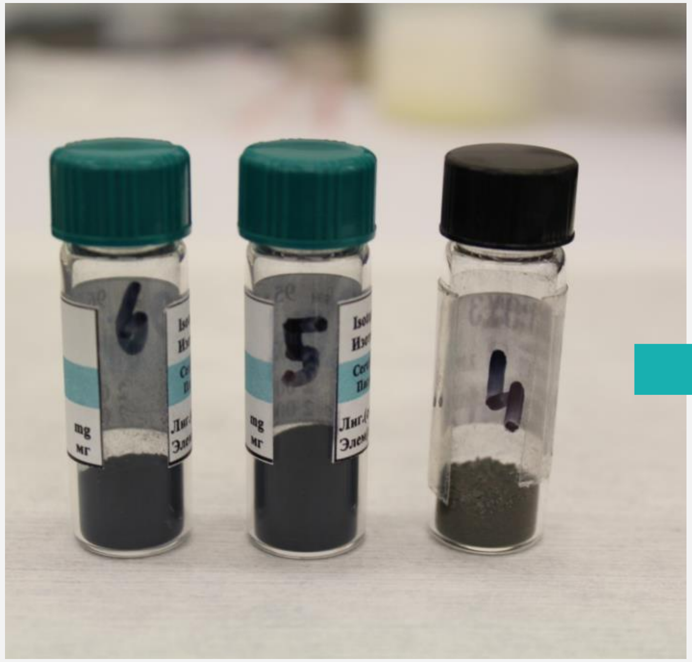


- Large uncertainties in the cross section reported in nuclear data libraries;
- Uncertainties in the **MACS** @ 30 keV around 10-15% for all isotopes;
- Resolved resonance region of ^{97}Mo limited to region below 2 keV.

ENDF/B-VIII: D. Brown et al., Nucl. Data. Sheets 148 (2012)

Samples

- Samples like the ones used in previous campaign;
- Metallic powder samples;
- Enrichment above **95%** in each sample;
- ~**2g** of material for each isotope in **2cm** diameter disks;
- Possible to press powder to create self-sustaining samples;
- Maybe possible to mount samples in standard Al ring with Mylar.

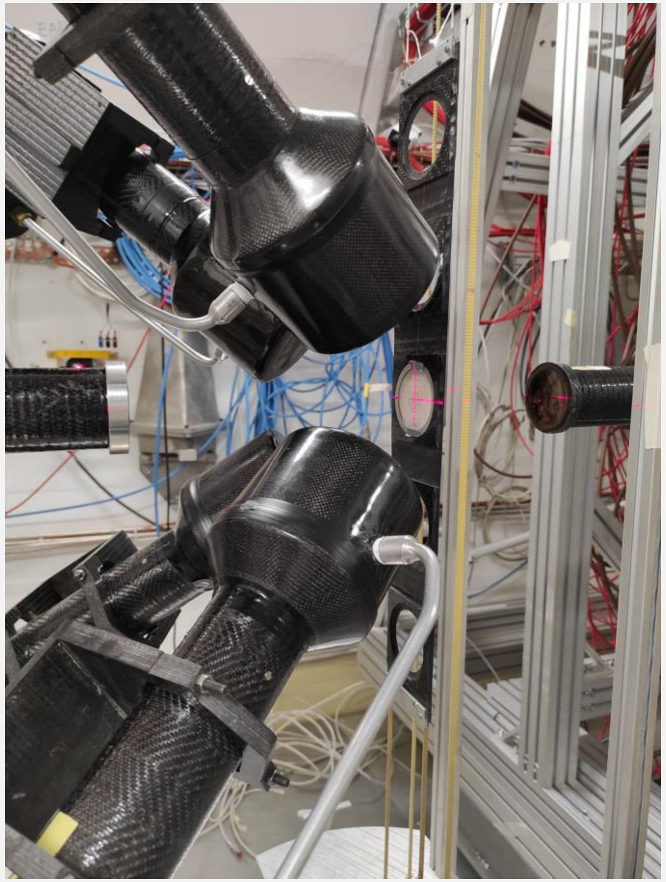


Sample preparation at n_TOF

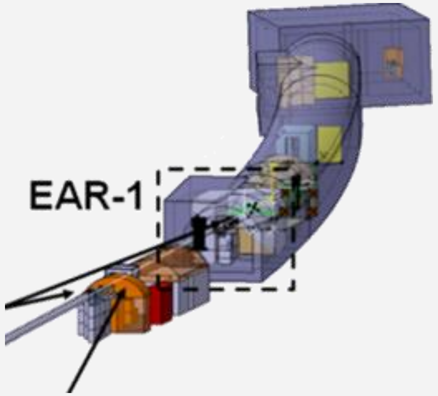
- Metallic powder of ^{nat}Mo with grain size like previous enriched samples;
- Sample prepared using 2g of material in a 2cm diameter disk;
- Preparation performed locally at n_TOF using hydraulic press;
- Minimal amount of material loss during preparation (<0,1%);
- Self sustaining samples, no sign of instability.

Measurements setup

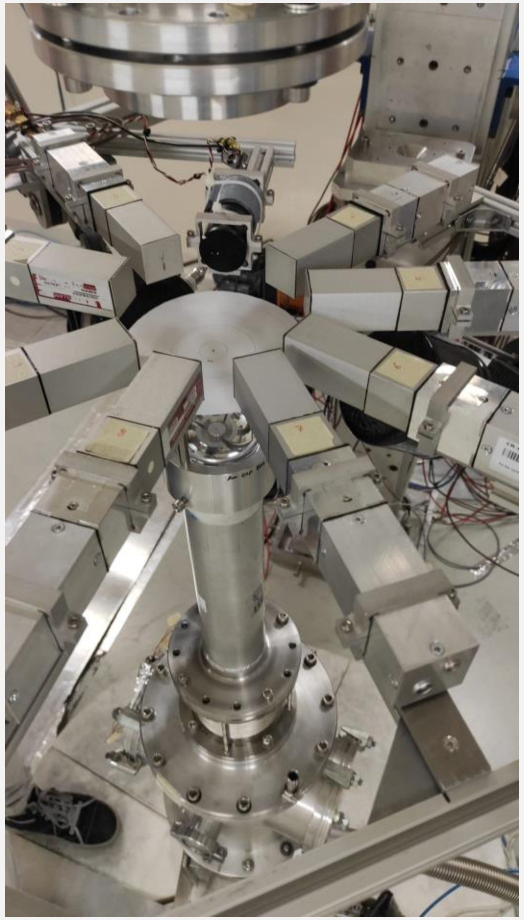
EAR1



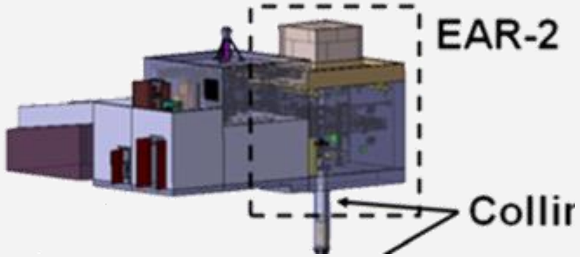
Setup:
- 4 C_6D_6



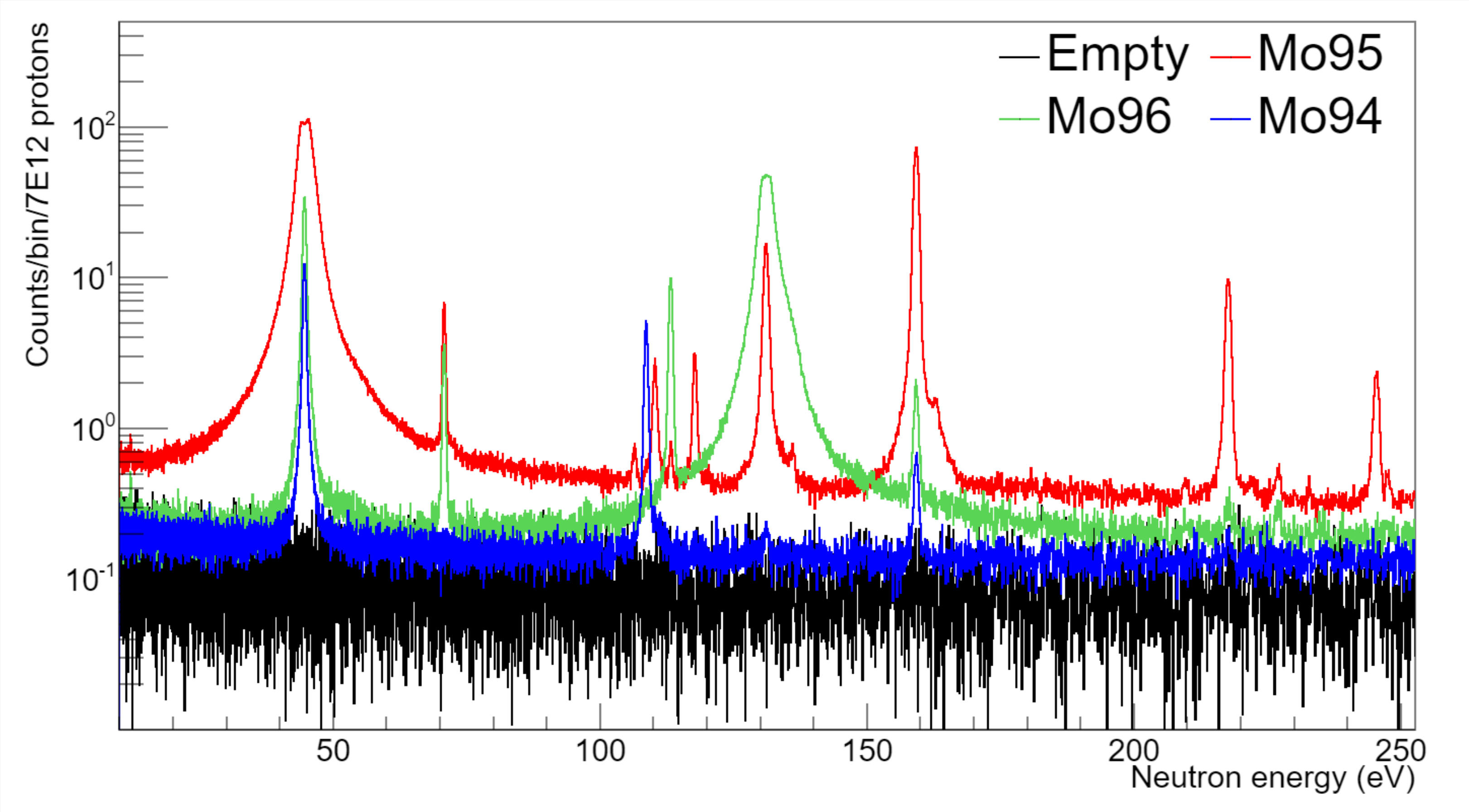
EAR2

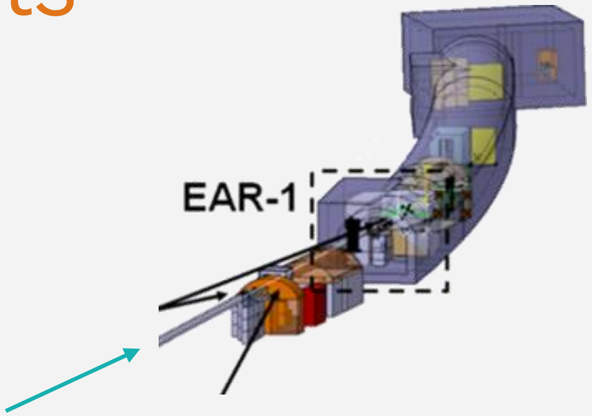


Setup:
- 9 sTED
- 2 C_6D_6



EAR1 spectra previous measurements

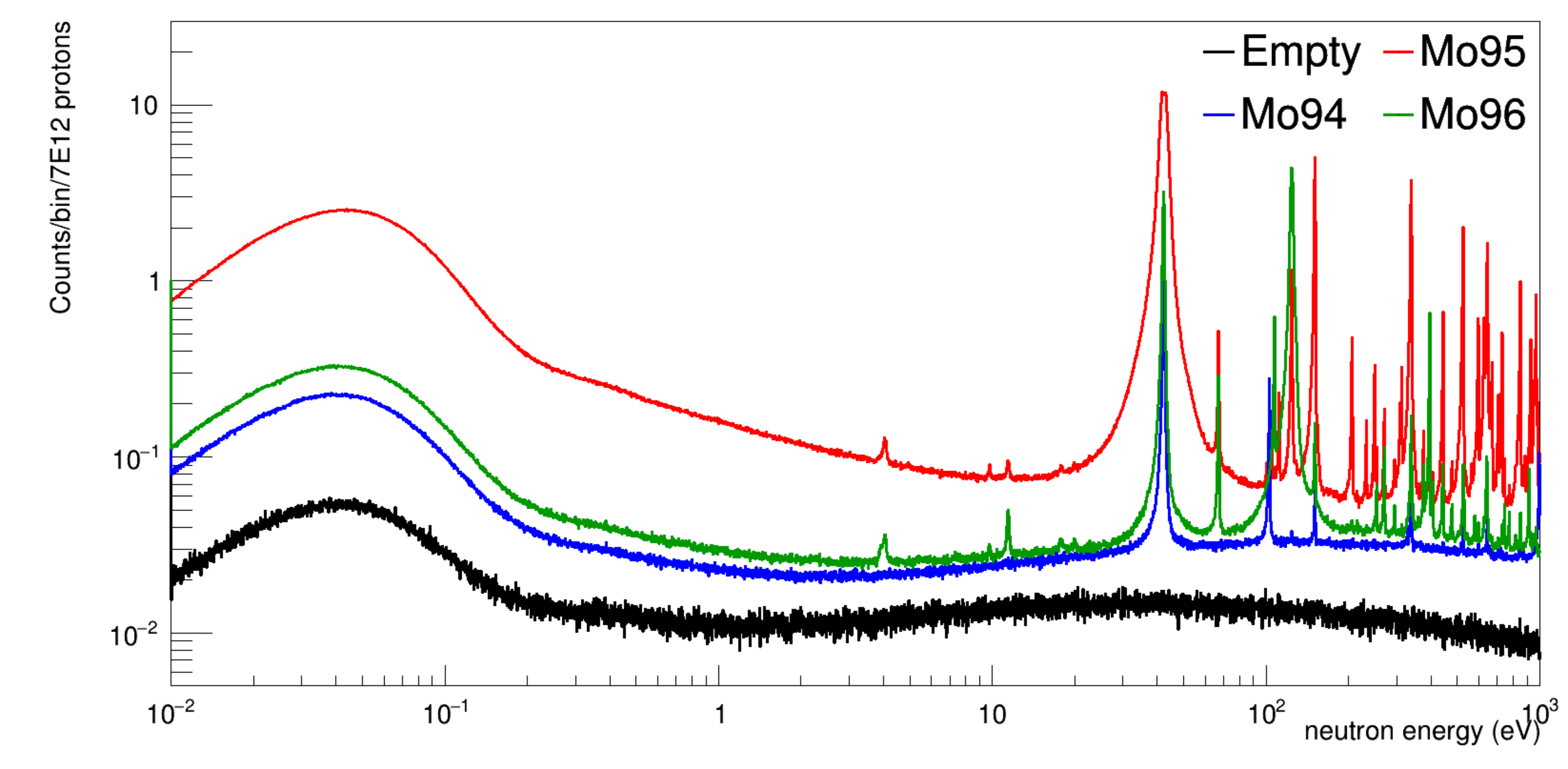


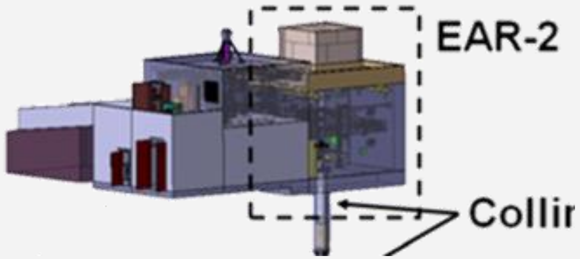


Good energy resolution up to tens of keV

EAR2 spectra previous measurements

High number of count at thermal region

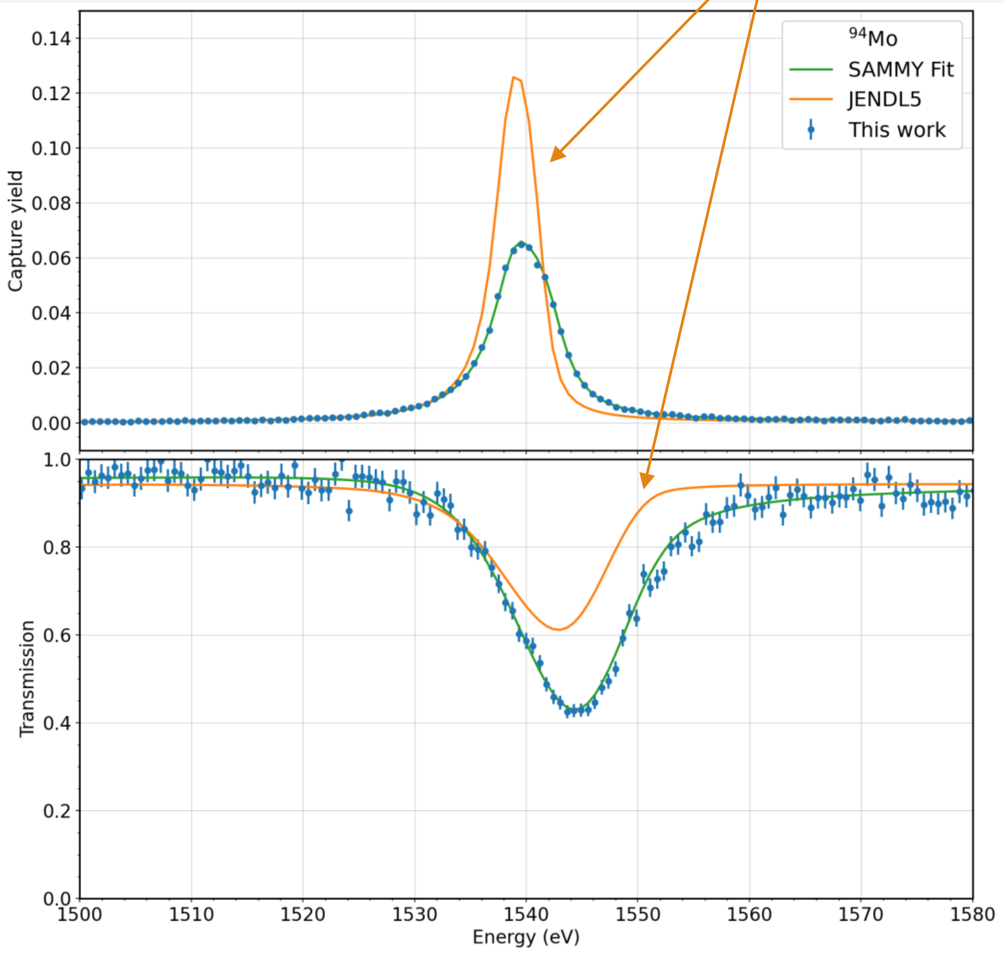




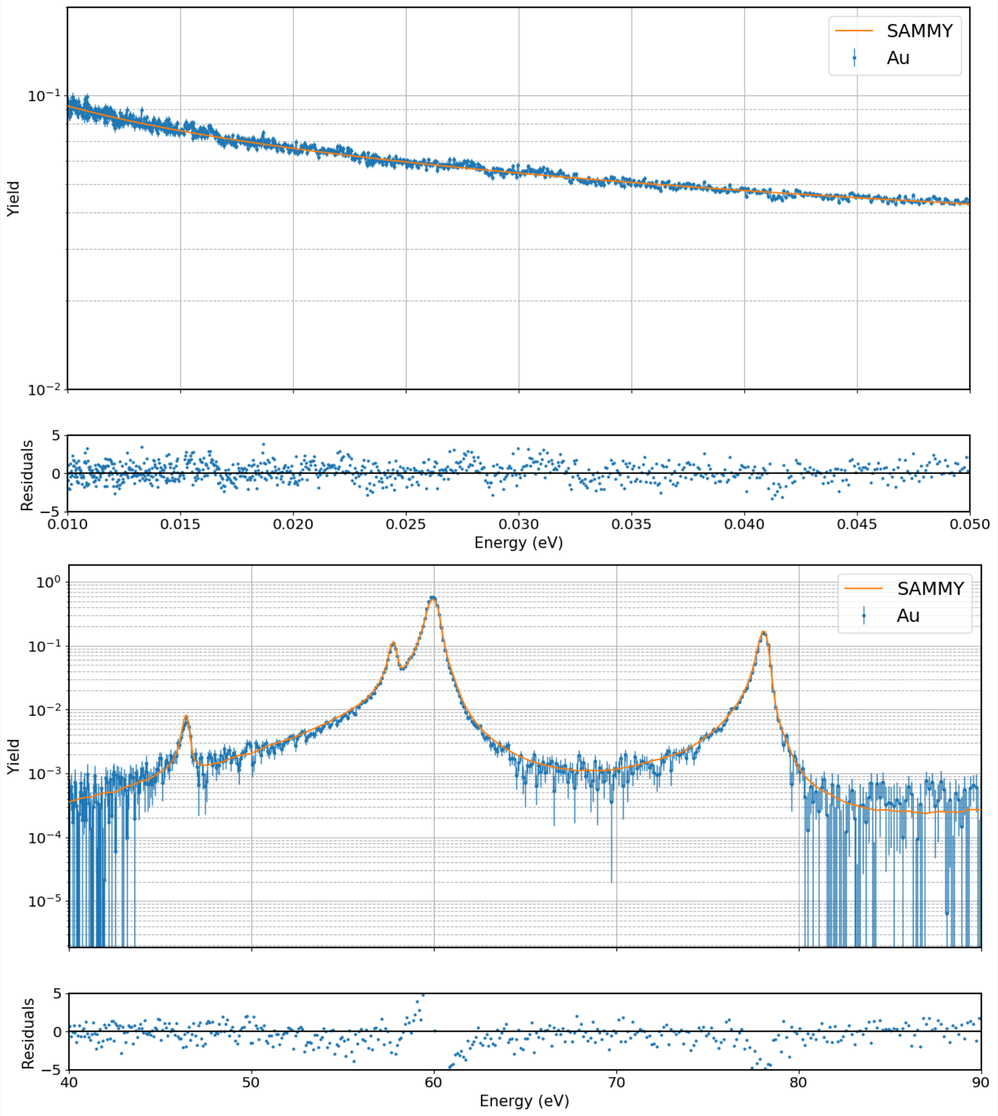
Preliminary results previous measurements

JENDL library doesn't reproduce the data accurately

- Analysis of **EAR1** data performed for all isotopes, resonance fitting currently ongoing;
- Example of preliminary fit for ^{94}Mo showed here compared to the calculation performed with **JENDL5** parameters;
- Good agreement between transmission and capture data with enriched samples.

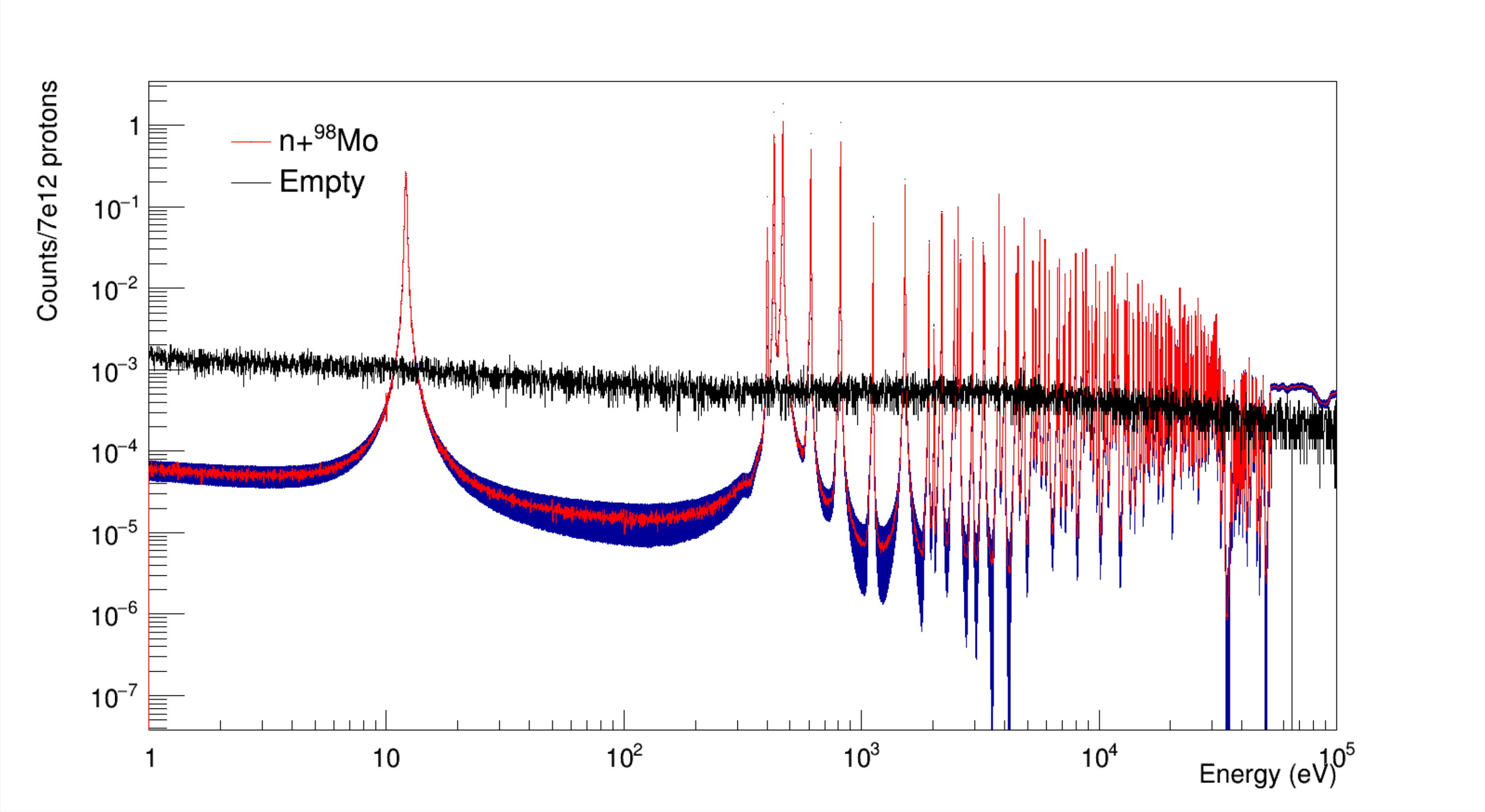


Preliminary results previous measurements



- Preliminary analysis of **EAR2** data with gold samples;
- Capture yield compared with values in **ENDF/B-VIII** using SAMMY;
- Good agreement of data with calculations in thermal region (0,025 eV) and in the resolved resonances.

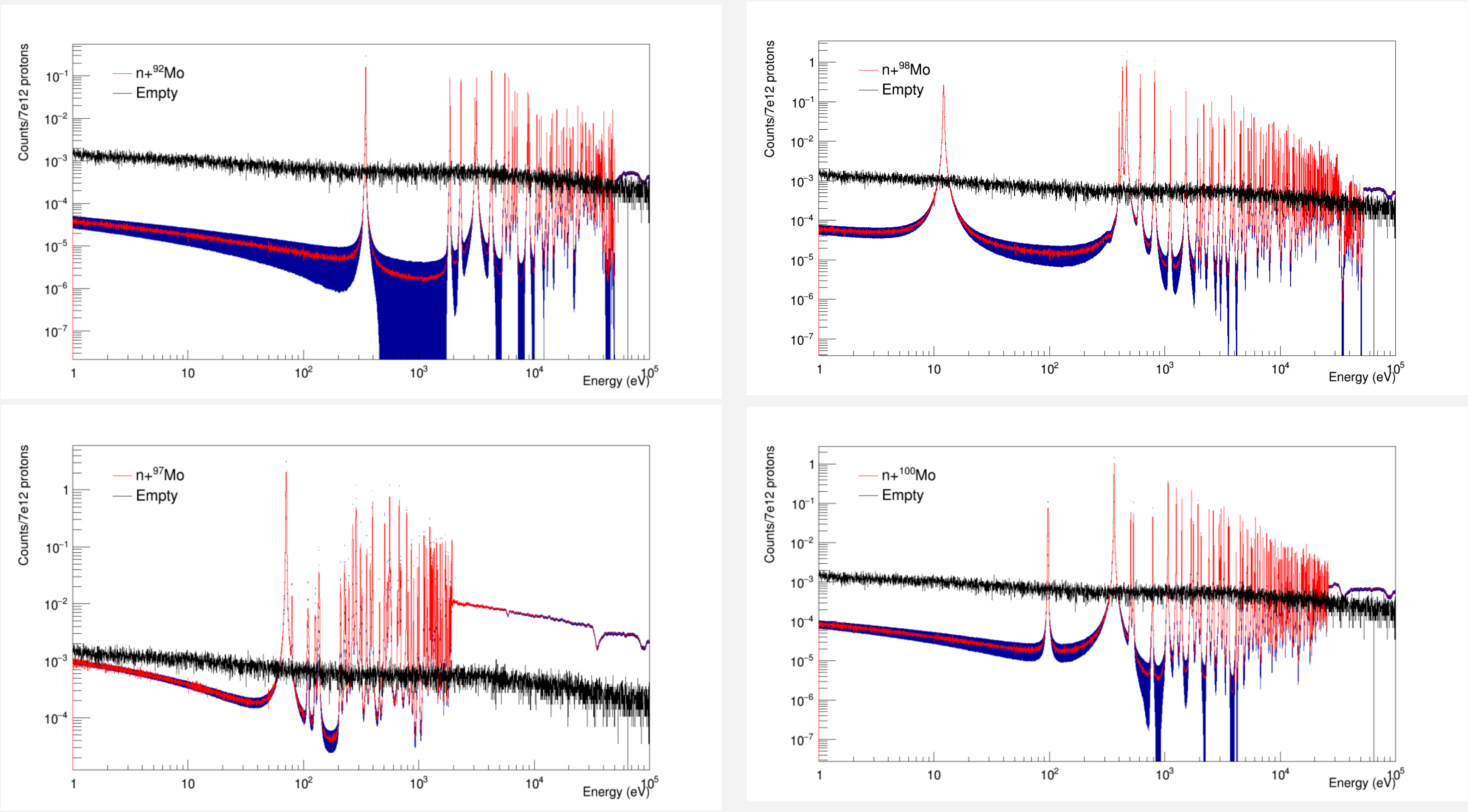
Count rates EAR1



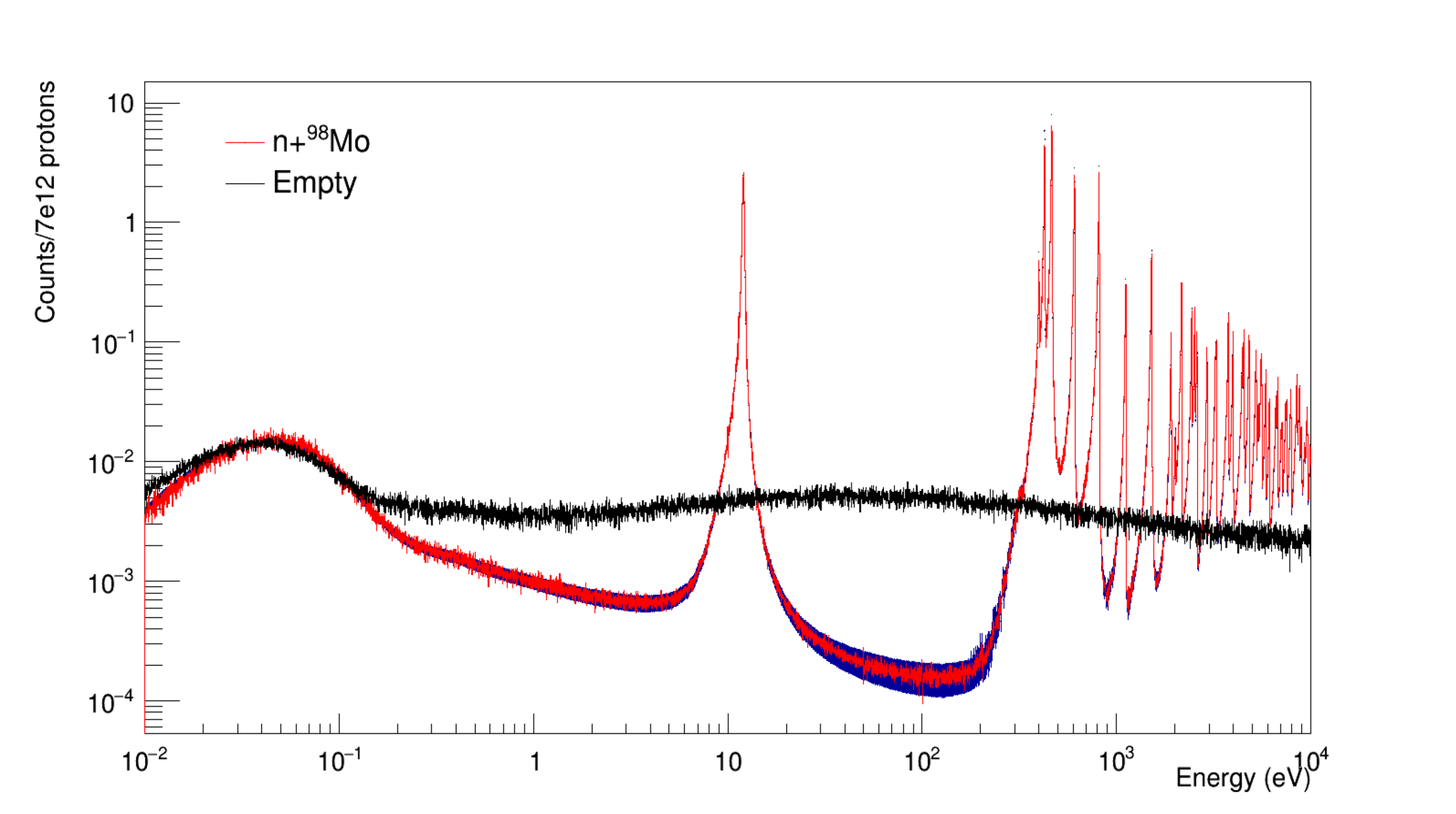
Count rates estimated for **EAR1** measurements

- Setup with 4 C_6D_6
- Cross section from ENDF/B-VIII.0
- Resolution of EAR1 included in the estimation using SAMMY
- Empty from previous Mo campaign in EAR1 (2022),
- Total of **20 x 10^{17}; 10 x 10^{17}; 17 x 10^{17}; 17 x 10^{17}** for ^{92}Mo, ^{97}Mo, ^{98}Mo, and ^{100}Mo respectively.

Count rates EAR1



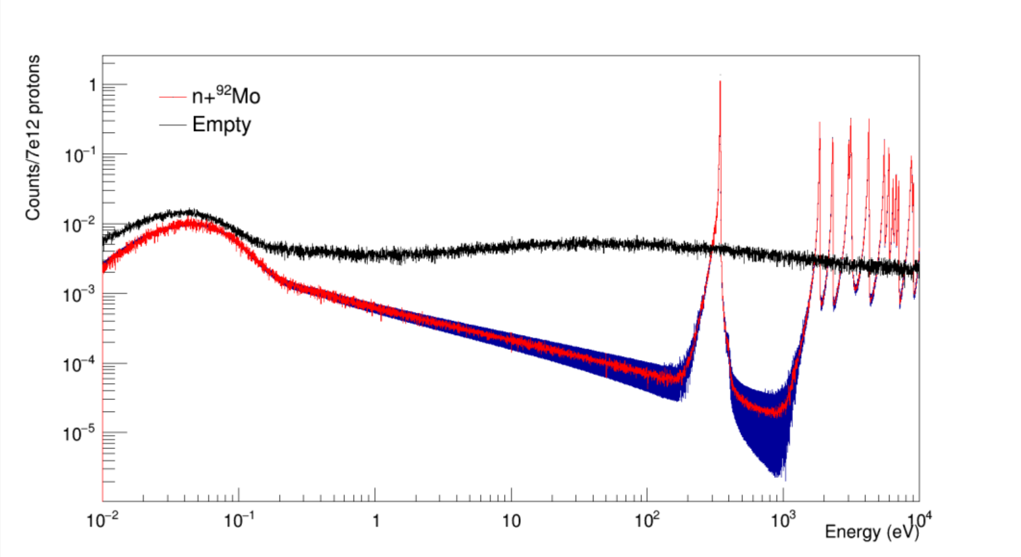
Count rates EAR2

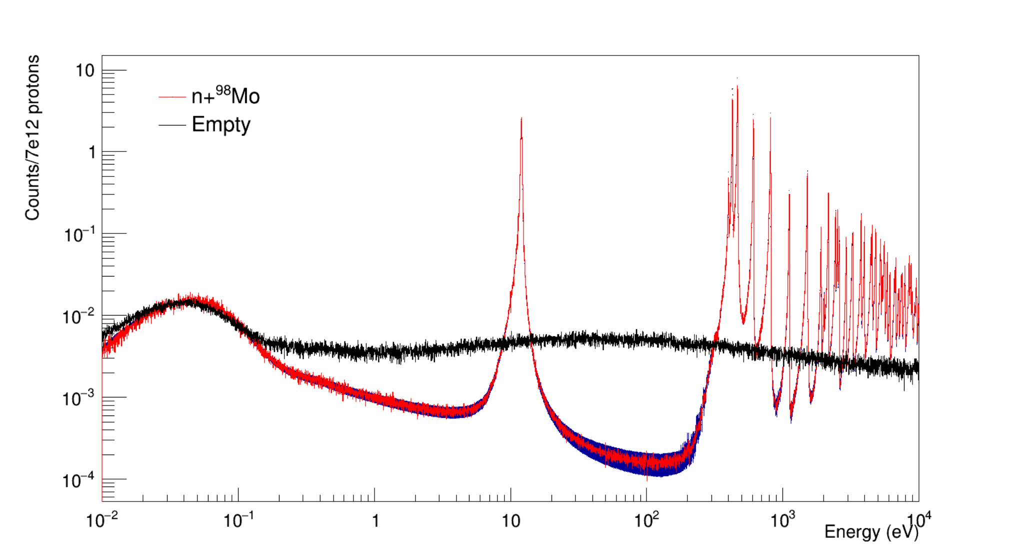


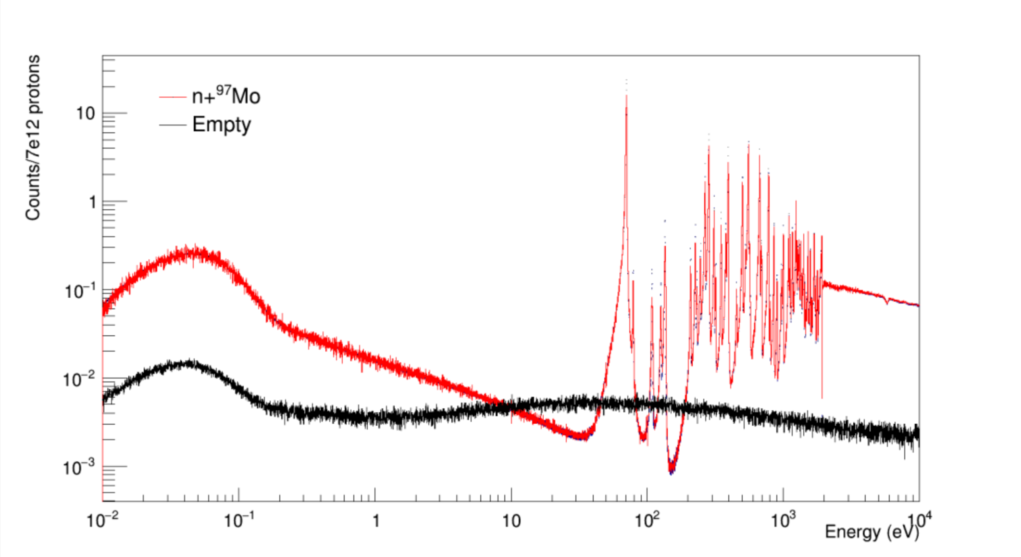
Count rates estimated for **EAR2** measurements

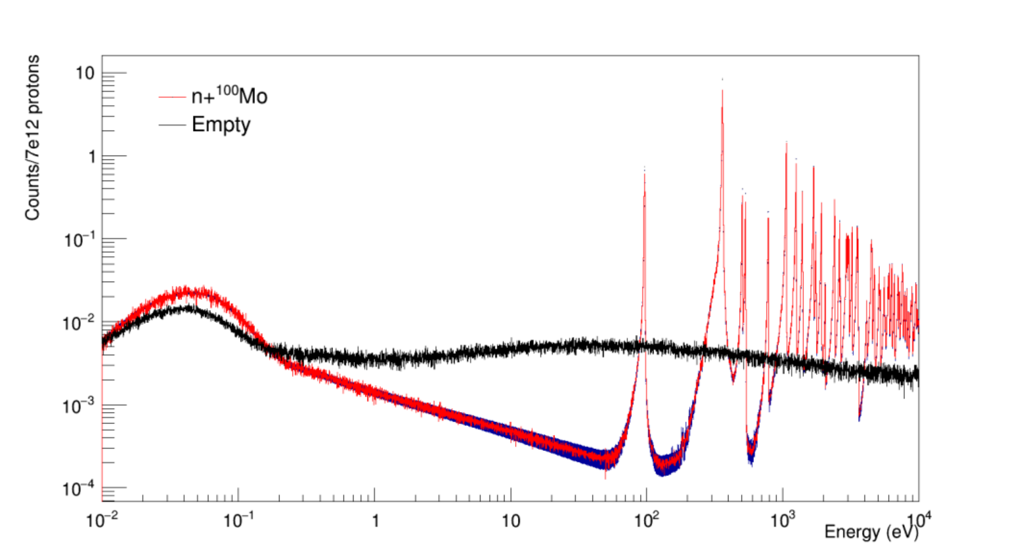
- Setup with 9 sTED
- Cross section from ENDF/B-VIII.0
- Resolution of EAR2 included in the estimation using SAMMY
- Empty from previous Mo campaign in EAR2 (2022),
- Total of **6,0 x 10^{17}; 4,0 x 10^{17}; 5,0 x 10^{17}; 4,0 x 10^{17}** for ^{92}Mo, ^{97}Mo, ^{98}Mo, and ^{100}Mo respectively.

Count rates EAR2









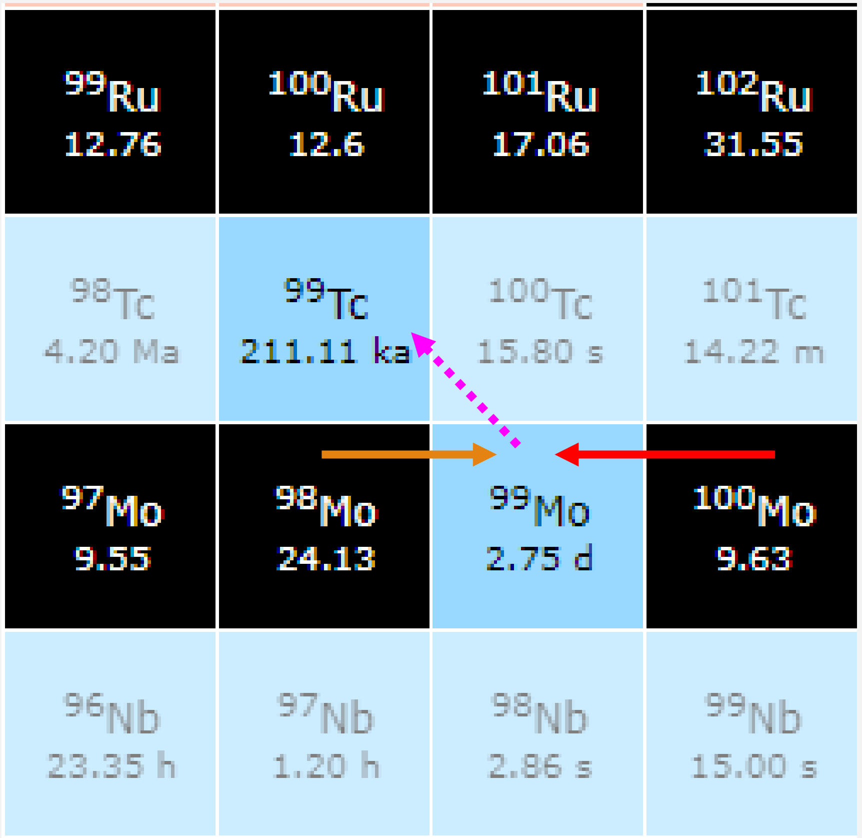
Conclusions

- Molybdenum cross section has strong physical motivations from astrophysics to nuclear technology and nuclear medicine;
- The accurate knowledge of the cross section for all the naturally occurring isotopes is crucial for nuclear reactors;
- High uncertainty in the literature data for these isotopes;
- Combination of measurements in **EAR1** with C_6D_6 and in **EAR2** with sTED to obtain cross section from thermal up to hundreds of keV;
- Preliminary analysis of previous measurements with other Mo isotopes in both experimental areas shows good performance and promising results;
- ...

Sample	EAR1 (C6D6)	EAR2 (sTED)
^{92}Mo	20 x 10^{17}	6 x 10^{17}
^{97}Mo	10 x 10^{17}	4 x 10^{17}
^{98}Mo	17 x 10^{17}	5 x 10^{17}
^{100}Mo	17 x 10^{17}	5 x 10^{17}
Au	2,0 x 10^{17}	1 x 10^{17}
Background (Empty/Dummy, C, Pb)	9,0 x 10^{17}	4 x 10^{17}
Total	75 x 10^{17}	25 x 10^{17}

Activation measurement at NEAR with ^{98}Mo

- Possibility of perform activation on ^{98}Mo and ^{nat}Mo samples at **NEAR** parasitically;
- Half life of ^{99}Mo is 66h, ideal candidate for activation;
- With natural sample two production channel available: **$^{98}Mo(n,\gamma)$** and **$^{100}Mo(n,2n)$;**
- Comparison between the two activation can be compared to the contribution of $^{100}Mo(n,2n)$;
- Production of ^{99m}Tc (6h), also measurable in the sample.



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- Preliminary analysis of previous measurements with other Mo isotopes in both experimental areas shows good performance and promising results;
- Possible parasitic activation measurement to confirm the MACS.

Sample	EAR1 (C6D6)	EAR2 (sTED)
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^{97}Mo	10×10^{17}	4×10^{17}
^{98}Mo	17×10^{17}	5×10^{17}
^{100}Mo	17×10^{17}	5×10^{17}
Au	$2{,}0 \times 10^{17}$	1×10^{17}
Background (Empty/Dummy, C, Pb)	$9{,}0 \times 10^{17}$	4×10^{17}
Total	75×10^{17}	25×10^{17}

Thanks for your attention

Backup

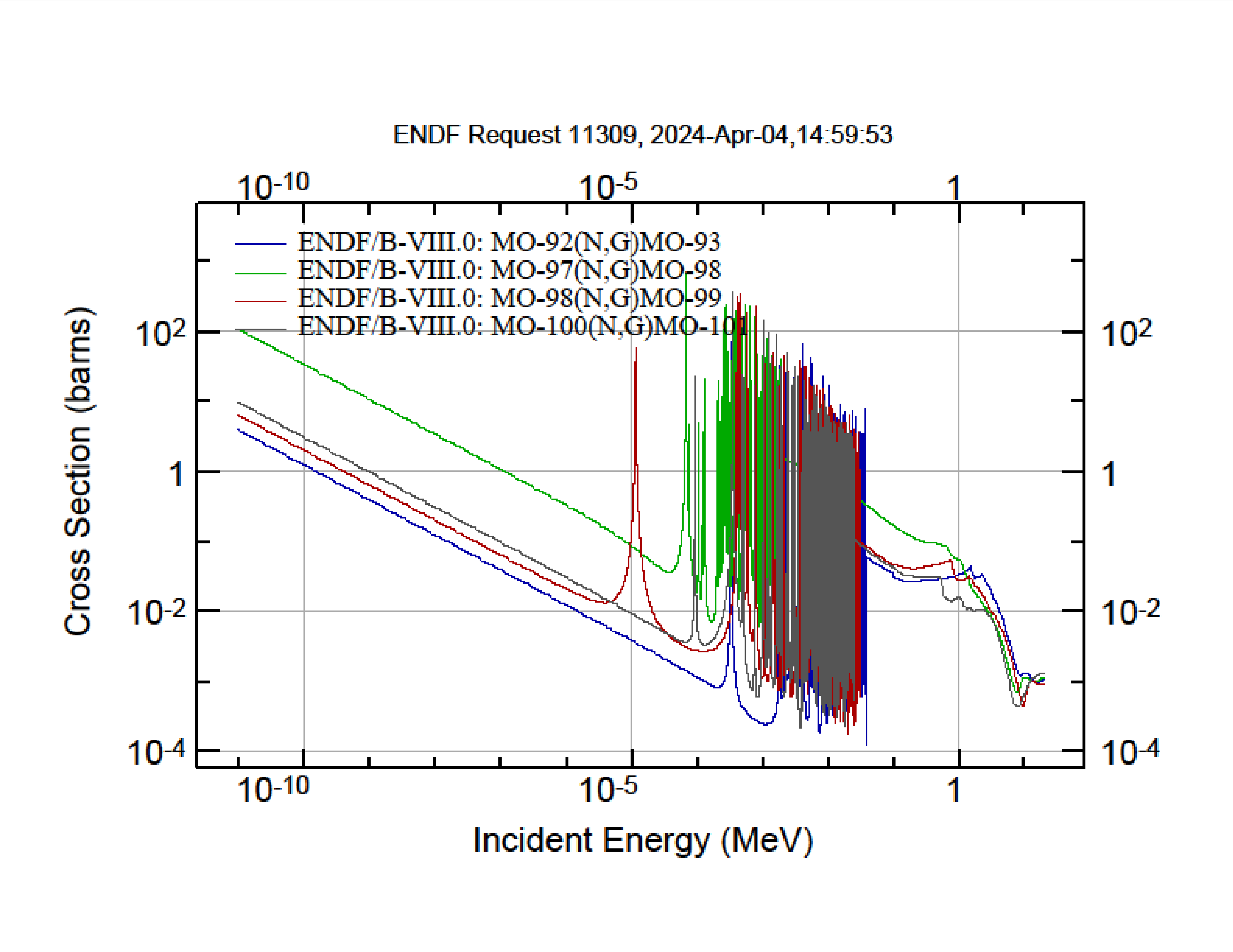
Mo literature study

Transmission			Capture		
Wang	^{nat}Mo	POHANG (<200 eV)	Weigmann	^{nat}Mo	GELINA (<25 keV)
Pevzner	$^{92,94,95,96,97,98,100}Mo$	DUBNA (<10 keV)	Weigmann	$^{92,94,95,96,97,98,100}Mo$	GELINA (<5 keV)
Wynchank	^{nat}Mo	Columbia Univ. (<5 keV)	Musgrove	$^{92,94,95,96,97,98,100}Mo$	ORELA (>3keV)
Shwe	$^{95,97}Mo$, ^{nat}Mo	Argonne (<1.5 keV)	Wasson	^{92}Mo	ORELA (<30 keV)
Chrien	^{98}Mo	ORELA (<50 keV)			
Babich	^{98}Mo	90m chopper (<2.5 keV)			
Leinweber	^{nat}Mo	RPI (<2 keV)			
Wasson	^{92}Mo	ORELA (<30 keV)			
Weigmann	^{100}Mo	ORELA (<4keV)			

Libraries sources

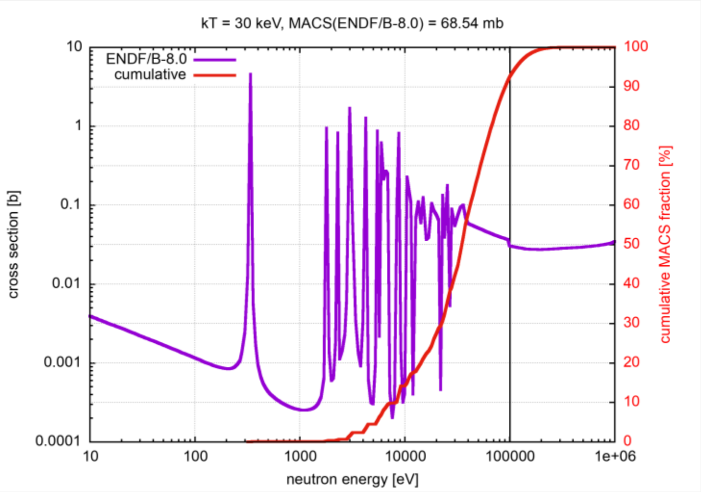
Isotope	JENDL-3.3	JENDL-4	ENDF-B/VIII	JEFF-3.3
^{92}Mo	Wasson, Weigmann, Musgrove	Wasson, Weigmann, Musgrove	Mughabghab	JENDL-4
^{94}Mo	Weigmann, Musgrove	Weigmann, Musgrove, Wang	JENDL-3.3	JENDL-4
^{95}Mo	Weigmann, Shwe	Weigmann, Shwe, Wang	Mughabghab	Mughabghab
^{96}Mo	Weigmann, Musgrove	Weigmann, Musgrove, Wang	JENDL-3.3	JENDL-4
^{97}Mo	Weigmann, Shwe	Weigmann, Shwe, Wang	JENDL-3.3	JENDL-4
^{98}Mo	Weigmann, Musgrove, Chrien	Weigmann, Musgrove, Chrien, Babich, Wang	JENDL-3.3	JENDL-4
^{100}Mo	Weigmann, Musgrove, Weigmann	Weigmann, Musgrove, Weigmann, Wang	JENDL-3.3	JENDL-4

Molybdenum cross section ENDF

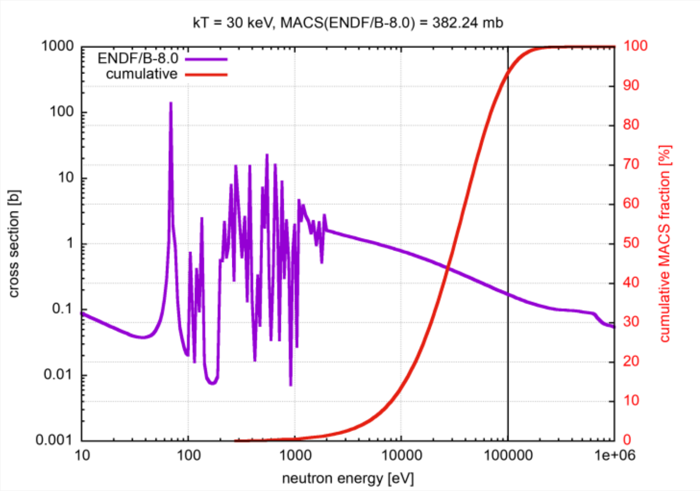


MACS fractions @ 30 keV

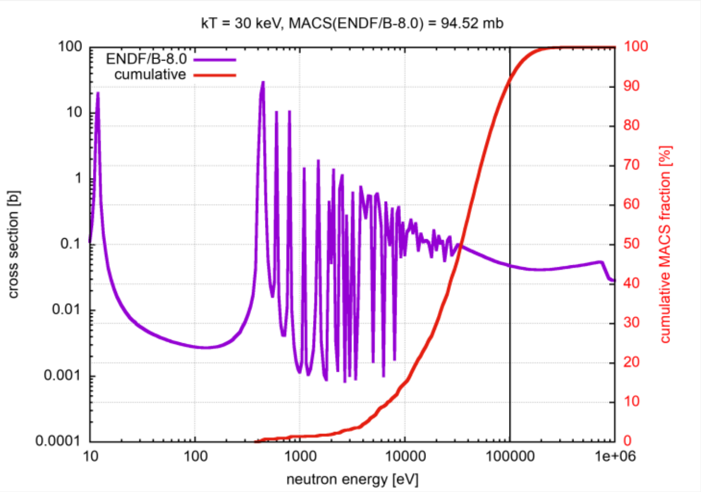
^{92}Mo



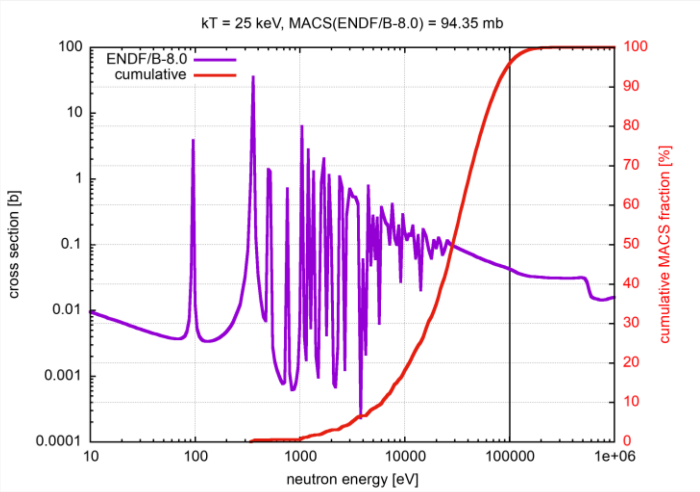
^{97}Mo



^{98}Mo



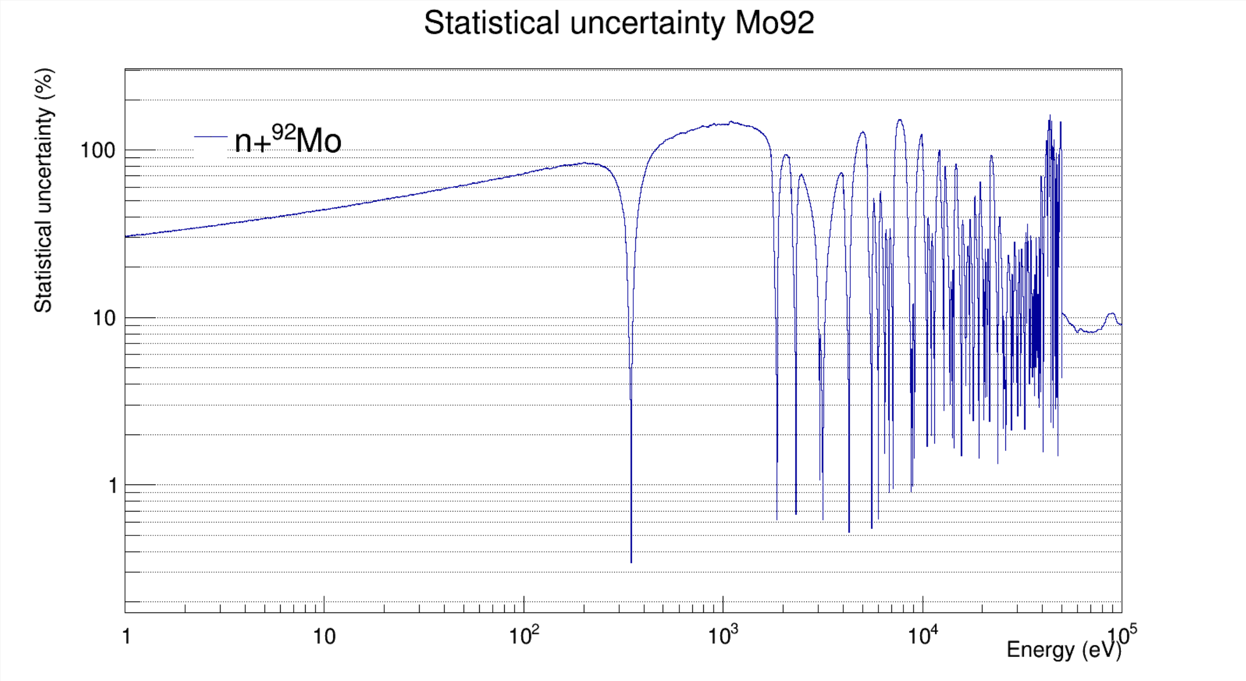
^{100}Mo

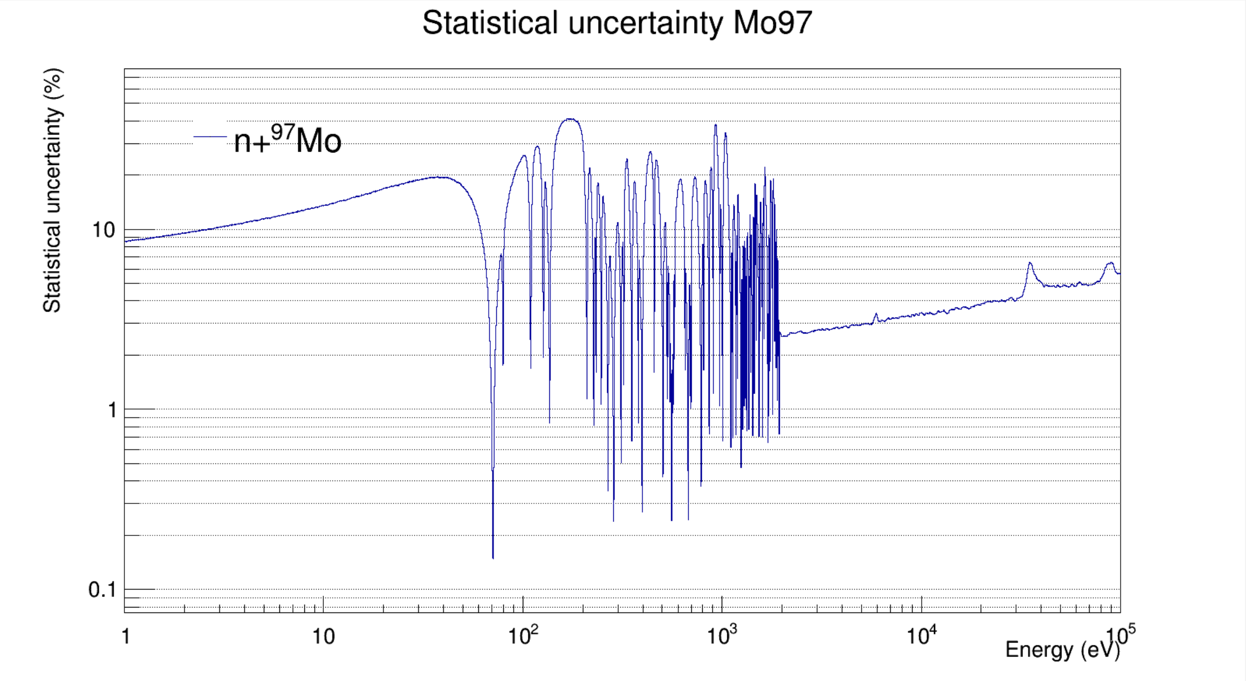


^{nat}Mo abundances

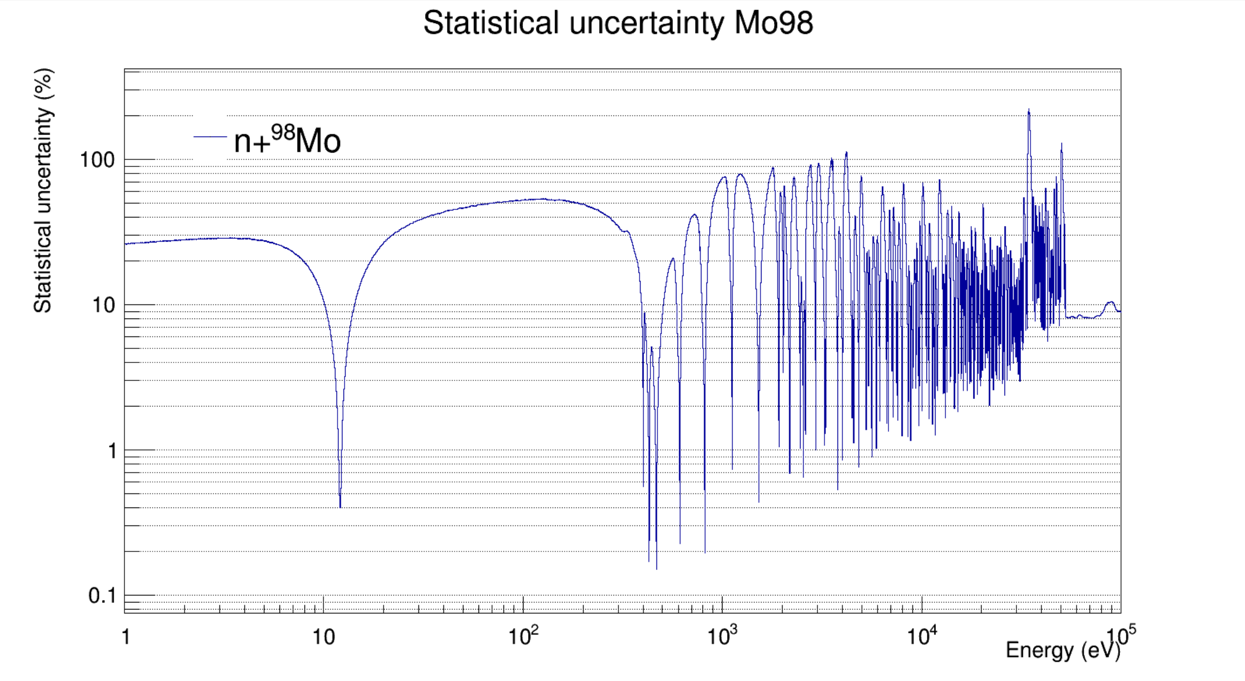
Isotope	Abundance
^{92}Mo	14.84%
^{94}Mo	9.25%
^{95}Mo	15.92%
^{96}Mo	16.68%
^{97}Mo	9.55%
^{98}Mo	24.13%
^{100}Mo	9.63%

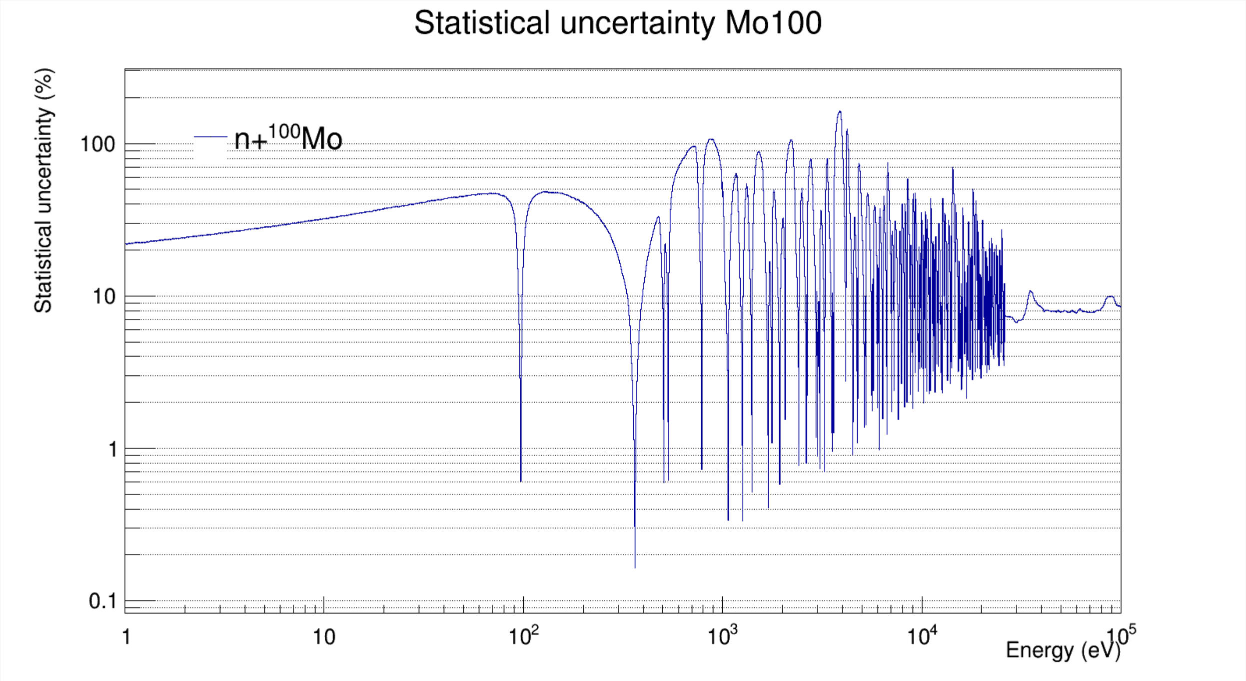
Statistical uncertainty EAR1



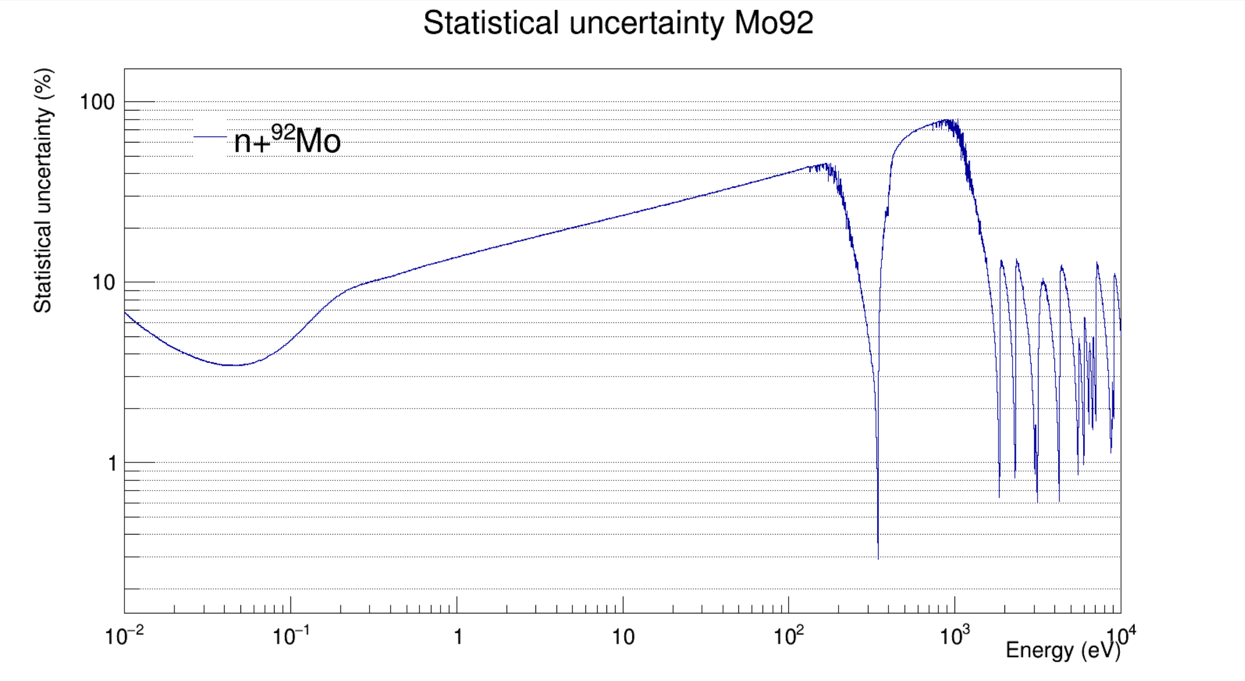


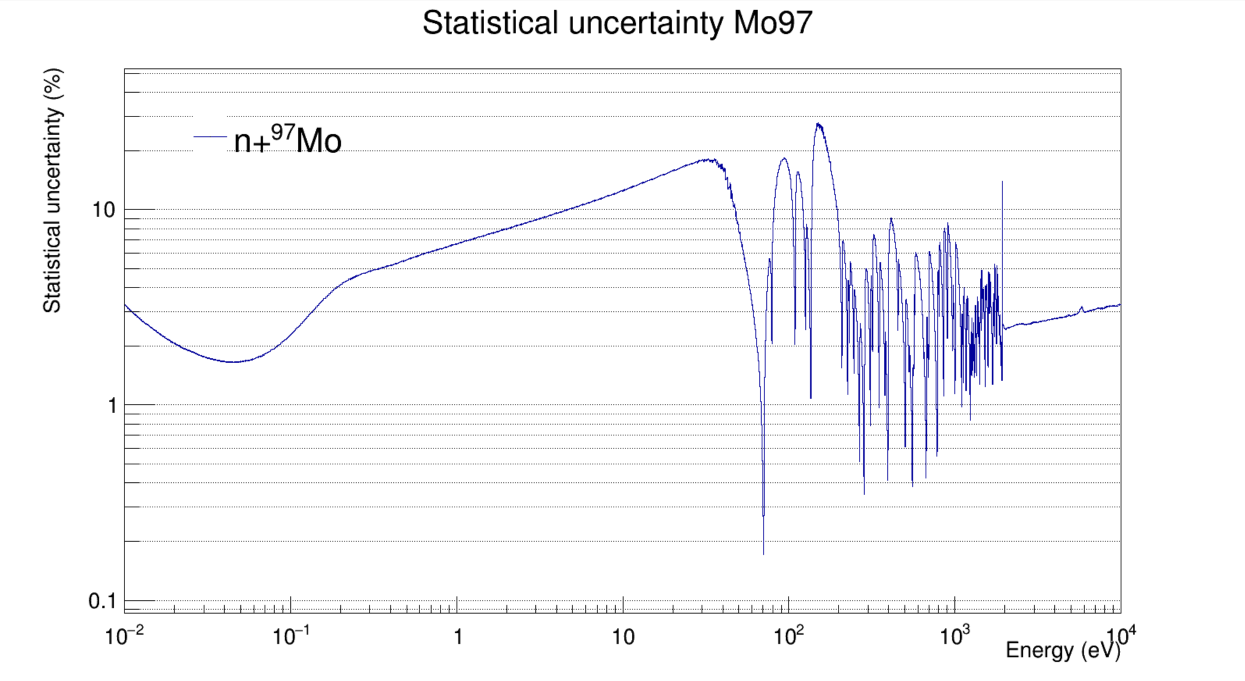
Statistical uncertainty EAR1





Statistical uncertainty EAR2





Statistical uncertainty EAR2