Neutron capture and total cross section measurements on Mo isotopes at n_TOF and GELINA

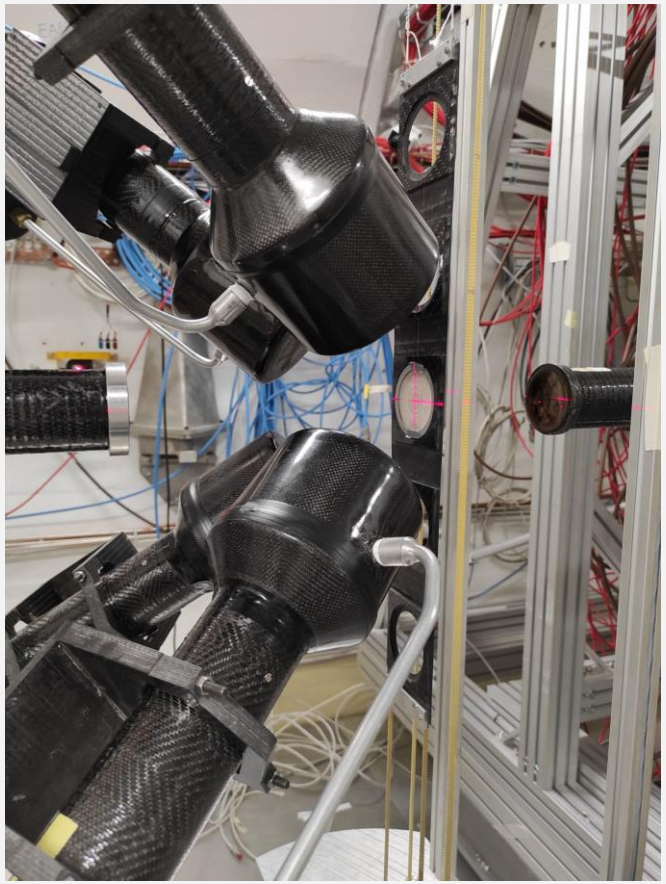
Riccardo Mucciola

Importance of molybdenum

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

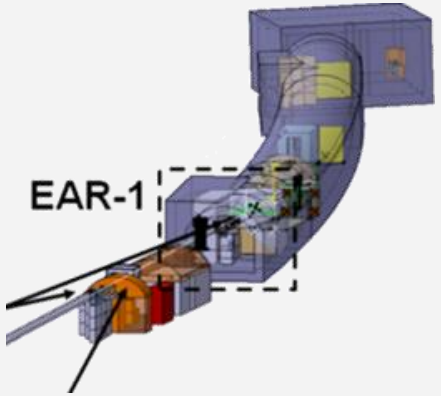
Measurements setup ^{94,95,96}Mo

EAR1

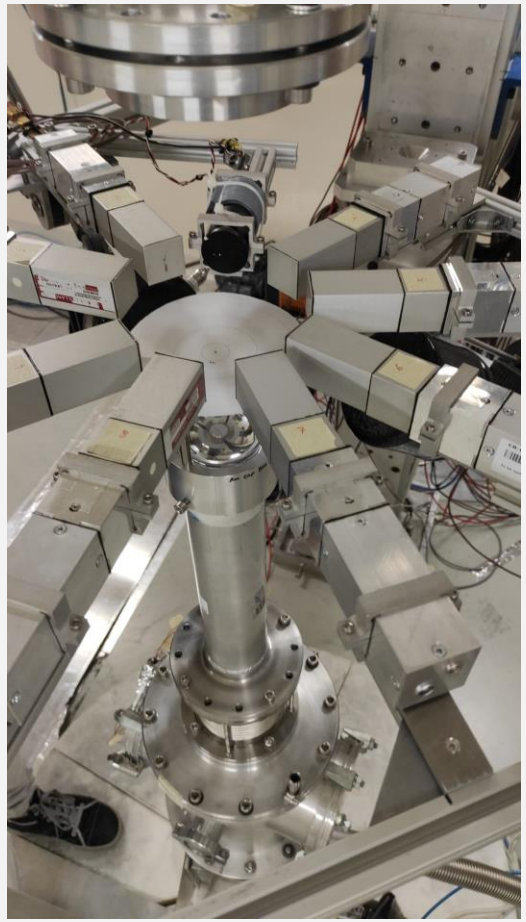


Setup:

- 4 C_6D_6

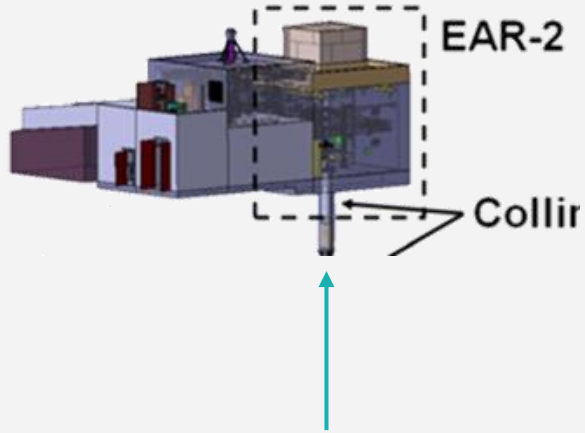


EAR2



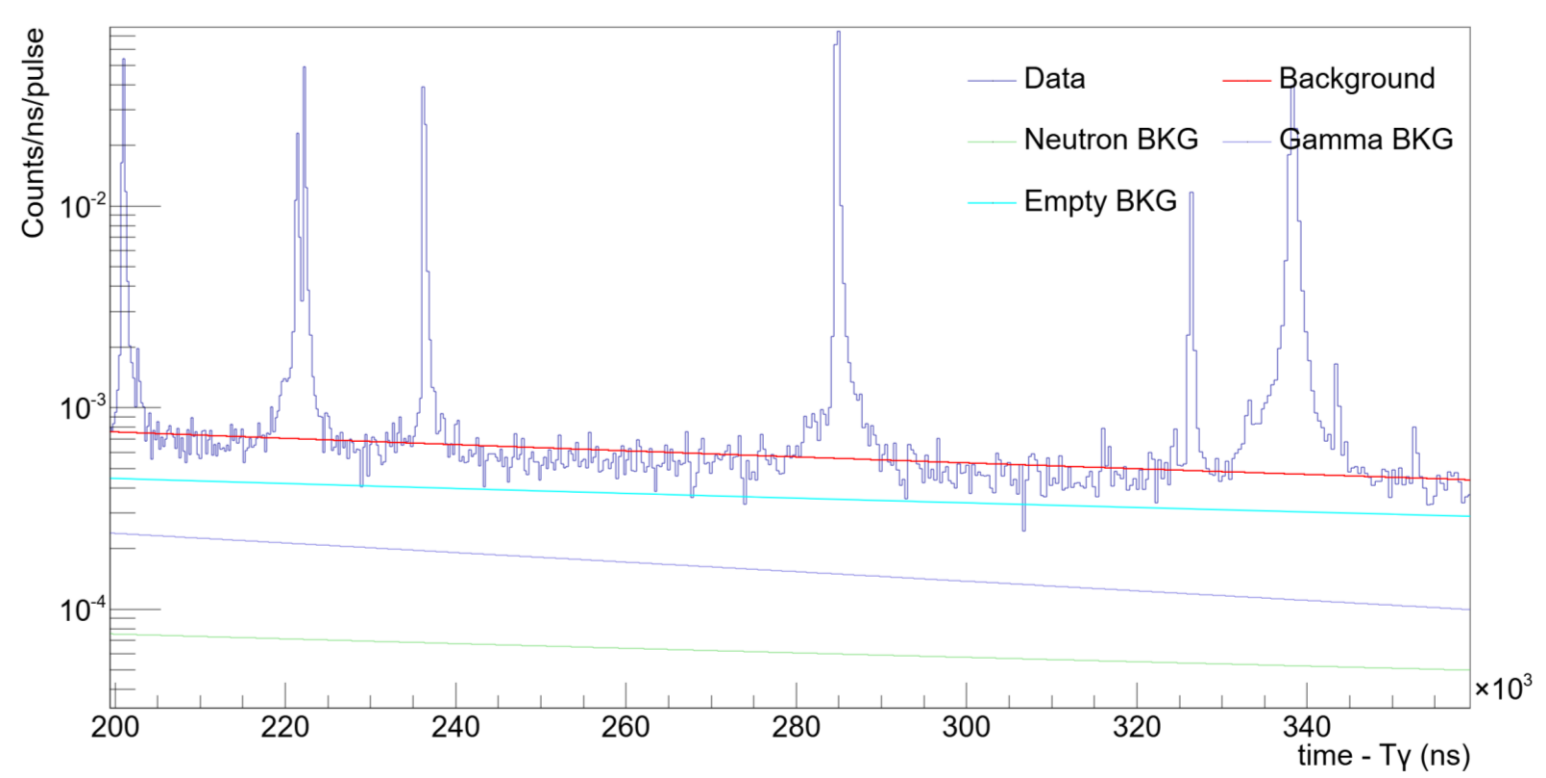
Setup:

- 8 sTED
- 1 DSTIL
- 2 C_6D_6



EAR1

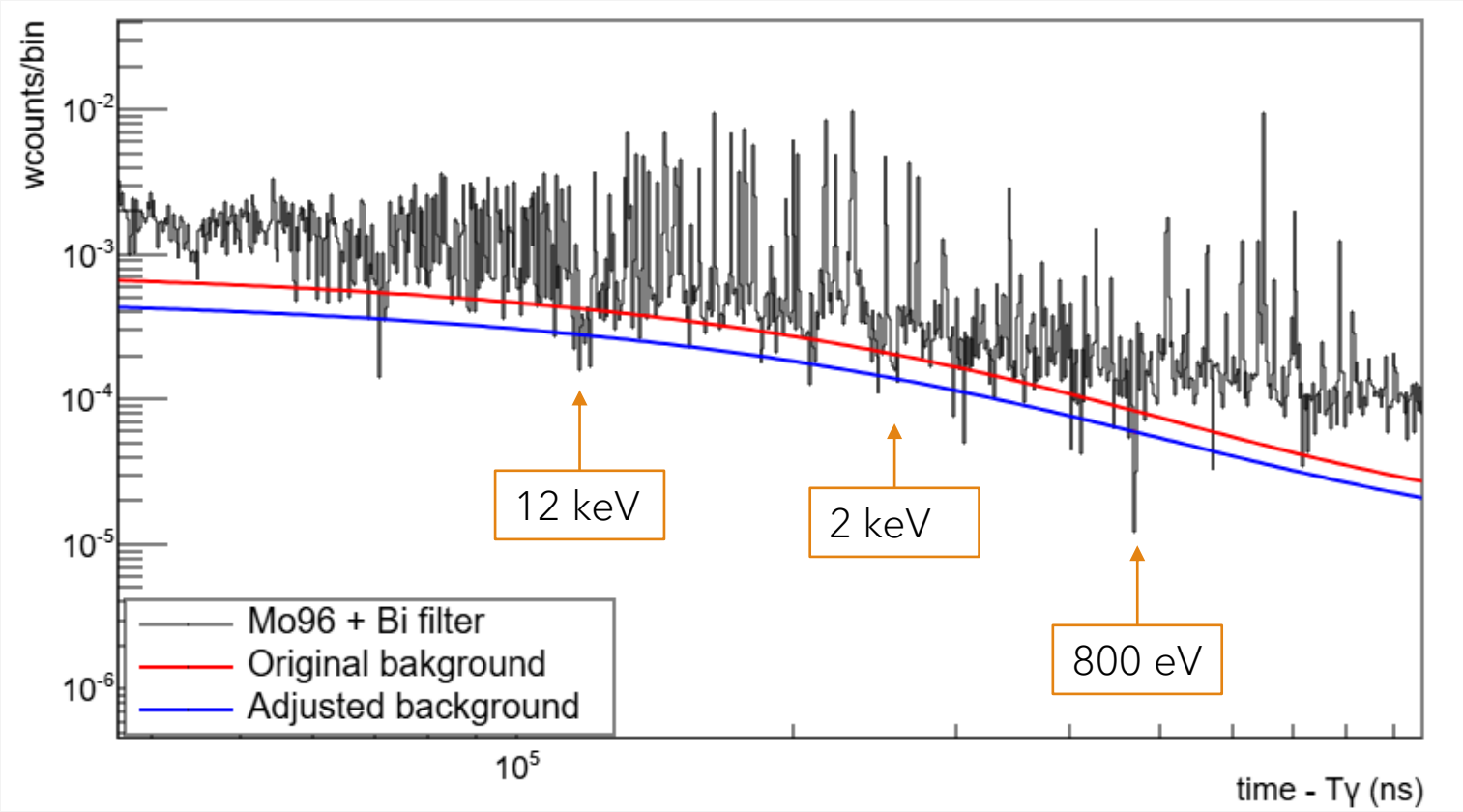
Background estimation ^{94}Mo



- Background estimated using Pb and C samples (in-beam gammas and neutron scattering);
- Small overestimation of background in keV region;
- Correction of background using measurements with filters

Background estimation ^{94}Mo

- Measurements performed using Bi filter;
- Several black resonances, main ones at 800 eV, 2 keV and 12 keV;
- Background shapes for neutron scattering and in-beam gamma obtained from Pb and C measurements;
- Contribution of background components adjusted to match dips of black resonances

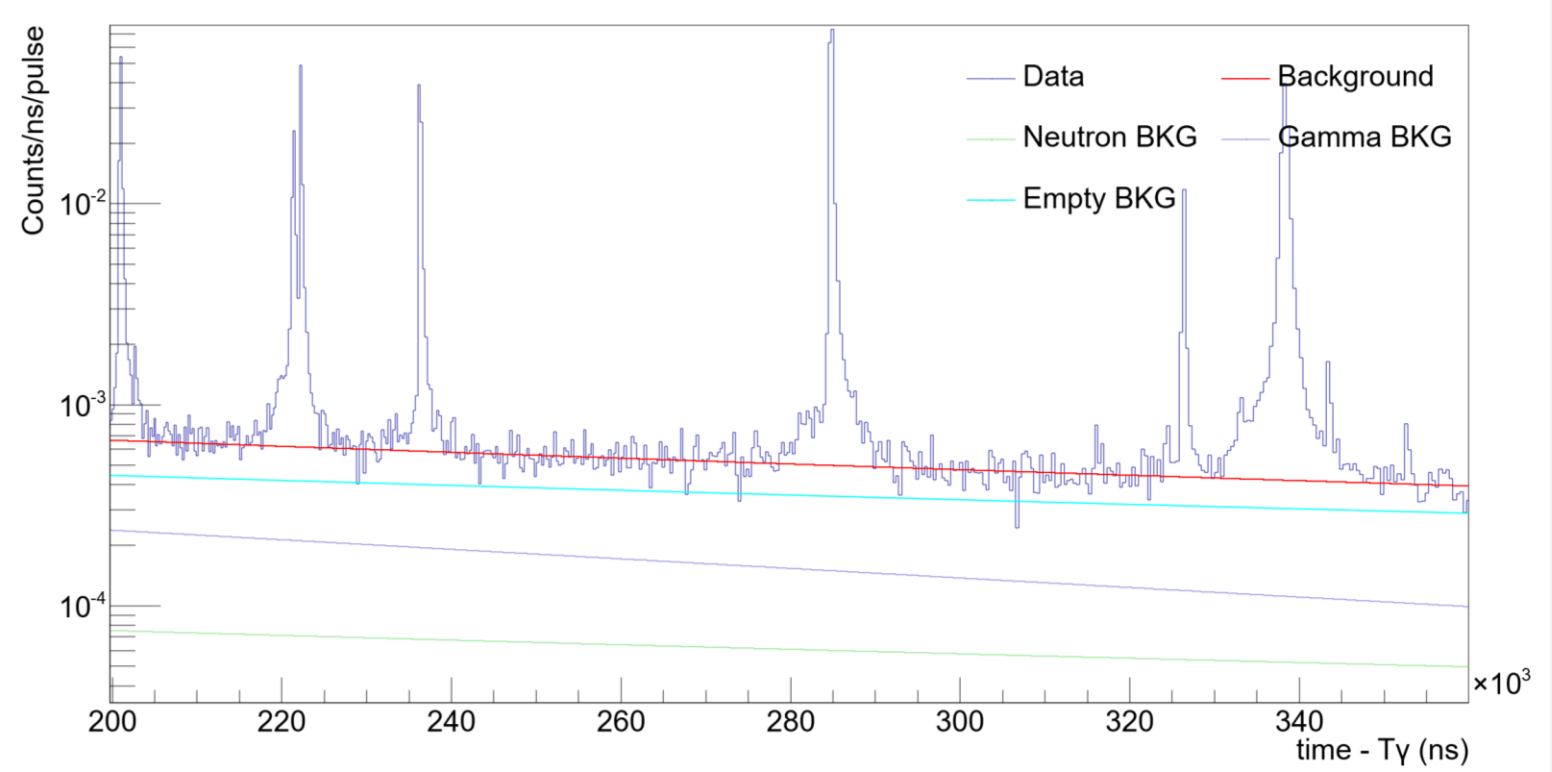


$$B(t) = B_0 + B_e(t) + f_\gamma B_\gamma(t) + f_n B_n(t)$$

f_γ=0,69 (5)

f_n=0,75 (5)

Background estimation ^{94}Mo



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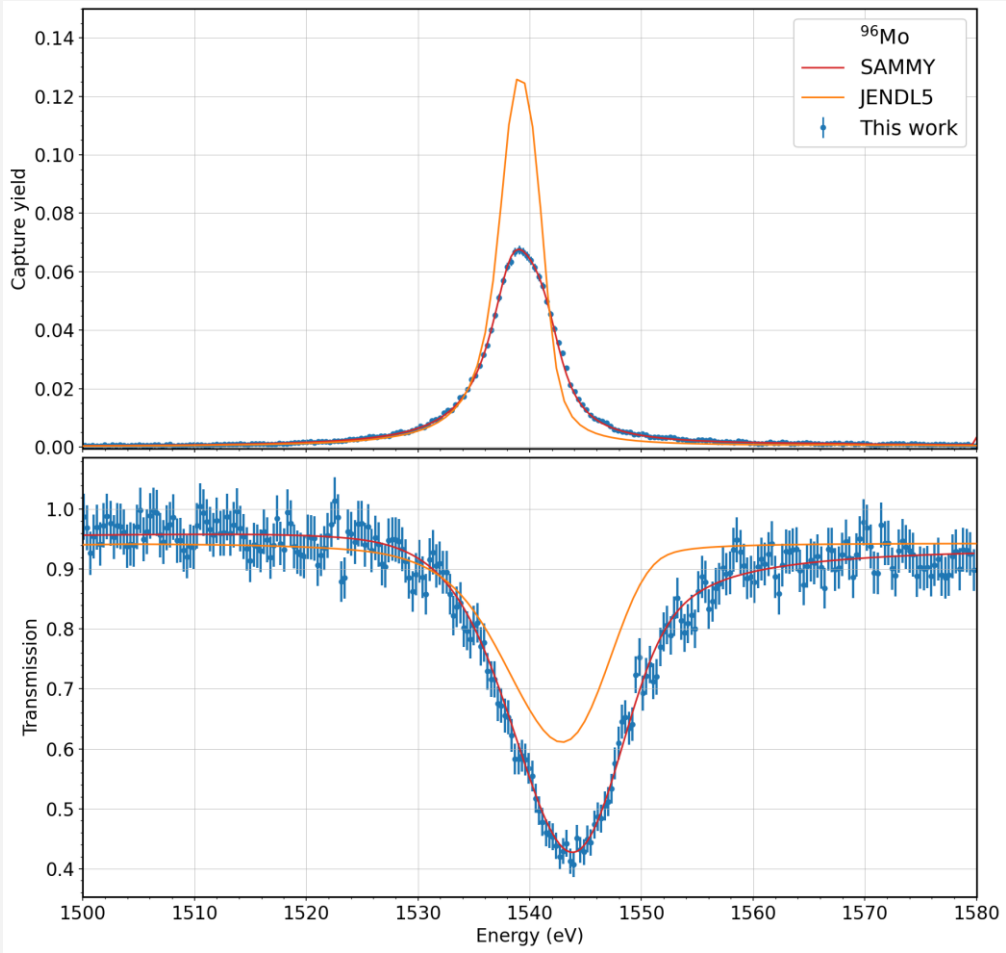
Preliminary resonance parameters ^{94}Mo

JENDL library doesn't reproduce the data accurately

- Preliminary resonance parameters have been obtained in all the resolved resonance region (<21 keV);
- Extended resolved resonance region with very preliminary parameters up to 75 keV;
- Example of fit showed here compared to the calculation performed with JENDL5 parameters;
- Good agreement between transmission and capture data with enriched samples.



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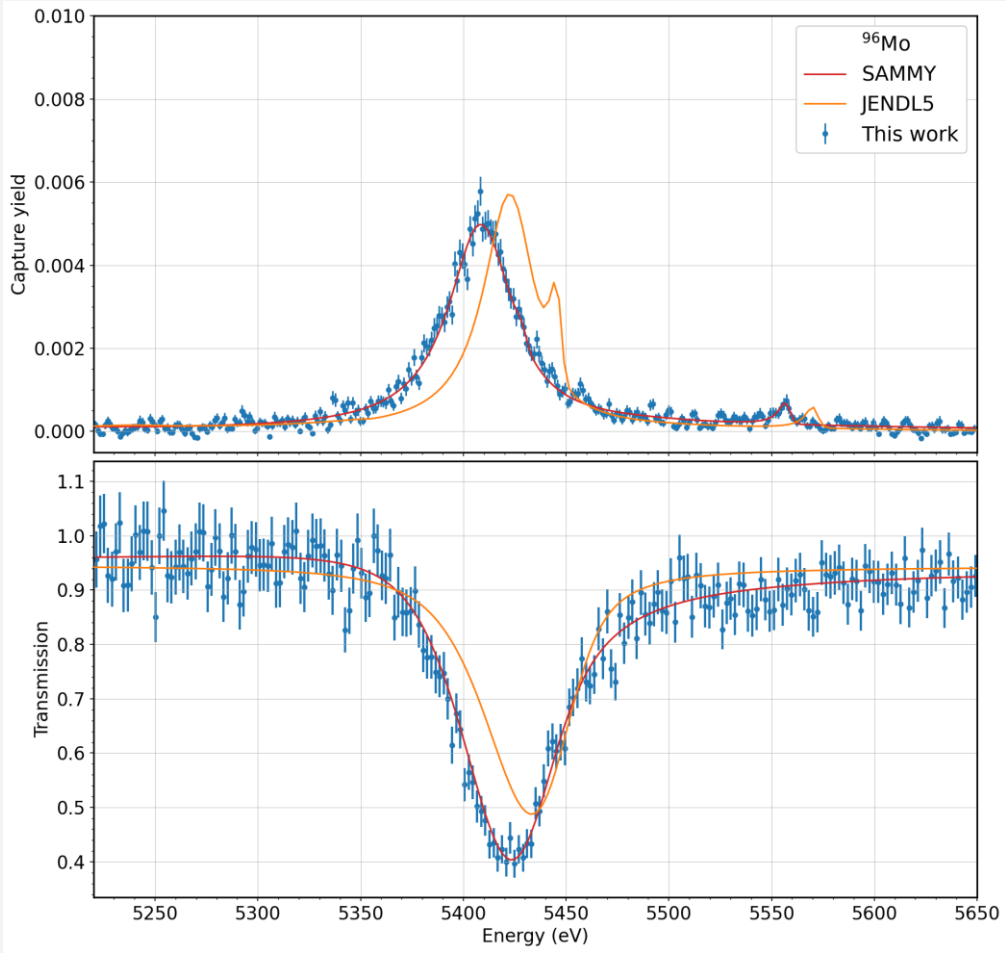

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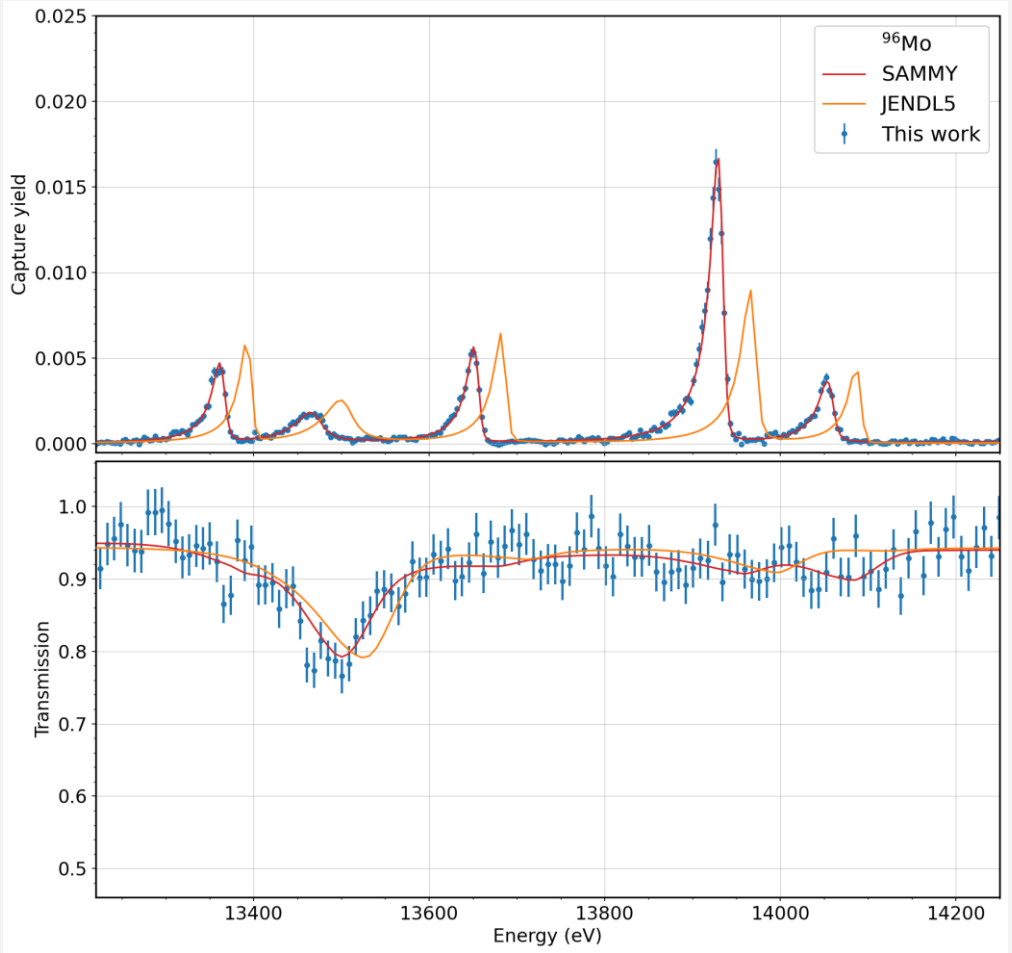
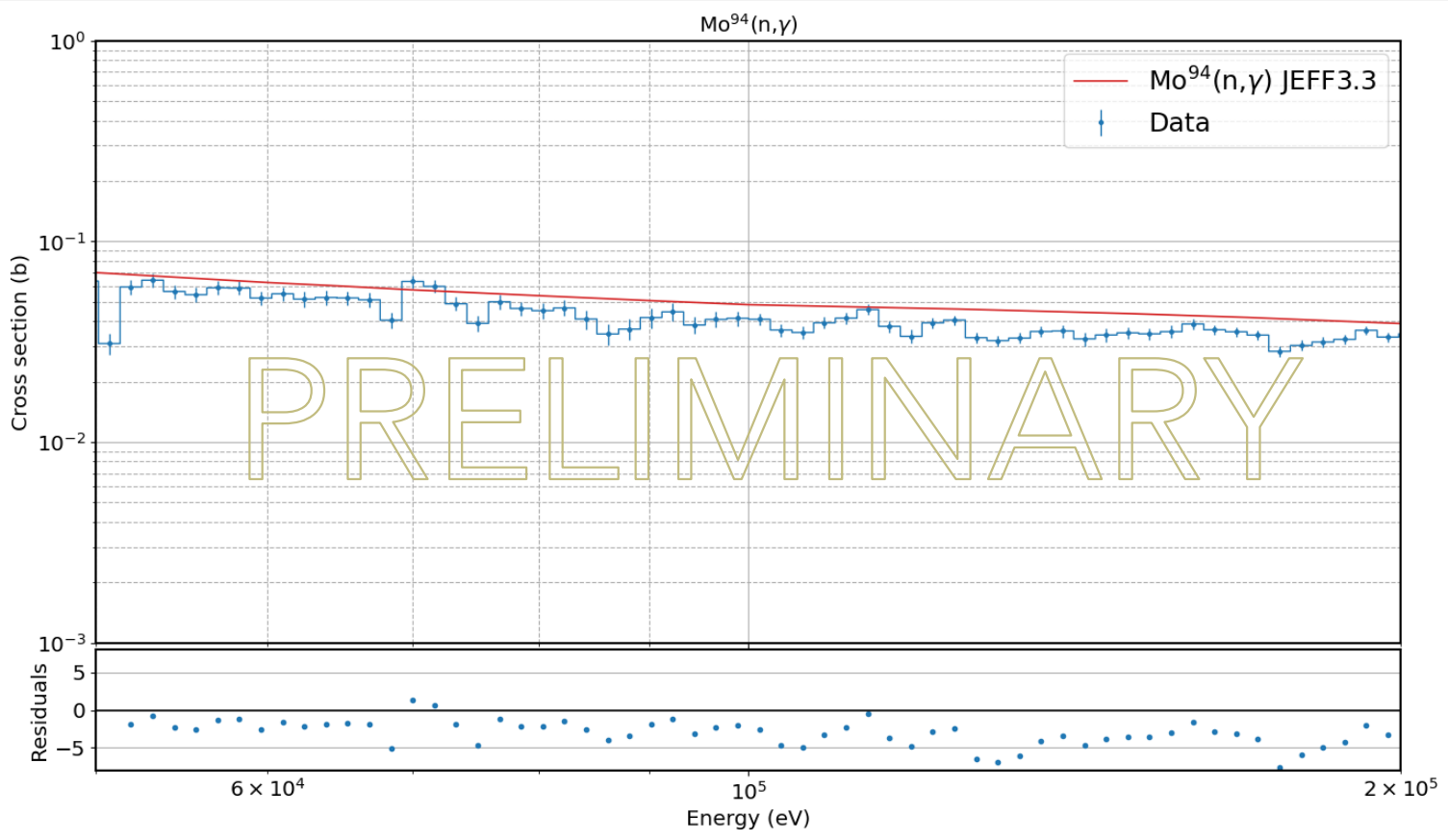
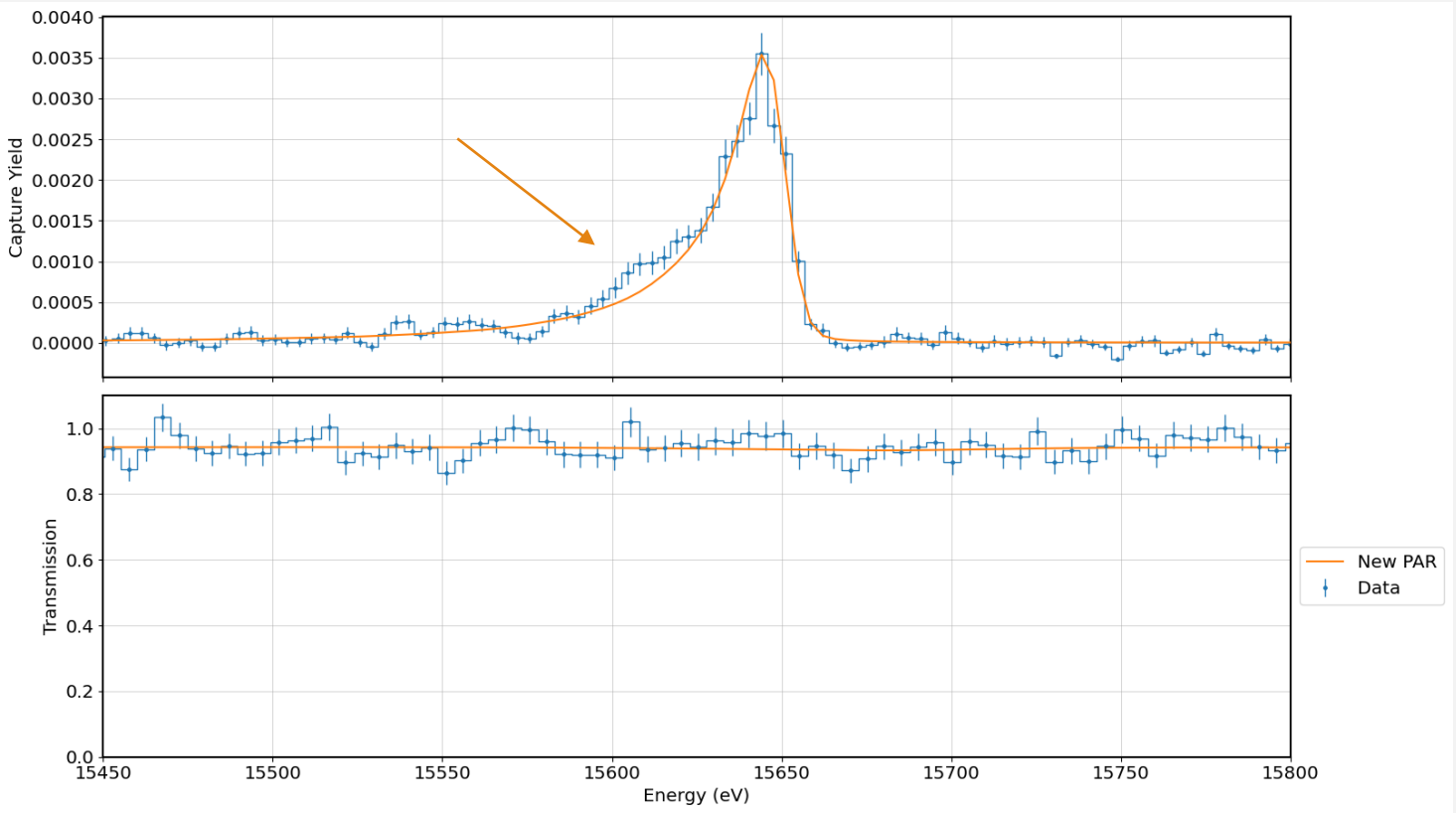


^{94}Mo Unresolved Resonance Region



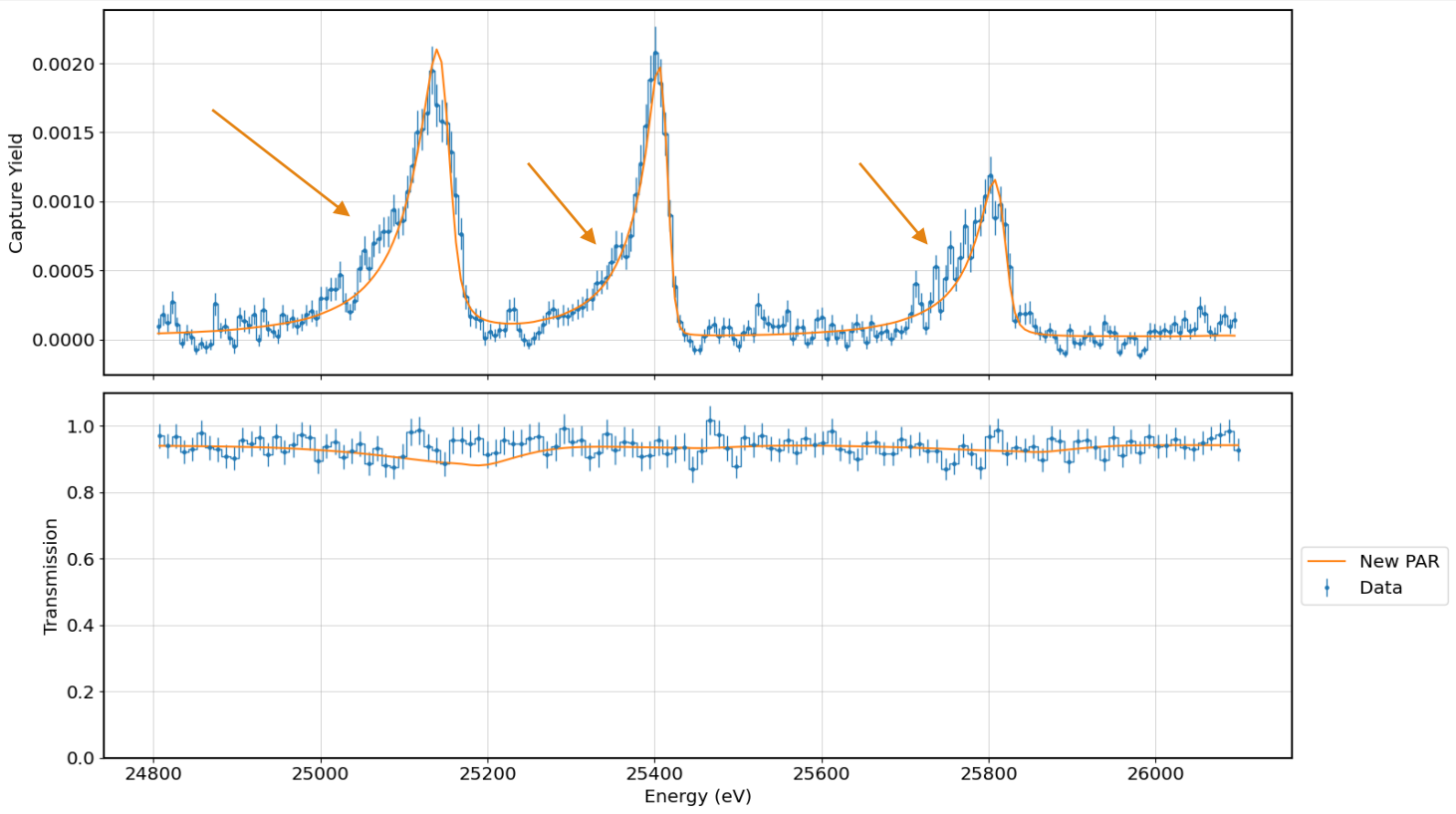
- Calculation of the preliminary cross section in the URR (>75keV);
- Comparison with JEFF 3.3 cross section data;
- This comparison shows a reduction of 10-20% in the cross section of ^{94}Mo.

Second bump in ^{94}Mo resonances



- Above 15 keV some resonances showed a “second bump” at lower energies;
- Similar behavior observed in different resonances, with different magnitudes;
- Same effect with both dedicated and parasitic pulses.

Second bump in ^{94}Mo resonances



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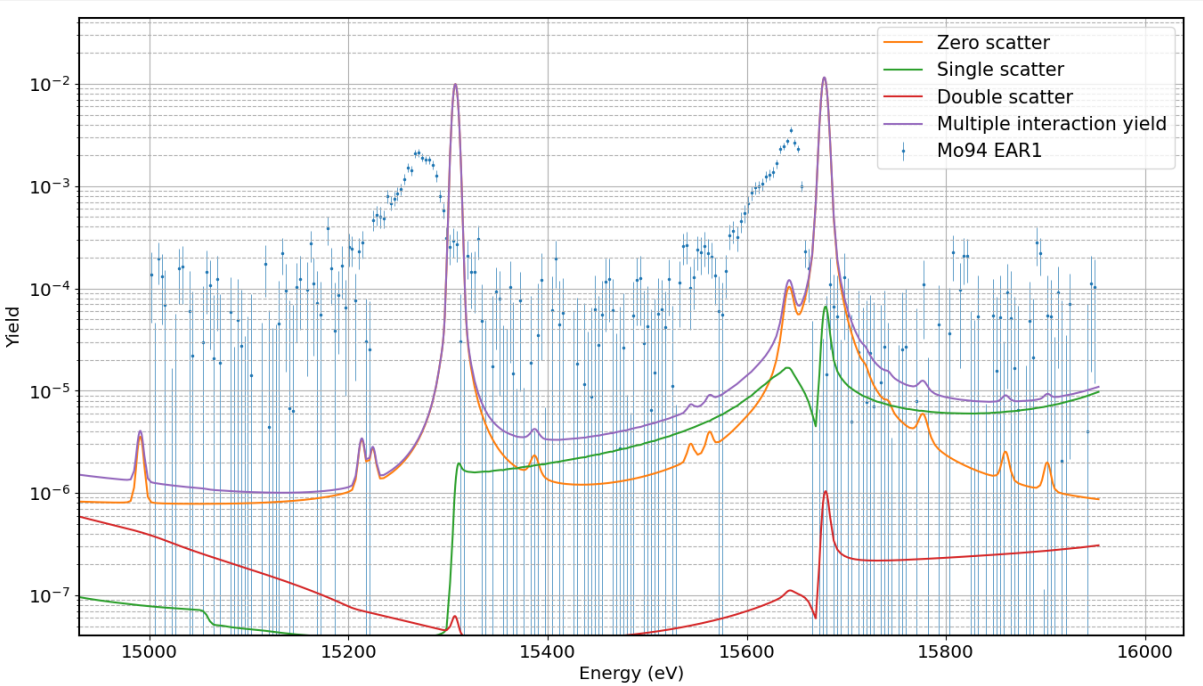
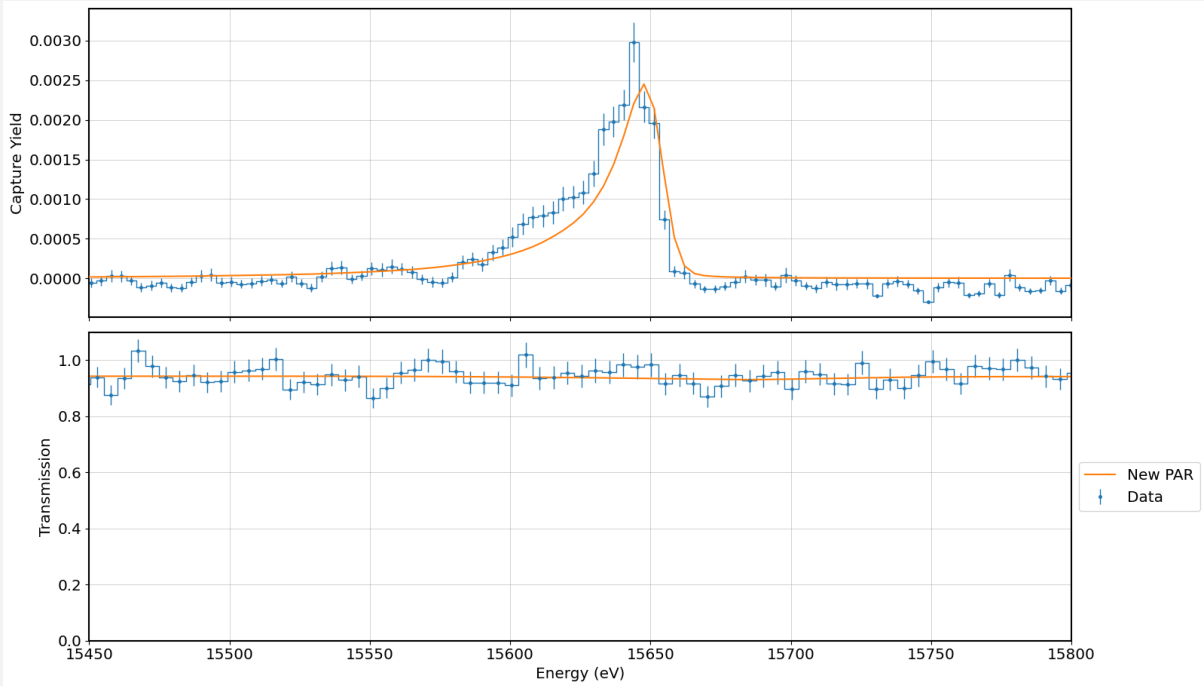
Possible excluded solutions

Multiple interaction



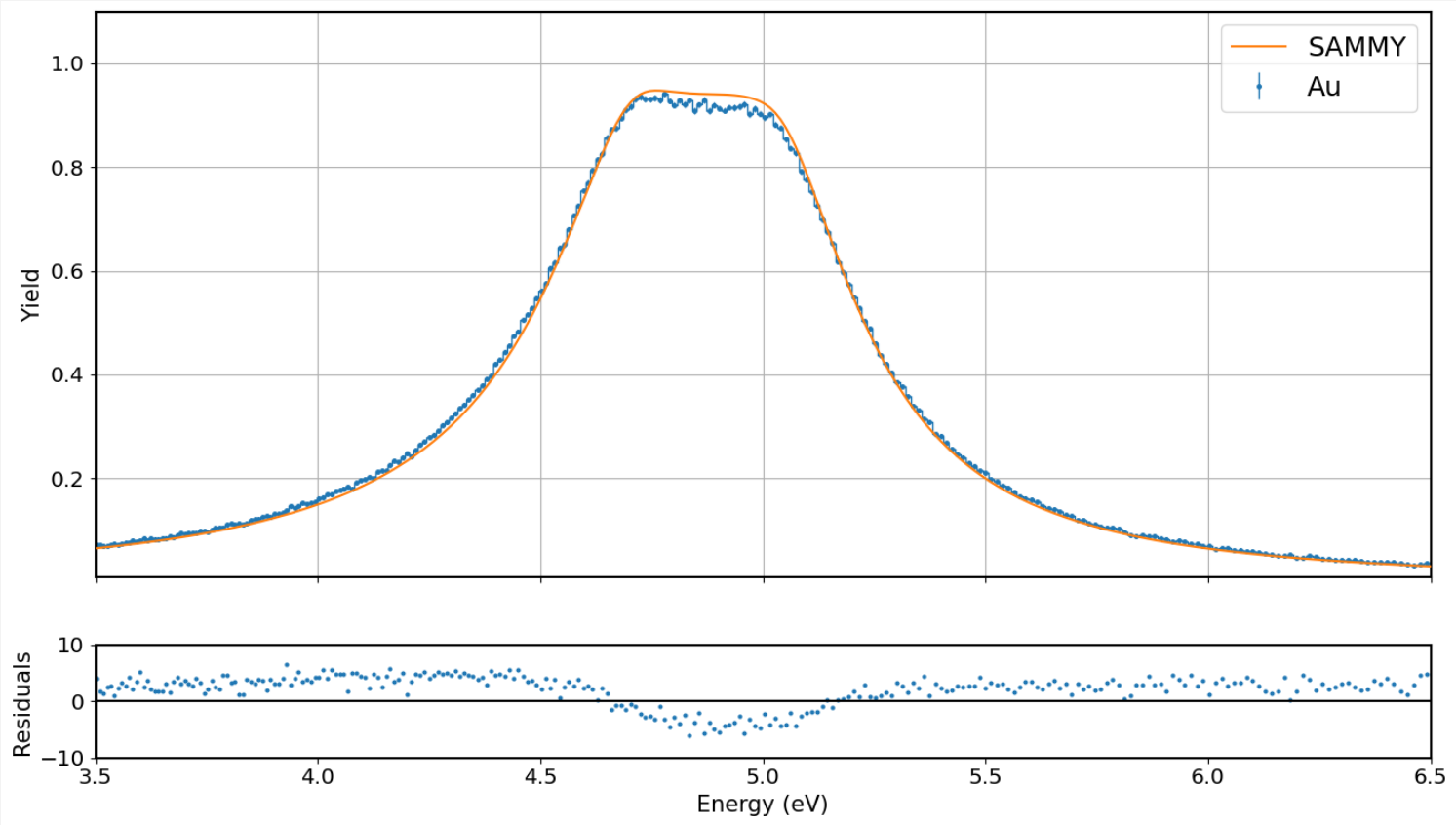
Afterpulses (1MeV threshold)



Welcoming suggestions!

EAR2

Very preliminary Au yield - Normalization

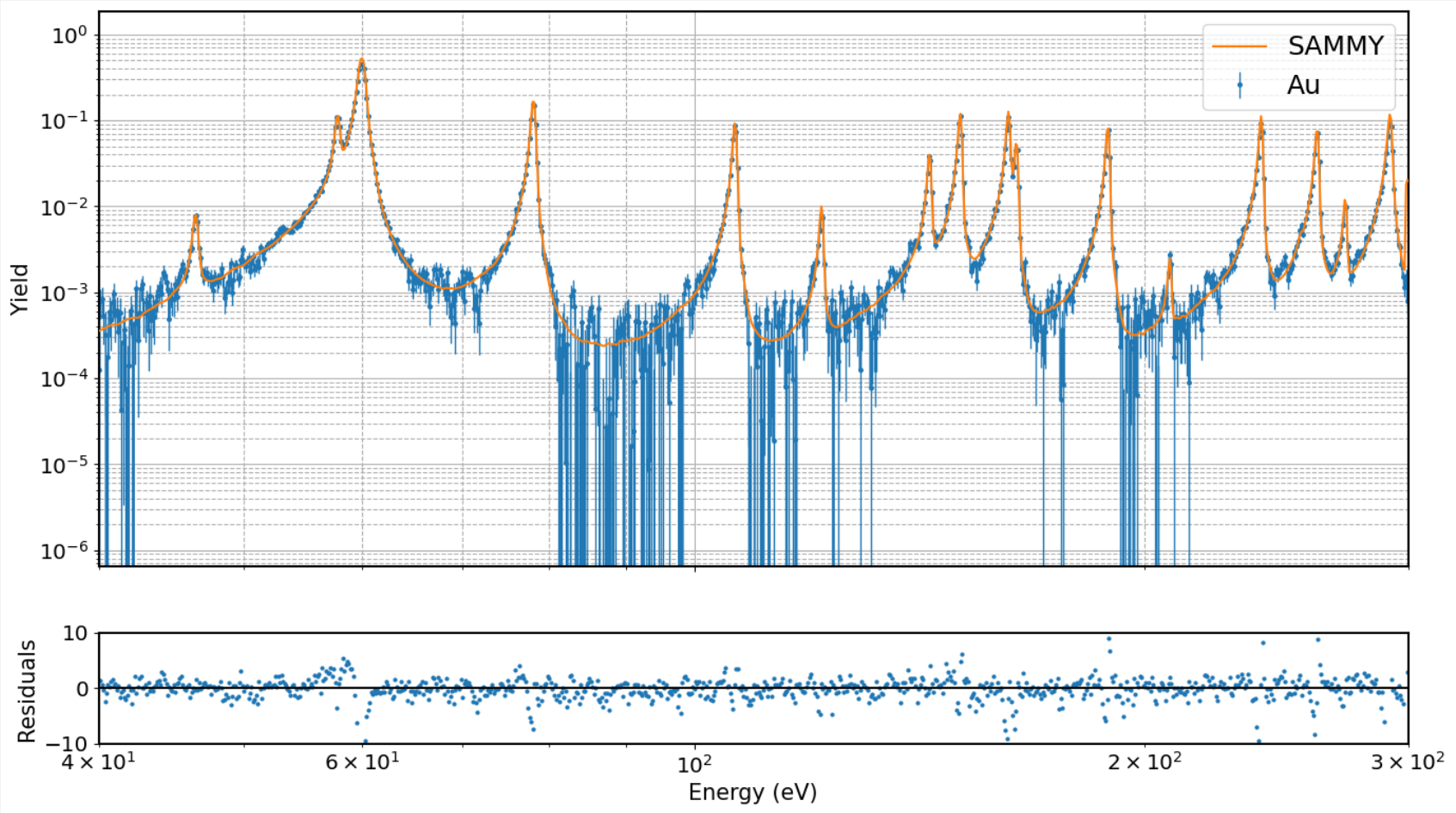


- Shape of saturated resonance is not reproduced in SAMMY;
- Probably given by dead time and coincidences events;
- Preliminary normalization using low energy resonances.

Very preliminary Au yield - Normalization

Low energy resonances of Gold are well reproduced

- Shape and peak of low energy resonances are in very good agreement with SAMMY calculation;
- Background level between resonances reproduced with higher empty contribution (x 1,7)



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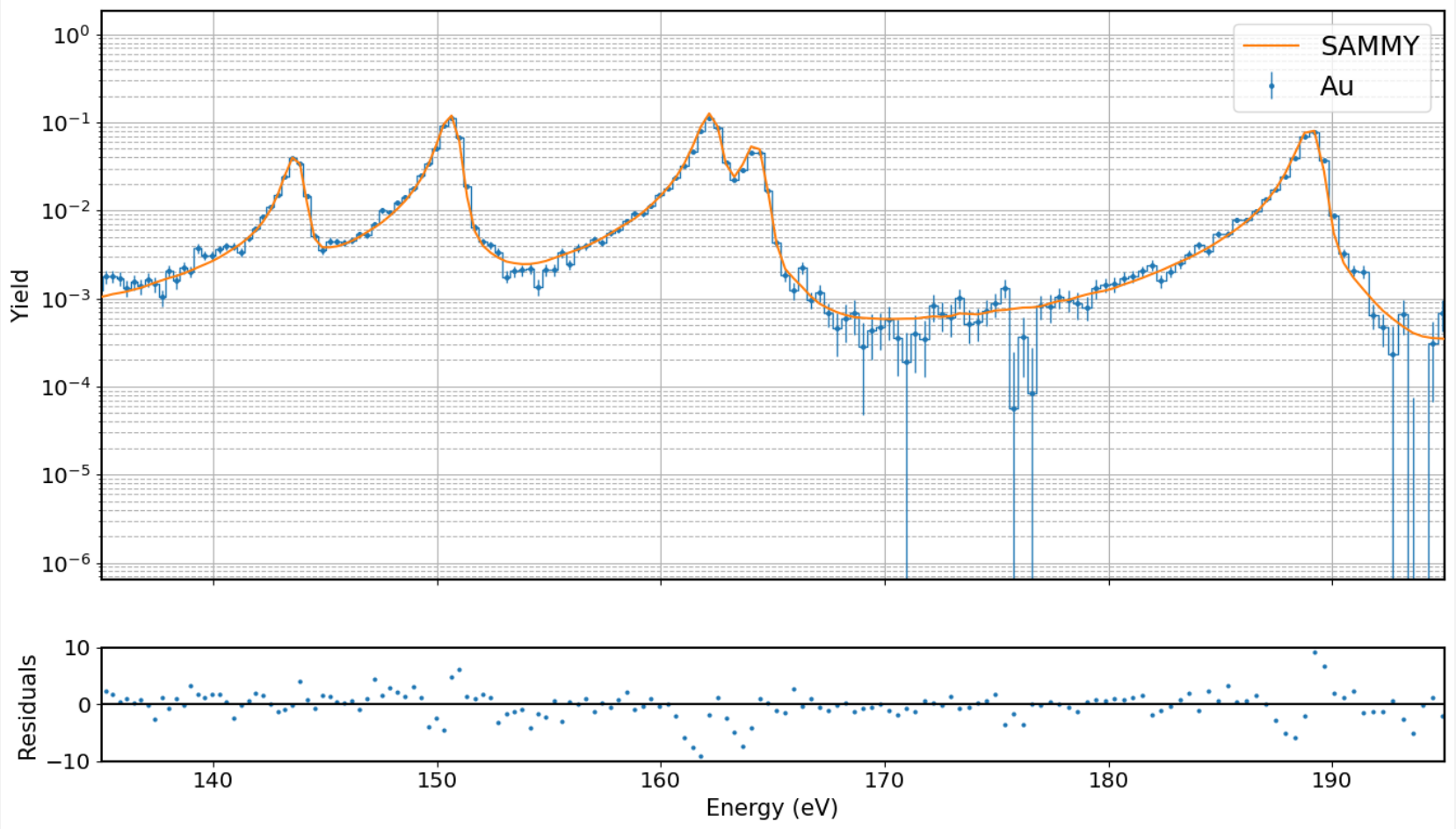
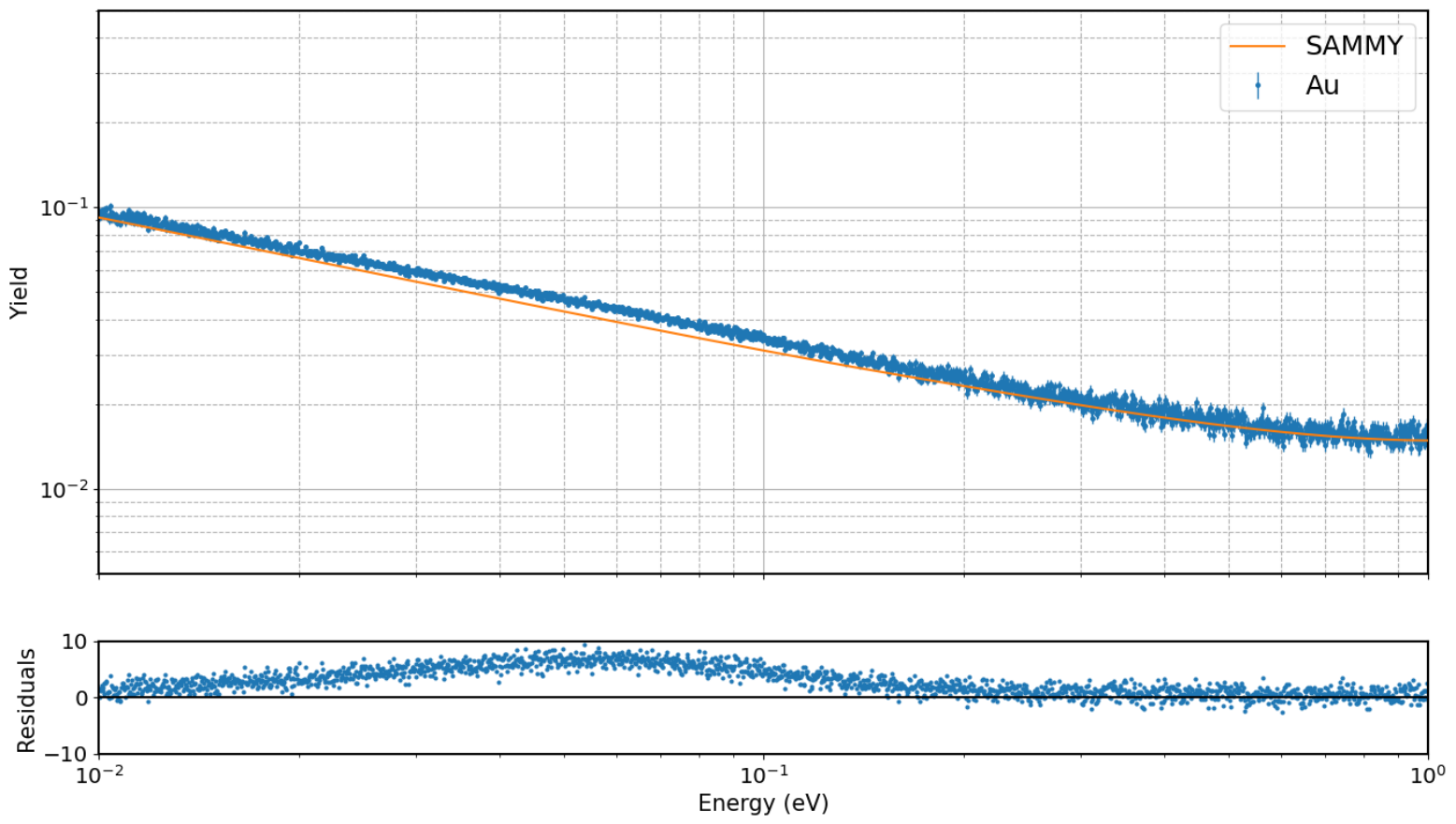


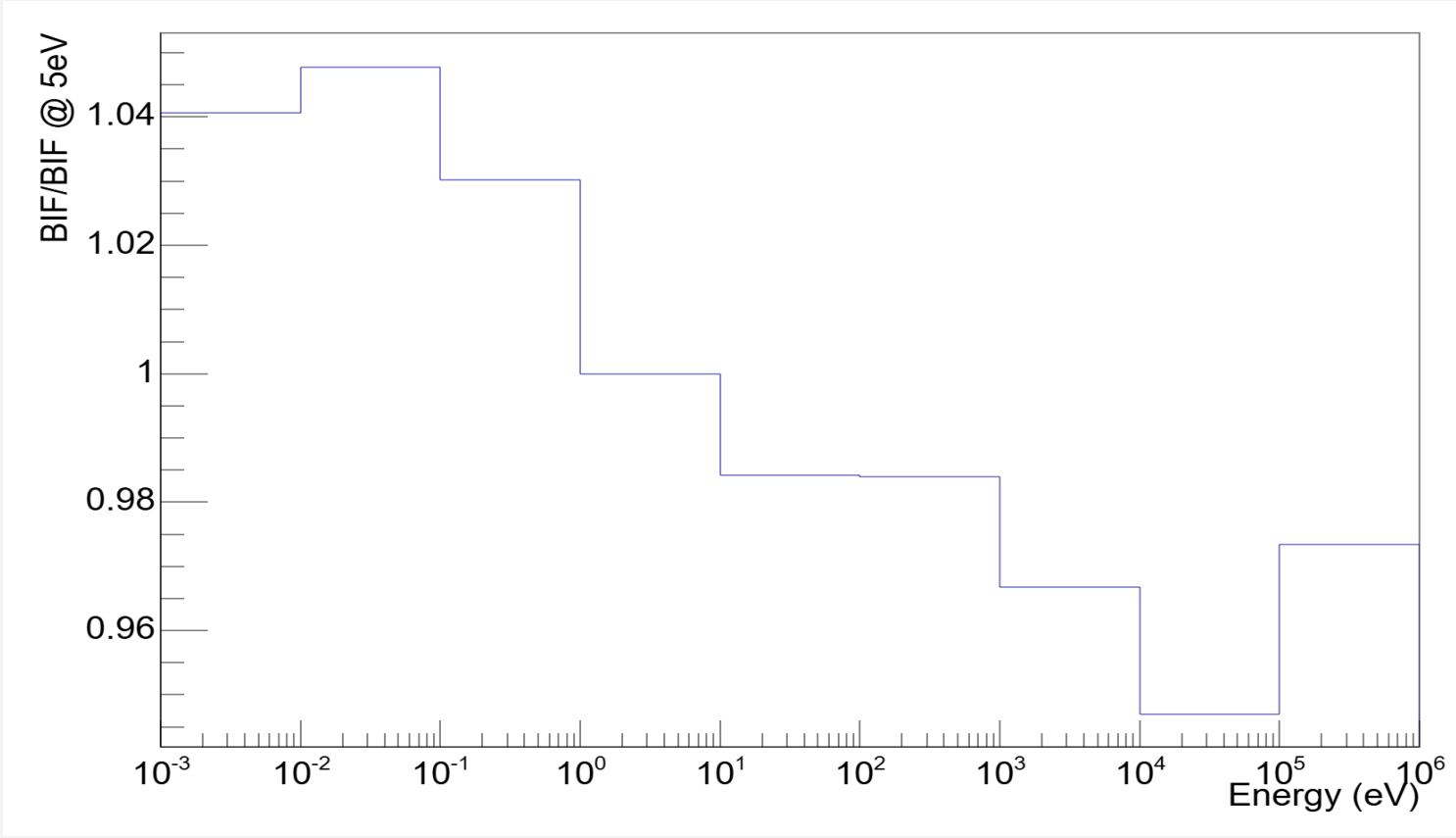
Very preliminary Au yield - Thermal



- Preliminary yield of Au shows a structure in thermal region;
- Structure compatible with thermal peak of neutron flux (~60 meV);
- Discrepancy at peak ~ 10%

Very preliminary Au yield - Thermal

- Possible solution: change in Beam interception factor (BIF) at lower energies;
- BIF calculated for a sample of 20mm diameter using data from PPAC of commissioning;
- BIF obtained as a ratio of value at 1-10 eV (Au resonance);
- Deviation of ~5% observed, both for higher and lower energies.



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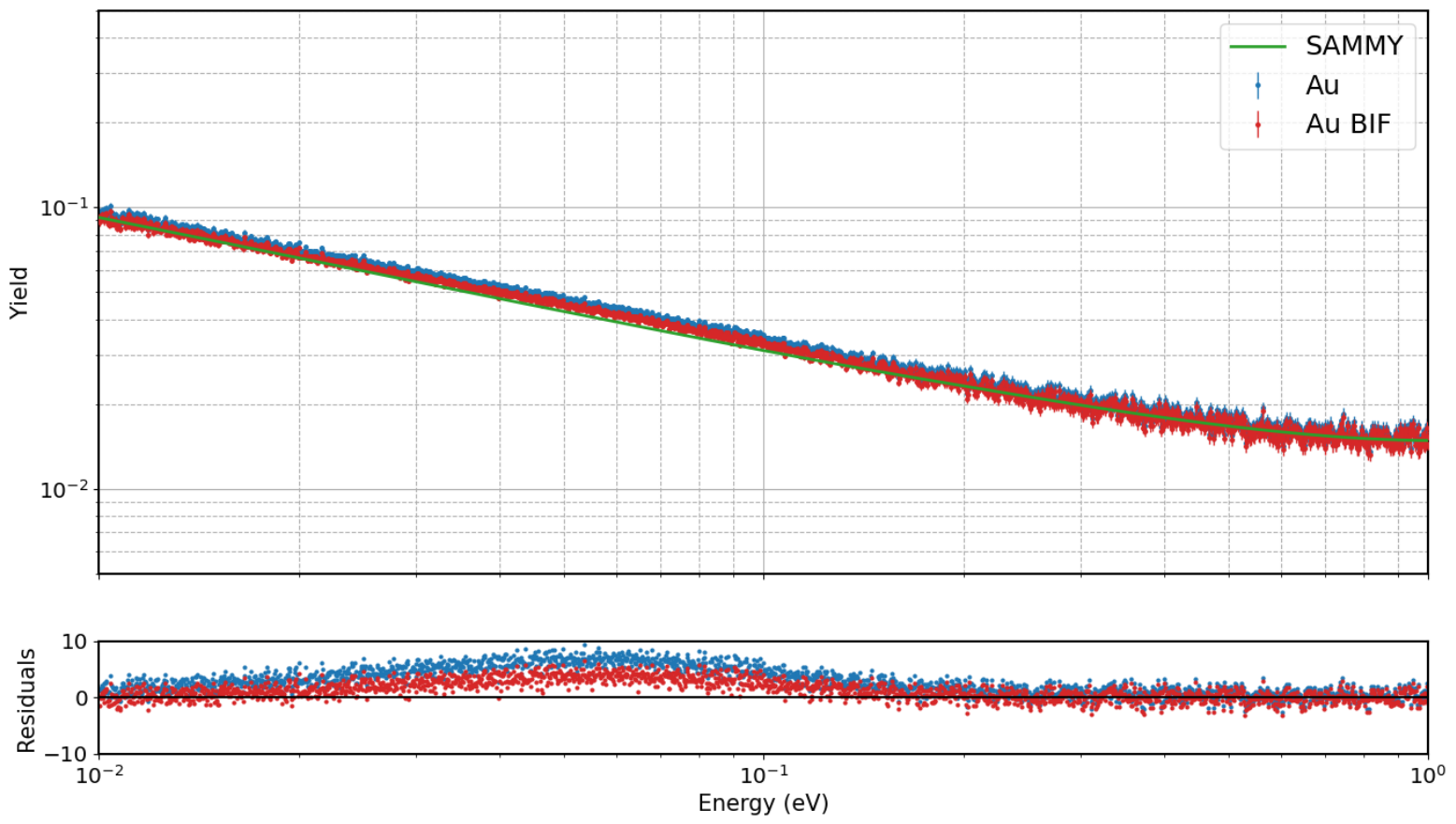
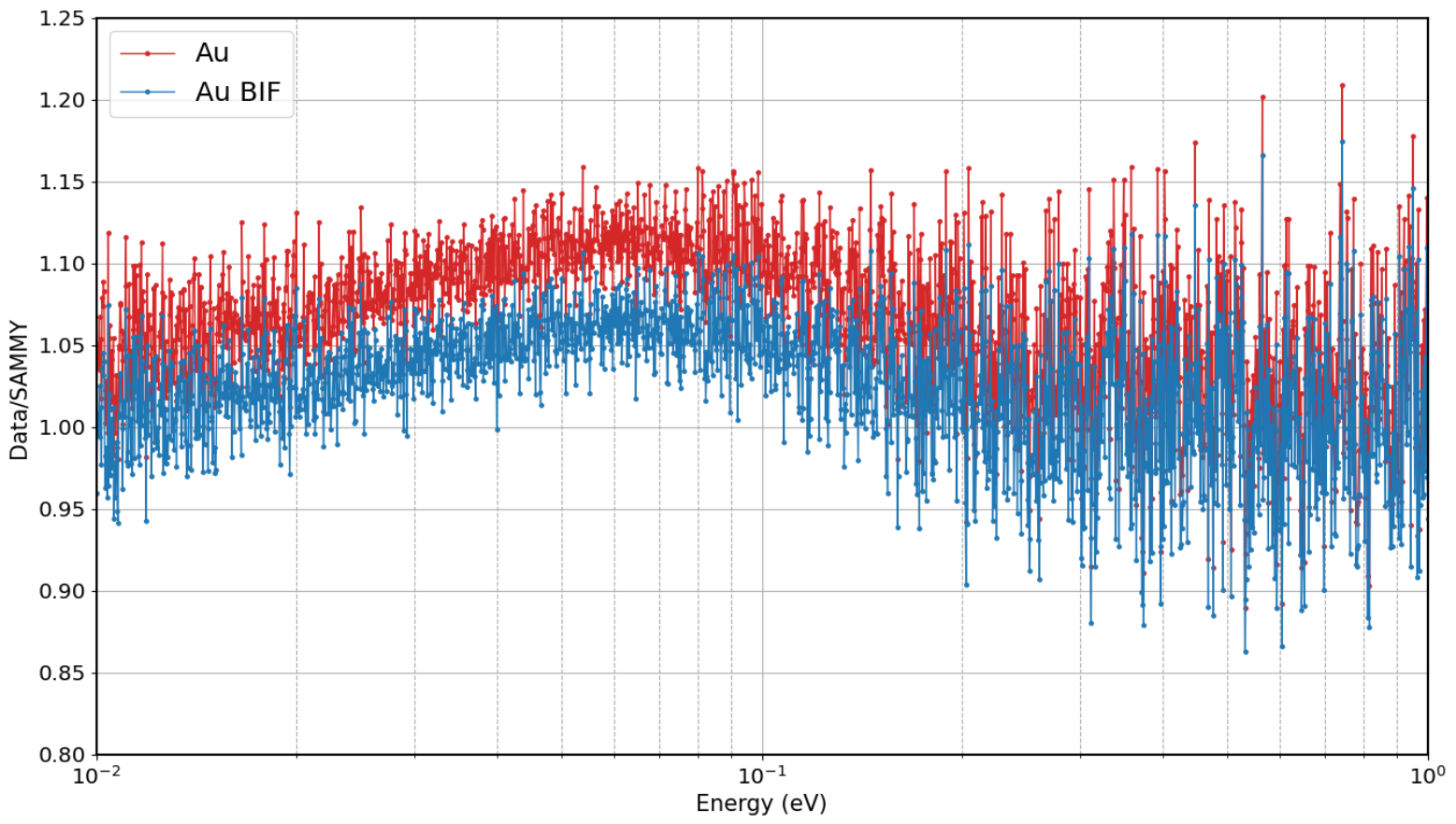


- Yield corrected for BIF variation with energy;
- Corrected yield shows better agreement with SAMMY calculation, but structure still clearly visible;
- Deviation of around 5% after BIF correction.

Very preliminary Au yield - Thermal



- Yield corrected for BIF variation with energy;
- Corrected yield shows better agreement with SAMMY calculation, but structure still clearly visible;
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New measurements of ^{97,98}Mo(n,γ)

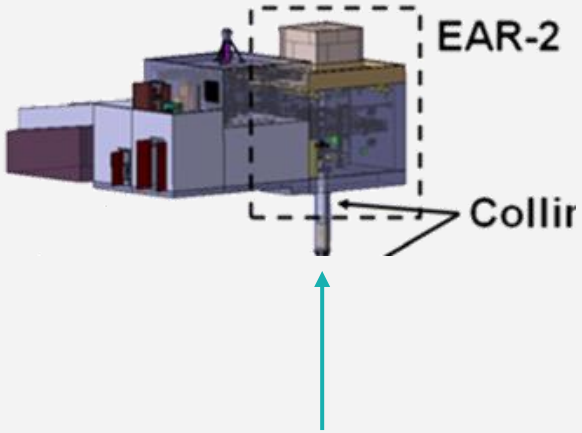
Sample preparation at n_TOF

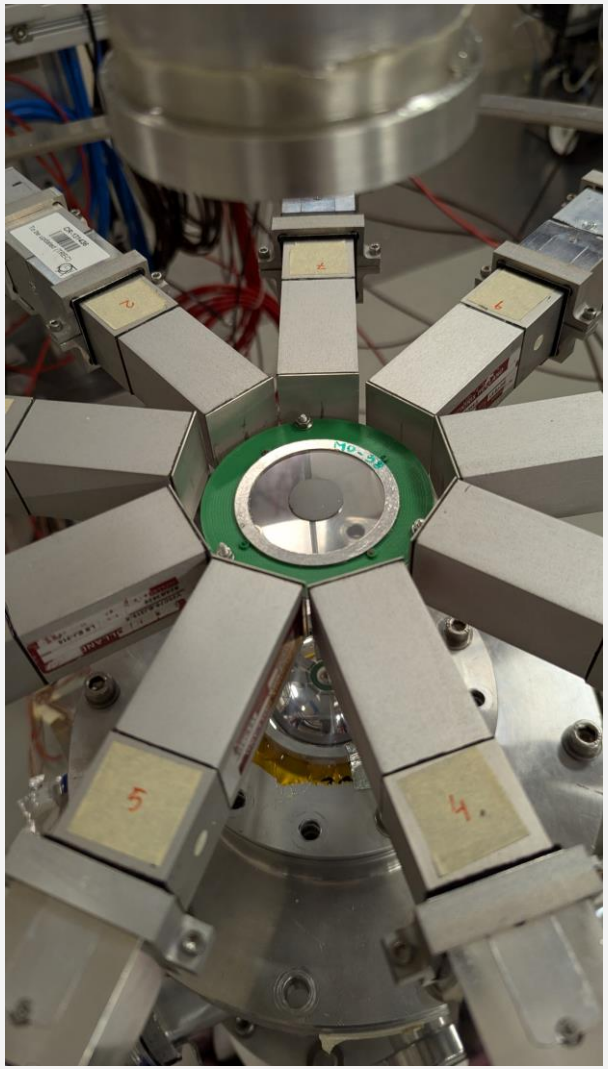
- Metallic powder of ^{nat}Mo with grain size like previous enriched samples;
- Sample prepared using 2g of material in a 2cm diameter disk;
- Preparation performed locally at n_TOF using hydraulic press;
- Minimal amount of material loss during preparation (<0,1%);
- Self sustaining samples, no sign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

Measurements in EAR2

Setup:

- 9 sTED placed at 90° at around 4,5cm from the target;
- New sample holder with less material;
- Same setup used for previous capture measurement (Bi, Nd, Argon)





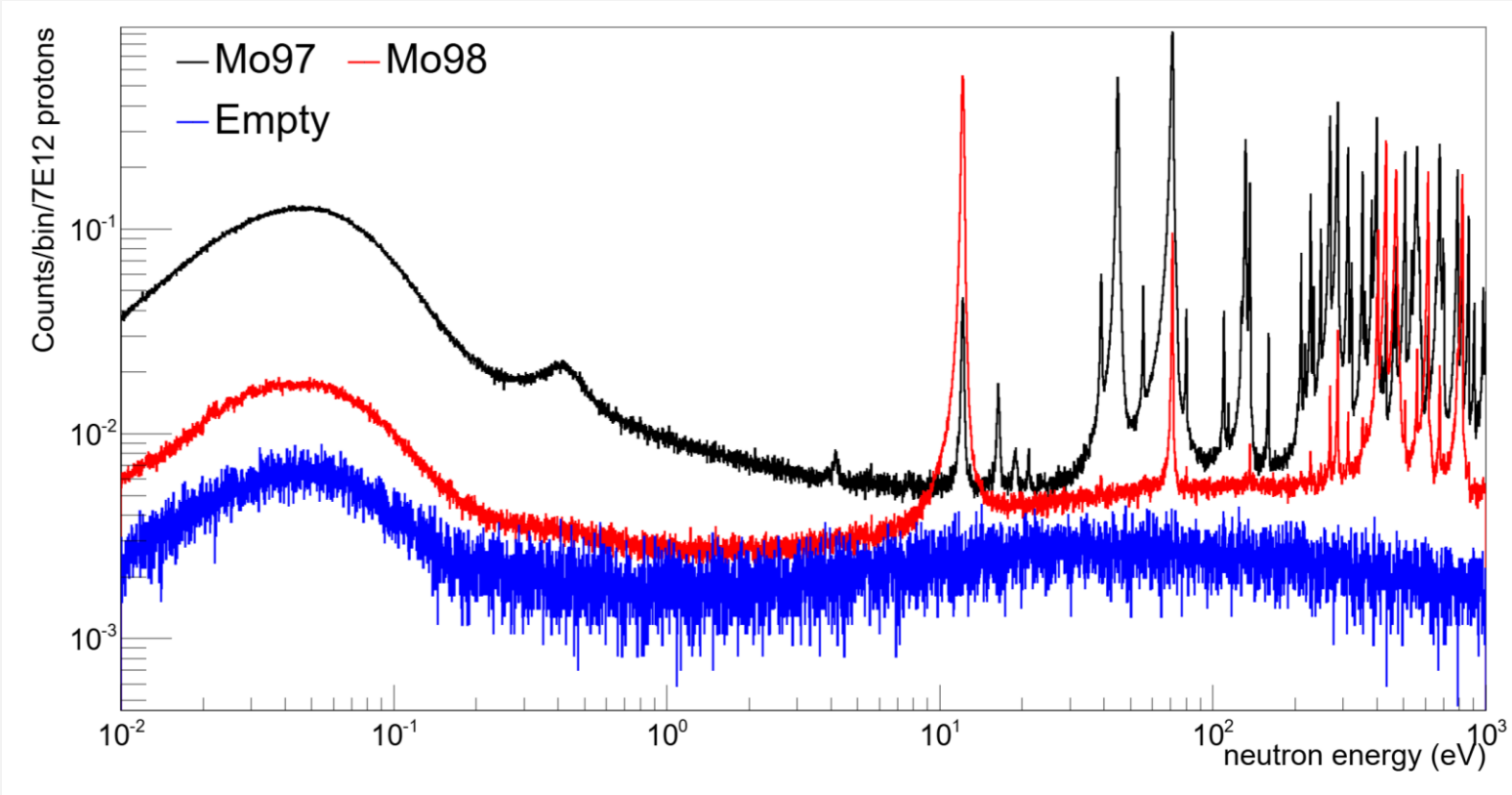
Measurements:

- Measurements performed with new ^{97,98}Mo samples and with additional ^{nat}Mo sample;
- Total of 2,3 x 10^{18} protons measured in June 2024.

Sample	Planned	Measured
Au	1.00E+17	1.361E+17
Mo97	4.50E+17	4.638E+17
Mo98	5.50E+17	6.393E+17
Empty	3.50E+17	4.032E+17
C	1.75E+17	1.884E+17
Pb	1.75E+17	2.198E+17
natMo	2.50E+17	2.673E+17
Total	2.05E+18	2.318E+18

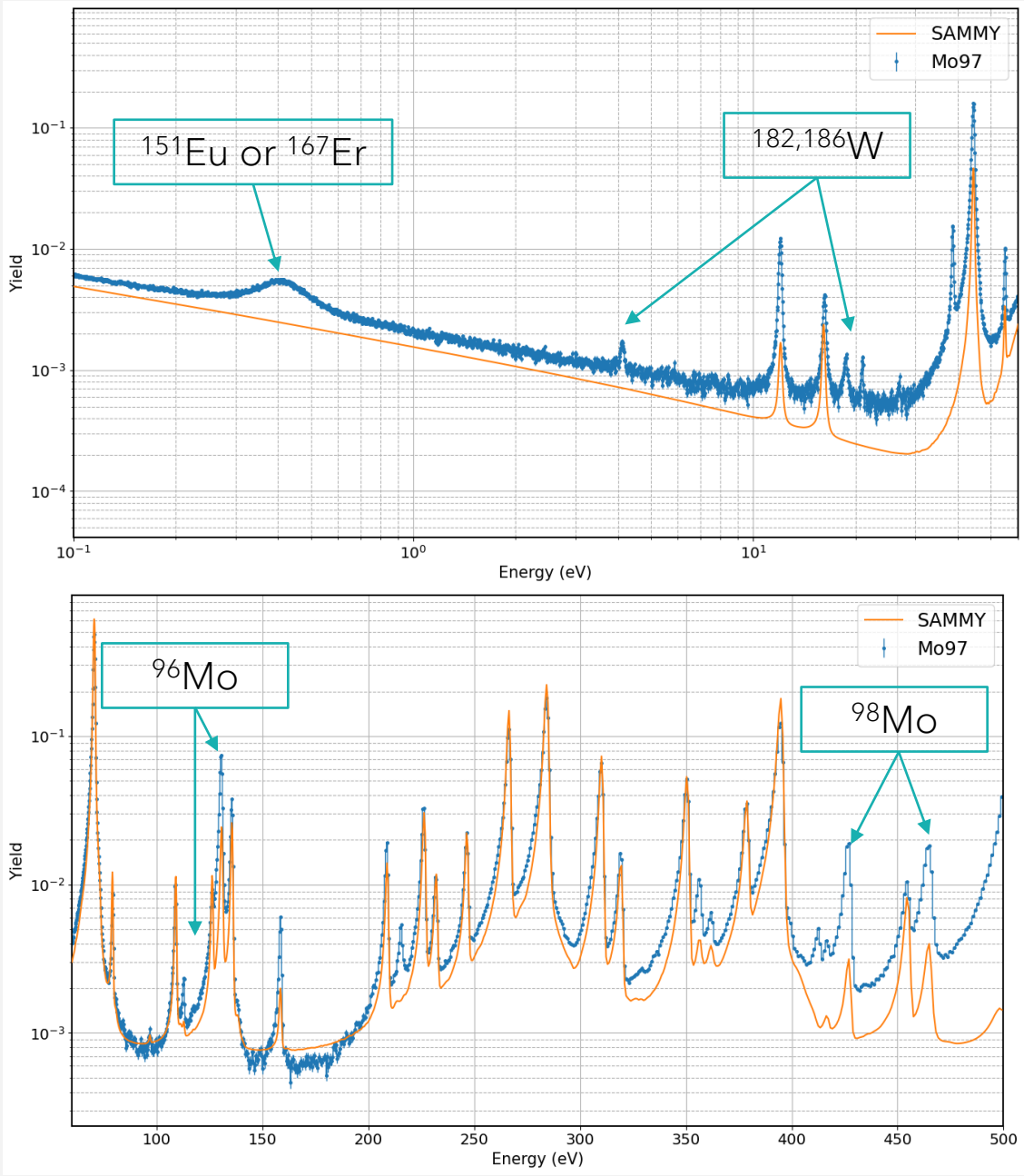
Preliminary count spectra ^{97,98}Mo

- First counting spectra of ^{97,98}Mo;
- Comparison with empty shows good statistics for both samples in all energy region;
- Good resolution for resonance region up to few keV;
- Mo97 samples shows several resonances from contaminants and other isotopes.



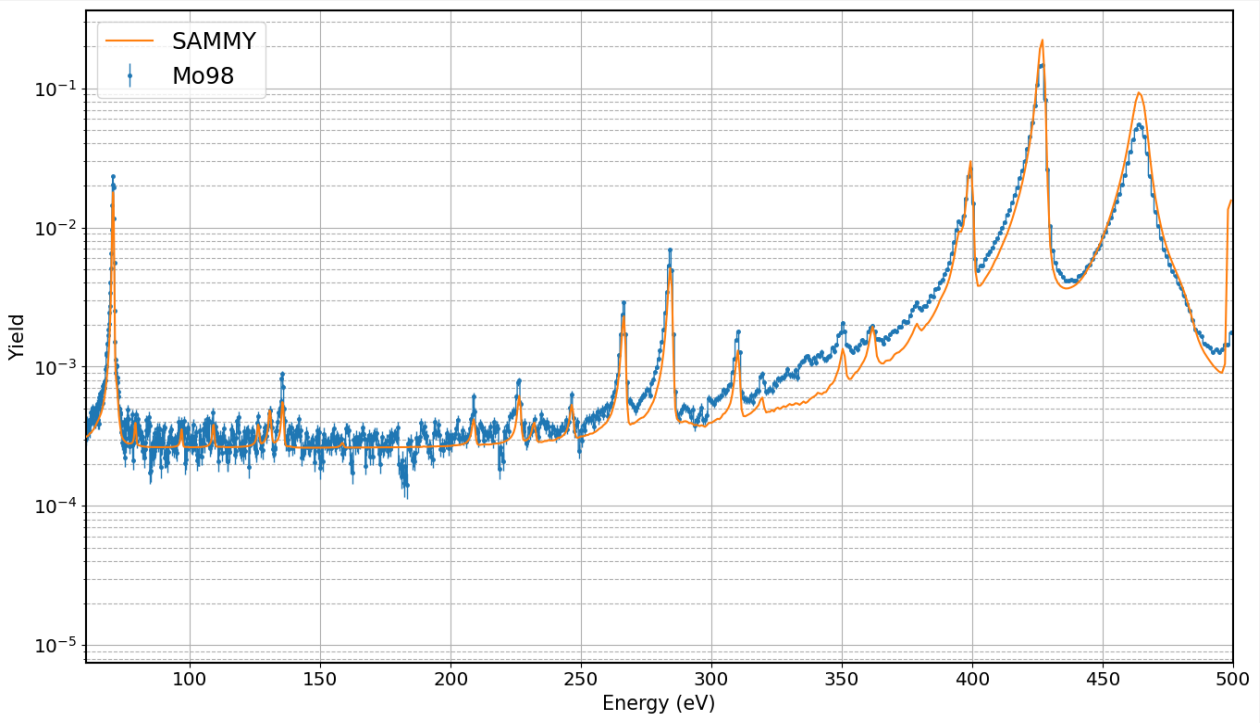
Preliminary spectra ^{97}Mo

- Comparison of observed data with expected composition from provider (using SAMMY);
- Small contamination with tungsten and probably Eu or Er;
- Higher presence than expected of other Mo isotopes (eg ^{96,98}Mo)



Preliminary spectra ^{98}Mo

- Comparison of observed data with expected composition from provider (using SAMMY);
- No evident contaminants observed in the data;
- Composition is in good agreement with values from provider



Conclusions

EAR1:

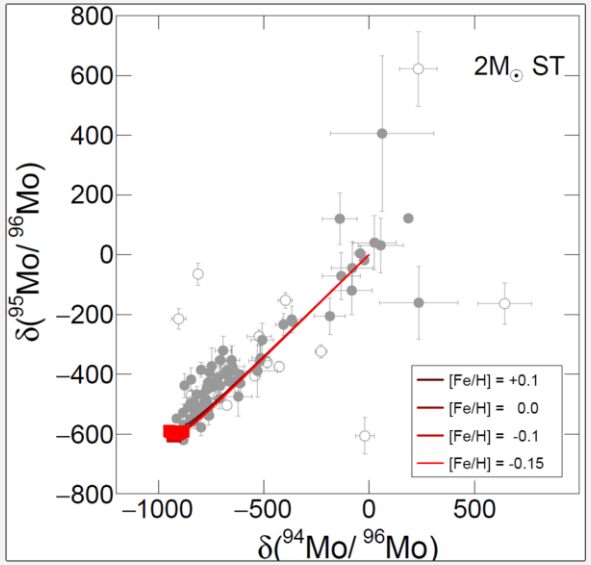
- Merged all statistics and adjusted the background;
- Resonance analysis in progress for ^{94}Mo, Resolved resonance region extended from 20 keV up to 75 keV;
- Deviation from expected resonance shape above 15 keV. Still under investigation…

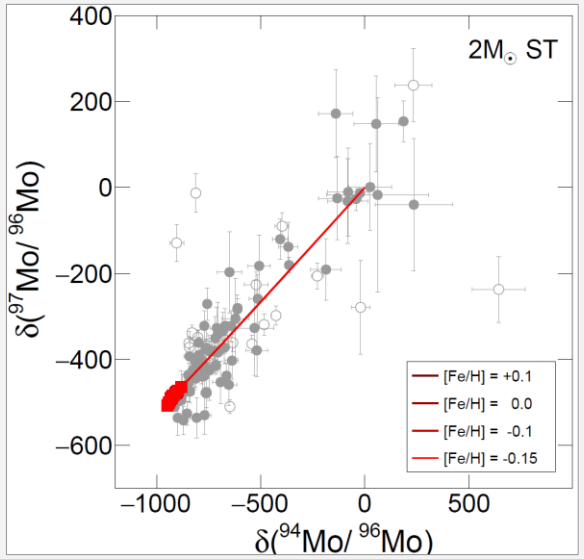
EAR2:

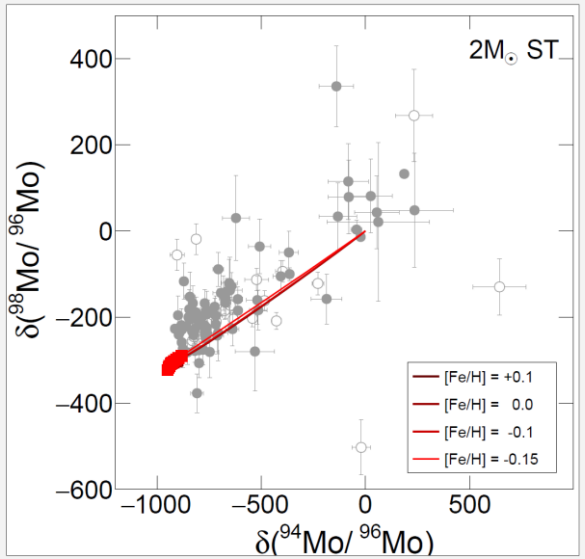
- Preliminary Au yield shows discrepancy in saturated resonance probably caused by dead time and/or coincidence events;
- Low energy resonances (<300 eV) are well reproduced in SAMMY;
- Deviation of low energy yield from expected 1/V.

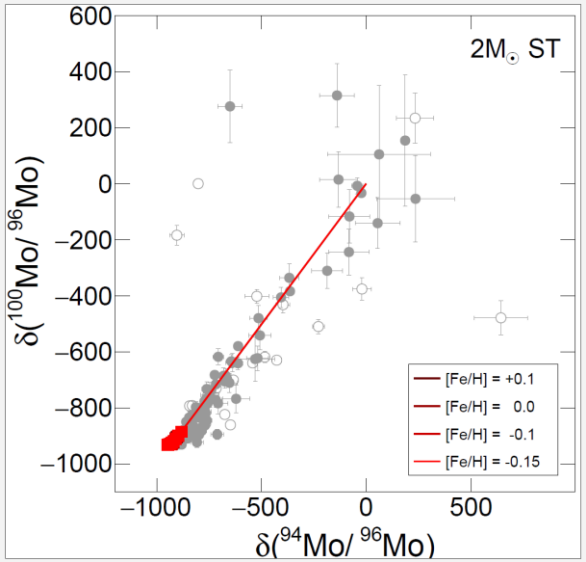
Thank you for your attention

Presolar grain composition









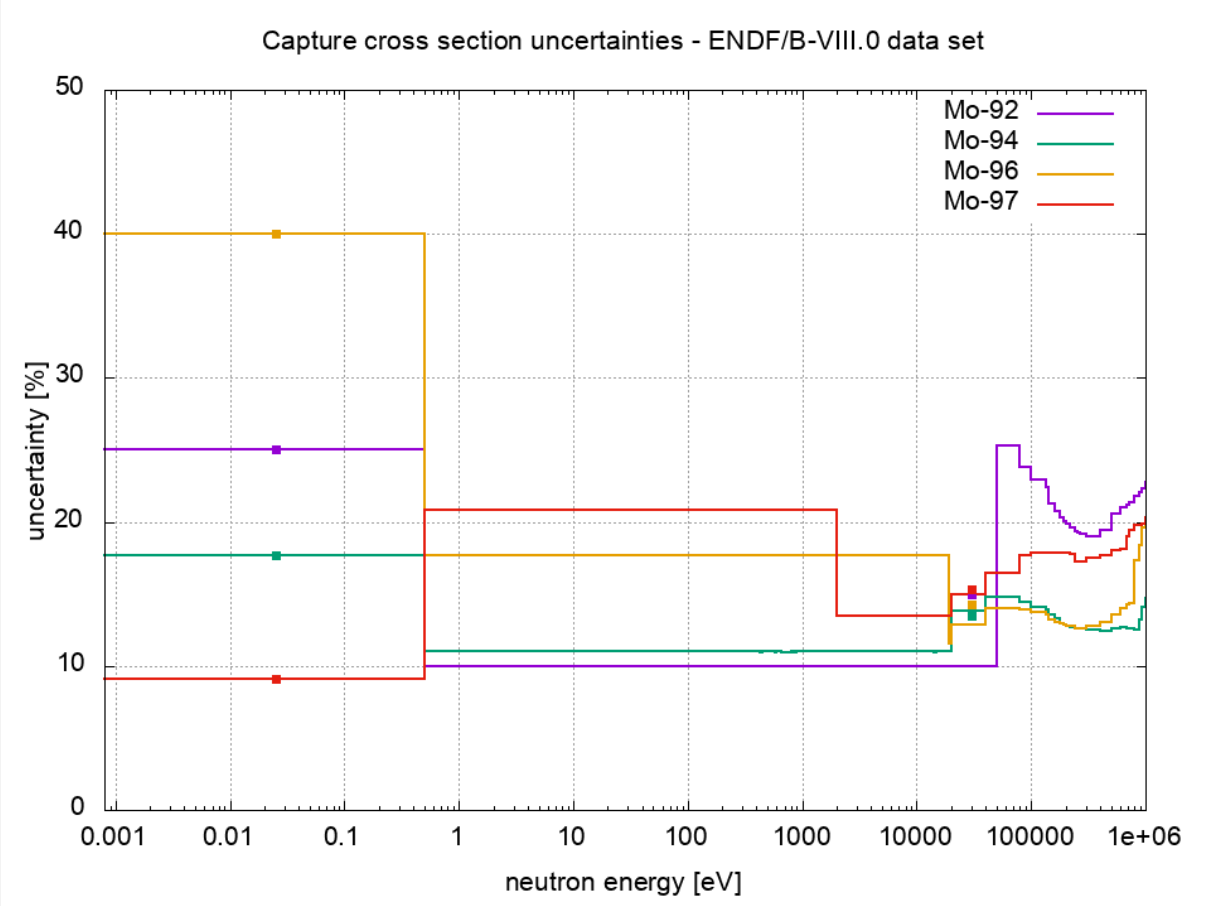
- Comparison of SiC grains composition versus stellar model (FRANEC) using delta notation:

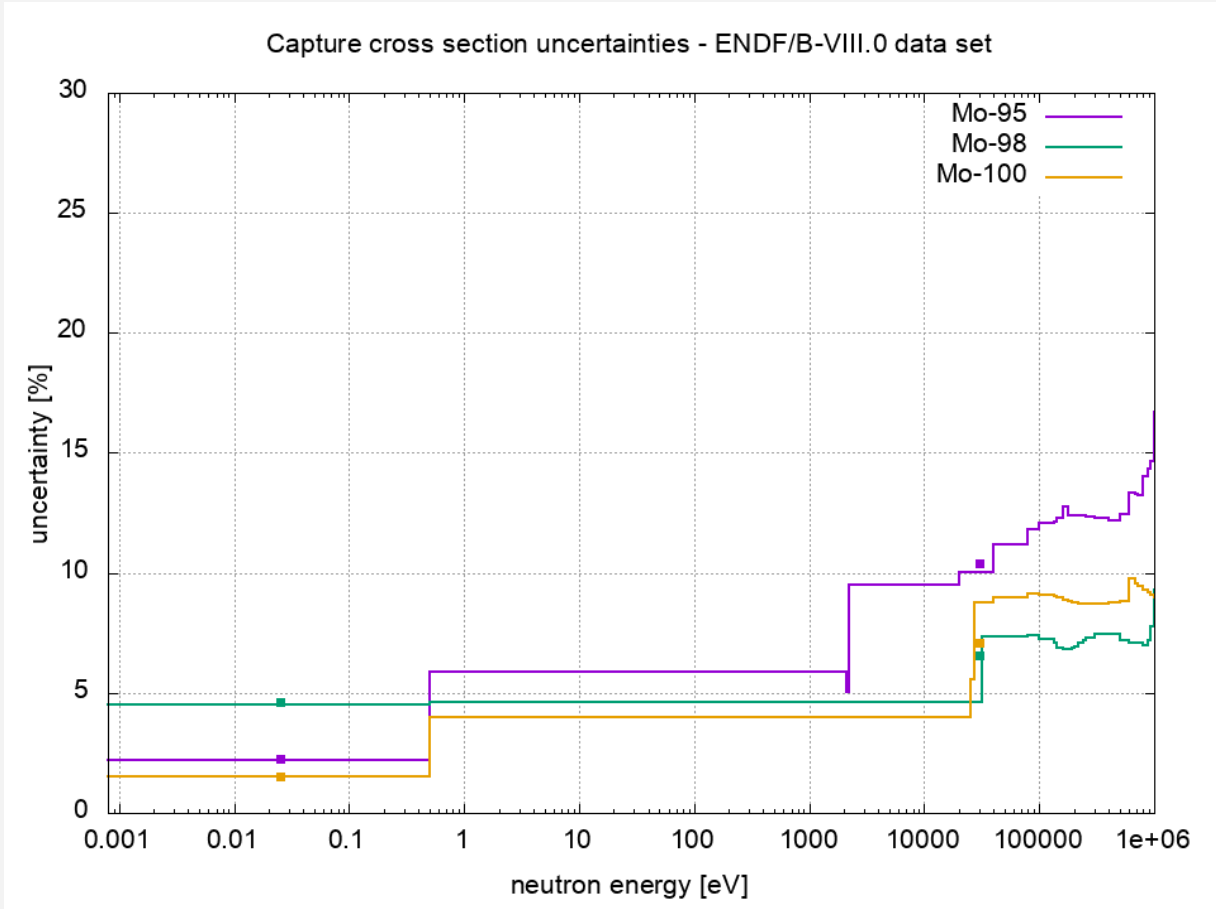
$$\delta\left(\frac{^{95}Mo}{^{96}Mo}\right) = 10^3 \times \left[\left(\frac{^{95}Mo}{^{96}Mo}\right) \Big/ \left(\frac{^{95}Mo}{^{96}Mo}\right)_{\odot} - 1\right]$$

- MACS from KADoNiS v1.0 database,
- Slight discrepancies between model and isotopic composition,
- Possible overestimation of MACS in KADoNiS.

S. Palmerini et al., ApJ 921 7 (2021)

Cross section uncertainties in ENDF/B-VIII



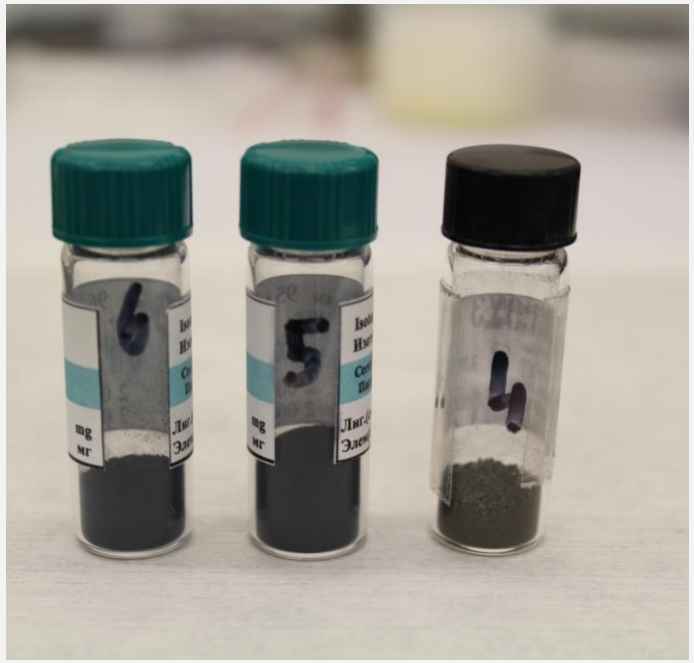


ENDF/B-VIII: D. Brown et al., Nucl. Data. Sheets 148 (2012)

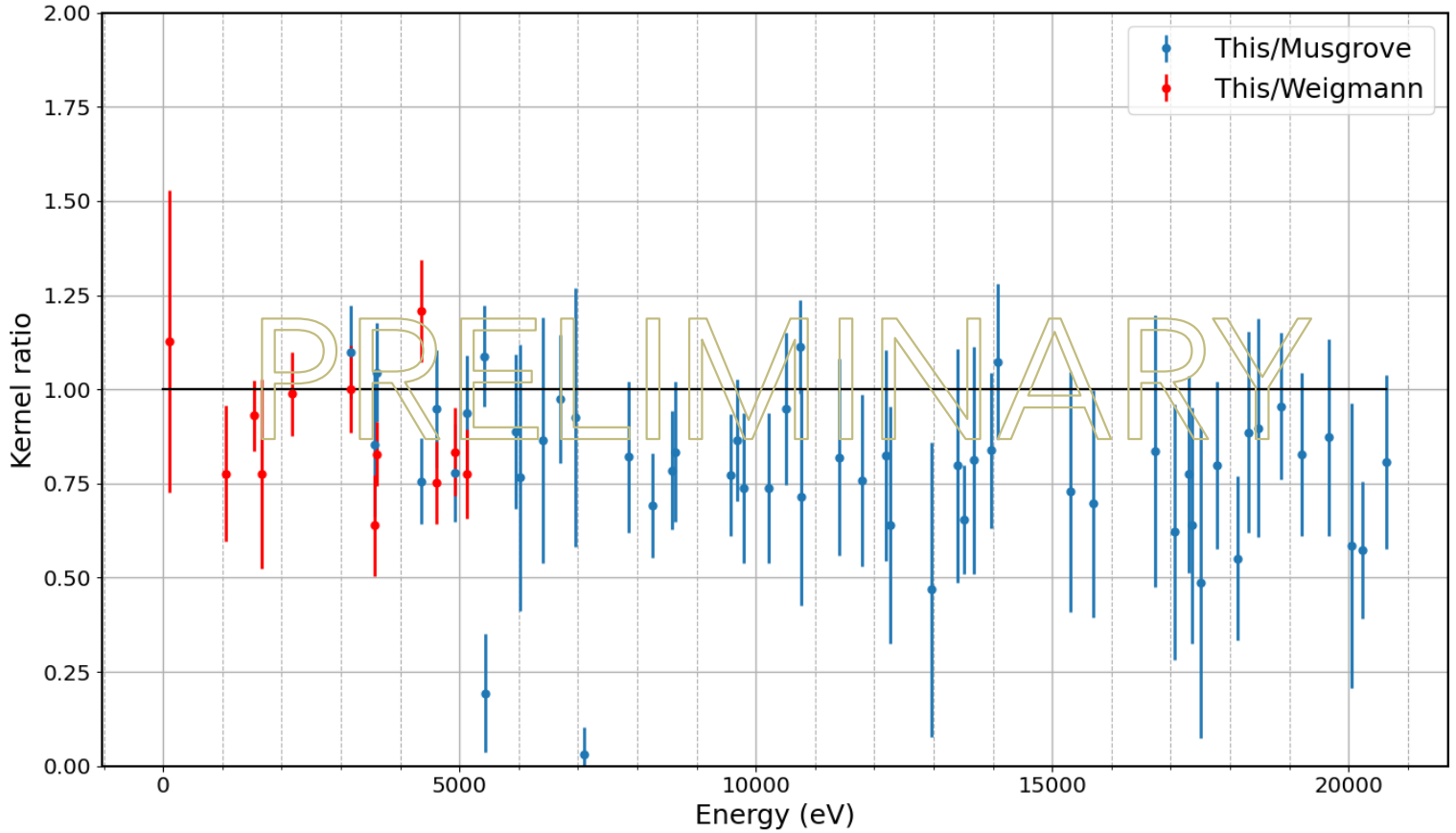
Enriched pellets preparation

To avoid the background coming from aluminum capsule three pressed pellets were prepared using enriched powder:

- Pellets prepared at JRC-Geel;
- Self sustaining pellets of ~ 2g;
- Additional ^{nat}Mo samples prepared using powder with different grain sizes;



Kernel ratio with literature ^{94}Mo

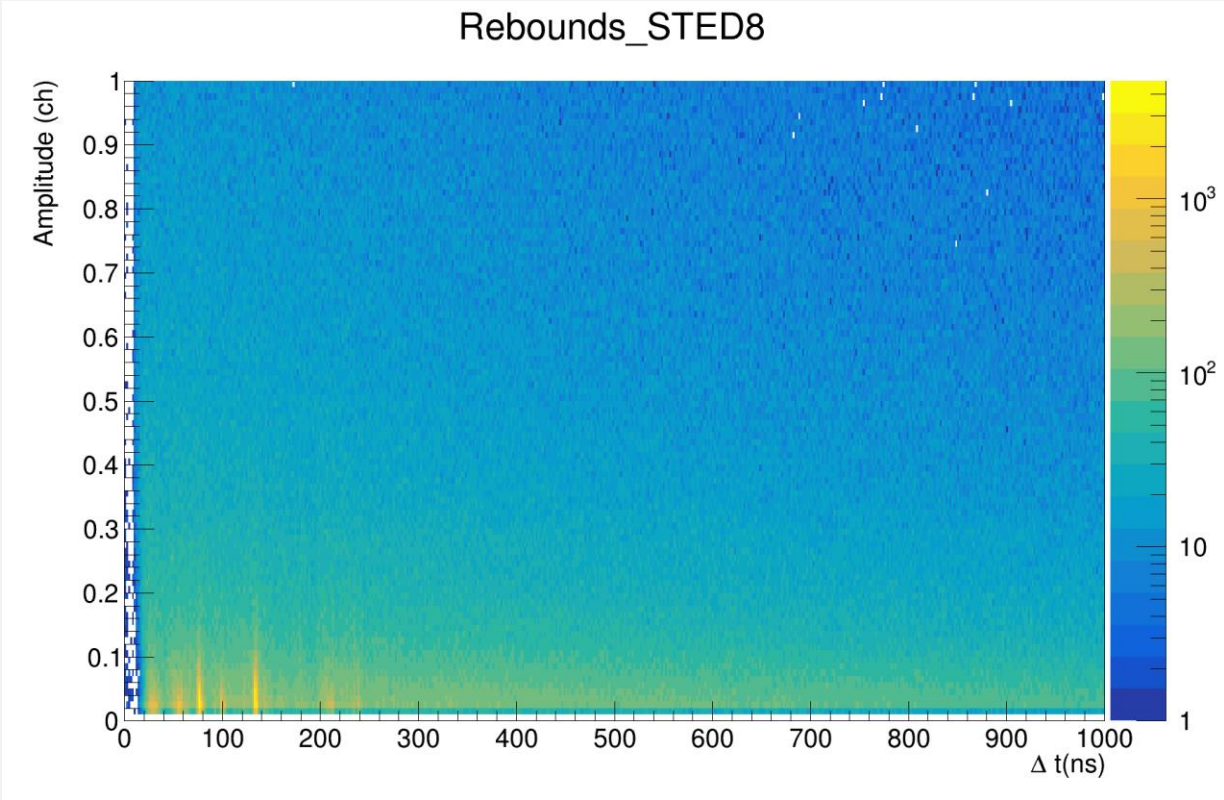


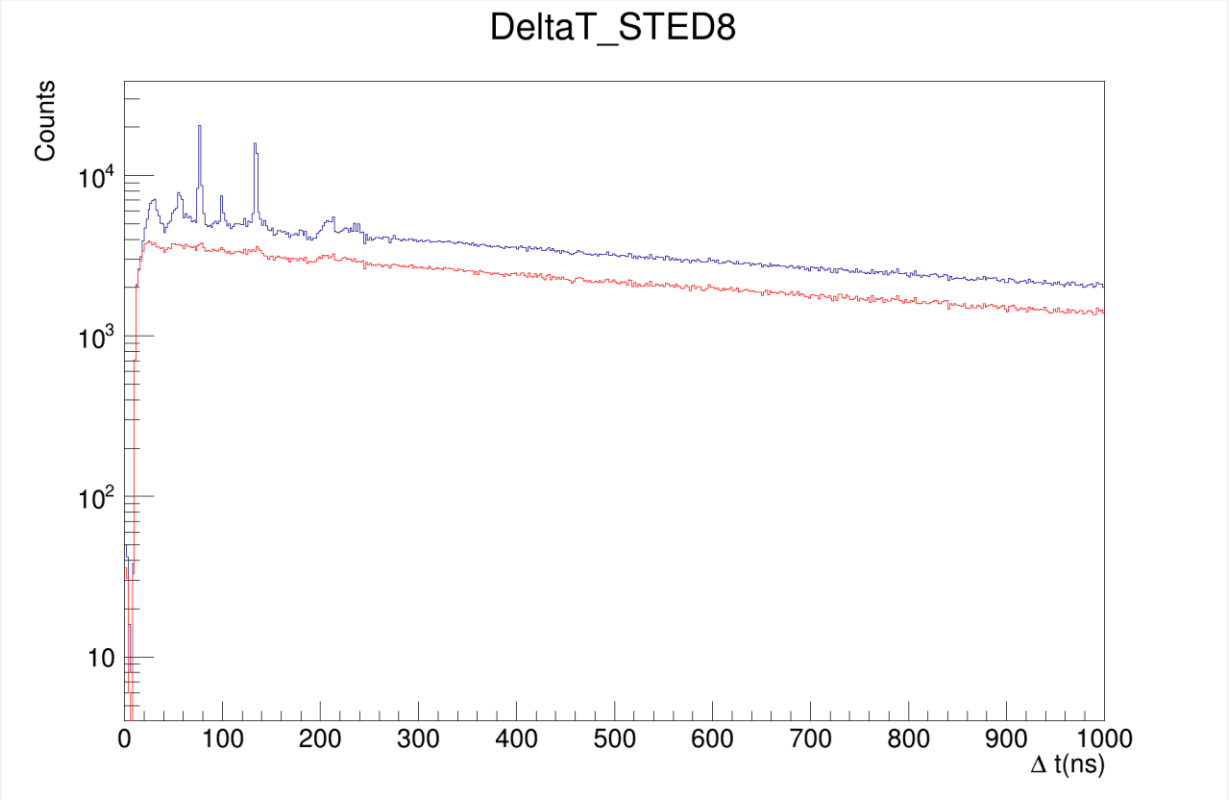
- The preliminary kernels obtained with SAMMY were compared to the ones in literature (Weigmann and Musgrove capture measurements);
- Main measurements used in libraries;
- Systematic deviation of around 20% observed

Rebounds STED

Small rebounds seen in all STED, always smaller than 150keV

This threshold remove all rebounds, dead time estimated from plot ~30ns





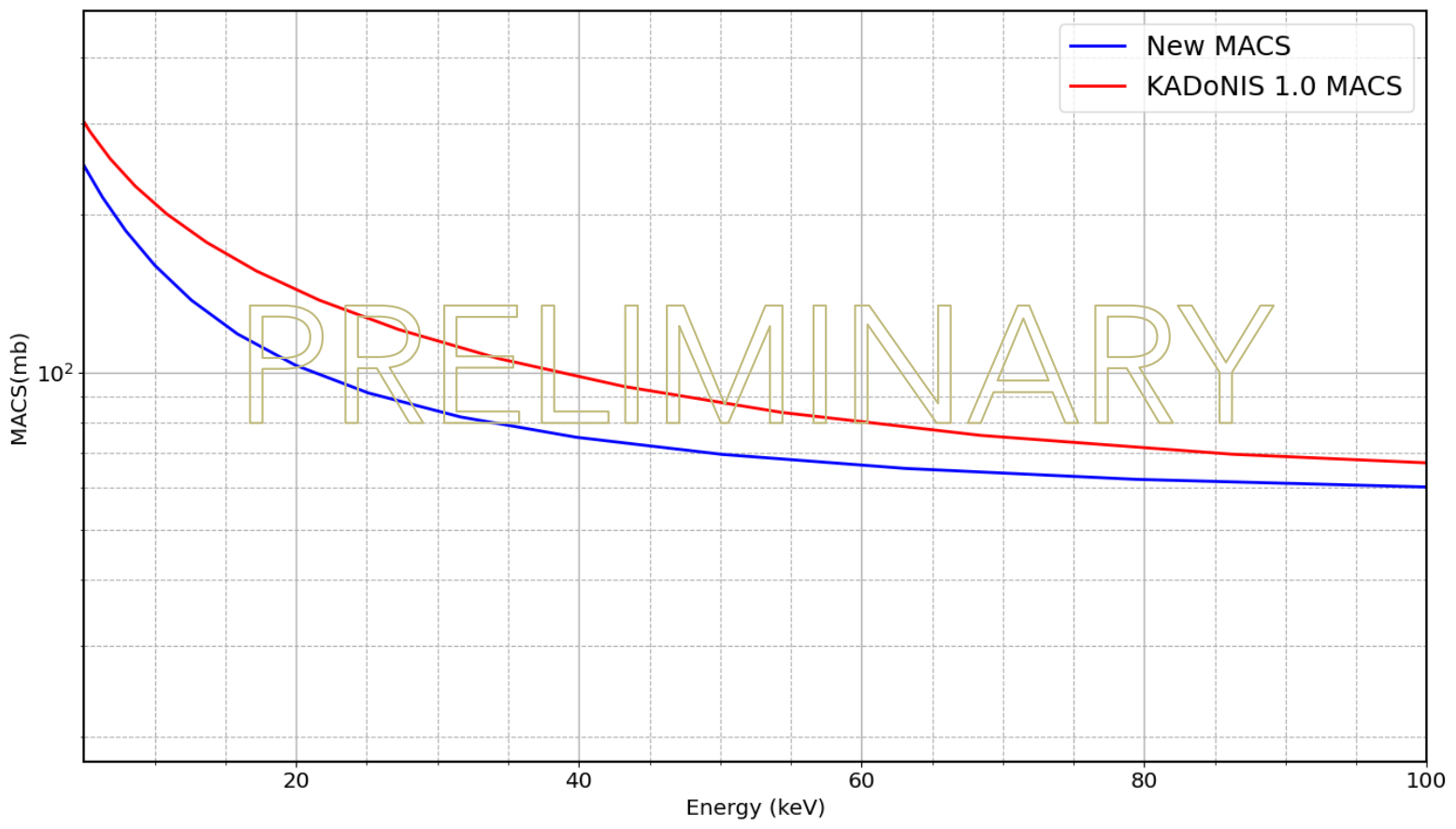
^{nat}Mo abundances

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%

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

Preliminary MACS of ^{94}Mo



- Preliminary values of the Maxwellian Averaged Cross Section (MACS) have been evaluated for ^{94}Mo,
- The new values of the MACS show a reduction between 10% and 30%.