New High Resolution Measurement of ^{56}Fe (n,γ) cross-section at n_TOF

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On behalf of the n_TOF Collaboration.

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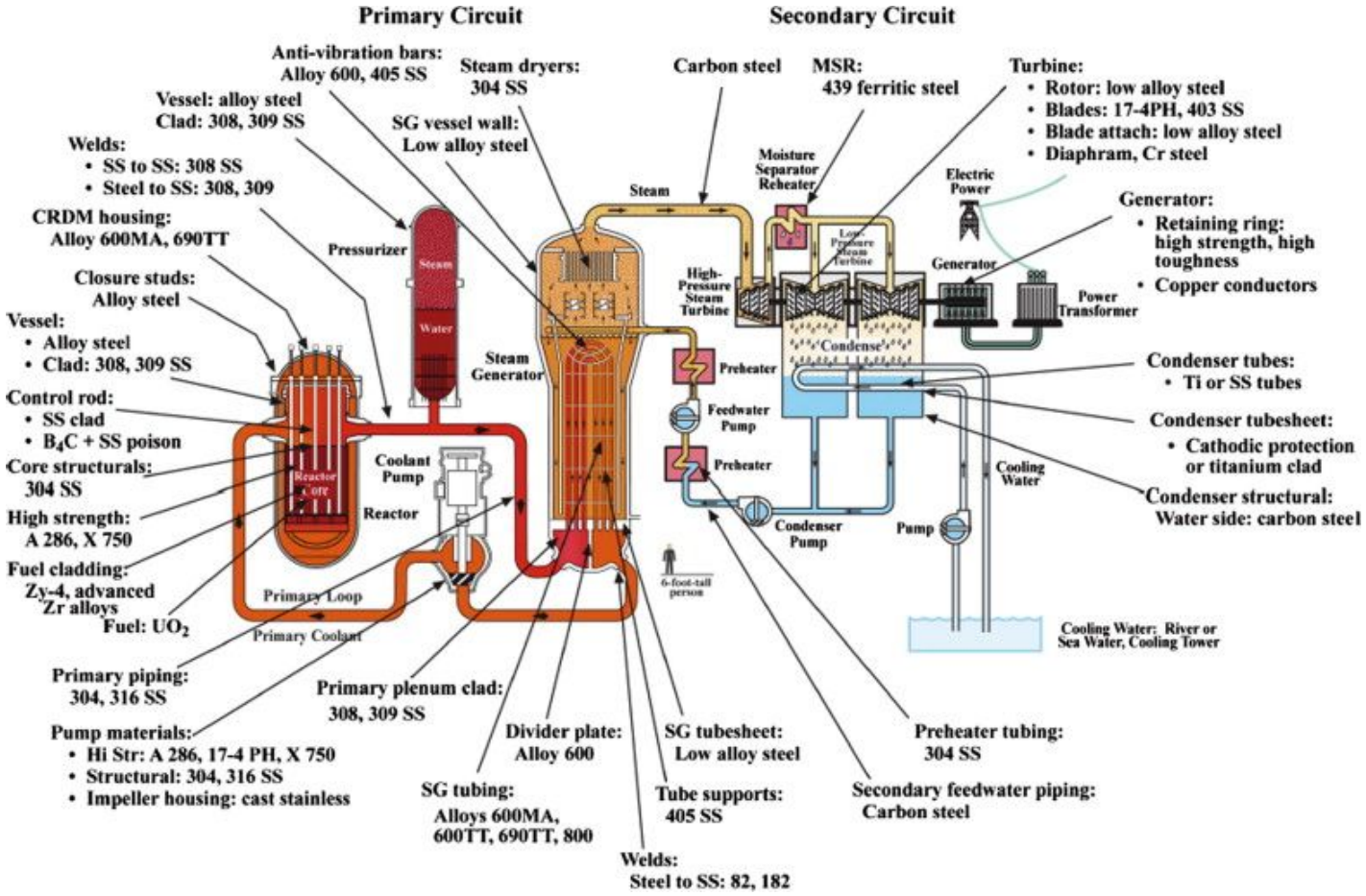
Motivation

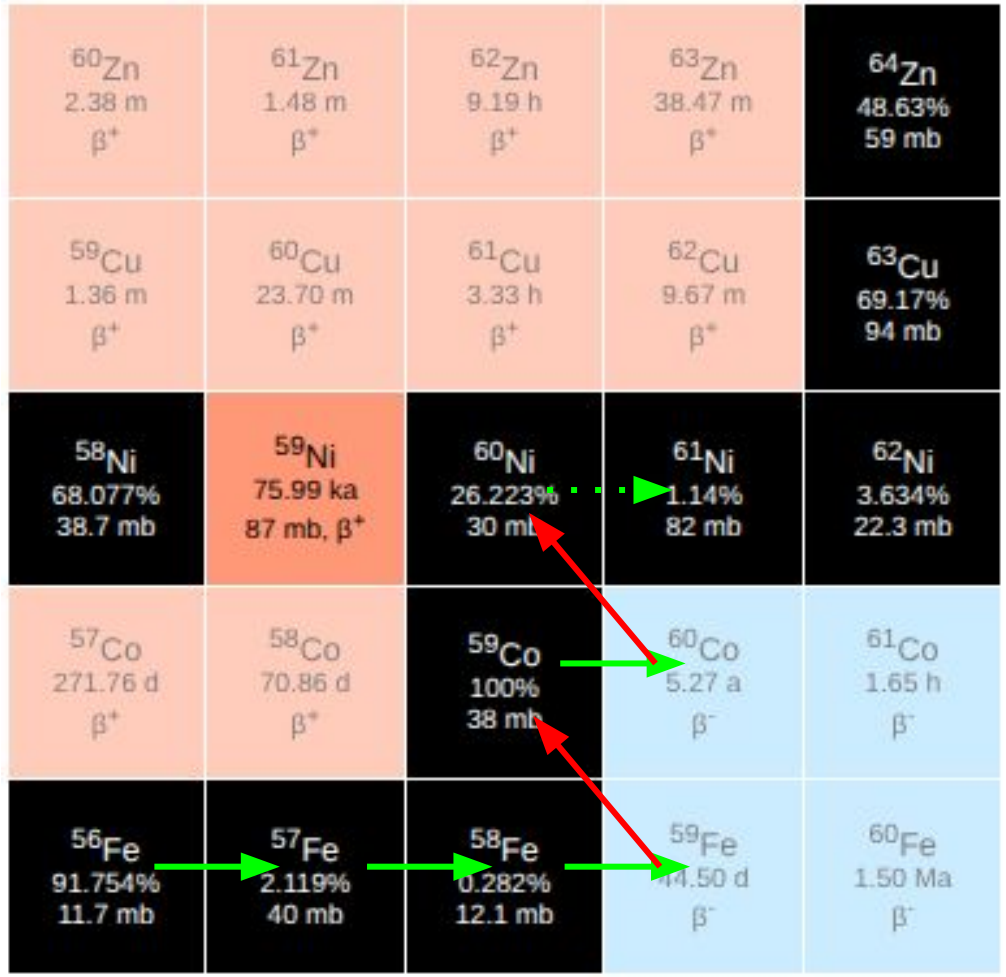
- Fe – an important element for both:
  1. Structural materials in nuclear technologies
  2. Shielding
- ^{56}Fe – 91.754% of natural Fe
- Presence as structural material in both primary and secondary circuits.
- Treated by CIELO evaluation as one of the "Major isotopes for reactor application" among ^{1}H, ^{16}O, **^{56}Fe**, ^{235}U, ^{239}Pu…
- Also taken up by the INDEN^{2} project.
- The EXFOR data is from measurements from the past decades - scope for higher resolution measurements in the current times.
- FeCrAl alloy cladding explored for their high corrosion resistance.



Motivation

- Astrophysics – stellar nucleosynthesis
  1. Seed of the s-process
  2. 6th most abundant isotope in the universe
  3. Determines the neutron to seed ratio

Significance as seed nuclei motivates efforts to lower the Maxwellian Averaged Cross-section (MACS) uncertainty for He-shell (MACS at 30 keV) and C-shell (MACS at 90 keV) weak s-process nucleosynthesis



Neutron capture

beta- decay

EXFOR entries

Major wide energy range capture measurement data (EXFOR):

Wang[1] (2010) : 10.0 keV – 90 keV (Tokyo, 30 cm, 6Li-glass)
Käppeler[2] (1983) : 22.80 keV – 113 keV (GELINA, 60 cm, C6D6)
Corvi[3] (1982) : 1.15 keV – 296 keV (GELINA, 58 m, C6D6)
Allen[4] (1976) : 2.50 keV – 870 keV (ORELA, 40 m, C6F6)
Macklin[5] (1964) : 14.20 keV – 59.4 keV (ORNL, 8 cm, C6F6)

The recent evaluations are based on relatively old data (~4 decades old).

Reacode	nReacstr	MF	MT	Target	Reaction	Quant	nPts	enMin	enMax	year1	author1
26-FE-56(N,G)26-FE-57,,SIG,,SPA	1	3	102	Fe-56	N,G	CS	5	15000	90000	2010	T.Wang+
26-FE-56(N,G)26-FE-57,,SIG	1	3	102	Fe-56	N,G	CS	136	731	1410	1977	O.A.Shcherbakov+
26-FE-56(N,G)26-FE-57,,SIG,,AV	1	3	102	Fe-56	N,G	CS	27	1000	850000	1976	B.J.Allen+
26-FE-56(N,G)26-FE-57,,SIG,,MXW,DERIV	1	3	102	Fe-56	N,G	CS	15	5000	75000	1975	H.Beer+
26-FE-56(N,G)26-FE-57,,SIG,,TTA	1	3	102	Fe-56	N,G	CS	464	5900	42900	1970	A.Ernst+
26-FE-56(N,G)26-FE-57,,SIG,,TTA	1	3	102	Fe-56	N,G	CS	370	19100	219000	1970	A.Ernst+
26-FE-56(N,G)26-FE-57,,SIG	1	3	102	Fe-56	N,G	CS	33	14200	59400	1964	R.L.Macklin+

1. T. Wang et. al., Nuclear Instruments and Methods in Physics Research Section B, 2,2010
2. F. Kaeppler et. al., Nuclear Science and Engineering, 1983
3. F. Corvi et. al., ND, 1982
4. B. J. Allen et. Al., Nuclear Physics A, 1976
5. R. L. Macklin et. al., Physical Review, 1964

Objective

To disseminate to the nuclear data community a new measurement with:

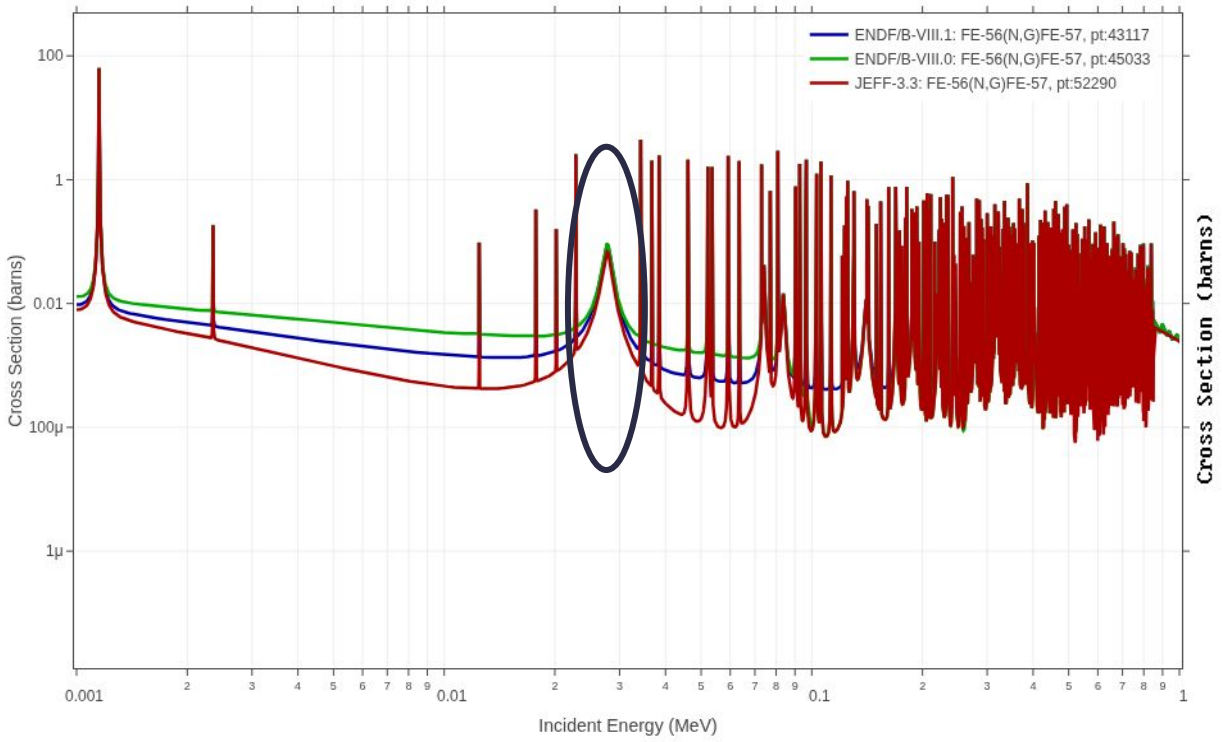
1. Broad energy range (upto 500 keV) : n_TOF white neutron source
2. High energy resolution : time-of-flight measurements with 184 m flight path
3. Good statistics : 4 C_6D_6 Detectors

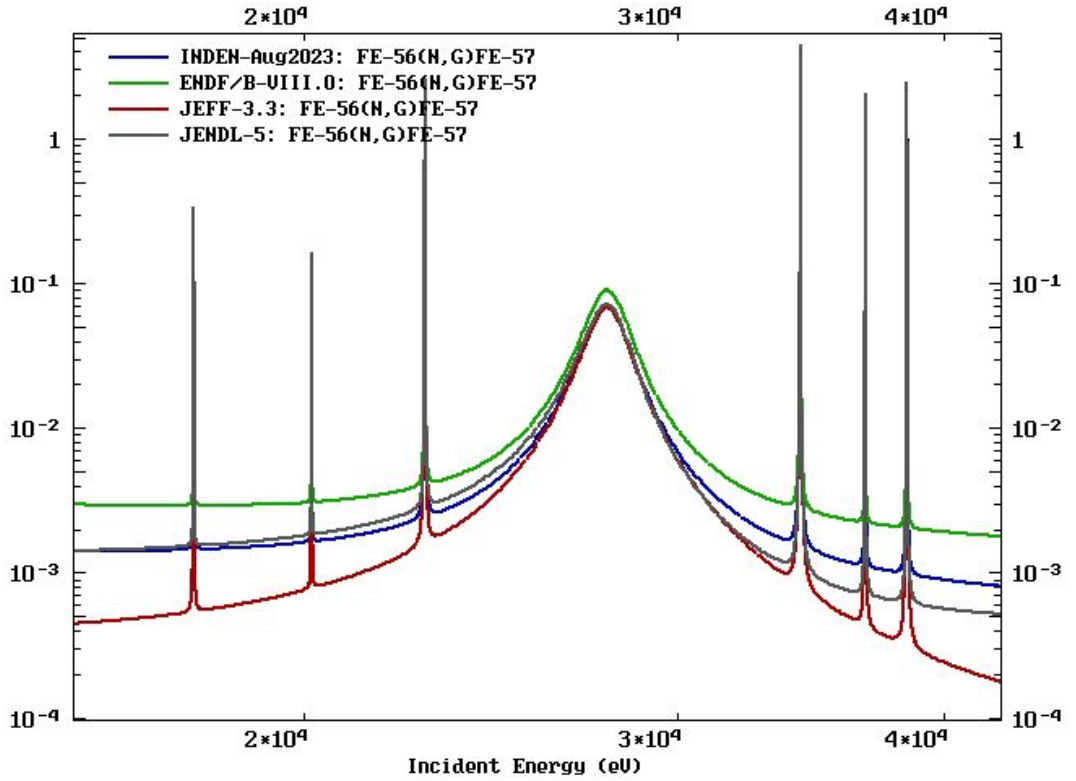
The experimental database used in the evaluation is summarized in Table IX of the primary reference (NDS 148,241(2018)). In doing this selection we favored: (i) broad energy range covered by the experiment, (ii) high energy resolution, and (iii) high (but reasonable) accuracy of the experiment. Thus the measurements providing possibly wide and reliable picture were given precedence over single energy-point experiments, especially within the energy range where strong fluctuations were observed. On the other hand, many single- or a few-point

A. Herman et. Al., Nuclear Data Sheets, 2018

Aspects to consider

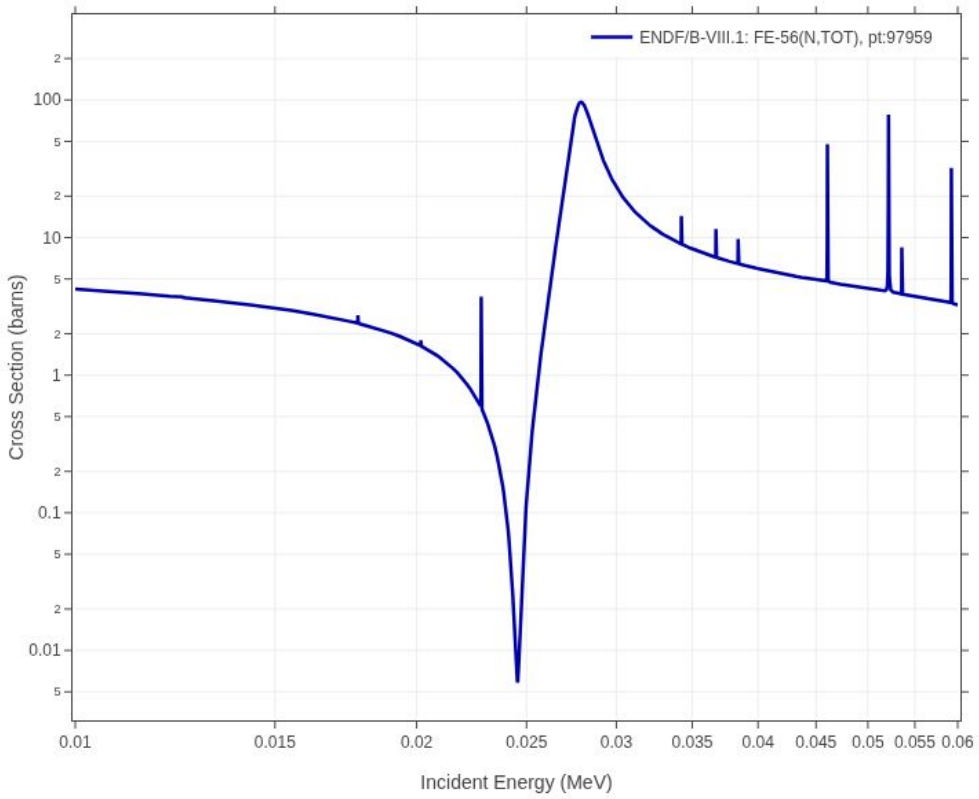
- Challenges in resolving the 27.7keV s-wave resonance
  - Mostly dedicated to multiple scattering and prompt background - Thinner sample, Monte Carlo studies and reduced background in EAR1 phase4 target.

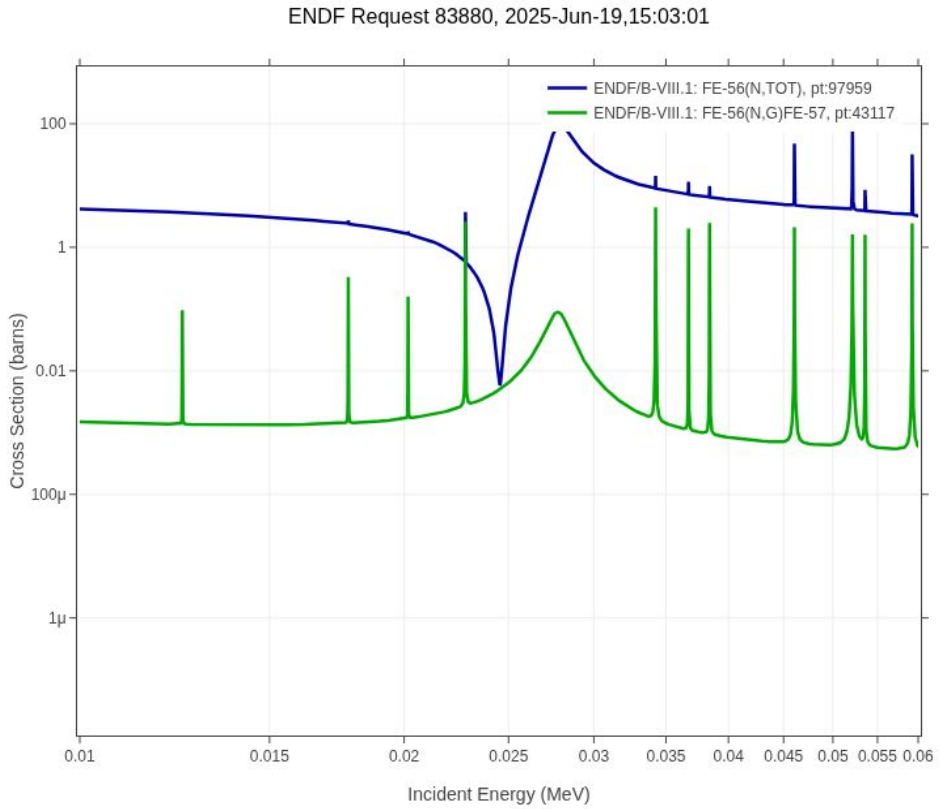




Aspects to consider

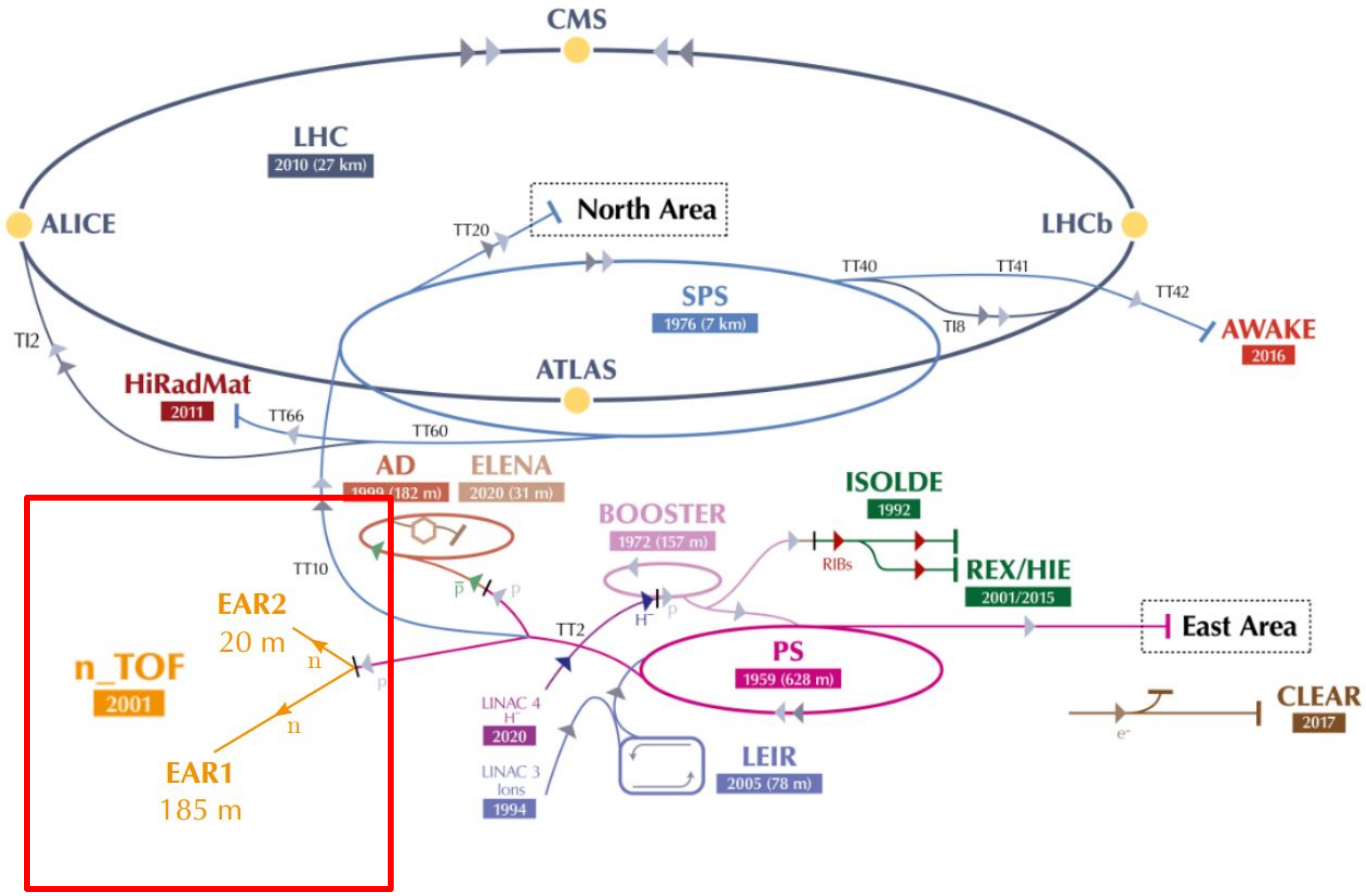
- 24 keV transmission
  - Fe^{56} transparent to neutrons of this energy - significant for shielding calculations.
  - Overlap with 27.7 keV capture resonance - call for efforts to measure this resonance more accurately.





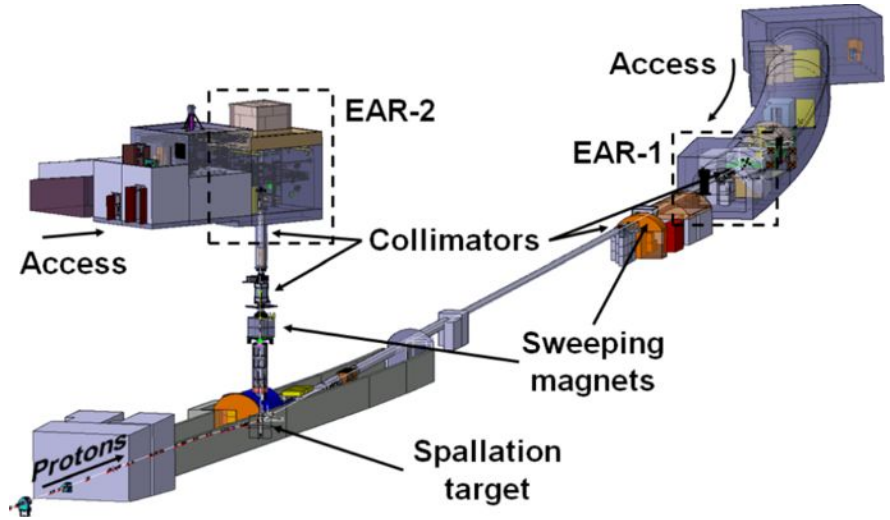
n_TOF (neutron time of flight) collaboration at CERN

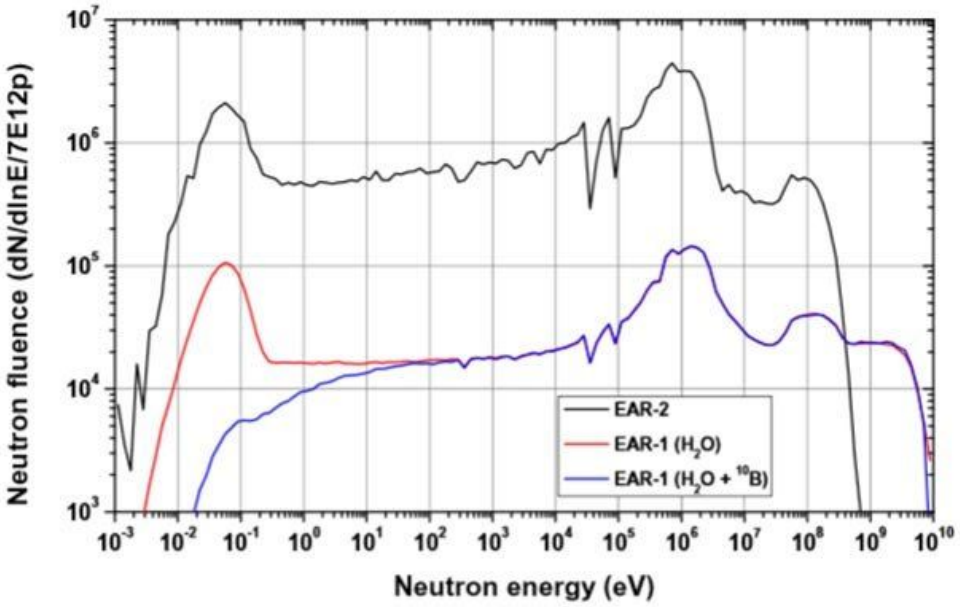
- High intensity spallation neutron source produced by 20 GeV/c protons from the PS at the CERN accelerator complex.
- Lead spallation target - conversion of PS proton beam (20 GeV/c) to a white neutron (and other particles) beam source.
- Beam “cleaned” off of charged particle with a sweeping magnet.
- Spallation gammas form gamma-flash.



Experimental areas at n_TOF

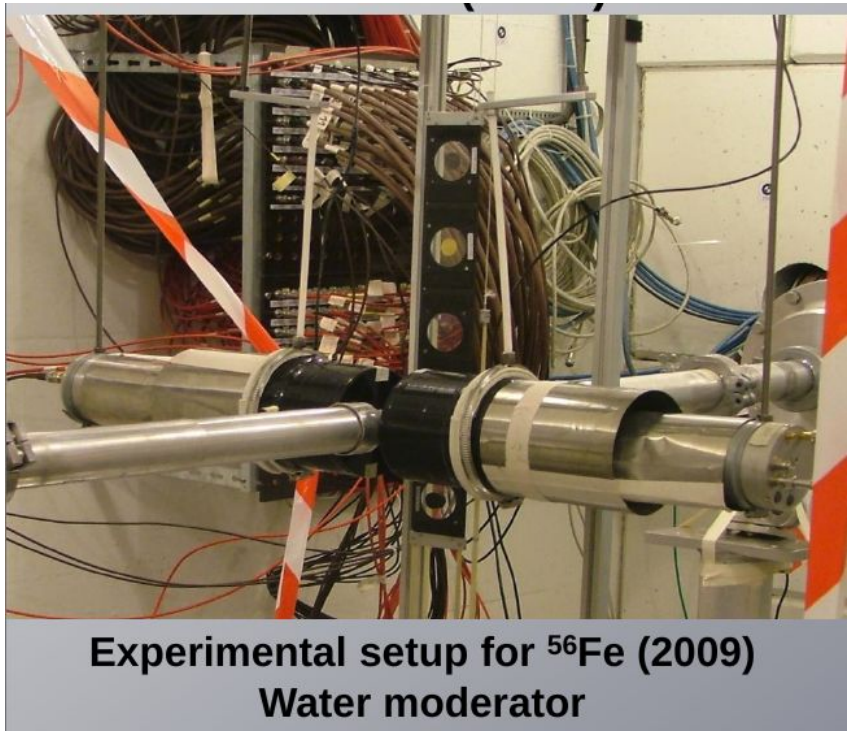
- Experimental ARea 1 (EAR1)
  - 186 m flight path
  - Borated moderator
- Experimental ARea 2 (EAR2)
  - ~19.5m flight path
  - Non-borated moderator
  - x100 flux compared to EAR1
- NEAR experimental area
  - 5m from the lead target
  - Activation measurements

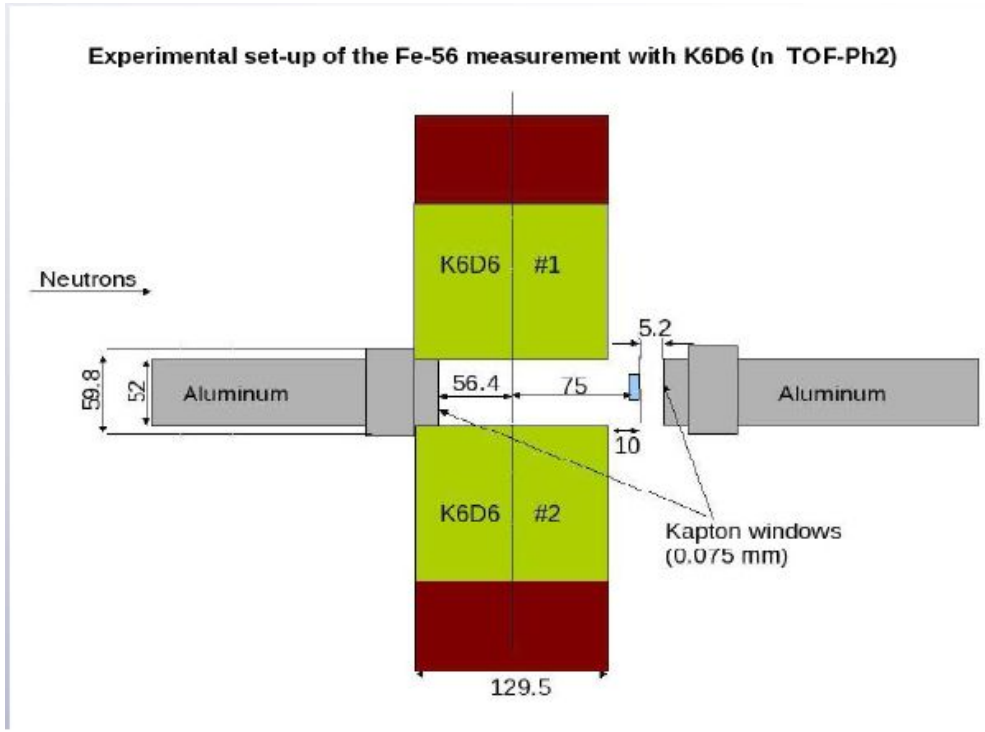




Previous Fe^{56} measurements at n_TOF

- 2009: Measurement of Fe^{56} at n_TOF
  - non-borated water moderator (phase2)
  - 2 C_6D_6 detectors
- Successful analysis of ^{54}Fe, challenges with ^{56}Fe



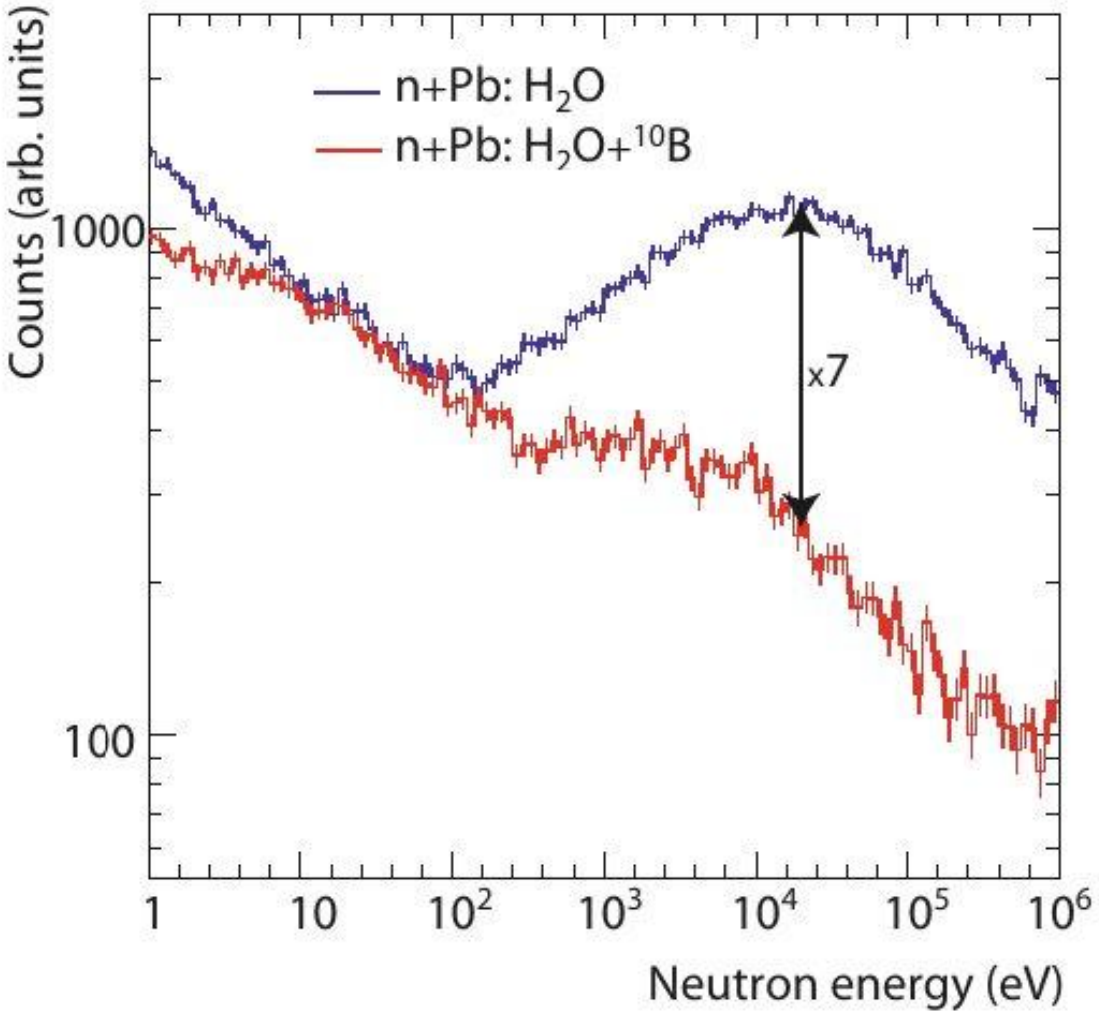


From G. Giubrone talks at n_TOF meetings, 2010-2012

Previous Fe^{56} measurements at n_TOF

- Previous ^{56}Fe measurement:
  - Significant in-beam gamma effect
  - Short distance between the sample and the detector
  - ~20% gain drift

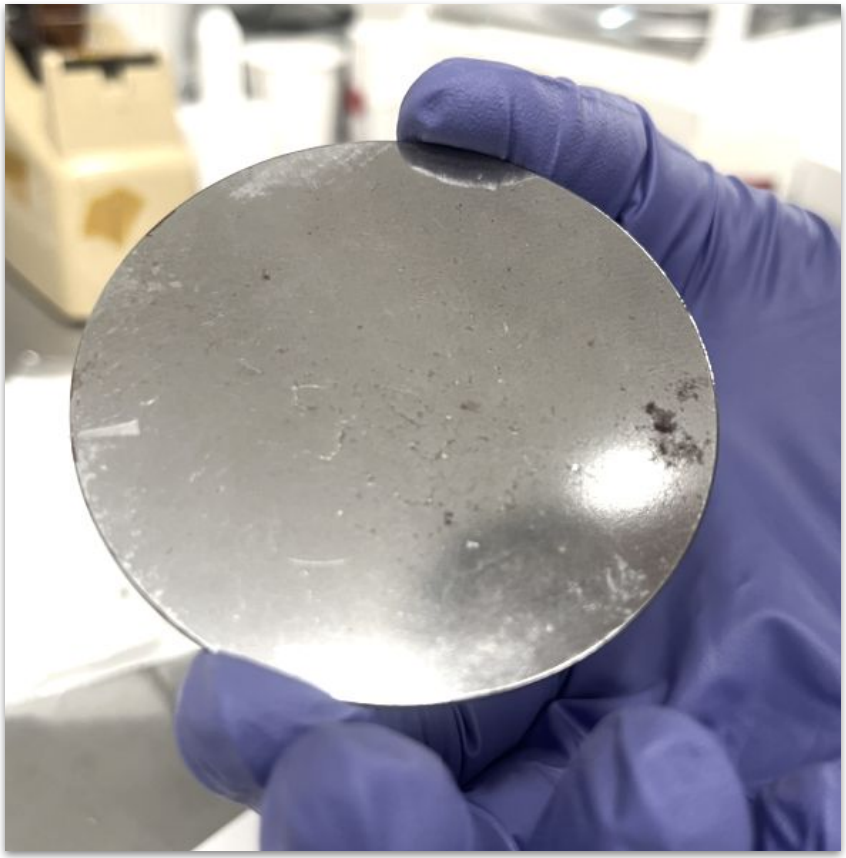
- Deduced and implemented new measurement standards:
  - Reduced in-beam gamma background with borated moderator
  - Distance between the sample and the detectors increased to 9 cm (deduced from Cr capture studies at n_TOF)
  - Frequent energy calibrations programmed



(Guerrero et al., EPJA, 2013)

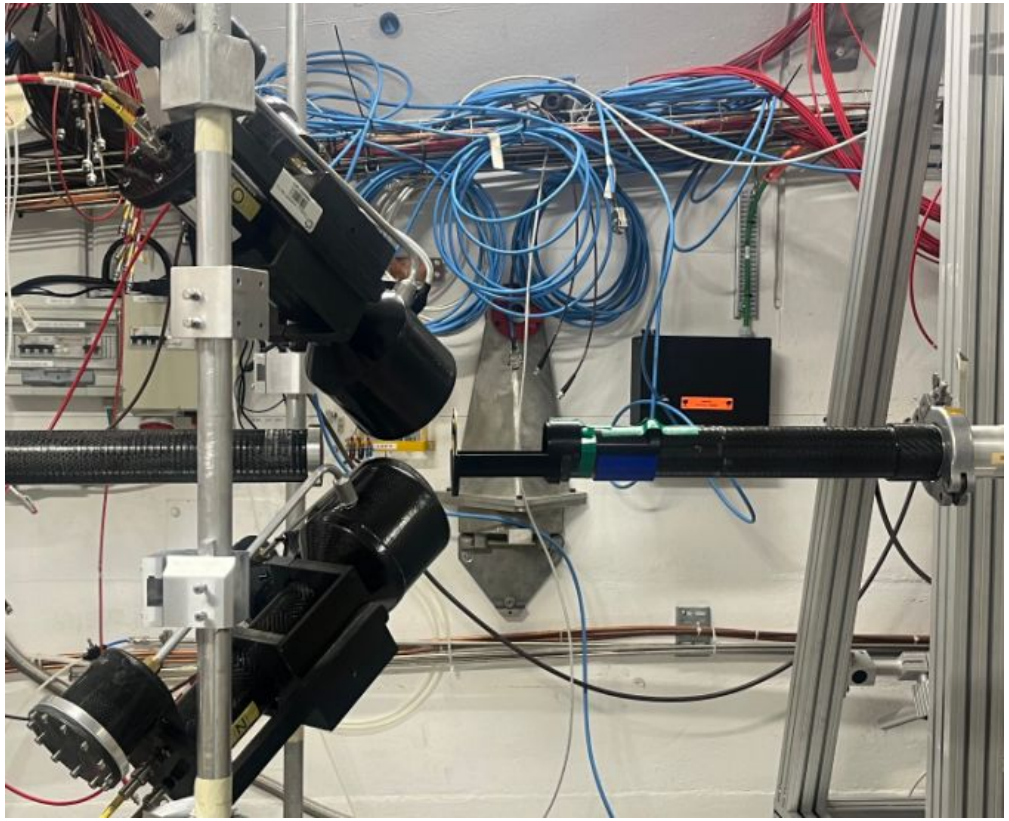
New measurement: July 2025 campaign

- Sample:
  - ~31.4g high-purity Fe^{56} (>99%),
  - Metallic
  - thick sample (1mm/8.8x10^{-3} atoms/barn)
  - 70mm diameter: BIF = 1
- ^{nat}Fe, thin sample (250 µm/2.12x10-3 atoms/barn) (multiple scattering – 27.7keV resonance.)
- ^{nat}Pb and ^{nat}C for background determination.



∅ 70 mm x 1mm high purity ^{56}Fe. Courtesy of C. Paradela, GELINA and A. Negret/M. Boromiza, IFIN (Romania)

Detector set-up



- 4 C_6D_6 detectors at 125° to the beam line – low efficiency for neutron detection
- Carbon fiber shell - reduction in scattered-neutron capture in Al body
- Frequent calibration with the full range of gamma sources (4 times - Ba^{133}, Cs^{137}, Y^{88}, AmBe, CmC)
- Immediate measurement of Au^{197} following calibration

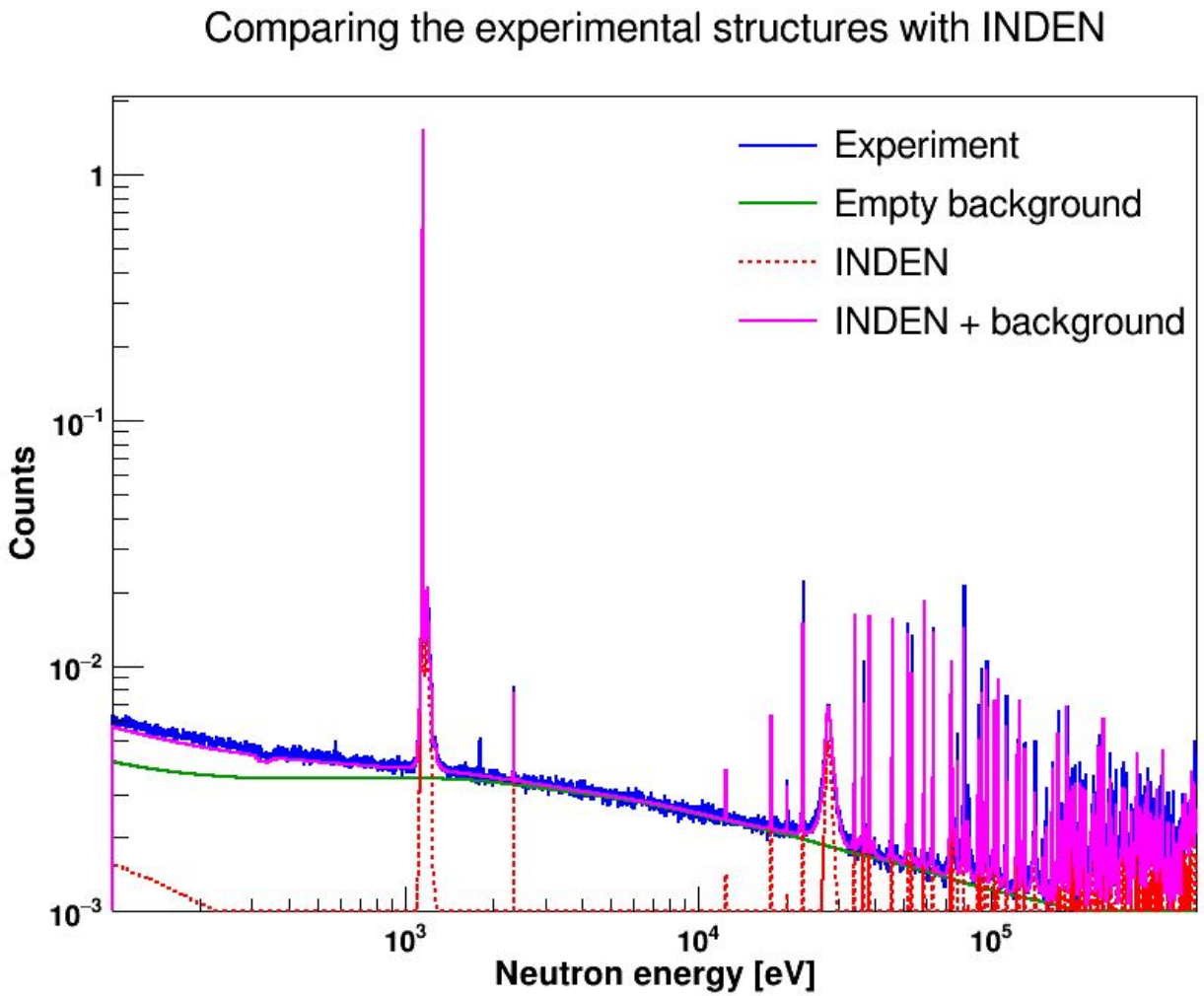
The campaign: protons and the beam

- Month-long beam-time at EAR1
- Thinner ^{nat}Fe sample: Multiple scattering effects
- Au^{197}: normalization
- Empty: Beam on background
- Measurements with high energy neutron filters
- Stable beam, frequent calibrations.
- Measurement of ^{nat}Pb, ^{nat}C for background estimation

Thanks to high-intensity beam from the PS, the campaign surpassed the planned number of protons.

Capture			
	Planned	**Measured**	%
56Fe	1.40E+18	1.56E+18	111.77%
natFe	6.00E+17	5.18E+17	86.26%
Au	1.00E+17	8.13E+16	81.29%
Ag	5.00E+16	2.01E+16	40.22%
Empty	2.00E+17	1.814E+17	90.69%
56Fe Al filters	1.50E+17	1.50E+17	99.83%
56Fe S filter	1.50E+17	1.37E+17	91.60%
56Fe Bi filter	1.50E+17	1.65E+17	109.68%
Empty Filter S	5.00E+16	1.20E+17	240.88%
Empty Filter Bi	5.00E+16	6.87E+16	137.43%
Empty Al filters	5.00E+16	8.35E+16	166.92%
natC	1.00E+17	9.95E+16	99.52%
natPb	1.00E+17	8.57E+16	85.67%
Total	**3.15E+18**	**3.27E+18**	**103.96%**
Total proposal	**3.00E+18**		

First look at the capture data: Comparing structures to INDEN

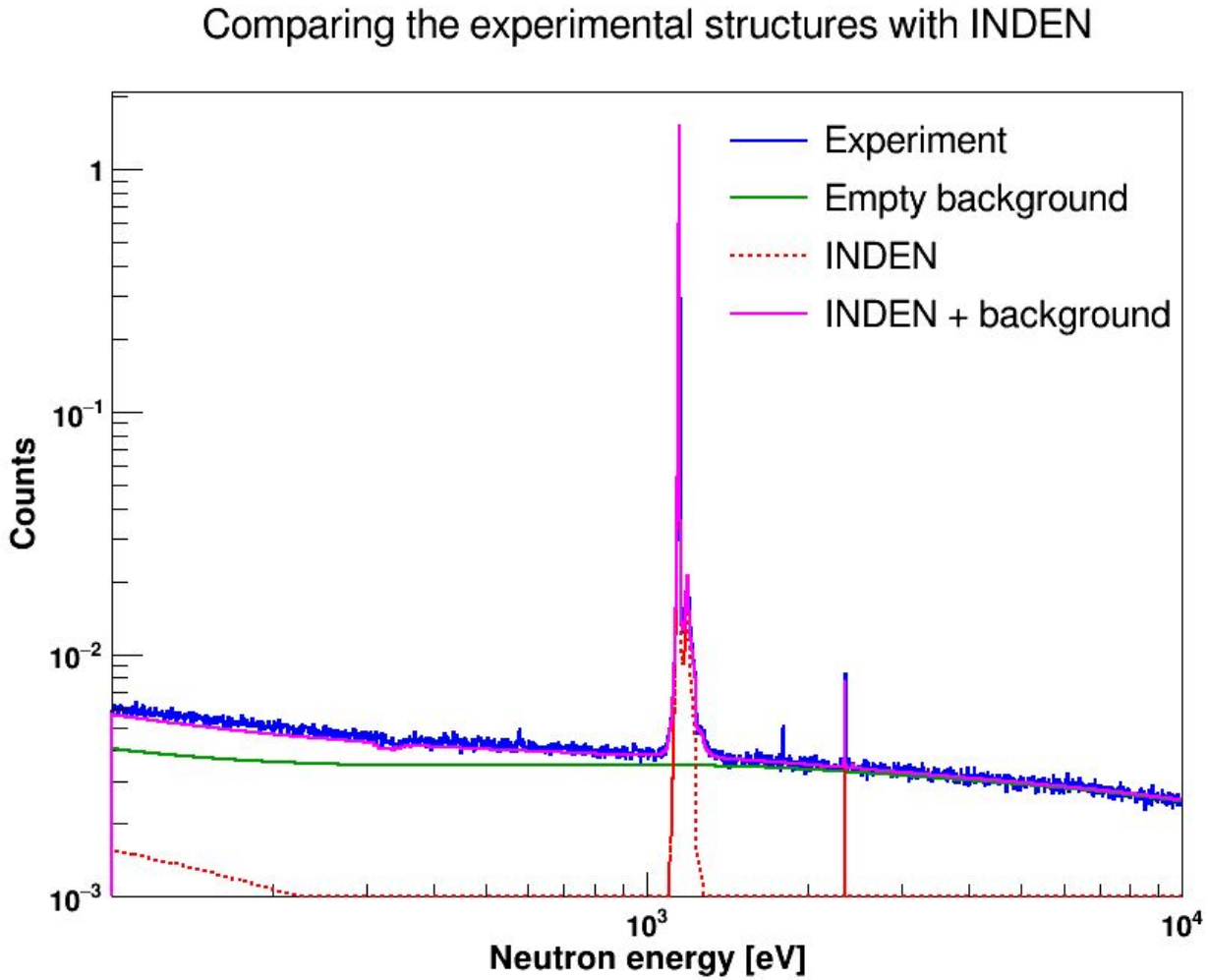


- Non-relativistic approximation for tof-energy conversion.
- Deposited energy threshold - 140 keV
- Calibration with sources and Geant4 simulation of energy deposition in the detectors.
- Fe^{56} structures clearly recognizable.
- Experimental empty background scaled to 1.8x
- Limiting to comparison of structures for the preliminary look.

Preliminary calculations

First look at the capture data: the 1.15 keV resonance

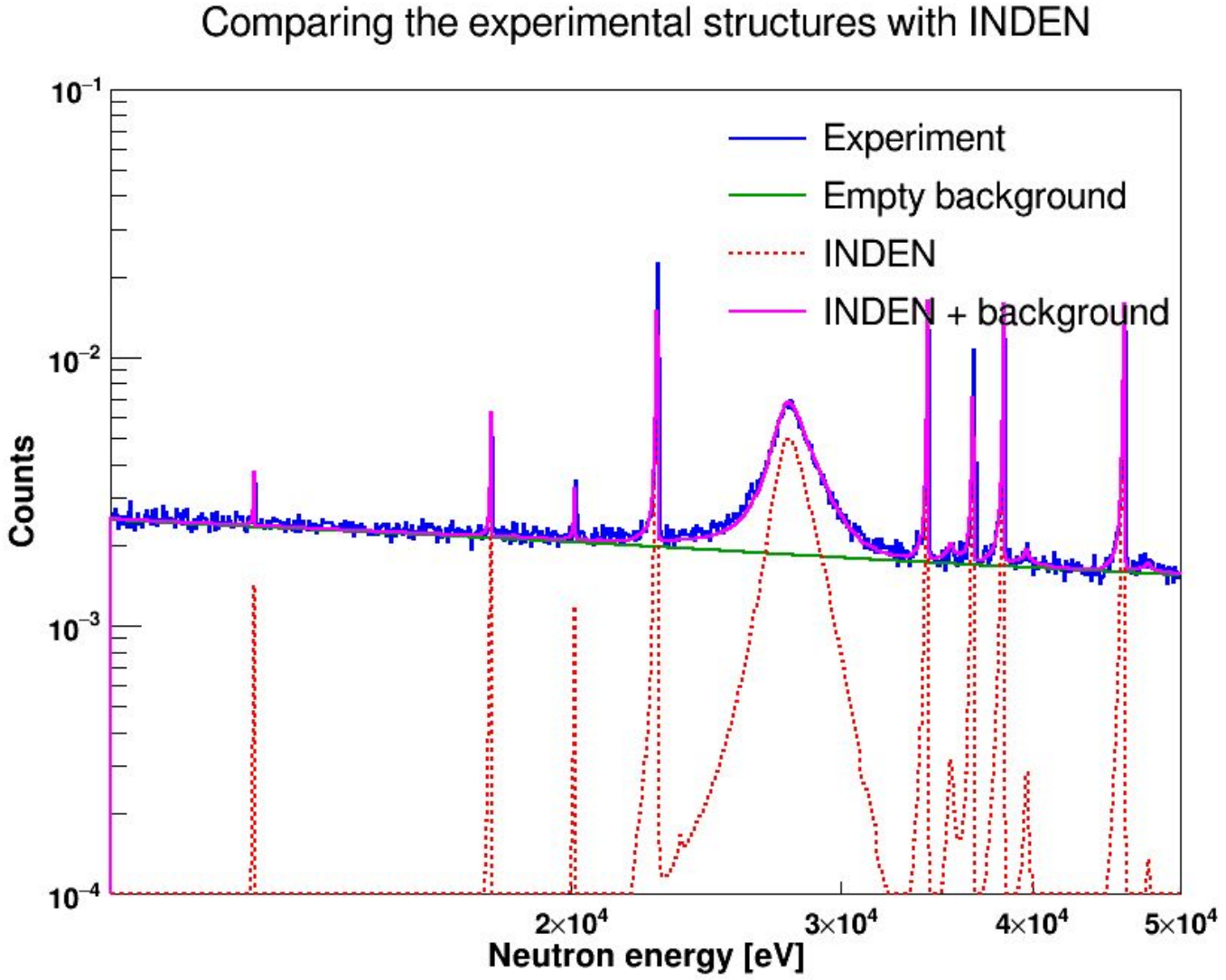
- Experimental background added to the SAMMY counting rate estimate of INDEN data for a first look at the structures.
- First resonance at 1.15 keV clearly marked and in agreement with the evaluation.



Preliminary calculations

First look at the capture data: Around the 27.7 keV s-wave

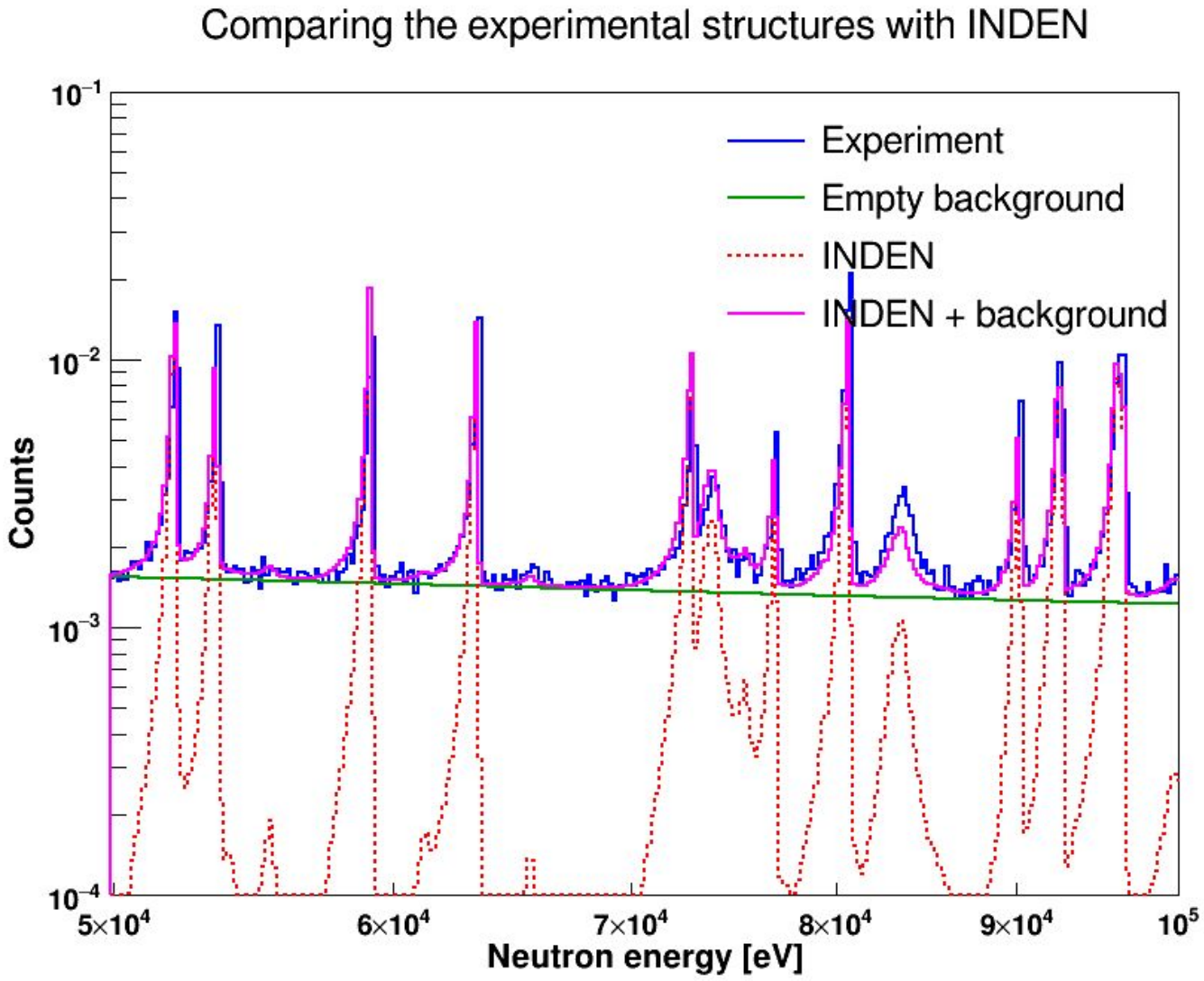
- Resonances between 10 keV and 50 keV.
- s-wave and other nearby resonance positions in agreement with INDEN.



Preliminary calculations

First look at the capture data: Around the 27.7 keV s-wave

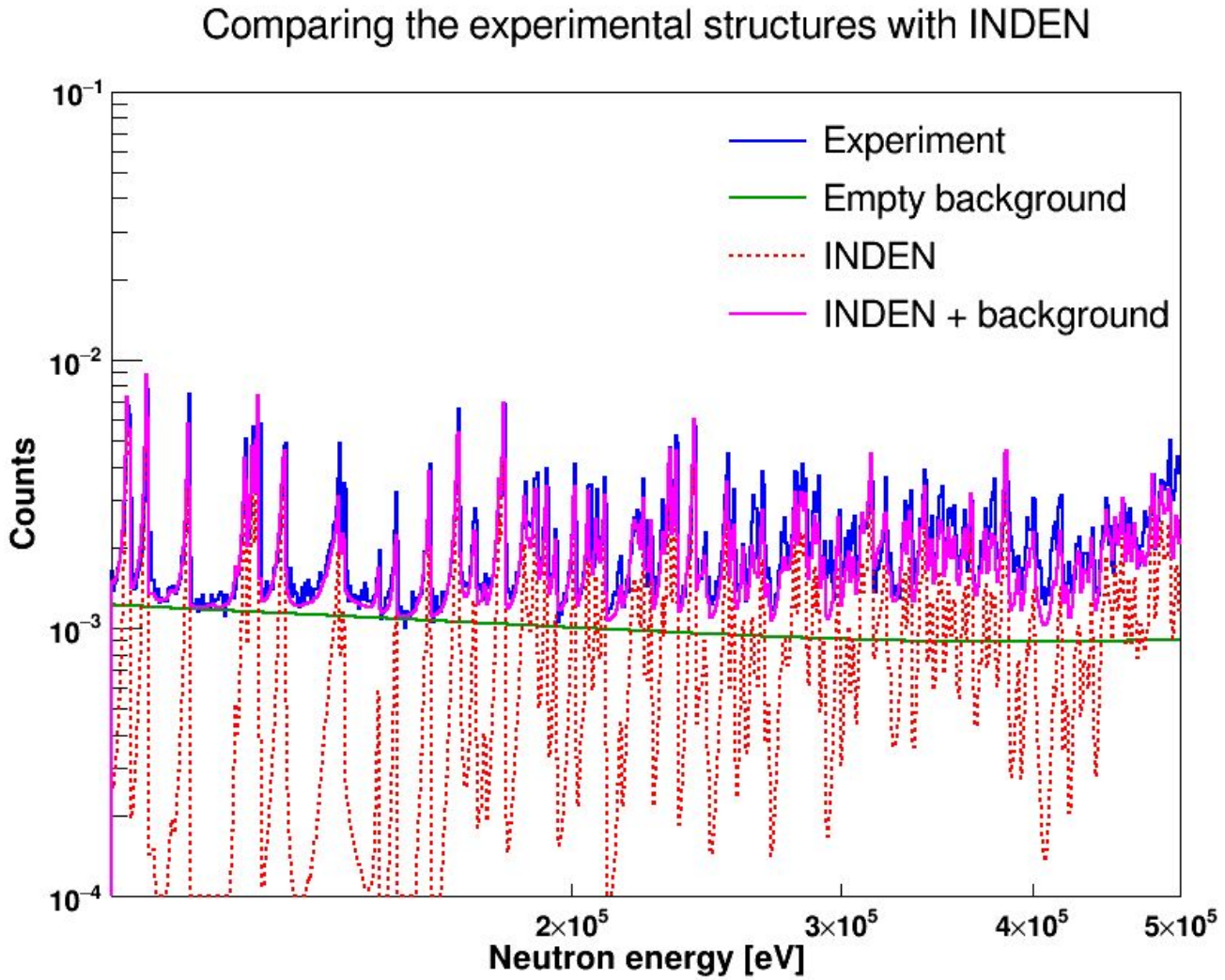
- Resonances between 50 keV and 100 keV.



Preliminary calculations

First look at the capture data: Around the 27.7 keV s-wave

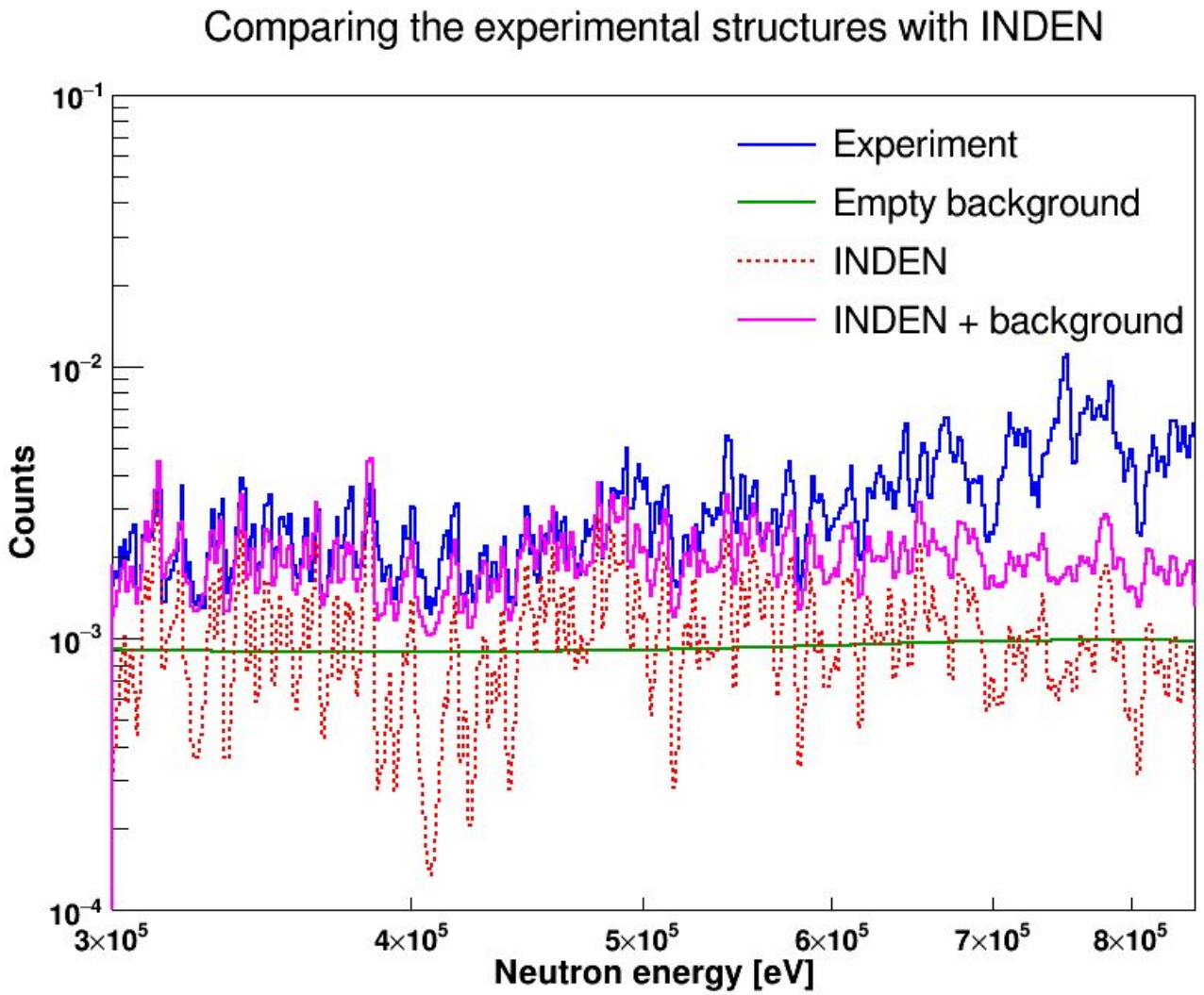
- Resonances between 100 keV and 500 keV.
- A first look shows a general good agreement.



Preliminary calculations

First look at the capture data: Other resonances (upto 500keV)

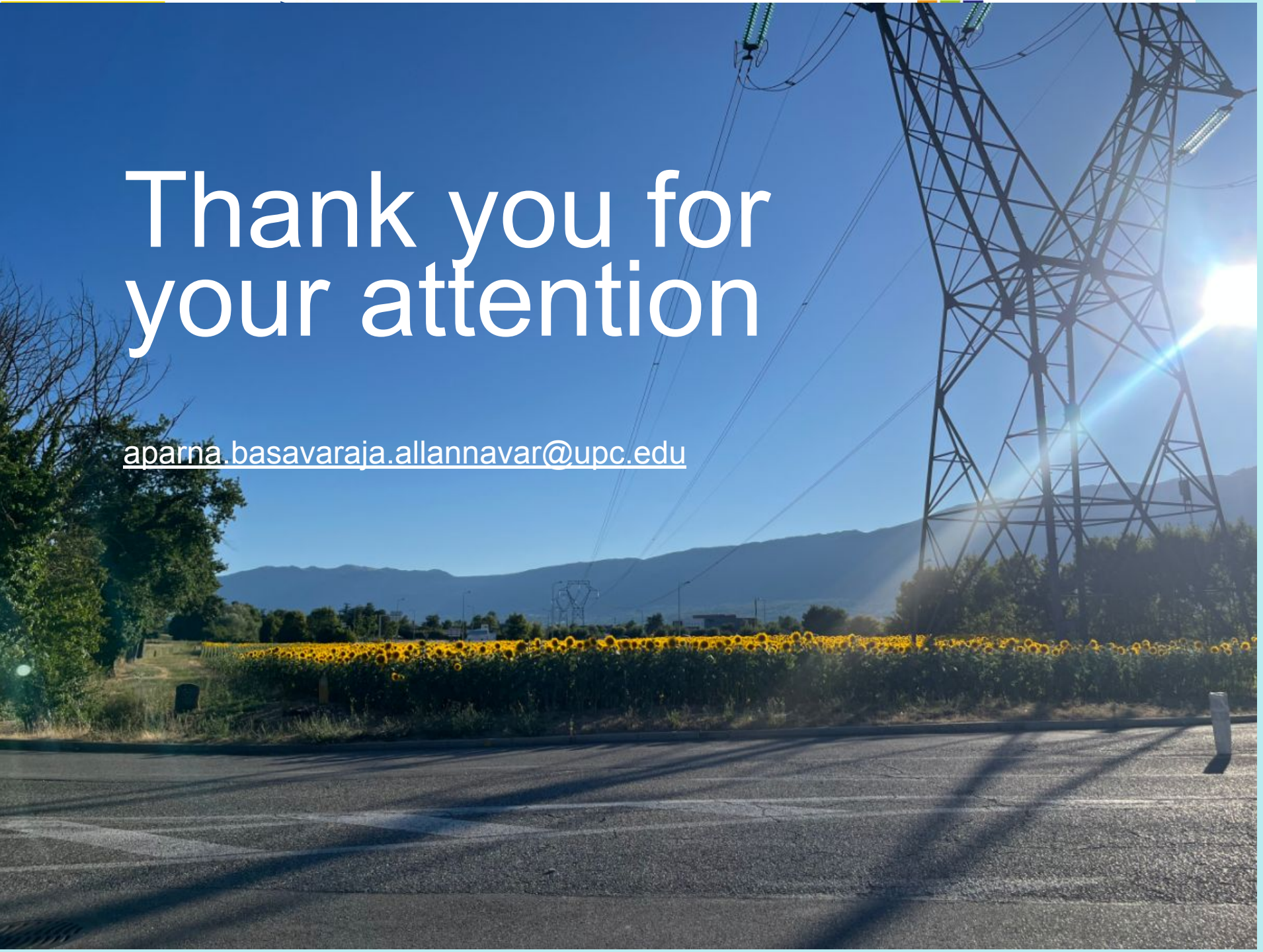
- Resonances in 300 keV - 850 keV.
- Plan to explore higher energy deposition threshold to obtain some average cross-section above 500 keV.



Preliminary calculations

Conclusions

- Measurement of Fe^{56} (n, gamma) reaction at CERN's n_tof with high a purity sample.
- Analysis to produce resolved resonances upto 500 keV; average cross-sections beyond 500 keV.
- Initial investigation into the structures of resonances in counts reveal good agreement with the latest evaluated resonance structures.



Thank you for your attention

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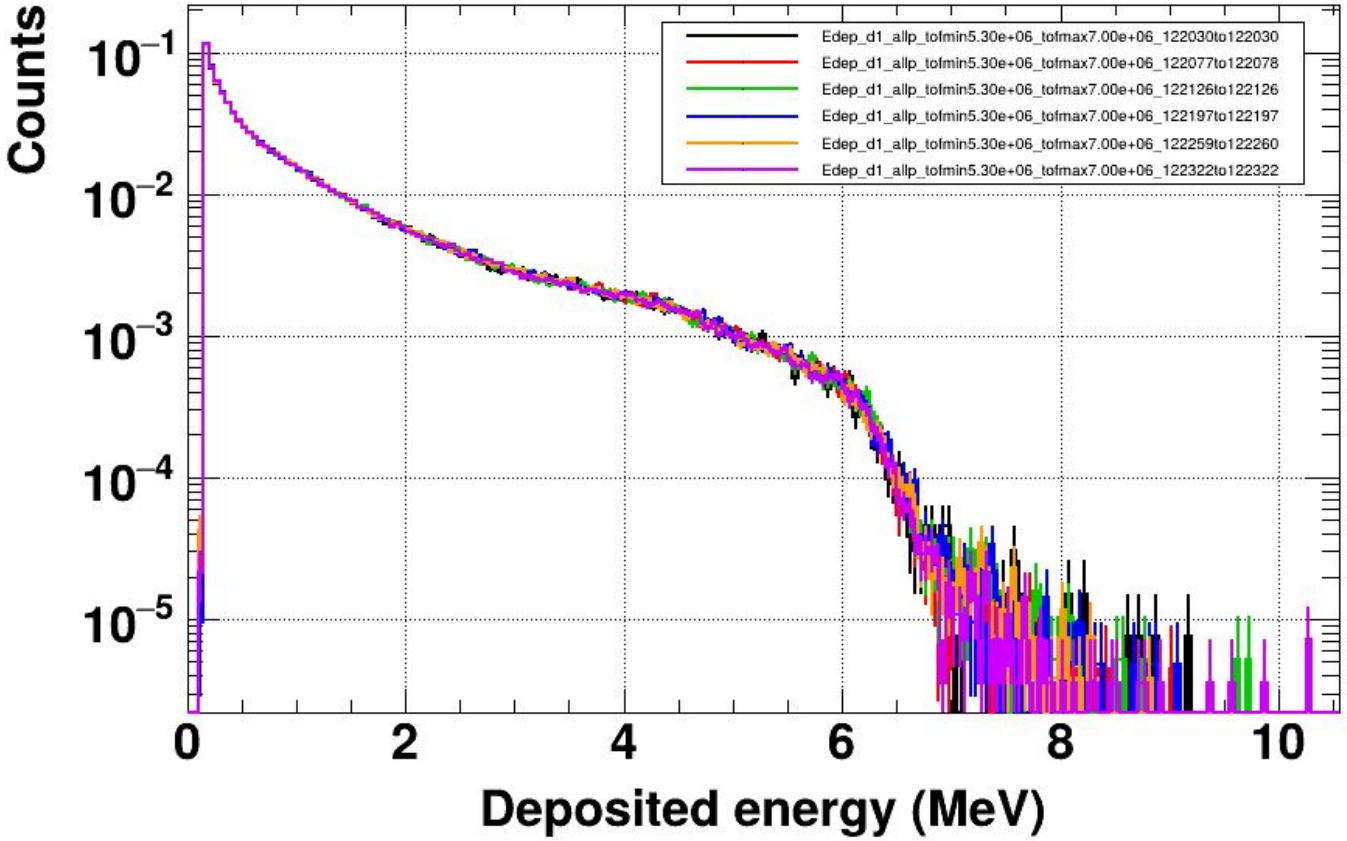
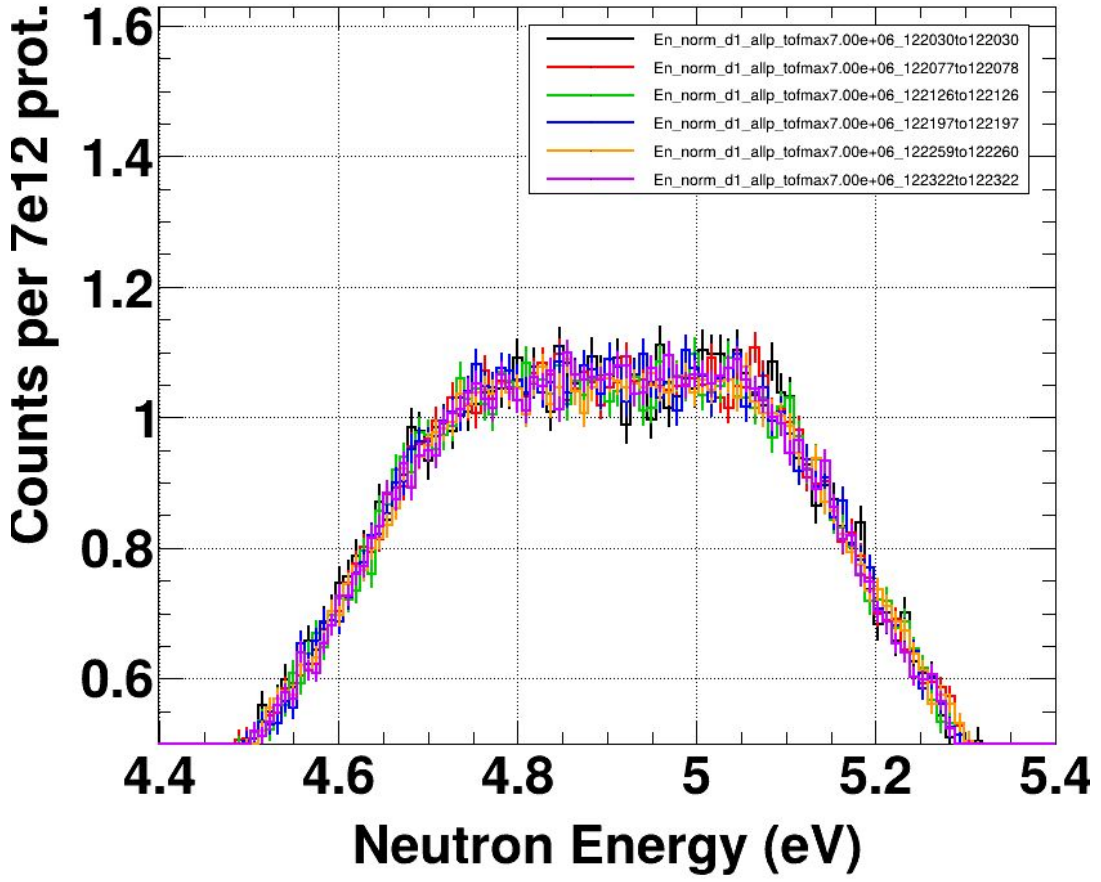
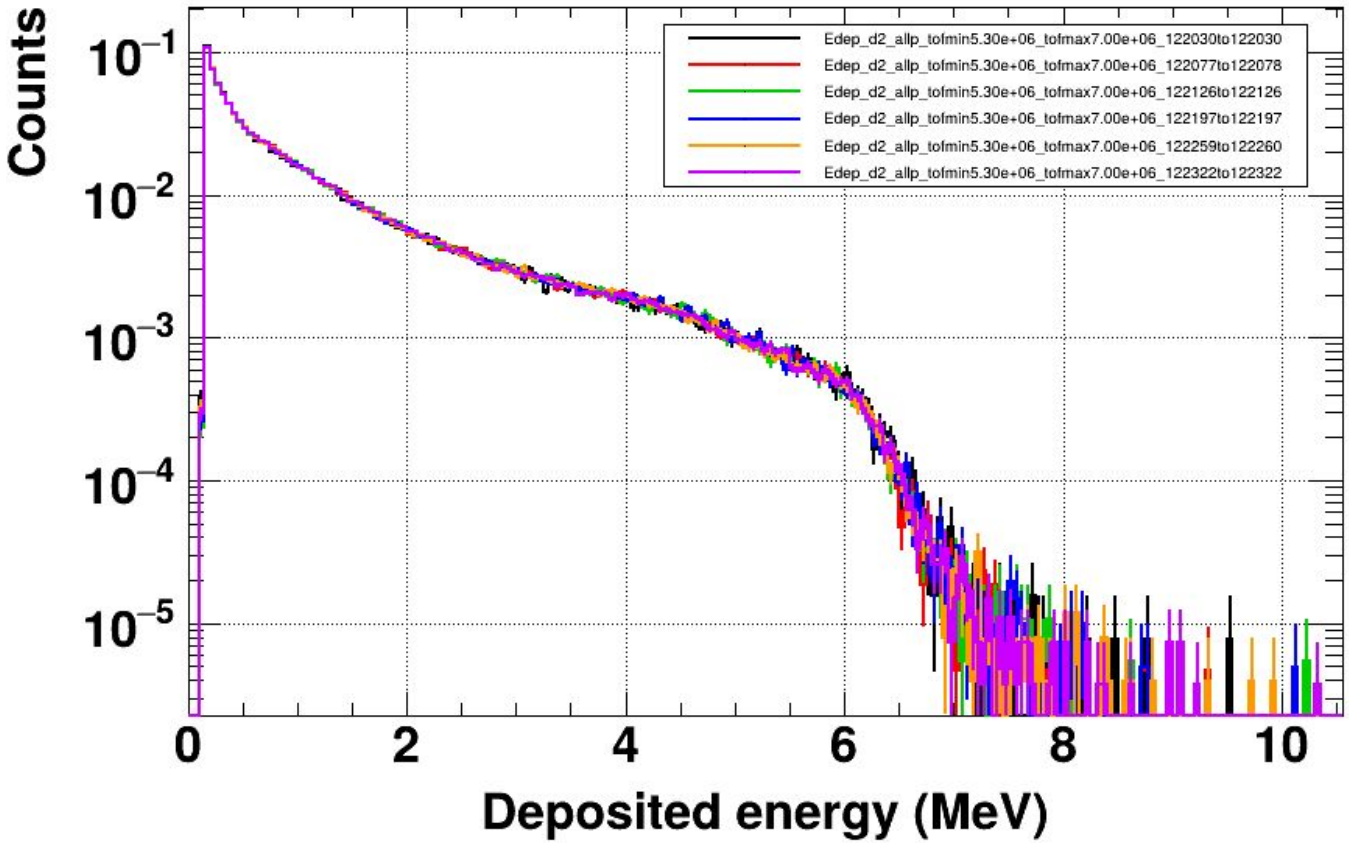
Funded by the European Union NextGenerationEU

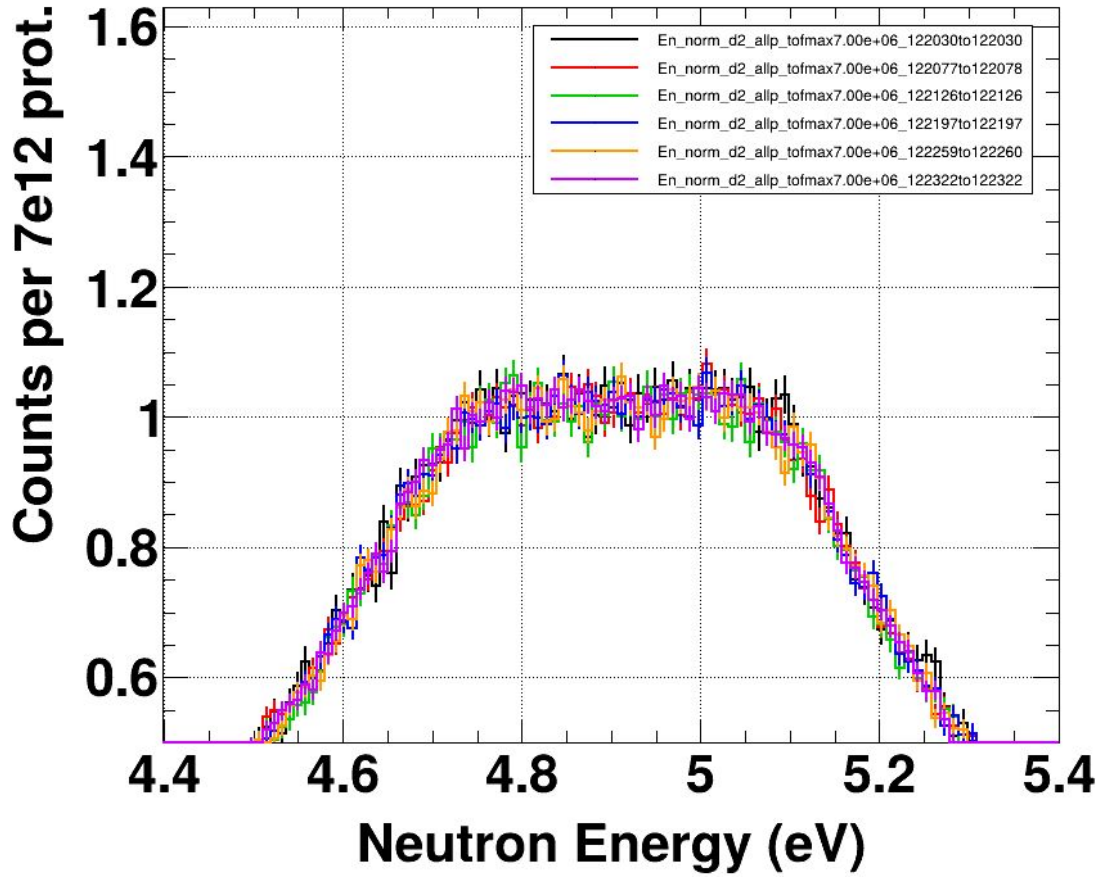
- ^{197}Au measurements distributed along the campaign
- Det #1



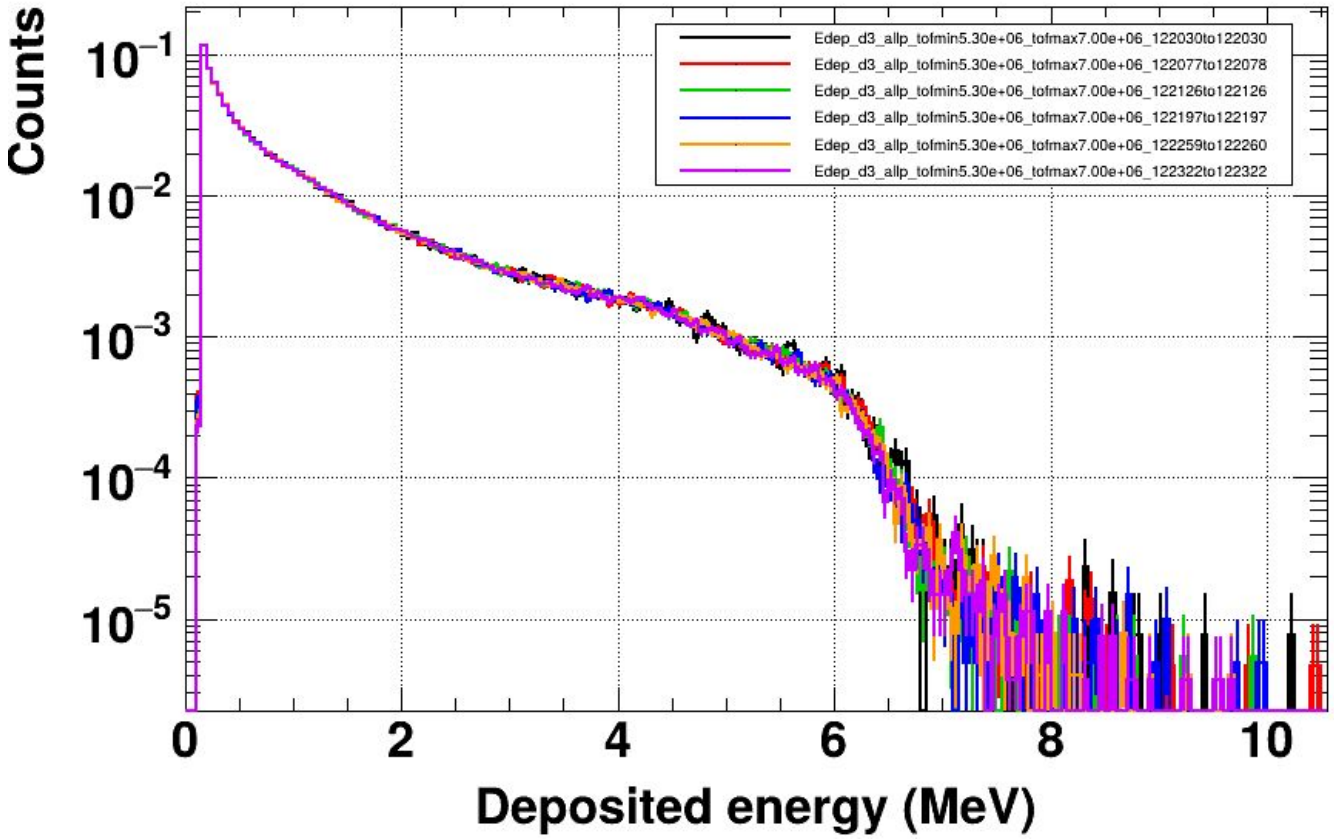


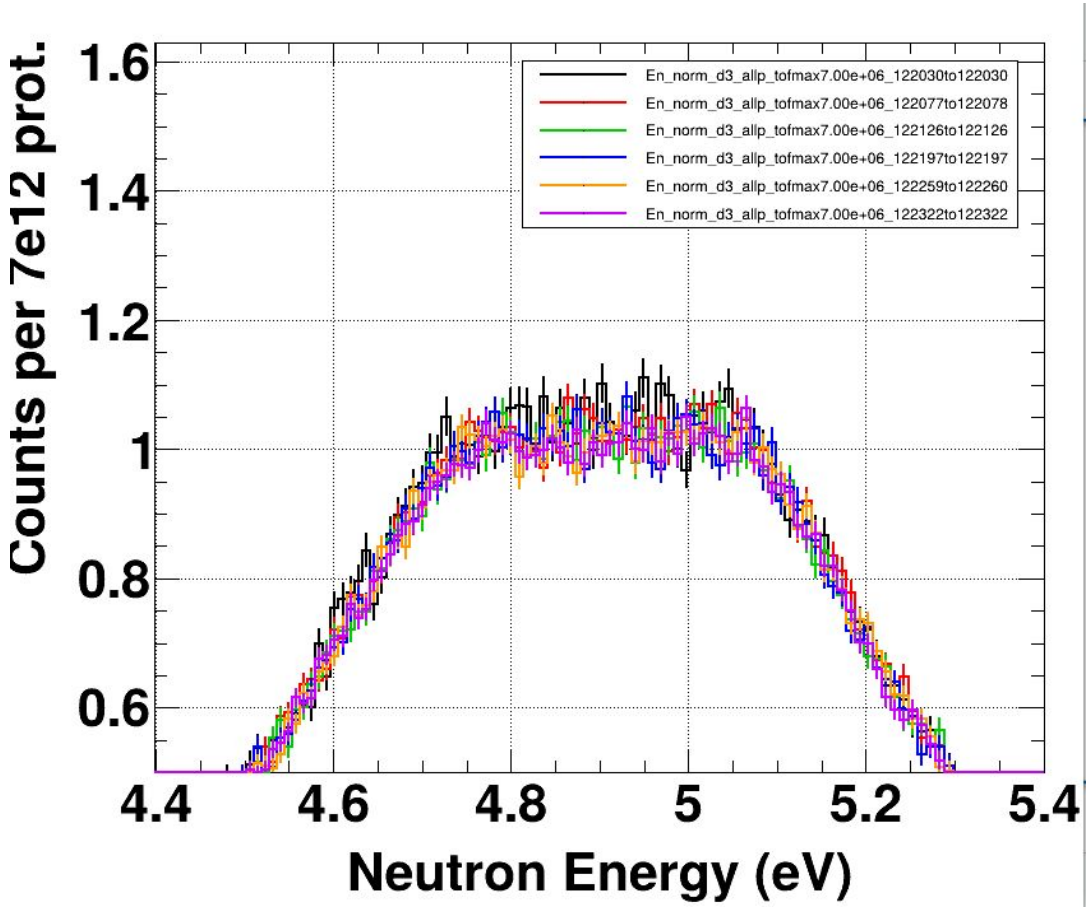
- ^{197}Au measurements distributed along the campaign
- Det #2





- ^{197}Au measurements distributed along the campaign
- Det #3





- ^{197}Au measurements distributed along the campaign
- Det #4