Proposal INTC-P-721 to the ISOLDE and Neutron Time-of-Flight Committee

New high-resolution measurement of ^{56}Fe(n,γ) at n_TOF EAR1 for Astrophysics and Nuclear Technology

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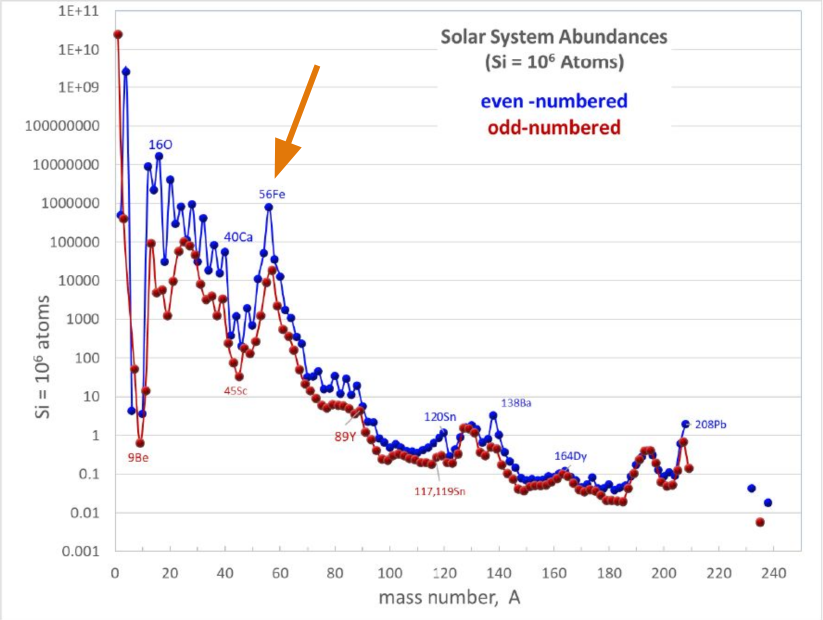
Motivations

- **Astrophysics**: ^{56}Fe (91.75% of ^{nat}Fe) is the last isotope produced (indirectly) by fusion in the core of massive stars
- 6th most abundant element in the Universe, seed of the s-process of stellar nucleosynthesis

- **Nuclear technology**: As the main component of steel, iron is a fundamental structural material for nuclear technology, knowledge of neutron interactions is crucial
  - Example: Importance of RRR data highlighted in sensitivity analysis for MYRRHA (Romojaro et al., An. of Nucl. Ene. 101 (2017) 330-338)
  - New evaluations by CIELO (2017, NEA) and INDEN (2023, IAEA) projects

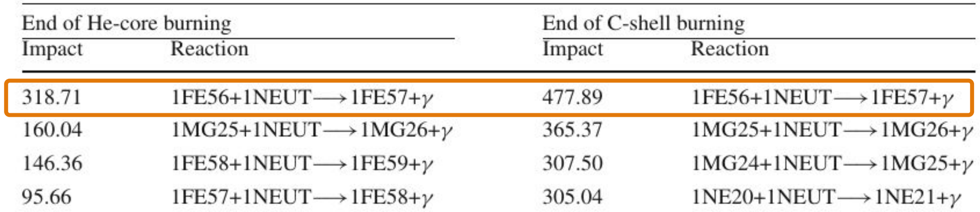


From Lodders, K. 2020, Solar Elemental Abundances, in The Oxford Research Encyclopedia of Planetary Science, Oxford University Press

^{56}Fe(n,γ) uncertainty impact in *weak* s-process

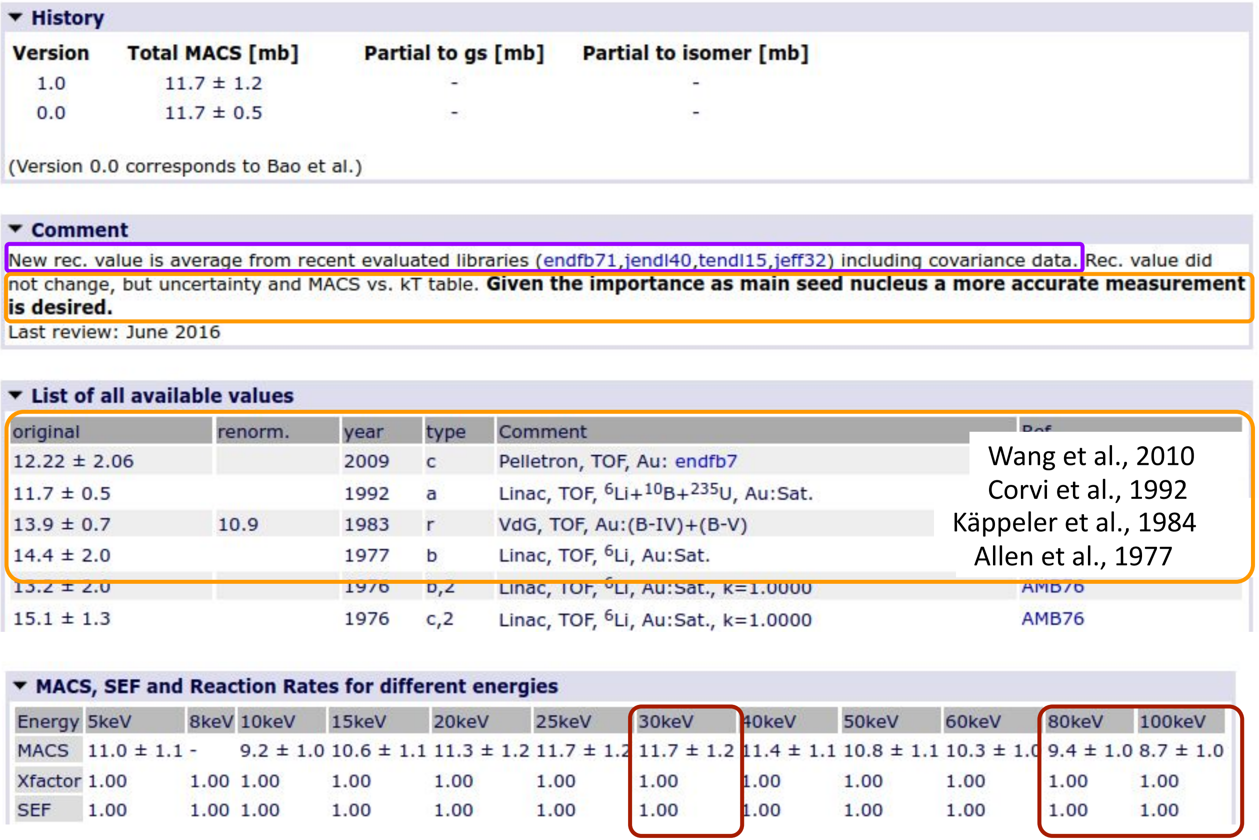
- Recent sensitivity study by **Pignatari et al. (Eur. Phys. J. A (2023) 59:302)** in Massive Stars ($\gtrsim$ 10 $M_\odot$) show the extensive impact of ^{56}Fe(n,γ) in overall weak s-process production (Fe to Sr)
  - 30% (n,γ) rate variation

- Local Equilibrium conditions not reached during weak s-process ⟶ **strong propagation effect**
- Due to its high abundance, **^{56}Fe acts as seed but also as a powerful “competitor”** for neutrons



End of He-core burning		End of C-shell burning	
Impact	Reaction	Impact	Reaction
318.71	1FE56+1NEUT⟶1FE57+γ	477.89	1FE56+1NEUT⟶1FE57+γ
160.04	1MG25+1NEUT⟶1MG26+γ	365.37	1MG25+1NEUT⟶1MG26+γ
146.36	1FE58+1NEUT⟶1FE59+γ	307.50	1MG24+1NEUT⟶1MG25+γ
95.66	1FE57+1NEUT⟶1FE58+γ	305.04	1NE20+1NEUT⟶1NE21+γ

Status of ^{56}Fe(n,γ) Maxwellian-average cross section (MACS)



History

Version	Total MACS [mb]	Partial to gs [mb]	Partial to isomer [mb]
1.0	11.7 ± 1.2	-	-
0.0	11.7 ± 0.5	-	-

(Version 0.0 corresponds to Bao et al.)

Comment

New rec. value is average from recent evaluated libraries (endfb71,jendl40,tendl15,jeff32) including covariance data. Rec. value did not change, but uncertainty and MACS vs. kT table. **Given the importance as main seed nucleus a more accurate measurement is desired.**
Last review: June 2016

List of all available values

original	renorm.	year	type	Comment	Ref
12.22 ± 2.06		2009	c	Pelletron, TOF, Au: endfb7	
11.7 ± 0.5		1992	a	Linac, TOF, ^{6}Li+^{10}B+^{235}U, Au:Sat.	
13.9 ± 0.7	10.9	1983	r	VdG, TOF, Au:(B-IV)+(B-V)	
14.4 ± 2.0		1977	b	Linac, TOF, ^{6}Li, Au:Sat.	
13.2 ± 2.0		1976	b,2	Linac, TOF, ^{6}Li, Au:Sat., k=1.0000	AMB76
15.1 ± 1.3		1976	c,2	Linac, TOF, ^{6}Li, Au:Sat., k=1.0000	AMB76

Wang et al., 2010
Corvi et al., 1992
Käppeler et al., 1984
Allen et al., 1977

MACS, SEF and Reaction Rates for different energies

Energy	5keV	8keV	10keV	15keV	20keV	25keV	30keV	40keV	50keV	60keV	80keV	100keV
MACS	11.0 ± 1.1	-	9.2 ± 1.0	10.6 ± 1.1	11.3 ± 1.2	11.7 ± 1.2	11.7 ± 1.2	11.4 ± 1.1	10.8 ± 1.1	10.3 ± 1.0	9.4 ± 1.0	8.7 ± 1.0
Xfactor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SEF	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Entry in KaDoNiS v1.0 database, reference for nucleosynthesis calculations

Assumption of 20% uncertainty in the 30 and 90 keV reasonable

^{56}Fe(n,γ) uncertainty impact in *weak* s-process

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  - 30% (n,γ) rate variation

End of He-core burning		End of C-shell burning	
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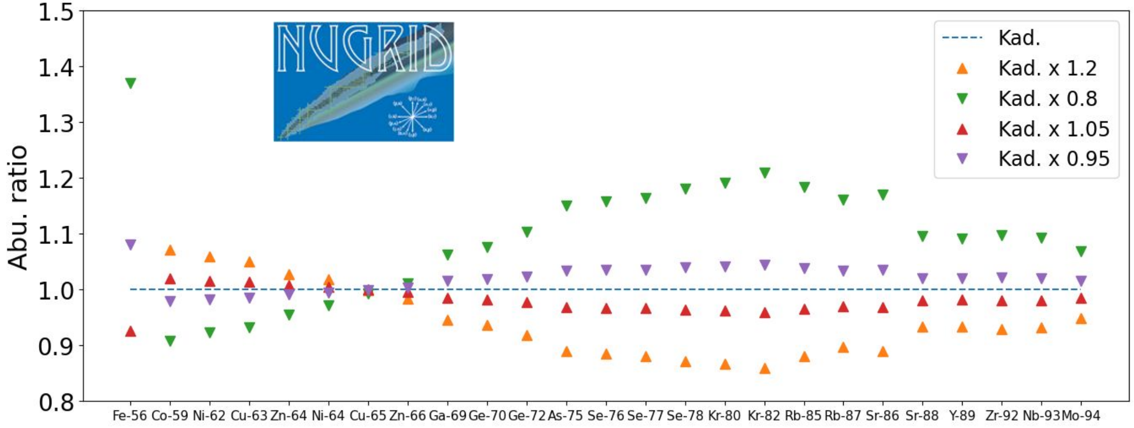
95.66	1FE57+1NEUT$\longrightarrow$1FE58+γ	305.04	1NE20+1NEUT$\longrightarrow$1NE21+γ

- Local Equilibrium conditions not reached during weak s-process → **strong propagation effect**
- Due to its high abundance, **^{56}Fe acts as seed but also as a neutron "competitor"**
- Example: Single-zone post-processing with NuGrid-PPN of a 25 $M_\odot$, $Z=Z_\odot$ star thermo. trajectory comprising H-burning and He-burning core, and C-burning shell
- Main neutron source: ^{22}Ne(α,n)^{25}Mg activated during **He-burning core (kT~30 keV)** and **C-burning shell (kT~90 keV)**



A new high-resolution measurement of the ^{56}Fe(n,γ) is highly desirable to reduce the uncertainty in the MACS for weak s-process calculations

^{56}Fe(n,γ) in nuclear data evaluations

- **The evaluation from the INDEN network (2023) is the most recent. From the dataset description:**
  - "The resonance range was **adopted from the JEFF-3.1 (=JEFF-3.3)**. The Gg of the 27.7keV resonance is 30% lower than in CIELO evaluation as proposed by Froehner (1995). "
  - "Resolved resonance range up to 850 keV basically **from JENDL-4.0** (Froehner evaluation for JEF-2-2)"

JEF-2.2 published
in April 2000

- **ENDF/B-VIII.0 and recent (Sep. 24) ENDF/B-VIII.1 eval. files are based on CIELO 2017 evaluation.**

Parameters were evaluated by Froehner's for JEF-2-2 but were taken from JENDL-4.0.

- Between 500 and 850 keV, background cross sections were applied to the elastic and capture cross sections to account for the missing resonances.

The following changes were done compared to JENDL-4.0:

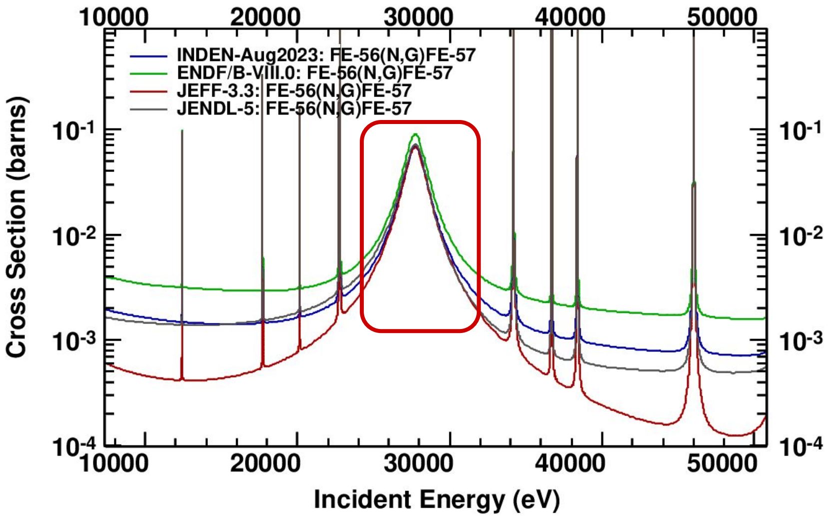
- Removed spurious p-wave resonance at 59.8 keV
- Background reduced by 40% (capture, elastic)

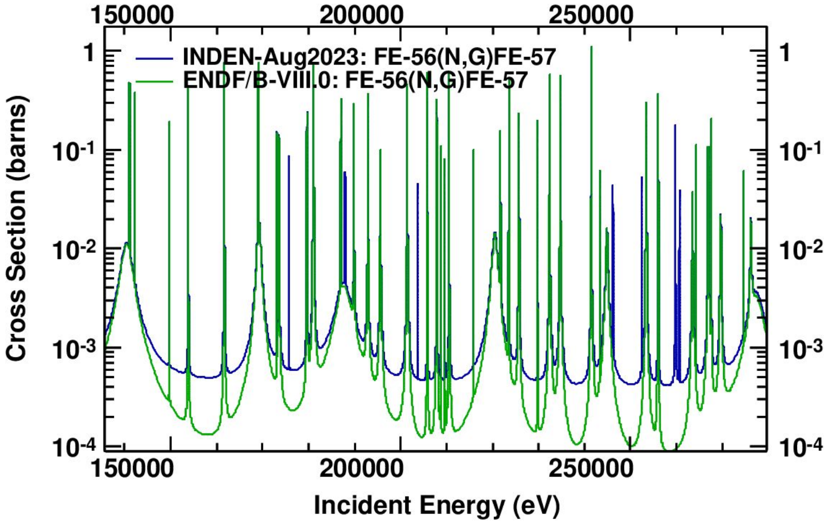
The difference was assigned to the elastic.

- Corrected resonance energy 7.67240+5 to 7.667240+5 eV
- **Between 10 eV and 100 keV background was added to capture to make the cross section approximately follow the 1/v behaviour.**

^{56}Fe(n,γ) in nuclear data evaluations

- Few but relevant discrepancies between INDEN and CIELO (ENDF/B-VIII.0)





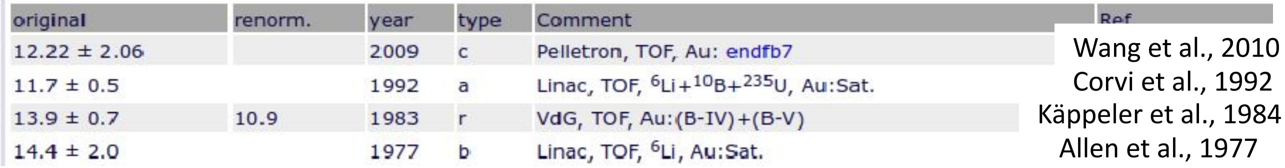
INDEN Γ_γ of 27.7 keV s-wave **reduced by 30%** compared to CIELO (still adopted in ENDF/B-VIII.1)

MACS:

	8 keV	30 keV	90 keV
CIELO (ENDF8)	9.70	12.15	8.60
INDEN	8.98	11.60	8.86
diff	-7.5%	-4.5%	+3%

Status of the data: previous measurements

- **Allen et al. (1977) at ORELA 40 m line**, C_6F_6 detectors, very thick target (0.041 at/b) + “thin” target (0.0082 at/b)
  - Resonance kernel information up to ~900 keV, Γ_γ for s-waves
  - **“The radiative width of the 27.7 keV resonance was not obtained from our data because of the large prompt background and multiple scattering corrections”**
- **Trans. by Perey et al. (1991) at ORELA, 200 m line**: RRR analysis up to 850 keV (Parameters up to 350 keV, including data from Corvi 1984)
- **Capture by Corvi et al. (1992) at GELINA (58 m line):** Capture data with two C_6D_6 detectors, **very thick oxide sample (0.015 at/b)** (RRR up to 300 keV)
  - neutron sensitivity $\varepsilon_n/\varepsilon_\gamma$ estimated to ($1.5\pm0.75 \times 10^{-4}$)
  - MS corrections could have been an issue in 27.7 keV resonance
- **Status of high-resolution experimental data not changed since last n_TOF proposal (INTC/P-208, 2006)**
  - Wang et al. 2010 is Li(p,n) promt g-rays detection, **limited E_n range 10 to 90 keV in bins of 10 to 45 keV**
  - Reported MACS 5% higher than Kadonis, 20% uncertainty



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14.4 ± 2.0		1977	b	Linac, TOF, ^{6}Li, Au:Sat.	Allen et al., 1977

Previous measurements: Corvi et al., 1992

- 1992 Corvi et al. data in the RRR extends **up to 300 keV**
- Data was taken in 1982, re-analyzed taking into account **new experimental WF obtained in 1991** (Corvi et al. Nucl. Sci. Eng. 107 (1991) 272) by (p,g) reactions on light targets to solve issue with 1.15 keV ^{56}Fe resonance
- The issue of the WF (quote): *"By comparing the present results to those obtained with the same data set but with the old WF,* ***one may note that the capture areas have varied by a relative amount going from -10% to +5%****. For each resonance the amount and the sign of this variation should be related to the shape of its capture spectrum"*

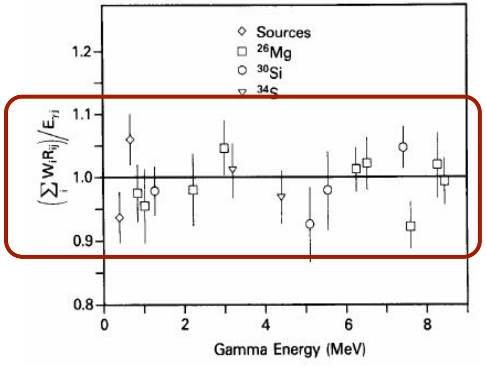


Fig. 5. Values of the ratios

$$r_j = \left(\sum_{i=4}^{200} W_i R_{ij}\right)\Big/E_{\gamma j}$$

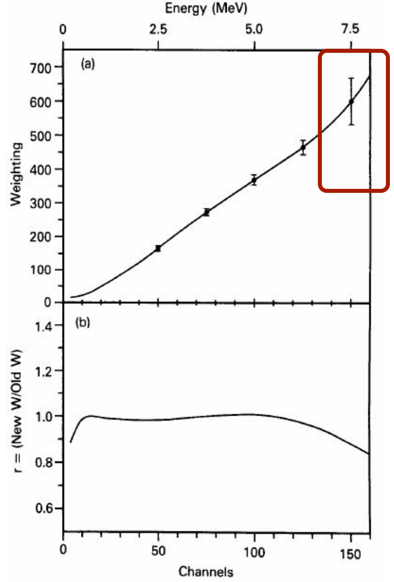
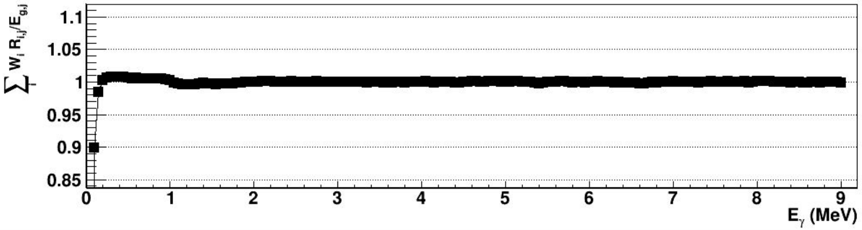


Fig. 6. (a) The weighting function W determined here plotted against the pulse height and (b) the ratio of the W determined here to the one determined in Ref. 5, normalized to unity at 1 MeV.

- Method shown to have limitations (particularly at high E_γ) in the WF n_TOF paper (Abbondanno et al., NIM-A 521 (2004) 454–467)
- Part of ^{54,56,57}Fe(n,γ) campaign at n_TOF in 2009-10 (Taín et al., CERN-INTC-2006-012)

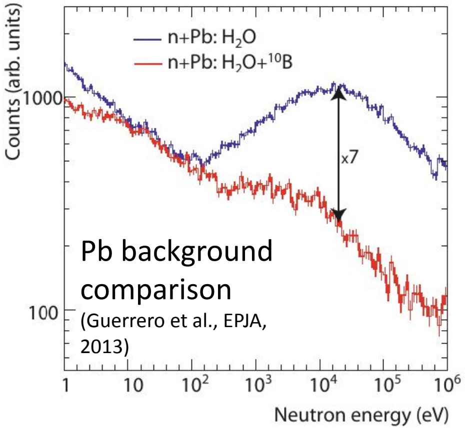
Geant4 calculated WF



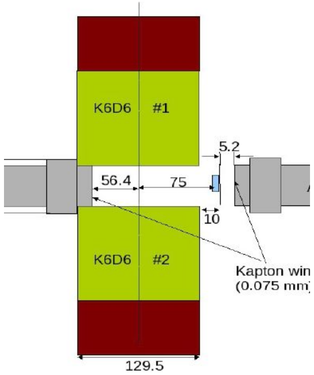
Some details about the 2009 ^{56}Fe(n,γ) measurement at EAR1*

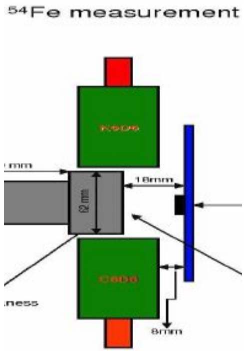
- Conducted in Ph.2, with **non-borated** moderator: in beam **g-rays effect quite apparent** (same samples thickness), probably also enhanced due to short distance of the detectors to beam

- Other issues important issues:
  - low statistics (10^{18} protons on ^{56}Fe target)
  - large detector gain drifts

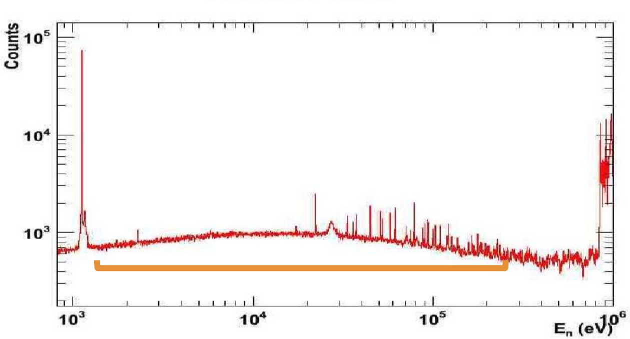


Pb background comparison
(Guerrero et al., EPJA, 2013)

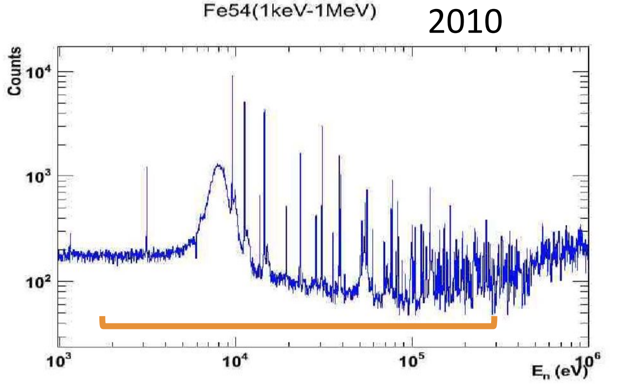




2009



2010

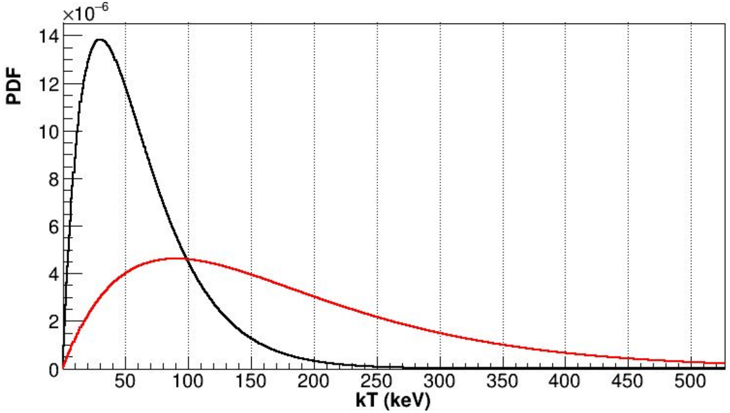


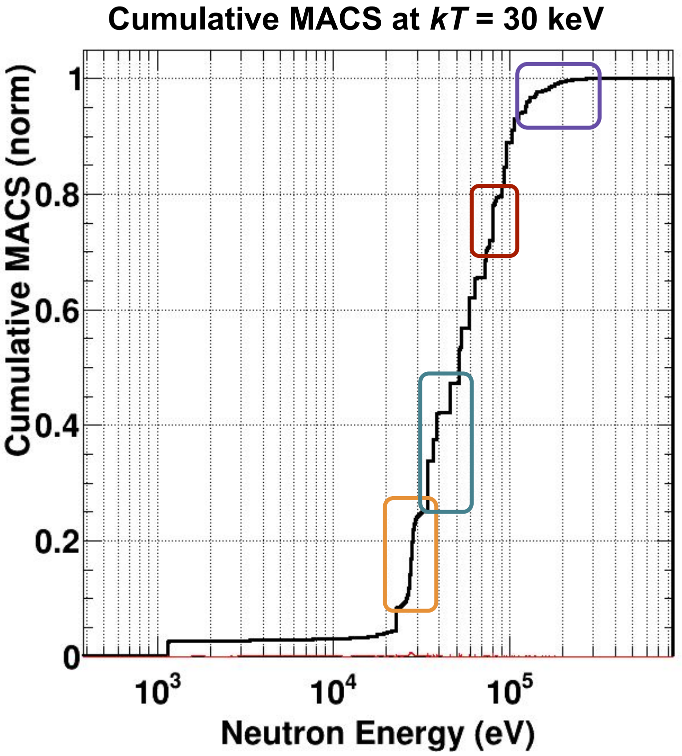
*From G. Giubrone talks at n_TOF meetings, 2010-2012

Requisites for new dataset: cumulative MACS review: 30 keV

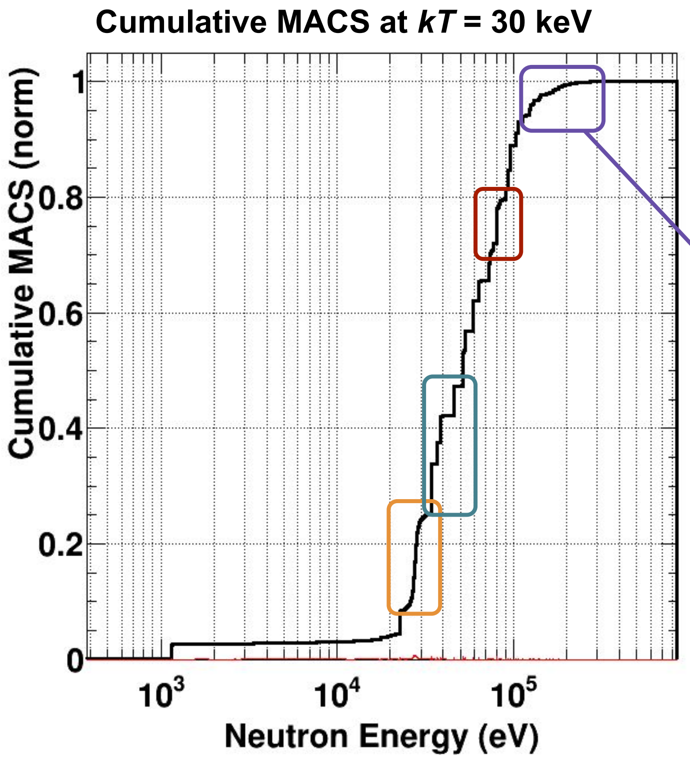
- **90% ^{56}Fe(n,γ) MACS achieved by ~100 keV, 99% by 200 keV**
- 2.5% contribution by the 1.15 keV, **17% by 27.8 keV broad s-wave (Γn/Γγ~1520)**
- 4% by 22.8 keV
- **17% combined by 32.4, 36.7, 38.4 keV**
- between 40 keV and 90 keV: individual resonances 5-7% (d-wave at 80.8 keV), **40% in total**

MB 30 keV and 90 keV dist.





Requisites for new dataset: cumulative 30 keV MACS



- **90% MACS achieved by ~100 keV, 99% by 200 keV**
- 2.5% contribution by the 1.15 keV, **17% by 27.8 keV broad s-wave (Γn/Γγ~1520)**
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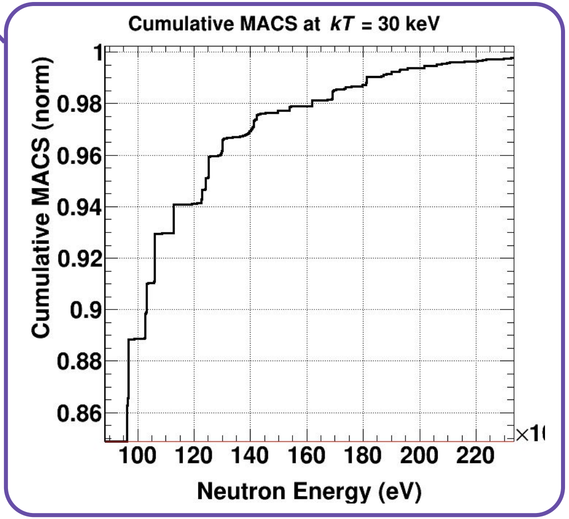
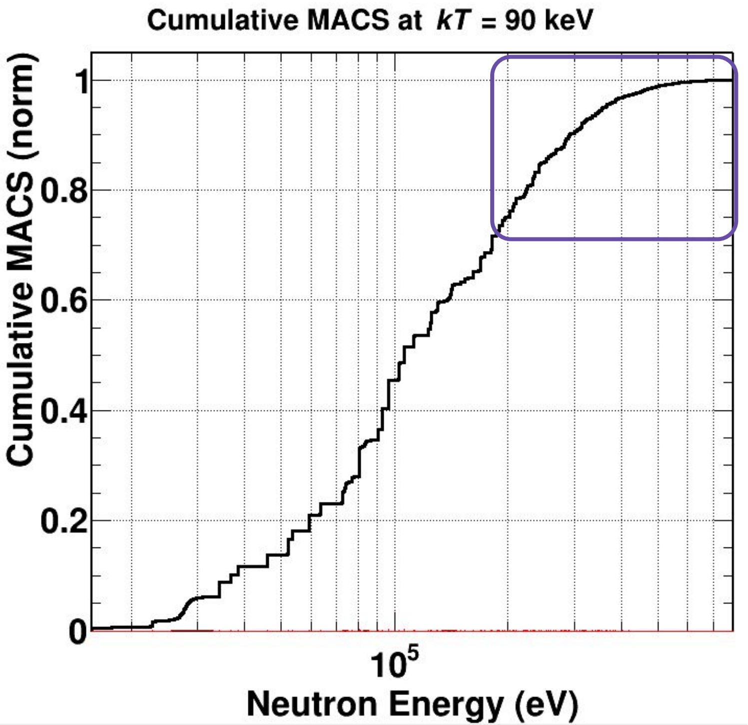


Aim is to achieve a ~**5-6% total uncertainty for the MACS at 30 keV**

Requisites for new dataset: cumulative 90 keV MACS



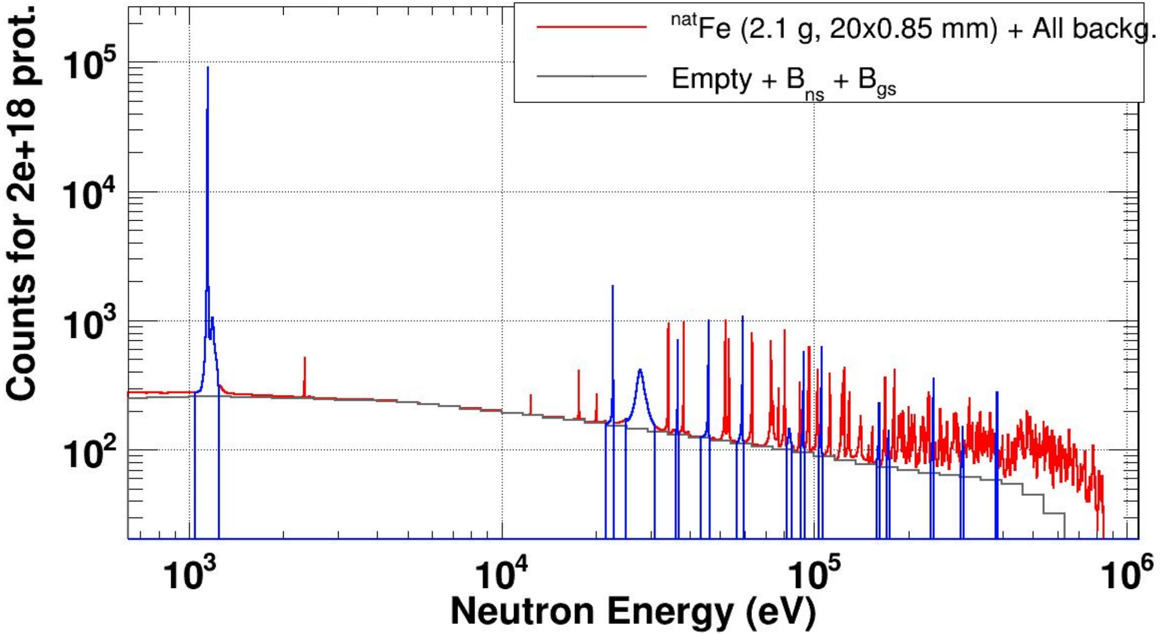
- **80% MACS achieved by ~220 keV, 90% by 300 keV**
- **4% by 27.8 keV broad s-wave**
- 4% by 22.8 keV
- 5% d-wave at 80.8 keV
- 3-4% each five d-waves between 92 keV and 112 keV
- **From ~180 keV, contribution from individual res. very small and very similar, continuous trend, use of statistical model**

Aim is to achieve **a ~5-6% total uncertainty** for the MACS at 30 keV
~7-8% MACS at 90 keV

Conclusion: High-precision measurement of RRR until 400 keV is desirable and should be enough to cover the interesting range

^{56}Fe(n,γ) new estimation: proton request

- EAR1 neutron beam, **only option for high resolution up to hundreds of keV**
- 4000 bpd, 14% efficiency full setup (4xC_6D_6 at 9 cm) (estimated from 2022 Cr(n,γ) campaign)
- Sample: 2.1 g, 0.0072 at/b, 20 mm d. x 0.85 mm thickness (same sample from 2009)
- Proton request based on **background-subtracted resonance capture-area statistics**



Background includes realistic estimation of both background components:

B_{ns}: Arising from neutrons scattered by the sample and captured elsewhere

B_{gs}: g-rays scattered by the sample

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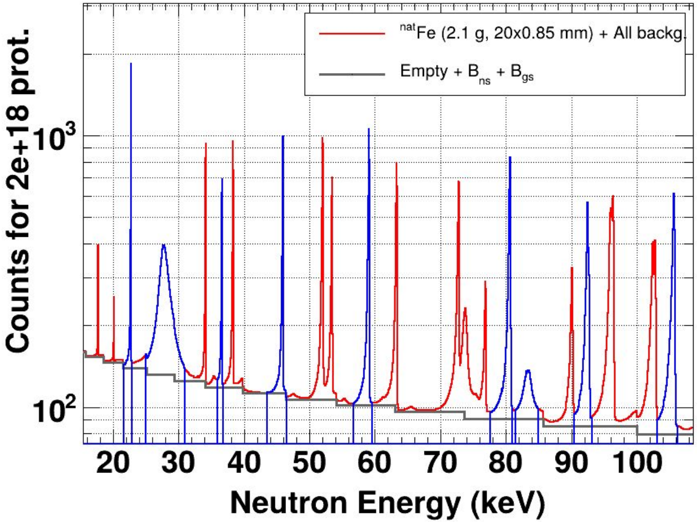

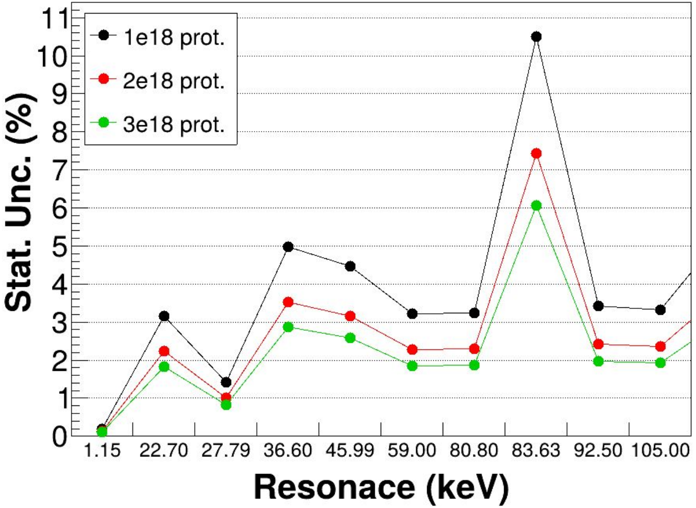

- **Total MACS uncertainty strongly dependent on systematic uncertainty (σ_{sys})** → main contributor is neutron flux uncertainty
- In previous capture experiments σ_{sys}~5%
- Preliminary Phase4 flux evaluation σ_{flux}~3.5-4% → **σ_{sys}<5% could be achievable**

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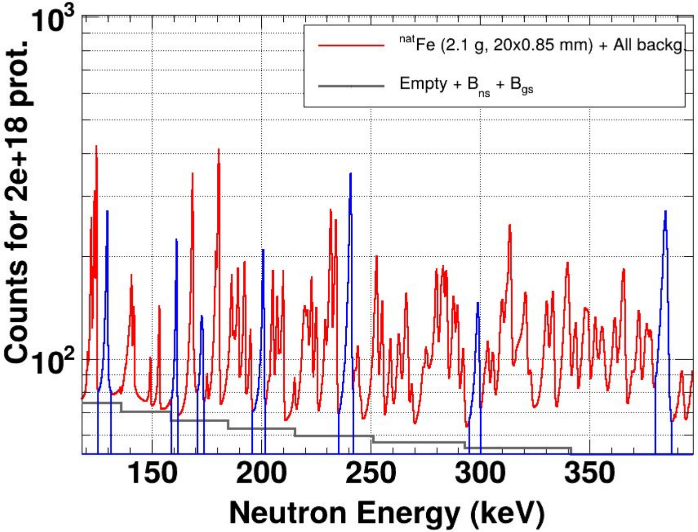

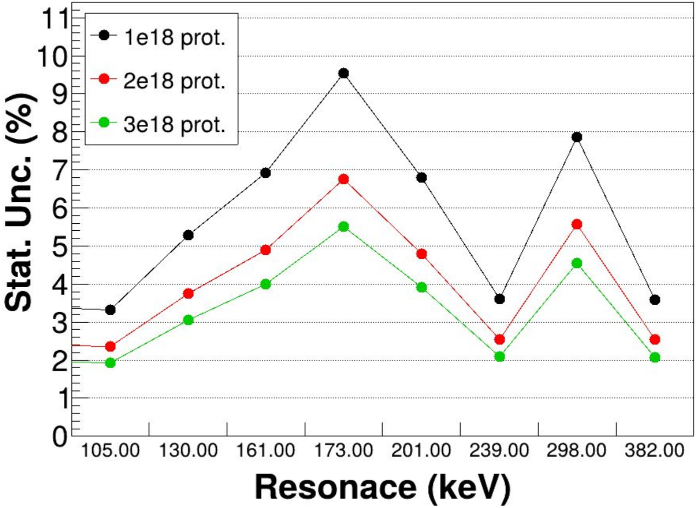

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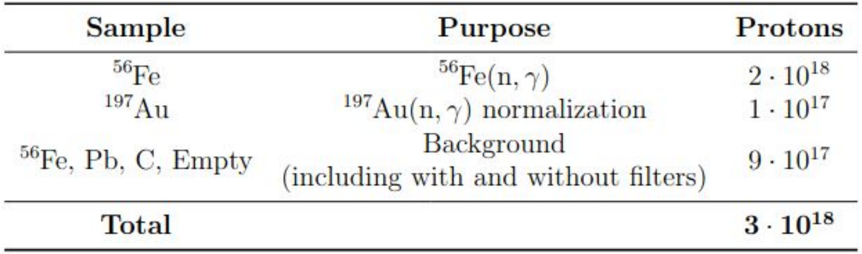
Proton request

- Total proton request, including background and normalization:



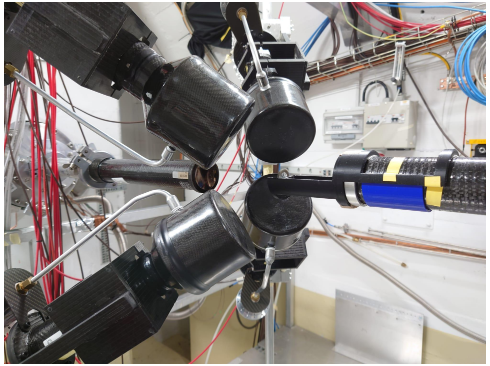
Sample	**Purpose**	**Protons**
^{56}Fe	^{56}Fe(n, γ)	$2 \cdot 10^{18}$
^{197}Au	^{197}Au(n, γ) normalization	$1 \cdot 10^{17}$
^{56}Fe, Pb, C, Empty	Background (including with and without filters)	$9 \cdot 10^{17}$
Total		$\mathbf{3 \cdot 10^{18}}$

- Background components are estimated from measurements of carbon (strong neutron scatterer) and Pb (g-ray scatterer) samples
- Use of filters together with ^{56}Fe, C, Pb samples as a crosscheck of background estimations

Summary and conclusions

- Although there is very recent evaluated data of ^{56}Fe(n,γ), they all are based in old experimental data sets
- ^{56}Fe(n,γ) was already measured at n_TOF, but the 2009 measurement suffered from several serious issues

- We propose a new high-precision measurement of ^{56}Fe(n,γ) in EAR1, **which would profit from latest improvements and advances in the setup and the facility:**
  - Take advantage of the **reduction in in-beam g-rays since 2010**, important for dense materials such as Fe and with a noticeable effect in old data
  - **Higher statistics: 2·10^{18} protons on sample**, in order to achieve low enough stat. unc. in the 1–200 keV RRR
  - **Use the Legnaro C_6D_6 standard setup for the smallest $\varepsilon_n/\varepsilon_\gamma$** (~5·10^{-5}), very important for 27.7 keV, 83 keV s-waves resonances
  - **Measure the RRR up to 350-400 keV**
  - **Measure the average XS/URR up to inelastic threshold** (E_n~850 keV), possibly up to 1 MeV and even 2 MeV thanks to recent upgrades in detectors (PMT) → **only one recent measurement** by McDermott et al. at RPI (EPJ Web of Conf. **146**, 11038 (2017)



V. Alcayne, "*Validation of the Legnaro-C6D6 detectors with the new PMT for capture measurements at EAR1 until at least 1 MeV*", n_TOF Collaboration meeting, June 2024 (https://indico.cern.ch/event/1403789/#33-validation-of-the-legnaro-c)

Thank you for your attention!

Backup

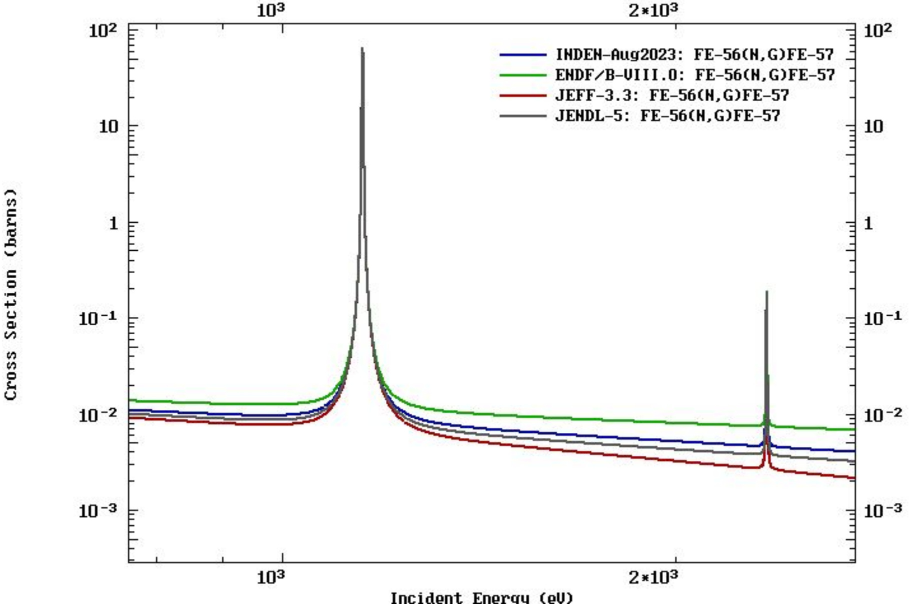
Brief review of past measurements

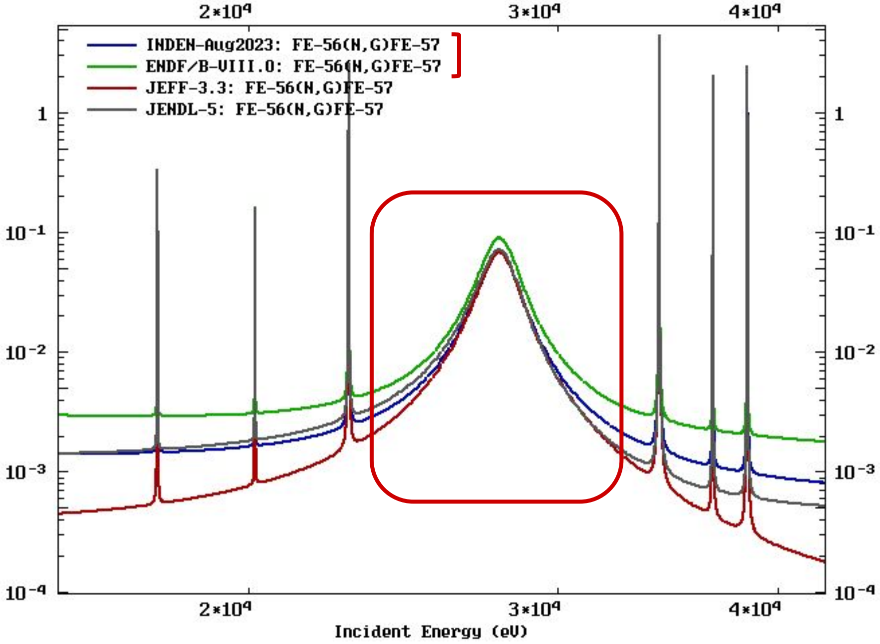
- TOF experiments: 1977 and 1982, last reanalysis done in 1992 (Corvi et al., 1992)
  - (very) thick samples (multiple scattering), neutron sensitivity issues
  - Experimental WF (Corvi)

- Previous experiment not successful at n_TOF (2009):
  - low statistics
  - higher in-beam gamma ray background (Phase2)
  - large detector gain drifts
  - Normalization problem

Status of the data: evaluations

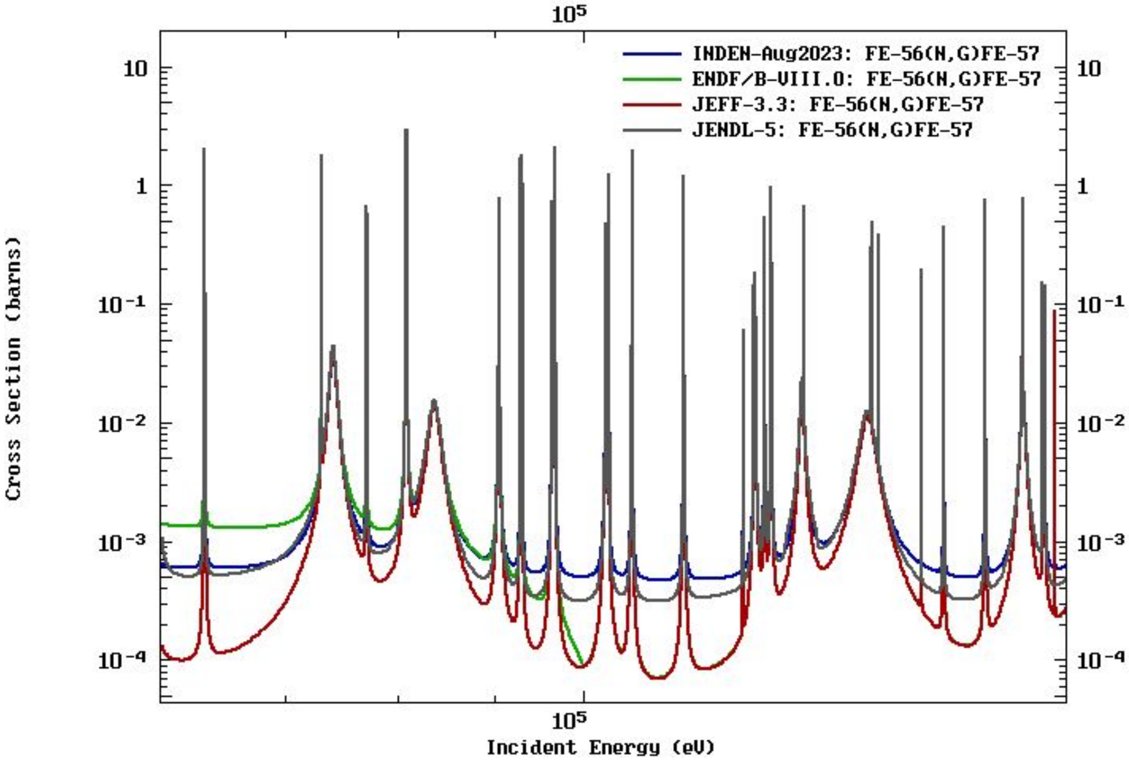
- 1 to 40 keV
- **27.7 keV s-wave: Γ_n/Γ_γ~1520**





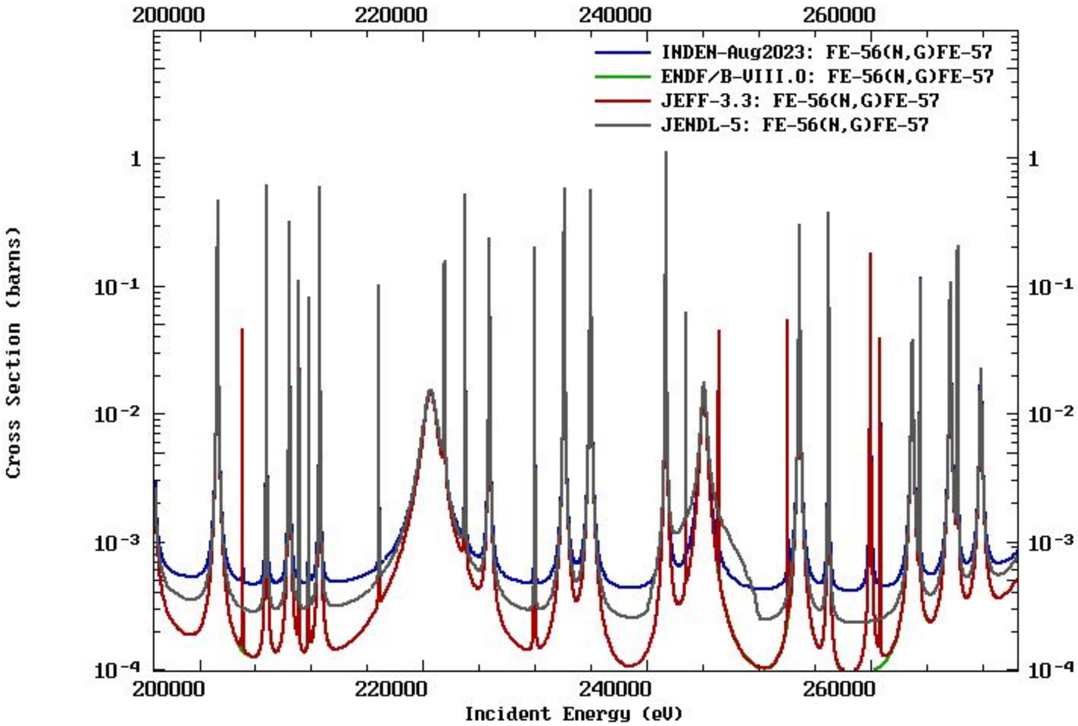
Status of the data: evaluations

- Between 50 keV and 200 keV Resonance data basically same
- Inden-23 XS between resonances higher



Status of the data: evaluations

- Between 200 keV and 300 keV some differences
- Inden-23 XS between resonances higher
- Some discrepancies in number of resonances



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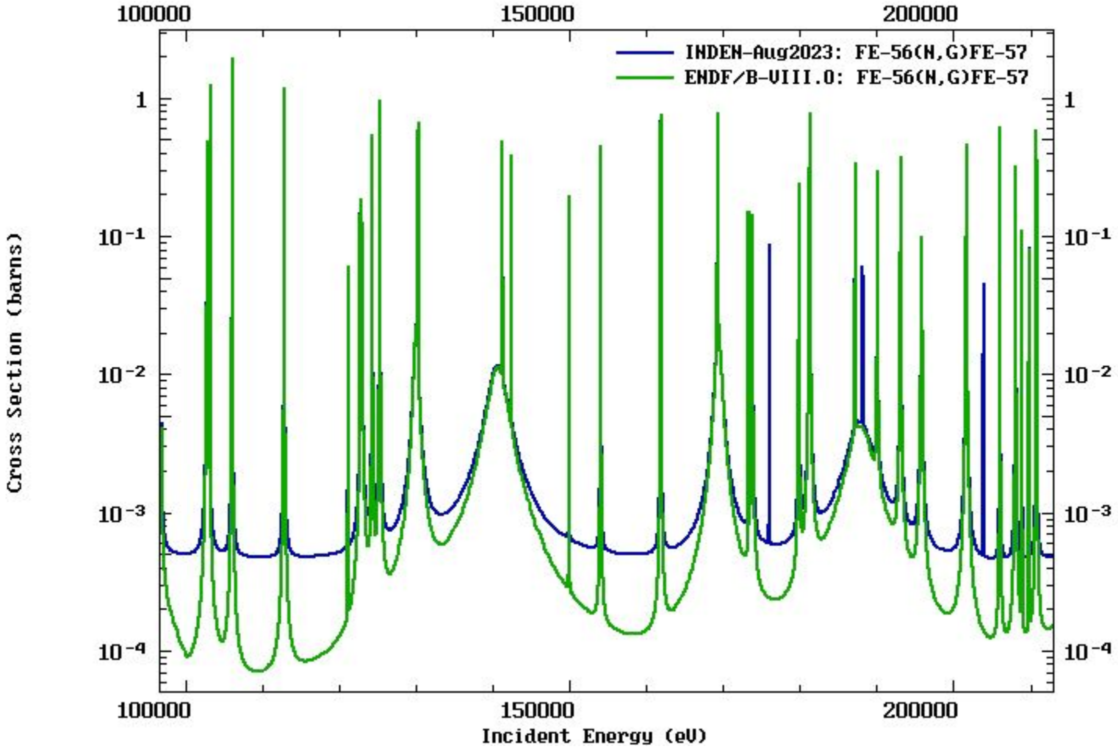

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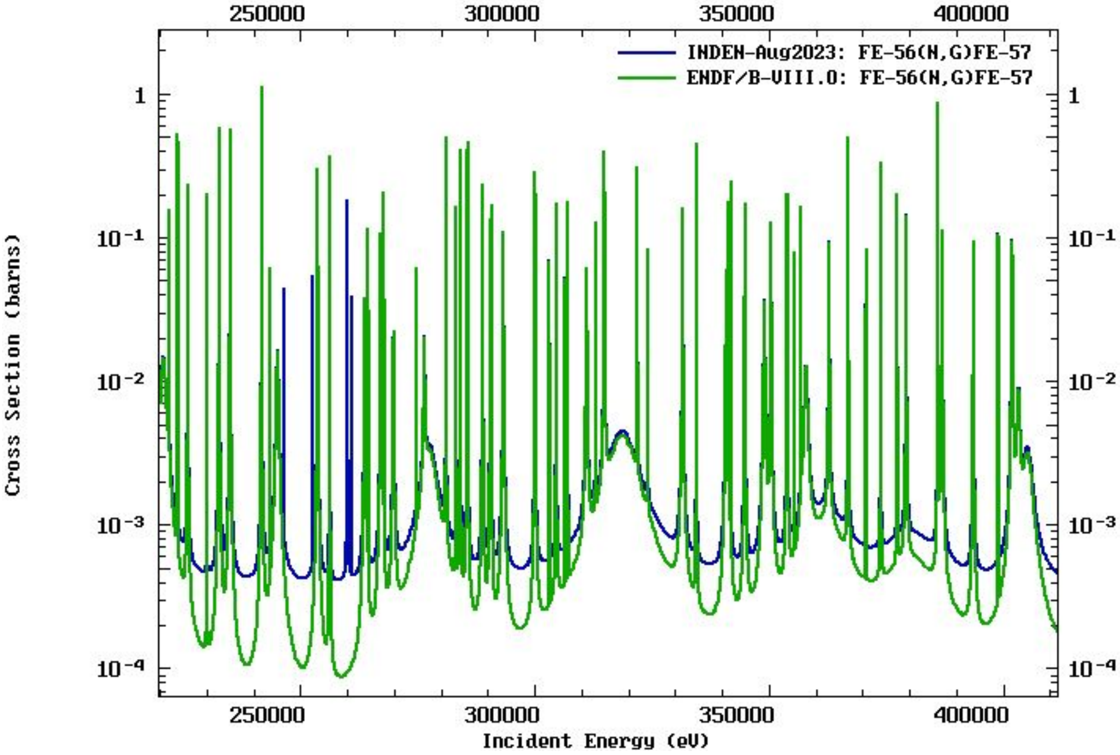
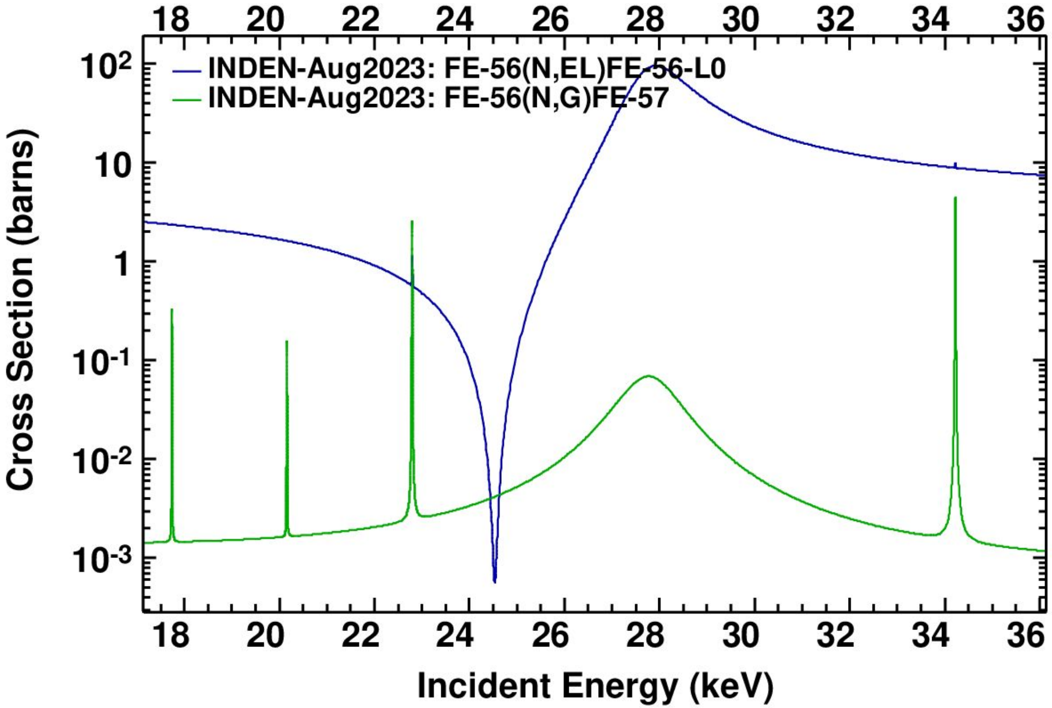
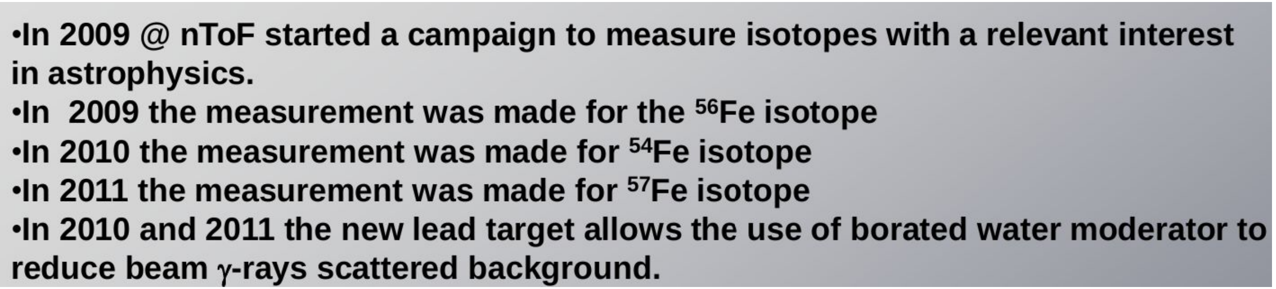


(n,el) vs (n,g) at 27.7 keV resonance



Some details about the 2009 ^{56}Fe(n,γ) measurement at EAR1*

- Conducted in Ph.2, with **non-borated** moderator



•In 2009 @ nToF started a campaign to measure isotopes with a relevant interest in astrophysics.

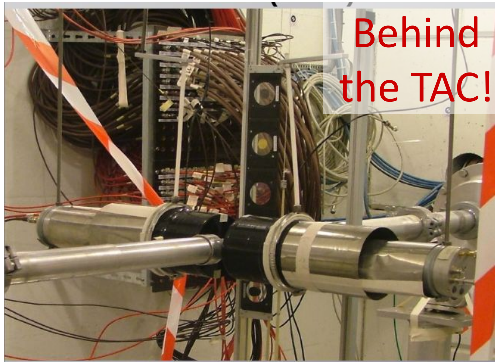
•In 2009 the measurement was made for the ^{56}Fe isotope

•In 2010 the measurement was made for ^{54}Fe isotope

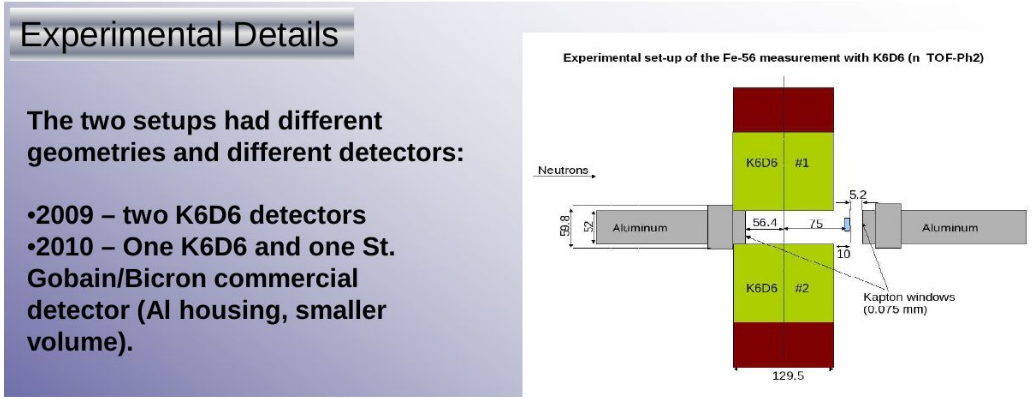
•In 2011 the measurement was made for ^{57}Fe isotope

•In 2010 and 2011 the new lead target allows the use of borated water moderator to reduce beam γ-rays scattered background.

- To maximize the setup efficiency, the FZK C6D6 detectors (“K6D6”) were positioned very close to the beam



**Experimental setup for ^{56}Fe (2009)
Water moderator**



Experimental Details

The two setups had different geometries and different detectors:

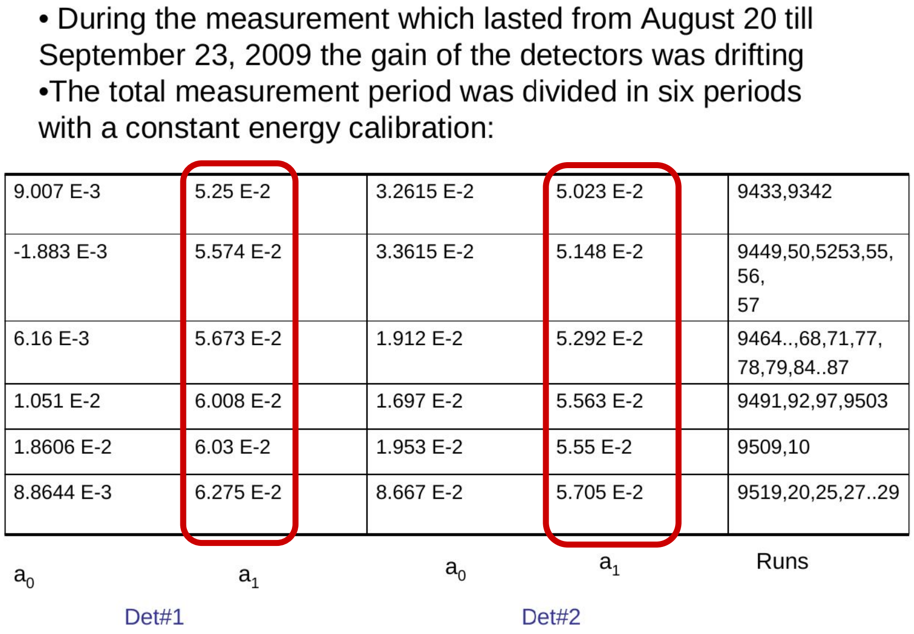
•2009 – two K6D6 detectors

•2010 – One K6D6 and one St. Gobain/Bicron commercial detector (Al housing, smaller volume).

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

Some details about the 2009 ^{56}Fe(n,γ) measurement at EAR1*

- The two K6D6 detectors **showed a considerable gain drift of 20% and 14% aprox.**, respectively



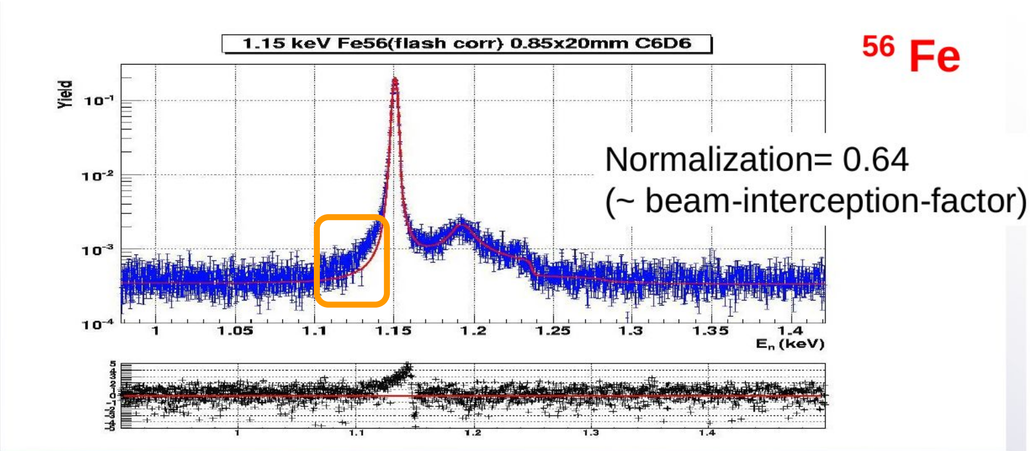
- During the measurement which lasted from August 20 till September 23, 2009 the gain of the detectors was drifting
- The total measurement period was divided in six periods with a constant energy calibration:

Det#1		Det#2		
a_0	a_1	a_0	a_1	Runs
9.007 E-3	5.25 E-2	3.2615 E-2	5.023 E-2	9433,9342
-1.883 E-3	5.574 E-2	3.3615 E-2	5.148 E-2	9449,50,5253,55, 56, 57
6.16 E-3	5.673 E-2	1.912 E-2	5.292 E-2	9464..,68,71,77, 78,79,84..87
1.051 E-2	6.008 E-2	1.697 E-2	5.563 E-2	9491,92,97,9503
1.8606 E-2	6.03 E-2	1.953 E-2	5.55 E-2	9509,10
8.8644 E-3	6.275 E-2	8.667 E-2	5.705 E-2	9519,20,25,27..29

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

Some details about the 2009 ^{56}Fe(n,γ) measurement at EAR1*

- Issue with 1.15 keV resonance tail and absolute normalization



Normalization= 0.64
(~ beam-interception-factor)

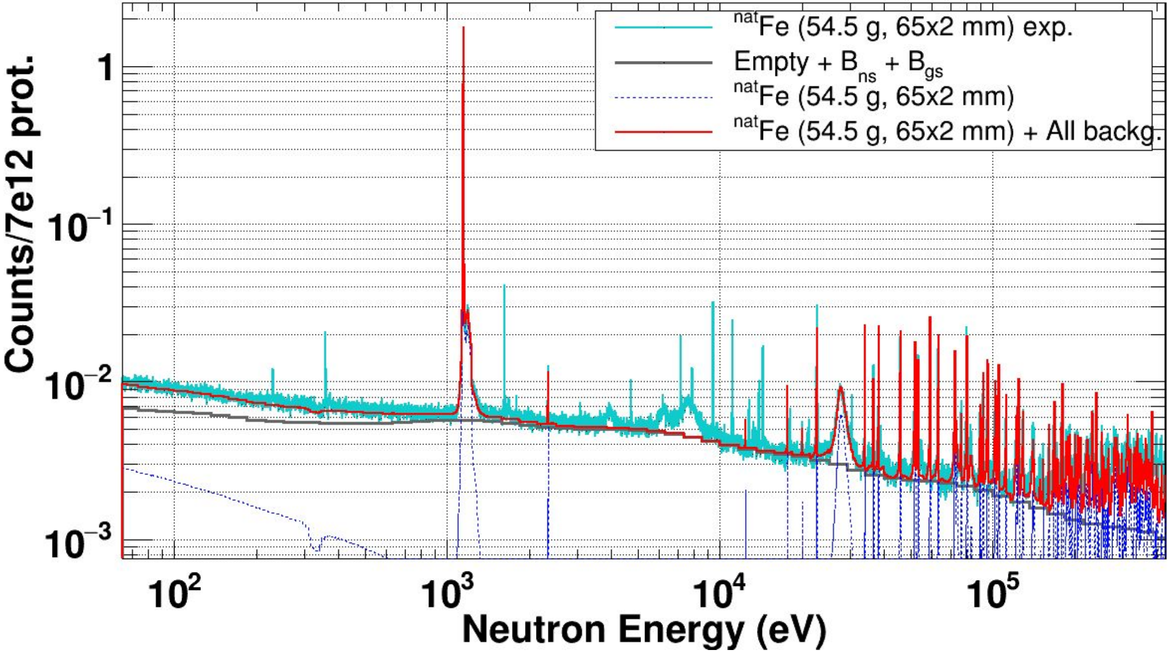
Normalization

	Gold	Fe(1.15keV)	Fe(22.8keV)	Fe(59.2keV)
no ToF	0.6236	0.6608	0.5229	0.5293
ToF corr		0.6424	0.5609	0.5683

2009 ^{56}Fe data analysis was not continued (unlike ^{54,57}Fe(n,γ), G. Giubrone Ph.D. Thesis, 2014)

^{56}Fe(n,γ) new estimation: background estimation

- An accurate (and conservative) estimation of the sample-related background is necessary
- Check with data from **54 g ^{nat}Fe sample (65x0.2 mm)** from 2021 RF campaign was used + natC and natPb from 176Yb campaign
- 4000 bpd, 4xC6D6, 8% full setup efficiency for 2021 (from Au sat. “calibration”, 275 keV threshold)



· **Yield produced directly with SAMMY (RF+MS included)**

· **Background:**

- **Neutron scattering, B_{ns}**: ^{nat}C-Empty, scaled by $R_{bif}*R_{XS}*R_{thick}$ where (R=sample/^{nat}C)
- **In-beam g-rays, B_{gs}**:

1. ^{nat}Pb-Empty-B_{ns} 2. Scaled by $R_{bif}*R_{att}$

- **Total: Empty + B_{ns} + B_{gs}**

- Smoothed and rebinned

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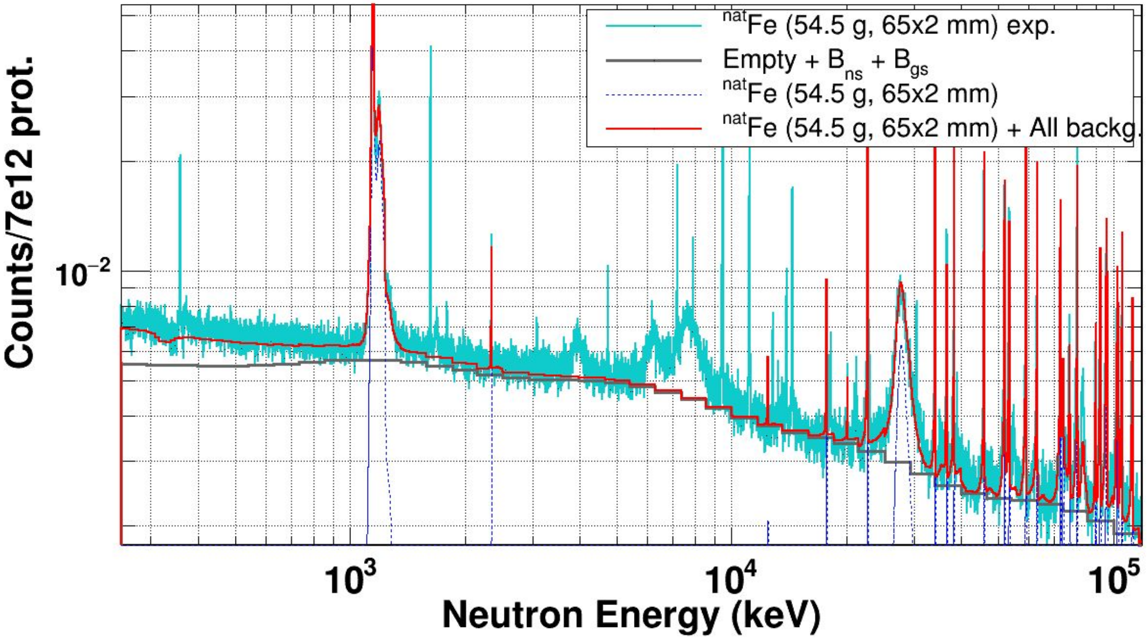

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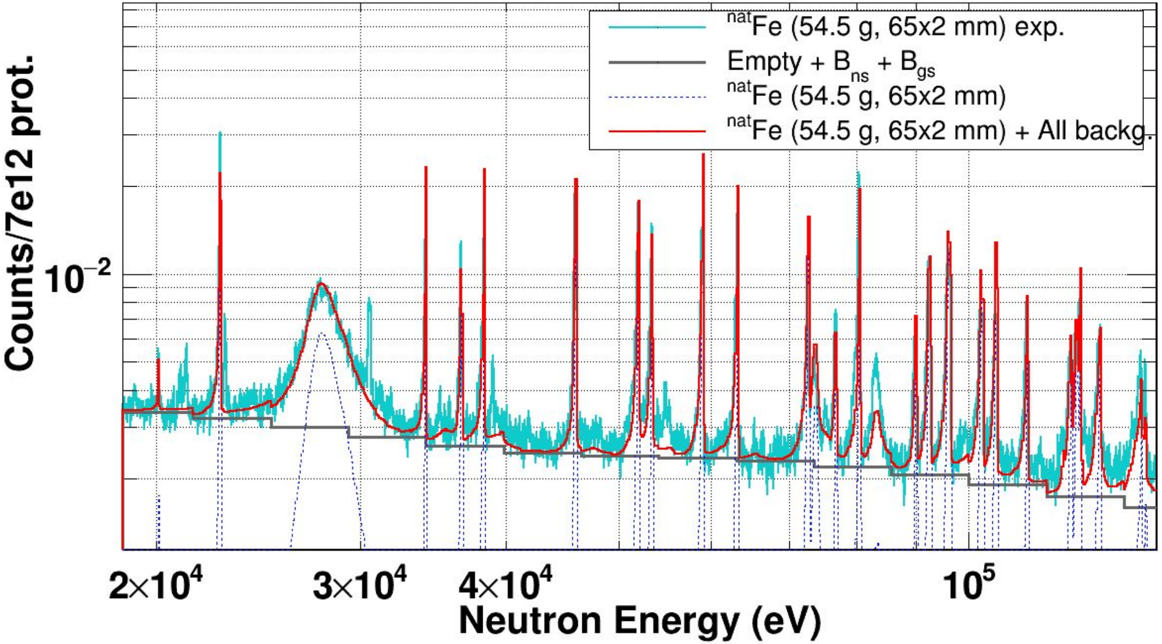

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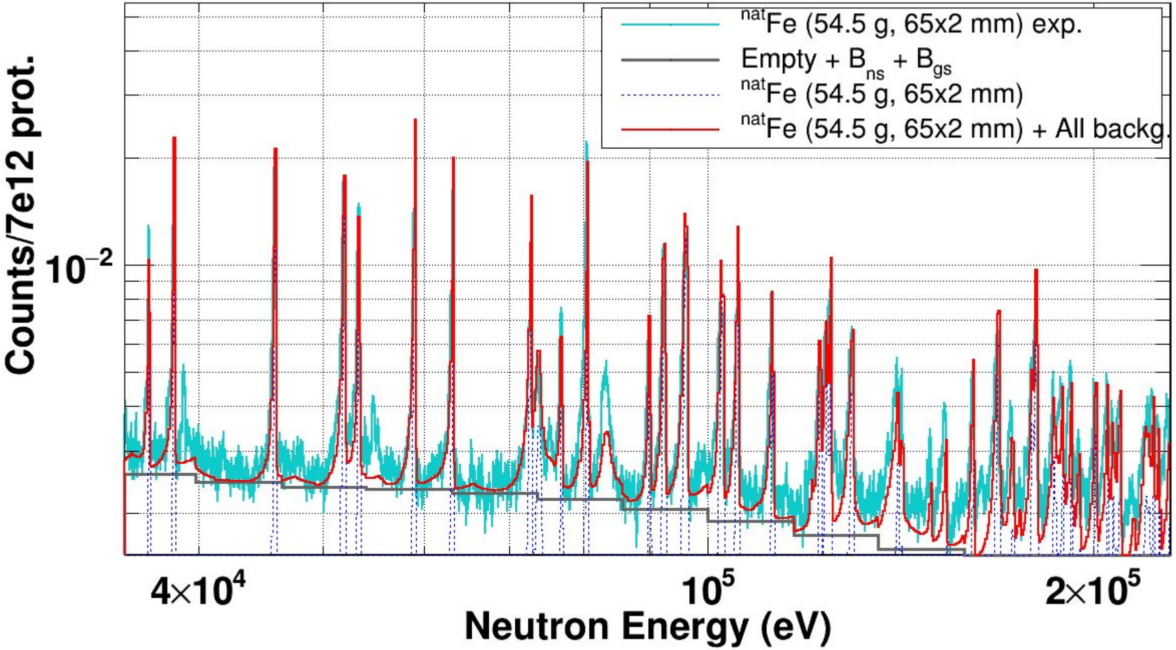

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- Smoothed and rebinned

^{56}Fe(n,γ) new estimation: thick natFe at higher E_n

- An accurate (and conservative) estimation of the sample-related background is necessary
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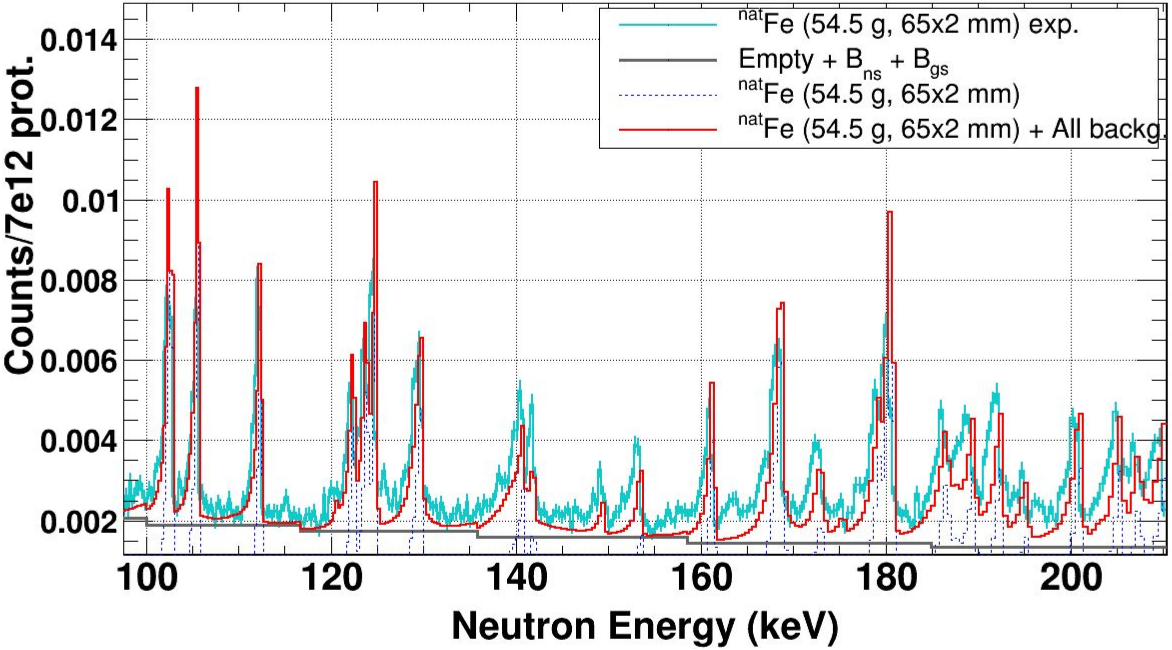

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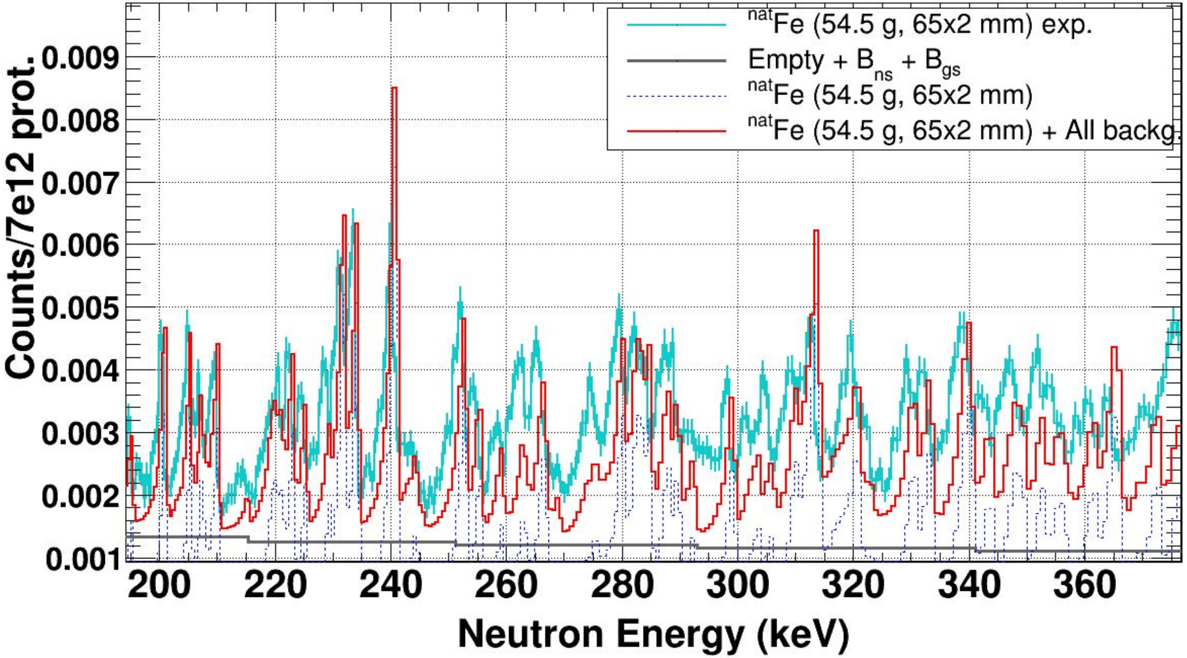
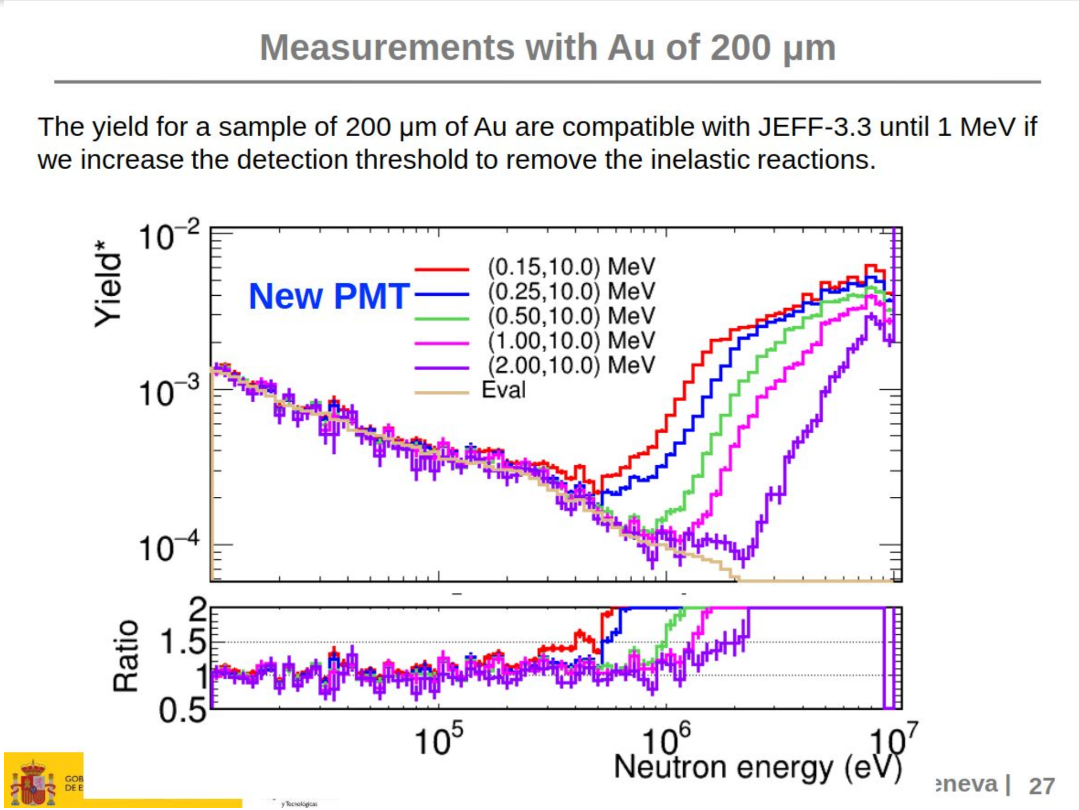


5×10^{17} (≲ 5 days of beam): good identification of resonances up to 360 keV

Performance of Legnaro C_6D_6 detectors at E_n~MeV



Measurements with Au of 200 μm

The yield for a sample of 200 μm of Au are compatible with JEFF-3.3 until 1 MeV if we increase the detection threshold to remove the inelastic reactions.

From V. Alcayne, "*Validation of the Legnaro-C6D6 detectors with the new PMT for capture measurements at EAR1 until at least 1 MeV*", n_TOF Collaboration meeting, June 2024
(https://indico.cern.ch/event/1403789/#33-validation-of-the-legnaro-c)

Outline of the presentation

- Motivations for a new ^{56}Fe(n,γ) measurement, status of the Maxwellian-averaged cross section (MACS)
- Review of the σ(E_n) in evaluated libraries
- Past experiments
- Counting rate estimations for ^{56}Fe(n,γ) in EAR1 and proton request