Updates on Fe isotopes: DRC calculations and experiments at GELINA

M. Diakaki[1], G. Gkatis[1,2], A. Mengoni[3,4], G. Noguere[2], C. Paradela[5], E. Pirovano[6], A. Plompen[5], M. Nyman[7], S. Kopecky[5], Peter Schillebeckx[5]

[1] *Department of Physics, National Technical University of Athens, 15780 Athens, Greece*

[2] *CEA/DES/IRESNE/DER/SPRC/LEPh, Cadarache, 13108 Saint Paul Lez Durance, France*

[3] *European Organisation for Nuclear Research (CERN), Switzerland*

[4] *ENEA Bologna / INFN, Sezione di Bologna, Italy*

[5] *European Commission, Joint Research Centre, 2440 Geel, Belgium*

[6] *Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany*

[7] *Department of Chemistry, University of Helsinki, FI-00014 Helsinki, Finland*

OUTLINE

- Direct Radiative Capture calculations since last year's meeting.

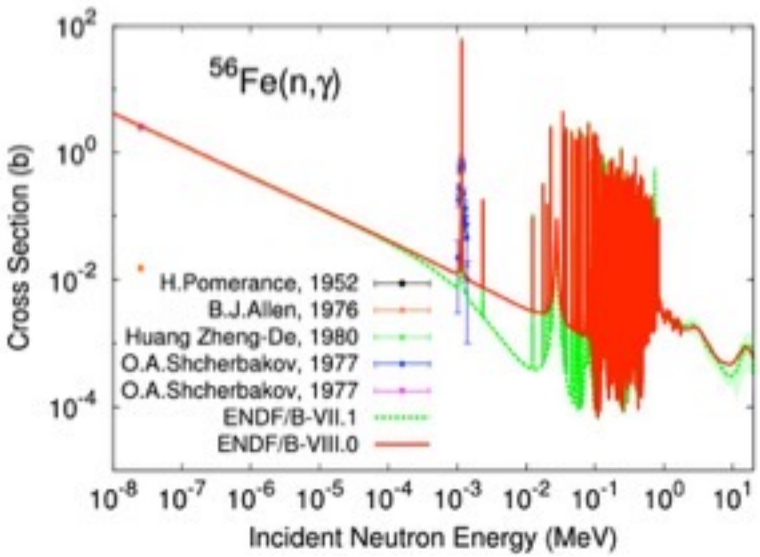
- Experiments at the GELINA facility for the production of new nuclear data on ^{54}Fe, ^{56}Fe:
  - Neutron scattering with the ELISA setup
  - Transmission measurements with natural Fe samples

This work is the PhD thesis of Georgios Gkatis (CEA Cadarache-NTUA).

Issues of ^{56}Fe(n,g) cross section

Issues with the ^{56}Fe(n,g) emerged within the CIELO project [1] / Implementation in ENDF/B-VIII.0:

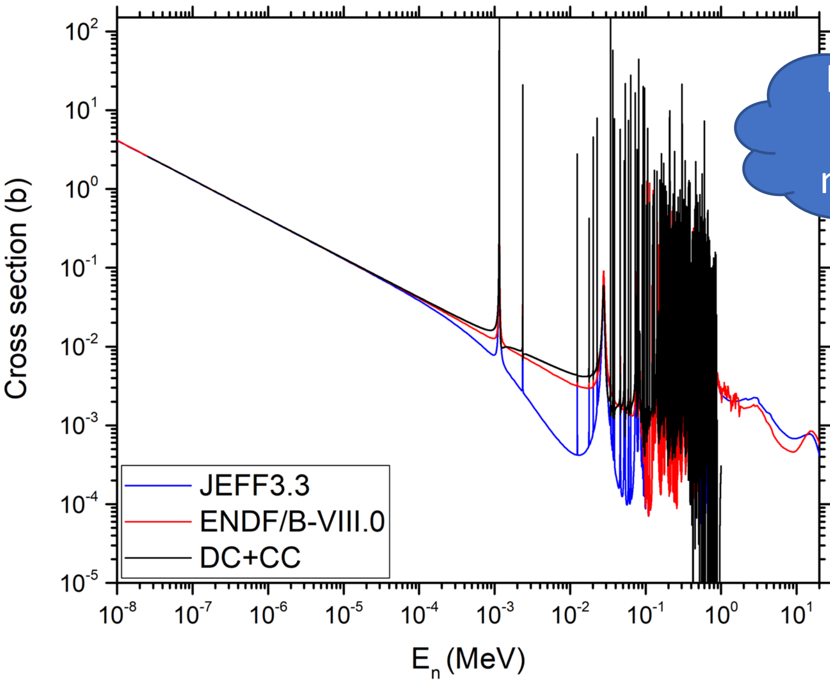
- “Artificial” background added between 10 eV-100 keV (supported by criticality benchmark **HEU-MET-INTER-001(ZPR9/34)**
- The results above 860 keV based on experimental data – RPI [2]: Increase of (n,g) when (n,inl) opens!



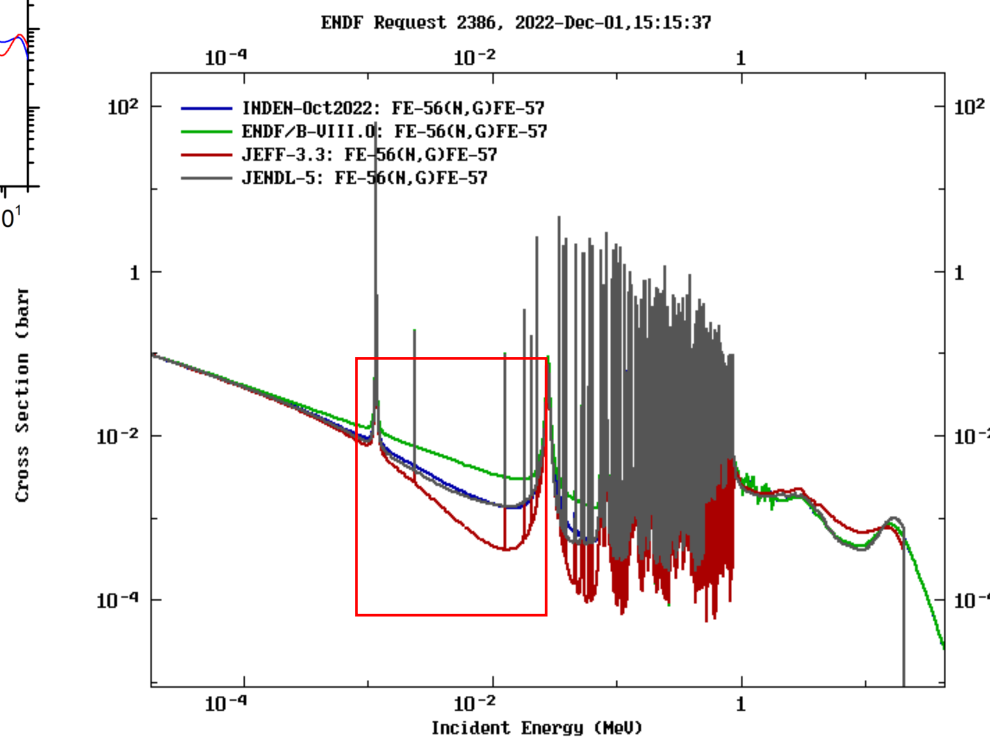
- We searched for possible physical interpretation of these issues via the **Calculation of direct capture (DRC) on ^{56}Fe -** Codes and expertise from **Alberto Mengoni, code pdix** [3-5].
- First results shown in 2021 and 2022 meetings.
- The model is **sensitive** to changes in the optical model parameters

[1] M. Herman et al., *Nuclear Data Sheets 148 (2018) 214-253.*
[2] B. McDermott et al., *EPJ Web of Conf. 146, 11038 (2017).*
[3] A. Mengoni et al., *Phys. Rev. C (rapid) 52, No 5 (1995).*
[4] T. Kikuchi et al., *Phys. Rev. C 57, No 5 (1998).*
[5] Y. Nagai et al., *Phys. Rev. C 102, 044616 (2020).*

Compound + Direct Capture (I)



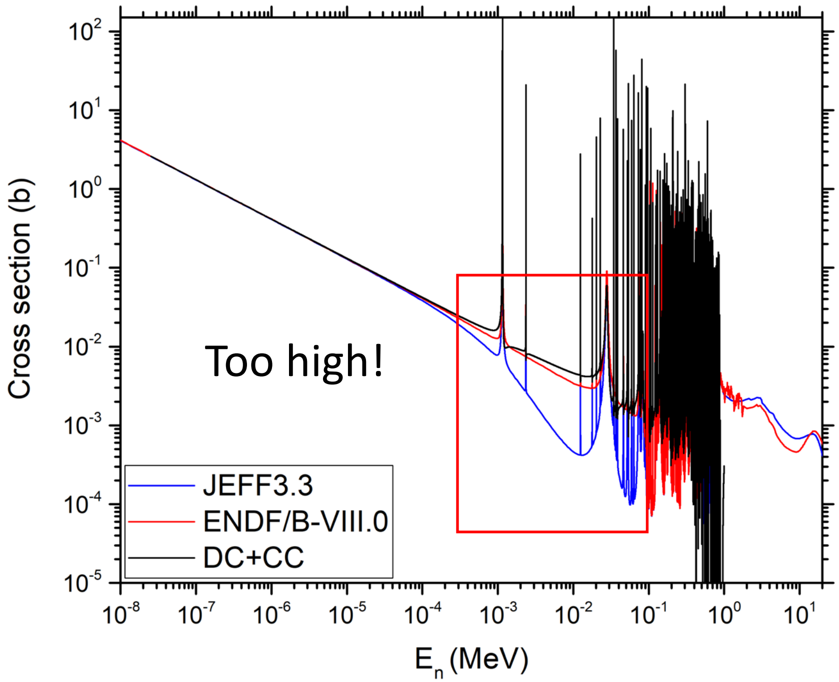
From last year's meeting…

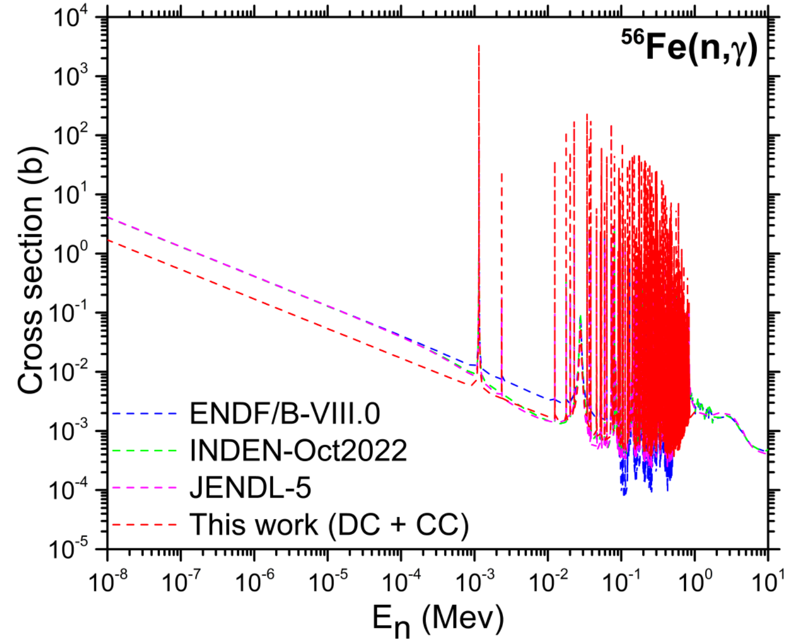


…But INDEN 2022 and JENDL-5 propose **~50%** less bgr at ~24keV than ENDF/B-VIII.0 (**ASPIS/Fe-88** benchmark)!! :

$\Rightarrow$ The DC + CC results needed tuning!

Compound + Direct Capture (II)





- If we decrease s-wave DRC to follow INDEN 2022 / JENDL-5 at the dip **we need to add negative resonances**, eitherwise too low at thermal point.
- pdix results need Doppler broadening.
- Attempted with pdix.

Compound + Direct Capture (III)

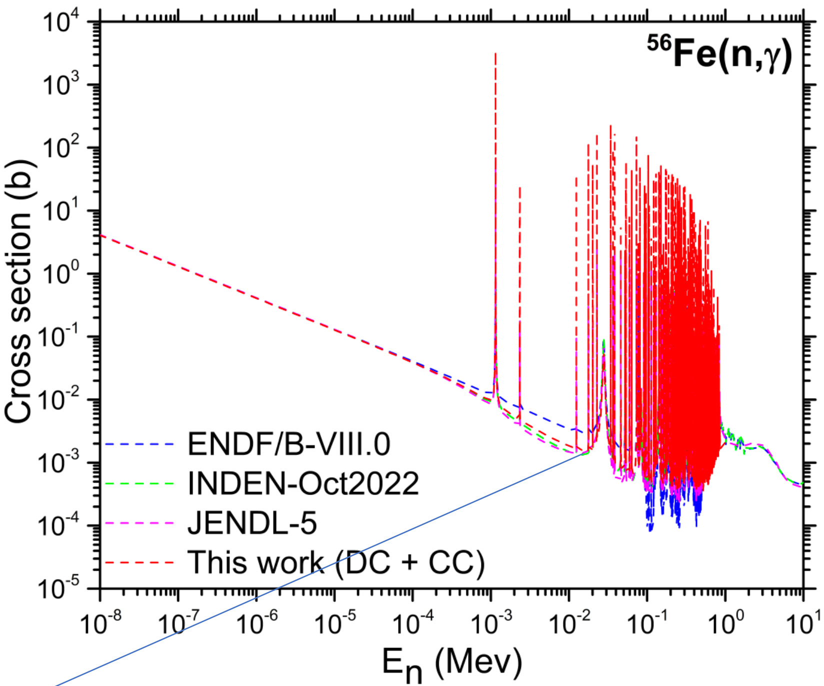
- One negative resonance was changed, from JEFF 3.1.1:

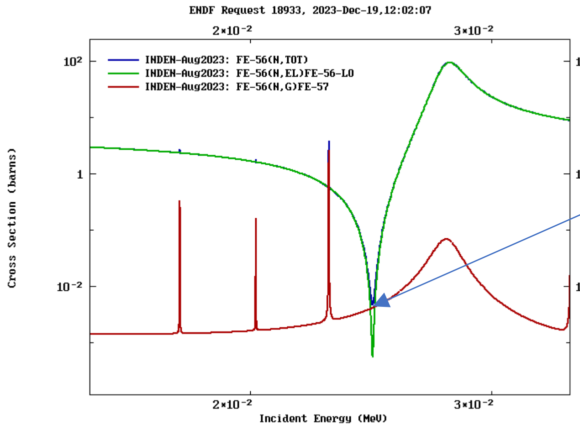
JEFF3.1.1

$$E_r = -2.44\ keV$$
$$J = {}^{1}/_{2}$$
$$l = 0$$
$$\Gamma_n = 0.271\ keV$$
$$\Gamma_\gamma = 0.00096\ keV$$

pdix

$$E_r = -2.44\ keV$$
$$J = {}^{1}/_{2}$$
$$l = 0$$
$$\Gamma_n = 0.103\ keV$$
$$\Gamma_\gamma = 0.001\ keV$$

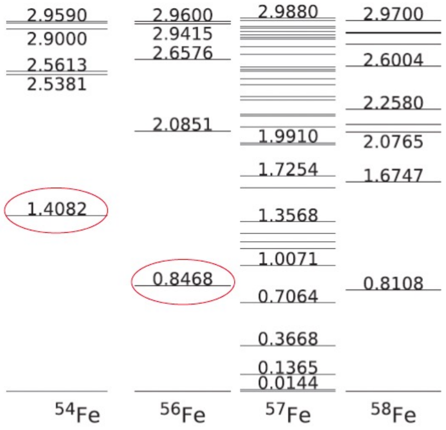




Next step: Implement this direct capture in the evaluation process.

Experimental campaign at GELINA

- Neutron induced Scattering (elastic/inelastic) on Iron isotopes at GELINA with **highly enriched targets**: **^{56}Fe, ^{54}Fe**



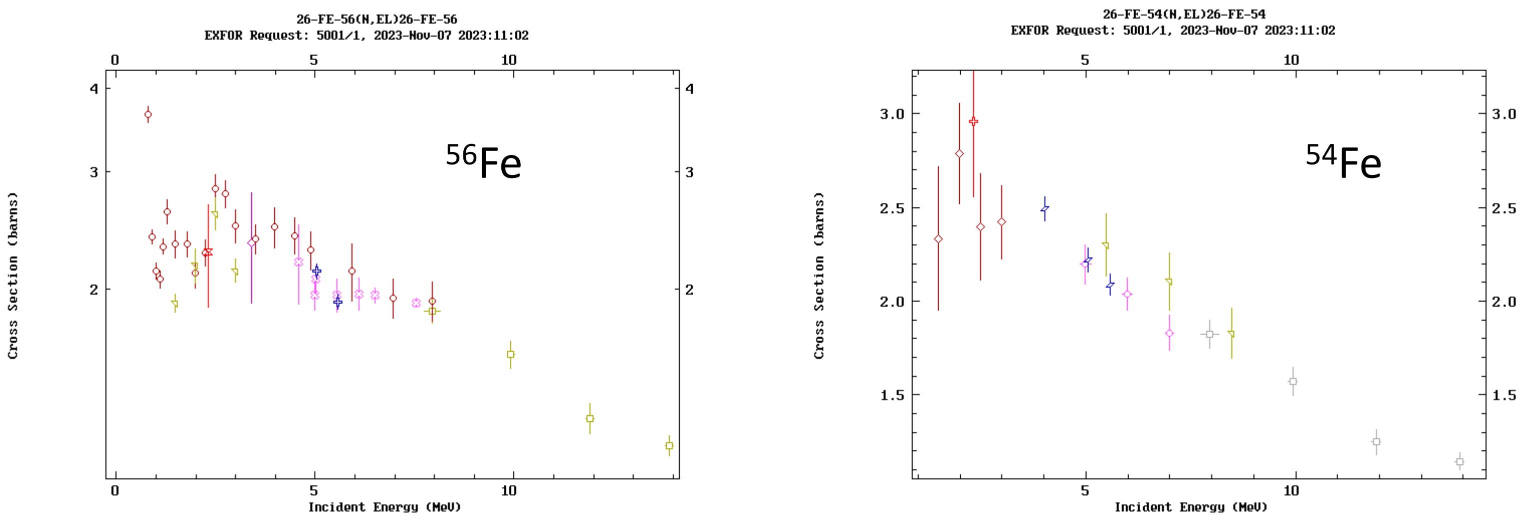
- Transmission measurements using **natural Fe samples** of different thicknesses
- Preliminary results for all measurements

Neutron scattering on ^{54}Fe and ^{56}Fe with the ELISA setup (JRC-Geel)

E_n ~1-6 MeV:

- No theoretical model able to reproduce the **fluctuating behavior present in medium-mass nuclei**
- Neutron scattering dominant BUT difficult to measure => Cross section data very limited and scarce even for very important isotopes (double differential and angle integrated)

EXFOR data on Fe(n,el)



=> Evaluated (n,el) data often obtained by subtracting total and competing reaction cross sections

Neutron scattering on ^{54}Fe and ^{56}Fe with the ELISA setup (JRC-Geel)

- <u>ELISA setup (Elastic and Inelastic Scattering Array)*</u>:

➢ **High-resolution neutron scattering double differential cross section data E_n ~1-8 MeV (unique setup in Europe)**

➢ **32 liquid organic scintillators at 8 scattering angles : *detection of scattered neutrons***

➢ 4 detectors per angle for redundancy/ cross checks (2 types of detectors per angle **: *EJ301, EJ315*).**

➢ **Fission chamber (1.37m from the sample) : *measurement of the neutron flux***

➢ The setup is placed at a **30 m** distance from the GELINA neutron source (FP1_30m).

➢ Already used for (n,el) on **natural Iron** [2].

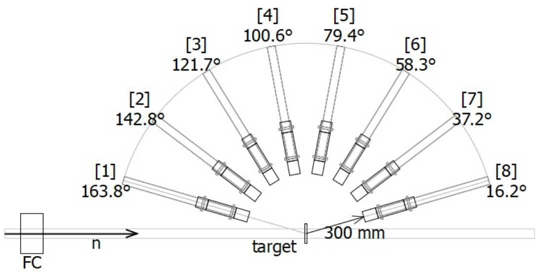
➢ Highly enriched targets:

^{54}Fe

Isotope	Atomic percent
^{54}Fe	**97.68**
^{56}Fe	2.24
^{57}Fe	0.04
^{58}Fe	0.04

^{56}Fe

Isotope	Atomic percent
^{54}Fe	0.16
^{56}Fe	**99.77**
^{57}Fe	0.07
^{58}Fe	<0.01



*[1]*M. Nyman et al., EPJ Web of Conferences 239, 17003 (2020)*

[2]*E. Pirovano et al., Phys. Rev. C 99, 024601 (2019)*

Neutron scattering on ^{54}Fe and ^{56}Fe with the ELISA setup (JRC-Geel)

1) **Detector characterization :**

   a) Resolution function: *g-ray sources* **/ b) Response function:** *$^{nat}C(n,el)$*

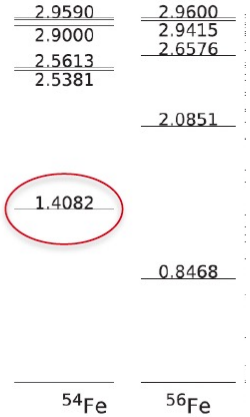
2) **Photon / neutron separation via Pulse Shape Analysis (charge integration method)**

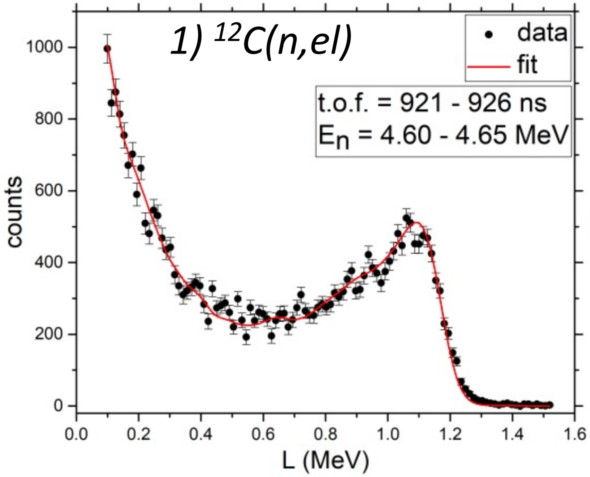
3) **Background subtraction (sample-out measurement)**

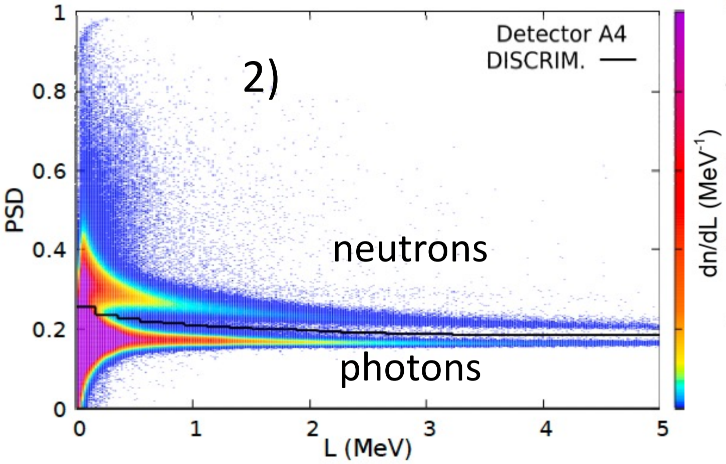
4) **Elastic–Inelastic separation**

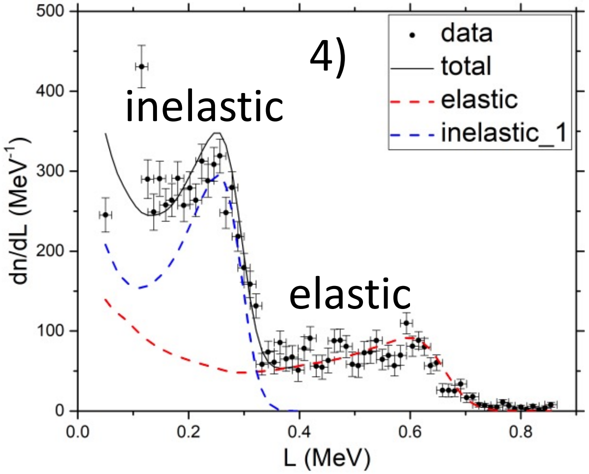
5) **Multiple scattering correction (Monte Carlo simulations)**

6) **Cross section calculation:** $\frac{d\sigma}{d\Omega}(E,\theta) = \frac{N_{el}(E,\theta)}{\Phi(E)\cdot\rho_T}$



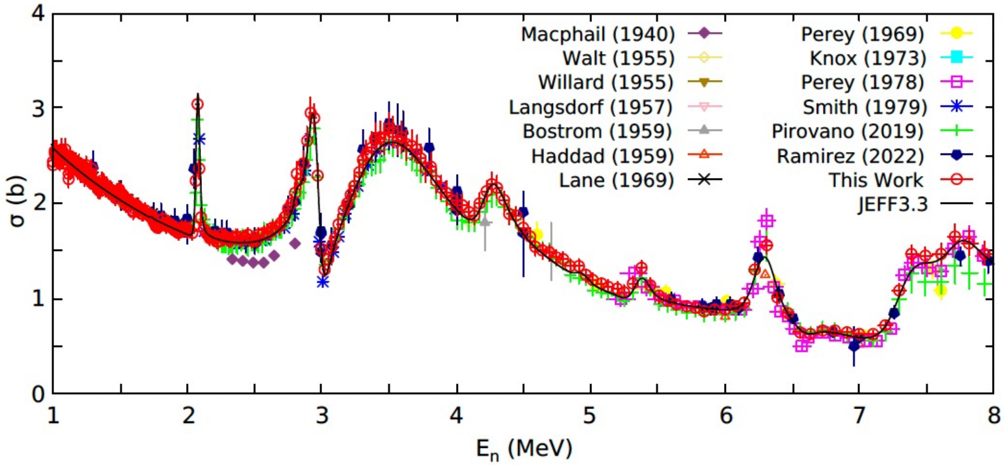




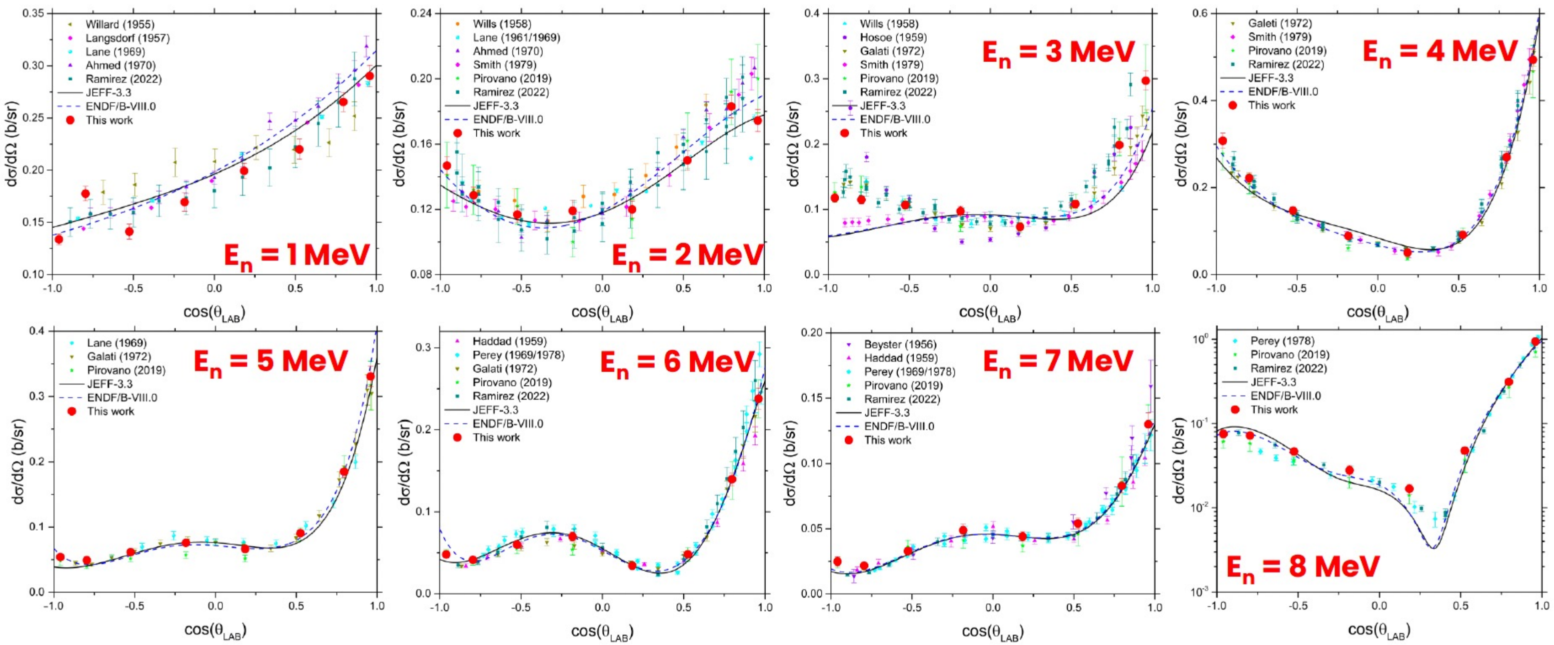


Neutron scattering on ^{54}Fe and ^{56}Fe with the ELISA setup (JRC-Geel)

Validation with $^{nat}C(n,el)$:

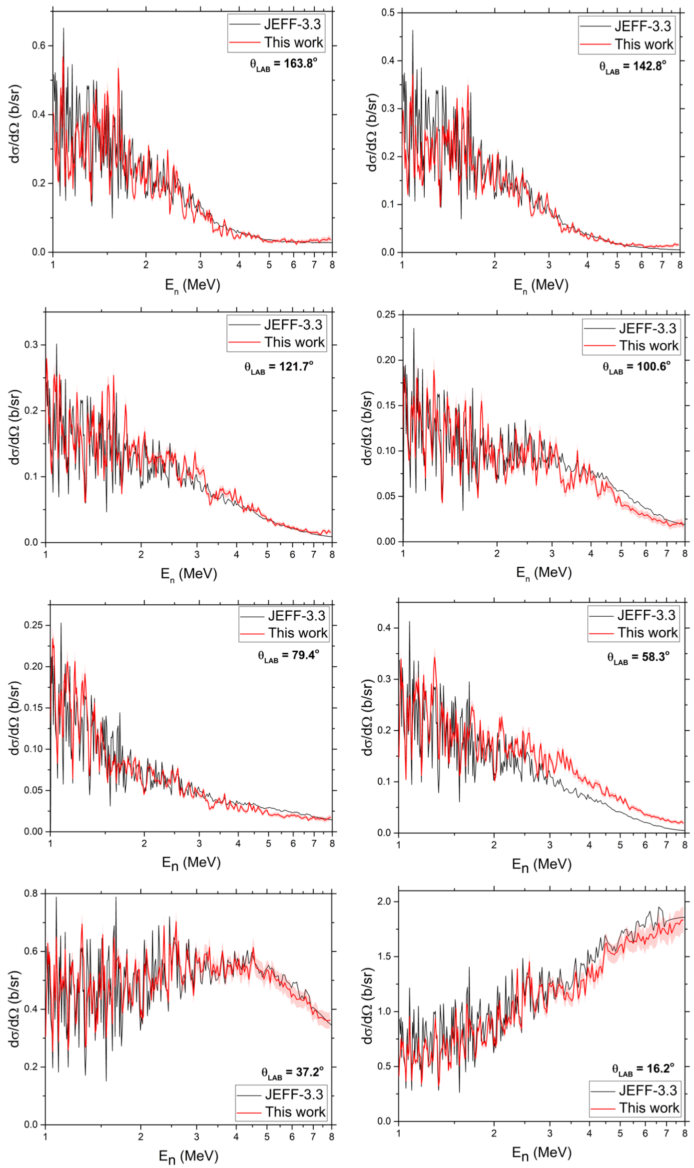


- Uncertainties 3-10%
- Good agreement with previous exp. data and evaluations

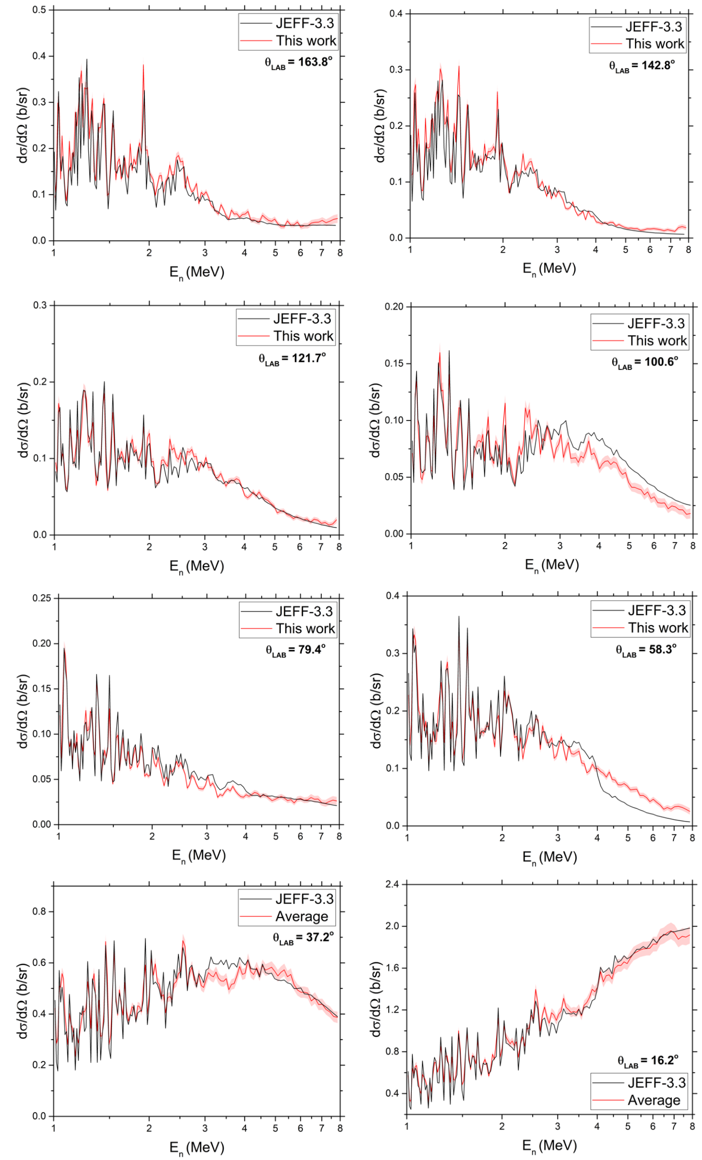


Neutron scattering on ^{54}Fe and ^{56}Fe with the ELISA setup (JRC-Geel)

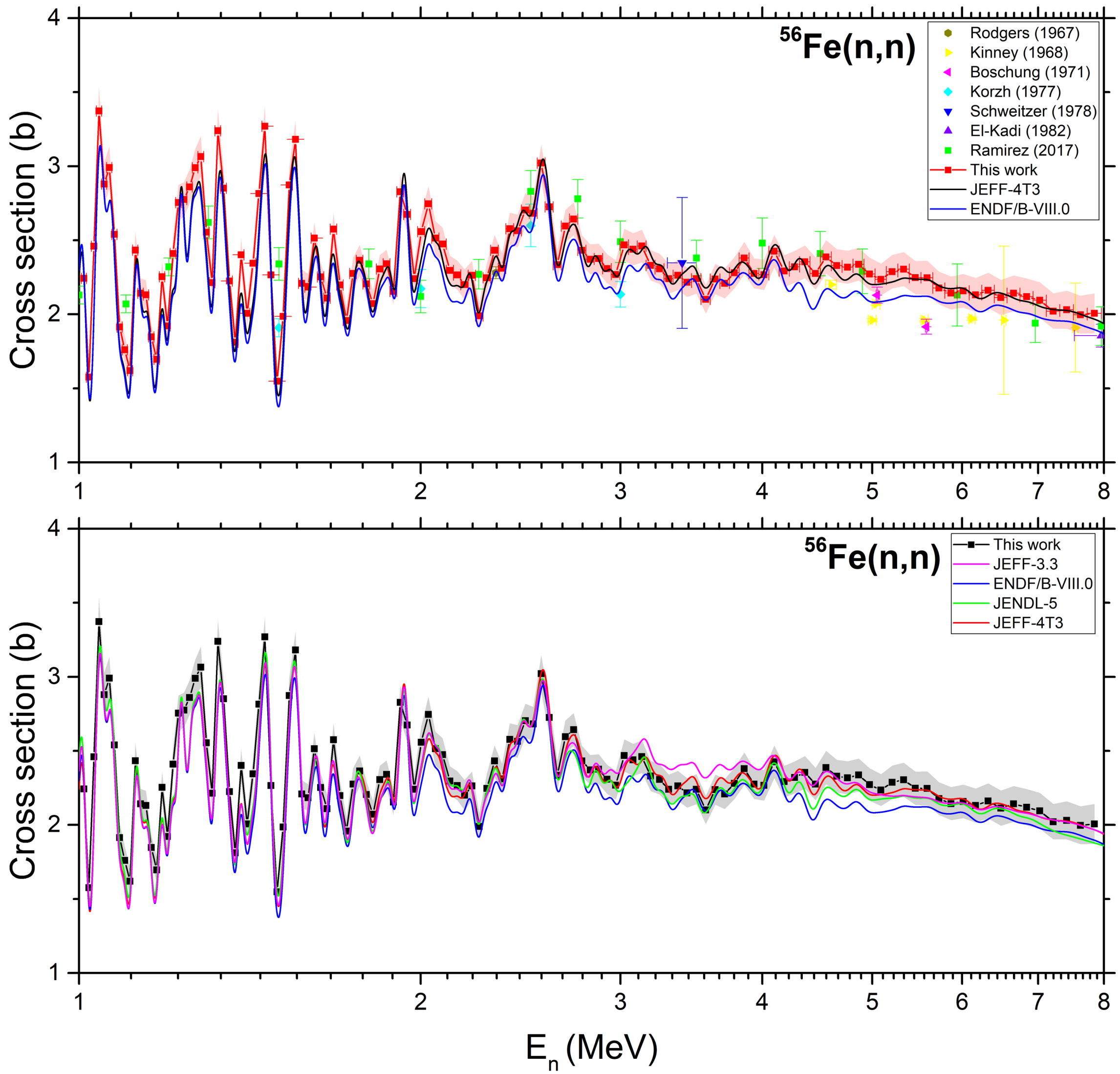
Differential cs of ^{54}Fe(n,el)



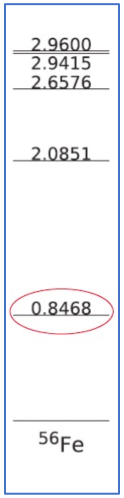
Differential cs of ^{56}Fe(n,el)

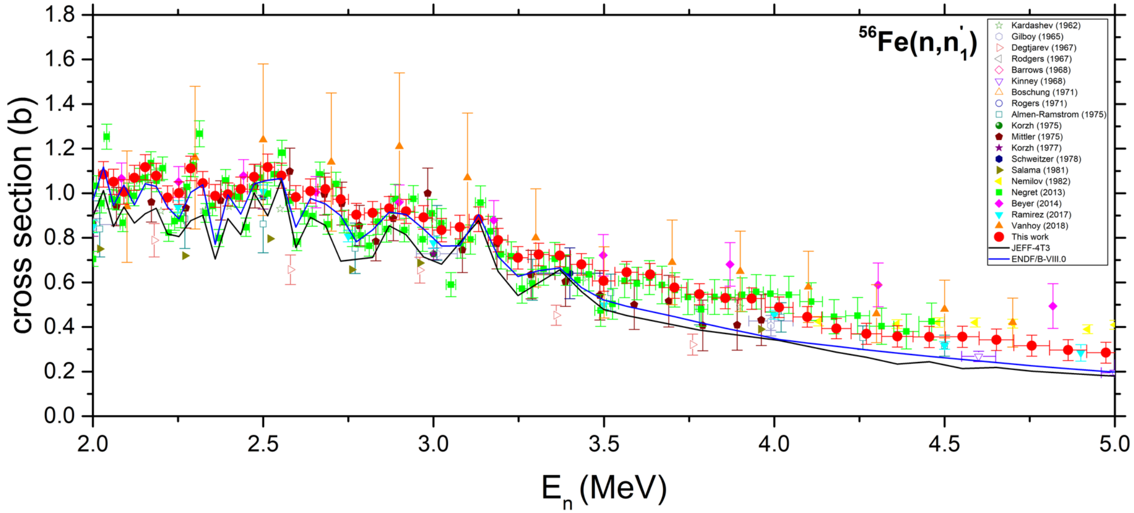


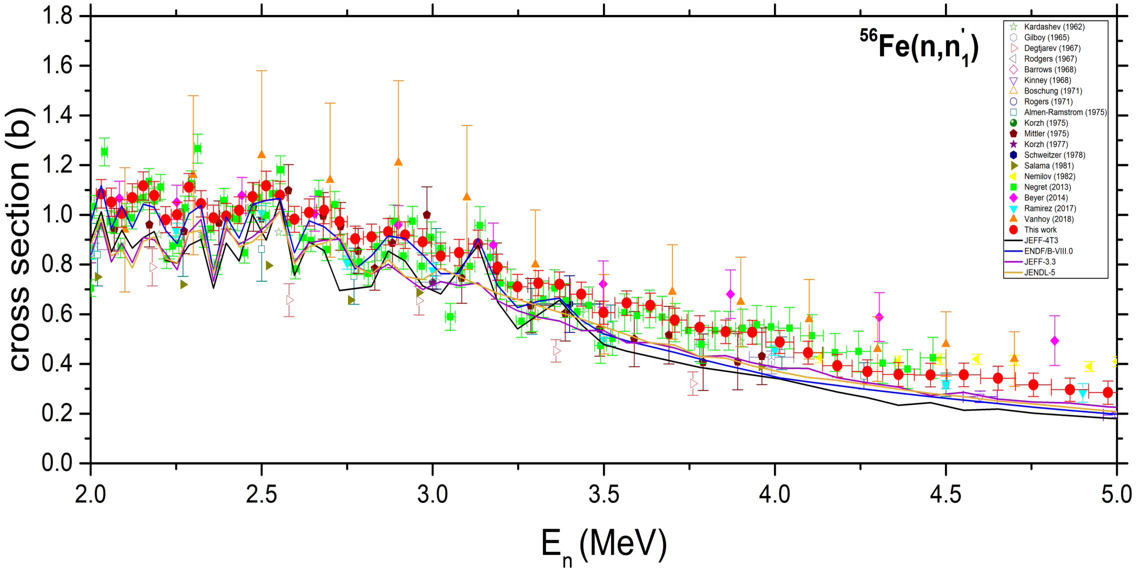
Neutron scattering on ^{56}Fe : Preliminary results ^{56}Fe(n,n)



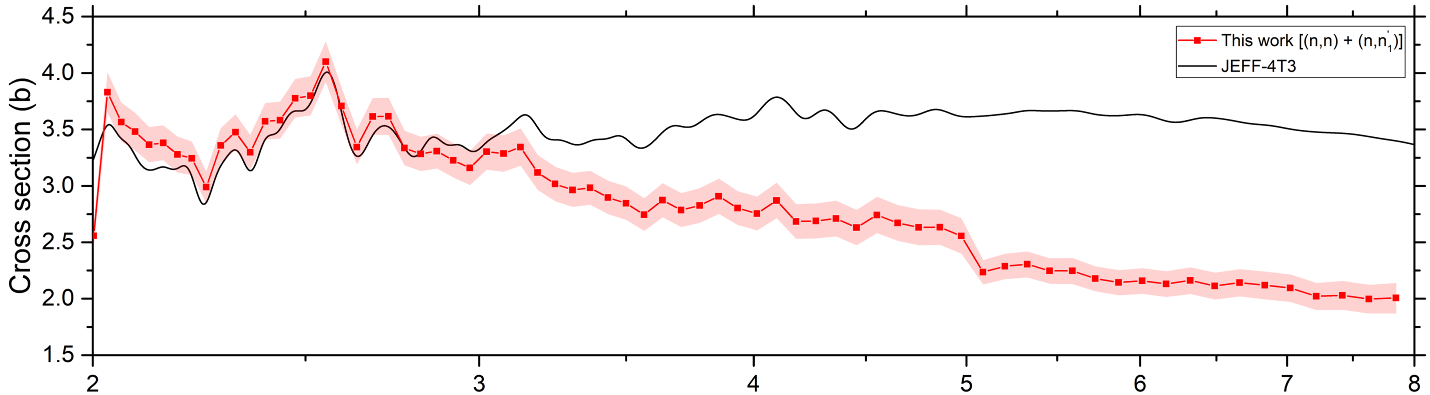
Neutron scattering on ^{56}Fe : Preliminary results ^{56}Fe(n,n'$_1$)

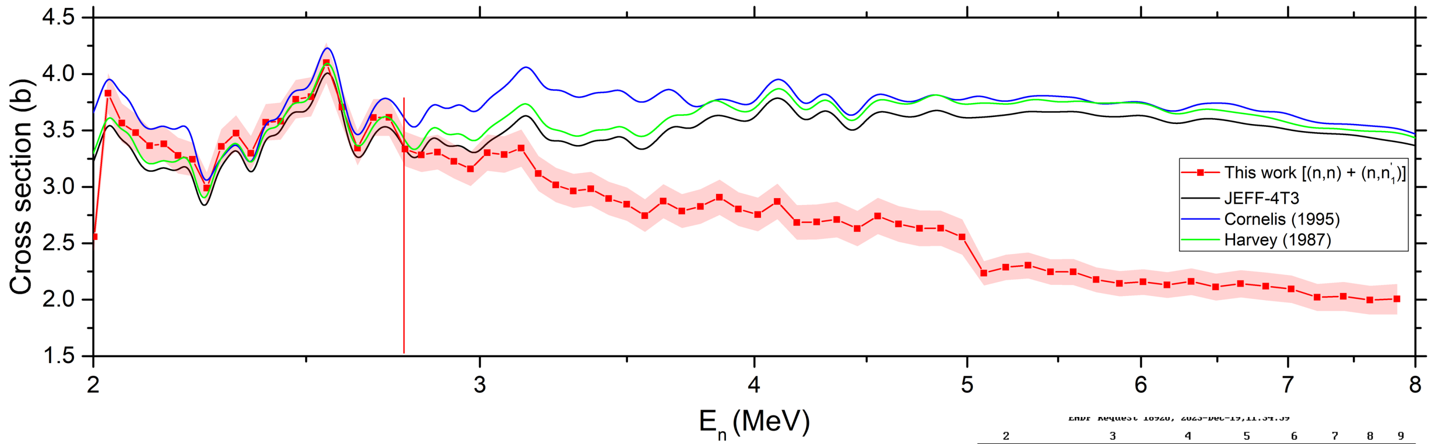




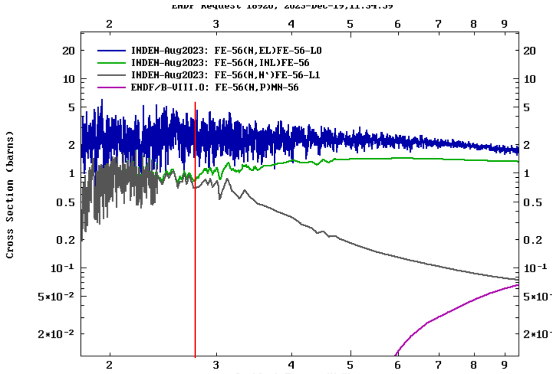


Neutron scattering on ^{56}Fe : Preliminary results ^{56}Fe(n,n) + ^{56}Fe(n,n'$_1$)

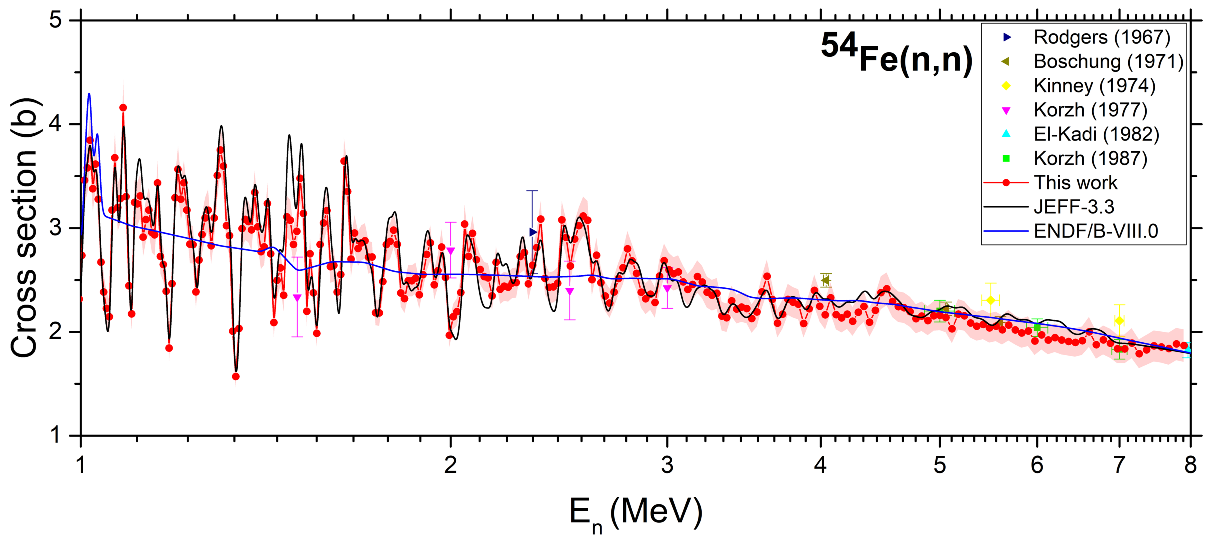


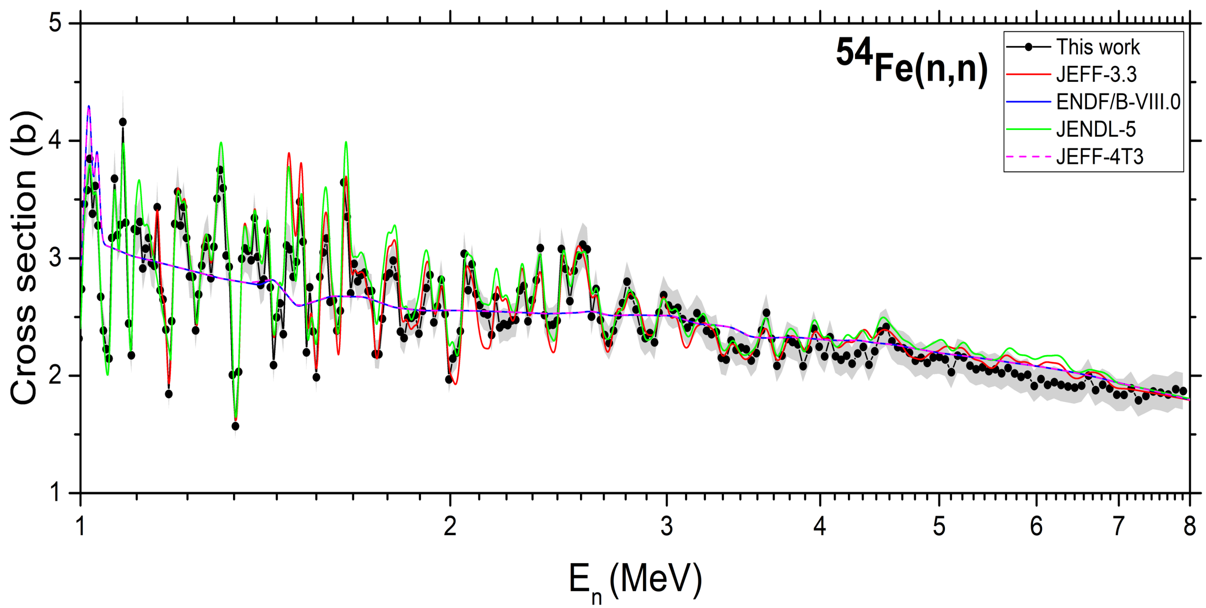


- Agreement within uncertainties with the (n,tot) of Harvey (1987).
- Analysis ongoing.

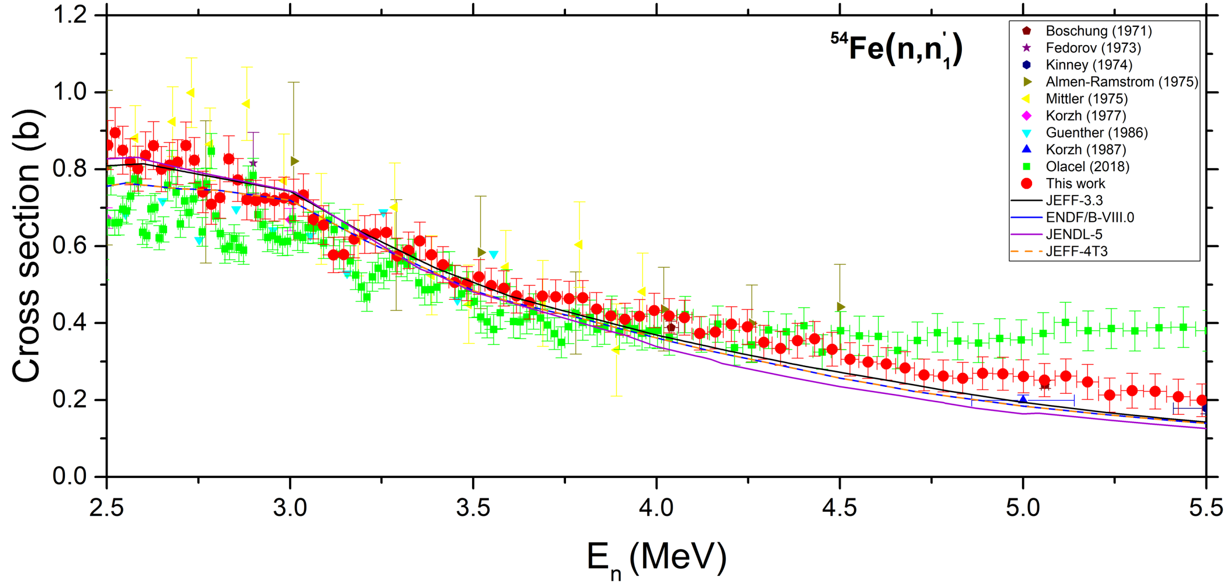


Neutron scattering on ^{54}Fe : Preliminary results ^{54}Fe(n,n)

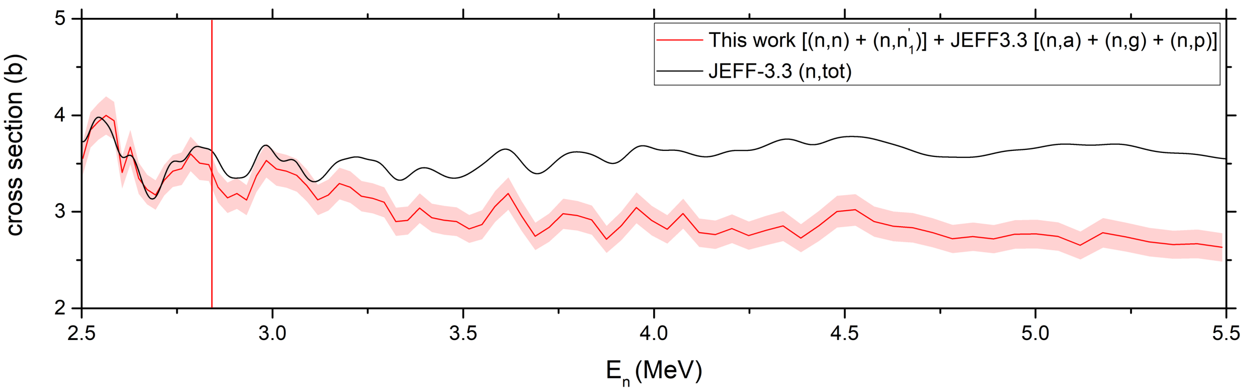


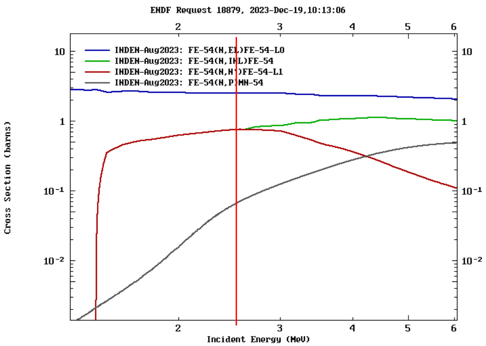


Neutron scattering on ^{54}Fe : Preliminary results ^{54}Fe(n,n'$_1$)



^{54}Fe(n,n) + ^{54}Fe(n,n'$_1$):

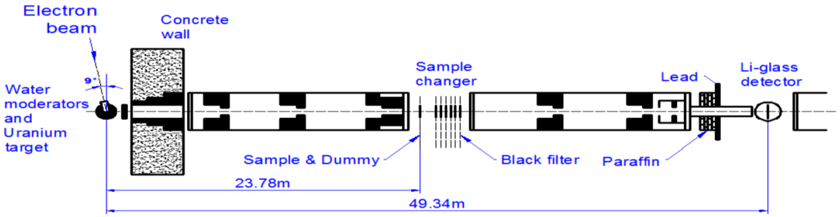




Good agreement with the (n,tot) of JEFF 3.3

Transmission measurements at GELINA (JRC-Geel)

- Li-glass detector used.
- Sample at ~24 m flight path, detector at ~50 m.
- Moderated neutron beam used (with ^{10}B and Pb filters)



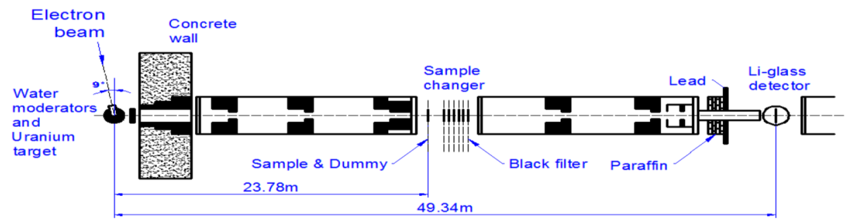
- ^{nat}Fe sample:

3 metallic discs available:

ID	Thickness (mm)	Mass (g)
1	1.194	667
2	4.486	2506.4
3	4.488	2504

- Samples **no. 1** and **no. 2** measured during summer 2023.

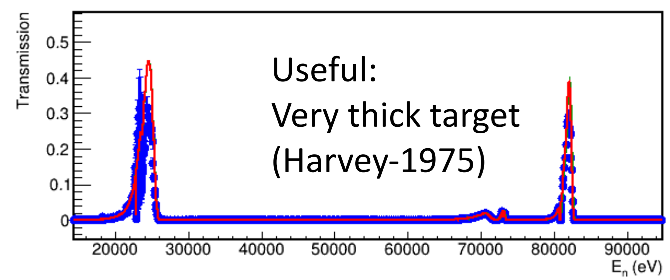
Transmission measurements at GELINA (JRC-Geel)



- Li-glass detector used.
- Sample at ~24 m flight path, detector at ~50 m.
- Moderated neutron beam used (with ^{10}B and Pb filters)
- ^{nat}Fe sample:

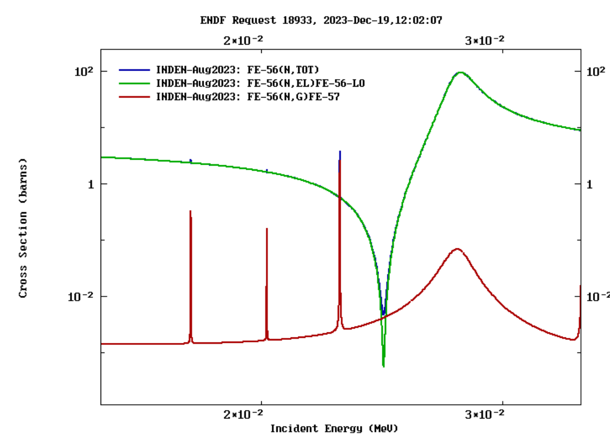
3 metallic discs available:

ID	Thickness (mm)	Mass (g)
1	1.194	667
2	4.486	2506.4
3	4.488	2504



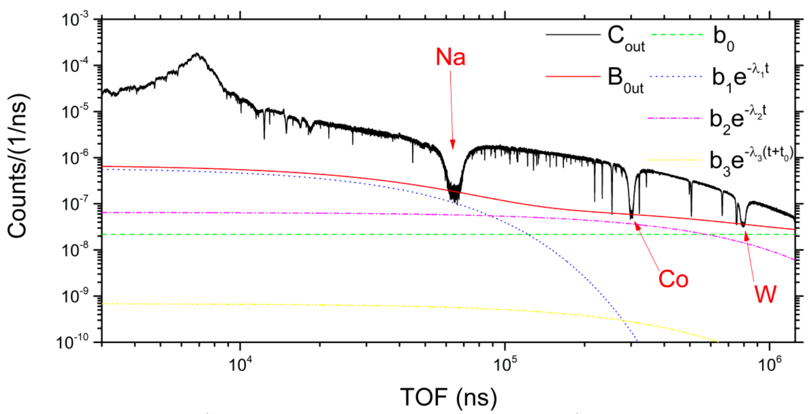
- Samples **no. 1** and **no. 2** measured during summer 2023.
- Combination of **no. 2** and **no. 3**

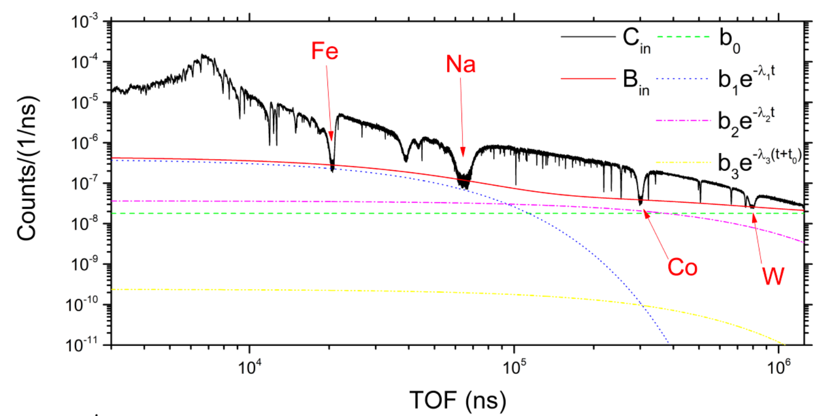
(=> 9cm, “thick” sample) to be measured as soon as GELINA is back to normal => probe into cross section minima with better statistics.

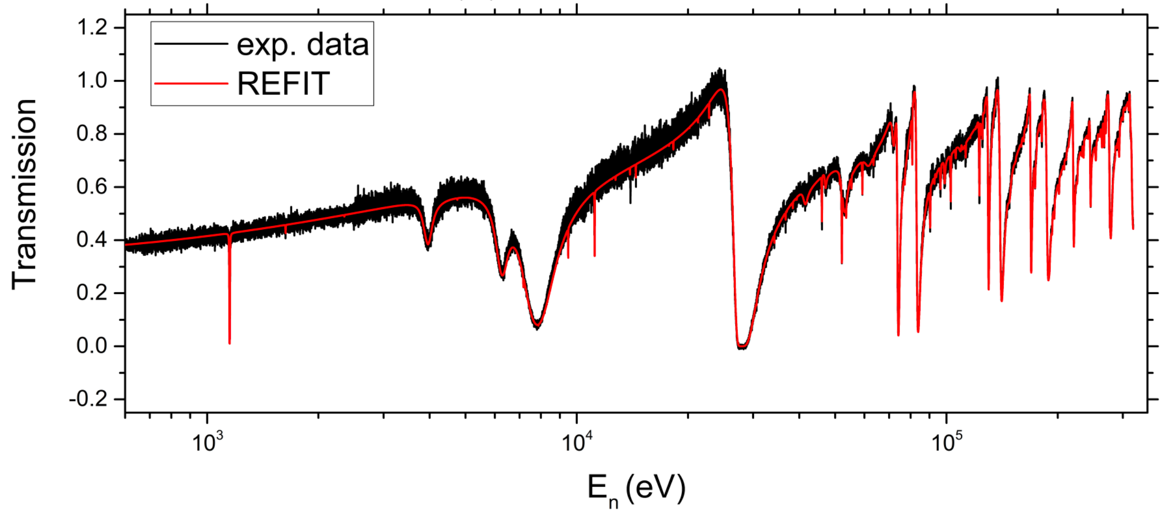


Transmission measurements at GELINA (JRC-Geel)

- The background contribution needs to be taken into account in a consistent way, with the black filters technique (*Na –Co –W).*
- $B(\mathrm{t}) = bo + b_1 e^{-\lambda 1 t} + b_2 e^{-\lambda 2 t} + b_3 e^{-\lambda 3 (t+t0)}$







- Data up to 300keV.
- First REFIT calculation with adjustment of the resonance Parameters of JEFF 3.3.

Will follow:
“Thick” sample measurement, RR analysis with CONRAD, with RRP file already available and other epxerimental data.

Calculations by Georgios with the help of Stephan Kopecky, C. Paradela, P. Schillebeckx.

Conclusions and future perspectives

Direct Capture Calculations:

- DC calculations with the pdix code completed.
- DC calculations to be continued with CONRAD => testing and adjusment of the RRP files already available and/or produced at CEA Cadarache.
- Direct capture seems important.

Neutron Scattering Measurements at GELINA:

- $^{54,56}Fe$(n,el/inl) reactions measured high resolution for the forst time with enriched targets. Finalisation of the analysis (^{56}Fe) is needed.
- New experimental campaign on Neutron Scattering Measurements on $^{63,65}Cu$ with enriched samples will be perfomed (APRENDE) at the ELISA setup, in the context of a new PhD thesis (NTUA/CEA).
- Improvement of the ELISA setup (discussions ongoing with the local staff at JRC-Geel).

Transmission Measurements at GELINA:

- Natural Fe samples of two thicknesses already measured at GELINA, analysis ongoing.
- A “thick” natural Fe sample (~9 cm) will also be measured once GELINA is functional again.

Checks at / Correction of RRP file produced with CONRAD.

THANK YOU

This work has been supported by the 2020 ARIEL EU project and EUFRAT project of the EURATOM.