

Back on the iron throne:

New measurements of the $^{56}\text{Fe}(n, \text{inl})$ and $^{56}\text{Fe}(p, \text{inl})$ cross sections

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The $^{56}\text{Fe}(n,n'\gamma)$ measurement performed at GELINA, published in 2014

PHYSICAL REVIEW C **90**, 034602 (2014)

Cross-section measurements for the $^{56}\text{Fe}(n, x n \gamma)$ reactions

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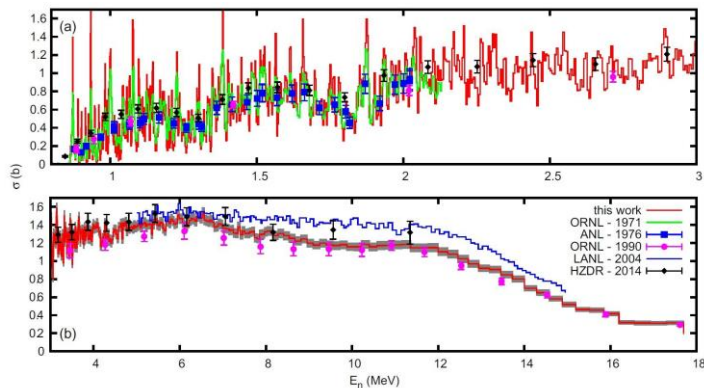
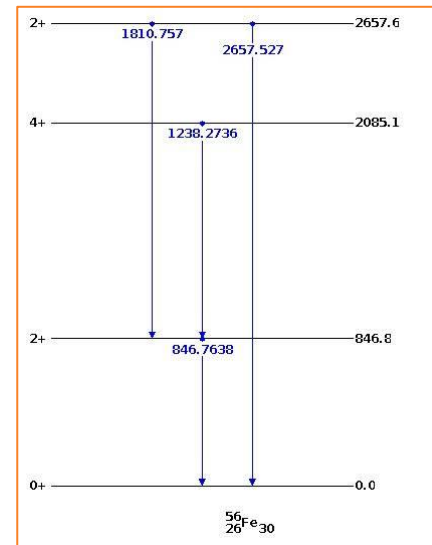


FIG. 6. (Color online) Integral production cross section for the 846.8 keV γ ray compared to several previous measurements. ORNL-1971, ANL-1976, ORNL-1990, LANL-2004, and HZDR-2014 label the results presented in Refs. [8–12], respectively. The gray band from panel (b) represents the uncertainties of our measurement.



The CIELO evaluation of $^{56}\text{Fe}(n,n'\gamma)$, published in 2018

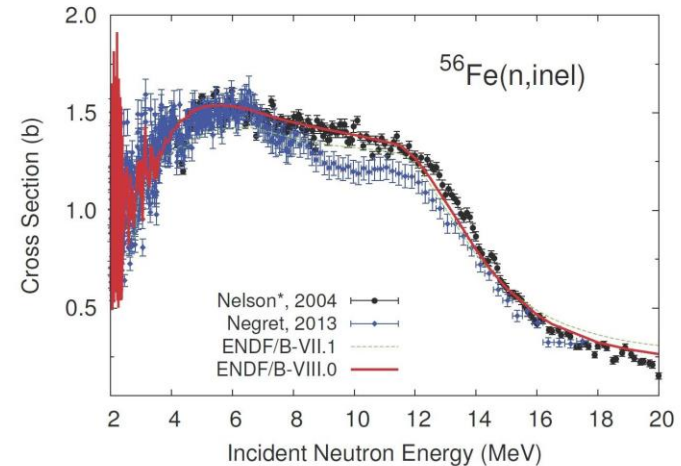


FIG. 9. (Color online) Evaluated $^{56}\text{Fe}(n, n')$ neutron inelastic cross section compared with data retrieved from EXFOR and with previous evaluation. The asterisk on the Nelson data indicates renormalization described in the text.

The INDEN evaluation of $^{56}\text{Fe}(n,n'\gamma)$, 2019

Re-evaluation of Fe-56 data based on CENDL-3.2b1

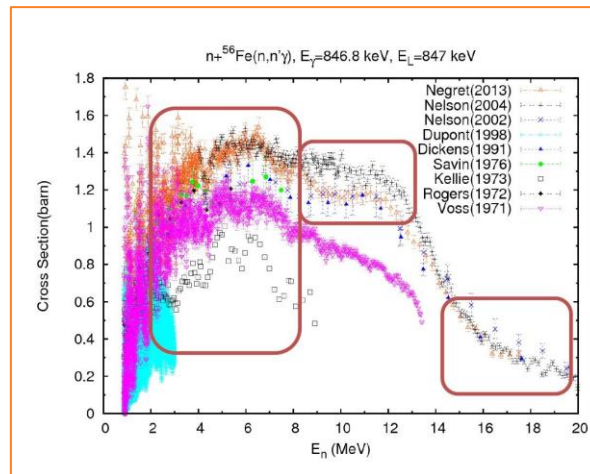
Haicheng WU

China Nuclear Data Center(CNDC)
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E-Mail: haicheng@ciae.ac.cn



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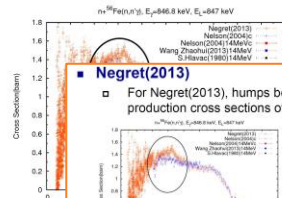
- However, the performance of these two libraries shown in iron shielding benchmarks were very poor.
 - Serious under predictions of the neutron leakage spectra are observed in the shielding benchmark testing with the IPPE iron sphere.
 - For 70cm-dia. sphere, the underestimation goes up to **50%**;
 - The bias is too large to be acceptable by shielding design.



The INDEN evaluation of $^{56}\text{Fe}(n,n'\gamma)$, 2019

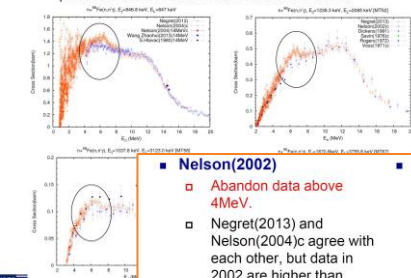
■ Nelson(2004)

- Multiplying Nelson's data with 91.754%, good agreements are shown with the Negret(2013) data above 8MeV.
- Another discrepancy region from 4-8MeV rises between Negret(2013) and Nelson(2004).



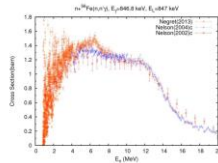
■ Negret(2013)

- For Negret(2013), humps between 4-8MeV are shown in gamma production cross sections of several discrete levels.



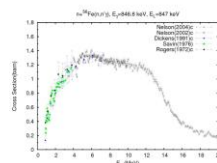
■ Nelson(2002)

- Abandon data above 4MeV.
- Negret(2013) and Nelson(2004)c agree with each other, but data in 2002 are higher than others above 14MeV.



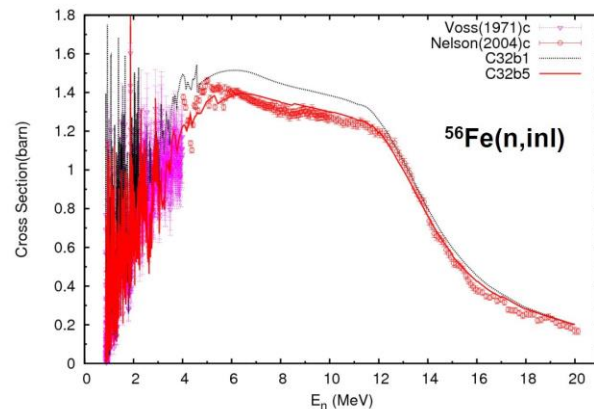
■ Dickens(1991)

- Between 7-13MeV, data of Dickens(1991) are lower than corrected Nelson(2004) which is agree with Negret(2013) above 8MeV.
- Abandon data above 4MeV.



■ Recommended data and C32b5 evaluation

- 4-20MeV, Nelson(2004)c; Below 4MeV, Voss(1971)c.
- C32b5 were evaluated based on recommended data by editing (n,inl) and (n,el) cross sections of C32b1.
- <4MeV, C32b5 was tuned to give better shielding benchmark results.



02

GAINS @ GELINA

- Experimental setup
- Measurement technique

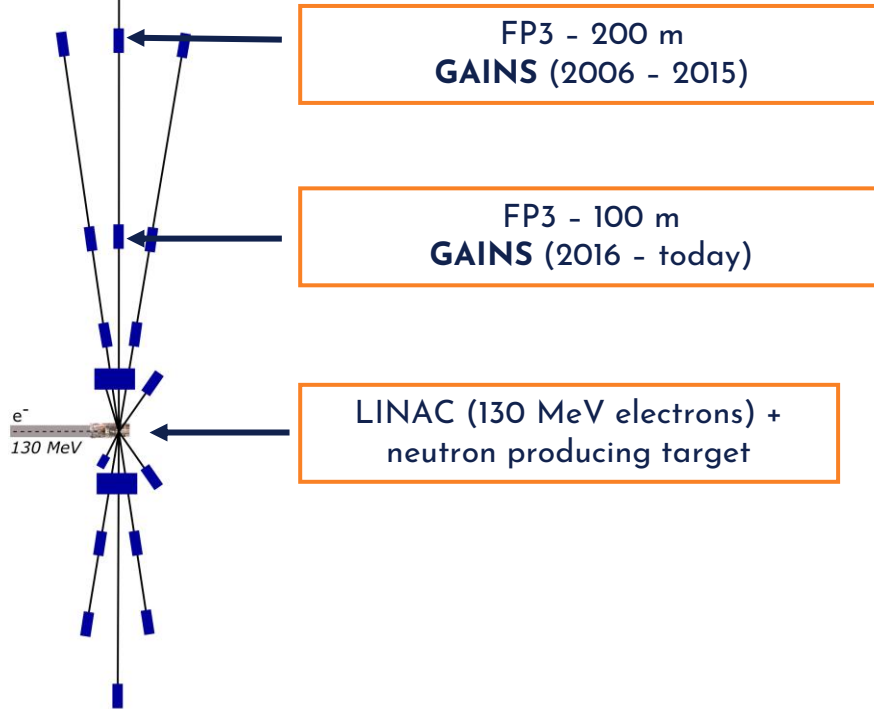


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GELINA – Geel Linear Accelerator

GELINA



GELINA

- 130-MeV electrons + ^{238}U target
- Repetition rate: 400 Hz
- Time resolution: ~ 2 ns
- Flight paths available: 10-400 m

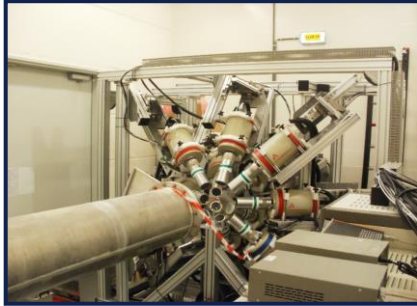
^{235}U Fission Chambers

to
monitor the beam

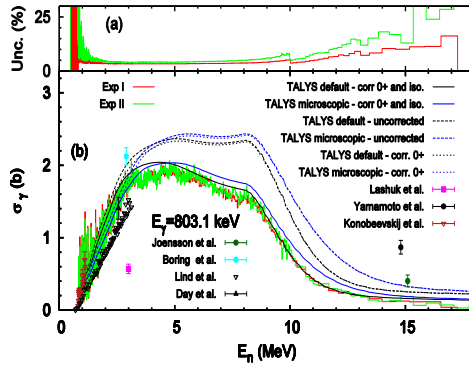
all absolute cross section values
scaled to $^{235}\text{U}(n,f)$

GAINS – Gamma Array for Inelastic Neutron Scattering

GAINS



$^{206}\text{Pb}(n, n'\gamma_{803})$



- Mostly for structural materials (light + medium elements)
- 12 HPGe detectors:
 - 4 @ 110°
 - 4 @ 150°
 - 4 @ 125°
- ^{235}U Fission chamber for beam monitoring
- Flight Path: 100 m
- Repetition rate: 400 Hz
- Neutron energy range: 0.07 - 18 MeV
- Gamma flash from bremsstrahlung
- Neutron flux ~ 2000 neutrons/cm 2 s

03

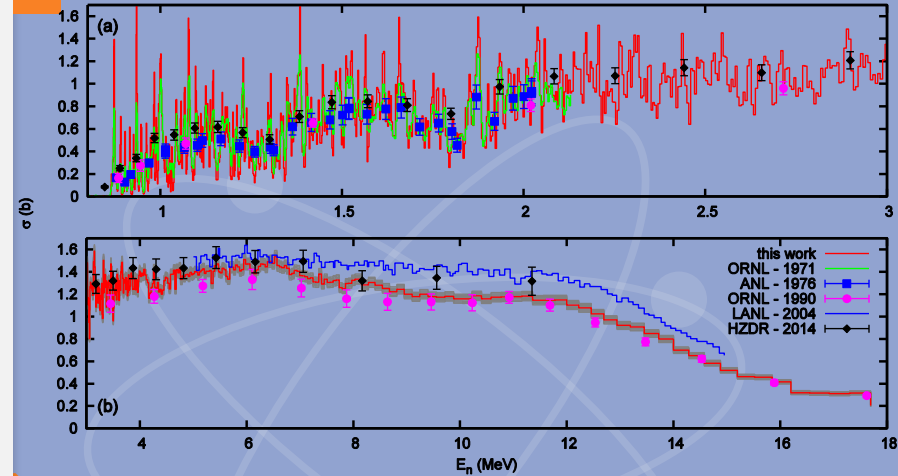
$^{56}\text{Fe}(n,n'\gamma)$

The old measurement

- Published in Physical Review C90, 034602 (2014)



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$^{56}\text{Fe}(n,n'\gamma)$: measured in 2007, final publication in 2014

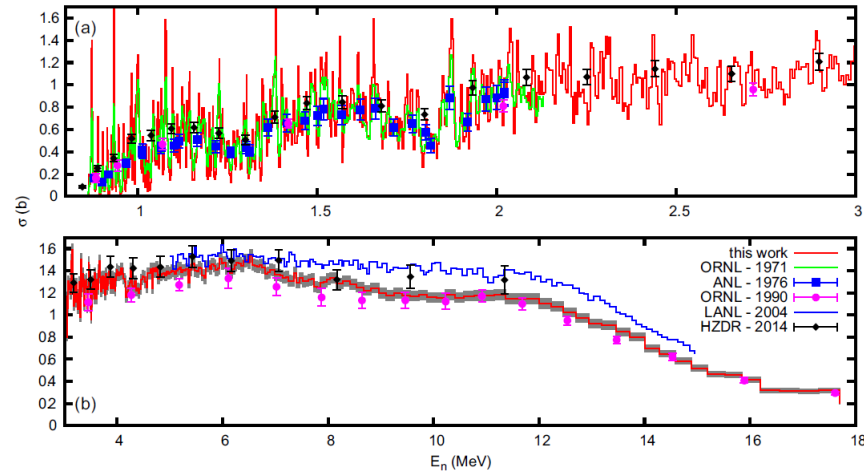
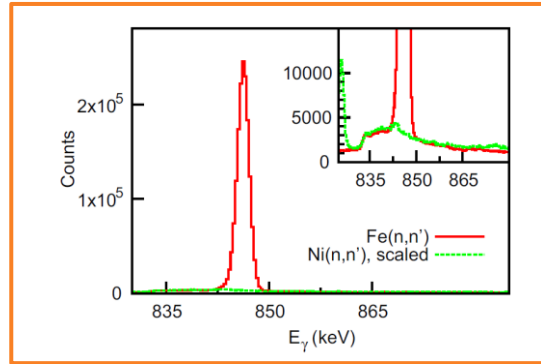
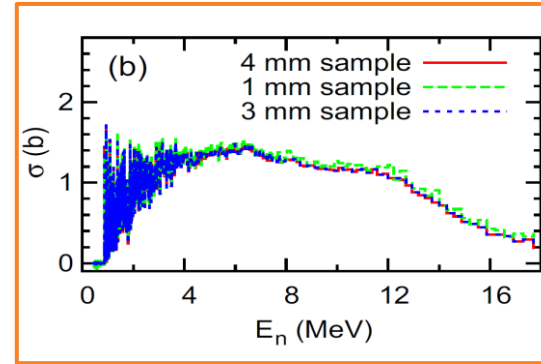


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$^{56}\text{Fe}(n,n'\gamma)$, 2014 – consistency checks



Background check
843.7 keV ^{27}Al
(834.0+recoil) keV ^{72}Ge



Sample thickness variation
(multiple scattering, self-absorption)

Other possible issues:

- $^{56}\text{Fe}(n,p)^{56}\text{Mn}$ (β^- , $T_{1/2}=2.6$ h) ^{56}Fe : continuous contribution, not significant within our effective measurement time (0.8% of the time), not observed
- Absolute scaling to the Fission Chamber yield [$^{235}\text{U}(n,F)$ cross section]: thoroughly analyzed, see A. Plompen *et al.*, J. Korean Phys. Soc. 59, 1581 (2011)

04

Back on the Iron Throne: *New measurements of $^{56}\text{Fe}(n,n'\gamma)$ and $^{56}\text{Fe}(p,p'\gamma)$*

- A project supported by UEFISCDI through the PCE2021 program



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$^{56}\text{Fe}(n,n'\gamma)$ at GAINS, JRC-Geel, Belgium

- Experiment scheduled for September 2023, postponed for the beginning of 2024

$^{56}\text{Fe}(p,p'\gamma)$ at the 9-MV Tandem of IFIN-HH, Romania

- Experiment performed in 2023, preliminary results available

Accelerator and Research reactor Infrastructures for
Education and Learning

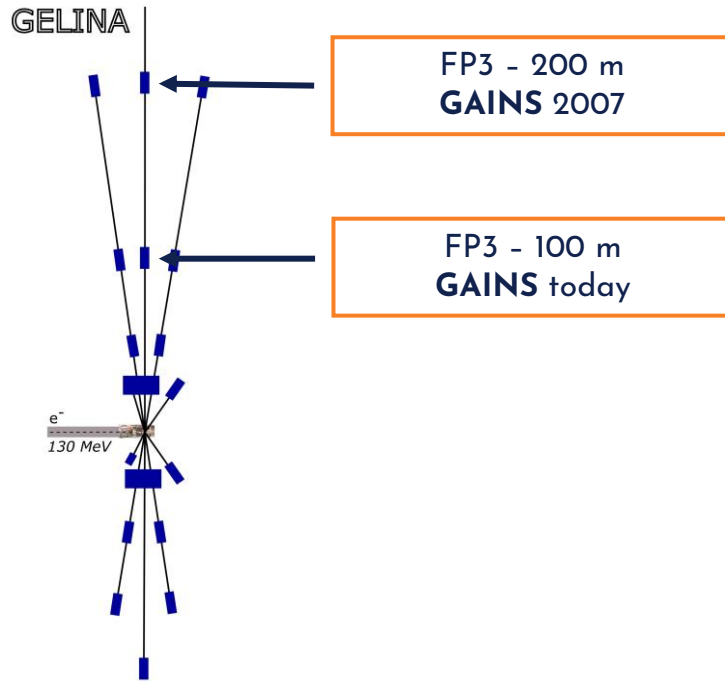
ARIEL



This project has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 847594 (ARIEL).

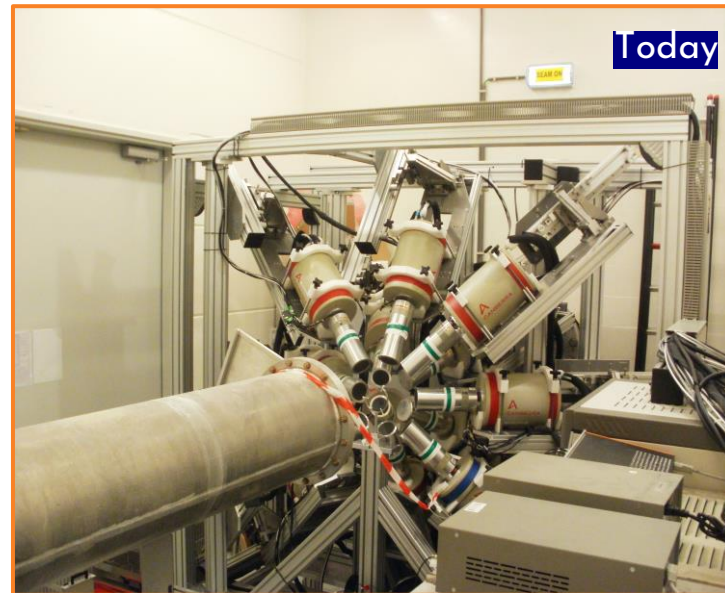


A new measurement proposed for $^{56}\text{Fe}(n,n'\gamma)$ at GAINS – main differences



Different flight path (slightly different neutron flux)

A new measurement proposed for $^{56}\text{Fe}(n,n'\gamma)$ at GAINS – main differences



Increased number of detectors (8→12), new detector holder

A new measurement proposed for $^{56}\text{Fe}(n,n'\gamma)$ at GAINS – main differences

2007-today



Acqiris DC440:

- 2 channels/card; 12 bit; 420 MHz sampling
- 1 trigger per card

Upgrade complete



Struck SIS3316-250-14 SADC:

- 16 channels; 14 bit; 250 MHz sampling
- GbE readout
- Internal triggering with external gate

New DAQ System

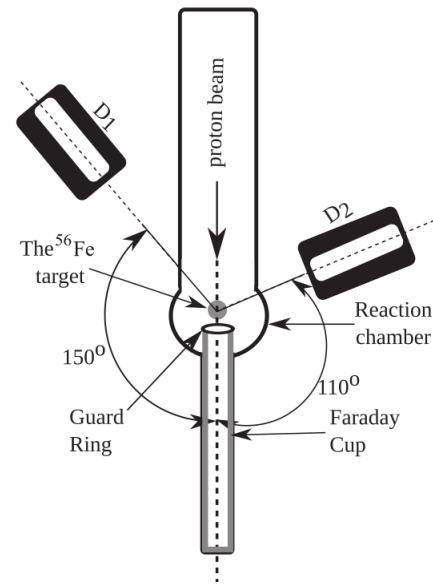
A new measurement proposed for $^{56}\text{Fe}(n,n'\gamma)$ at GAINS – main differences

- Enriched target (2024, a very expensive business!) vs. natural target (2007)
- Possibly a double normalization: Fission Chamber [$^{235}\text{U}(n,F)$] + inelastic standard (^7Li)

EXPERIMENT SCHEDULED FOR FEBRUARY-MARCH 2024

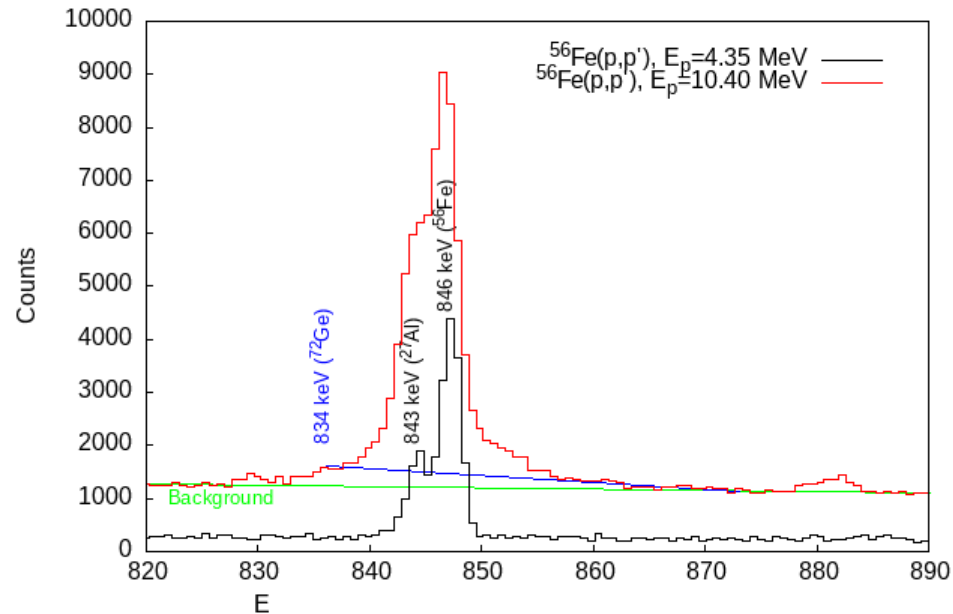
$^{56}\text{Fe}(p,p'\gamma)$ at the 9-MV Tandem

- Experiment performed in June 2023, analysis ongoing

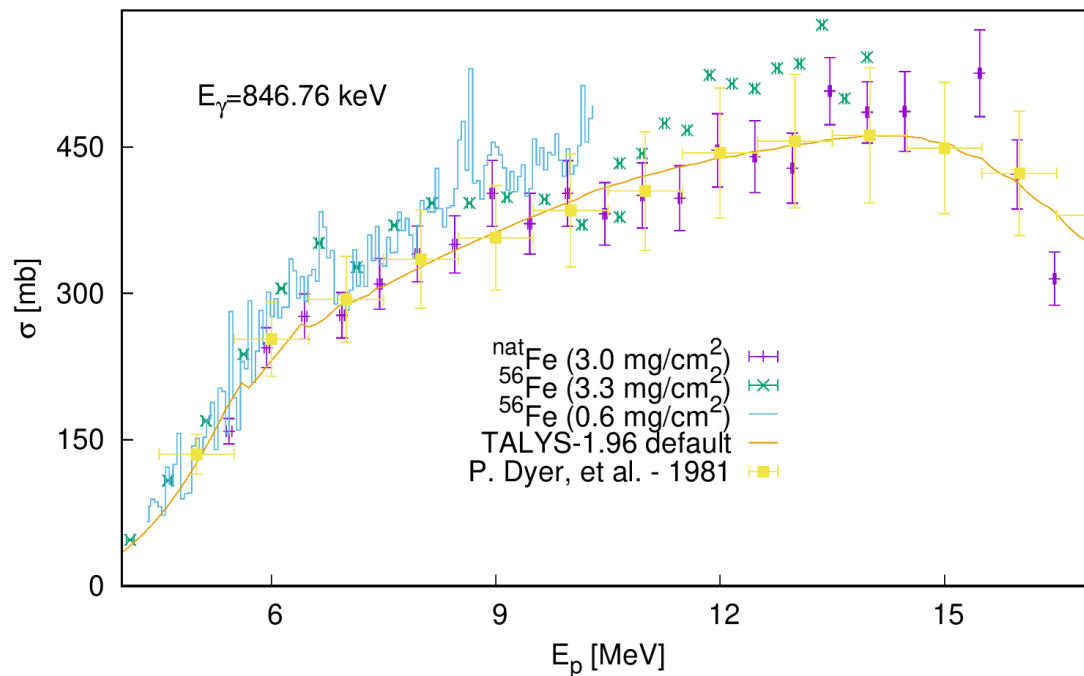


- Targets: ^{56}Fe (0.6 mg/cm^2), ^{56}Fe (3.3 mg/cm^2), $^{\text{nat}}\text{Fe}$ (3 mg/cm^2), ^{58}Ni (1.57 mg/cm^2),
- Empty frame + decay measurements
- $E_p = 4 - 17 \text{ MeV}$ in steps of 50 keV (thin ^{56}Fe target) and 300 keV (thick ^{56}Fe target)
- 2 x HPGe detectors + Faraday Cup used to integrate the beam

$^{56}\text{Fe}(p,p'\gamma)$ at the 9-MV Tandem – γ spectrum around 847 keV



$^{56}\text{Fe}(p,p'\gamma)$ at the 9-MV Tandem – very preliminary cross section for the 847-keV transition.



05

Bonus:

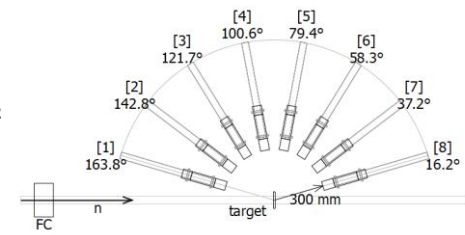
New measurement of $^{56}\text{Fe}(n,\text{elastic})$ and $^{56}\text{Fe}(n,\text{inl})$ with ELISA at GELINA

- Slides provided by Georgios Gkatis



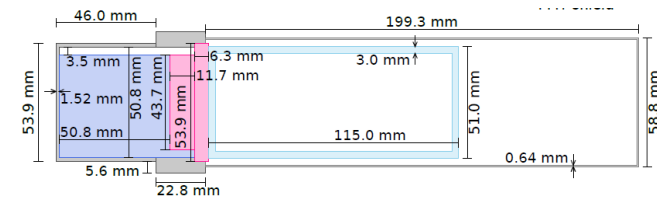
The ELISA setup

- ELISA (ELastic and Inelastic Scattering Array)
 - ^{235}U fission chamber (neutron flux)
 - **32 liquid organic scintillators** (scattered neutrons)
- **30 m** distance from the GELINA neutron source (**FP1_30m**)
- Fission chamber placed **1.37 m** from the sample
- Four sets of **8 detectors** each – mounted at specific angles
- The goal is to produce **high-resolution cross section data** of neutron scattering in the fast neutron energy range



Neutron detectors

- 32 liquid organic scintillators:
 - 16 **EJ301** – xylene (C_8H_{10}) – (**n-p**)
 - 16 **EJ315** – deuterated benzene (C_6D_6) – (**n-d**)
- Scintillation **fluorescent light** when ionizing radiation interacts with the liquid
- Two types of detection:
 - **Photons:** via Compton scattering
 - **Neutrons:** via elastic scattering on the hydrogen nuclei



Experimental details – ^{56}Fe sample

- Date: **Spring/Summer 2023**
- Duration: **700 hours** (Sample in + Sample out)
- Resolution: **10ns**
- **Enriched ^{56}Fe sample**
 - Diameter: 70 mm
 - Thickness: 1 mm
 - Mass: 31.396 g

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



Analysis

- Step 1: Characterization of the detectors (determination of the *resolution + response functions*)
- Step 2: Separate photon from neutron induced events via pulse shape analysis (*charge integration method*)
- Step 3: Background subtraction (*sample-out* measurement)
- Step 4: Elastic – Inelastic separation (*kinematics* calculations)
- Step 5: Multiple scattering correction (*Monte Carlo* simulations)
- Step 6: Calculation of the neutron fluence (*fission chamber* data analysis)
- Step 7: Cross section calculation

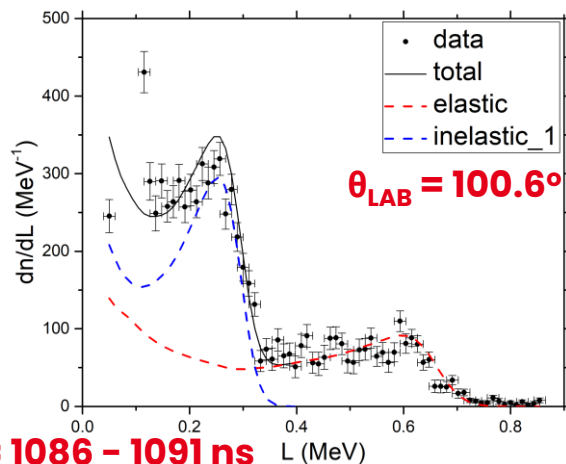
Step 3 + 4: Background subtraction/Elastic-Inelastic separation

Background contribution from beam neutrons scattering on air or various materials around the setup once or twice before reaching the detectors.

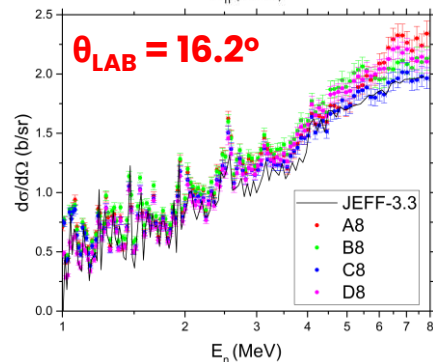
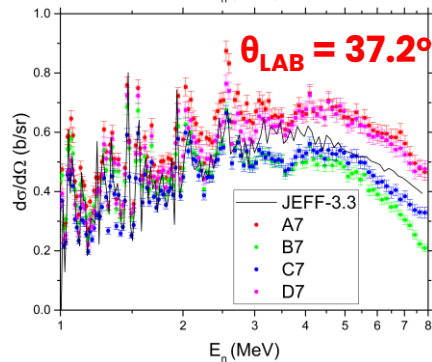
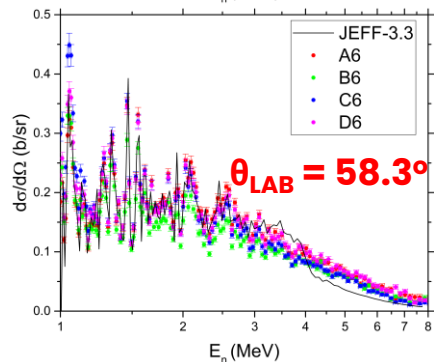
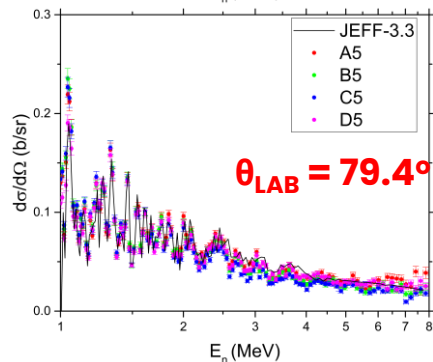
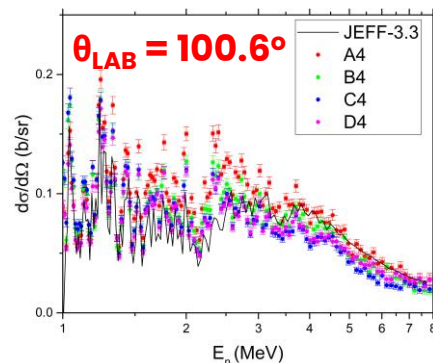
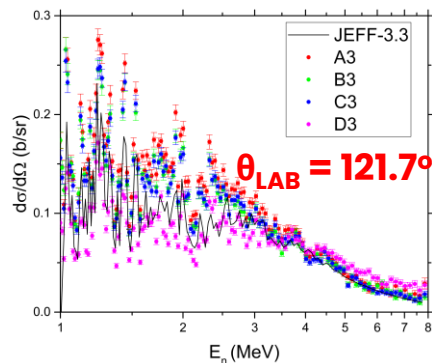
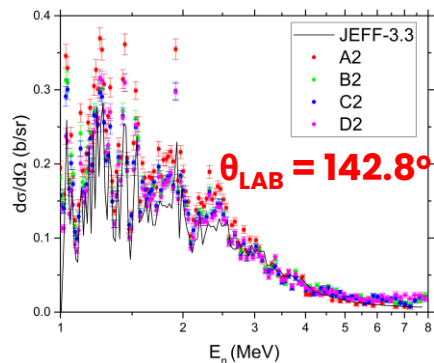
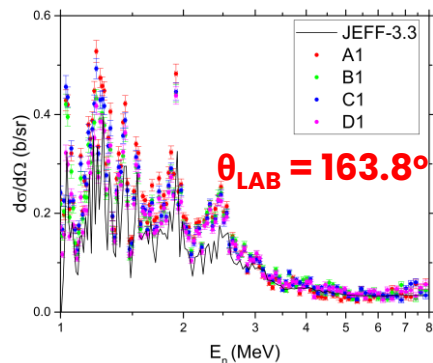
- Sample-out data (*measurement with beam but without the sample*)
- Sample-in – Sample-out normalization according to the fission counts recorded with the ^{235}U chamber

Split the neutron t.o.f. spectrum in small intervals of **5 ns** each (*time resolution of the measurement*)

- Knowing the neutron incident energy and the detection angle – via kinematics calculation determine the energy of the neutrons scattered elastically E'_{el} and inelastically E'_{inl}
- Overlaps in the LO distribution of these 2 neutron energies – proper threshold application



Preliminary results of the $^{56}\text{Fe}(n,n) - (\text{JEFF-3.3})$

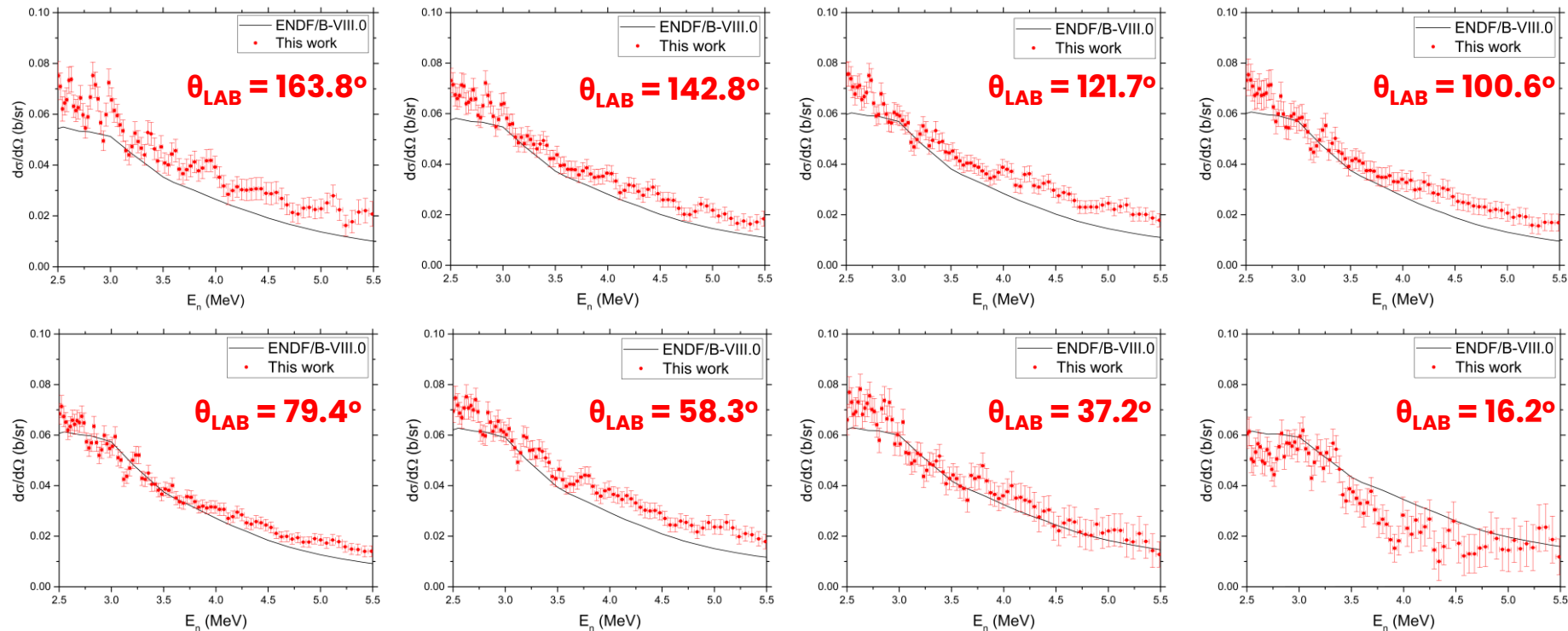


Inelastic scattering with the ELISA setup

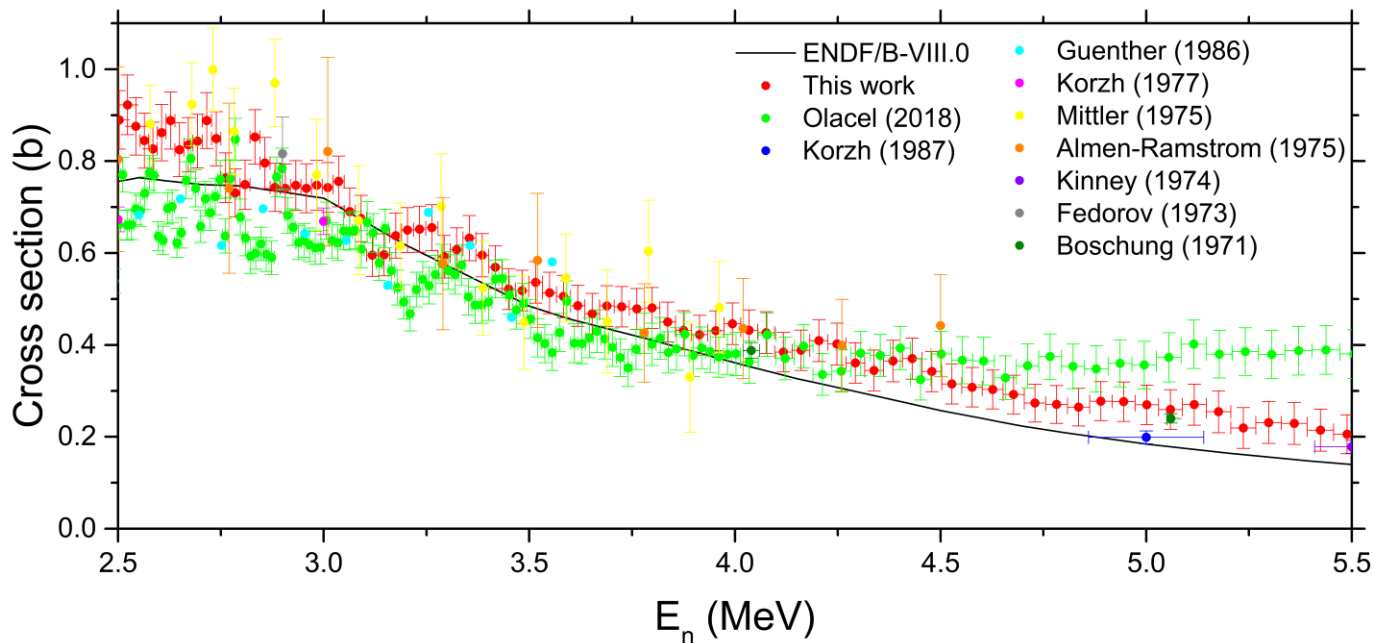
- Inelastic scattering can be extracted using the ELISA setup via **neutron spectrometry**
- $^{54}\text{Fe}(n,n_1')$ cross section was calculated from the first excited state of ^{54}Fe ($E_x = \mathbf{1.4082\text{ MeV}}$) in an old experiment
- $^{56}\text{Fe}(n,n_1')$ cross section from the first excited state of ^{56}Fe ($E_x = \mathbf{0.8468\text{ MeV}}$) will be explored soon
- Resolution of the detectors does not allow to distinguish between neutrons scattered from levels close to each other

2.9590	2.9600	2.9880	2.9700
2.9000	2.9415		
2.5613	2.6576		2.6004
2.5381			
			2.2580
	2.0851	1.9910	2.0765
		1.7254	1.6747
		1.3568	
		1.0071	
		0.8468	0.8108
		0.7064	
		0.3668	
		0.1365	
		0.0144	
^{54}Fe	^{56}Fe	^{57}Fe	^{58}Fe

Results of the $^{54}\text{Fe}(n,n_1')$ – ($E_x=1.408$ MeV)



Results of the $^{54}\text{Fe}(n,n_1')$ - (Angle-integrated)



06

Conclusions



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Conclusions

- A new measurement of the $^{56}\text{Fe}(n,n'\gamma)$ cross sections is planned at GELINA using the GAINS spectrometer, numerous differences/upgrades compared to the previous measurement (2007) are foreseen,
- A new measurement of the $^{56}\text{Fe}(p,p'\gamma)$ cross sections was performed at the 9-MV Tandem of IFIN-HH, preliminary results were shown,
- A new measurement of the $^{56}\text{Fe}(n,\text{elastic})$ cross section was performed using the ELISA setup at GELINA, data analysis is ongoing.

Thanks

Do you have any questions?

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