Investigating neutron scattering with surrogate proton induced reactions

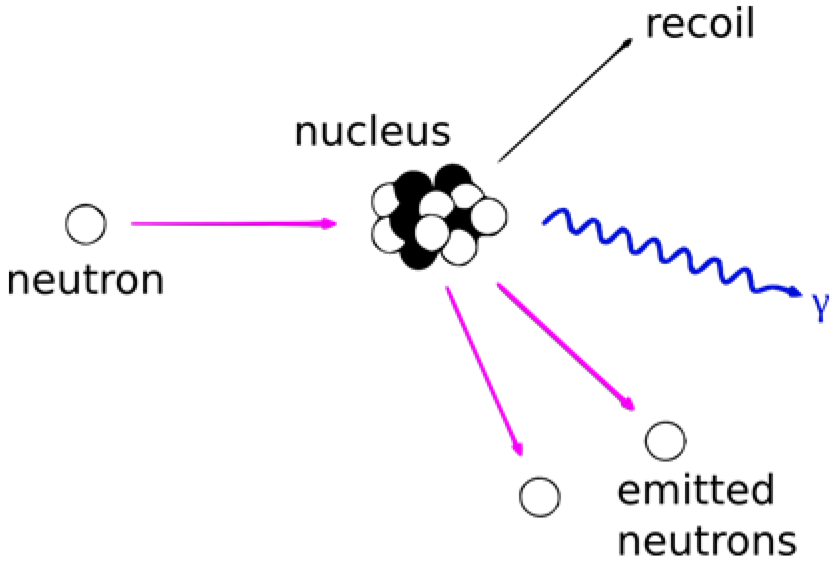
Greg Henning, M. Kerveno, Ph. Dessagne, N. Dari-Bako (Université de Strasbourg, Centre National de la Recherche Scientifique, IPHC UMR 7178, F-67000 Strasbourg, France)
A. Coman-Olacel, M. Boromiza, C. Borcea, A. Negret, A. Gandhi, D. Chiriac (Horia Hulubei National Institute for Physics and Nuclear Engineering, Reactorului 30, 077125 Bucharest-Măgurele, Romania)
A. Plompen, M. Nyman, A. Oprea, C. Paradela (European Commission, Joint Research Centre, Retieseweg 111, B-2440 Geel, Belgium)

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

Neutron scattering reactions

(n, n’) and (n, n’ γ) reactions

- Energy loss mechanism for neutrons
- Production of gamma rays
- Interaction by nuclear force only
- Modify neutron multiplicity and creates new isotopes
- Contribute to non-local couplings in power map of reactors.



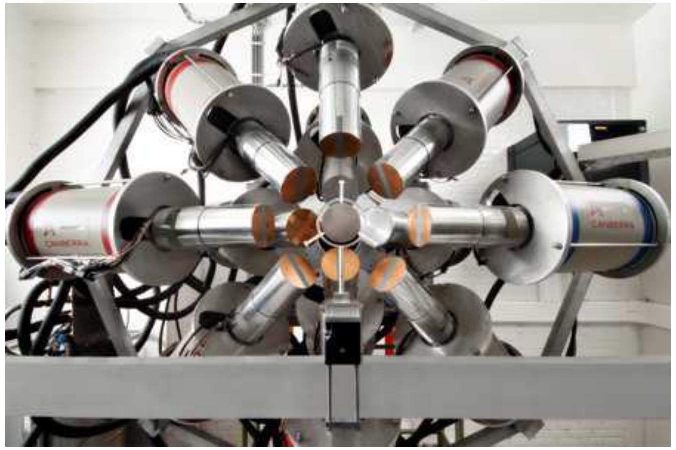
Improving evaluations for new fuel cycles

- With new fuel cycles using fast neutrons and/or different isotopes, current knowledge focused on $^{235}U(n_{thermal},*)$ reaction is not enough to characterize properly Gen IV designs [1].
- Including O, F, Na, Pb, ^{232}Th, ^{233}U, ^{239}Pu, …
- With a focus on fast neutrons

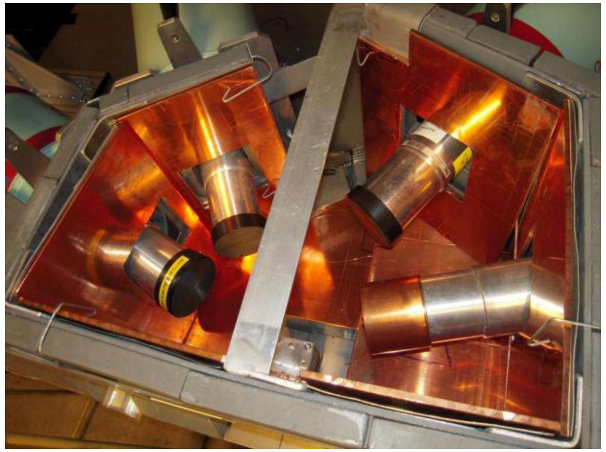
[1] NEA, International Evaluation Co-operation, Volume 26 (2008)

GAINS and GRAPhEME

- Two γ ray detector setups installed at the Gelina facility (JRC-Geel).
- **GAINS**: 12 HPGe, 100 m flight path, focus on lighter nuclei with high energy γ rays
- **GRAPhEME**: 6 planar HPGe, 30 m flight path, focus on radioactive samples (Th, U, Pu), low E_γ.



GAINS

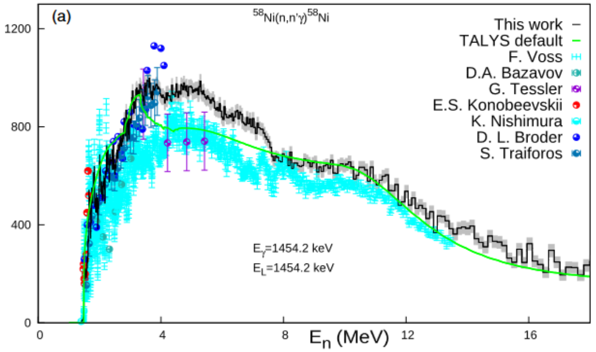


GRAPhEME

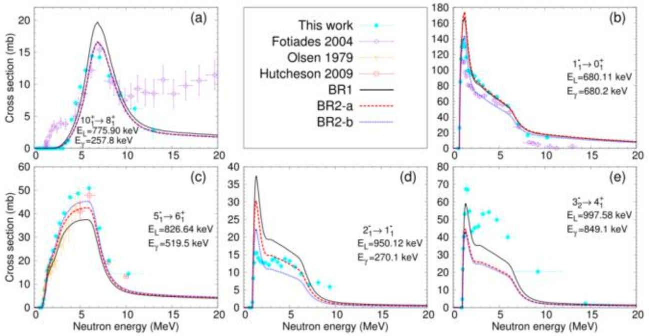
M. Kerveno et al,. EPJ Web of Conferences 239, 01023 (2020)

Previous results

- **GAINS**: ^{7}Li, ^{12}C, ^{16}O, ^{23}Na, ^{24}Mg, ^{28}Si, ^{nat}Mo, ^{52}Cr, ^{56}Fe, ^{57}Fe, **^{58}Ni**, ^{76}Ge, ^{nat}Zr, ^{206,207,208}Pb, ^{209}Bi
- **GRAPhEME**: ^{57}Fe, ^{90}Zr, ^{232}Th, ^{235,233,}**^{238}U**, ^{nat,182,184,186}W, ^{239}Pu



A. Olacel et al, Phys. Rev. C 106, 024609 (2022)



M. Kerveno et al. PRC 104 , 44605 (2021)

Surrogate-like proton induced reactions

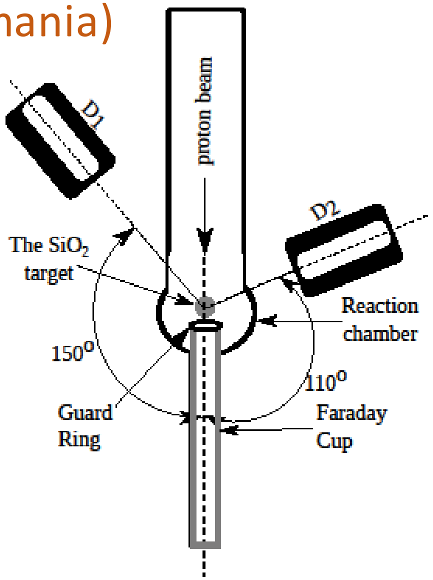
(p, p’) reactions

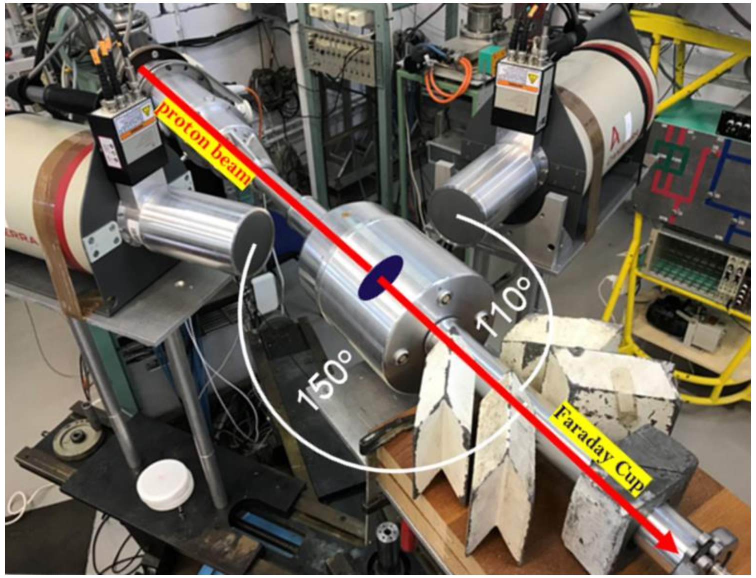
+ Small size beam, need less target material.
+ Precise energy control → down to 25 keV energy steps.

- Extracting information about the isospin-dependent term & Lane consistency of the nucleon-target OMP.
- Also provide nuclear data relevant for other fields (e.g. for proton therapy on O).

(p, p’ γ) measurements at the 9 MV Tandem of IFIN-HH (Romania)

- 2 HPGe detectors @ 110° and 150 °
- FASTER digitizers
- Faraday cup for beam integration
  → absolute cross sections





A. Olacel et al, “The past and the future of the GAINS spectrometer @ GELINA”, ND 2022

••• Data analysis

Differential cross-section

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi} \frac{N_{\gamma} \cdot A}{N_p \cdot \varepsilon_{\text{det}} \cdot \rho_x \cdot f} \cdot d$$

$\frac{d\sigma}{d\Omega}$ ⟶ Differential cross section
Ω ⟶ Solid angle
N_p ⟶ Number of incident protons on the target
ε_{det} ⟶ HPGe detector efficiency
ρ_x ⟶ Areal density of the target
f ⟶ Atomic mass scaling factor
d ⟶ Dead time correction factor
N_{γ} ⟶ Number of counts from a given gamma peak

→ Efficiency determined by combination of experimental data(^{152}Eu)and MCNP-6 simulation for extrapolation to higher gamma energies.

Integrated cross-section

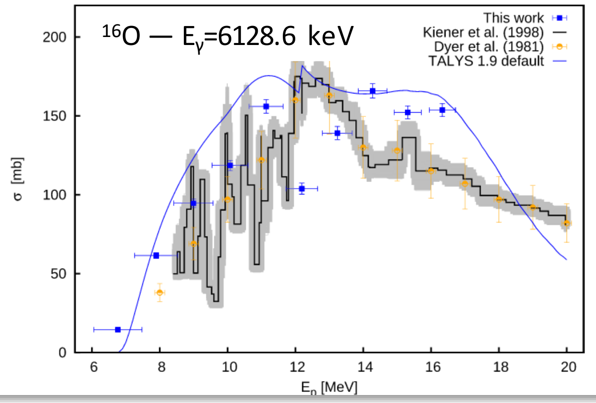
Combine differential cross section at two specific angles (110° and 150°) following the Quadratic Gaussian method that relies on Legendre Polynomial expansion of the γ-emission spatial emission distribution.

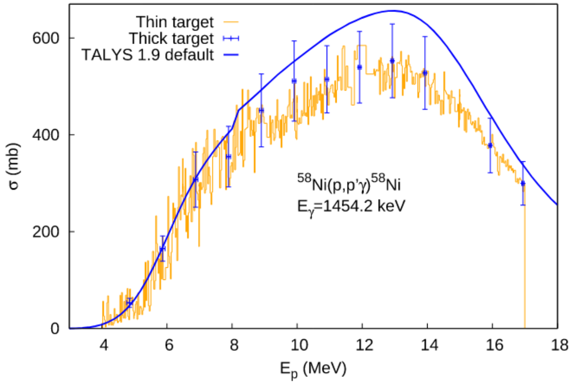
$$\sigma_{\text{int}} = 2\pi[w_{110^\circ} \cdot \frac{d\sigma}{d\Omega}(110^\circ) + w_{150^\circ} \cdot \frac{d\sigma}{d\Omega}(150^\circ)]$$

Surrogate-like proton induced reactions

Previous studies:

- ^{24}Mg (A. Olacelet al. Phys. Rev. C 90, 034603 (2014))
- ^{16}O, ^{28}Si (M. Boromiza et al. Phys. Rev C 101, 024604 (2020))
- ^{57}Fe (D. Stoicescu et al., AIP Conf.Proc. 2076 (2019) 1, 06000S
- ^{58}Ni (A. Olacel et al. Phys. Rev. C 106, 024609 (2022))

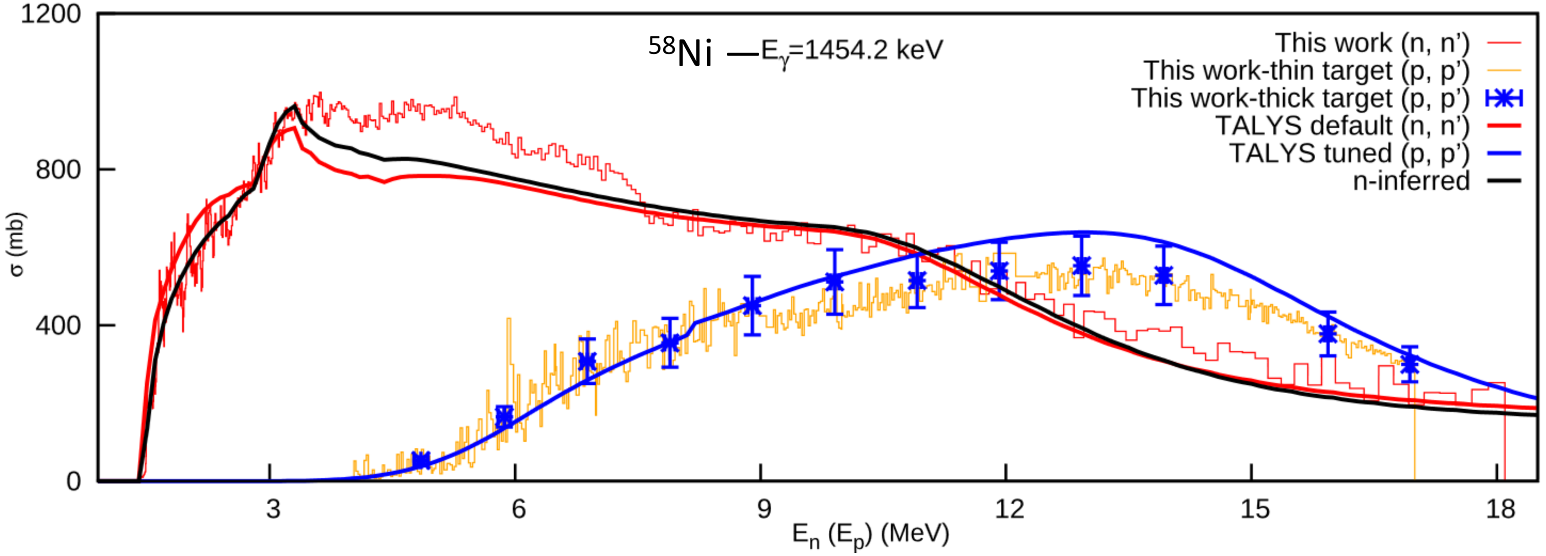




Inferring OMP parameters from (p, p' γ)

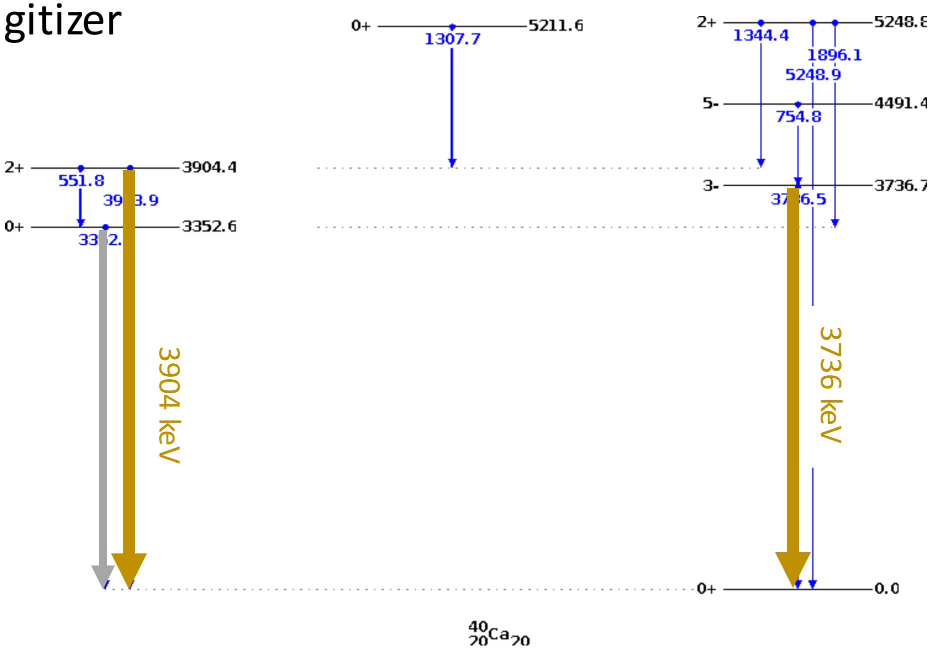
- Exploring the Lane-term of the OMP with Z≠N
- Tuning the OMP parameters on proton induced data and using them in the neutron calculations (after removing Coulomb part).

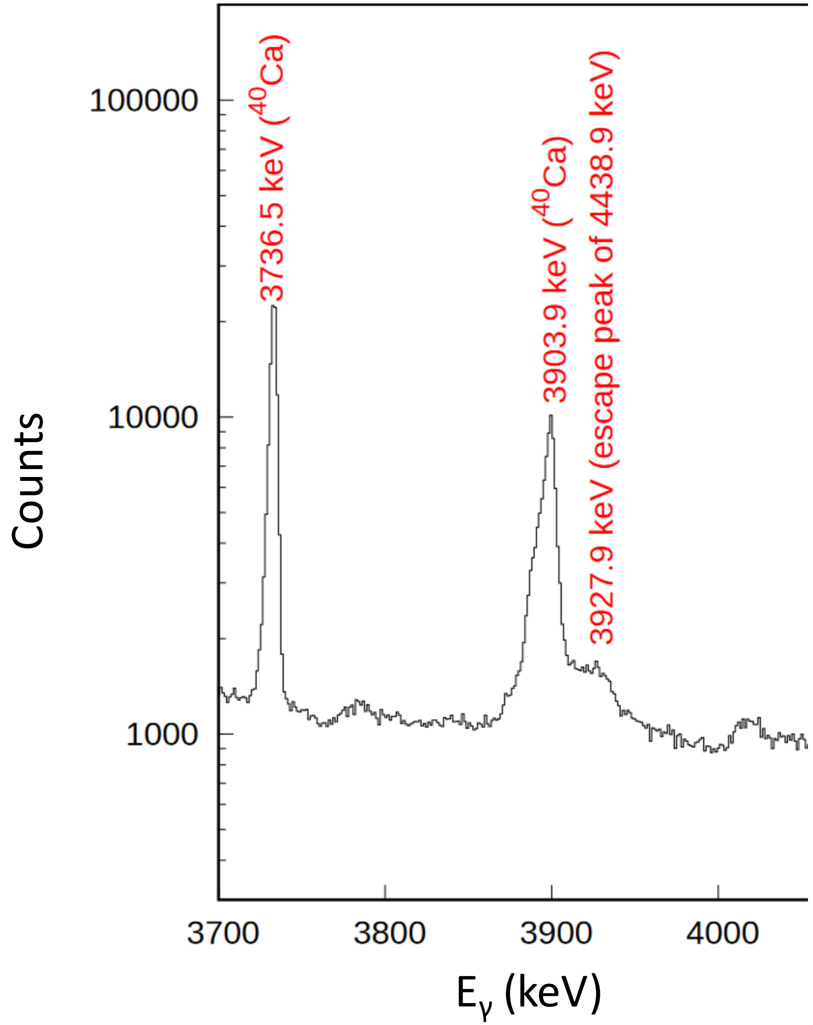
(A. Olacel et al. Phys. Rev. C 106, 024609 (2022))



(p, p' γ) experiment

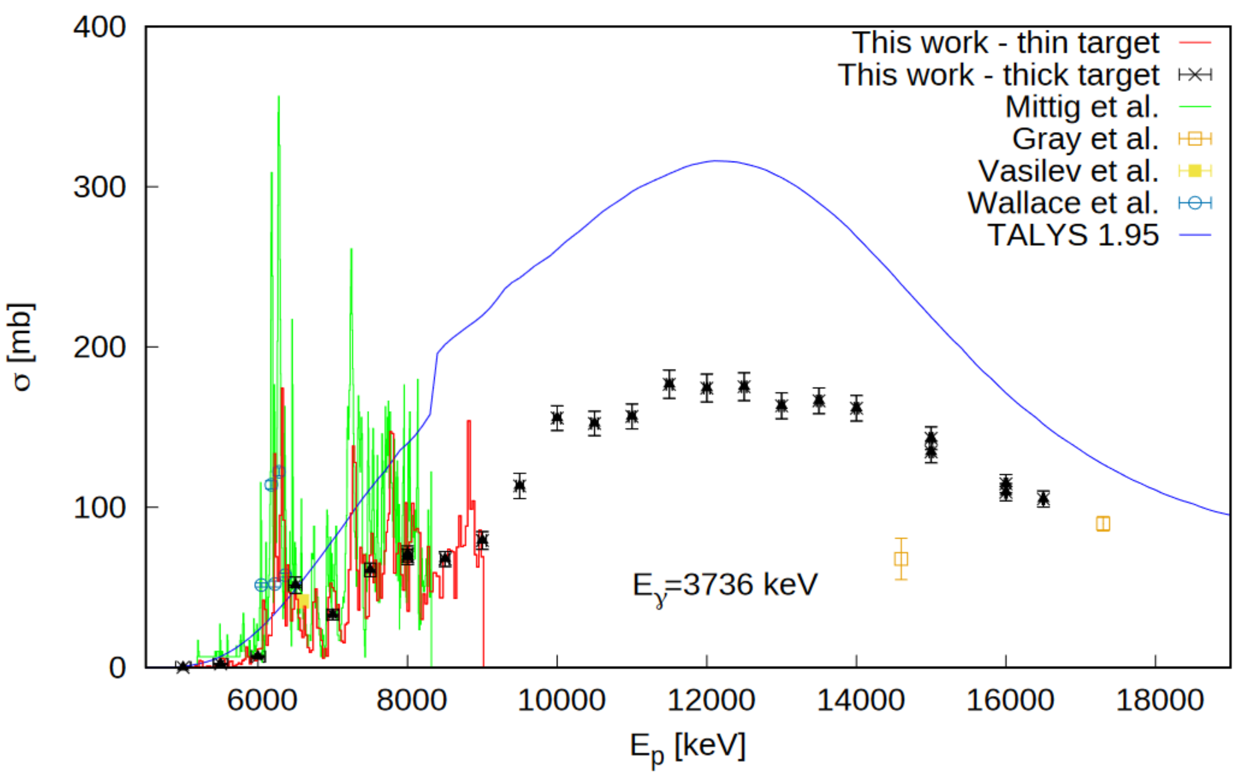
- Ran in spring 2022
- Around 200 recorded points : 5 to 9 MeV with 25-keV steps ; 9 to 16.5 MeV with 0.5 MeV steps.
- Two CaF_2 targets: thin (0.4 mg/cm^2) and thick (2.7 mg/cm^2)
  - Proton Energy loss in the target leads to some Ep uncertainty.
- Two HPGe @ 110 and 150 degrees + Faraday cup
- FASTER digitizer



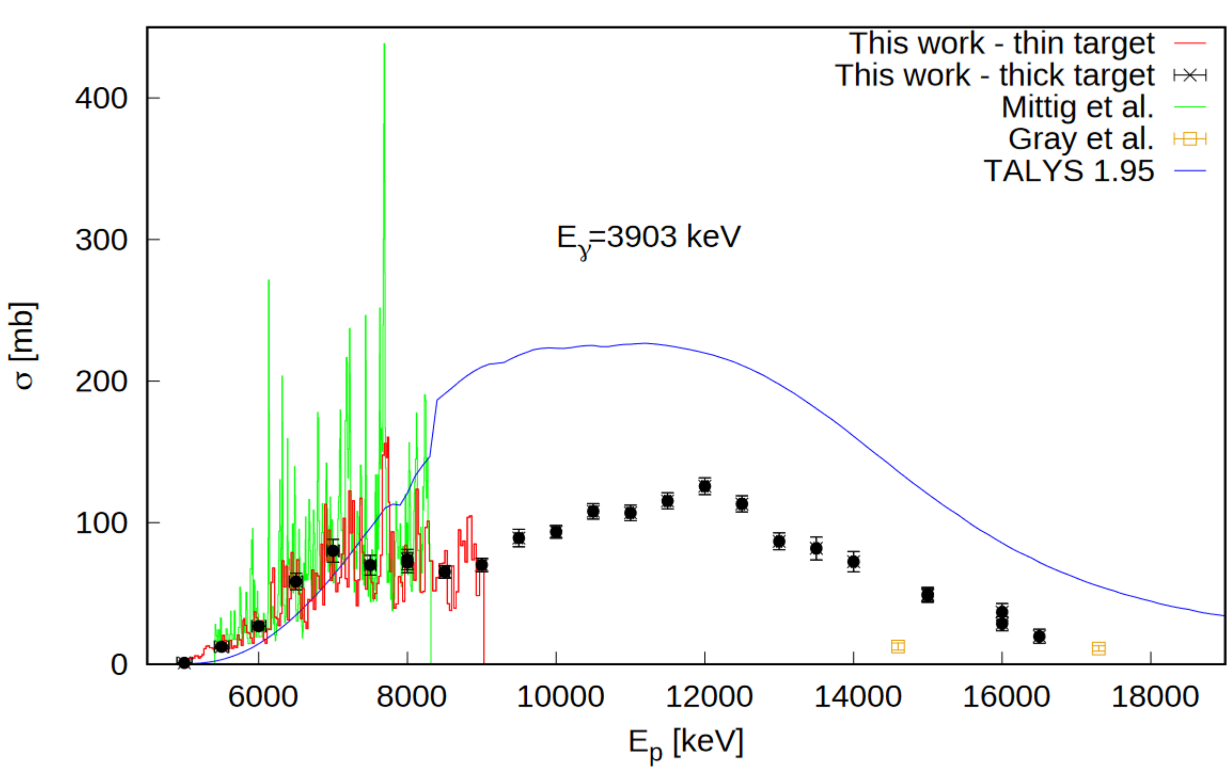


••• $^{40}Ca(p, p' \gamma)$ measurements at IFIN-HH – ARIEL Support TAA_2_2

3736 keV transitions



3903 keV transitions

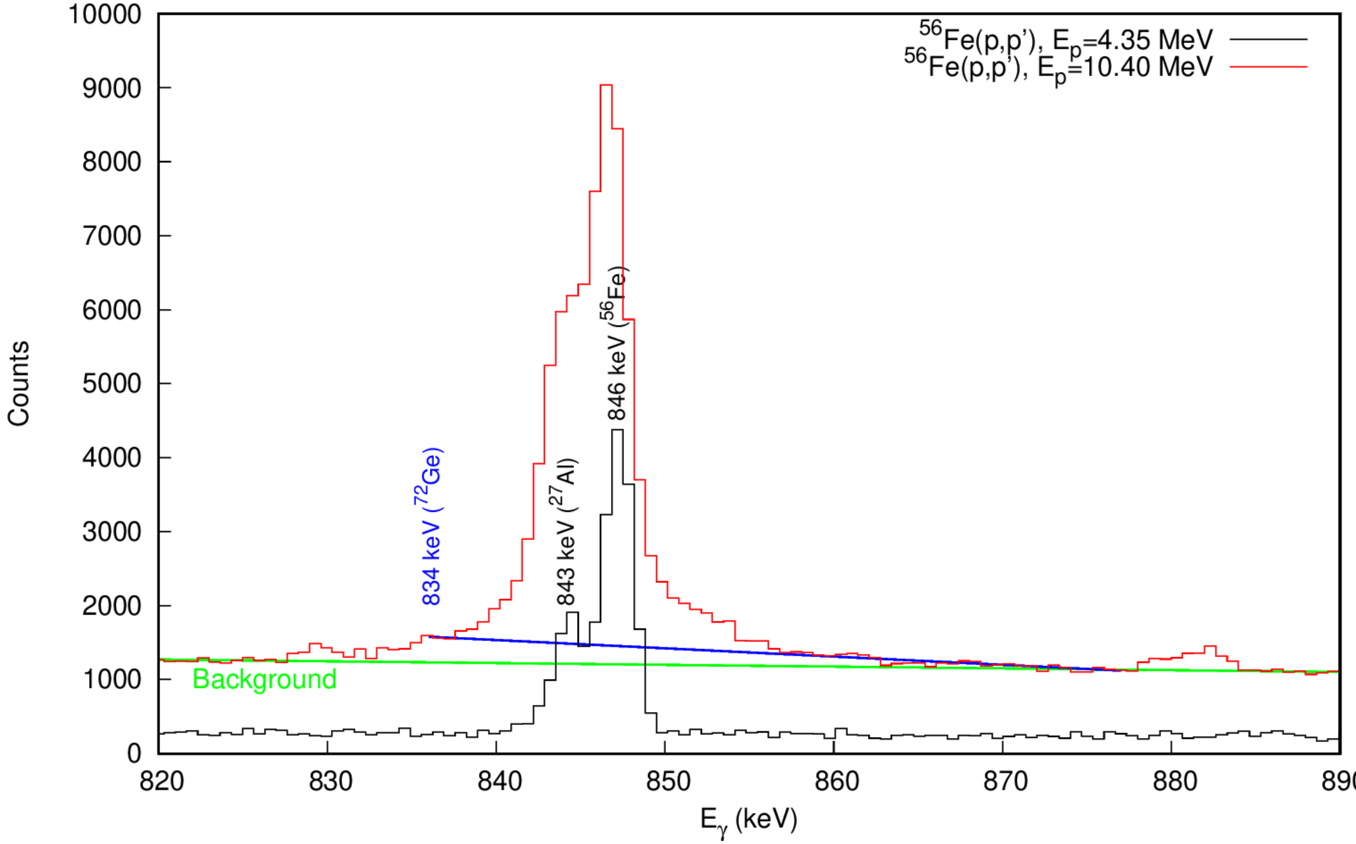


Agreement between thick and thin target gives confidence in results.

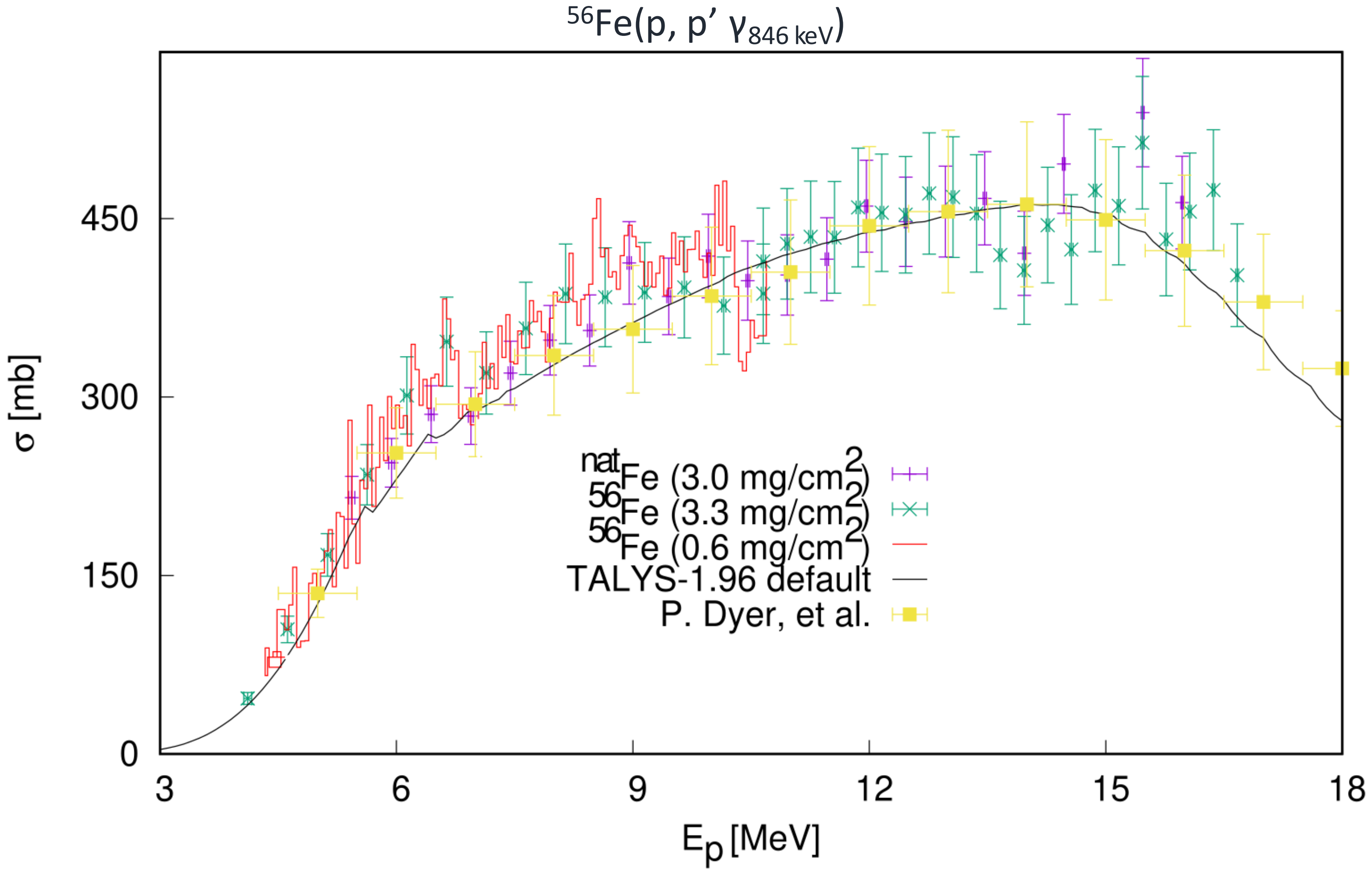
^{56}Fe(p, p' γ) measurements at IFIN-HH – ARIEL Support TAA_6_6

(p, p' γ) experiment

- Ran in spring 2023 at IFIN-HH
- 99.77 % ^{56}Fe enriched target
- Primarily looking at the 846.7 keV γ ray (decay from 1st excited state).
- 4 to 10 MeV with 50-keV steps with thin target (0.6 mg/cm^2)
- 4 to 17 MeV with 300 keV steps, with thick target(3.3 mg/cm^2)
- Beam off recording to estimate the (p,n)^{56}Co contribution ($T_{1/2}$= 77.21 days).
- Recording with ^{58}Ni target to estimate ^{27}Al backing contribution in 843 keV peak.



^{56}Fe(p, p' γ) measurements at IFIN-HH – ARIEL Support TAA_6_6



Agreement between different targets, and with other data.

Conclusion and perspectives

Conclusions

- ^{40}Ca (p, p' γ) has been obtained at IFIN-HH in Spring 2022.
- ^{56}Fe (p, p' γ) in summer 2023.
- Experimental results consistent across different target thickness and with other data.
- First results with OMP tuned on (p, p') reaction for (n, n') inference are promising (See on 58Ni, A. Olacel et al. Phys. Rev. C 106, 024609 (2022)).
- Continuous and fruitful collaboration between IFIN, JRC and IPHC

Work left to be done

- ^{56}Fe(n,n'γ) to be measured at Gelina (delayed due to beam issues)
- Calculations & Comparison of the proton and neutron inelastic data

Outlook

- Corresponding (n, n' γ) data recorded (or to be recorded) with GAINS at Gelina (JRC-Geel) (analysis in progress.)
- Articles writing (🎯 mid-2024 for ^{40}Ca)
- Data to be sent to Exfor.

- (n, n') OMP inference from (p, p') tuning to be continued.