

Nuclear Structure and Reaction Data for Reactor Applications at IPHC

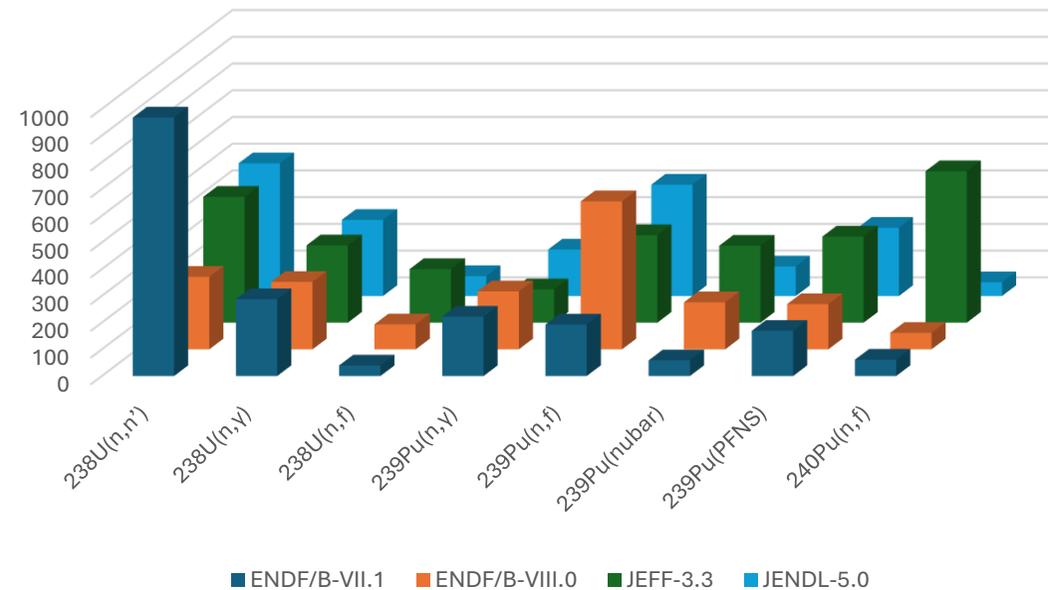
- Context and motivation
- Work and results from IPHC
- Perspectives for the next decade
- Summary and conclusions

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Context and motivation

The development and study of Nuclear application projects rely on numerical simulations, themselves making use of evaluated data bases to model microscopic processes.

Top contributors to the k_{eff} uncertainty by isotope and reaction in SFR



Oscar Cabellos, et al., EPJ Web of Conf., 294 (2024) 05003

Hence, world wide effort in providing new data, improve models and better evaluations .

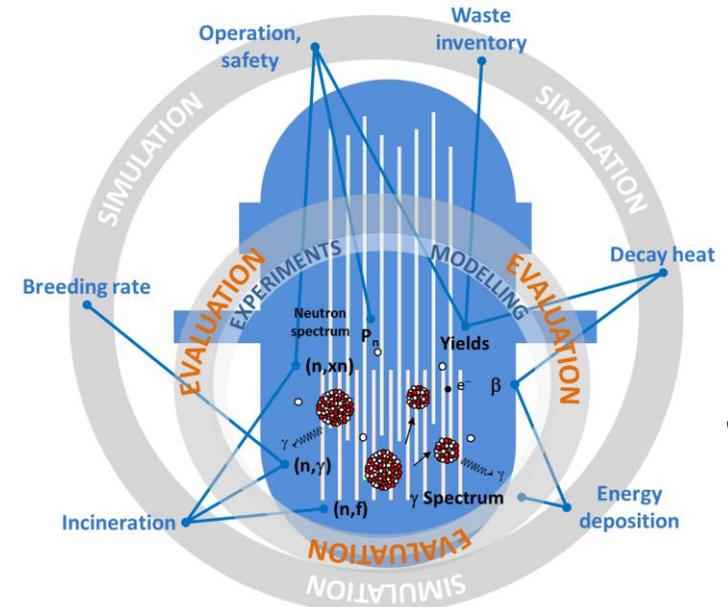


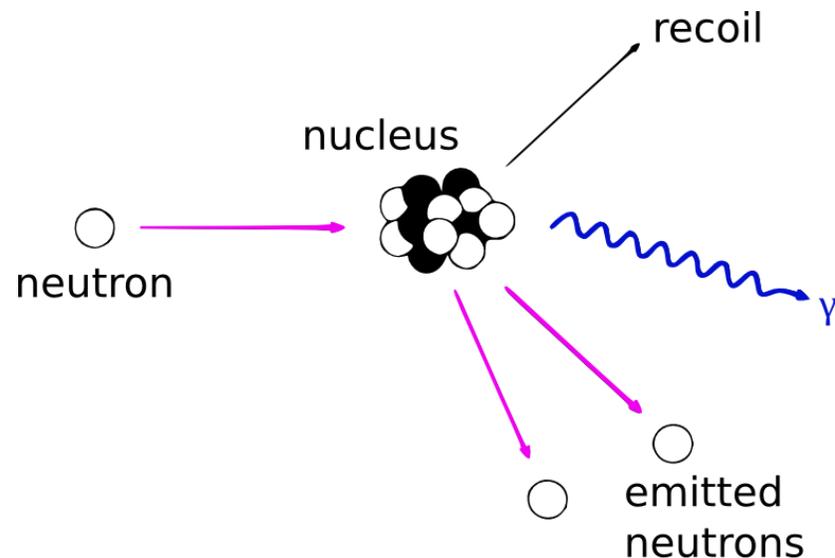
Image : M. Kerreno

But, current evaluation do not provide accurate enough data to reach the target precision for future reactor applications.

ID	Type	Target	Reaction	Quantity	Energy	Accuracy (%)	Status	Last update
120	H	95-Am-241	(n,g)Am-242g,m	BR	0.2 eV - 1.5 eV	5	Work in progress	2023-Jun-06
121	S	8-O-16	(n,xα)	DE	20 MeV - 200 MeV	10	Work in progress	2023-May-20
119	H	17-Cl-35	(n,p)	SIG	100 keV - 5 MeV	5-8	Work in progress	2022-Apr-17
118	H	68-Er-167	(n,g)	SIG RP	0.01 eV - 100 eV	2	Work in progress	2021-Aug-30
117	H	3-Li-0	(d,x)H-3	SIG TTY	5 MeV - 40 MeV	10	Work in progress	2021-May-31
116	H	3-Li-0	(d,x)Be-7	SIG	10 MeV - 40 MeV	10	Work in progress	2021-May-31
115	H	94-Pu-239	(n,tot)	SIG	Thermal - 5 eV	1	Work in progress	2019-Apr-08
114	H	83-Bi-209	(n,g)Bi-210g,m	BR	500 eV - 300 keV	10	Work in progress	2018-Nov-09
113	S	69-Tm-169	(n,2n)	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06
112	S	53-I-127	(n,2n)	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06
111	S	41-Nb-93	(n,2n)Nb-92m	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06
110	S	40-Zr-90	(n,2n)	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06
109	S	39-Y-89	(n,2n)	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06
108	S	33-Ag-75	(n,2n)	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06
107	S	28-Ni-58	(n,2n)	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06
106	S	27-Co-59	(n,2n)	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06
105	S	25-Mn-55	(n,2n)	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06
104	S	9-F-19	(n,2n)	SIG/SPA	239Pu(n,f)	3	Work in progress	2018-Jun-06

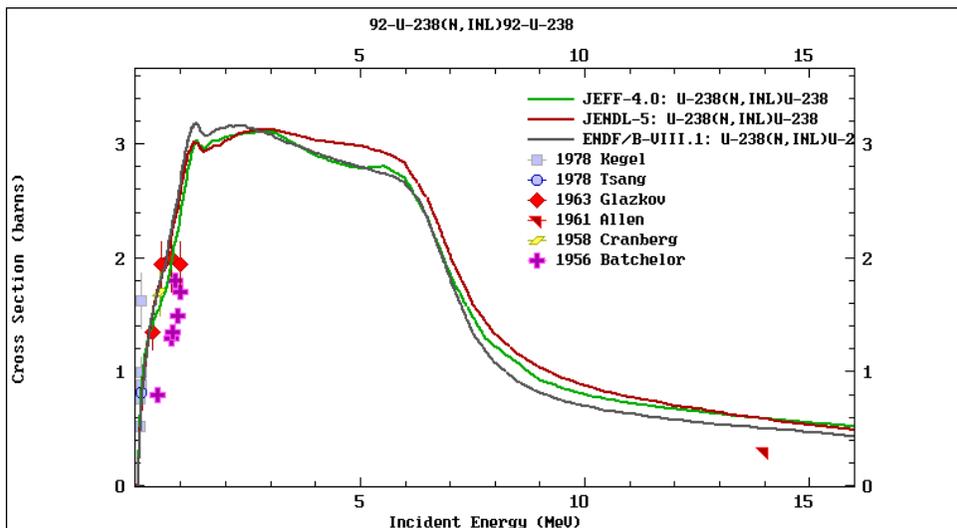
HPRL Nuclear Energy Agency

Inelastic neutron scattering (n, n') and (n, xn) has some special interest: it modify the neutron energy spectrum, and, when $x \geq 2$, their number, and create new isotope.



ID ↓	Type	Target	reaction (n, inl)	Quantity	energy Min	Max	Accuracy (%)	Status	Last update ↑
42	H	82-Pb-207	(n, inl)	SIG	0.5 MeV	6 MeV	3-9	Pending new evaluation or validation	2008-Sep-15
41	H	82-Pb-206	(n, inl)	SIG	0.5 MeV	6 MeV	3-9	Pending new evaluation or validation	2008-Sep-15
40	H	14-Si-28	(n, inl)	SIG	1.4 MeV	6 MeV	3-8	Archived	2008-Sep-15
34	H	26-Fe-56	(n, inl)	SIG	0.5 MeV	20 MeV	2-13	Work in progress	2008-Sep-12
29	H	11-Na-23	(n, inl)	SIG	0.5 MeV	1.3 MeV	4-10	Archived	2008-Sep-12
18	H	92-U-238	(n, inl)	SIG	65 keV	20 MeV	2-12	Work in progress	2008-Sep-11

HPRL Nuclear Energy Agency

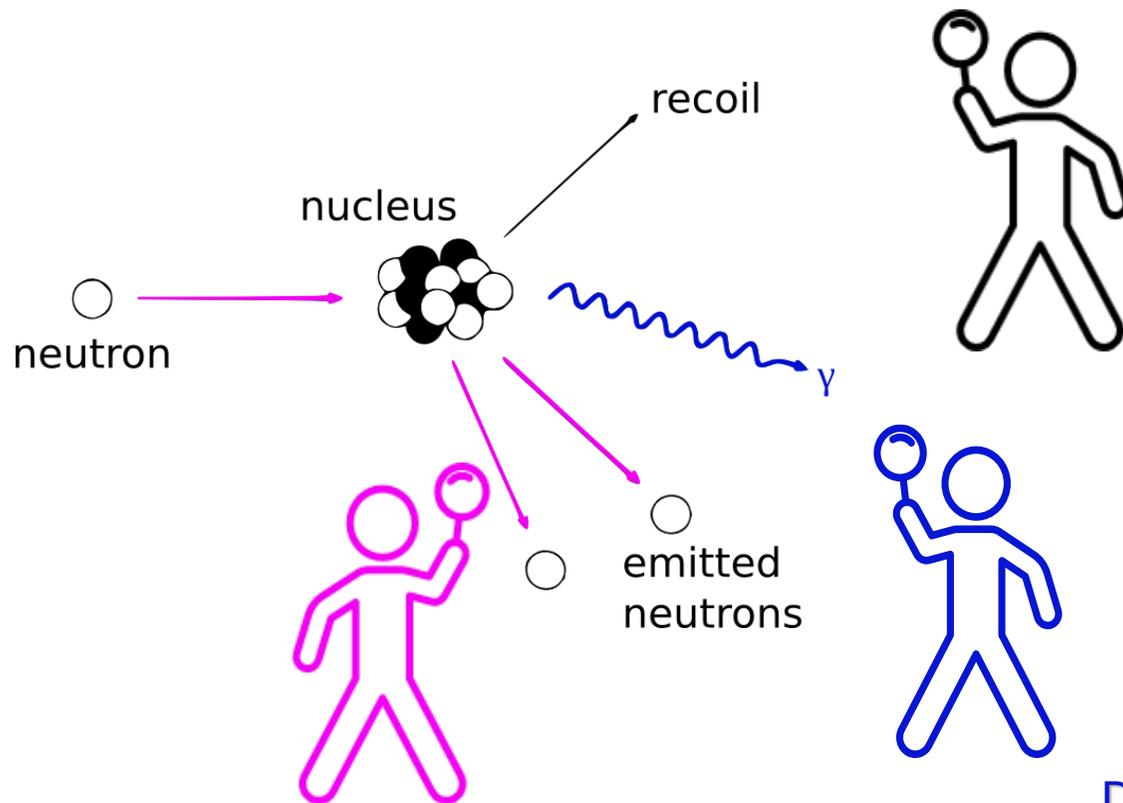


EXFOR

These reaction have a strong impact on reactor integral parameters (k_{eff} , power map, ...) computation.

Lack of measurements is, in part, responsible for evaluation uncertainties

- Context and motivation
- **Work and results from IPHC**
 - *The GRAPhEME setup*
 - Experimental results, impact on models
 - New data from NFS
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Detecting activated residual

- ! Only if the (n, xn) reaction produces an unstable nucleus.
- 👍 Very clear signal.
- 😞 Only possible in some cases.

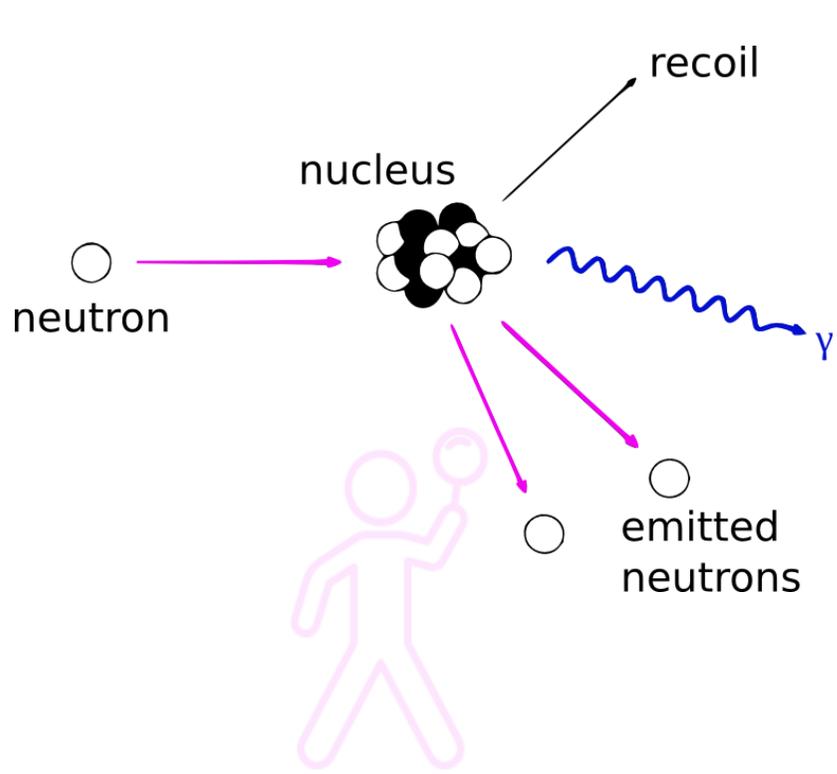
Detecting scattered neutrons

- 👍 Direct measurement of the process of interest.
- 😞 hard to identify the neutrons from the (n, xn) reactions from other channels.

Detecting γ rays emitted in the reaction

- 👍 Clear signal
- 😞 Only a partial view of the process

à la SCONE, Chi-nu



Detecting activated residual



Detecting γ rays emitted in the reaction

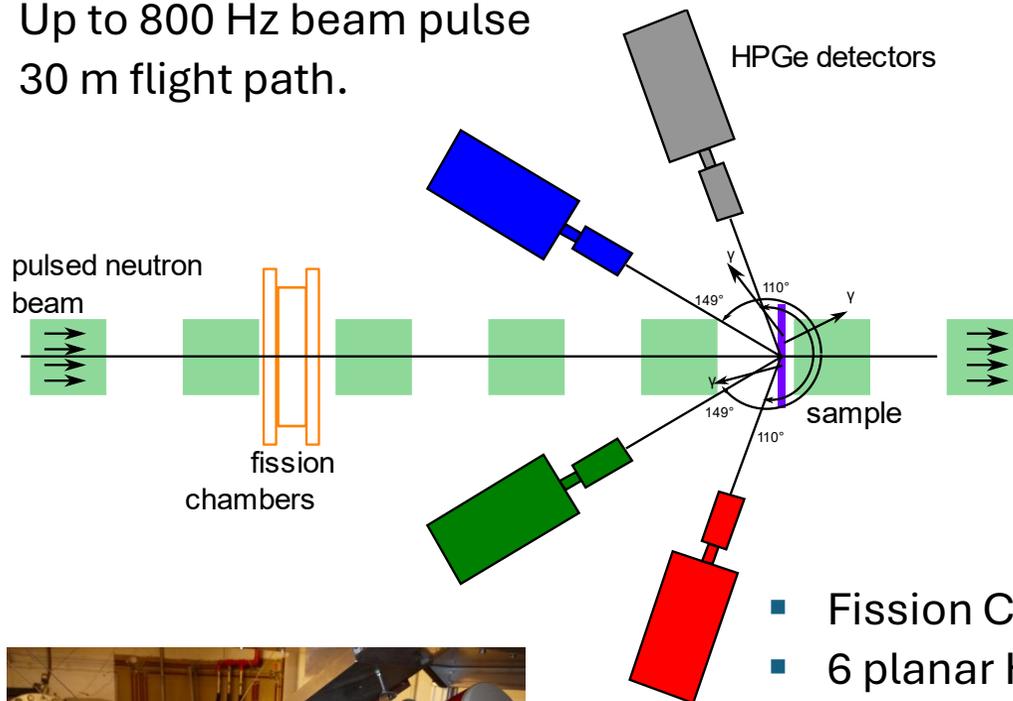
- 👍 Clear signal
- 😞 Only a partial view of the process

Detecting scattered neutrons

- γ spectroscopy measurements :
 - (n, n') channel at Gelina/JRC-Geel.
 - (n, 2n) and (n, 3n) channels at NFS.
- Comparison with theoretical predictions to deduce total cross sections, improve models and evaluations.
 - Collaboration with CEA/DAM on reaction models,
 - And with CEA/DES for the choice of nuclei of interest and evaluations.

The GRAPhEME setup

- Installed at the Gelina facility (JRC-Geel),
- Designed for Actinides study
- Up to 800 Hz beam pulse
- 30 m flight path.

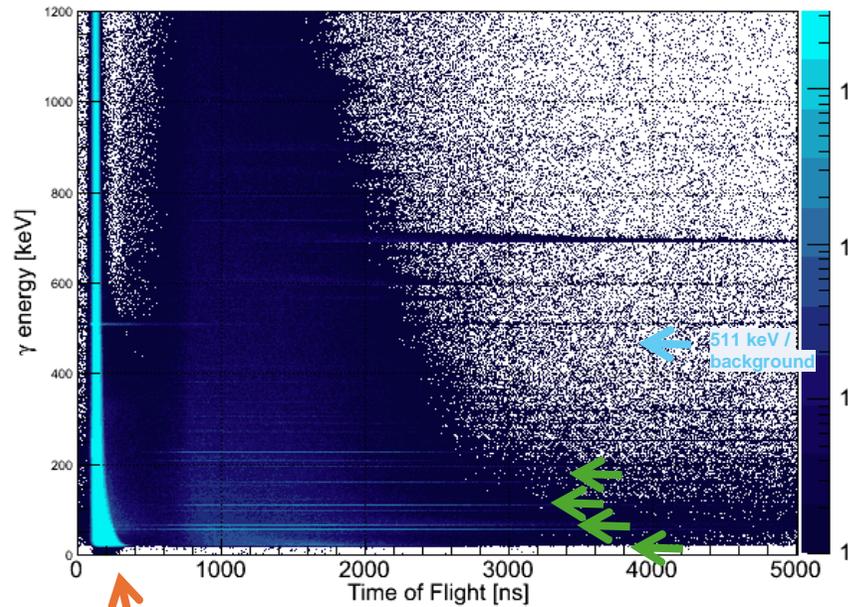


JRC via Youtube

- Fission Chamber to measure incoming neutron flux.
- 6 planar HPGe, high efficiency and resolution at low E_{γ} .
- Large sample (diameter ~ 55 mm), Active targets prepared by JRC-Geel Target lab.
- Digital acquisition.
- Measured : ^{235}U , ^{232}Th , $^{\text{nat}}, 182, 183, 184, 186}\text{W}$, ^{238}U , $^{\text{nat}}\text{Zr}$, ^{233}U , ^{57}Fe , ^{239}Pu , ...

"GRAPhEME : a setup to measure $(n, xn \gamma)$ reaction cross sections." Greg Henning, et al.. Adv. in Nuc. Instr. Meas. Met. and App., 2015.
Jean-Claude Thiry, "Mesure de sections efficaces des réactions $(n, xn\gamma)$...", Thèse, Univ. de Strasbourg, 2010

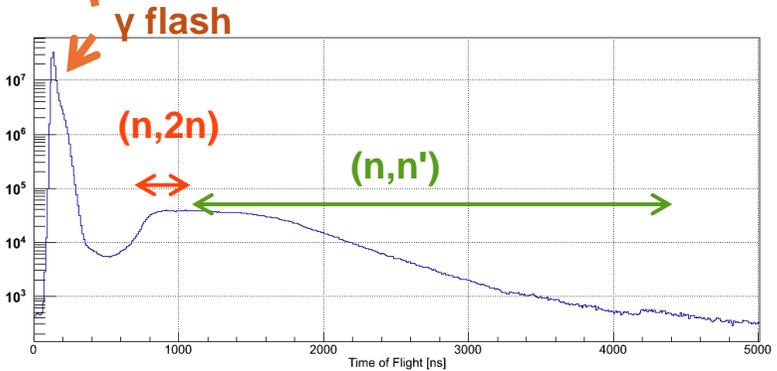
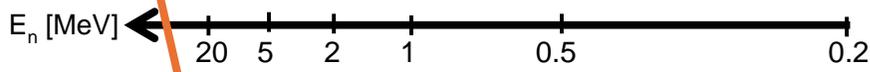
The GRAPhEME setup: Analysis method



- The intensity of the γ line is determined for different time intervals / Neutron energy windows.
- The ratio to the flux (from fission chambers) gives the production angular cross section.

$$\frac{d\sigma}{d\Omega}(E_n, \gamma; \theta) = \frac{N_\gamma(E_n, \gamma; \theta)}{\varepsilon(E_\gamma)} \frac{1}{N_{target}} \frac{\sigma_{^{235}\text{U}(n,f)}(E_n)\varepsilon_{CF}}{N_{CF}(E_n)}$$

- The angle integrated cross section is obtained by linear combinations of the angular one.



$$\sigma_{total} = 4\pi \left[w_1 \times \frac{d\sigma}{d\Omega}(\theta_1) + w_2 \times \frac{d\sigma}{d\Omega}(\theta_2) \right]$$

With $w_1 = 0,3479$, $w_2 = 0,6521$

C.R. Brune, NIM A 493 (2002) 106-110
L.C. Mihailescu NIM A 531 (2004) 375-391

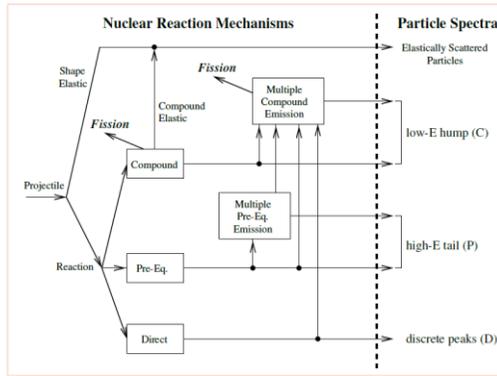
- Special care for the sources of uncertainty and bias to provide the most precise measurement possible (5-15 %)
- Full Monte Carlo Analysis to produce uncertainties and covariance matrices (since 2024)

"How to produce accurate inelastic cross sections from an indirect measurement method?"
M. Kerveno et al., EPJ Nuclear Sci. Technol. 4, 23 (2018)

- Our method is indirect, gives only a partial view of the process
- Experimentally, not all the γ are visible (intensity, electronic conversion, detection efficiency, ...).
- The precise σ_{γ} experimentally measured are compared to model predictions and used to constraint the reaction models and codes.

Reaction models Calculation codes

(input: **structure**, optical potential, ...)



Total (n, xn) cross section computed with models constrained by our measures.

Lower bound on the total (n, xn) cross section.

Weights summing method (only input: structure)

$$\sigma_{(n,xn)} \geq \sum_{\gamma \rightarrow g.s.} \sigma_{(n,xn\gamma)} \times (1 + \alpha_{\gamma})$$

🙄 These methods presents a dependency on structure data.

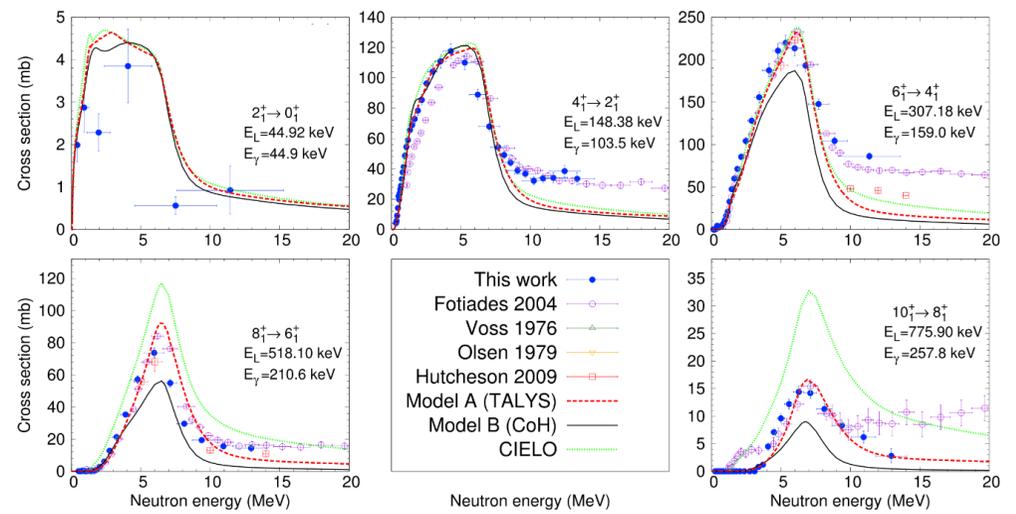
Precise experimental (n, xn γ) cross sections

$$\sigma_{\gamma i \rightarrow f} \propto \sigma_{(n, xn) \rightarrow i \text{ direct}} + \sigma_{(n, xn) \downarrow i}$$

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- 18 (n, n' γ) cross section extracted from the data
- The first state (2^+) to ground state transition, 44.9 keV carries about 90% of the total cross section, but is highly converted (ICC=610), making it difficult to extract a precise cross section.

See talks from 1st day morning



- Microscopic modeling of the preequilibrium emission improves the description of the spin distributions of the residual nucleus

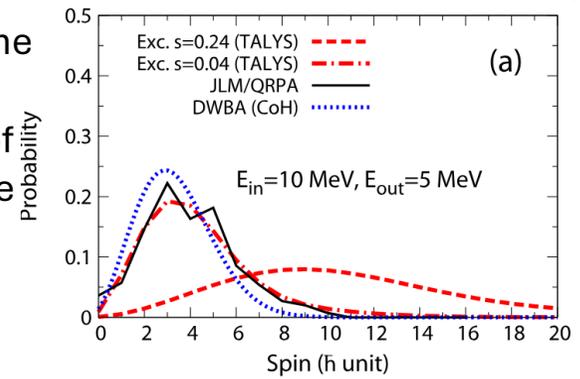


FIG. 10. (a) Spin distribution for the incident energy 10 MeV and an excitation energy of 5 MeV. Average spin as a function of the excitation energy for the two incident energies 10 MeV (b) and

- Studied the impact of structure: Uncertainties on Branching ratio impacts calculated cross section with up to 4% uncertainty from structure data alone.
- Prompted an experiment collaboration with the nu-Ball collaboration to perform new spectroscopy of ^{238}U .

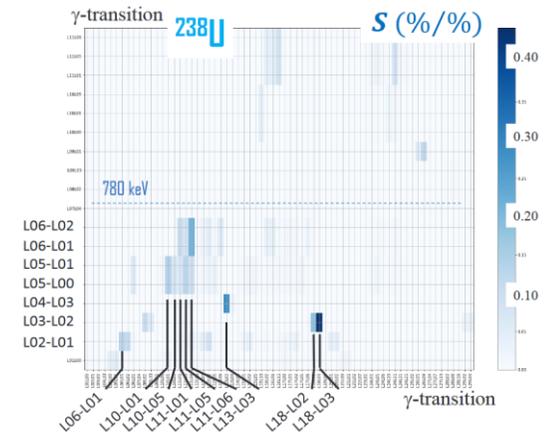


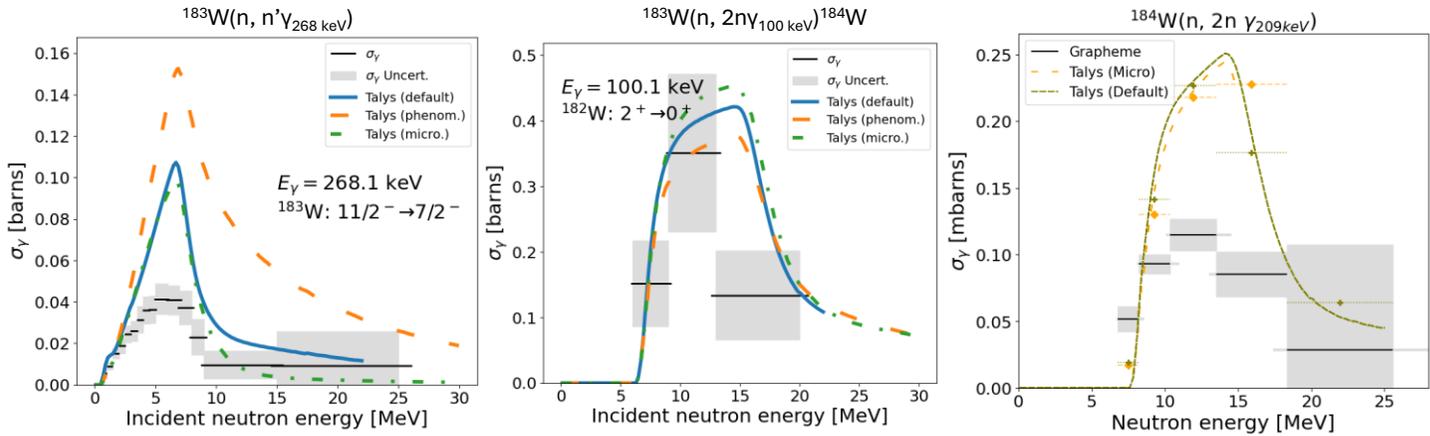
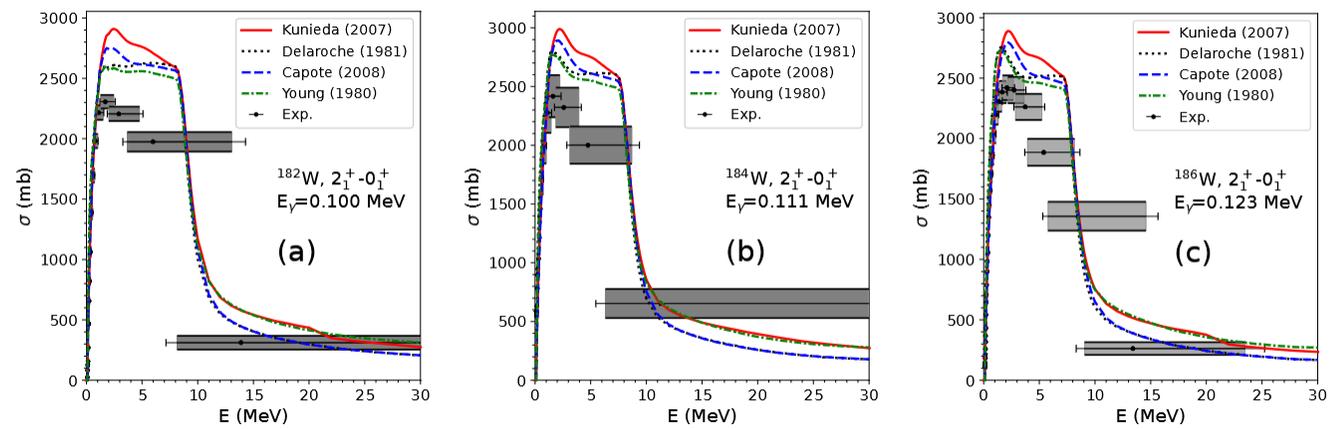
Figure 7. (color online) Sensitivity matrix for γ -production cross sections to Branching Ratios in ^{238}U . L_j is the number of the level in TALYS.

"Measurement of $^{238}\text{U}(n, n'\gamma)$ cross section data and their impact on reaction models" M. Kerveno, M. Dupuis, et al. Phys. Rev. C 104, 044605 (2021) Carole Chatel, et al. 16th International Workshop On Nuclear Data Evaluation for Reactor applications, 2024

Experimental results : $^{182-186}\text{W}$

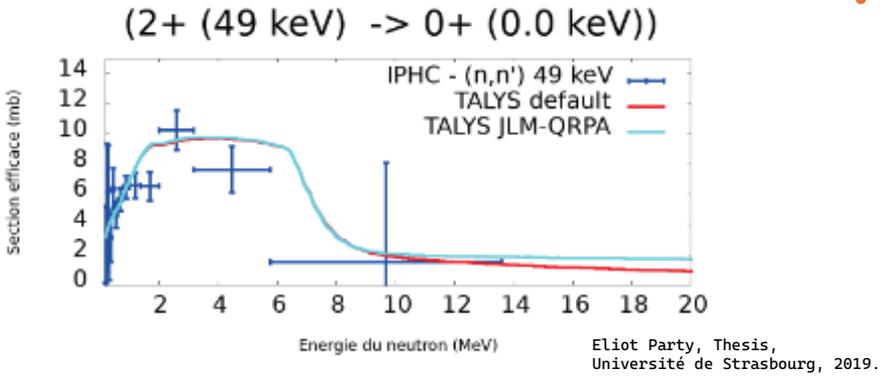
- Measured with natural W target, And isotopically enriched ^{182}W , ^{183}W , ^{184}W and ^{186}W . From K.H. Guber (Oak Ridge National Lab)
- The comparison of isotopic vs. natural targets allow a cross check on $(n, xn \gamma)$ cross section.
- Analysis using a Full Monte Carlo approach to produce uncertainties.
- ~20 transitions per even-even isotopes, 6 $^{183}\text{W}(n, n' \gamma)$ and 4 $^{183}\text{W}(n, 2n \gamma)$, 6 in $^{184}\text{W}(n, 2n \gamma)$

Experimental $2^+ \rightarrow \text{g.s.}$ cross section *overestimated* by model calculations. Possible sources of bias, uncertainty, ...have been investigated without finding any element that could account for the discrepancy.

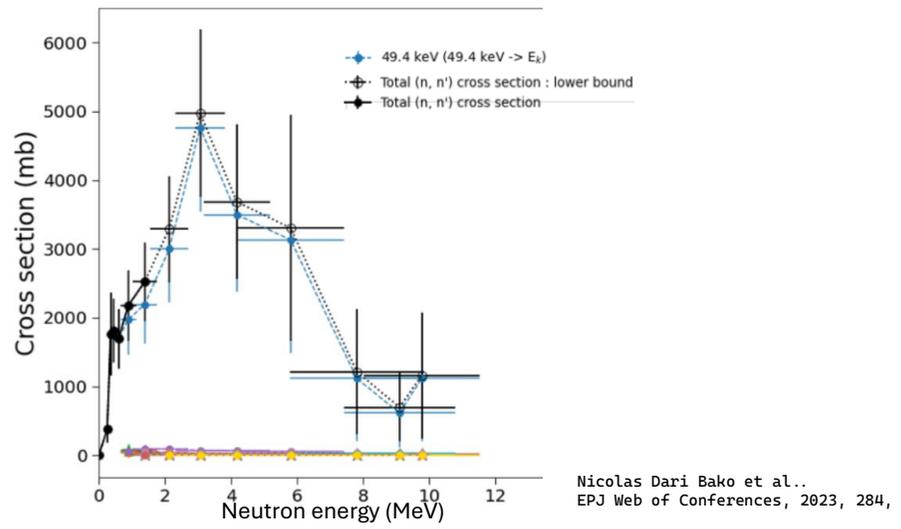


Overlapping channels and information for 182 , 183 and ^{184}W

- ^{232}Th : 81 (n, n' γ) cross section extracted from recorded data.
- Extension of available data at higher neutron energy compared to previous data (Dave, *et al.* 1985)



- Tentative reconstruction of the total (n, n') cross section from $\sigma_{(n,n'\gamma)}$ (lower bound)



- ^{233}U : Disentangle the γ -rays from (n, xn) from fission product background thanks to a highly pixelated planar HPGe
- 12 experimental $^{233}\text{U}(n, n'\gamma)$ cross sections

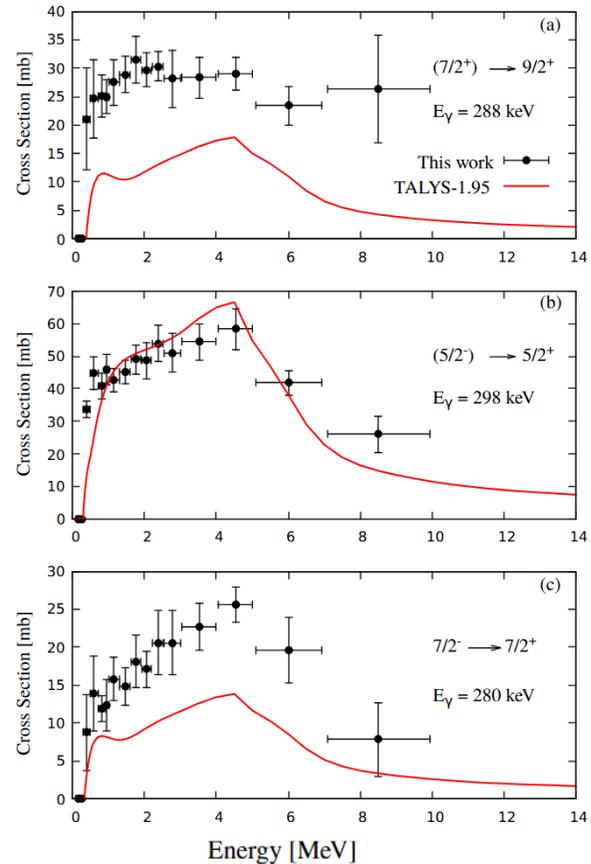
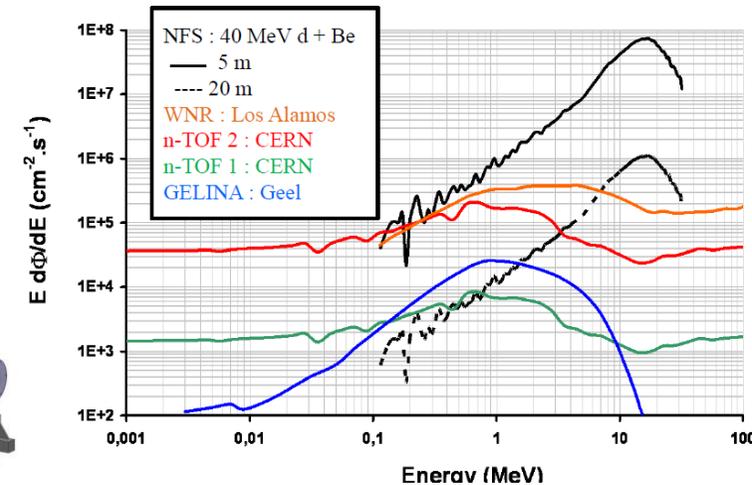
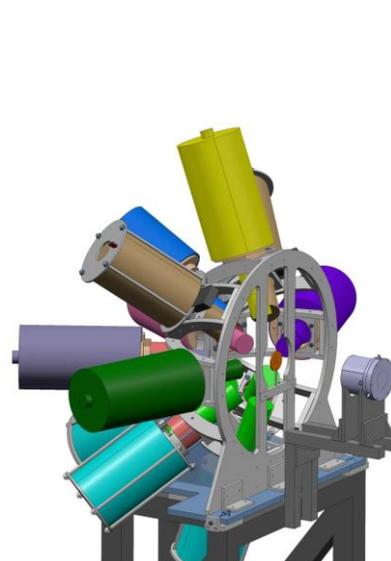
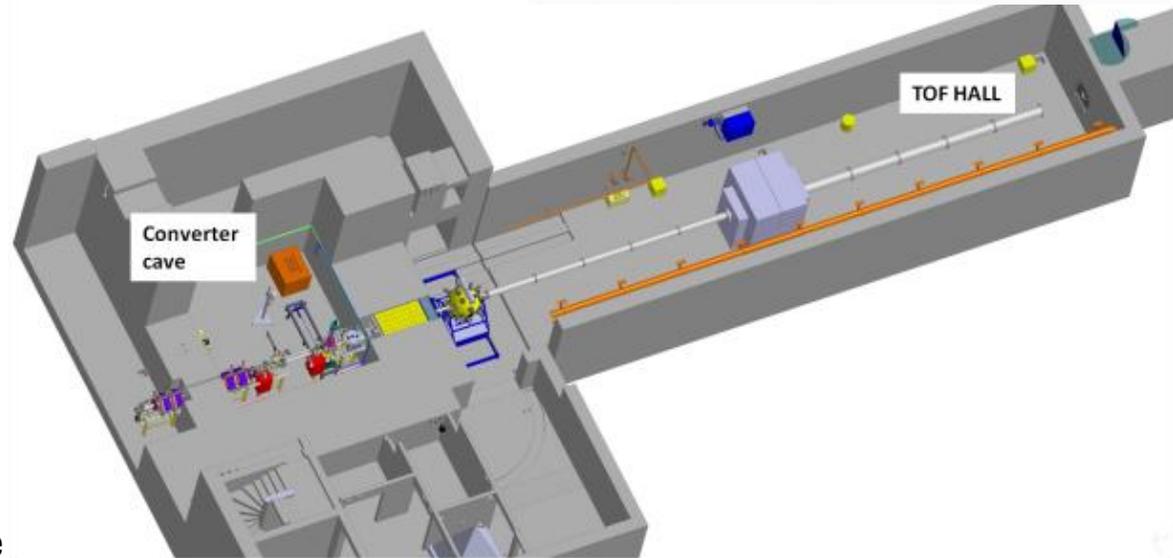


Figure 3. (color online) Experimental $^{233}\text{U}(n, n'\gamma)$ reaction cross sections (black dots) for a selection of characteristic analysed γ transitions compared to TALYS-1.95 calculations (red lines).

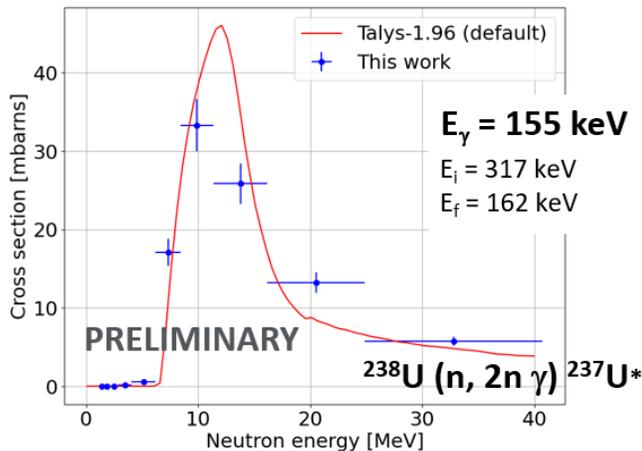
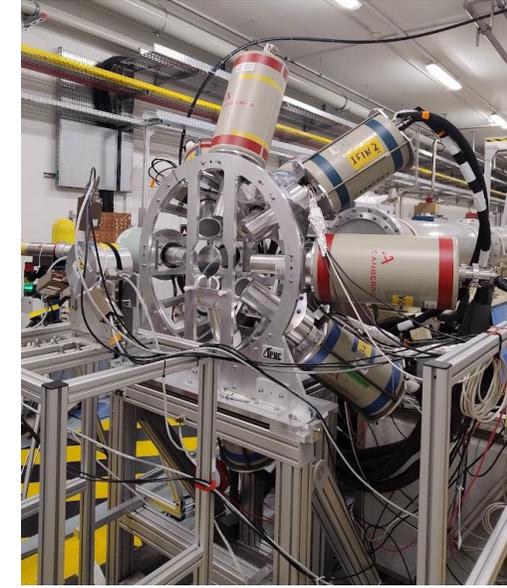
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- Production of neutrons by reaction of light ions accelerated by the Spiral2 Linac.
- Neutron energies higher than at Gelina and better suited to the study of (n, 2n) and (n, 3n) reactions.
- Use of the long flight path (~30 meters).
- Design and construction of the neutron line and second collimator at IPHC.
- In October/November 2024: Measurement of inelastic neutron scattering cross sections on ^{238}U , using a support frame designed at IPHC, bringing together detectors from Grapheme, JRC-Geel, and IFIN-HH (Bucharest) to form the MAELS setup (Multi germanium Array for inelastic Scattering)

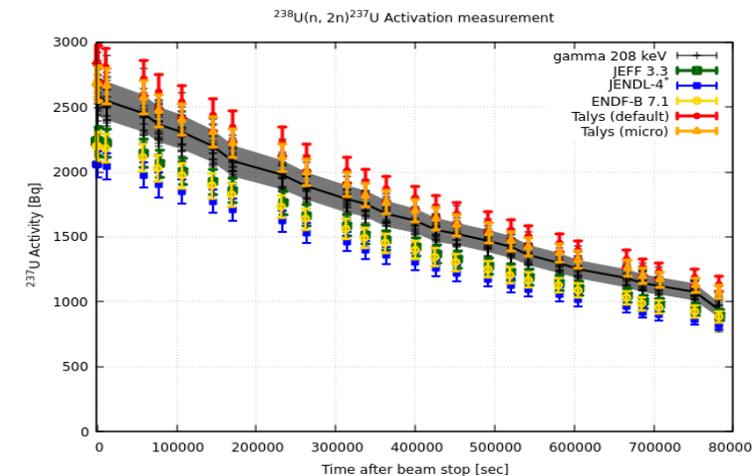


$^{238}\text{U}(n, 2n \gamma)$ and $(n, 3n \gamma)$ cross section measurements

- In 2024
- Using prompt γ spectroscopy **and** activation (^{237}U decay activity measurement for integrated $\sigma_{(n, 2n)}$)
- 12 HPGe.
- ^{238}U fission chamber (IPHC) for neutron flux measurement.
- Depleted ^{238}U targets provided by JRC-Geel
- 2 weeks in-beam, 16 days of decay observation.



- Preliminary results are encouraging
- Detailed analysis in progress

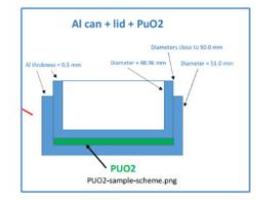
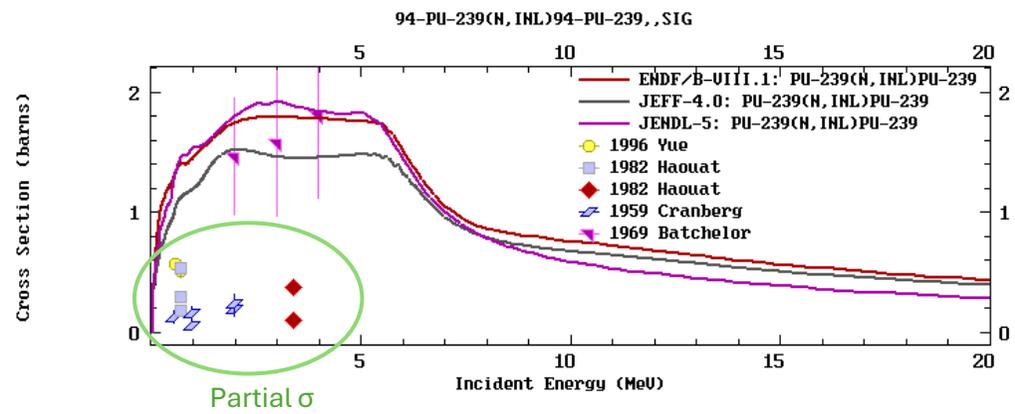


$^{238}\text{U}(n, xng)$ measurements at the new SPIRAL2/NFS facility Maëlle Kerveno. 16th Nuclear Data for Science and Technology Conference, 2025

G. Henning, S Ouafiki, 2025

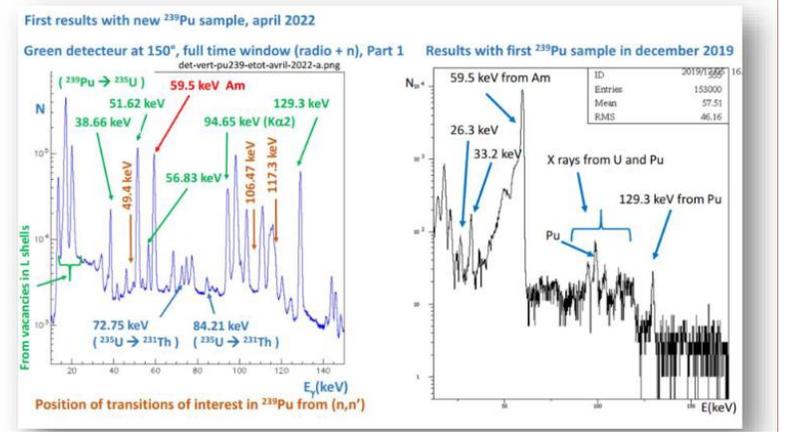
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$^{239}\text{Pu}(n, n'\gamma)$ cross sections with Grapheme



$m = 2,3 \text{ g}$
 $\varnothing = 49,95 \text{ mm}, A = 5,2 \text{ GBq}$

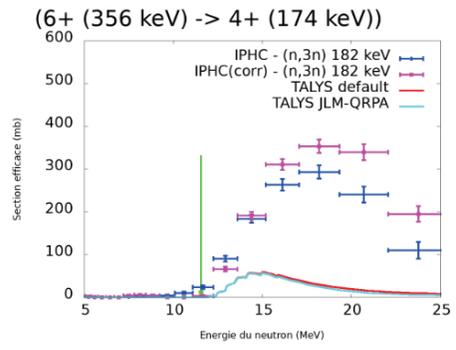
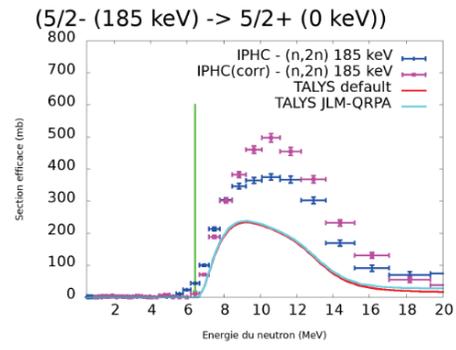
- Currently recording data
 - High radioactivity (Am) background requires long data taking
- Data analysis 2026-2028



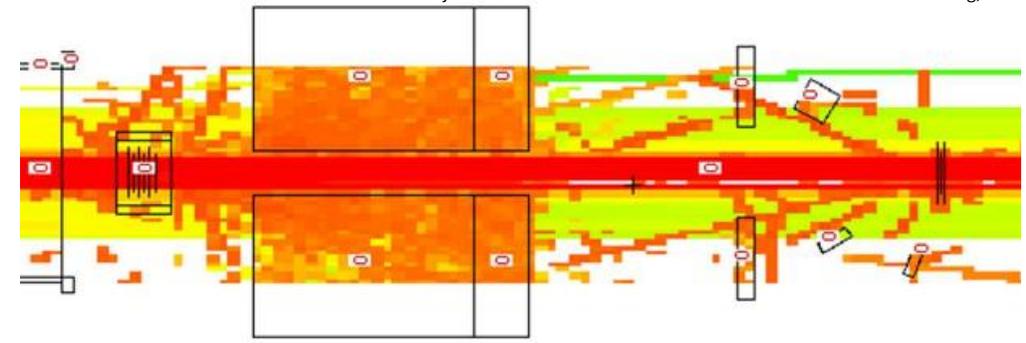


At NFS, next step is $^{232}\text{Th}(n, 2n\gamma)$ and $(n, 3n\gamma)$

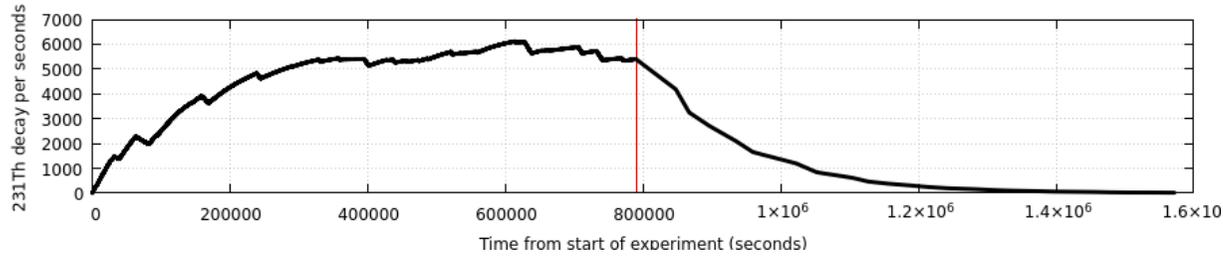
- GRAPhEME data set studied 11 $(n, 2n\gamma)$ and 7 $(n, 3n\gamma)$.
- Evolution of the MAELS setup :
 - Adding shielding to protect the detectors from scattered neutrons.
 - Use of ^{235}U fission chamber in addition to the ^{238}U ones.
- Also with an activation measurement for $^{232}\text{Th}(n, 2n)$ ($T_{1/2} = 25$ hours) to perform integral $(n, 2n)$ cross section measurement.



Eliot Party. Etude des réactions (n, xn) pour les noyaux fertiles / fissiles du cycle du combustible innovant au Thorium. Université de Strasbourg, 2019.



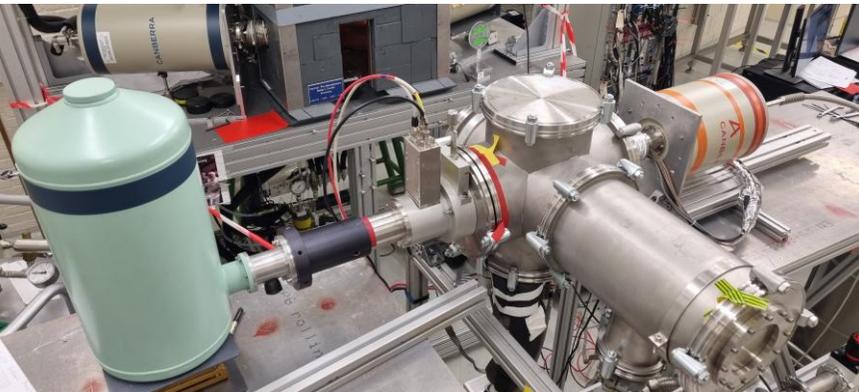
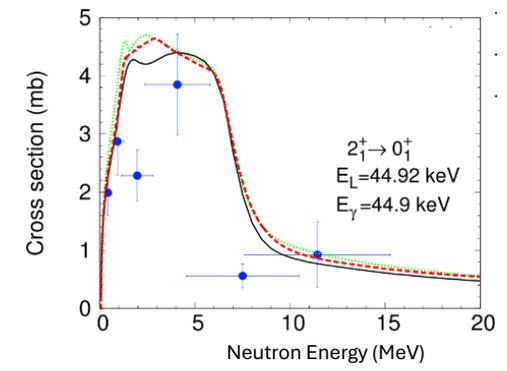
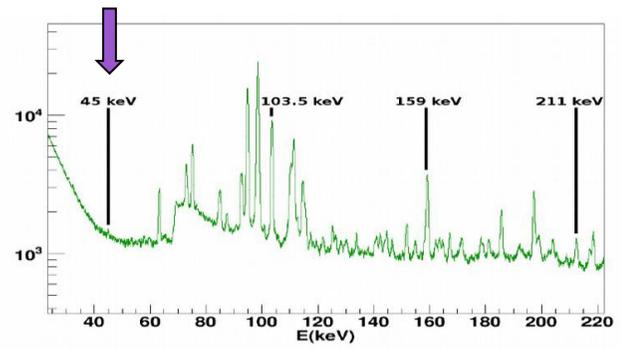
Simulation of ^{231}Th activity production for 10 days of irradiation, and the subsequent activity decay



Further down the road, we hope to perform measurements on ^{239}Pu , ^{233}U . Requires to accommodate radioprotection rules, and scale up our own data recording capability.

Electron conversion Detector setup *DELCO* (Détecteur d'Electrons de COversions)

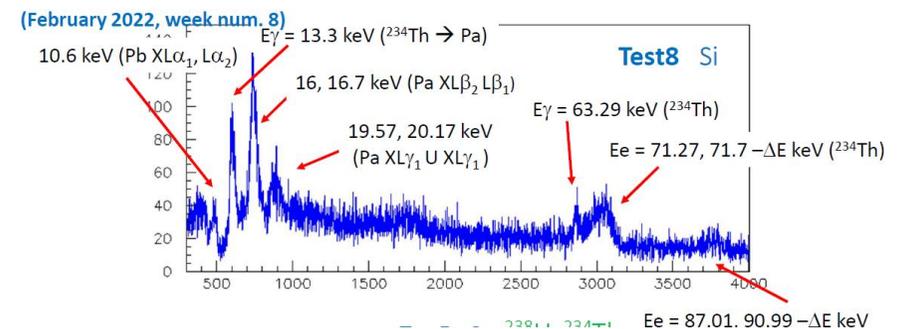
- In ^{238}U , ^{232}Th , the transitions from the 1st excited state to the ground state carries ~90% of the total (n, n') cross section, but is highly converted, leading to large uncertainties in γ measurements with GRAPHEME



- We are developing a Conversion electron spectrometer.
- Currently at the « proof of concept » stage, following successful ^{238}U « radioactivity » (γ , X, e-) tests in 2022
- Si detecteur in Vacuum chamber
- Coupled to HPGe,
- In front of a ^{238}U target

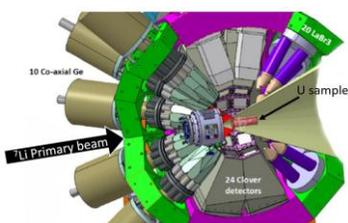
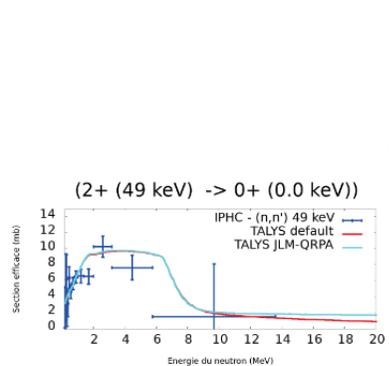
Markus Nyman, et al.. New equipment for neutron scattering cross-section measurements at GELINA. EPJ Web Conf., 239 (2020) 17003

Tests under beam to come in 2026.
Design and building of a prototype/setup will follow depending on the results.

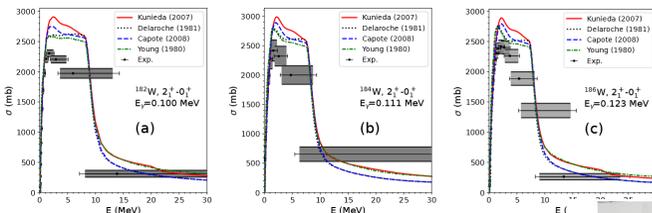


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Past works and results



2021-2026: ^{238}U
 spectroscopy
 with nu-Ball

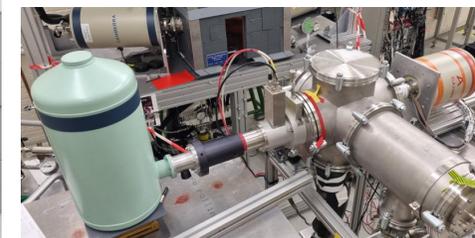


2024-2026: ^{18}xW
 @ Gelina

2018-2023: ^{232}Th
 @ Gelina

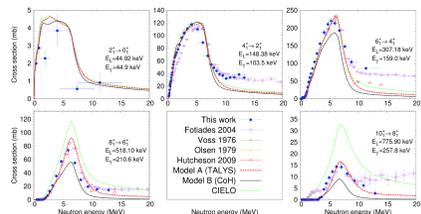


2026-2028:
 ^{239}Pu @ Gelina

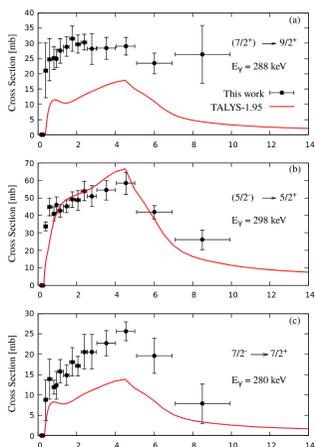


2026-2030
 ^{238}U w/ Delco
 @ Gelina

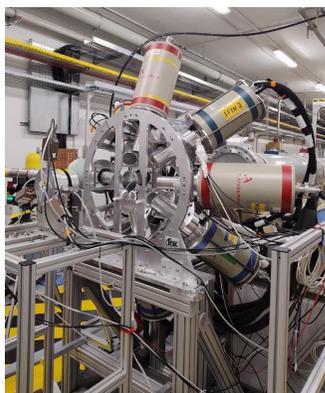
2021:
 ^{238}U @ Gelina



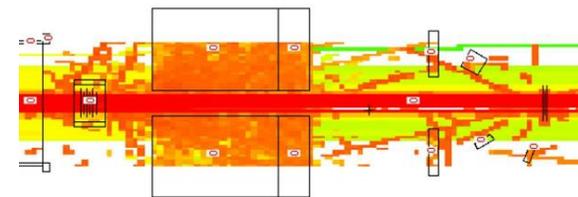
2023: ^{233}U
 @ Gelina



2024: ^{238}U @ NFS



2027-2028: ^{232}Th @ NFS





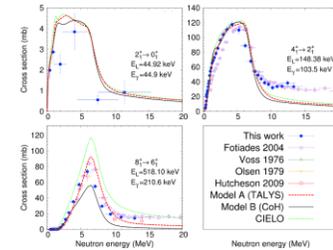
We chose a unified approach, performing experiments and closely collaborating with theoreticians and evaluators to understand the full lifecycle of the nuclear data.

Key achievements with GRAPhEME:

Provided high-spin transitions in ^{238}U , the first-ever $(n, n'\gamma)$ data for ^{233}U , a large and consistent data set on $^{182-186}\text{W}$, and more (^{235}U , ^{232}Th , $^{\text{nat}}\text{Zr}$, ^{57}Fe , ...)

Challenged models on spin distributions, level densities, γ strength functions

Highlighted the impact of structure information, leading to new collaboration (v-Ball)



NFS Potential:

$(n, 2n\gamma)$ and $(n, 3n\gamma)$ measurements will fill critical gaps for fast reactors.

Designed and assembled a dedicate setup MAELS

^{238}U data to analyze prompt $(n, 2-3n\gamma)$ and activation for integral $(n, 2n)$ cross section study

Future experiment ^{232}Th , and 🧠 ^{233}U , ^{239}Pu

Future Tools:

DELCO (conversion electrons) to complete our study of $(n, n'\gamma)$ cross sections



Continuing our strong collaborations (theoretical advances, evaluation), and making our findings easier to find and use, via a more open distribution of results, codes, ...

Collaborators:

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