Advancing Nuclear Data for Next-Generation Reactors: (n, xn γ) Cross Section Measurements at NFS

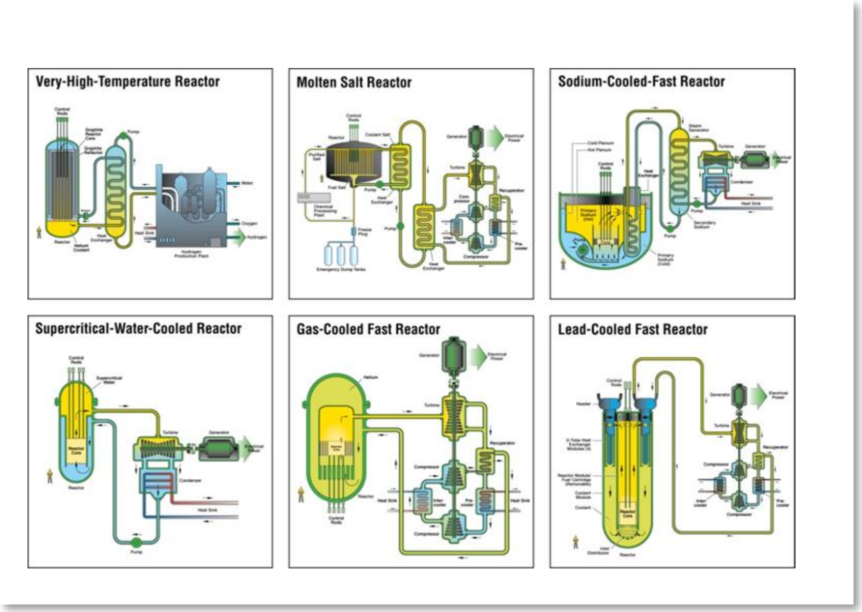
G. Henning, M. Kerveno, Ph. Dessagne, A. Tsinganis (IPHC)

Outline

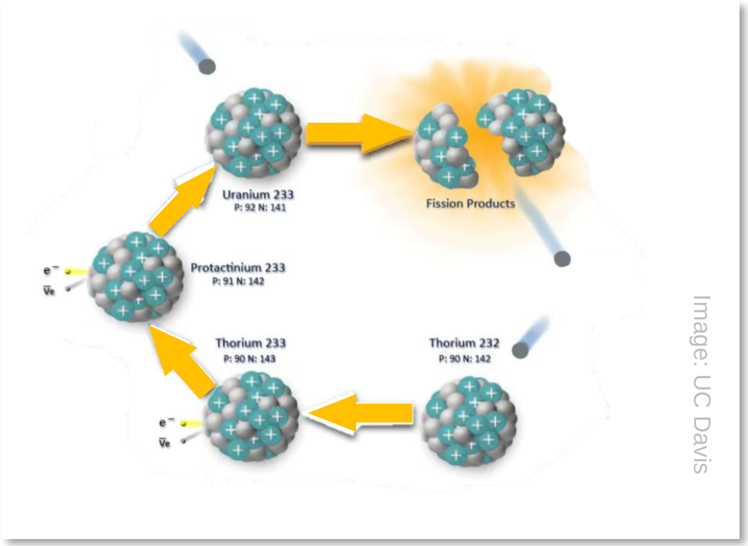
- Context and motivation
- (n, xn γ) cross section measurement method
- The NFS Facility and MAELS setup
- Recent results ^{238}U(n, 2-3n γ)
- Perspectives
- Summary and conclusions

Nuclear energy production today relies on fission of ^{235}U, induced by slow neutrons.

This entails economical, safety and sustainability challenges.



Some of these challenges can be met with new reactors designs and the use of new fuels



- Waste reduction: Fast neutronss → Isotope transmutation
  New fuels (^{232}Th) → Reduce the production of radioactive actinides
- Safety → Sub-critical Reactors
- Raw Uranium availabilty→ Breeding cycles ($^{232}Th/^{233}U$, $^{238}U/^{239}Pu$)

Nuclear Data for applications (The case of fission reactors)

Application development is primarily done with numerical simulations
Multi physics (Nuclear physics, heat transport, fluid dynamic, Material resistance, chemistry, …) and multi-scale.

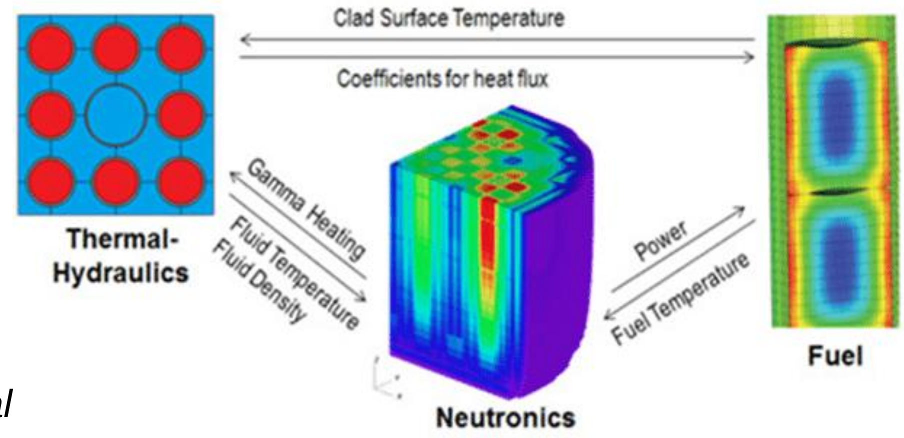


Image: T Valentine, DOI:10.1115/ICONE26-81571

For nuclear physics alone, many processes on many material are involved in the reactor:

- Neutron induced reactions
- Radioactive decay
- Interaction particle/matter,

… for the fuel, structure material, heat exchange fluid, …

For

- Neutron energies from 0.025 eV to a few 10 MeV
- Elements: Z from 1 to 98 (and above)
- Reactions: (n,f), (n,g), (n,*cp*), (n,*x*n), …
- Reaction products : n, g, e^-,*cp*, PF

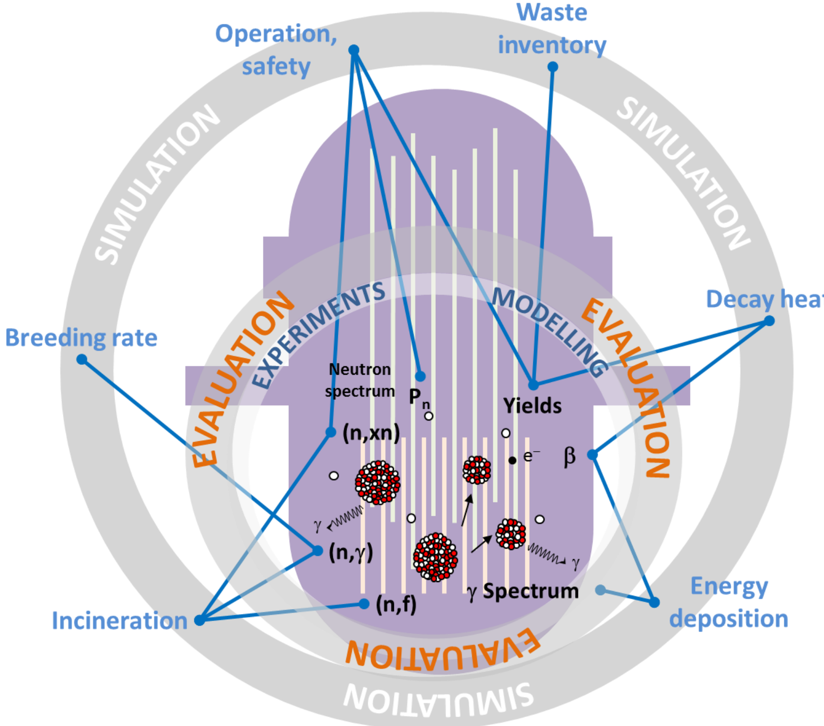
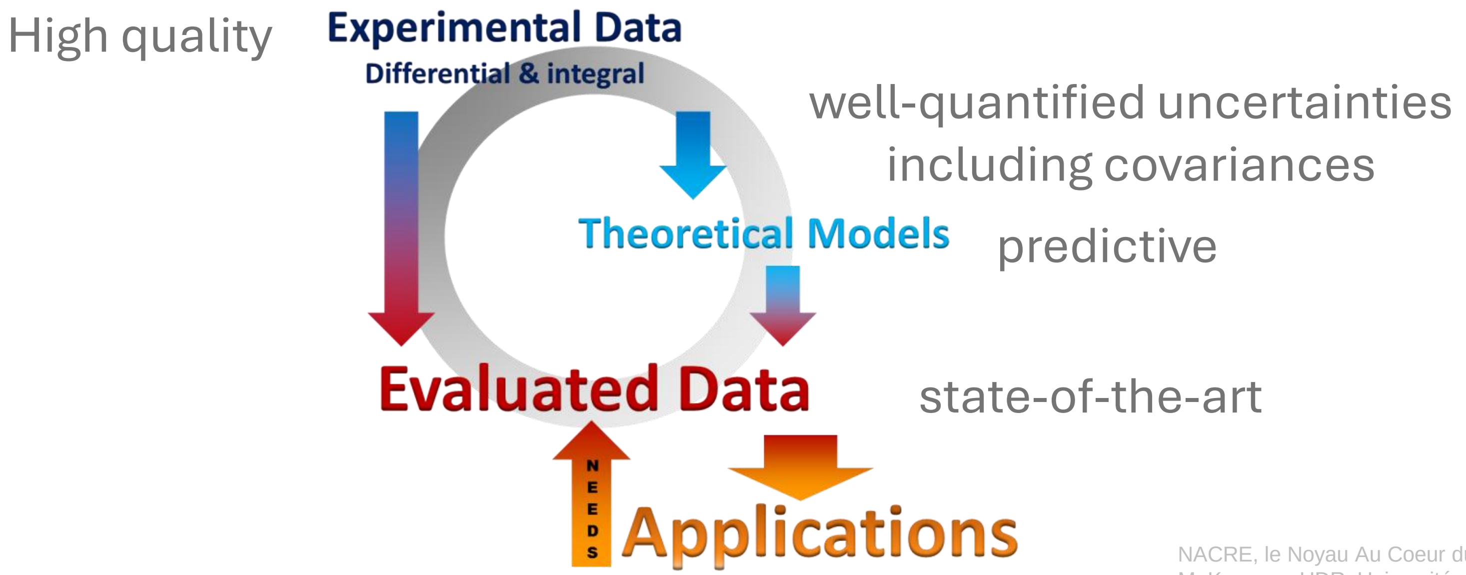


Image: M. Kerveno

Nuclear reactor simulations are based on evaluated nuclear data which allow the full description of all involved reactions.

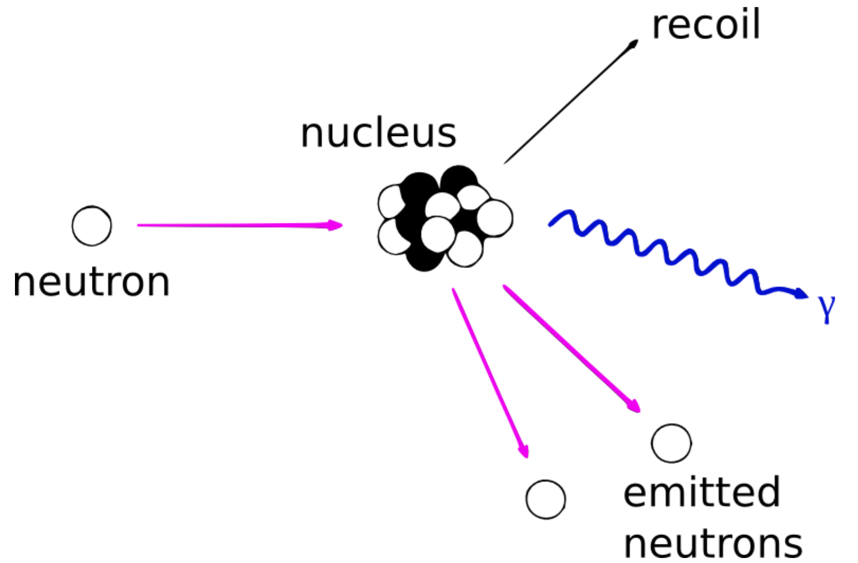


NACRE, le Noyau Au Coeur du RéactEur,
M. Kerveno, HDR, Université de Strasbourg, 2018

To meet target uncertainties on nuclear data for applications, all the steps of the evaluation process must be improved.

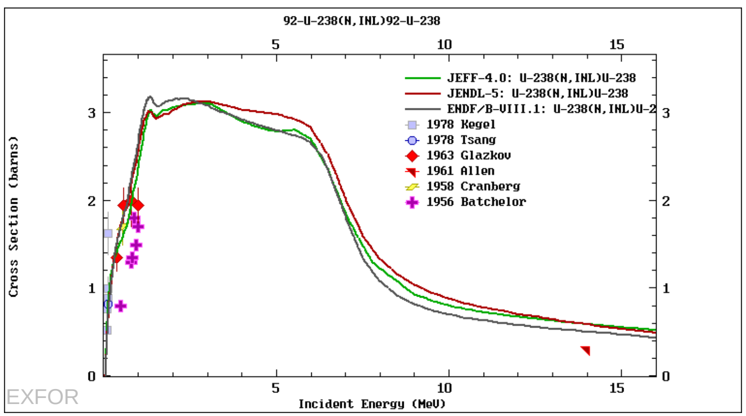
A large international community is involved in this effort on all front: new/accurate data, model improvement, evaluation.

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



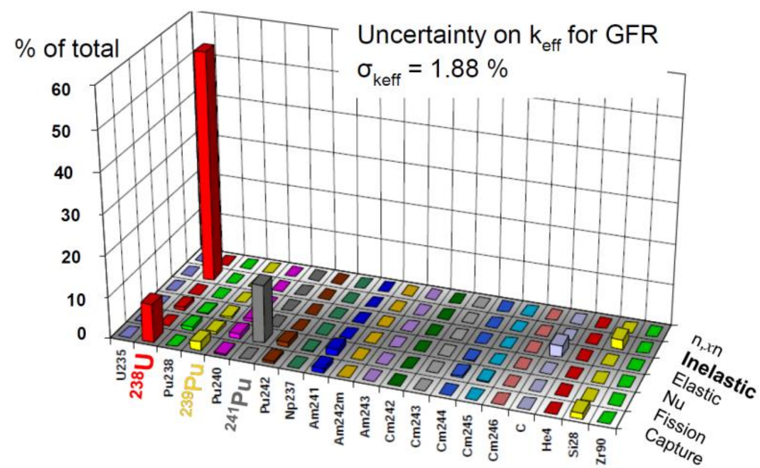
ID	Type	Target	Reaction (n,inl)	Quantity	Energy Min	Energy Max	Accuracy (%)	Status	Last update
42	H	82-Pb-207	(n,inl)	SIG	0.5 MeV	6 MeV	3-9	Pending new evaluation or validation	2008-Sep-15
41	H	82-Pb-206	(n,inl)	SIG	0.5 MeV	6 MeV	3-9	Pending new evaluation or validation	2008-Sep-15
40	H	14-Si-28	(n,inl)	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



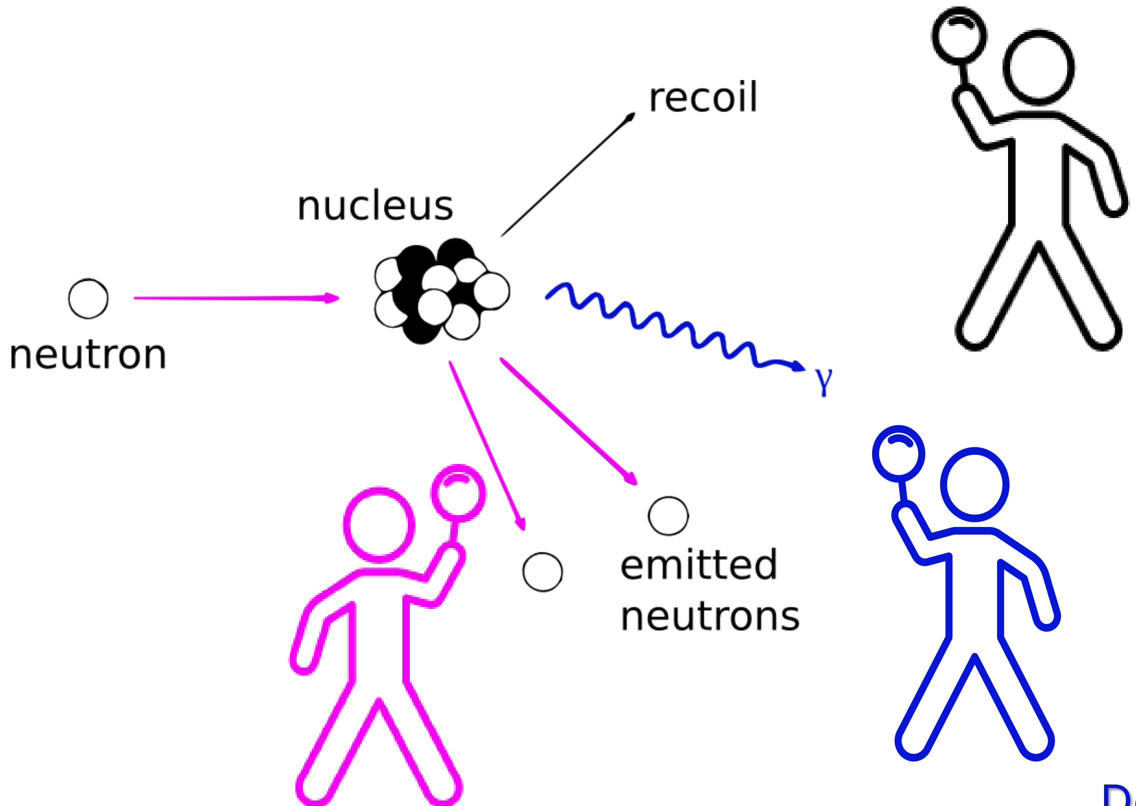
EXFOR

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



NEA SG26

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



Detecting activated residual

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

Detecting scattered neutrons

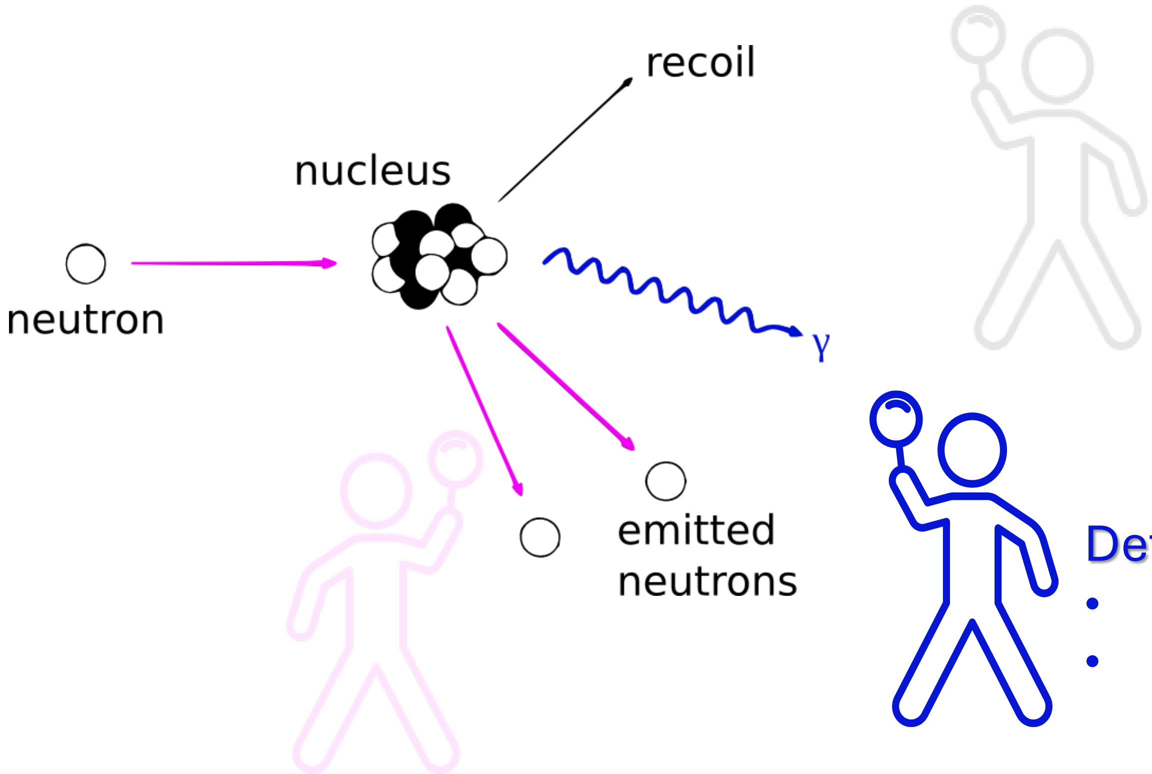
- 👍 Direct measurement of the process of interest.
- 😔 hard to identify the neutrons from the (n, xn) reactions from other channels.

Detecting γ rays emitted in the reaction

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

(n, xn) experimental study

Detecting activated residual



Detecting scattered neutrons

Detecting γ rays emitted in the reaction

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

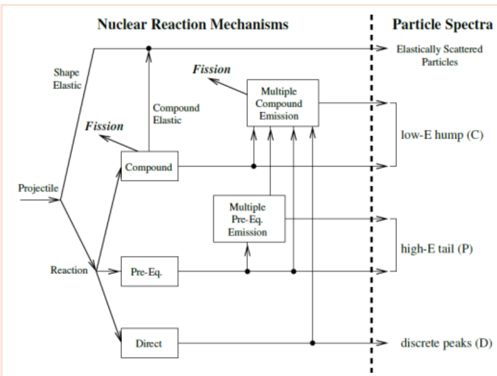
- γ spectroscopy measurements :
  - (n, n’) channel at Gelina/JRC-Geel, with the Grapheme Setup
  - (n, 2n) and (n, 3n) channels at NFS.

- 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.

Measuring (n, xn) cross sections

- 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)

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

😔 These methods presents a dependency on structure data.

Precise experimental (n, xn γ) cross sections

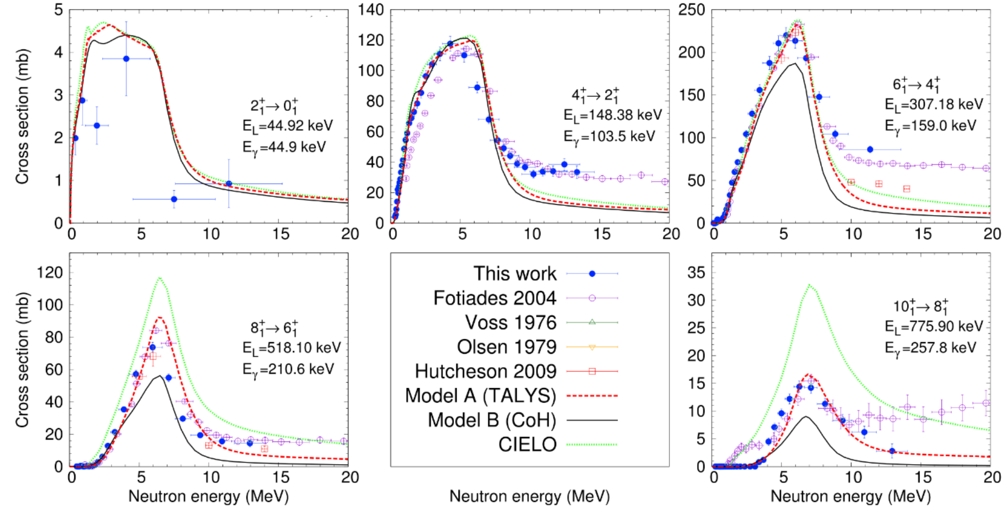
$$\sigma_{\gamma_{i\to f}} \propto \sigma_{(\mathrm{n},\, x\mathrm{n})\to i_{\mathrm{direct}}} + \sigma_{(\mathrm{n},\, x\mathrm{n})\downarrow i}$$

The GRAPhEME setup @ JRC-Geel

"How to produce accurate inelastic cross sections from an indirect measurement method?" M. Kerveno et al., EPJ Nuclear Sci. Technol. 4, 23 (2018)
Nicolas Dari Bako, et al. EPJ Web of Conferences, 2023, 284
Greg Henning, et al. 16th Nuclear Data for Science and Technology Conference, 2025

Past experimental results : ^{238}U

- 18 (n, n’ γ) cross section extracted from data collected at JRC-Geel with the Grapheme setup
- 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.



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

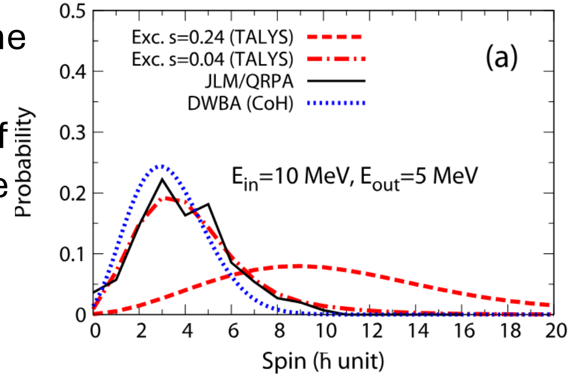


FIG. 10. (a) Spin distribution for the incident energy 10 MeV and an excitation energy of 5 MeV. Average spin as a function of the excitation energy for the two incident energies 10 MeV (b) and

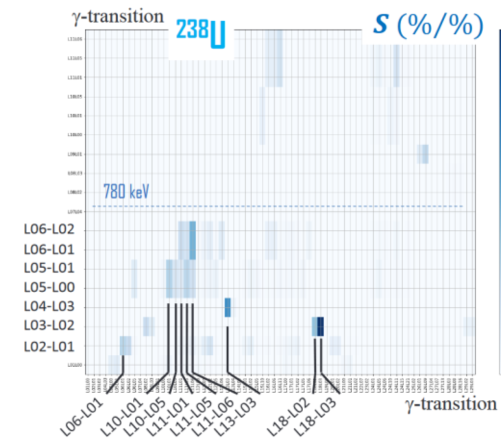
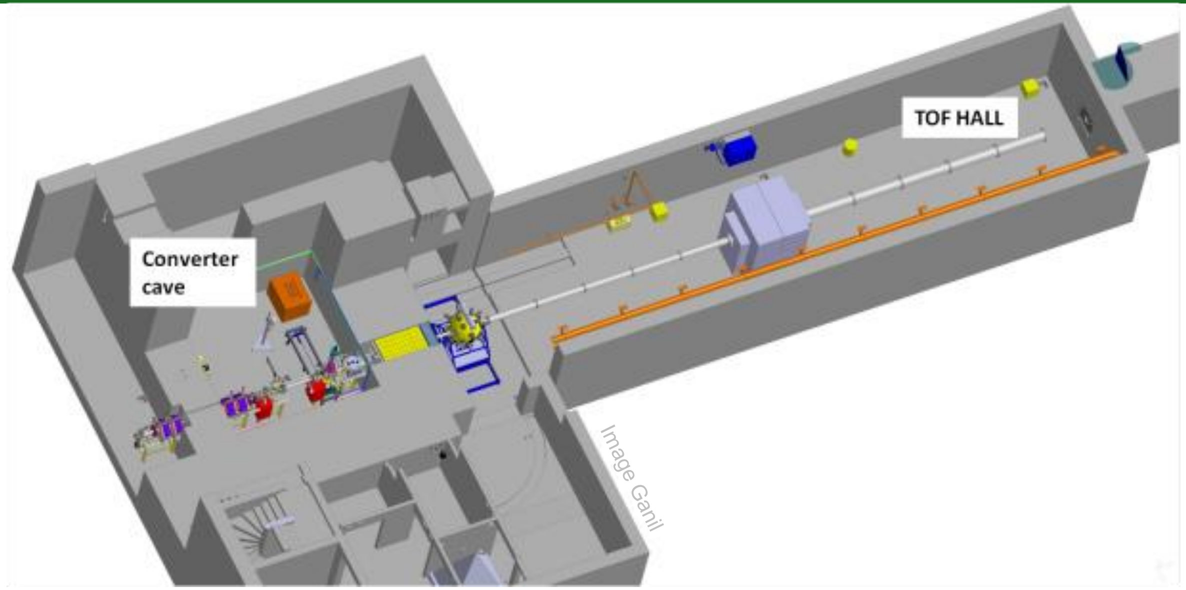


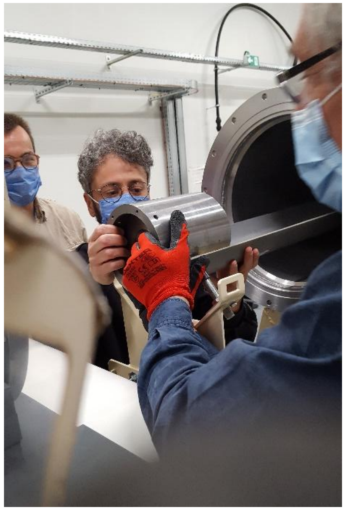
Figure 7. (color online) Sensitivity matrix for γ-production cross sections to Branching Ratios in ^{238}U. L_i is the number of the level in TALYS.

- 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.

"Measurement of 238U(n,n'γ) 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

- 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.





Images (IPHC)

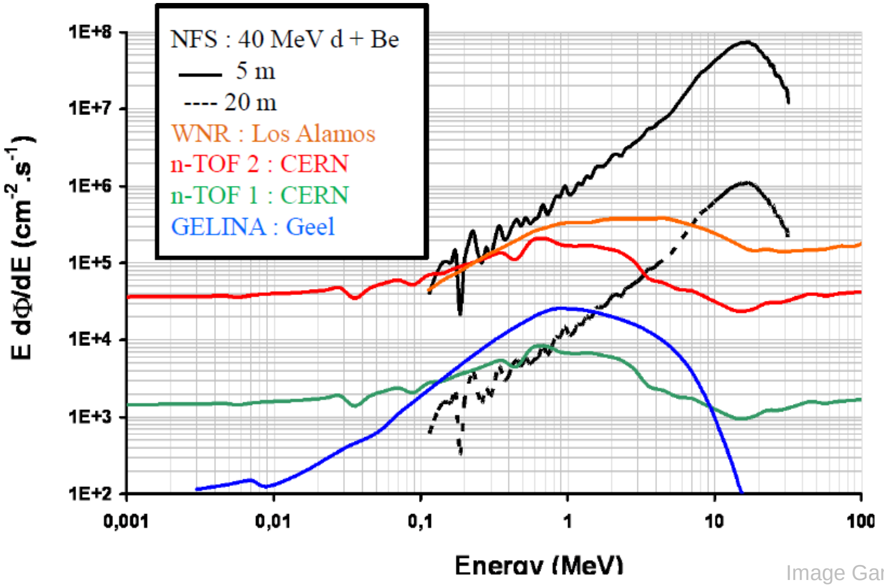
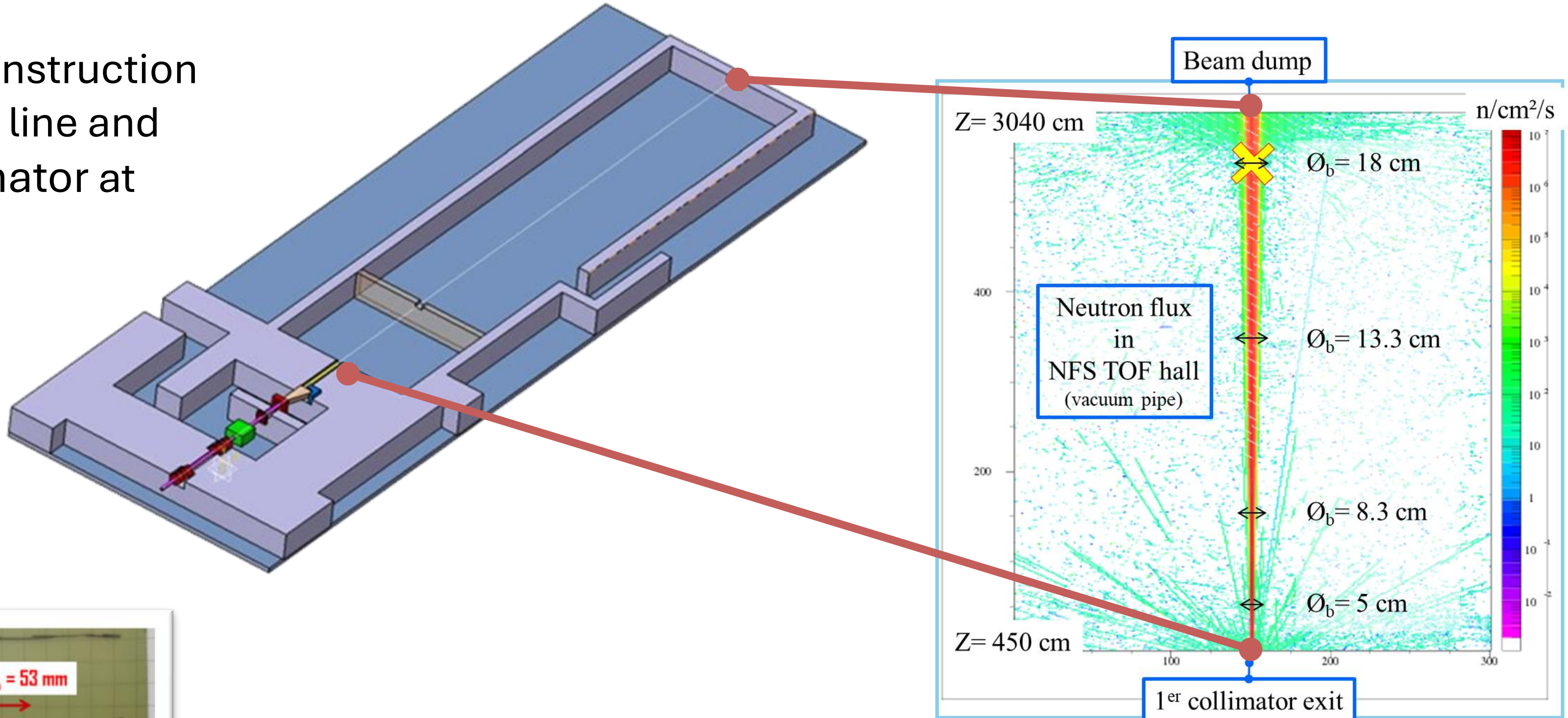
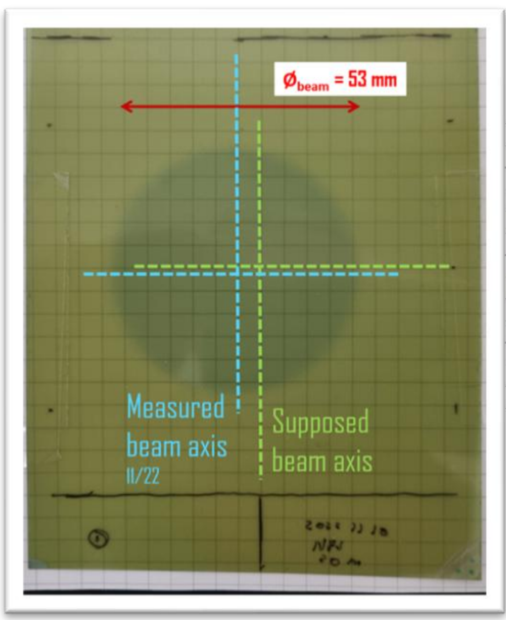
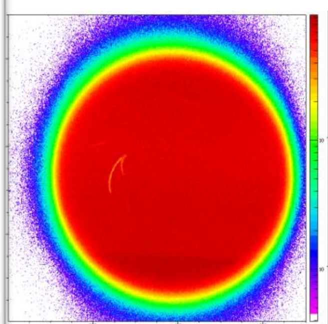


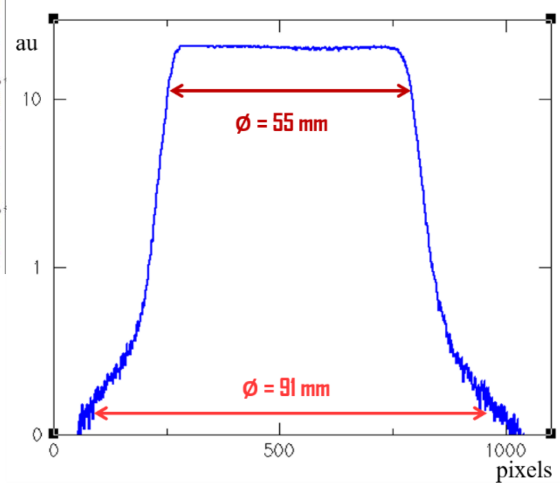
Image Ganil

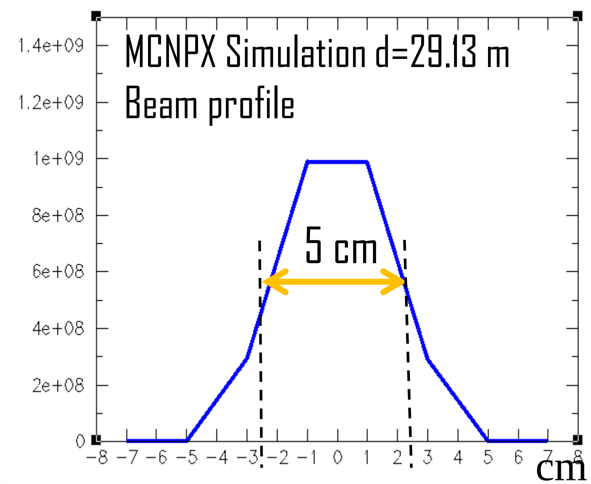
- Design and construction of the neutron line and second collimator at IPHC.





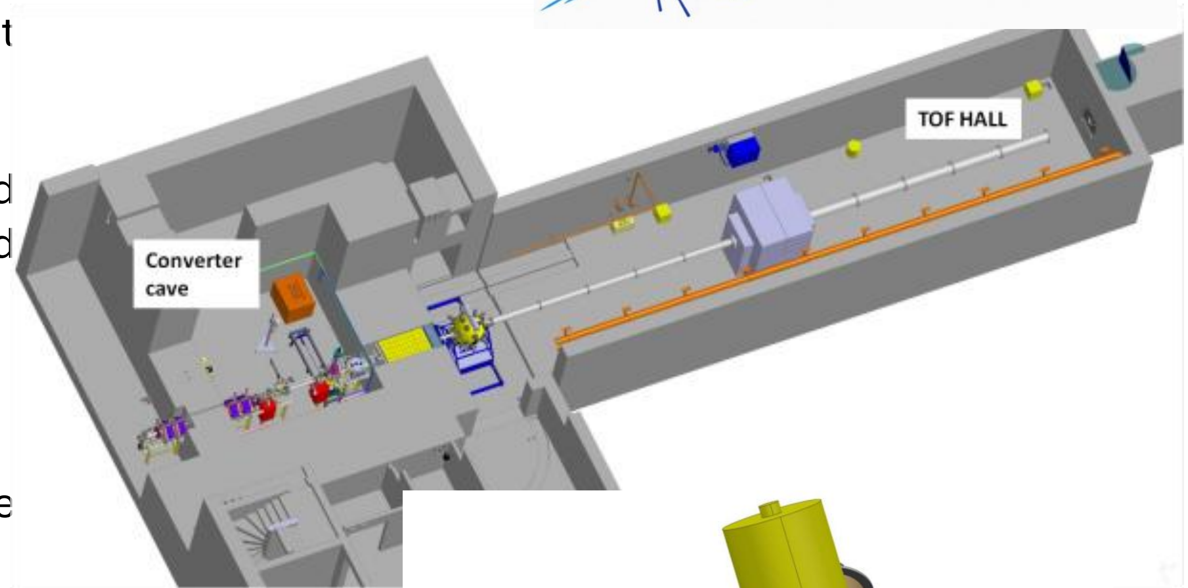






Images Ph. Dessagne (IPHC)

- 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)



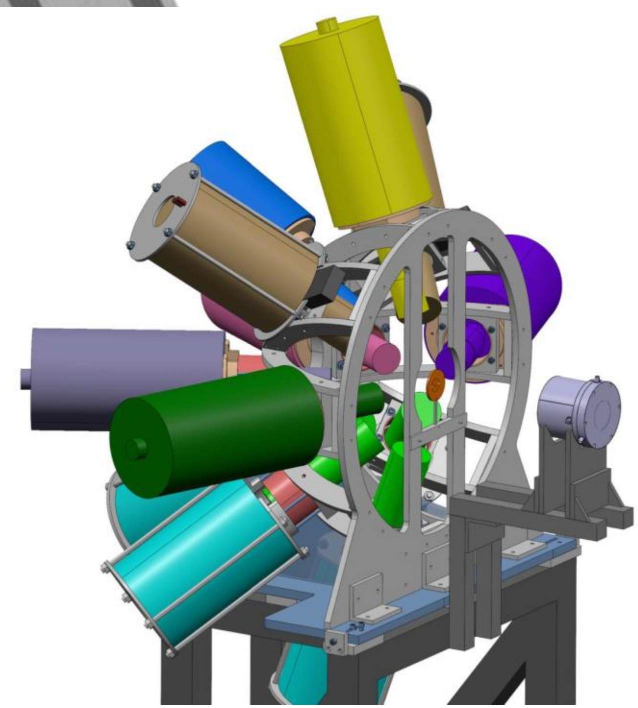
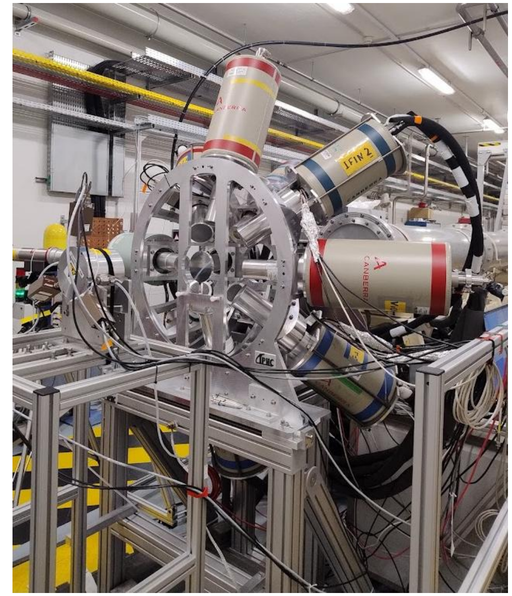
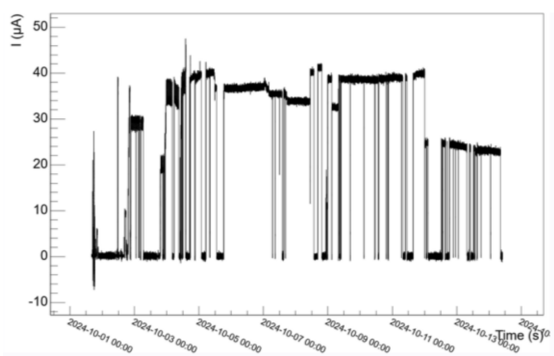


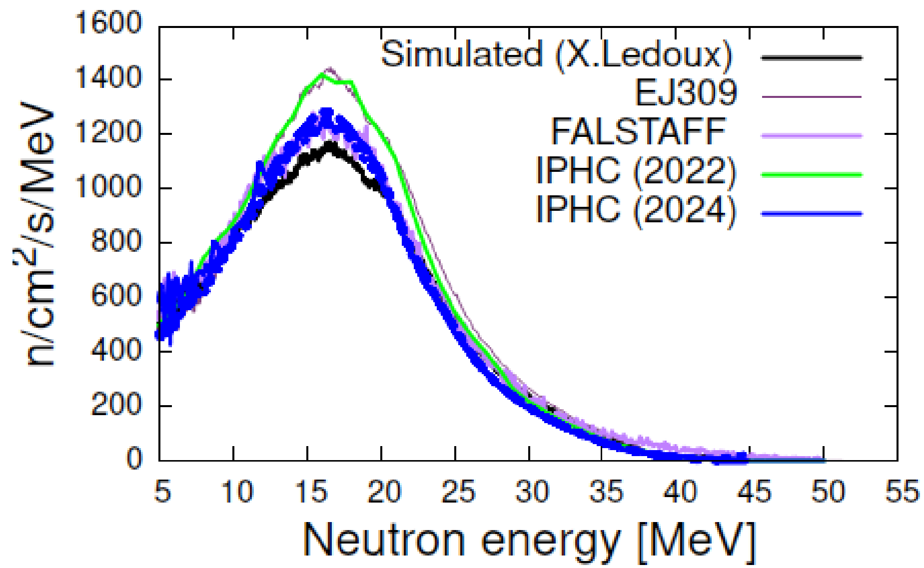
Image: C. Schwab (IPHC)

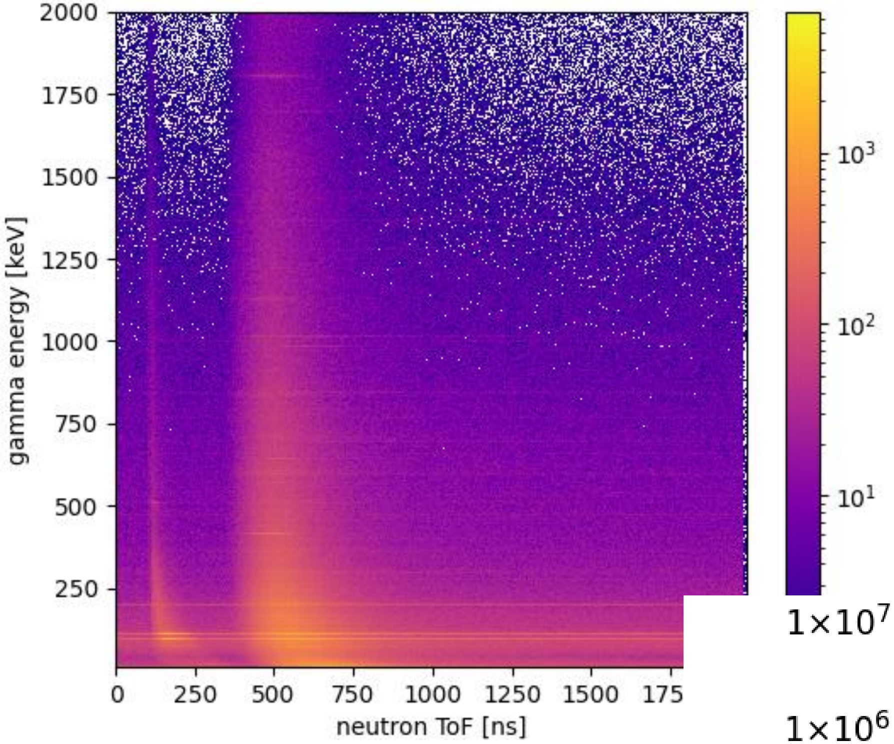
^{238}U(n, 2n γ) and (n, 3n γ) cross section measurements

- In October/November 2024
- Collaboration between JRC-Geel, IFIN-HH, ESRIG / Univ. Groningen.
- HPGe detectors gathered from different setups/labs (IPHC, JRC-Geel, IFIN-HH).
- Mechanical support specially designed at IPHC.
- 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.

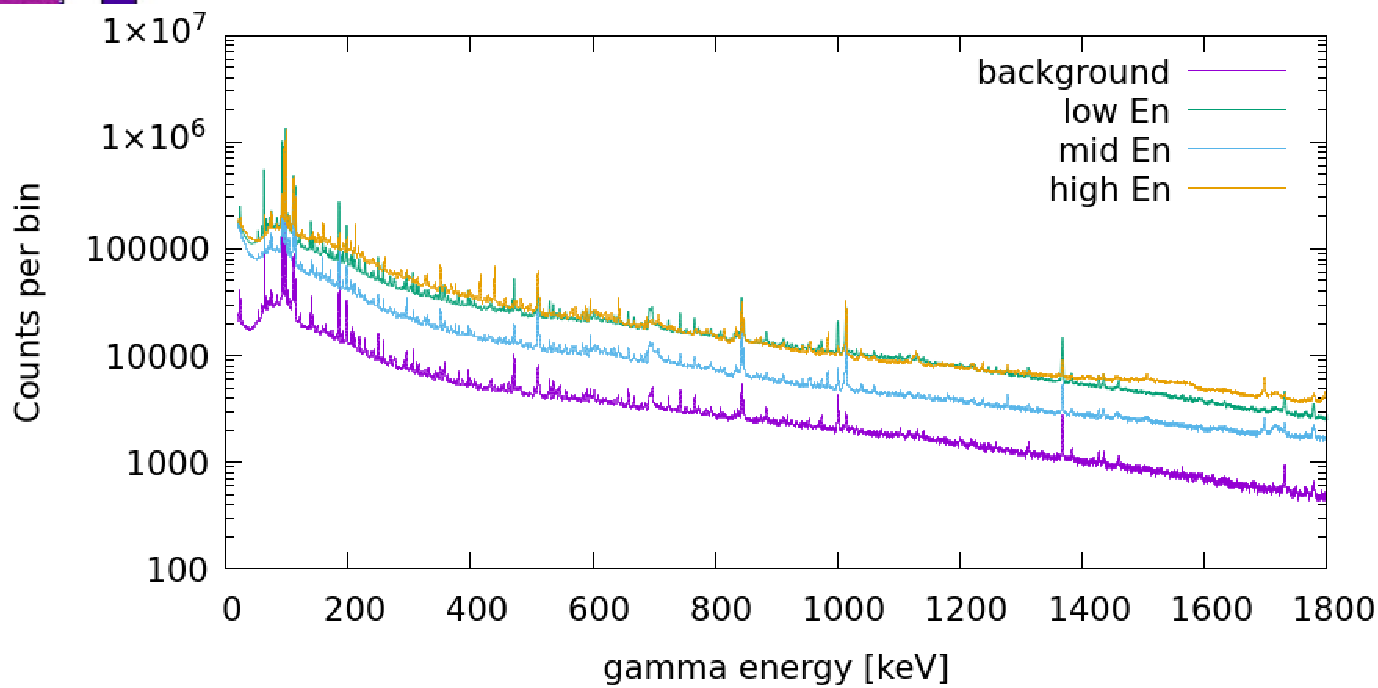






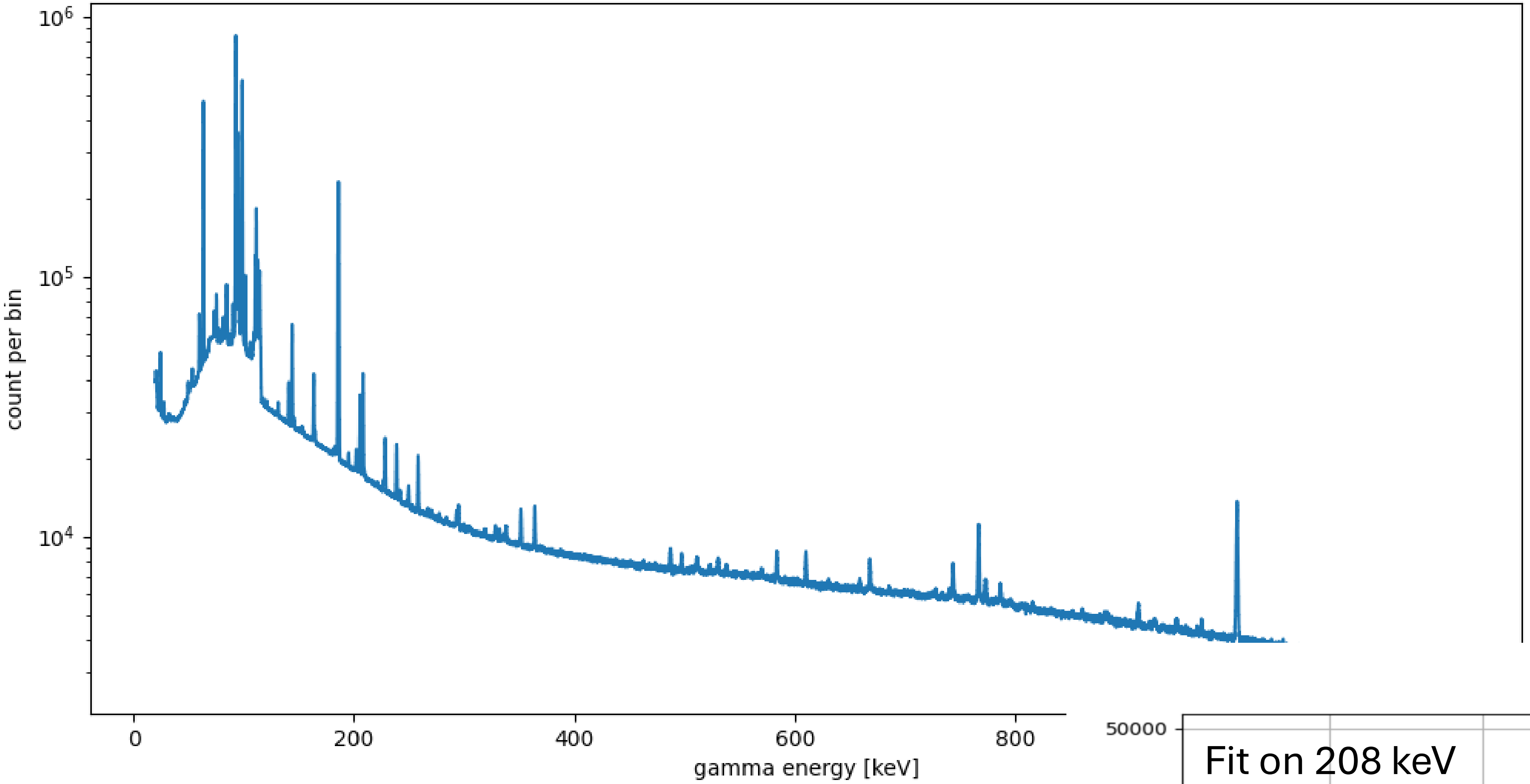


2000
1750
1500
1250
1000
750
500
250
gamma energy [keV]
0
250
500
750
1000
1250
1500
175
neutron ToF [ns]
10^3
10^2
10^1

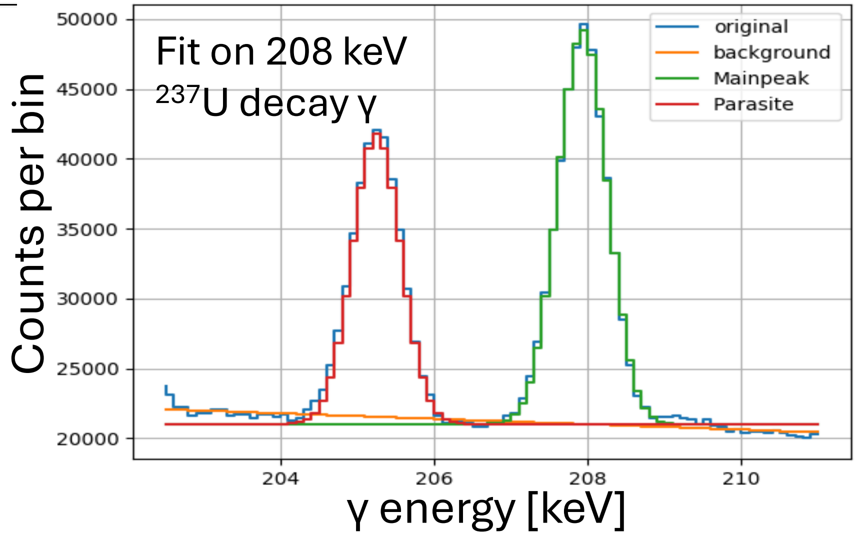


1×10^7
1×10^6
100000
10000
1000
100
Counts per bin
0
200
400
600
800
1000
1200
1400
1600
1800
gamma energy [keV]
background
low En
mid En
high En

Decay γ Data



10^6
10^5
10^4
count per bin
0
200
400
600
800
gamma energy [keV]



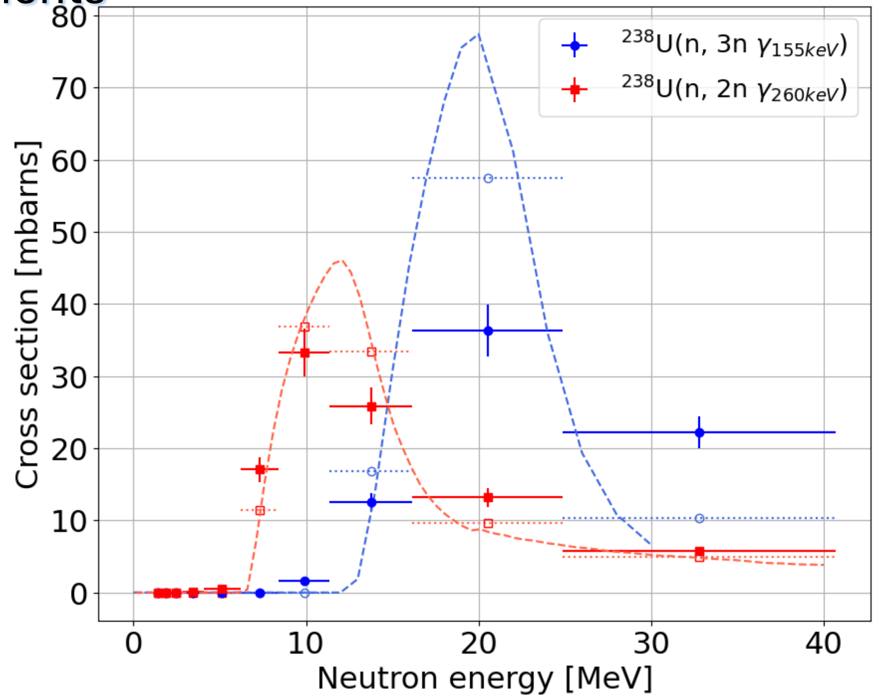
Fit on 208 keV
^{237}U decay γ
original
background
Mainpeak
Parasite
50000
45000
40000
35000
30000
25000
20000
Counts per bin
204
206
208
210
γ energy [keV]

APRENDE

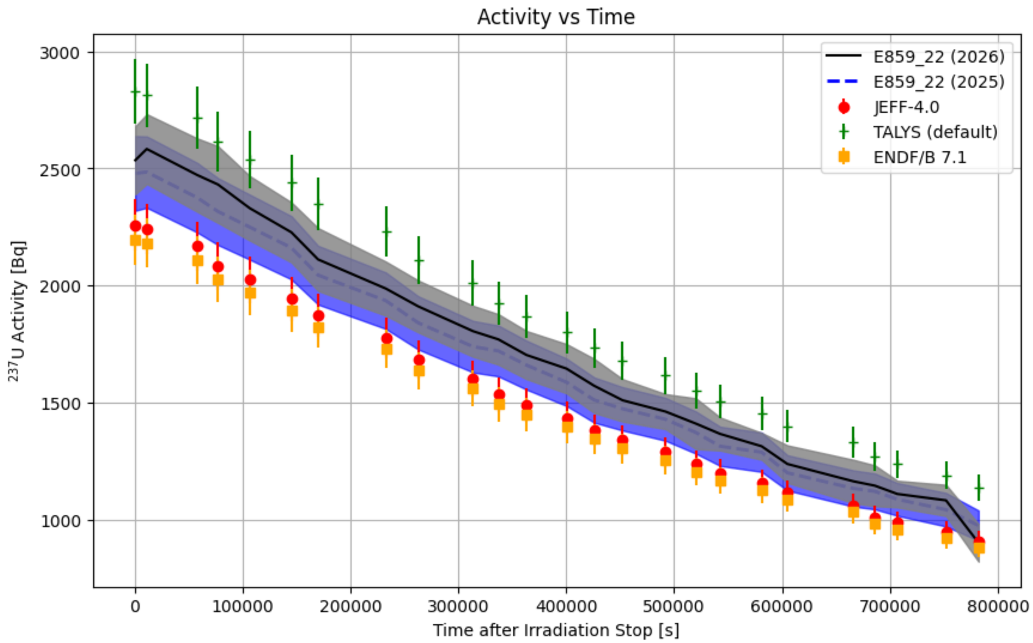
^{238}U(n, 2n γ) and (n, 3n γ) cross section measurements

- Preliminary results from prompt (n, 2nγ) and (n, 3nγ) transitions show reasonable uncertainties, agreement with model predictions is similar to what was seen in previous (n, n'γ) measurements.
- Full analysis starting as PhD work (PEPR SciAm)

anr France 2030



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



G. Henning, S Ouafiki, 2026

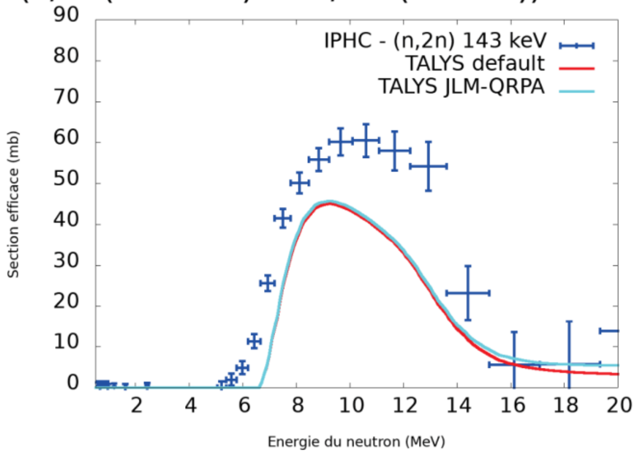
- Preliminary analysis of ^{237}U decay hints at under-estimation of produced activity → total (n, 2n) cross section higher than in evaluation ?
- The trend holds for different characteristic decay γ, and target irradiation.
- Need to check for bias in Φ_n, ε_γ, mass of target, …

APRENDE

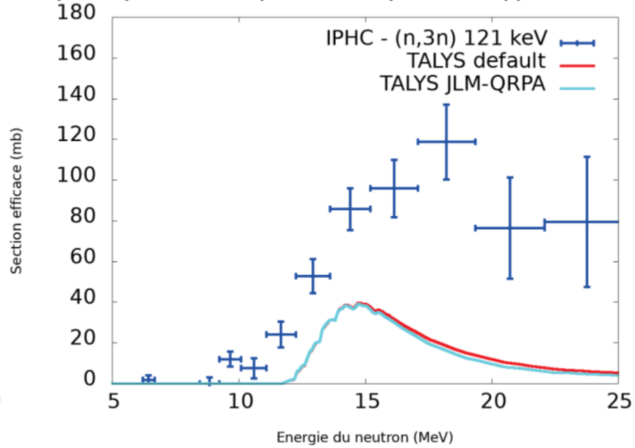
Next step: ^{232}Th(n, 2nγ) and (n, 3nγ)

- Previous study with GRAPhEME saw 11 (n, 2n γ) and 7 (n, 3n γ) [in addition to 50+ (n,n'γ)].

(5/2- (185 keV) -> 7/2+ (42 keV))



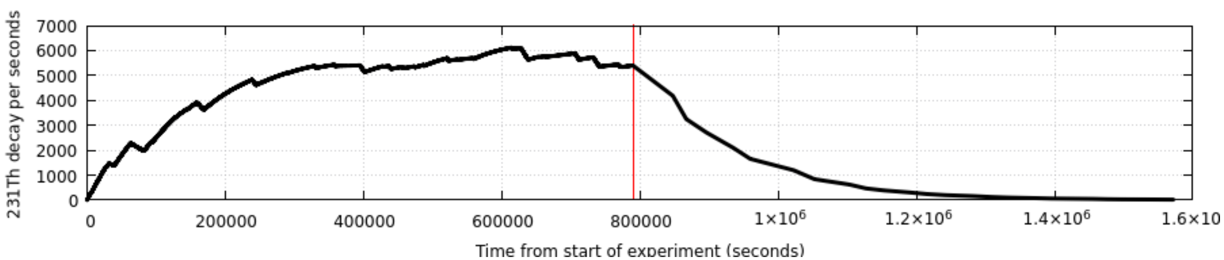
(4+ (174 keV) -> 2+ (53 keV))



E. Party. Thèse, Univ. Strasbourg (2019)

- Activation measurement for ^{232}Th(n, 2n)

($T_{1/2}$ = 25 hours) to perform integral (n, 2n) cross section measurement.



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

Improvement of the MAELS setup

- Following high background of scattered neutrons on detectors during the 2024 experiment.

- Preparing a *Mini Collimator* upstream from the target/HPGe detectors

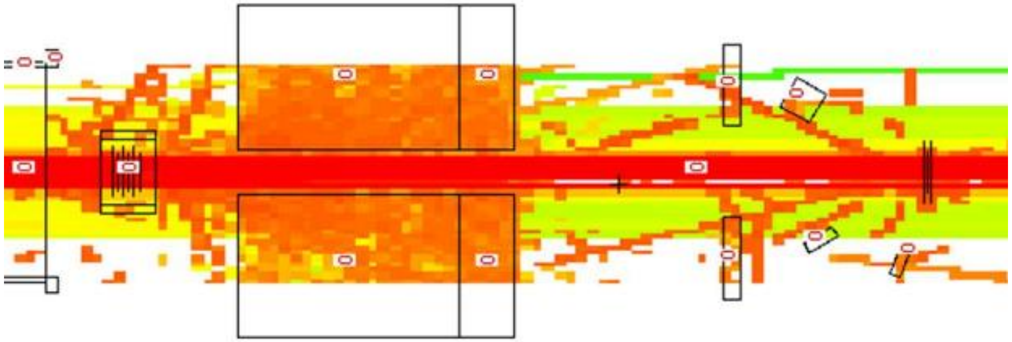


Image: P. Dessagne (IPHC)

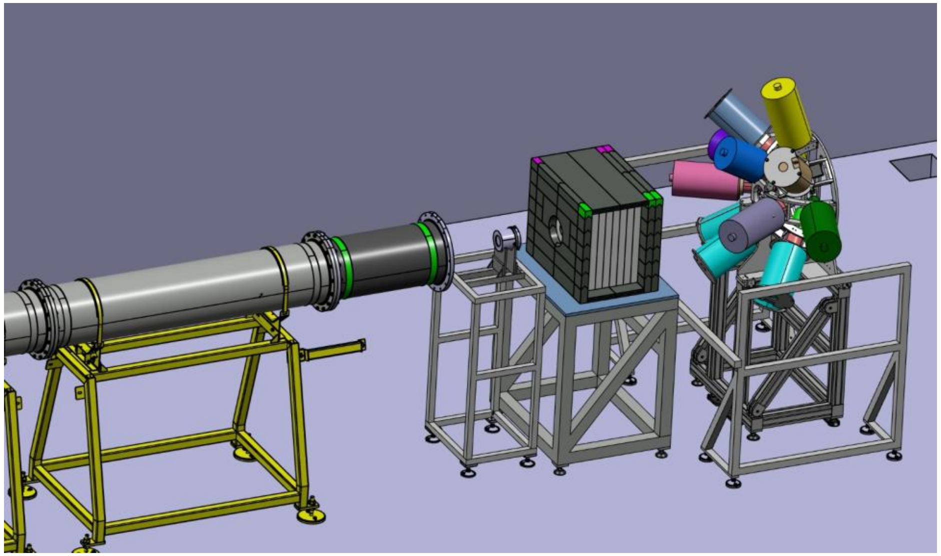


Image: C. Schwab (IPHC)

- Use of ^{235}U fission chamber in addition to the ^{238}U ones for better neutron flux characterization.

Further down the road, we hope to perform measurements on ^{235}U, ^{233}U, ^{239}Pu.

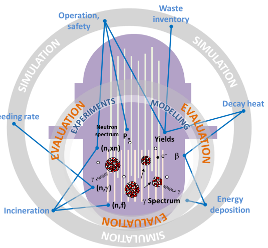
This requires to accommodate radioprotection rules.

- Hard limit of 3g of ^{239}Pu or ^{233}U on the Ganil (whole site)
- Radioactivity limit in the NFS Hall : 10 GBq in the Hall (4.4 grams of ^{239}Pu (pure), 8.4 grams of ^{233}U)

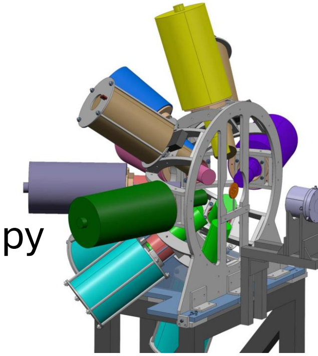
→ limits the size of the target sample. How much beam time would we need to get results ?

Scale up our own data recording capability (high radioactivity generates a lot of γ ray data that are not useful)

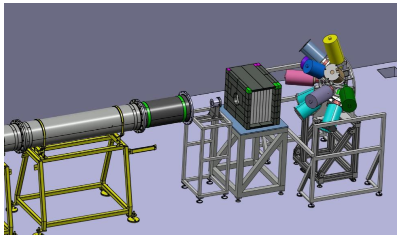
Summary and conclusions



- Next-generation reactors aim to address sustainability, safety, and waste reduction in nuclear energy.
- Computer simulations of future reactors rely on evaluated nuclear data, but gaps and uncertainties persist, impacting the accuracy of calculations.
- Inelastic neutron scattering (n,xn) plays a critical role in neutron spectrum modification and isotope production, yet lacks comprehensive experimental data.



- At NFS, high-energy neutrons enable study of (n,2nγ) and (n,3nγ) reactions, complementing lower-energy measurements at Gelina/JRC-Geel.
- 2024 Experiment: ^{238}U(n,2nγ) and (n,3nγ) cross-section measurements with Multi-Germanium array (MAELS), combining detectors from JRC-Geel, IFIN-HH, and IPHC for prompt γ spectroscopy and activation measurements.
- Preliminary results show reasonable uncertainties and alignment with model predictions for (n,2nγ)/(n,3nγ) transitions.
- Activation analysis (^{237}U decay) suggests underestimated (n,2n) cross sections in current evaluations.



- Future Plans: ^{232}Th(n,2nγ)/(n,3nγ): Build on prior experiment, with setup upgrade (Shielding, ^{235}U Fission Chamber)
- Long-Term Goals: Measurements on ^{235}U, ^{233}U, ^{239}Pu (radioprotection constraints, scale data recording capacity)

- Cross-section data help constrain reaction models and reduce uncertainties in reactor simulations.
- Continued partnerships with JRC-Geel, IFIN-HH, CEA, to advance nuclear data for next-gen reactors.

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