



LAST NEWS FROM GRAPHEME @EC-JRC/GELINA AND FUTURE MEASUREMENTS @ GANIL/SPIRAL2/NFS

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3- IAEA Nuclear Data Section, Vienna, Austria

4- CEA, DES, IRESNE, DER, SPRC, LEPH, Saint-Paul-lez-Durance, France

5- CEA, DAM, DIF, Arpajon, France

6- Université Paris-Saclay, CEA, Laboratoire Matière sous Conditions Extrêmes, Bruyères-Le-Châtel, France

7- European Commission, Joint Research Centre, Geel, Belgium

8- Los Alamos National Laboratory, Los Alamos, New Mexico, USA

9- University of Helsinki, Department of Chemistry, Helsinki, Finland

Some context



GRAPhEME @ EC-JRC-GELINA facility
last news on ^{232}Th , ^{238}U , ^{233}U & ^{239}Pu



Towards (n, 2n) and (n, 3n) reaction studies
@ GANIL/SPIRAL2/NFS facility



Conclusions & Perspectives



Some context

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Towards (n, 2n) and (n, 3n) reaction studies
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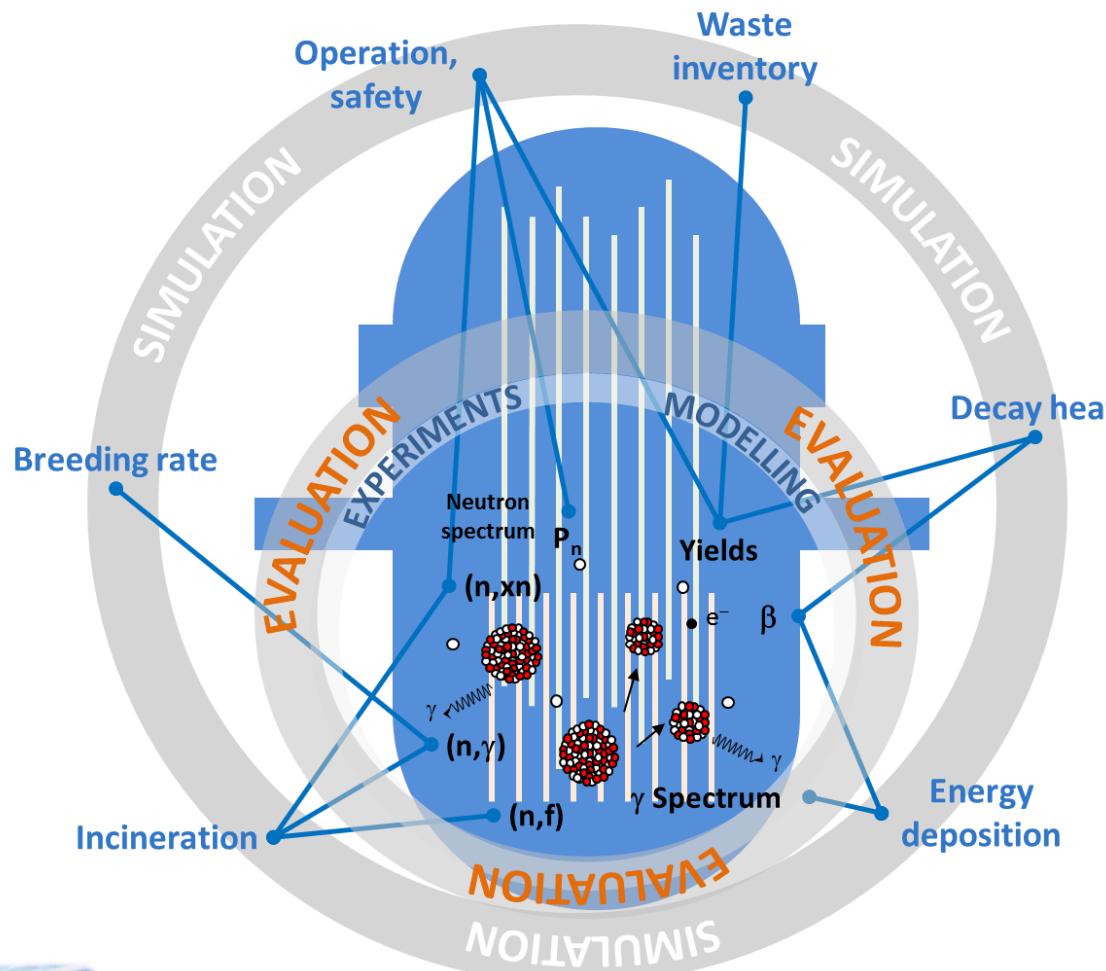
Conclusions & Perspectives





Accuracy improvement of (actual or future) reactor core simulations requires :

A better knowledge of the neutron population evolution which is partially driven by inelastic scattering and (n,xn) reactions



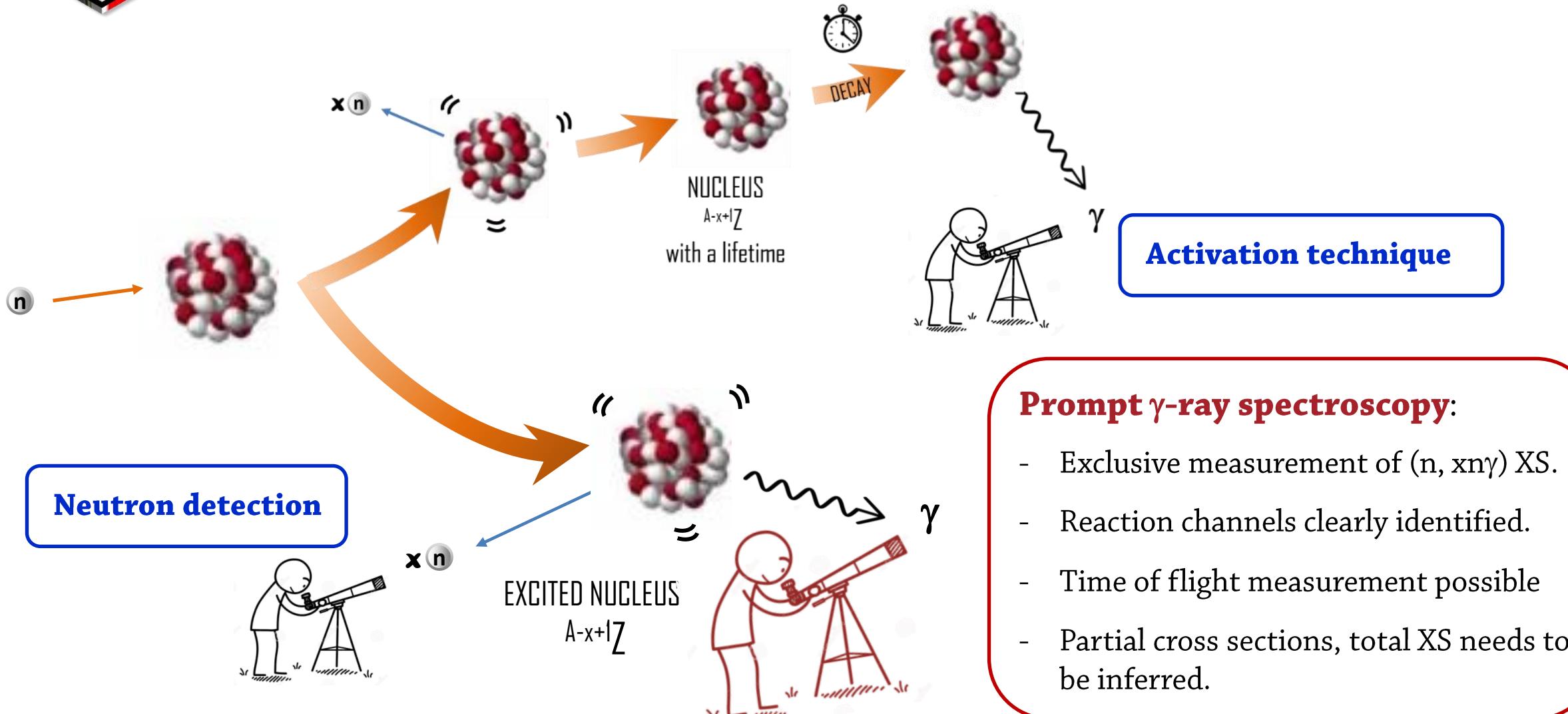
=> accuracy issues for (n,xn) reactions

- 1990's : strong demand for improvement of the inelastic scattering XS.
NEA/WPEC-4, vol. 4, 1999.
- Impact on core parameters in various future reactor designs (Vol. 26).
NEA/WPEC-26, Vol. 26, NEA No 6410., 2008.
- Entries in HPRL (reduction of uncertainty from 20% to 5% or less).
- Overestimation by about $(10 \pm 2)\%$ of the JEFF-3.1.1 $^{238}\text{U}(n, n')$ XS
Nucl. Data Sheet 118, 118 (2014)
- Experimental efforts to address the challenges

but **improvements are still required.**



Experimental studies : 3 main methods exist for (n, xn) reactions

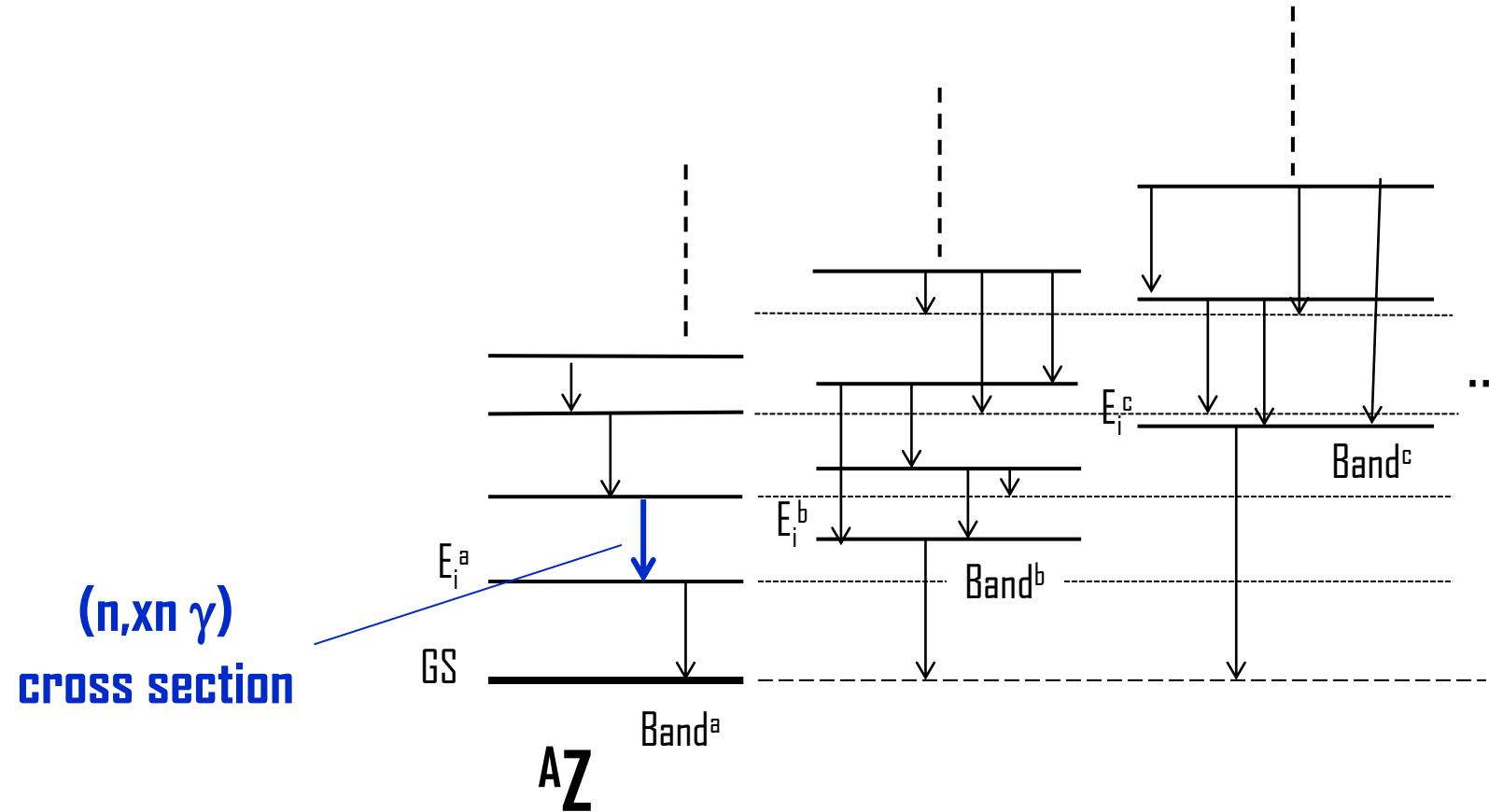




Inferring (n, xn) cross sections from (n, xny) ones

Powerful method which provides a lot of cross sections :

- (n, xny)

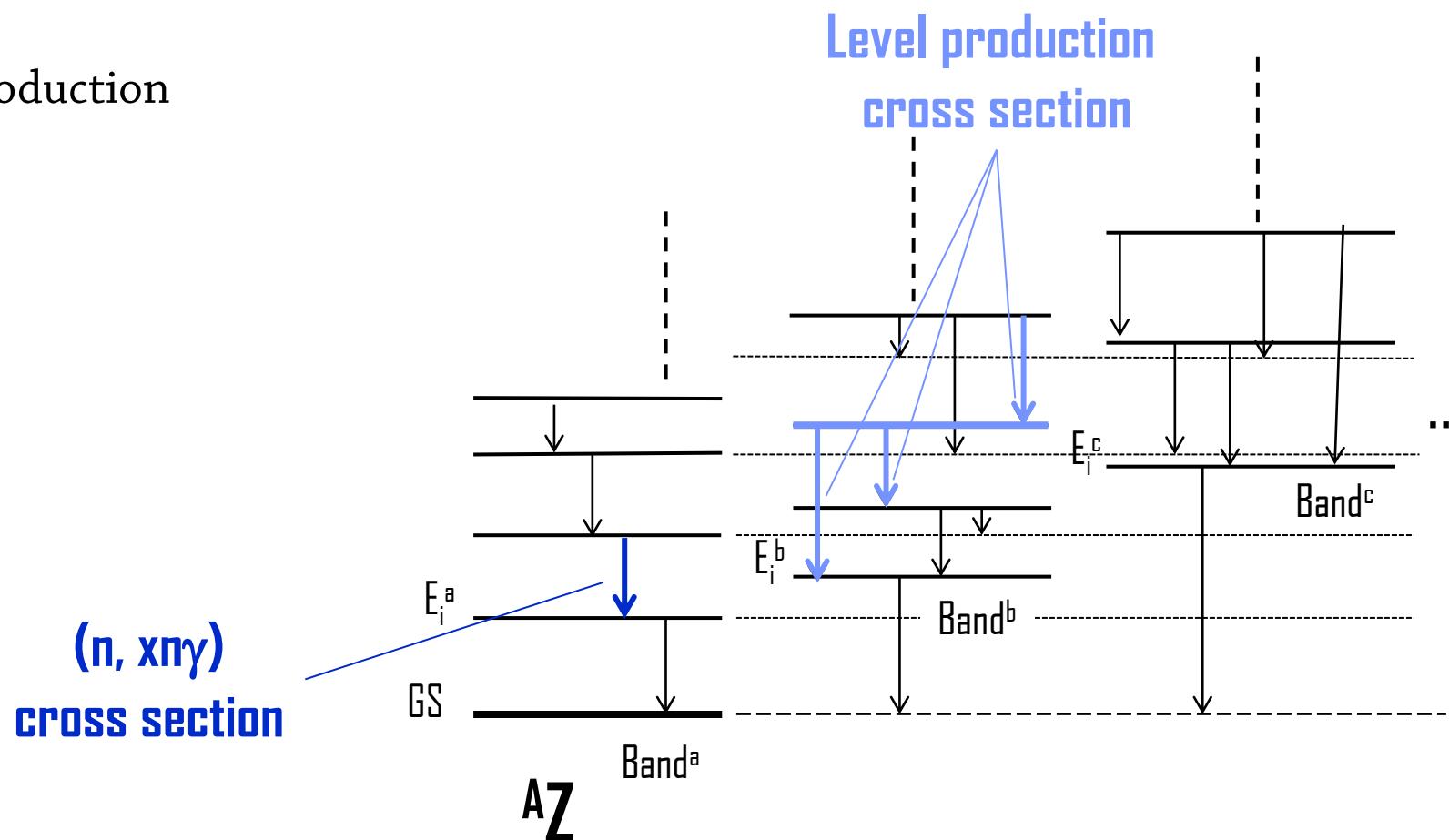




Inferring (n, xn) cross sections from (n, xny) ones

Powerful method which provides a lot of cross sections :

- (n, xny)
- level production

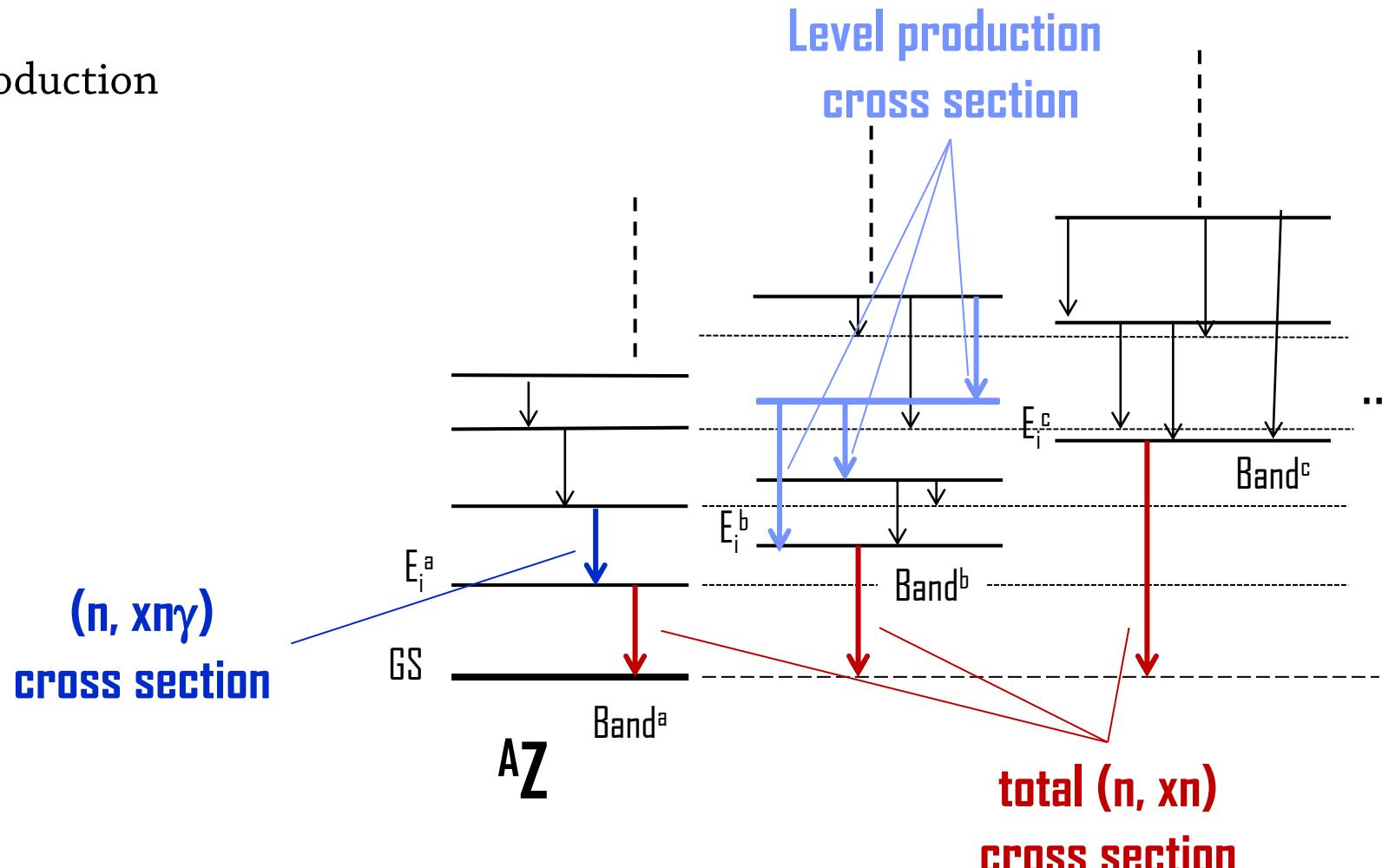




Inferring (n, xn) cross sections from (n, xny) ones

Powerful method which provides a lot of cross sections :

- (n, xny)
- level production
- total



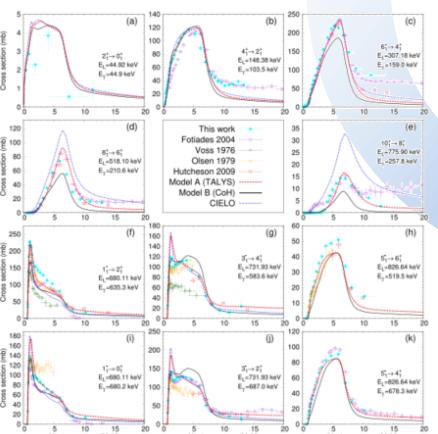


Inferring (n,xn) cross sections from (n,xn γ) ones

With the γ -ray prompt spectroscopy

XS (n,xn) for En < Emax

Nuclear Structure Data



Measured (n,xn γ) XS
ACCURATE

⌚ A method used already since the **70's**

@ the **cyclotron of KIT**

by Voss *et al.*

^{238}U , ^{56}Fe , ^{27}Al

@ the **Linear accelerator of ORNL**

by Dickens *et al.*, Olsen *et al.*

^7Li , ^{24}Mg , ^{28}Si , ^{65}Zn , ^{208}Pb , ...

⌚ in the **90's and 2000's**

@ **WNR, LANL**

with the **GEANIE** spectrometer

by Vonach *et al.*, Bernstein *et al.*,

Younes *et al.*, Fotiades *et al.*,

Dashdori *et al.*, ...

Pb, Al, Pt, mo, Ti, Sm, U, Pu, ...

⌚ today since ~20 years

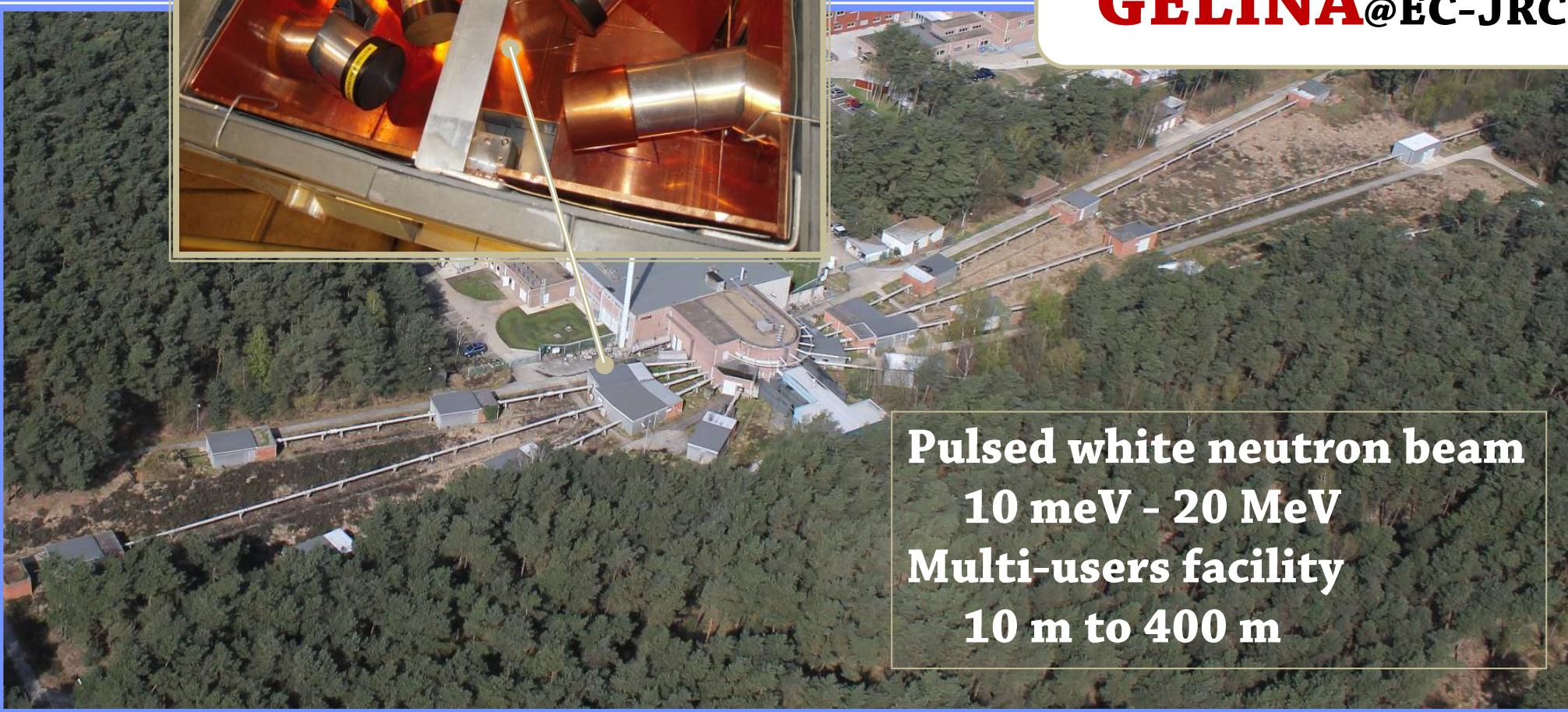
@ **GELINA – EC-JRC Geel**

With **GAINS & GRAPhEME**



A. Olacel *et al.*, WINS2023

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Neutron Time of flight facility
GELINA@EC-JRC(Geel)

GRAPHEME @ GELINA: today

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10-12/10/2023 - Troy, NY, US

Maëlle Kerveno

IPHC
Institut Pierre-Simon Laplace
Habert-Gouet

CNRS 1
IN2P3
Les deux infinis

Université de Strasbourg



GRAPhEME main specificities

1 Fission Chamber,
5 HPGe Planar,
1 HPGe seg
(110°,150°)
 ^{232}Th , $^{233,235,238}\text{U}$
 $^{\text{nat}}\text{Zr}, \text{nat}, 182, 3, 4, 6\text{W}, ^{57}\text{Fe}$,
In progress ^{239}Pu

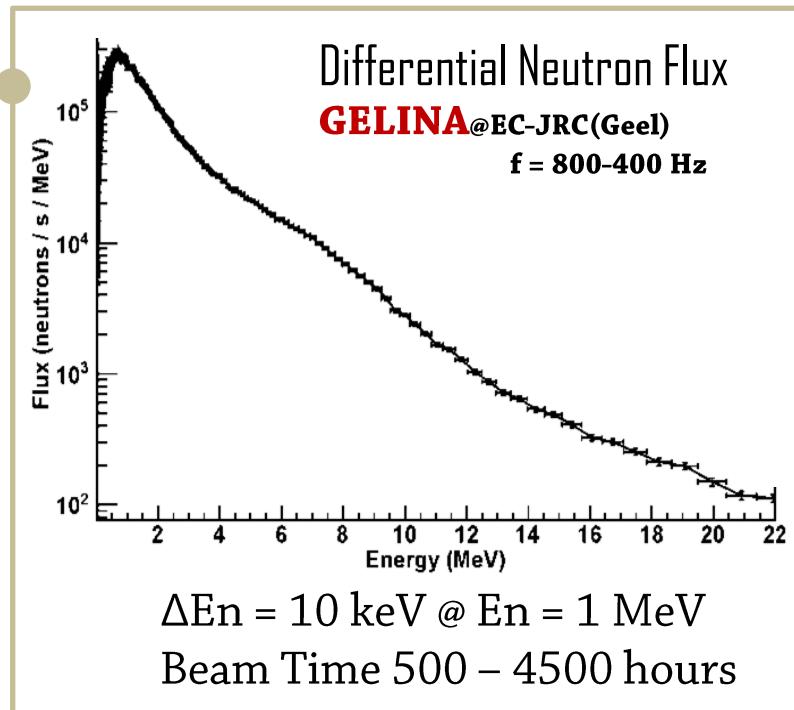
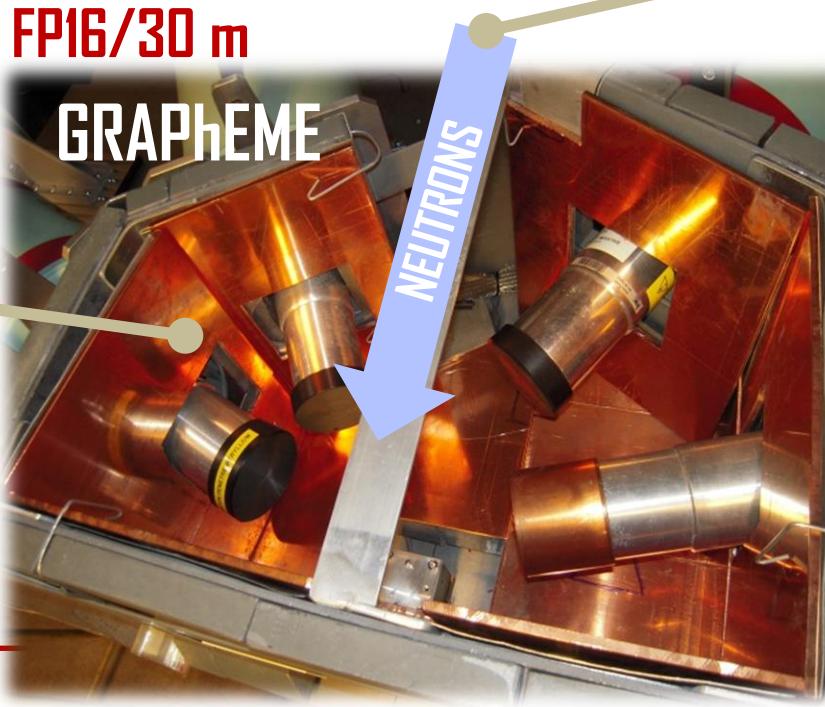


G. Henning et al., WINS2023

FP16/30 m

GRAPhEME

NEUTRONS



XS uncertainties

3 to 5% - $E_n < 9 \text{ MeV}$

Up to 20% - $E_n > 9 \text{ MeV}$

Correlation and covariance
matrices provided

- M. Kerveno et al. PRC **87**, 24609 (2013)
- G. Henning et al. EPJ Web of Conf. **284**, 01045 (2023)
- M. Kerveno et al. EPJN **4**, 23 (2018)
- M. Kerveno et al. PRC **104**, 04605 (2021)

$$\frac{d\sigma^{(n,xn\gamma)}}{d\Omega}(\theta, E_n) = \frac{n_{det}(E_n)}{N_{at} \cdot \phi_n(E_n) \cdot \varepsilon_\gamma \cdot t}$$

1 to 3%

0.4 - 0.6 % ; 0 to 10 MeV
1 - 2 % ; 10 to 20 MeV

2 %

Some context



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Towards (n, 2n) and (n, 3n) reaction studies
@ GANIL/SPIRAL2/NFS facility

Conclusions & Perspectives



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232Th



10-12/10/2023 - Troy, NY, US

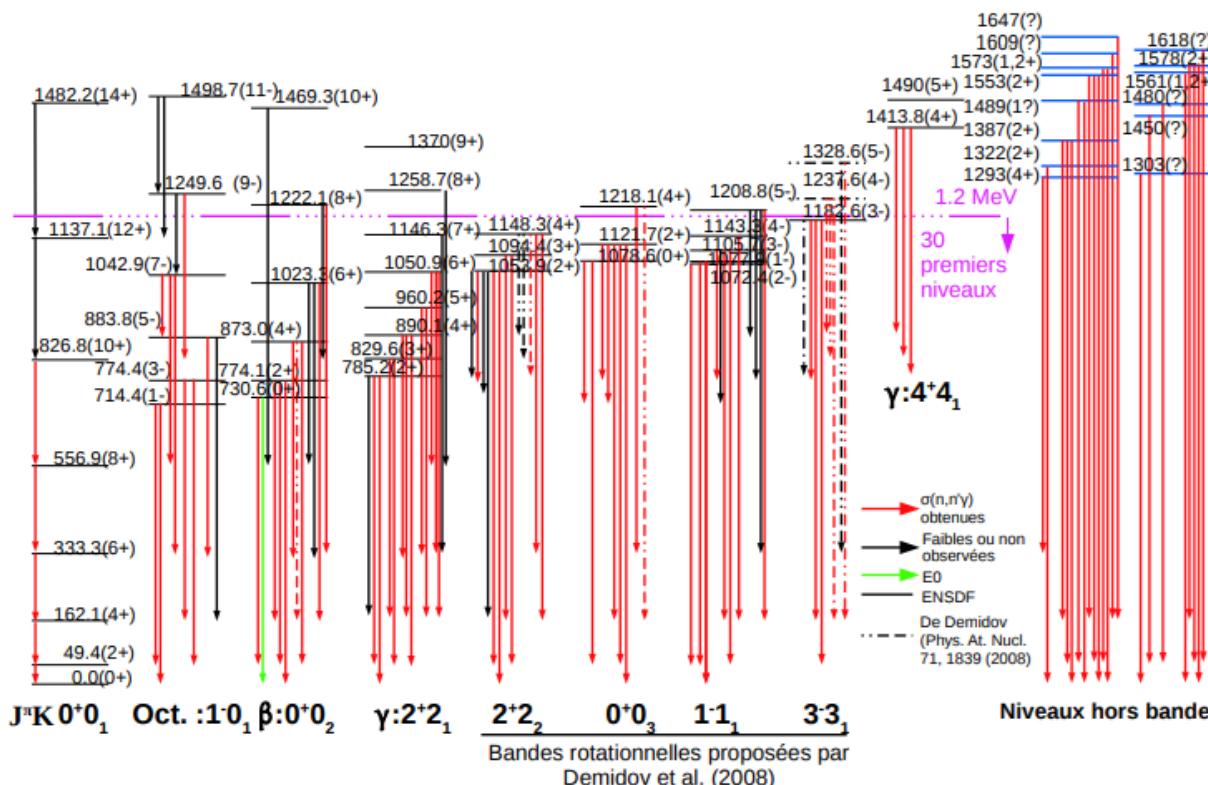
Maëlle Kerveno





Exploitation of $^{232}\text{Th}(\text{n}, \text{n}'\gamma)$ XS (from E. Party thesis) for publication purposes

800 h beam time, sample mass : 12 g, 4 HPGe detectors and TNT2 acquisition system



Cross section data for **81 γ -transitions in ^{232}Th , 11 γ -transitions in ^{231}Th , 7 γ -transitions in ^{230}Th .**

Very good agreement with Dave *et al.* data but significant discrepancies observed with TALYS calculations for numerous γ -transitions (even with “best files” input).

New information (some are contradictory with ENSDF) about **branching ratios** have been obtained.

PhD, E. Party, University of Strasbourg, 2019





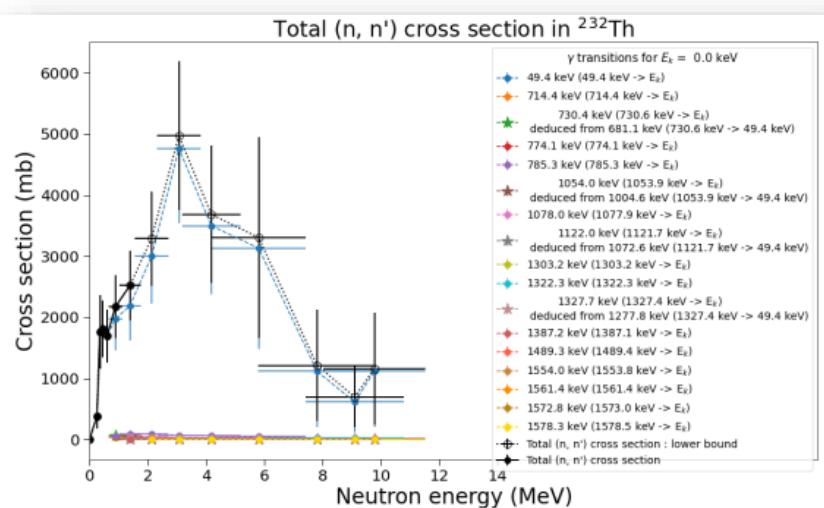
Exploitation of $^{232}\text{Th}(\text{n}, \text{n}'\gamma)$ XS (from E. Party thesis) for publication purposes

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- From nuclear structure and internal conversion coefficient information,

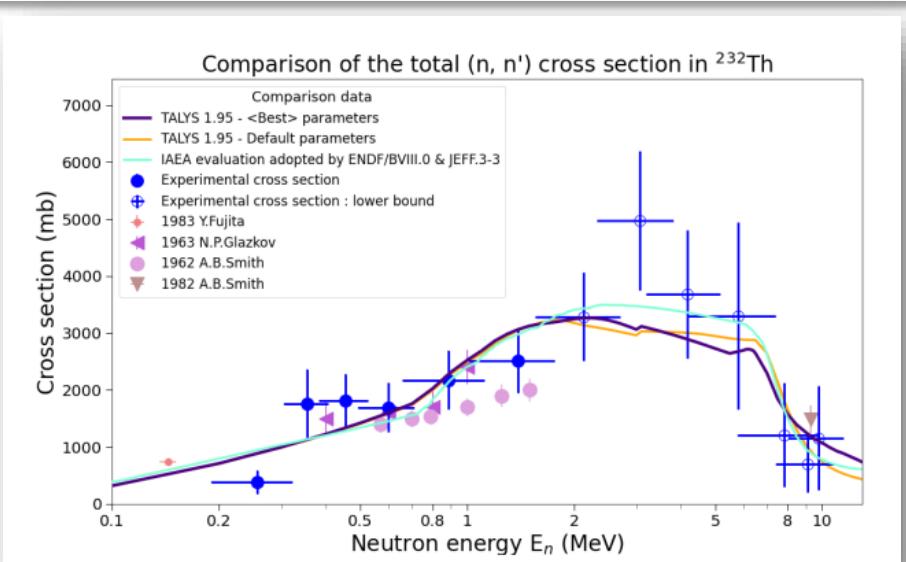
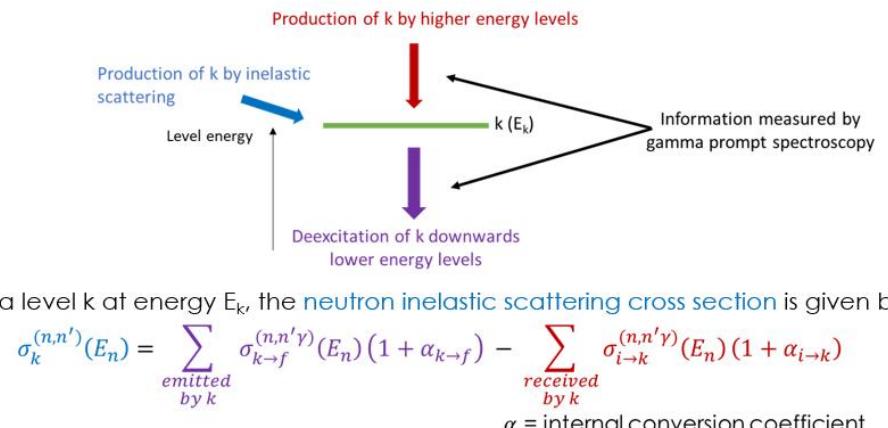
27 level production XS and total (n, n') XS have been calculated. The total uncertainty is driven by the uncertainty on the cross section of the 49 keV γ -transition ($2^+ \rightarrow 0^+$).



IN PROGRESS

(work done by N. Dari Bako, PhD student IPHC)

- For the final publication, collaboration work with **M. Dupuis** (TALYS) and **R. Capote** (EMPIRE) for theoretical comparisons.



N. Dari Bako et al. EPJ Web of Conf., 284, 08005 (2023)



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238U



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(n, n'γ) XS published with large theoretical development

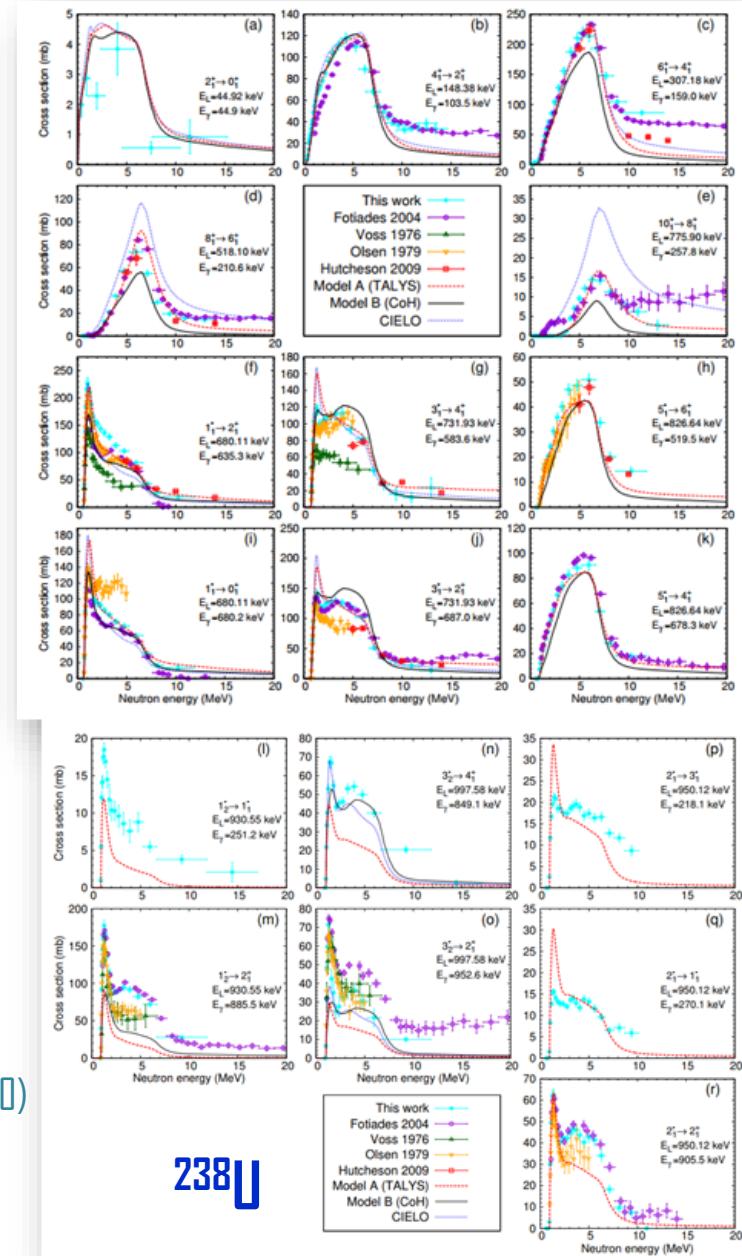
In collaboration with M. Dupuis et al., CEA/DAM, T. Kawano, LANL, R. Capote, IAEA

3000 h beam time, sample mass : 10.6 g, 4 HPGe detectors
and TNT2 acquisition system

- ▣ New exp. information about branching ratio
- ▣ Large uncertainties in the current modeling are related to the knowledge of the decay scheme: poorly known branching ratios and an incomplete information of the discrete states above 1.3 MeV.
- ▣ Some of the interband transitions are shown to be very sensitive to the choice of prescription for discrete levels γ decay that are not given in the RIPL3 library.
- ▣ Microscopic modeling of the preeq. emission improved the spin distr. description then improve (n, n'γ) transition prediction at high spin level in the GS band. A new prescription for the spin cut-off in the exciton model has been proposed for ²³⁸U.

M. Dupuis et al. EPJ Web of Conf., 284, 03003 (2023)

- ▣ Variation of the E1 and M1 strength functions that define the γ decay from continuum, were shown to be of importance M. Kerveno et al., EPJ web of conf. 239, 01023 (2020)
=> more studies are required.
- ▣ Another dozen (n, n'γ) cross sections can be determined and some (n, 2-3nγ) as well.
=> total neutron inelastic cross section will be inferred.



238U

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233U



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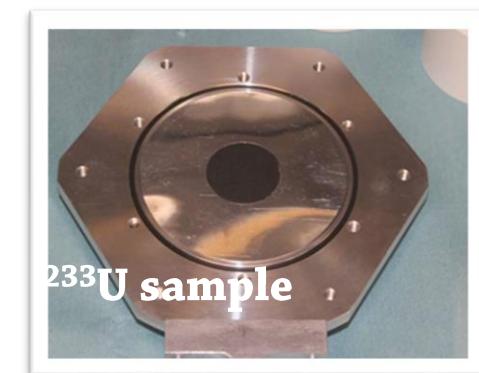
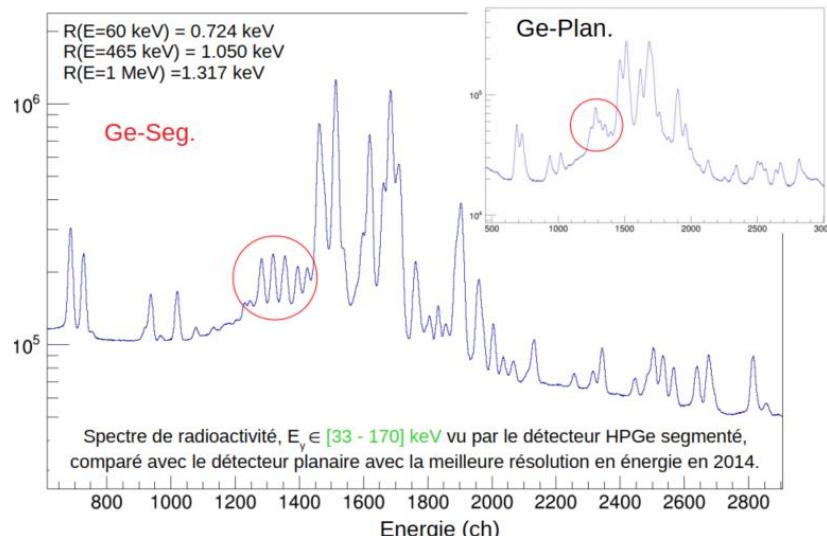




233U(n, n'γ) XS ever measured

4500 h beam time, sample mass : 8.3 g, 5 classic & 1 segmented HPGe detectors and TNT2 acquisition system

- ❖ Upgrade of the GRAPhEME setup with a **Segmented HPGe** detector 54x54 mm², t=20 mm, 36 pixels (6.66 x 6.66 mm²) to deal with the **high counting rate** due to **radioactivity from the sample**. The **excellent energy resolution** allows very good separation of γ-peaks (useful to separate γ coming from fission fragments).



- ❖ New data analysis methodologies and semi MC determination of the XS

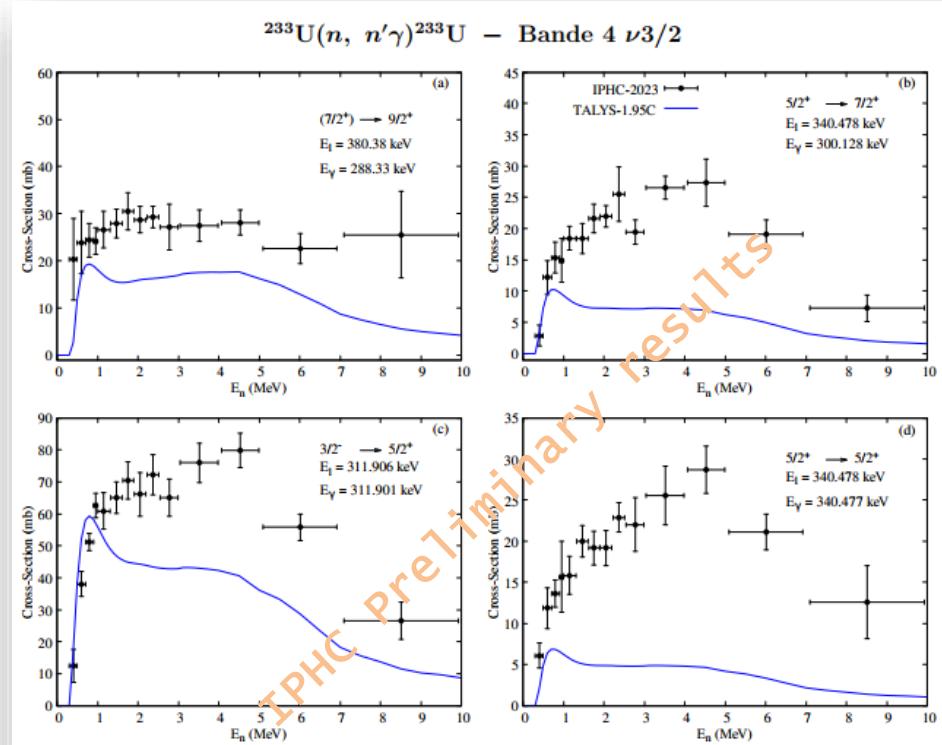
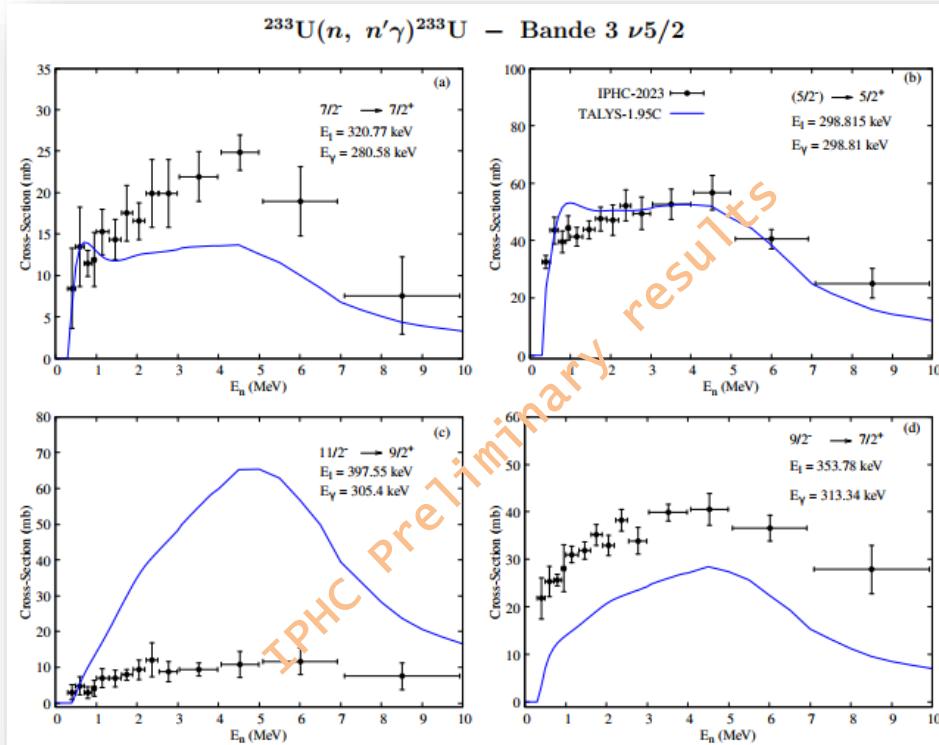
G. Henning et al. EPJ Web of Conf., 284, 01045 (2023)

Made by EC-JRC Geel,
m = 8.3 g, thick.= 0,64 mm,
A ~ 3 GBq.



233U(n, n'γ) XS ever measured

- ☒ Cross section data for 12 γ transitions in ^{233}U (ever measured),
- ☒ Important disagreements with TALYS calculations (best files input), especially on the shape of the XS.



- ☒ Collaboration work with M. Dupuis (TALYS) and R. Capote (EMPIRE) for theoretical comparisons/improvements.

Paper in preparation

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239Pu



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²³⁹Pu(n, n'γ) XS : another challenging measurement

sample mass : 2.3 g, 5 classic & 1 segmented HPGe detectors
and FASTER acquisition system

☒ The **first challenge** was to obtain a **Pu sample as free as possible from ²⁴¹Am**.

Work done by SCK-CEN (Mol Belgium) from PuO₂ powder provided by EC-JRC-Geel.
Separation and purification of Am and Pu by peroxide precipitation

In γ spectrum of the sample, one sees

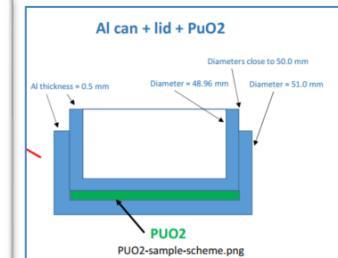
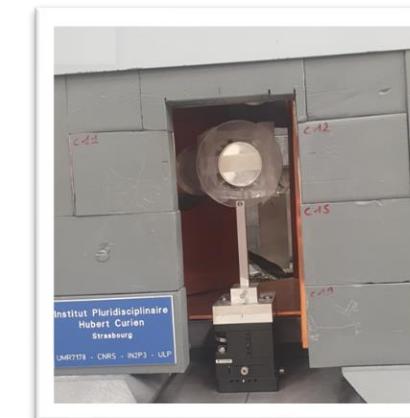
- mainly γ-lines from the decay of ²³⁹Pu → ²³⁵U
- main lines from the decay of ²⁴¹Am → ²³⁷Np

A. Moens et al. EPJ Web of Conf. **285**, 04002 (2023)

☒ **determination of accurate mass of ²³⁹Pu** : γ counting
(as done for ²³³U)

☒ **A new DAQ has been installed :**
FASTER [<https://faster.in2p3.fr/>]

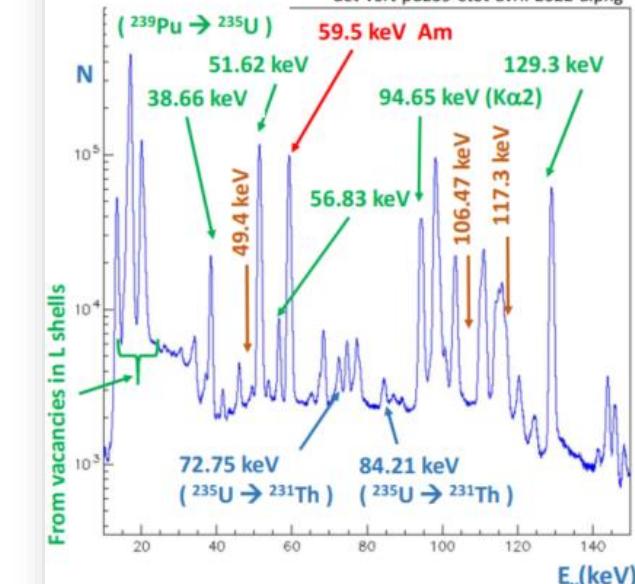
☒ **Up to now: a few weeks of beam time only.**
COVID + pb with the LINAC
+ reduction of GELINA operation time (electricity costs...)



m = 2,3 g
Ø = 49,95 mm, A = 5,2 GBq

First results with new ²³⁹Pu sample, april 2022

Green detecteur at 150°, full time window (radio + n), Part 1
det-vert-pu239-etot-avril-2022-a.png



GRAPHENE CONCLUSIONS



Overcome the weakness of the prompt γ -ray spectroscopy

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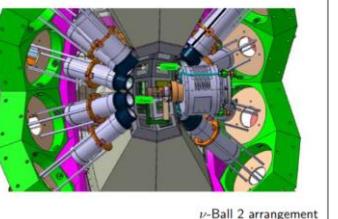
Acting with nuclear structure specialists

Proposed setup – ν -Ball 2

@ALTO, LICORNE

Optimised LaBr₃ arrangement

- 20 LaBr₃ detectors (FATIMA type)
- 1.5" x 2" crystals, R9779 PMT
- one upstream, one downstream ring
- Efficiency 2% (ν -Ball 1 ≈ 0.7%)
- Half-lives accessible with fast-timing: 10 ps - 100 ns



Collaboration:

ν -Ball 2 induced-fission collaboration

-> New measurements of

^{238}U & ^{232}Th nuclear structure

in neutron induced reaction ($E_n \sim 1.7$ MeV)

C. Chatel et al. submitted to EPJ Web of Conf.,

WONDER conf. 2023

XS (n,xn)

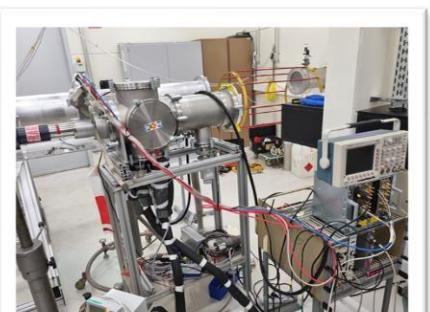
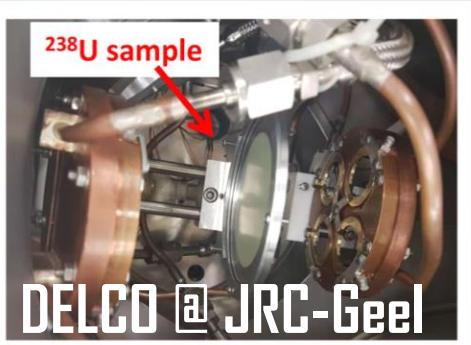
for $E_n < E_{\text{max}}$

highly converted transitions in actinides

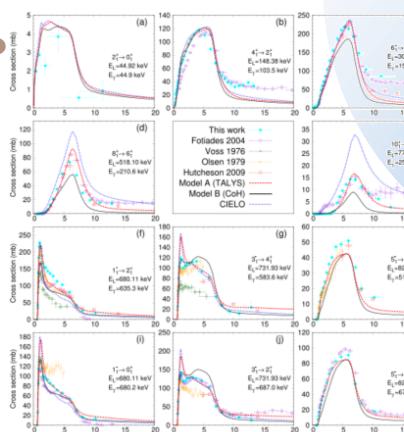
Develop **instrumentation** to measure
conversion electrons : **DELCO setup**

Cooled Si detector, 300 mm²

e(Si) = 5000 μm



Nuclear Structure Data



Measured (n,xn γ) XS
ACCURATE

Some context



GRAPHEME @ EC-JRC-GELINA facility
last news on ^{232}Th , ^{238}U , ^{233}U & ^{239}Pu



Towards $(n, 2n)$ and $(n, 3n)$ reaction studies
@ GANIL/SPIRAL2/NFS facility

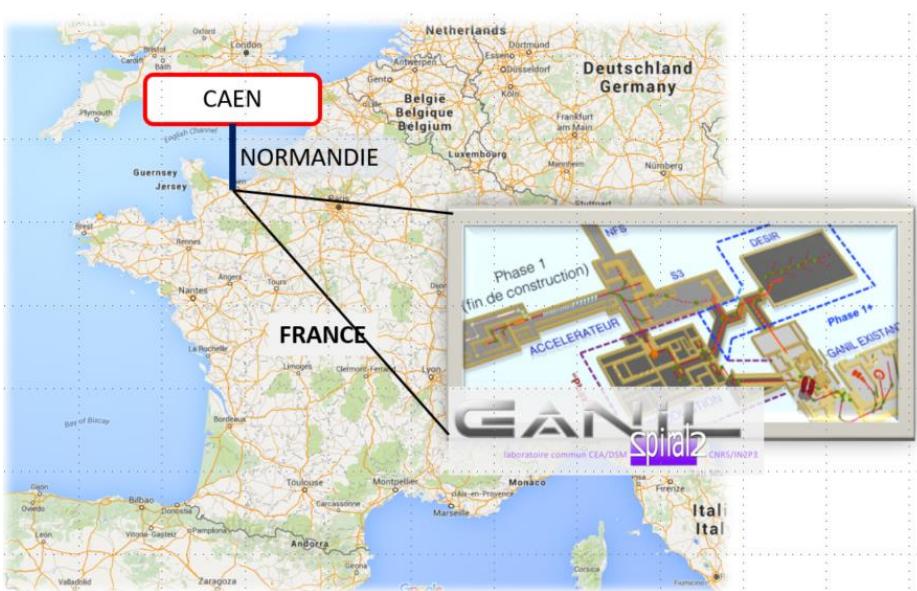


Conclusions & Perspectives

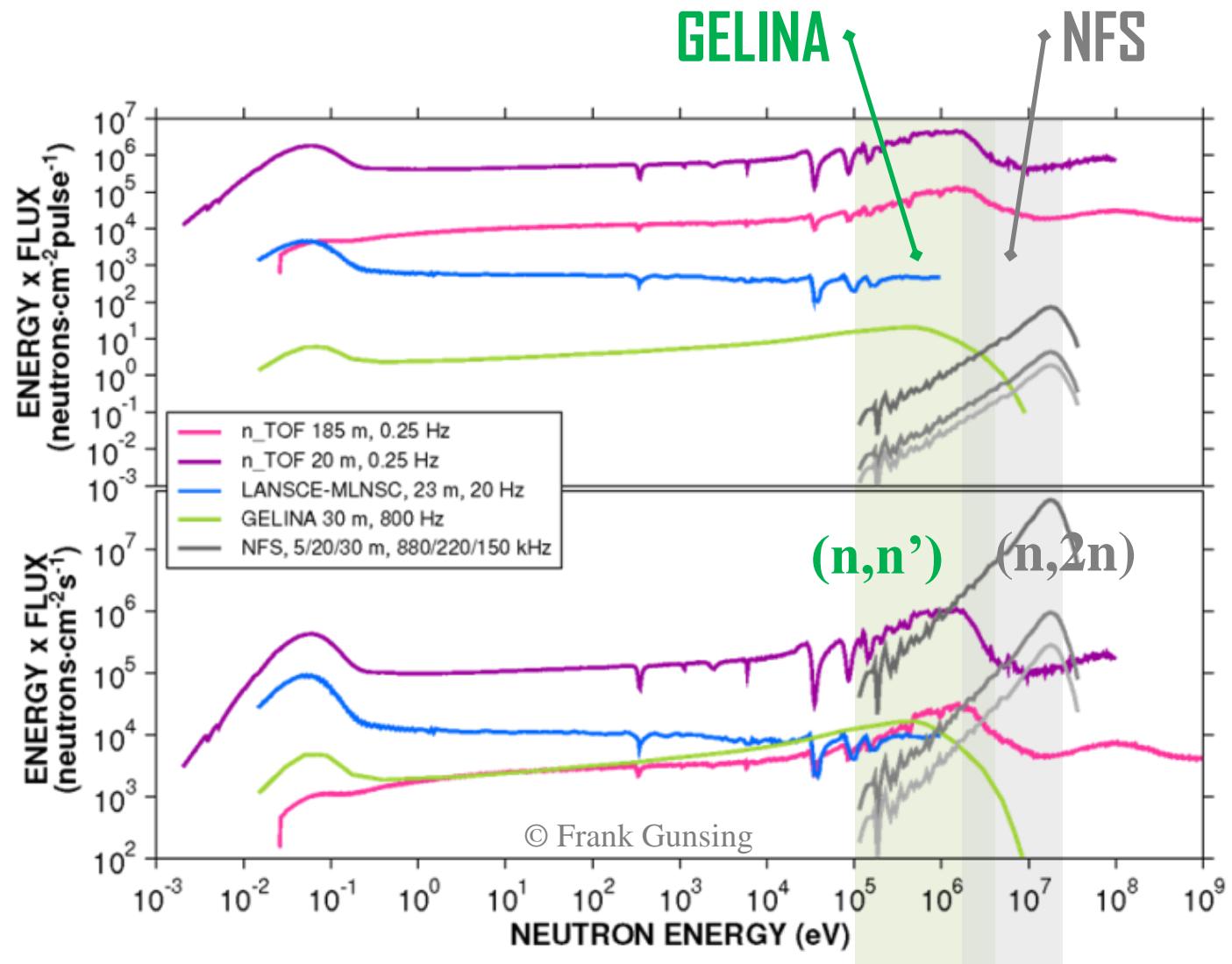




Neutron beam available @ NFS



- 1st beams in 2020,
Third beam campaign (falls 2021, 22, 23)

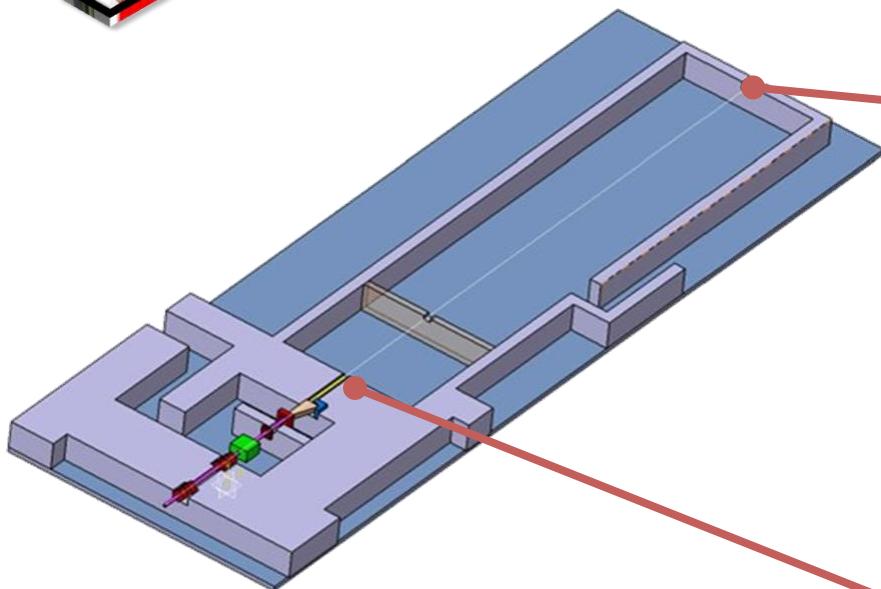


first stage: setting up the long-distance flight path

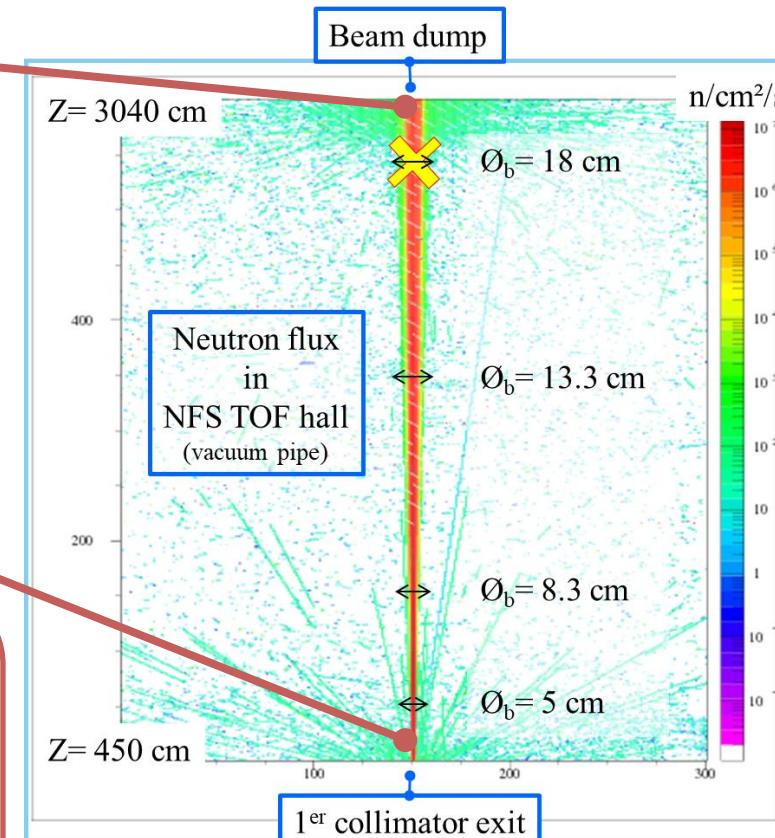




NFS flight path for time of flight measurement

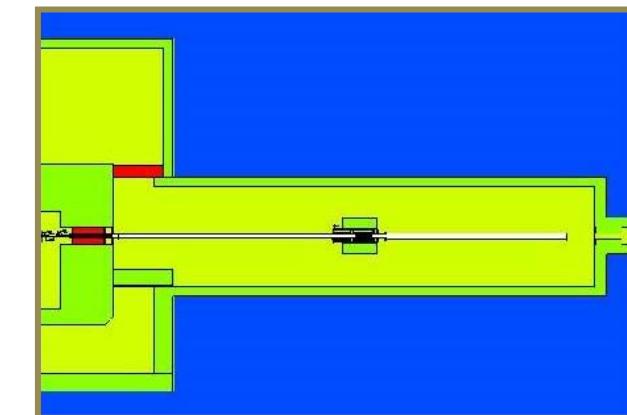


IPHC was in charge of the **design, construction** and **installation** of the **neutron beam line & 2nd collimator** to allow measurements at long flight path (focused beam, low background).



MCNPX-2.6 simulations

- NFS convertor room + hall entirely simulated

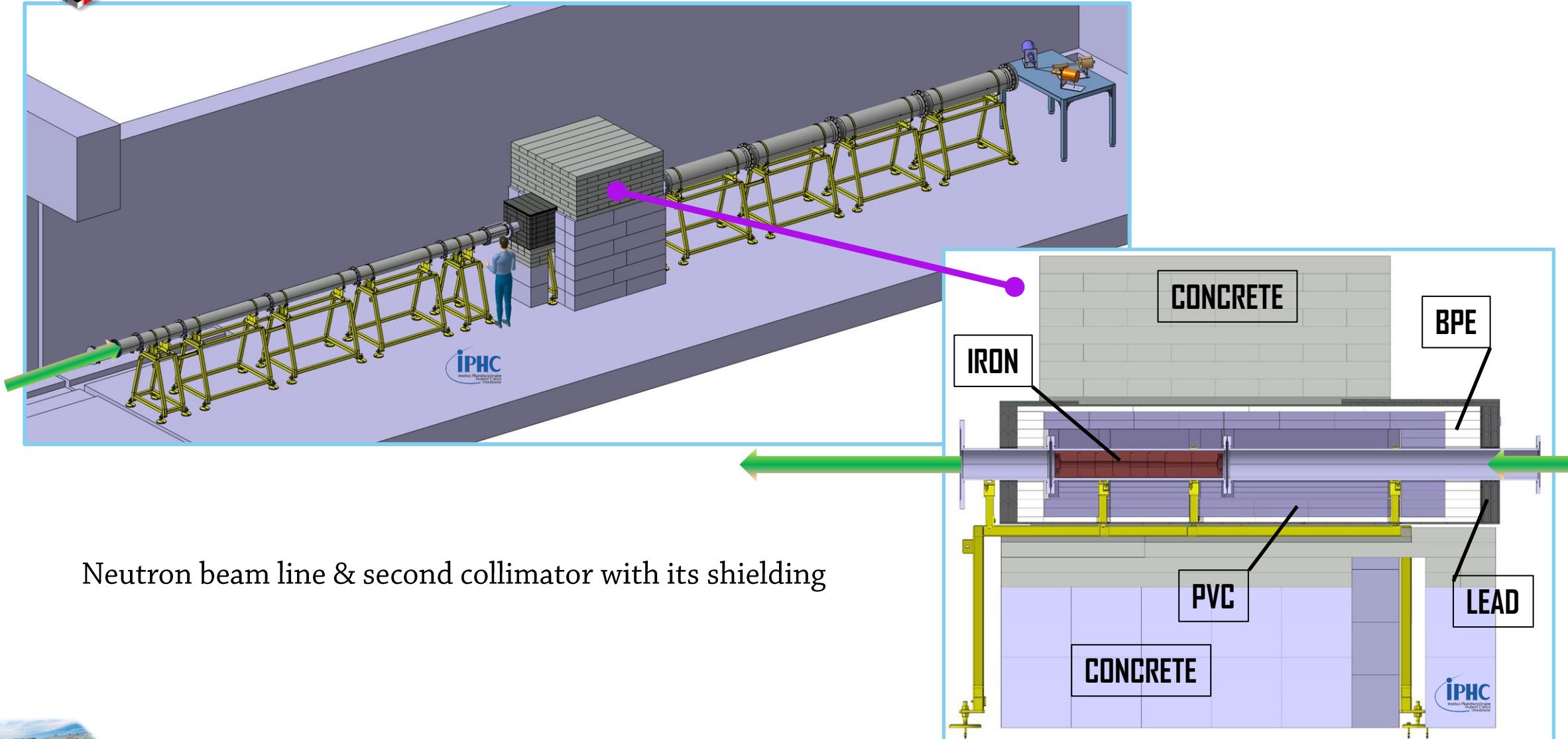


- Neutron production : d (50 µA ; 40 MeV) + Be
- Reduced inner aperture of the first collimator
- constraints of background minimization, weight and costs with the **objective** of $\Omega_b = 6 \text{ cm} @ z=2850\text{cm}$



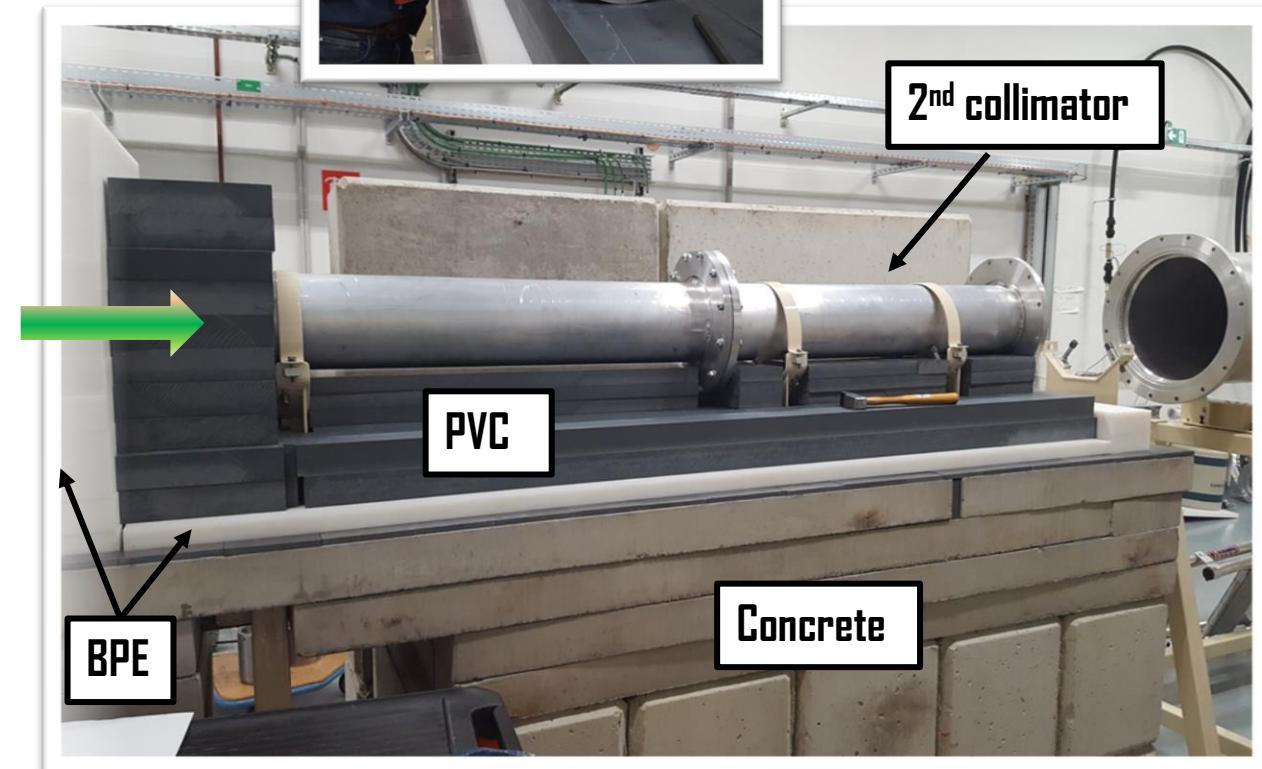
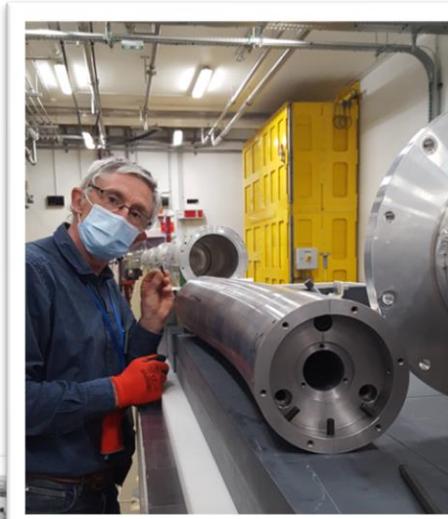


NFS flight path for time of flight measurement



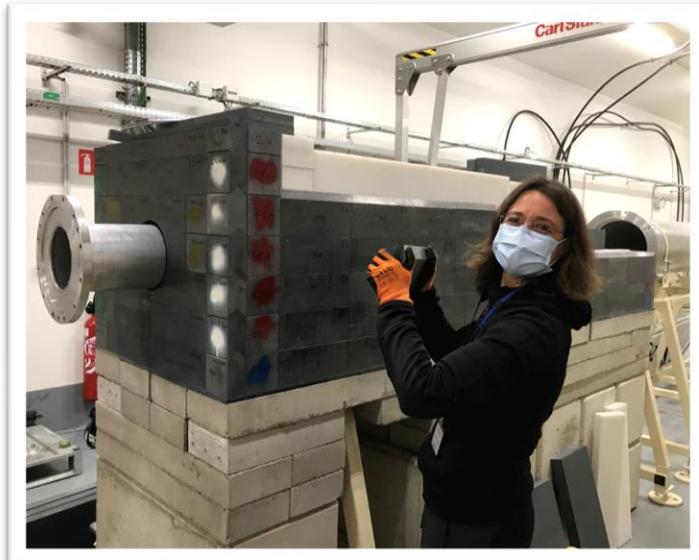


2nd collimator mounting 01; 05; 06/2021



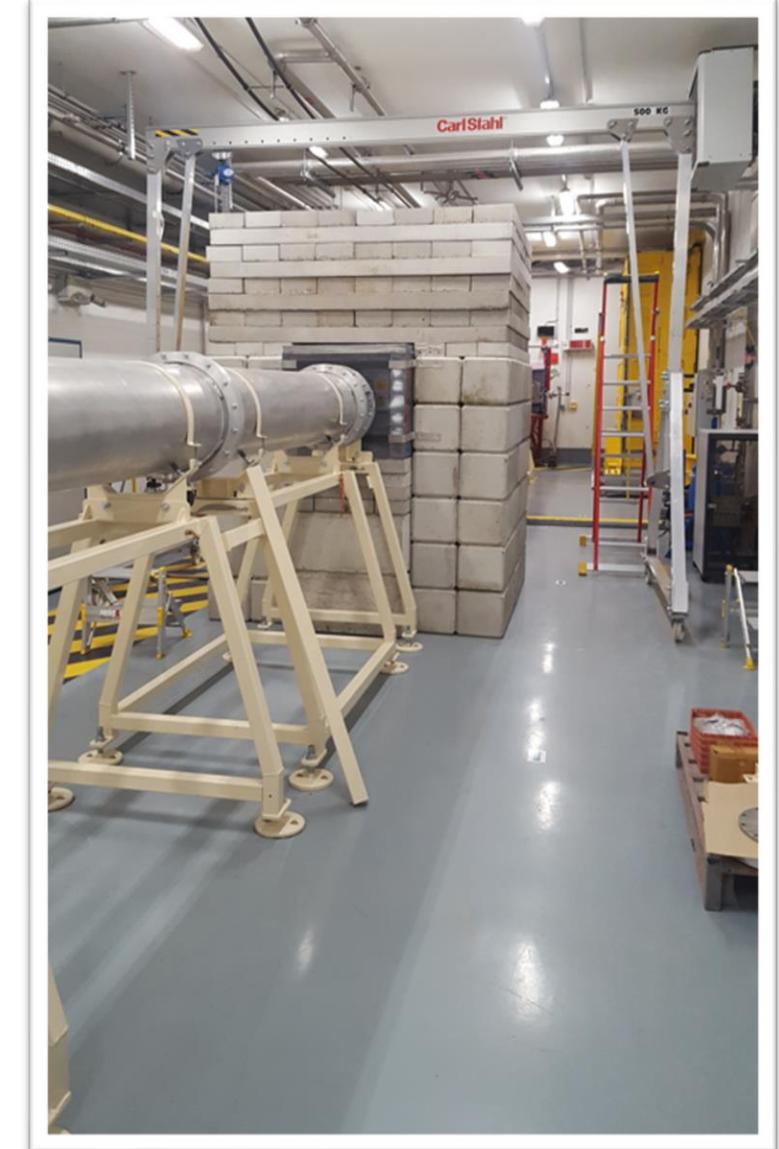


2nd collimator mounting 01; 05; 06/2021





2nd collimator mounting 01; 05; 06/2021



second stage: Test the prompt γ -ray spectroscopy method





LoI-9 :

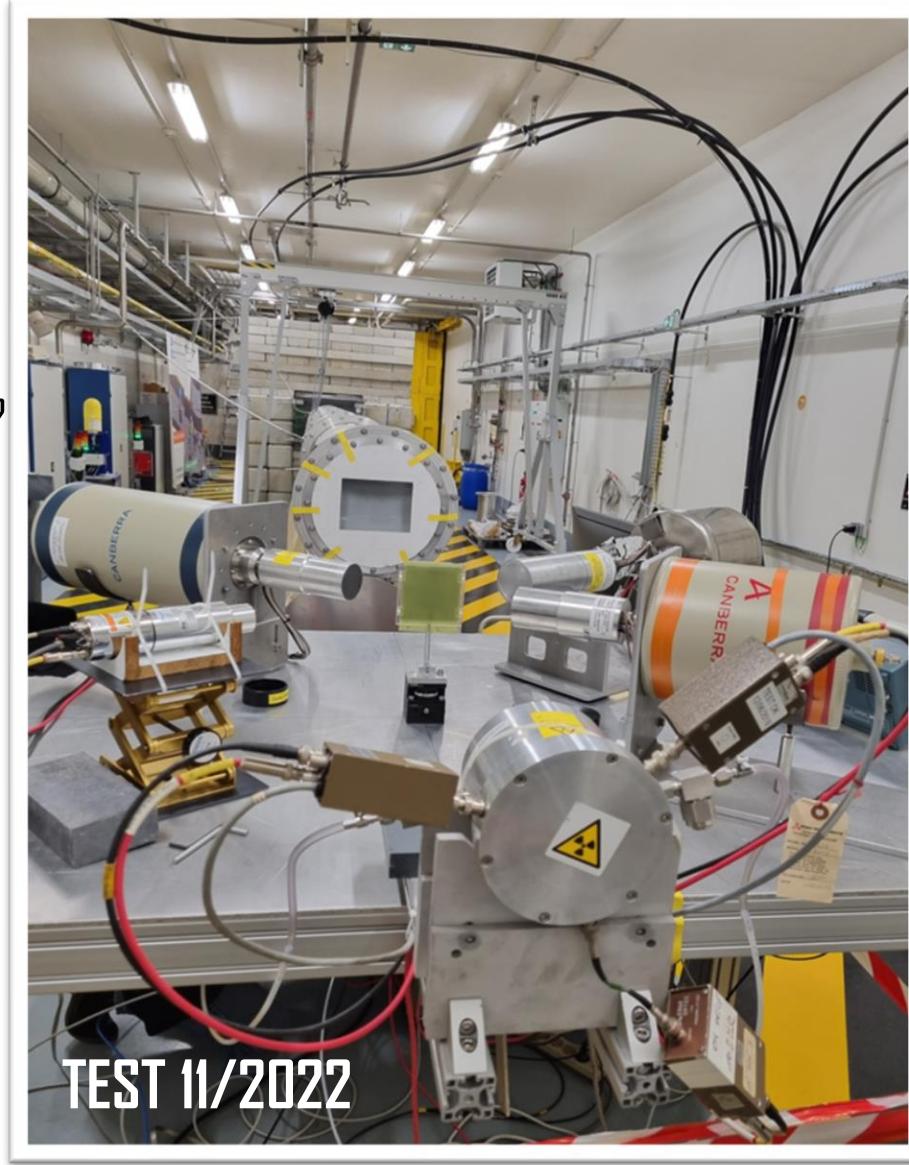
Check the feasibility of the prompt γ -ray spectroscopy method at 30 m from the neutron source.



Questions :

- ☒ How well defined is the beam at 30 m (after the second collimation)?
- ☒ How are the backgrounds (n & γ) conditions?
- ☒ How to deal with low γ -flash for tof measurement in the Fission Chamber?

	09/2021	11/2022
Detectors	3 HPGe	3 HPGe, Fission chamber (3^{238}U), 1 LaBr ₃
Acquisition syst.	FASTER	FASTER
sample	^{nat}W @ 28.936 m Thick. =0.2 mm, m=41.2 g	^{nat}W @ 29.2 m Thick. =0.2 mm, m=41.2 g
Beam d + Be	$\sim 16\mu\text{A}$; $E_d = 40\text{ MeV}$; $F=440$; 220 KHz	$\sim 7.5\ \mu\text{A}$; $E_d = 40\text{ MeV}$; $F=880$; 440; 220 kHz (Be target fixed)
effective UT	~ 1	~ 25 (11 parasitic mode @220 kHz)



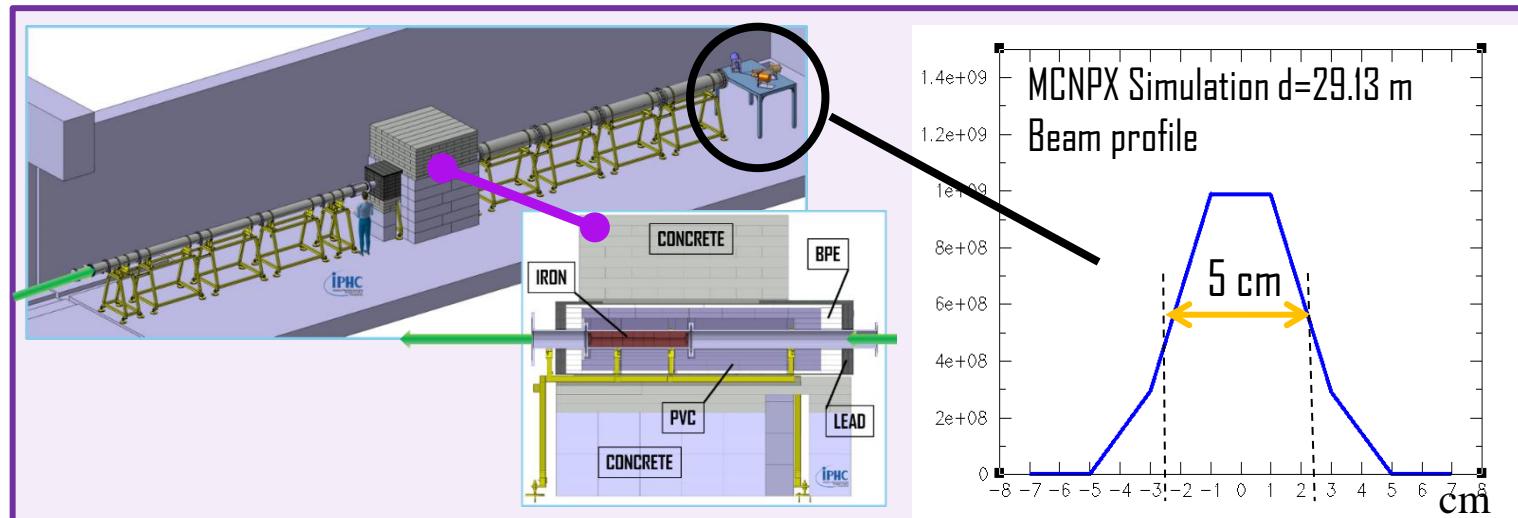
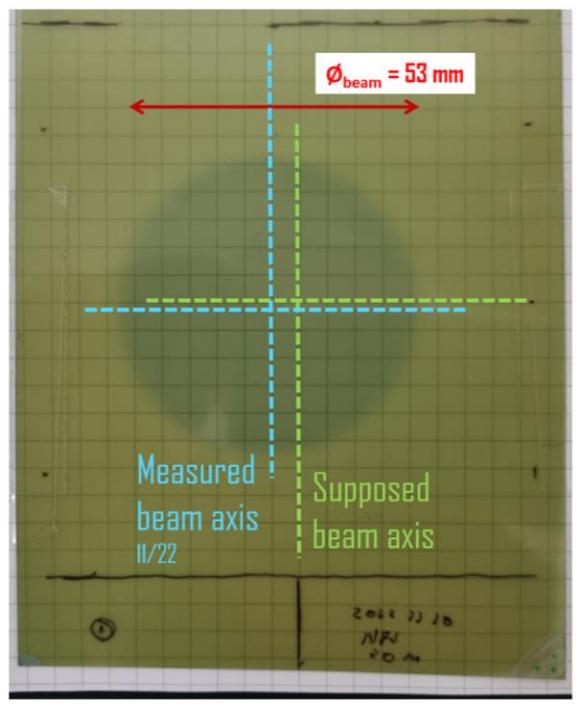
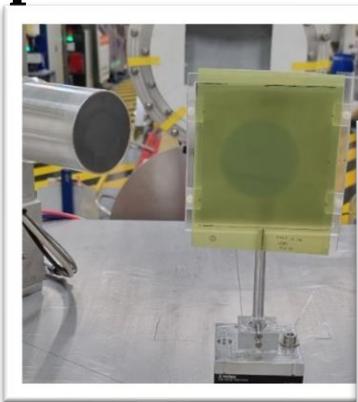


collimation of the neutron beam

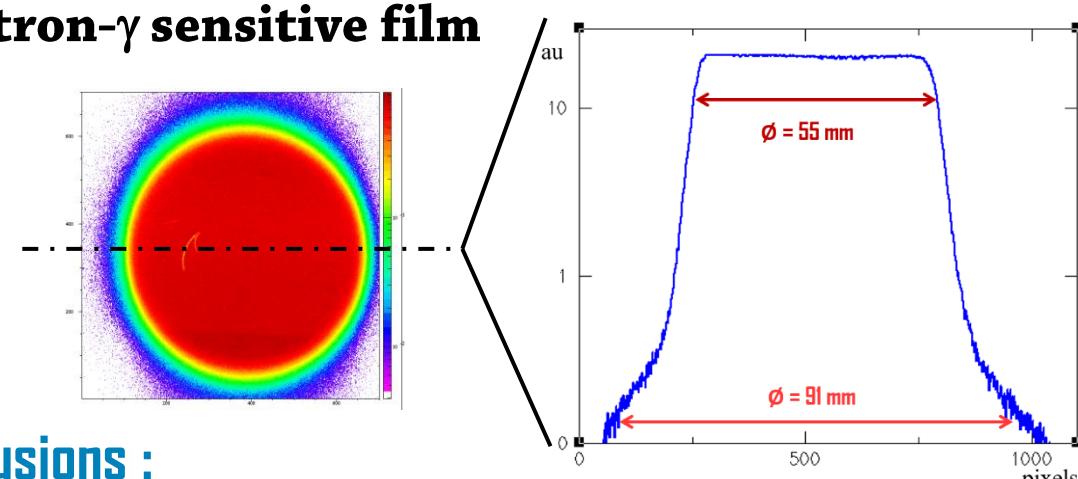
Beam size and alignment

2 measurements :

- Radiographic film at the W sample position



- Neutron- γ sensitive film



Conclusions :

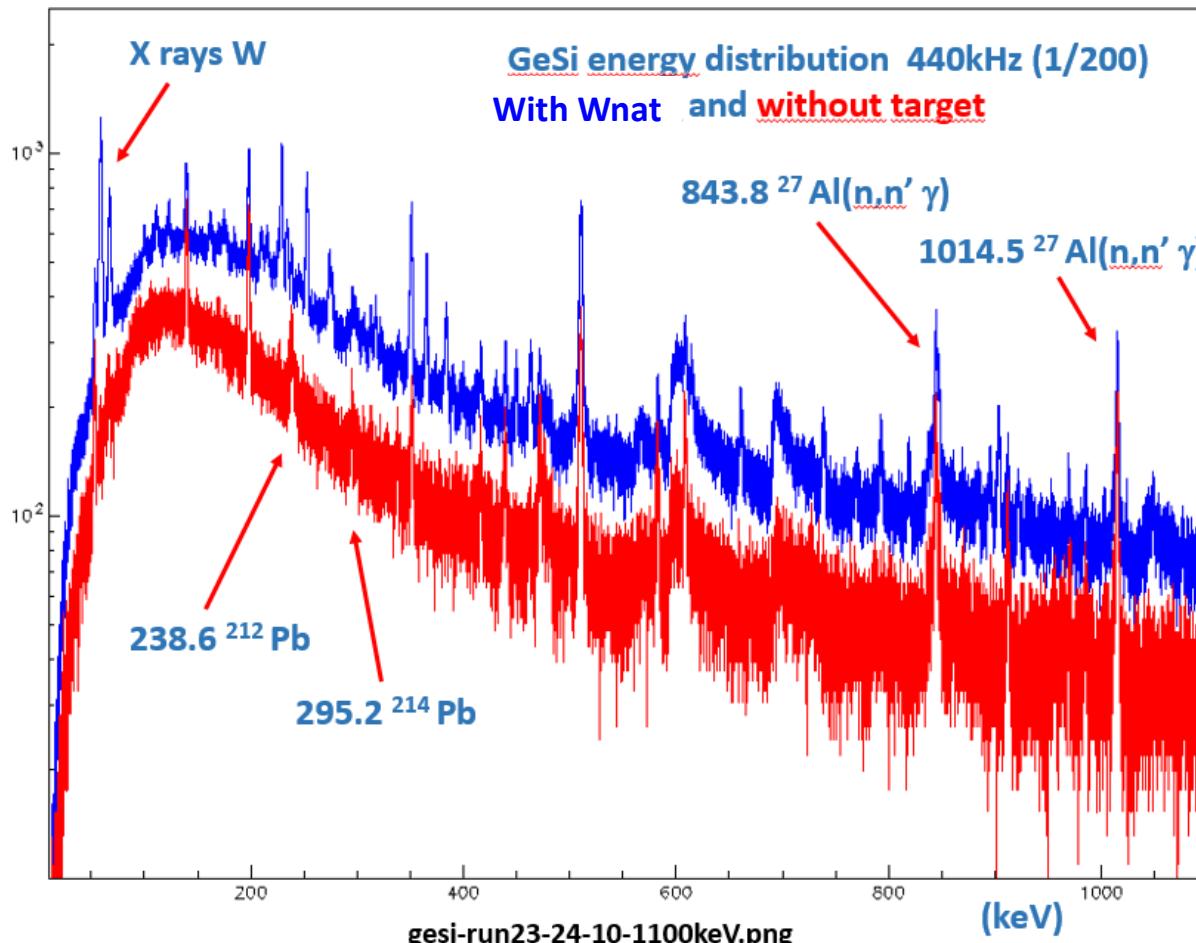
- ☒ Beam size and halo as expected (following MCNP simulations)
- ☒ Special care has to be taken when (re)mounting the second collimator to guarantee the alignment





background conditions

HPGe spectra



- Background from the tof area : no problematic source of background, acceptable level.
- Background induced by neutron beam (run without W sample) : level of scattered neutron (in air) seem more important than at GELINA. We may see also some return from the beam dump but in a range of energy which is not problematic

Conclusion :

- ☒ No major problem identified with background at this stage of the analysis.

W
I
N
S
2
0
2
3





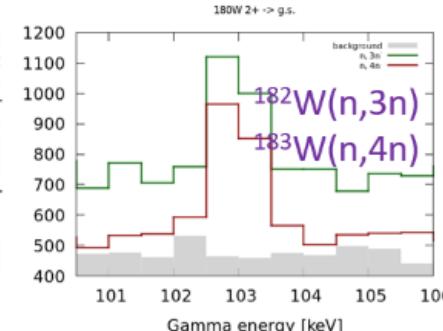
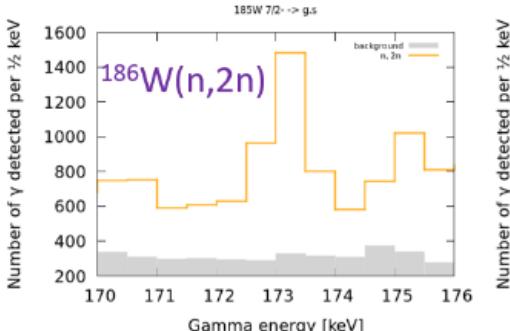
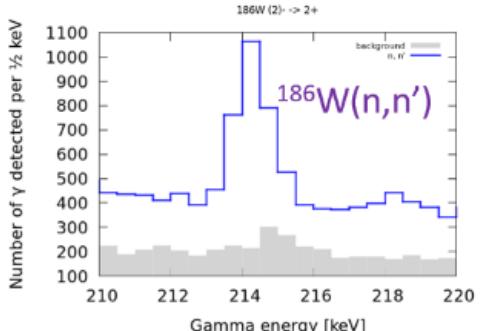
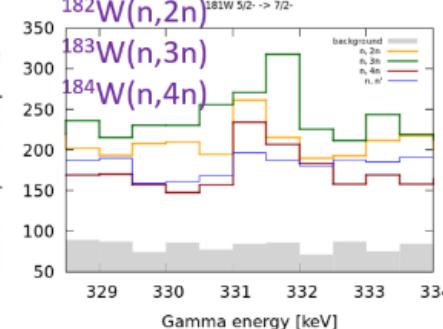
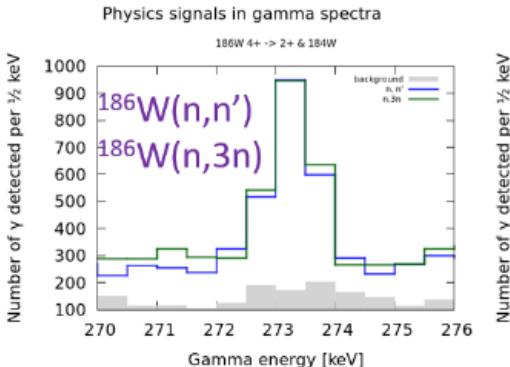
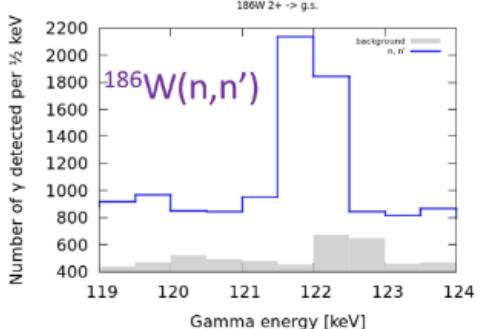
Time of flight measurements

HPGe & ^{238}U Fission Chamber spectra

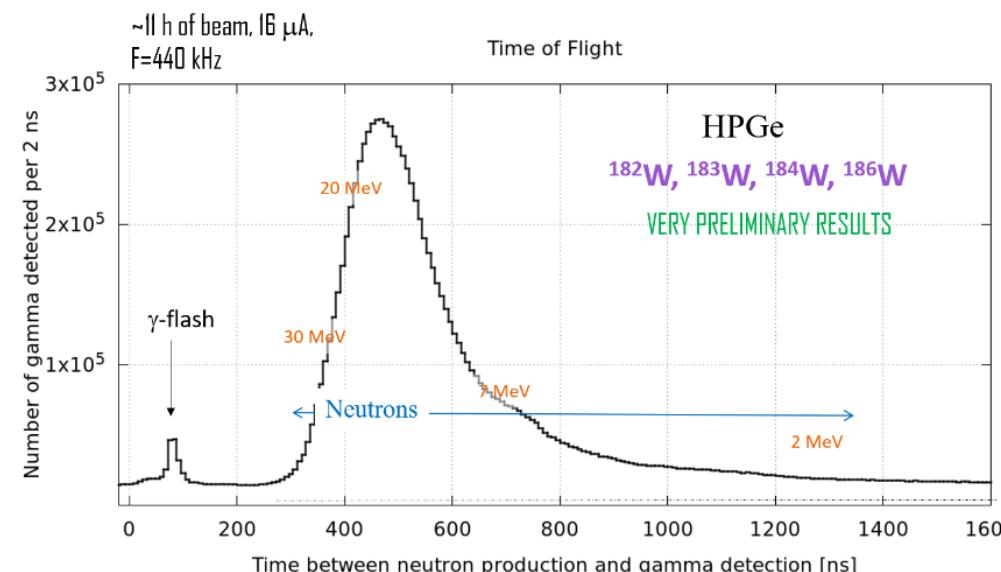
- **E γ spectrum from HPGe**

^{186}W , ^{184}W , ^{183}W , ^{182}W

VERY PRELIMINARY RESULTS



- **Tof spectrum from HPGe**



Conclusions :
x tof measurements possible with HPGe

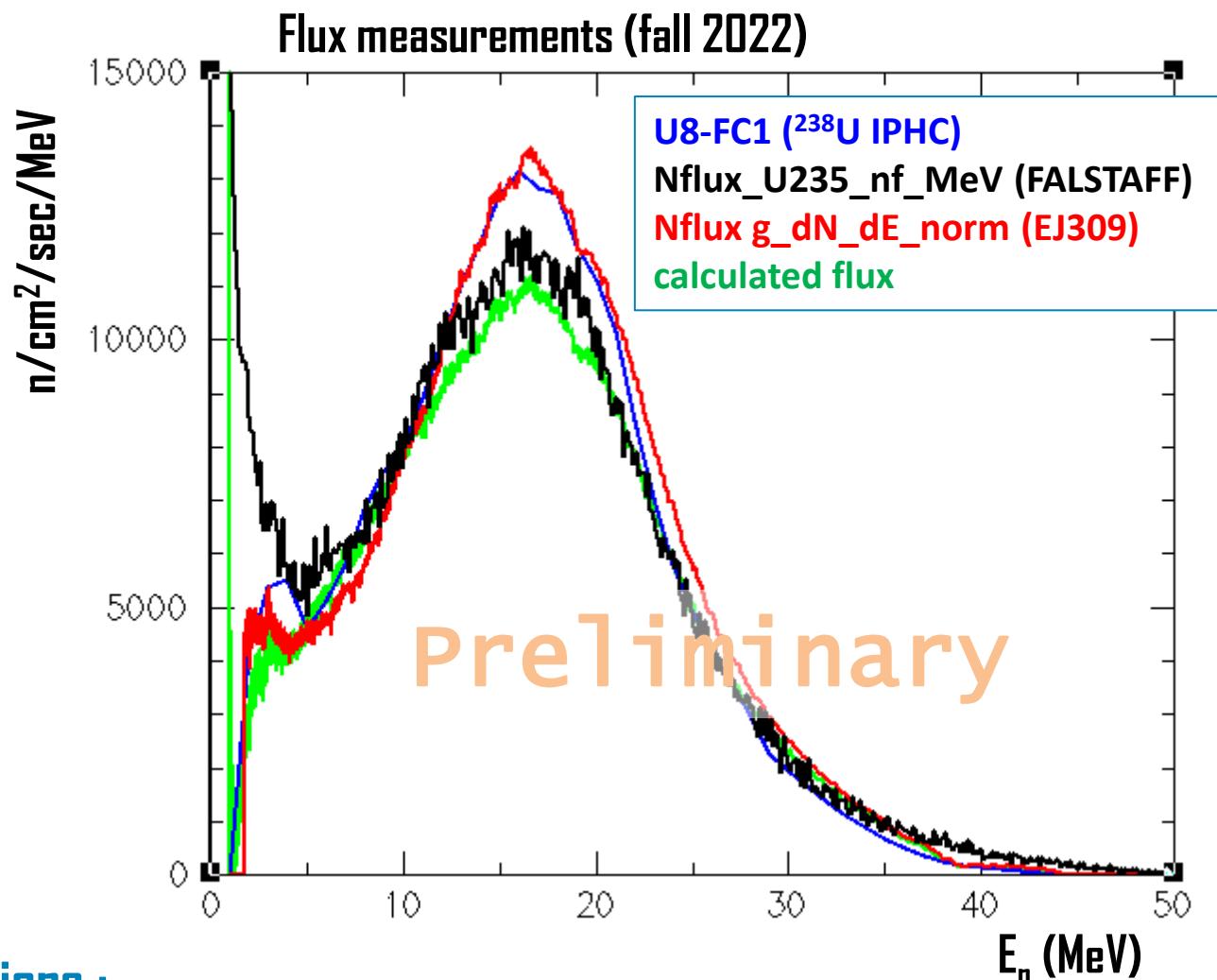
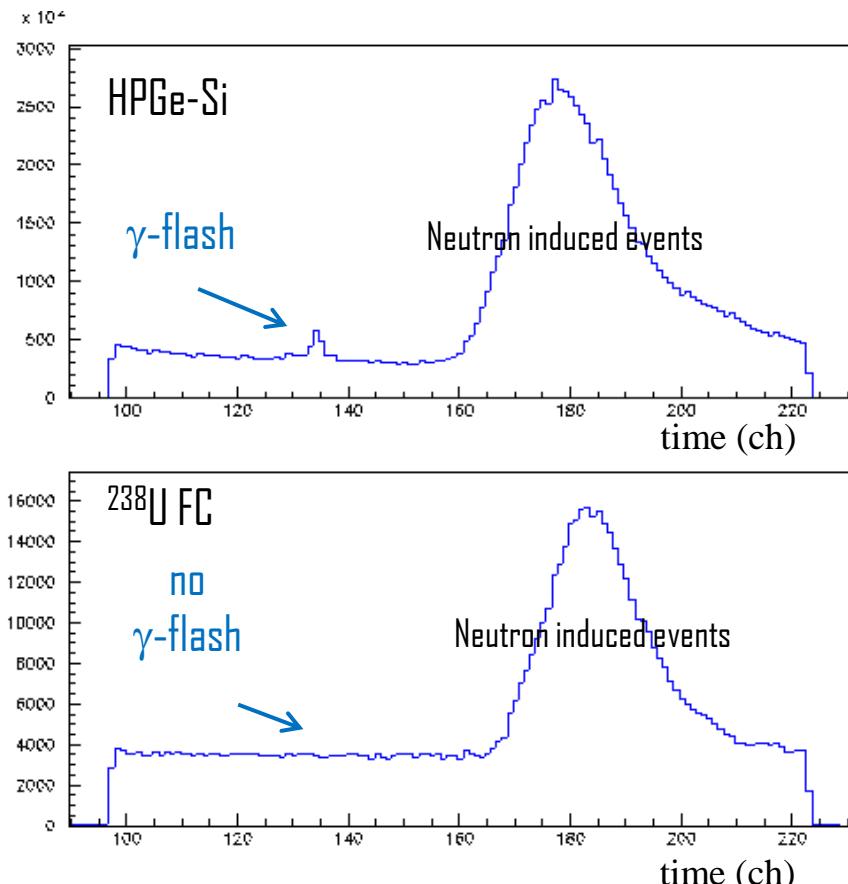




Time of flight measurements

HPGe & ^{238}U Fission Chamber spectra

- Tof spectrum from Fission Chamber



Conclusions :

- For tof measurement with FC, special care must be taken for the calibration of the time spectrum. Additional work is needed to confirm the neutron flux. 
- Proposal for dedicated measurements in fall 2024.



third stage (coming next): Measurement campaigns





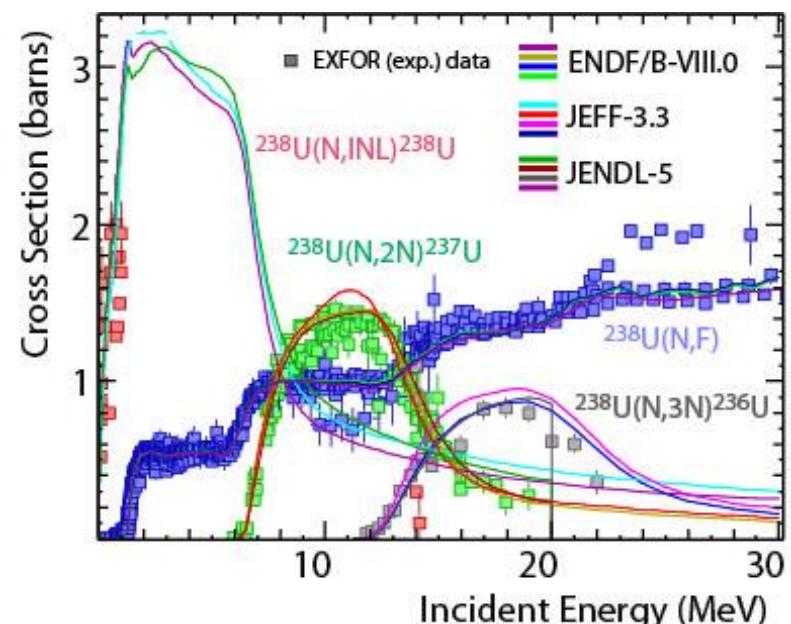
Why starting with $^{238}\text{U}(\text{n}, 2\text{-}3n\gamma)$ XS measurements ?



^{238}U :

- is a very suitable case
- can be used as a benchmark measurement at NFS with actinides

(before the measurements with more difficult actinides as ^{235}U , ^{233}U and ^{239}Pu)

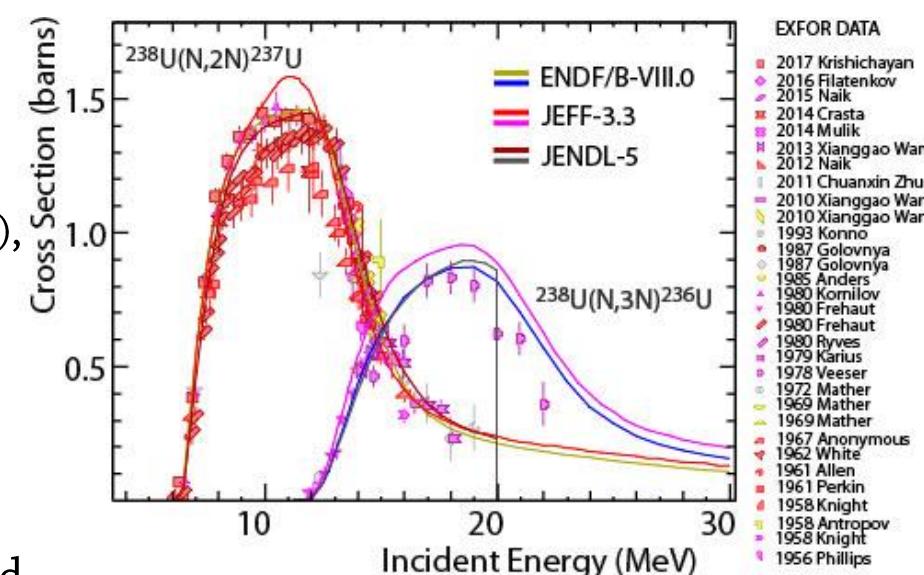


⦿ $(\text{n}, 2\text{n})$ and $(\text{n}, 3\text{n})$ XS
are significant and fission XS is not
so high

⦿ exp. data exist, measured with
different techniques ($(\text{n}, 2\text{n})$ via
activation is possible and widely used),
but discrepancies are present

⦿ we can try to perform an
activation measurement in the
same experiment

⦿ Our collaboration has measured
some $(\text{n}, \text{n}'\text{-}2\text{-}3n\gamma)$ at JRC-GELINA
=> Comprehensive set of data



EXFOR DATA

- 2017 Krishchayan
- 2016 Filatenkov
- 2015 Naik
- 2014 Crasta
- 2014 Mulik
- 2013 Xianggao Wang
- 2012 Naik
- 2011 Chuanxin Zhu
- 2010 Xianggao Wang
- 2010 Xianggao Wang
- 1993 Konno
- 1987 Golovnya
- 1987 Golovnya
- 1985 Anders
- 1980 Komilov
- 1980 Frehaut
- 1980 Frehaut
- 1980 Ryves
- 1979 Karius
- 1978 Veeser
- 1972 Mather
- 1969 Mather
- 1969 Mather
- 1967 Anonymous
- 1962 White
- 1961 Allen
- 1961 Perkin
- 1958 Knight
- 1958 Antropov
- 1958 Knight
- 1956 Phillips



Preparation of $^{238}\text{U}(\text{n}, 2\text{-}3\text{n}\gamma)$ XS measurement ; fall 2024

⌚ A combination of GRAPhEME, GAINS & IFIN-HH detectors will be used.

12 detectors at 110° , 150° and 125° , design & construction by IPHC-CNRS,

2 Fission Chambers (^{235}U & ^{238}U) coupled to FASTER DAQ.

⌚ Station of activation measurement

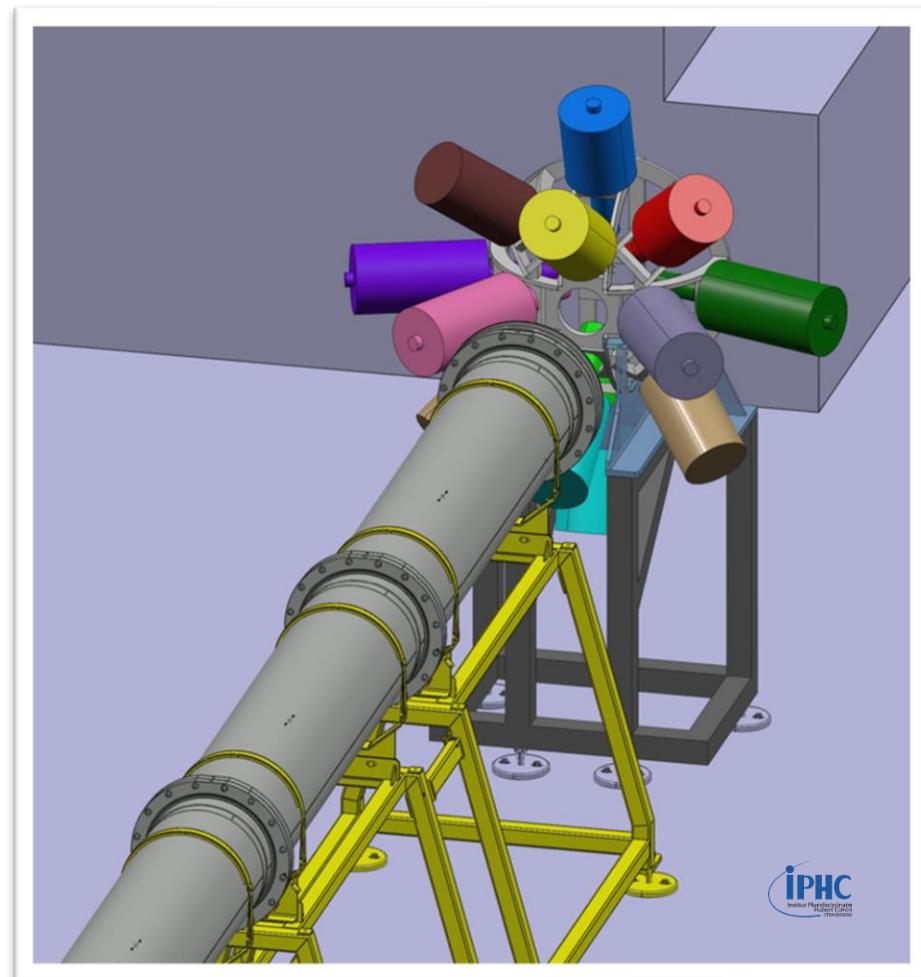
For the decay of ^{237}U

To be “designed”.

⌚ BEAM specifications

- d+Be ; $E_d = 40 \text{ MeV}$
- Intensity : $25 \mu\text{A}$
- Frequency : 220 kHz
- Second collimator is required
- $4 \cdot 10^4 \text{ n/MeV/cm}^2/\text{s}$
at max. (30 m)
- Possibility to work in parallel mode

=> **10 days of beam obtained**



Some context



GRAPHEME @ EC-JRC-GELINA facility
last news on ^{232}Th , ^{238}U , ^{233}U & ^{239}Pu



Towards (n, 2n) and (n, 3n) reaction studies
@ GANIL/SPIRAL2/NFS facility



Conclusions & Perspectives



GRAPhEME is a **federative instrument** to **study**, in a **comprehensive way** from **experiments** to **modeling**, the **neutron inelastic scattering** with the **prompt γ -ray spectroscopy method.**



In the frame of the IPHC, EC-JRC-Geel, IFIN-HH experimental collaboration, **GRAPhEME@GELINA**, operated by IPHC, has produced numerous **(n, n'γ) cross sections** data on **$^{233,235,238}\text{U}$, ^{232}Th , nat, $^{182,183,184,186}\text{W}$, ^{57}Fe , ^{239}Pu** .



Theoretical developments, constrained with (n, n'γ) XS obtained by **GRAPhEME**, are in progress to **calculate reliable neutron inelastic scattering cross sections for actinides and W isotopes**.



Instrumental developments are in progress to **measure conversion electron de-excitation in actinides**.



Actions are carried out to **improve the nuclear structure knowledge** of nuclei of interest.



A **new experimental program** is foreseen @**NFS** dedicated to the **study of (n, 2n) reactions**.

A part of this project has received funds from the Euratom research and training programme 2014-2018 under grant agreement n°847552 (SANDA)

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Thank you for your attention