26 SEP > 1 OCT 2021 Autrans-Méaudre en Vercors, FRANCE

XXII^nd COLLOQUE GANIL

(n, xnγ) cross section measurements at NFS and nuclear structure needs for nuclear energy applications.

Maëlle Kerveno,
IPHC-CNRS/Université de Strasbourg

Outline

- NFS time of flight area

- (n, xnγ) studies at NFS with the prompt γ-ray spectroscopy

P. Dessagne, G. Henning, M. Kerveno, F. Claeys, N. Dari Bako, Univ. de Strasbourg, CNRS, IPHC/DRS
C. De Saint Jean, M. Dupuis, S. Hilaire, CEA/DAM/DIF
C. Paradela, A. J. M. Plompen, EC-JRC-Geel
C. Borcea, M. Boromiza, A. Negret, A. Olacel, IFIN-HH
R. Capote, NDS, AIEA
T. Kawano, LANL
M. Nyman, Univ. Helsinki

- Nuclear structure needs for nuclear energy application

NACRE – le Noyau Au Cœur du RéactEur

A. Chebboubi, M. Fallot, G. Henning, M. Kerveno, X. Mougeot,
O. Serot, V. Vallet *et al.* CNRS, CEA

Outline

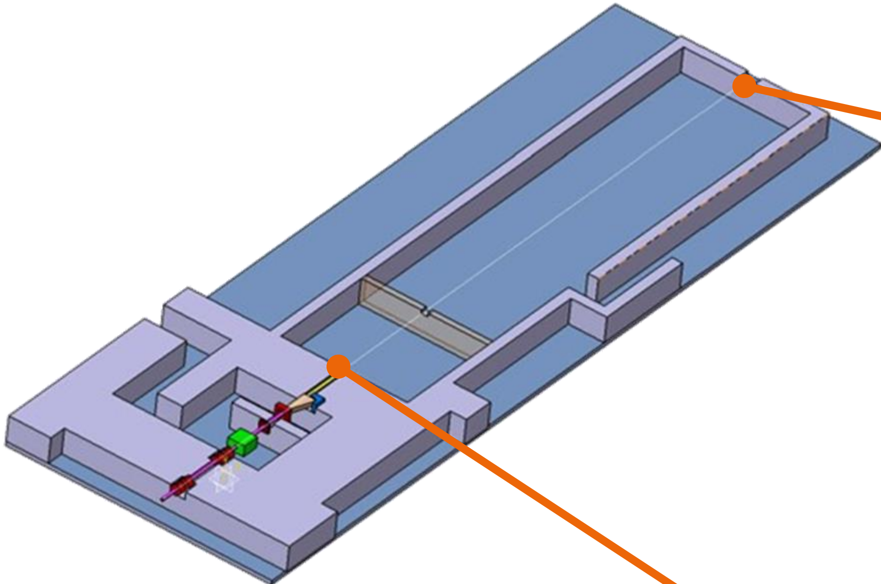
NFS time of flight area

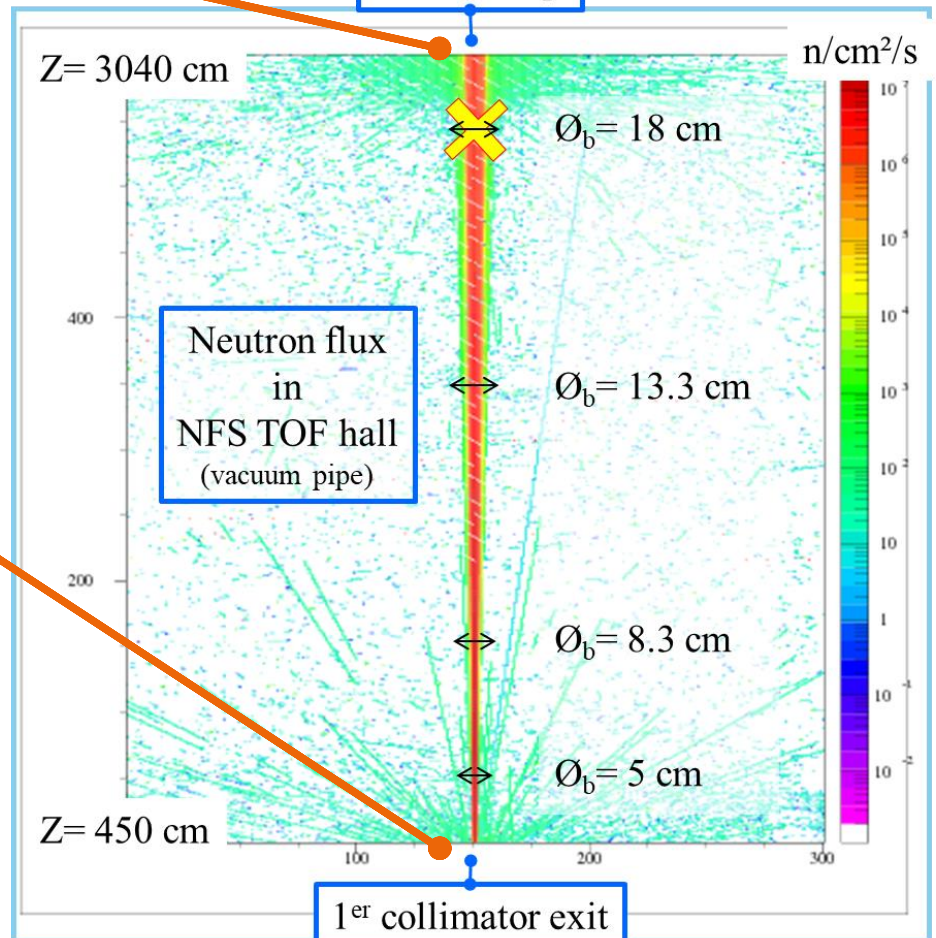
(n,xn γ) studies at NFS
with the prompt γ-ray spectroscopy

Nuclear structure needs
for nuclear energy application

NFS time of flight area

NFS flight path for time of flight measurement





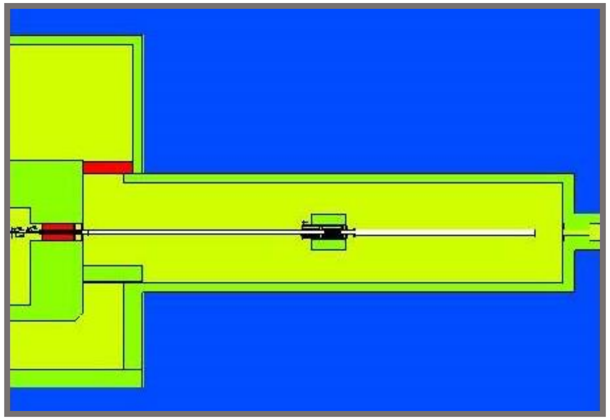
IPHC was in charge of the **design**, **construction** and **installation** of the **neutron beam line** & **2nd collimator** to allow measurements at long flight path (focused beam, low background).

NFS time of flight area

NFS flight path simulations

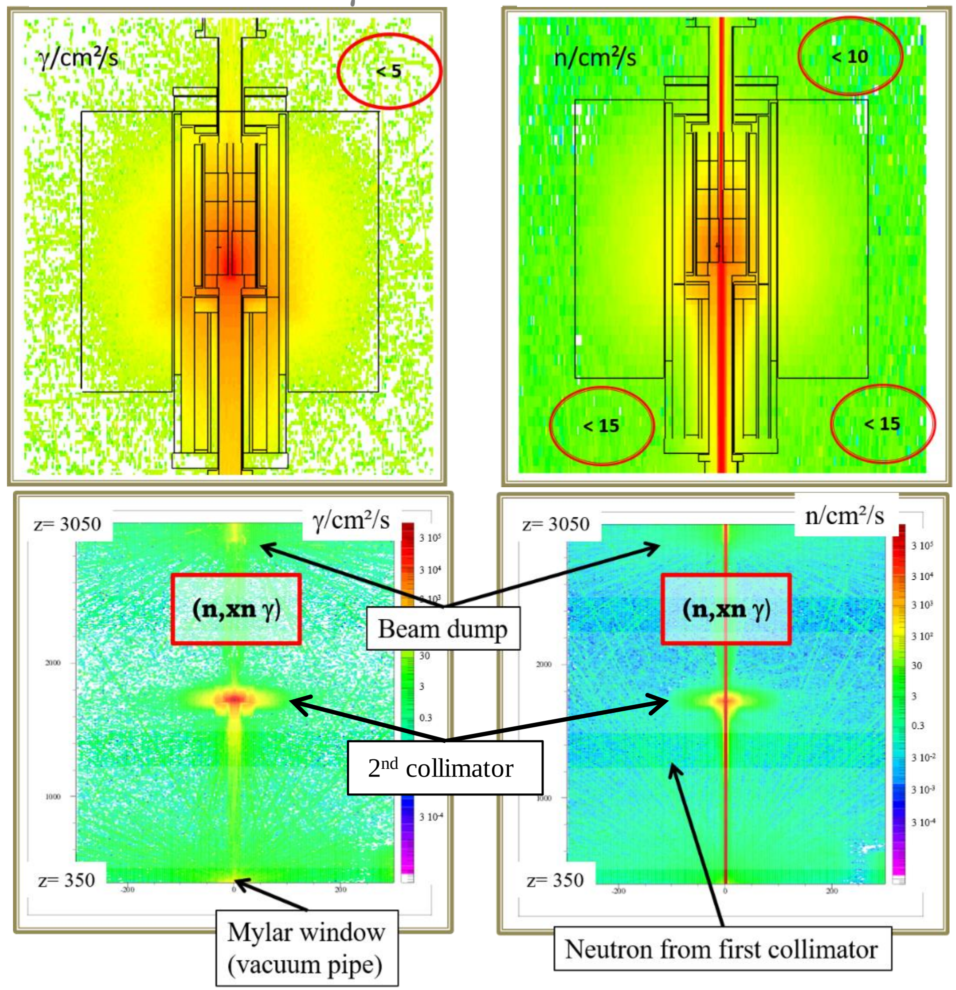
MCNPX-2.6 simulations

- NFS convertor room + hall entirely simulated



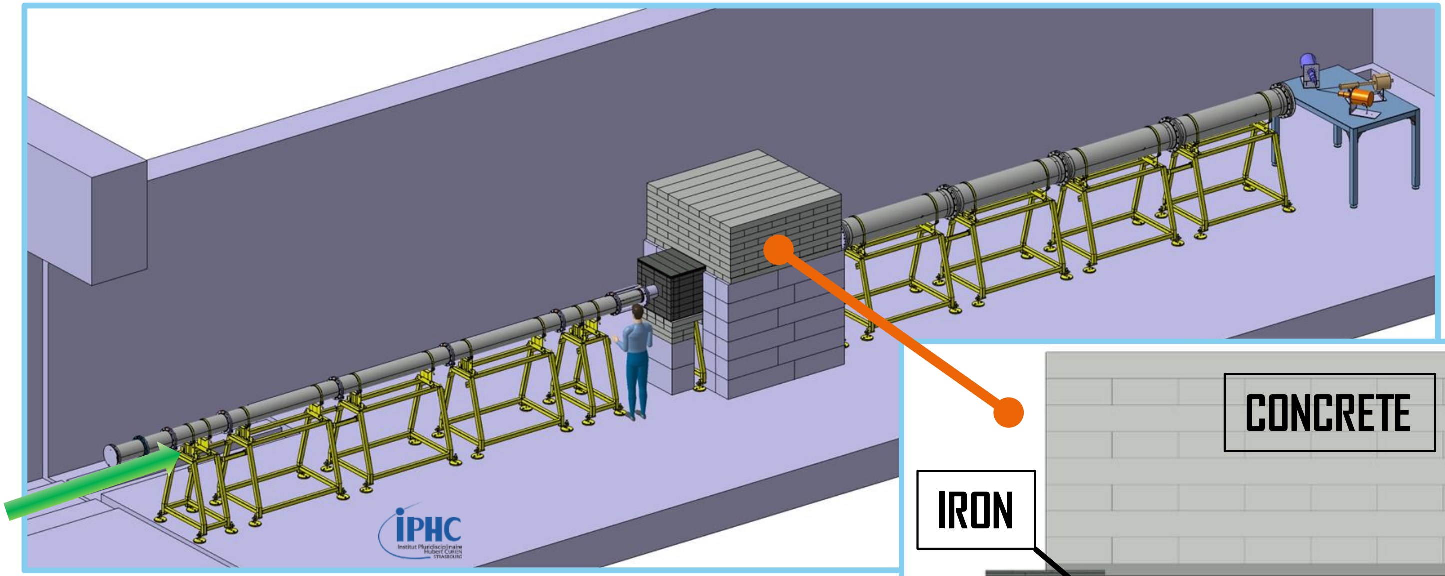
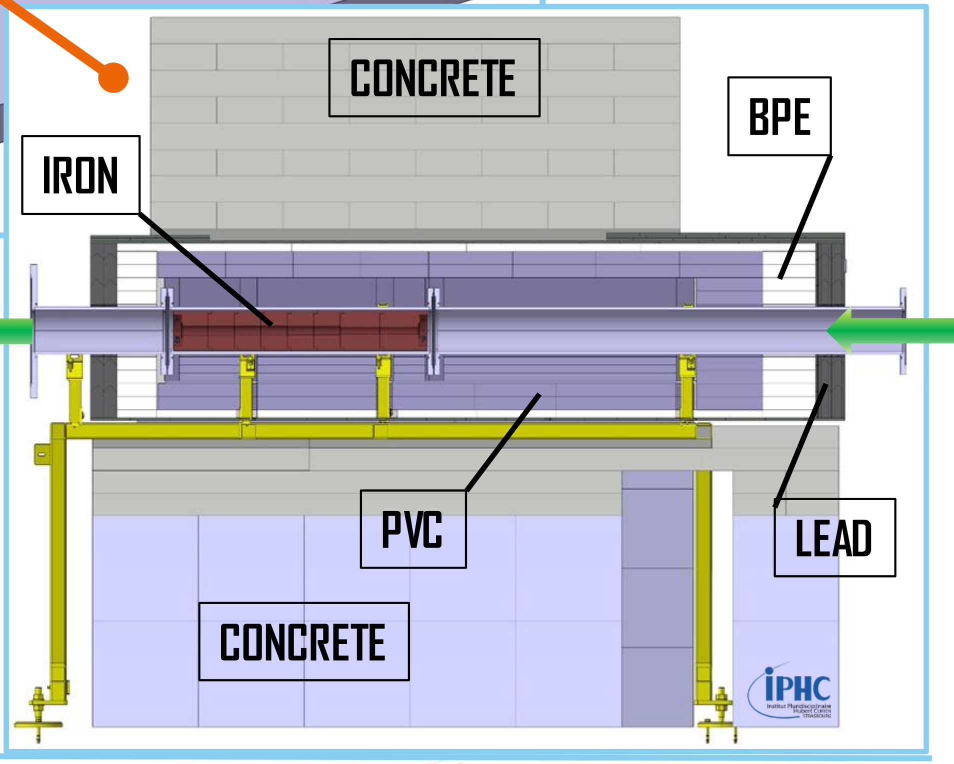
- Neutron production :
  d (50 μA ; 40 MeV) + Be
- Reduced inner aperture of the first collimator
- constraints of background minimization, weight and costs with the **objective** of
  $Ø_b$ = 6 cm @ z=2850cm

γ bg for all $E_γ$ | neutron bg for all E_n



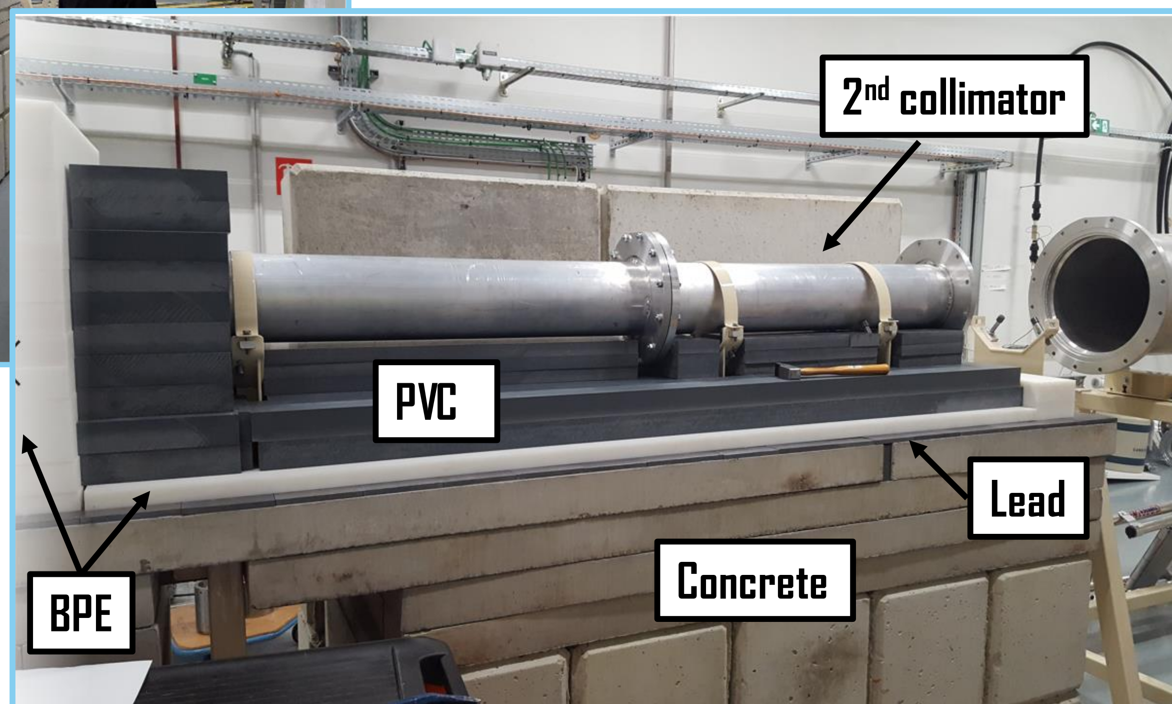
NFS time of flight area

NFS flight path for time of flight measurement

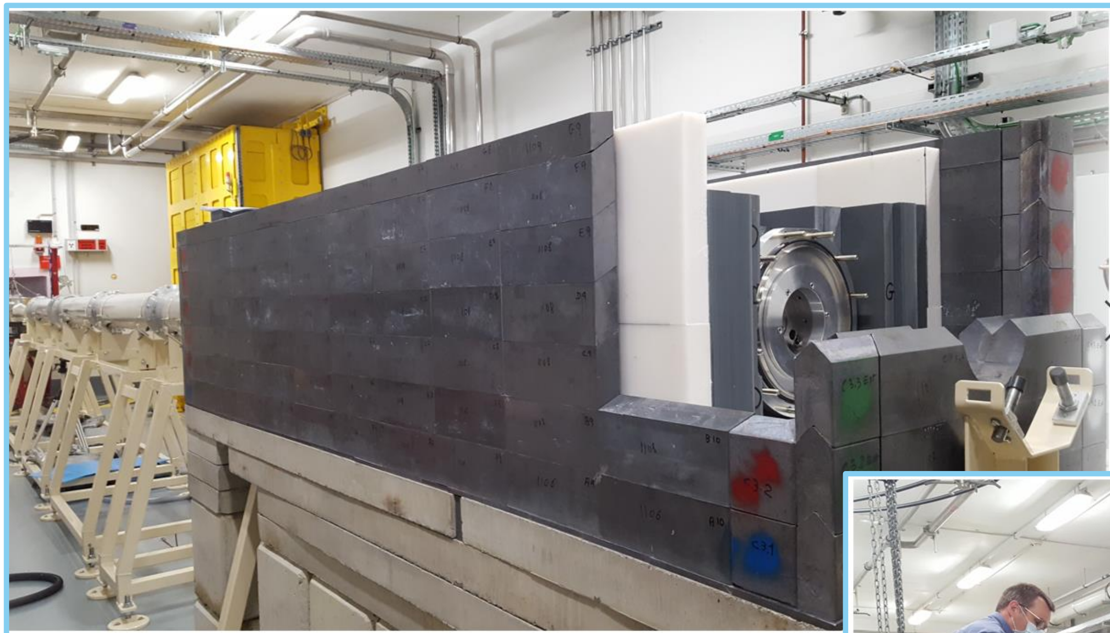
NFS time of flight area

2nd collimator mounting 01; 05; 06/2021



NFS time of flight area

2nd collimator mounting



NFS time of flight area

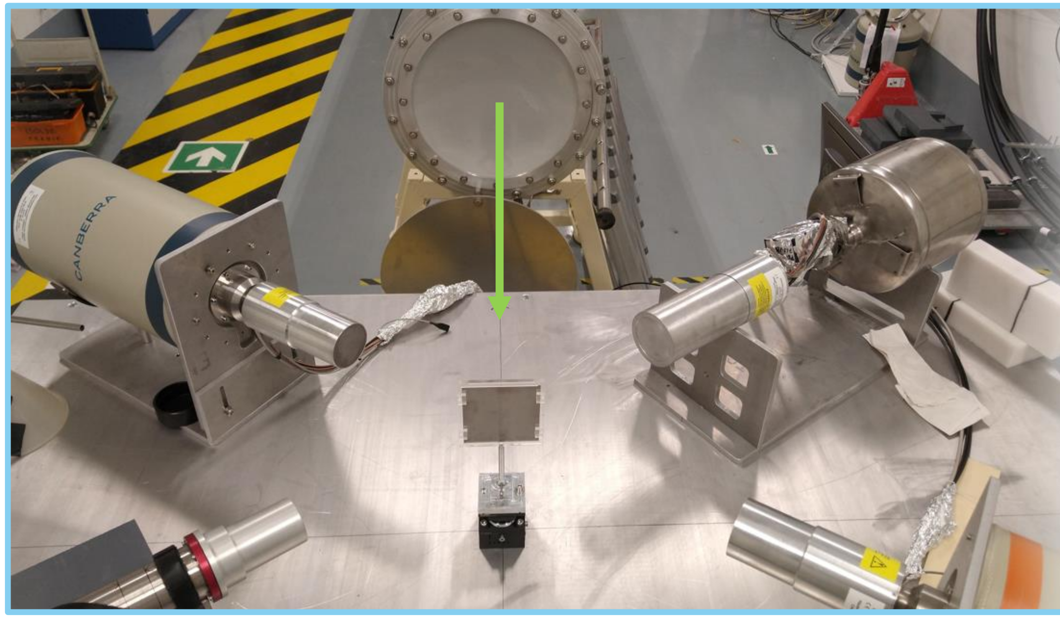
2^{nd} collimator mounting

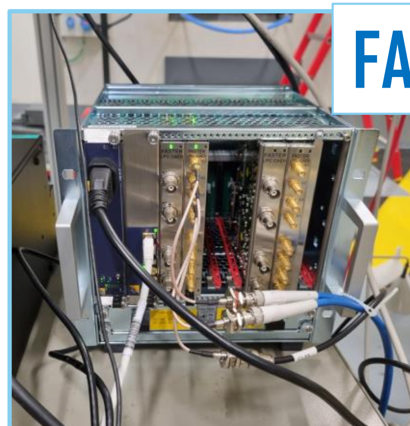
NFS time of flight area

Test measurements ; setup 22-24/09/2021

Test conditions

- Neutron production :
  d (~**16 µA ; 40 MeV**)
  + Be (**8 mm**)
  Buncher 1/200; 1/400
  F= 440 kHz, 220 kHz
- **3 HPGe** detectors, **FASTER** acquisition system
- Neutron monitors: liquid scintillator (cf. talk X. Ledoux)
- **^{nat}W target** @ 28.936 m
  Thickness =0.2 mm, m=41.2 g)
- Effective time : less than the
  10 UT allocated





FASTER

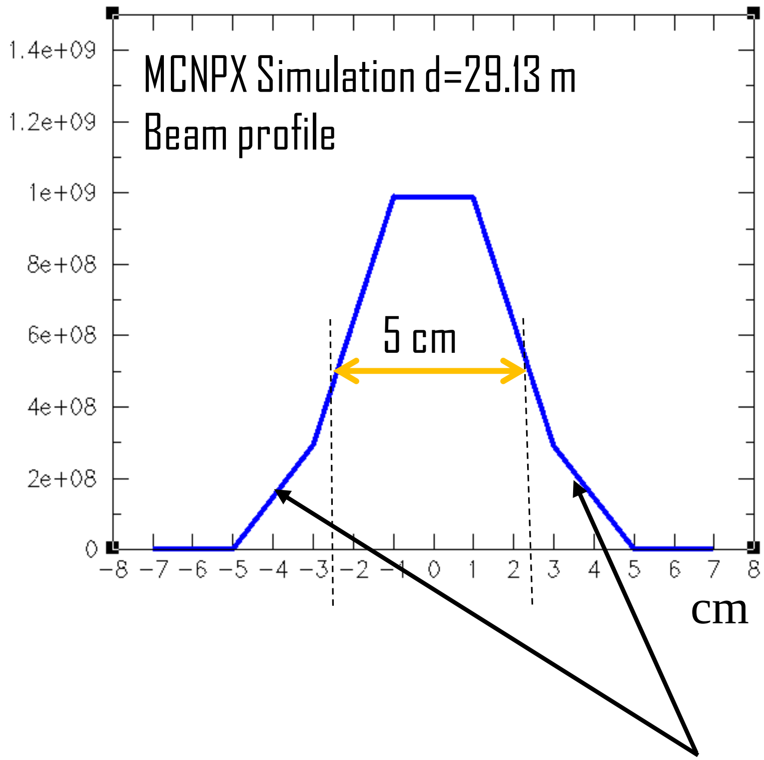
W sample

NFS time of flight area

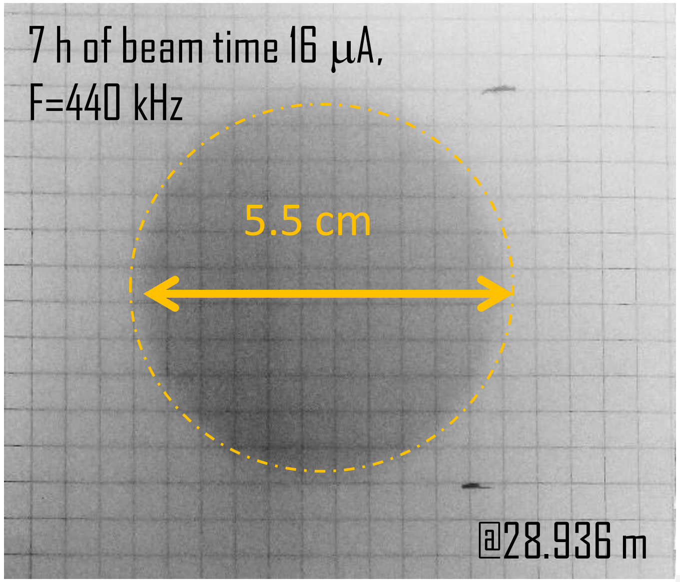
Test measurements ; beam size @ LFP

Test conditions

- Neutron production :
  d (~16 µA ; 40 MeV) + Be (8 mm)
  Buncher 1/200; F= 440 kHz,
- 3 HPGe detectors + FASTER DAQ
- Neutron monitors: liquid scintillator
- ^{nat}W target @ 28.936 m
  Thickness=0.2 mm, m=41.2 g)



In a next step, need to check the halo.



* Reduction of the beam size with the second collimator ✓
* Alignment of the collimator ✓

NFS time of flight area

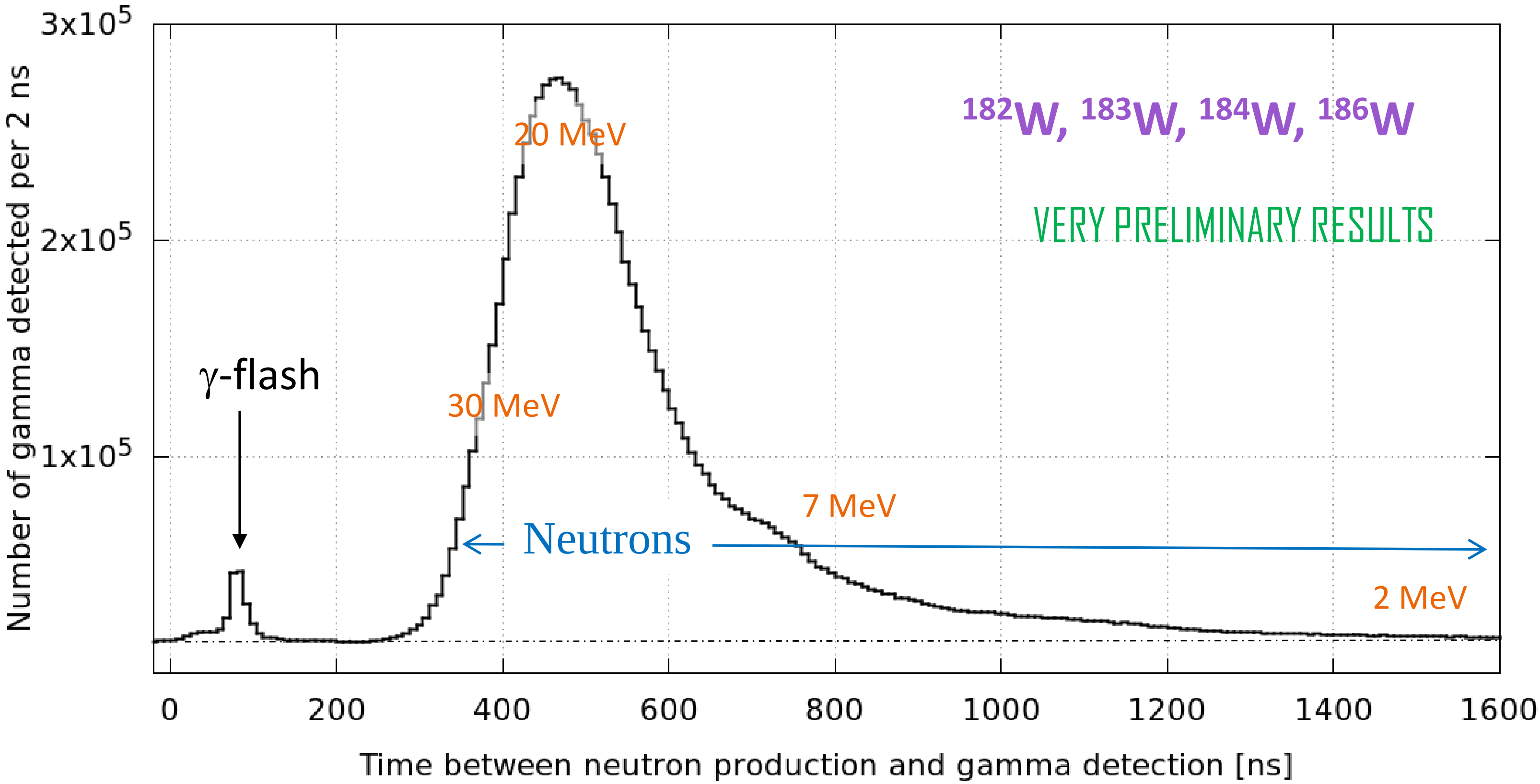
Test measurements ; (n, xn) reactions

Test conditions

- Neutron production :
  d (~16 μA ; 40 MeV) + Be (8 mm)
  Buncher 1/200; F= 440 kHz,
- 3 HPGe detectors + FASTER DAQ
- Neutron monitors: liquid scintillator
- ^{nat}W target @ 28.936 m
  Thickness=0.2 mm, m=41.2 g)

~11 h of beam, 16 μA,
F=440 kHz

Time of Flight HPGe



NFS time of flight area

Test measurements ; (n, xn) reactions

Test conditions

- Neutron production :
  d (~16 µA ; 40 MeV) + Be (8 mm)
  Buncher 1/200; F= 440 kHz,
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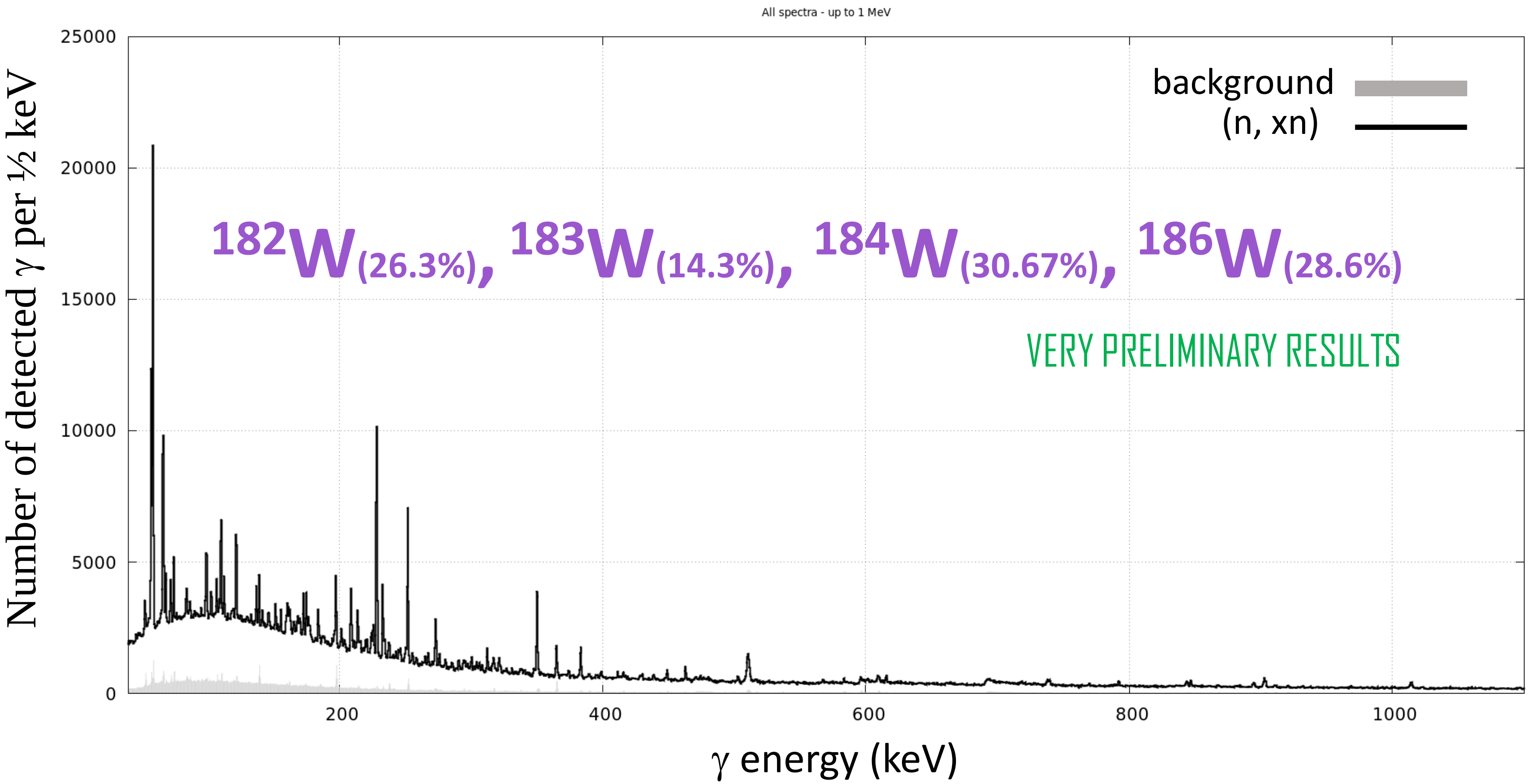


NFS time of flight area

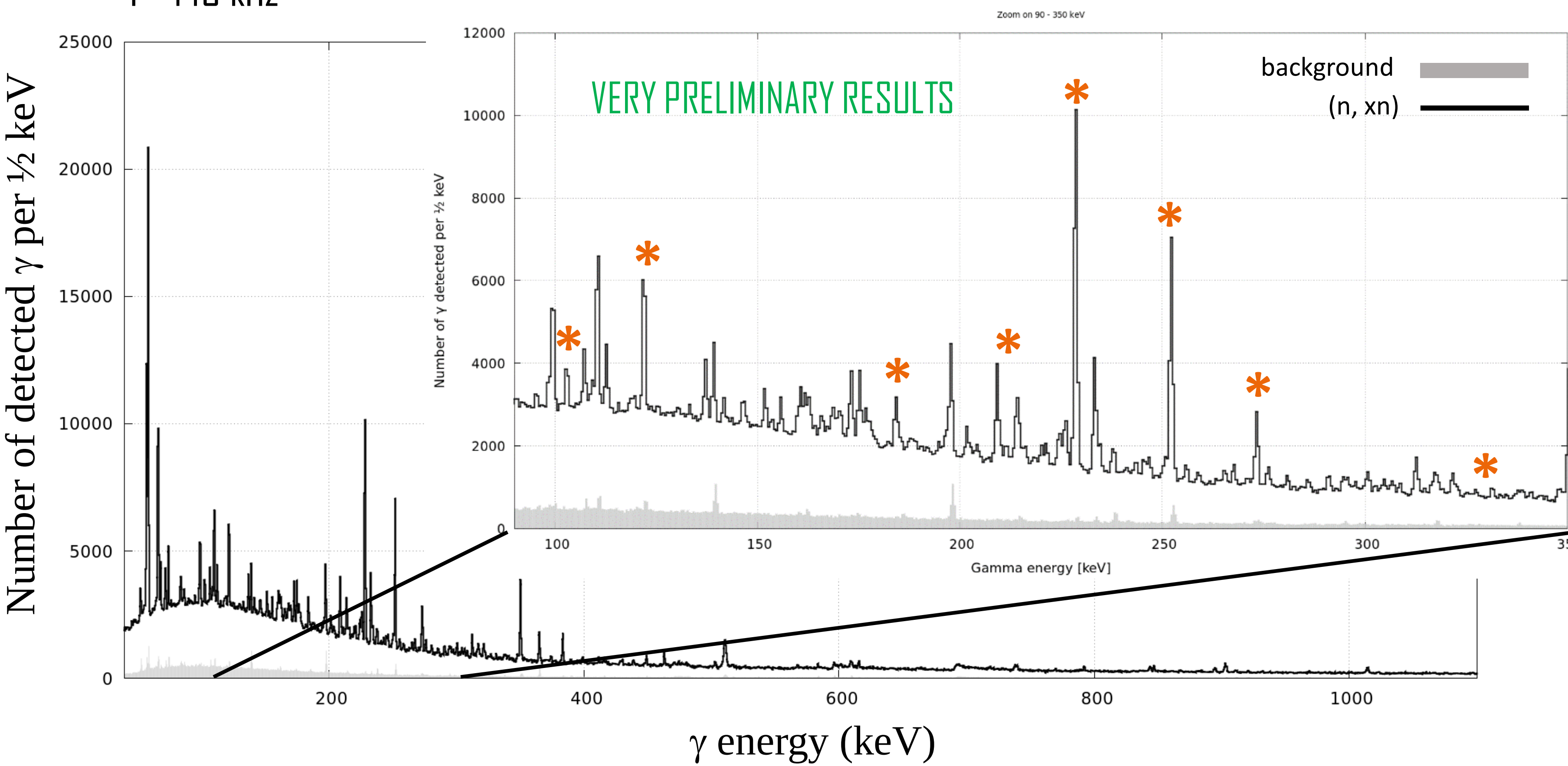
Test measurements ; (n, xn) reactions

Test conditions

- Neutron production :
  d (~16 µA ; 40 MeV) + Be (8 mm)
  Buncher 1/200; F= 440 kHz,
- 3 HPGe detectors + FASTER DAQ
- Neutron monitors: liquid scintillator
- ^{nat}W target @ 28.936 m
  Thickness=0.2 mm, m=41.2 g)

~11 h of beam, 16 µA,
F=440 kHz

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



NFS time of flight area

Test measurements ; (n, xn) reactions

~11 h of beam, 16 µA,
F=440 kHz

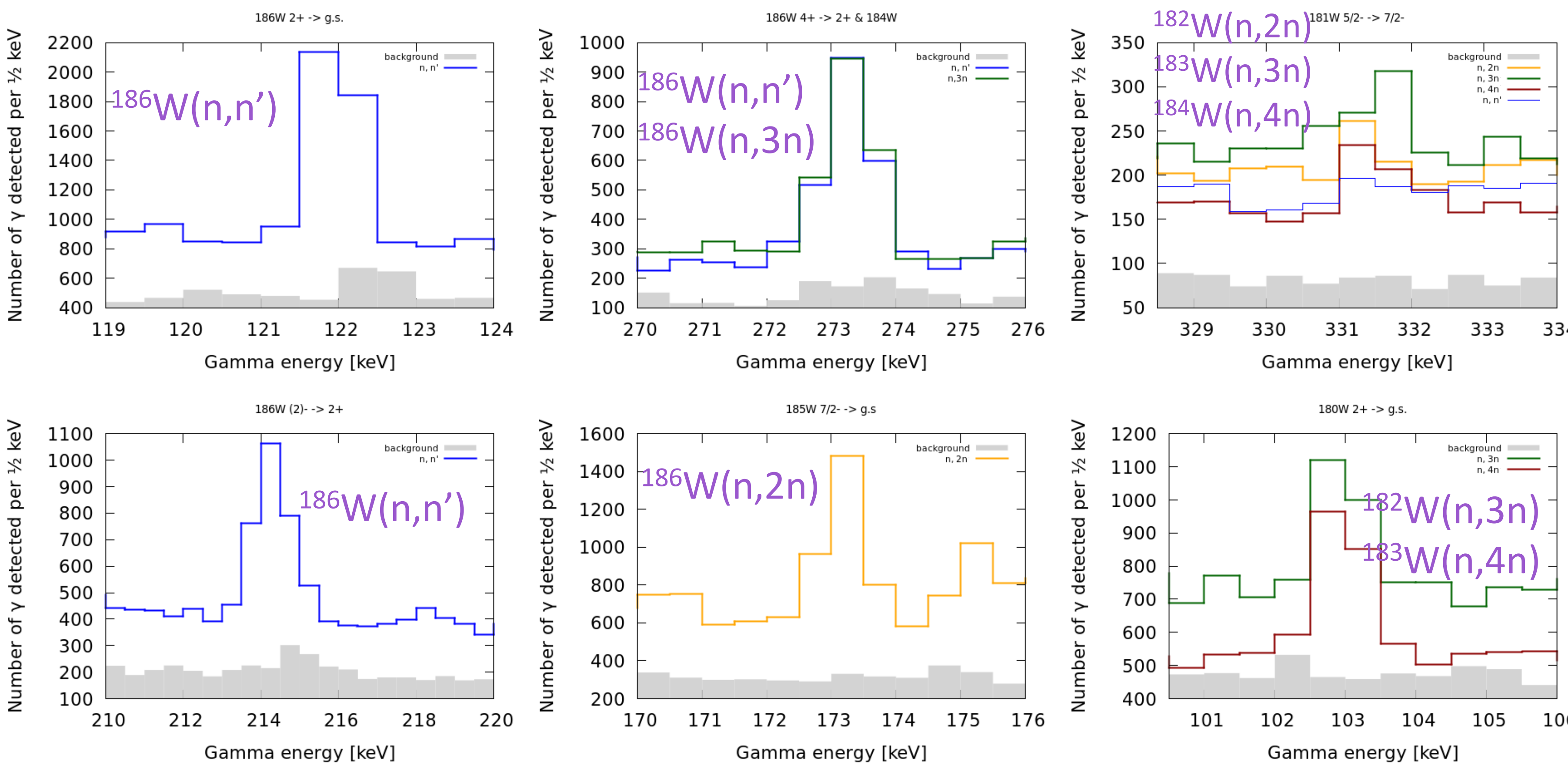
^{186}W, ^{184}W, ^{183}W, ^{182}W

Test conditions

- Neutron production :
  d (~16 µA ; 40 MeV) + Be (8 mm)
  Buncher 1/200; F= 440 kHz,
- 3 HPGe detectors + FASTER DAQ
- Neutron monitors: liquid scintillator
- ^{nat}W target @ 28.936 m
  Thickness=0.2 mm, m=41.2 g)

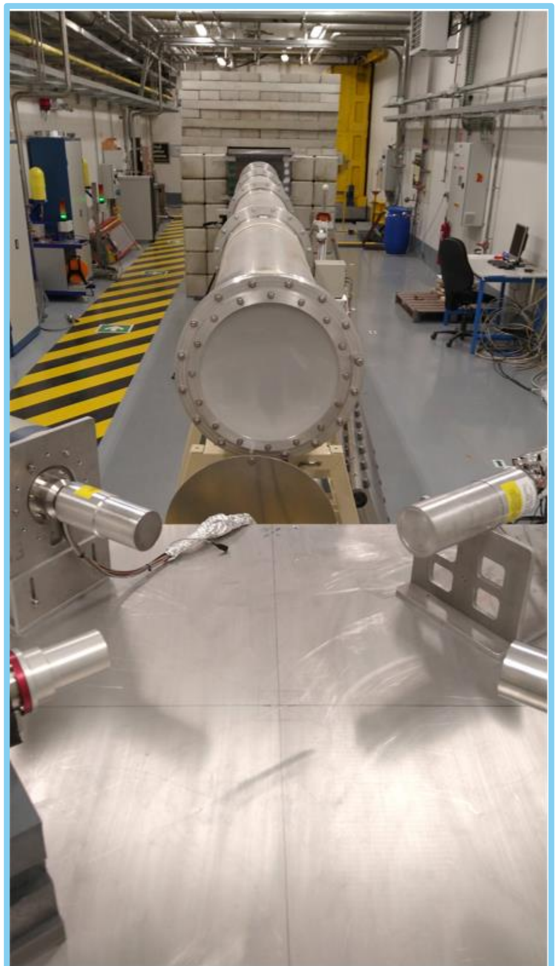
VERY PRELIMINARY RESULTS

Physics signals in gamma spectra



NFS time of flight area

Test measurements ; (n,xn) reactions



Preliminary conclusions

- Second collimator OK. Measurements at long flight path are possible with a well collimated beam
- Precise characterization of the beam profile is now required
- Flux measurements with our FC have to be done
- γ background seems compatible with (n, xnγ) measurements at LFP
- FASTER acquisition system is well adapted for this type of measurements
- (n,xn) reactions have been seen up to x=4

Outline

- NFS time of flight area

- **(n, xnγ) studies at NFS with the prompt γ-ray spectroscopy**

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T. Kawano, LANL
M. Nyman, Univ. Helsinki

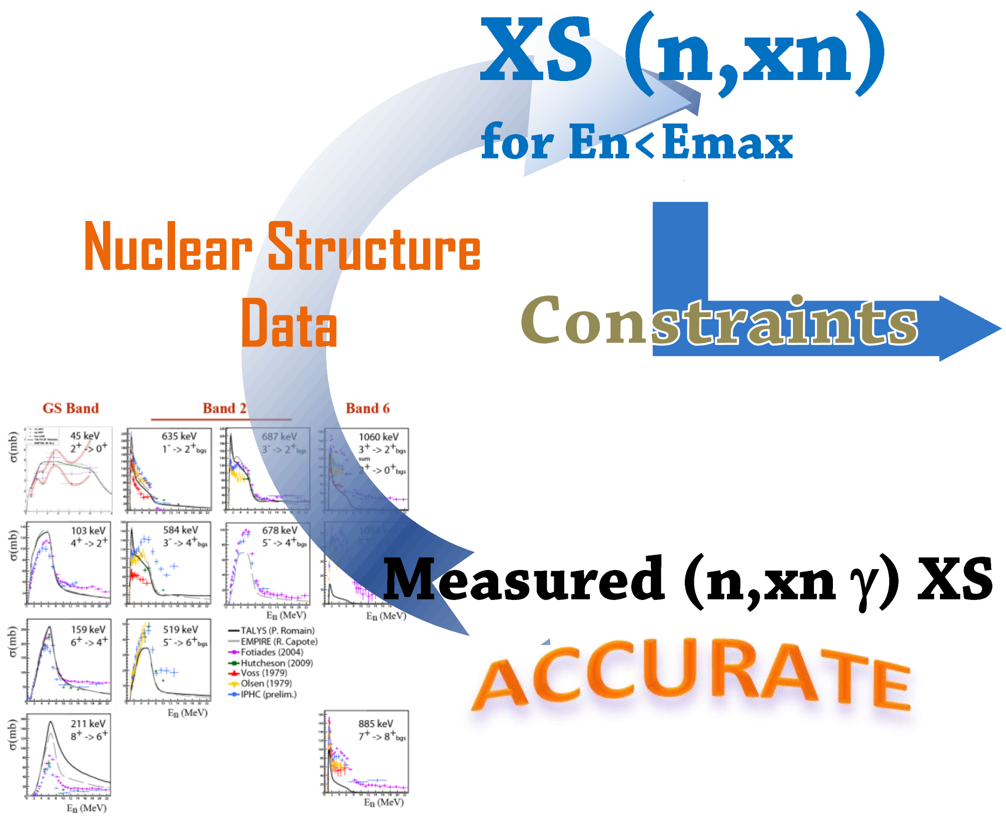
- Nuclear structure needs for nuclear energy application

The prompt γ-ray spectroscopy for (n, xn) XS measurements

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

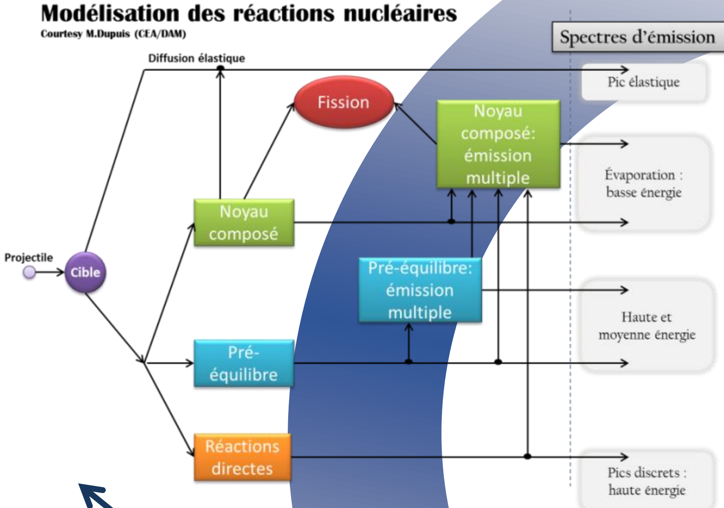
Powerful method which provides a lot of cross sections data :

- (n, xnγ)
- level production
- total



The prompt γ-ray spectroscopy for (n, xn) XS measurements

Inferring (n, xn) cross sections from (n, xnγ) ones
Towards predictive models



Valid XS (n,xn γ)

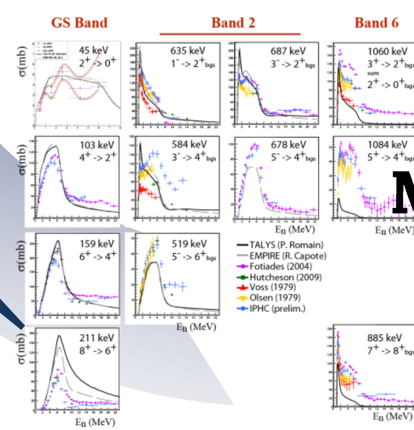
Reliable XS (n,xn)

Constraints

E V A L U A T I O N

Structure Parameters

Reaction Mécanismes



Measured (n,xn γ) XS

ACCURATE

Constraints

For modeling

The prompt γ-ray spectroscopy for (n, xn) XS measurements

Collaboration IPHC/CNRS (Fr) – **EC-JRC Geel** (Be)– **IFIN-HH** (Ro) has developed two germanium arrays at EC-JRC-GELINA neutron facility

¤ GAINS *A.Negret et al., EPJ Web of Conferences 239, 01005 (2020)*

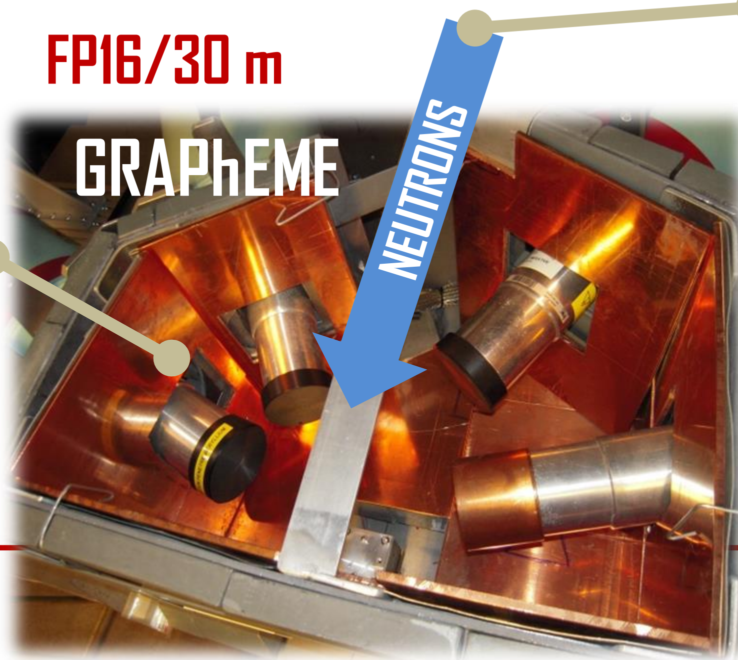
¤ **GRAPhEME** dedicated to measurements with actinides

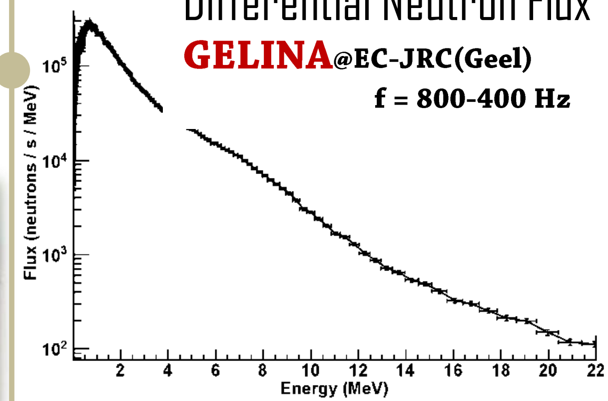
The prompt γ-ray spectroscopy for (n, xn) XS measurements

GRAPhEME main specificities

1 Fission Chamber,
5 HPGe Planar,
1 HPGe seg
(110°,150°)
^{232}Th, ^{233,235,238}U
^{nat}Zr, ^{nat,182,3,4,6}W,
^{57}Fe,
To come ^{239}Pu
Thick. 0.2 – 1.3 mm

FP16/30 m





ΔEn = 10 keV @ En = 1 MeV
Beam Time 400 – 3000 hours

XS uncertainties

3 to 5% - En < 9 MeV
Up to 20% - En > 9 MeV
Correlation and covariance matrices provided

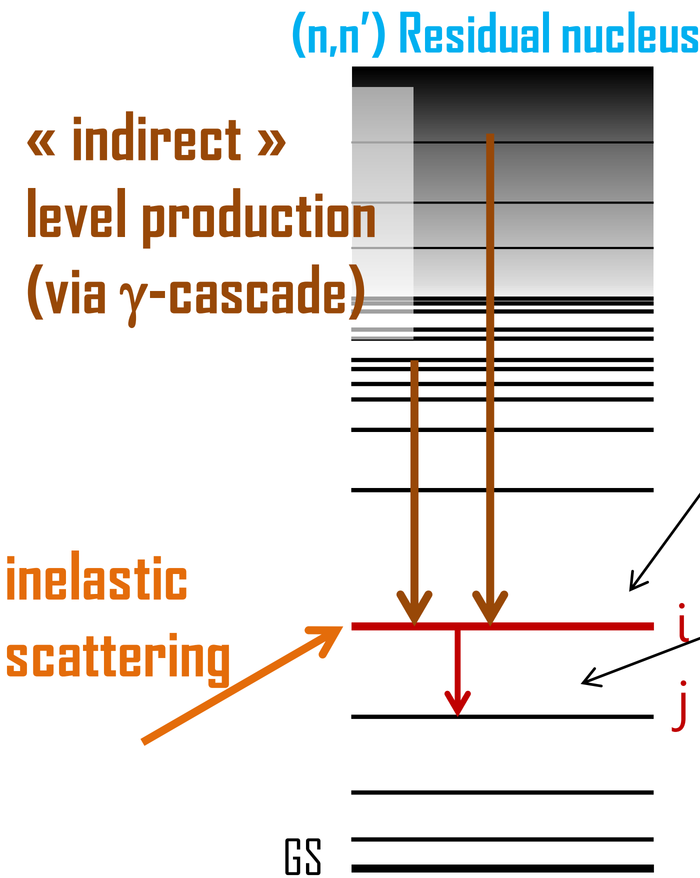
$$\frac{d\sigma^{(n,xn\gamma)}}{d\Omega}(\theta, E_n) = \frac{n_{det}(E_n)}{N_{at}\cdot\phi_n(E_n)\cdot\varepsilon_\gamma\cdot t}$$

- $n_{det}(E_n)$: 2 to 20%
- N_{at}: 1 to 3%
- $\phi_n(E_n)$: 0.4 - 0.6 % ; 0 to 10 MeV / 1 - 2 % ; 10 to 20 MeV
- ε_γ: 2 %

M. Kerveno et al. PRC **87**, 24609 (2013)
G. Henning et al. EPJ Web of Conf., **146**, 11016 (2017)
M. Kerveno et al. EPJN **4**, 23 (2018)

Modeling (n, xnγ) XS

The role of structure knowledge and reaction modeling



"Simplified cross sections" for

Production of the level i

$$\boldsymbol{\sigma(n,n'_i) =}$$

$$\boldsymbol{(feeding\ of\ the\ level\ i)}$$

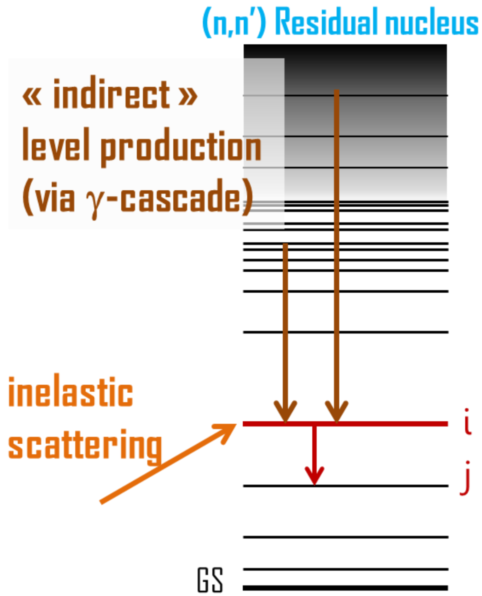
Production of the γ for transition i → j

$$\boldsymbol{\sigma(n,n'\gamma_{i\to j}) =}$$

$$(feeding\ of\ the\ level\ i) * IC * \boldsymbol{BR_{\gamma}^{i\to j}}$$

Modeling (n, xnγ) XS

The role of structure knowledge and reaction modeling



"Simplified cross section"

$$\sigma(n,n'\gamma_{i\to j}) = (\,\boldsymbol{feeding\ of\ the\ level\ i}\,) * BR_{\gamma}^{i\to j}$$

Test of **Reaction modeling**

inelastic scattering

$$\sigma(n,n'\gamma_{i\to j}) = \left(\begin{array}{c}\sigma^{i}_{Direct} + \sigma^{i}_{Comp} \\ + \\ \sigma^{i}_{discrete\ cascade} + \sigma^{i}_{continuum\ cascade}\end{array}\right) * IC * BR_{\gamma}^{i\to j}$$

Test of **Structure knowledge**

For investigations **3 codes* are used**

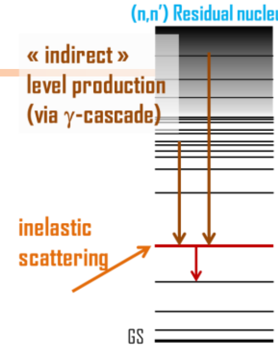
- **TALYS**, M. Dupuis (CEA/DAM) *et al.*
- **EMPIRE**, R. Capote (IAEA) *et al.*

^{238}U CIELO file that was adopted as ENDF/B-VIII.0

- **CoH**, T. Kawano (LANL)

* state of the art for modeling of the n+^{238}U reaction

Modeling (n,xn γ) XS



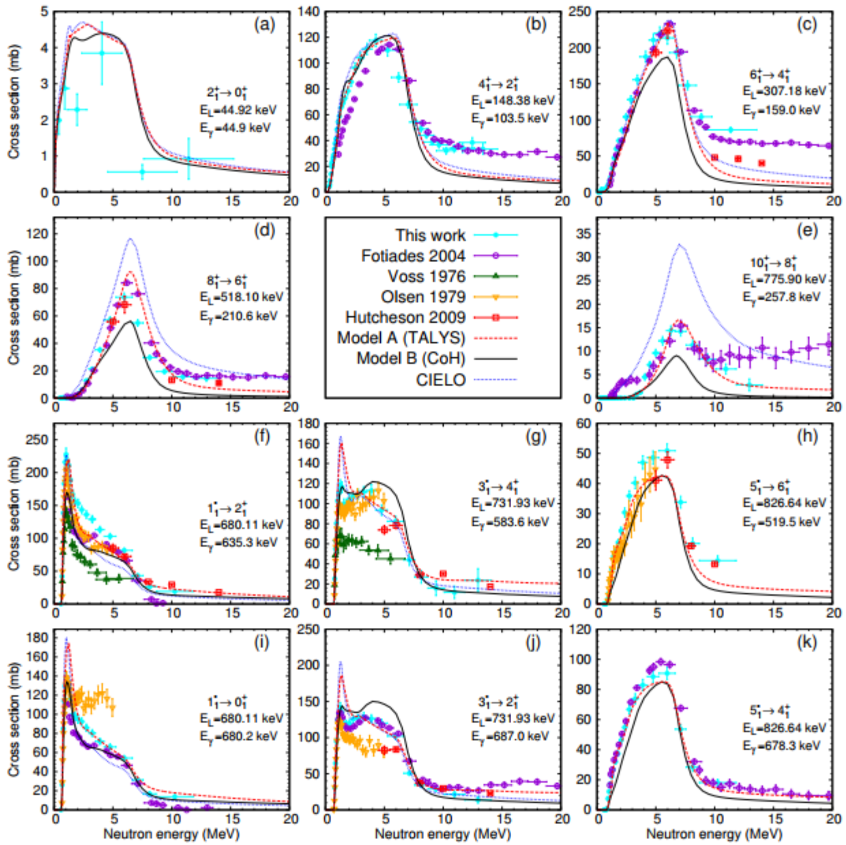
A brief summary of what we learned up to now

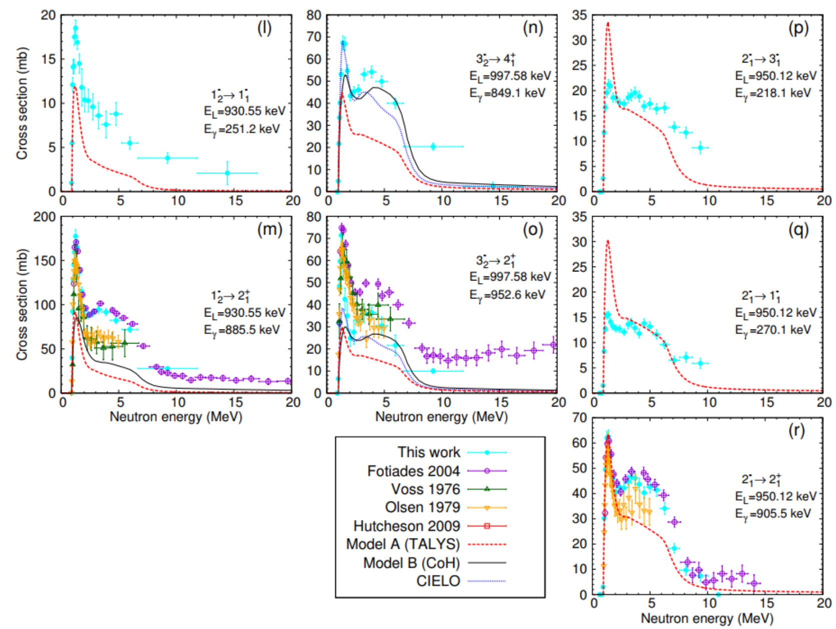
Measurement of ^{238}U$(n,n'\gamma)$ cross section data and their impact on reaction models

M. Kerveno, M. Dupuis, A. Bacquias, F. Belloni, D. Bernard, C. Borcea, M. Boromiza, R. Capote, C. De Saint Jean, P. Dessagne, J. C. Drohé, G. Henning, S. Hilaire, T. Kawano, P. Leconte, N. Nankov, A. Negret, M. Nyman, A. Olacel, A. J. M. Plompen, P. Romain, C. Rouki, G. Rudolf, M. Stanoiu, and R. Wynants

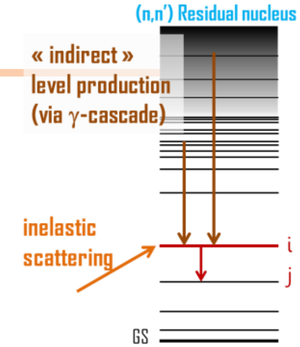
Accepted 25 August 2021

PHYSICAL REVIEW C
covering nuclear physics





Modeling (n, xnγ) XS



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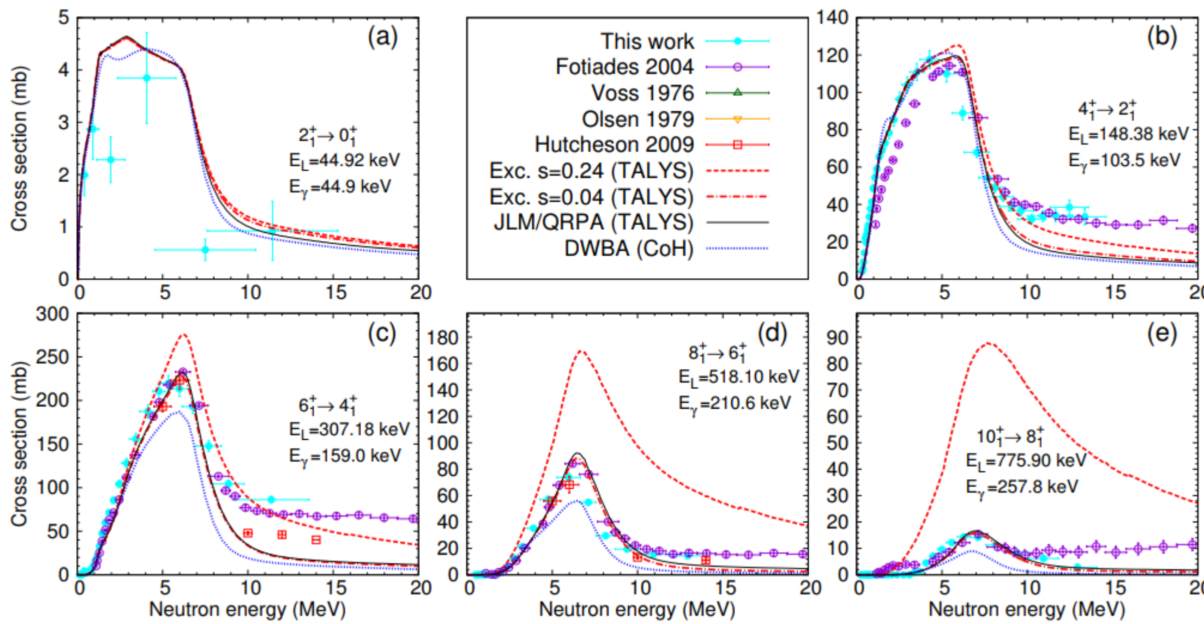
Reaction modeling – Pre equilibrium

Spin distribution
of the excited states

Calculations compared with:
* 2 inelastic micro. appr. (JLM/QRPA and DWBA/1p-1h)
* 2 classical exciton calc. with defaut spin cut-off or fitted cut-off parameter



=> **microscopic approach** (JLM/QRPA or DWBA/1p-1h)
improved situation for γ transitions at high spin in the GS band.

=> A **new prescription** for the **spin cut-off** in the **exciton** model has been proposed for ^{238}U

Modeling (n, xnγ) XS

A brief summary of what we learned up to now

PHYSICAL REVIEW C
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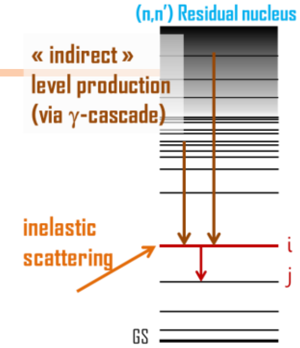


Structure knowledge

Branching Ratio check

* In the data, we have seen BR discrepancies compared to ENSDF
* Impact of knowledge structure is around 4% on the (n, n'γ) XS (MC study)
* In ^{238}U, discrete states embedded in continuum do not impact (n, n'γ) XS (contrary to W isotopes)

TABLE IV. γ intensities calculated in this work compared to ENSDF and Govor *et al.* [70] values.

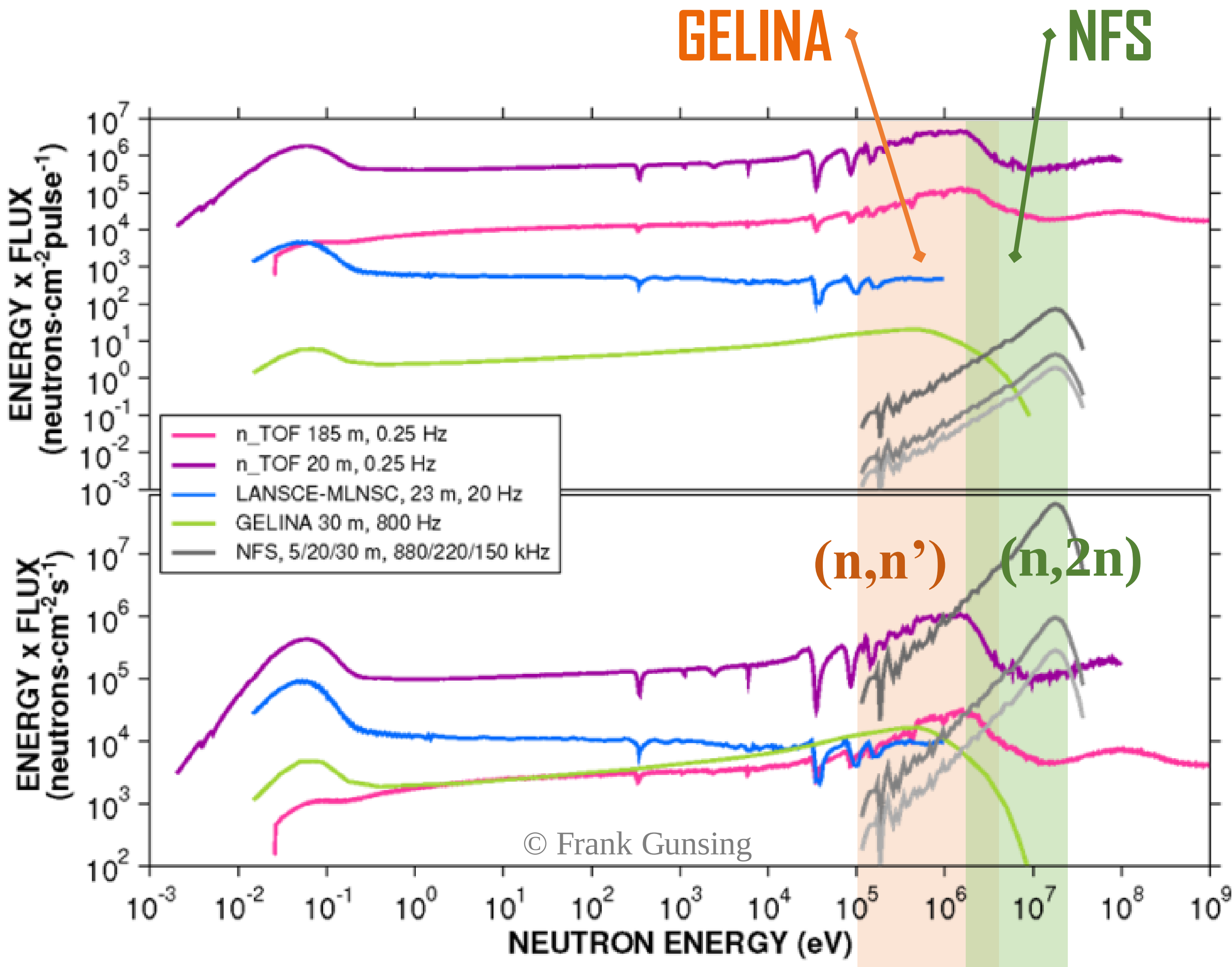
E_{level} (keV)	E_γ (keV)	I_γ (this work)	I_γ (ENSDF)	I_γ Govor *et al.*
680.11	680.2	61 (7)	79 (4)	61
*	635.3	100	100 (2)	100
731.93	583.55	84 (3)	81.4 (16)	85
	686.99	100	100 (2)	100
826.64	519.46	55 (2)	50 (3)	56
	678.3	100	100 (6)	100
930.55	251.2	11 (2)	13.1 (4)	8.7
	885.46	100	100 (4)	100
950.12	270.1	28 (3)	48 (8)	37
*	218.1	41 (8)	53 (6)	27
	905.5	100	100 (6)	100
997.58	952.65	64 (9)	56.8 (13)	55
	849.1	100	100 (3)	100

=> **New information** on **^{238}U nuclear structure** is clearly needed
=> Variation of the **E1** and **M1 strength functions** (define the γ decay from cont. levels), were shown to be of importance (interband γ rays), **to be studied**

(n, xnγ) studies at NFS with the prompt γ-ray spectroscopy

The proposed experimental program @ NFS

To produce **new evaluation** of a nucleus, **all reaction channels** must be **well known**



(n, xnγ) studies at NFS with the prompt γ-ray spectroscopy

The proposed experimental program

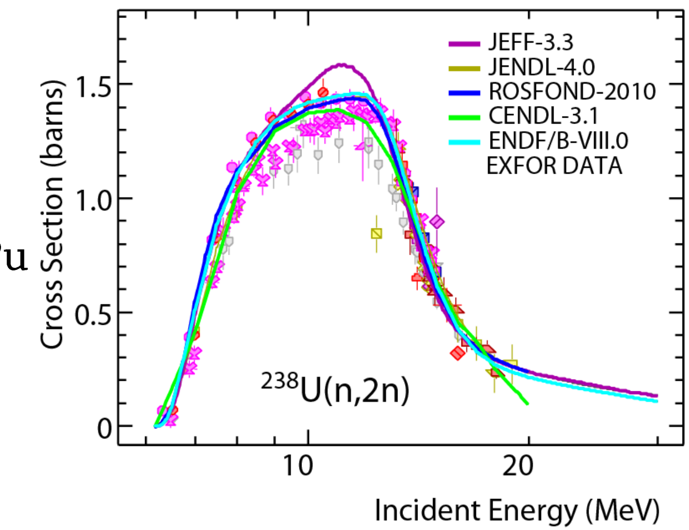
We want to take advantage of the neutron energy range of NFS to **continue investigations for x>1 to complete the datasets obtained at GELINA**.

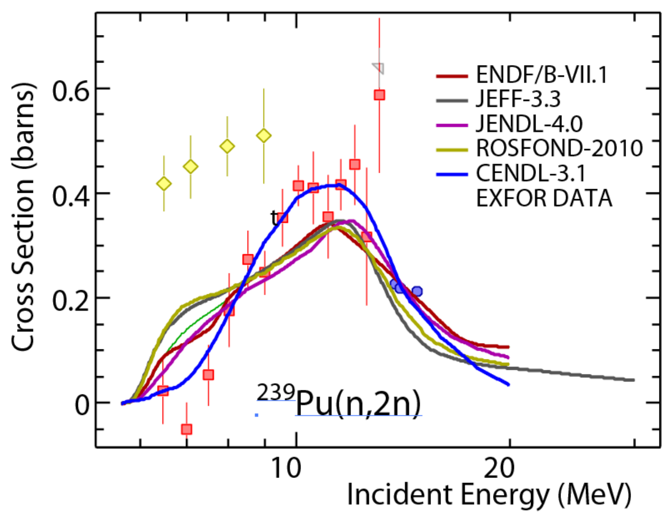
Interesting cases:

PWR Reactor physics improvements:

^{238}Pu amount underestimation in reactor

^{238}U(n, 2n)^{237}U -> ^{237}Np(n,γ) ^{238}Np -> ^{238}Pu





^{238}Pu amount underestimation in reactor

^{239}Pu(n, 2n)^{238}Pu

(n,xn γ) studies at NFS with the prompt γ-ray spectroscopy

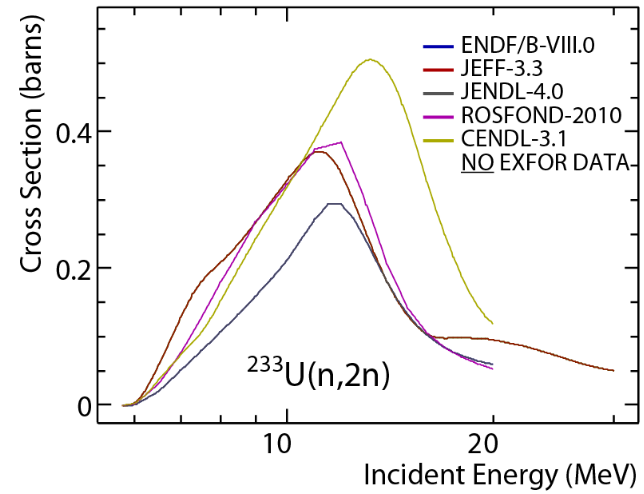
The proposed experimental program

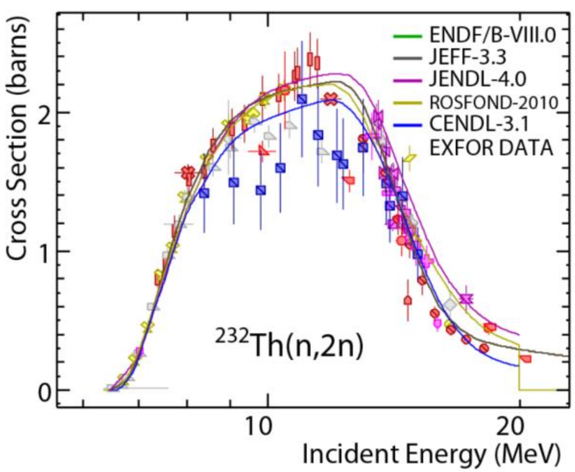
We want to take advantage of the neutron energy range of NFS to **continue investigations for x>1 to complete the datasets obtained at GELINA**.

Interesting cases:

Development of Th/U cycle

^{232}U amount in reactor
(problematic for radioprotection)
^{233}U(n, 2n)^{232}U





^{232}Th bad modeling and discrepancies in exp. data
^{232}Th(n, 2n)^{231}Th

The proposed experimental program

Coupling of 2 γ spectrometers

to increase efficiency (for low and high γ energy)

¤ GAINS

dedicated to measurements
with light and intermediate masses

12 high-efficiency HPGe det.

¤ GRAPhEME

dedicated to measurements
with actinides

5 Planar HPGE and
1 segmented Planar HPGE det.

This program could be complementary to the one proposed by CEA/DAM with the SCONE setup

Outline

NFS time of flight area

(n, xnγ) studies at NFS
with the prompt γ-ray spectroscopy

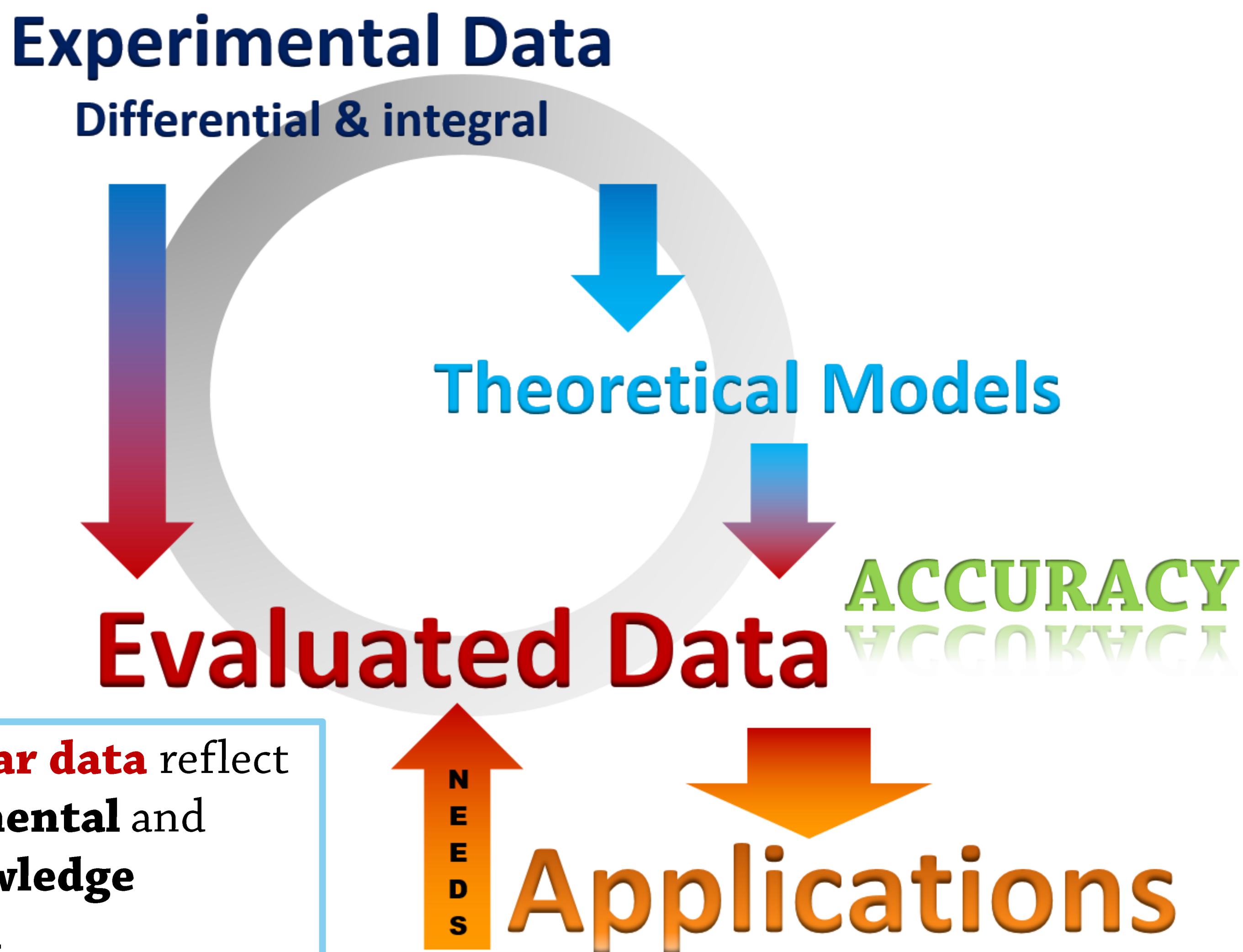
**Nuclear structure needs
for nuclear energy application**

NACRE
le Noyau Au Cœur du RéactEur

A. Chebboubi, M.Fallot, G. Henning, M. Kerveno, X. Mougeot, O. Serot, V. Vallet *et al.* CNRS, CEA

Nuclear structure needs for nuclear energy application

Nuclear data for energy application

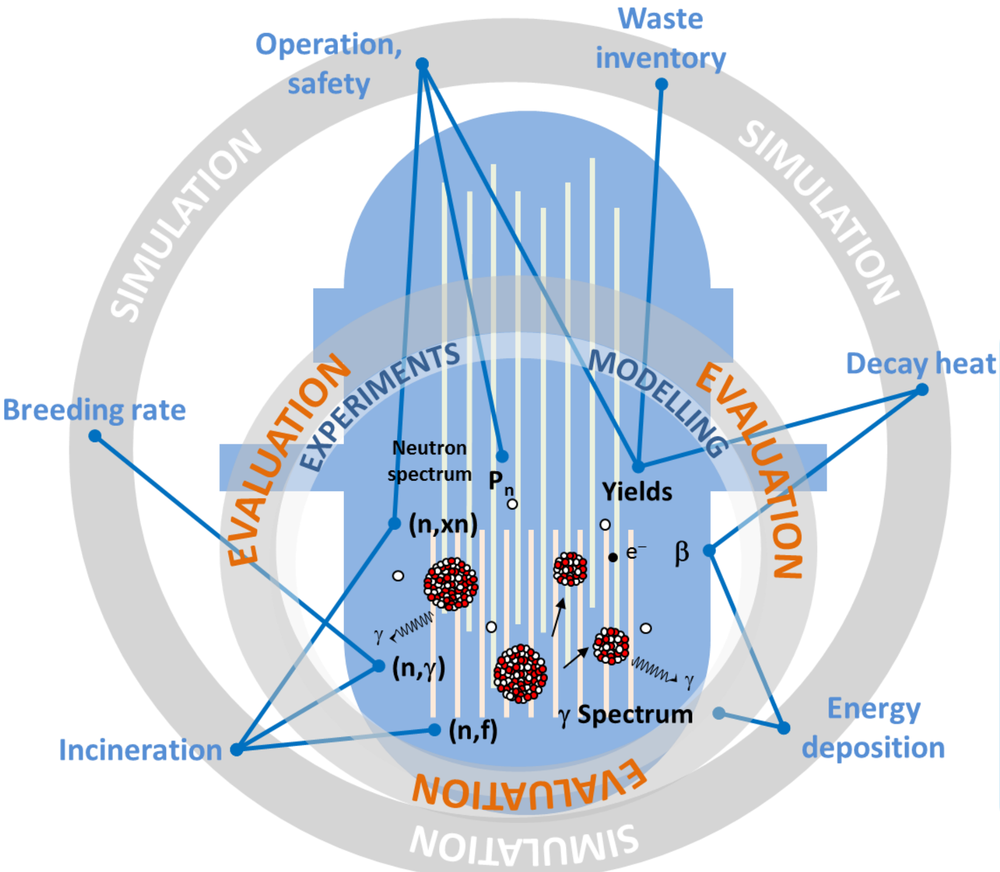


Evaluated nuclear data reflect the **best experimental** and **theoretical knowledge** of a **nuclear data**

Nuclear structure needs for nuclear energy application

An initiative from the NACRE Project

CNRS with Andra, BRGM, CEA, EDF, Framatome, IRSN, Orano.



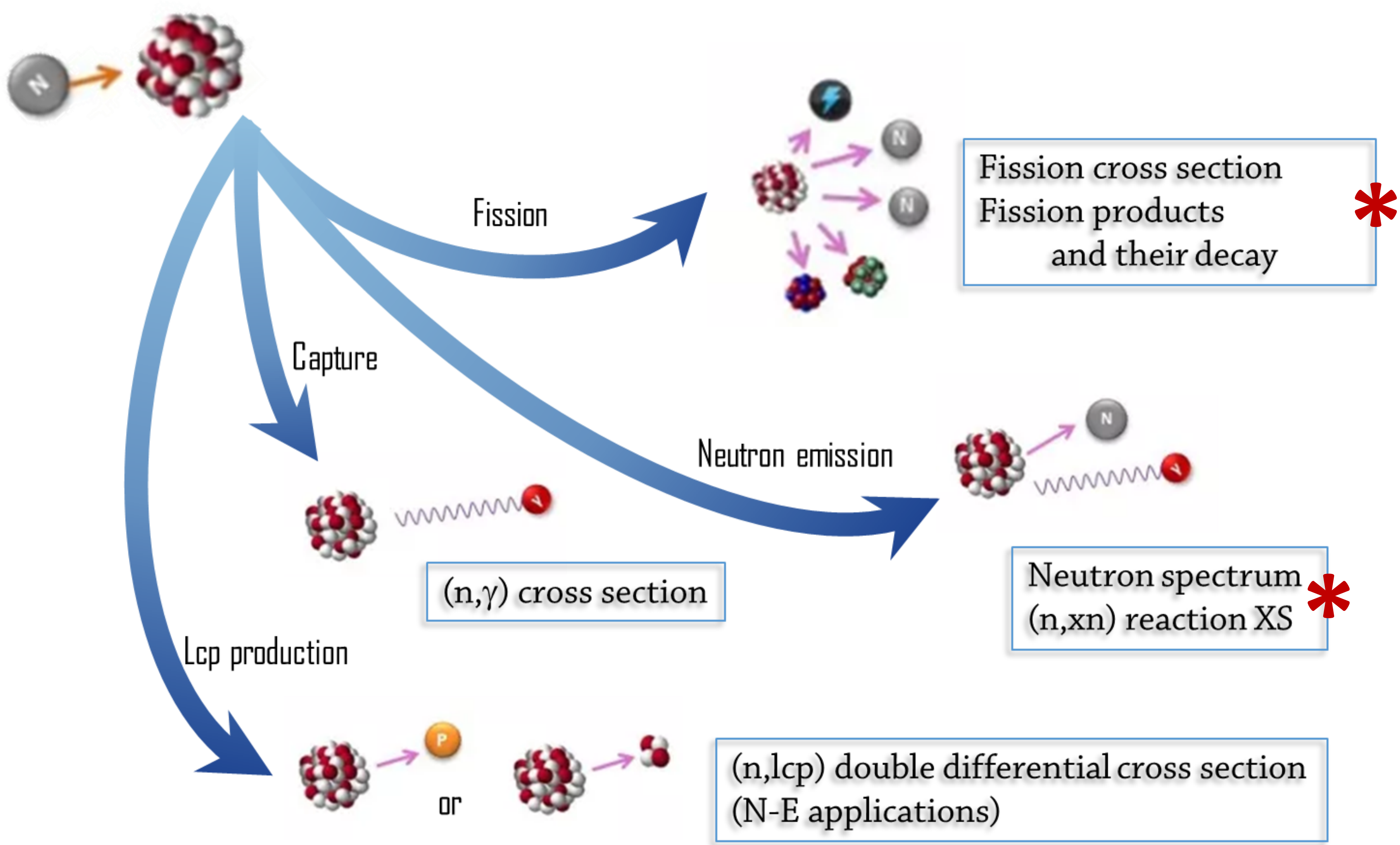
NACRE aims:

Improvement of **evaluated nuclear data bases** for reactor applications by the development of

- **new experimental techniques** for microscopic measurements of nuclear processes to **improve** their **modeling**,
- new **uncertainties control** and,
- new **evaluation technique**.

Nuclear structure needs for nuclear energy application

An initiative from the NACRE Project

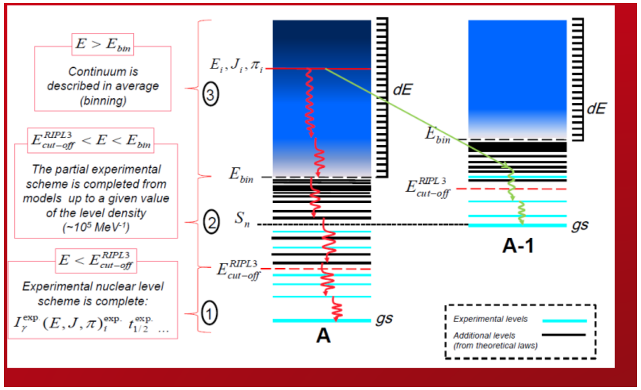


Nuclear structure needs for nuclear energy application

Nuclear Structure needs in NACRE

Fission :

FRIFRELIN code for the modeling of fission product decay based on RIPL-3 database (E_{level}, spin, parity, life time, Pn, Branching ratio,…). A lot is missing for comprehensive calculations.



O. Litaize et al.

Fission yields measurements rely on γ detection and precise knowledge of γ intensity. In ENSDF, I_{norm} is known with 10-20% of uncertainty -> main impact on the cumulated yield uncertainty. ^{141}Xe, ^{139}Cs, ^{137}Te, ^{136}Sb, …

LPSC Grenoble – Laboratoire de Physique Subatomique et de Cosmologie

A. Chebboubi et al.

Nuclear structure needs for nuclear energy application

Nuclear Structure needs in NACRE

Fission :

– **β Decay data of Fission Fragments**: for decay heat (U/PU & Th/U fuel cycles), antineutrino spectra and info about β-n emitters. Lists have been already published with nuclei of interest.

M. Fallot et al.

Table bilan

Table 3. Summary of priorities for TAGS measurements of importance in decay-heat calculations for U/Pu and Th/U fuel cycles and for determining the antineutrino spectra produced by standard nuclear power plants. Radionuclides that have already been studied by means of TAGS are ticked in the 5th column, where the initials stand for the experimental groups responsible for measurements: V for IFIC-Univ. Valencia group, N for Subatech-Univ. Nantes group, O for Oak Ridge National Laboratory group.

Radionuclide	Q_β-value (keV)	Half-life	Comments	TAGS measurements	Priority		
					U/Pu fuel	Th/U fuel	Antineutrinos Total [3-8] MeV
34-Se-85	6161(4)	31.7 s	-			1	
34-Se-86	5129(4)	14.3 s	-			2	
35-Br-84	4656(26)	31.76 min	-			2	
35-Br-86	7633(3)	55.1 s	-	✓ V, O	1	1	
35-Br-87	6818(3)	55.65 s	(β^-,n) branch	✓ V, O	1	1	
35-Br-88	8975(4)	16.29 s	(β^-,n) branch	✓ V	1	1	
35-Br-89	8262(4)	4.40 s	(β^-,n) branch			1	
36-Kr-87	3888.27(25)	76.3 min	-	✓ O		1	
36-Kr-89	5176(6)	3.15 min	-	✓ O	1	1	
36-Kr-90	4405(7)	32.32 s	-	✓ O	1	1	
36-Kr-91	6771(8)	8.57 s	-			1	2
37-Rb-88	5312.4(11)	17.773 min	-			2	1
37-Rb-90	6584(7)	158 s	-				1
37-Rb-90m	6691(7)	258 s	repeat of INL TAGS		2		
37-Rb-92	8095(6)	4.492 s	small (β^-,n) branch	✓ V-N, O	2	2	1
37-Rb-93	7466(9)	5.84 s	(β^-,n) branch	✓ V-N			1
37-Rb-94	10283.0(26)	2.702 s	(β^-,n) branch	✓ V-N		1	2

...

Presursor	$^{87}_{35}Br$	$^{141}_{55}Cs$	$^{137}_{53}I$	$^{136}_{52}Te$	$^{88}_{35}Br$	$^{72}_{29}Cu$	$^{146}_{57}La$	$^{138}_{53}I$	$^{93}_{37}Rb$
$T_{1/2}$, s	55.65	24.84	24.5	17.63	16.29	6.49	6.27	6.23	5.84
Presursor	$^{92}_{37}Rb$	$^{89}_{35}Br$	$^{79}_{31}Ga$	$^{94}_{37}Rb$	$^{139}_{53}I$	$^{119}_{47}Ag$	$^{85}_{33}As$	$^{90}_{35}Br$	$^{114}_{45}Rh$
$T_{1/2}$, s	4.49	4.40	2.85	2.70	2.28	2.1	2.02	1.91	1.85
Presursor	$^{143}_{55}Cs$	$^{119}_{46}Pd$	$^{142}_{55}Cs$	$^{80}_{31}Ga$	$^{135}_{51}Sb$	$^{103}_{41}Nb$	$^{148}_{57}La$	$^{129}_{49}In$	$^{120}_{47}Ag$
$T_{1/2}$, s	1.79	1.76	1.684	1.68	1.68	1.5	1.26	1.23	1.23
Presursor	$^{81}_{31}Ga$	$^{134}_{50}Sn$	$^{144}_{55}Cs$	$^{147}_{56}Ba$	$^{140}_{53}I$	$^{113}_{44}Ru$	$^{129m}_{49}In$	$^{148}_{56}Ba$	$^{145}_{55}Cs$
$T_{1/2}$, s	1.22	1.05	0.99	0.89	0.86	0.8	0.61	0.61	0.59
Presursor	$^{91}_{35}Br$	$^{120}_{46}Pd$	$^{141}_{53}I$	$^{95}_{37}Rb$	$^{92}_{35}Br$	$^{146}_{55}Cs$	$^{130}_{49}In$	$^{147}_{55}Cs$	$^{96}_{37}Rb$
$T_{1/2}$, s	0.54	0.5	0.43	0.38	0.34	0.32	0.29	0.23	0.2
Presursor	$^{97}_{37}Rb$	$^{98}_{37}Rb$							
$T_{1/2}$, s	0.17	0.11							

P. Leconte et al.

- **Structure data for delayed neutron :** reactor operation and safety concerns. Need of P_n, $T_{1/2}$ and neutron spectrum for precursors nuclei.

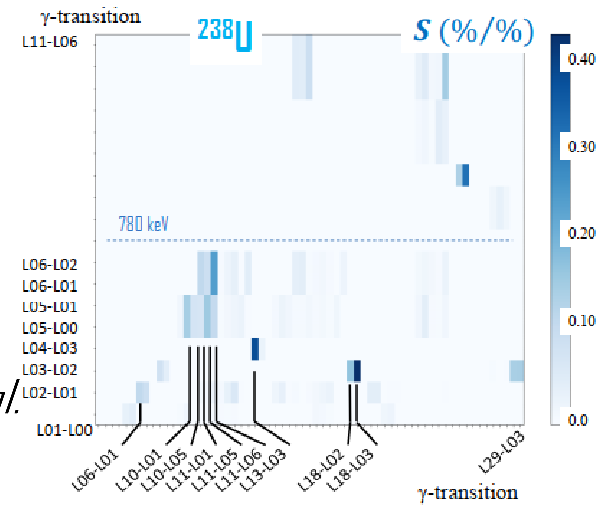
Nuclear structure needs for nuclear energy application

Nuclear Structure needs in NACRE

Inelastic and (n, xn) :

- To infer the (n, n'), (n, xn) XS from the measured (n, n'γ) and (n, xnγ) ones, need of good structure knowledge (levels, Eγ, Iγ, ICC, multipolarities) for ^{238}U, ^{232}Th, ^{233}U, ^{239}Pu, W isotopes, ….

G. Henning et al.



- A **paper** is in **progress** to list our needs
- A **workshop** will be organized (**06/2022**) to gather the ND com. with the « structure » com.

=> start discussion about possible collaboration in

nuclear structure measurements for nuclear energy application

Need of precise nuclear structure data for reactor studies.

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Abstract **Keywords** Nuclear data · Nuclear structure

In this paper, we present the reason for … need for **precise** nuclear structure and decay data … surements in order to perform quality reactor and other applications) studies. We will explain why such high precision data is necessary for evaluation and the interpretation of nuclear data experimental measurements. Use cases where an improvement in nuclear data precision can be reached by new structure data will be presented.

… these structure information comes with uncertainty (although, in some cases, the uncertainty may not even be known or quoted). Therefore, it impacts directly the precision of experimentally obtained nuclear data, regardless of how well the measurement is done.

However, the reactor and nuclear application studies need the extra level of precision that is not yet reached. As a consequence, one need to loewer the uncertainties on structure and decay data, so that it reflects directly on the precision of experimentally derived nuclear data.

IN PROGRESS

Outlooks

- **NFS time of flight** area is **ready** for measurements at long flight path; **precise characterization** of the **neutron beam** (flux and profile) is now required.
- A **new experimental program** dedicated to **(n, xnγ)** measurements on **actinides**, leaded by IPHC, EC-JRC-Geel and IFIN-HH, could start @NFS. **New** and **comprehensive** sets of **data are expected**.
- The French nuclear data community is willing to inform and to gather the interest of the nuclear structure community to the **needs of accurate nuclear structure data** and **new experiments**.

Thank you for your attention…