Prompt Fission Neutron Multiplicity in the Resolved Resonance Energy Range of ^{239}Pu

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CEA-Cadarache DES/IRESNE/DER/SPRC/LEPh

Project APPRENDRE/WP2/REMUS

Content

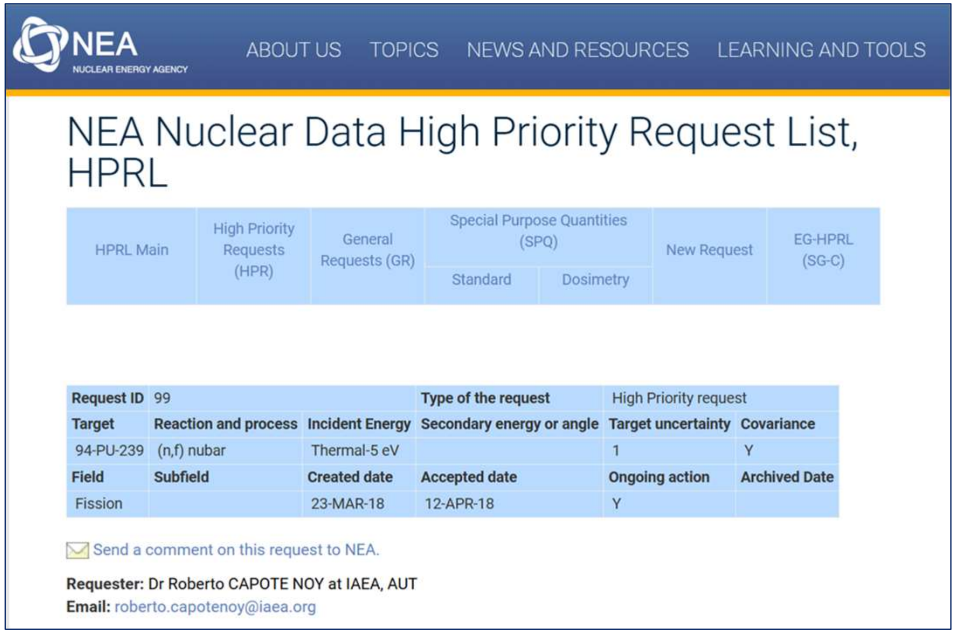
1. Context

Context
High Priority Request List

NEA Nuclear Data High Priority Request ID 99

- Neutronic calculations provide **an overestimation of keff:** may be due to the average energy of the PFNS and/or the prompt neutron multiplicity in the region between 3 meV and 100 eV (RRR).

- " Therefore **a reduced criticality is needed for high-leakages solutions**. Such reduced criticality may arises due to the (n,γf) process in ^{239}**Pu resonance nubar**."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NEA Nuclear Data High Priority Request List, HPRL

HPRL Main	High Priority Requests (HPR)	General Requests (GR)	Special Purpose Quantities (SPQ)		New Request	EG-HPRL (SG-C)
			Standard	Dosimetry		

Request ID	99		**Type of the request**	High Priority request	
Target	**Reaction and process**	**Incident Energy**	**Secondary energy or angle**	**Target uncertainty**	**Covariance**
94-PU-239	(n,f) nubar	Thermal-5 eV		1	Y
Field	**Subfield**	**Created date**	**Accepted date**	**Ongoing action**	**Archived Date**
Fission		23-MAR-18	12-APR-18	Y	

Send a comment on this request to NEA.

Requester: Dr Roberto CAPOTE NOY at IAEA, AUT
Email: roberto.capotenoy@iaea.org

According to the HPRL request: "Statistical precision below about 1% at the resonances is required in order to unambiguously identify resonant fluctuations"

Context
Current available measurements

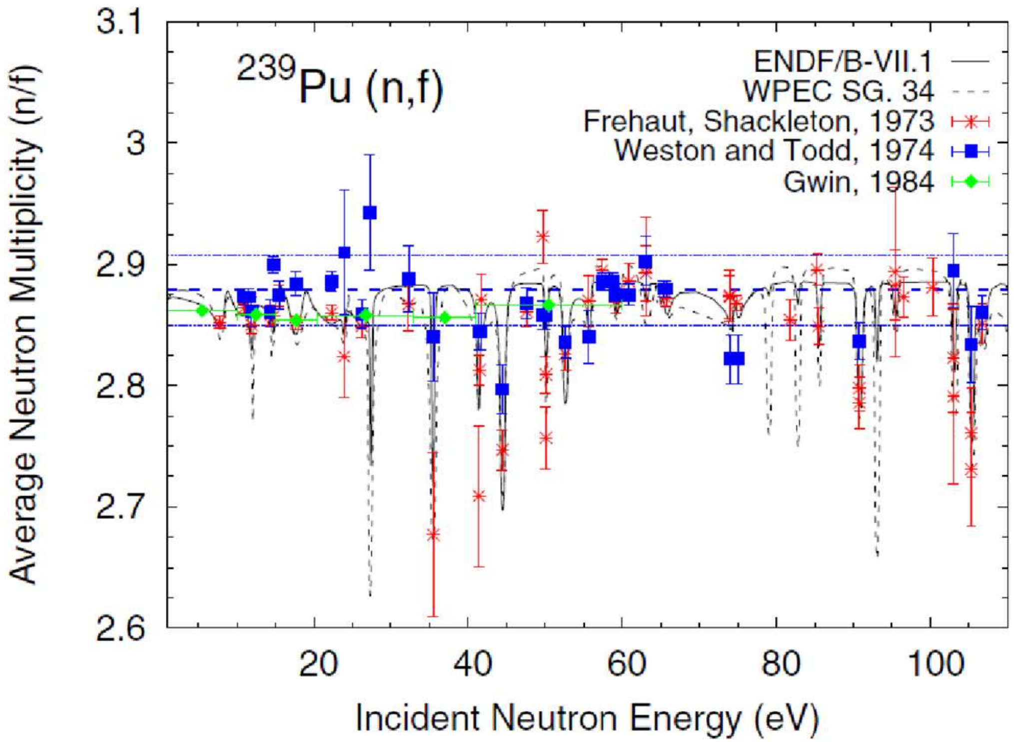


Figure from E. Lynn, P. Talou and O. Bouland, Phys. Rev C 97, 064601 (2018)

- D. Shackleton, J. Trochon, J. Frehaut, and M. Le Bars, Phys. Lett. **42B**, 344 (1972)
- L. W. Weston and J. H. Todd, Phys. Rev. C 10, 1402 (1974)
- R. Gwin, R. R. Spencer, and R. W. Ingle, Nucl. Sci. Eng. 87, 381 (1984)

- Data used from 1970s-80s
- Strong uncertainties
- High dispersion between the measurements

Context

Origin(s) of the ν_P fluctuations

- Possible correlation between the FF characteristics mass and TKE (total kinetic energy) with the prompt neutron multiplicity
- Competition between (n,f) and (n, γf) processes
- Possible impact of the spin of the resonance (1^+ most likely) on the (n, γf) process. The probability of (n,γf) in higher in J = 1^+ resonances because of the kind of authorized transitions E1 or M1.
  - J = 0^+ : 99% E1 mainly to 1^- state which has a low fission probability.
  - J = 1^+ : E1 lead to 0^-, 1^- and 2^- and M1 to 0^+, 1^+ and 2^+. Even if the emission probability of M1 in lower than for E1, the fission probability of final states is higher so M1 transitions has an important contribution to the (n, γf) process.

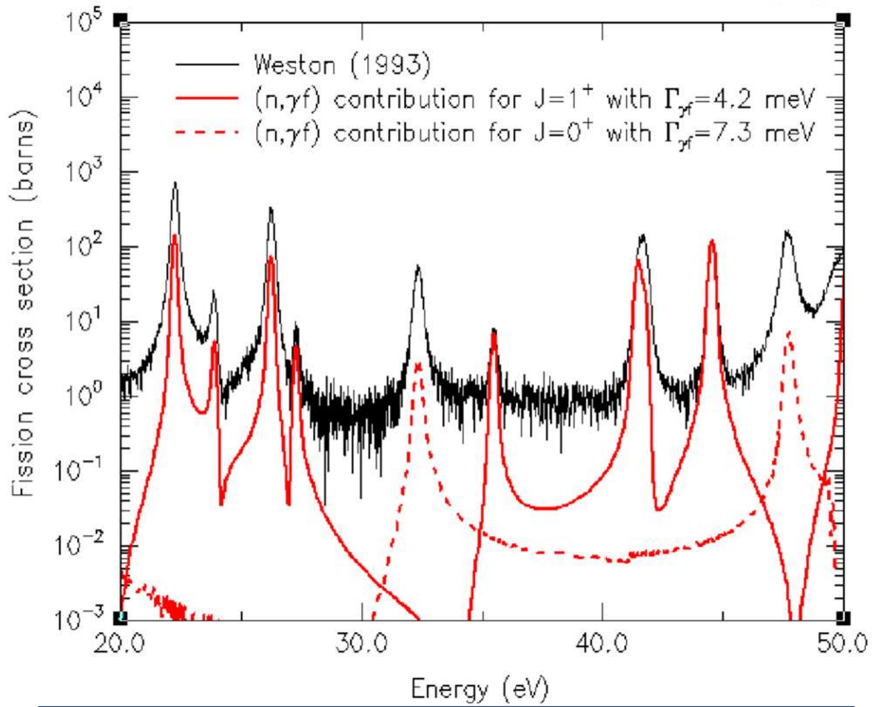


Figure from C. De Saint Jean, R. McKnight, NEA/WPEC, Report NEA/NSC/WPEC/DOC(2014)34(2014)

Target	J^π	E_{res} (eV)	Γ_f(meV)
^{239}Pu	1^+	27.29	2.8
		35.49	3.5
		41.46	6.4
		44.53	4.4
		50.14	5.0
		82.77	5.2

J. E. Lynn, P. Talou and O. Bouland, Phys. Rev. C97 (2018) 064601

E. Leal-Cidoncha, G. Noguere, O. Bouland and O. Serot, EPJ Web of Conferences 211 (2019) 02004

C. De Saint Jean, R. McKnight, NEA/WPEC, Report NEA/NSC/WPEC/DOC(2014)34(2014)

2. Experimental Setup

EC-JRC Geel and SCINTIA setup

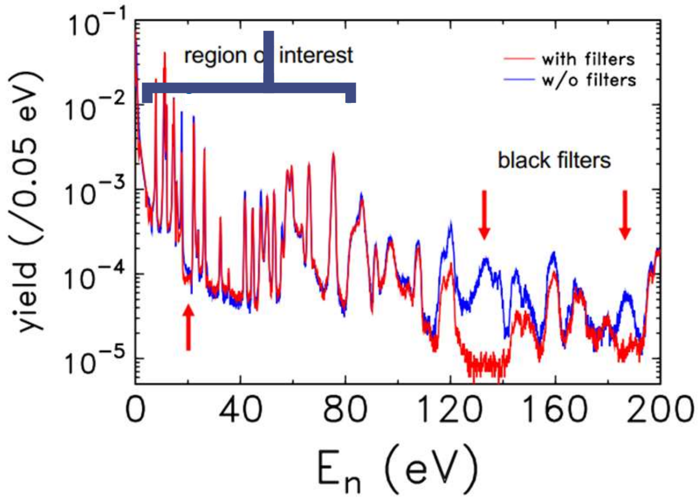
Experimental Setup
EC-JRC Geel

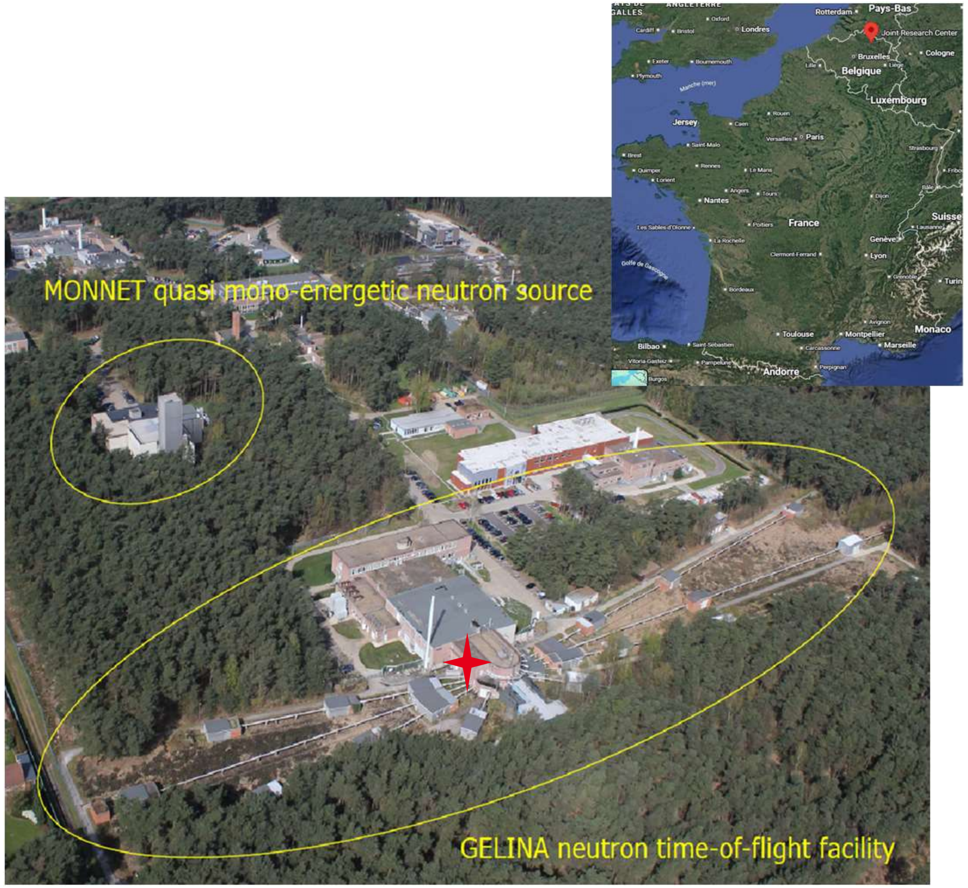
European Comission Joint Research Centre in Geel (Belgium)

GELINA neutron ToF facility :

- ❑ Pulsed white neutron beam operating at 400 Hz repetition frequency

→ High incident neutron energy resolution

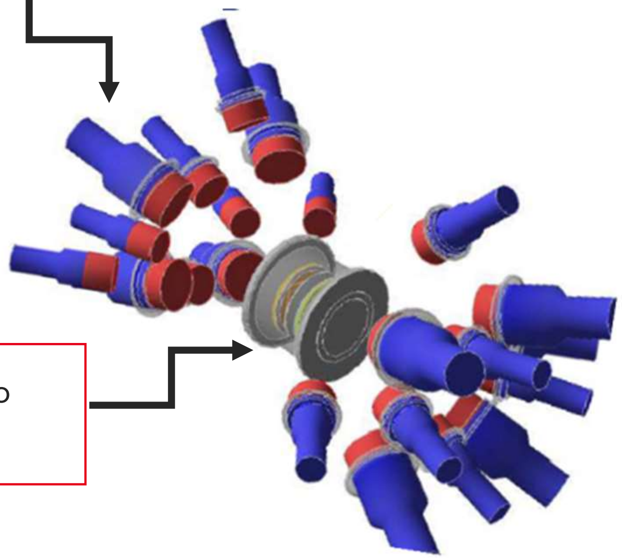




Experimental Setup
SCINTIA overview

SCINTIA (neutron SCINTIllator Array)

Neutron detectors measuring prompt neutron in coincidence with FF



Ionisation chamber used to detect fission events

- **Neutron detectors array coupled to a fission chamber**
- Located on a flight path at 8.81m from the neutron source

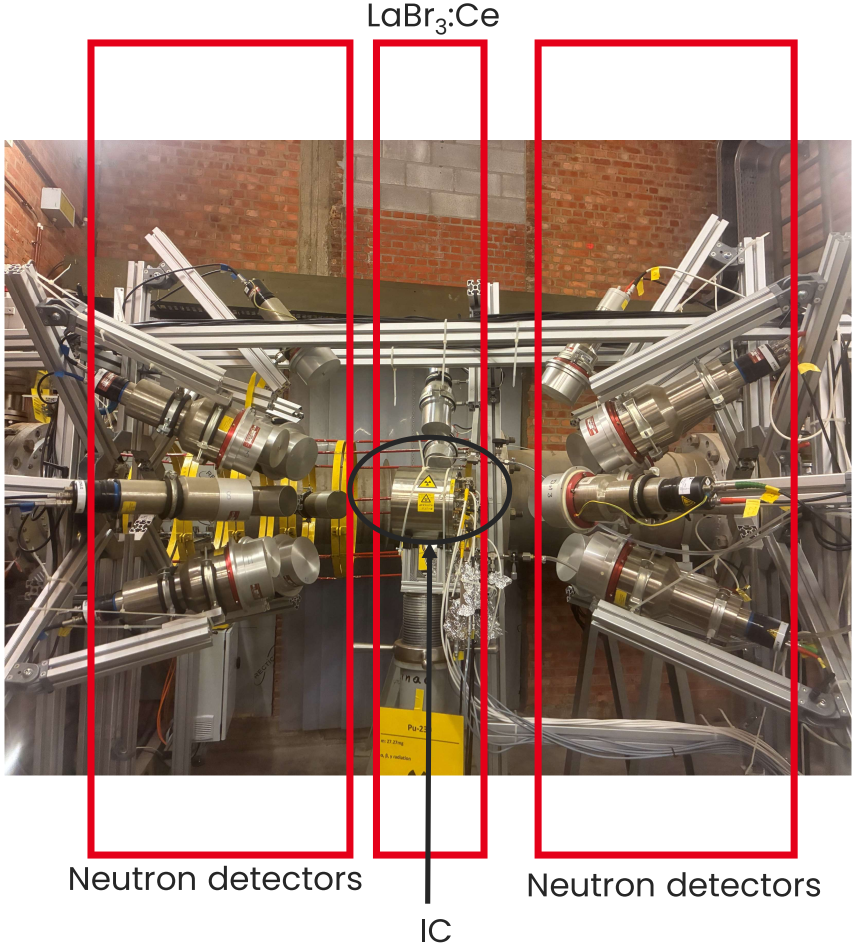
- A. Göök et al., EPJ Web of Conferences 239, 05009 (2020)
- A. Göök et al., Nuclear Instruments and Methods in Physics Research A 830 (2016) 366–374

Experimental Setup
SCINTIA : the detectors

Type	Nbr	Size (diameter x length)
EJ301	10	102 mm x 510 mm
EJ 301	8	127 mm x 510 mm
Para-therphenyl	3	80 mm x 50 mm
Stilbene	1	80 mm x 50 mm
$LaBr_3$:Ce	4	76 mm x 76 mm

$LaBr_3$:Ce detectors used to measure PFGS

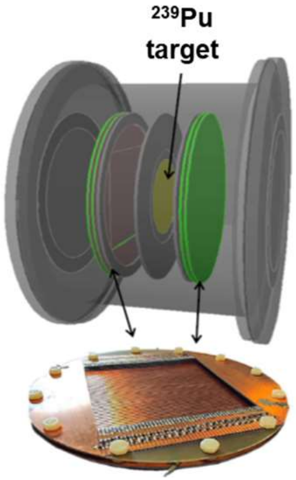
→ **Study of PFNS and PFGS in correlation with the incident neutron energy**



3. Measurements

Measurements
First experiment : twin position-sensitive IC

- Started in 2017 by Alf Göök
- GELINA at 50 Hz repetition frequency (for thermal region) and 800 Hz (for resonance region)
- Aim : measure correlations between the average ν_P and FF characteristics (A and TKE)
- Succesfull study for $^{235}U(n,f)$ reaction
- These experimental data still have to be interpreted for $^{239}Pu(n,f)$ reaction with **the Monte-Carlo code FIFRELIN**

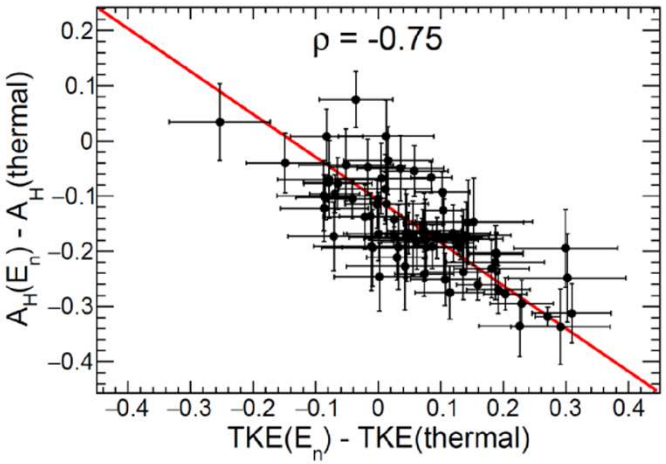


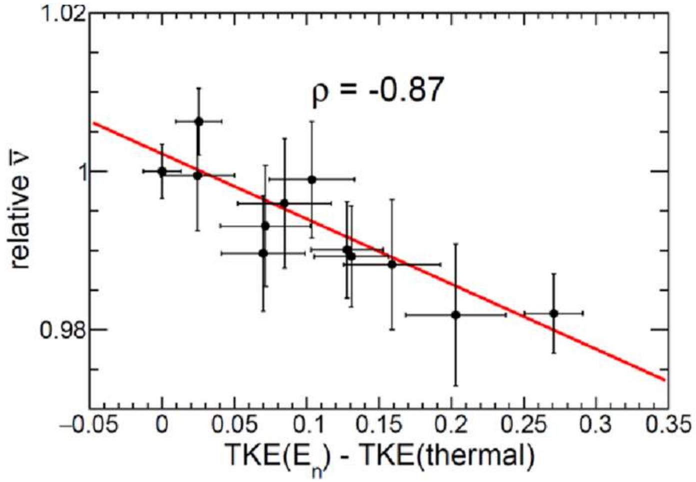
Twin position-sensitive ionization chamber for measuring the fission fragments characteristics

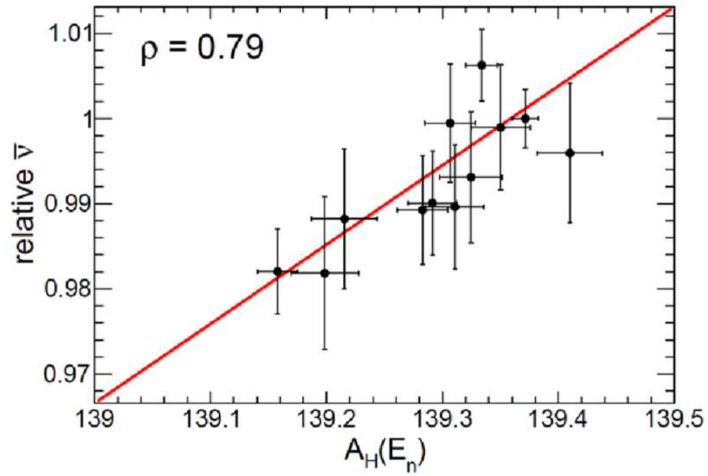
Thin spectroscopic sample:
29.95 μg/cm² Pu of PuF_4 on a backing of gold covered polyimide:
~ 0.6 mg ^{239}Pu

Measurements
Correlations Analysis

Done for ^{235}U to show correlations between FF characteristics and neutron multiplicity :







If TKE decreases, A_H increases

If TKE decreases, the nucleus is more deformed and ν_P increases

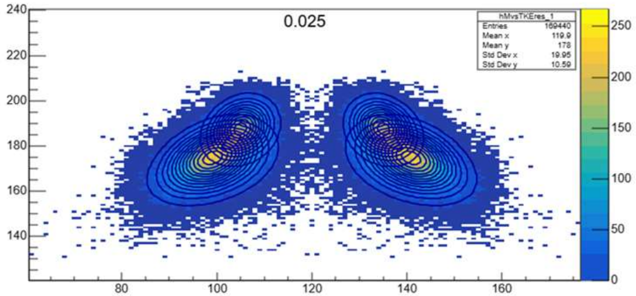
→ A_H and TKE are correlated (as expected)

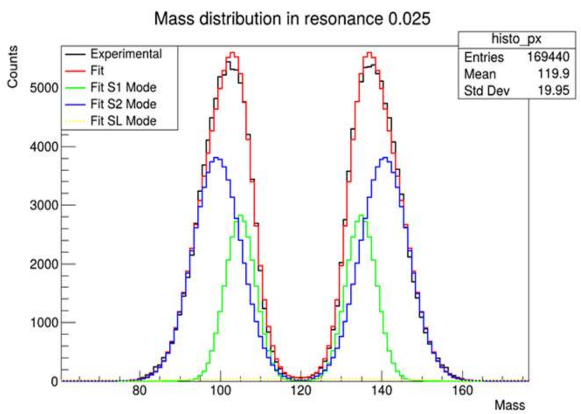
→ ν_P is correlated to both A_H and TKE

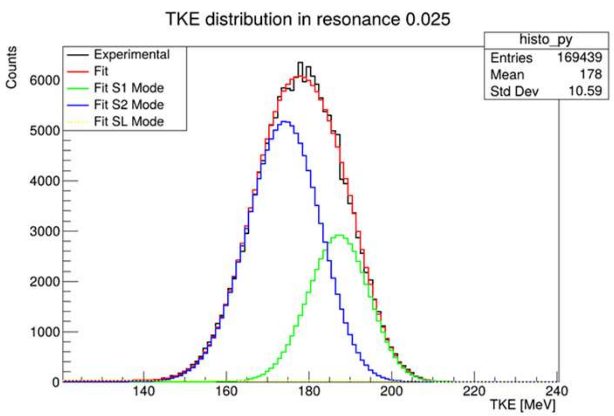
A. Göök, Fiesta 2017

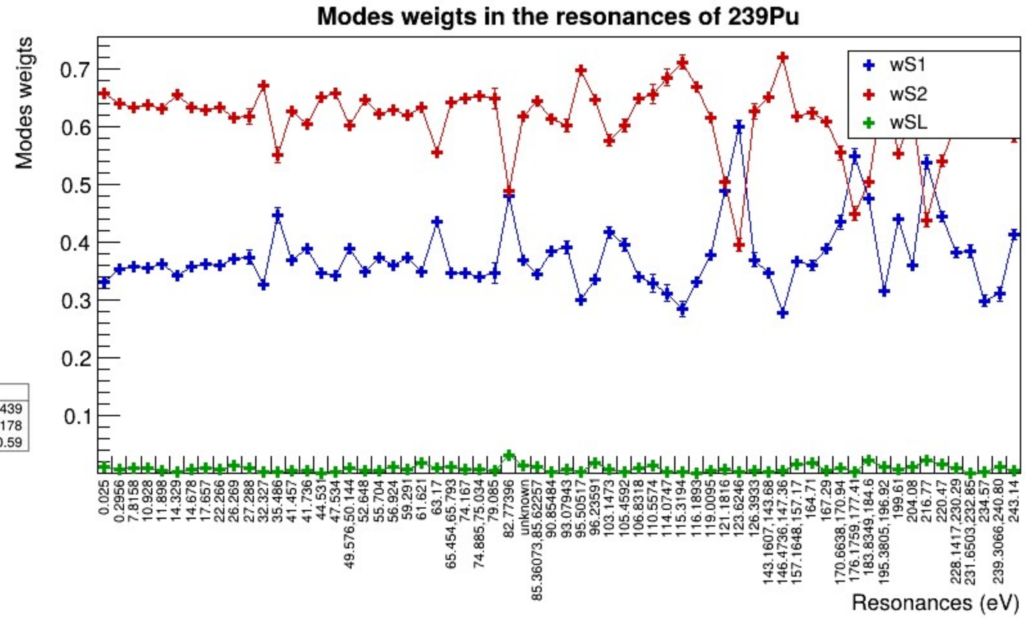
The measurements
Correlations Analysis

Interpretation of FF properties measurements in the RRR of ^{239}Pu(n,f) with the MMRNR model considering S1, S2 and SL.





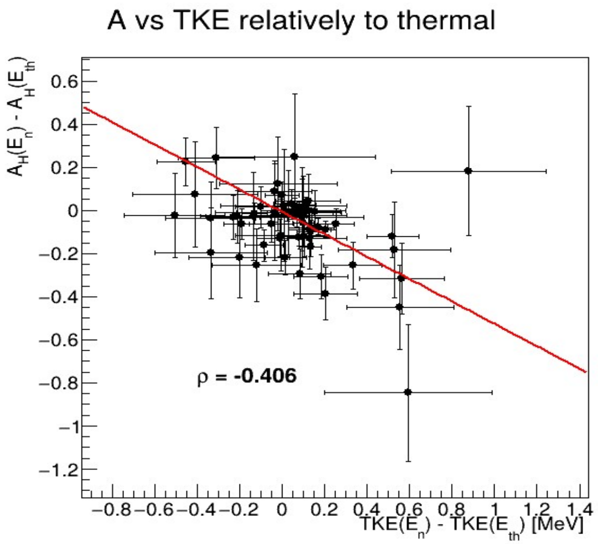


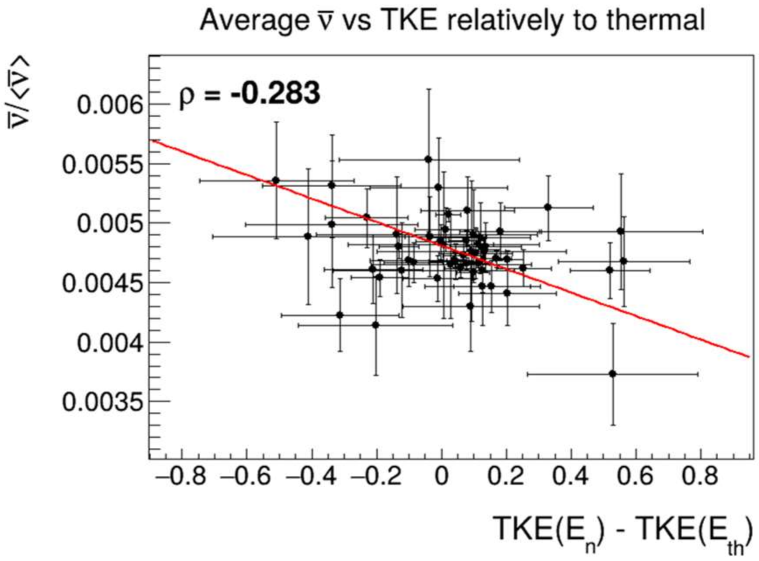


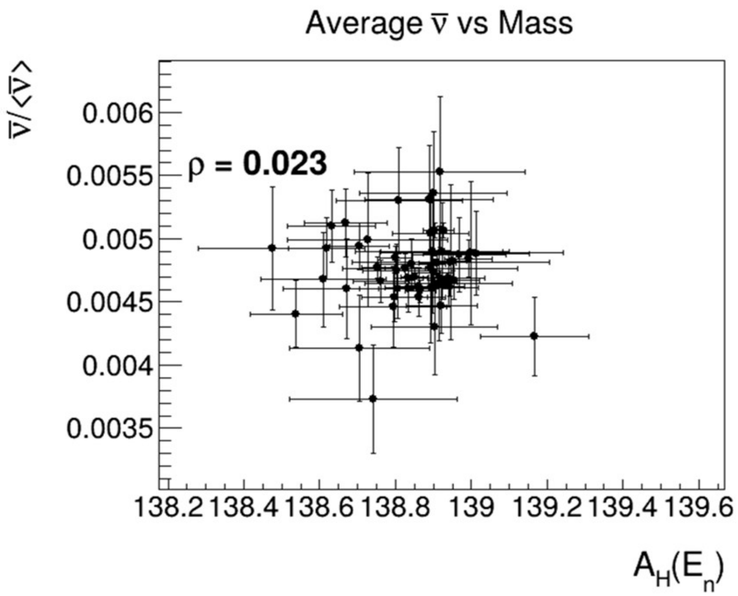
Measurements
Correlations Analysis

^{239}Pu

Results for ^{239}Pu with the data taken by Alf Göök during the first experiment :
Focus on resonances without (n,γf) (J = 0⁺)







A_H and TKE are correlated (as expected)

The correlation coefficient for ν_P- A_H and ν_P-TKE is inferior for ^{239}Pu than ^{235}U

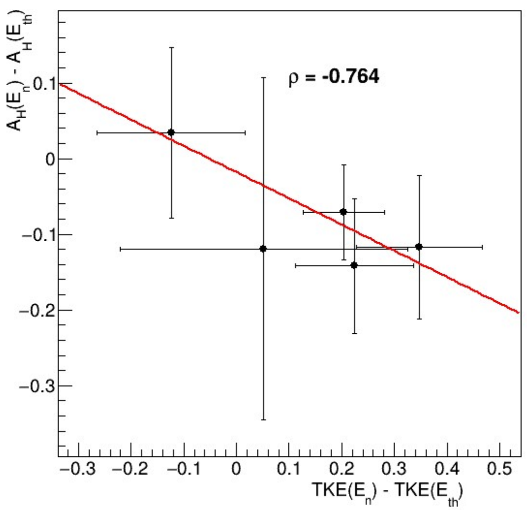
The main correlation is with TKE but like S2 is the dominant fission mode, it has a limited effect on ν_P fluctuations.
FF characteristics can explain at least a part of ν_P fluctuations in J = 0⁺ resonances.

Measurements
Correlations Analysis

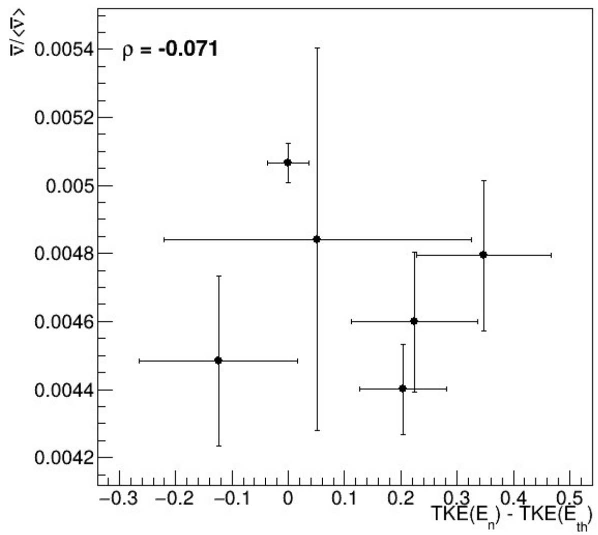
^{239}Pu

Results for ^{239}Pu with the data taken by Alf Göök during the first experiment :
Focus on probable (n,γf) resonances (J = 1$^+$)

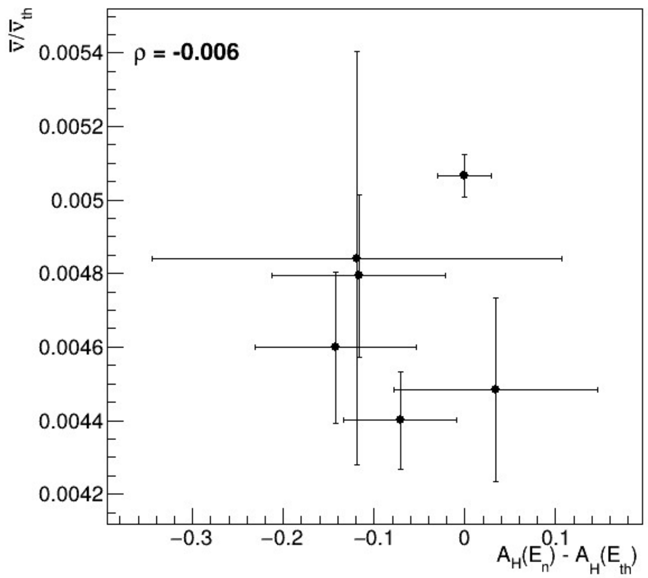
A vs TKE relatively to thermal



Average $\bar{\nu}$ vs TKE relative to thermal



Average $\bar{\nu}$ vs Mass relatively to thermal



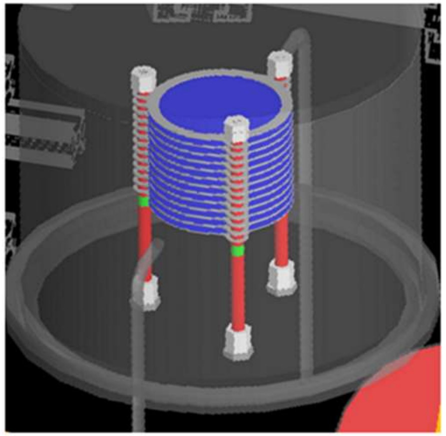
A_H and TKE are correlated

The correlation coefficient is close to 0 → ν_P is not correlated to A_H or TKE
ν_P fluctuations in J = 1$^+$ resonances can not be explained with changing FF characteristics

Measurements
Correlations Analysis : Summary

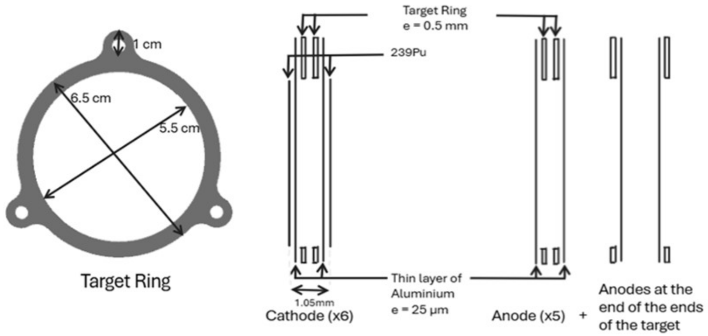
Isotope	ν_P/TKE	ν_P/A
^{235}U	-0.87	0.79
^{239}Pu ($J = 0^+$)	-0.283	0.023
^{239}Pu ($J = 1^+$)	-0.071	-0.006

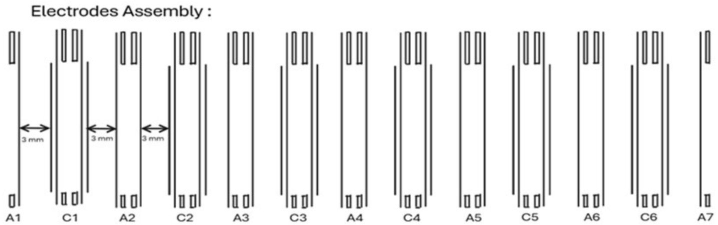
Measurements
Second experiment : parallel plates fission chamber



Ionization chamber with multi-layer targets: 12 layers of ^{239}Pu, 127.7 µg/cm² each

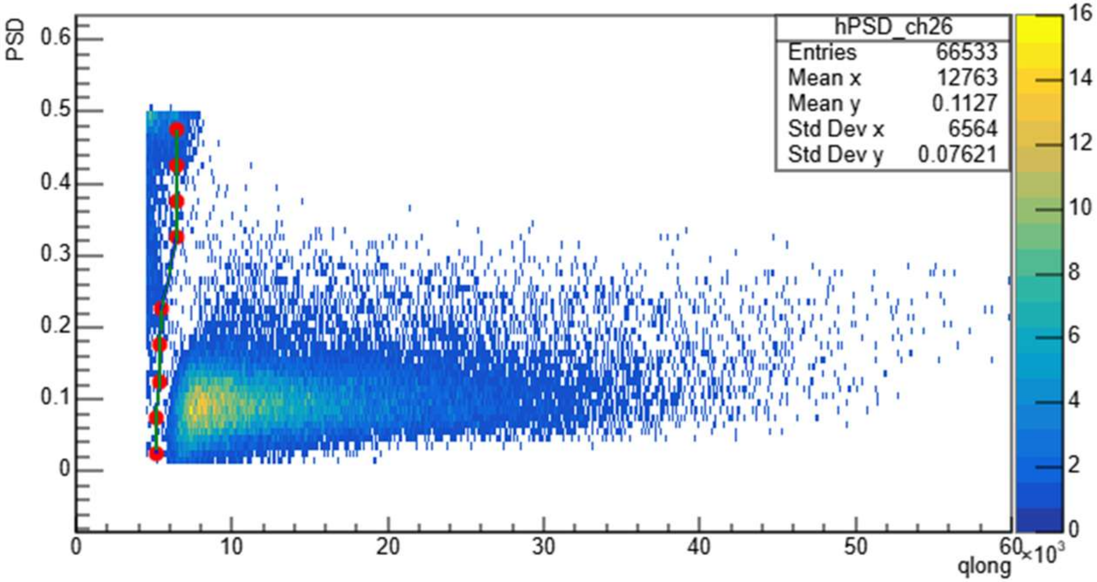
- Parallel plates fission chamber with 12 layers of ^{239}Pu
- Setup updated after years stopped
- Measurement campaign from october 2025 and until at least the end of the year (excluding summer break, holidays, problems of the accelerator).
- ~ 12 fissions/s (with GELINA at 400 Hz)

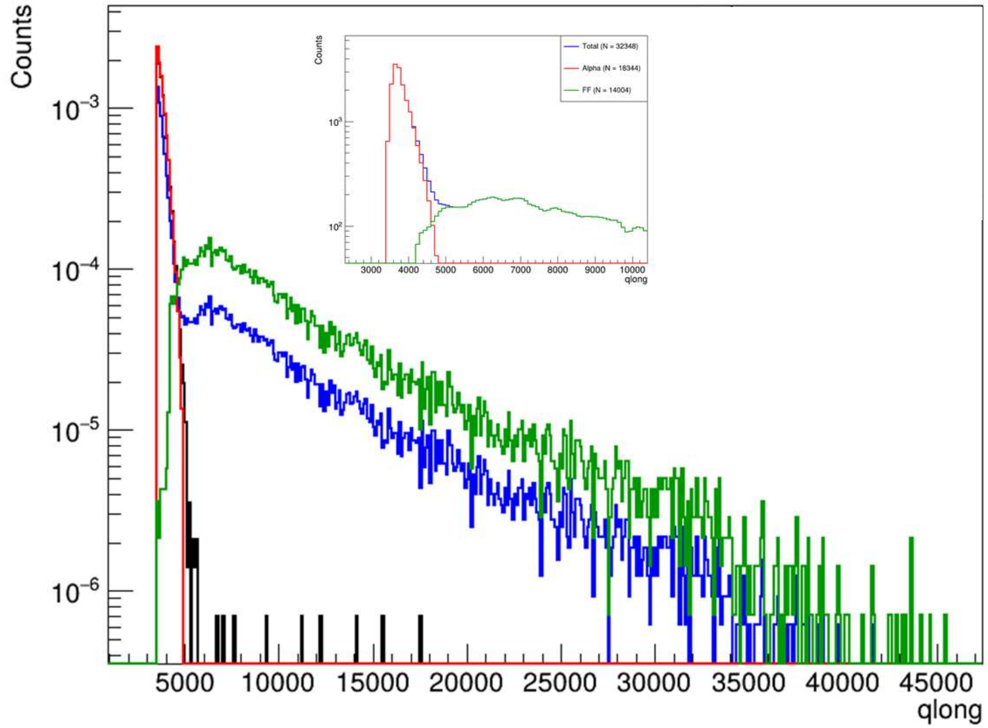




→ Focus on the measurement of the prompt neutron multiplicity as a function of incident neutron energy only (no more correlation between ν_P and FF characteristics);

Measurements
Ongoing work : α / FF discrimination

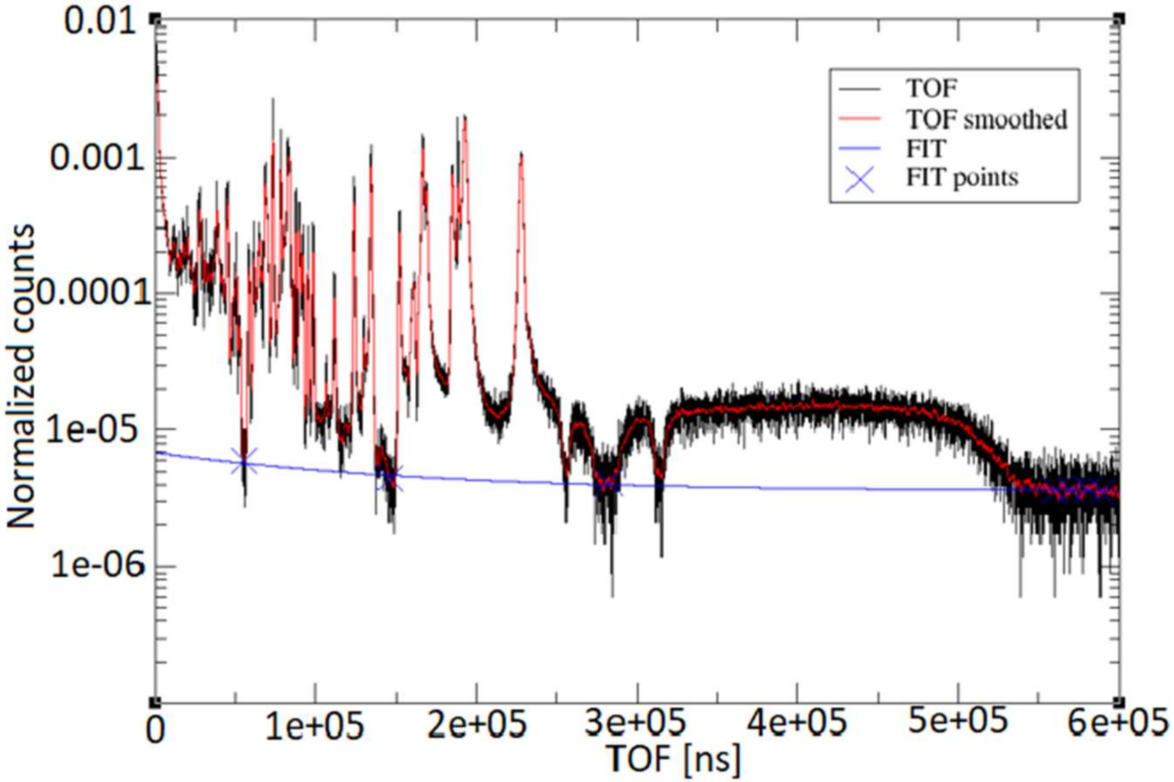




$$PSD = \frac{q_{long} - q_{short}}{q_{long}}$$

→ PSD permits almost 100% of discrimination between α and FF

Measurements
Ongoing work : thermal background estimation



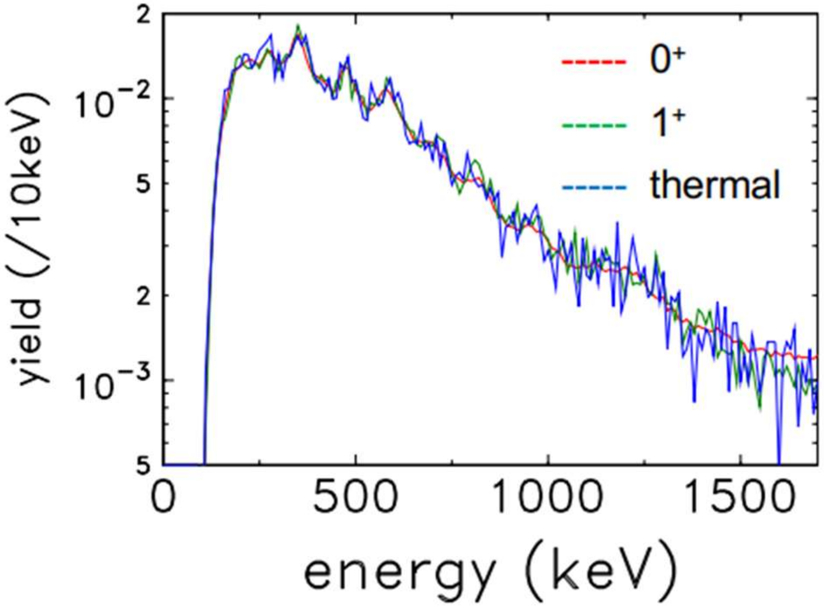
Cd	Rh	Ag	W	Co
Overlap	1.3 eV	5.19 eV	18 eV	132 eV

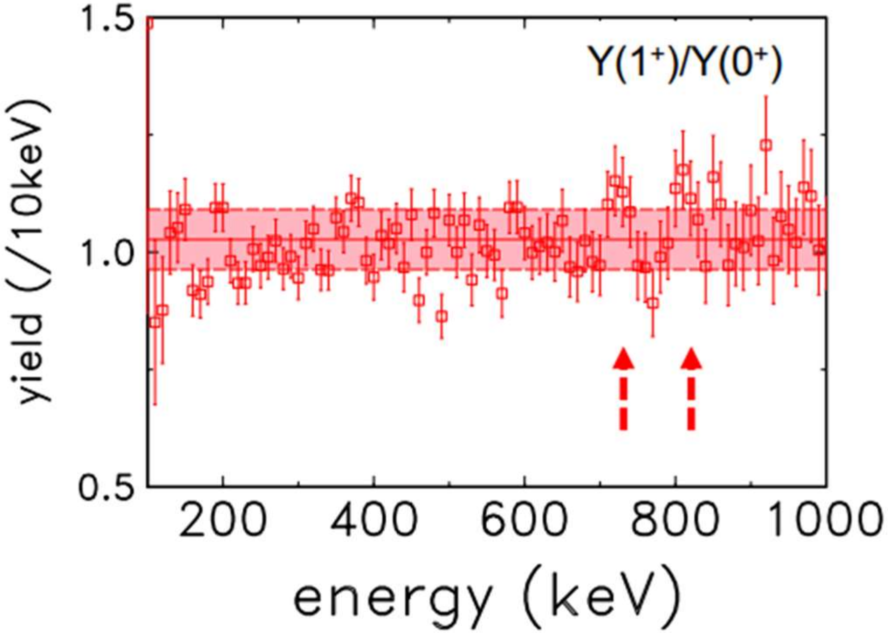
Exponential fit :

$$f(t) = p_0 + p_1 e^{-p_2 t + p_3}$$

p_0	$3{,}58.\,10^{-6} \pm 5{,}18.\,10^{-8}$
p_1	$3{,}27.\,10^{-6} \pm 4{,}43.10^{-7}$
p_2	$-7{,}56.\,10^{-6} \pm 1{,}22.\,10^{-6}$
p_3	0 (fixed)

Measurements
Ongoing work : PFGS and (n, γf) process





- Spectra from 4 $LaBr_3$ summed and normalized.
- Looking for a signature of (n, γf) process in the PFGS according to the spin of the resonance.

→ Drop of ν_P expected when the ratio $1^+/0^+$ increases.

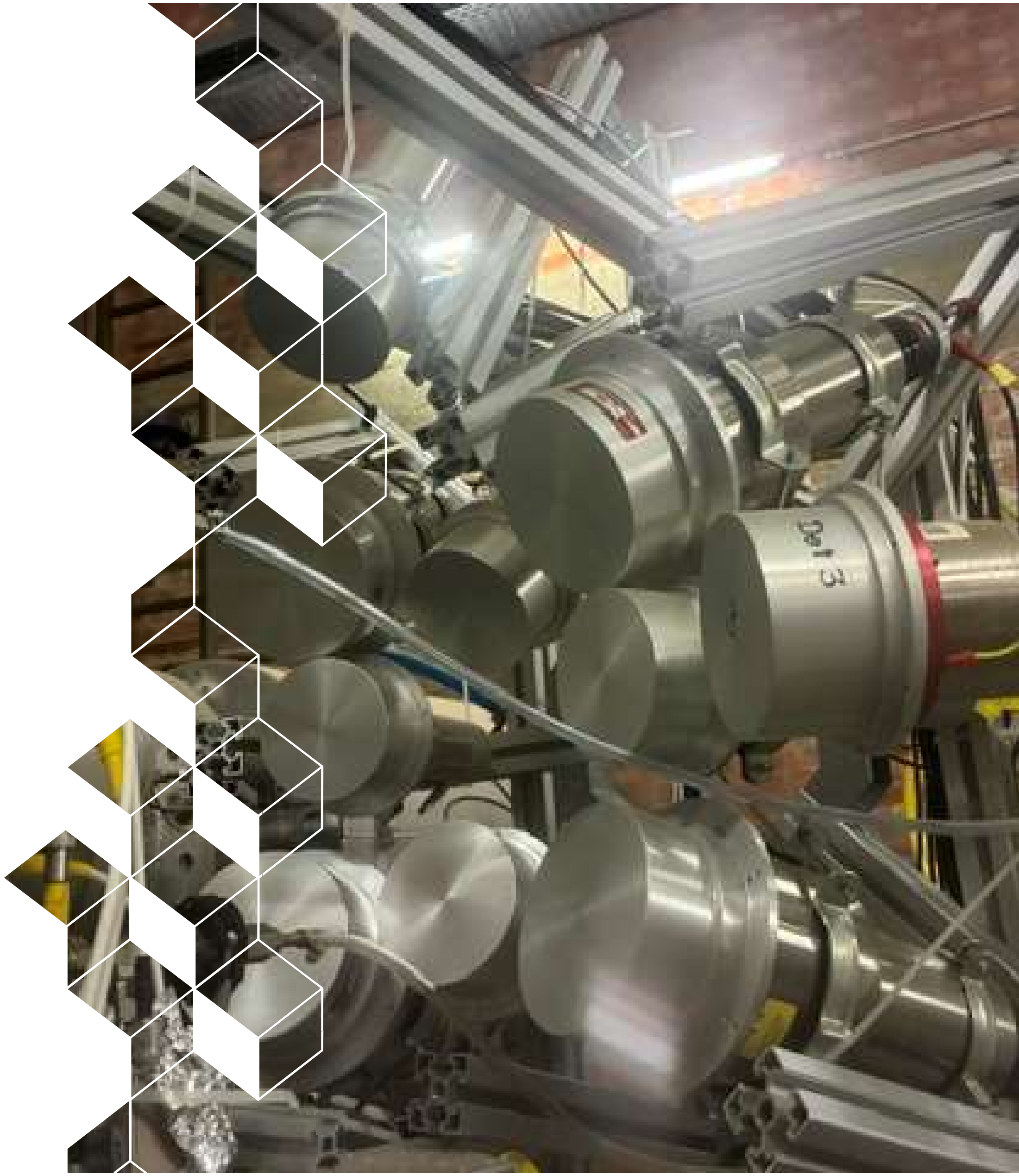
Outlook

Experimental analysis :

- Focus on neutron detectors but need of more statistic to have a reliable analysis routine applied to each detector and merge the results
- Use of simulations and ToF for calibration

FIFRELIN :

- Interpretation of experimental results
- Implementation of (n, γf) process and study of the impact on fission observables
- Fission modes charactiristics for each resonance available → FIFRELIN calculations already possible



Thank you !

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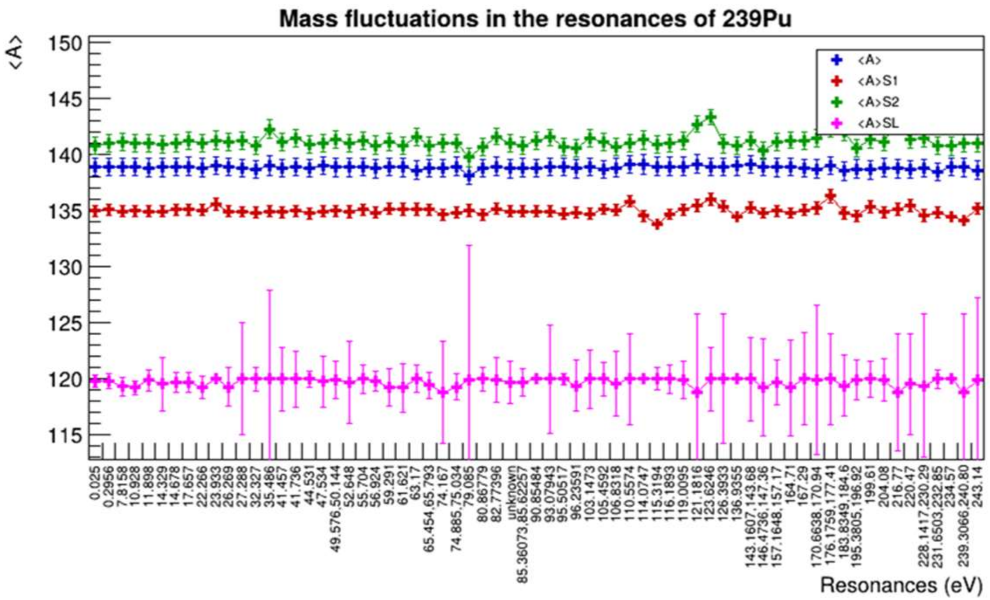
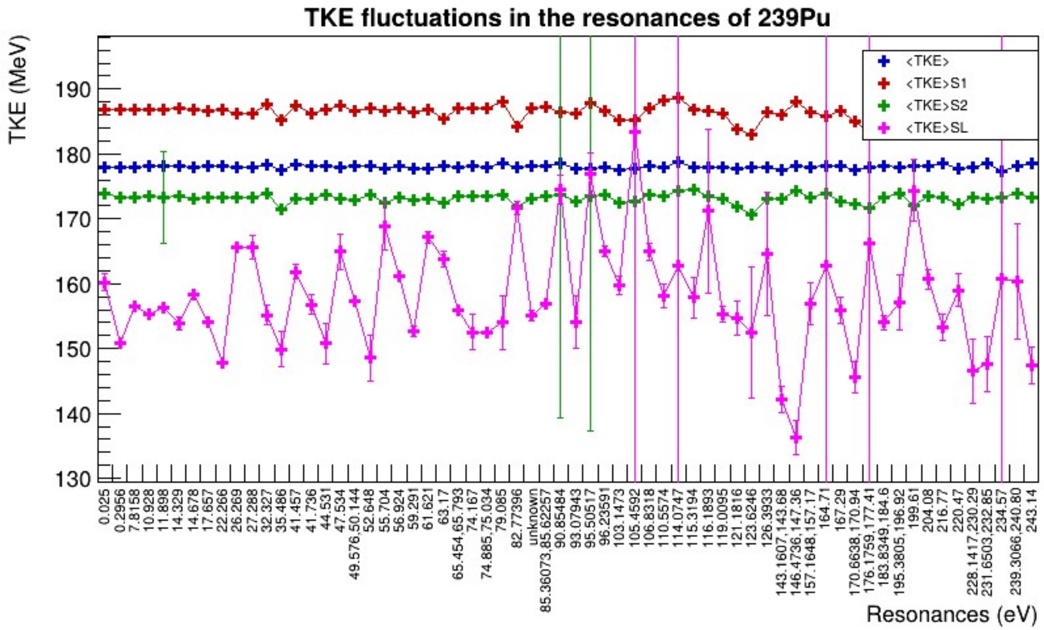
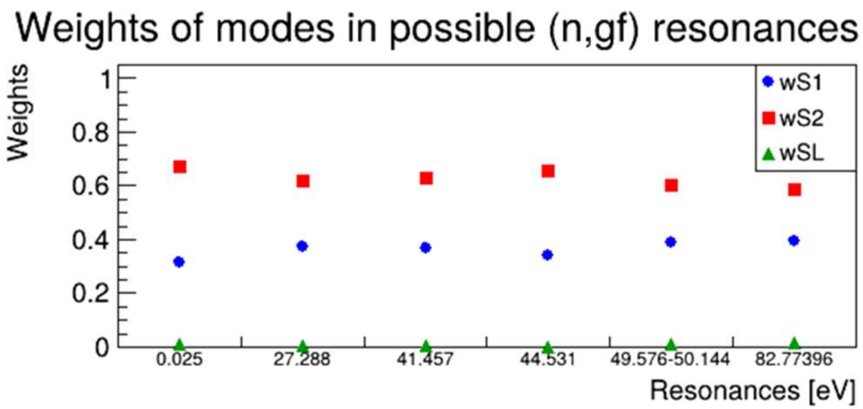
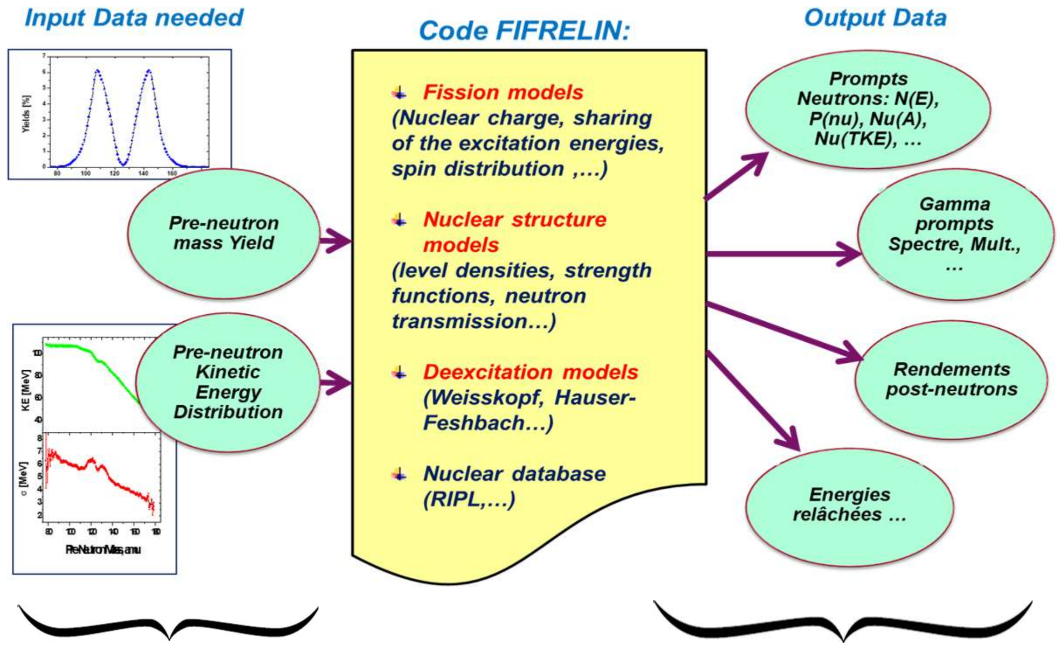

Mass fluctuations in the resonances of 239Pu
<A>
<A>S1
<A>S2
<A>SL
Resonances (eV)

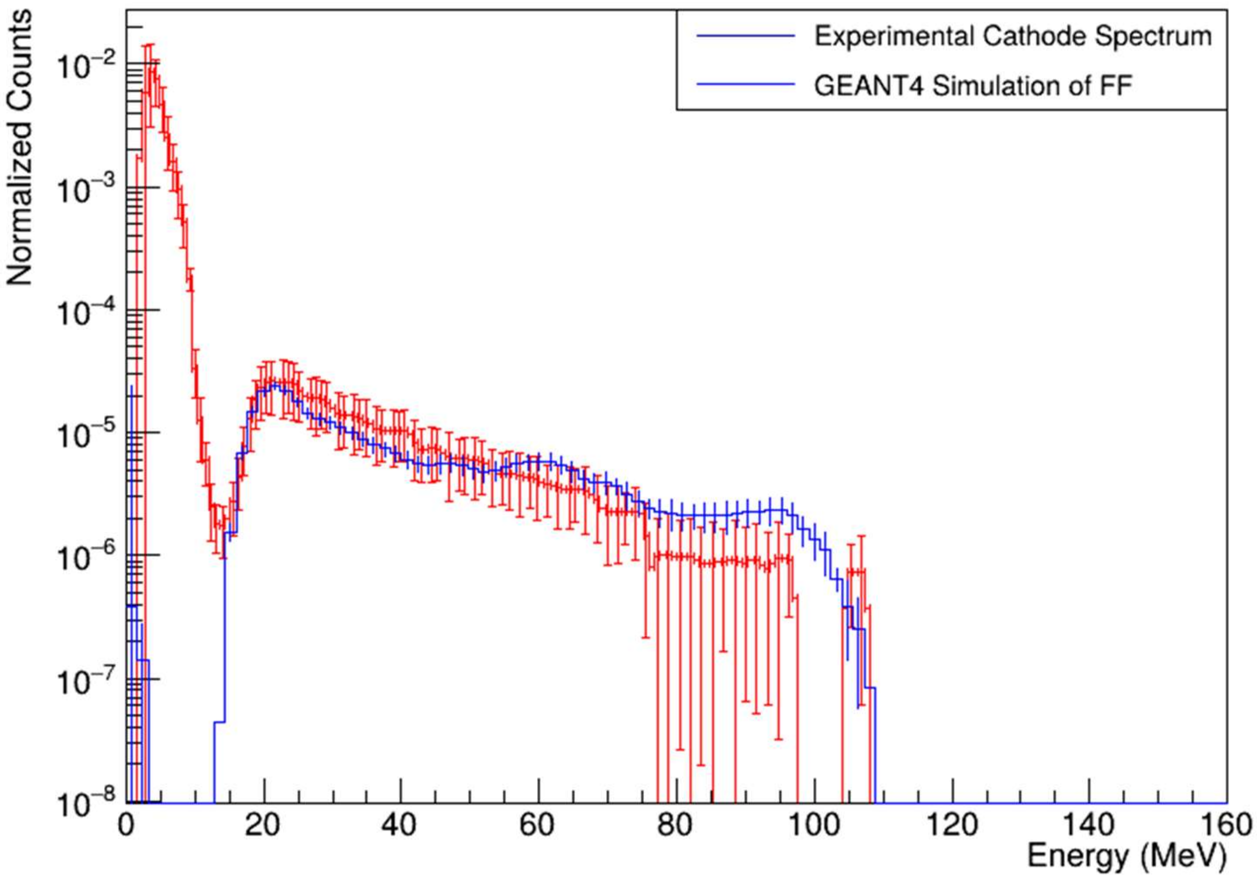

TKE fluctuations in the resonances of 239Pu
TKE (MeV)
<TKE>
<TKE>S1
<TKE>S2
<TKE>SL
Resonances (eV)


Weights of modes in possible (n,gf) resonances
Weights
wS1
wS2
wSL
0.025
27.288
41.457
44.531
49.576-50.144
82.77396
Resonances [eV]



Experimental data provided by SCINTIA (JRC-Geel)

Fission observables calculated by FIFRELIN (CEA-Cadarache)



Normalized Counts
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
20
40
60
80
100
120
140
160
Energy (MeV)
Experimental Cathode Spectrum
GEANT4 Simulation of FF