



Study of fission products characteristic with the LOHENGRIN spectrometer

20/07/2023, CGS17, Grenoble

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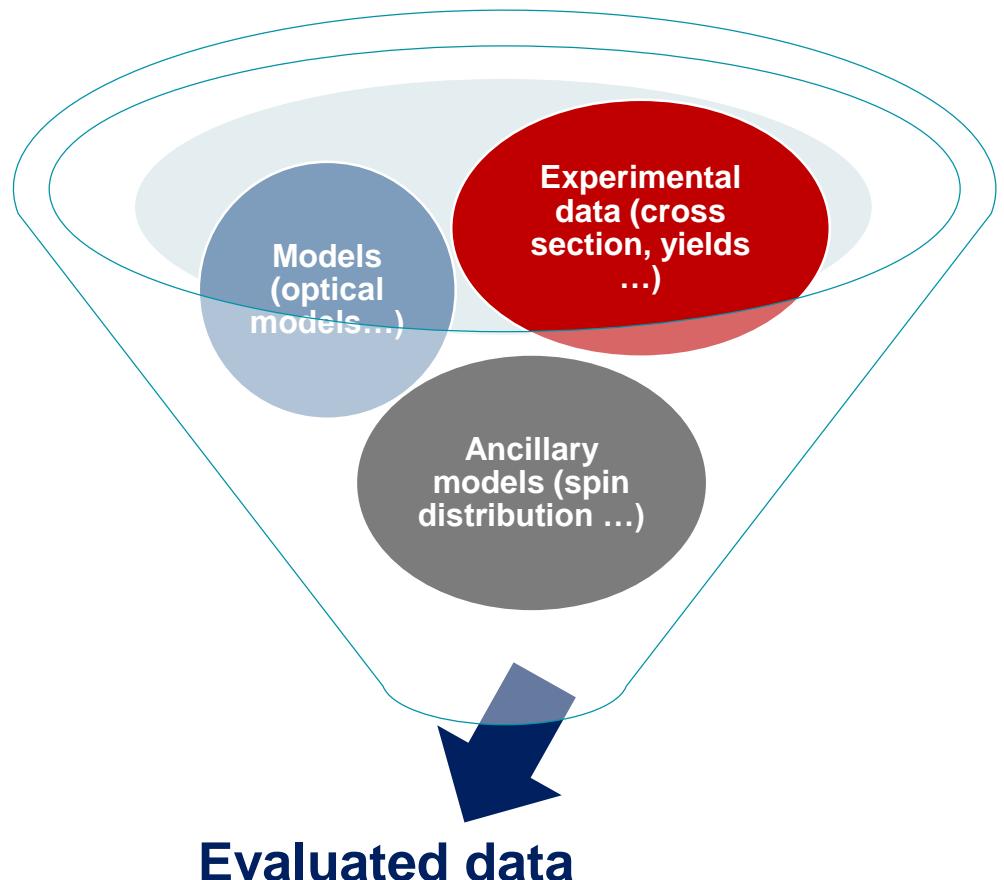
National Technical University of Athens, Athens, Greece



Evaluated nuclear data



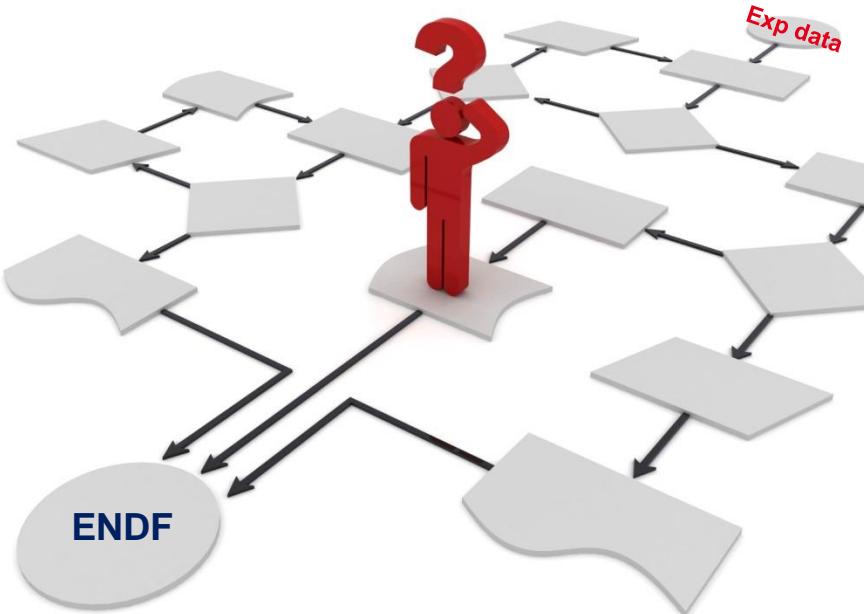
- **Evaluated Nuclear Data Files (ENDF)** : input parameters for nuclear reactor simulations !
- **How is build an evaluated file (ENDF) ?**
 → models
 → experimental data ($Y(A)$, $Y(A,Z)$, $Y(TKE|A)$...)
- **Why do we use models?**
 → get data which cannot be measured
 → reduce uncertainties



Evaluated nuclear data

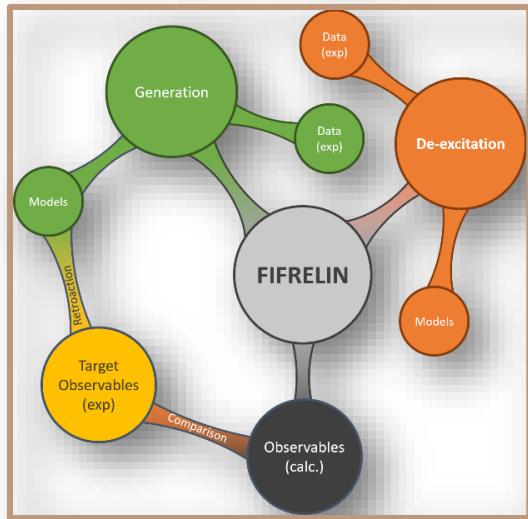
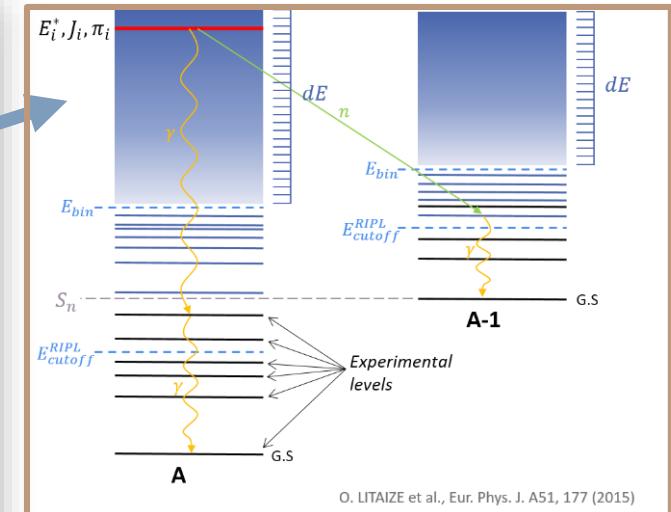
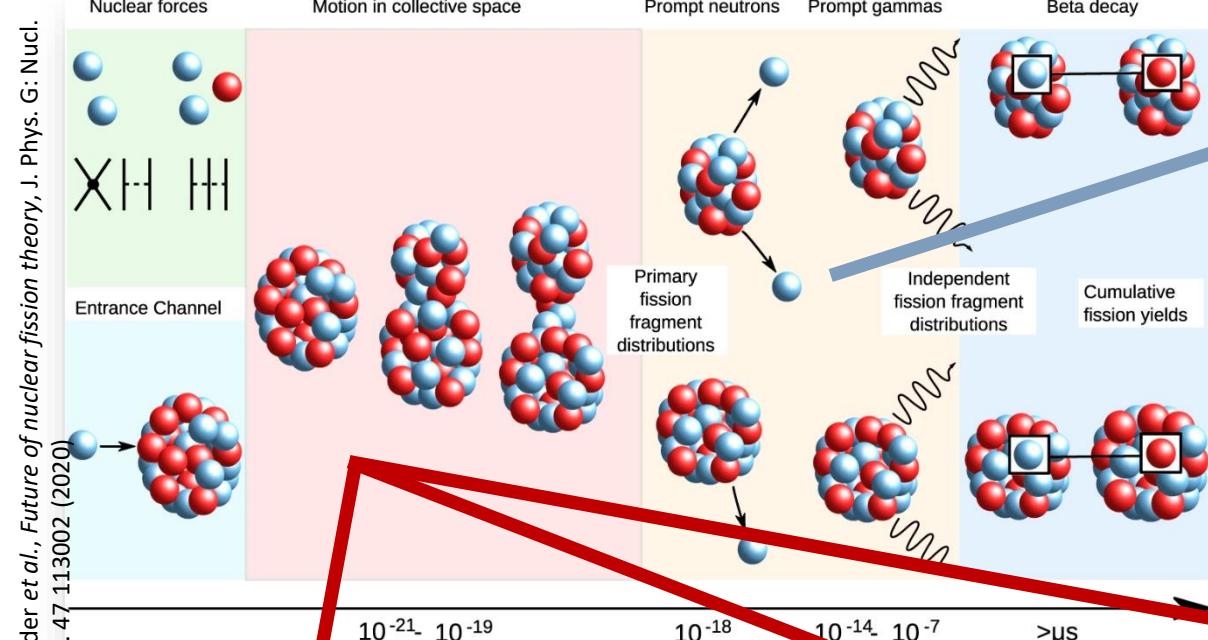


- **Evaluated Nuclear Data Files (ENDF)** : input parameters for nuclear reactor simulations !
- **How is build an evaluated file (ENDF) ?**
 - models
 - experimental data ($Y(A)$, $Y(A,Z)$, $Y(TKE|A)$...)
- **Why do we use models?**
 - get data which cannot be measured
 - reduce uncertainties
- **How to improve the evaluation process?**
 - more “physical” models: improve knowledge of the fission process
 - new methods
 - Better control of systematic uncertainties
 - More accurate data
 - Evaluation process
 - complementary measurements
 - Substitution reaction
 - Isomeric ratio

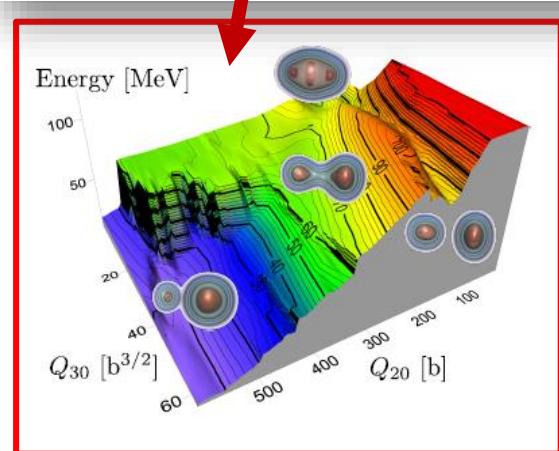




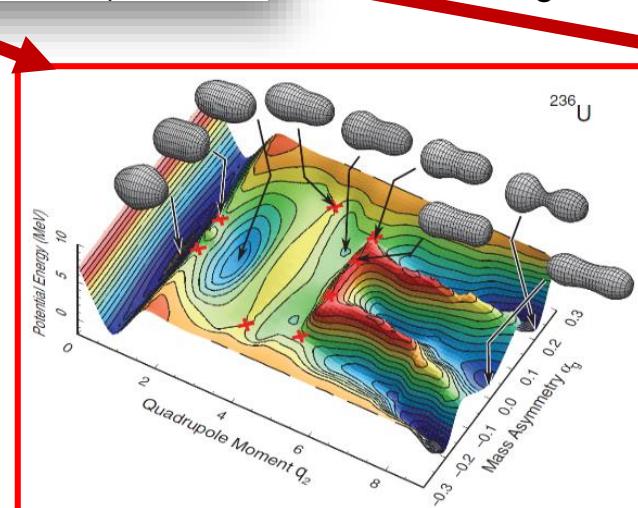
The nuclear fission process



FIFRELIN : generation and de-excitation of fission fragment. Developed by DES/IRESNE

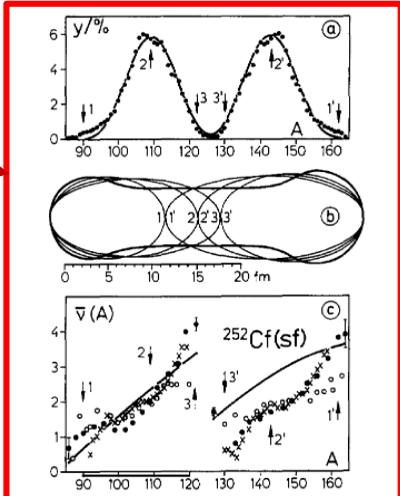


© N. Schunck and D. Regnier, Theory of Nuclear Fission, Prog. Part. Nucl. Phys., 125, 103963 (2022)



A. Chebboubi et al, CGS17, Grenoble

© Ichikawa et al., Contrasting fission potential energy structure of actinides and mercury isotopes, Phys. Rev. C 40, 770 (1989)



© U. Brosa et al., Nuclear scission, Phys. Reports 197 (4), 167 (1990)
20/07/2023

Definition of fission yields

Fission yields = **production rate** of fission fragment for a given mass A, nuclear charge Z, excitation energy E^* , kinetic energy E_k , angular momentum J , parity π , and isomeric state m

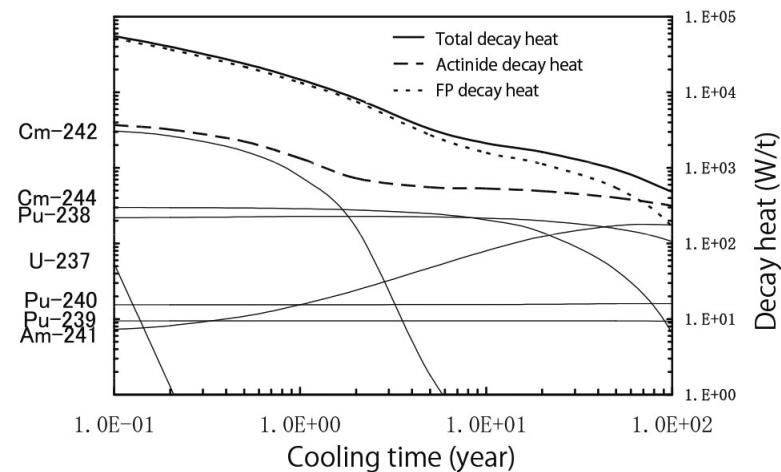
$$Y(A, Z, E_k, E^*, J^\pi) = Y(A) \times P(Z|A) \times P(E_k|A, Z) \times IR(m|A, Z, E^*, E_k)$$

Independent fission yields $Y(A, Z) = Y(A) \times P(Z)|_A$ are used in nuclear reactor studies

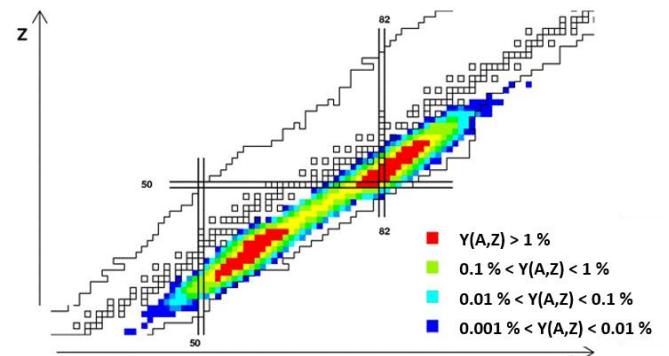
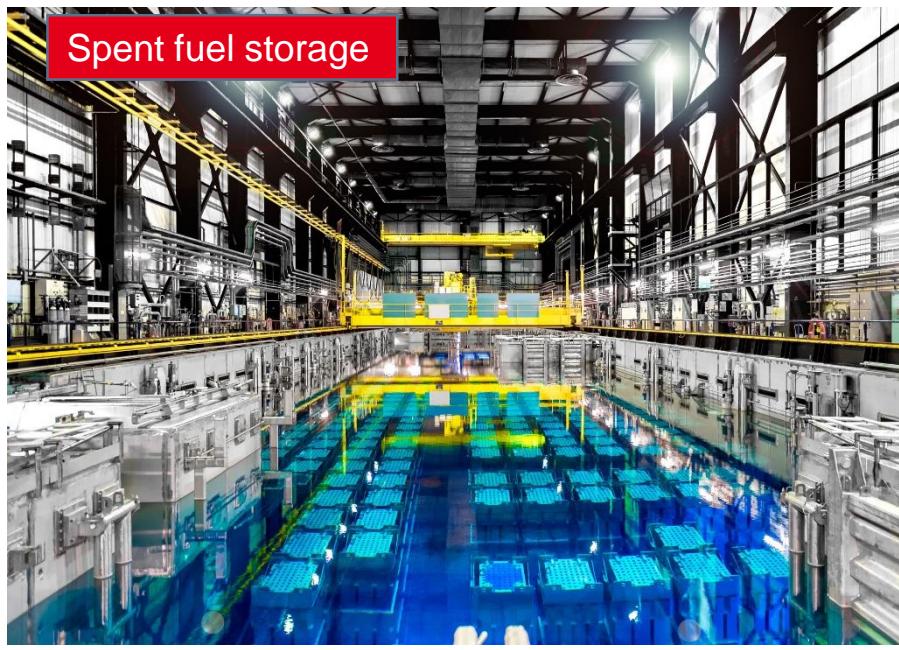
Isotopic composition

- Residual power
- Radiotoxicity of spent fuel

Decay Heat



T. Yoshida, Atomic Energy Society of Japan,
10.15669/fukushimainsights.Vol.1.88, 2021

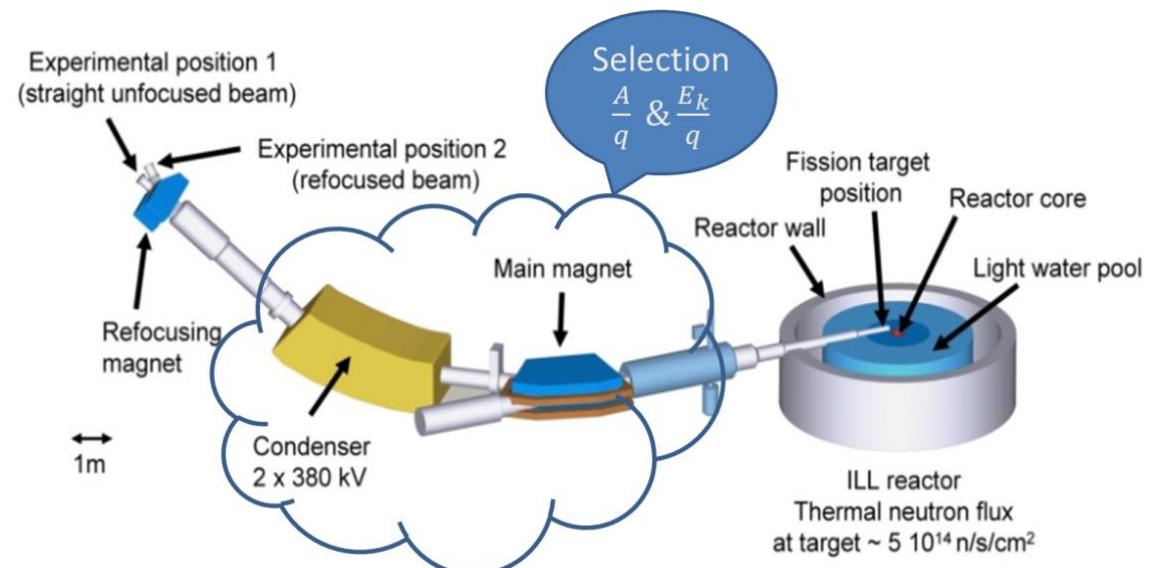
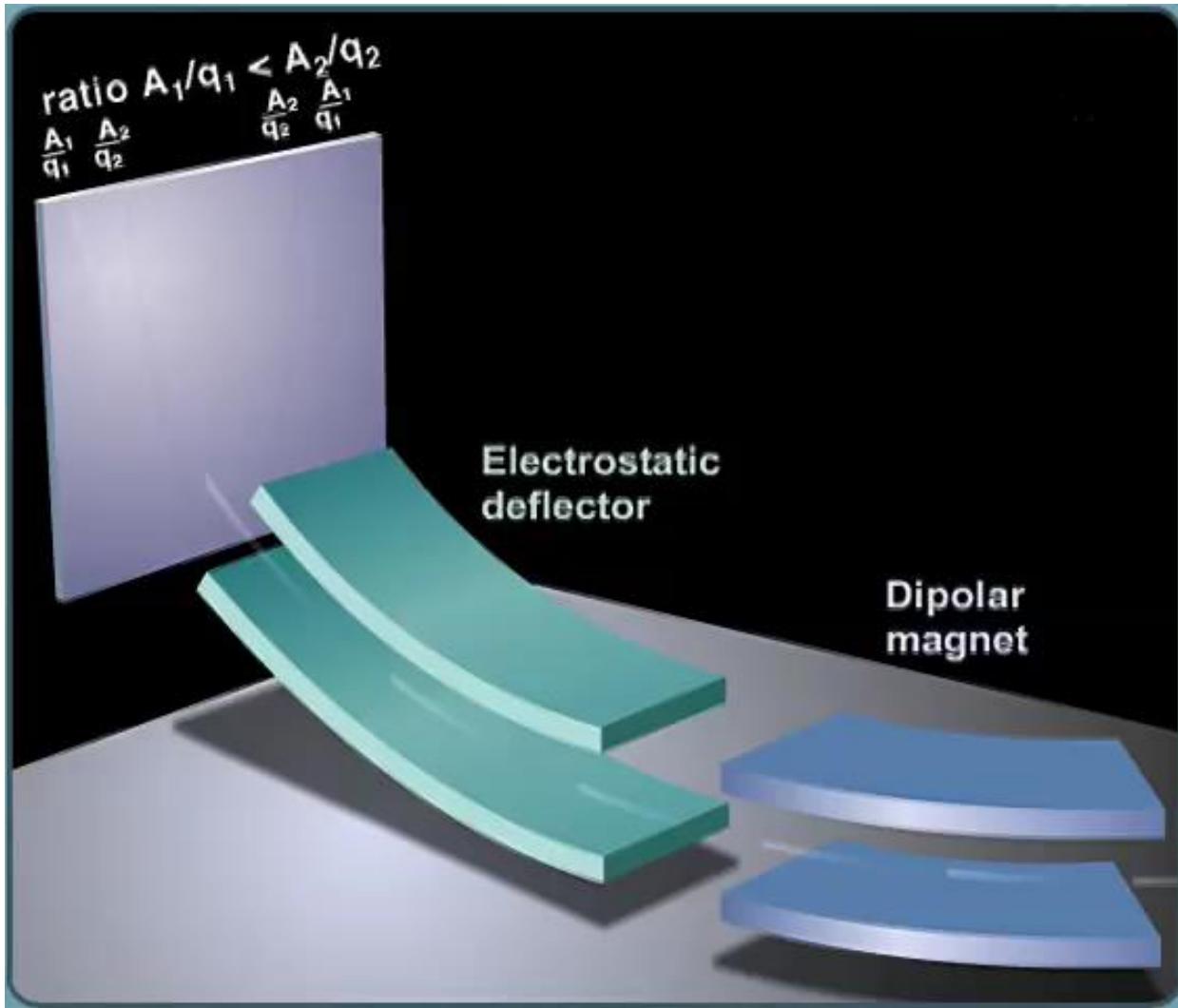




1 Measurements of independent fission product yields



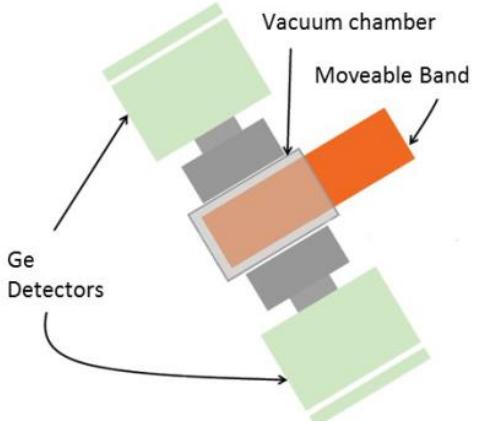
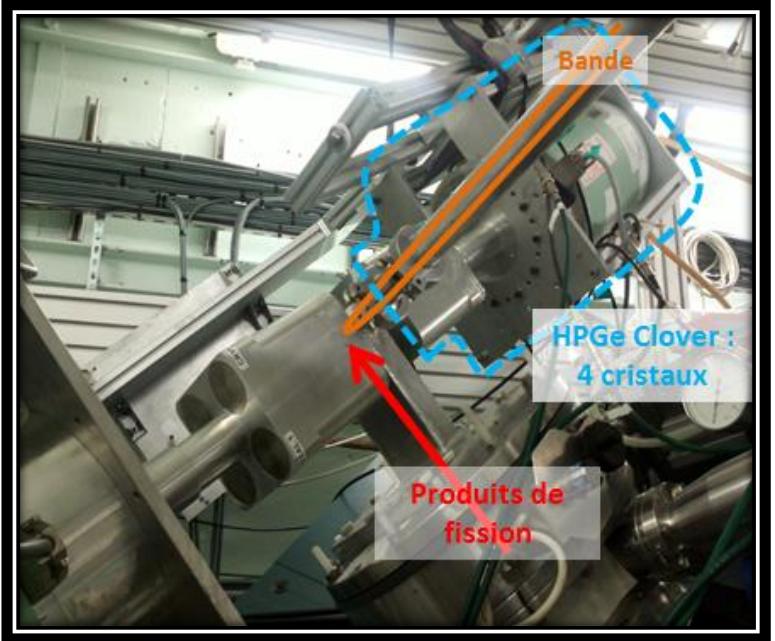
LOHENGRIN working principle



Lohengrin : selection with the mass over ionic charge $\frac{A}{q}$ and Kinetic energy over Ionic charge $\frac{E_k}{q}$ ratios

$$(A_1, E_1, q_1) \equiv (A_2, E_2, q_2) \equiv (A_3, E_3, q_3)$$

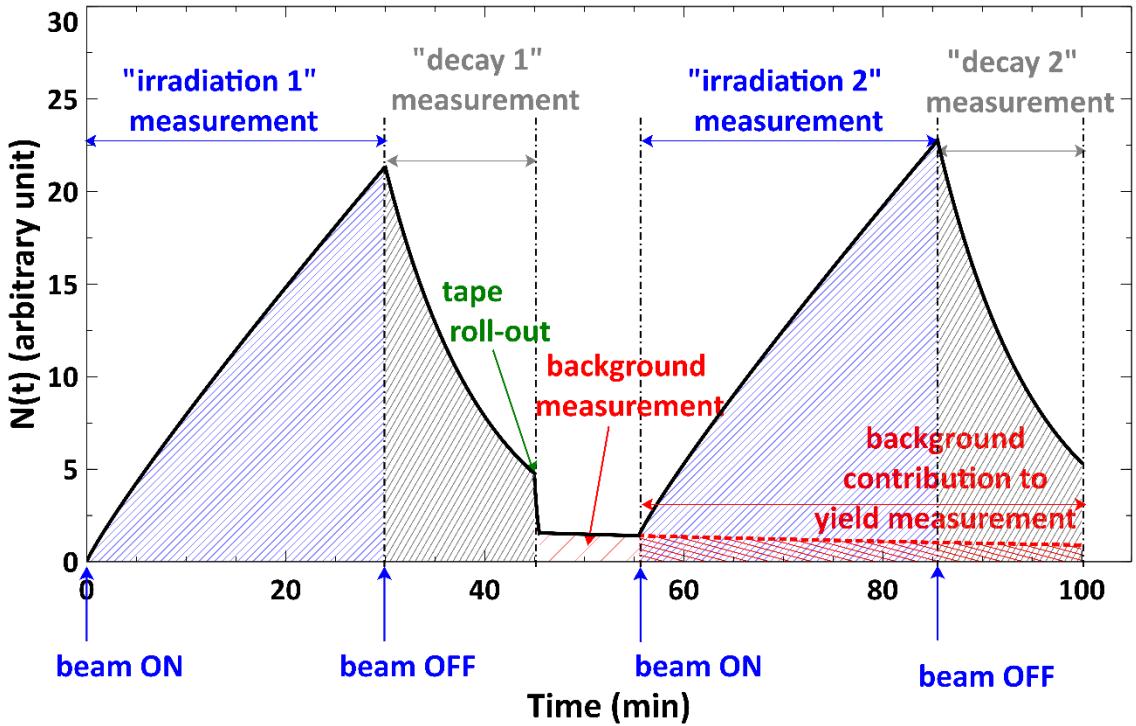
Experimental setup



High Purity Germanium (HPGe)

Assess fission fragment nuclear charge through γ measurements

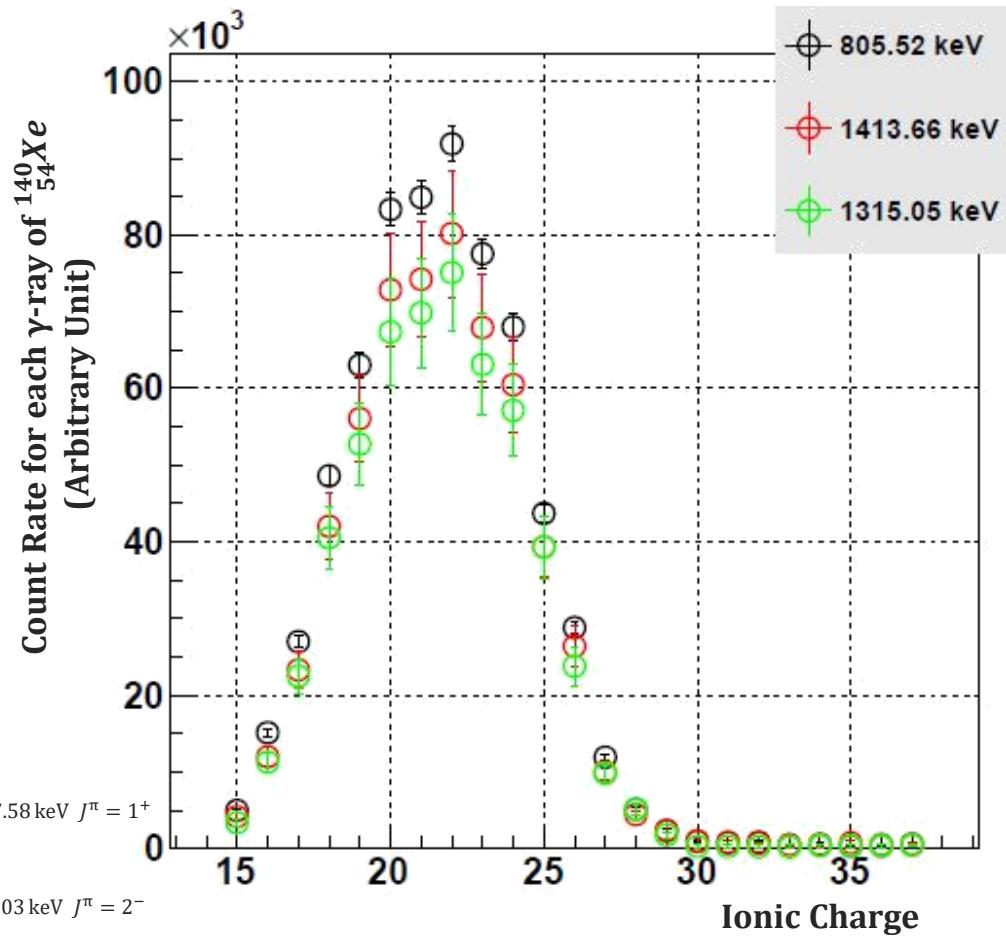
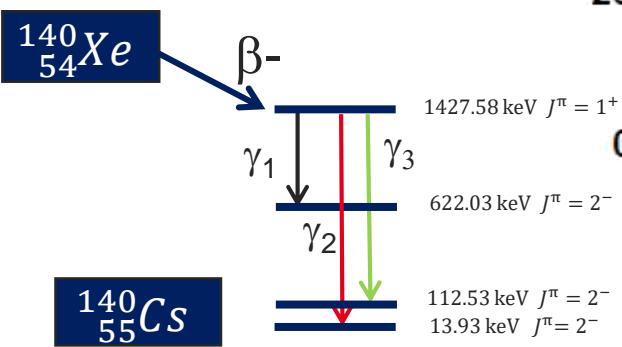
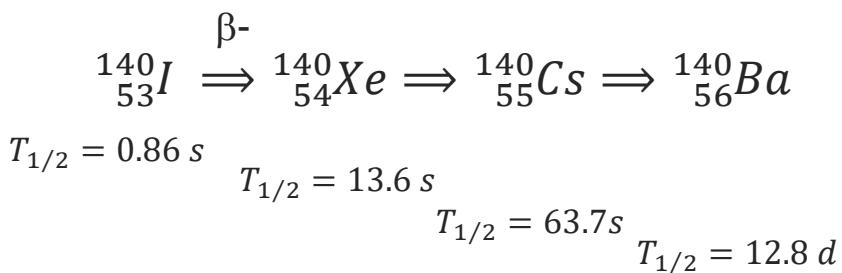
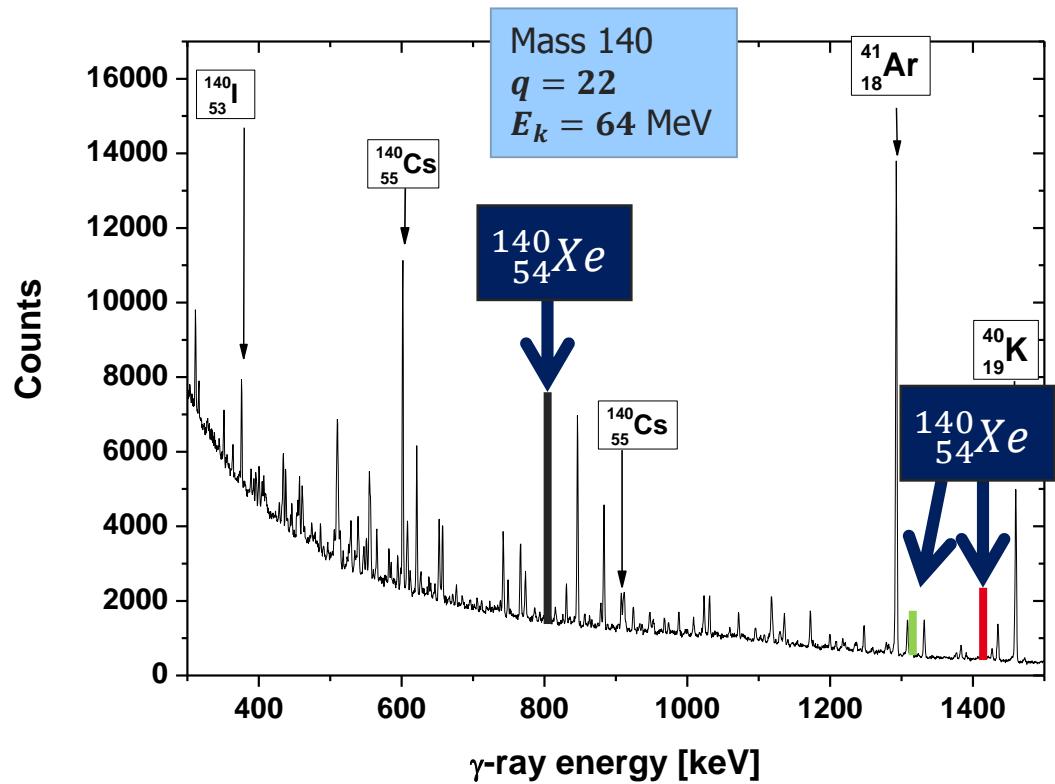
- Current solution to study isotopic yields in the heavy mass region
- Results are dependent of the knowledge of fission fragment nuclear structure scheme



- Implantation of isotopes on the tape and the vacuum chamber
- Tape roll out : only the chamber frame “contains” isotopes
- Measurement of the “frame decay”



Gamma spectra: example for mass 140

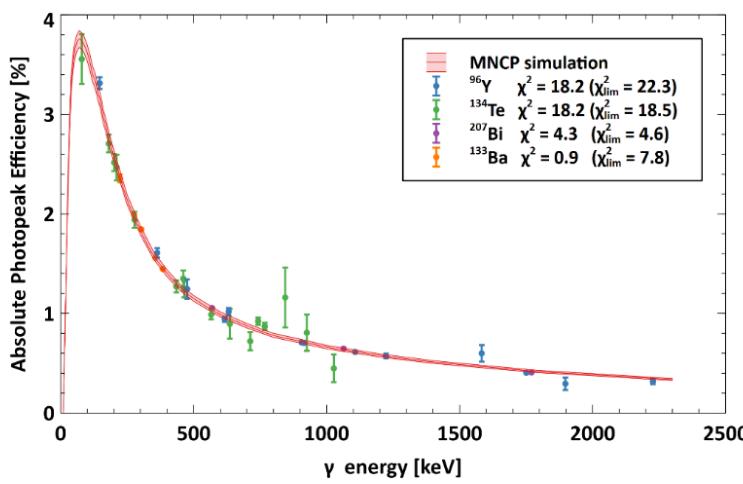


Analysis: example $^{241}\text{Pu}(n_{\text{th}}, f)$ reaction

Julien-Lafferrière et al.,
Phys. Rev. C 102, 034602

$$N_d = \frac{N_\gamma(Z, q|E_k)}{\epsilon_\gamma I_\gamma f_\gamma}$$

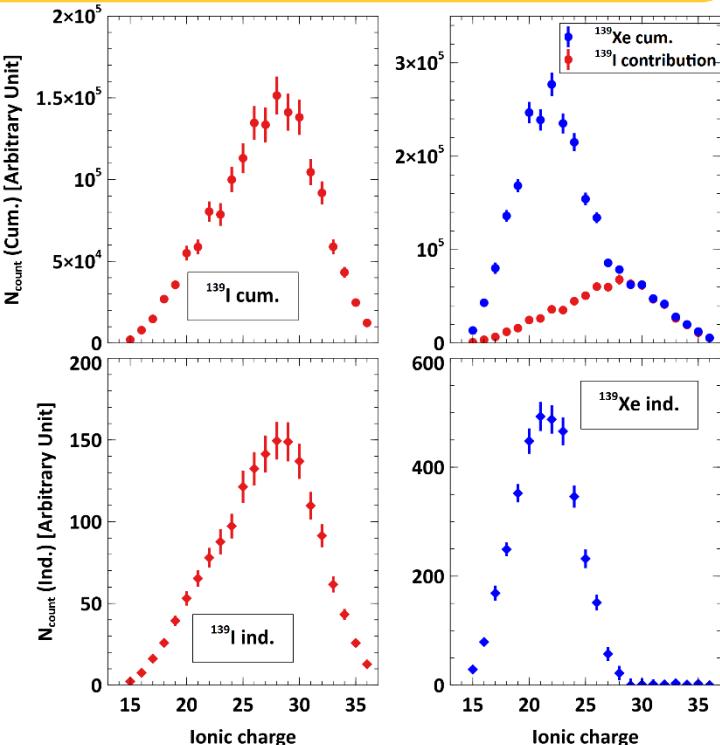
- The count rate N_γ is extracted using the Program Tv
- The efficiency ϵ_γ is extracted from a Monte Carlo simulation and validated against experimental points
- The intensity I_γ is coming from nuclear database
- The sum effect F_γ factor is calculated with the TrueCoinc software



$$\tau(q|E_k) = Q \overline{N_{df}}(q|E_k)$$

- Averaging number of decay :
- The average number of decay N_d coming from fission f is corrected from the background bkg (from the frame):

$$\overline{N_{df}}(Z, q|E_k) = \overline{N_d}(Z, q|E_k) - \overline{N_{dbkg}}(Z, q|E_k)$$
- Solving the Bateman equation Q to extract the production rate τ coming from fission

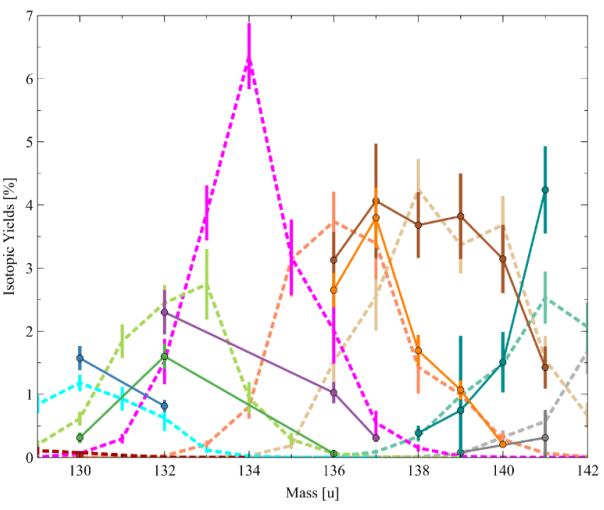
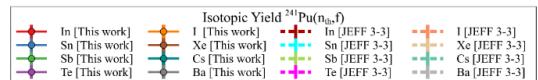


$$Y(A, Z) = N(Z|A) \times k_{139}$$

- Correction of kinetic energy dependency $P(E_k)$
- Correction from target evolution $BU(t)$
- Sum over all ionic charge:

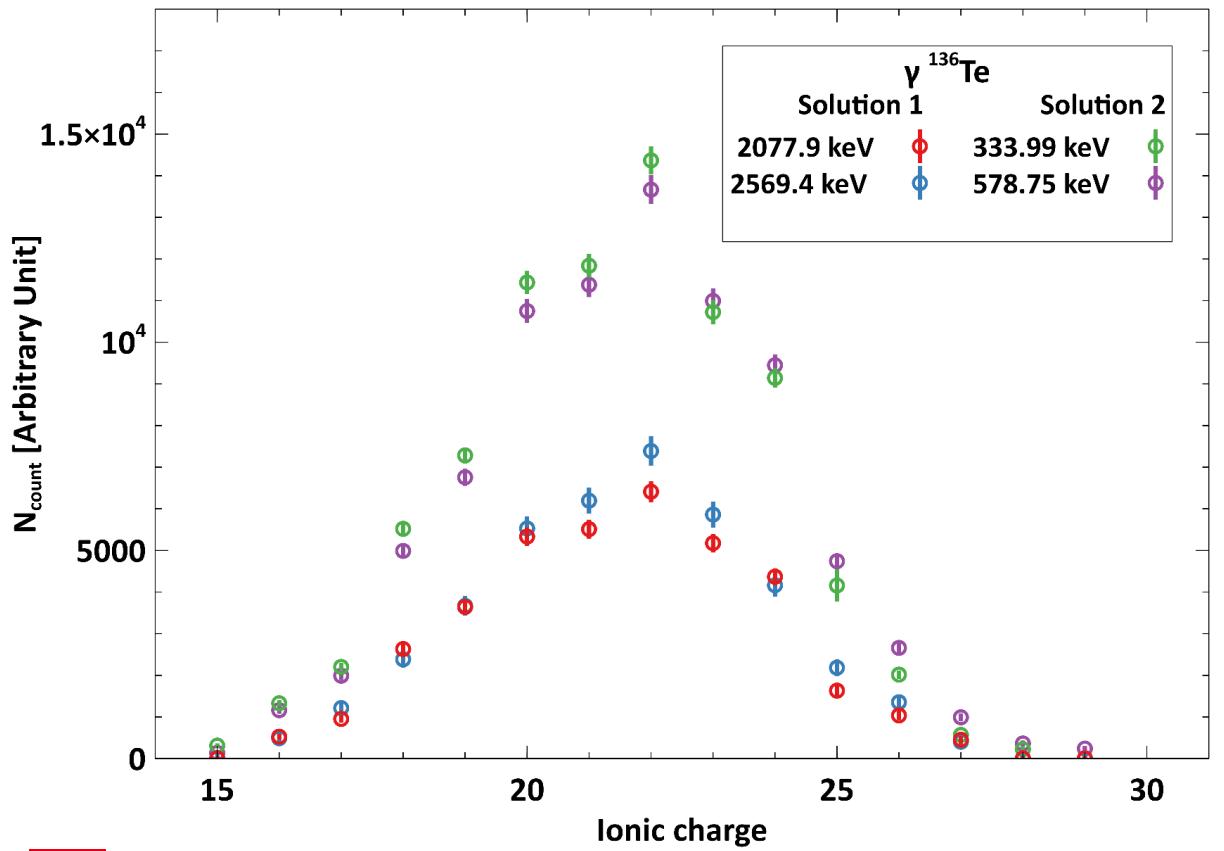
$$N(Z|A) = \sum_q \frac{\tau(Z, q, t|E_k, A)}{BU(t)P(E_k)}$$
- Normalisation with $A = 139$:

$$k_{139} = Y(A = 139) / \sum_Z N(Z|A = 139)$$

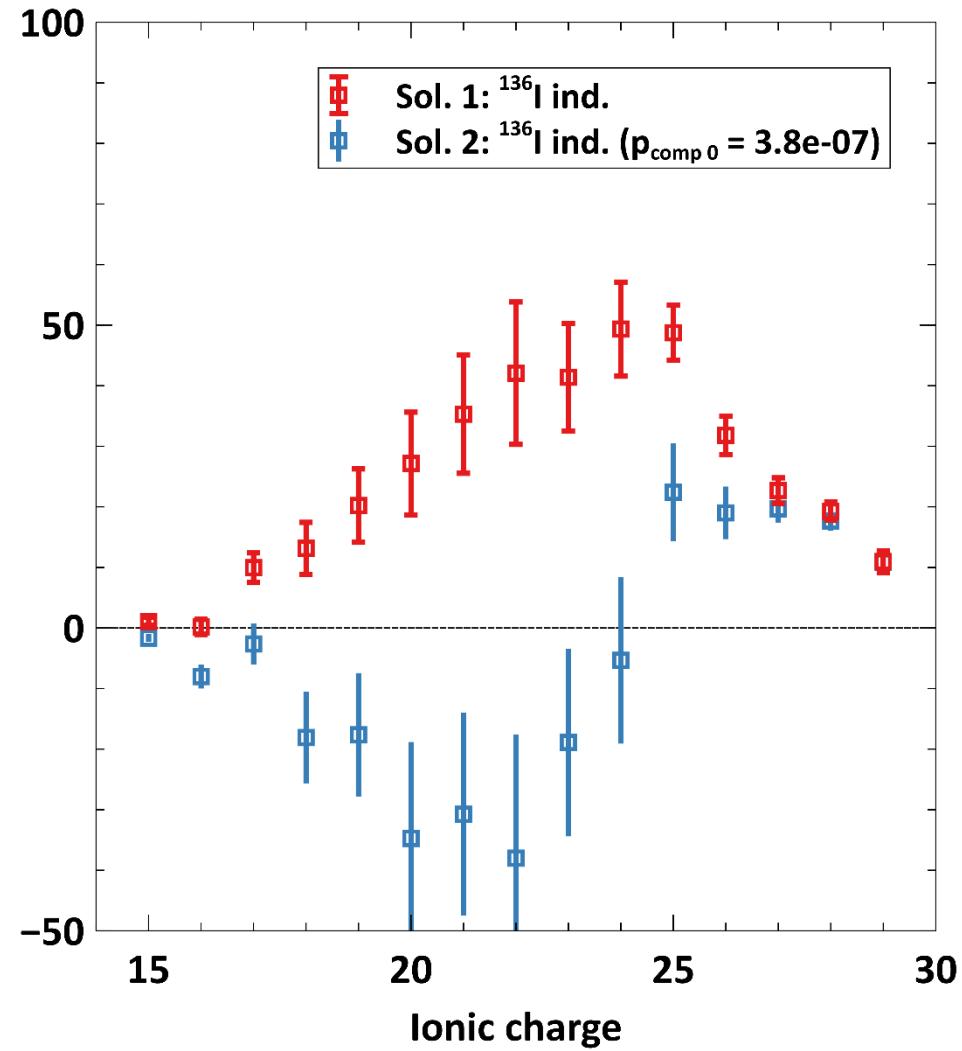




Impact of nuclear structure data on yields

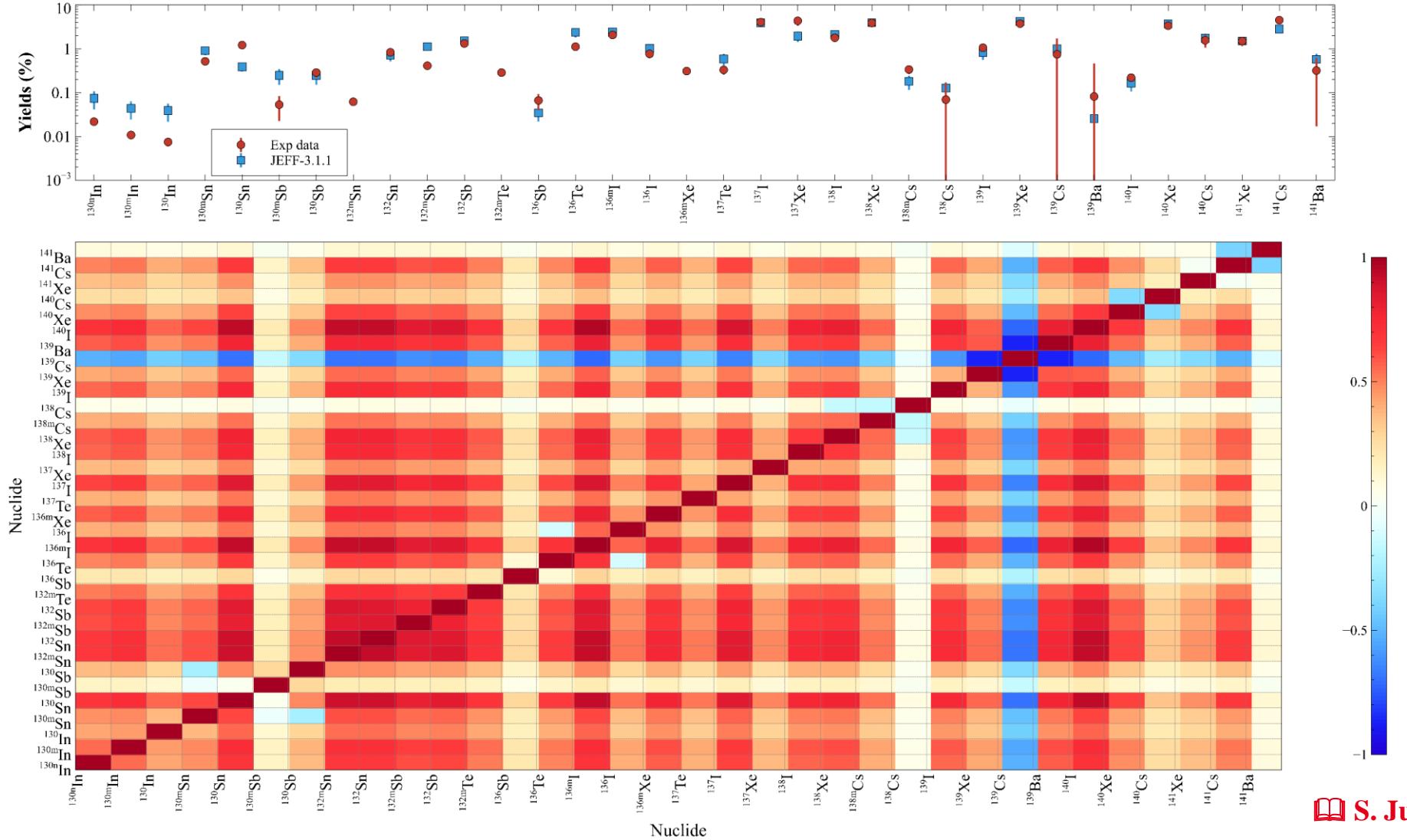


Bateman
resolution





Some highlights



BOOK S. Julien-Lafferrière PhD thesis (2018)

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Other observables of interest to study the fission process : isomeric ratios

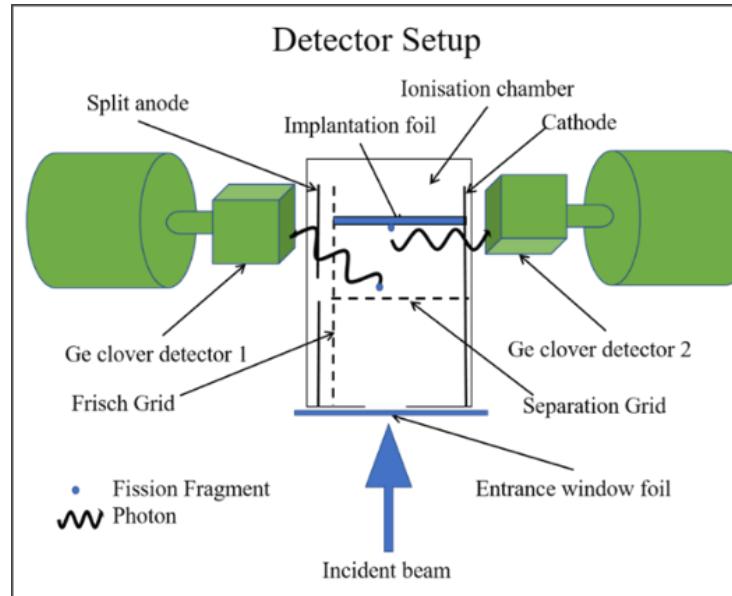
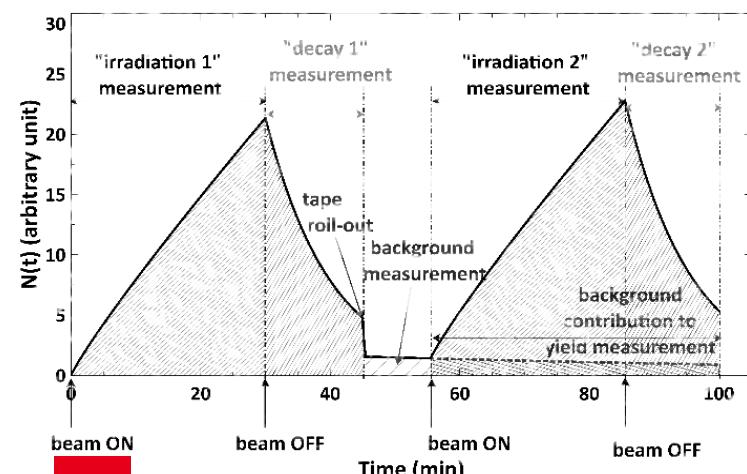
Review of different techniques to assess Isomeric Ratio on LOHENGRIN

ms to min Isomers

By product of isotopic yield analysis

Difficulty : Some Isomeric states have the same γ lines as ground state

Solution : Measurement of increasing and decreasing count rates of both states



ns Isomers

Difficulty : Isomeric states have a period

$T_{1/2} \ll tof (\sim 2\mu s)$
→ no direct measurement

Solution : Statistical analysis of the ionic charge distribution

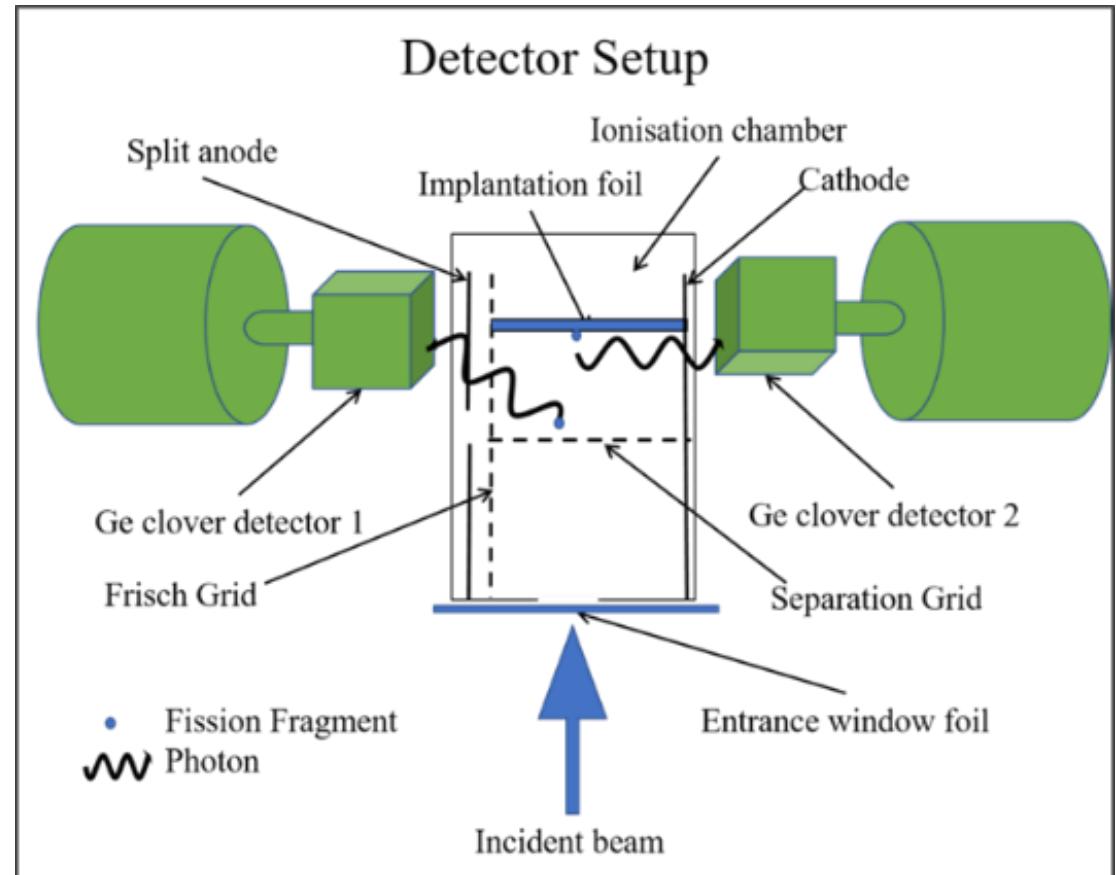
μs Isomers

Difficulty : Isomeric states can be filled by the β decay of the father nuclei

Solution : **Coincidence** between ionization chamber and γ detectors

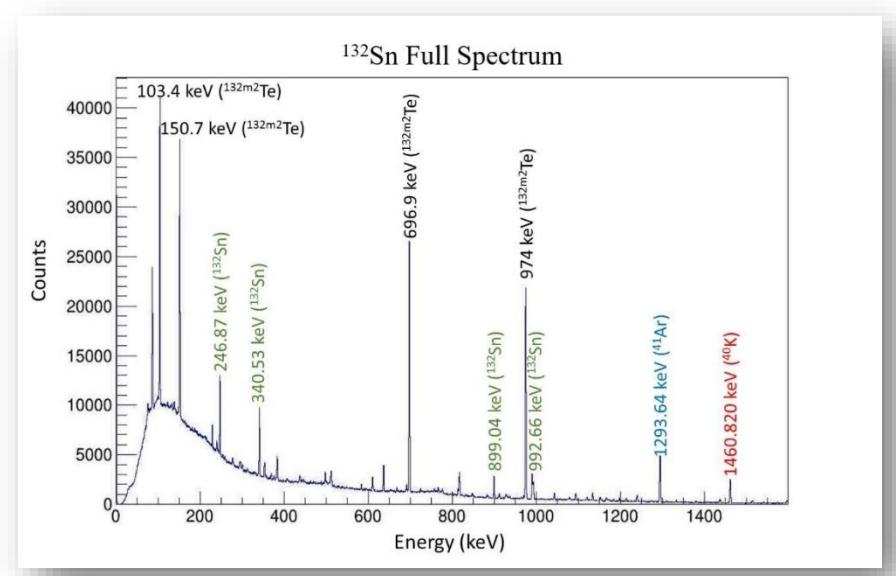
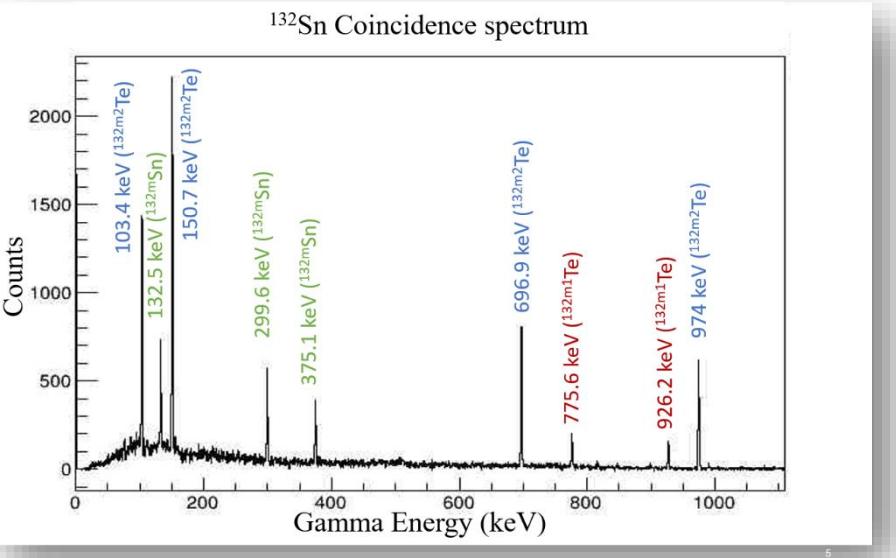
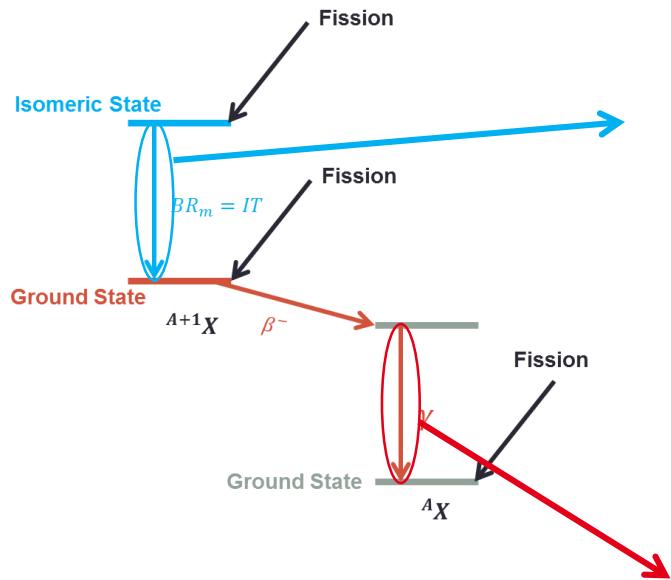


μ s isomer experimental setup

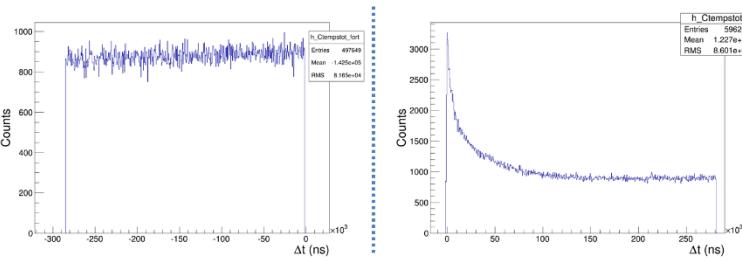
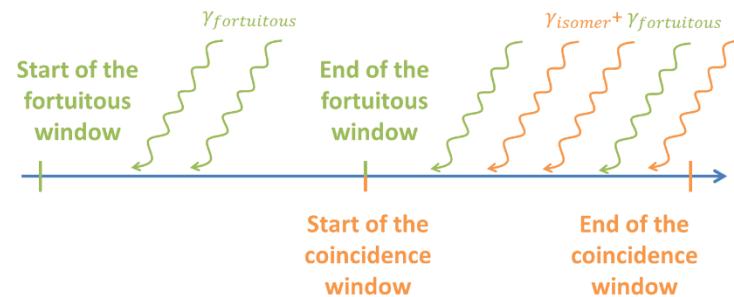




Analysis of μ s isomers



Coincidence between ionization chamber and γ detectors
 \rightarrow Isomeric state measurement
 $\Delta T_{\text{Gate}} = 10T_{1/2}$



$$IR = \frac{\tau_f(^{132m}\text{Sn})}{\tau_f(^{132m}\text{Sn}) + \tau_f(^{132gs}\text{Sn})}$$

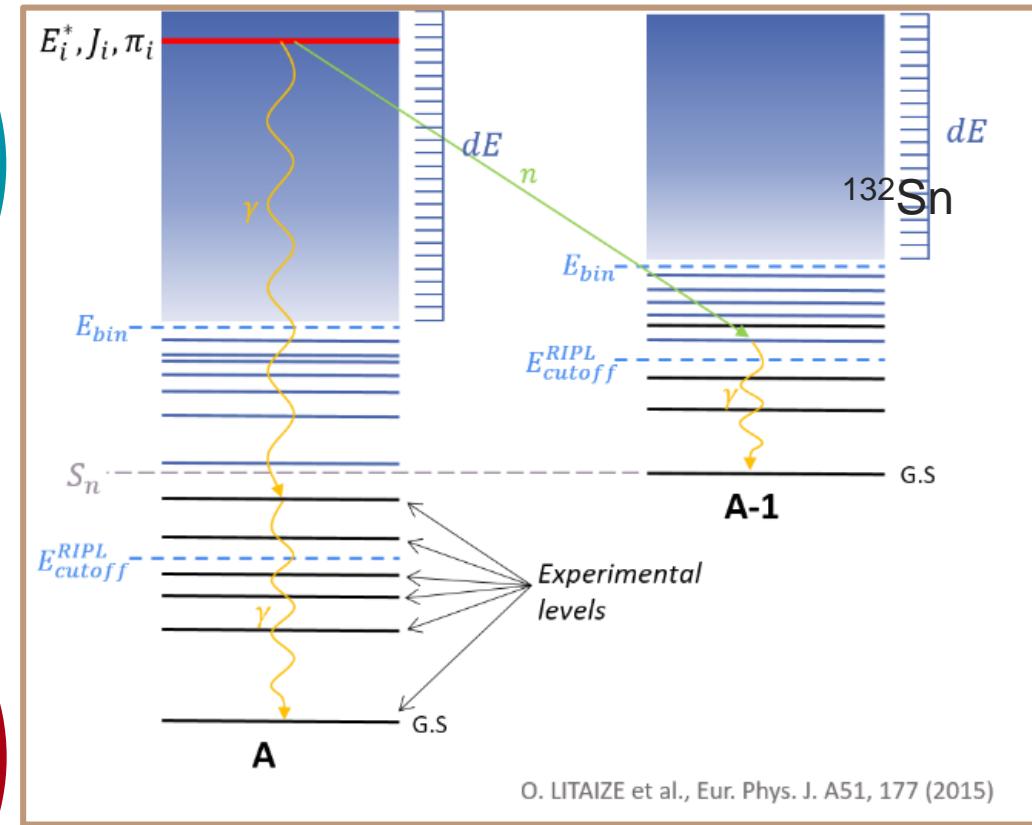
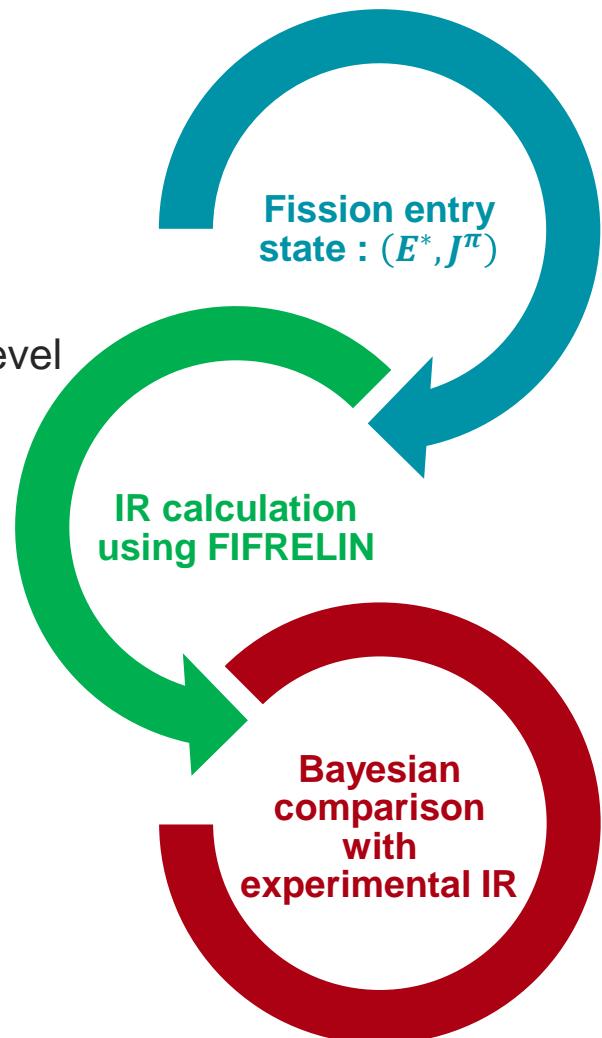
Ungated γ Spectrum i.e. without coincidence
 \rightarrow Ground state measurement
 \rightarrow Extraction more difficult because of the S/B ratio

How to assess angular momentum using FIFRELIN

In this work, FIFRELIN (developed by CEA Cadarache) is used **only as a nuclear de-excitation code**

What is required for FIFRELIN :

- experimental level scheme (RIPL-3)
 - Model of nuclear density to **complete** the level scheme (CGCM)
 - Model of γ strength function (EGLO)
 - Electron conversion coefficients (Brlcc)



How to assess angular momentum using FIFRELIN

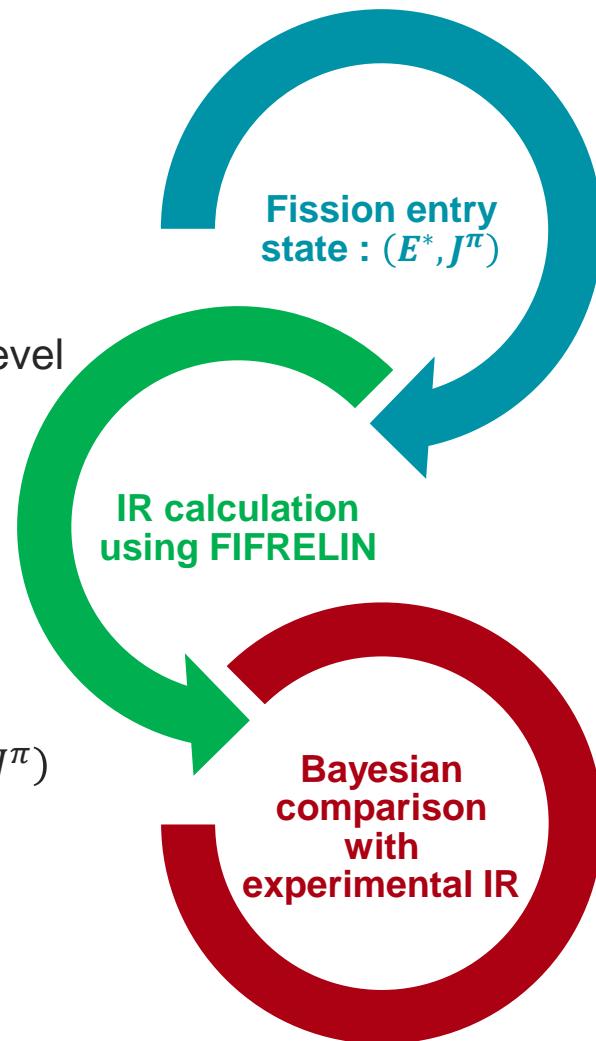
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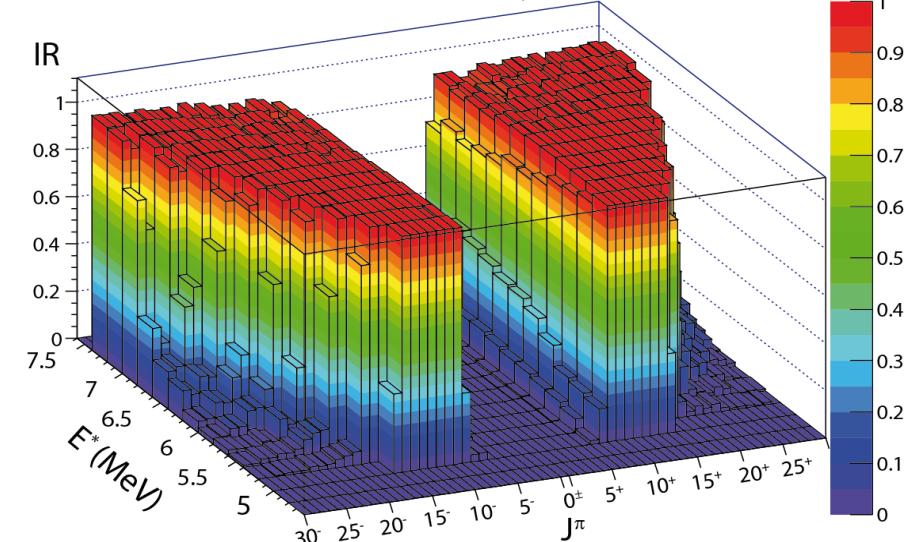
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For comparison with experimental results standard spin distribution:

- $IR_{FIF}(E^*, J_{RMS}) = \sum_E \sum_\pi P(\pi) P(J) IR_{FIF}(E^*, J^\pi)$
- $P(J) \propto (2J + 1) \exp\left(-\frac{(J+\frac{1}{2})^2}{J_{cutoff}^2}\right)$
- $P(\pi) = \frac{1}{2}$

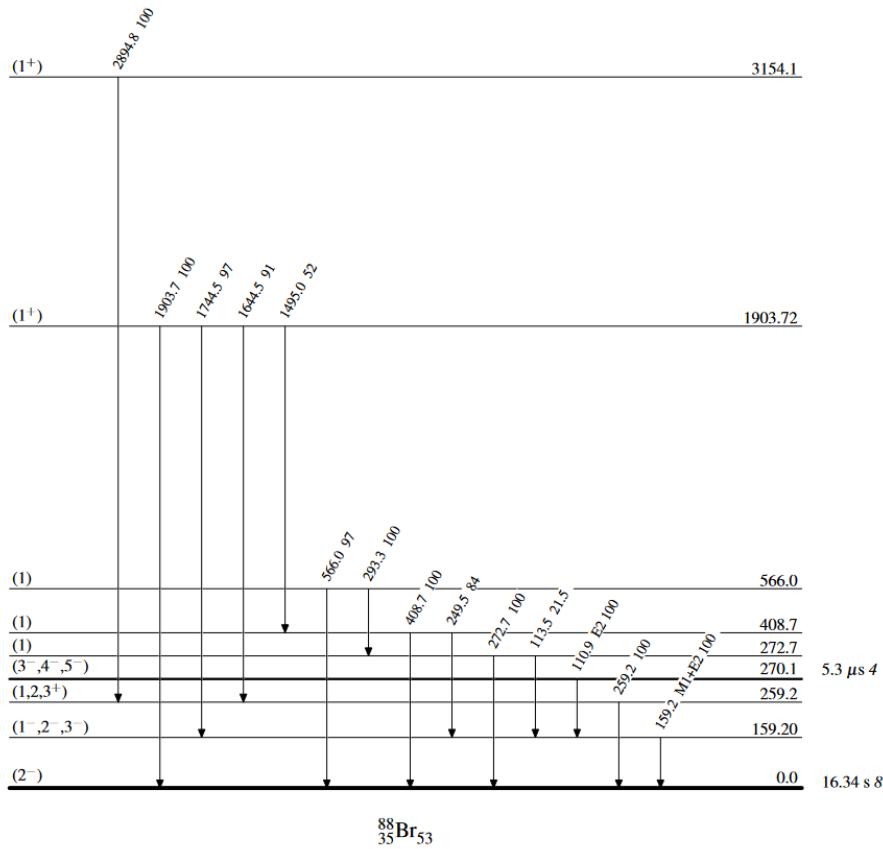


Isomeric Ratio calculated by FIFRELIN ^{132}Sn as a function of entry state (E^*, J^π)



Impact of nuclear structure : ^{88}Br case

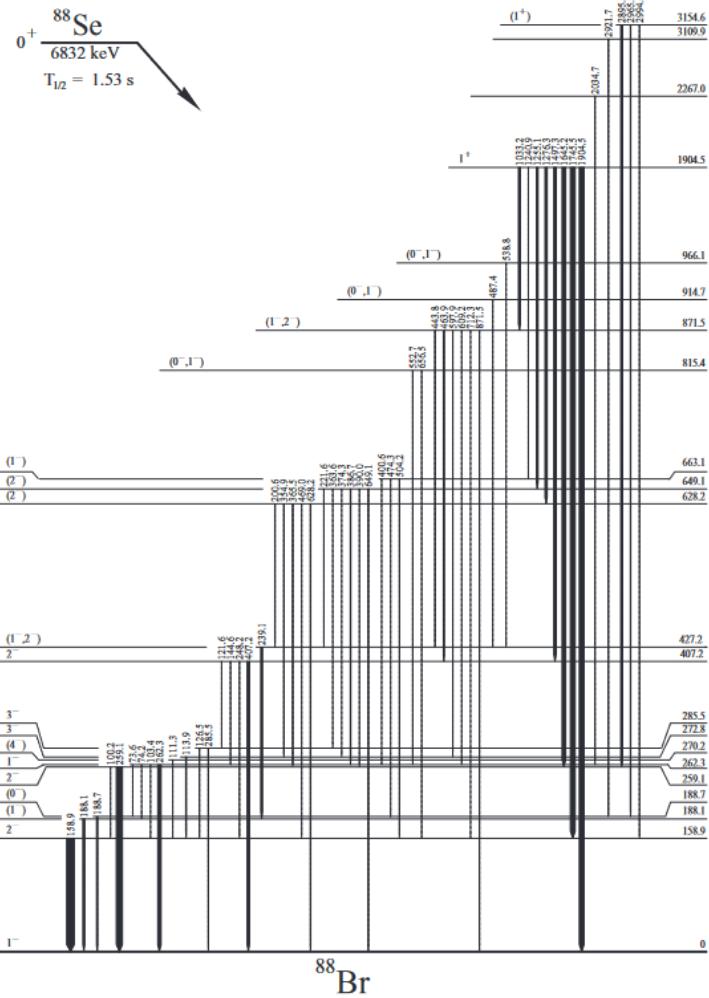
Picture in 2014 (ENSDF)



Picture in 2017 after
measurements at ILL
(EXILL) and at University of
Jyväskylä

M. CZERWIŃSKI *et al.*

PHYSICAL REVIEW C 95, 024321 (2017)

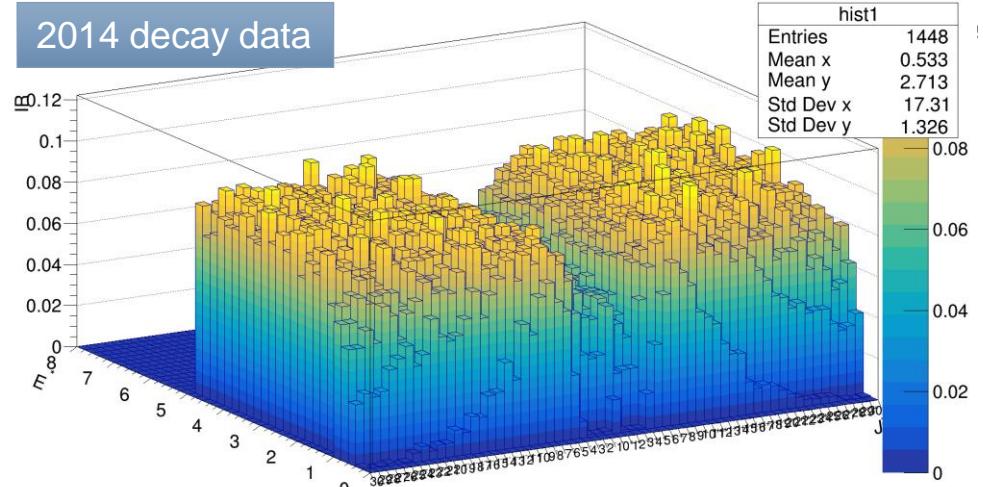




Example : ^{88}Br

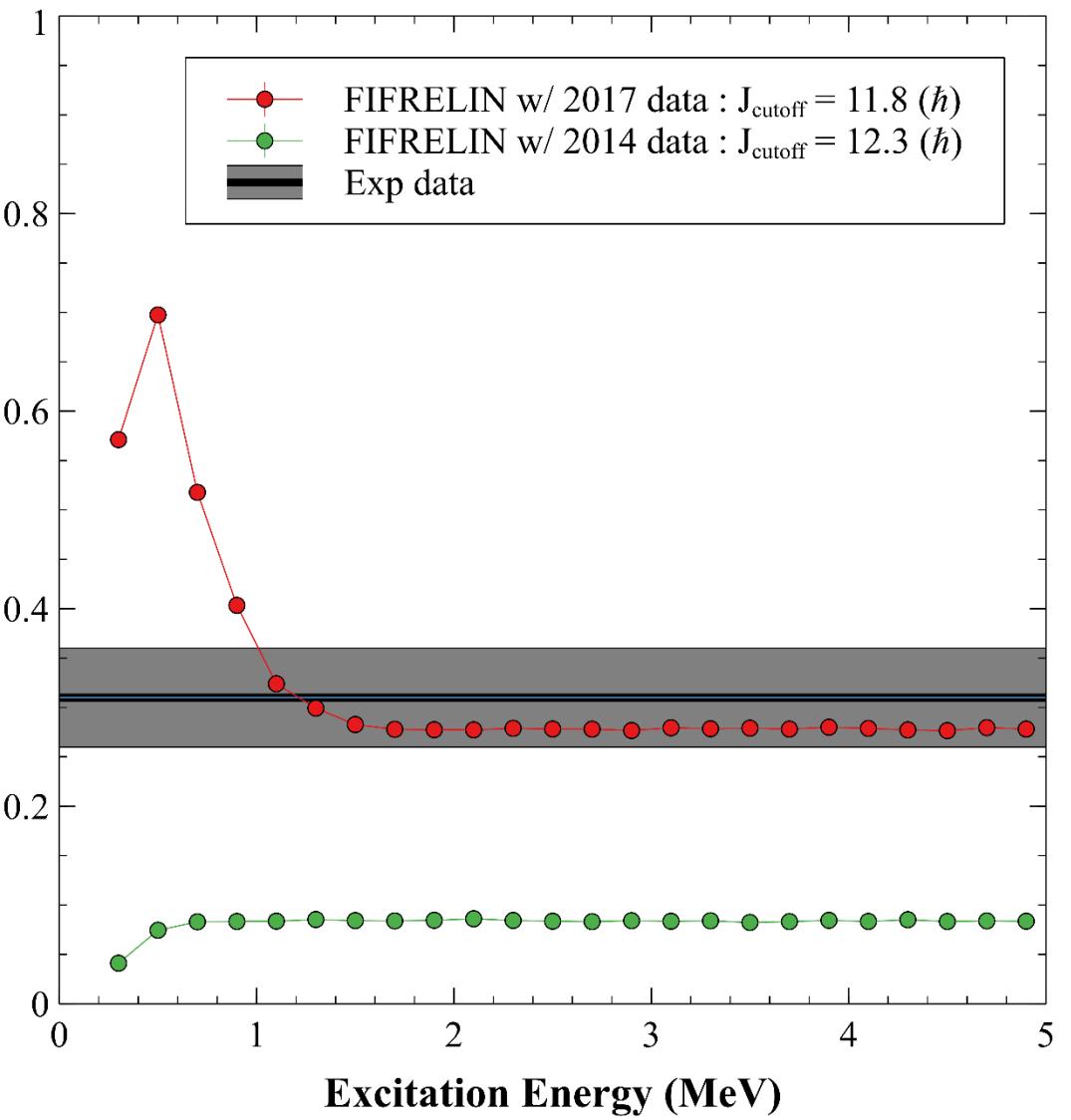
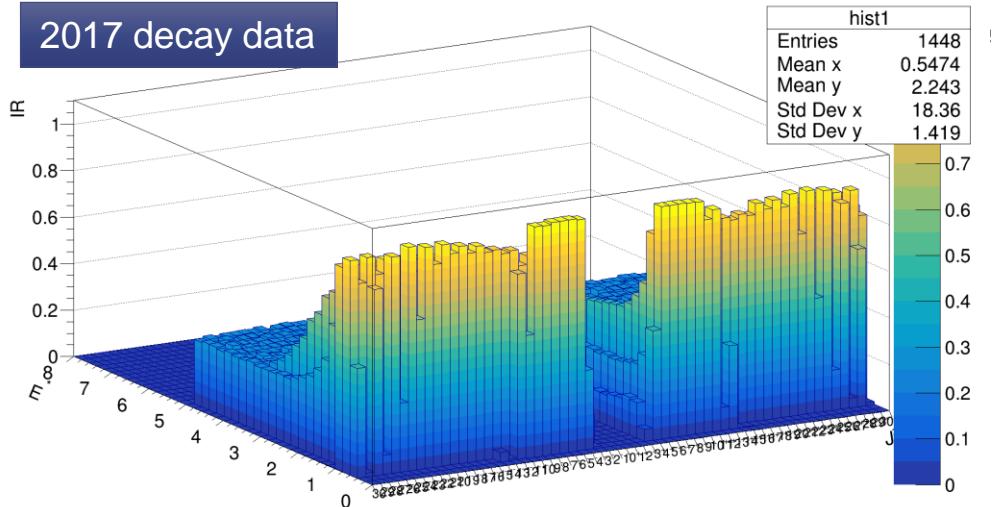
Isomeric Ratio calculated with FIFRELIN

2014 decay data



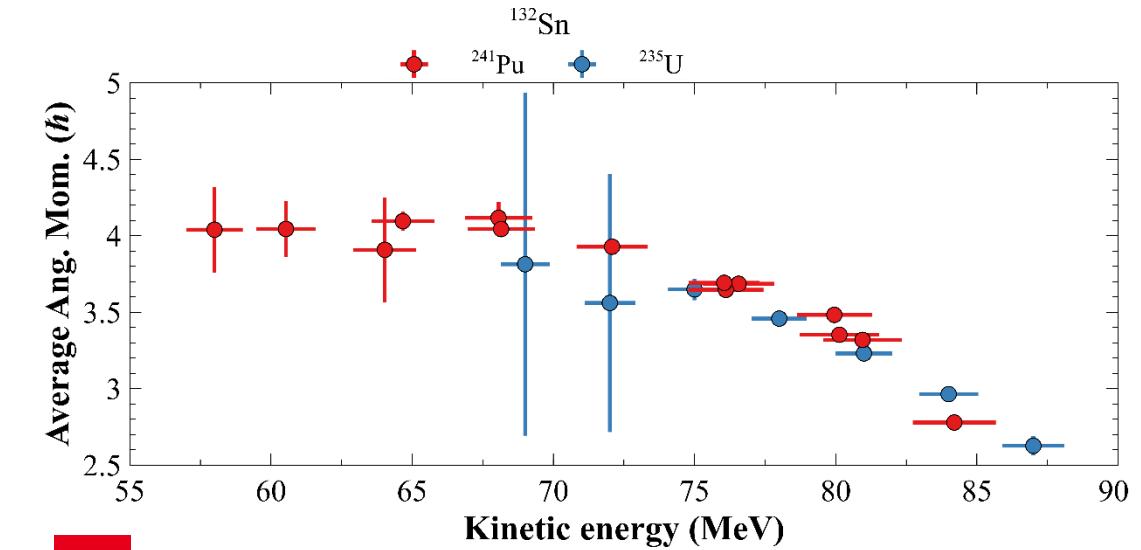
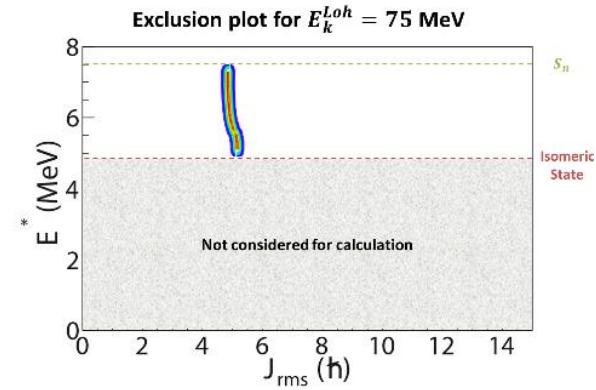
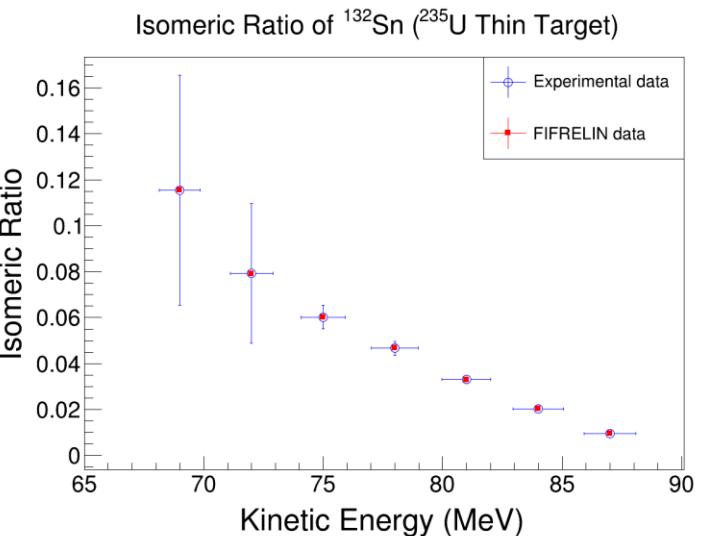
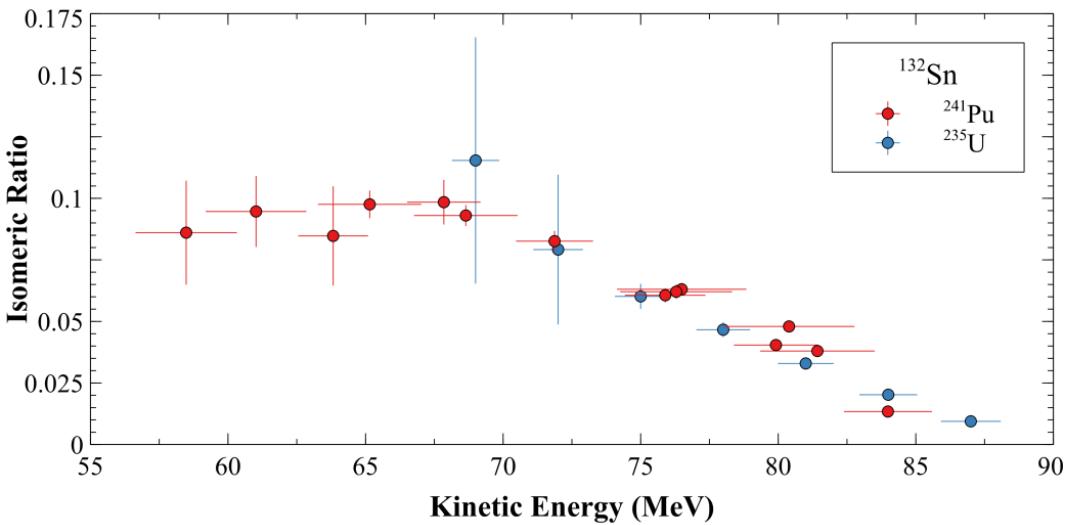
Isomeric Ratio calculated with FIFRELIN

2017 decay data





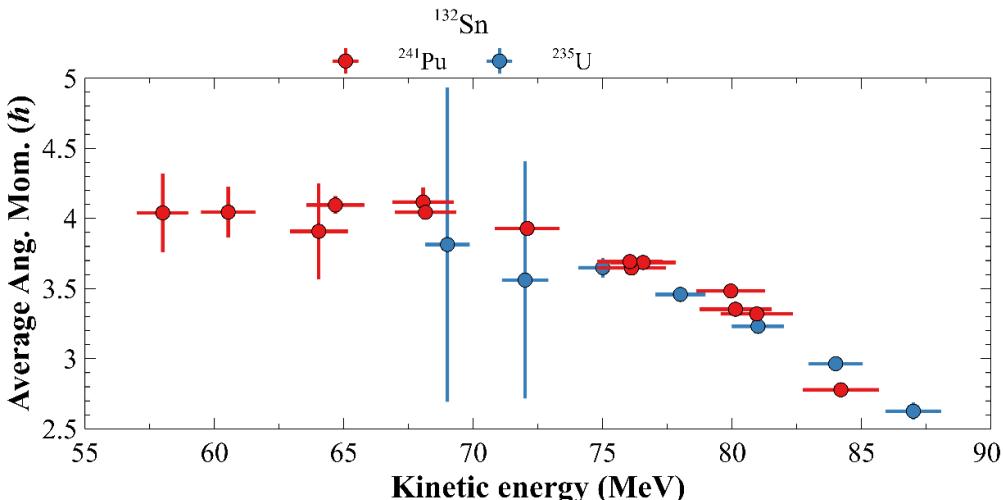
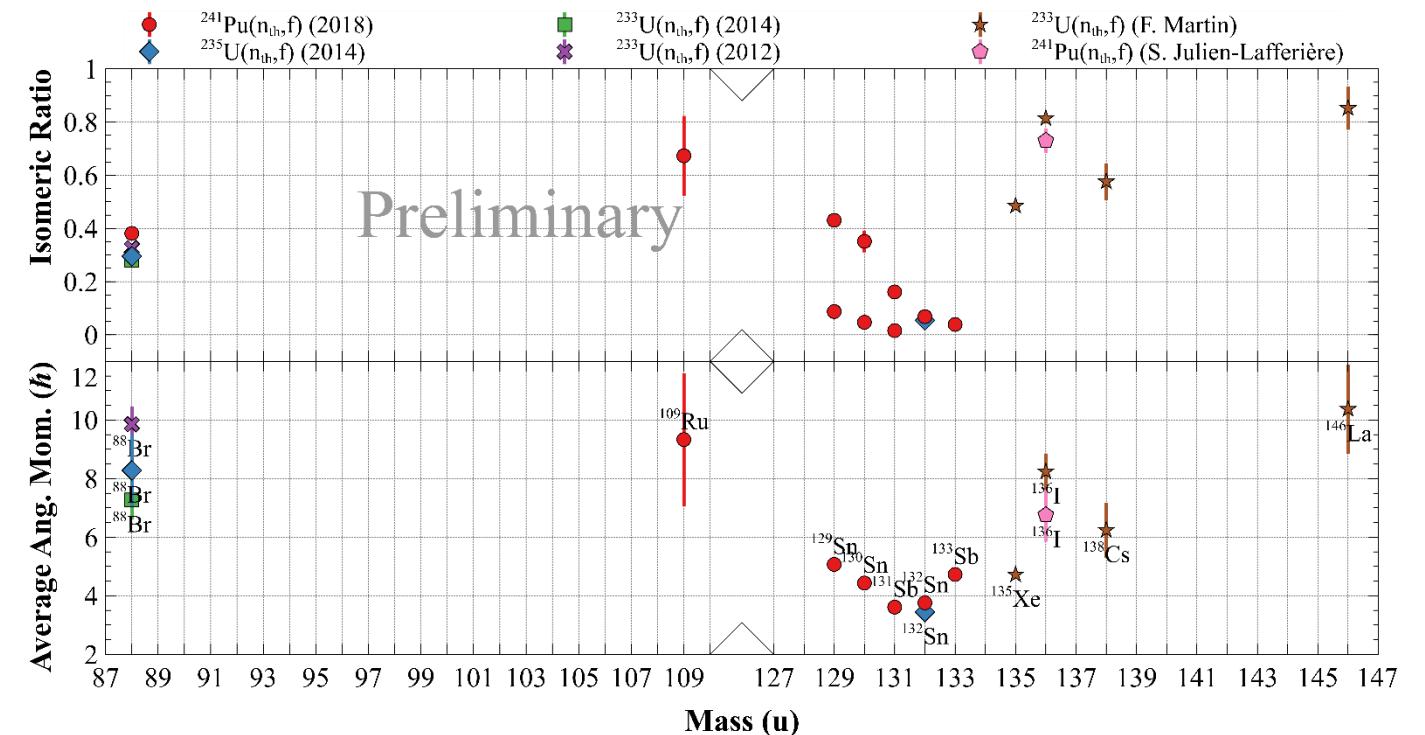
Example : ^{132}Sn



- IRs are compared with FIFRELIN calculations starting from arbitrary initial nuclear state
- The derived **average angular momentum** is dependent on the fission fragment **kinetic energy**
- HFB (from P. Marevic et al.) predicts $2.5 \hbar$ (with ^{239}Pu)
 - Neutron emission ?
 - Thermal excitation ?

Chebboubi et al., *Phys. Lett. B* 775, 190-195 (2017)
 J. Nicholson PhD thesis (2021)

Conclusion



- We measure independant yield through γ spectroscopy
- Dependency to the nuclear structure level scheme
- Isomeric ratios can be measured with the LOHENGRIN spectrometer : probe for fission fragment angular momentum
- **The derived average angular momentum is dependent on the fission fragment kinetic energy**
- Role of the complementary fragment ?

cea

**Thank you for your
attention**

