DE LA RECHERCHE À L'INDUSTRIE

FIRST RESULTS ON 235U(N_{TH},F) INDEPENDENT ISOTOPIC FISSION YIELDS USING PROMPT GAMMA RAYS AT FIPPS

06/06/2023

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Collaboration

IRFU/DPhN :

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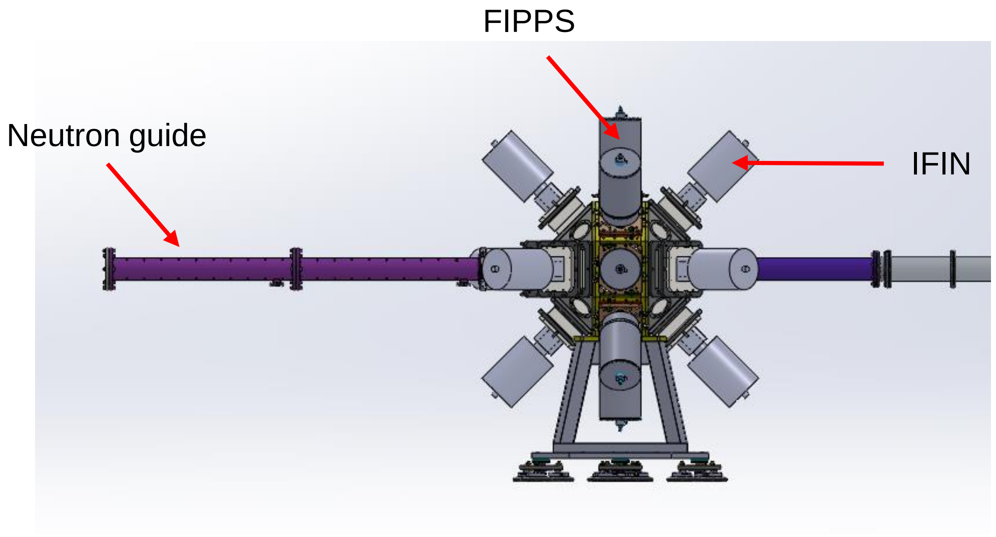
ILL : C. Michelagnoli, Y.H. Kim, F. Kandzia, U. Köster,

D. Reygadas, …

FIPPS spectrometer

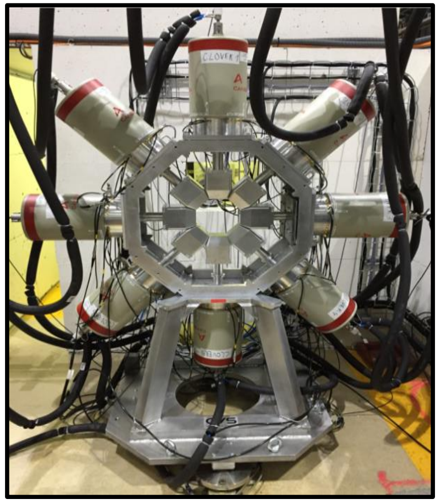


FIPPS (FIssion Product Prompt γ-ray Spectrometer)

Installed at the ILL (Grenoble)

Thermal neutron guide + Collimators

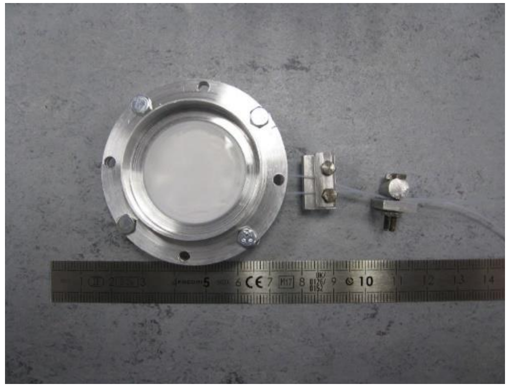
Neutron flux at target : 10^8 n/s/cm^2

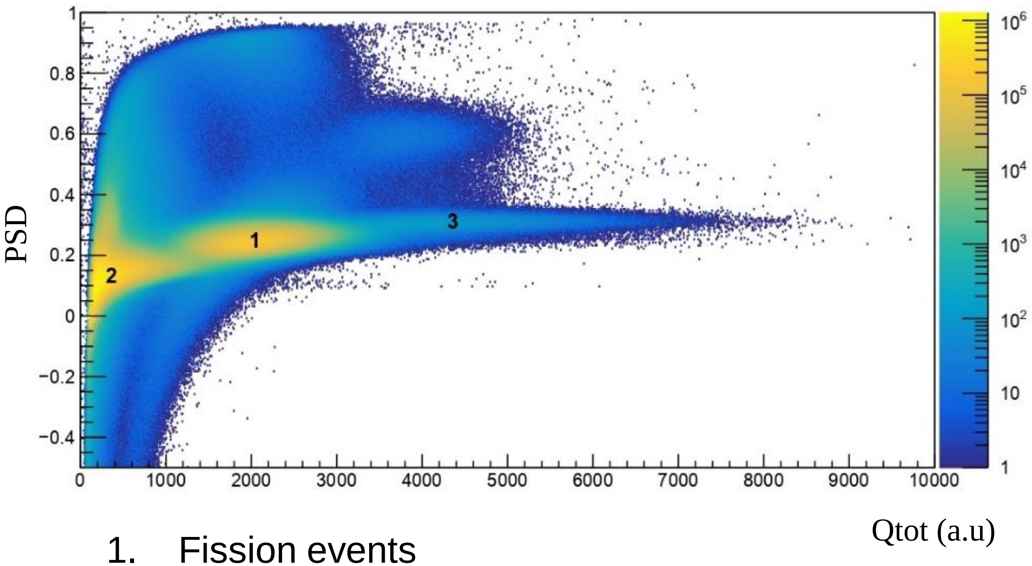


- 8 FIPPS + 8 IFIN HPGe clovers (64 crystals) with very good resolution in energy
- BGO anti Compton around IFIN clover
- Active target : U-235

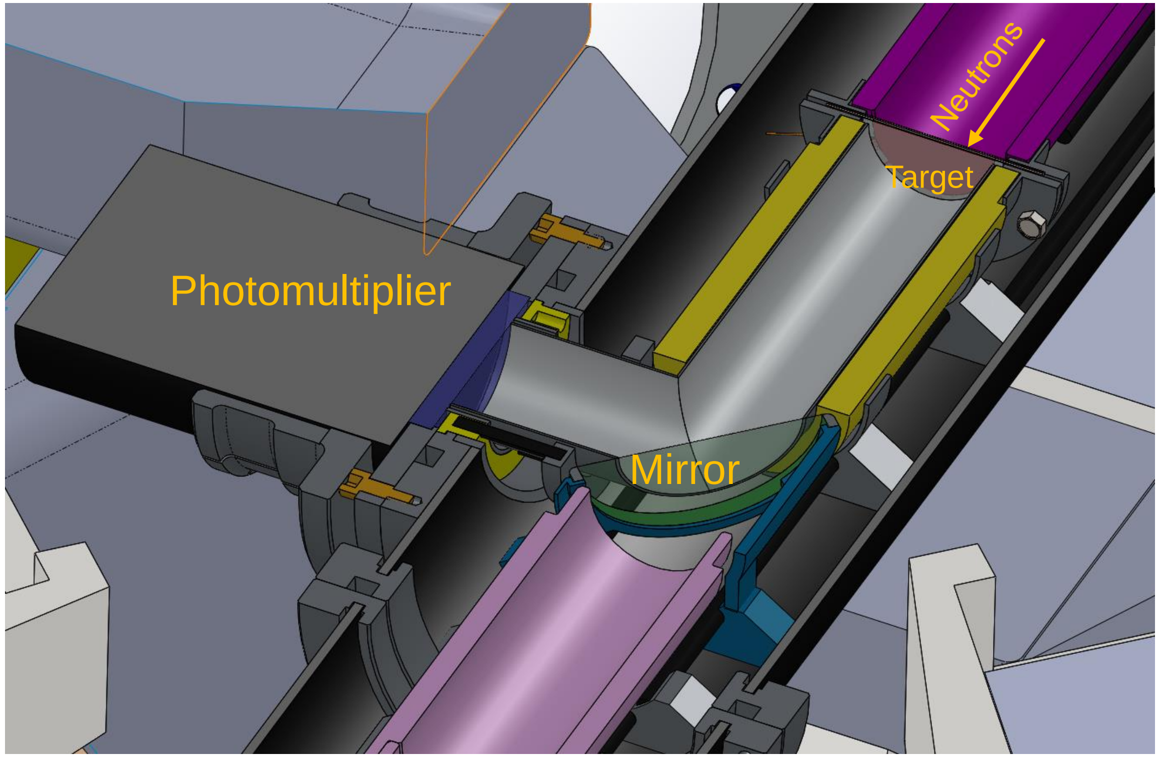
Active target

- U-235 solution diluted in a scintillator liquid (CEA/DAM)
- Saphir (Al_2O_8) window
- Photomultiplier → Fission tag



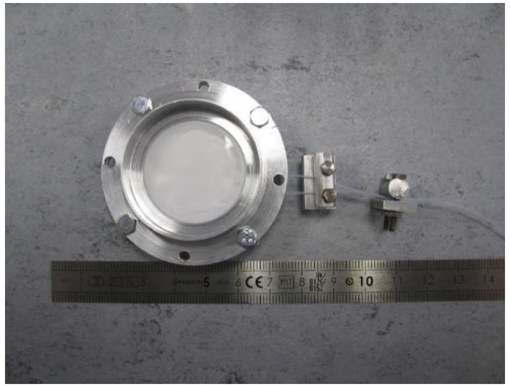


1. Fission events
2. Beta decay
3. Ternary fission



F. Kandzia et al. EPJA 2020

Active target



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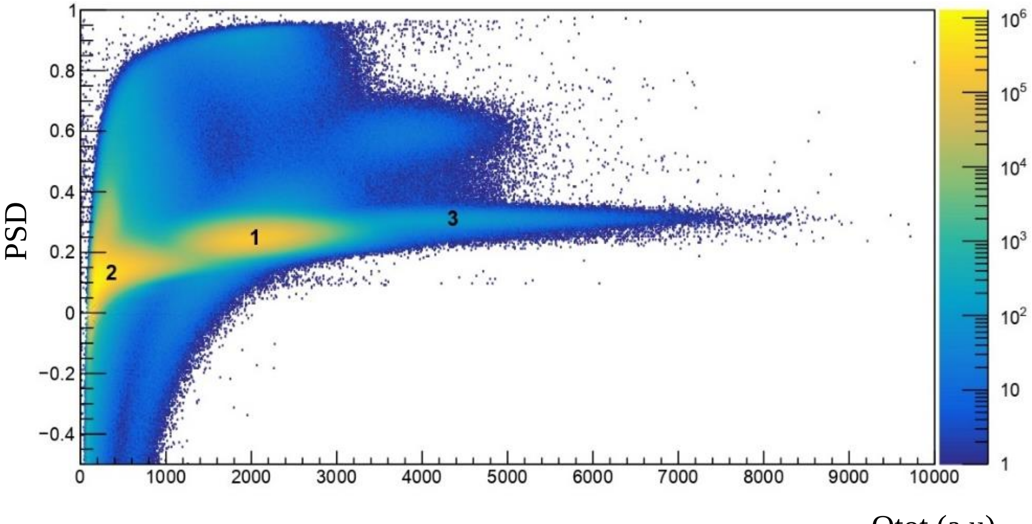

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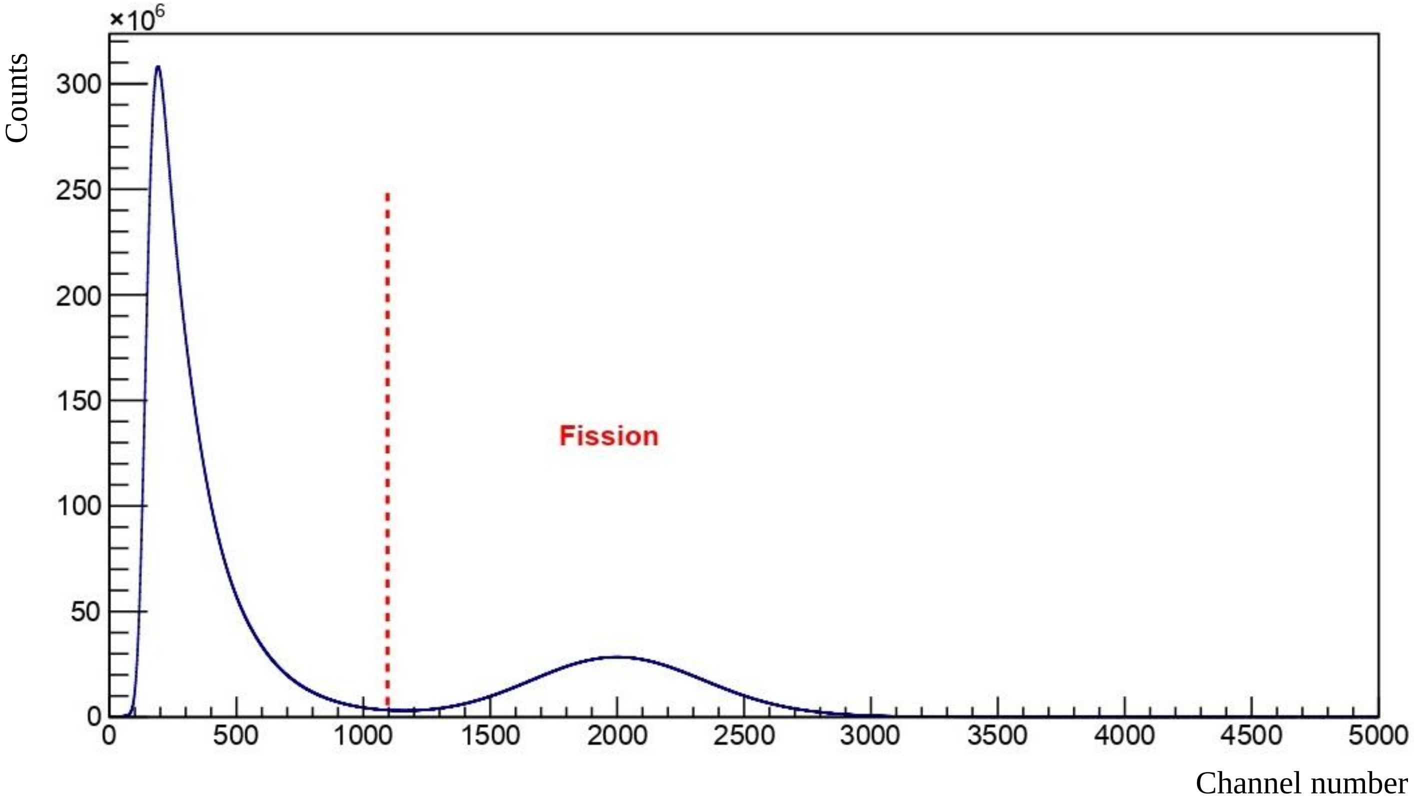


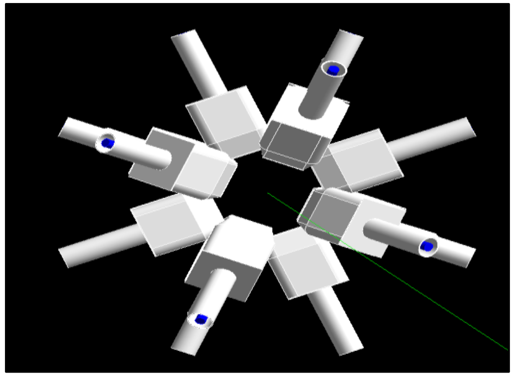
Context and objectives

- Test of a method for measuring independent isotopic fission yields using prompt gamma-rays and search for anomalies

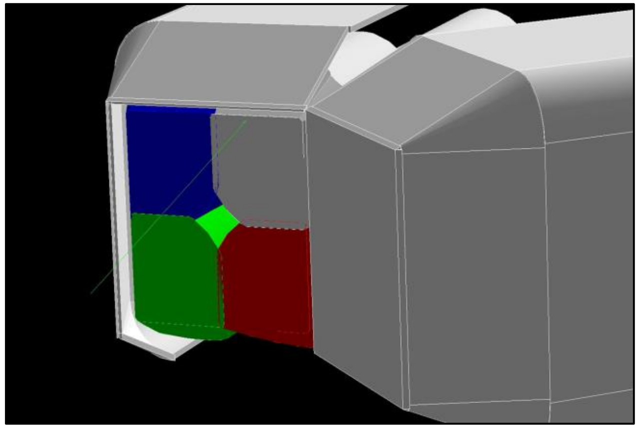
- Study of the fission process via the prompt gamma cascade
  - Angular momentum distribution
  - Sharing of the excitation energy
  - Comparison with the fission fragment de-excitation code FIFRELIN

- Delayed gamma-ray measurements
  - Cumulative fission yields
  - Validity of delayed gamma-ray intensities (Pandemonium effect)

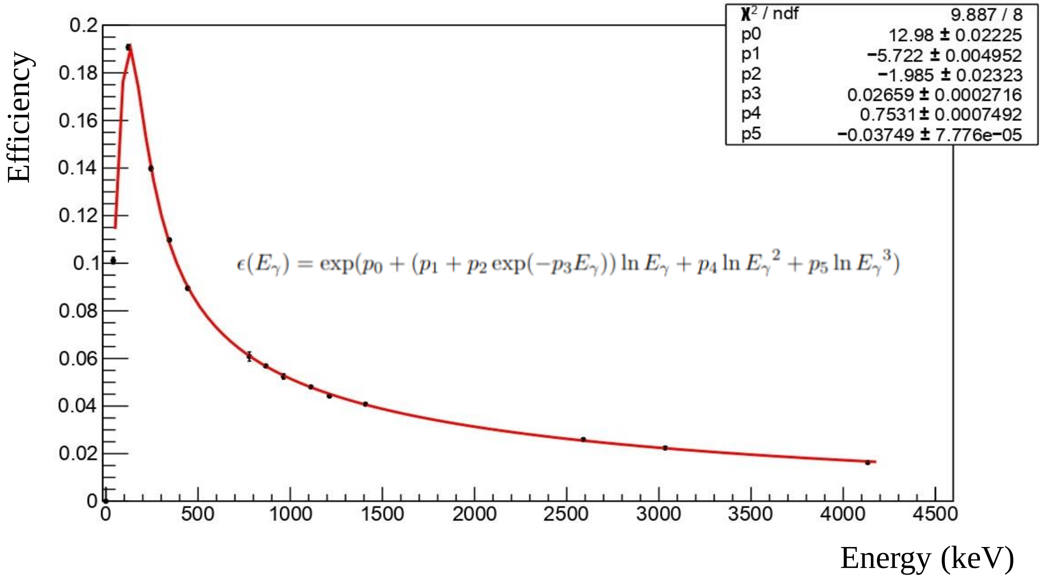
Geant4 simulation of FIPPS and gamma-ray efficiency

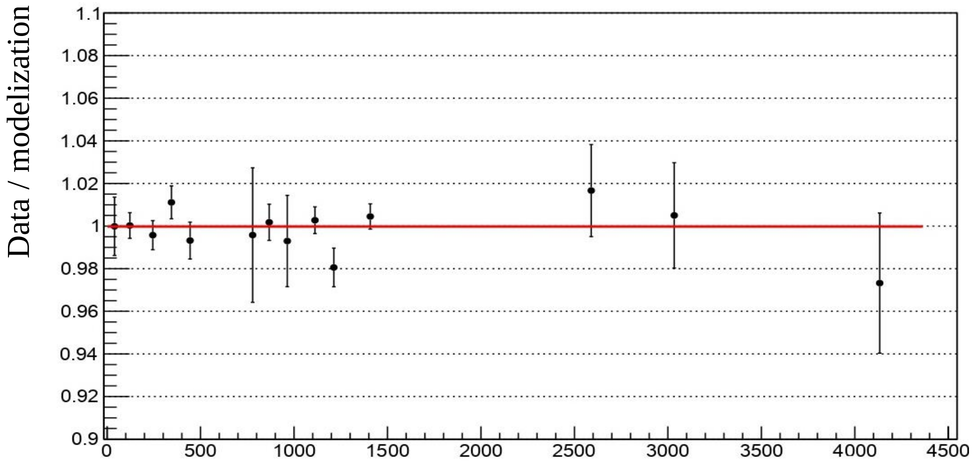


FIPPS spectrometer and its 16 clovers



Zoom in on a clover with 4 crystals





Energy (keV)

Efficiency curve of FIPPS spectrometer

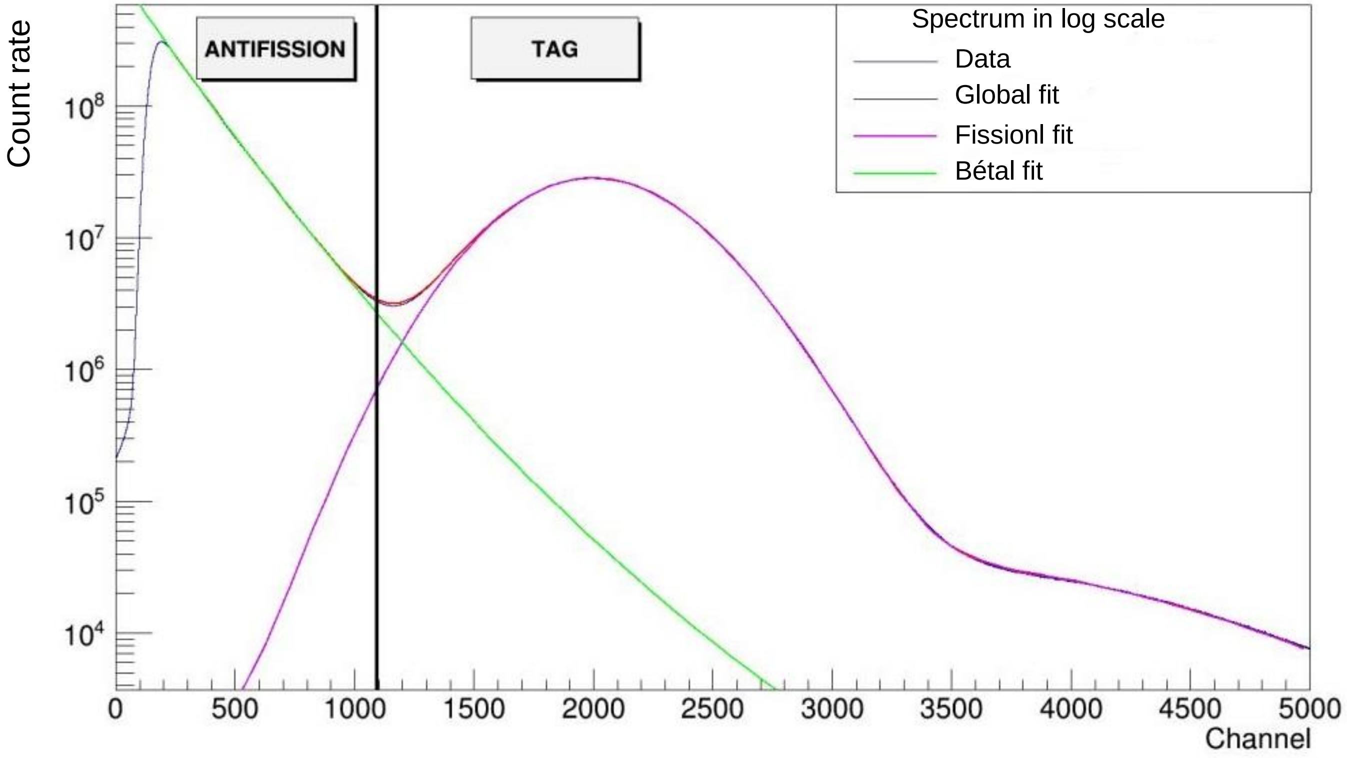
Efficiency of FIPPS with :

- Eu-152 source
- Al-27(n,γ)Al-28

Absolute efficiency with uncertainties < 0,5%

Estimation of the number of fissions

PMT spectrum (U-235 active target)



Threshold to select ß-decay or fission events

2.436 10^{10} fissions in 35 days

2.2 % (events > threshold) = beta
0.3 % (events < threshold) = fission

Check with Zr-100 and Sr-94 prompt gamma
0.4 – 0.5 % (events < threshold) = fission

Number of fission validated with delayed gamma rays (back up slide)

Independent fission yields with FIPPS

$$Y({}^{A}_{Z}X) = \frac{N(E_\gamma)}{N_f \times \varepsilon(E_\gamma)}$$

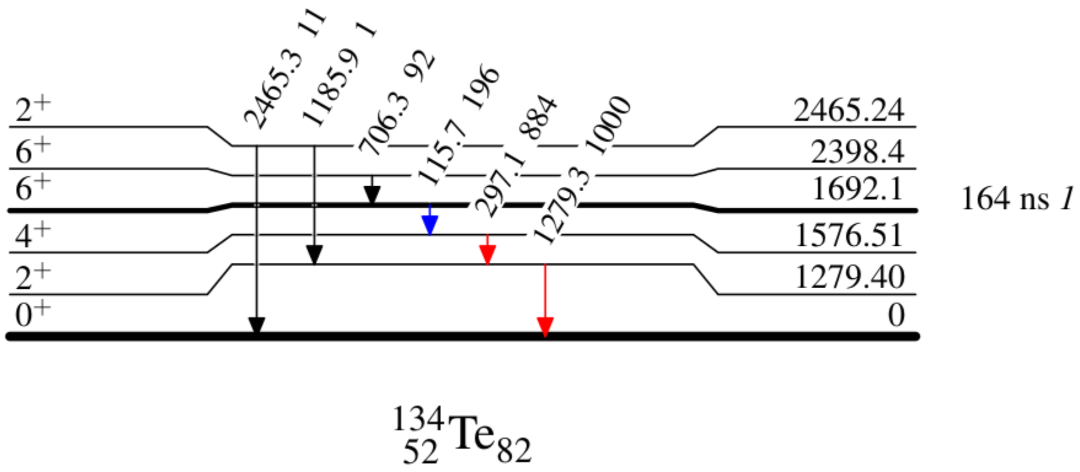
$N_f : number\ of\ fission$

$N(E_\gamma) : number\ of\ gamma - rays\ that\ fall\ on\ the\ ground\ state$

$\varepsilon(E_\gamma) : efficiency\ at\ given\ energy$

Independent isotopic fission yield of U-235 :

- Sum of all gamma falling on the ground state
- Normalized to total number of fissions



Independent fission yields with FIPPS

N_f: fission number

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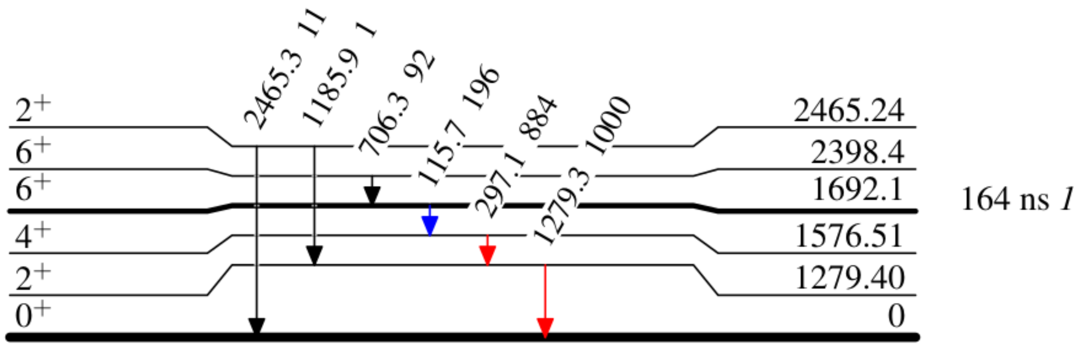
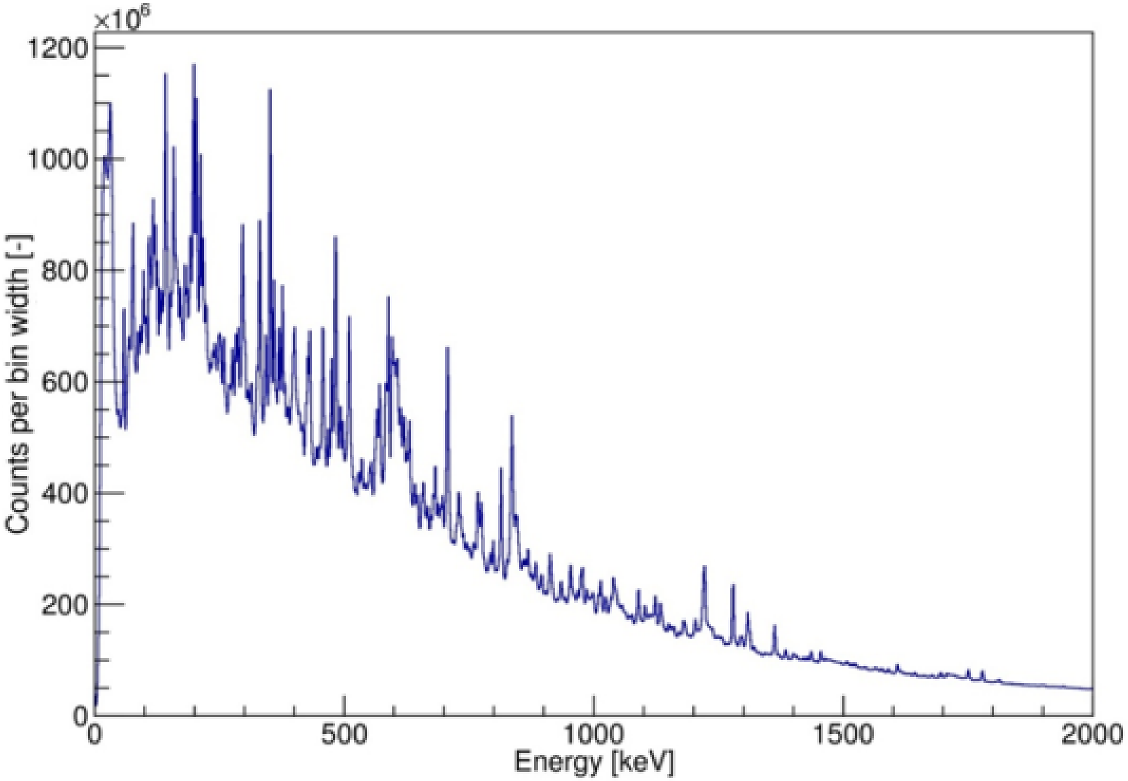


${}^{134}_{52}Te_{82}$

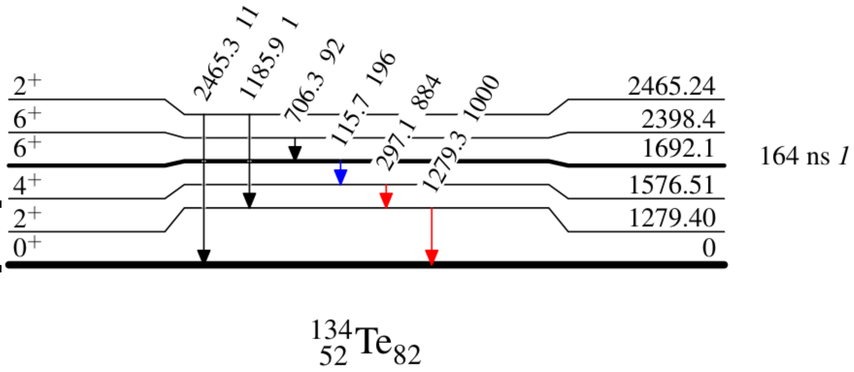


In practice, prompt-gamma-ray spectrum is too dense
→ use of prompt $\gamma\gamma$ matrix and $\gamma\gamma\gamma$ cube

Independent fission yields on FIPPS

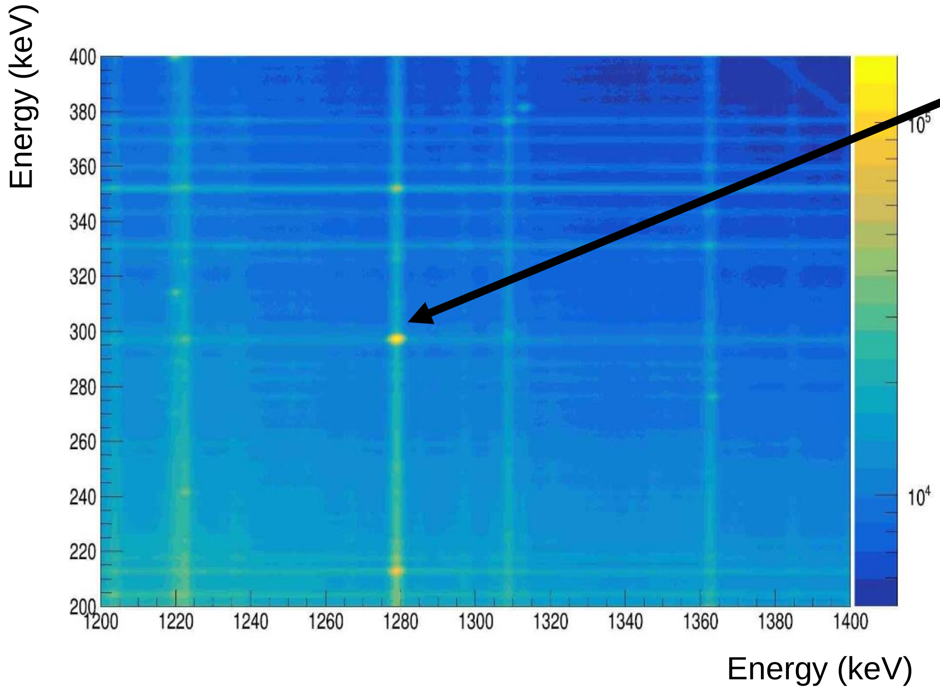
$$Y({}^{A}_{Z}X) = \frac{N(E_{\gamma1}, E_{\gamma2})}{N_f \times \varepsilon(E_{\gamma1}) \times \varepsilon(E_{\gamma2})} \times \frac{1}{R}$$

$R: intensity\ ratio$



(1279.3 & 297.1)

$N(E_{\gamma1}, E_{\gamma2})$

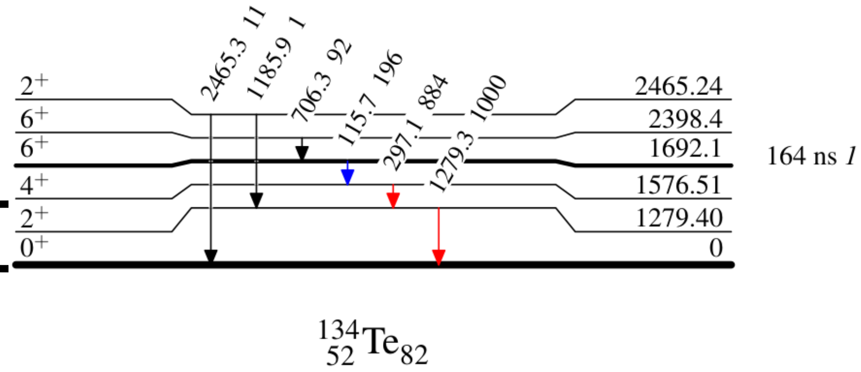


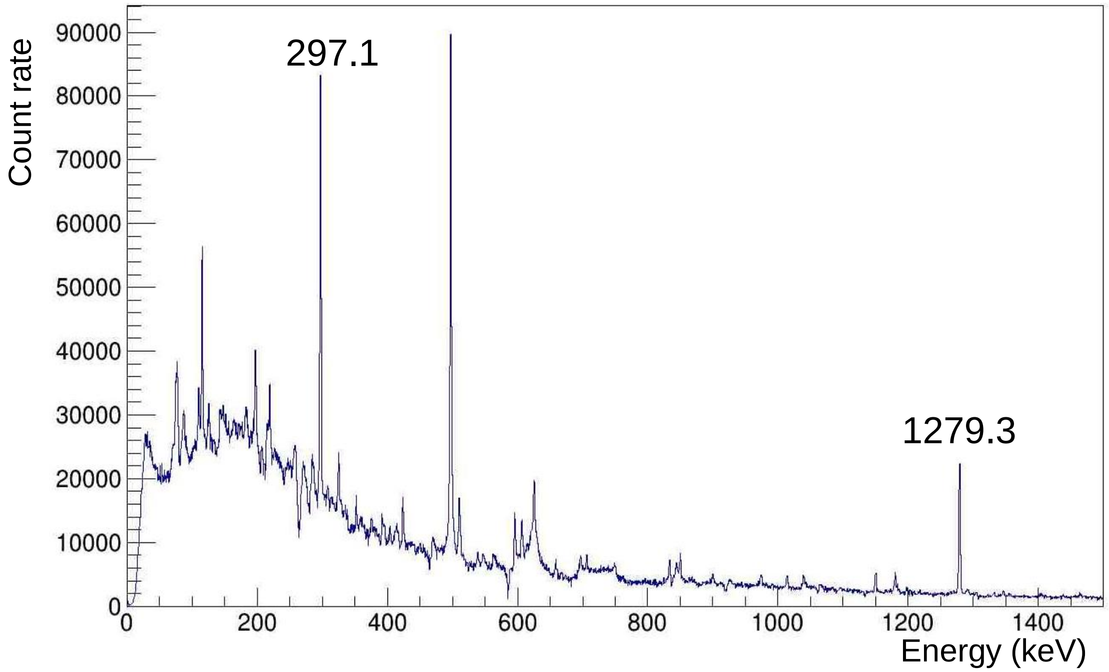
Independent fission yields on FIPPS

$$Y({}^{A}_{Z}X) = \frac{N(E_{\gamma1}, E_{\gamma2})}{N_f \times \varepsilon(E_{\gamma1}) \times \varepsilon(E_{\gamma2})} \times \frac{1}{R}$$

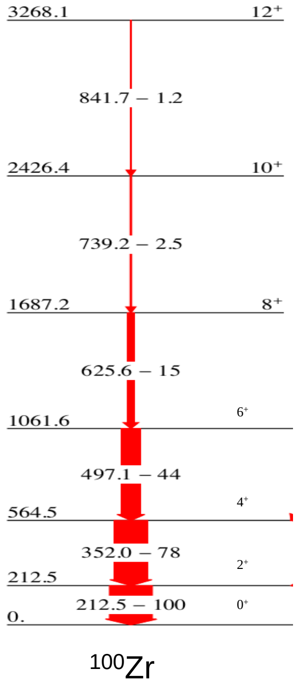
$$R = \frac{N(E_{\gamma1})}{N(E_{\gamma2})} \times \frac{\varepsilon(E_{\gamma2})}{\varepsilon(E_{\gamma1})} \qquad R: intensity\ ratio$$

(1279.3 & 297.1)



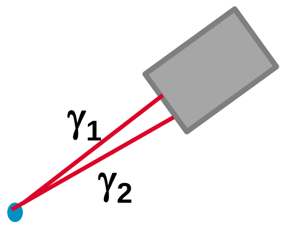


Spectrum obtained after selection on the complementary and subtraction of the background noise



Corrections

<u>Summation effects :</u>



Efficiency of a crystal ~ 0.3 %
Efficiency of a clover ~ 1.3 %

Summation effects ~ 1 – eff x (multiplicity-1) so ~ $(1 - \text{eff} \times (\text{multiplicity}-1))^2$ for the coincidences of 2 gamma-rays

→ deficit of 10 - 15 % of counts in the peak

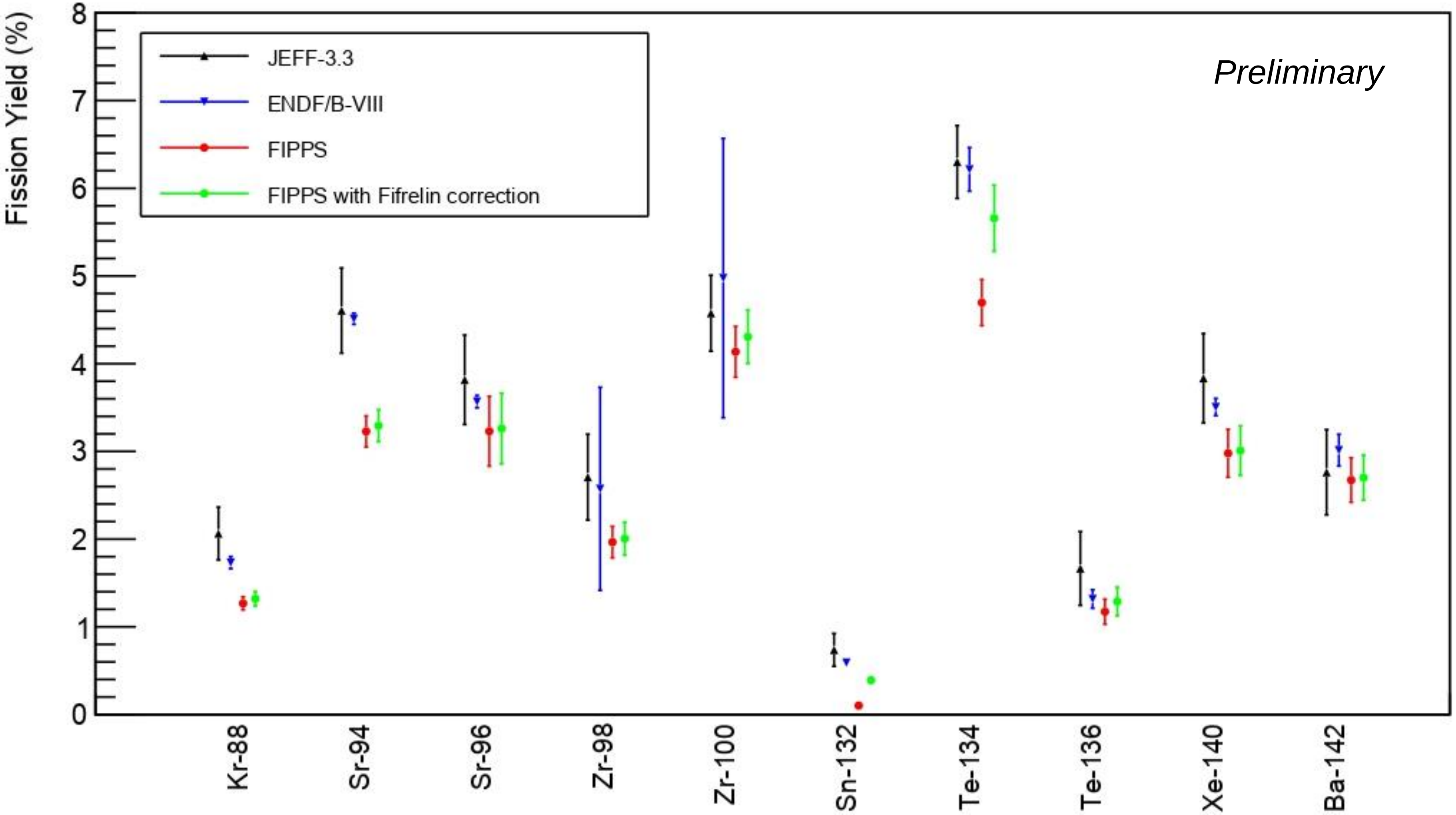
In practice, the deficit depends on the fragment is obtained from simulations :

- Geant4 simulation of the device adjusted on the calibration data with a Eu-152 source
- Simulation of fission prompt gamma cascades with the FIFRELIN code as input to the Geant4 simulation of FIPPS

<u>Other effects :</u>

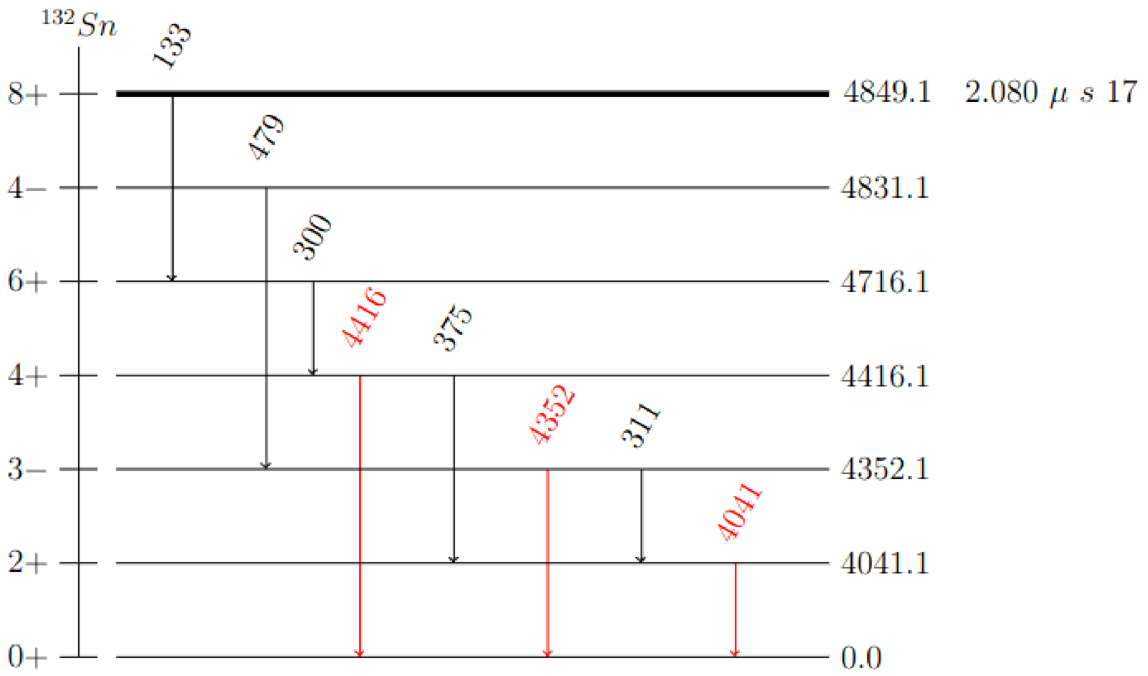
FIFRELIN simulation allows us to estimate correction from :
- Low-produced transitions to ground state
- Production directly at the ground state without prompt gamma emission

Results on independant isotopic absolute fission yields



The case of Sn-132

Diagram of the known levels of Sn-132 with transitions for Cm-248(sf, f)



Y(Sn-132) = $\dfrac{\frac{N(\gamma_1)}{\varepsilon_1}+\frac{N(\gamma_2)}{\varepsilon_2}+\frac{N(\gamma_3)}{\varepsilon_3}}{N_f}(1+\alpha)$

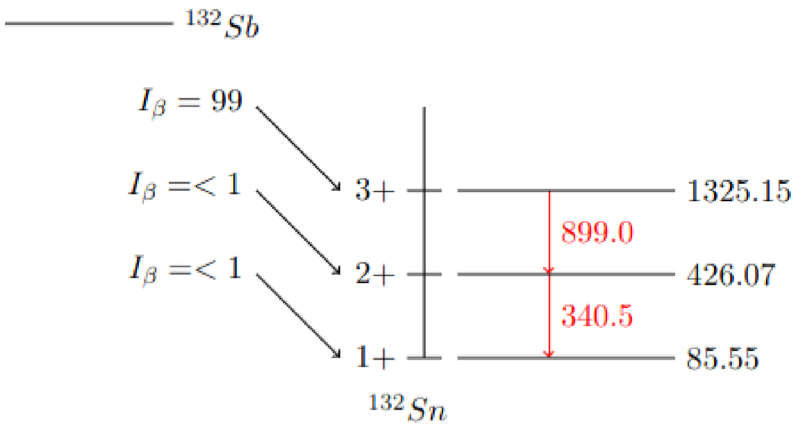
FIPPS : Y(Sn-132) = 0.102 ± 0.005

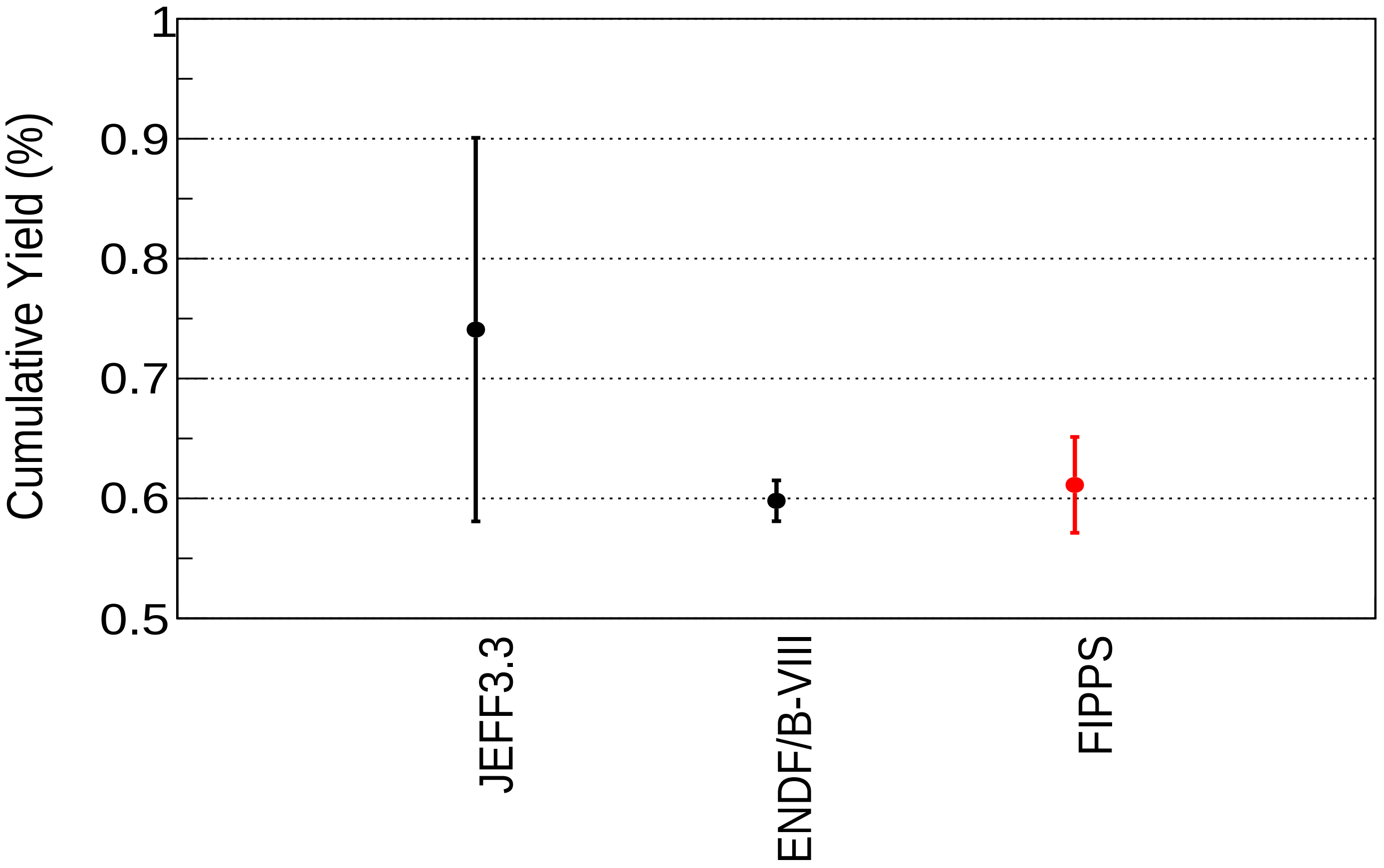
ENDF B-VIII : Y(Sn-132) = 0.59 ± 0.02

→ **Discrepancies around a factor 6**

Check with delayed gamma

The case of Sn-132 : study with delayed gamma rays



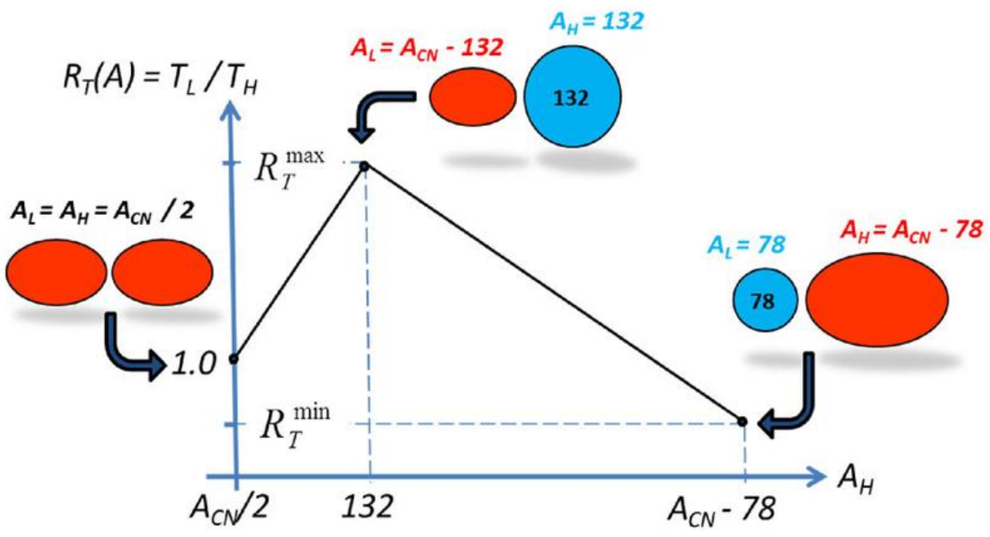


Yc(Sn-132) = Y(Sn-132) + Yc(In-132)
$\simeq$ 0.999 Y(Sn-132)

$N_{\gamma\gamma}(899, 340.5) = N_{fissions} \cdot Y_c \cdot I_\gamma(899) \cdot \varepsilon(899, 340.5) \cdot \alpha_{deadtime}$

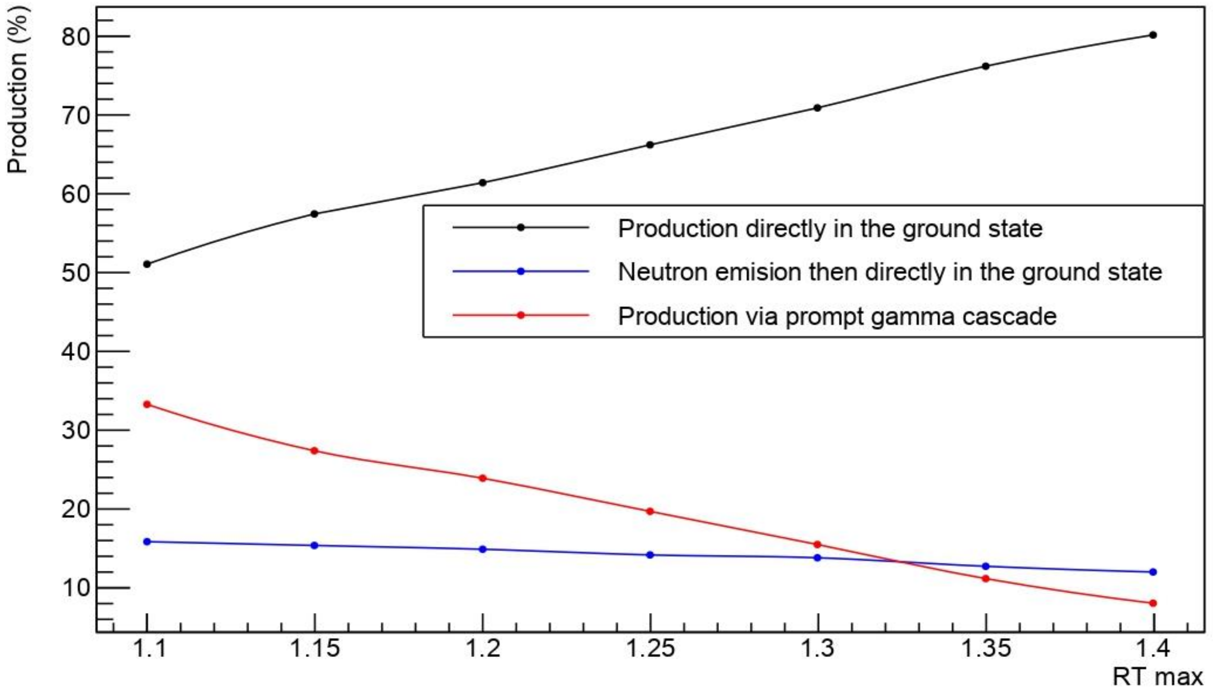
→ FIPPS : Yc(Sn-132) = 0.61(4) % *(preliminary)*
with uncertainty dominated by I_γ = 45(3)

The case of Sn-132 : FIFRELIN



$R_T(A)$: temperature ratio between light and heavy fragments

Optimized for neutron multiplicity



Evolution of the production mechanism of Sn-132 fragment as a function of the FIFRELIN RT factor

Interpretation according to FIFRELIN:

- 66% directly produced in the ground state
- 14% directly in the ground state after neutron emission

→ 80% total without gamma rays

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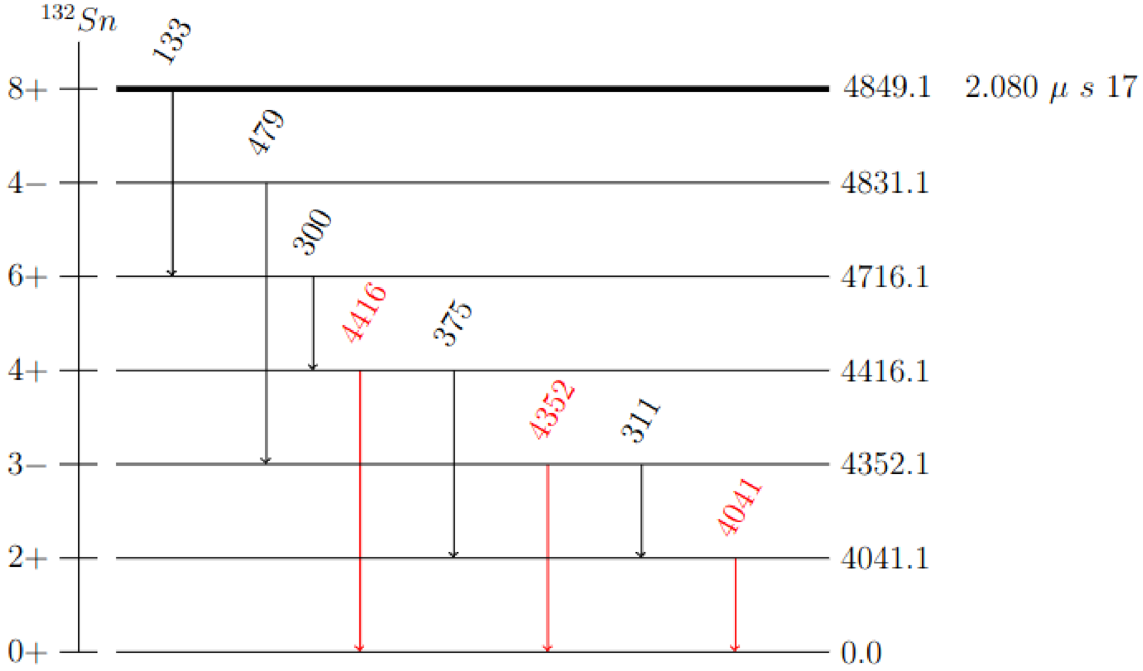


$$Y(\text{Sn-132}) = \frac{\frac{N(\gamma_1)}{\varepsilon_1} + \frac{N(\gamma_2)}{\varepsilon_2} + \frac{N(\gamma_3)}{\varepsilon_3}}{N_f}(1+\alpha)$$

FIPPS : Y(Sn-132) = 0.102 ± 0.005

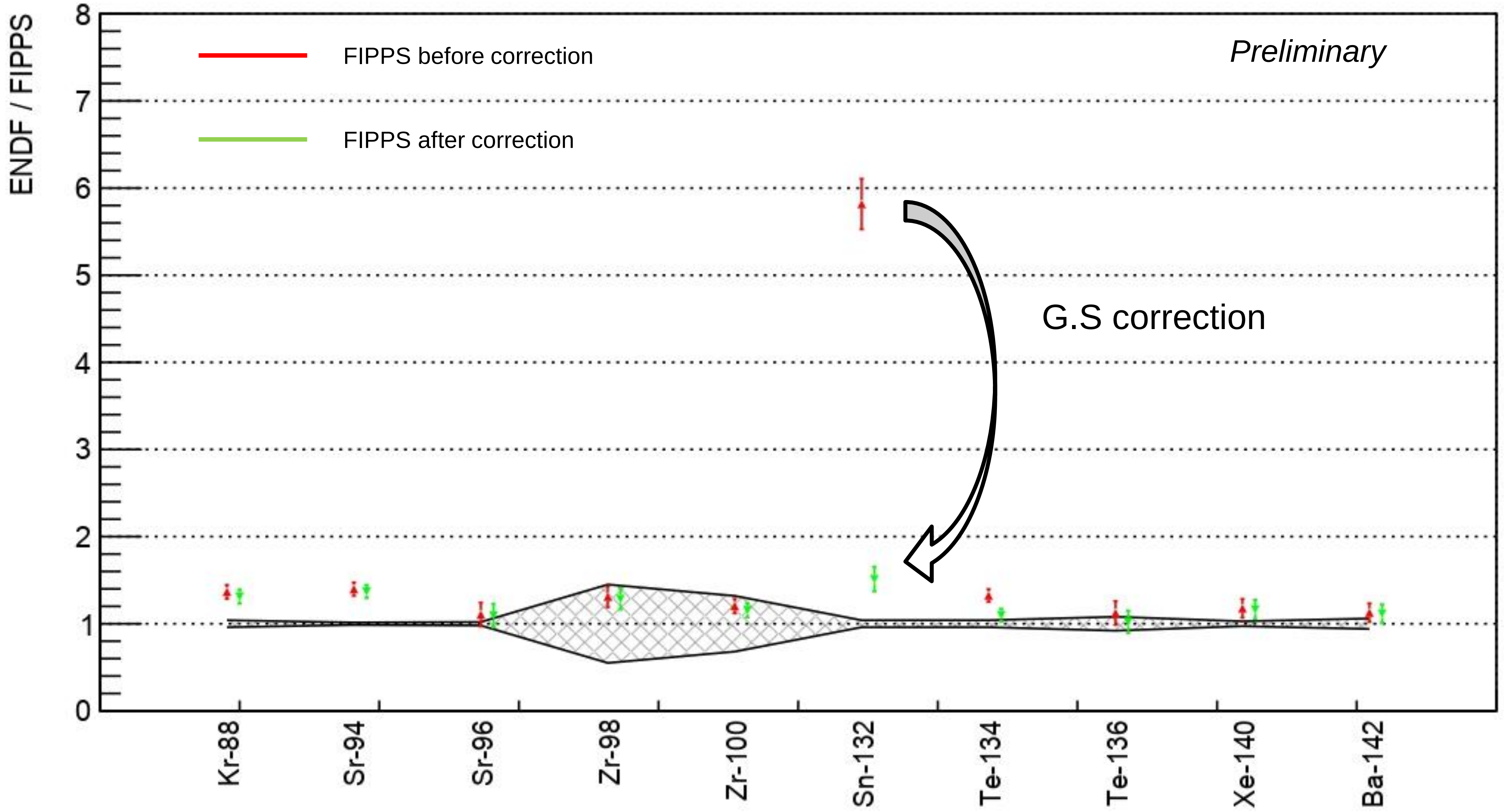
ENDF B-VIII : Y(Sn-132) = 0.59 ± 0.02

→ Discrepancies around a factor 6

Production directly in the ground state

FIPPS after correction : Y(Sn-132) = 0.52 ± 0.04

Comparison on independant isotopic fission yields with ENDF B-VIII



Conclusion

Test of an alternative method for measuring independent isotopic fission yields of $^{235}U(n_{th},f)$
using prompt gamma-rays, which takes advantage of an active target

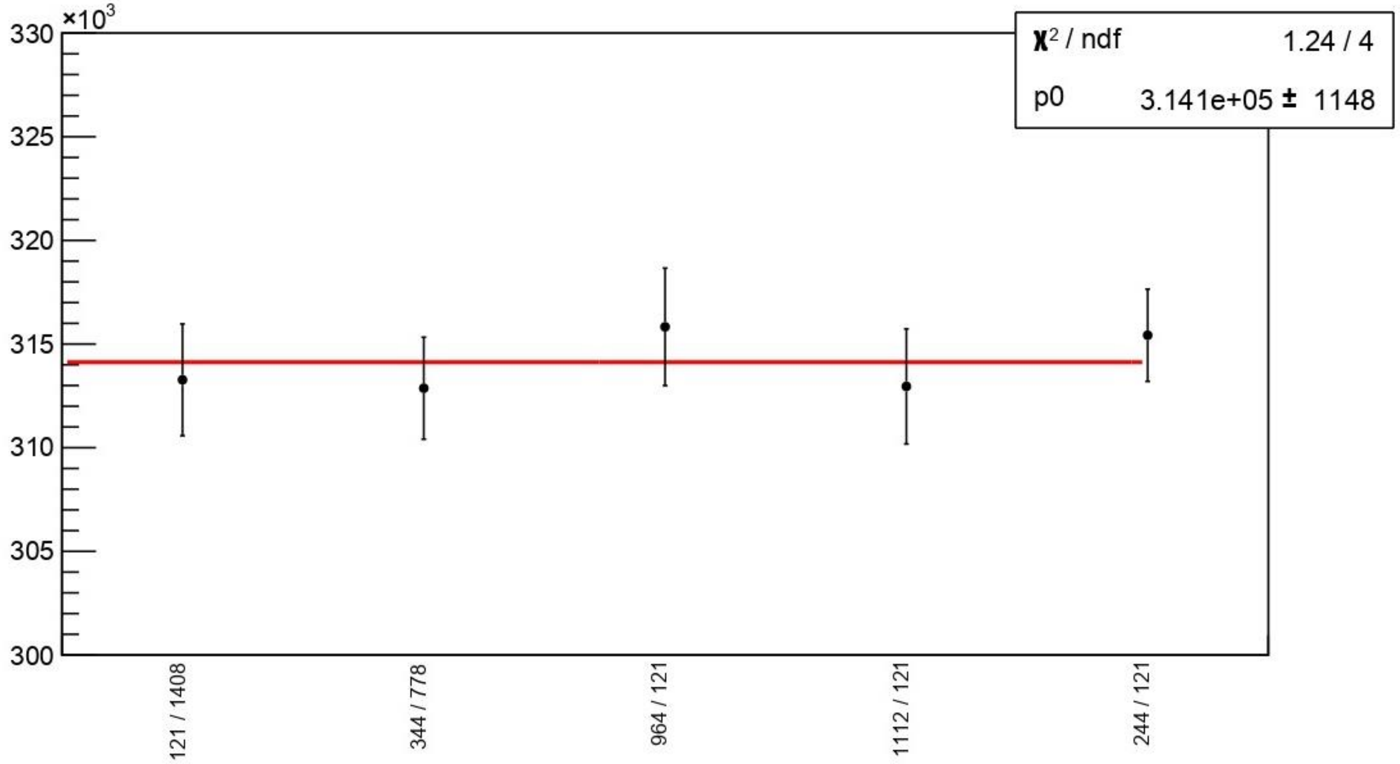
Limits :
- All the gamma-rays of the cascade are not necessarily known
- Direct production to the ground state (after fission or neutron emission) obtained from simulation (FIFRELIN)

Advantages :
- Access to fragments that are difficult to measure at Lohengrin (heavy fragments)
- Indirect but absolute measurement (no normalization)
- Applicable to other actinides if validated for U-235 (validation per fragment)
- Search for anomalies

A difference of a factor of 6 was observed in the yields of Sn132
→ This can be interpreted thanks to FIFRELIN simulation

THANK YOU FOR YOUR ATTENTION

Efficiency



$$\epsilon(E_\gamma) = \frac{N_m(E_\gamma)}{I_\gamma \times A\Delta t} \times \tau$$

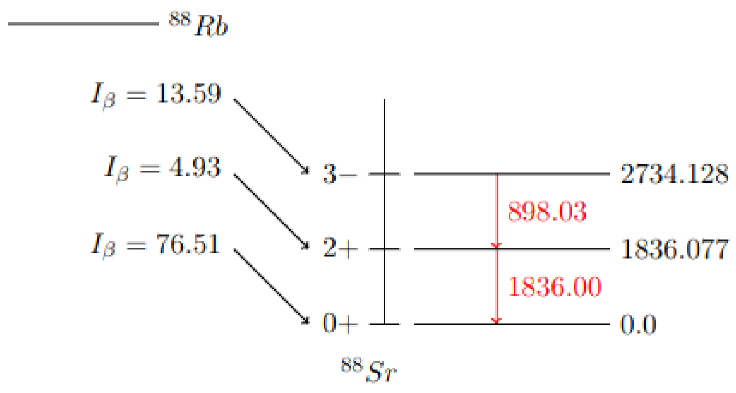
$$A = \frac{1}{T}\frac{I_{12}}{I_1 I_2}\frac{\alpha^s_{\gamma_1\gamma_2}}{\alpha^s_{\gamma_1}\alpha^s_{\gamma_2}}\frac{N-1}{N}\frac{n_m(E_1)n_m(E_2)}{n^v_m(E_1,E_2)}$$

Cross-check of the number of fissions with delayed gamma rays

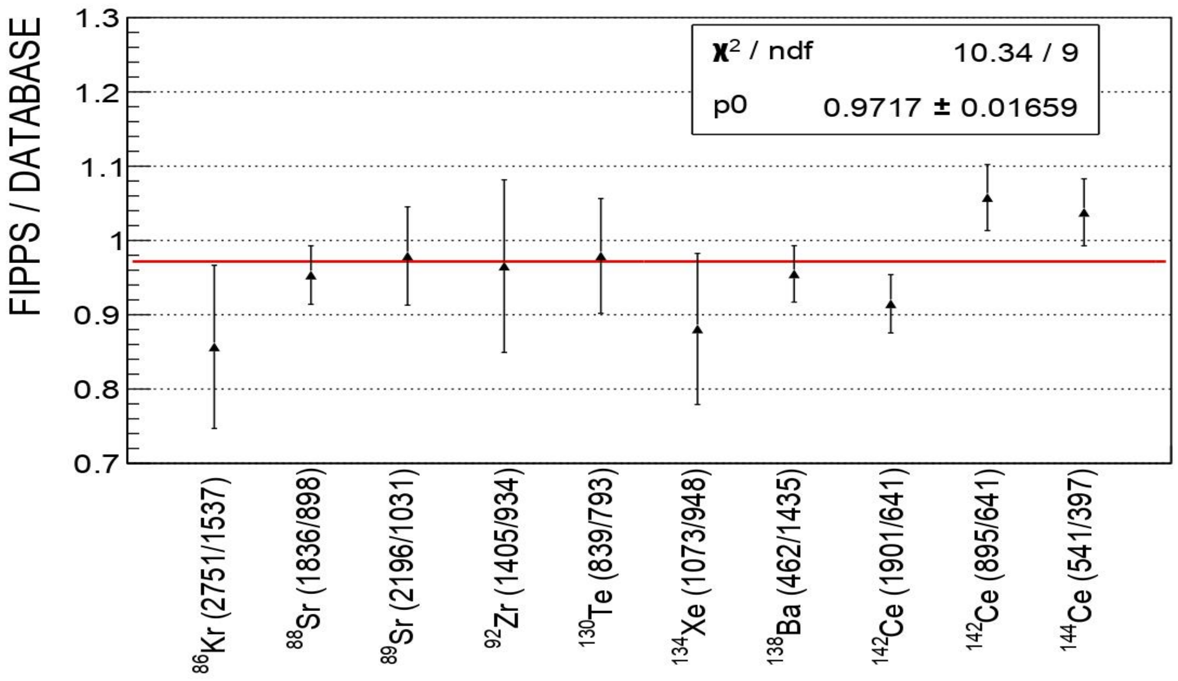
Cross-check of the number of fissions with the delayed gamma-rays of a set of fission products

Selection of the fission products :

- Simulation of the delayed gamma cascades of U-235 fission using
    - Geant-4 module RadioactiveDecay
    - FISPACT to correct cumulative yields
- Criterion of peak "cleanliness" and signal / background noise



Number of measured gamma-gamma coincidences / number of expected coincidences



Fission product daughter and used gamma-ray energies

Monte Carlo code FIFRELIN

- Fission models (nuclear charge, excitation energy partitioning, spin distribution,…)
- Nuclear structure models (level density, gamma strength functions, neutron transmission,…)
- Deexcitation models (Weisskopf, Hauser-Feshbach,…)
- Experimental database (RIPL,…)

Observables

Post-neutron yields, kinetic energies

Prompt neutrons and gamma-ray spectra and multiplicities

Gamma-ray cascades in fission fragments

data

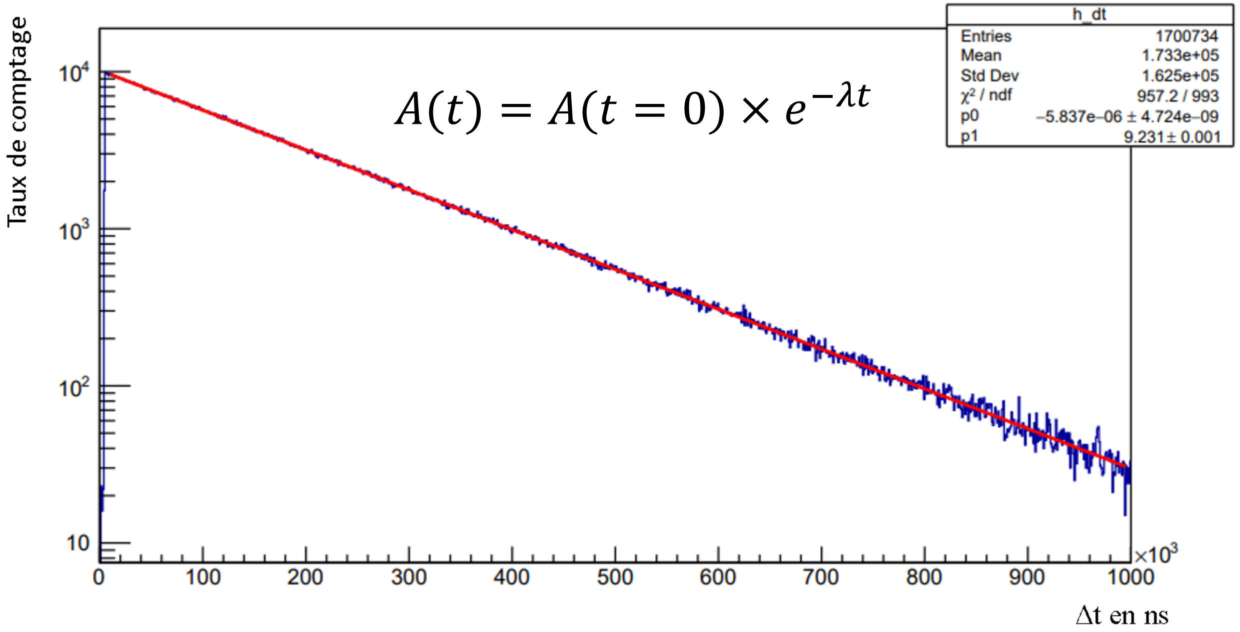
Useful data for applications

- Residual power
- Reactor gamma heat
- Neutron fluence

O. Litaize et O. Sérot, PRC 82, 054616 (2010)

Efficacité : temps mort

Différence de temps entre 2 évènements consécutifs



$1/\lambda$ = espérance = temps moyen (en seconde) entre 2 évènements -> λ = taux de comptage

->-λ = pente de la droite en log/lin

Par ailleurs :

$A(t=0) = \lambda * N_{tot}$

où N_{tot} = nombre total d'évènements

et $N_{tot} = T_{acq} * \lambda$

-> deux possibilités pour calculer N_{tot}

Si « *Entries* » : nombres d'évènements enregistrés par le système d'acquisition

τ : Facteur correctif à appliquer est simplement en 1ère approche :

$$\boldsymbol{\tau = \frac{N_{tot}}{Entries} = 1,030 \pm 0,004}$$