

Total gamma-ray energy in ^{252}Cf spontaneous fission

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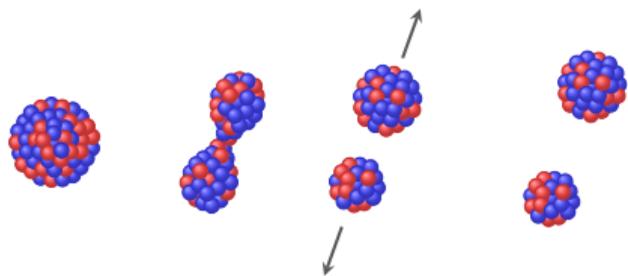


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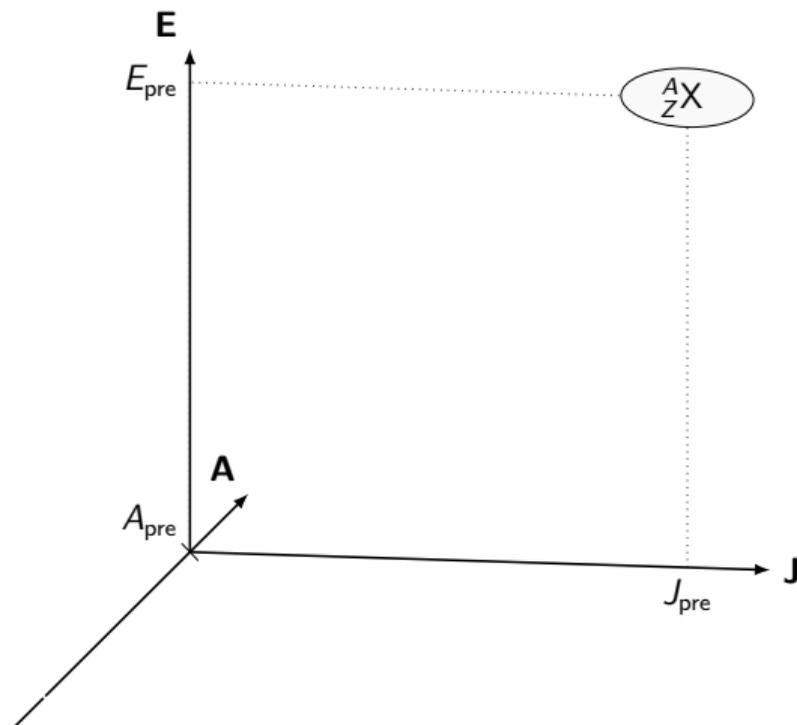


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 - The VESPA-I setup
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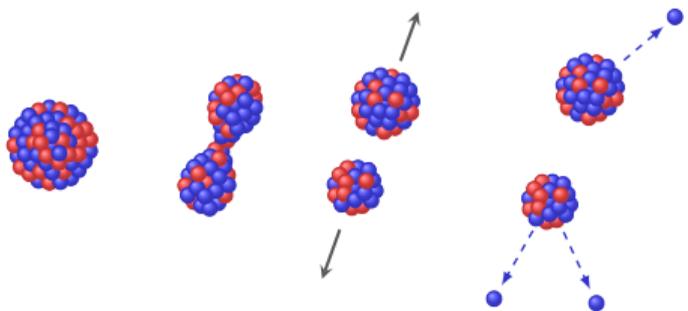
Introduction : Prompt fission γ -ray emission



Nuclear fission \rightarrow excited fission fragments

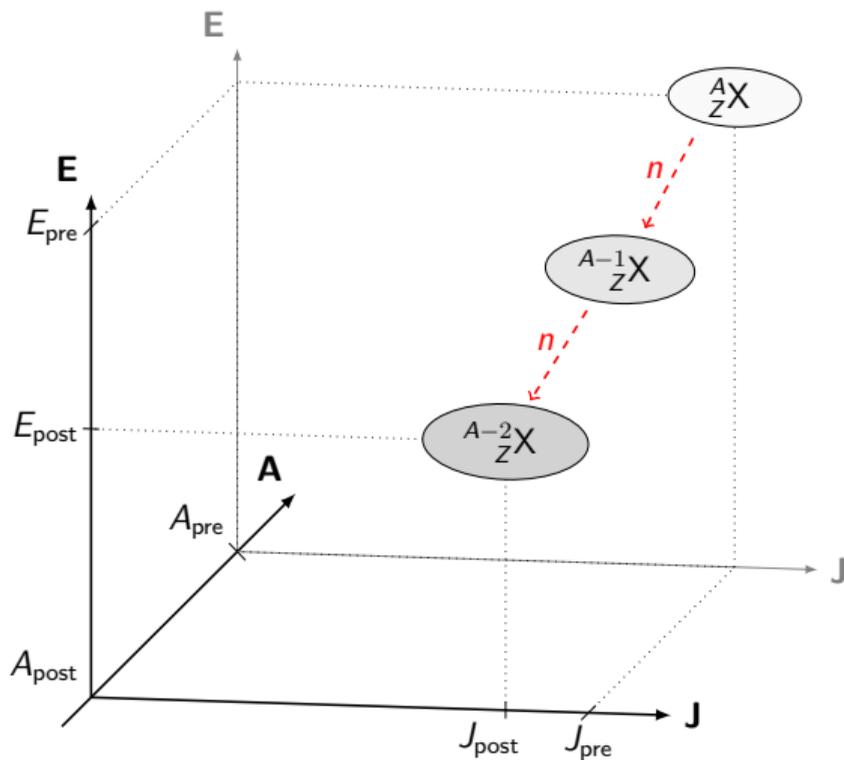


Introduction : Prompt fission γ -ray emission

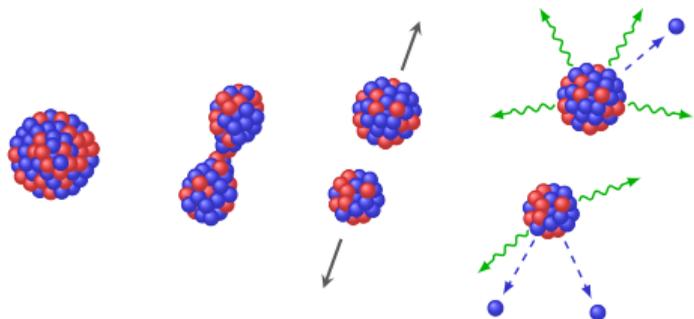


Nuclear fission \rightarrow excited fission fragments

Prompt neutron emission ($t \sim 10^{-18}/10^{-14}$ s)



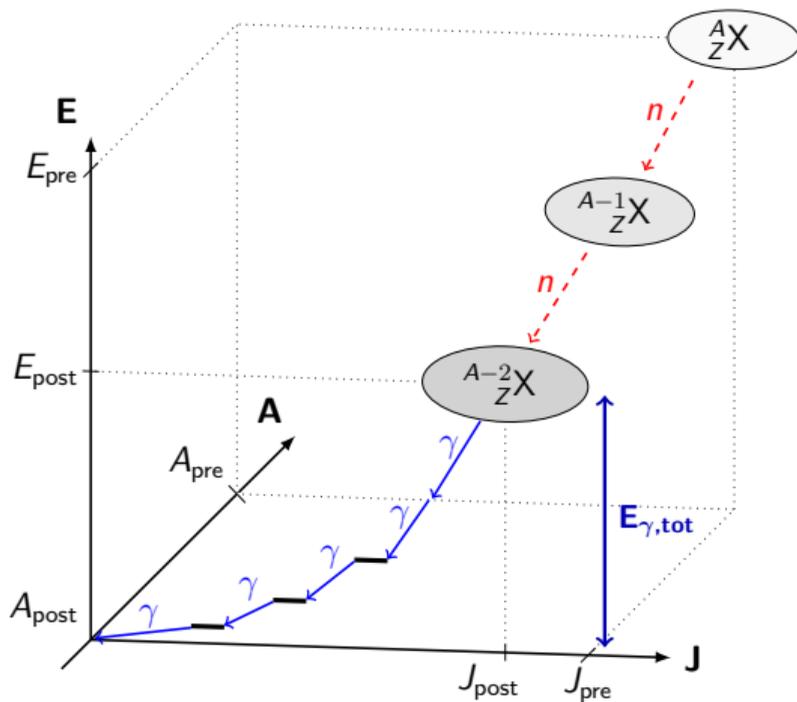
Introduction : Prompt fission γ -ray emission



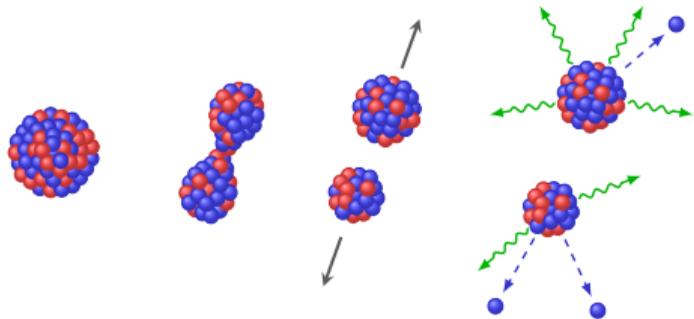
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Prompt neutron emission ($t \sim 10^{-18}/10^{-14}$ s)

Prompt γ -ray emission ($t \sim 10^{-14}/10^{-6}$ s)



Introduction : Prompt fission γ -ray emission

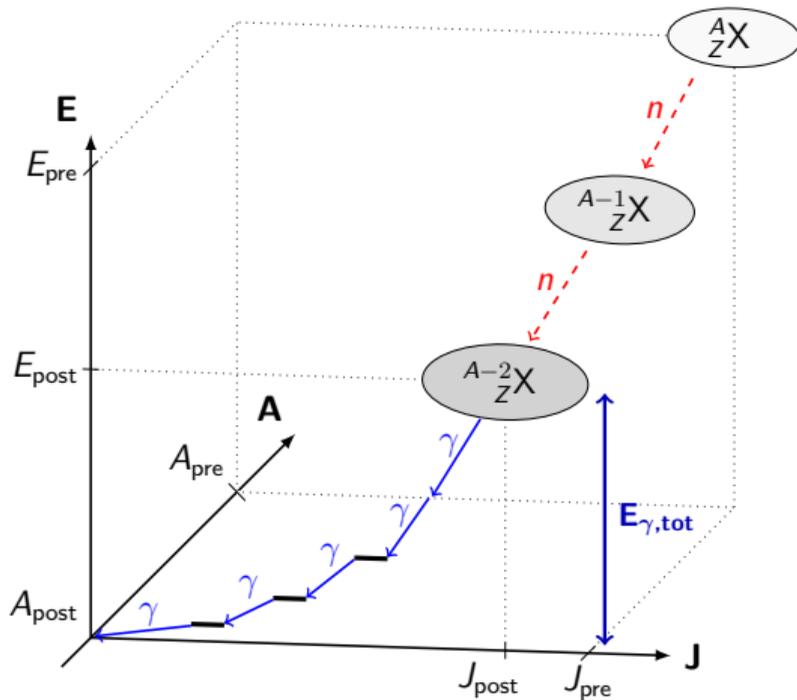


Nuclear fission \rightarrow excited fission fragments

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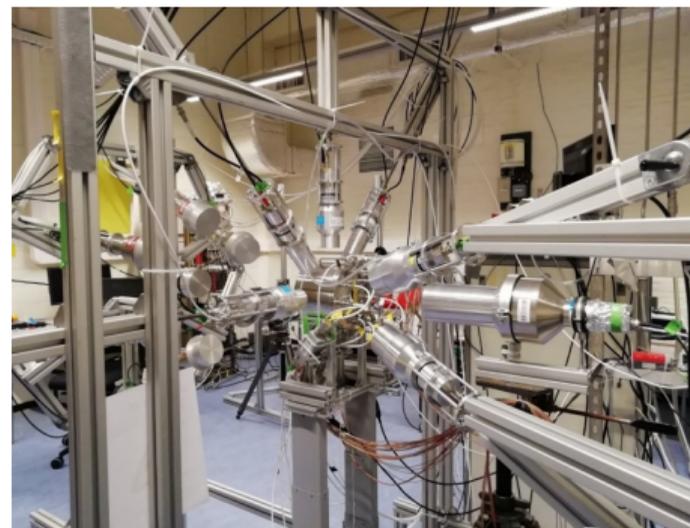
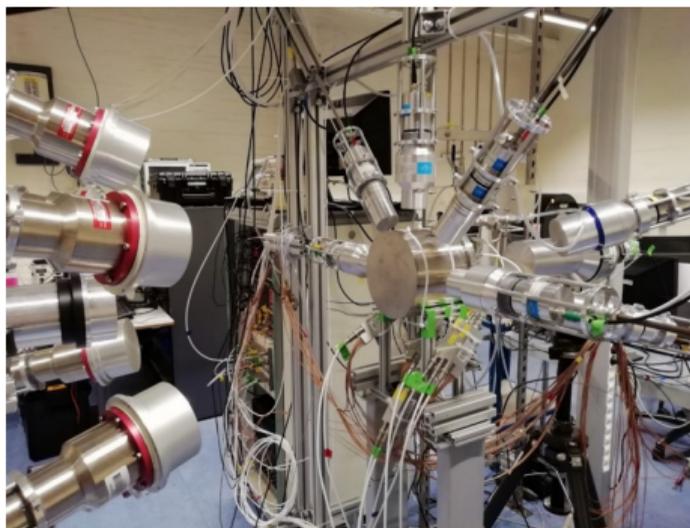
Prompt γ -ray emission ($t \sim 10^{-14}/10^{-6}$ s)

Delayed γ -ray & neutron emission :
 β -decay ($t \gtrsim 10^{-6}$ s)



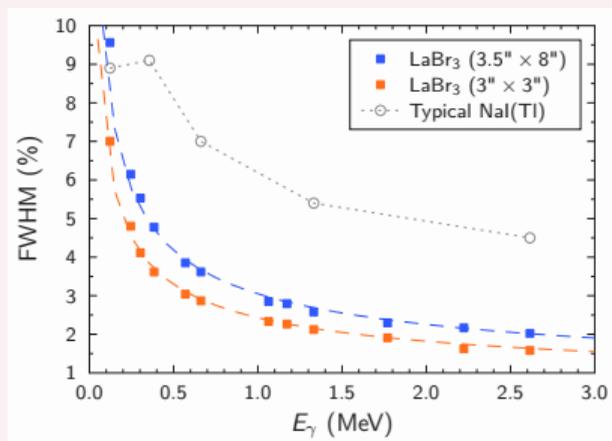
The VErsatile SPectrometer Array (VESPA++)

- ▶ 8 LaBr₃(Ce) scintillators
 - ▶ + 1 twin Frish-grid ionization chamber
 - ▶ + 7 organic scintillators
- Prompt fission γ -rays
 - Fission fragments
 - Prompt fission neutrons



LaBr₃ scintillators

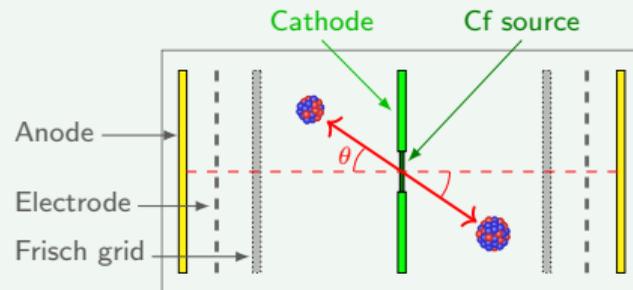
- ▶ Cylindrical modules
Various sizes, from 2" × 2" to 3.5" × 8"
- ▶ Excellent γ -ray detectors
 - ▶ **Good energy resolution**



- ▶ **Fast response**
(CRT \leq 0.9 ns @1.2 MeV)

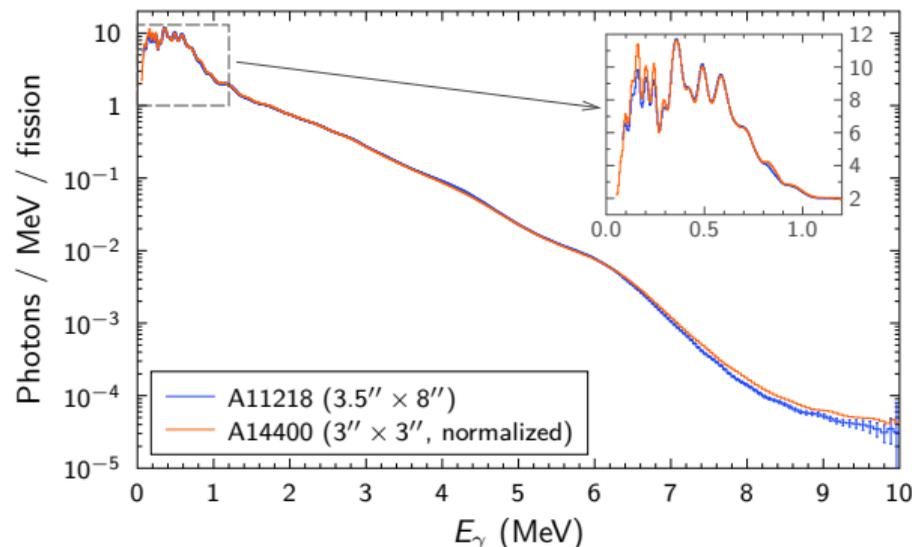
Ionization chamber

- ▶ Simultaneous measurement of FFs kinetic energies
→ **2E method** to extract pre-neutron mass and kinetic energy
⇒ Mass resolution : FWHM \sim 5 u
- ▶ **Angle** from electron drift time and position-sensitive electrodes
→ Gök *et al.*, NIMA 830, 366 (2016)



Prompt Fission Gamma-ray Spectra (PFGS)

Integral PFGS obtained with VESPA-I :

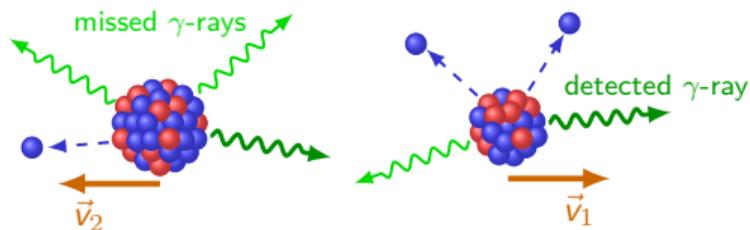


- ▶ Unfolded with an iterative algorithm (EM/'Bayes')
- ▶ Results from module A11218 ($E_\gamma \geq 80$ keV and $\Delta t = \pm 3$ ns)
 - ▶ Average γ -ray multiplicity : $\bar{M}_\gamma = 8.37(8)$ γ /fission \rightarrow integral
 - ▶ Average total γ -ray energy : $E_{\gamma,\text{tot}} = 6.89(7)$ MeV/fission \rightarrow first moment

Analysis procedure for correlated observables

Correlated observables

- ▶ Fission fragments are detected in the IC → masses and TKE + fission axis
- ▶ γ -rays emitted by **both fission fragments** are detected in the LaBr₃ modules
→ The weighting method is used to estimate the individual contributions



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Weighting method

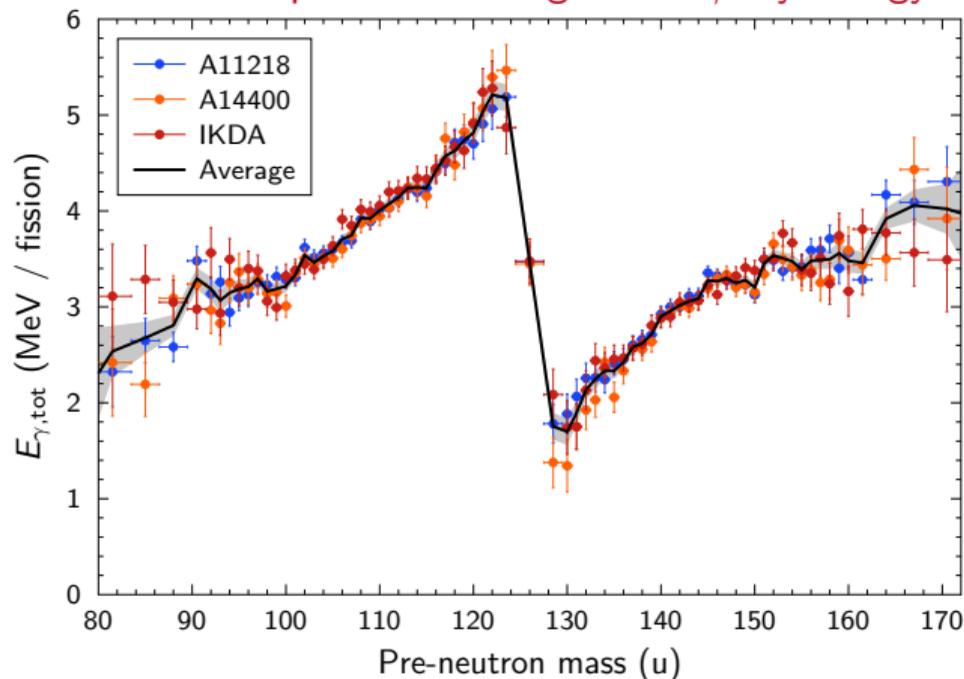
Maier Leibnitz *et al.*, Physics and Chemistry of Fission II, 143 (1965)

- ▶ Fragments are not stopped while emitting γ -rays ($t \lesssim 0.1$ ns)
- ⇒ Doppler effect → anisotropy of the γ -ray emission in the lab frame
 - ▶ Number of photons (multiplicity) : $\alpha_N(\theta \simeq 0) \simeq 2\beta$
 - ▶ Energy of the photons : $\alpha_E(\theta \simeq 0) \simeq 3\beta$

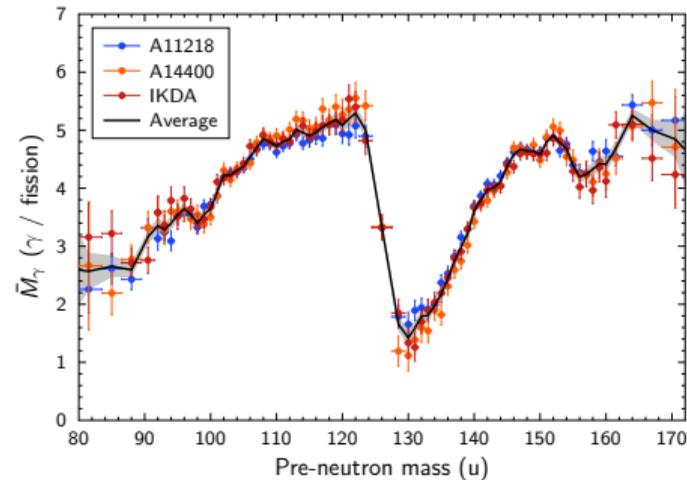
$$E_\gamma(A_1, \text{TKE}) = \frac{e_\gamma(A_1, \text{TKE})}{N_F(A_1, \text{TKE})} f_1(\alpha_E) - \frac{e_\gamma(A_2, \text{TKE})}{N_F(A_2, \text{TKE})} f_2(\alpha_E)$$

Experimental results – Mass-dependent γ -rays observables

Mass-dependent average total γ -ray energy



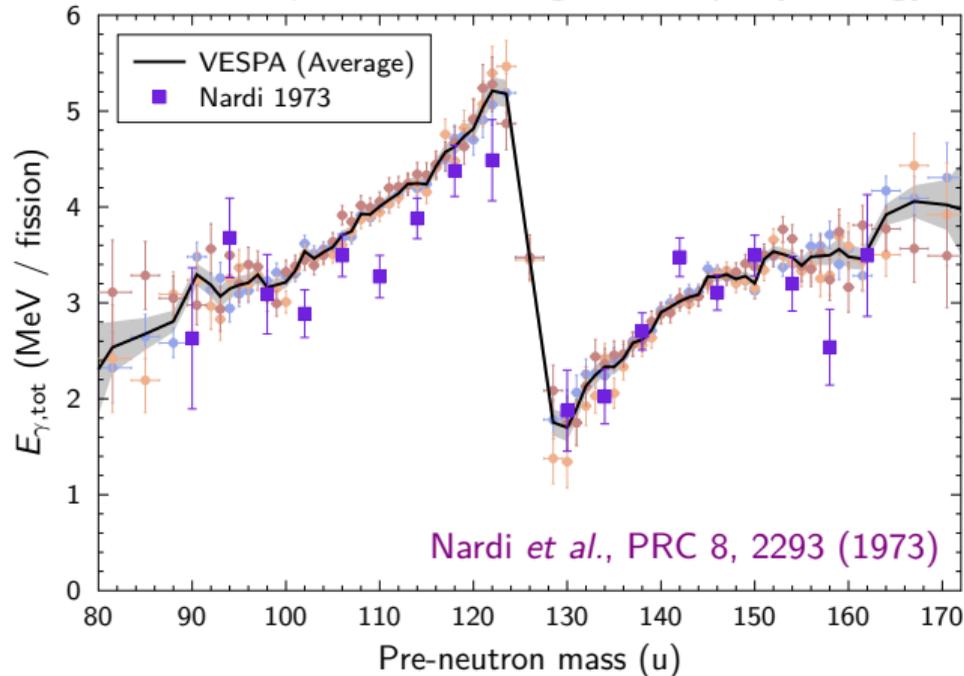
Mass-dependent average γ -ray multiplicity
→ Travar *et al.*, PLB 817, 136293 (2021)



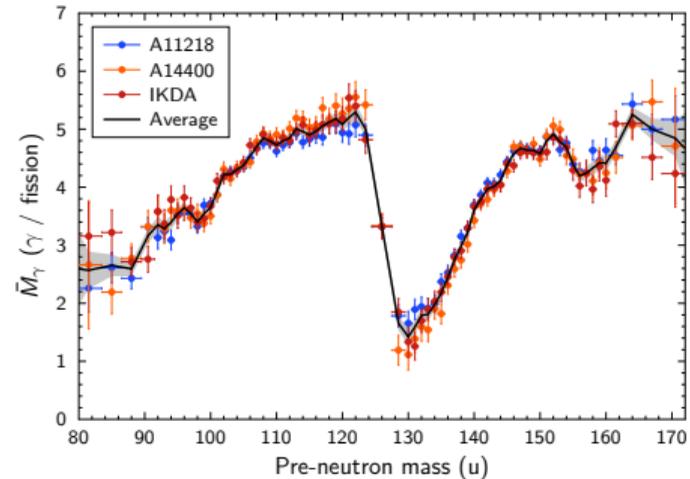
⇒ Saw-tooth shape with a minimum around $A \approx 130$ u

Experimental results – Mass-dependent γ -rays observables

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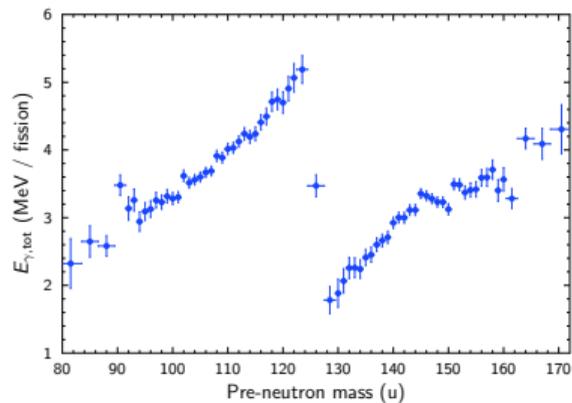


Mass-dependent average γ -ray multiplicity → Travar *et al.*, PLB 817, 136293 (2021)

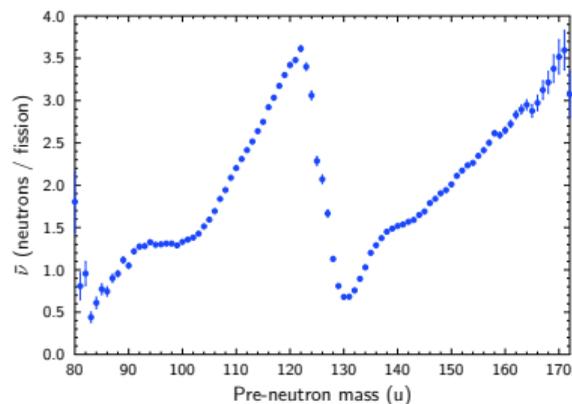


⇒ Saw-tooth shape with a minimum around $A \simeq 130$ u

Experimental results – n/γ correlations

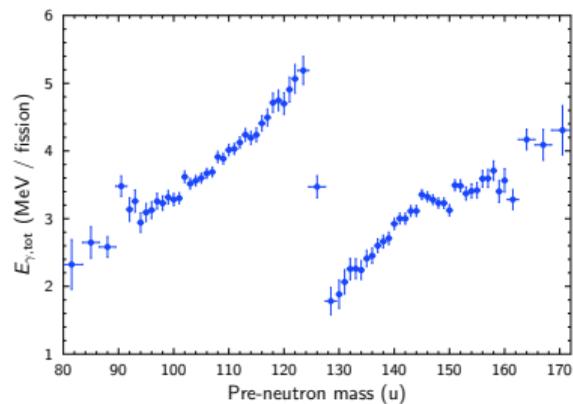


$E_{\gamma, \text{tot}}(A)$: VESPA data

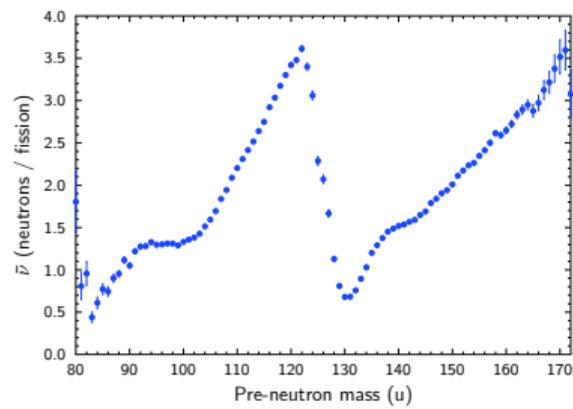


$\bar{\nu}(A)$: Gök et al., PRC 90, 064611 (2014)

Experimental results – n/γ correlations

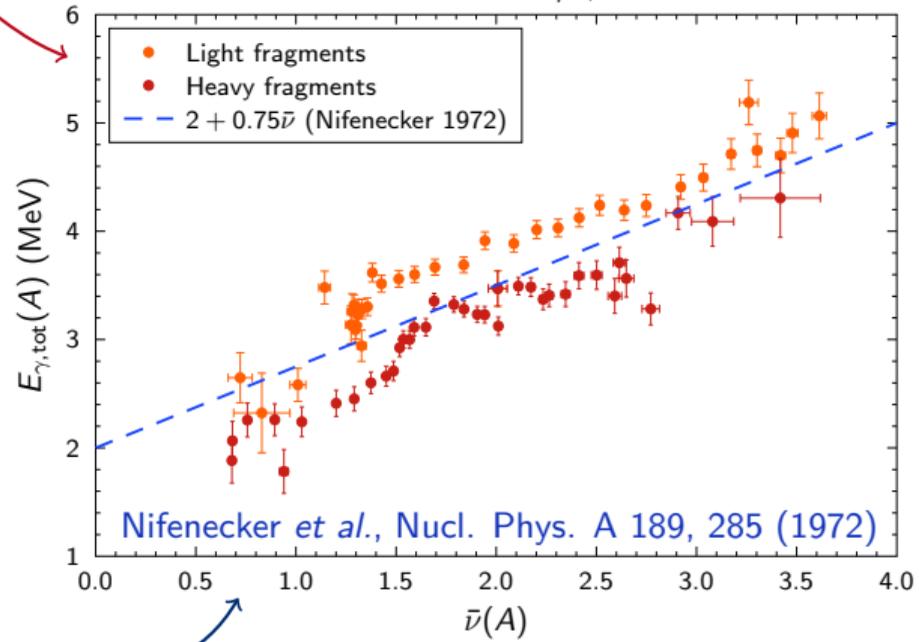


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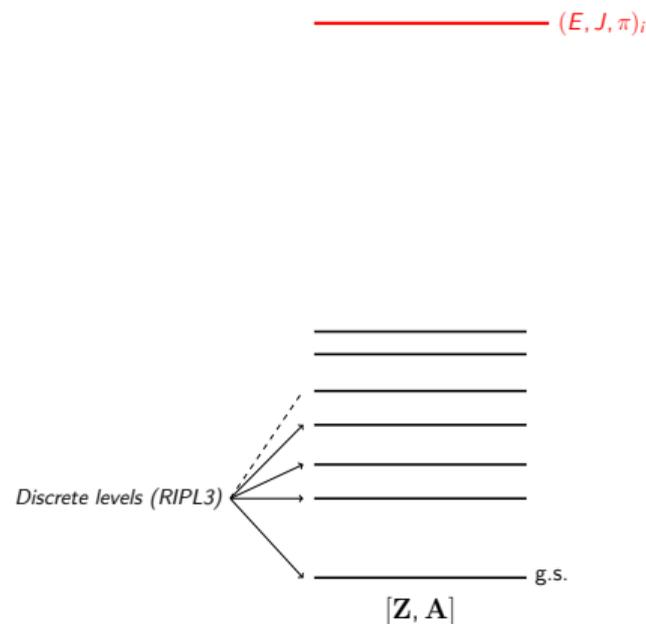
Mass-wise n/γ correlations



Stochastic code developed at CEA Cadarache for modeling nuclear de-excitation by coupled emission (n, γ, e^-) after fission (or neutron capture)
→ Litaize *et al.*, Eur. Phys. J. A 51, 177 (2015)

Two-step fission calculation

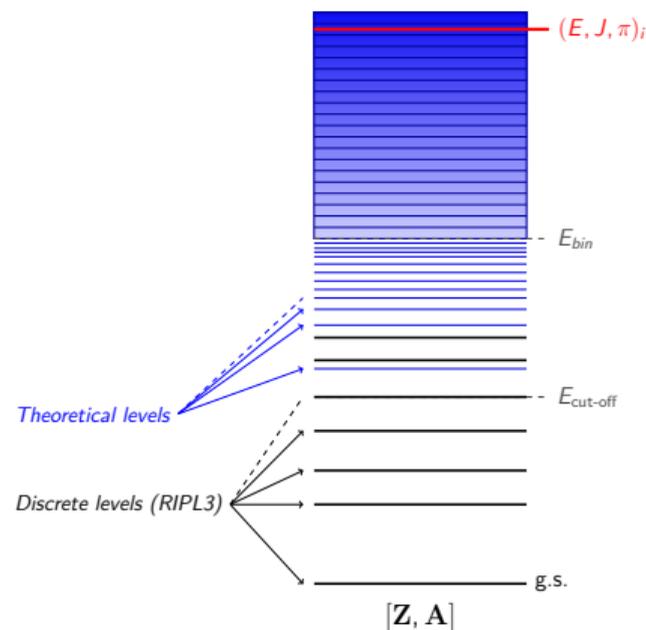
- ▶ Definition of the entry zone
 - ▶ A, Z, E^*, J, π of primary fission fragments
 - ▶ From input data and nuclear models
 - ▶ 4 free parameters (spin and excitation energy sharing)
- ▶ Scheme construction and de-excitation
 - ▶ Discrete levels from RIPL-3 database



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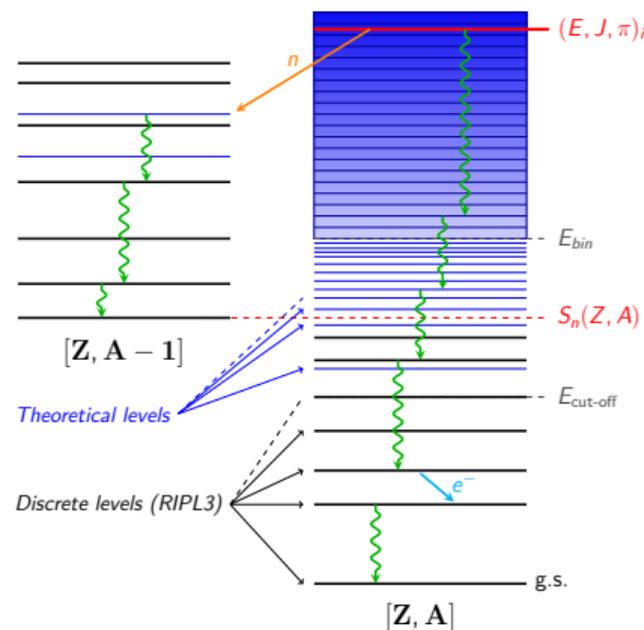
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 - ▶ Hauser-Feshbach algorithm : coupled neutron and EM emissions ($\gamma + e^-_{IC}$)

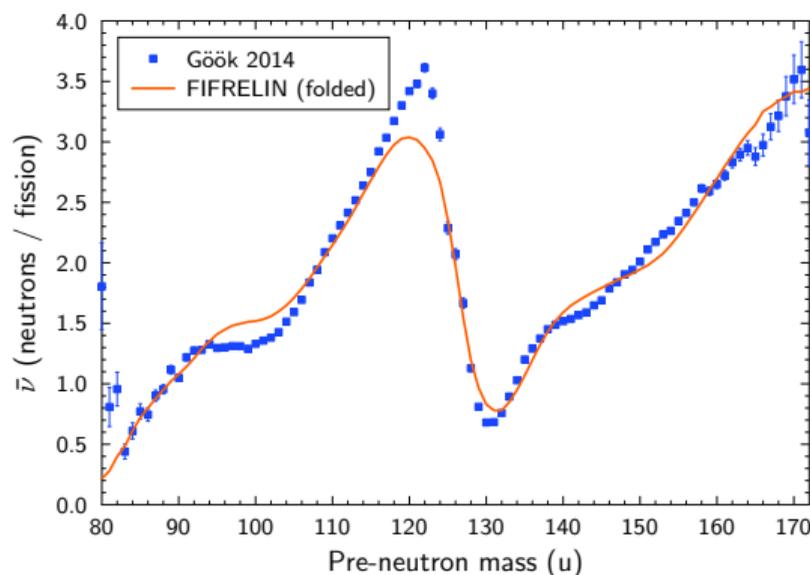
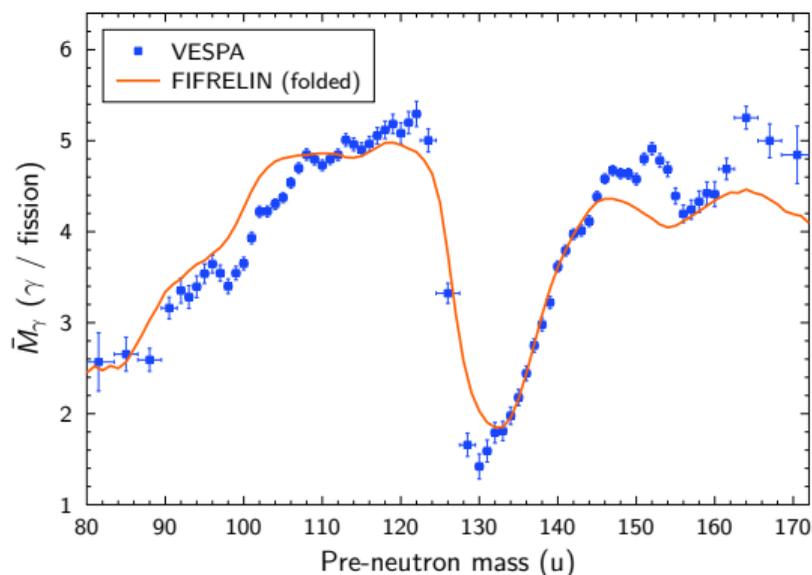


Comparison with the experiment

FIFRELIN reproduces well neutron and γ -ray multiplicity distributions

→ Piau *et al.*, PLB 837, 137648 (2023)

⇒ **Reference calculation** used in this work



FIFRELIN results are folded with experimental mass resolution (FWHM $\simeq 5$ u)

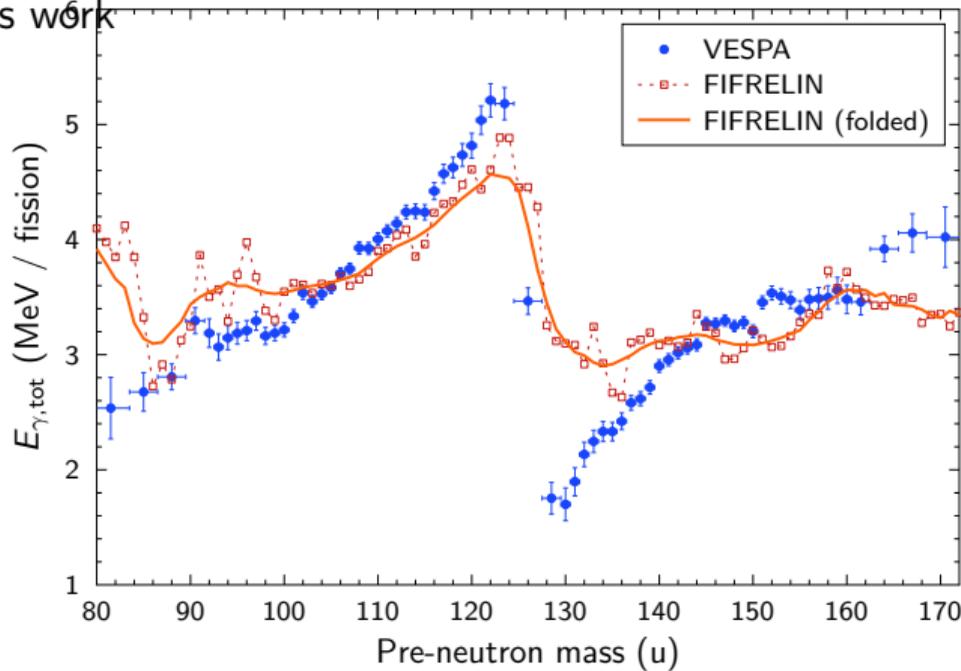
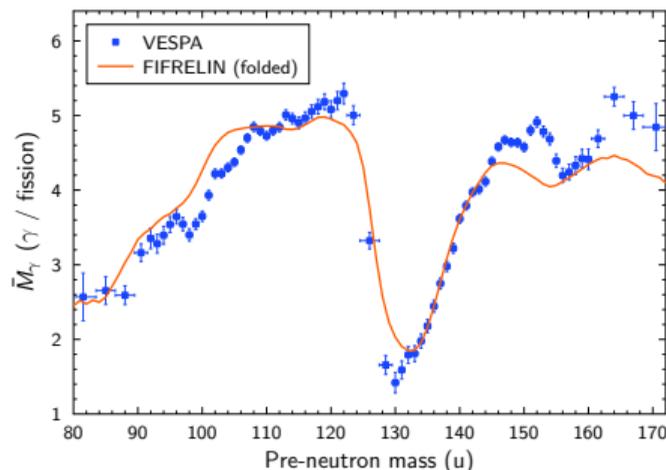
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...but fails to reproduce $E_{\gamma,\text{tot}}(A)$



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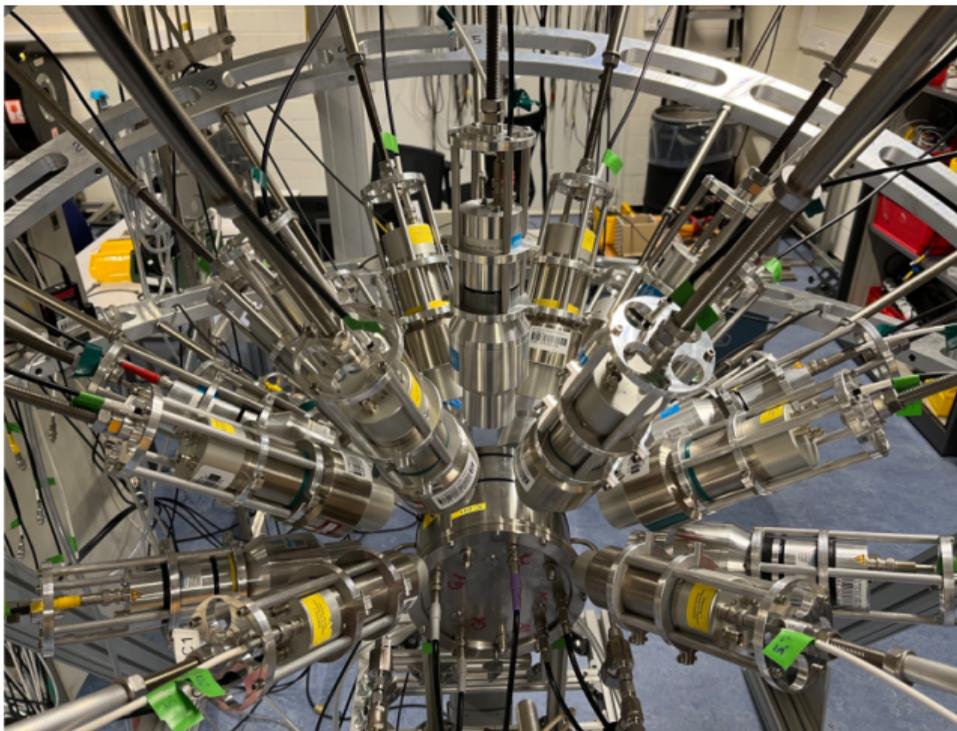
- ▶ The VESPA-I setup was used to measure prompt fission γ -rays from $^{252}\text{Cf}(\text{sf})$ using LaBr_3 detectors during the 2019/2022 campaign.
- ▶ Saw-tooth patterns were observed in the mass-dependent distribution of the γ -ray multiplicity and total energy distributions.
- ▶ Although FIFRELIN reproduces well the multiplicity distributions (neutrons and γ), its description of the total energy distributions needs improvements :
 - ▶ the calculation follows the experimental trend,
 - ▶ but it overestimates the $A \in [129 - 140]$ region.

⇒ Such prompt fission γ -rays measurements are of great interest to constrain nuclear models and data used in FIFRELIN.

Similar measurements are now carried on with VESPA-II setup (30 $\text{LaBr}_3/\text{CeBr}_3$ detectors) as part of the PhD thesis of Alan Danilo.

Thank you for your attention !

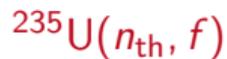
Backup



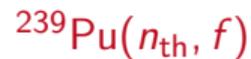
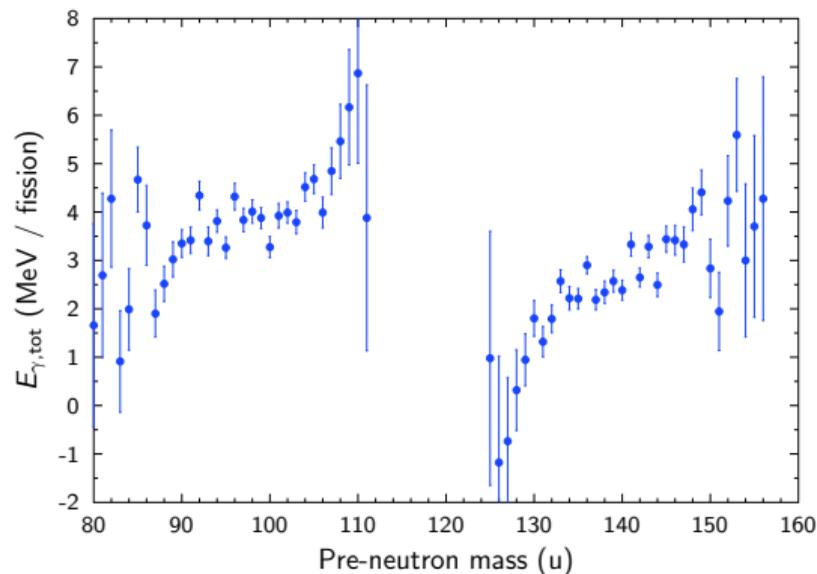
- ▶ Twin Frisch-grid IC
+ 30 γ -rays detectors :
 - ▶ 15 CeBr₃ (2" \times 2")
 - ▶ 10 LaBr₃(Ce) (2" \times 2")
 - ▶ 2 LaBr₃(Ce) (3" \times 3")
 - ▶ 1 LaBr₃(Ce) (3.5" \times 8")
 - ▶ 2 LaBr₃(CeSr) (2" \times 3")
 - ▶ 1 HPGe (in the near future)
- ▶ @17 cm from the source
- ▶ ²⁴⁸Cm(sf) fission source

Courtesy of S. Oberstedt

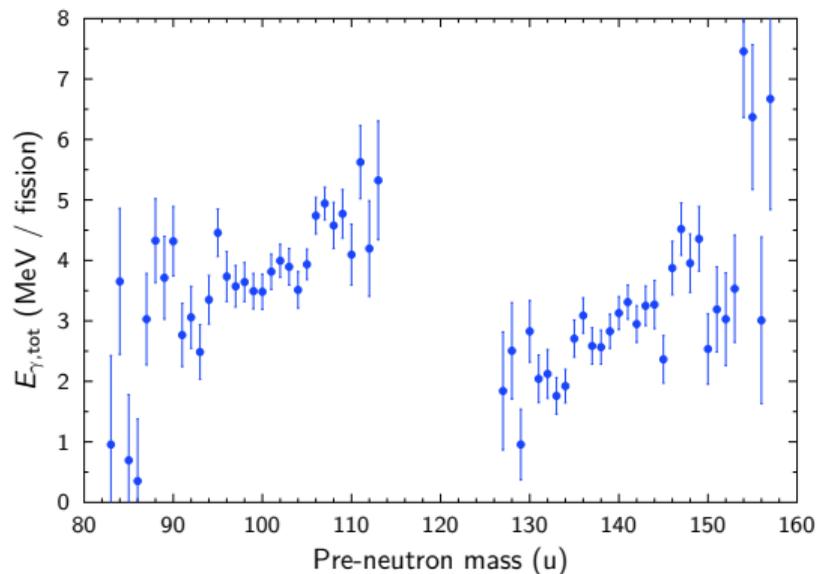
Other fissioning systems



Pleasanton *et al.*, PRC 6, 1023 (1972)

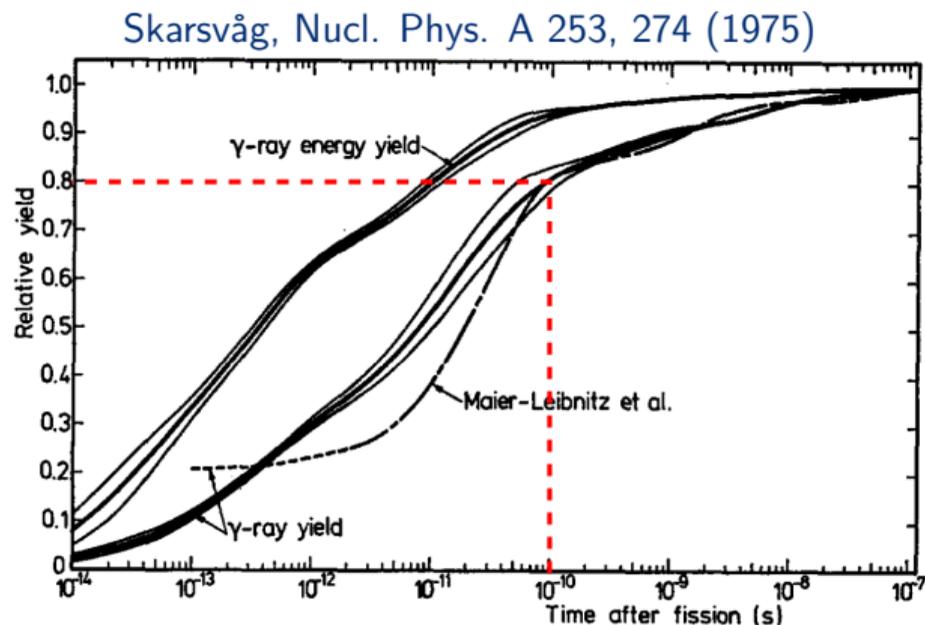


Pleasanton, Nucl. Phys. A, 213 (1973)



Emission time of prompt fission γ -rays

80 % of the prompt γ -ray yield is emitted within 0.1 ns after scission :



- Fragments are not stopped in the IC while emitting γ -rays
- Moving FF during γ emission : Doppler effect $\Rightarrow \theta_{\text{lab}} \neq \theta_{\text{cm}}$

Applying the weighting method

3 LaBr₃ modules were aligned with the IC :

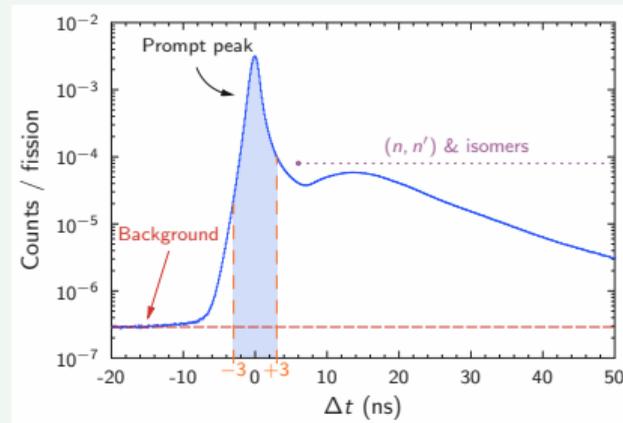
- ▶ A11218
- ▶ IKDA
- ▶ A14400



© Travar *et al.*, PLB 817 (2021)

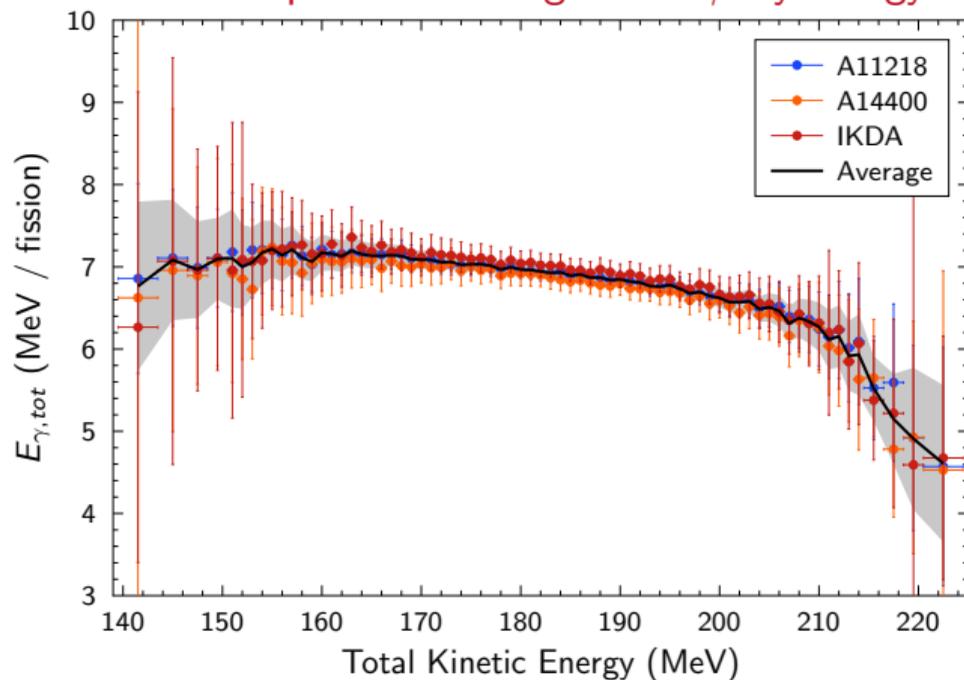
Experimental cuts

- ▶ Emission angle relative to the detector $\cos(\vartheta) > 0.9 \Rightarrow \vartheta \lesssim 26$ deg
- ▶ Time cut : ± 3 ns to remove background
 - ▶ inelastic scattering of prompt neutrons
 - ▶ decay of isomers
- ▶ Low γ -ray energy limit : 80 keV

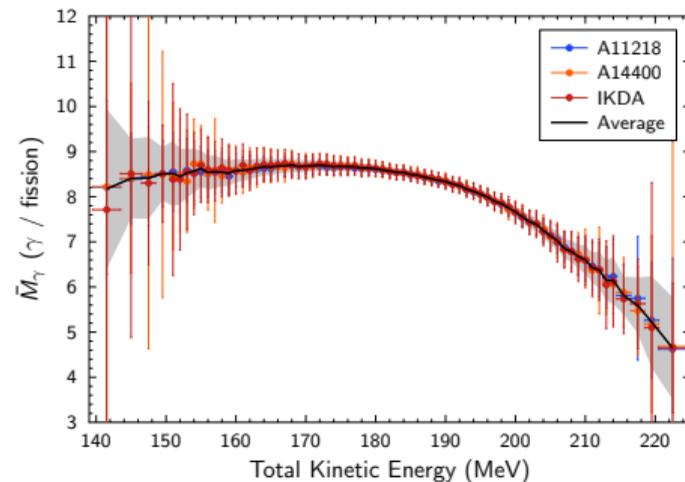


Experimental results – TKE-dependent γ -rays observables

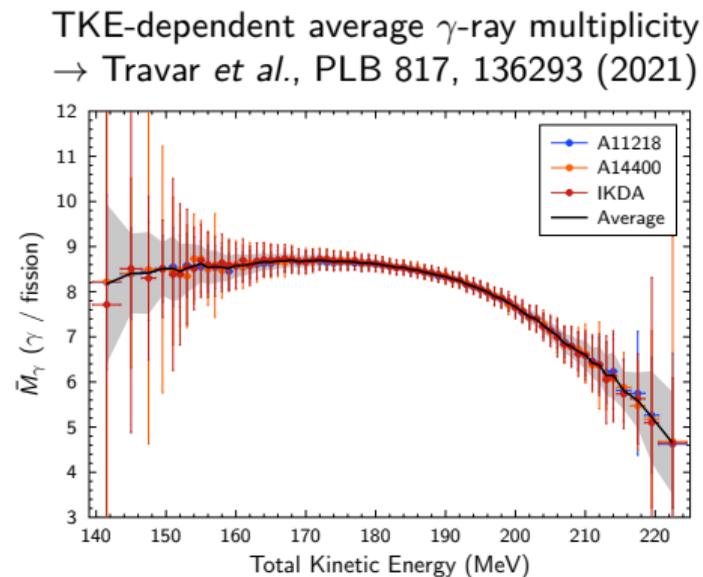
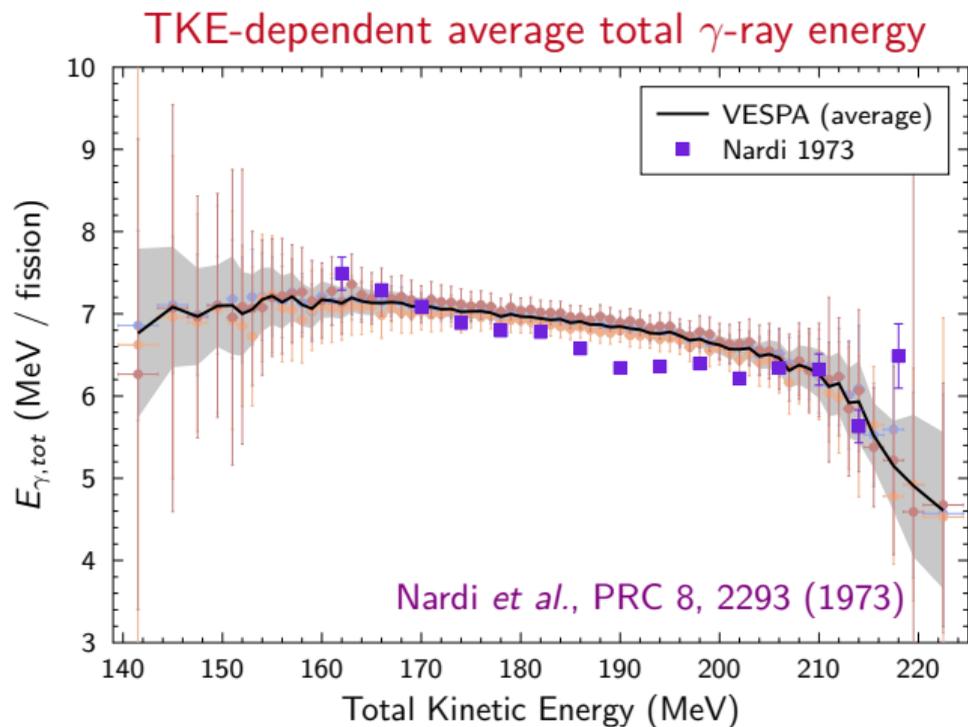
TKE-dependent average total γ -ray energy



TKE-dependent average γ -ray multiplicity → Travar *et al.*, PLB 817, 136293 (2021)

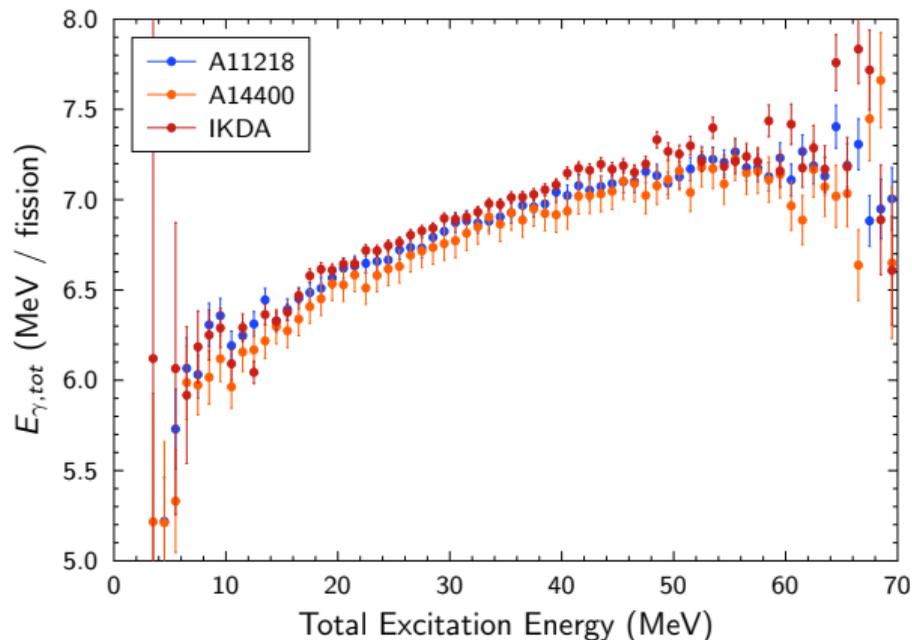


Experimental results – TKE-dependent γ -rays observables



Experimental results – TXE-dependent γ observables

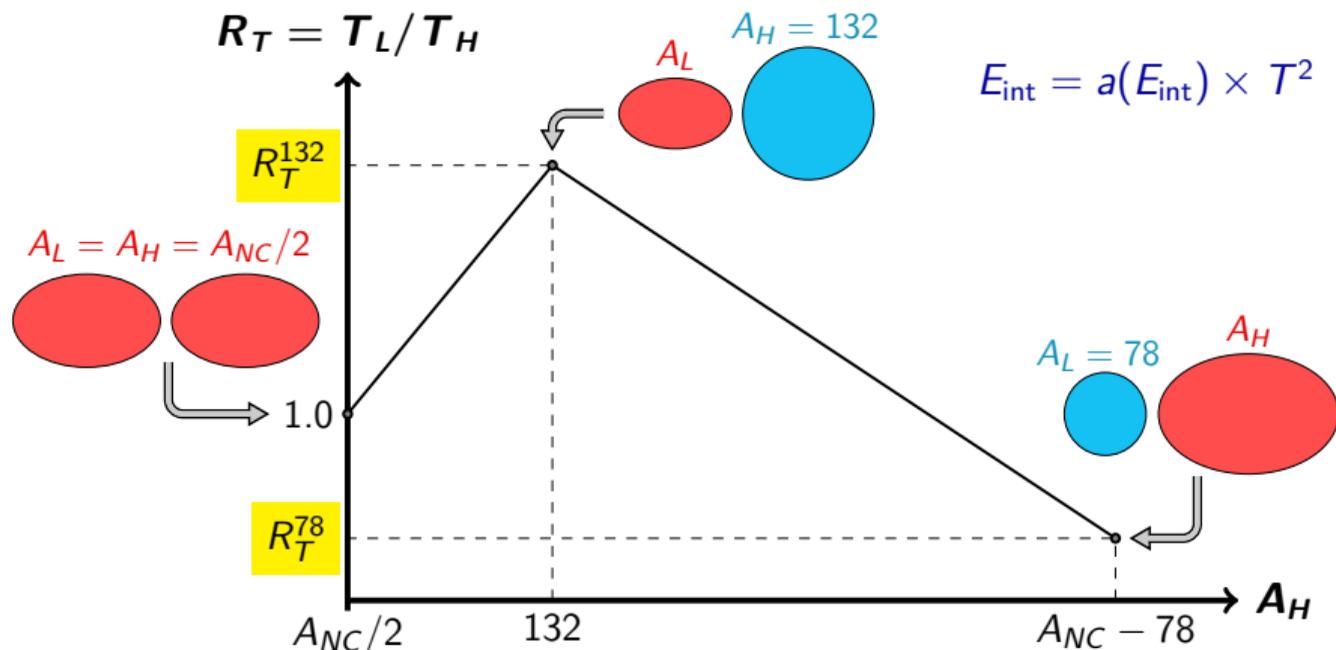
$$\text{TXE}(A) \simeq \langle Q \rangle(A) - \text{TKE}(A)$$



FIFRELIN free parameters

→ 4 free parameters

- ▶ R_T^{78} and R_T^{132} for the sharing of the intrinsic excitation energy between the FF

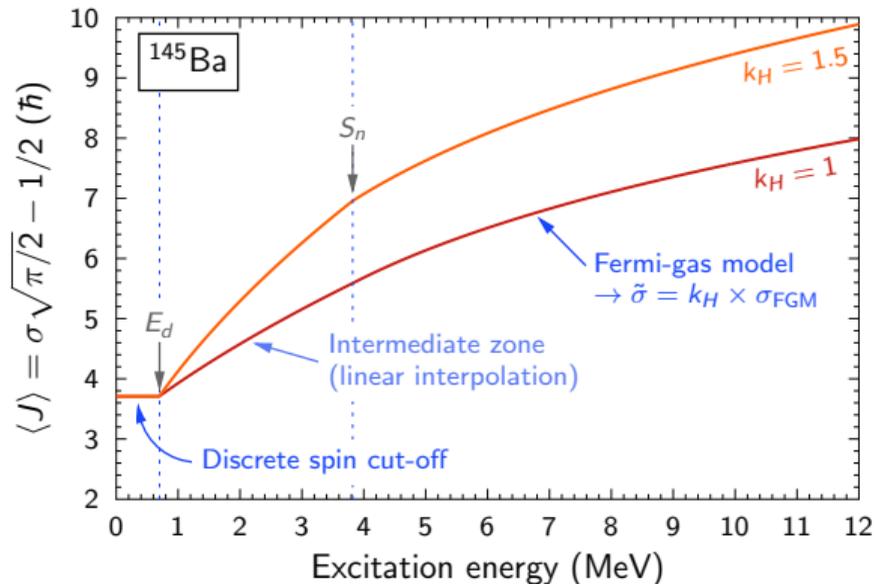
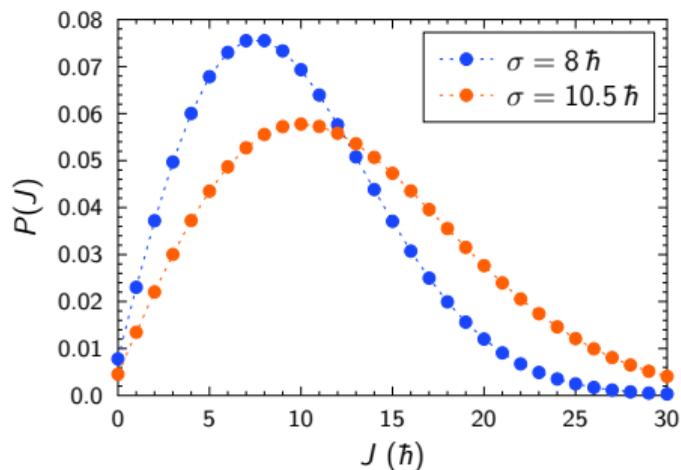


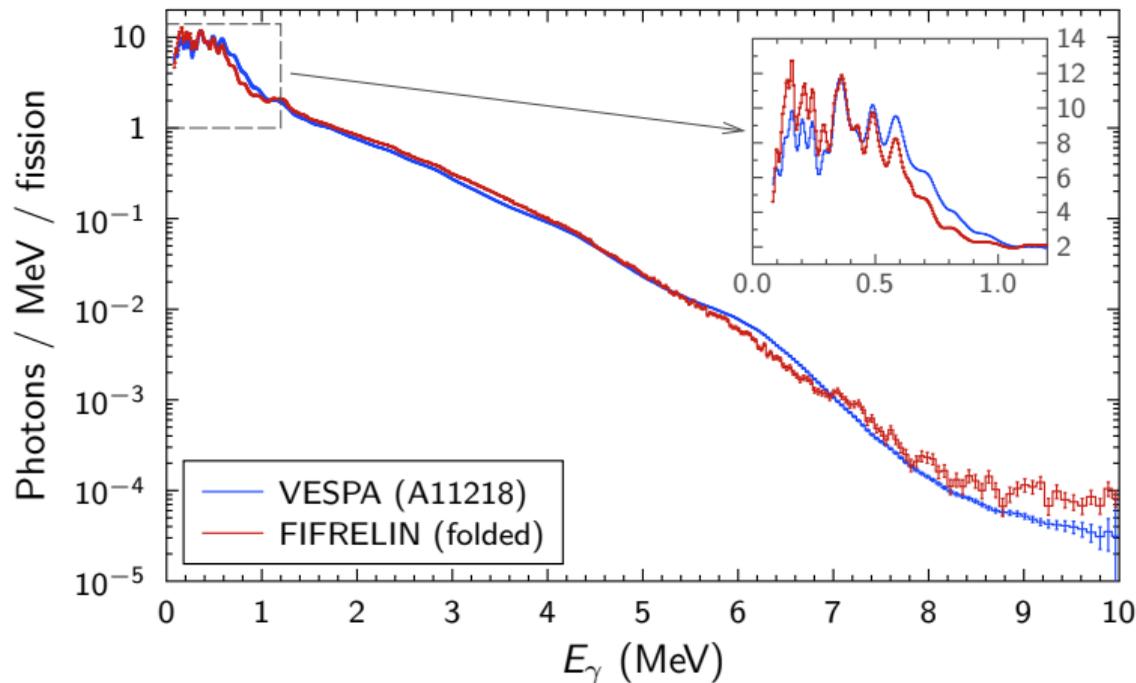
FIFRELIN free parameters

→ 4 free parameters

- ▶ R_T^{78} and R_T^{132} for the sharing of the intrinsic excitation energy between the FF
- ▶ k_L and k_H for the spin cut-off (σ^2) of light and heavy fragments, respectively

$$P(J) = \frac{2J+1}{2\sigma^2} \exp\left(-\frac{(J+1/2)^2}{2\sigma^2}\right)$$





PFGS folded by the experimental energy resolution