Measurement of prompt fission γ-rays with the VESPA setup

(Measurement of the prompt neutrons and gamma rays)

V. Piau(1), S. Oberstedt[2], A. Göök(2), A. Oberstedt[3], A. Chebboubi[1], O. Litaize[1]

1 - CEA Cadarache (SPRC/LEPh), France
2 - EC-JRC Geel, Belgium
3 - ELI-NP, IFIN-HH, Romania

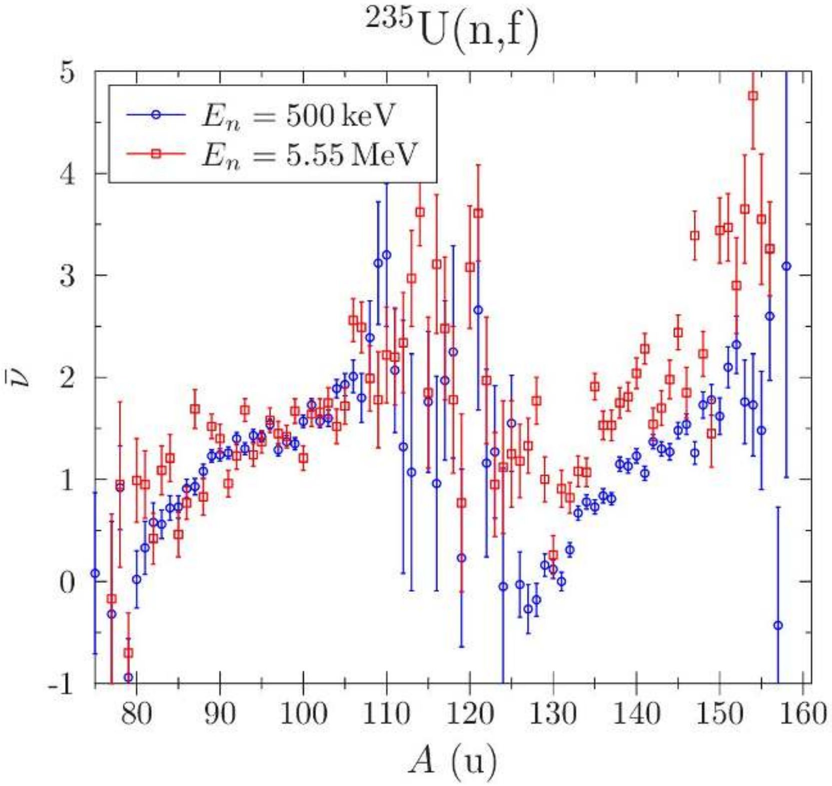
Outline

1. Introduction
2. The VESPA setup
   - Description of the detectors
   - Unfolding the prompt fission gamma-ray spectrum
3. Measurement of prompt fission gamma-rays and neutrons
   - Mass- and TKE-dependent average gamma multiplicity and total energy from VESPA
   - Prompt fission neutron measurements
   - About mass resolution
   - Angular distribution of gamma-rays
   - Identification and analysis of isomers
4. Summary

Why measuring prompt fission neutrons/γ-rays?

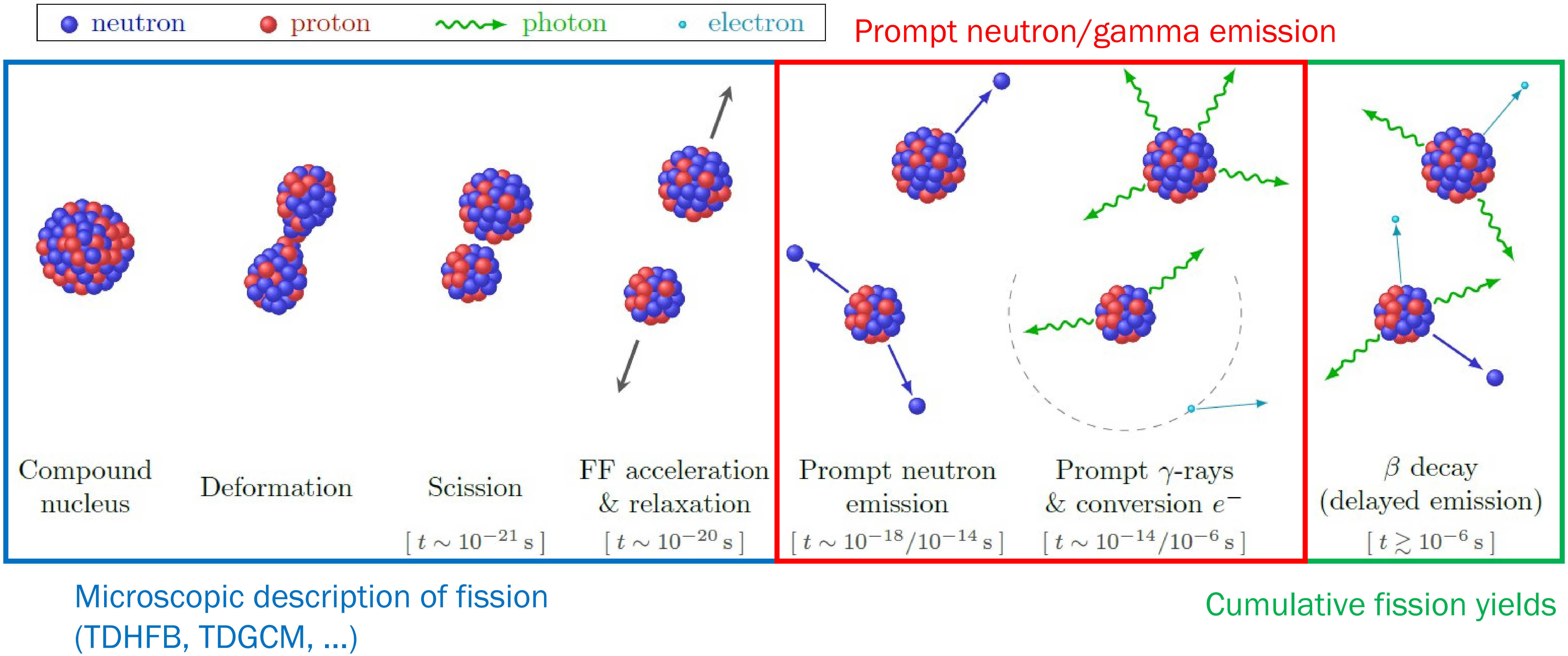
- **Nuclear data** for nuclear energy applications
  - Neutron energy and multiplicity ⟶ nuclear reactor
  - γ-ray energy ⟶ γ heating
  - Yields of secondary fission fragments (post-neutron)

- Understanding the **fission process**
  - Angular momentum generation
  - Excitation energy sharing

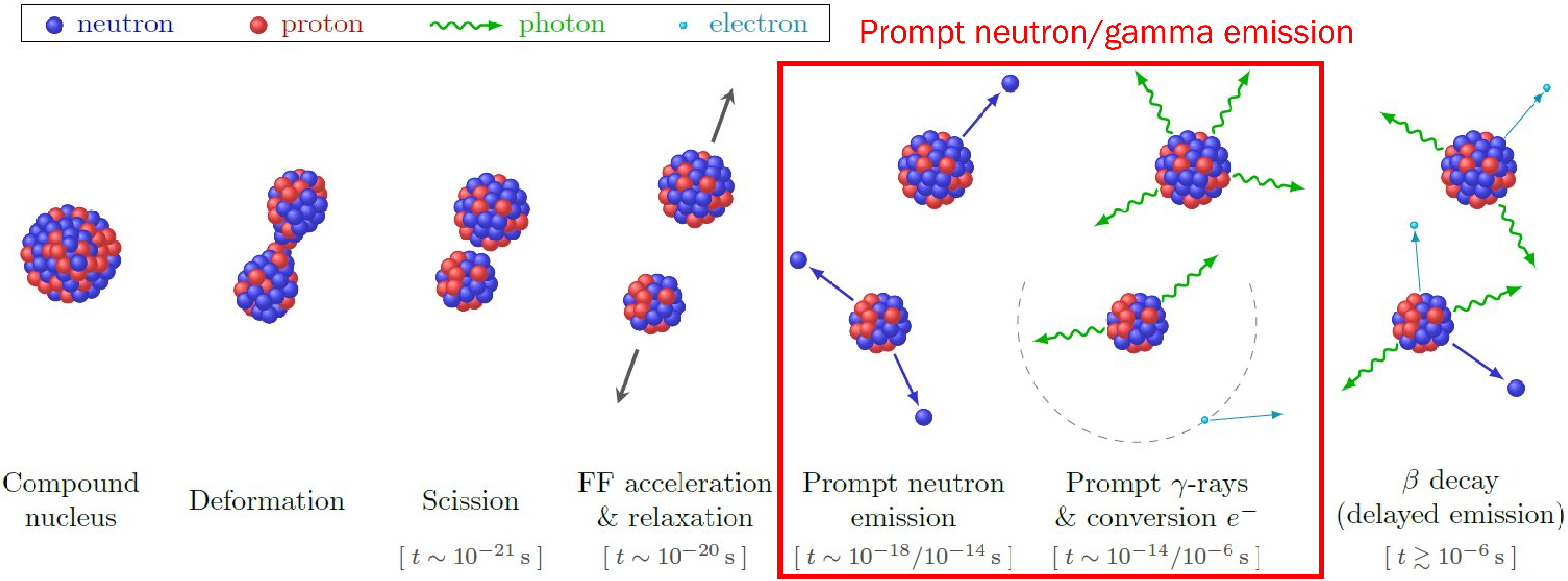


Müller et al., Phys. Rev. C 29, 885 (1984)

Neutron/gamma emission in fission



Neutron/gamma emission in fission

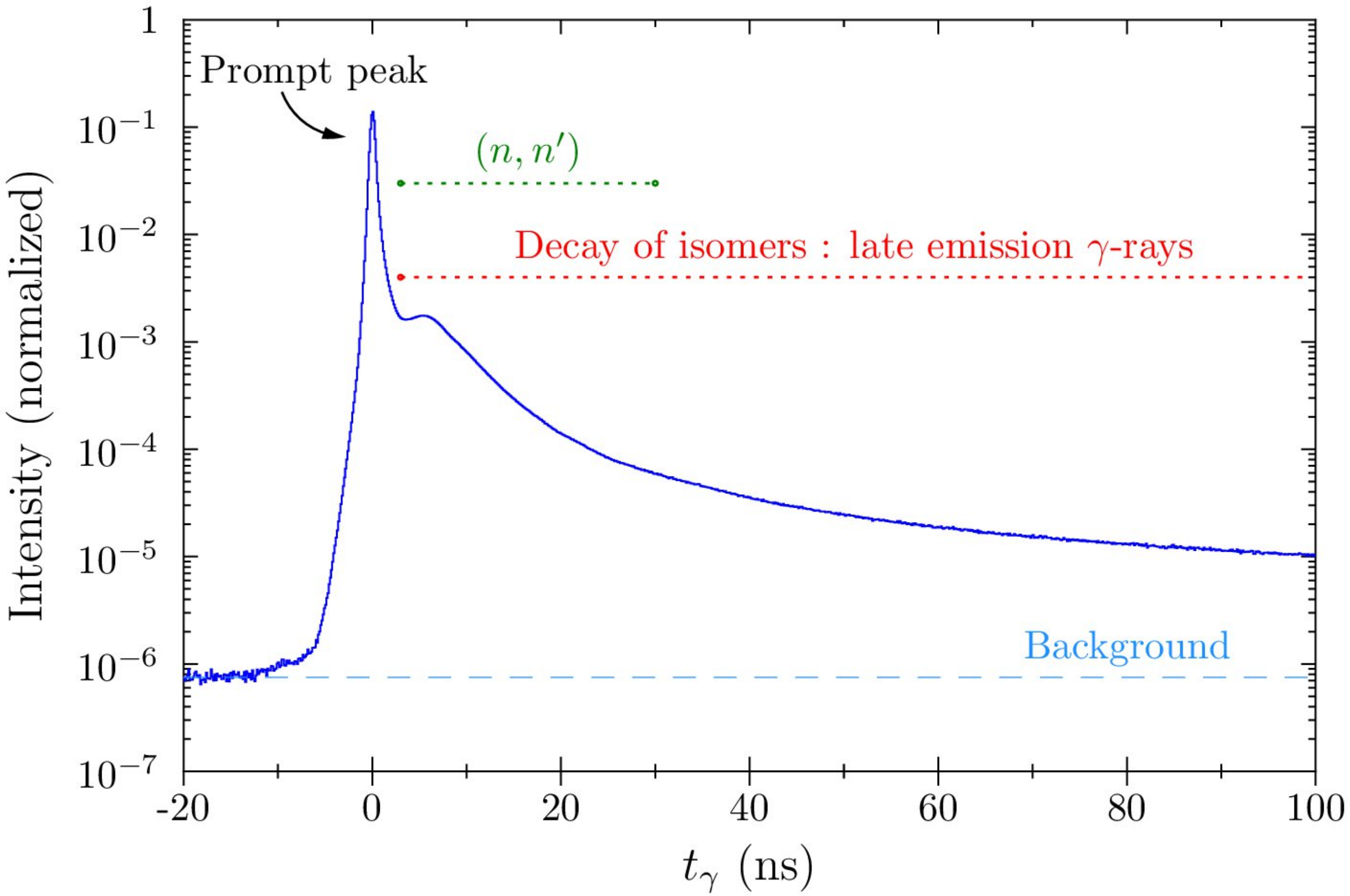


$\tau \ll \sigma_t$ *(time resolution of the detectors)*

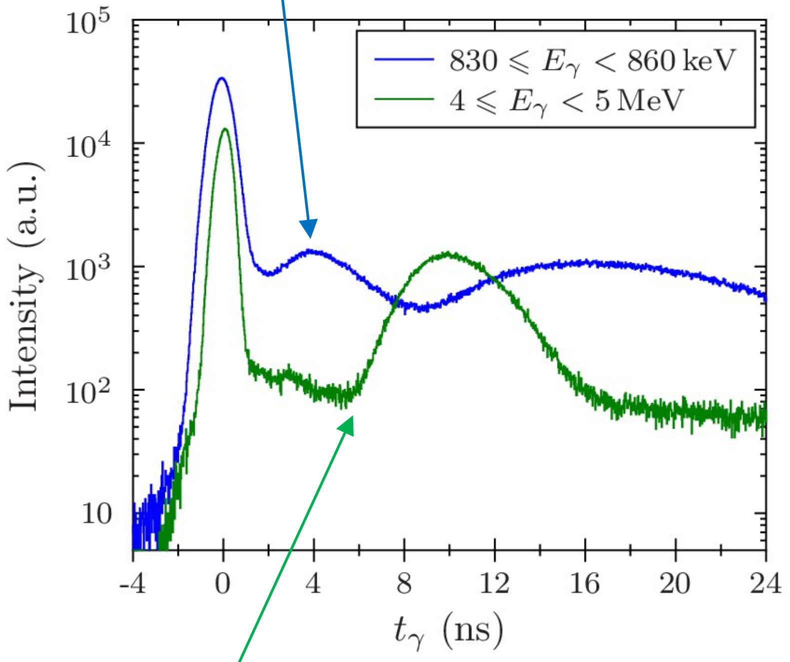
Late emission γ-rays ⟶ isomers ($\tau \gtrsim \sigma_t$)

Experimental time spectrum – γ-rays

Prompt peak + neutrons (inelastic scattering) + isomers



(n,n') in the surrounding materials (Fe)



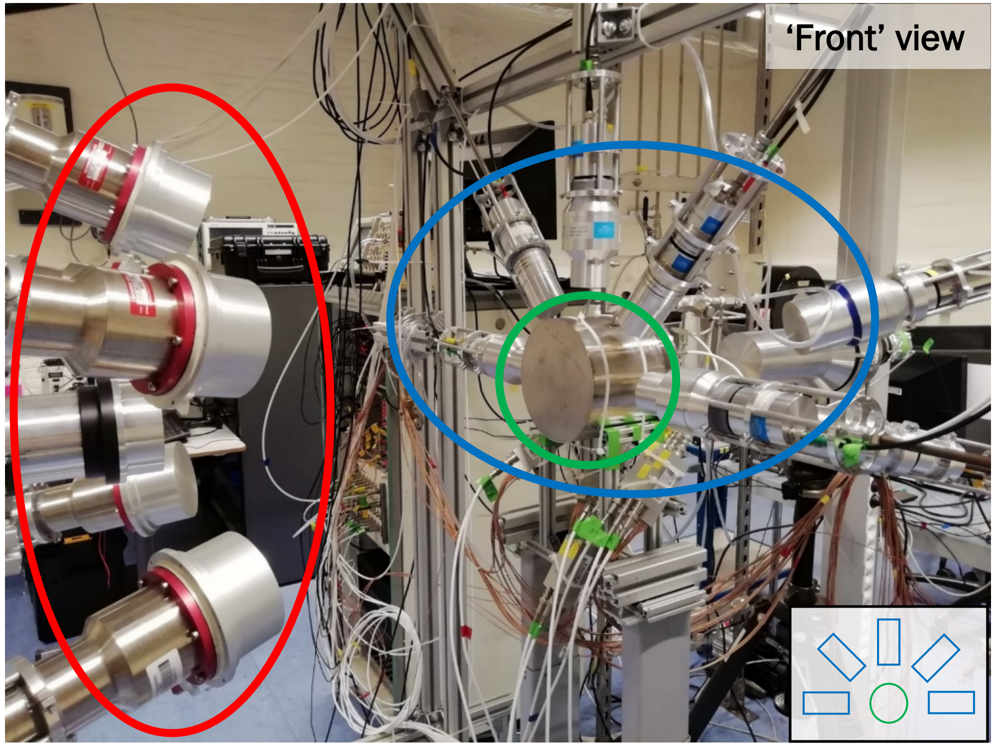
(n,n') in the γ-rays detectors

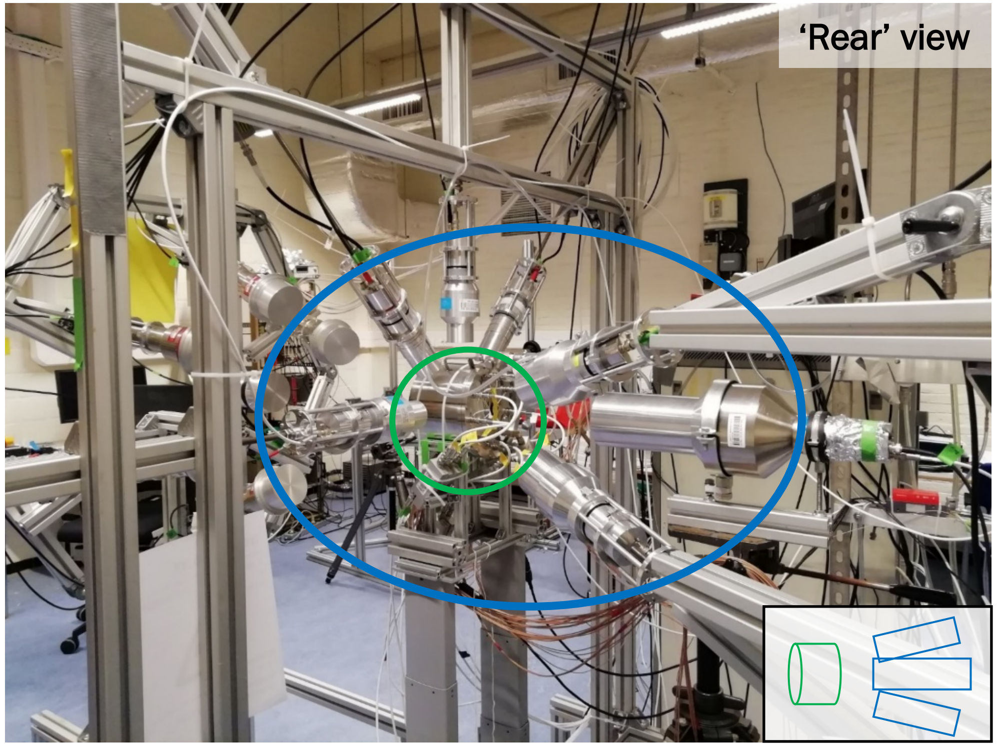
The VErsatile SPectrometer Array (VESPA)

1 Twin Frisch-grid Ionization Chamber → Fission fragments

8 $LaBr_3(Ce)$ scintillators → Prompt fission gamma-rays

7 Organic scintillators → Prompts fission neutrons

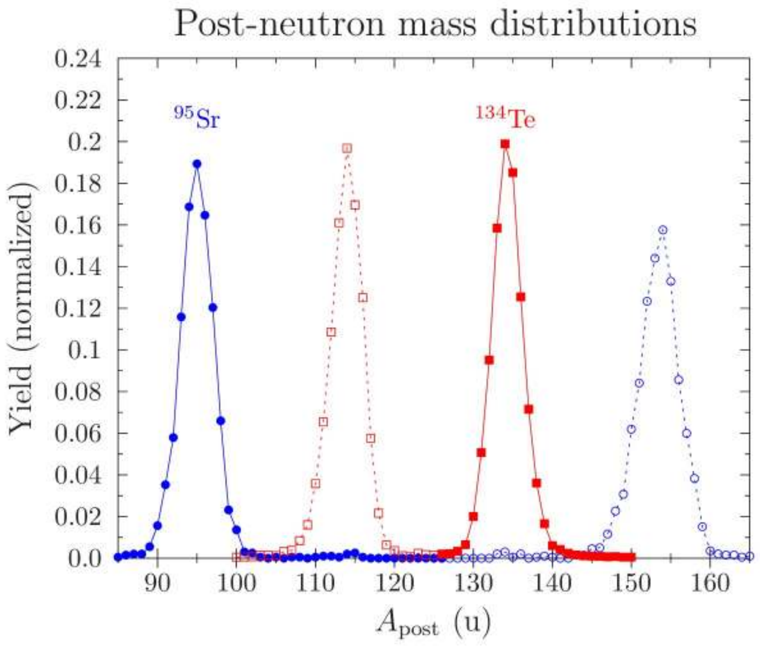


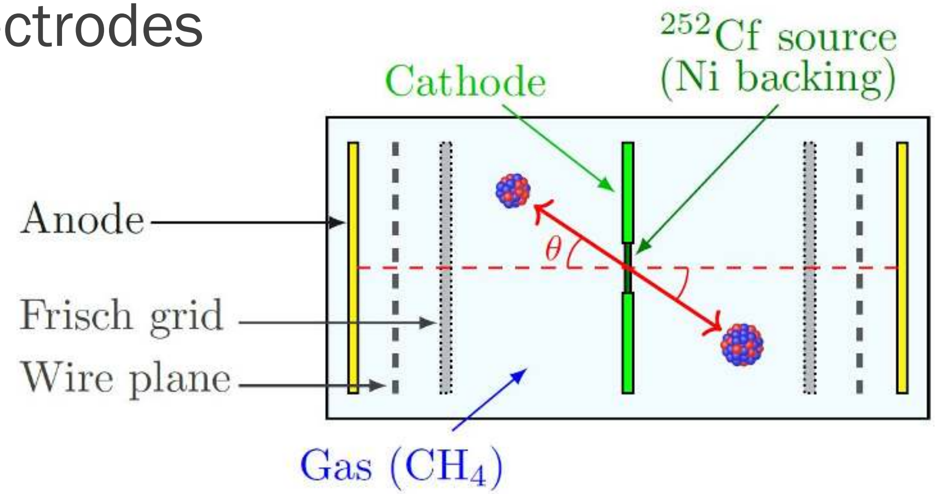


Twin Frisch-grid Ionization Chamber

- Manufactured by JRC Geel
  - ➢ see A. Göök et al., Nucl. Instr. Meth. A 830, 366 (2016)
- Simultaneous measurement of FFs kinetic energies

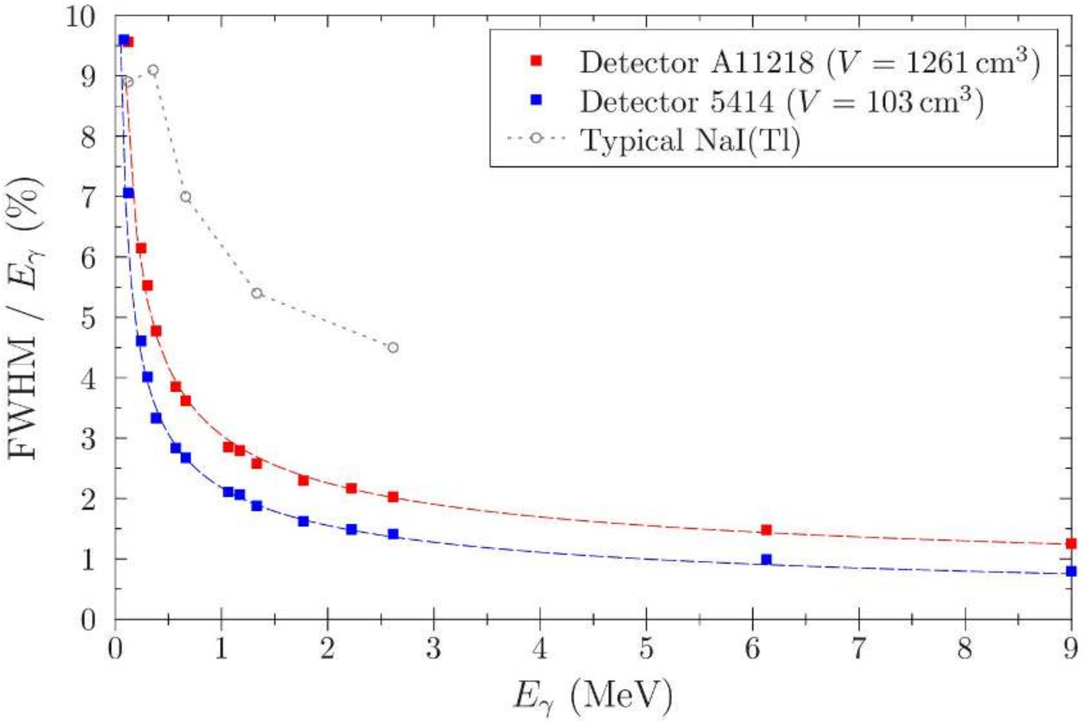
  → **2E method** to extract the mass of the fragments
- Angle determination from electron drift-time
- Position-sensitive electrodes





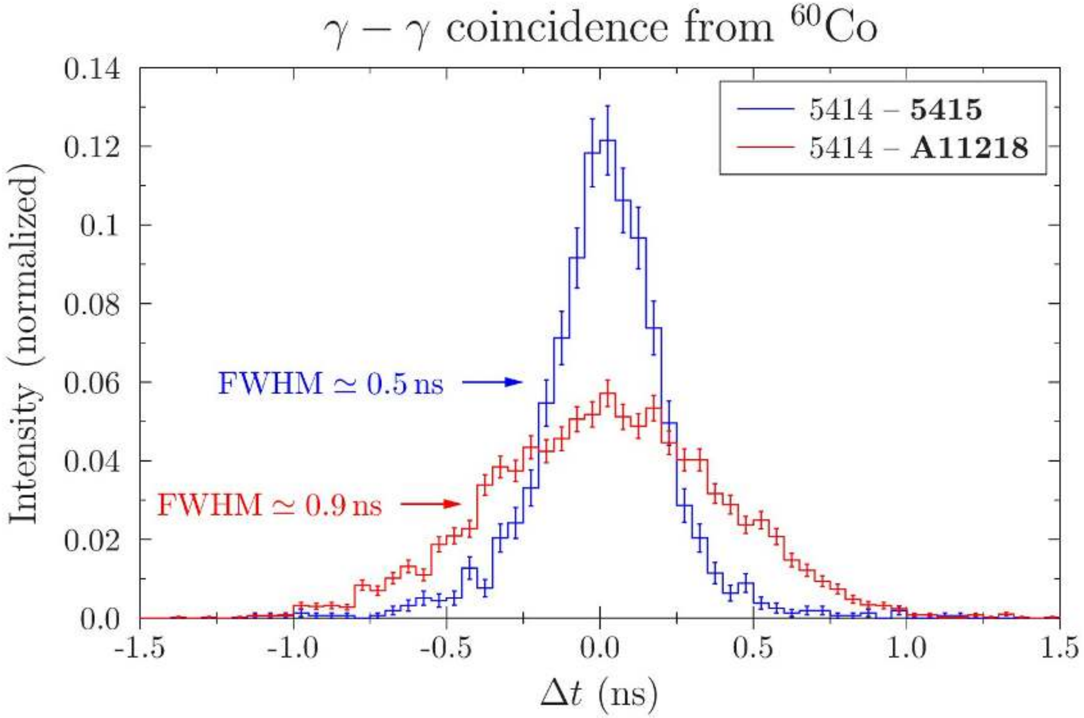
$LaBr_3(Ce)$ scintillators

Energy and time resolution



Different detector sizes :

- 1 x { 3.5'' x 8'' }
- 2 x { 3'' x 3'' }
- 5 x { 2'' x 2'' }



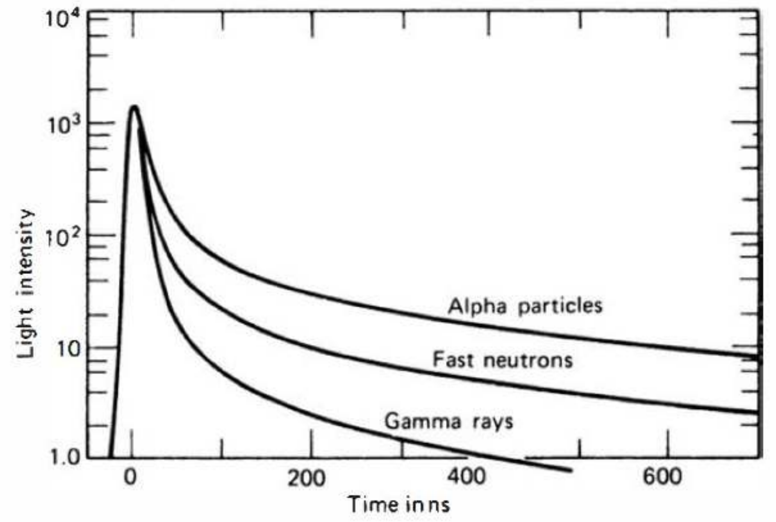
Organic scintillators

Liquid & stilbene: low-Z material, fast decay constant

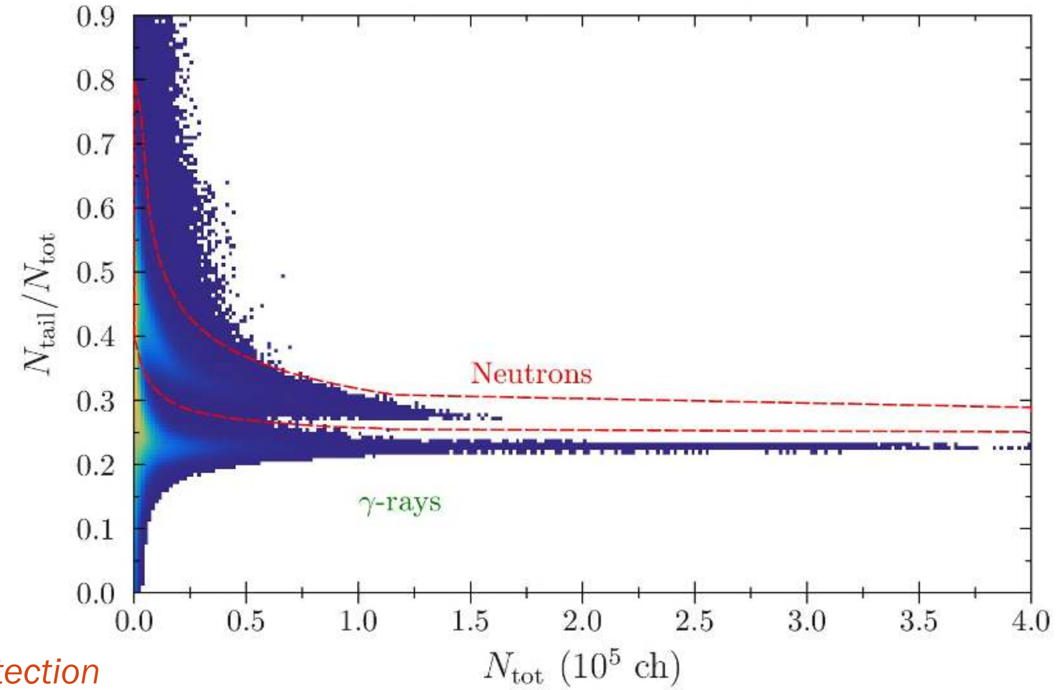
Sensitive to neutrons and gamma-rays

⟶ Pulse Shape Discrimination

- Neutrons ⟶ recoil proton
- γ-rays ⟶ electrons



Knoll, Radiation detection and measurement (2010)



Energy of the neutrons ⟶ Time-of-flight: $ToF \simeq d\sqrt{\frac{m_n}{2E_n}}$

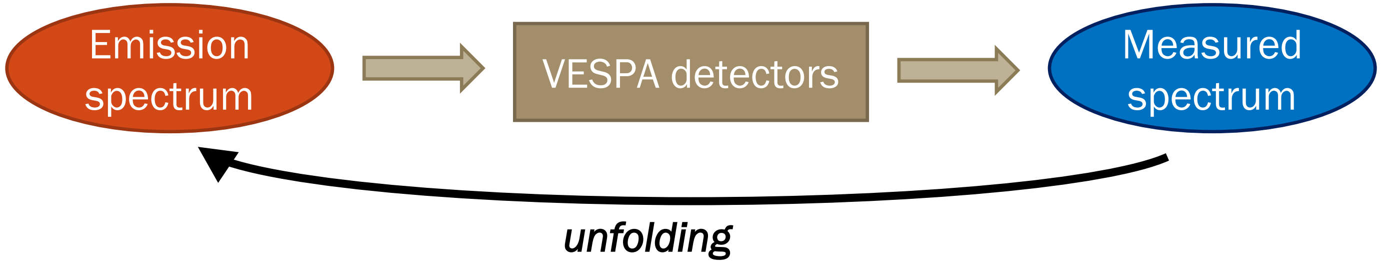
Data unfolding

The emission spectrum is folded by the experimental setup (smearing, partial energy deposit,…):

$$N(E_j) = \sum_i N(E_i) \times P(E_j|E_i)$$

Measured spectrum (discrete) — Emission spectrum (discrete) — Response matrix of the detector

To get back the emission spectrum, the measured spectrum has to be unfolded:



- The response matrix can be estimated from **Geant4 simulation** of the setup (see next slide)
- Several unfolding techniques are available. We use **the iterative method** (EM algorithm), see *D'Agostini, Nucl. Instr. Meth. A 362, 487 (1995)*
- Ill-posed problem (inverse problem) → **regularization** is necessary. (e.g., number of iterations)

Geant4 simulation of VESPA

Response matrix construction

Primary event definition

Photon emission
$E_\gamma \in [0.05, 16]$ MeV

Doppler effect

Photon emitted by a moving fission fragment

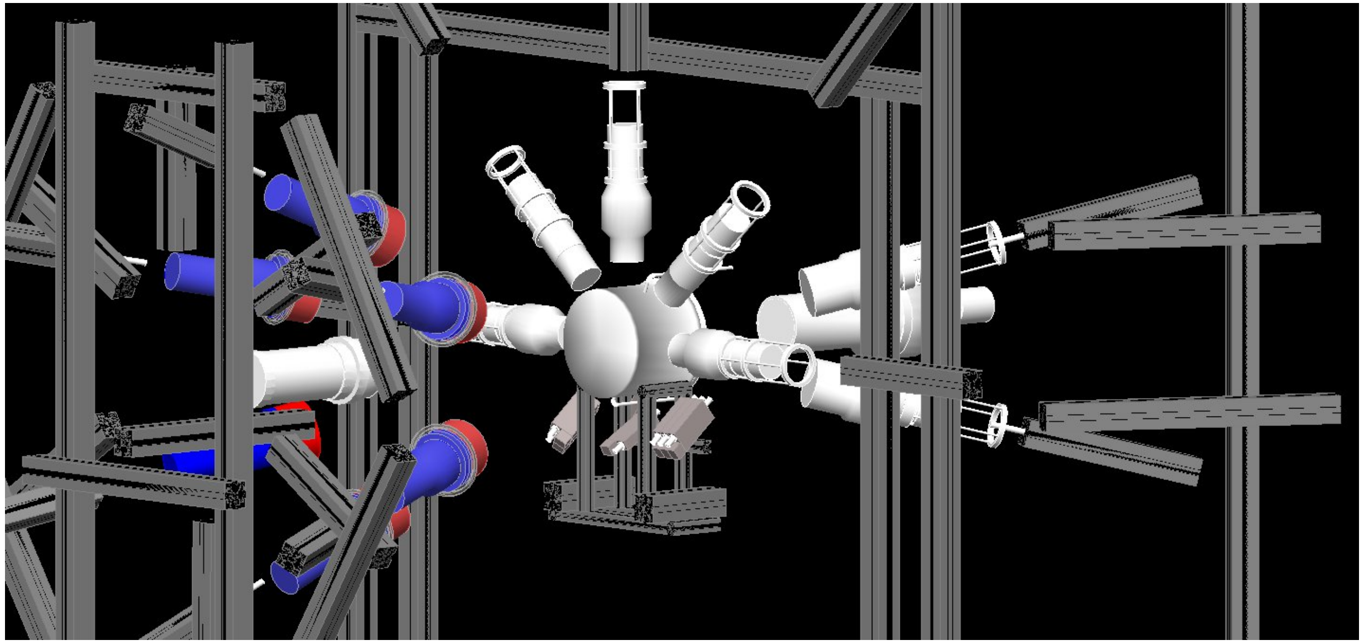
Interaction with the setup

- Geometrical description of the setup
- Physical models

Folding the results

Taking into account the experimental energy resolution of the detectors

CERN, Geant4 Collaboration

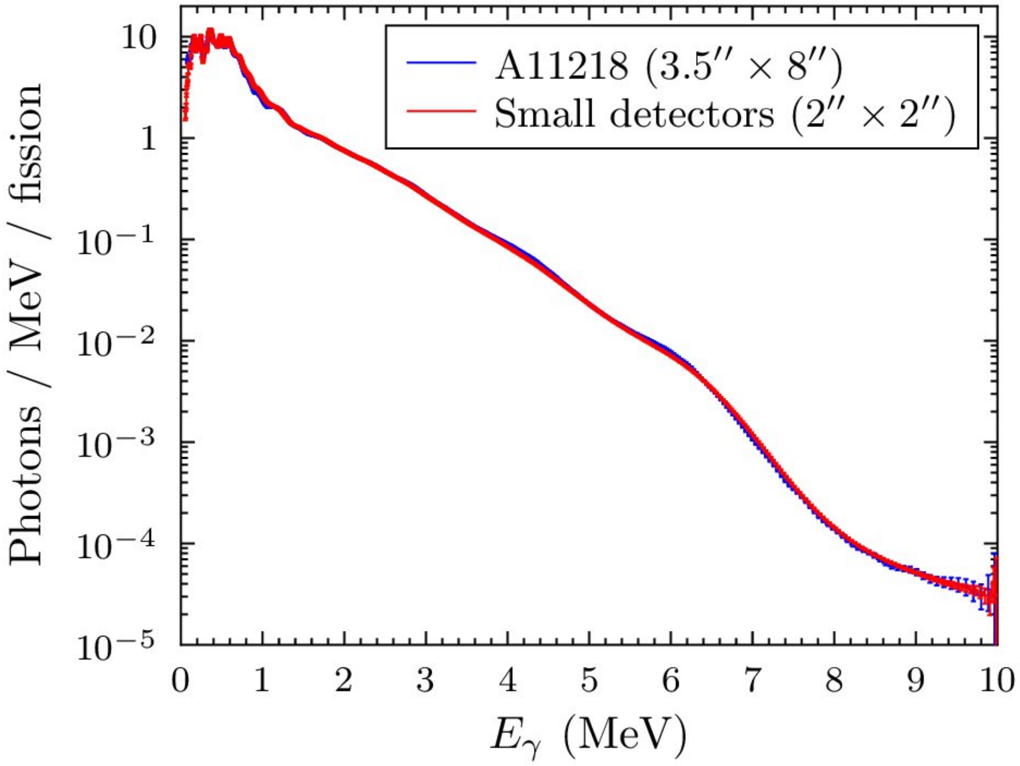


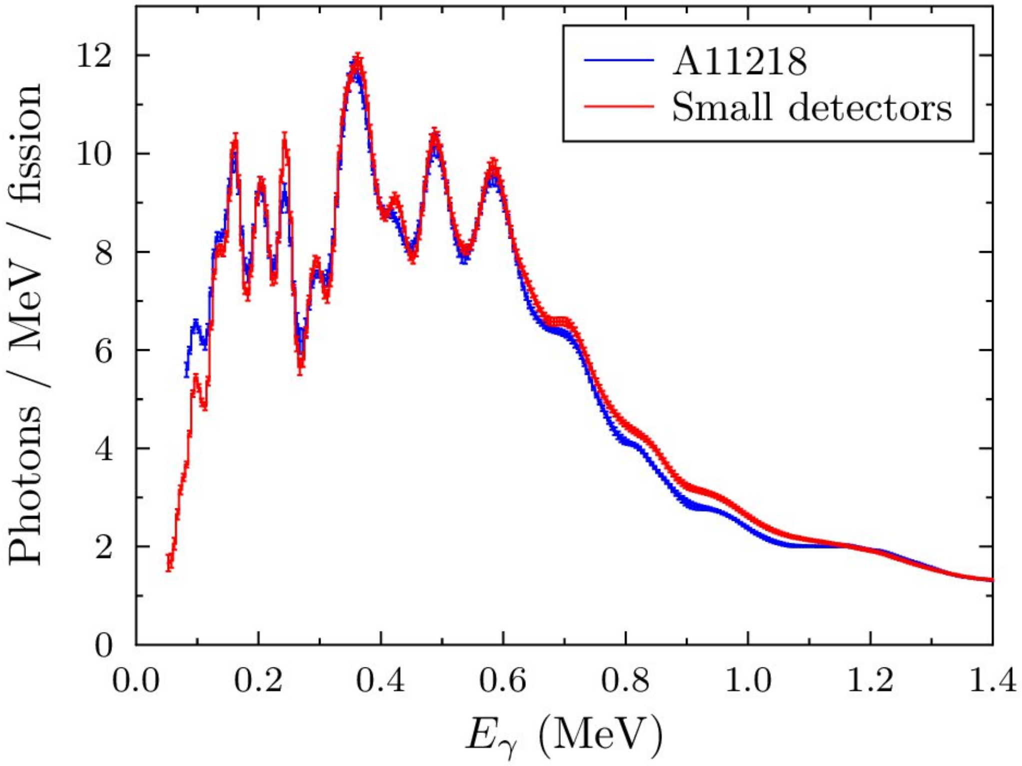
Simulation originally developed by A. Göök (2019/2020)

VESPA – Prompt Fission Gamma-ray Spectra

Unfolded prompt fission γ-rays spectrum (PFGS) of ^{252}Cf

- Average γ-ray multiplicity from A11218 (± 3 ns, 80 keV ⟶ 8 MeV): $\overline{M}_{\gamma} = \mathbf{8.37 \pm 0.08}$
- Average total γ-ray energy from A11218 (± 3 ns, 80 keV ⟶ 8 MeV): $\mathbf{E_{\gamma,tot} = 6.89 \pm 0.07}$ **MeV**

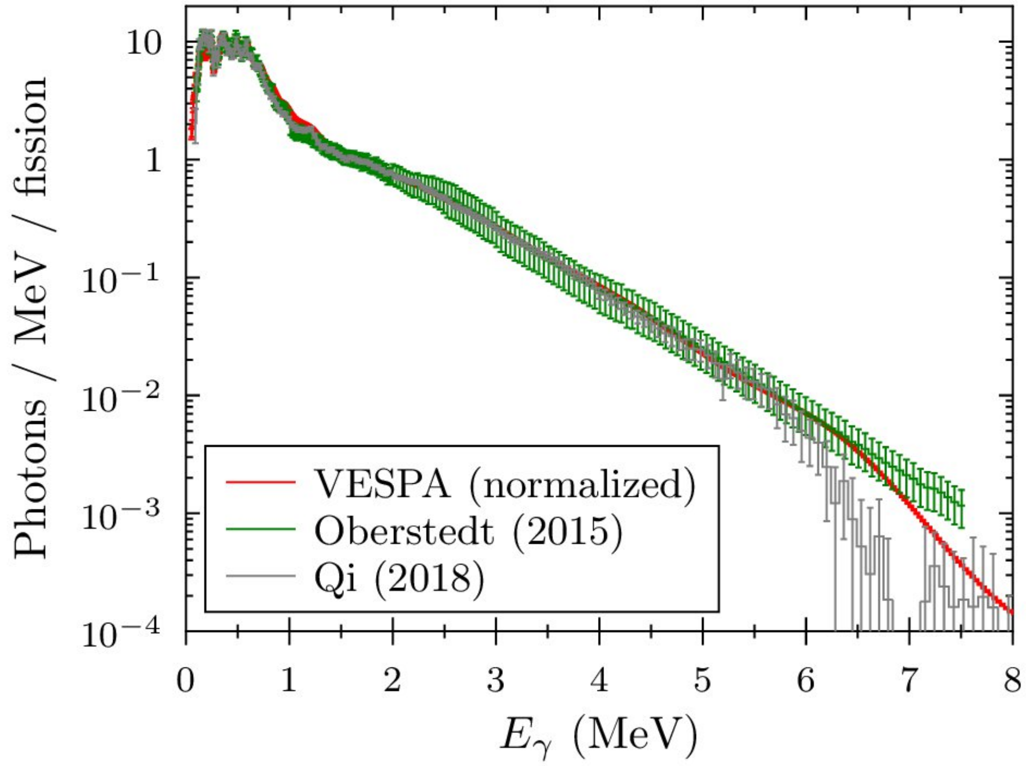


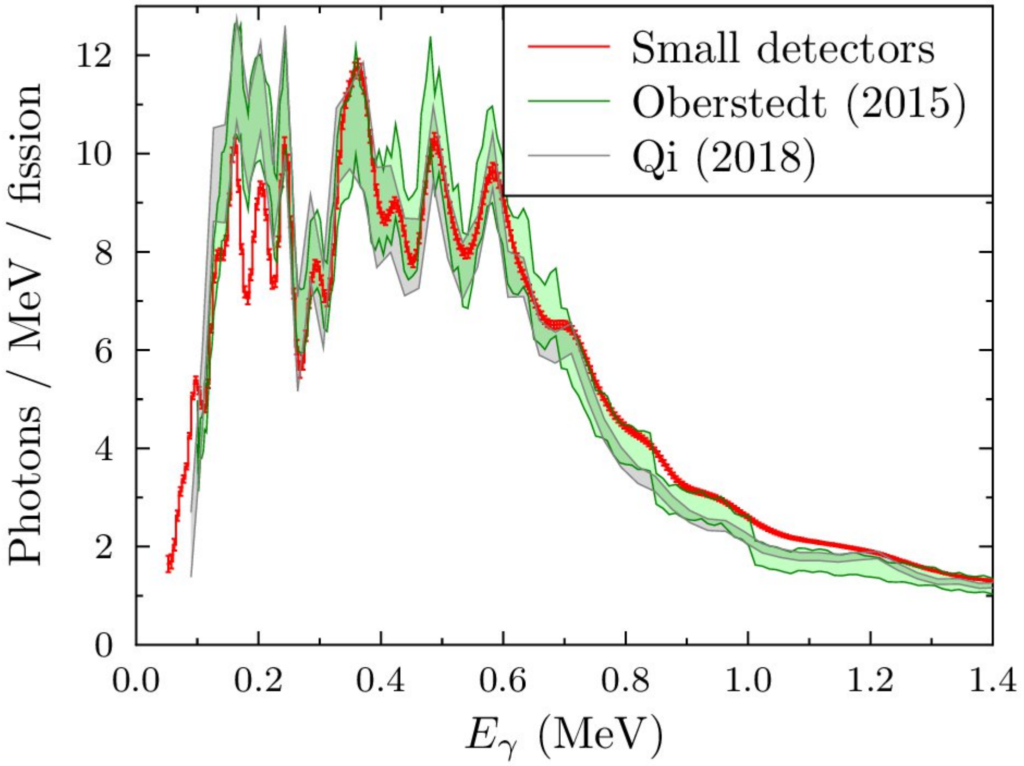


VESPA – Prompt Fission Gamma-ray Spectra

Unfolded prompt fission γ-rays spectrum (PFGS) of ^{252}Cf – comparison

- A. Oberstedt *et al.*, Phys. Rev. C 92, 014618 (2015) ⟶ JRC Geel ($LaBr_3$)
- L. Qi *et al.*, Phys. Rev. C 98, 014612 (2018) ⟶ ALTO, nu-ball array ($LaBr_3$)





Analysis of the prompt fission γ-ray data

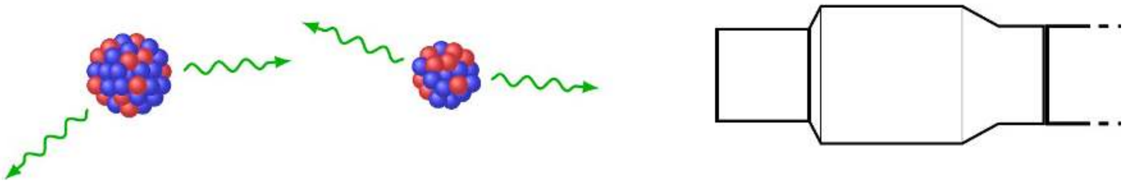
Coincidence condition between FF and prompt γ-rays

Fission fragments are detected in the IC

- 2E method ⟶ pre-neutron masses and TKE

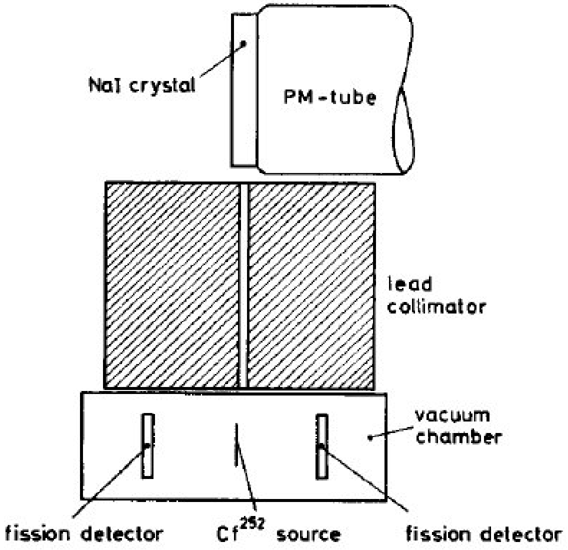
Gamma-rays from both fragments are detected in the $LaBr_3$

- cannot be easily disentangled



There are two methods to separate these contributions:

- ➢ Lead collimator
- ➢ **Weighting method**



Johansson, Nuclear Physics A 60, 378 (1964)

Analysis of the prompt fission γ-ray data

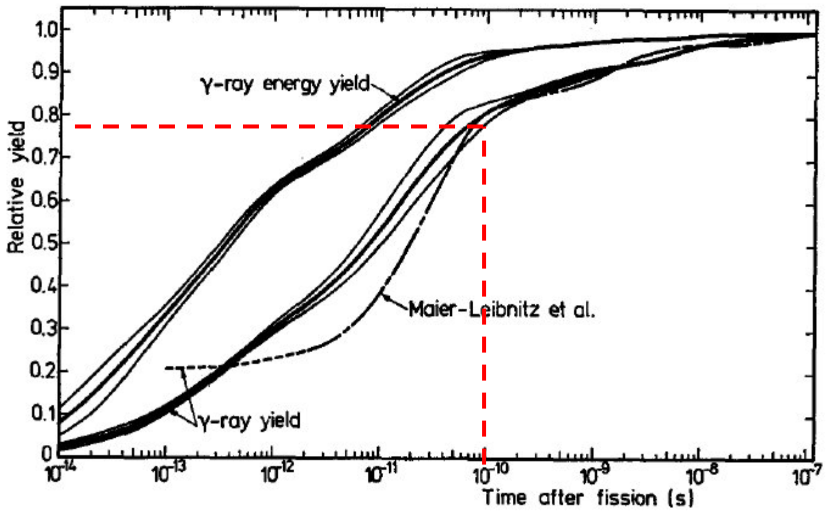
The weighting method

80% of the prompt γ-ray yield is emitted within 0.1 ns after scission (Skarsvåg, 1975)

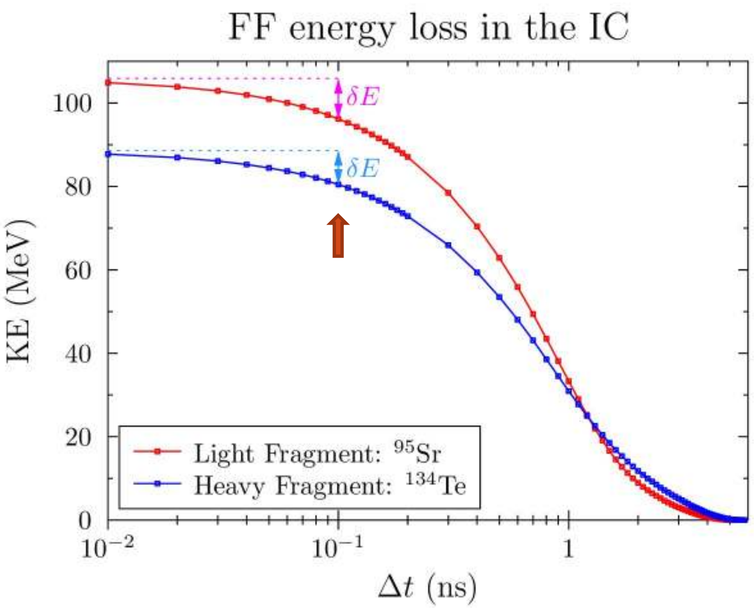
⟶ Fragments are not stopped while emitting γ-rays

⟶ Thus, they undergo Doppler effect

- Doppler shift: $E_{lab} \neq E_{cm}$
- Doppler aberration: $\theta_{lab} \neq \theta_{cm}$



Skarsvåg, Nucl. Phys. A 253, 274 (1975)



SRIM-2013 calculations

Analysis of the prompt fission γ-ray data

Analysis procedure : **weighting method**

- Maier Leibnitz *et al.*, Physics and Chemistry of Fission II, 143 (1965)
- The Doppler effect creates an anisotropy of the γ-ray emission in the lab frame

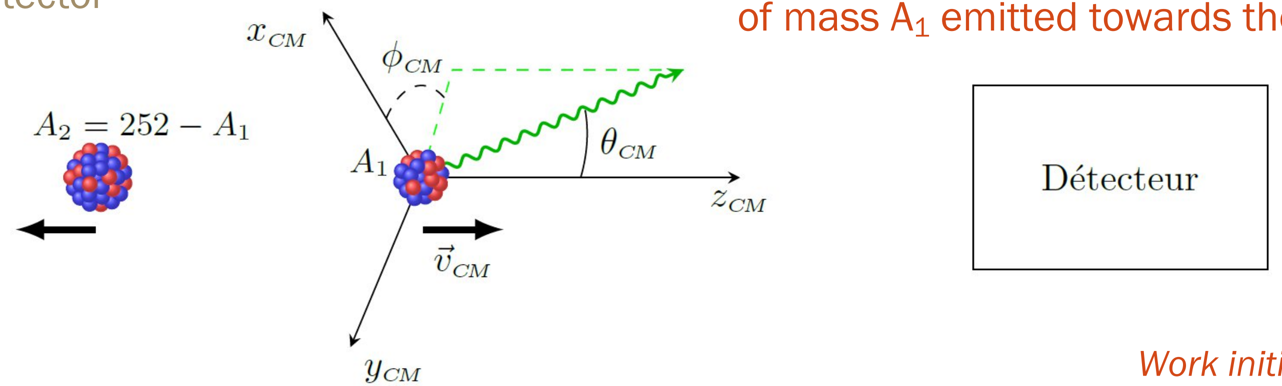
$$\alpha_N(\theta) = \frac{N_\gamma^{lab}(\theta) - N_\gamma^{lab}(\theta+\pi)}{N_\gamma^{lab}(\theta) + N_\gamma^{lab}(\theta+\pi)} \simeq 2\beta\cos\theta \xrightarrow[\theta\to 0]{} 2\beta$$

- The average multiplicity of the prompt fission γ-rays can be obtained as:

$$M_\gamma(A_1,TKE) = \frac{n_\gamma(A_1,TKE)}{N(A_1,TKE)} \times f_1(\alpha_N) - \frac{n_\gamma(A_2,TKE)}{N(A_2,TKE)} \times f_2(\alpha_N)$$

Number of fragments of mass A_1 emitted towards the detector

Measured γ-ray multiplicity from fragments of mass A_1 emitted towards the detector



Work initialized by M. Travar and A. Göök (2019)

Analysis of the prompt fission γ-ray data

Analysis procedure : **weighting method**

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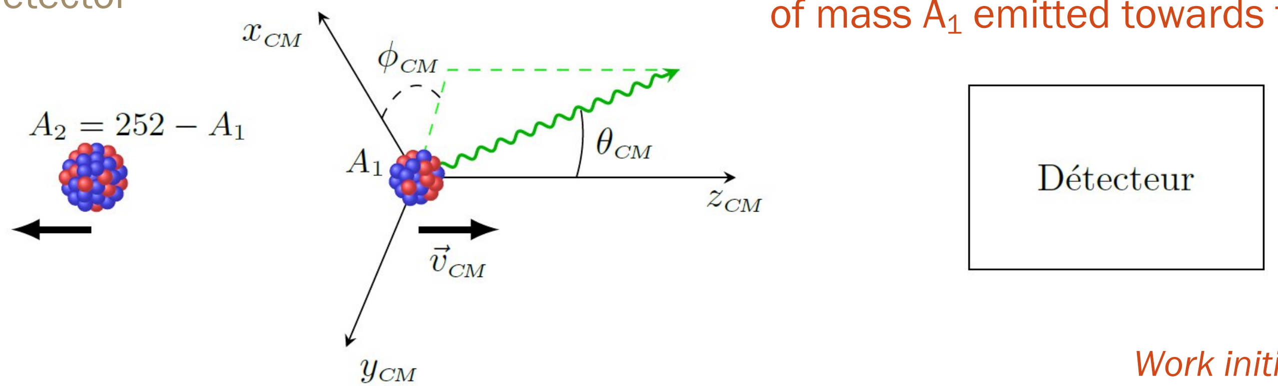
$$\alpha_E(\theta) = \frac{E_\gamma^{lab}(\theta) - E_\gamma^{lab}(\theta+\pi)}{E_\gamma^{lab}(\theta) + E_\gamma^{lab}(\theta+\pi)} \simeq 3\beta\cos\theta \xrightarrow[\theta\to 0]{} 3\beta$$

- The average total energy of the prompt fission γ-rays can be obtained as:

$$E_{\gamma,tot}(A_1,TKE) = \frac{e_\gamma(A_1,TKE)}{N(A_1,TKE)} \times f_1(\alpha_E) - \frac{e_\gamma(A_2,TKE)}{N(A_2,TKE)} \times f_2(\alpha_E)$$

Number of fragments of mass A_1 emitted towards the detector

Measured total γ-ray energy from fragments of mass A_1 emitted towards the detector

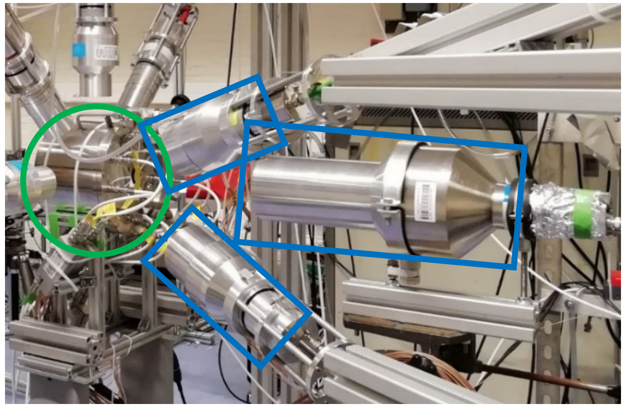


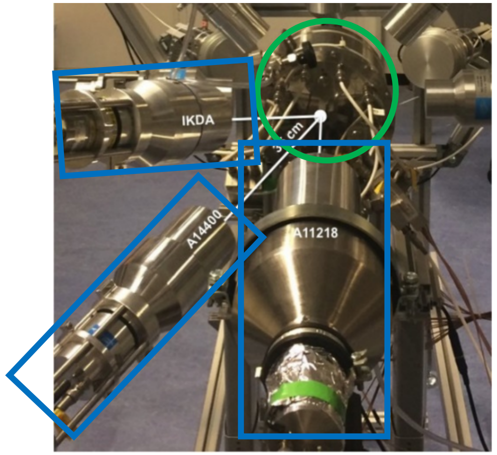
Work initialized by M. Travar and A. Göök (2019)

The VESPA measurement

3 detectors aligned with the IC

- A11218 (3.5'' x 8'')
- IKDA (3'' x 3'')
- A14400 (3'' x 3'')





Travar et al., Phys. Lett. B 817 136293 (2021)

Time and angular cuts

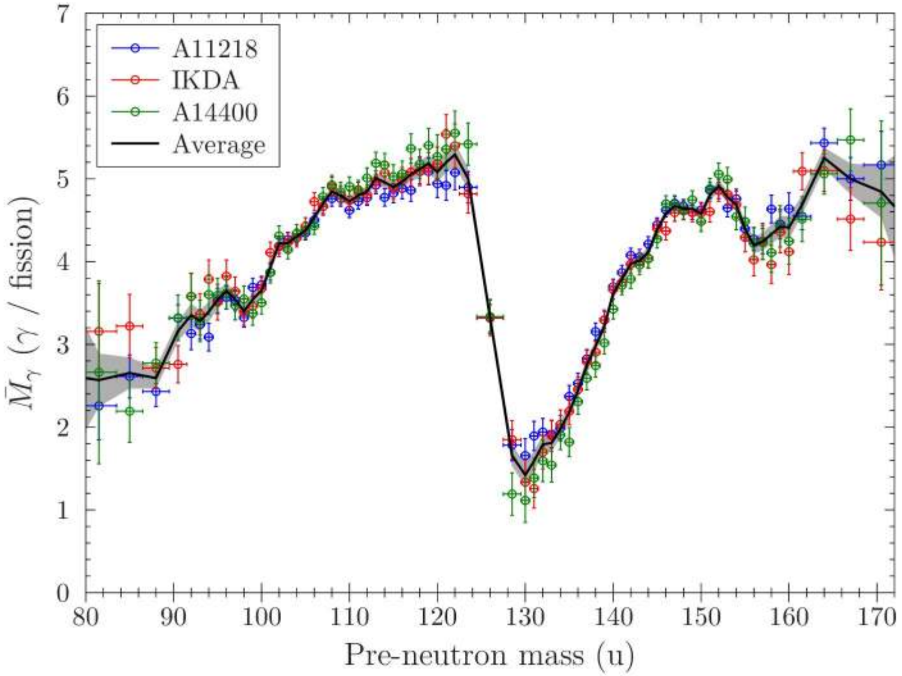
- Emission angle relative to the detector : $\cos(\vartheta) > 0.9$ ($\Rightarrow |\vartheta| \lesssim 26°$)
- Coincidence window : ± 3 ns
  - Reject events due to inelastic scattering of prompt neutrons in detectors material
  - Reject events due to the decay of isomers

Mass- and TKE- dependent measured spectra

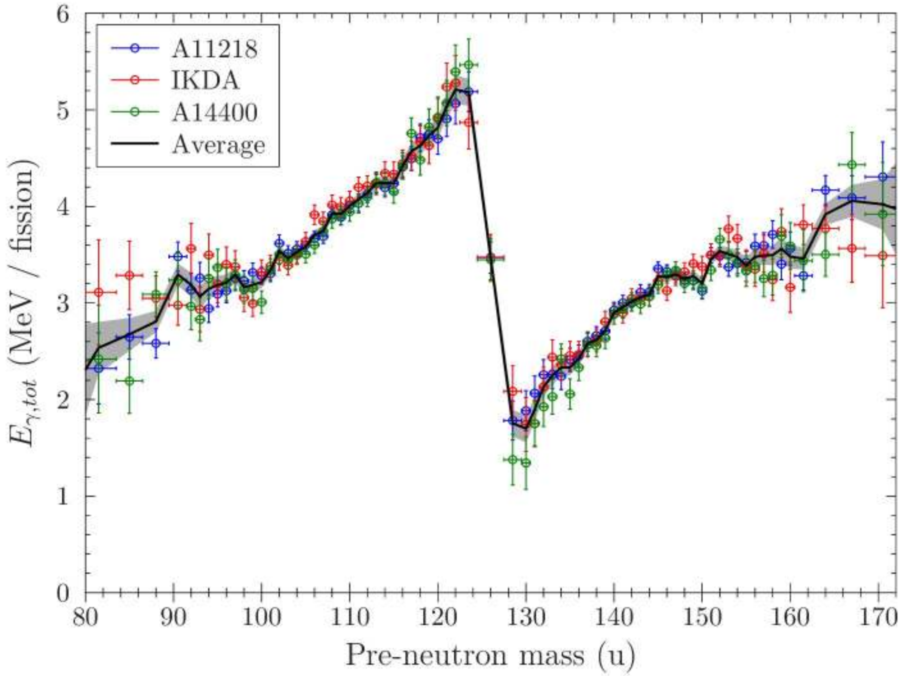
$\rightarrow$ unfolding $\rightarrow n_\gamma(A,TKE)$ and $e_\gamma(A,TKE)$

Mass-dependent γ-ray multiplicity and energy

Average γ-ray multiplicity



Average total γ-ray energy

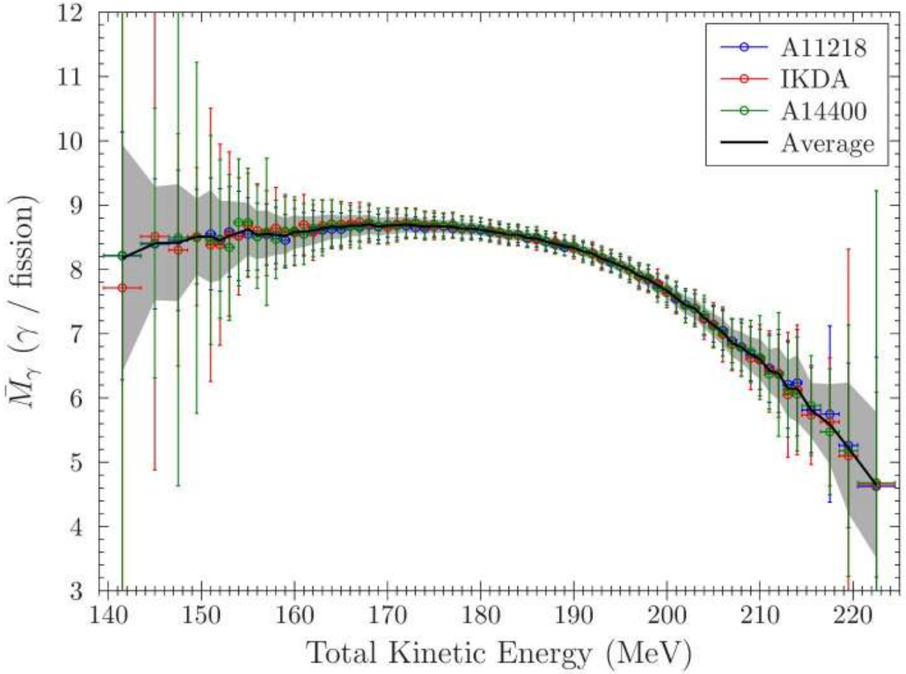


Travar et al., Phys. Lett. B 817 136293 (2021)

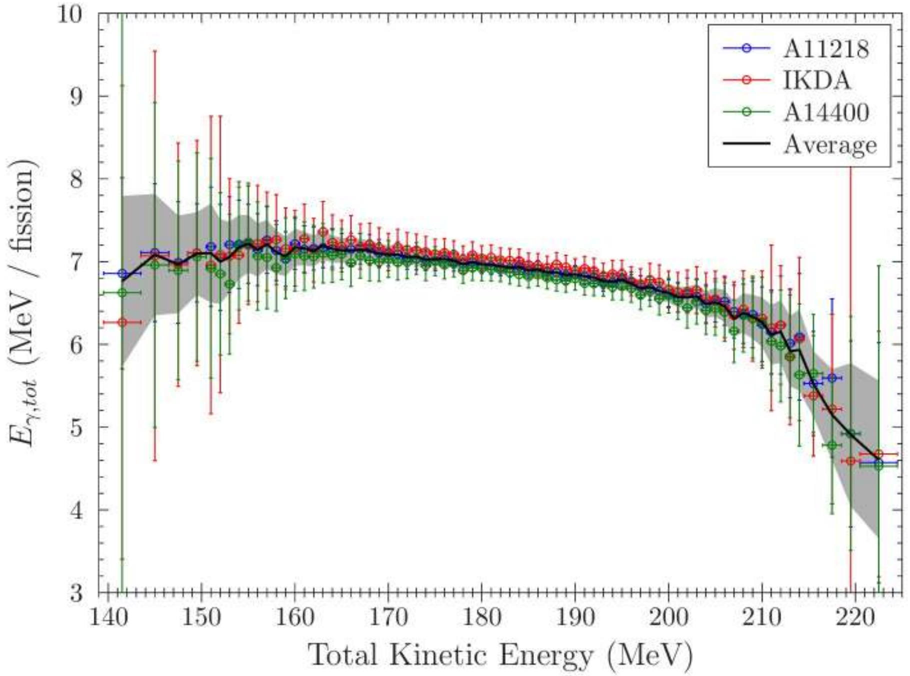
	Light Fragments	Heavy Fragments	Total
Multiplicity	4.53 ± 0.03	3.83 ± 0.03	8.36 ± 0.02
Total energy (MeV)	3.88 ± 0.03	3.01 ± 0.03	6.89 ± 0.02

TKE-dependent γ-ray multiplicity and energy

Average γ-ray multiplicity



Average total γ-ray energy



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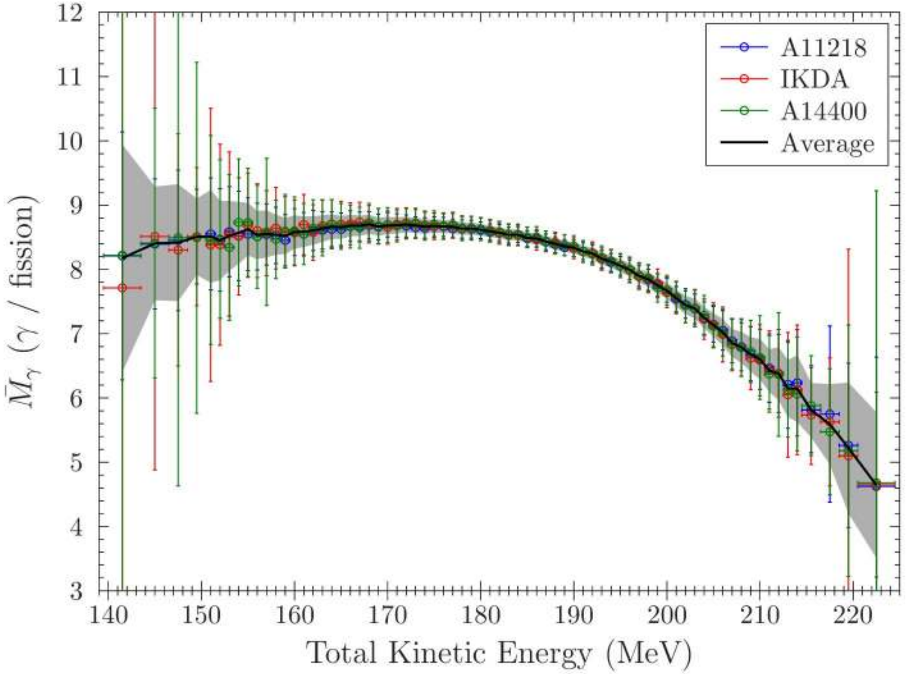
TKE-dependent γ-ray multiplicity

Average γ-ray multiplicity



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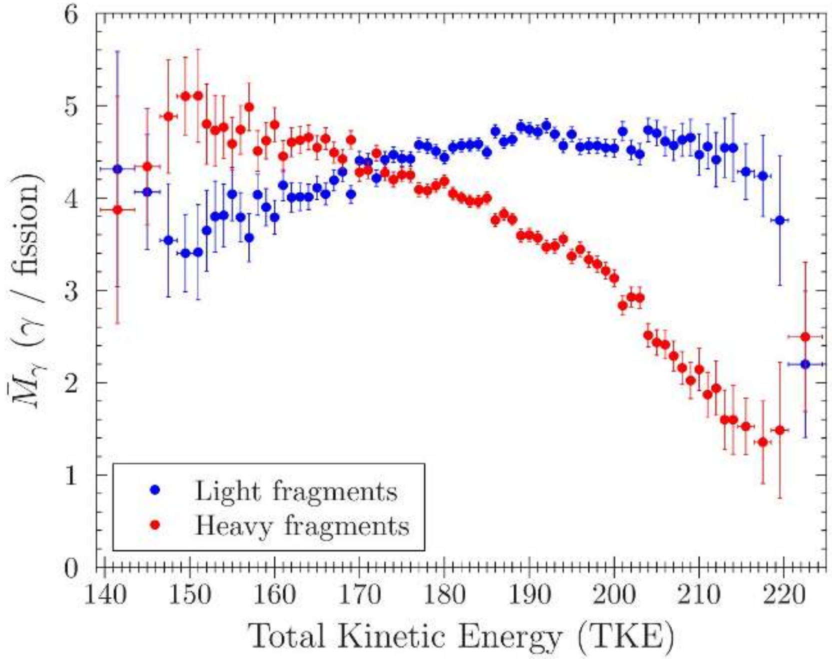

V. Piau et al., Phys. Lett. B 837 137648 (2023)

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Prompt fission γ-ray multiplicity - ^{252}Cf

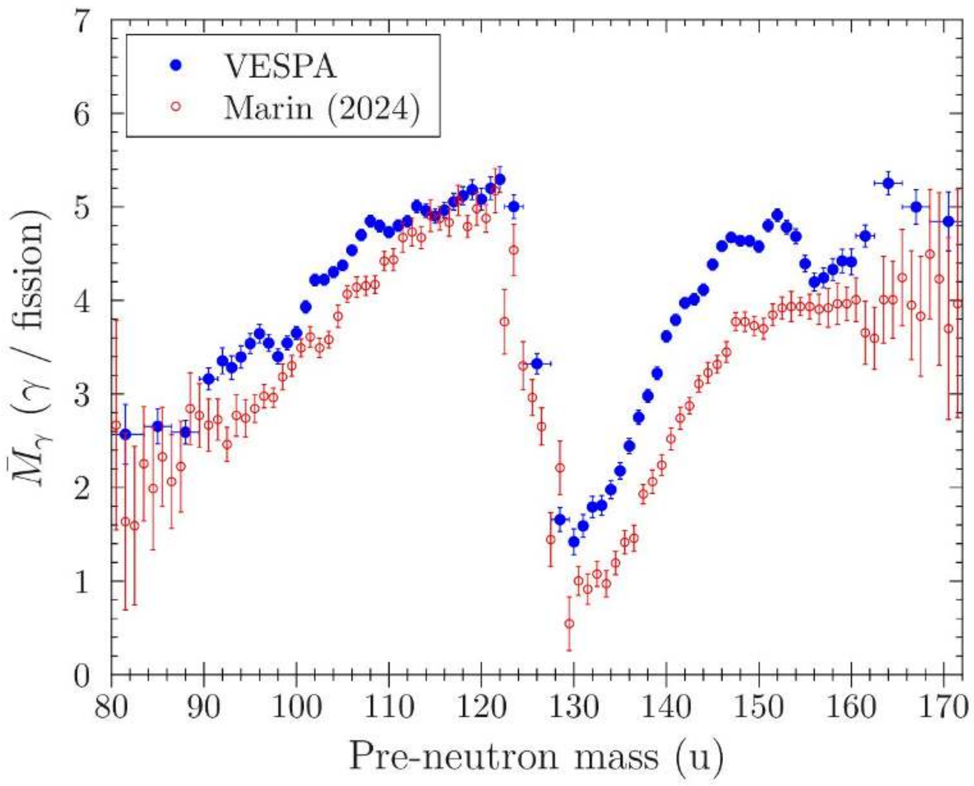
Comparison with recent experiment @ANL with FS-3 array

- 40 trans-stilbene detectors (organic scintillators)
- Twin Frisch-grid ionization chamber loaded with ^{252}Cf

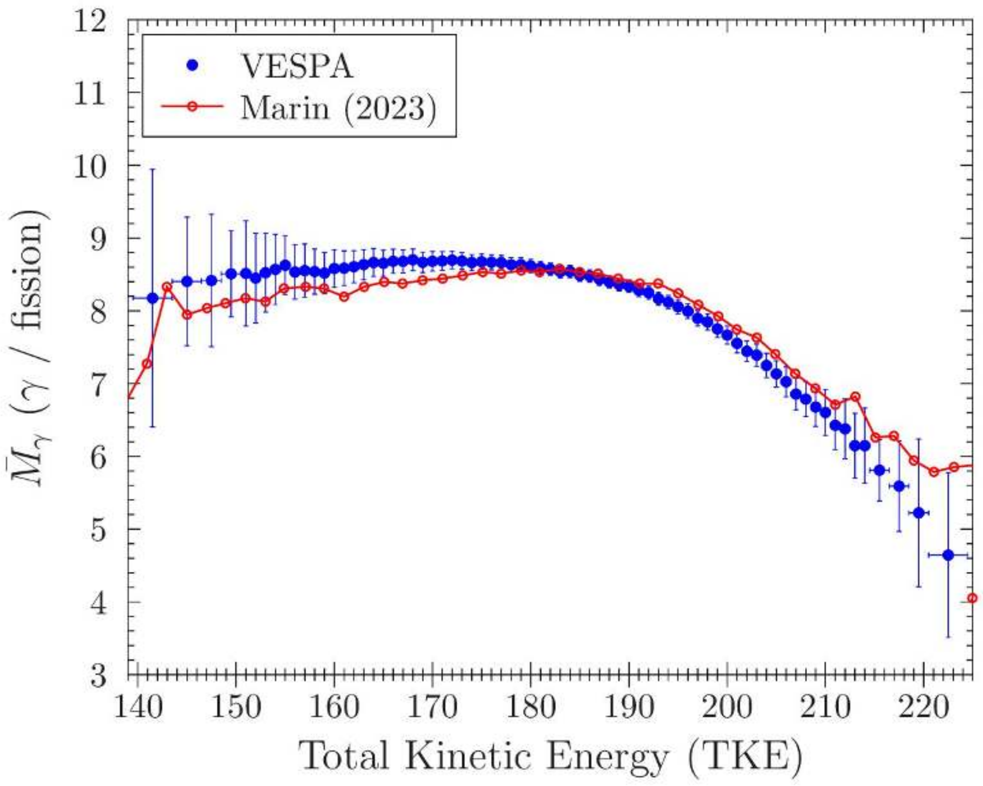
Marin et al., Nucl. Instr. Meth. A 1048, 168027 (2023)

Prompt fission γ-ray multiplicity - ^{252}Cf

Comparison with recent experiment @ANL with FS-3 array



Marin et al., Phys. Rev. C 109, 054617 (2024)

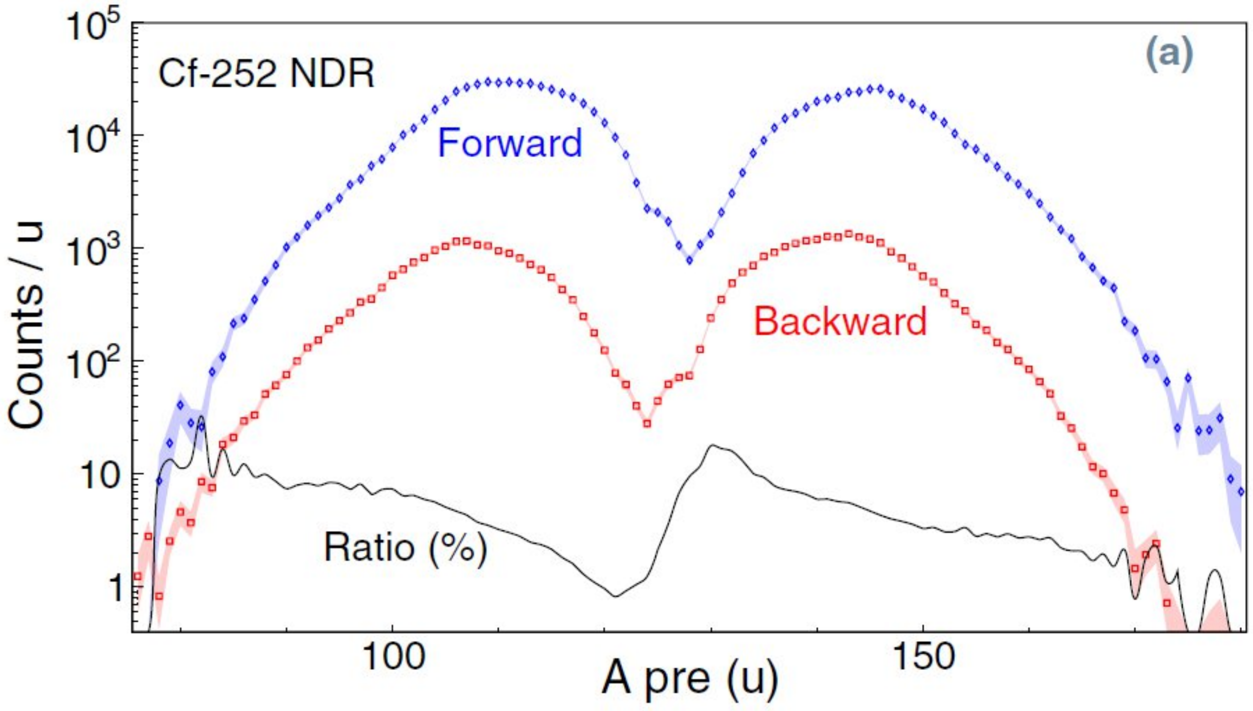


Marin et al., Nucl. Instr. Meth. A 1048, 168027 (2023)

Prompt fission neutron multiplicity

Neutron and γ-ray measurements face similar challenges:

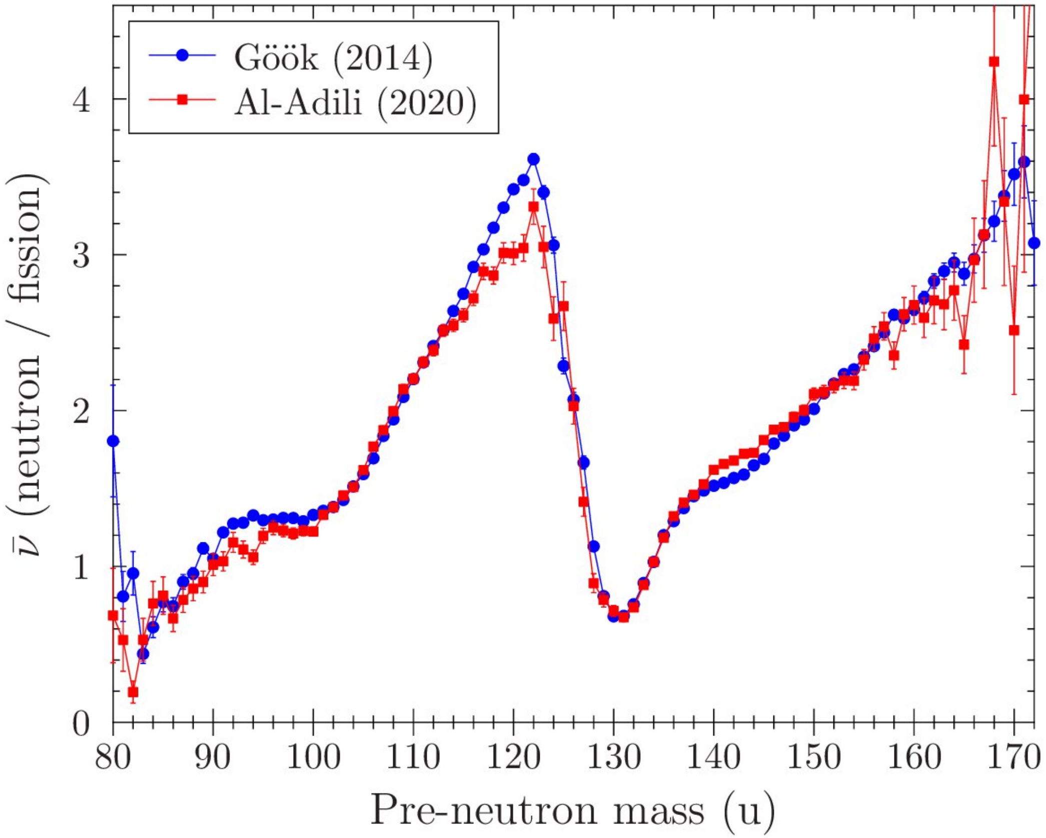
- γ-ray **contamination** (especially at low energy where PSD is less efficient)
- Response function: scattering & absorption of neutrons → **unfolding**
- Emission by **both fragments**
- **Doppler** effect → kinematic boost



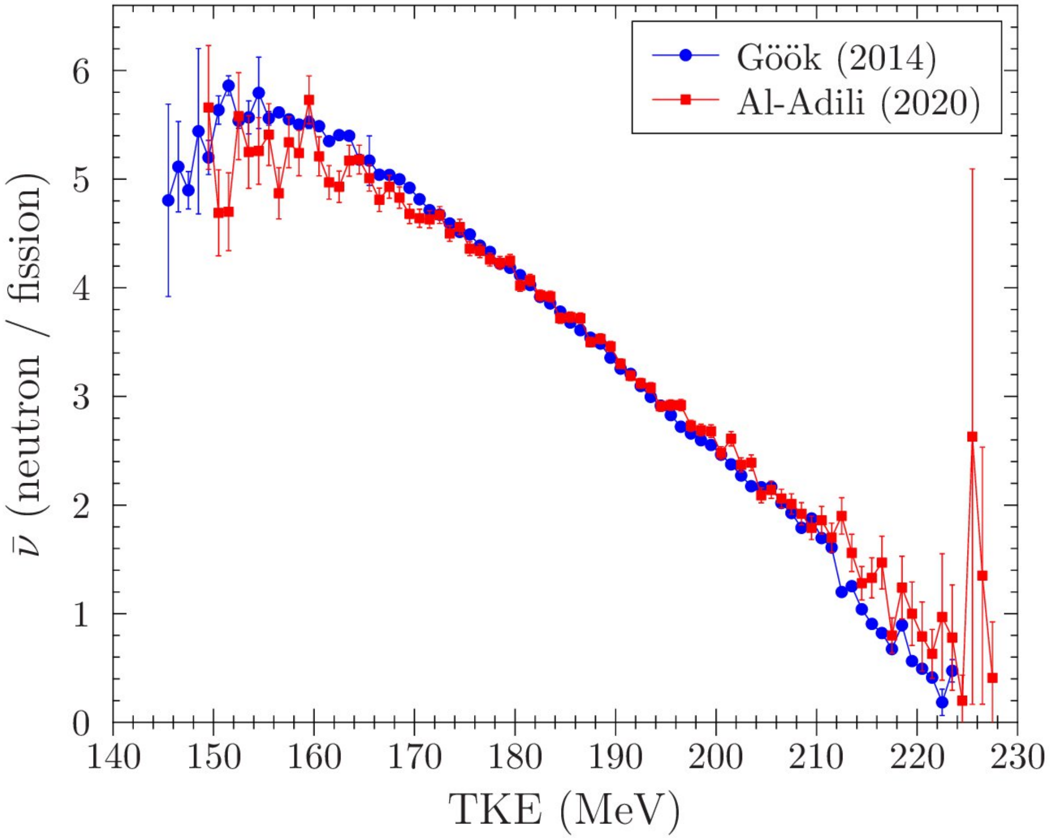
Al-Adili et al., Phys. Rev. C 102, 064610 (2020)

Prompt fission neutron multiplicity - ^{252}Cf(sf)

Mass-dependent multiplicity



TKE-dependent multiplicity



Al-Adili et al., Phys. Rev. C 102, 064610 (2020)
Göök et al., Phys. Rev. C 90, 064611 (2014)

About mass resolution

VESPA mass resolution is ~5u (FWHM) from IC + 2E method

It can be applied to calculations, e.g., FIFRELIN

→ See A. Chebboubi talk for more details about FIFRELIN calculations

Folding method:

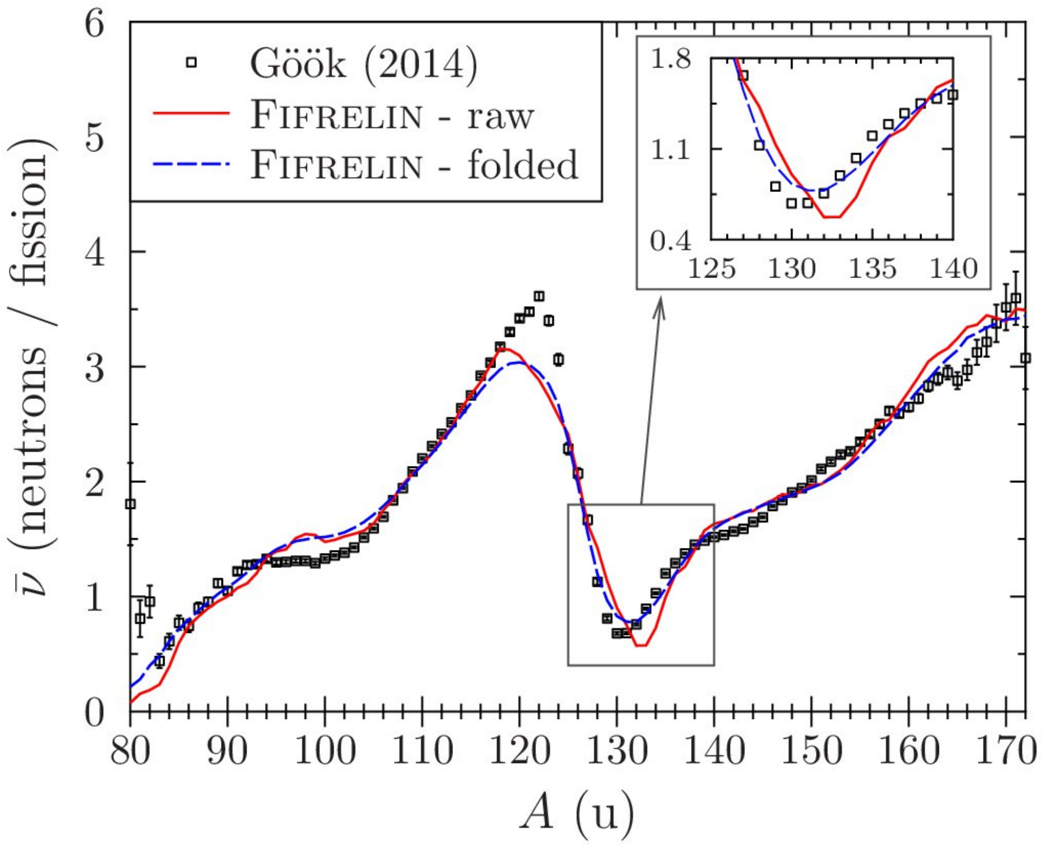
- **Event-wise** convolution → $A' = A + \mathscr{G}(0,\sigma)$ where $\mathscr{G}$ is a random number (Gaussian)

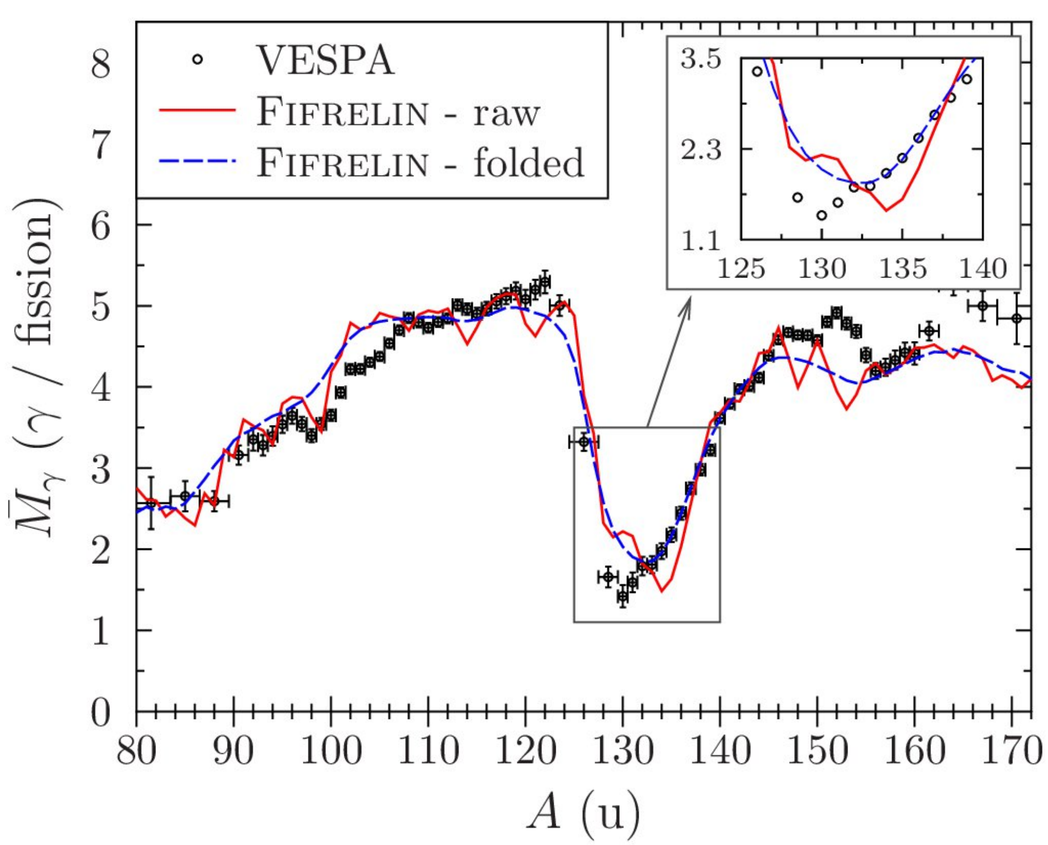
→ convolution of $M_\gamma(A) \times Y(A)$ and $Y(A)$ distributions

$$M'_\gamma = \frac{\left[M_\gamma(A) \times Y(A)\right]'}{Y'(A)}$$

About mass resolution

VESPA mass resolution is ~5u (FWHM) from IC + 2E method





→ Minimum shifts !

Angular distribution of γ-rays

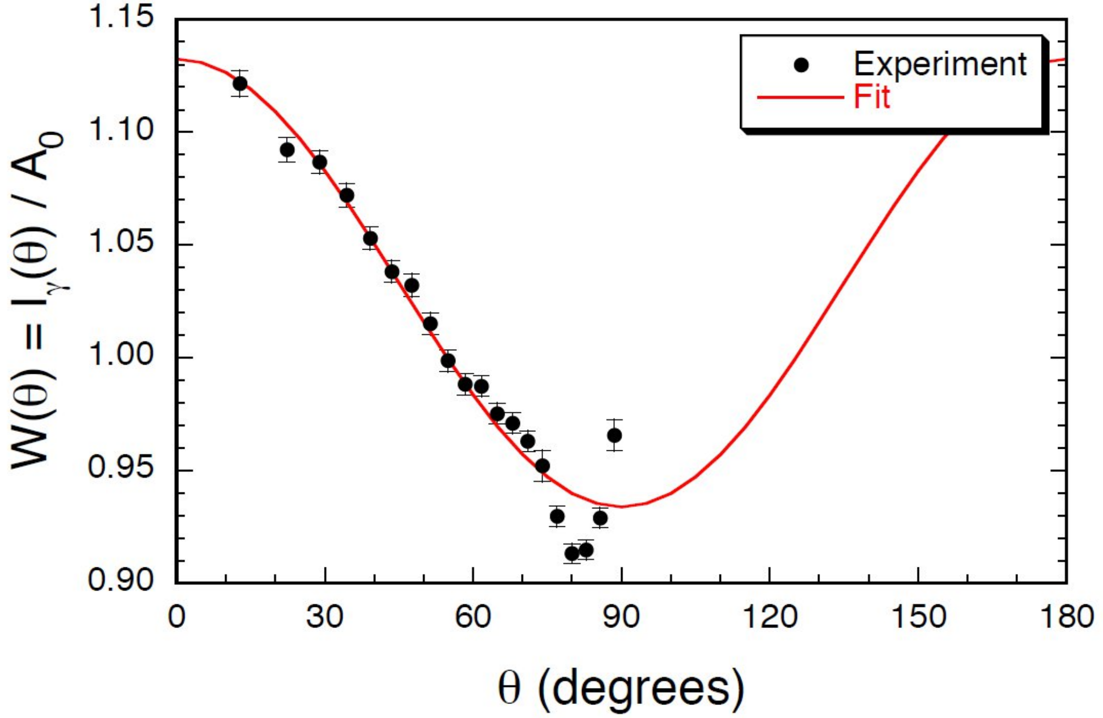
$$W(\theta) \propto 1 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)$$

a2 and a4 parameters are related to:

- Spin alignement
- Post-neutron spin
- Multipolarity of transitions

→ See A. Chebboubi talk

Oberstedt et al., EPJ Web Conf. 169, 00014 (2018)



→ Interesting fission observable

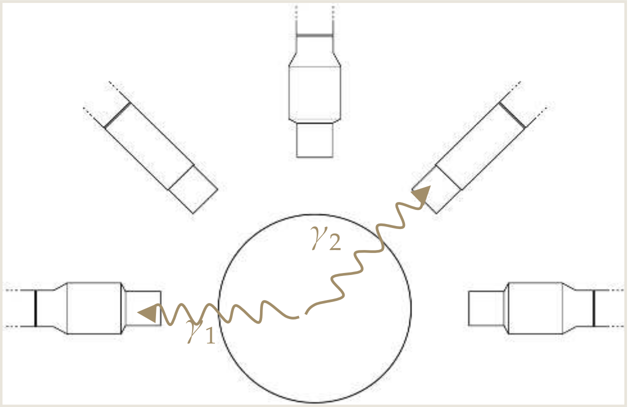
→ Can be measured using the VESPA setup

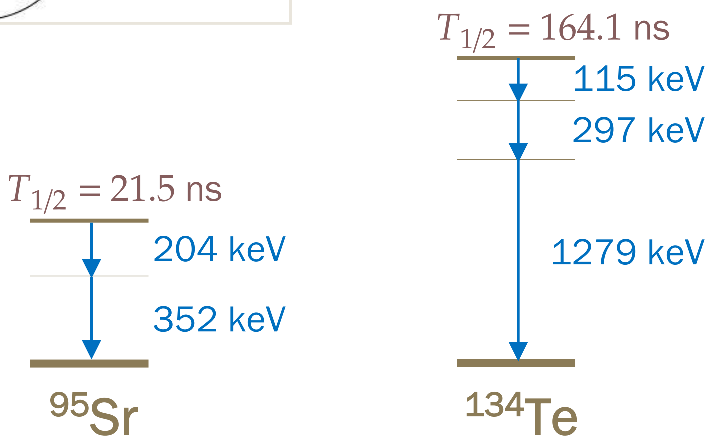
- Angle from the IC
- 3 γ-rays detectors are facing the IC

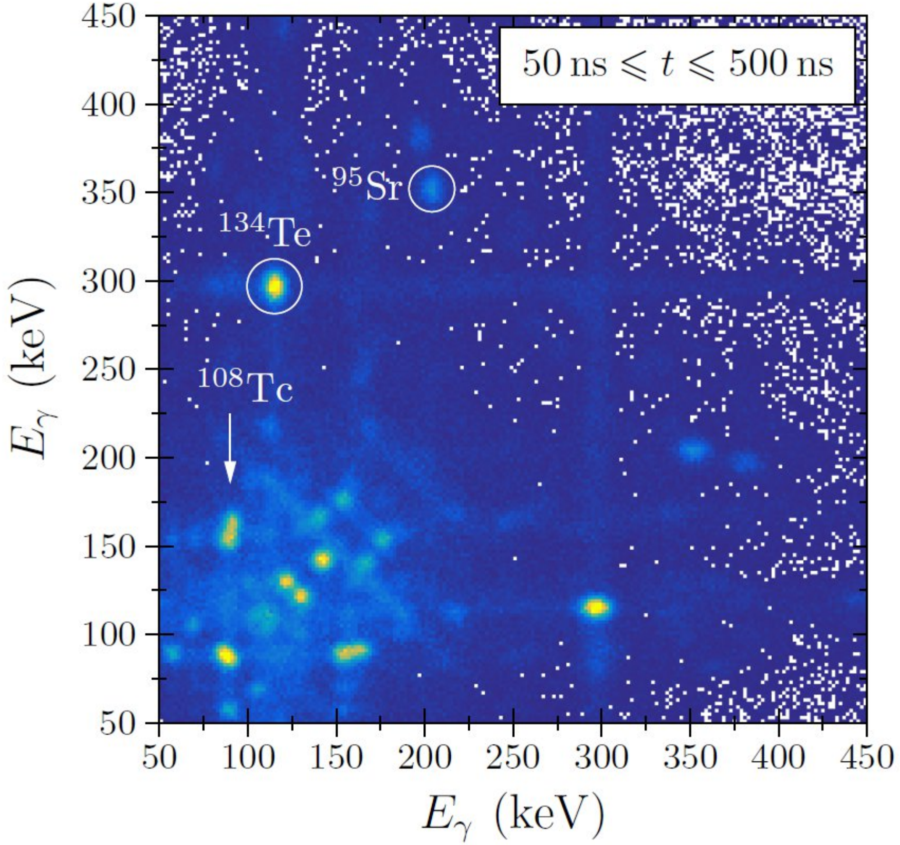
Isomers

Gamma-Gamma coincidences of late-emission γ-rays

- **t>35 ns** to avoid neutron contamination







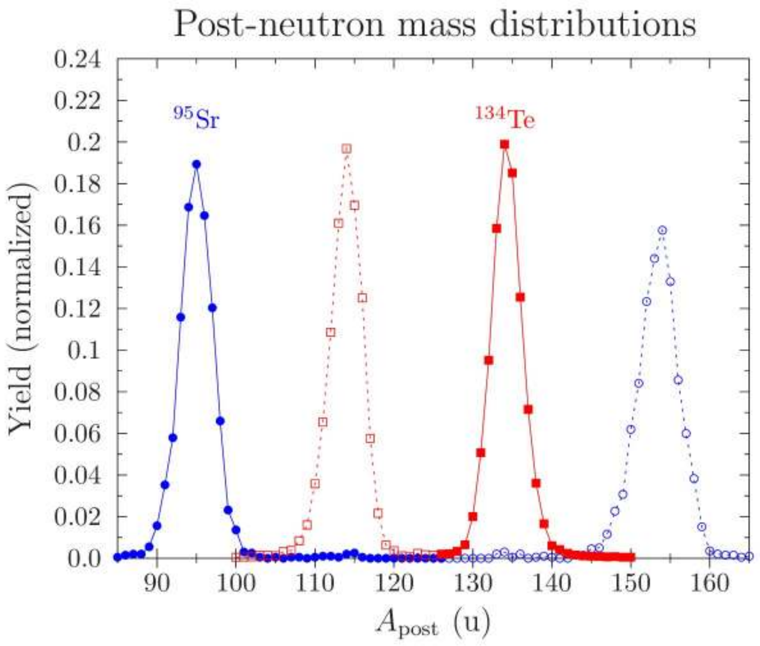
Isomers

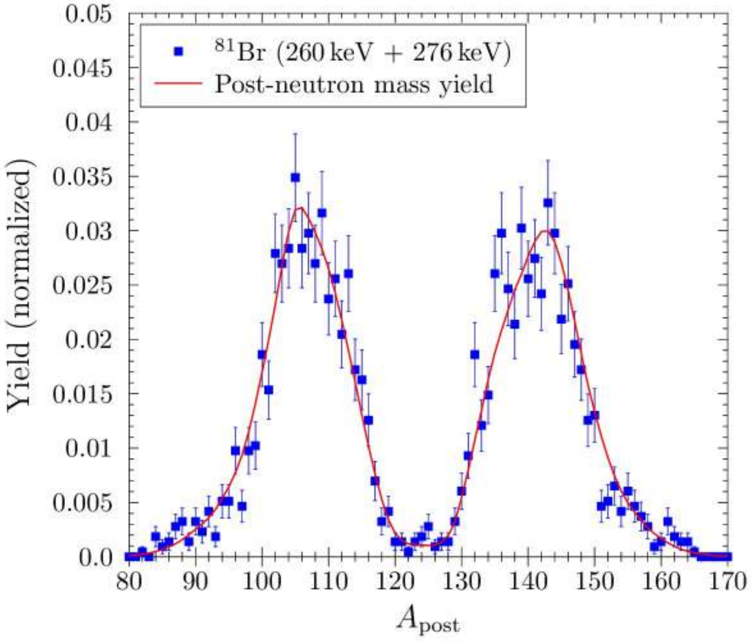
Gamma-Gamma coincidences of late-emission γ-rays

- t>35 ns to avoid neutron contamination

Mass distribution

- Double Gaussian distributions (FWHM~5u) ⟶ the **isomer** and its **complementary fragment**
- If not an isomer ⟶ post-neutron mass distribution, e.g. ^{81}Br from $LaBr_3$





Isomers

Gamma-Gamma coincidences of late-emission γ-rays

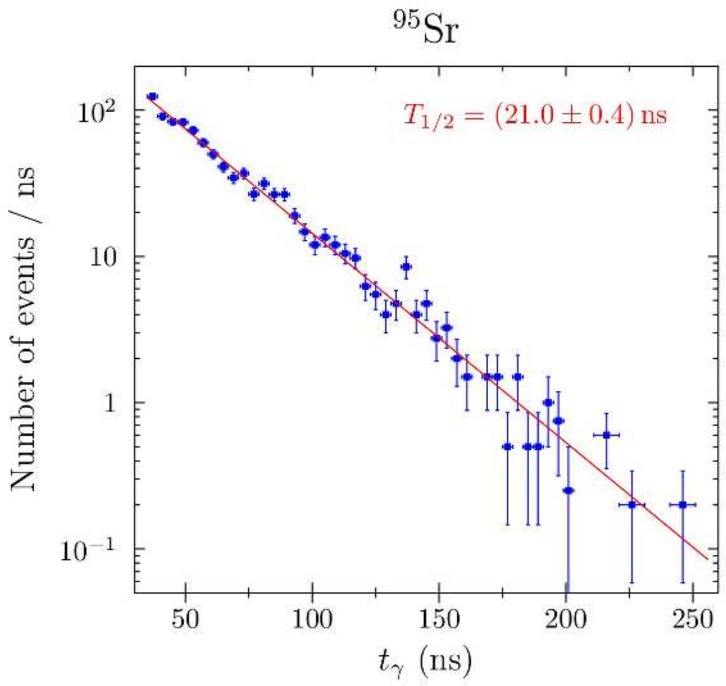
- t>35 ns to avoid neutron contamination

Mass distribution

- Double Gaussian distributions ⟶ the isomer and its complementary fragment
- If not an isomer ⟶ post-neutron mass distribution, e.g. ^{81}Br from $LaBr_3$

Time distribution

- Exponential decay ⟶ **half-life** of the isomer



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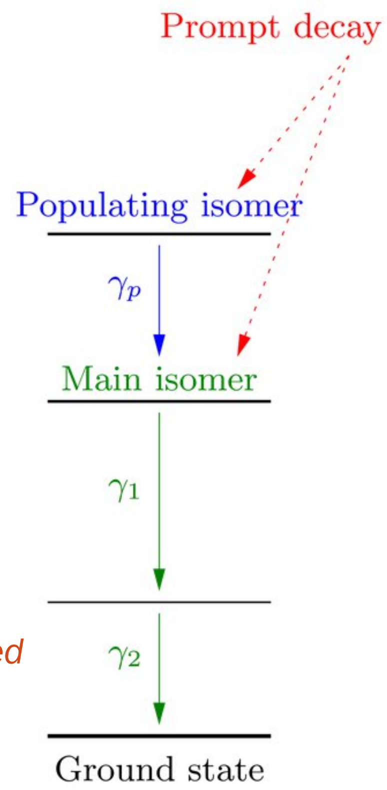
- Not valid if there are more than one isomeric state

⟶ Dedicated method (**multiple isomer analysis**) for consecutive isomeric states



V. Piau et al., accepted in Eur. Phys. J. A

Isomers

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→ Dedicated method (**multiple isomer analysis**) for consecutive isomeric states

New short-lived isomeric states have been found with VESPA in ^{94}Rb, ^{108}Tc, and ^{147}Ce.

V. Piau *et al.*, accepted in Eur. Phys. J. A

Summary

The VESPA setup was used to **measure prompt fission γ-rays** using $LaBr_3$(Ce) scintillation detectors and a twin Ionization chamber.

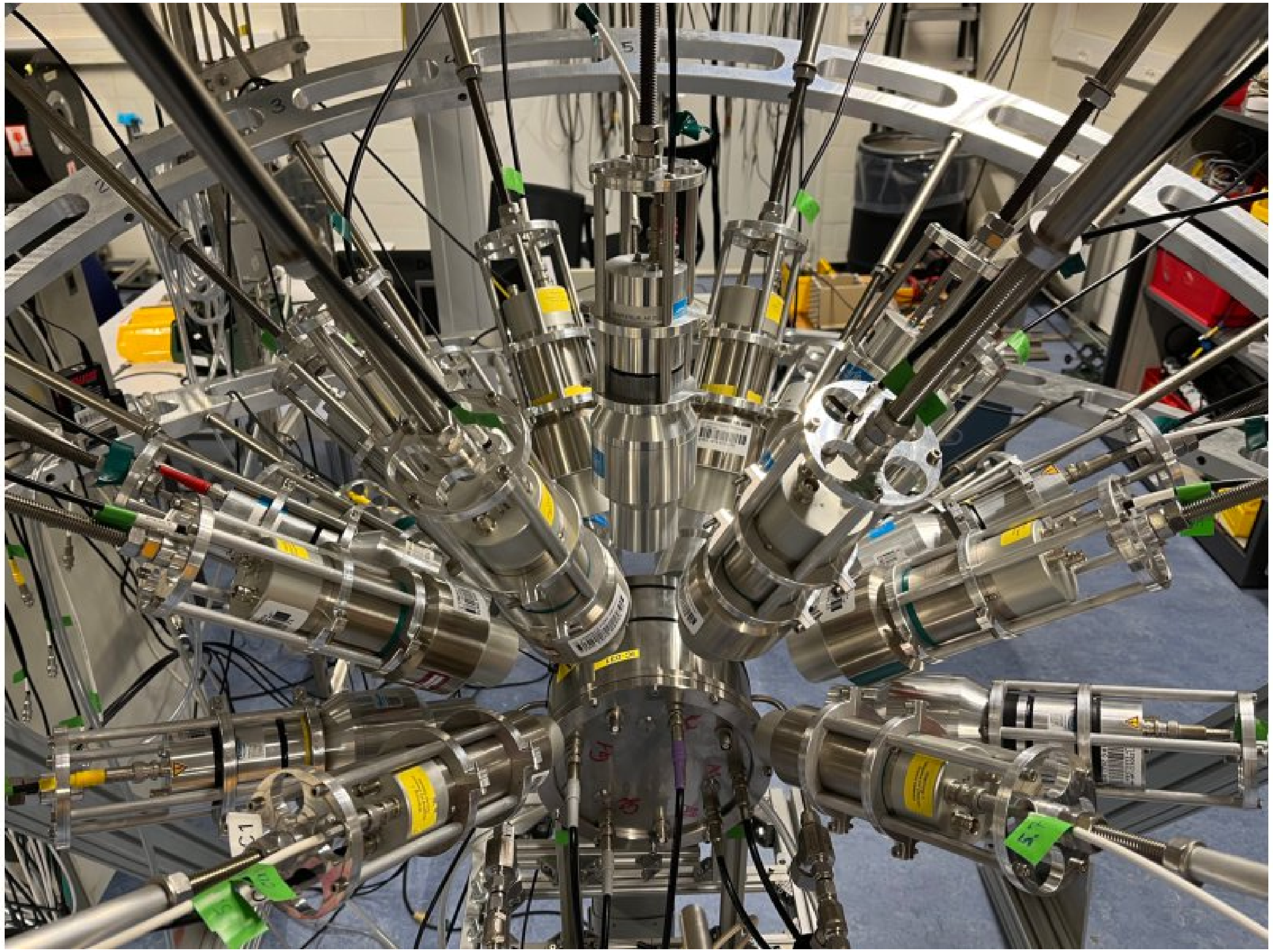
- Prompt Fission Gamma-ray Spectra (PFGS) up to 10 MeV
- Mass- and TKE-dependent prompt fission γ-ray multiplicity and total energy
- Isomeric half-lives of fission fragments

These results are consistent with recent independent measurements.

Prompt fission neutrons and γ-rays, especially when **correlated to fission fragments** properties, are of great interest to **better understand the underlying mechanisms of the fission process**, and to constraint nuclear models used in calculation codes, like FIFRELIN

→ see next talk: A. Chebboubi

VESPA is dead, long live VESPA 2.0 !



S. Oberstedt, private communication (2024)

Twin Frisch-grid **ionization chamber**
+ 30 gamma-rays detectors

- 15 $CeBr_3$ (2'' x 2'')
- 10 $LaBr_3$:Ce (2'' x 2 '')
- 2 $LaBr_3$:Ce (3'' x 3'')
- 1 $LaBr_3$:Ce (3.5'' x 8'')
- 2 $LaBr_3$:CeSr (2'' x 3'')
- + 1 HPGe (near future)

@17 cm from the source

^{248}Cm source (sf)

- ➢ Study **PFGS** properties
- ➢ **Angular distributions** & correlations
- ➢ Double and triple **gamma-ray coincidences** for isomer yields, prompt isotopic yields

⟶ PhD thesis of Alan Danilo (CEA)