MC1 – Advances in nuclear fission detection and modeling

26th General Congress of the French Physical Society

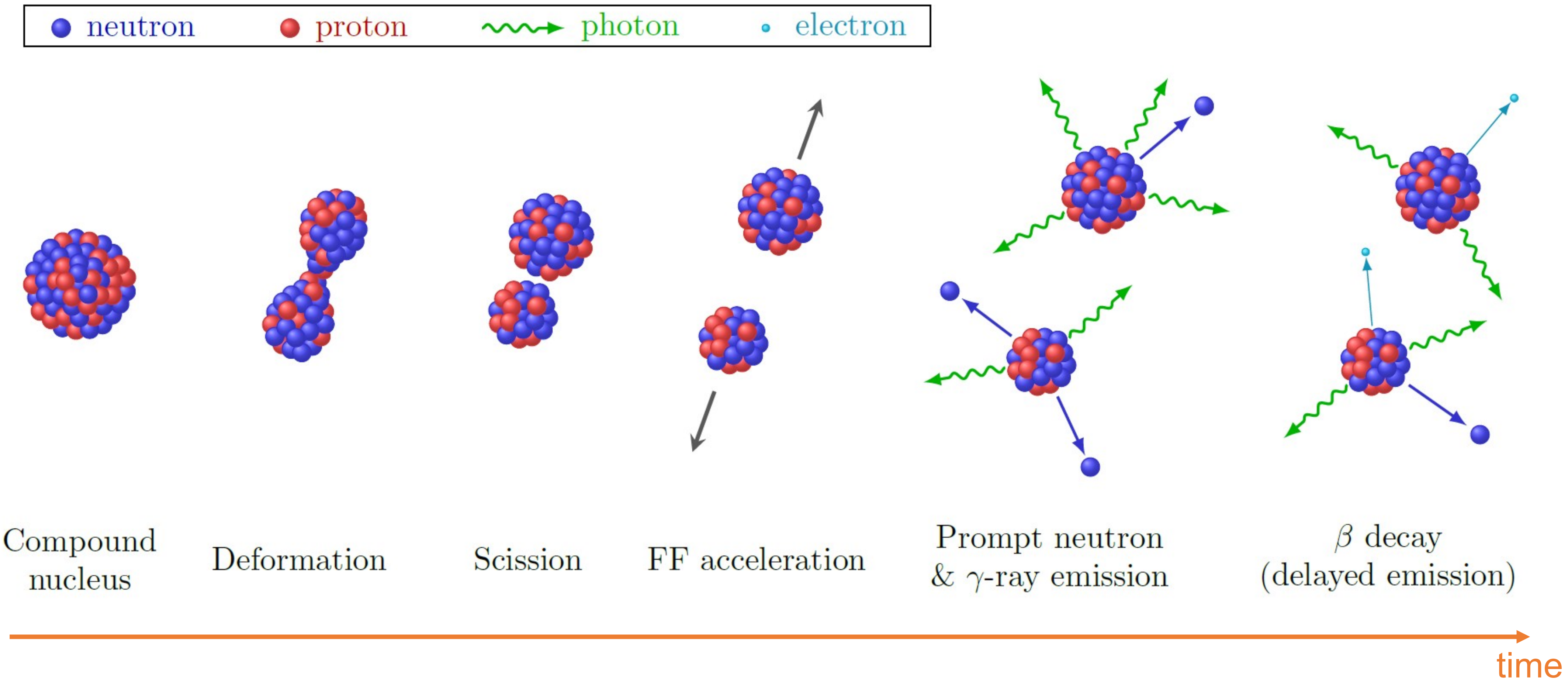
Modeling fission fragments de-excitation

Valentin Piau

CEA/DES/IRESNE/DER, Cadarache, 13108 Saint-Paul-lez-Durance

present address : Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay

The fission process



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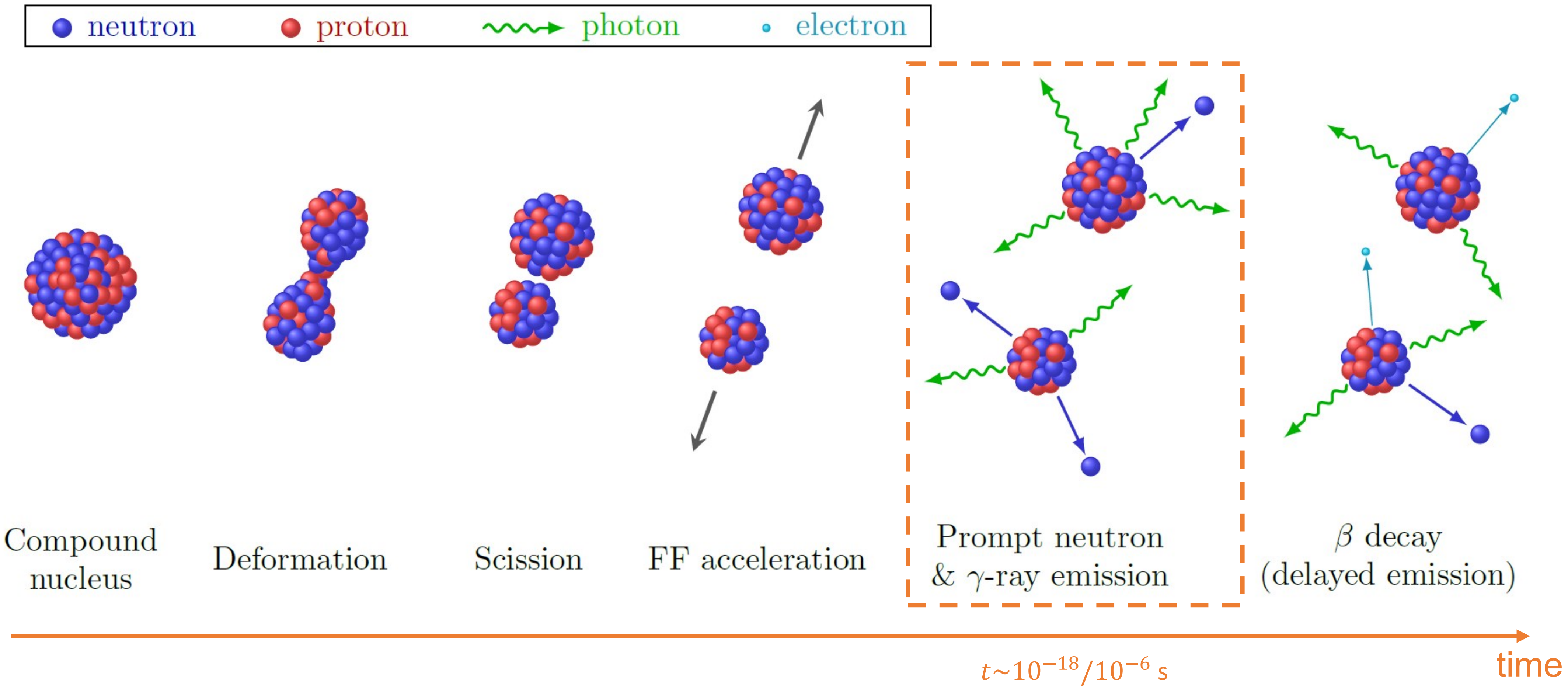
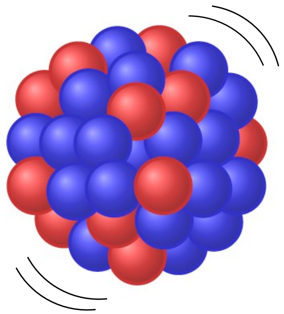


Prompt de-excitation of the fragment

Fission fragments are left in an excited, unstable state



Fission fragment

Mass (A)

Charge (Z)

Excitation energy (E)

Total angular momentum (J)

Parity (π)

Characterize the excitation state of the fission fragment

Particle emission

➔ Remove the excess of excitation energy to reach a more stable state

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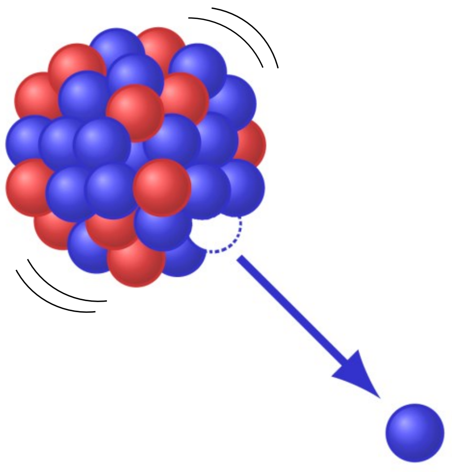

<u>Particle emission</u>

➔ Remove the excess of excitation energy to reach a more stable state

Neutron emission

a neutron is expelled from the nucleus : A → A -1

threshold reaction : $E > S_n$

Prompt de-excitation of the fragment

Fission fragments are left in an excited, unstable state

<u>Fission fragment</u>

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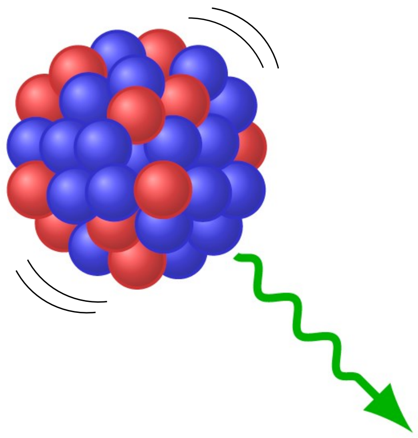


<u>Particle emission</u>

➔ Remove the excess of excitation energy to reach a more stable state

γ-ray (photon) emission

electromagnetic transition

mostly occurs after the neutron emission

How is this measured ?

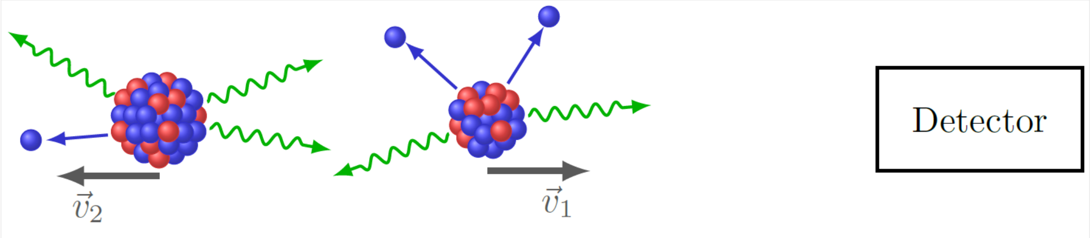
Measuring the de-excitation

- Experiments to measure neutrons and/or γ-rays emitted after fission
  - Neutron / gamma-ray multiplicities (number of emitted particles)
  - Neutron / gamma-ray spectra (energy distribution)

  } *Fission observables*

- Correlations with other parameters, e.g. fragment mass

Challenges : particles emitted by both fragments, fragments in motion (Doppler effect)



- 'classical' systems : ^{252}Cf, ^{235,238}U, ^{239}Pu,…

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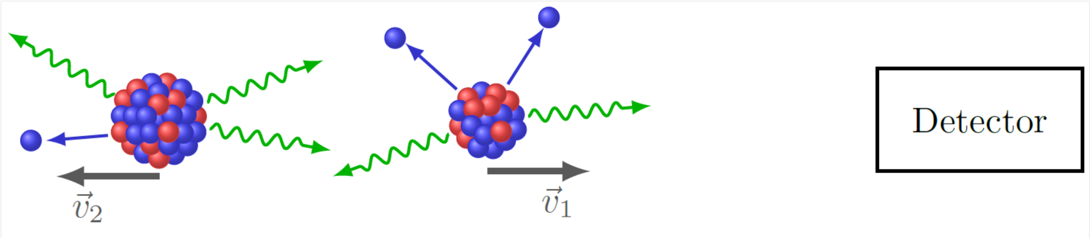

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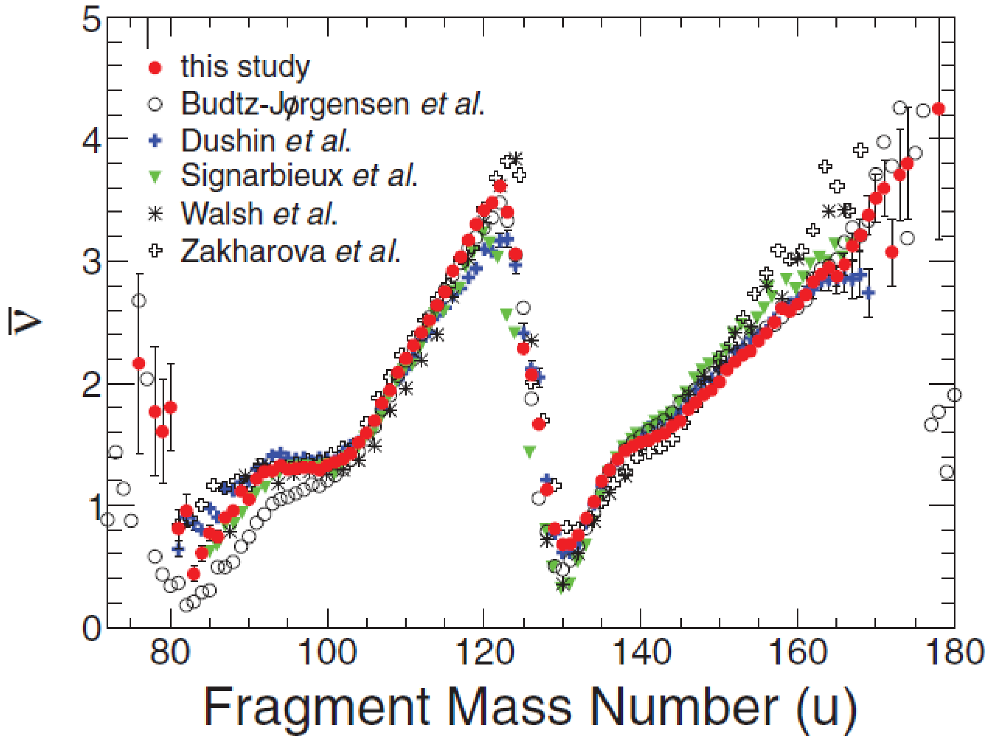
Spontaneous fission
→ CORA @IPHC (Strasbourg)
→ VESPA @EC-JRC (Geel, Belgium)
→ …

Neutron-induced fission
→ LICORNE + nu-ball @ALTO (Orsay)
→ FIPPS @ILL (Grenoble)
→ SCINTIA @GELINA (EC-JRC Geel, Belgium)
→ …

Prompt neutron multiplicity

Number of neutrons emitted in the spontaneous fission of ^{252}Cf as a function of fission fragment mass

A. Göök et al., Phys. Rev. C 90, 064611(2014)



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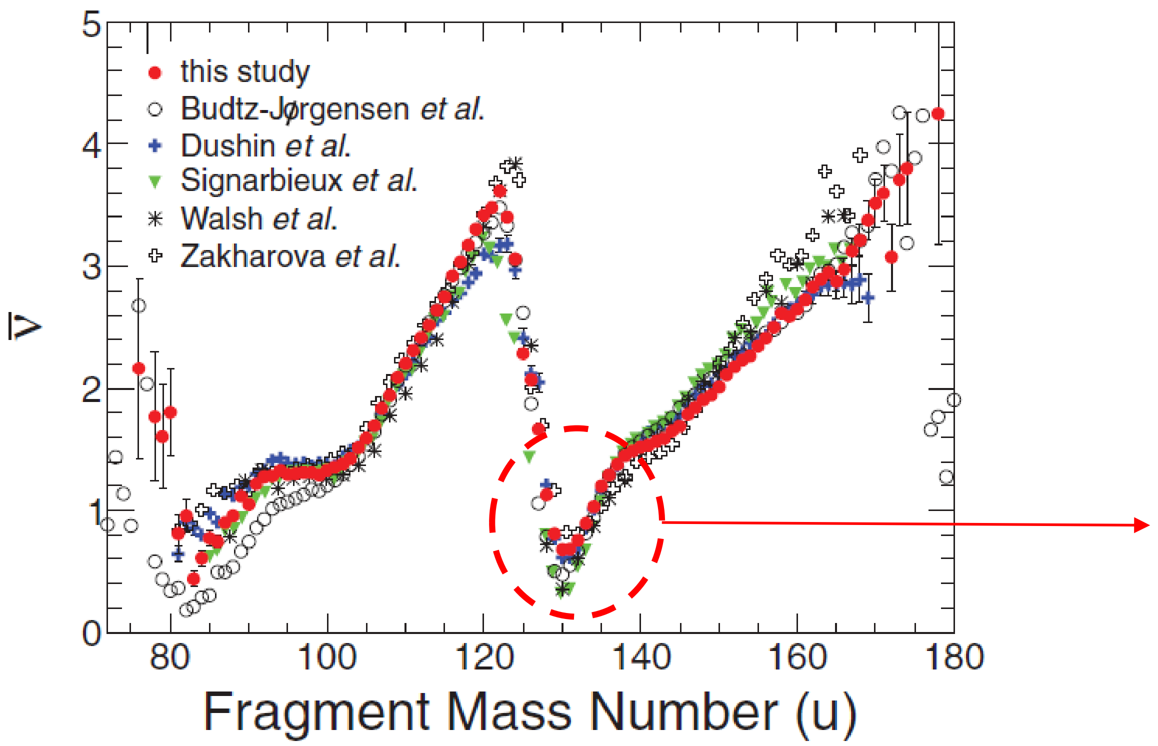


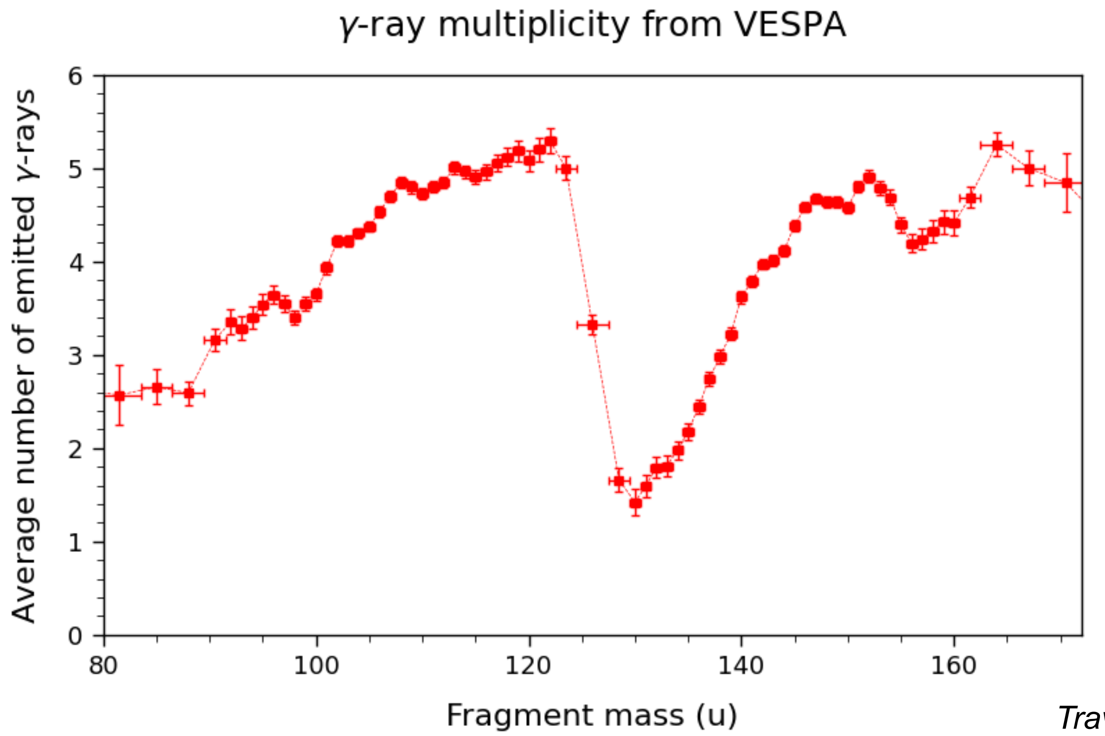
Typical saw-tooth shape

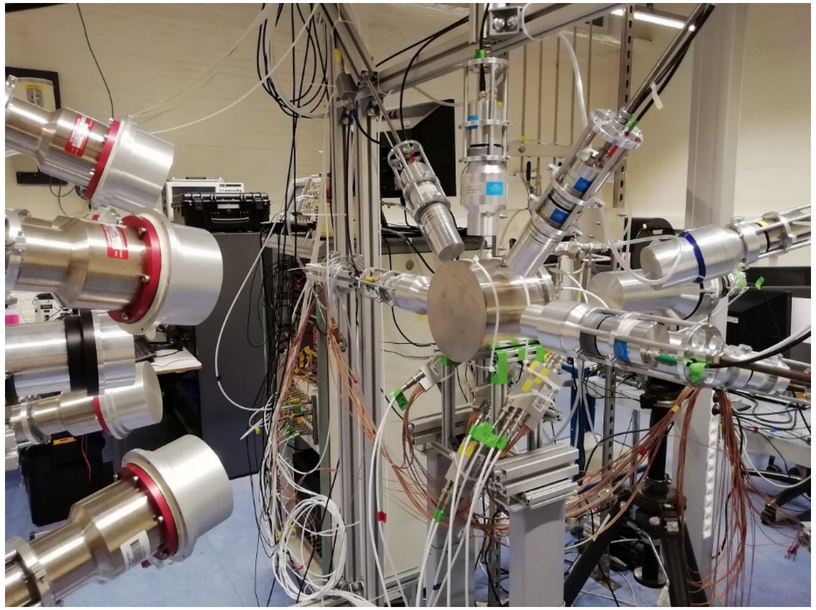
Minimum around A=132
➔ Shell closure
➔ « spherical » nuclei

Prompt γ-ray multiplicity

VESPA++ setup @EC-JRC Geel

→ Fission fragments,neutrons & γ-ray detectors





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

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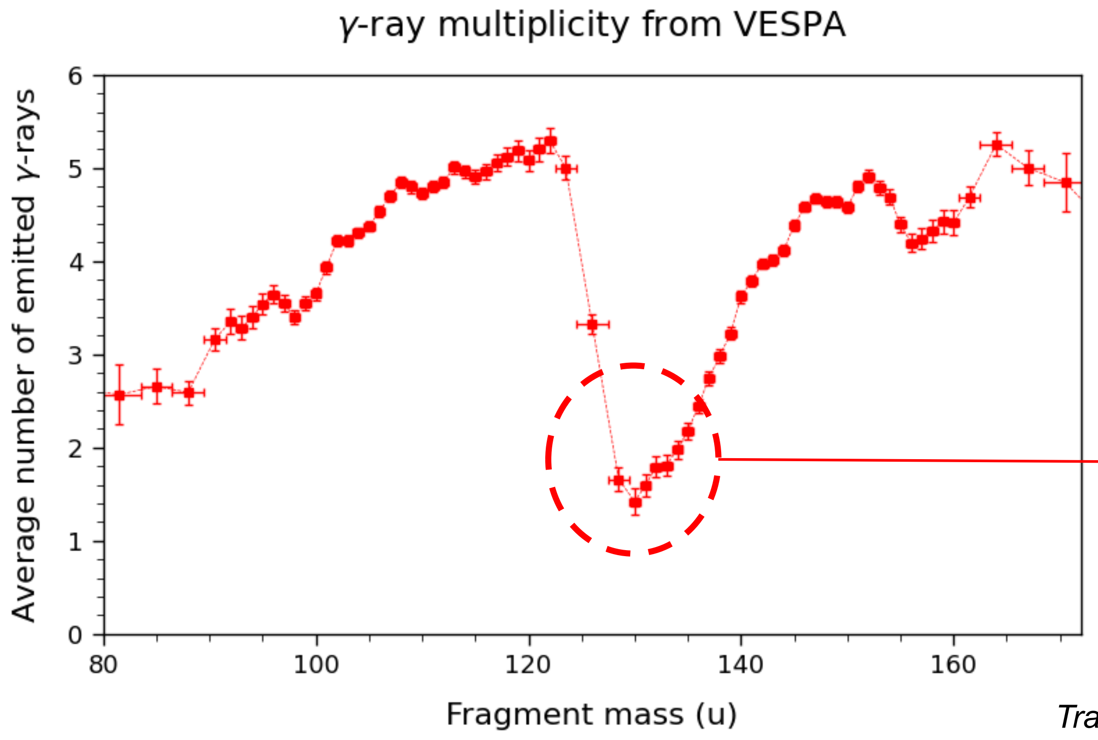
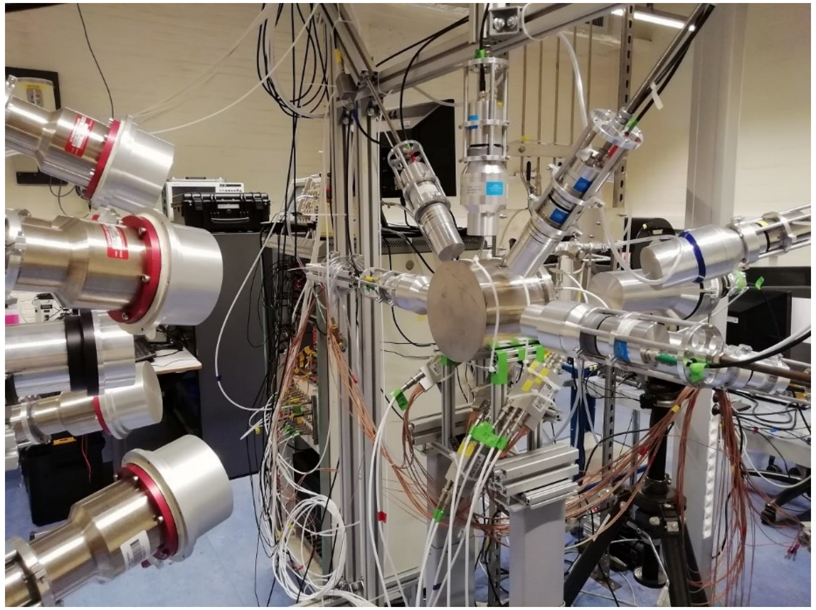




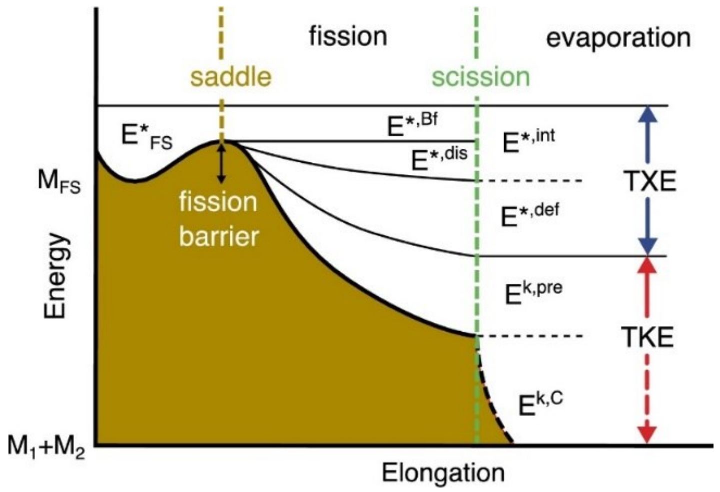
Also a minimum around A=132

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

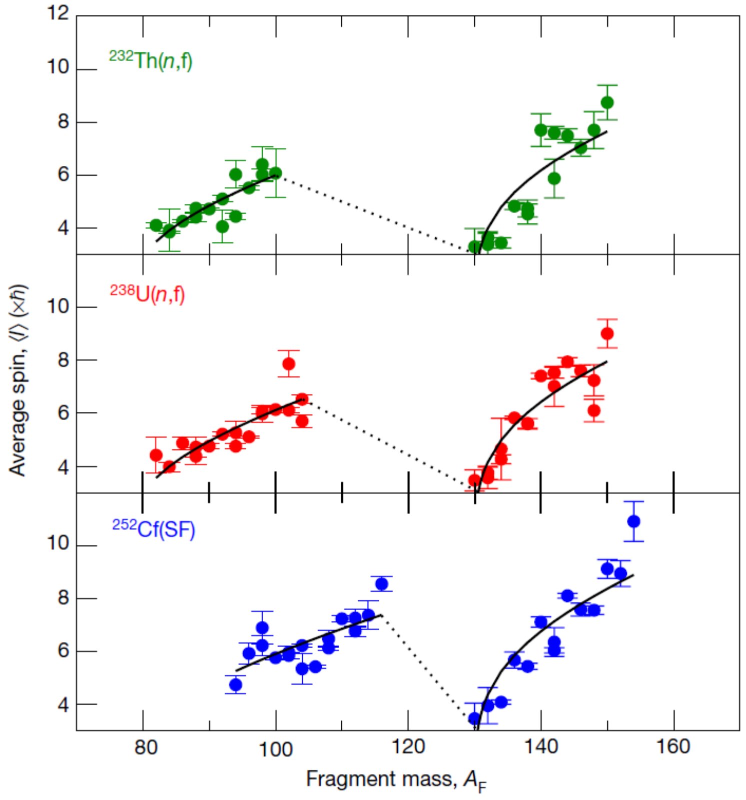
Modeling this complex process

Nuclear models

- Initial state of the fragments
  - energy, total angular momentum, parity
  - experimental & theoretical challenges



Caamaño et al., Phys. Let. B 770, 72 (2017)



Wilson et al., Nature 590, 566 (2021)

Nuclear models

- Initial state of the fragments
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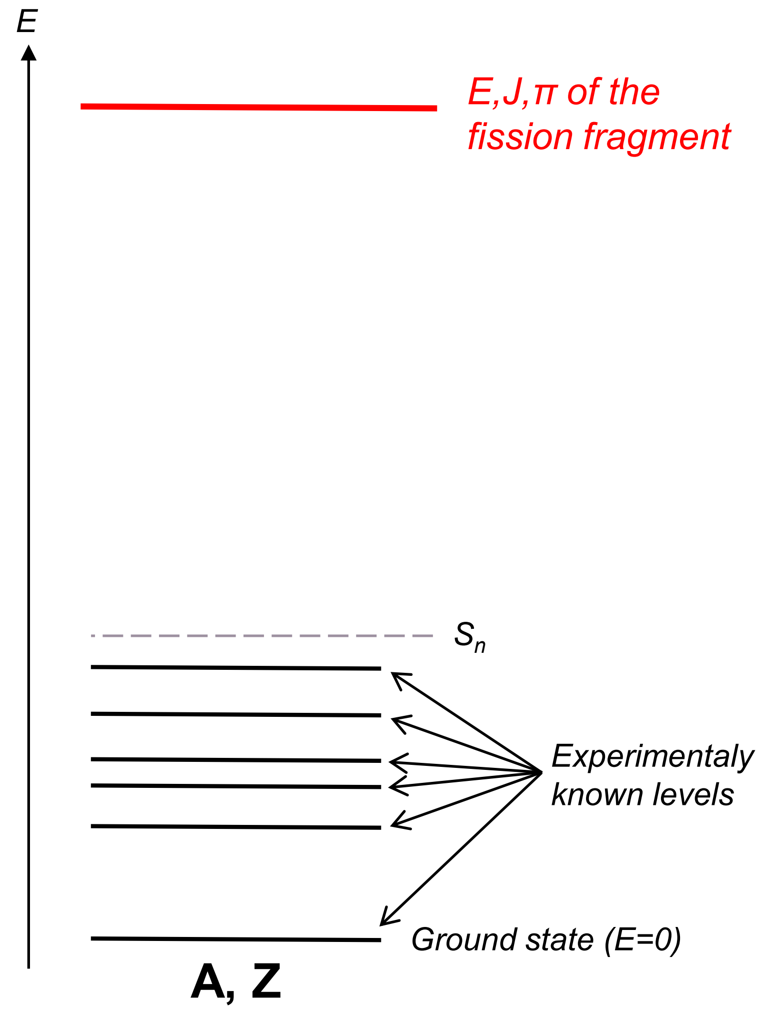
  - experimental & theoretical challenges

- Nuclear level scheme
  - represents the excited states of a given nucleus
  - unknown excited states at high energies



Litaize et al., Eur. Phys. J. A51, 177 (2015)

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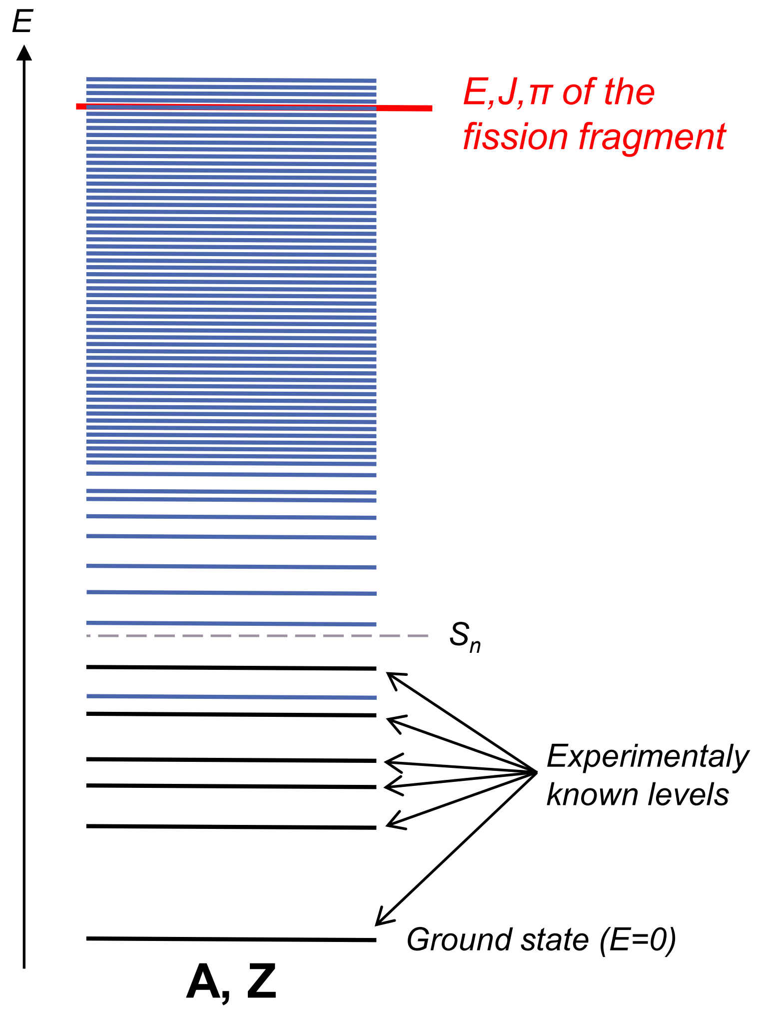

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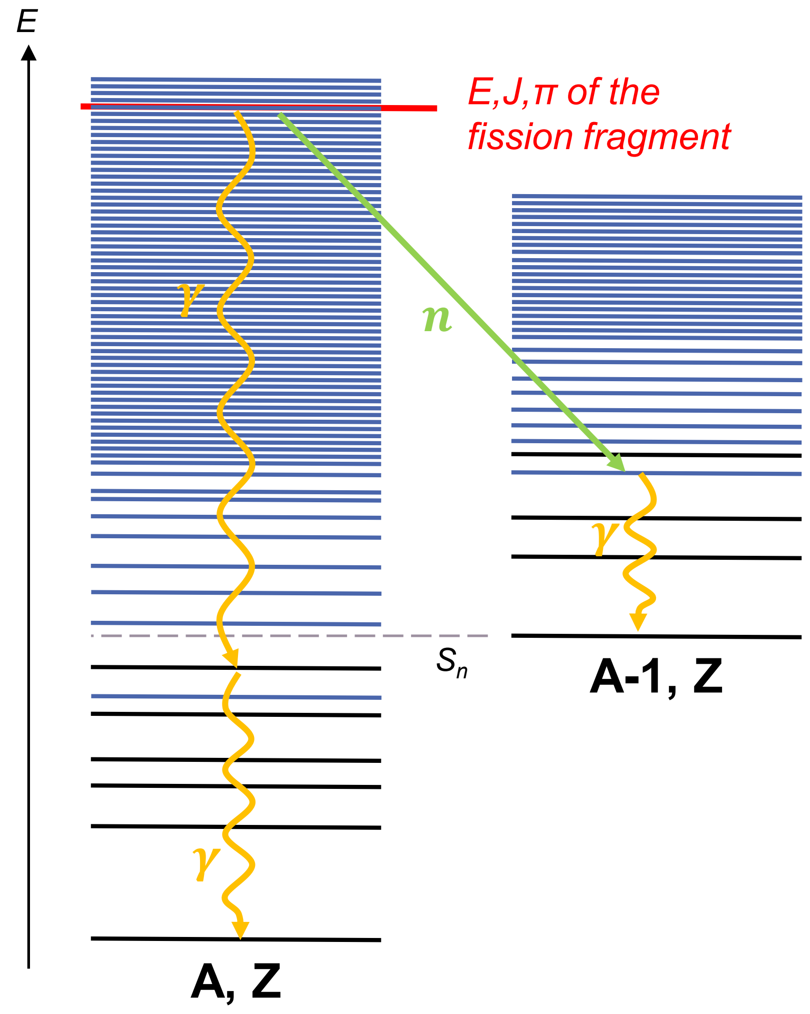
Nuclear models

- Initial state of the fragments
  - energy, total angular momentum, parity
  - experimental & theoretical challenges
- Nuclear level scheme
  - represents the excited states of a given nucleus
  - unknown excited states at high energies
  - ➔ theoretical excited states (E,J,π)
- Probabilities of emission
  - measured transitions at low energy only
  - different models for different particles (n/γ/e$^-$)



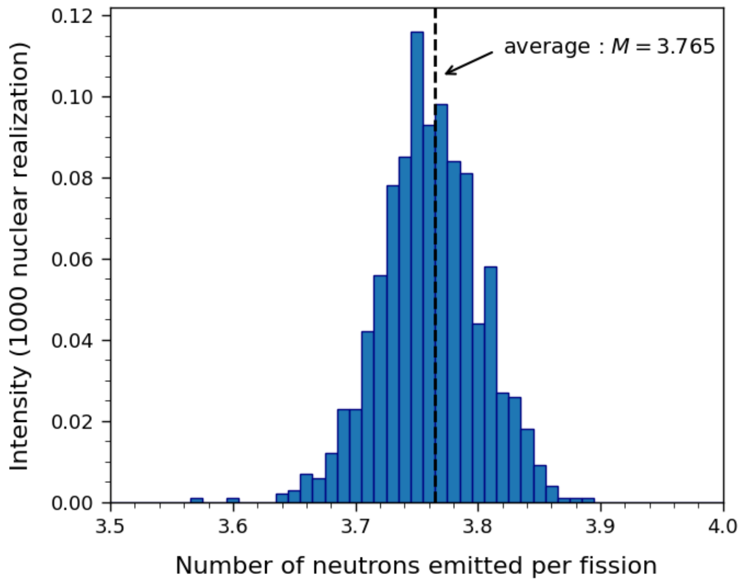
Litaize et al., Eur. Phys. J. A51, 177 (2015)

FIFRELIN

FIssion **FR**agment **E**vaporation **L**eading to an **I**nvestigation of **N**uclear data

Monte Carlo code written in C++ and developed by CEA Cadarache.

- ❑ Event-by-event simulation of fission
- ❑ Sampling of physical variables
- ❑ Statistical estimators
  - Fission observables
  - Correlations of observables
  - Non-measurable physical quantities (e.g. angular momentum)



O. Litaize and O. Serot, Phys. Rev. C 82, 054616 (2010)

O. Litaize et al., Eur. Phys. J. A 51,177 (2015)

O. Litaize et al., EPJ Web of Conf. 284, 04014 (2023)

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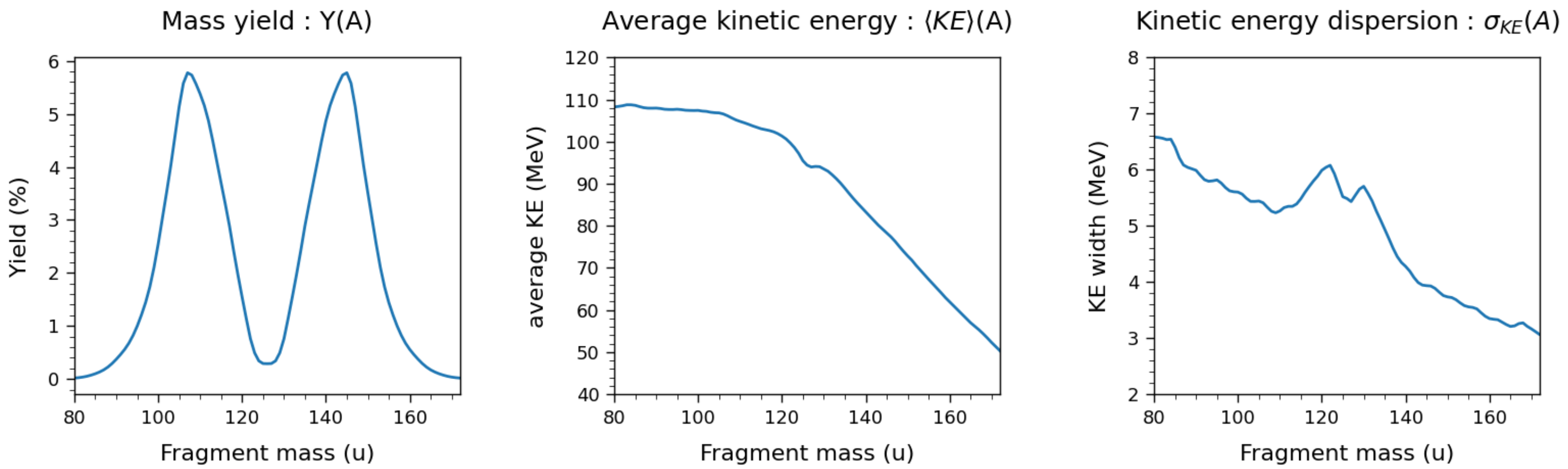
------------------------- Prompt Neutrons Results -------------------------
Mean neutron energy in CoM                          = 1.477     statError= 3.46e-04
Mean neutron energy in Lab                          = 2.238     statError= 4.70e-04
<Nu(L)> (true statistical mean)                     = 2.066     statError= 4.48e-04
<Nu(H)> (true statistical mean)                     = 1.7       statError= 4.17e-04
< Nu  > (true statistical mean)                     = 3.765     statError= 6.28e-04
```

FIFRELIN

FIssion **FR**agment **E**vaporation **L**eading to an **I**nvestigation of **N**uclear data

Principle of operation :

- ❑ Based on several nuclear models (macroscopic and/or microscopic)
- ❑ Fission fragments yields as input (before neutron emission)



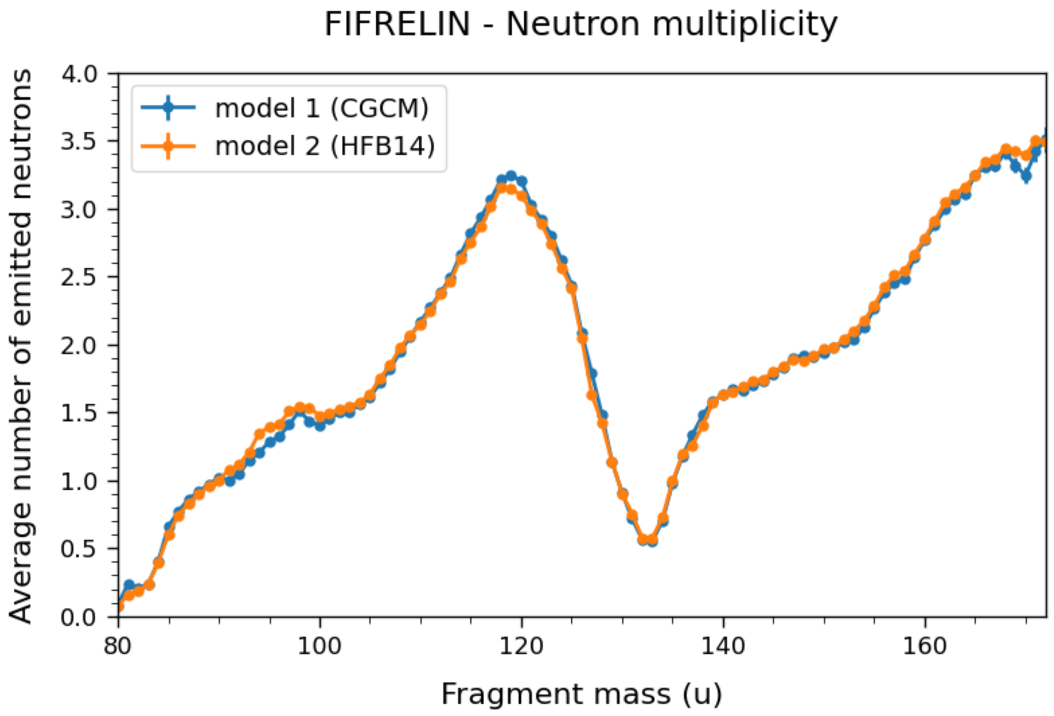
- ❑ 4 free parameters tuned to reproduce 1 to 2 scalar observables (average number of emitted neutrons)

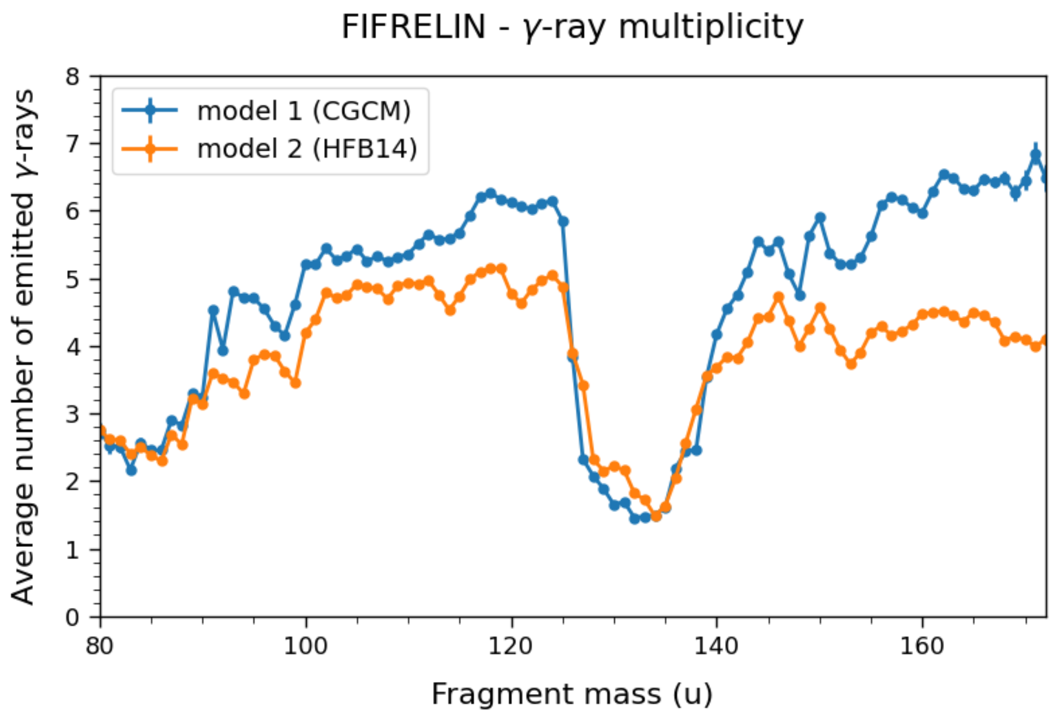
Impact of nuclear models

- Models of nuclear level density (number of levels in scheme)

Semi-empirical model (CGCM) vs microscopic+combinatorial model (HFB14)

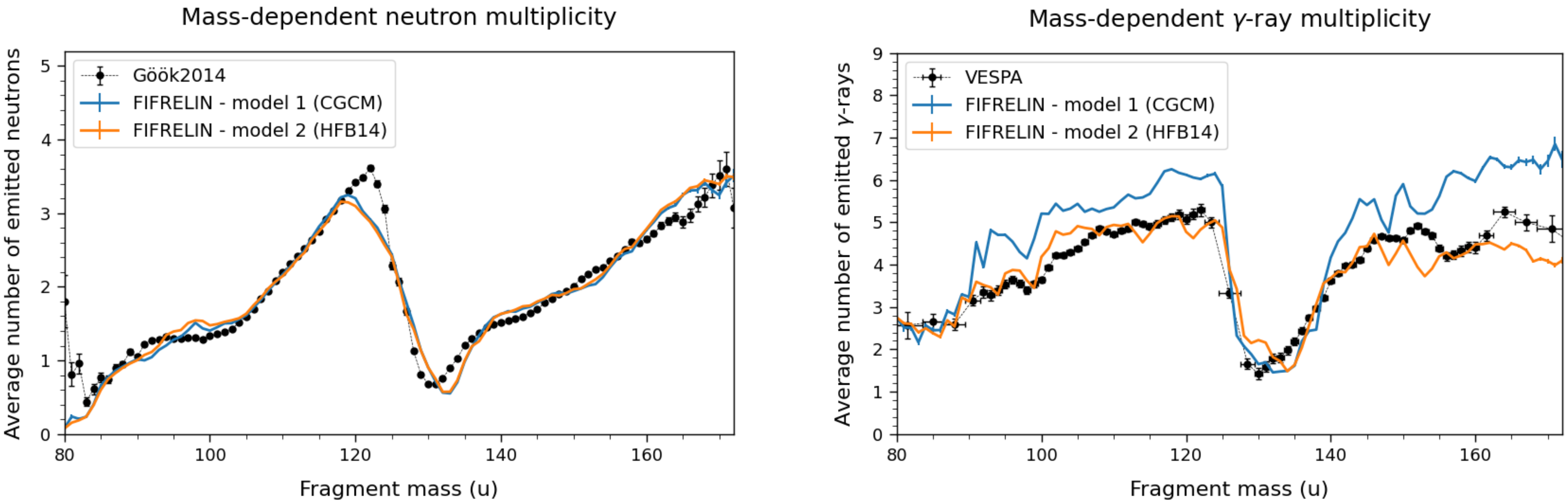
- Observables : neutron / γ-ray multiplicities as a function of fragment mass





Comparison with experimental data

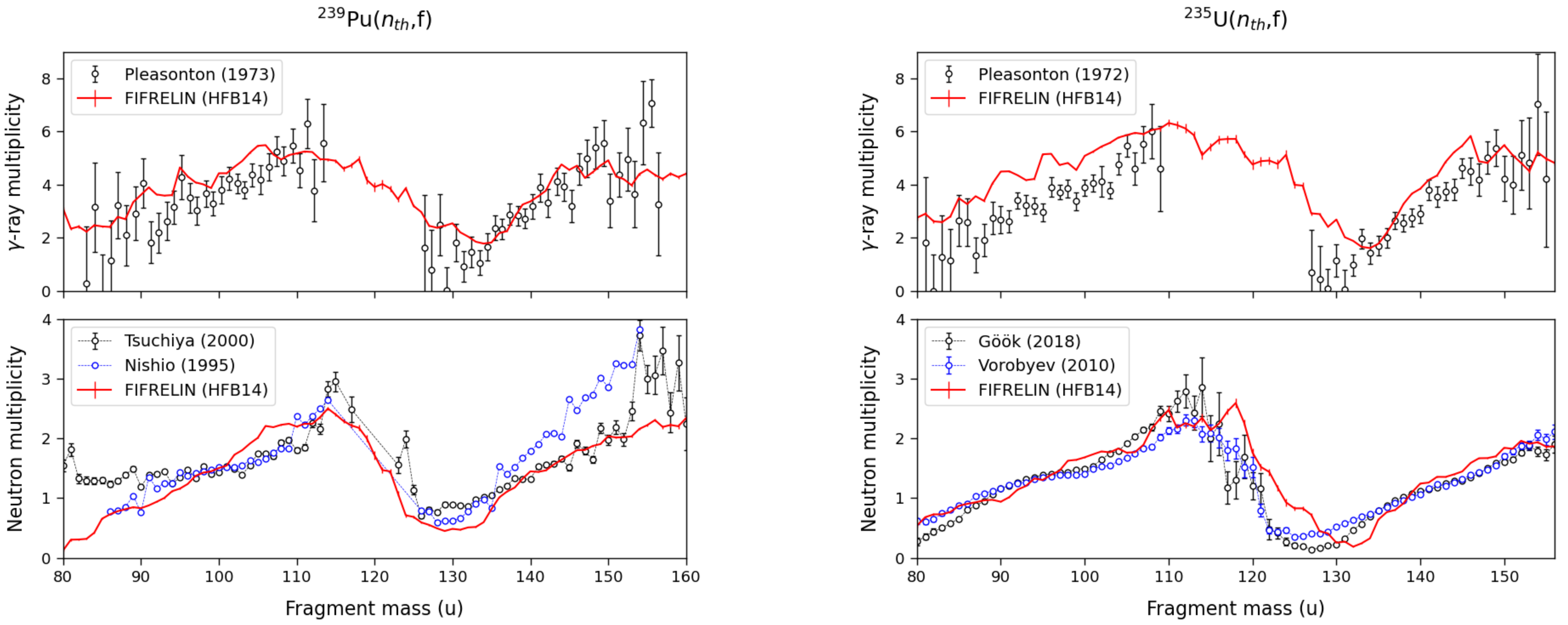
- Observables : neutron / γ-ray multiplicities as a function of fragment mass



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

Application to other fissionning systems

Neutron-induced fission of ^{235}U & ^{239}Pu



Conclusion

- Fission fragments de-excitate through the emission of several particles : **neutrons, γ-rays and electrons**

- Continuous progresses
  - Experimentaly : better detectors, advanced setups
  - Theorically : more & more advanced nuclear models

- FIFRELIN benefits from these progresses

  ➔ simultaneous reproduction of neutron and γ-ray multiplicities after the introduction of a new model

- Applications beyond fission

  ➔ de-excitation of a single nucleus following neutron capture

  ➔ G. Soum poster (this afternoon)