IN2P3-COPIN Collaboration Agreement 12-145

Advanced Monte-Carlo and GEANT4 simulations for optimizing future experiments dedicated to nuclear dynamics

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IDEA:

Use the decay of excited nuclei as a mean to study fundamental nuclear properties

Static aspects
(binding energy, level density, ...)
vs.
Dynamical effects
(inertia, viscosity, ...)

⇄

Macroscopic
("bulk" properties of nuclear matter)
vs.
Microscopic
(s.p. structure, pairing correlations, ...)

Challenge

- ❒ Many aspects of various origin, possible « perverse » interplay
- ❒ (In-)sensitivity of given observables to specific physics aspects

↪ **Request:** Large set of observables and their correlations

Our strategy combines

- ❒ Realistic **theoretical description** of the decay of hot and rotating nuclei
- ❒ **Simulations of the response function of the experimental setup** and optimization for a specific physics case

↪ **Unambiguous physics interpretation of the measurement**

A. Modelling the decay of excited and rotating nuclei

❒ **Langevin approach** within the Omsk model of Adeev, Karpov, Nadtochy et al.

PRC89(2014) 014616 and therein

↪ Time evolution of the system from classical multidimensional equation of motion

collective coordinate | conjugate momentum

$$\frac{dq_i}{dt} = \mu_{ij}p_j, \qquad (1)$$

$$\frac{dp_i}{dt} = -\frac{1}{2}p_j p_k \frac{\partial \mu_{jk}}{\partial q_i} - \frac{\partial F}{\partial q_i} - \gamma_{ij}\mu_{jk}p_k + \theta_{ij}\xi_j\,(t)$$

inertia | potential | friction | fluctuations

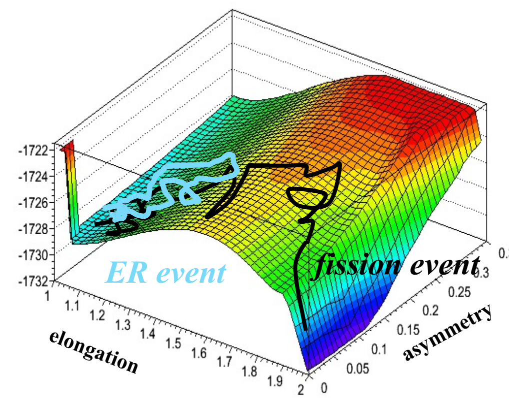
✓ **Restriction to 4D**

- elongation
- neck thickness
- reflection asymmetry
- *K* quantum number

✓ **Macroscopic ingredients**

❒ **Coupling to particle evaporation**

❒ In case of fission: calculation of the **fragment properties and decay**



A.1. So-far realization (2012-2023)

❒ **Continuous contribution to the enhancement of the code**

in collaboration with the developers (namely, P.N. Nadtochy, Omsk)

❒ **Study of various aspects of fission dynamics in heavy-ion collisions**

- Determination of uncertain model parameters (specific terms of the energy functional, viscosity of nuclear matter, charge diffusion,…) Phys.Rev. C 88, 054614 (2013), Phys.Scr. T154, 014004 (2013), Phys.Lett. B 737, 289 (2014), Phys.Rev. C 94, 064602 (2016)

- Businaro Gallone transition (pioneering study with a dynamical model) Phys.Rev. C 97, 024604 (2018)

- Influence of the entrance channel, *i.e.* fusion dynamics, for proper interpretation of fission observables Phys.Rev. C 97, 014616 (2018)

- Innovative method to extract quasi-fission properties from inclusive measurements Phys.Rev. C 100, 064606 (2019)

- Nuclear level density away from β - stability Phys.Lett. B 840, 137873 (2023)

A.2. Nuclear level density away from β - stability

❒ **N**(uclear) **L**(evel) **D**(ensity) = number of excited levels in a given energy interval

✓ **discrete states** at low excitation energy

→ microscopic models with explicit account of nuclear structure

✓ transition to **continuum** at high excitation energy

→ phenomenological models

❒ **NLD can drastically change when moving away from stability**

✓ **modification of *N, Z* shell gaps** at low E^*

→ different predictions depending on the model

↪ Irrefutable signature: spectrum of discrete states!

✓ **isospin/distance from stability-dependence** at high E^*

→ different predictions depending on the model

Proposed evolution of the level density parameter "*a*"

$$\tilde{a}_{N-Z} = \alpha A / \exp[\beta (N-Z)^2]$$

$$\tilde{a}_{Z-Z_0} = \alpha A / \exp[\gamma (Z-Z_0)^2]$$

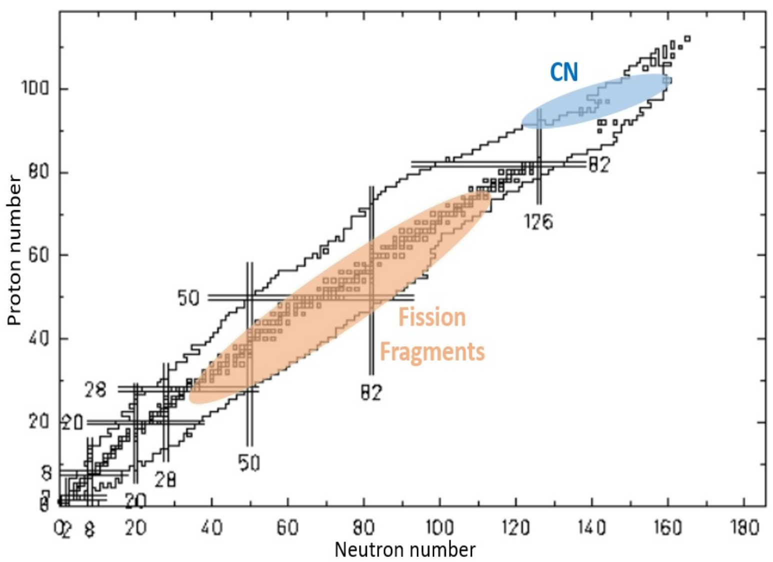
Al-Quraishi et al., PRC63(2001)065803.

↪ Lack of "direct" signature

Usual probe: **Energy spectrum of the particles emitted in the decay of excited compound nuclei**

Need of an evaporation code → model dependence → no consistent conclusion

Fusion-fission as a relevant probe of the NLD away from β - stability



- ❒ Fissile nucleus → **heavy** nucleus
- ❒ Fusion production mechanism → **neutron-deficient** compound nucleus
- ❒ Fission produces **medium-mass** fragments
- ❒ Fission fragments are typically **neutron-rich**
- ❒ Fission produces a couple of **hundreds of different fragments**

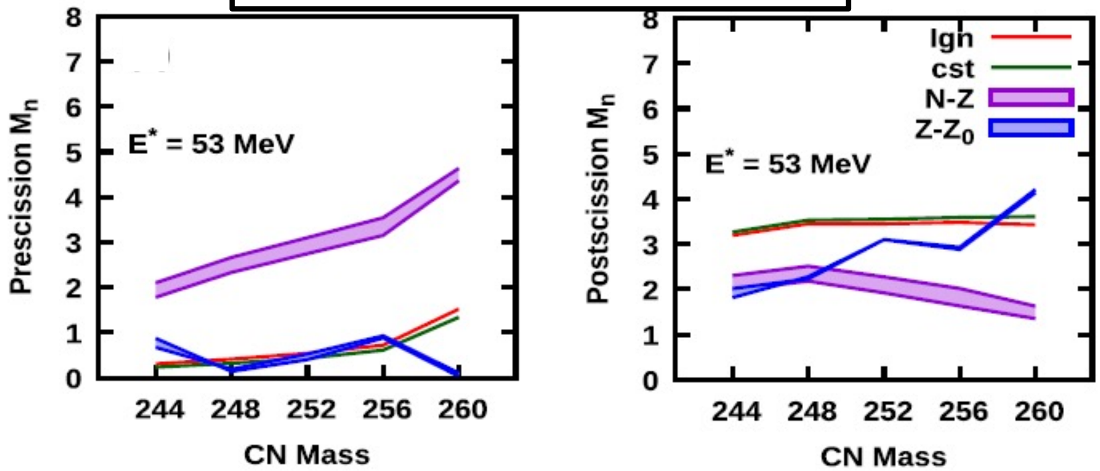
Strategy:

- ✓ Dynamical 4D Langevin model with different NLD prescriptions and evolution with *N, Z*
- ✓ Calculate an ensemble of reactions scanning the isotopic chain of a compound nucleus *Z*, *i.e.* scanning in isospin/distance from stability line
- ✓ Compare the predictions of typical and new fission observables from different NLD's

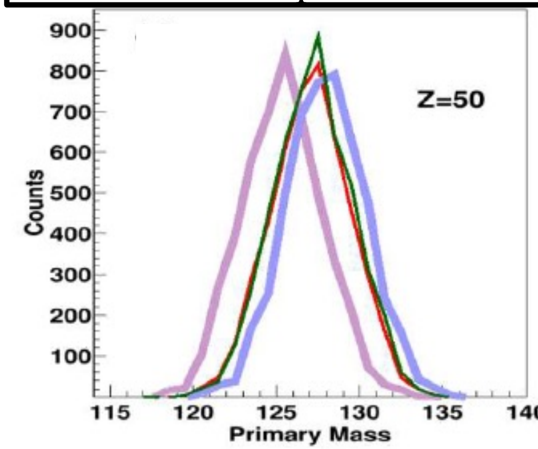
Fusion-fission as a relevant probe of the NLD away from β - stability

❐ ^{40,48}Ca+^{204,208}Po and ^{22}Ne+^{238}U → $^{244\text{-}260}$No at various E^* around the barrier

« Standard » neutron observables



Innovative isotopic distribution



- Fission is complex… Many nuclei, many steps, etc.
- High degree of correlation between *i)* each step and *ii)* the observables
- Fission can be characterized by a variety of observables…

  At the end « everything has to come correct »

  Strong constraints to the modelling

B. Simulations of complex experiments

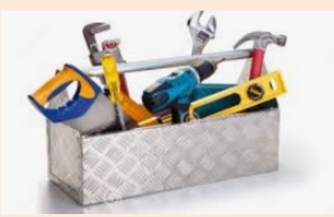
❒ To unravel the complexity of the physics mechanism, measuring the **correlations between different observables** is crucial

↳ Sophisticated coupling of various detectors, advanced instrumentation and electronics, etc

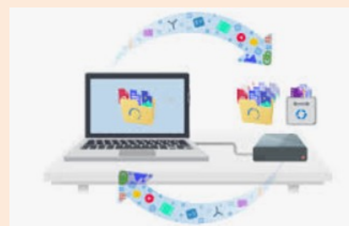
❒ There exists **no perfect, no 100% efficient set up**…
(limited coverage, intrinsic efficiency, inhomogeneities, etc)

↳ **To prevent mis-interpretation requires controlling any experimental bias**

Elaborate and versatile simulations within MC & GEANT4 framework



PLATFORMER TOOLKIT



B.1. So-far realization (2012-2023)

❒ **Continuous contribution to the enhancement of the Monte Carlo physics generators**

- **GEMINI++** (focus on accurate description of Giant Resonances)
- **GEF** (fragment yields and energetics, prompt and delayed decay)
- **Langevin** (« everything »)

Phys.Rev. C 91 (2015) 054313,

Phys.Rev. C 98 (2018) 044605

INPUT for the experimental filter

❒ **Detailed simulations of various detection systems and configurations**

- **PARIS** (array of La/CeBr3 – NaI phoswich scintillators)
- **VAMOS++** (large acceptance magnetic spectrometer)
- **KRATTA** (light particle detector)
- some more ancillary detection systems

Phys.Rev. C 101 (2020) 021303, EPJ A 57 (2021) 156,
Phys.Rev. C 105 (2022) 014310, EPJ A 56 (2020) 98

For data analysis (in particular for the PARIS community)

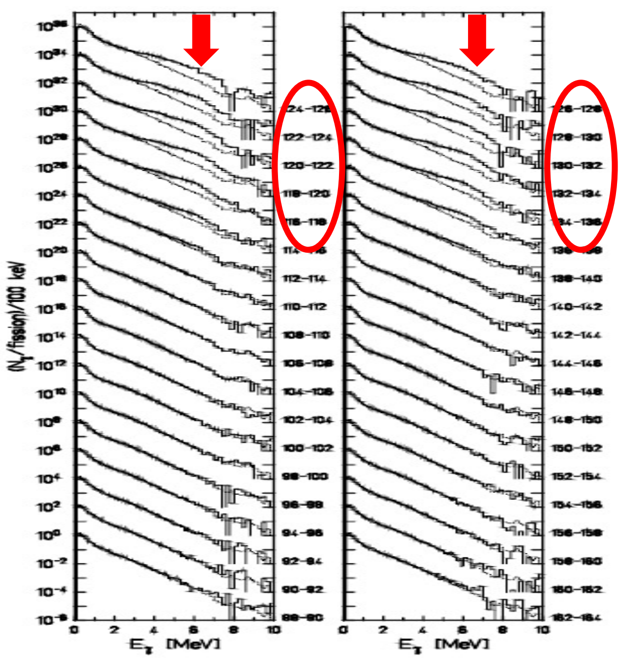
For new proposals (CCB, GANIL, IJCLab, INFN)

B.2. Energetic of fission with PARIS@VAMOS

- **First measurement of (A, Z) identified fission fragments in coincidence with their decay by neutron and γ-ray emission**
  - ➥ Reconstruct the situation @ scission: E^* and L of the primary fragments

- <u>Physics case</u>: **Origin and nature of high-energy photons in fission of actinides**
  - ➥ In addition to statistical and *y*-rast γ-rays, there is an excess at E_γ =(4-8)MeV

Mass-gated PFGS from ^{252}Cf (sf)



Holtzel et al., Z fuer Phys. (1996)

➥ Which fragments (A, Z) are at the origin of the γ bump?

➥ What is its nature (collective, s.p. driven) ?

Combine the unique performance of:
PARIS
(efficient detection of low to high energy γ-rays)
VAMOS++
(precise fragment A and Z identication)

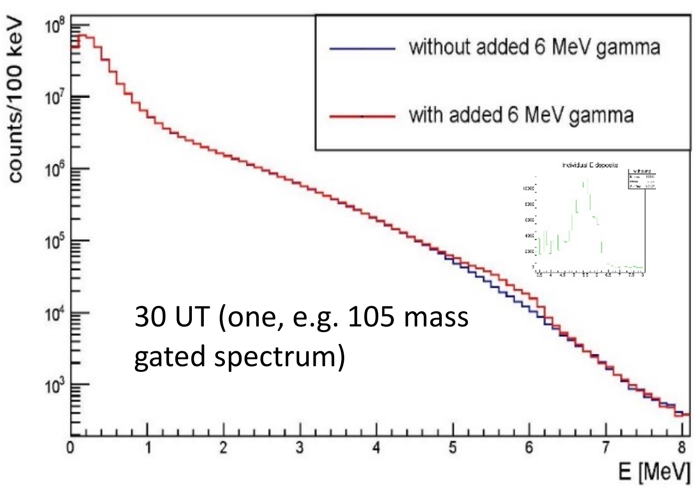
Simulations of the PARIS@VAMOS set up

Request: **Statistically significant PFGS up to 10MeV for each fission partition**
↳ Is a sufficiently efficient set up available for this endeavor?

❐ Challenge addressed in 2022 with the advent of the enhanced 8-cluster PARIS !

❐ Simulations framework:
- GEF as the fission generator for ^{238}U (5.88AMeV) + ^{9}Be → $^{247}Cm^*$ (E^*~ 43MeV) containing PFGS w/o an excess of high energy photons for few fragments
- Well-established VAMOS++ acceptance software
- **Enhanced simulation of the 8-cluster PARIS configuration**

❐ **Result of the simulations for revealing the γ bump**



- **Experiment run in 2022**
- **Under analysis (promising!)**

- **Simulations will be next explored for investigating and correcting any possible experimental bias**

Conclusion & Perspectives

❒ **Combine calculations based on the Langevin approach, the GEF fission code and the Hauser-Feschbach based FIFRELIN de-excitation model**

↳ Emphasis on the interpretation of the recent PARIS@VAMOS experiment

(generation of E^* and L in fission, NLD, γ-strength, etc)

❒ **Develop further the GEANT4 toolkit**

↳ Emphasis on the enhanced 8-cluster PARIS configuration

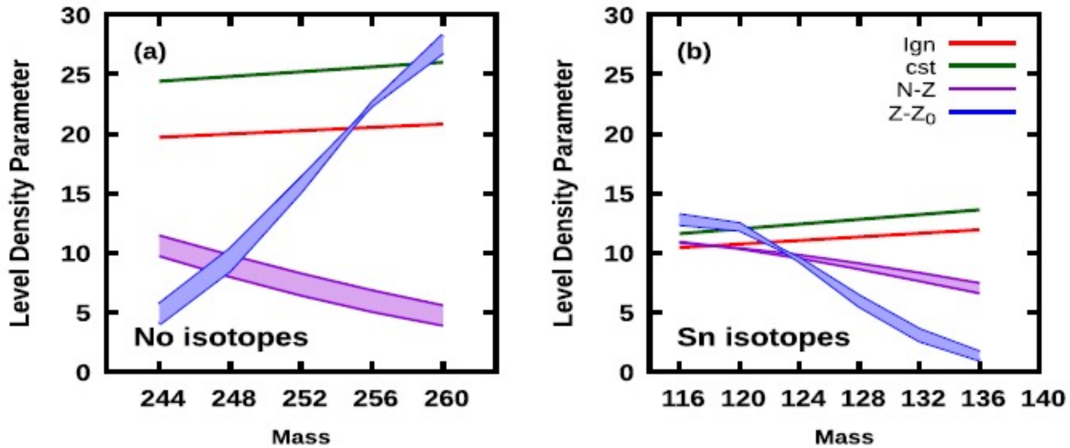
Request

IV.2 Estimated duration for IN2P3 scientists in COPIN	
Total time requested for 2024	28
List of scientists	1. C. SCHMITT (10 days) 2. O. DORVAUX (6 days) 3. L. STUTTGE (6 days) 4. I. MATEA (2 days)
IV.3 Estimated duration for COPIN scientists in France	
Total time requested for 2024	28
List of scientists	1. M. CIEMALA (10 days) 2. A. MAJ (6 days) 3. M. KMIECIK (6 days) 4. A. MAZUREK (4 days)

THANK YOU

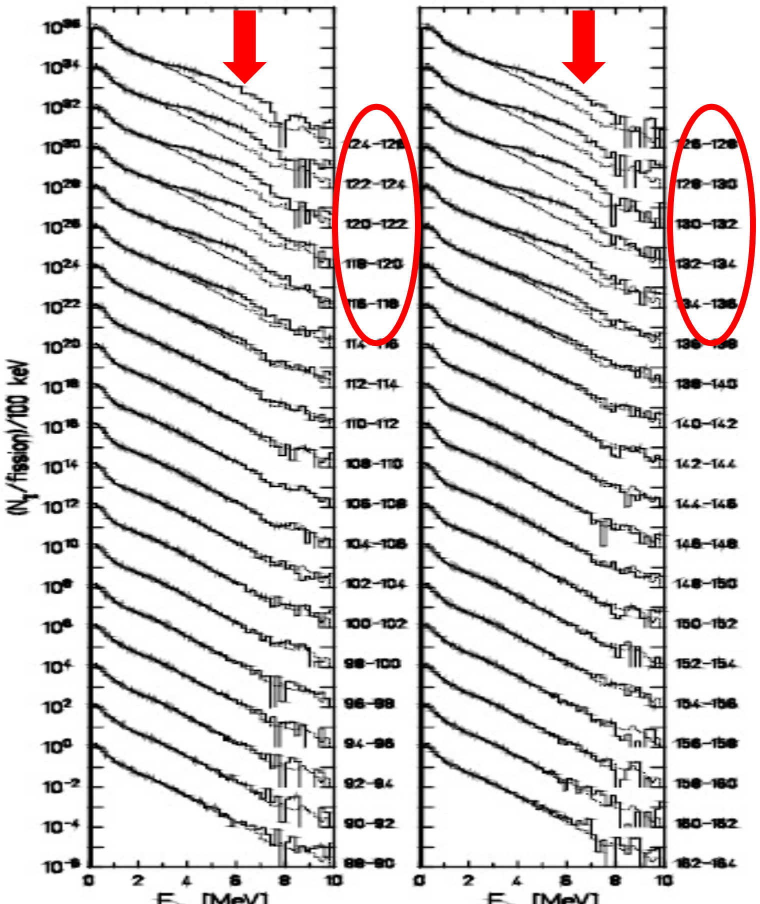
BACK UP

Evolution of the NLD away from β-stability



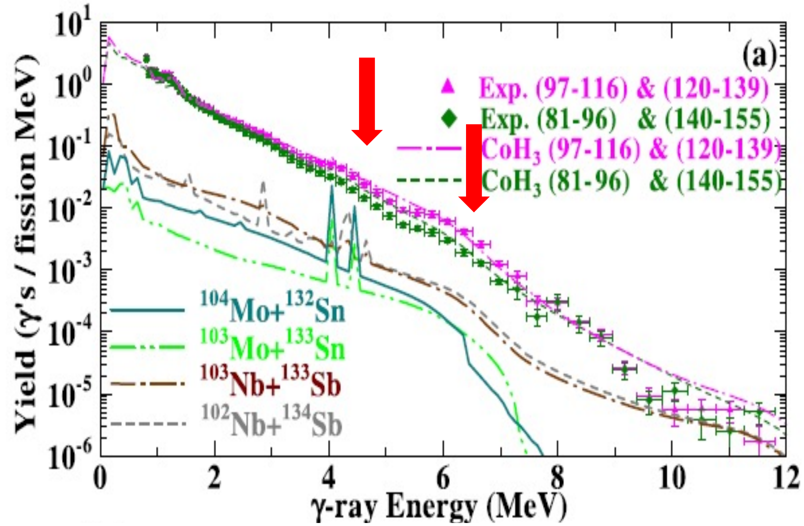
The intriguing "γ-bump" phenomenon

^{252}Cf (SF) with Crystall Ball (NaI)



Holtzel et al., Z fuer Phys. (1996)

^{235}U(n,f) with ensemble of three LaBr3



Makii et al., PRC (2019)

↪ **Origin and nature of the bump**

{ due to *n* (*N*~68,82) and/or *p* (*Z*~40,50)?
collective character or single-particle excitation?

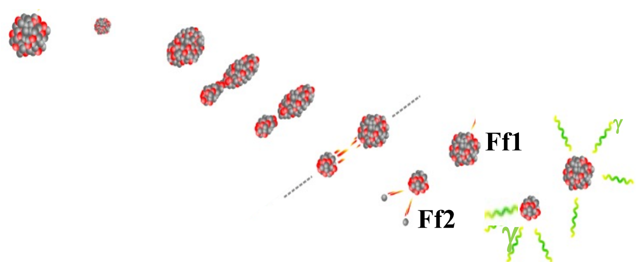
↪ **Better identification of the emitter in *A* <u>and</u> *Z***

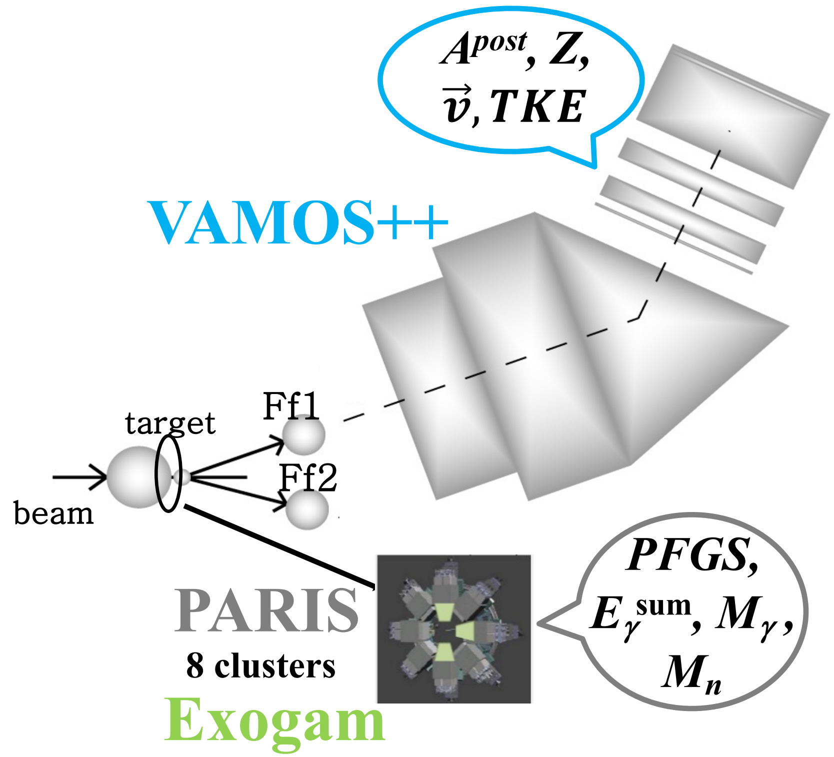
PARIS@VAMOS: Experimental approach

Fusion-fission in inverse kinematics

^{238}U + ^{9}Be → ^{247}Cm* (E^*~ 43MeV)

(5.88MeV/u) (500µg/cm2)





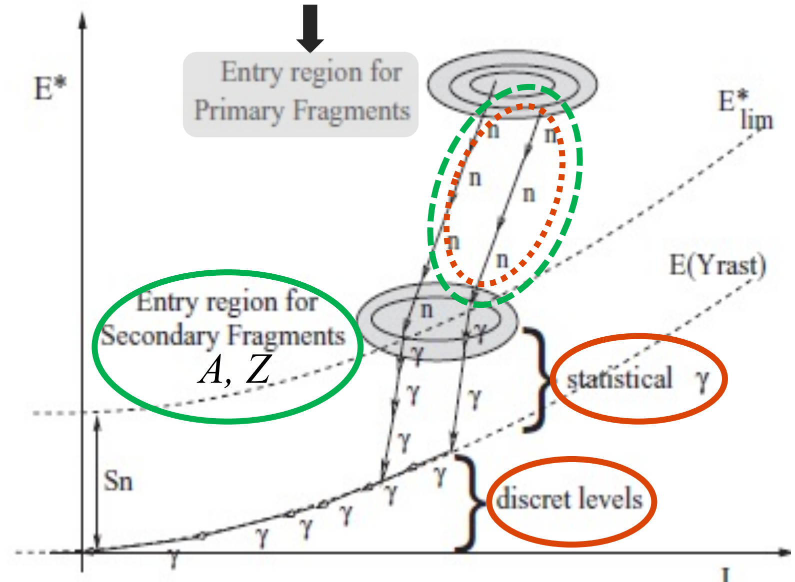
event by event →

- ✓ Accurate Ff's (A, Z, v, TKE)
- ✓ PFGS and properties (E_γ^{sum}, M_γ)
- ✓ Neutron multiplicity

PARIS@VAMOS: Our proposal

Reconstruct the fission-fragment "entry point" to get insight into the generation and sharing of E^* and L

VAMOS++
⇨ A, Z, v, TKE
~ (M_n , E_n^{sum})



Courtesy O. Litaize

PARIS ⇨ M_n , E_n^{sum}

PARIS ⇨ *PFGS*, M_γ , E_γ^{sum}

VAMOS++ ⊗ PARIS ≡ KEY POINT of the investigation

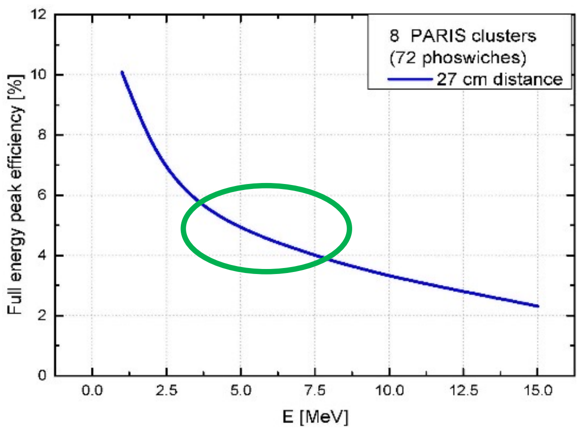
- ↪ uniquely resolved Ff (A, Z) + accurate $\vec{v}$ + TKE
- ↪ *PFGS* over [0-30] MeV with sufficient efficiency, resolution and granularity
- ↪ low E_γ to get M_γ and high E_γ to get E_γ^{sum}
- ↪ estimate of M_n

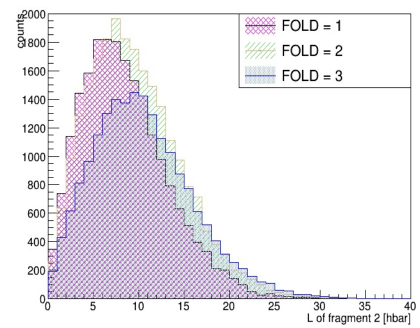
Set Up simulations

by M. Ciemala

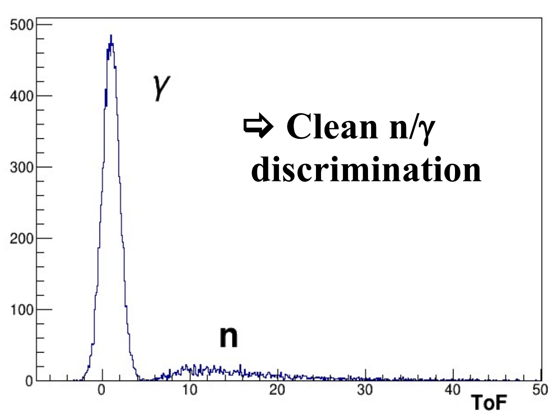
VAMOS++: Under control

PARIS: Detailed study of realistic simulations, including PARIS, VAMOS++ and fission generator

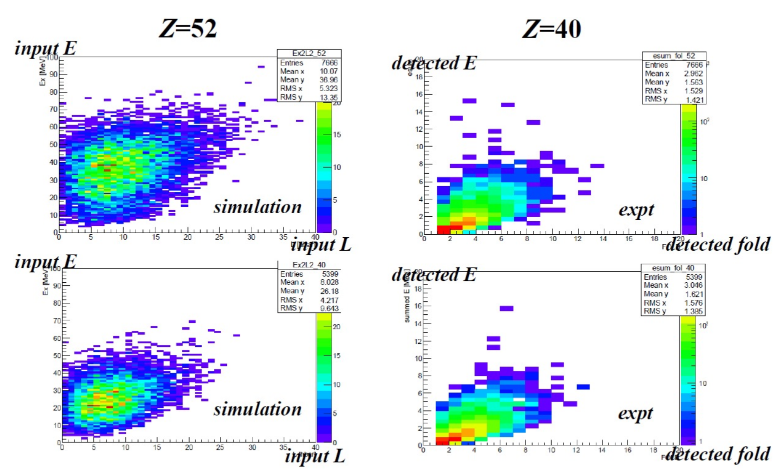




⇨ **Fold is sensitive to *L***



⇨ **Clean n/γ discrimination**



⇨ **Correlation is preserved**

Theory / Interpretation/Prediction

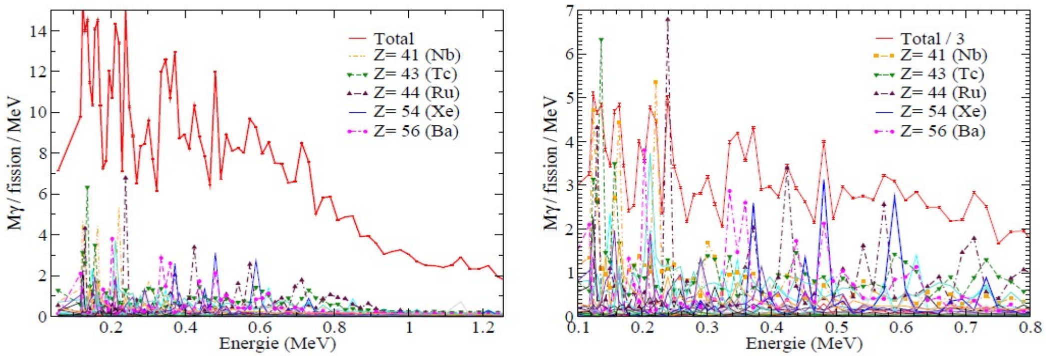
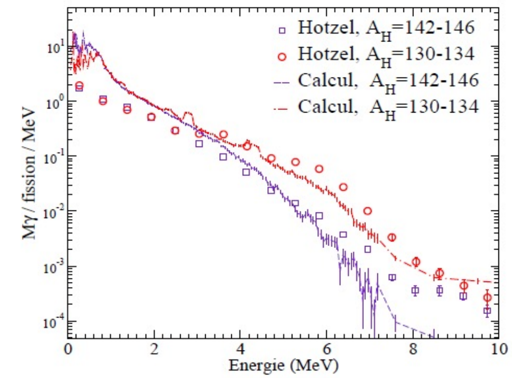
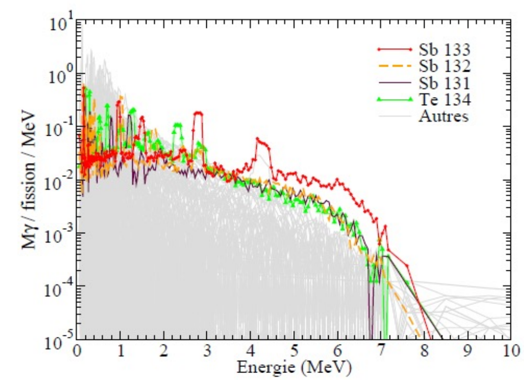
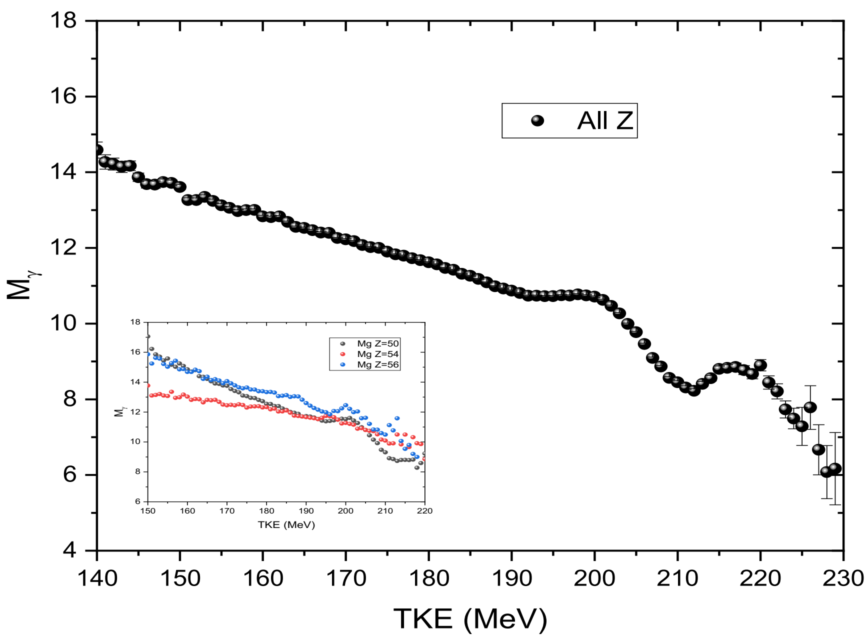


FIG. 5.13. *Contribution des fragments d'une charge donnée au spectre gamma prompt de fission dans le référentiel du centre de masse*





D. Regnier et al.

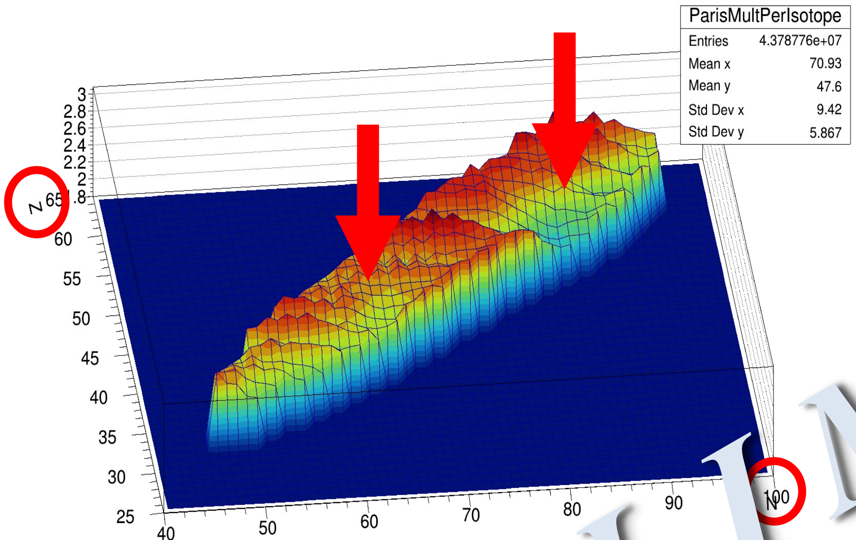


FIFRELIN code

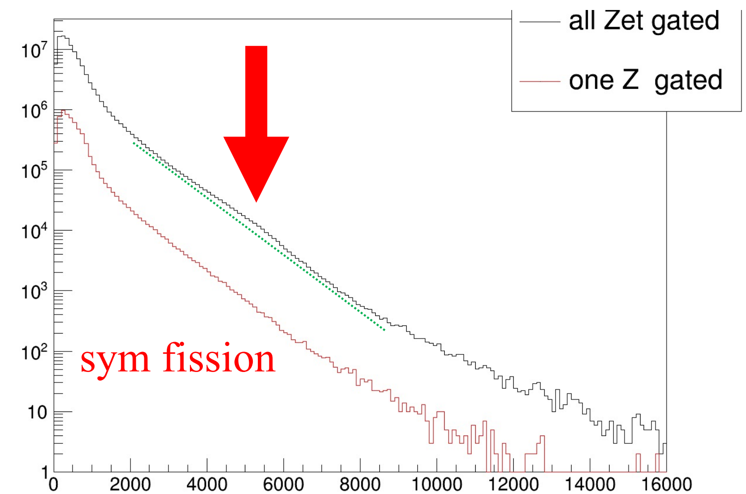
O. Litaize (2021)

Preliminary results

γ fold in PARIS vs. Z,N in VAMOS++



PFGS in PARIS Z-gated in VAMOS++



J. Dudouet, M. Ciemala, C.S.