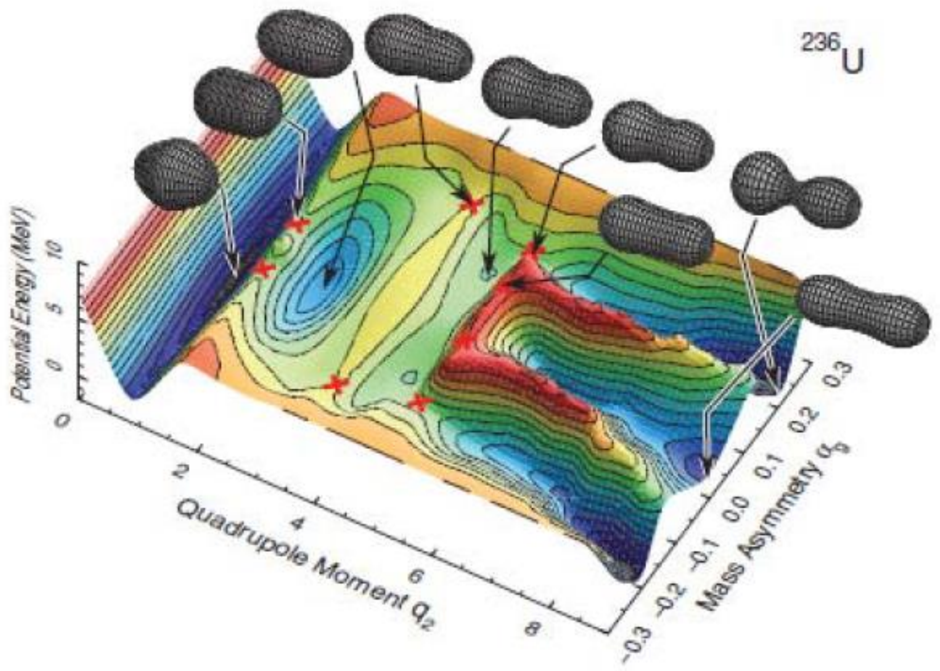
Advances in Experimental Nuclear Fission: Fission with New Observables and Correlations

Zakopane Conference on Nuclear Physics

Extreme of the Nuclear Landscape !

Session : « When one nucleus becomes two !»



Antoine Lemasson, GANIL, Caen, France

Challenging Fission

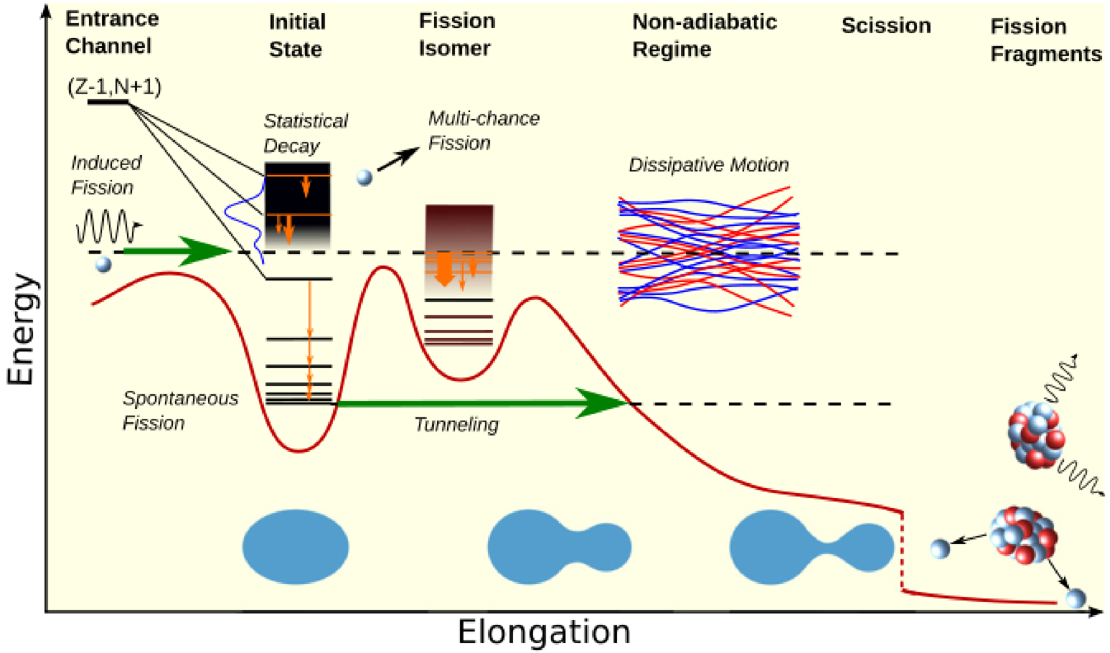
- Large-amplitude collective motion
  coupled to quantum/shell effects
- Non-equilibrium, dissipative many-body dynamics
- Predictive theory struggles with
  fragment distributions, Kinetic Energies, prompt emission
- A comprehensive, universal, microscopic description across the nuclear chart is missing

Sensitive to (so) many nuclear physics aspects

Experimentally challenging !

- Wide range of objects to detect and identify
  - slow and heavy fission fragments
  - neutrons, gamma-rays, ...
  - short and long time scales
    (prompt n-emission, isomers, decay)
- Complex coupled observables

Impressive progress in the last decade

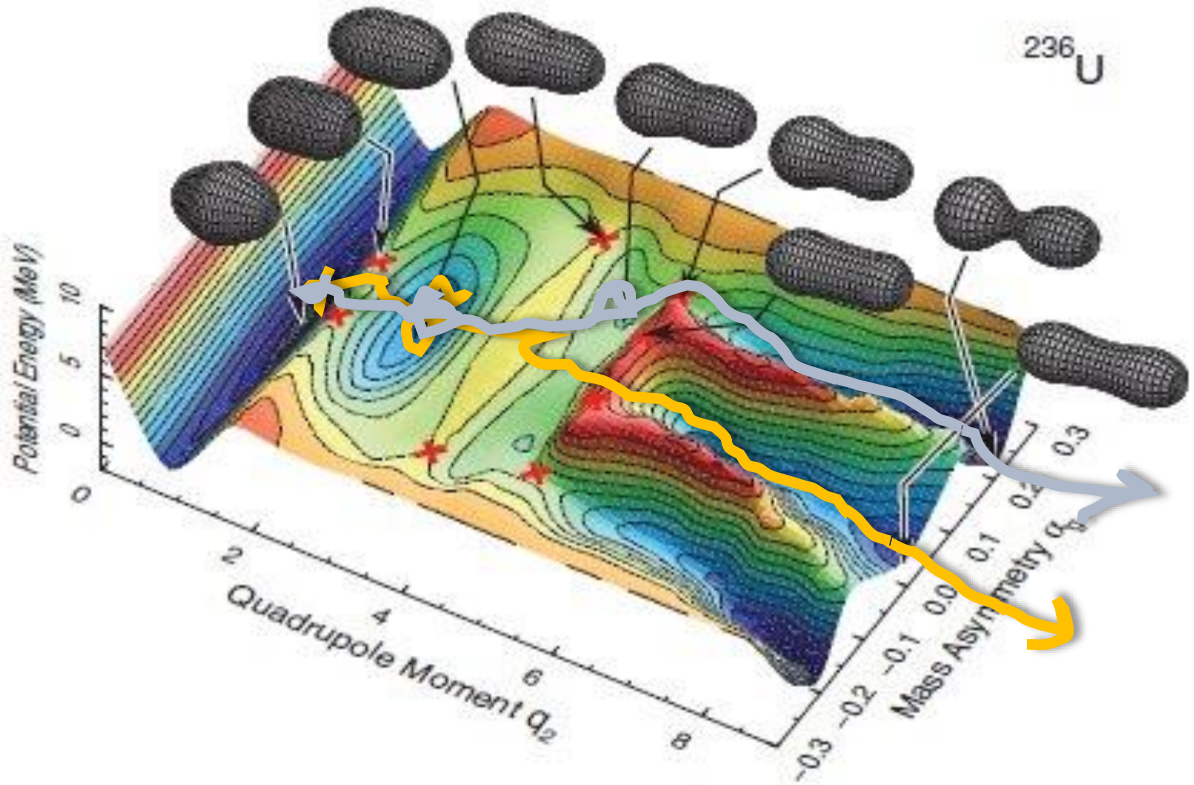


J. Phys. G: Nucl. Part. Phys. 47 113002

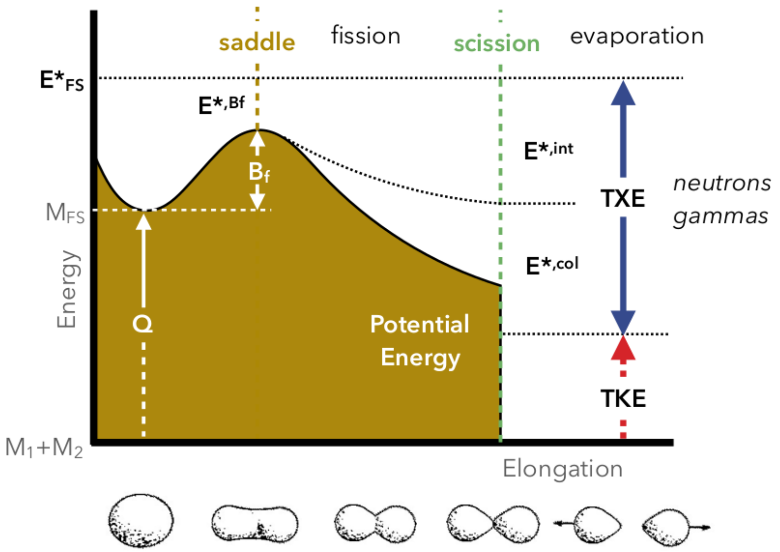
Fission Process

Large scale collective motion

– Static forces (nuclear, Coulomb)
– Dynamics of the nuclear medium



Ichikawa et al., PRC (2012)



Shell-Structure + Dynamics

↓

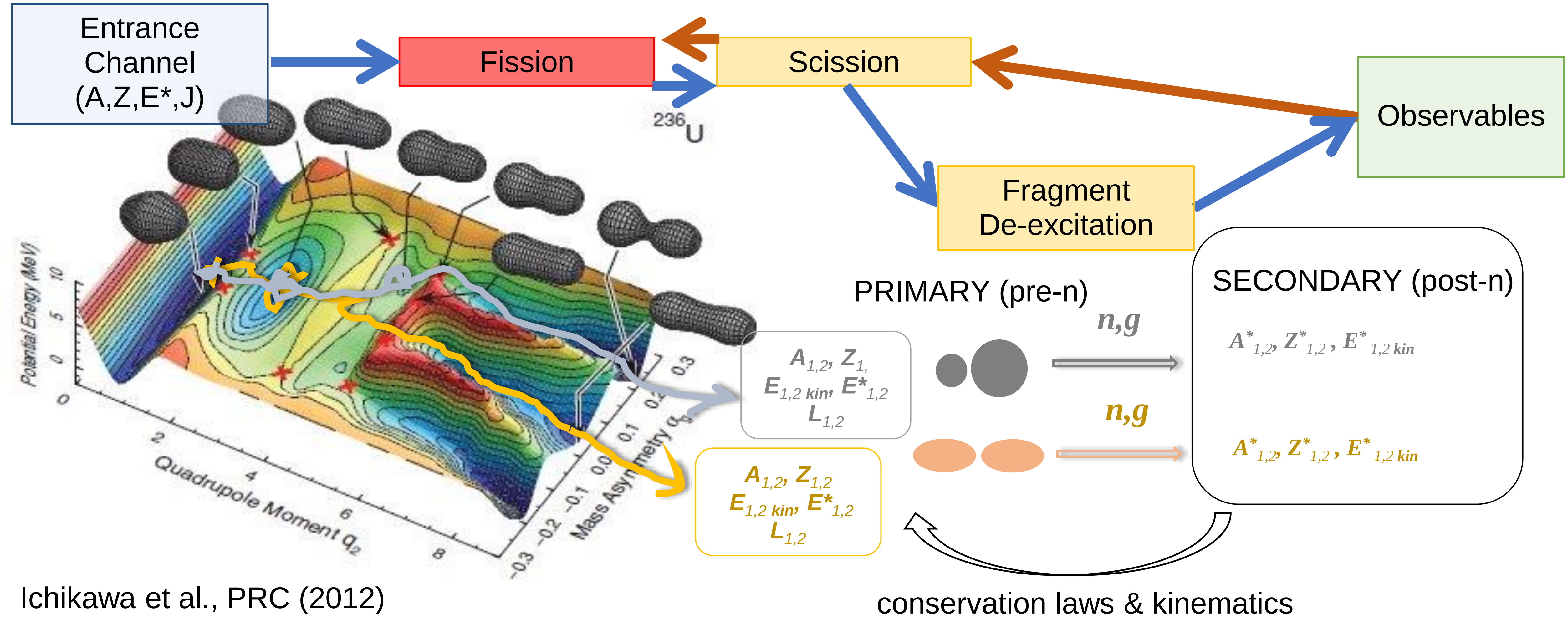
Favoured paths + Energy sharing

↓

Fragment properties (A, Z, E*, TKE)

Intertwinned Theories and Expriments

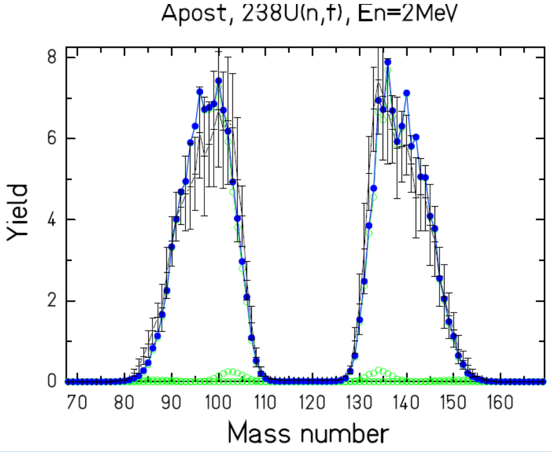
Back-tracing, theory-aided :
from initial and final observables to the fundamental fission driving laws



Ichikawa et al., PRC (2012)

Correlations give insight to the fission process

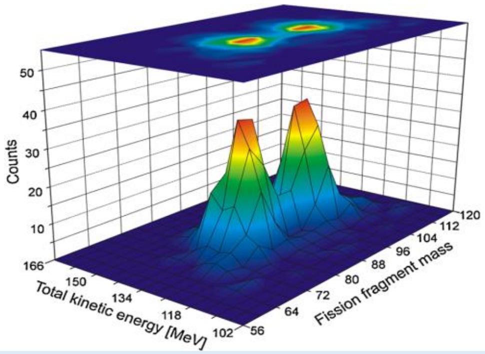
Fissioning system-E*
and
Fission Fragment **Mass-TKE** correlations



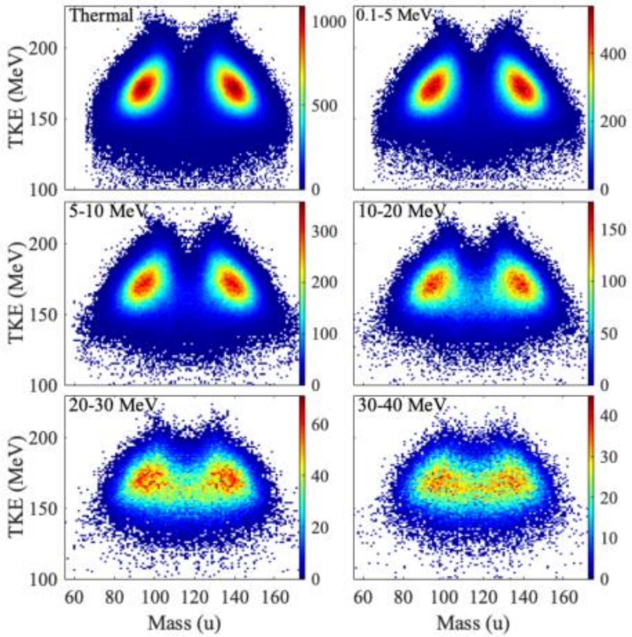
- Symmetric / Assymetric distributions
- Multimodal distributions

- Evolution as function of :
  - Excitation Energy (E*)
  - Fissionning system (A,Z)

Shell Stabilization
Competition
Microscopic / Macroscopic properties

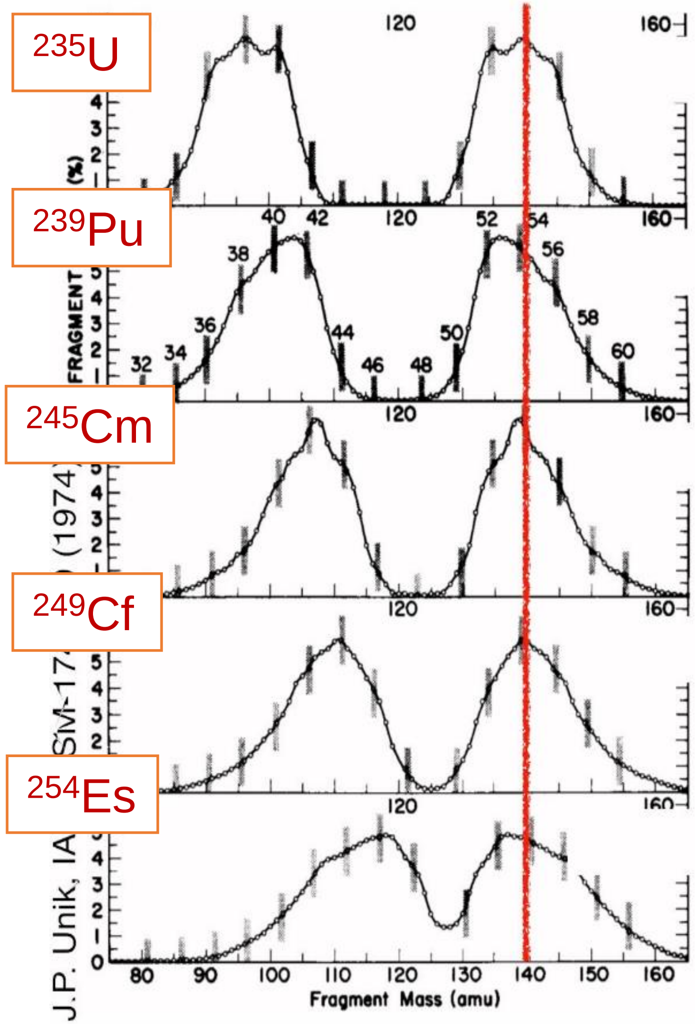


^{180}Hg (Andreyev et al PRL (2010))



^{233}U(n,f) Higgins et al,
PRC 101, 014601 (2020)

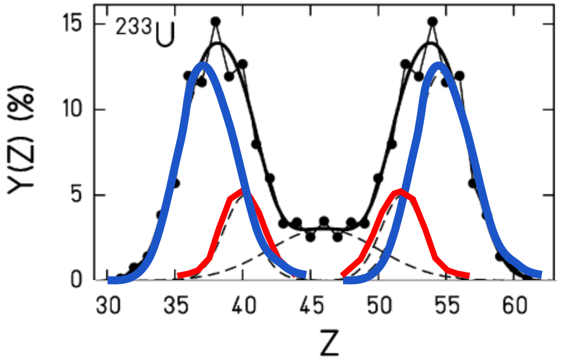
Fission Fragment Mass Distributions

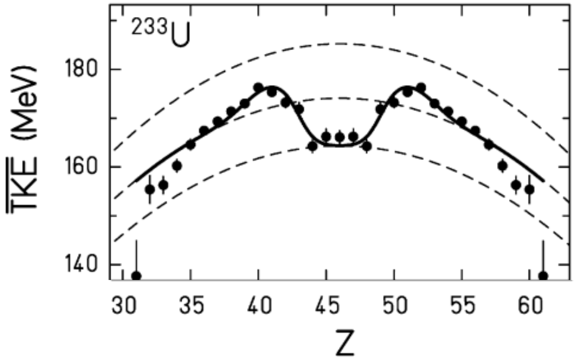


Unik et al. (1973)

Correlations give insight to the fission process

Fissioning system
and
Fission Fragment **Z-TKE correlation**

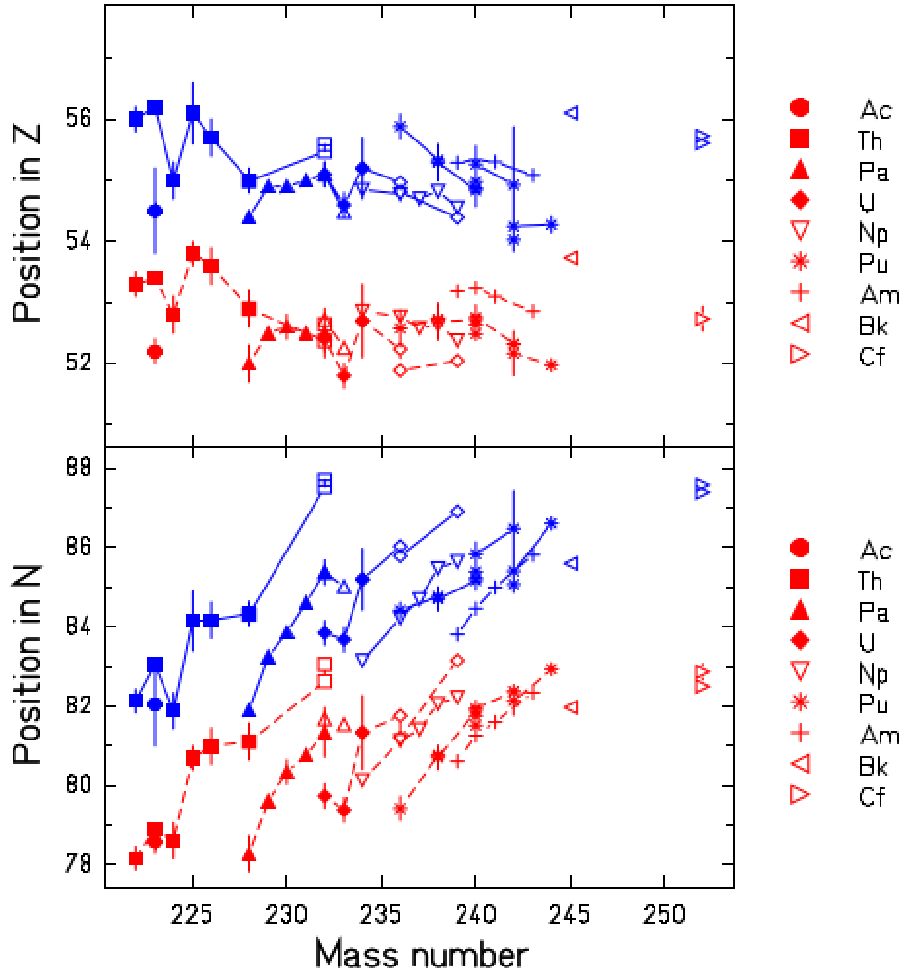




- Asymetric distributions
- Multimodal distributions
- Evolution as function of fissionning system
- Heavy fragment located at :
  - Z~52 in S1
  - Z~55 in S2

Proton Shells stabilization
Competition between modes

Wide range of fissioning systems (Ac-Cf)

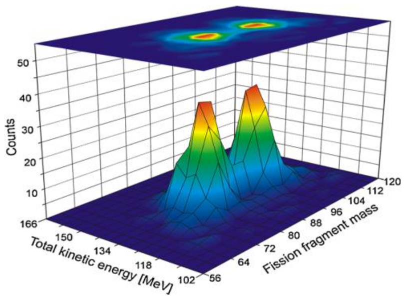


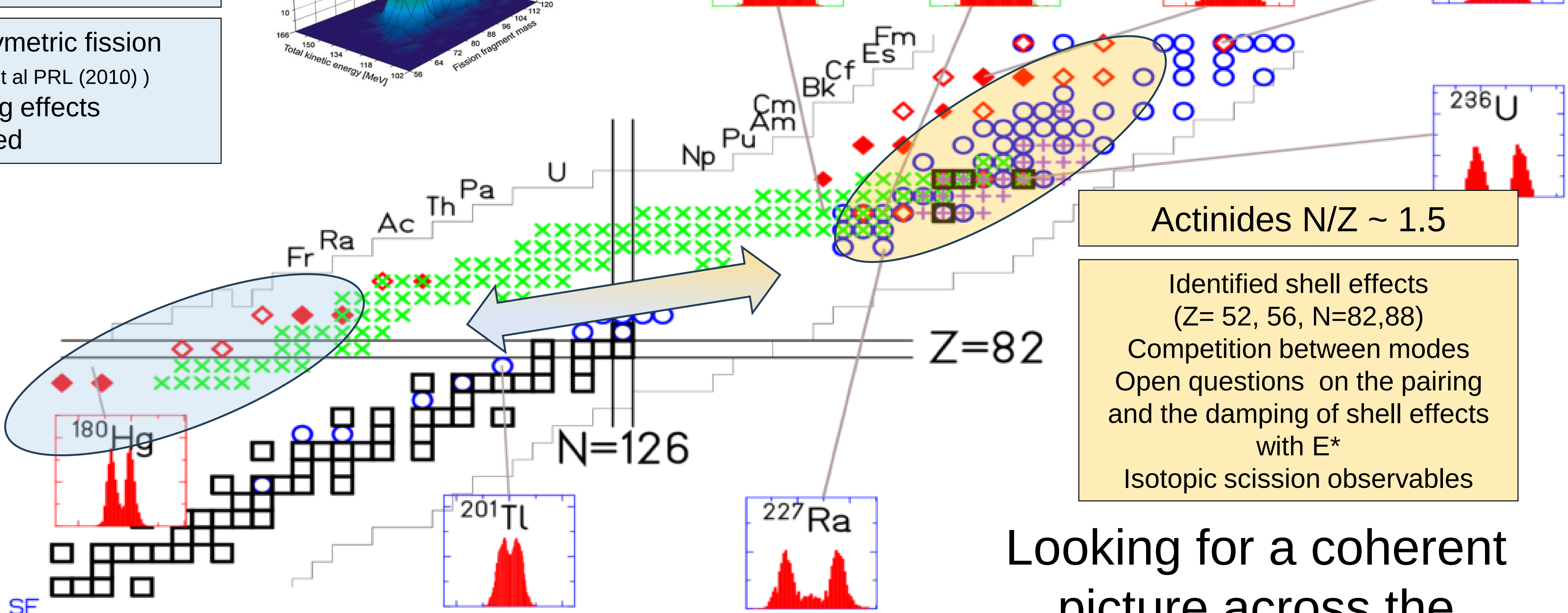
Schmidt et al., NPA (2000)
Bockstiegel et al., NPA (2008)

« Universality » of shell effects across fission landscape

Pre-Actinides N/Z ~ 1.2

Unexpected Assymetric fission
in ^{180}Hg (Andreiev et al PRL (2010))
=> New stabilizing effects
at Z ~ 36 deformed





Actinides N/Z ~ 1.5

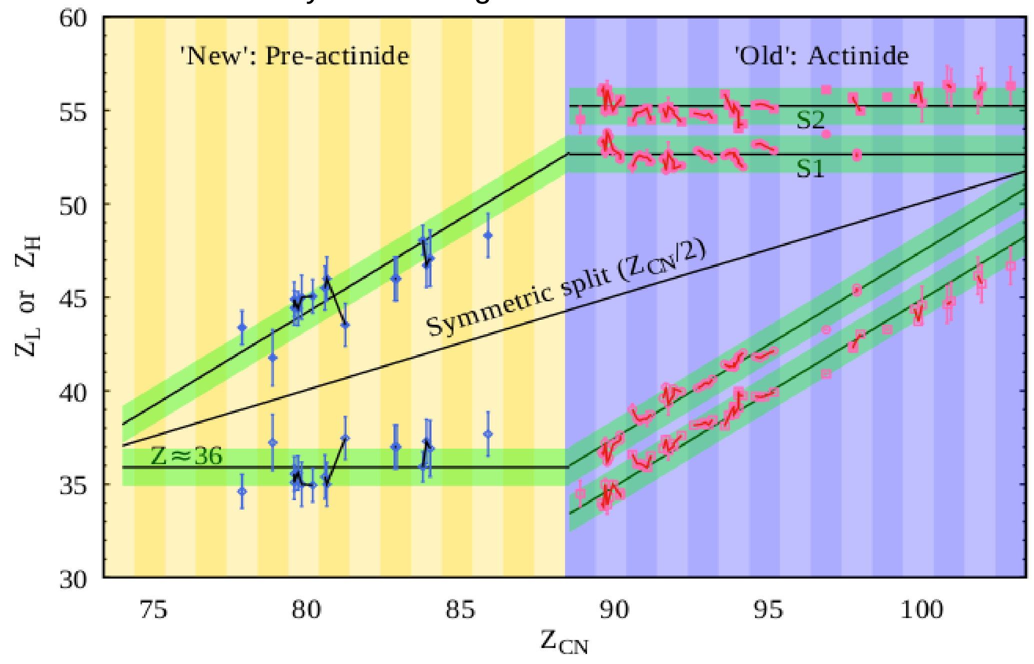
Identified shell effects
(Z= 52, 56, N=82,88)
Competition between modes
Open questions on the pairing
and the damping of shell effects
with E*
Isotopic scission observables

Looking for a coherent picture across the landscape

Universality of shell effects: proton configurations steer fission

Pre-actinide Fusion Fission / β-delayed

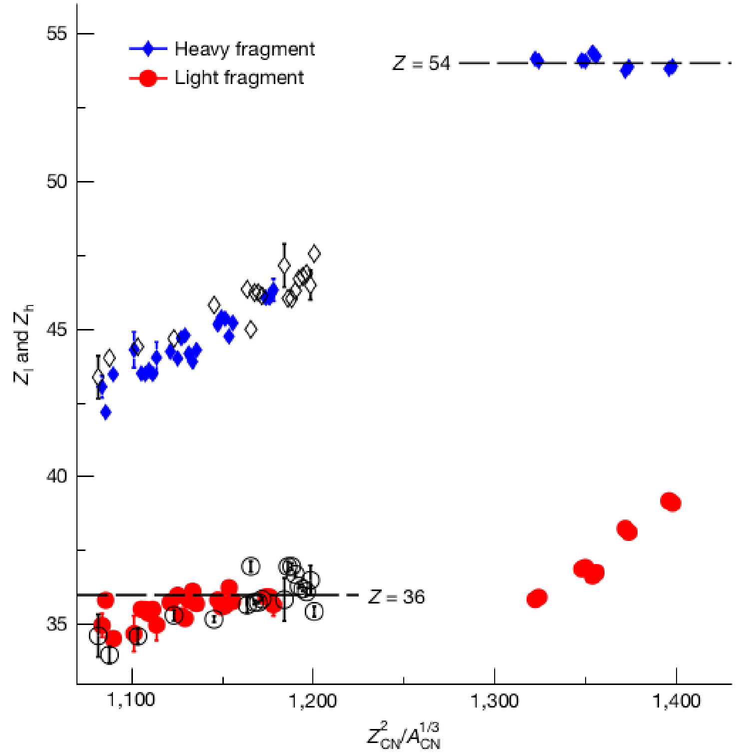
Z_{heavy} and Z_{Light} inferred



K. Mahata *et al.* PLB (2022)

EM Fission Induced

Z_{heavy} and Z_{Light} measured



P. Morfouace *et al.* Nature (2025)

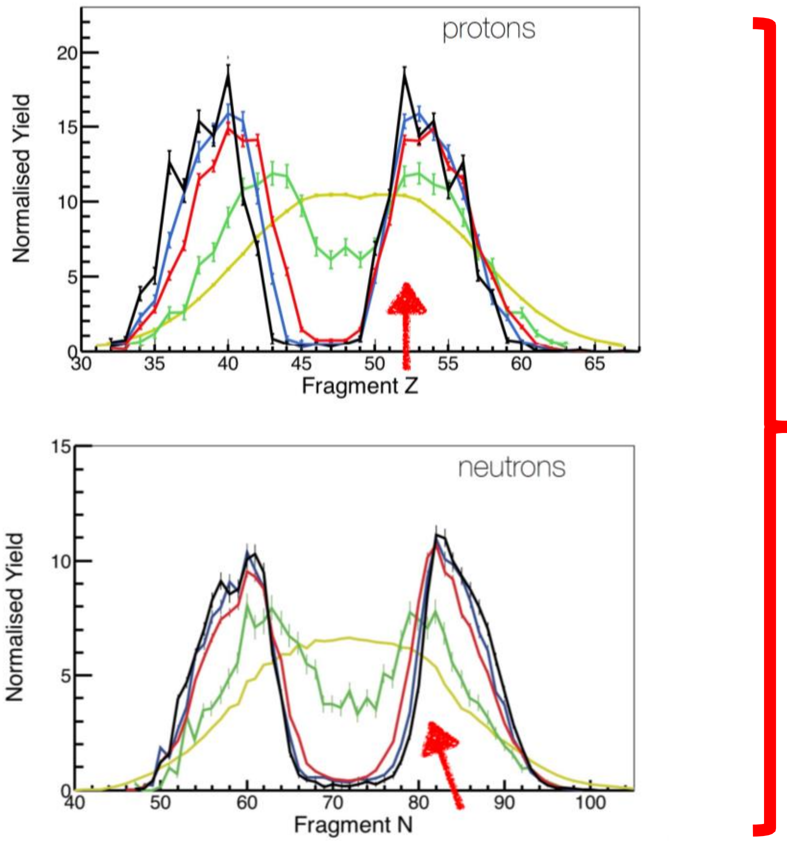
Protons emerge as dominant drivers accros the fission landscape

C. Schmitt *et al.*, *Phys. Rev. Lett.* **126**, 132502 (2021);
K. Mahata *et al.*, *Phys. Lett. B* **825**, 136859 (2022);
P. Morfouace *et al.*, *Nature* **641**, 339 (2025);
J. Buete *et al.*, arXiv:2503.23681 (2025).

Talks : P. Morfouace for recent results on n-deficient systems

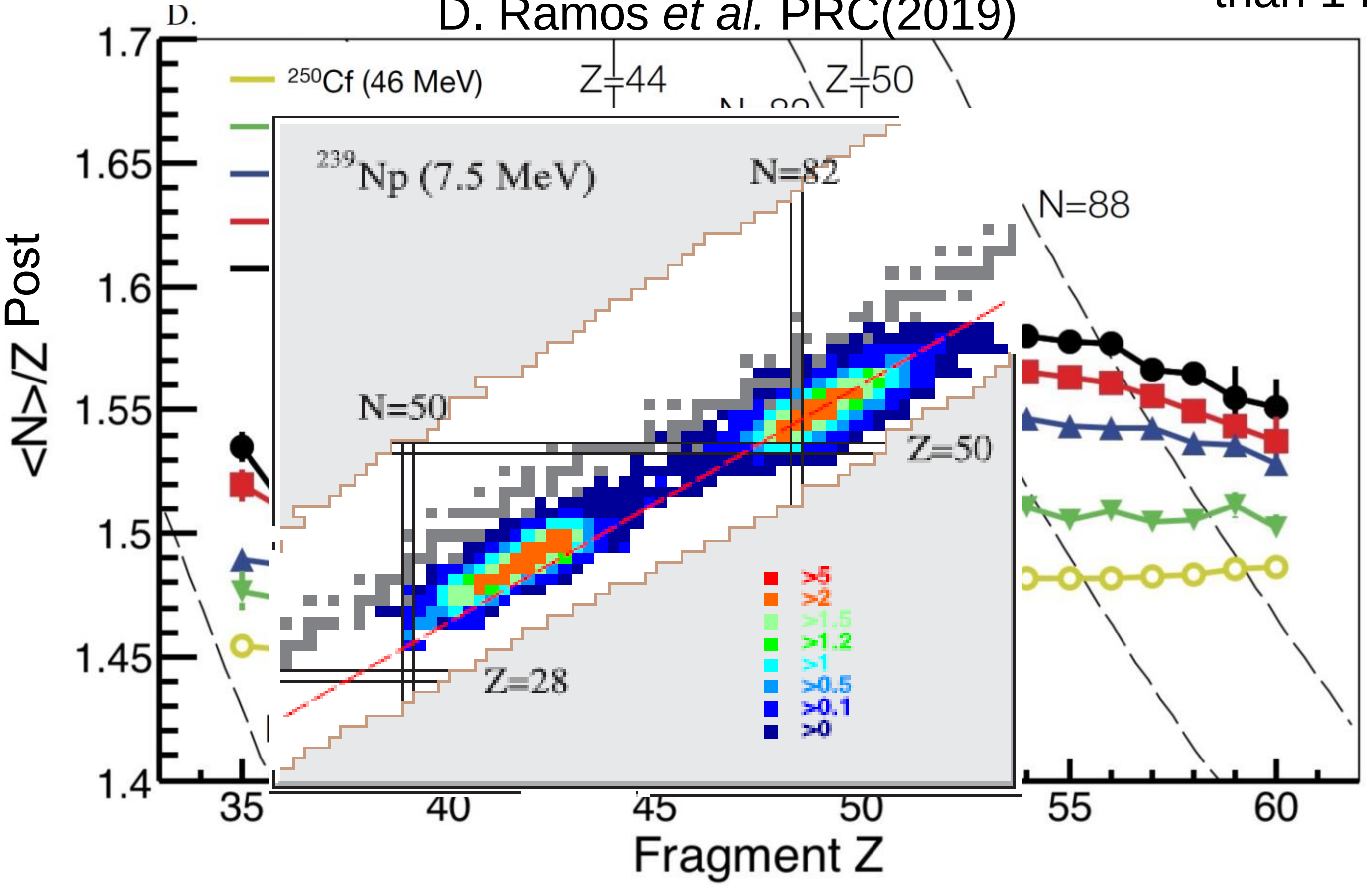
Correlations give insight to the fission process

Fissioning system-E*
and
Fission Fragment A-Z correlations



M. Caamano *et al.* PRC (2015)
D. Ramos *et al.* PRC(2019)

0.1 in N/Z
=> Sensitivity better than 1 neutrons

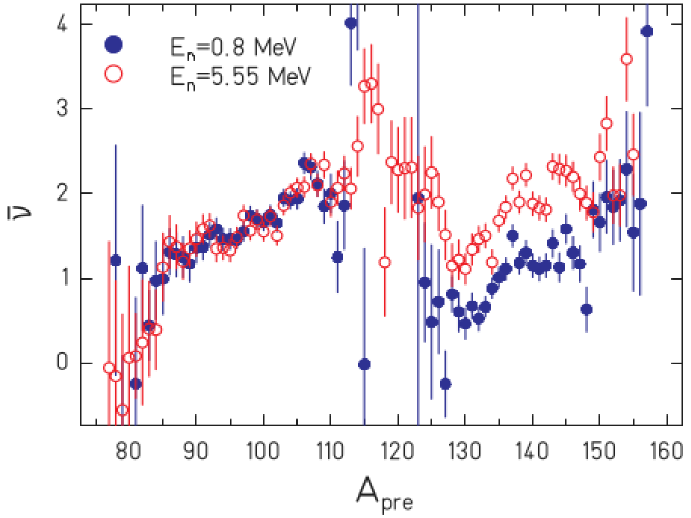


Reveals fine structural effects otherwise unknown

Correlations give insight to the fission process

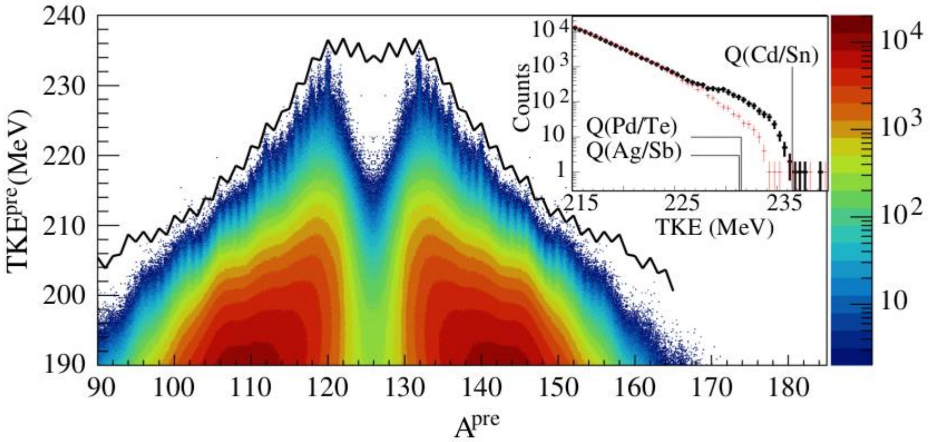
Fissioning system-E*
and
Fission Fragment **Mass-neutron/γ-ray** correlations

<ν> (A,E*)



K-H Schmidt and B. Jurado
PRL 104, 212501 (2010)

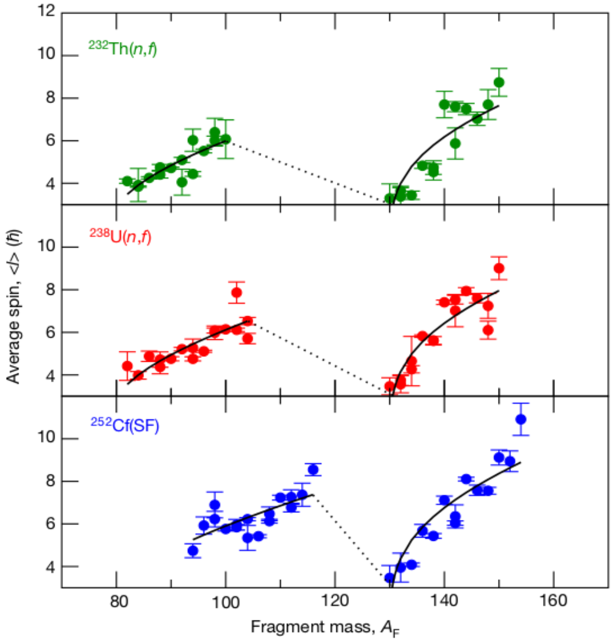
A-TKE-γ-rays



Francheteau et al. PRL 132, 142501 (2024)

- Competition between Shell Effects
- Energy sharing among fragments
- Energy Sorting (Level Densities)
- De-excitation of FF
- Angular momentum generation

Average spin <J> of FF

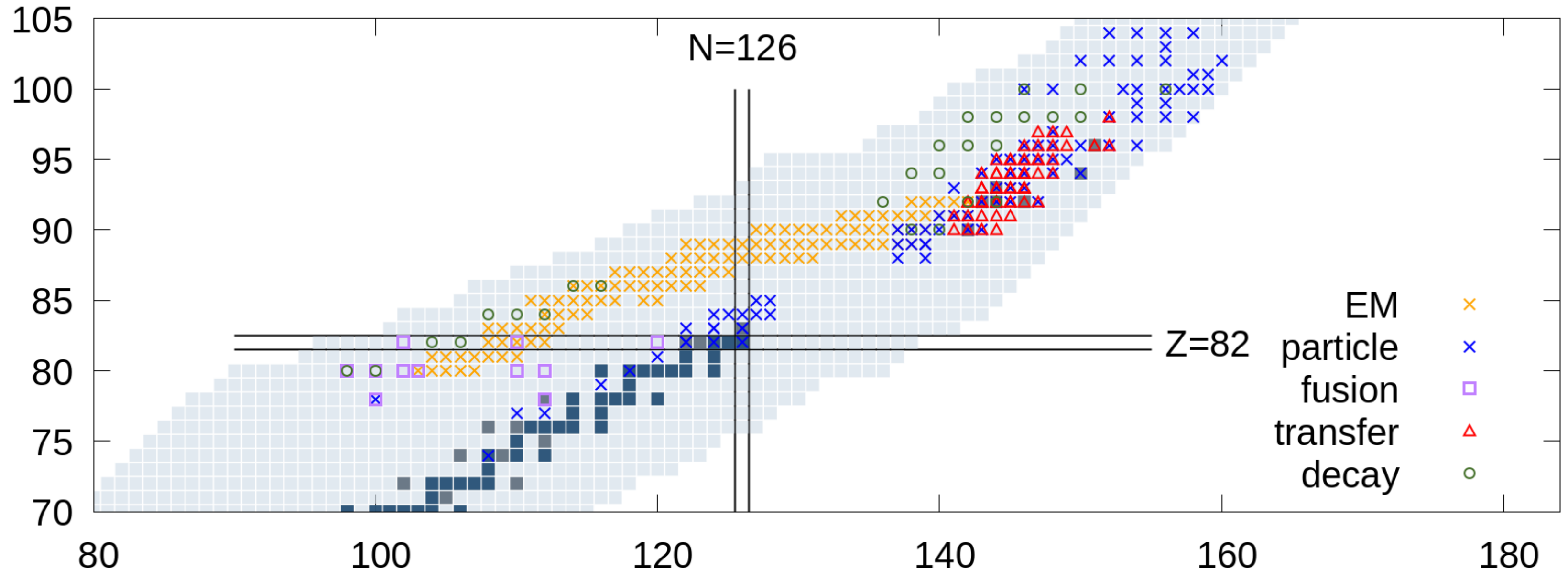


Wilson et al, Nature 590, 566 (2021)

Talks by
A. Al-Adili, M. Ciemala,
J. Wilson, B. Mauss

The Experimental Fission Landscape Today

- **Many complementary experimental routes:**
  direct kinematics, inverse kinematics, storage rings, spontaneous fission, ISOL beams, in-flight fission, ...
- Different facilities reach different regions of the nuclear chart and different observables
- This session reflects that diversity : GANIL, GSI, ISOLDE, IGISOL, OSLO, LANL, ...

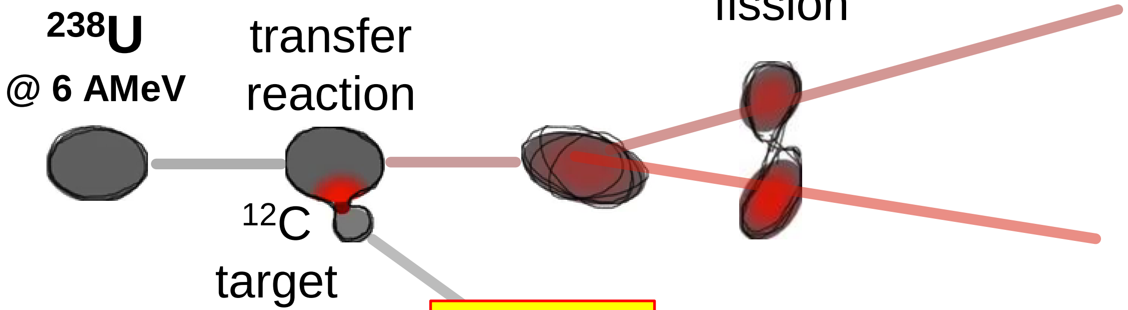


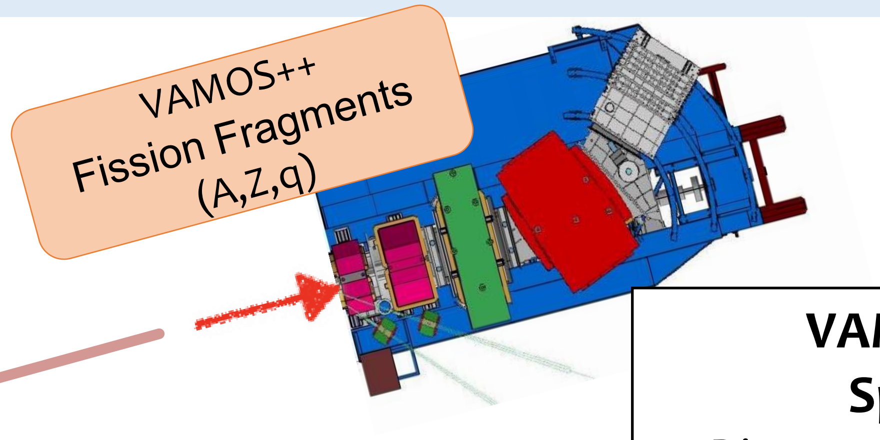
In the following, I will further exemplify
insight on the fission process
gained from correlations measured at VAMOS

Fission in inverse kinematics at VAMOS++

Inverse Kinematics using beams of $^{238}U/^{232}Th$ around Coulomb Barrier

⇒ Access to a range of exotic fissioning systems heavier than ^{238}U

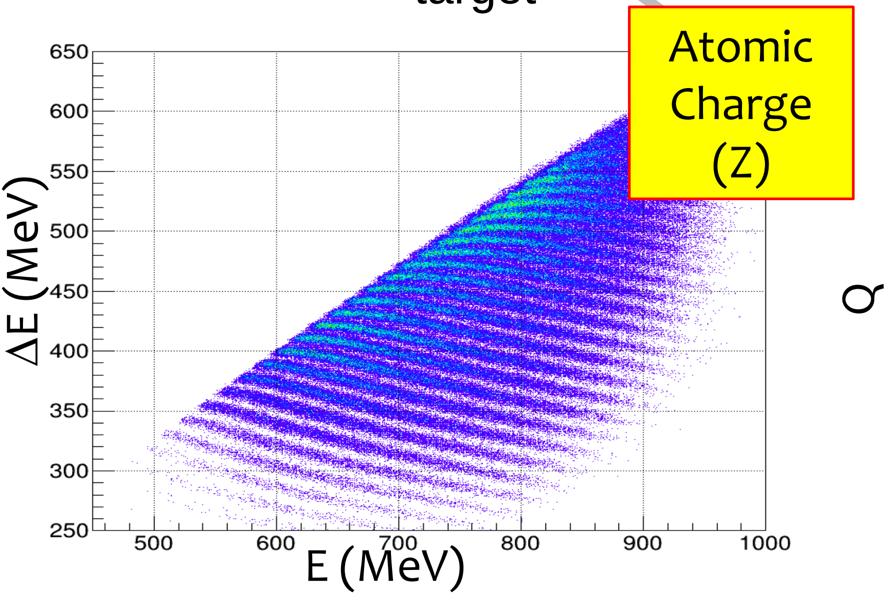


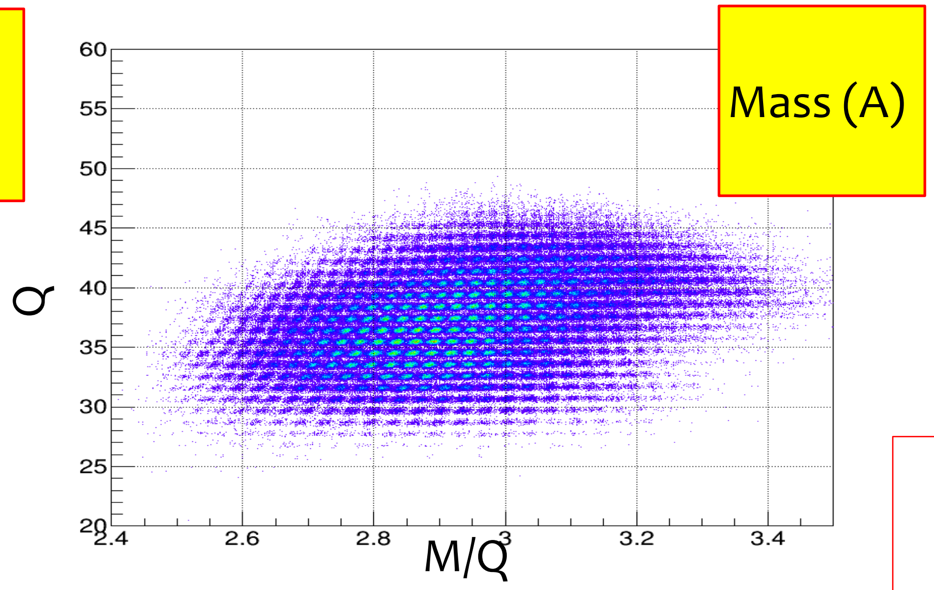


VAMOS Magnetic Spectrometer

⇒ Direct and Complete isotopic identification of fission fragments

⇒ Precise center-of-mass fission fragment velocities





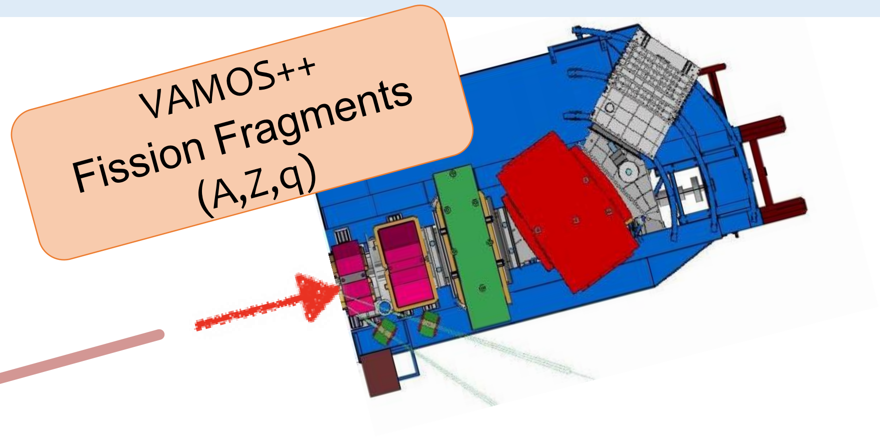
M. Rejmund *et al.*, NIM A (2011)
Y-H Kim *et al.*, EPJA (2018)
A. Lemasson *et al*,. EPJA (2023)

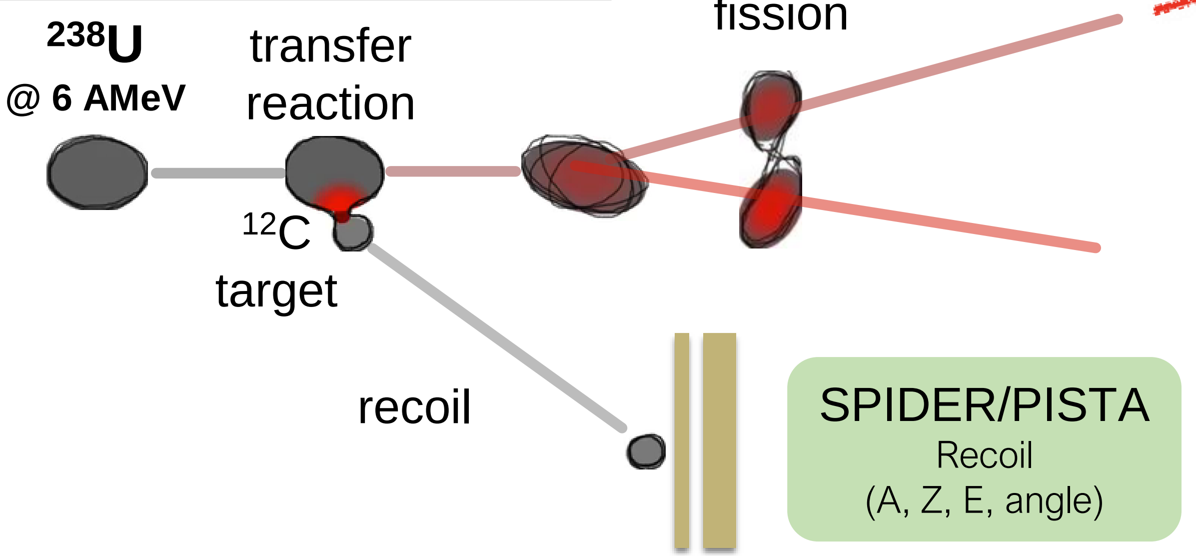
Inverse KinematicsTalks :
A. Cobo Zarzuelo, B. Errandonea
P. Morfouace, B. Jurado

VAMOS++ and PISTA/SPIDER

Inverse Kinematics using beams of $^{238}U/^{232}Th$ around Coulomb Barrier

⇒ Access to a range of exotic fissioning systems heavier than ^{238}U

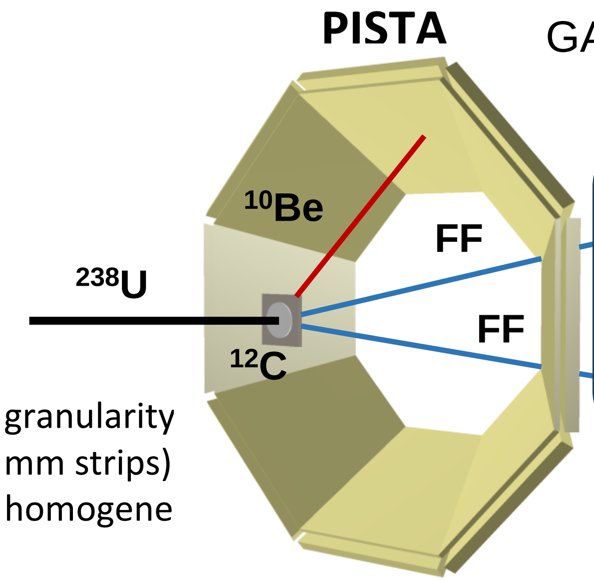




Surrogate reactions
(transfer induced fission)

⇒ Identification of the fissionning system
⇒ Measurement of the fissionning system excitation energy

VAMOS++ and PISTA/SPIDER



GANIL-CEA/DAM collaboration

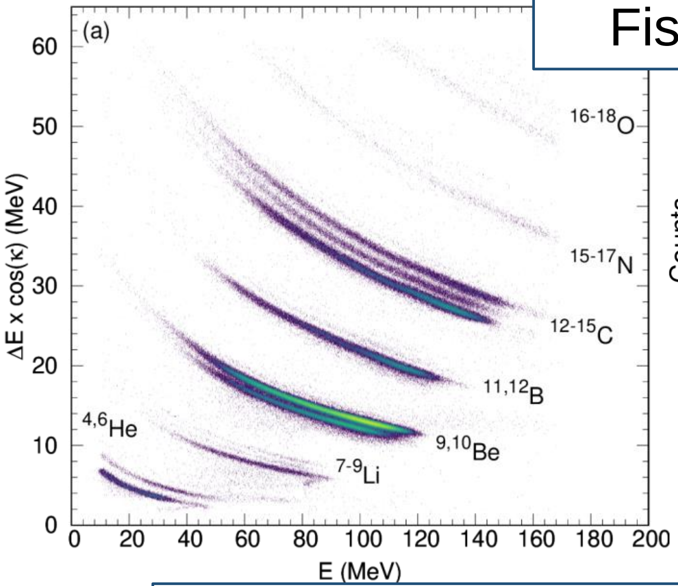
ΔE
100 µm thickness
0.5 mm strips (θ)
10 cm from target
E
1 mm thickness
1.2 mm strips (ϕ)

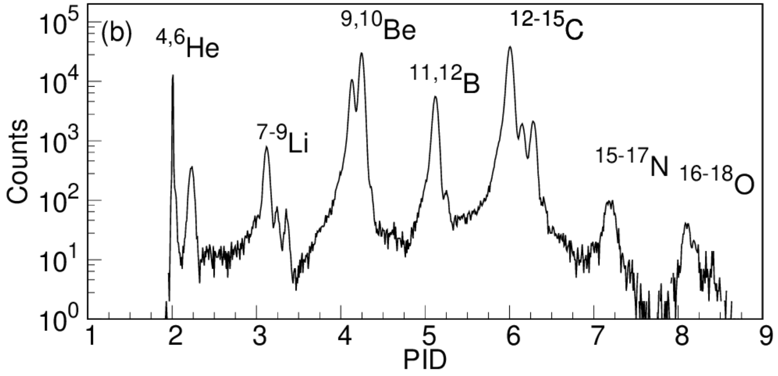
- High granularity (0.5 mm strips)
- High homogene

ΔE_x~800 keV (FWHM)

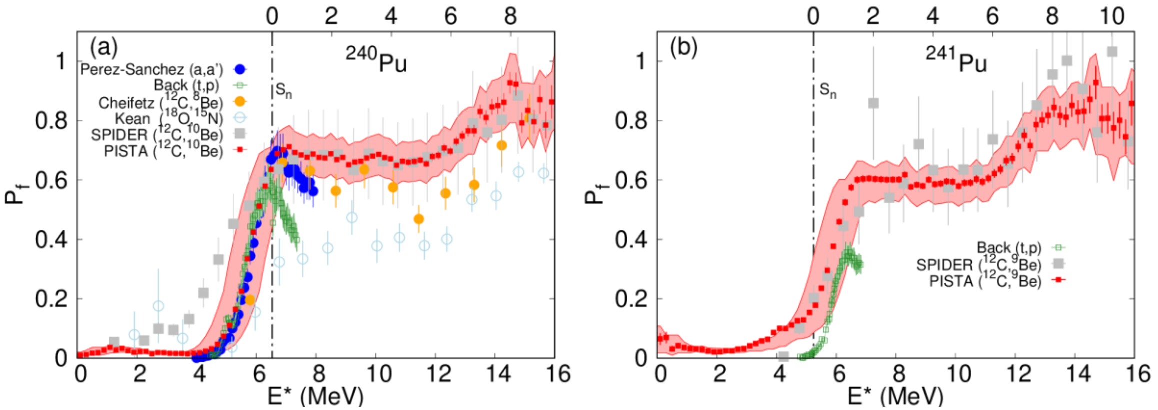
L. Begué—Guillou et al. NIM A **1090**, 171671 (2026)
[10.1016/j.nima.2026.171671](https://doi.org/10.1016/j.nima.2026.171671)

Fissioning System Identification





Precise Excitation Energy, Fission Probability

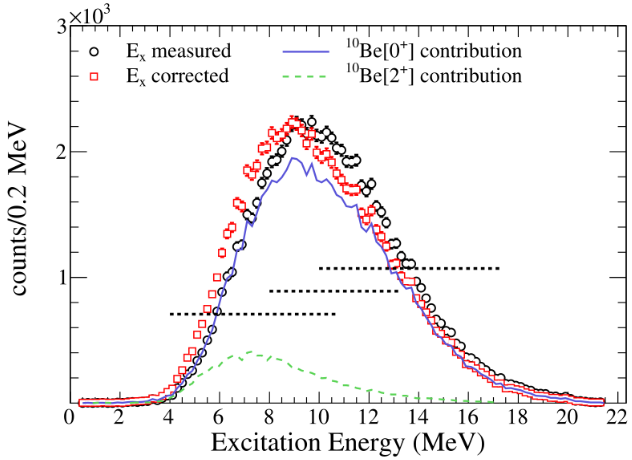


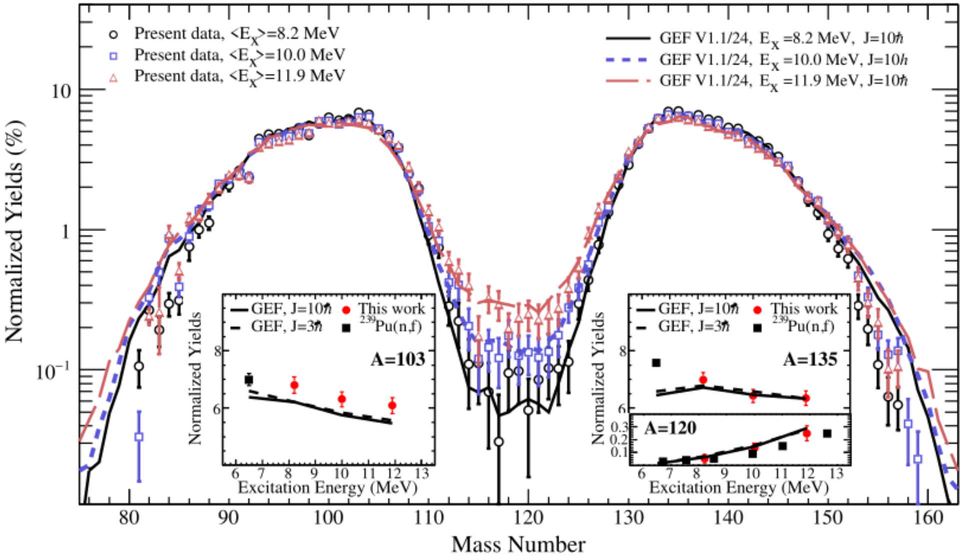
Talk by B. Jurado (P_f,P_n,P_g at Storage Rings / Surrogate Methods)

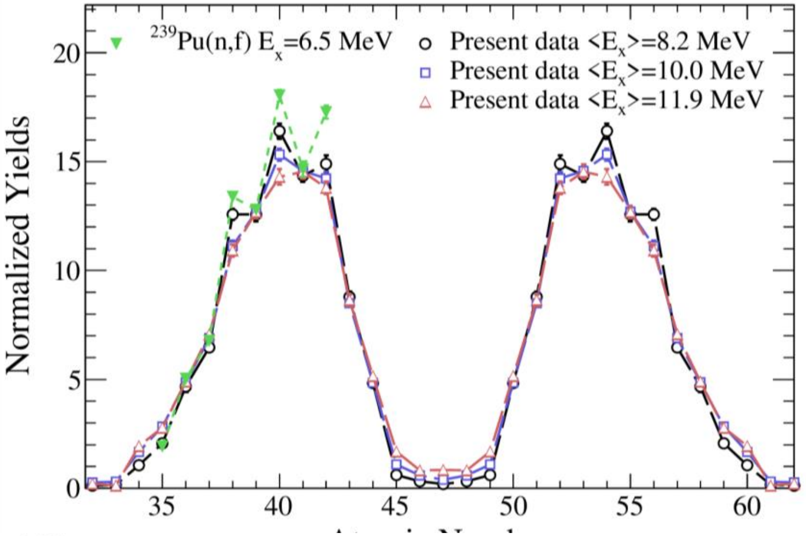
VAMOS++ and PISTA/SPIDER

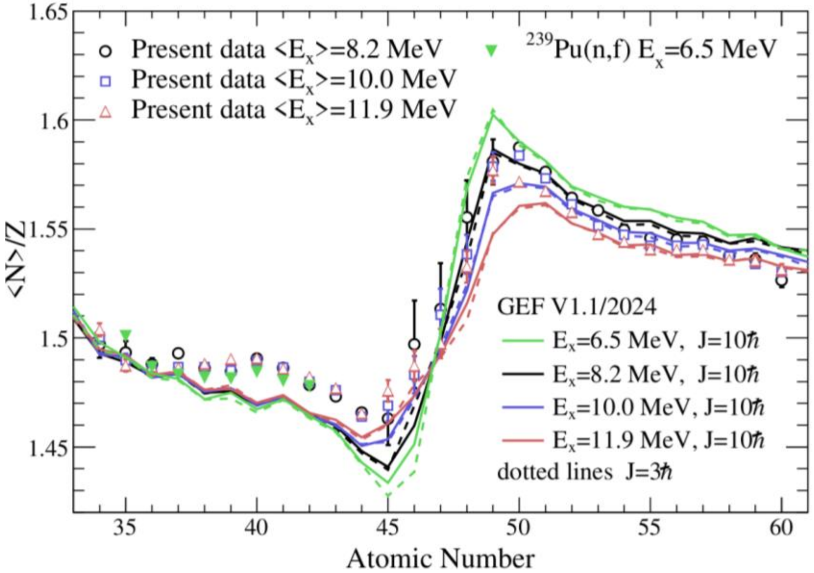
E* and Isotopic Yields

^{240}Pu









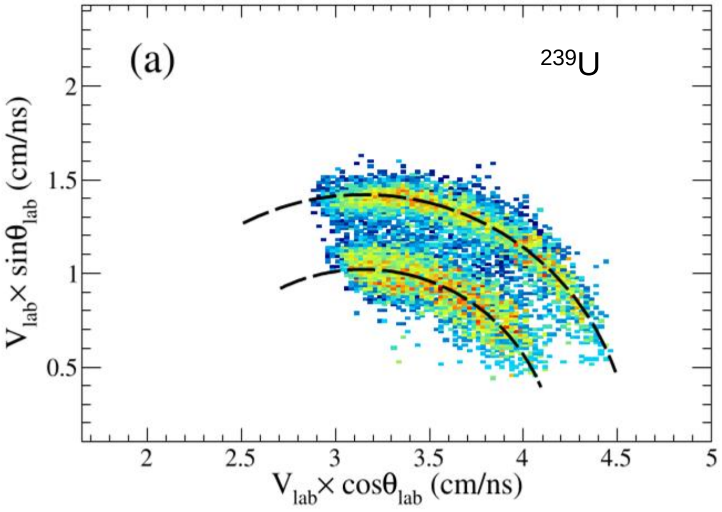
D. Ramos *et al*. Phys. Rev. C **113**, 054611 (2026)

- Progressive damping of shell effects.
- Damping of even-odd staggering
- Reduction of neutron richness of fnal heavy fragment with increasing E*
  => energy is mainly dissipated through **neutron evaporation from the heavy fragment.**

Talks by :
B. Errandonea and A. Cobo-Zarzuelo

Tracing back to scission

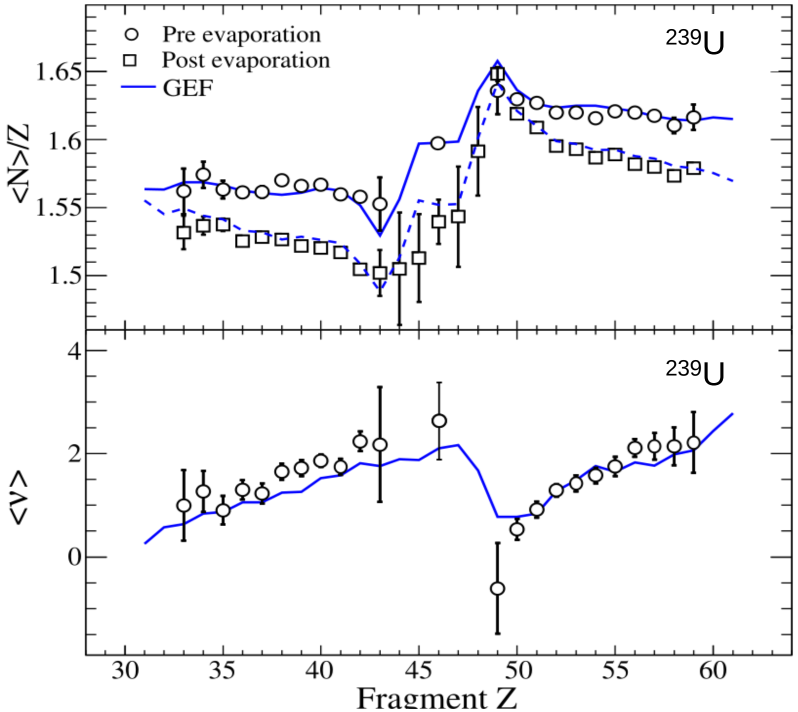
(Z,A)-neutron multiplicity-TKE

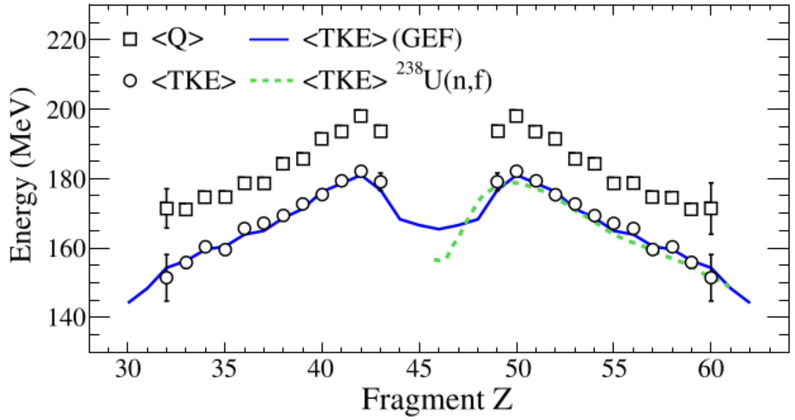


using one fragment velocity
+ conservation laws
at Coulomb barrier energies

Tracing back
to scission quantities

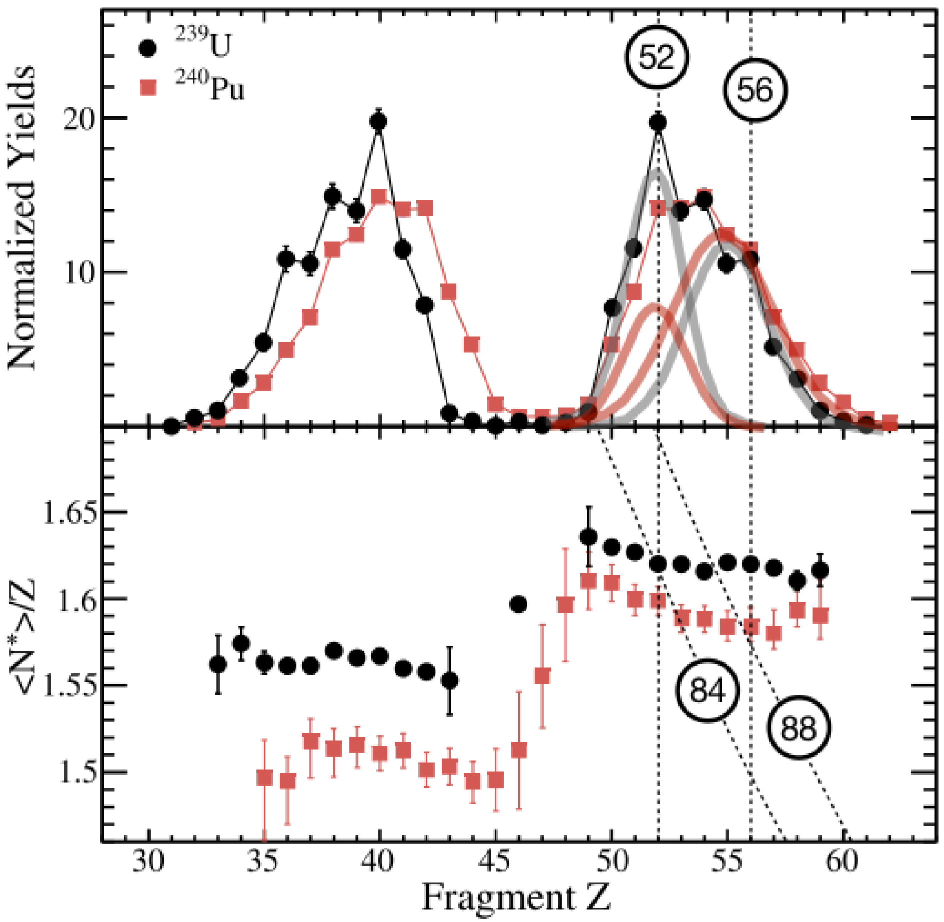
- $\langle N_{pre} \rangle / Z$ (Z)
- $\langle \nu \rangle$ (Z)
- <TKE> (Z)
- <TXE> (Z)





D. Ramos *et al.*,
Phys. Rev. C 101, 034609 (2020)

Tracing back to scission



D. Ramos *et al.*,
Phys. Rev. C 101, 034609 (2020)

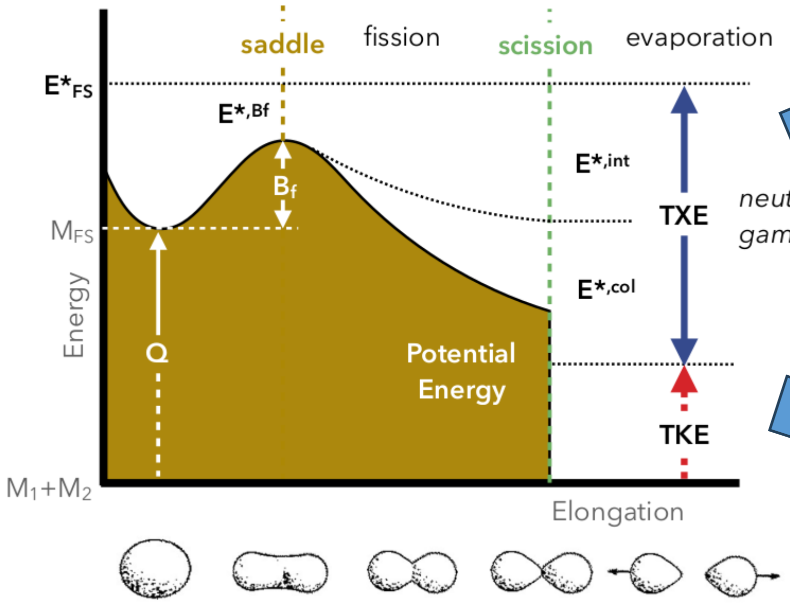
The neutron excess (N/Z) at scission allows to study the correlation between neutron and proton shells.

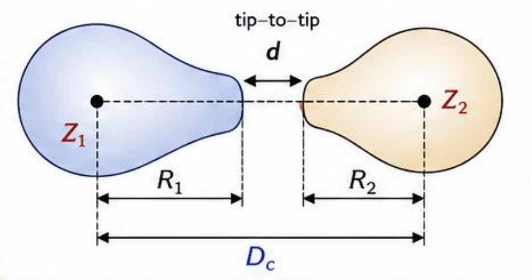
By combining several systems the **role of proton- and neutron- octupole deformed shells** [G. Scamps, C Simenel, Nature 564, 382 (2018)] is revealed :

- The enhanced yields of Te in ^{239}U can be explained by the combined effect of the octupole shells in Z=52 and N=84
- The enhanced yields of Ba can be explained by combined effect of the N=88 and Z=56

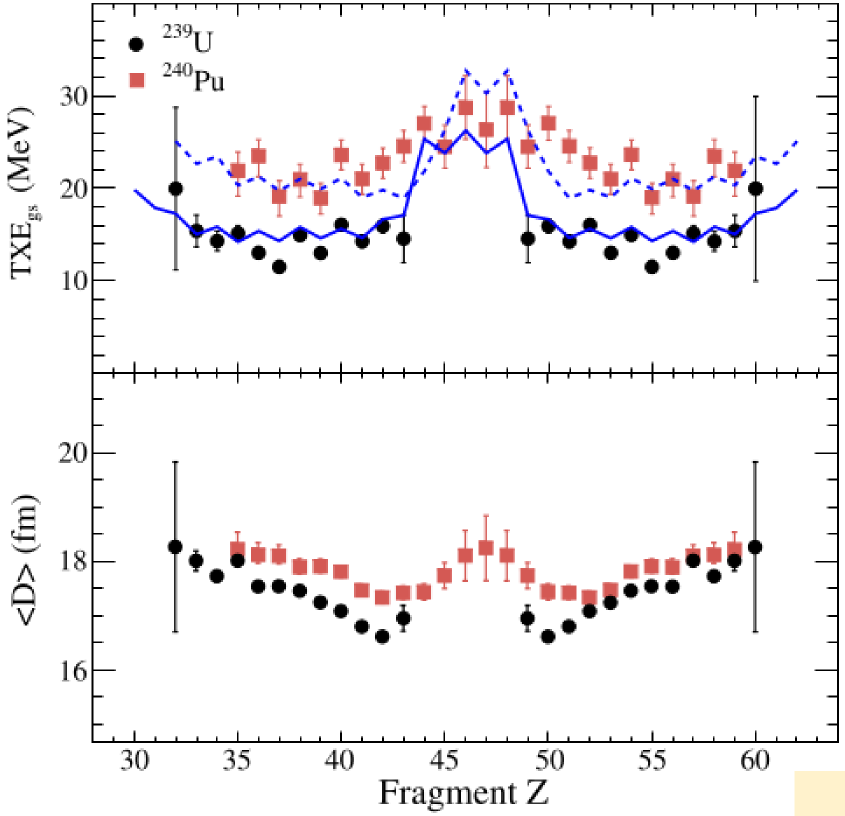
Tracing back to scission

(Z,A)-TXE-Distance





D. Ramos et al. PRC **101**, 034609 (2020)



D. Ramos et al., Phys. Rev. C 101, 034609 (2020)

The excitation energy of the fission fragments and their relative distance at scission are related to the dynamics and shape of the potential surface

Where are we heading today ?

Towards complete measurements at VAMOS++

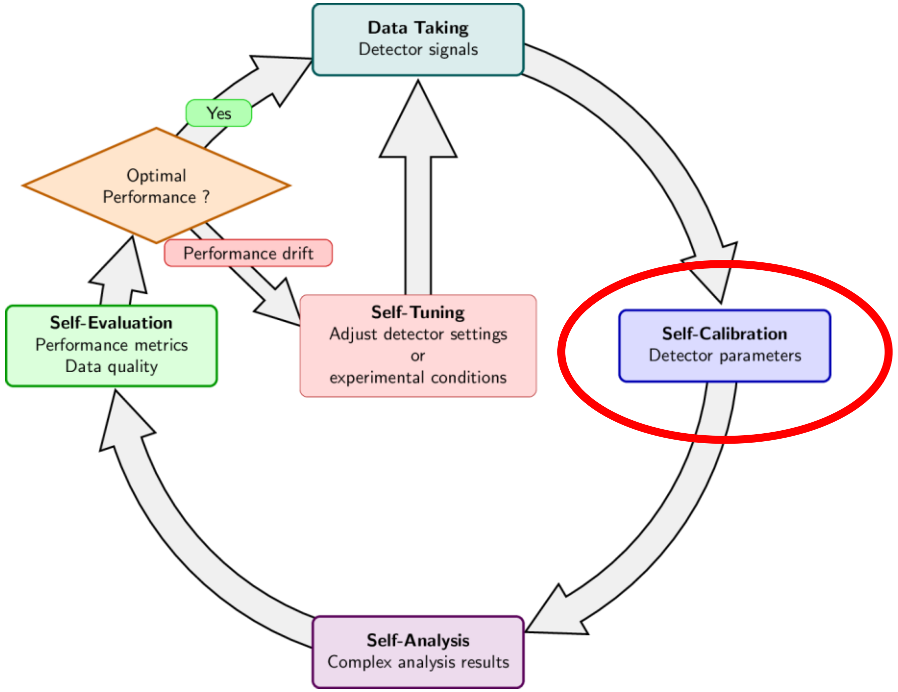
- **Done :** Isotopic distribution of FF (VAMOS++) (A,Z,q)
- **Done :** Entrance Channel control (A,Z,E*) (PISTA)
- **On way to Scission :** 2v method

  => Second Fragment as precisely as possible
  - Pre-neutron evaporation fission yields
  - Kinetic Energies
  - Isotopic neutron evaporation multiplicities
- **Future (and past !) :** Gamma-rays
  - Multiplicties, Spin Distributions, Angular Distributions and Correlations

Efficient AI-driven instrument
for reliable high quality and precision results

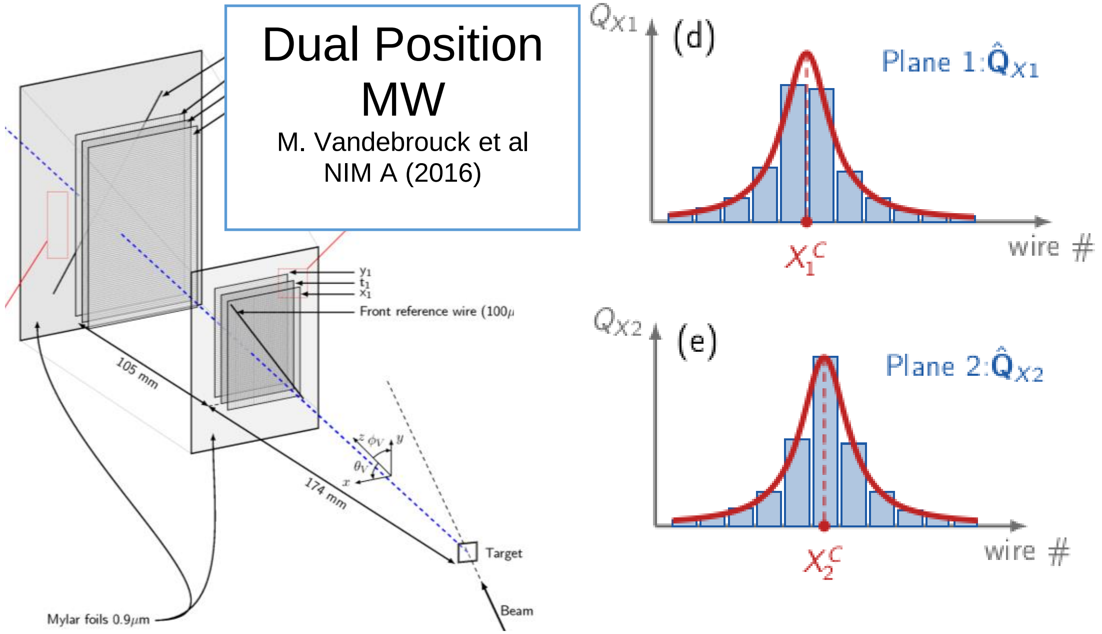
- Precision / Reproducibility
- Speed
- Scalability

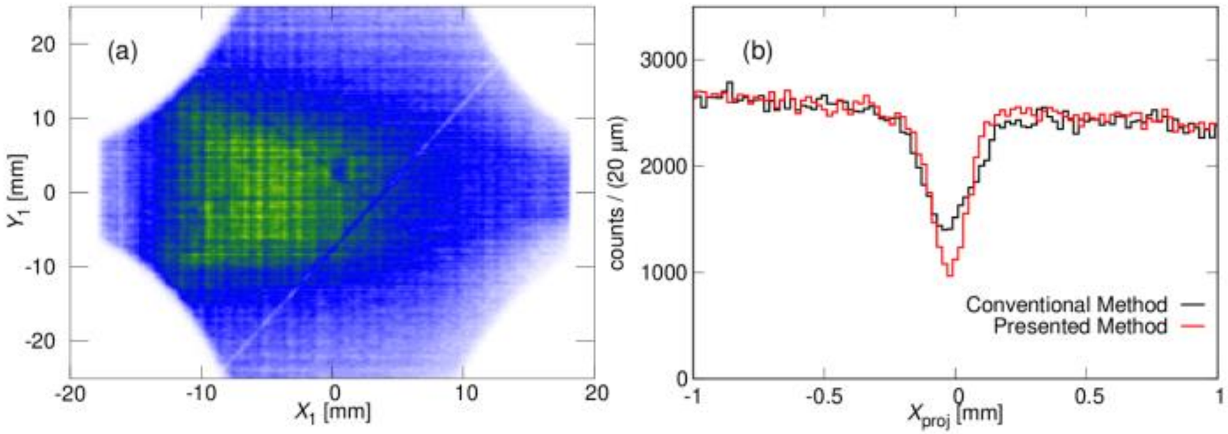
AI’s perception of the instrument



Self-Calibration (no labels !)
Learning from the production data :
- Calibration of all wires
- Charge Profile

Fast process (minutes)
Improved position resolution um->um
Online circular/repetitive process
Online optimization of detector

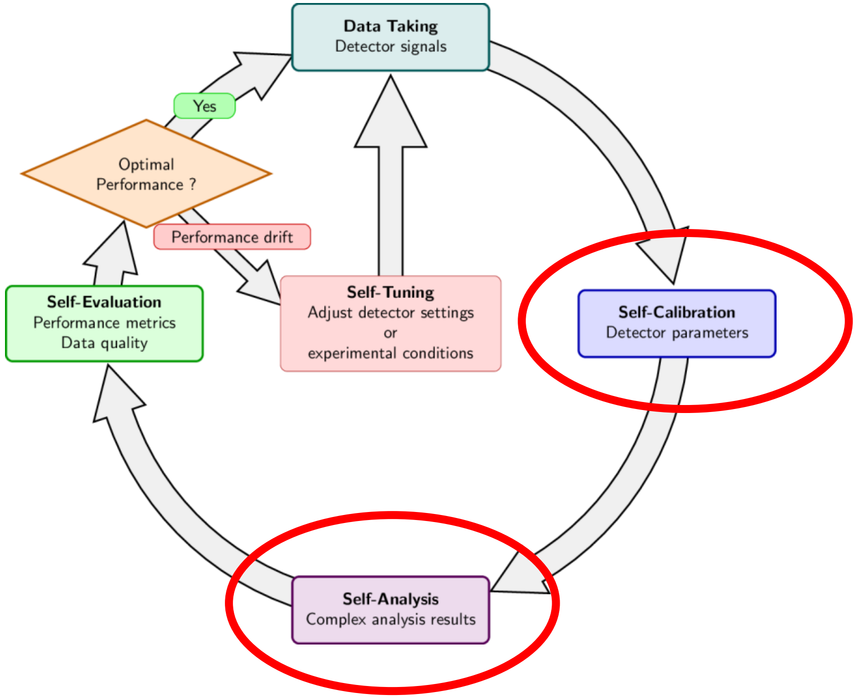




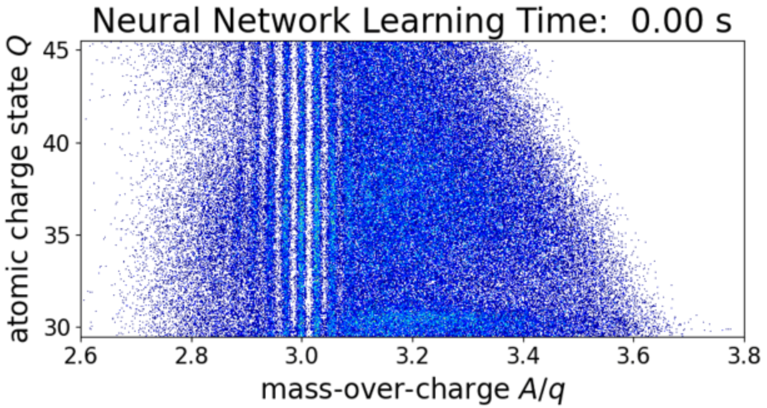
A. Lemasson, M. Rejmund, In Prep. (2026)

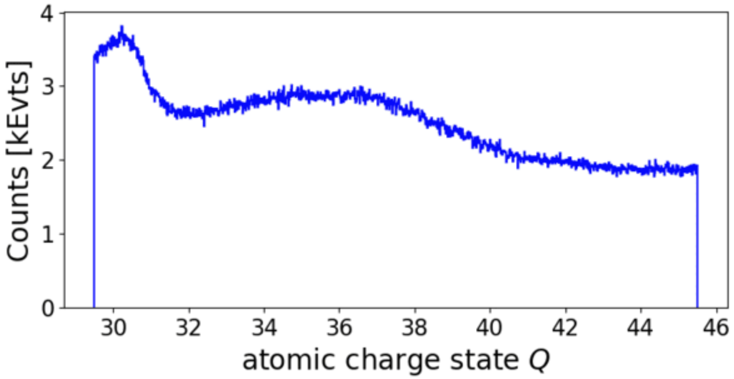
σ = 60 (2) μm
σ = 92 (2) μm

AI’s perception of the instrument



How it happens





Self-Calibration + Self Analysis

Learning from the production data :

- Calibration of all IC Pads
- detector imperfections
  (downstream specialized model accounting for it)

Fast process (minutes)

Improved resolution (ion charge state [q] and atomic number [Z])

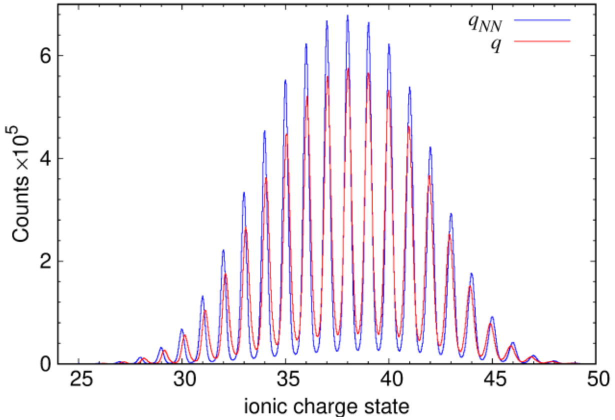
Online cicular/repetitive process

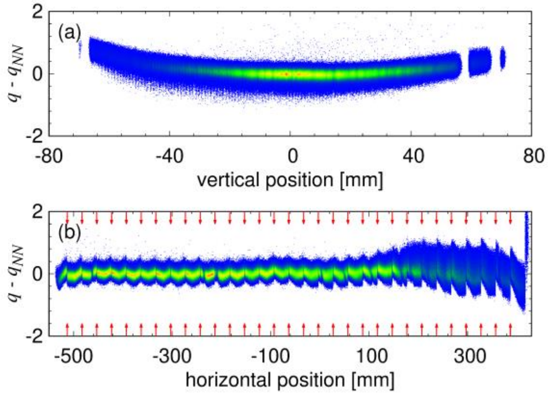
Online optimization of detector

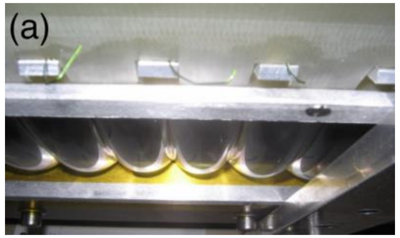
Spatial detector imperfection tracking

Self-Calibration

=> Specialized Model







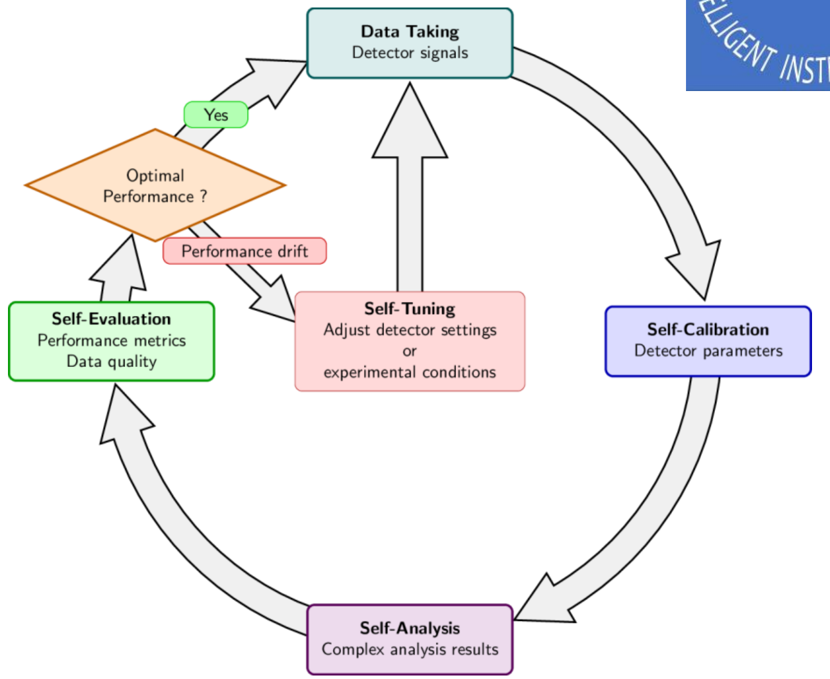
AI's perception of the instrument

VAMOS++ Large Acceptance Spectrometer :

- 7D Ion Trajectory Reconstruction in Spectrometer
  M. Rejmund, A. Lemasson, NIMA 1076 170445 (2025)
- Self-Calibration : Ion Trackers
  A. Lemasson, M. Rejmund (In prep., 2026)
- Self-Calibration and Self-Analysis : Ion Identification (Z, A, q)
  M. Rejmund, A. Lemasson, submitted / arxiv : 2606.29466v1 (2026)

PISTA :

- Self-Calibration : Highly segmented Silicon Detectors
- Ion Identification (Z, A)
  M. Rejmund et *al.*, submitted (2026)



Gains :

- Labelling-less + Human-Bias-less
  - Precision
  - Reproducibility
  - Speed
  - Scalability
- Detection Optimizability
- Detection Imperfection Tracking

Upcoming :

- Self-Tunning : Machine Learning Optimization
- Full Online Implementation

VAMOS is now
an Intelligent Instrument to
provide even higher quality data

Almost twenty years of Fission at VAMOS++

- We learned to experimentally trace fission fragments back toward scission, revealing the deformation, energy and proton/neutron structure of the nascent fragments.

M. Caamaño *et al.*, PRC 92, 034606 (2015);
M. Caamaño & F. Farget, PLB 770, 72 (2017);
D. Ramos *et al.*, PRC 101, 034609 (2020).
D. Ramos *et al.*, PRC 97, 054612 (2018);
D. Ramos *et al.*, PRL 123, 092503 (2019) ;
D. Ramos *et al.*, PRC 113, 054611 (2026).

- We showed that the proton structure of the emerging fragments is a major driver of asymmetric fission, with common fingerprints extending from neutron-deficient Hg to the actinides.

C. Schmitt *et al.*, PRL 126, 132502 (2021);
A. Jhingan *et al.*, PRC 106, 044607 (2022),
D. Ramos et al., PRC 97, 054612 (2018);

- We showed that nuclear shells influence not only the yields but the dynamics itself, modifying dissipation and potentially the saddle-to-scission time.

D. Ramos *et al.*, PRC 107, L021601 (2023).

\+ Fission Fragments Spectroscpy program already discussed this week !

A. Navin and M. Rejmund, Yearbook of Science & Technology (2018),
A. Lemasson *et al*, EPJA (2023)
….

We ≡ Long Standing Fission (Dynamics) Collaboration around VAMOS

Path followed :

Continuous improvement of fission products measurement →
reconstructing scission quantities →
identifying the microscopic structures controlling the path →
experimentally probing the dissipation along that path

Nuclear fission has entered a new era of precision and correlation

Hunting for high-quality, unique datasets :

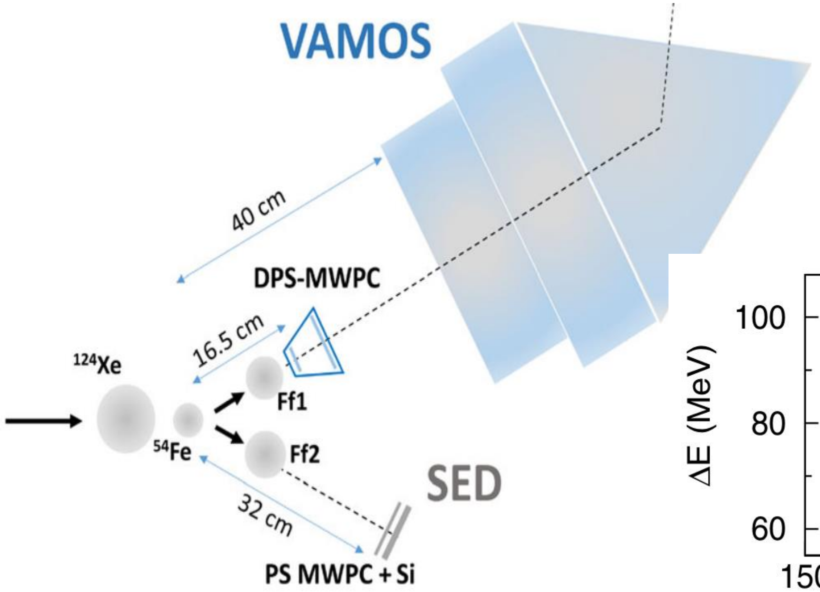
- New experimental setups provide simultaneous access to multiple correlated observables
- Increasingly complete kinematics allow us to trace the system back toward scission using isotopic information on fragments
- ML/AI offers new opportunities to push resolution, identification and reconstruction beyond traditional limits

Unprecedented experimental information available :

- Multi-dimensional observables: $Y(A,Z,E^*)$,$\nu(A,Z,E^*)$,$M_\gamma(A,Z?)$,$S(A,Z?)$, $TKE(A,Z,E^*)$,
- Measurements across an increasingly broad range of fissioning systems, excitation energies and angular momenta

We entered an exciting period for nuclear-fission research:
richer experiments, more complete correlations and rapidly advancing theory
towards a deeper understanding the fission dynamics universal drivers

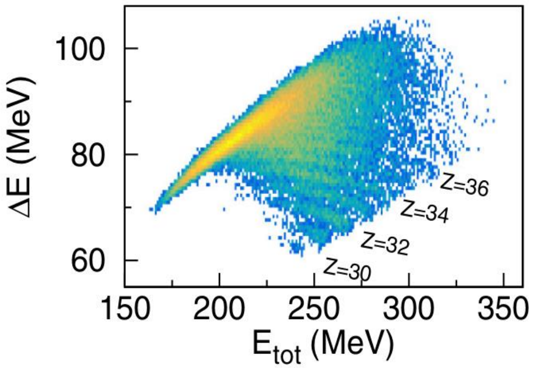
Fusion-Fission in n-deficient pre-Actinides

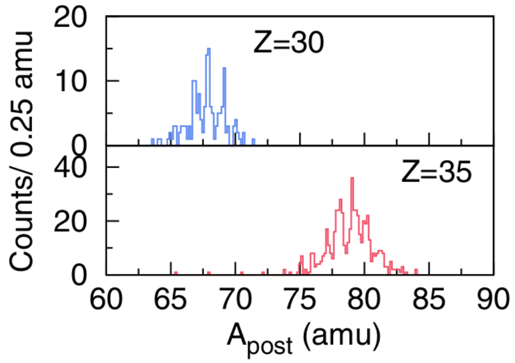


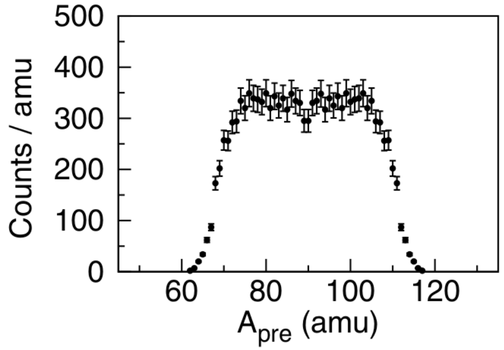
- ^{124}Xe (4.3 MeV/u) + ^{54}Fe → ^{178}Hg (E_x=34 MeV)
- 2 arms at 64° (folding angle)
- Complete-Kinematics Measurement

2V method

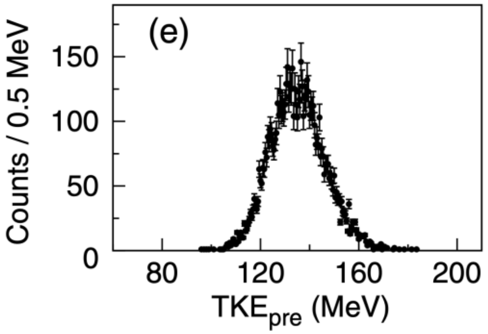
$$\frac{M_1^*}{M_2^*} = \frac{\gamma_{\mathrm{c.m.}_2} v_{\mathrm{c.m.}_2}}{\gamma_{\mathrm{c.m.}_1} v_{\mathrm{c.m.}_1}}$$

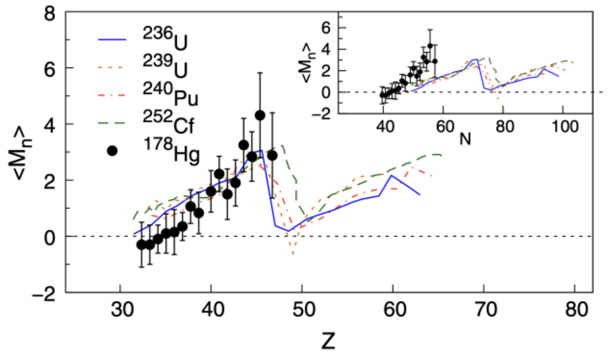






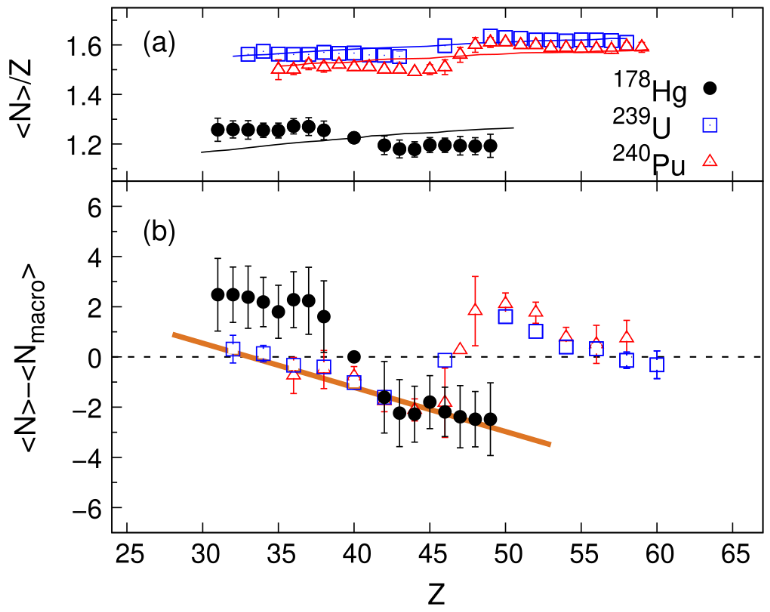
- First isotopic FF measurement in n-defficient pre-actinides
- **Confirmed presence of asymetric fission in ^{178}Hg**
- **Pre-evaporation mass, TKE, neutron multiplicity**





C. Schmitt et al. PRL 126, 132502 (2021)

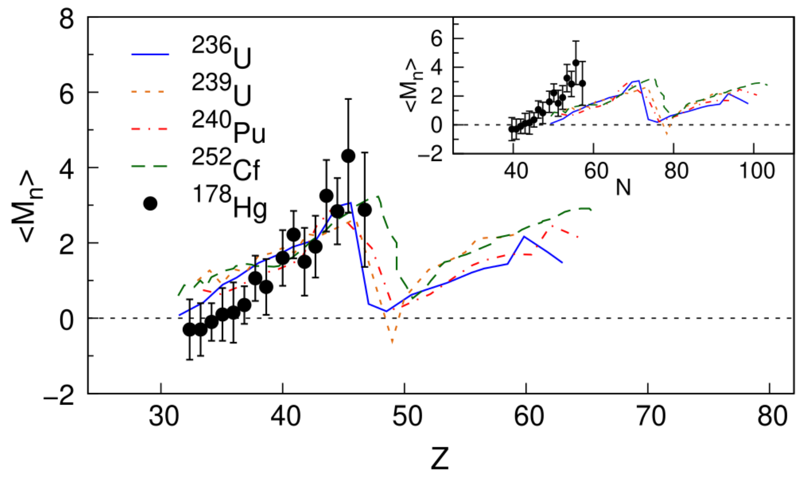
From a proton content perspective



Same microscopic contribution to *N/Z* **at given *Z* for different *N*'s**

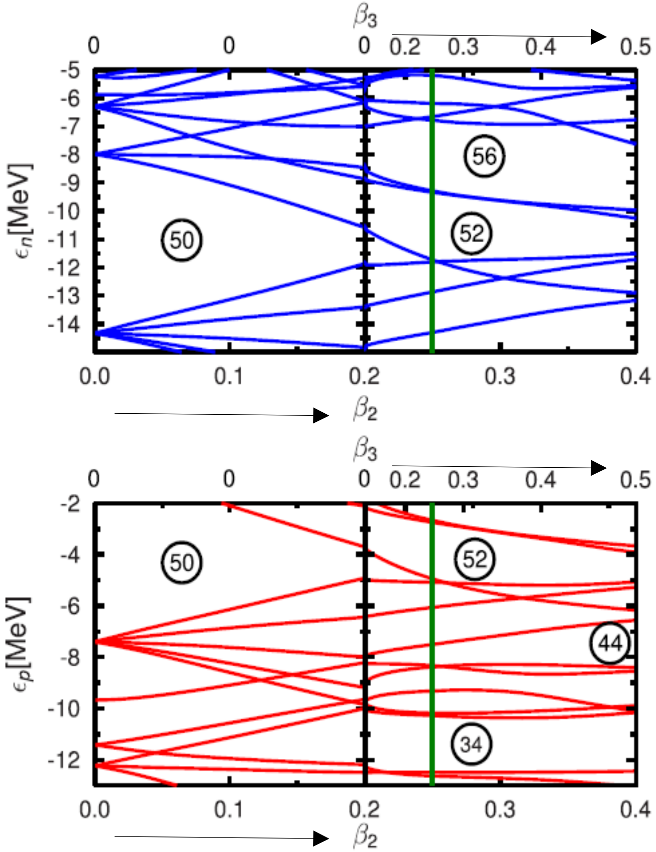
Shell effect Z~34-36 (quadrupole + octupole)
Single isotopic experiment so far…
Additional experimental data needed

M_n **= M$_{post}$ – M$_{pre}$** ~ *Shape relaxation after scission*



Same magnitude of shape relaxation **at given *Z* for different *N*'s** **deformed** fragments with 28 < *Z* < 50 favored

neutrons

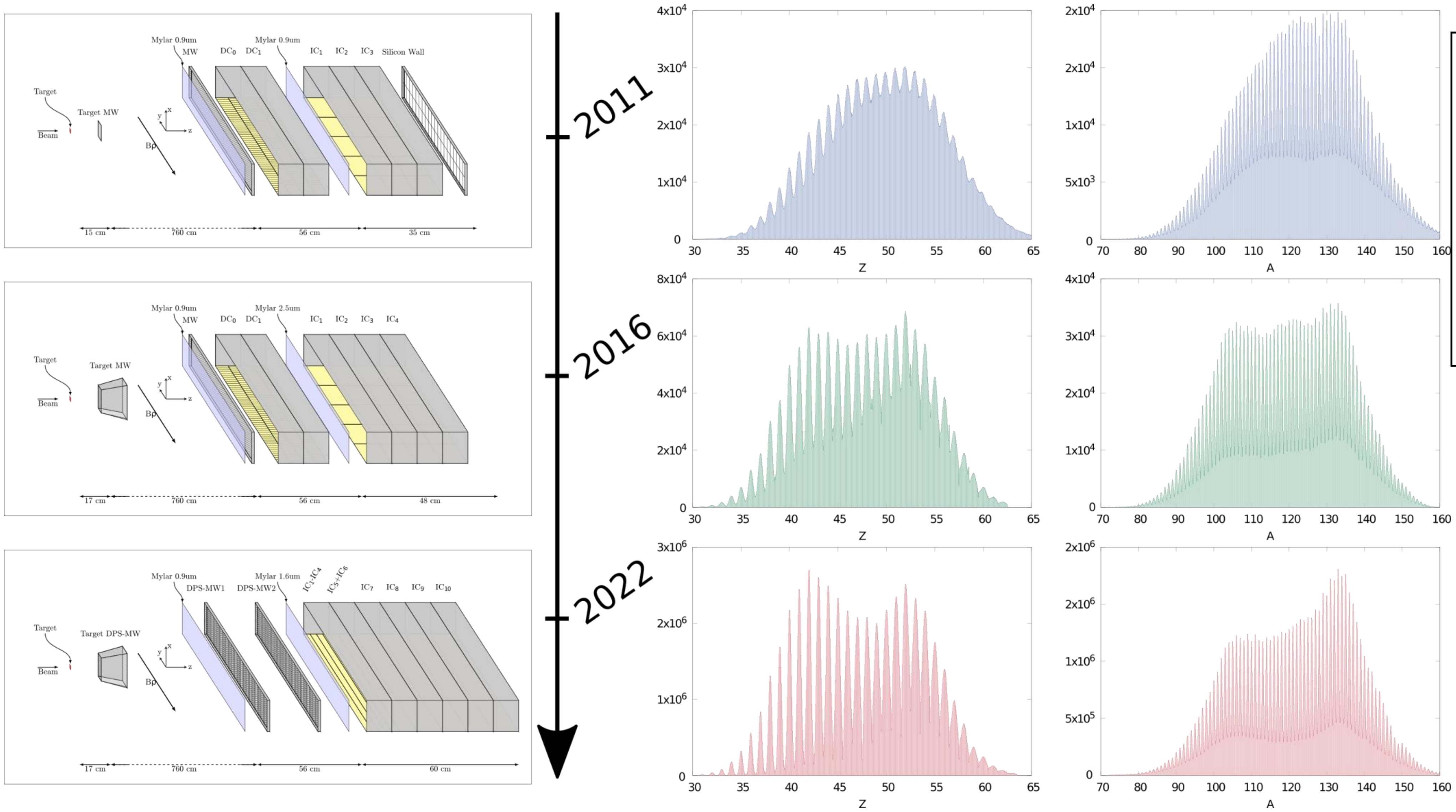


protons

Scamps and Simenel, PRC 100 (2019)

Continuous improvements of VAMOS

Focal Plane Configuration | Charge(Z) | Mass(A)



Improvements :

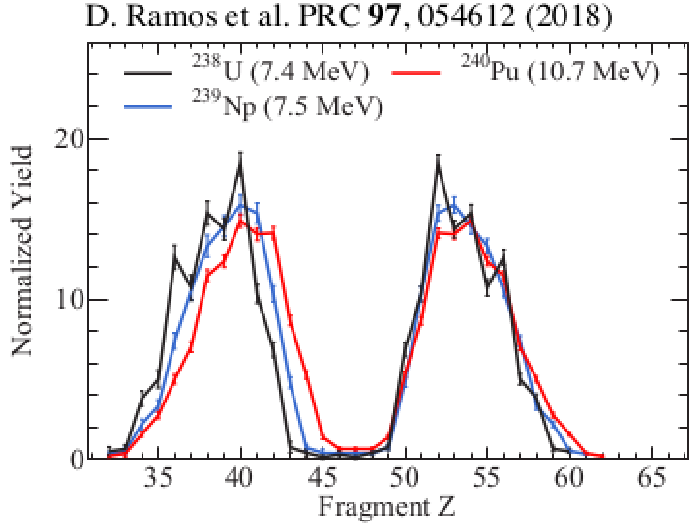
- High Pressure Ionisation chambers
- Target MWPC
- Focal Plane MWPC
- Reconstruction methods
- Software Standardisation

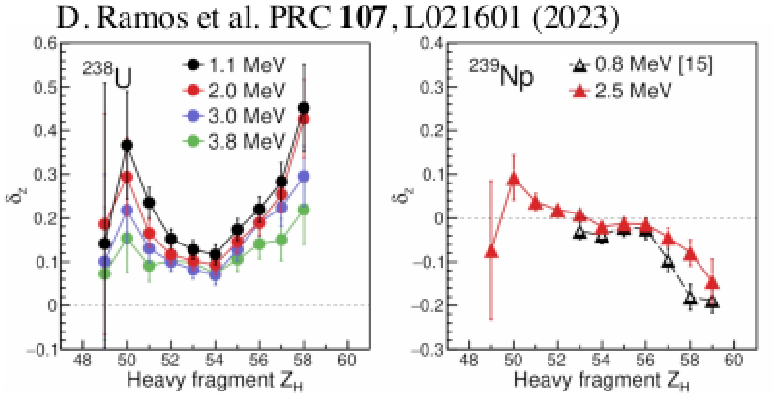
- Machine Learning / AI

And much more at VAMOS

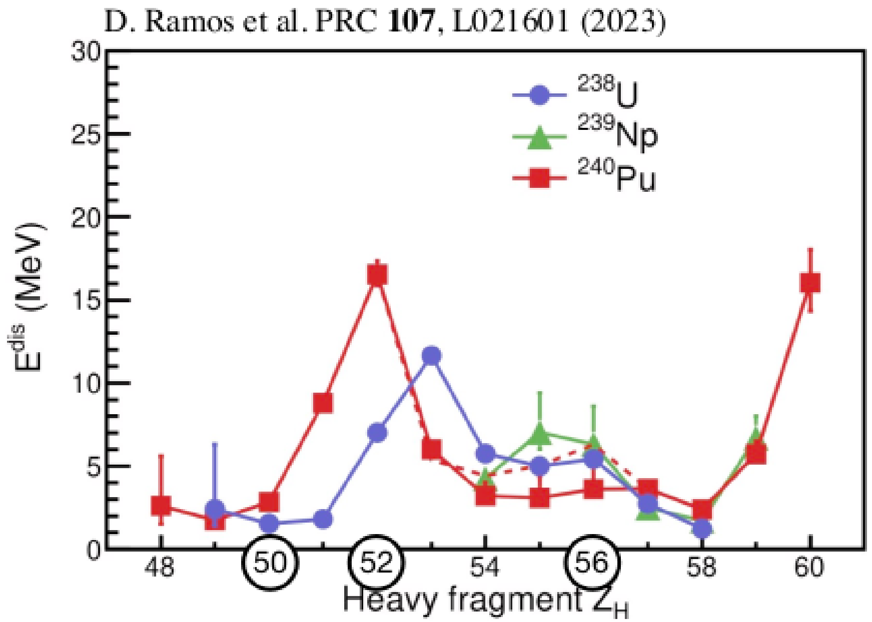
Dissipation, time, and shell effects

D. Ramos *et al.*, PRC 107, L021601 (2023).





The relative production of even- and odd-Z fragments (the even-odd effect) reflects the amount of **intrinsic excitation energy**.



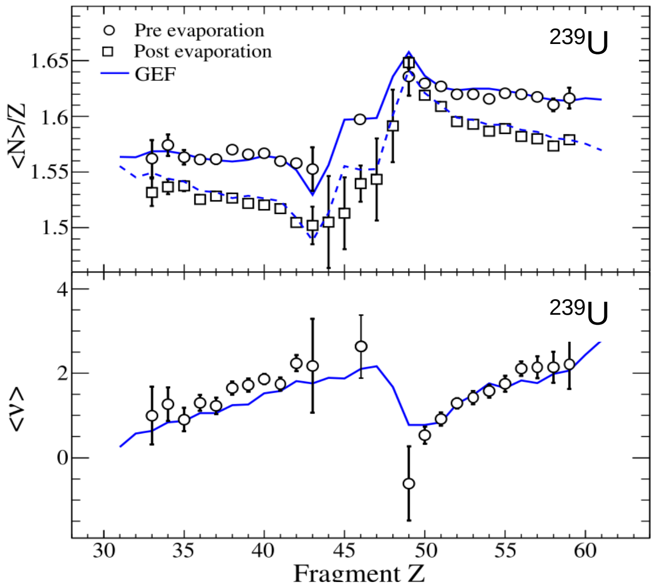
From the intrinsic excitation energy we can deduce the **dissipation energy**.

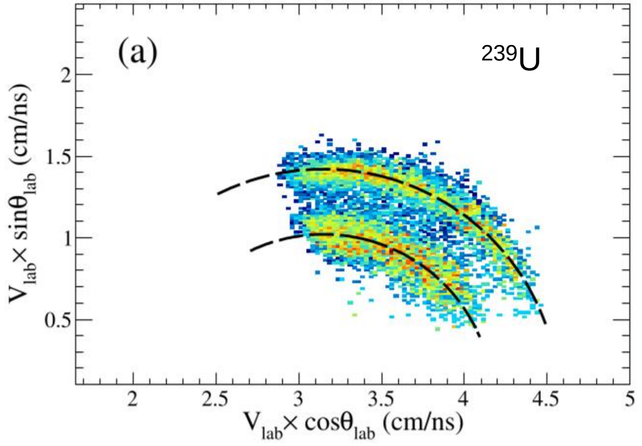
We observe a **link between dissipation and shells**: a minimum at Z≈50 and a maximum at Z≈52.

Fission is **slower** for octupole deformed fragments than for spherical ones.

Tracing back to scission

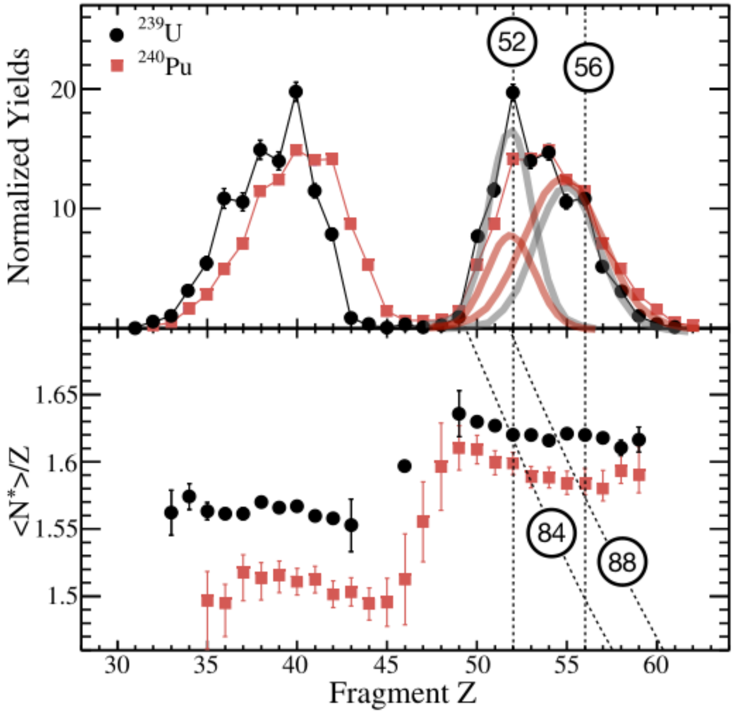
(Z,A)-neutron multiplicity-TKE





D. Ramos et al., Phys. Rev. C 101, 034609 (2020)

D. Ramos et al. PRC **101**, 034609 (2020)



2v method

$$\frac{M_1^*}{M_2^*} = \frac{\gamma_{c.m._2} v_{c.m._2}}{\gamma_{c.m._1} v_{c.m._1}}$$

The neutron excess N/Z also helps the study of the correlation between neutron and proton shells.

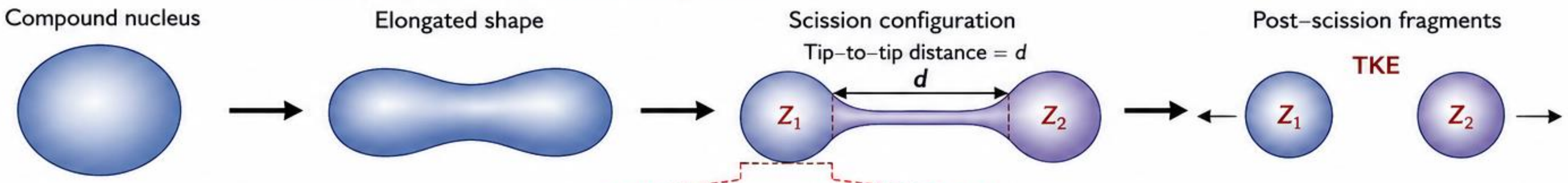
- By combining several systems the **role of proton- and neutron- octupole deformed shells [G. Scamps, C Simenel, Nature 564, 382 (2018)]** are reflected
- The large production of Te in ^{239}U can be explained by the combined effect of the octupole shells in Z=52 and N=84
- The production of Ba is explained by the effect of N=88 in ^{240}Pu and N=56 in ^{239}U

$Y(A_{pre},Z)$, $\langle N_{pre}\rangle/Z(Z)$, $\langle\nu\rangle(Z)$

The picture can't be displayed.

Relating Total Kinetic Energy (TKE) to Tip–to–Tip Distance at Scission

Fission process and scission configuration

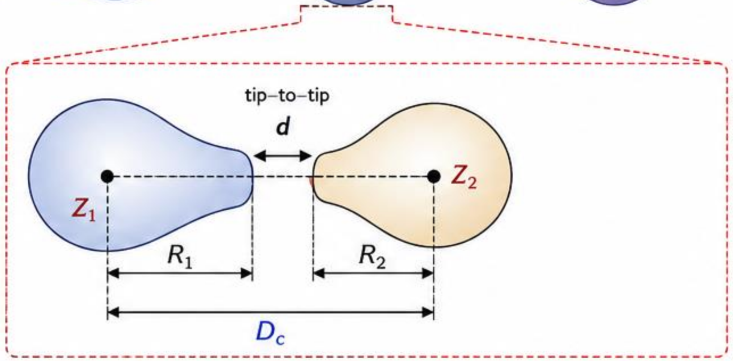


1. Coulomb repulsion at scission

$$\mathrm{TKE} \simeq \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{D_c}$$

In nuclear units ($e^2/4\pi\varepsilon_0 = 1.44$ MeV·fm)

$$\boxed{\mathrm{TKE\ [MeV]} \simeq 1.44\,\frac{Z_1 Z_2}{D_c\ [\mathrm{fm}]}}$$



R_i = effective radius of fragment i

D_c = distance between centers of charge

d = tip–to–tip distance

2. Relation between D_c and tip–to–tip distance

$$D_c = R_1 + R_2 + d$$

For (nearly) spherical fragments:

$$R_i = r_0\,A_i^{1/3} \qquad (r_0 \simeq 1.2\ \mathrm{fm})$$

3. TKE in terms of d

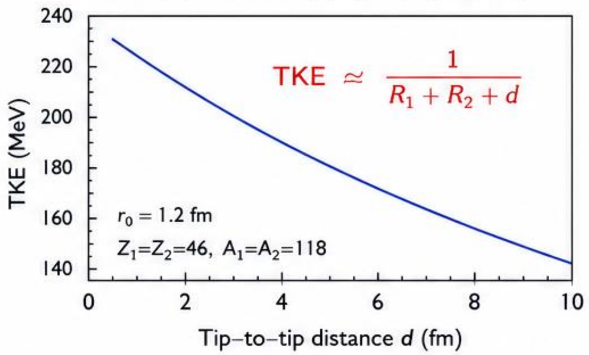
$$\mathrm{TKE} \simeq \frac{1.44\;Z_1 Z_2}{r_0\,(A_1^{1/3}+A_2^{1/3})+d} \quad [\mathrm{MeV}]$$

Conversely,

$$\boxed{d \simeq \frac{1.44\,Z_1 Z_2}{\mathrm{TKE\ [MeV]}} - r_0\,(A_1^{1/3}+A_2^{1/3}) \quad [\mathrm{fm}]}$$

4. Illustration (symmetric example)

Example: ^{236}U fission (Z_1=Z_2=46, A_1=A_2=118)



Remarks

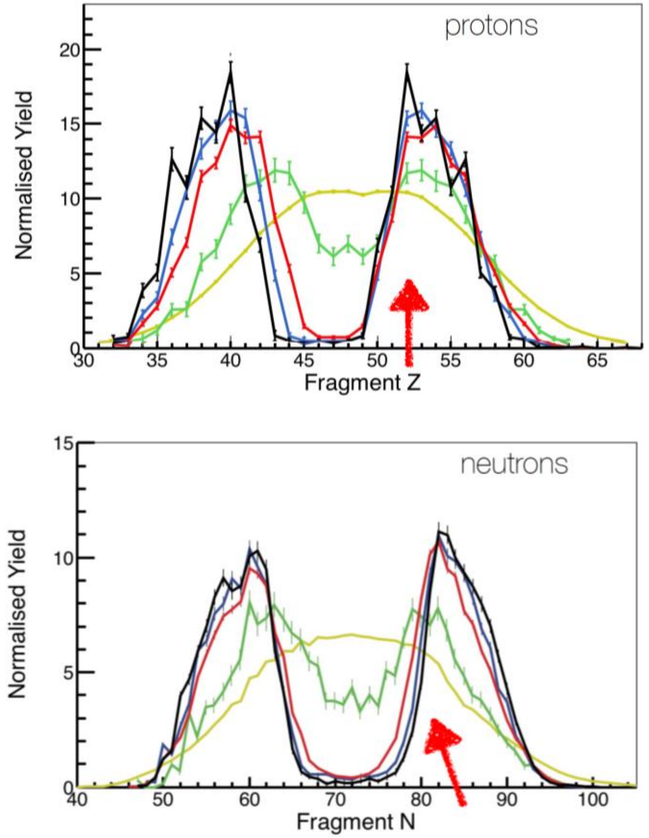
- Higher TKE $\Rightarrow$ smaller $(R_1 + R_2 + d)$: more compact scission configuration.
- Lower TKE $\Rightarrow$ larger d and/or larger deformations: more elongated configuration.
- Strictly, $\mathrm{TKE}_{\mathrm{final}} \simeq V_{\mathrm{Coulomb}}^{\mathrm{scission}} + E_{\mathrm{kin}}^{\mathrm{pre\text{-}scission}}$; extraction of d assumes the pre-scission kinetic energy is small or corrected for.

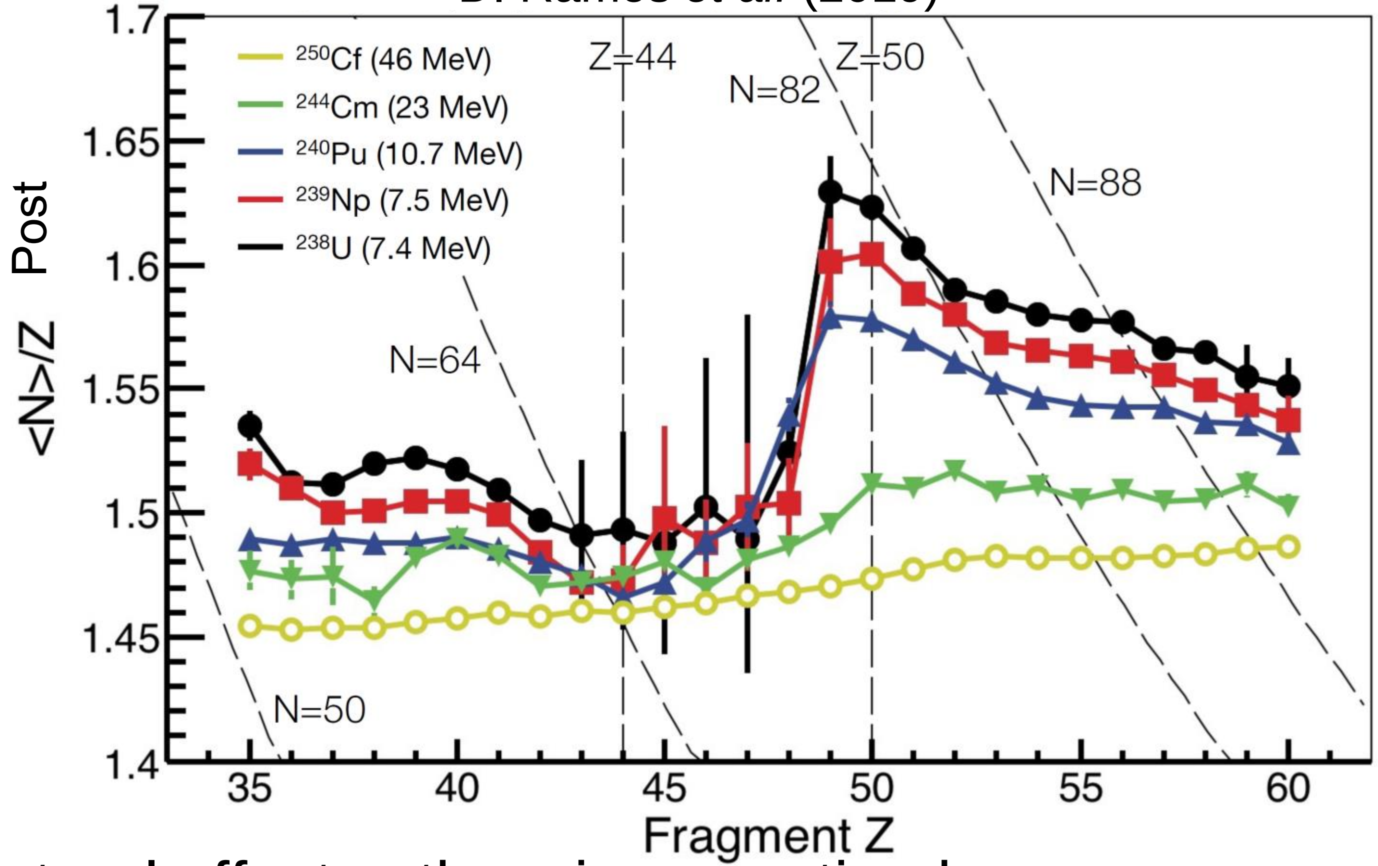
$$\mathrm{TKE} \approx \frac{Z_1 Z_2}{R_1 + R_2 + d} \quad \Rightarrow$$

TKE measures the compactness of the scission configuration.

A set of revisited and new observables
Fragments N excess (<N>/Z)

D. Ramos *et al.* (2019)

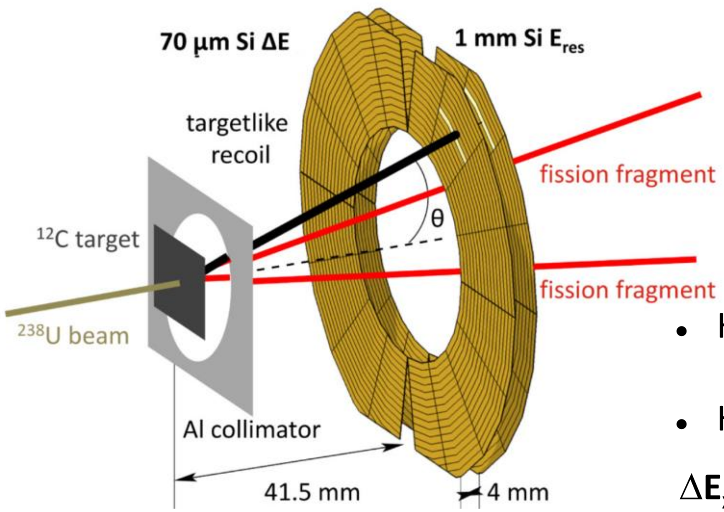




Reveals fine structural effects otherwise unnoticed
N=82 (~spherical) and N=88 (deformed / Octupolar)

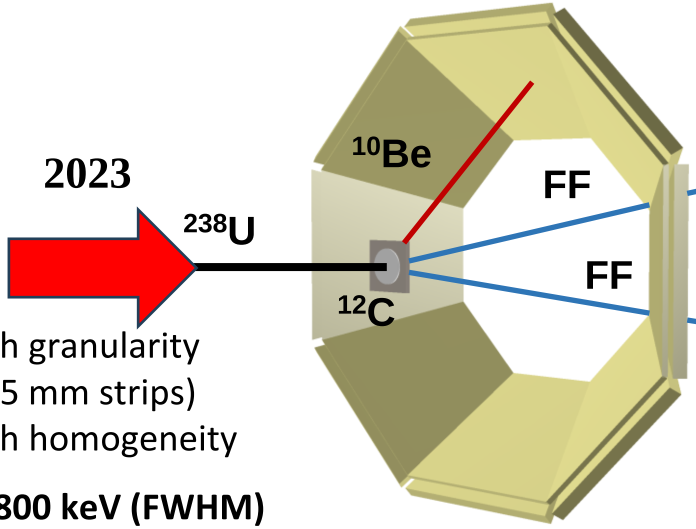
PISTA : Improving fissioning system identification

SPIDER



2023

PISTA

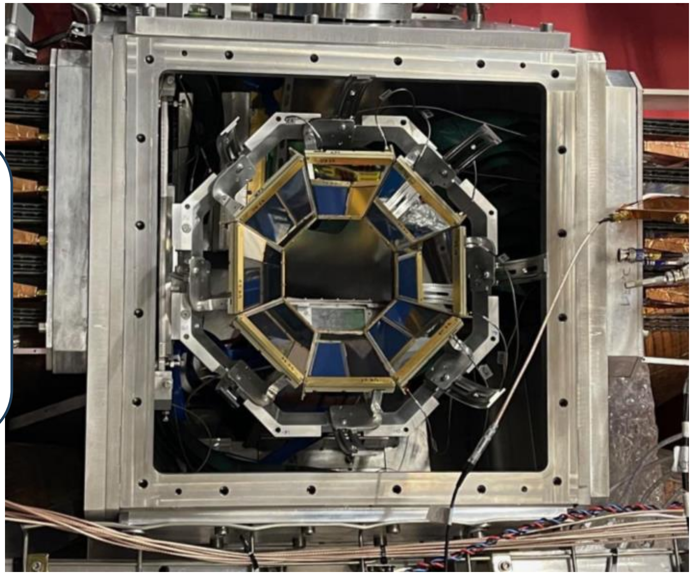


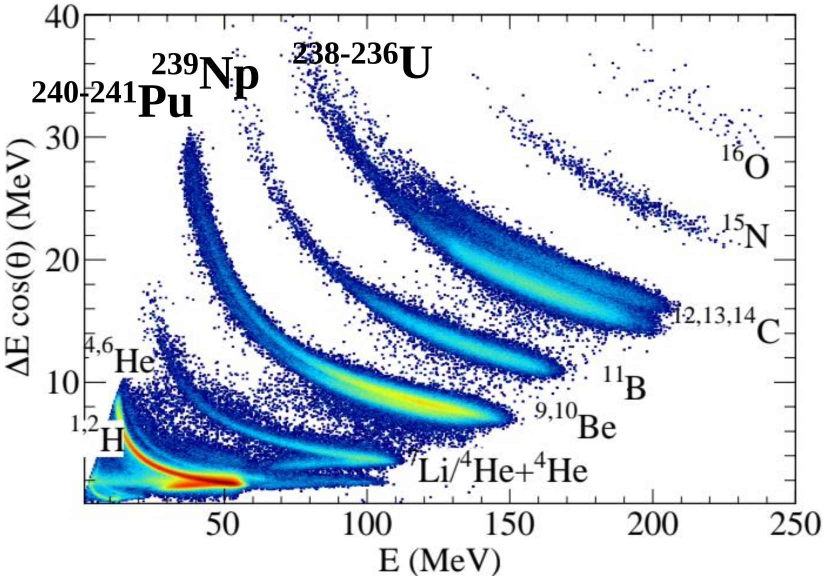
- High granularity (0.5 mm strips)
- High homogeneity

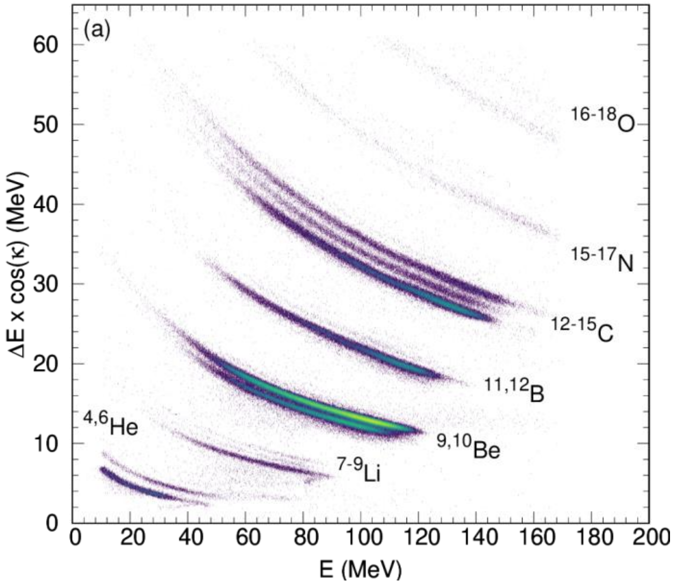
ΔE_x~800 keV (FWHM)

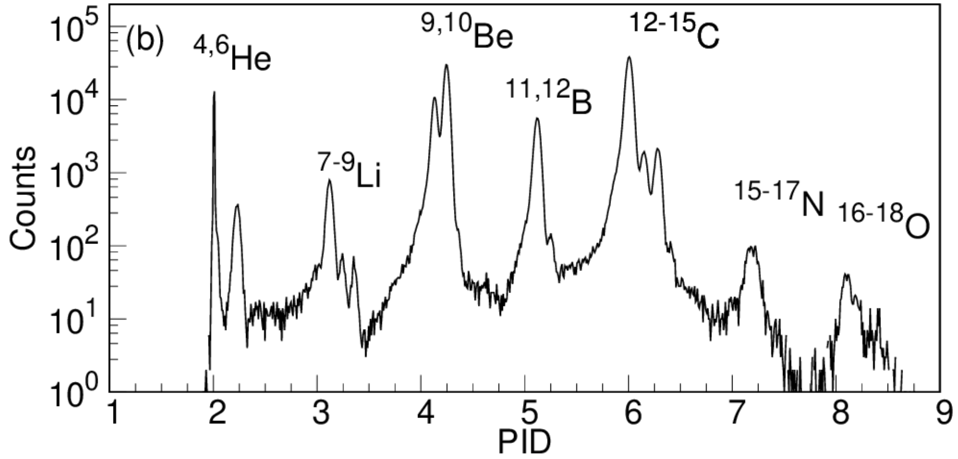
GANIL-CEA/DAM collaboration

ΔE
100 μm thickness
0.5 mm strips (θ)
10 cm from target
E
1 mm thickness
1.2 mm strips (ϕ)







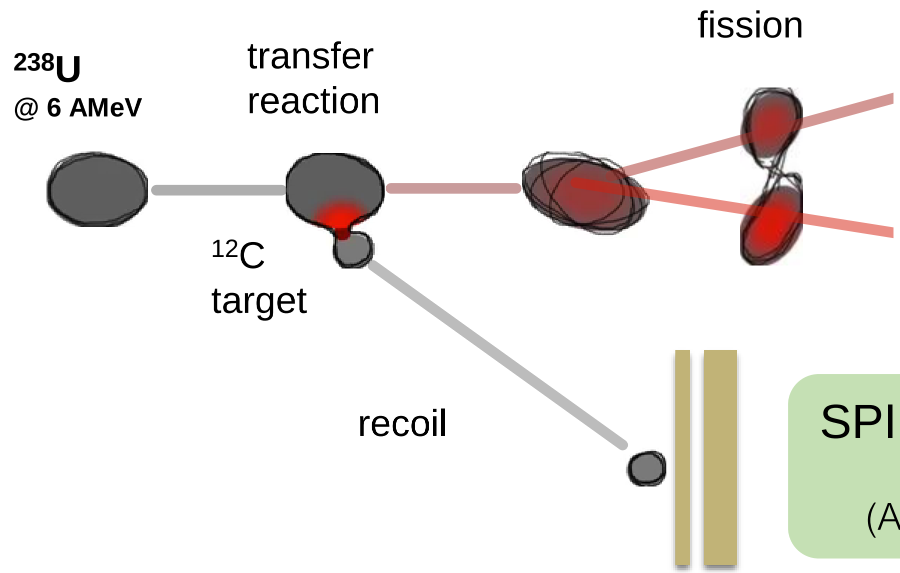


L. Begué—Guillou et al. NIM A **1090**, 171671 (2026)
[10.1016/j.nima.2026.171671](https://doi.org/10.1016/j.nima.2026.171671)

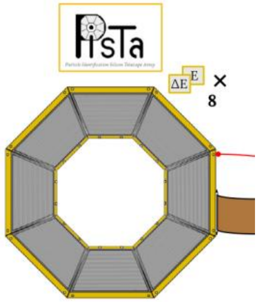
Fission in inverse kinematics at VAMOS/GANIL

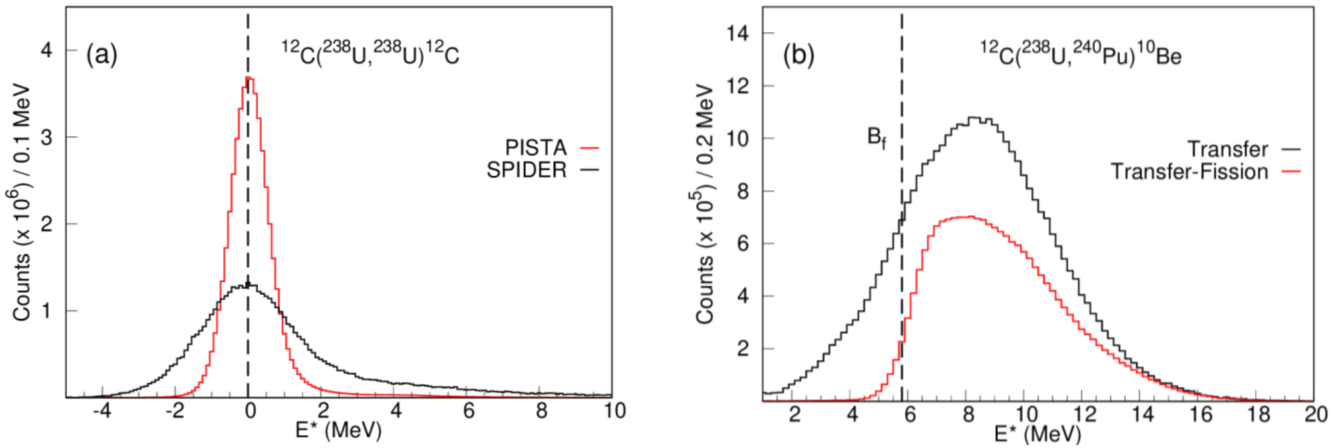
Inverse Kinematic using beams of $^{238}U/^{232}Th$ around Coulomb Barrier

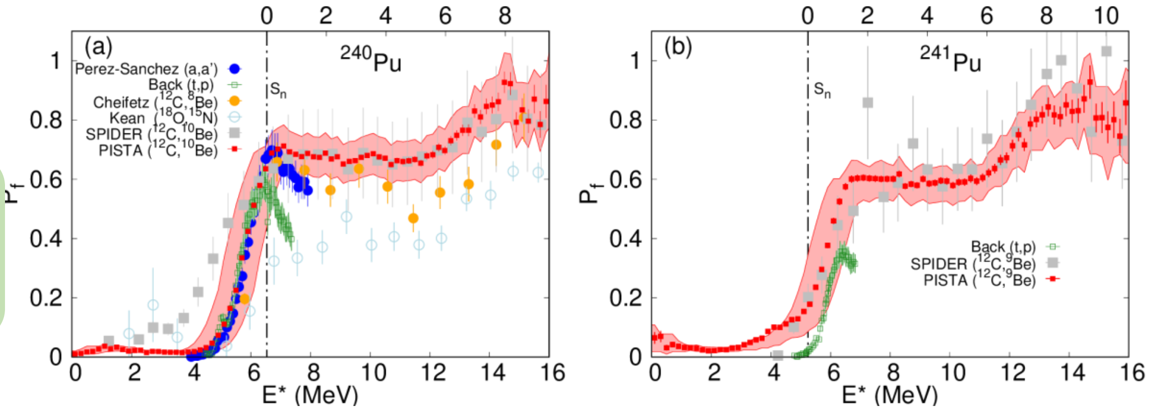
⇒ Access to « exotic » fissioning systems heavier than ^{238}U



SPIDER/PISTA
Recoil
(A, Z, E, angle)







Surrogate reactions (transfer induced fission)

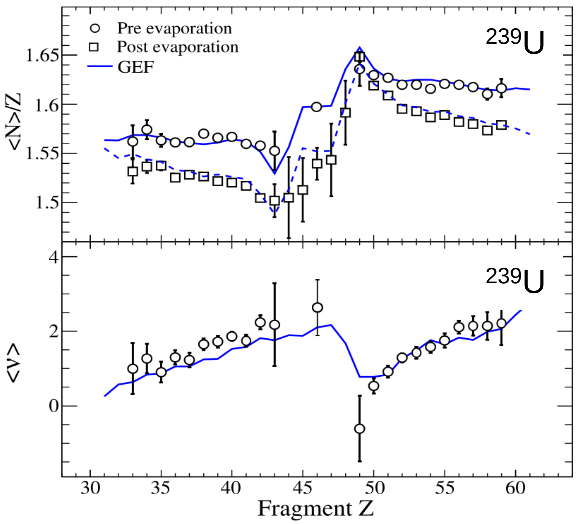
⇒ Selection of the fissionning system

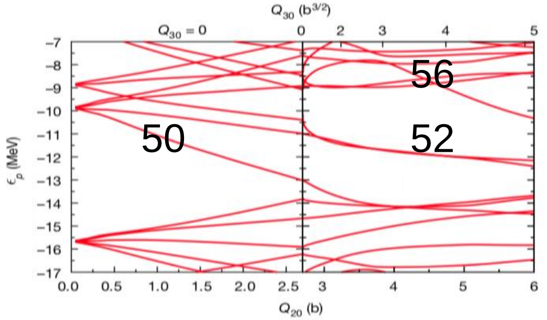
⇒ Measurement of the excitation energy

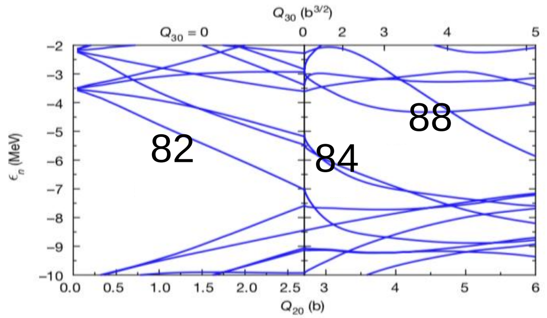
L. Begué—Guillou et al. NIM A **1090**, 171671 (2026)
[10.1016/j.nima.2026.171671](https://doi.org/10.1016/j.nima.2026.171671)
L. Begué—Guillou et al. (PhD GANIL/CEA-DAM)

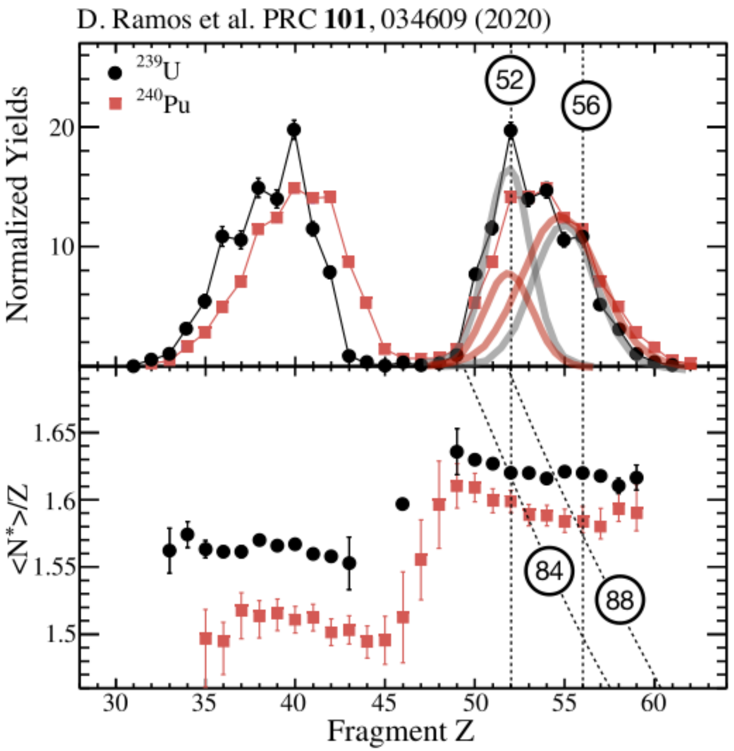
The reconstruction of the binary reaction also provides information on the fission barrier

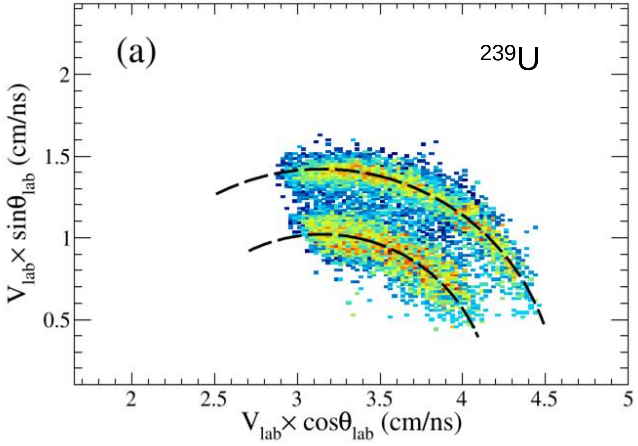
Scission Observables - Detection of both fragments











- By combining several systems the **role of proton- and neutron- octupole deformed shells [G. Scamps, C Simenel, Nature 564, 382 (2018)]** are reflected
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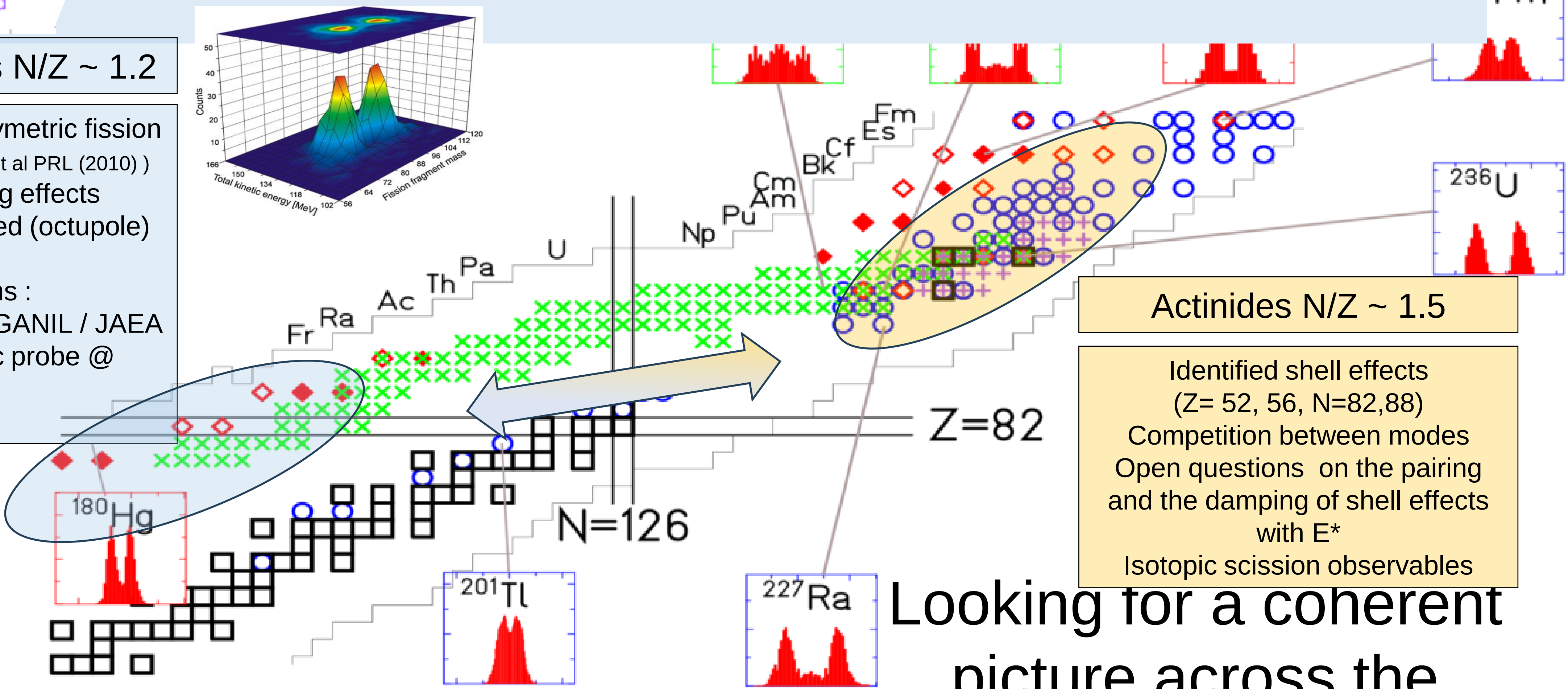
- The production of Ba is explained by the effect of N=88 in ^{240}Pu and N=56 in ^{239}U

The neutron excess N/Z also helps the study of the correlation between neutron and proton shells.

D. Ramos et al., Phys. Rev. C 101, 034609 (2020)

Exploring further the fission landscape



Pre-Actinides N/Z ~ 1.2

Unexpected Assymetric fission in ^{180}Hg (Andreiev et al PRL (2010))
=> New stabilizing effects at Z ~ 36 deformed (octupole) configuration
Ongoing programs :
- Fusion Fission GANIL / JAEA
- Electromagnetic probe @ GSI

Actinides N/Z ~ 1.5

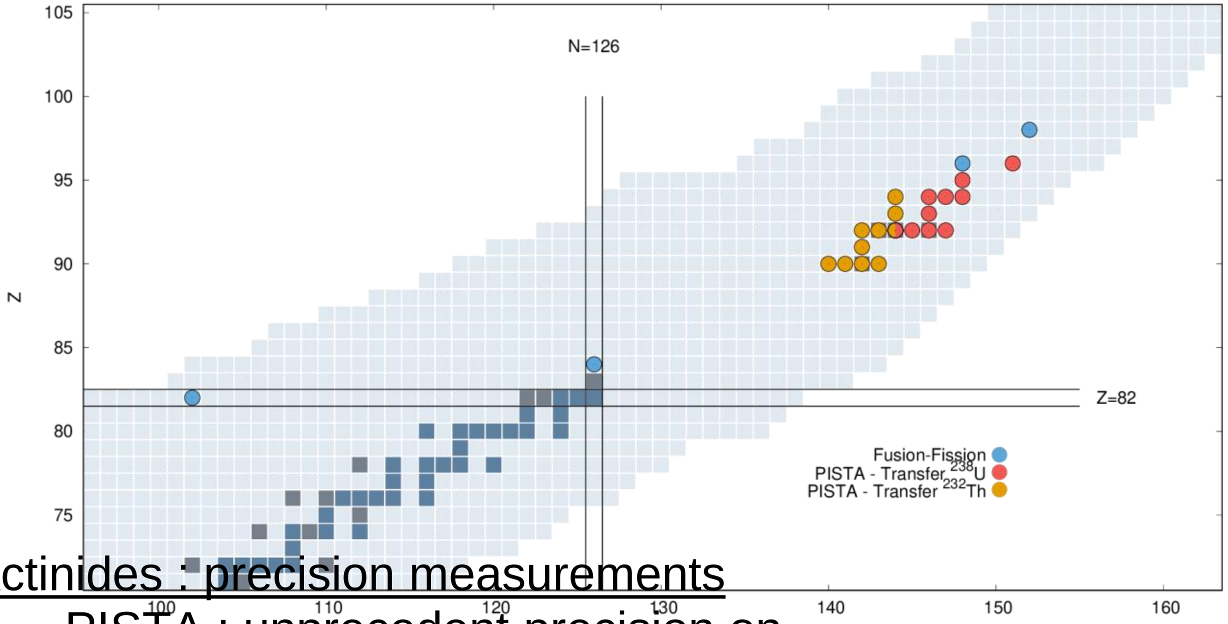
Identified shell effects
(Z= 52, 56, N=82,88)
Competition between modes
Open questions on the pairing and the damping of shell effects with E*
Isotopic scission observables

Looking for a coherent picture across the landscape

Rich ongoing and future studies at VAMOS

- <u>Actinides : precision measurements</u>
  - PISTA : unprecedent precision on the entrance channel (A,Z,E*)
    - shell effect damping with E*
    - even-odd effect
  - ^{232}Th beams : new systems available
  - Two velocities measurements
  - γ-rays : Calorimetry and Angular Momentum

  Towards nuclear data standards



<u>Actinides : precision measurements</u>
PISTA : unprecedent precision on the entrance channel (A,Z,E*)
shell effect damping with E*
even-odd effect
^{232}Th beams : new systems available
Two velocities measurements
γ-rays : Calorimetry and Angular Momentum
Towards nuclear data standards

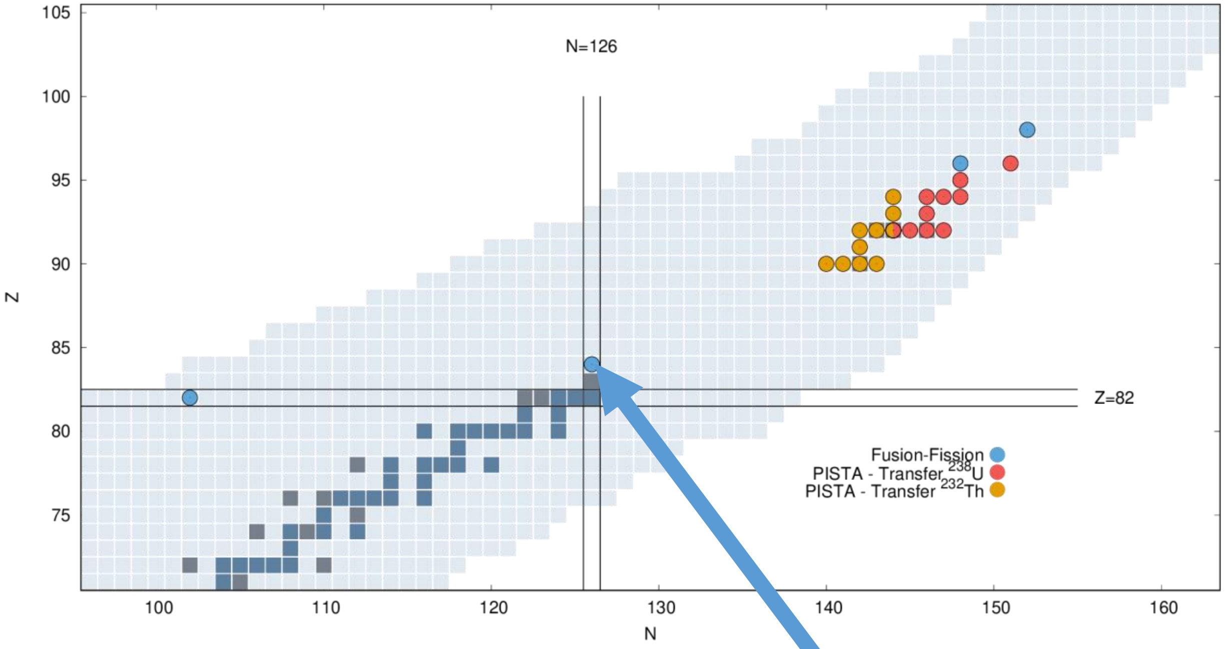
Rich ongoing and future studies at VAMOS

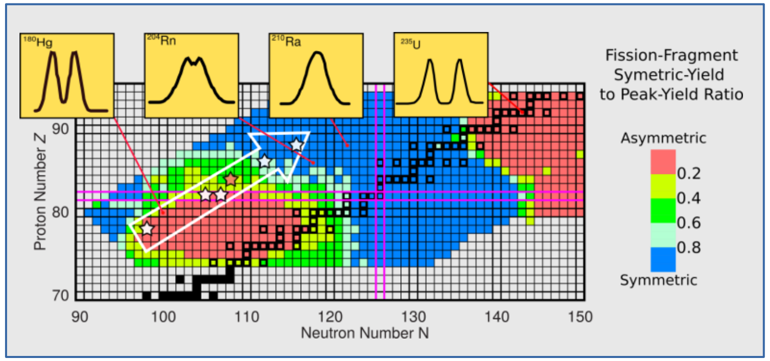
- <u>Actinides : precision measurements</u>
  - PISTA : unprecedent precision on the entrance channel (A,Z,E*)
    - shell effect damping with E*
    - even-odd effect
  - ^{232}Th beams : new systems available
  - Two velocities measurements
  - γ-rays : Calorimetry and Angular Momentum

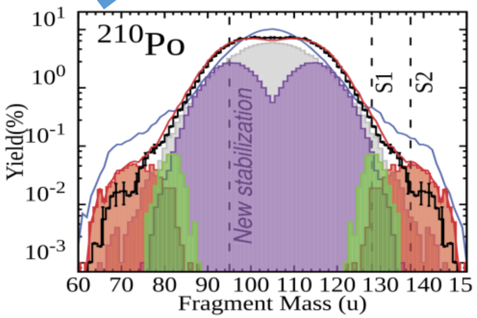
  Towards nuclear data standards

- <u>Pre-Actinides : uncharted territory</u>
  - Exploring the island of asymmetry ^{184}Pb (E851 , June 2024)
  - ^{210}Po : Fusion fission on ^{4}He cooled gaz target (E882, March 2025), at the crossroads

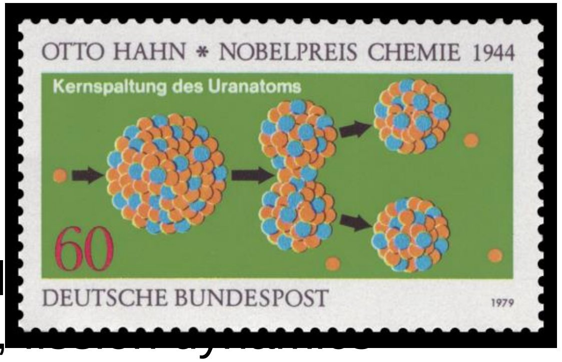
Unified view of fission



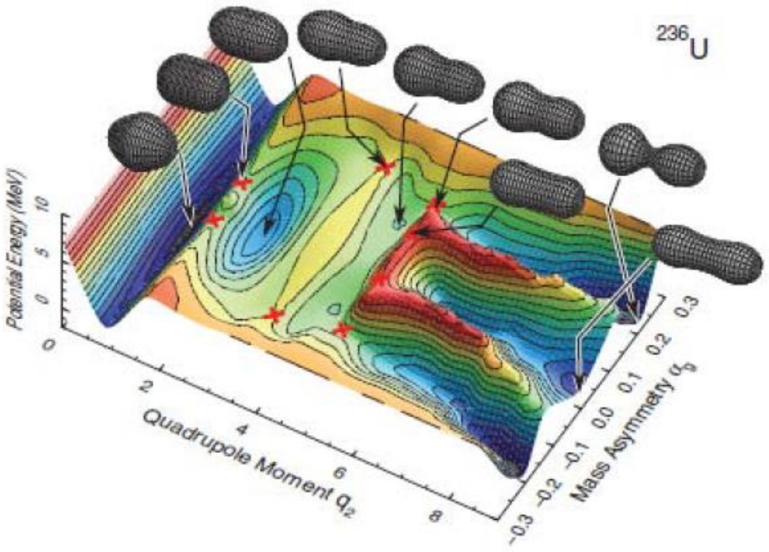




Fission studies at VAMOS/GANIL



- Key Open Questions (Not all addressed here !):
  - Dynamical evolution of complex quantum system
  - At the crossroad of many research topics of nuclear physics with essential **interplay between structural and dynamical properties of nucl**
  - Fully microscopic description of the whole fission process (fissioning system, and fission fragment distributions and properties) is not yet available
  - What is the importance of dissipation in the process ?



- Relevant observables for what ?
  - **Direct isotopic (A,Z) fission fragments data**
  - **Complete fission yields**
    => Probing the role of shell effect in fission and dissipation
  - **Kinetic energies and excitation energies of the fission fr**
    => Probing the scission configurations (A, Z, Energy sharing)
  - **Fission Barriers (evolution as function of excitation ener**
    => Probing the the potential energy surface as function of E
    => Exploring the fission paths (different modes of fission)

Why fission still matters ?

- **How does the nucleus evolve from saddle to scission?**
  What are the relevant collective coordinates, timescales, dissipation and fluctuations along the fission pathway?
- **How do nuclear structure effects shape the fragment distribution?**
  When and how do shell effects, pairing and deformation select preferred mass/charge splits and scission configurations?
- **How are excitation energy and angular momentum shared between fragments?**
  What determines fragment N/Z, intrinsic excitation, deformation energy, neutron/γ emission and spin?
- **How does the fission mechanism change with the initial conditions?**
  How do excitation energy, angular momentum and entrance channel modify shell damping, fission modes, multichance fission and fragment observables?

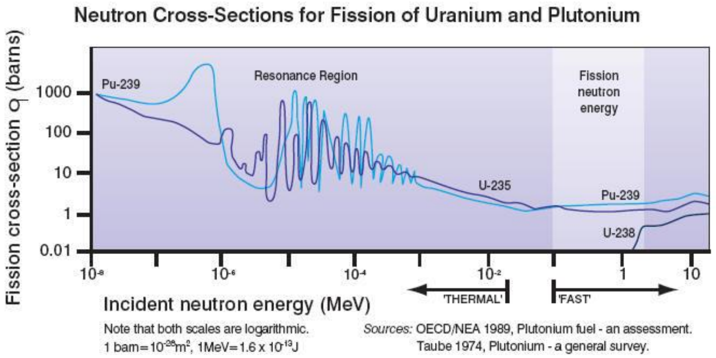
- **Test nuclear many-body dynamics in extreme conditions**
  Fission probes the interplay of collective motion, shell structure, pairing, dissipation and fluctuations far from equilibrium.
- **Constrain nuclear models and fundamental properties**
  Fragment yields, TKE, neutron/γ emission and correlations constrain potential-energy surfaces, level densities, barriers, energy sharing and scission dynamics.
- **Improve nuclear data for reactors and the fuel cycle**
  Accurate fission yields, prompt-neutron multiplicities and decay properties are essential for reactor calculations, decay heat, inventories, safety and transmutation.
- **Enable applications from astrophysics to safeguards**
  Fission data impact r-process nucleosynthesis and fission recycling, while also supporting nuclear forensics, safeguards, waste management and evaluated nuclear-data libraries.

Fission connects fundamental many-body physics to applications.
From shell effects and quantum dynamics → to fragment yields, neutrons and nuclear data.

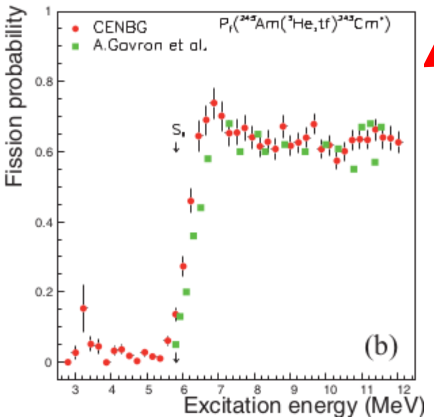
But experimentally, we limted number of observabkes…

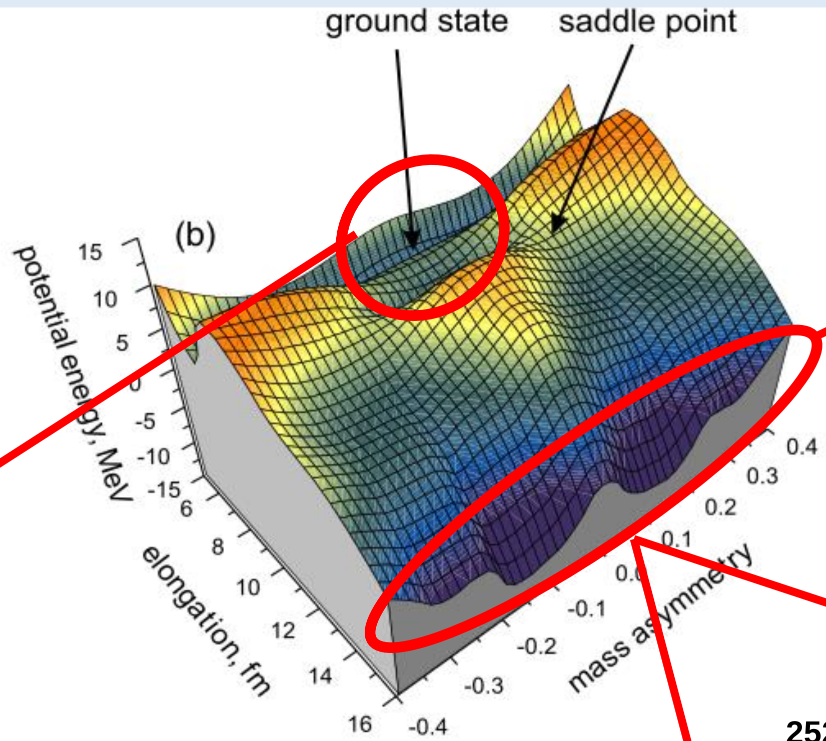
The richness of fission observables

Capture cross sections

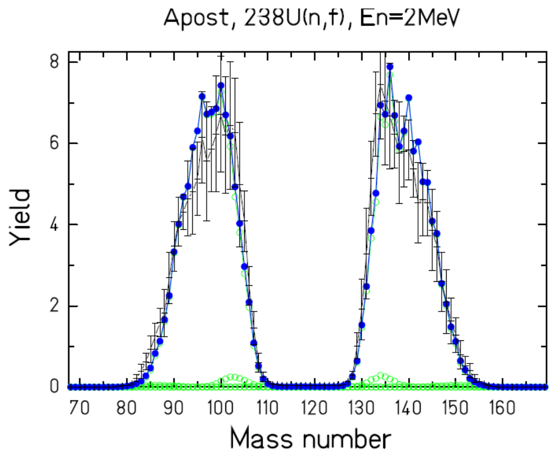


Ground-state to barrier :
Fission probability (P_f), P_n, P_g



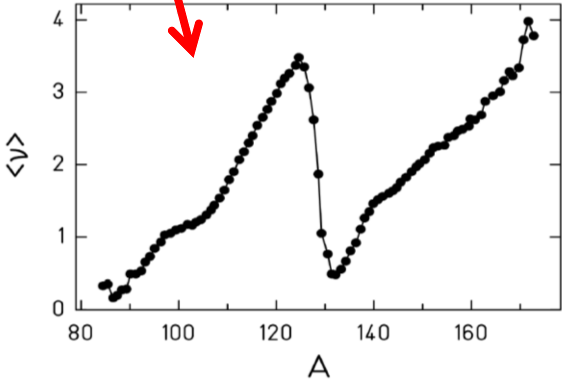


Barrier to well after scission:
Fission fragment yields



Prompt neutrons & gammas

^{252}Cf



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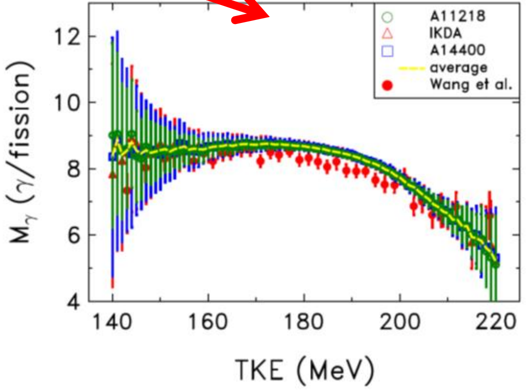
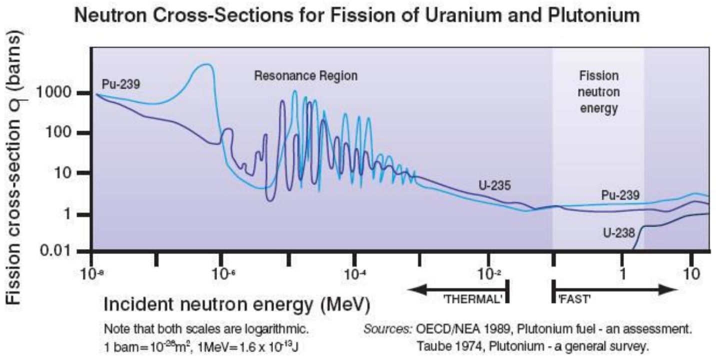


- neutron capture cross sections
- Fission Barrier (Fission probability)
- Fission Fragment Yields (A , (N,Z))
- Kinetic Energies

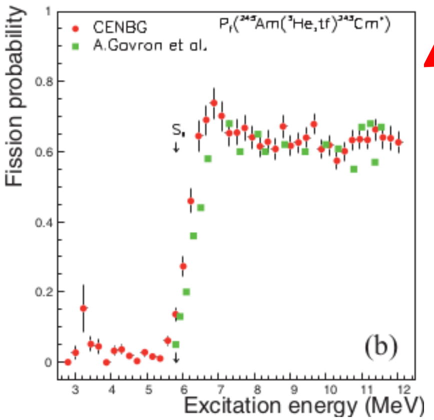
- Neutron multiplicities
- Gamma-ray Emission
- Cummulative yields
- ...

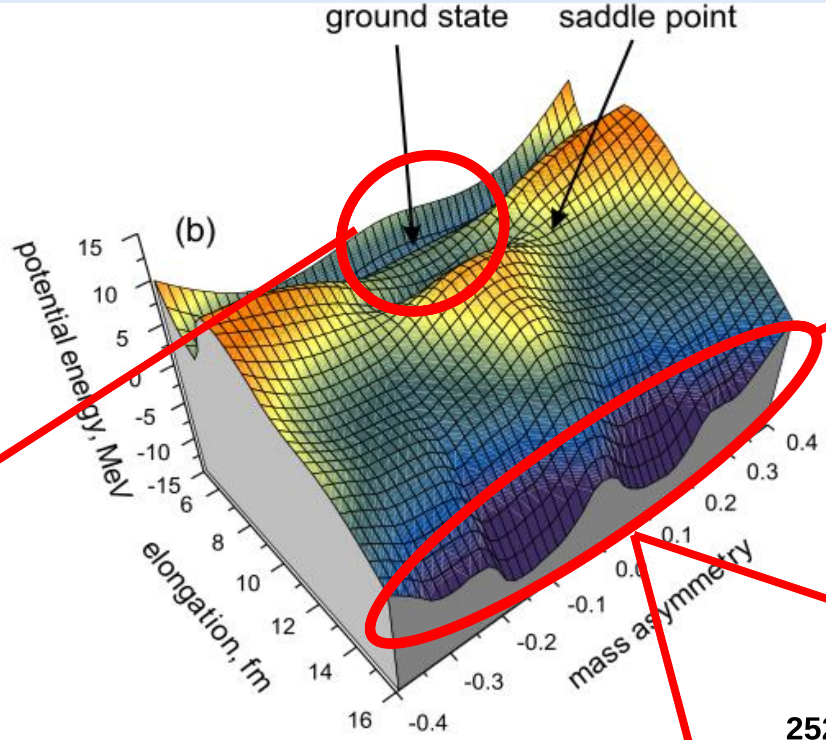
The richness of fission observables

Capture cross sections

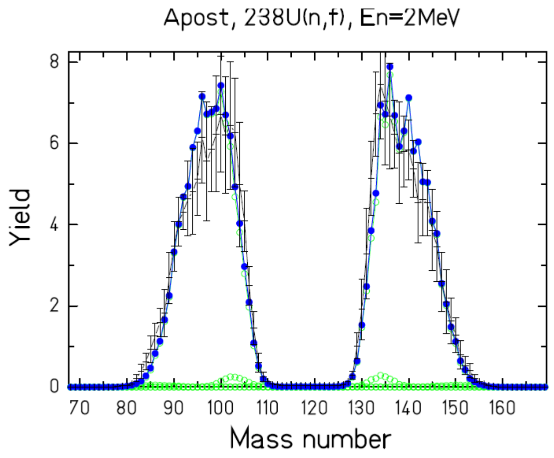


Ground-state to barrier :
Fission probability (P_f), P_n, P_g





Barrier to well after scission:
Fission fragment yields



Prompt neutrons & gammas

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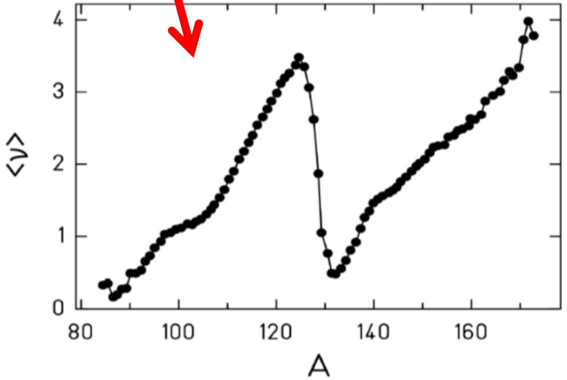

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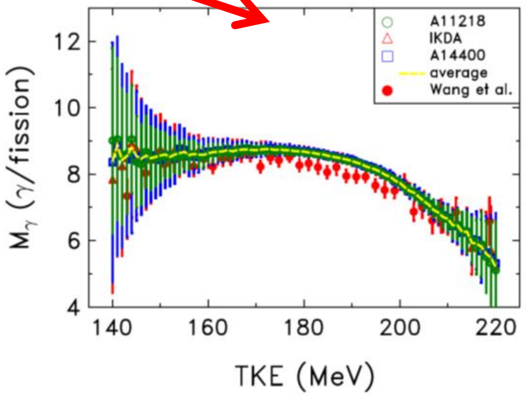

Scientific Questions :
- Large Collective motion
- Microscopic effects (shell effects, paring,)
- Dynamics : Dissipation, Energy Sharing

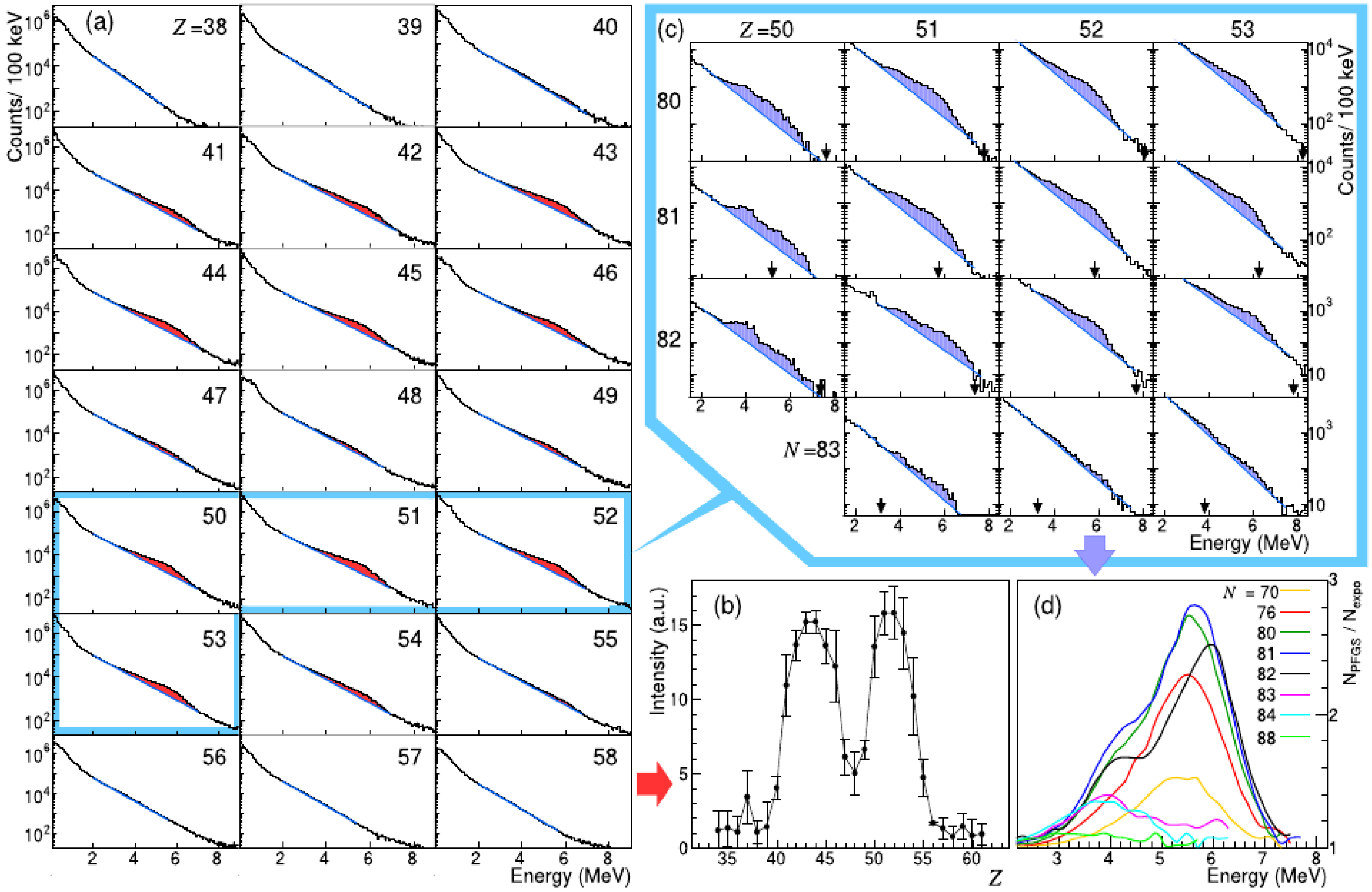

Fig. 1. (a) PFGS for selected Z's in VAMOS++ (most extreme Z's are not shown). (b) Intensity of the γ-bump as a function of detected Z. Error bars include statistical and systematic errors. The latter reflects the uncertainty in the fitting procedure, which was evaluated by varying the E_γ range of the fit. It dominates the error bar (around 95%). (c) Sample of spectra gated additionally on A (equivalently, N) for Z from 50 to 53 and N from 80 to 83. Arrows indicate the value of S_n. (d) Excess of γ yield as a function of E_γ for selected N values (integrated over Z). Error bars, similar to (b), are omitted for legibility. In panels (a) and (c), blue lines display the exponential fits of the statistical γ-ray contribution. Shadowed areas (red in (a), blue in (c)) highlight the excess of yield above the exponential.