The role of nuclear structure and dynamics in fission

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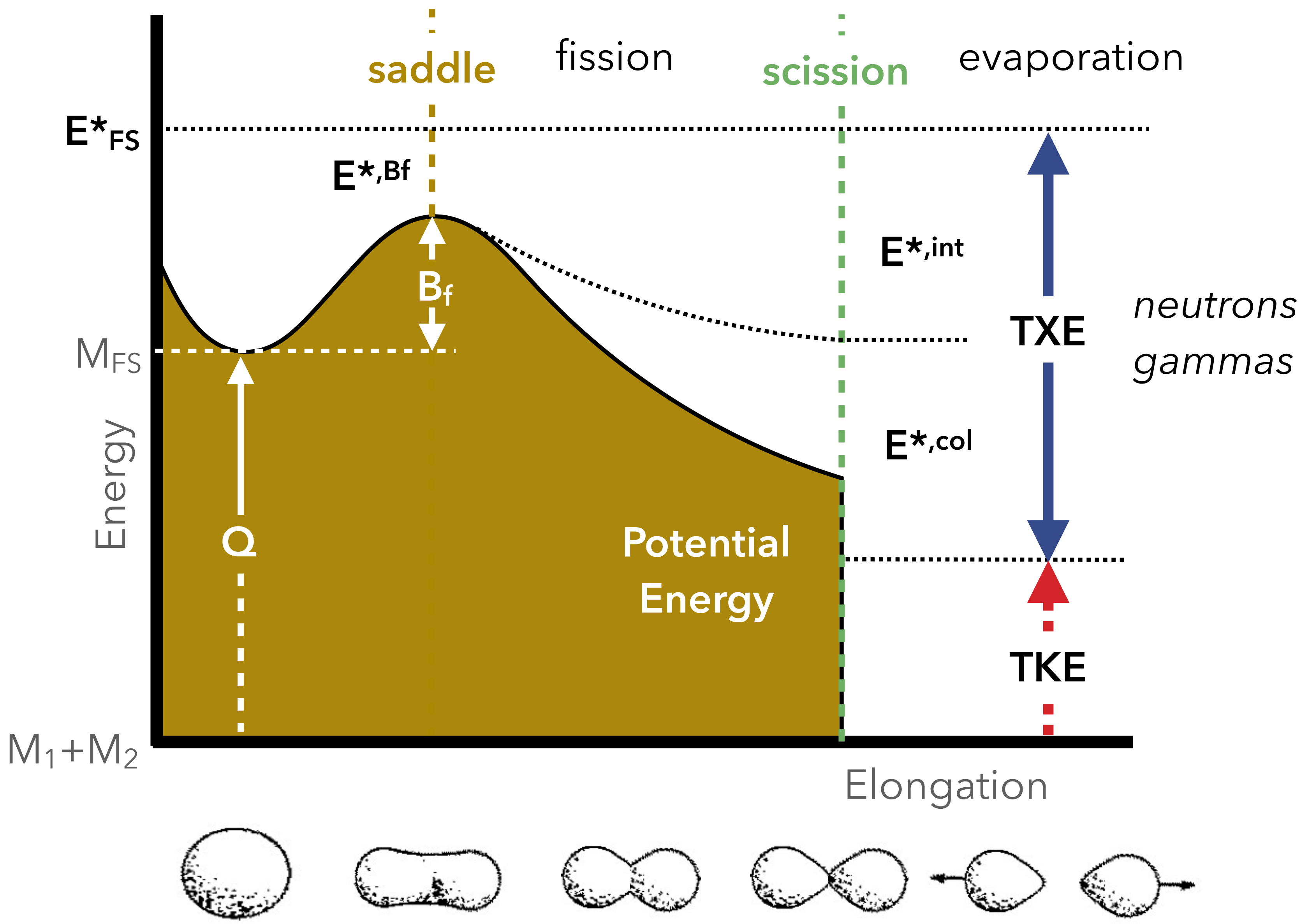
A *macroscopic* Liquid Drop behaviour

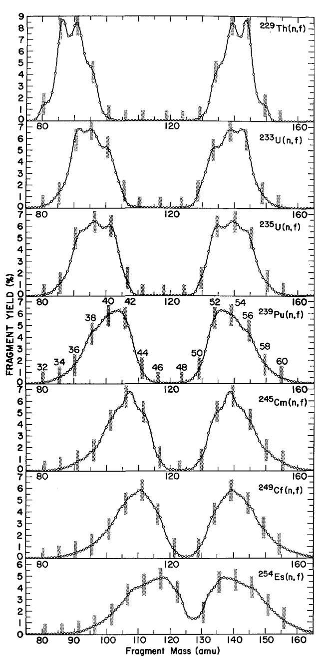


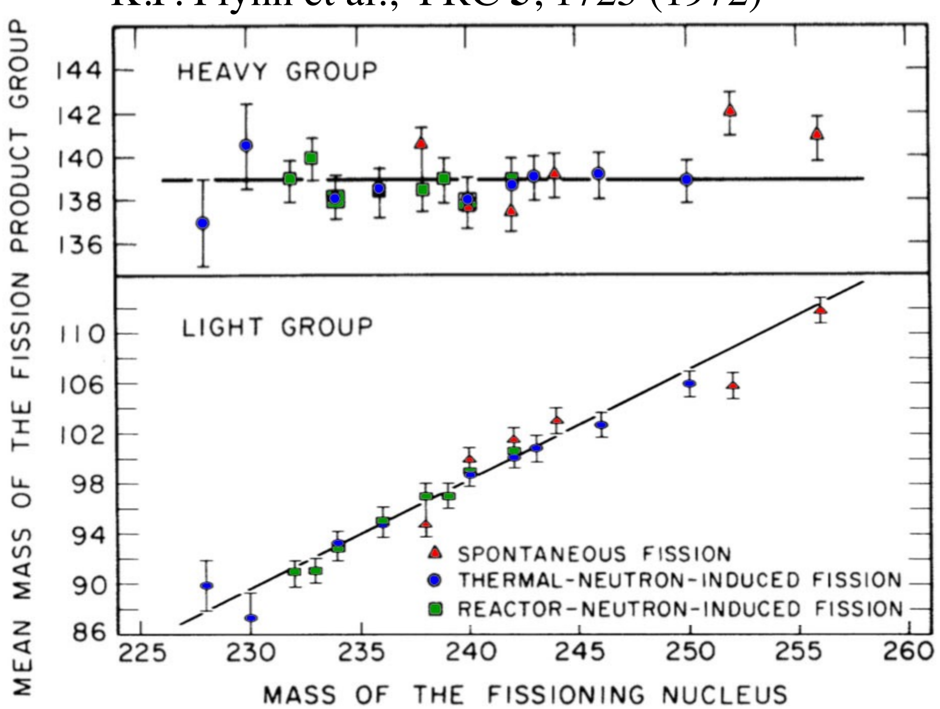
A *macroscopic* Liquid Drop behaviour shaped by *microscopic* properties

V.M. Strutinsky, NPA **95**, 420 (1967)

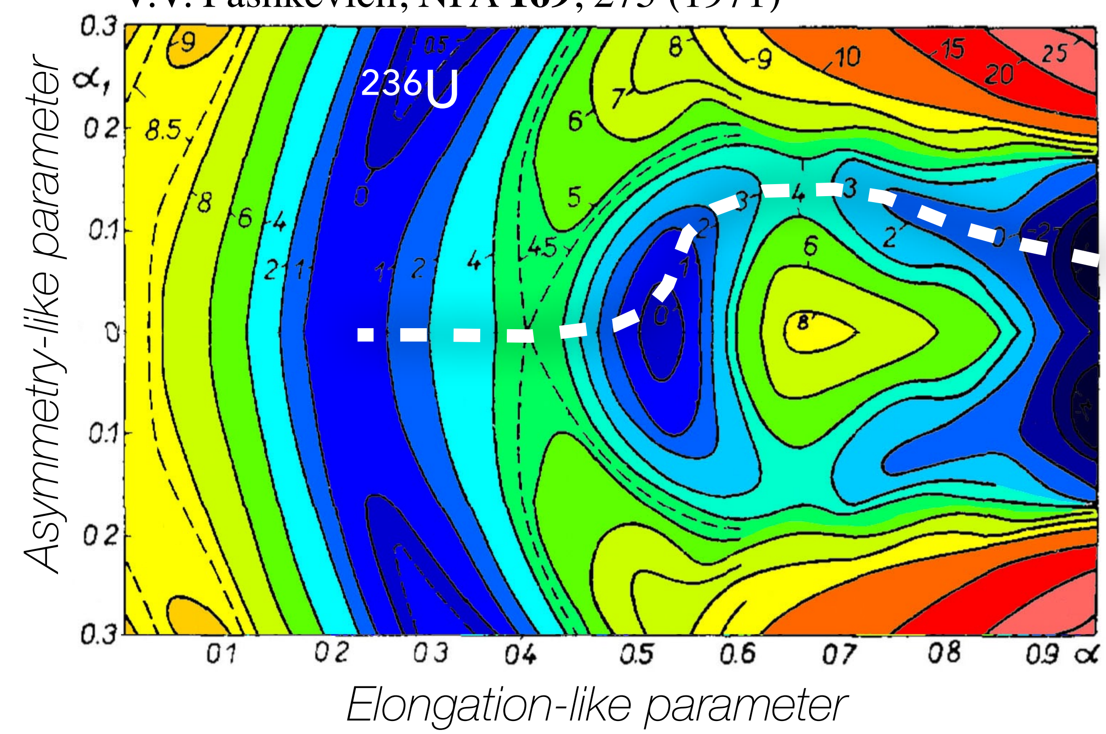
$$W = \tilde{W} + \sum_{p,n} (\delta U + P).$$

K.F. Flynn et al., PRC **5**, 1725 (1972)





V.V. Pashkevich, NPA **169**, 275 (1971)

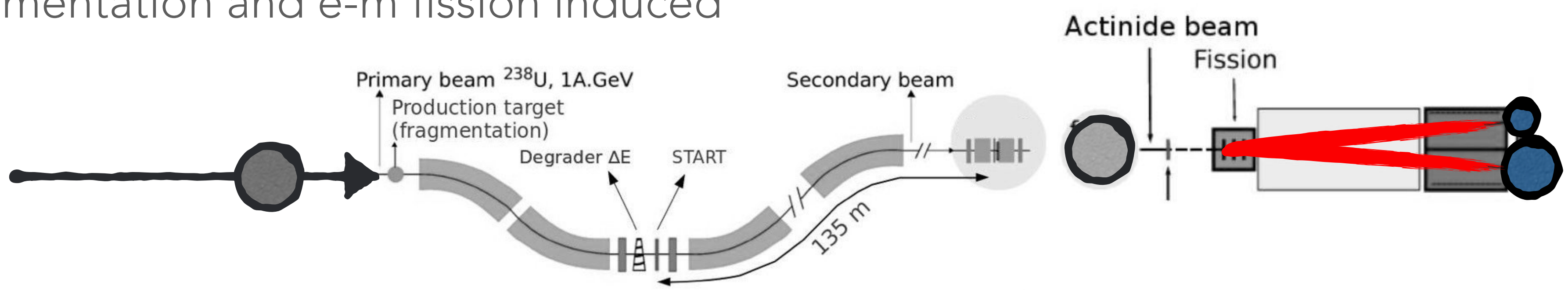


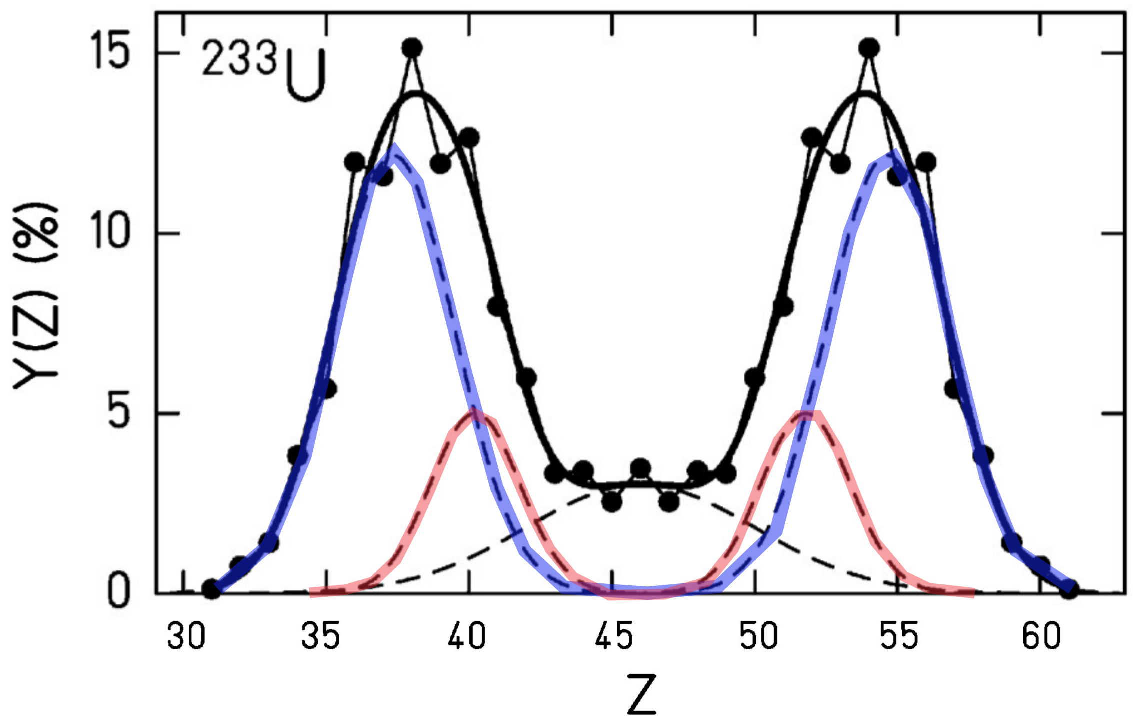
Structure effects help to understand the asymmetric distributions.
But, which shells? ^{132}Sn? deformed?

Inverse kinematics at GSI: proton numbers are revealed

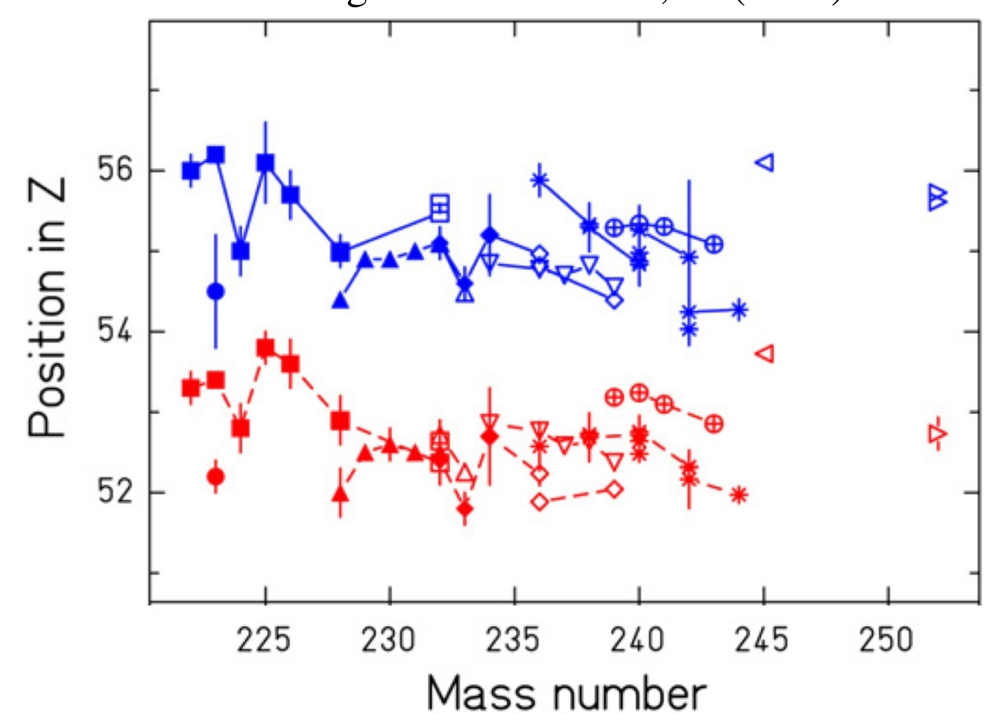
Production from fragmentation and e-m fission induced

K.-H. Schmidt et al.





C. Böckstiegel et al. NPA **802**, 12 (2008)

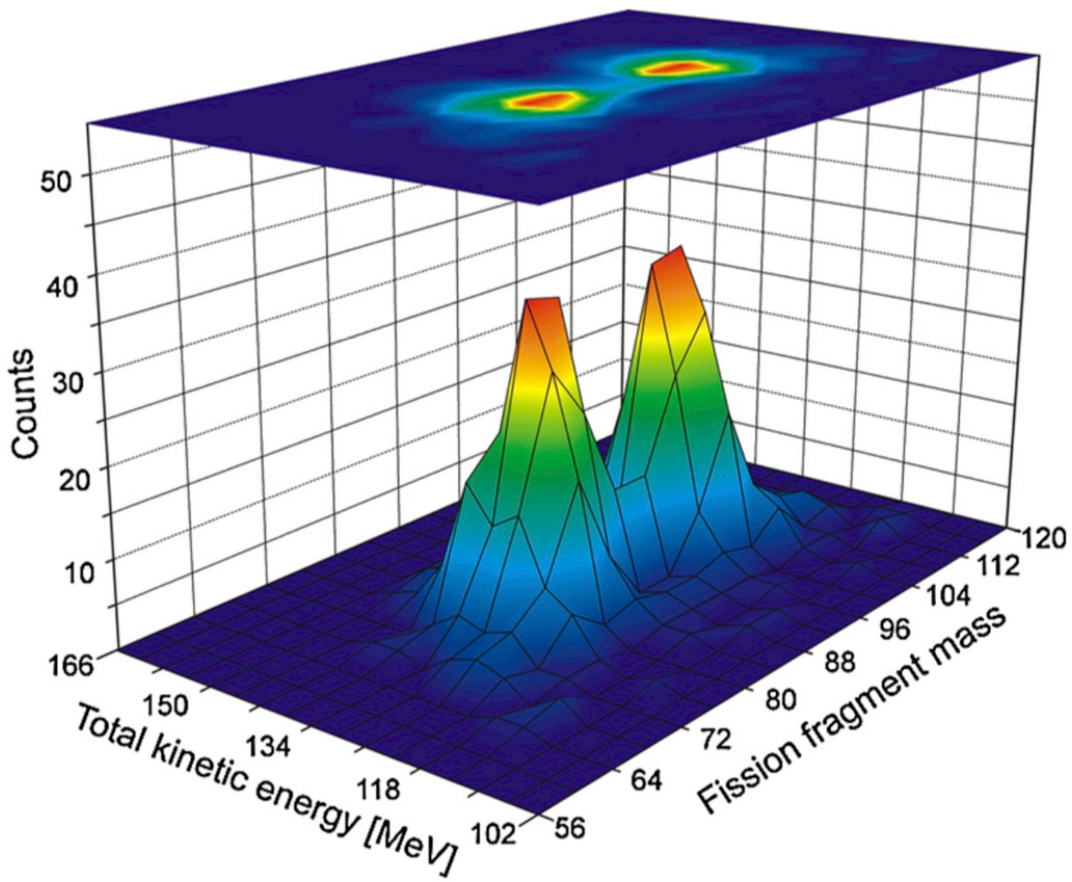


Two asymmetric fission modes are identified, but around **Z~52** and **Z~55**.
No sign of the expected spherical or prolate shells.

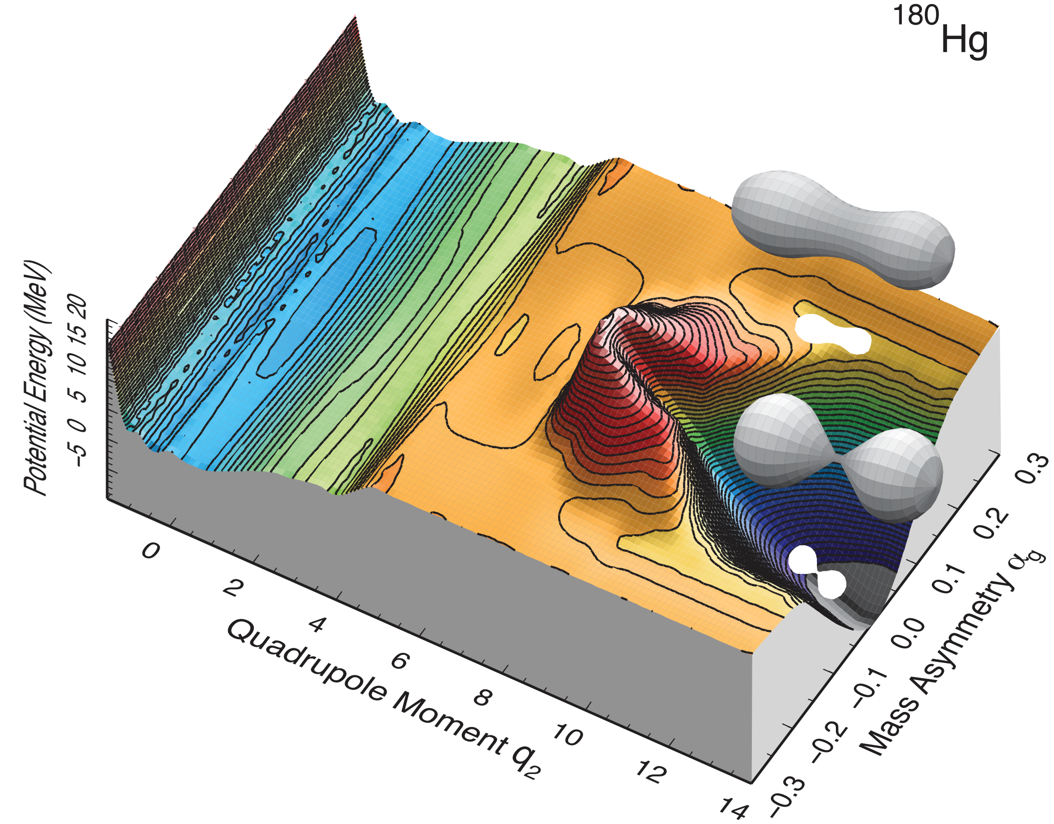
An asymmetric surprise around mercury:

Beta-delayed fission of ^{180}Hg at ISOLDE:

A.N. Andreyev et al. PRL **105**, 252502 (2010)



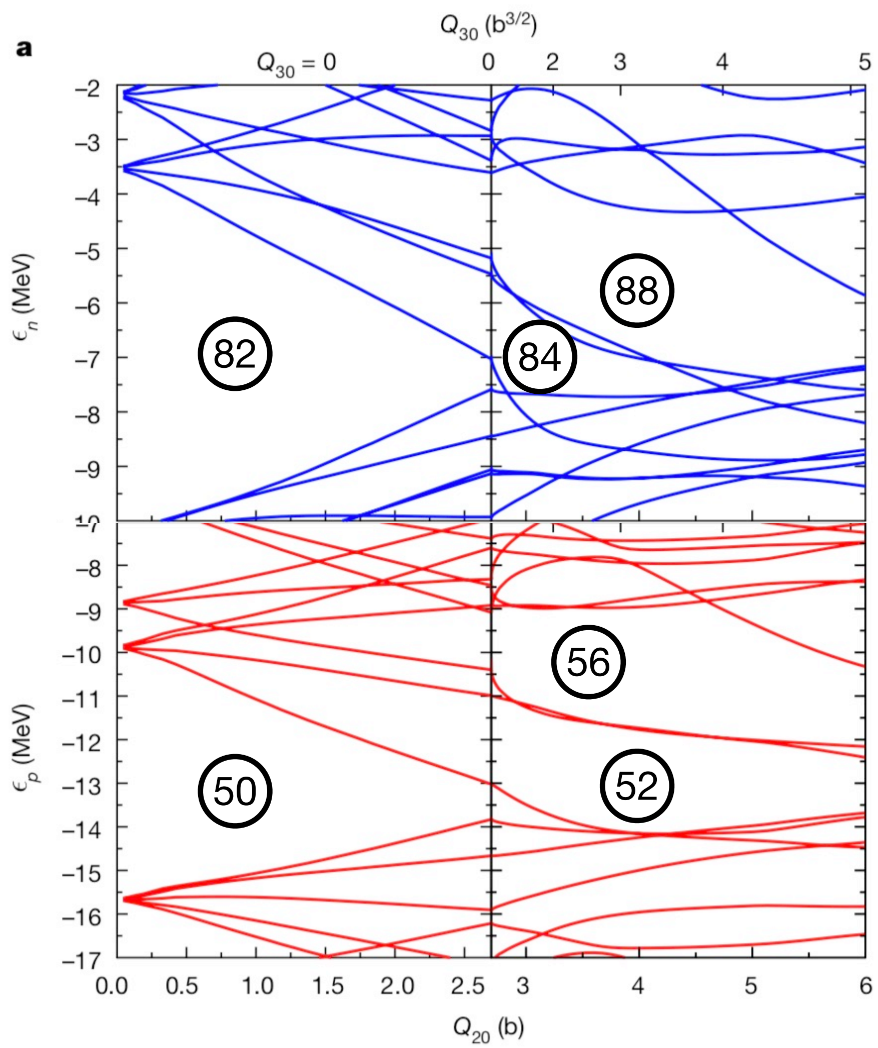
T. Ichikawa et al. PRC **86**, 024610 (2012)



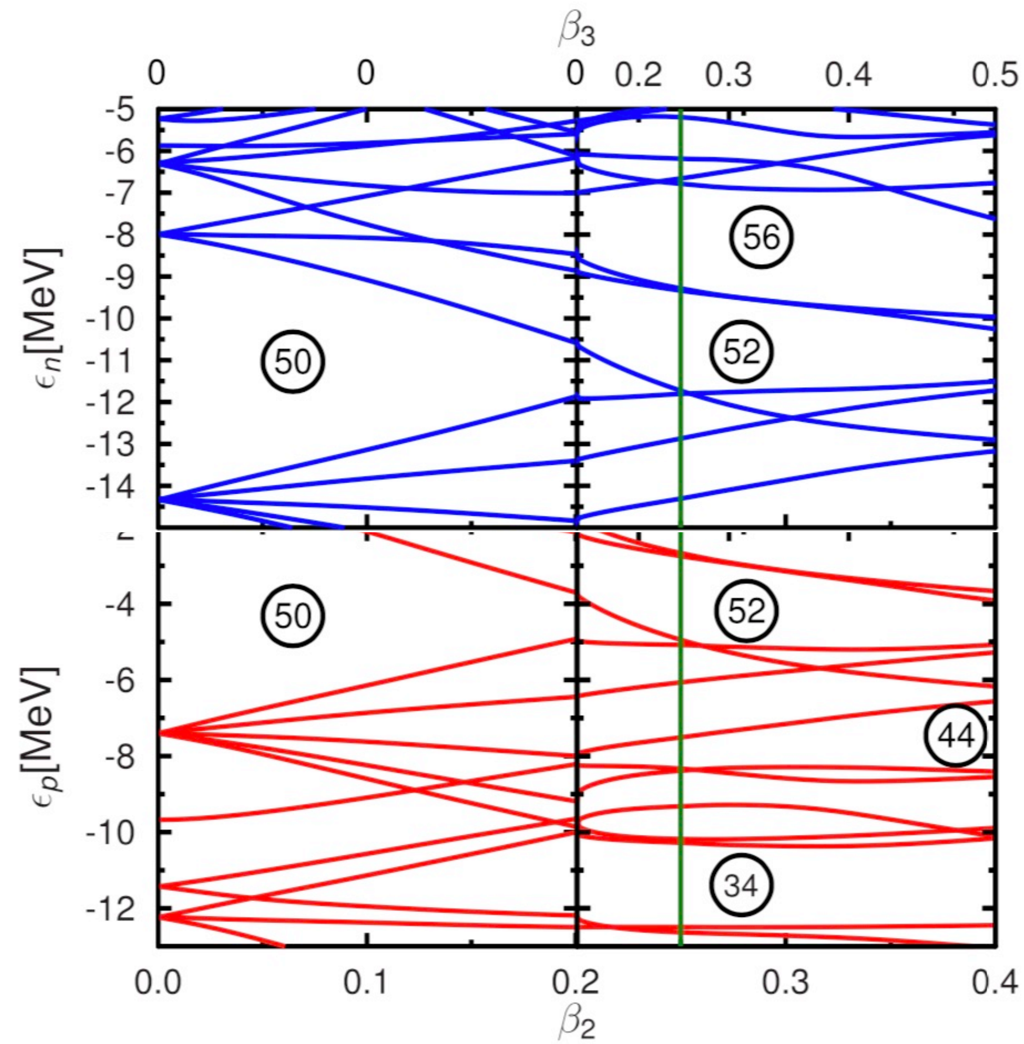
Asymmetric fission is measured in ^{180}Hg, instead of two symmetric, semi-magic ^{90}Zr fragments.
The resulting fragments N and Z are not expected as strong deformed shells.
Maybe a *dynamic* origin?

Theory finds an answer:

G. Scamps and C. Simenel, Nature **564**, 382 (2018)

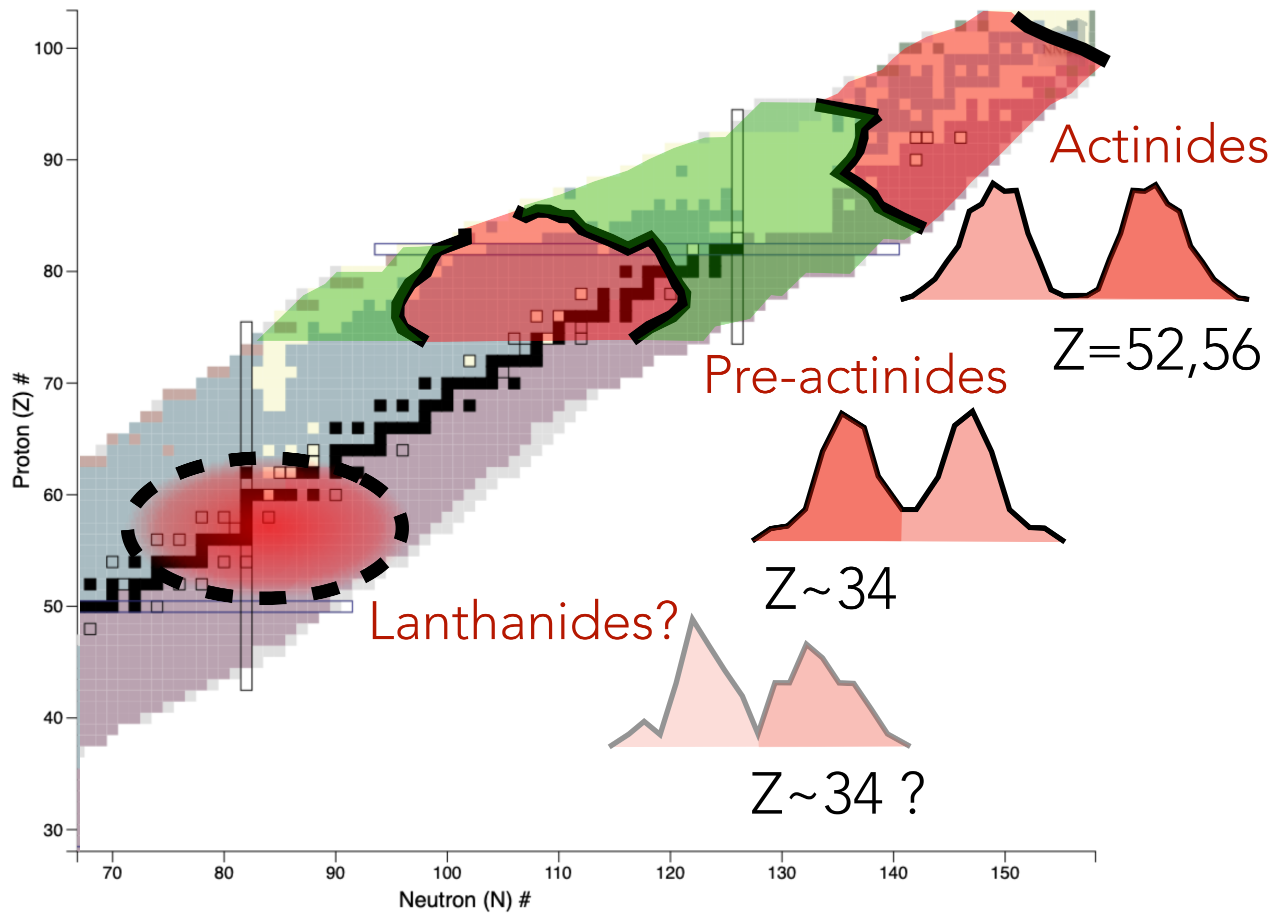


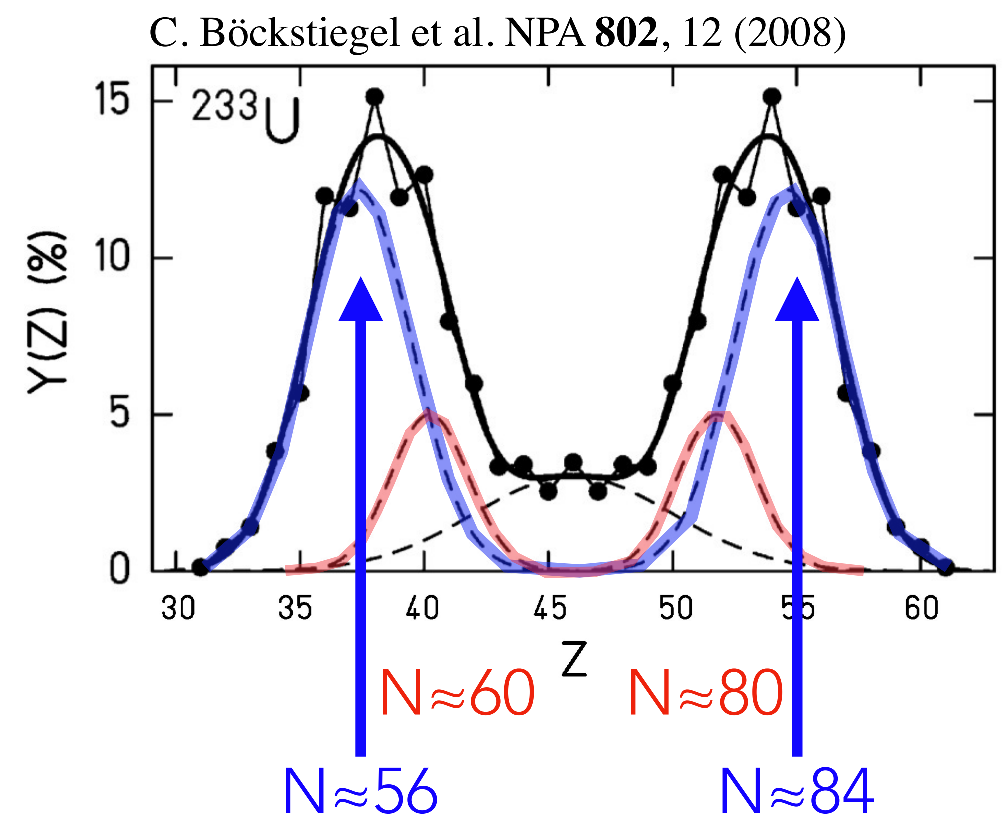
G. Scamps and C. Simenel, PRC **100**, 041602(R) (2019)



TDHF calculations find new ***octupole deformed shells*** in the path towards scission.
They are consistent with the heavy fragments in actinides and in mercury fission.

Still several questions opened:





Do neutron shells play the same role?

Is there any other asymmetric regions, besides actinides and pre-actinides?

Are actually all fissioning systems driven by structure?

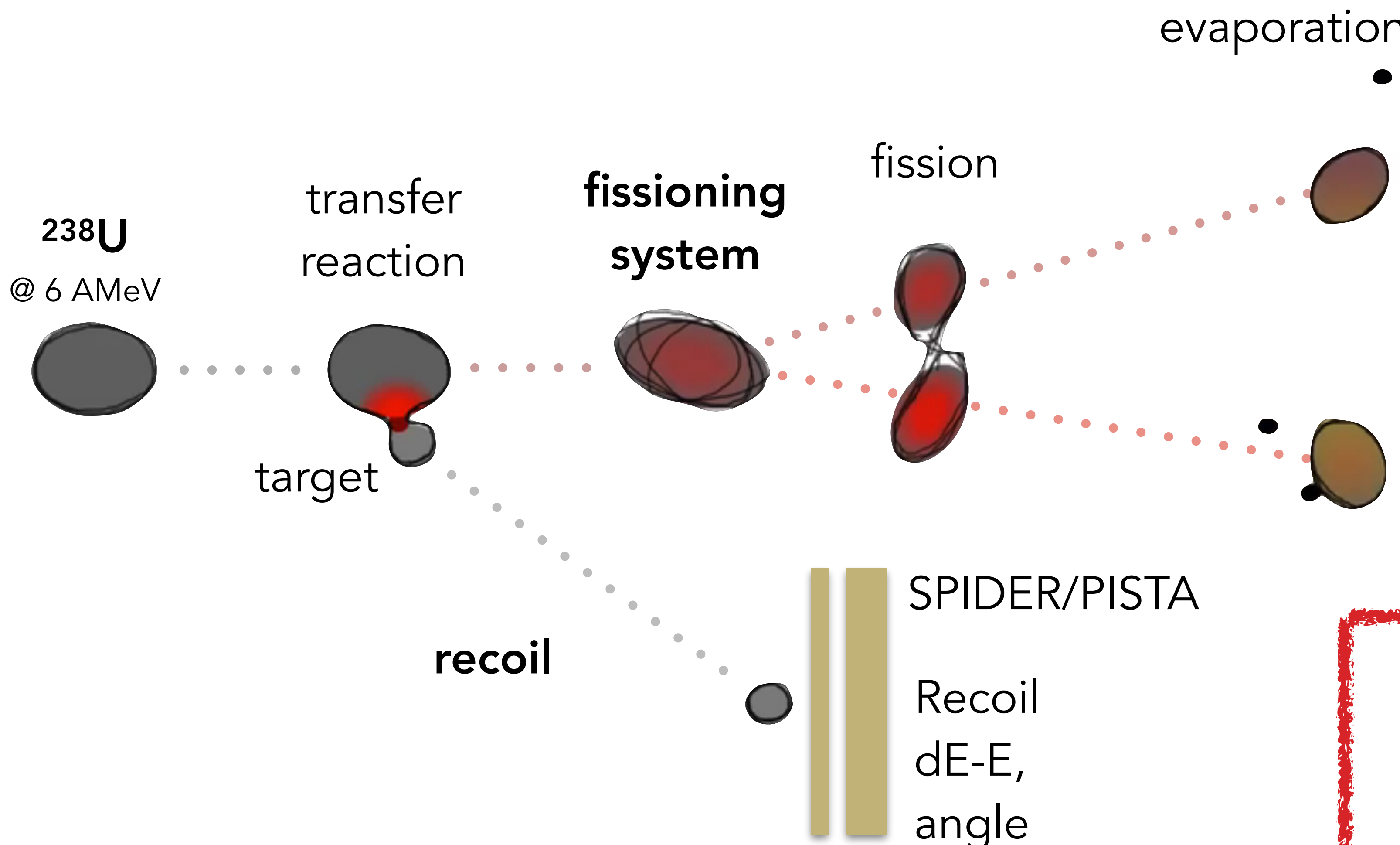
*INTC-P-665 performed at **n_TOF***
*E866_2 scheduled at **GANIL***

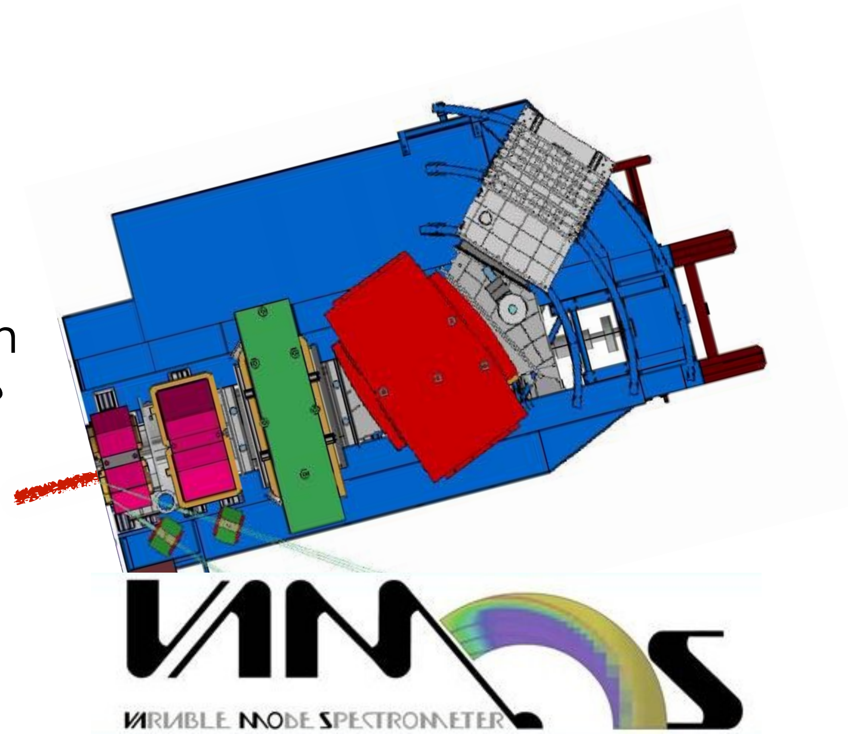
How are structure and dynamics linked?

Inverse kinematics at VAMOS/GANIL

Production and fission from fusion and multi-nucleon transfer

F. Farget et al.





observables:

Fissioning System:

- A, Z, E*, angle, velocity

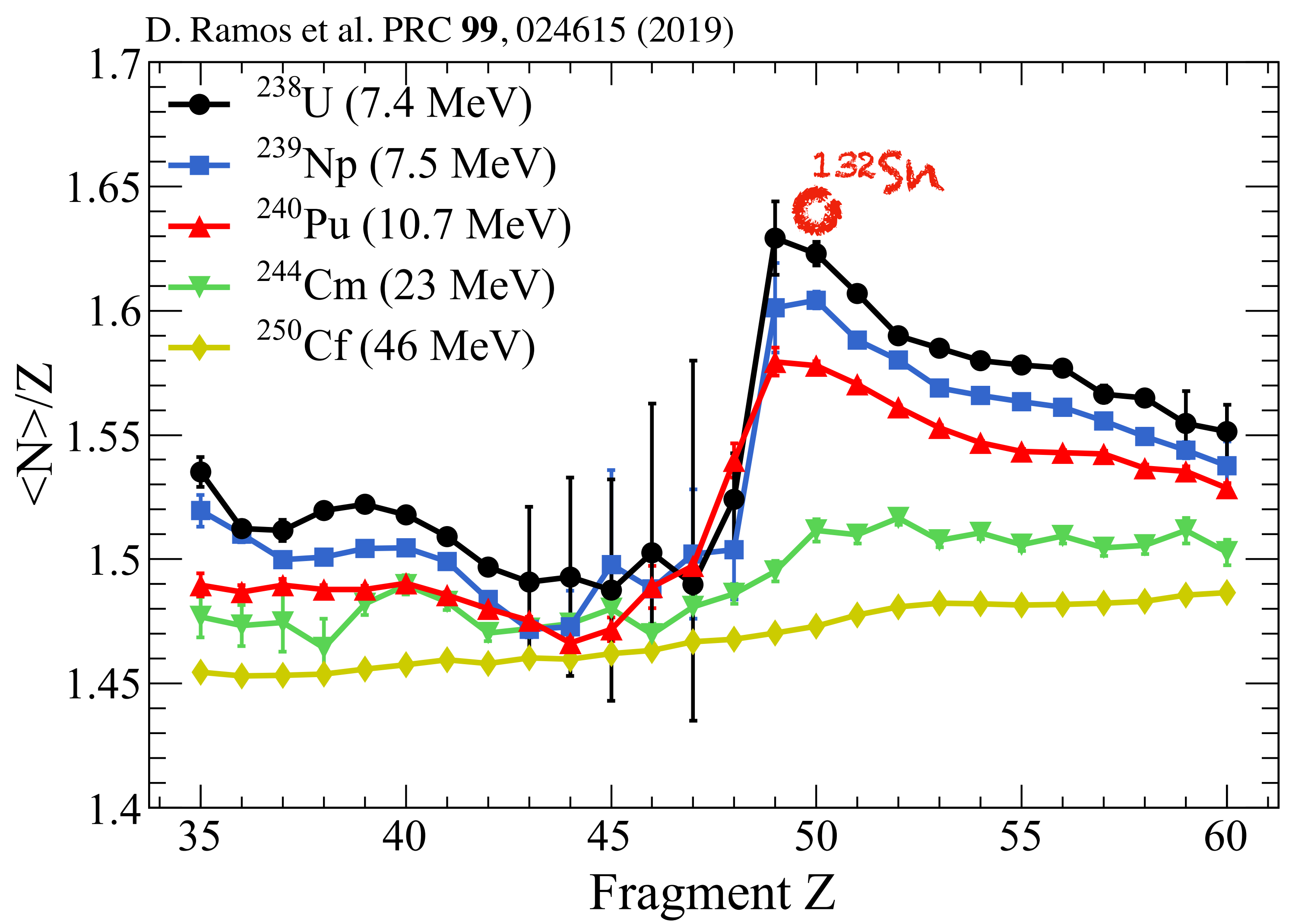
Fission Fragments:

- A^{post}, Z, q, angle, velocity

Inverse kinematics at VAMOS/GANIL

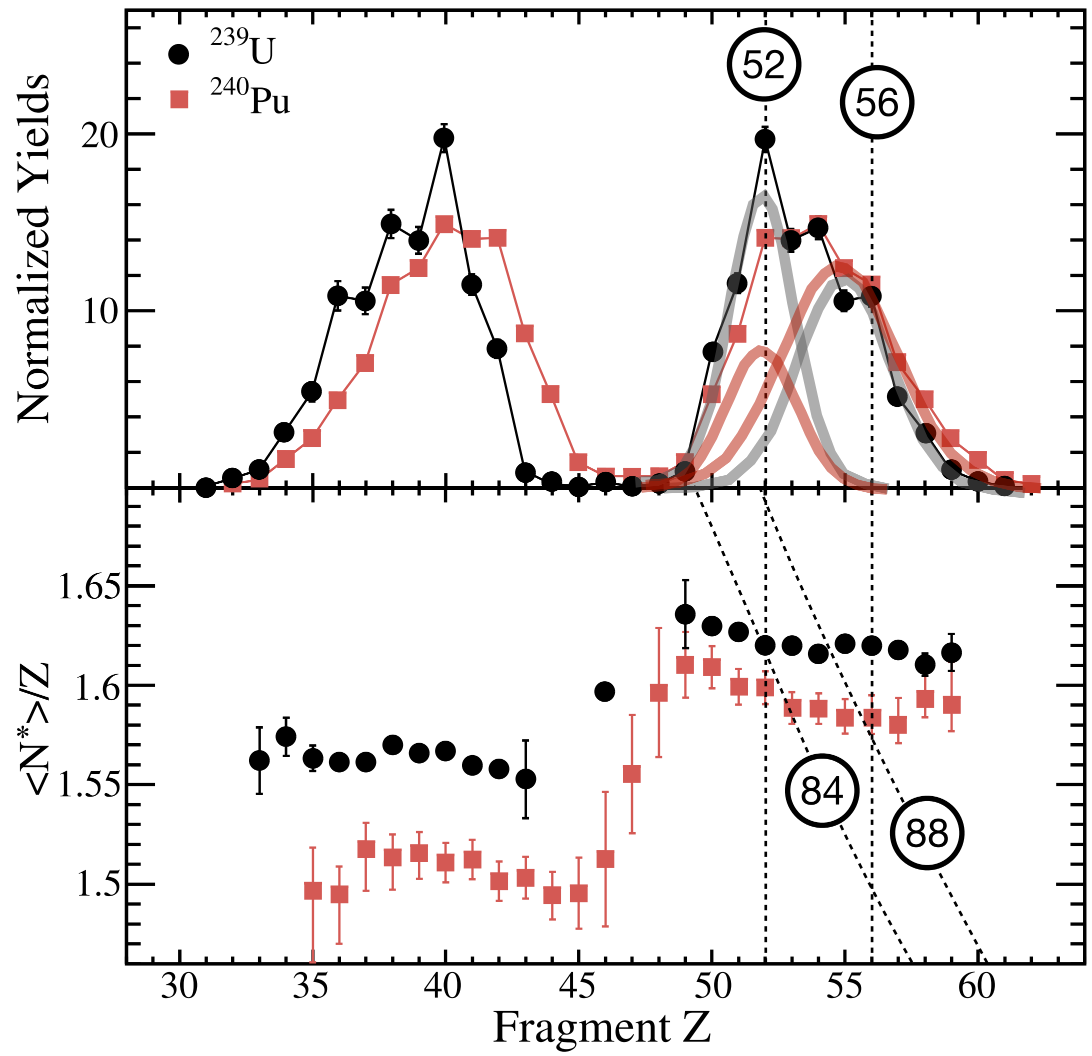
First measurement of fully identified fragment distributions.

The impact of proton and neutron shells can be evaluated in every fission property
In addition, we have access to **new observables, like N/Z:**



Role of shells in the production yields

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



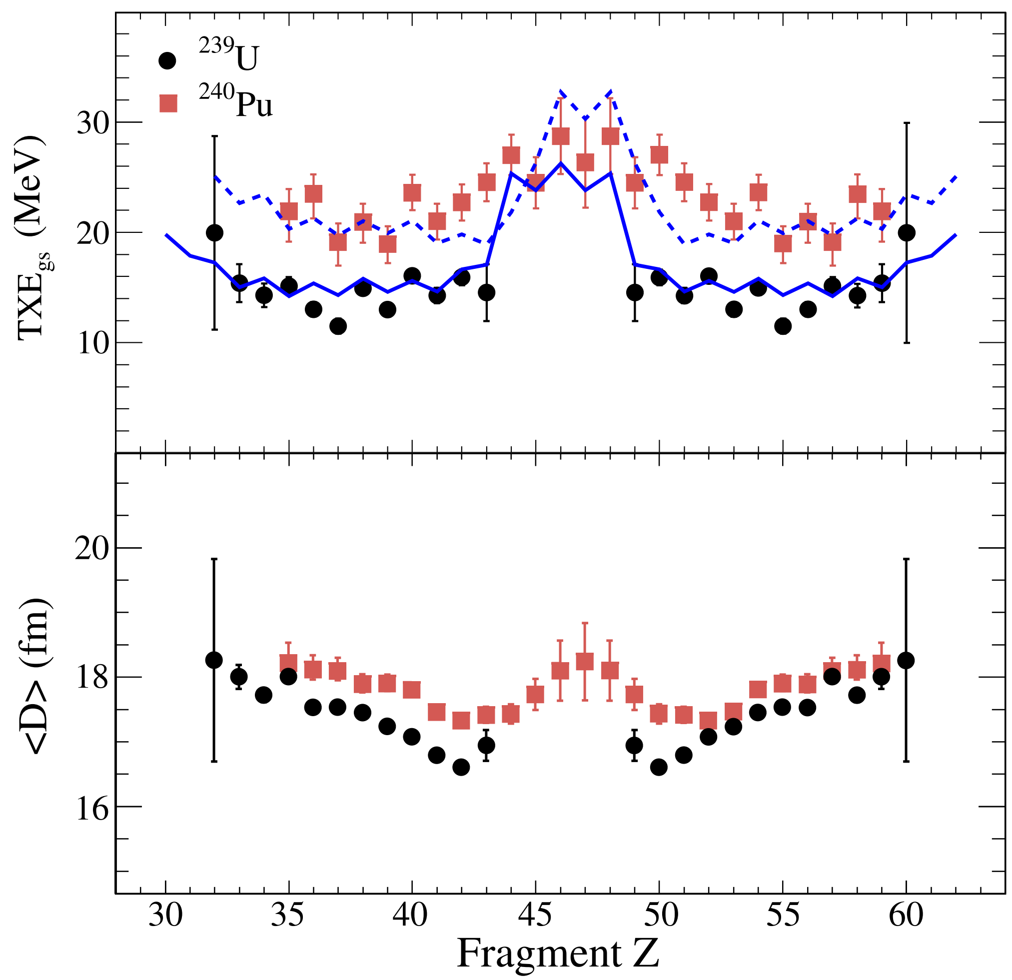
The Z=56 mode is less pronounced than the Z=52 one in **^{239}U**, whereas in **^{240}Pu** is the opposite.

The N=84 mode is very close to Z=52 in both, whereas N=88 seems to "help" only the Z=56 in ^{240}Pu.

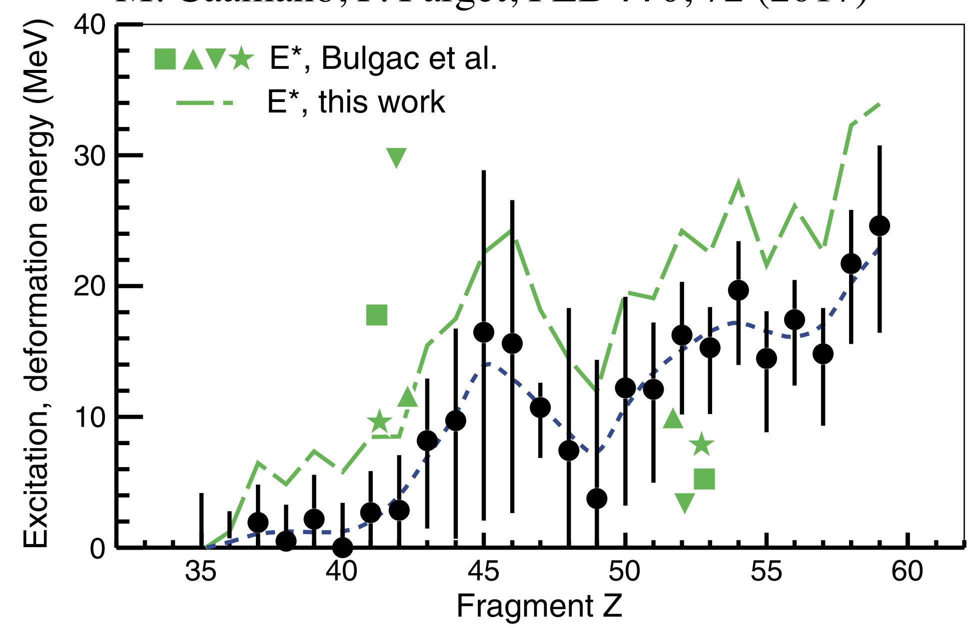
The neutron excess N/Z also helps the study of the correlation between neutron and proton shells.
A larger systematic is being built to reach a definitive answer.

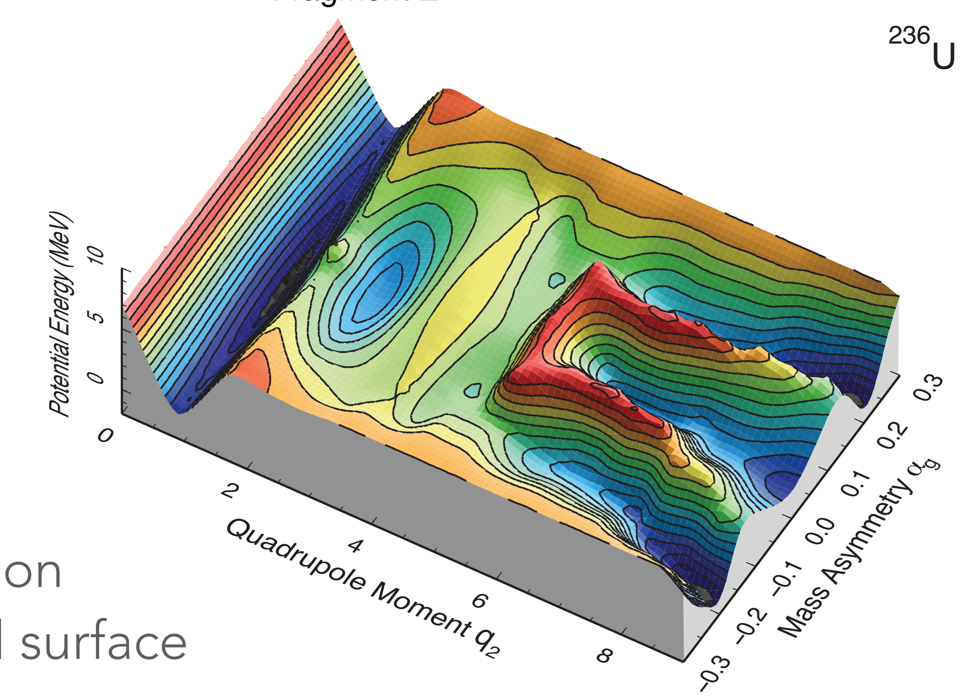
A glimpse of the potential surface

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



M. Caamaño, F. Farget, PLB **770**, 72 (2017)

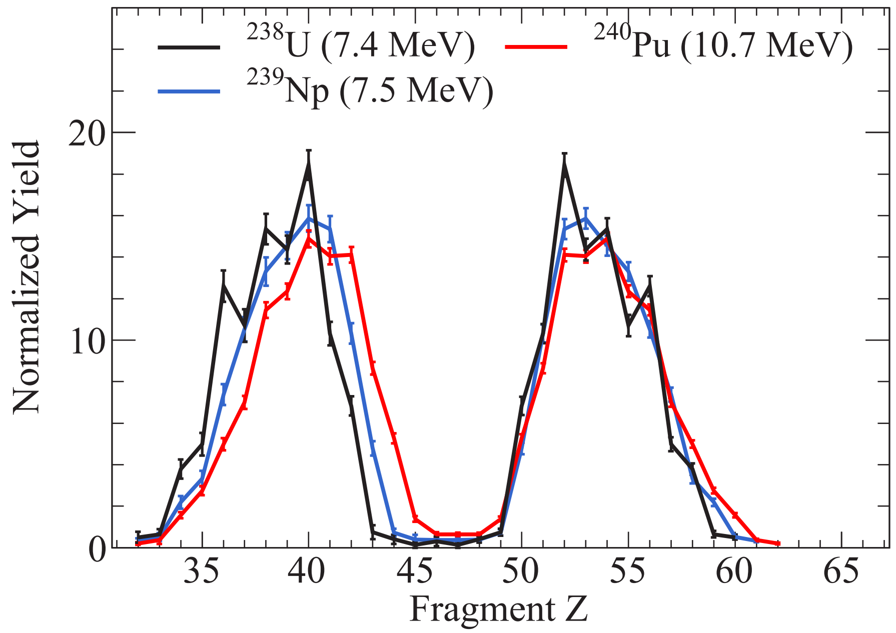




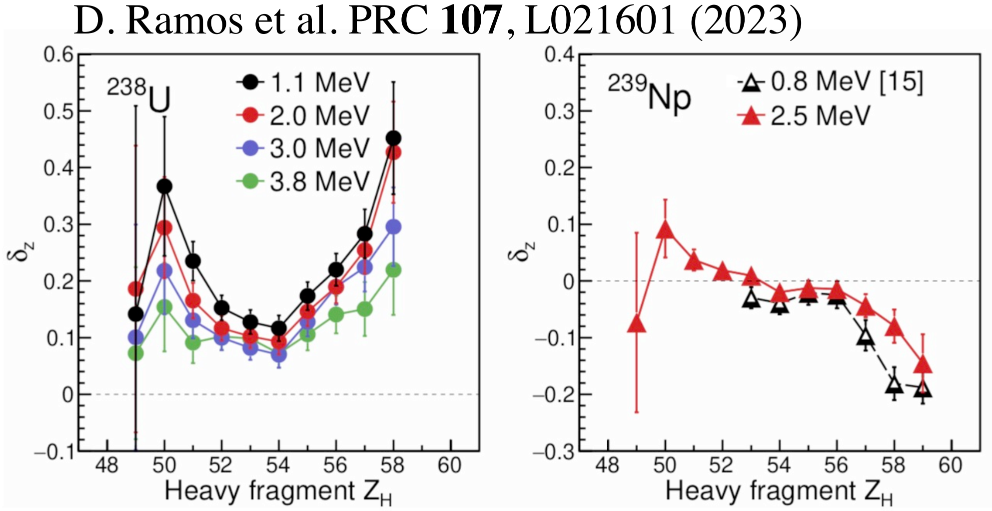
The excitation energy per fragment and their distance at scission are directly related to the dynamics and shape of the potential surface

Dissipation, time, and shell effects

D. Ramos et al. PRC **97**, 054612 (2018)

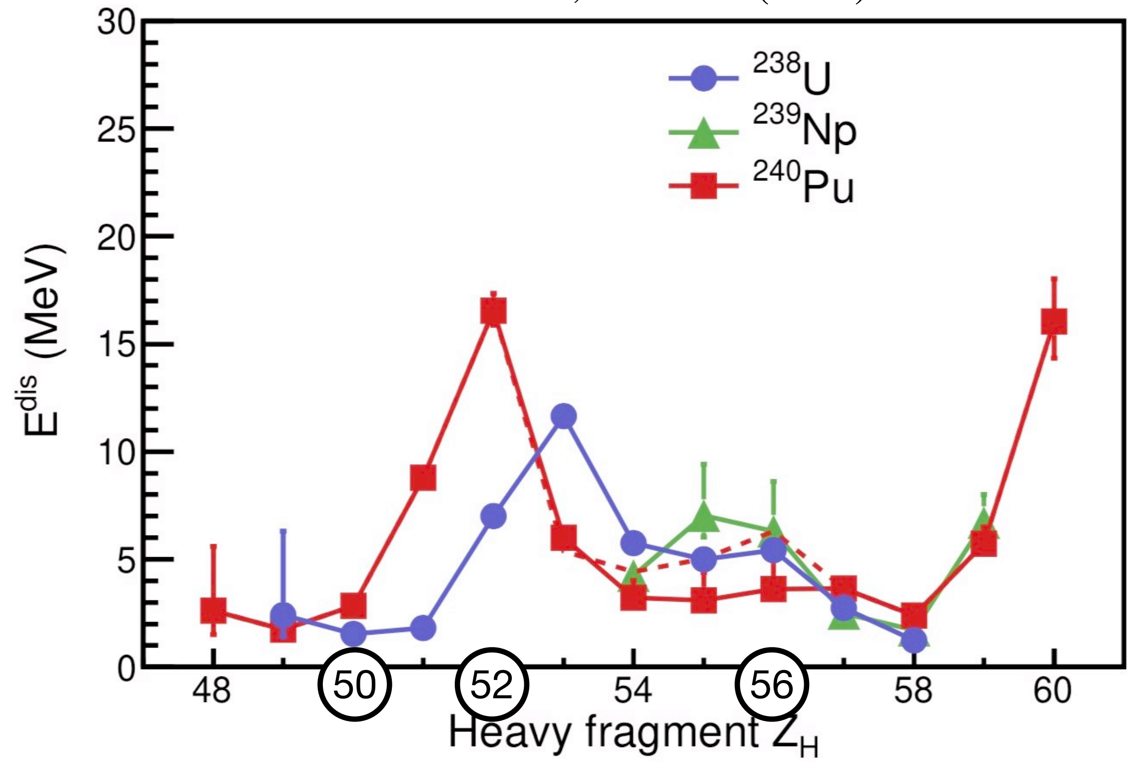


D. Ramos et al. PRC **107**, L021601 (2023)



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

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



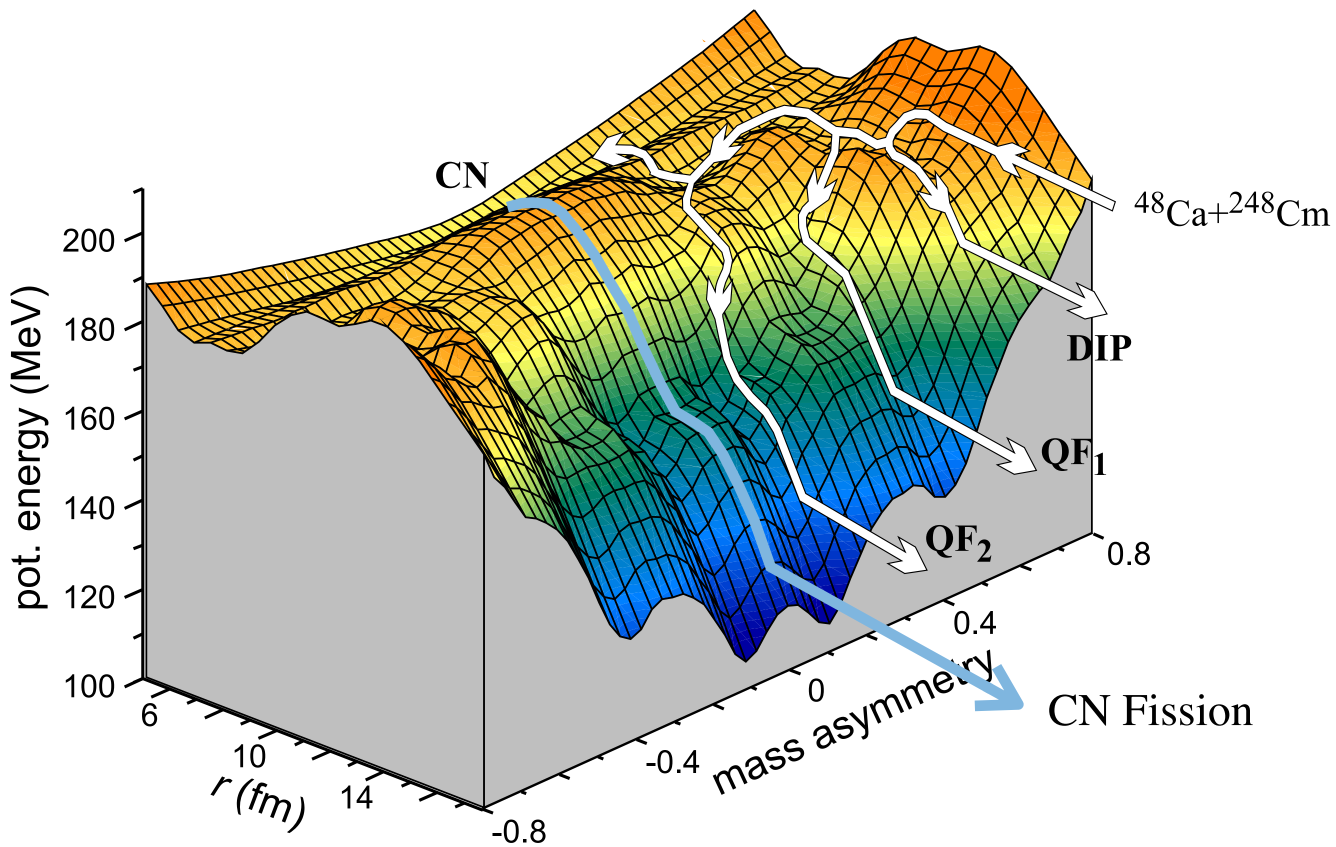
From the intrinsic excitation energy we can deduce the **dissipation energy**.

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

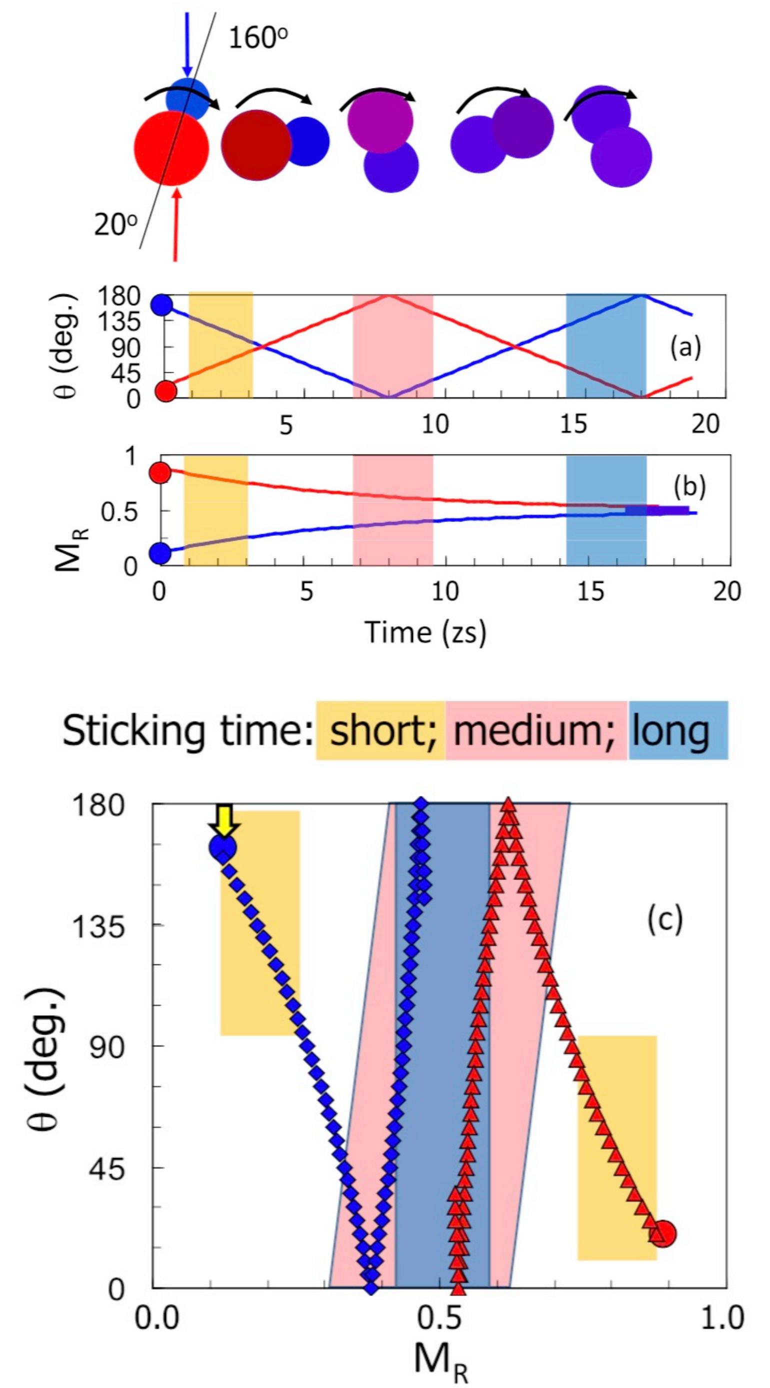
Fission is **slower** for octupole deformed fragments than for spherical ones.

And now quasi-fission!

V.I. Zagrabaev, W. Greiner, NPA **944**, 257 (2015)



D. Hinde et al., PPNP **118**, 103856 (2021)

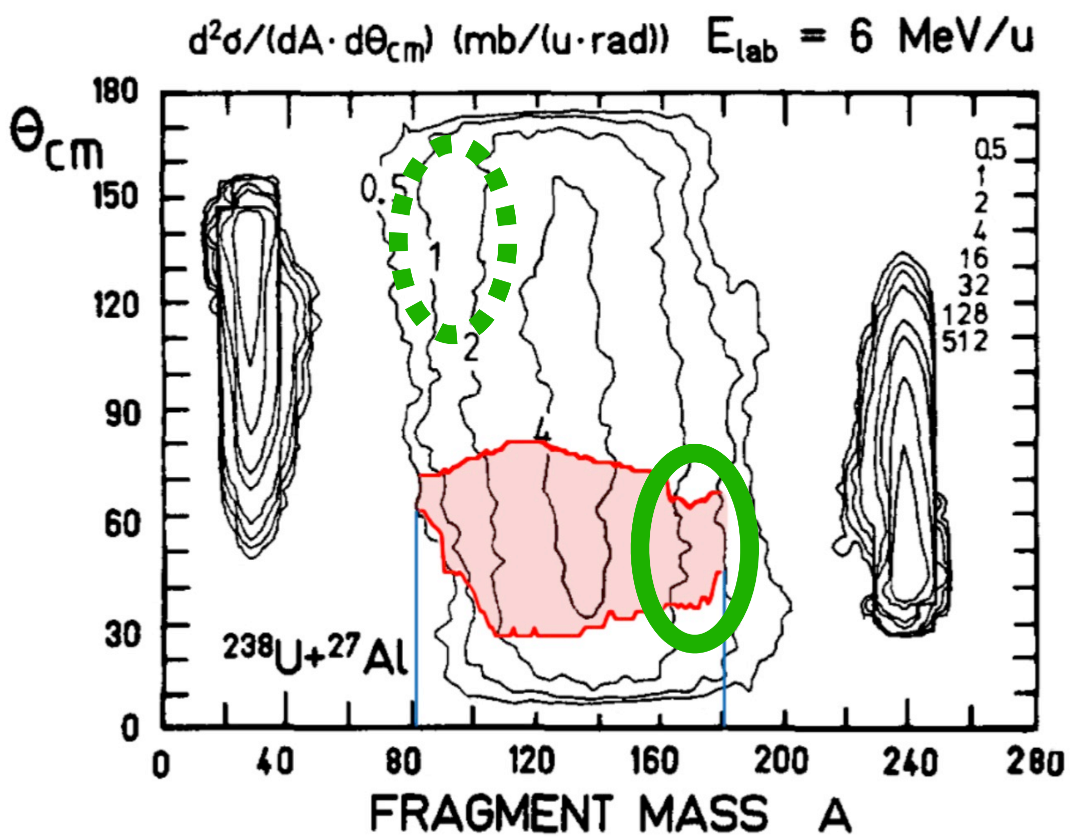


Quasi-fission can be regarded as a fission from an out-of-equilibrium quasi-compound system that explores part of the potential after the barrier.

Experimentally, the fragments keep some memory of the entrance channel and the time of the reaction.

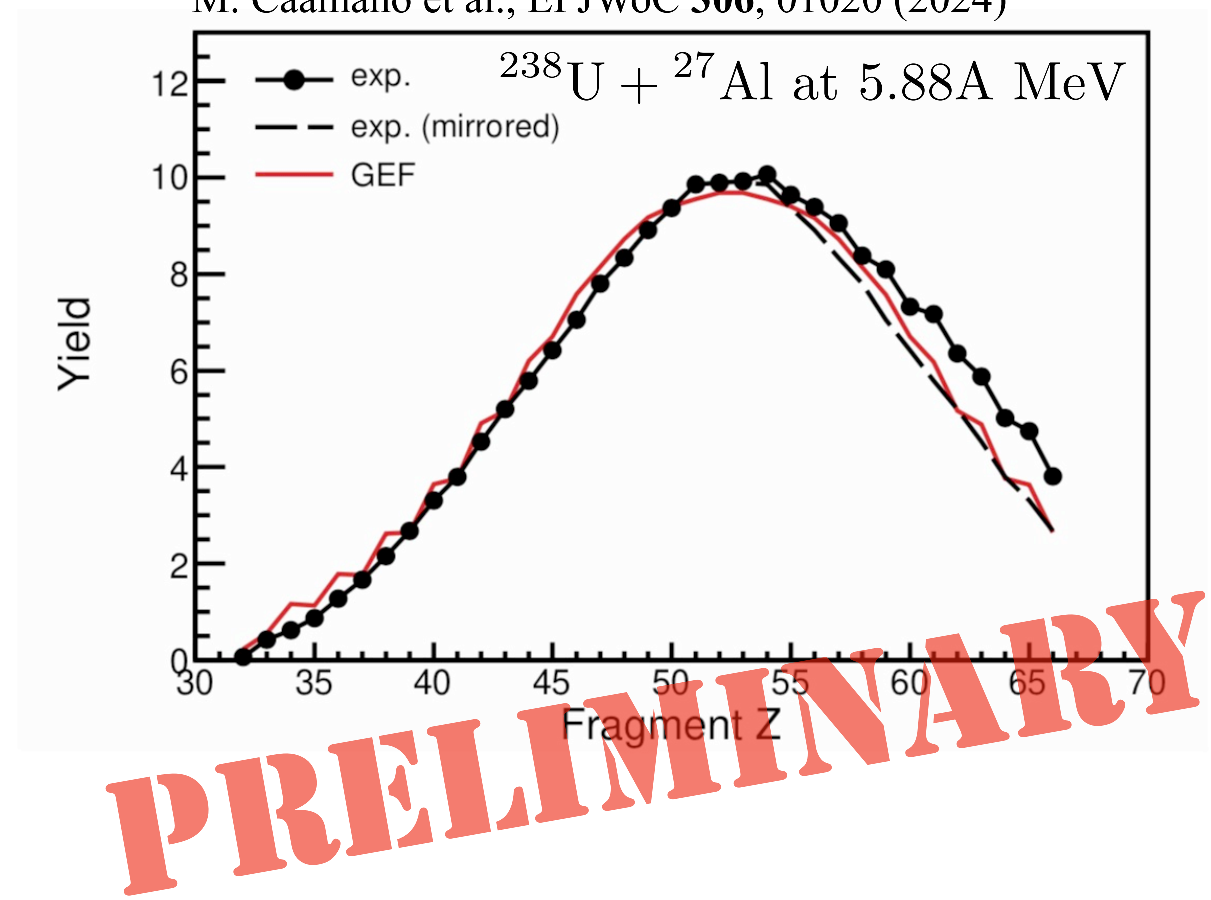
Quasi-fission in VAMOS

J. Tõke et al., NPA **440**, 327 (1985)



D. Fernández, PhD Thesis U. Santiago de Compostela (2023)

M. Caamaño et al., EPJWoC **306**, 01020 (2024)



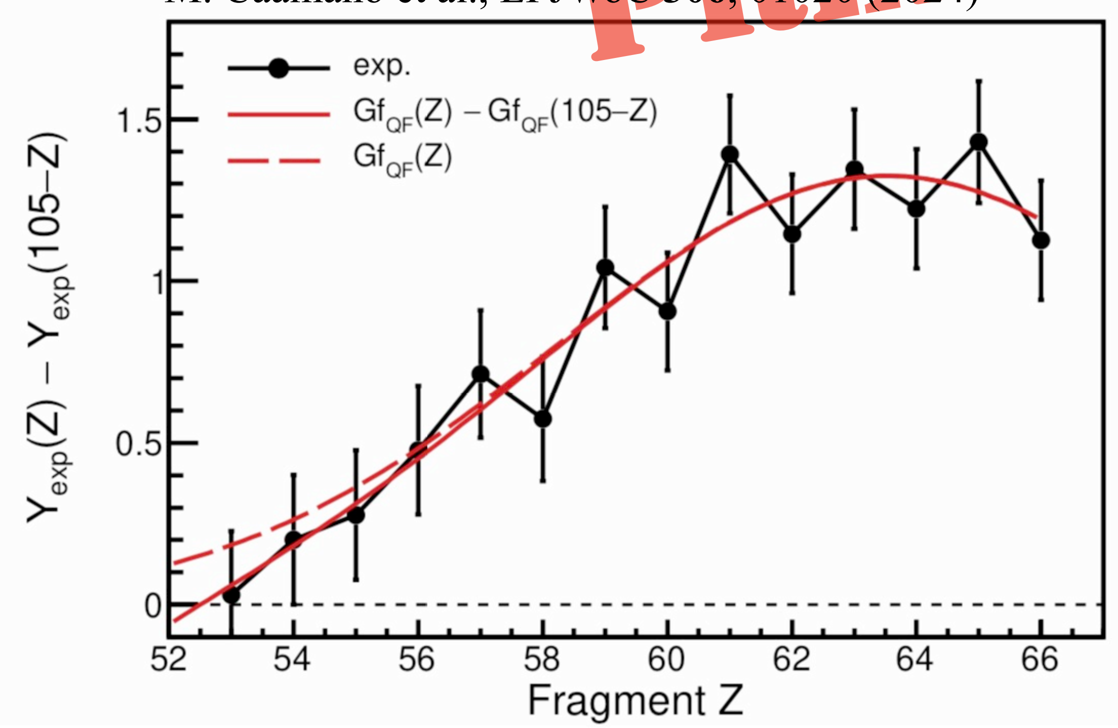
First measurement of Quasi-Fission with completely identified (A,Z) fragment distributions.
VAMOS did not cover the full c.m. angular distribution: skewed distribution.

Quasi-fission in VAMOS

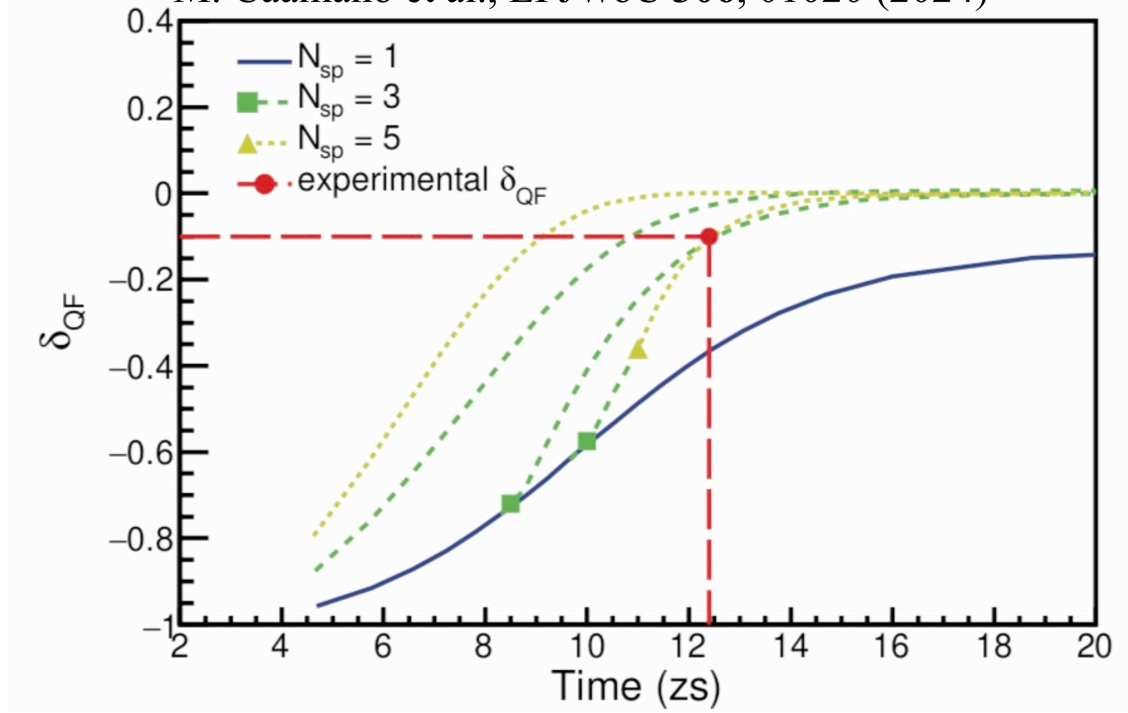
PRELIMINARY

D. Fernández, PhD Thesis U. Santiago de Compostela (2023)

M. Caamaño et al., EPJWoC **306**, 01020 (2024)



M. Caamaño et al., EPJWoC **306**, 01020 (2024)



The QF population displays a huge even-odd effect, **signature of a low dissipation**.
The quasi-compound system spends half of the time without dissipating energy through pair-breaking.
Probably the dissipation kicks in as it reaches the fission descend in the potential energy.

Quick summary

In the last decades, the role of nuclear structure in collective processes such as fission has been identified as a critical ingredient.

In order to study it, the characterisation of the fissioning system and the isotopic identification of fragments are fundamental. The VAMOS setup is the only experimental approach able to provide such full identification.

VAMOS also provides new observables that allow for a detailed study of the dynamics of the fission process and the role of nuclear shells.

The successful ongoing stream of results is now extended to quasi-fission reactions, where the role of structure and dynamics are likely related to those of fission but are yet to be fully determined.

Thanks!

M. Caamaño[1], **F. Farget[2], D. Ramos[1,2], C. Rodríguez-Tajes[2], O. Delaune[2], X. Derkx[2], G. Mantovani[1,3], D. Fernández[1], M. Rejmund[2], A. Lemasson[2],** K.-H. Schmidt[2,4], C. Schmitt[5], B. Fernández-Domínguez[1], **D. Tarrío[6], A. Manna[7], L. Audouin[8], I. Durán[1]**, D. Ackermann[2], H. Álvarez-Pol[1], C.-O. Bacri[8], J. Benlliure[1], S. Biswas[2], E. Casarejos[9], E. Clement[2], D. Cortina[1], A. Dijon[2], D. Doré[10], D. Durand[11], G. de France[2], J.D. Frankland[2], M.O. Fregeau[2], D. Galaviz[12], E. Galiana-Baldó[1,12], L. Gaudefroy[2], C. Golabek[2], A. Heinz[13], A.I. Henriques[12], B. Jacquot[2], B. Jurado[4], Y.H. Kim[14], P. Morfouace[15], C. Paradela[1], J. Piot[2], D. Ralet[16], T. Roger[2], M.-D. Salsac[10], A. Shrivastava[2], P. Teubig[12], I. Tsekhanovich[4], **VAMOS** team, **n_TOF/CERN** collaboration

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