Fission in Inverse Kinematics

A new window to experimental observables

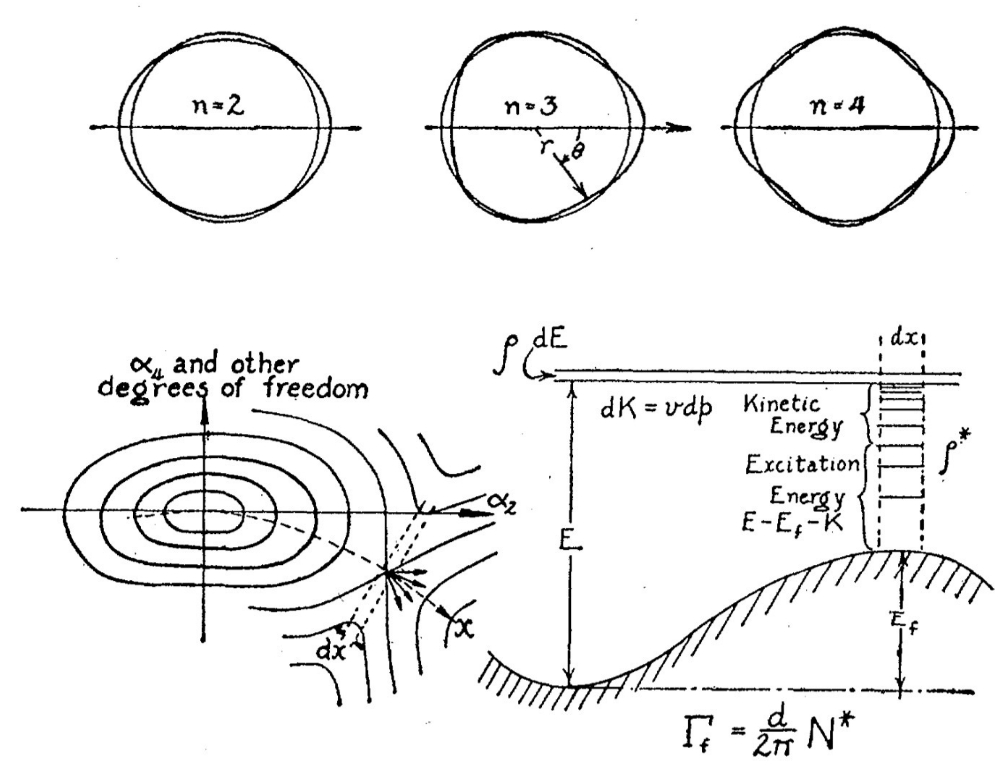
M. Caamaño
U. Santiago de Compostela, Spain

A macroscopic LD behaviour

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

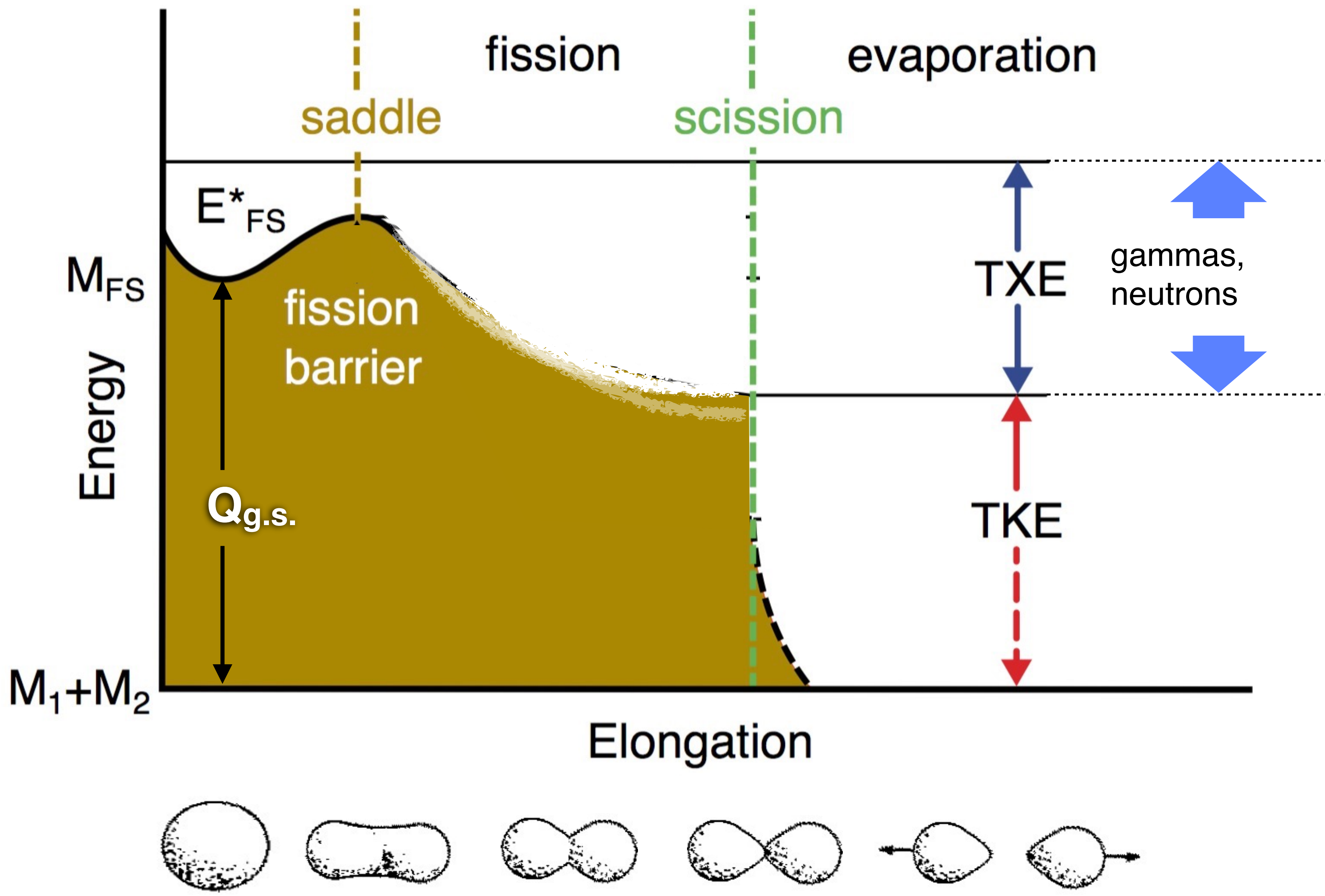
It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of *c.* 200 Mev., as calculated from nuclear radius and charge.

L. Meitner, O. R. Frisch, Nature 11, 239 (1939)



N. Bohr, J.A. Wheeler, PR 56, 426 (1939)

A macroscopic LD behaviour



A macroscopic LD behaviour?

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

Hahn and Strassmann were forced to conclude that *isotopes of barium (Z = 56) are formed as a consequence of the bombardment of uranium (Z = 92) with neutrons.*

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of *c.* 200 Mev., as calculated from nuclear radius and charge.

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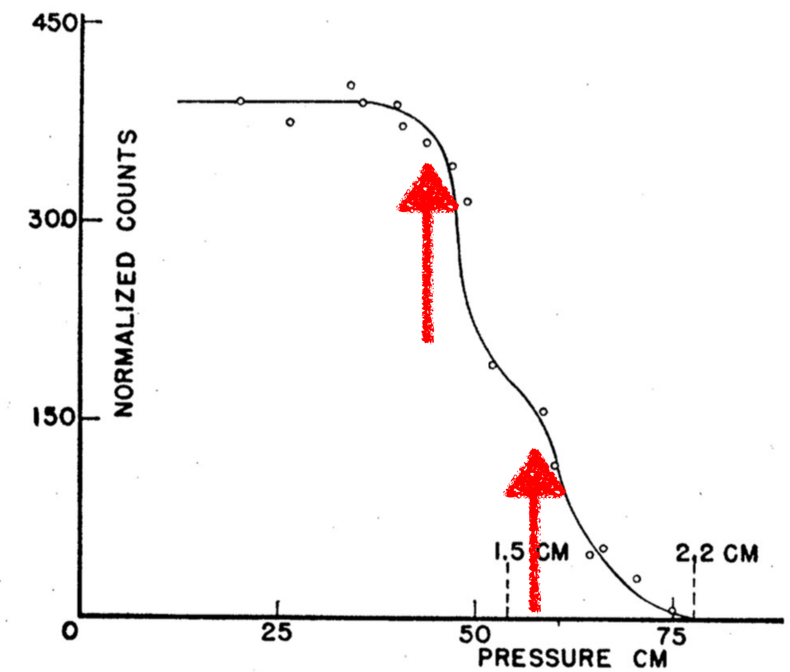


E.T. Booth et al., PR 55, 982 (1939)

IX. ASYMMETRIC FISSION

It is somewhat tempting to associate the existence of the closed shells of 50 and 82 neutrons with the dissymmetry of masses encountered in the fission process. U^{235} contains $143=82+50+11$

M.G. Mayer, PR 74, 235 (1948)

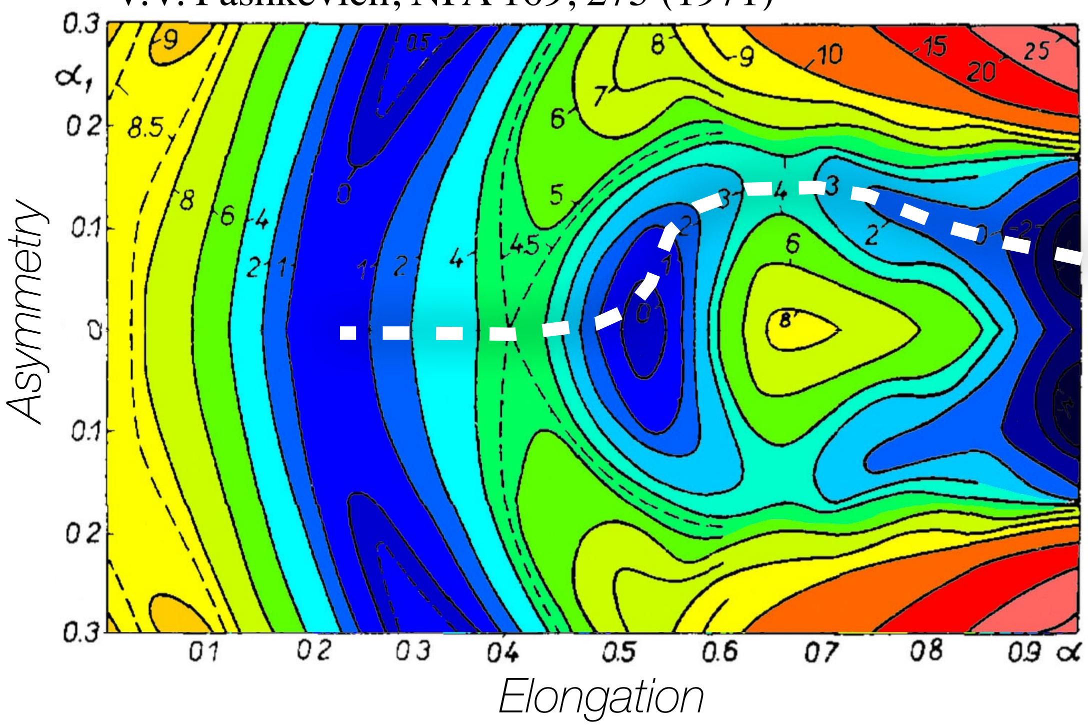
A macroscopic LD behaviour shaped by structure

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

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

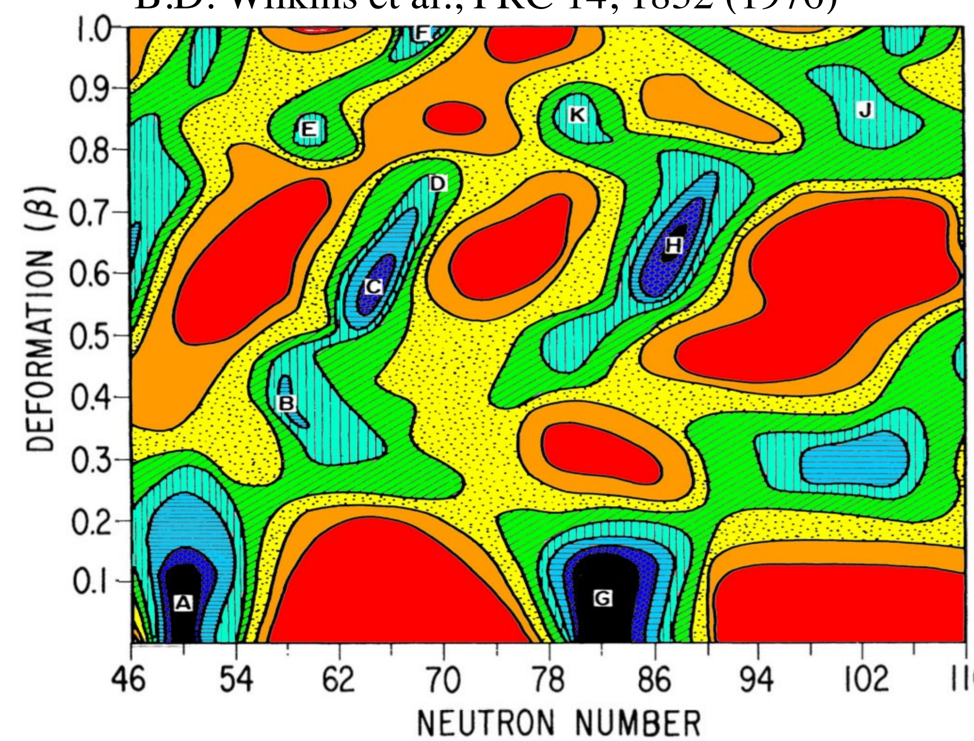
at the barrier

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



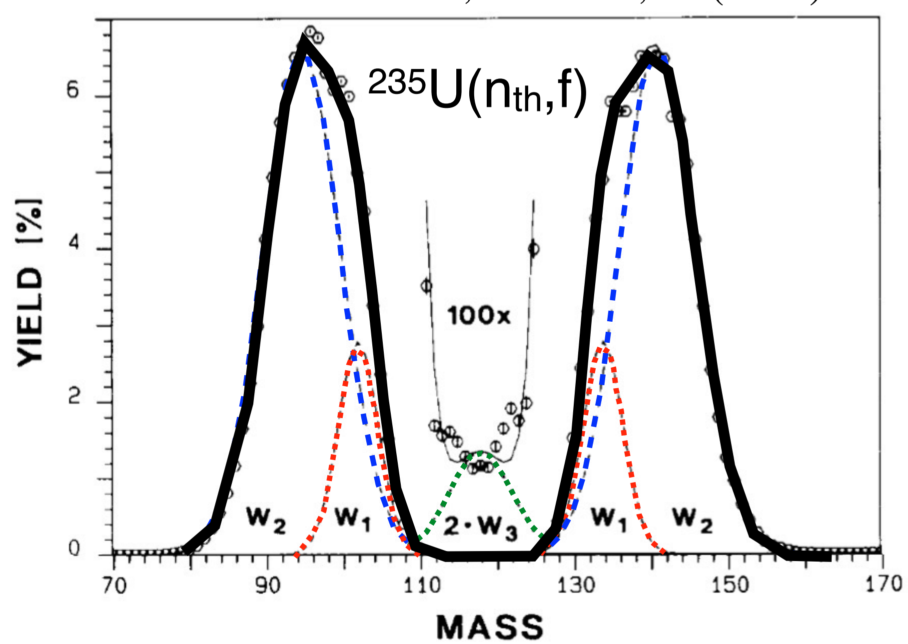
and at scission

B.D. Wilkins et al., PRC 14, 1832 (1976)

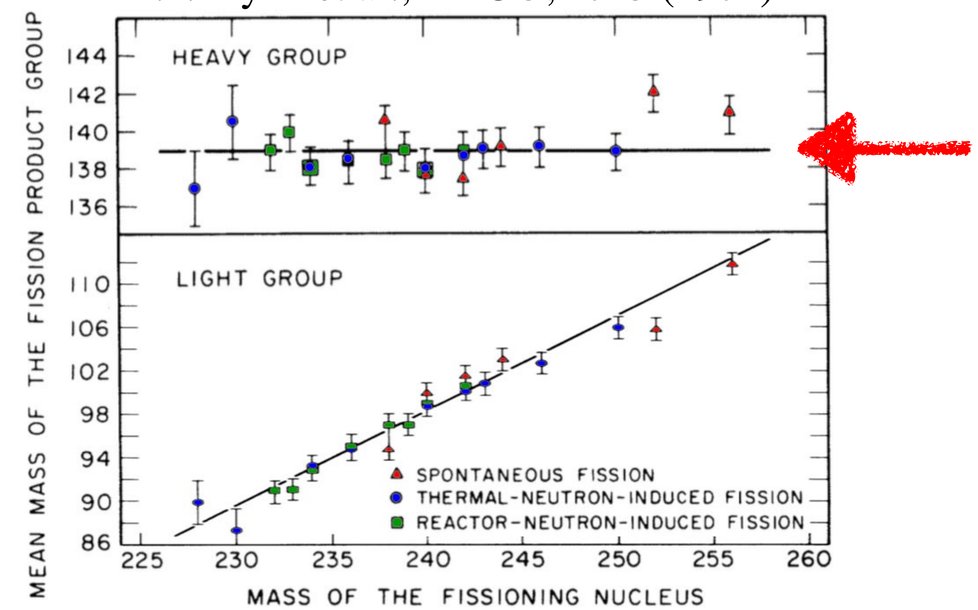


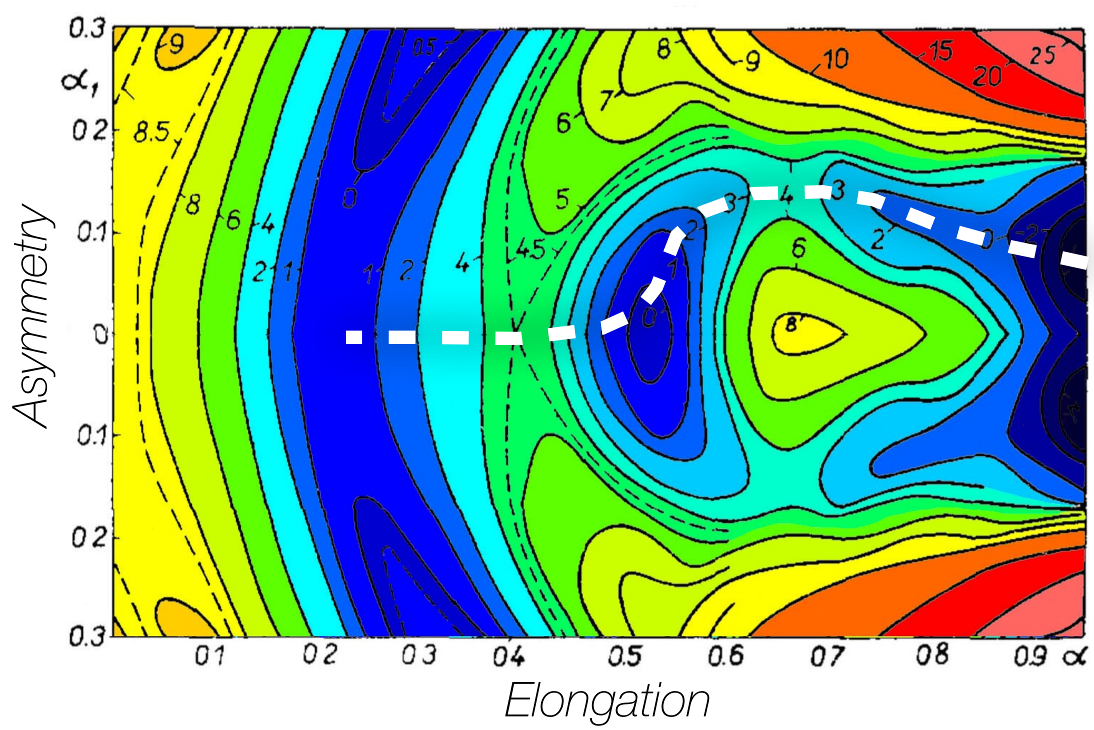
Consistent with a number of observables

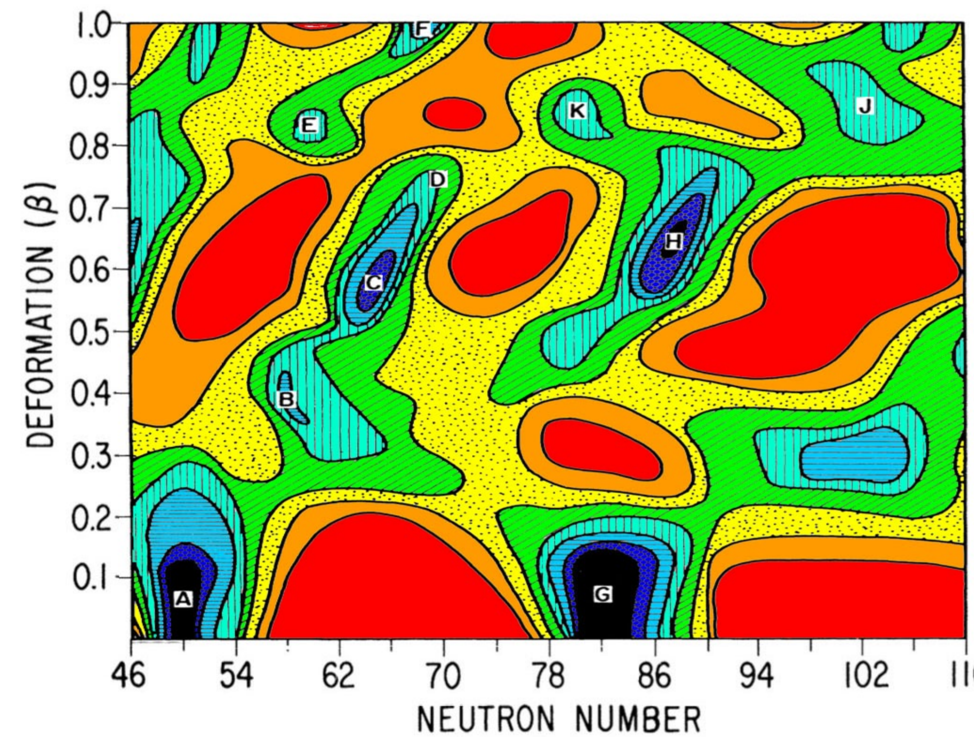
F.-J. Hambsch et al., NPA 491, 56 (1989)



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

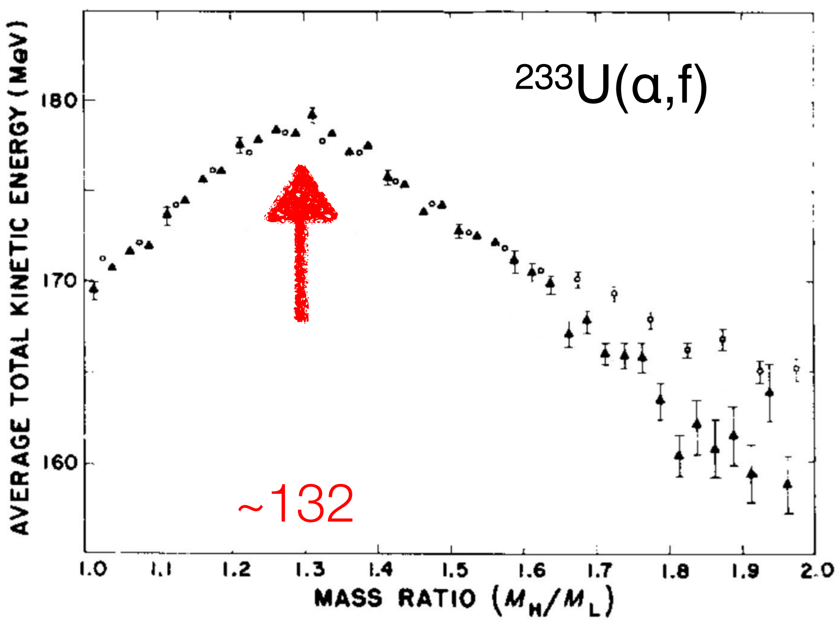




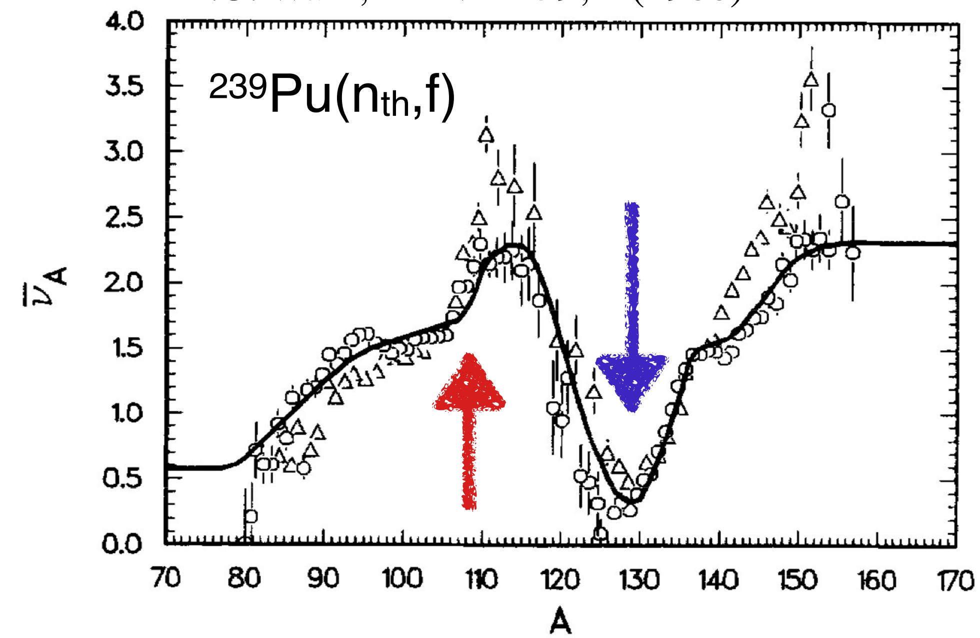


Consistent with a number of observables

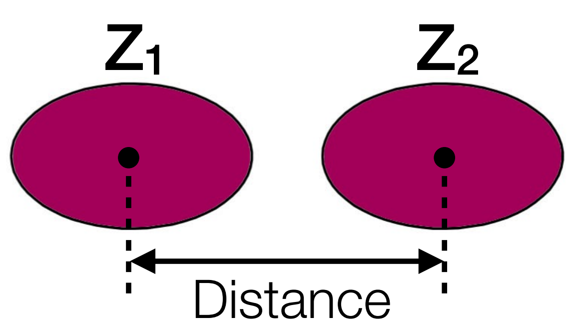
H.C. Britt et al., NIMA 24, 13 (1963)



A.C. Wahl, ADNDT 39, 1 (1988)

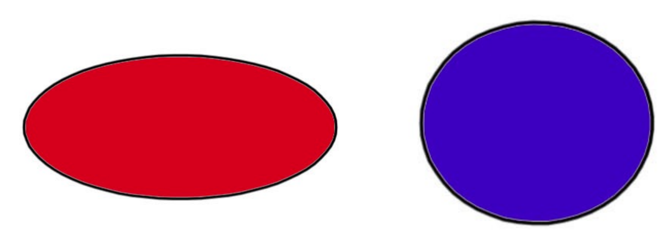


Total kinetic energy (TKE)



$$TKE \propto \frac{Z_1 Z_2}{D}$$

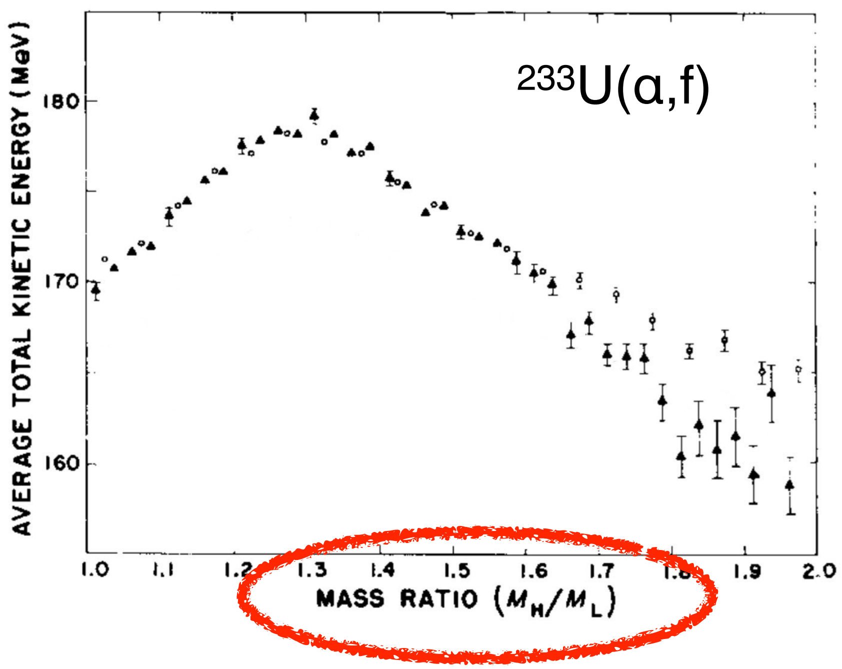
Neutron evaporation



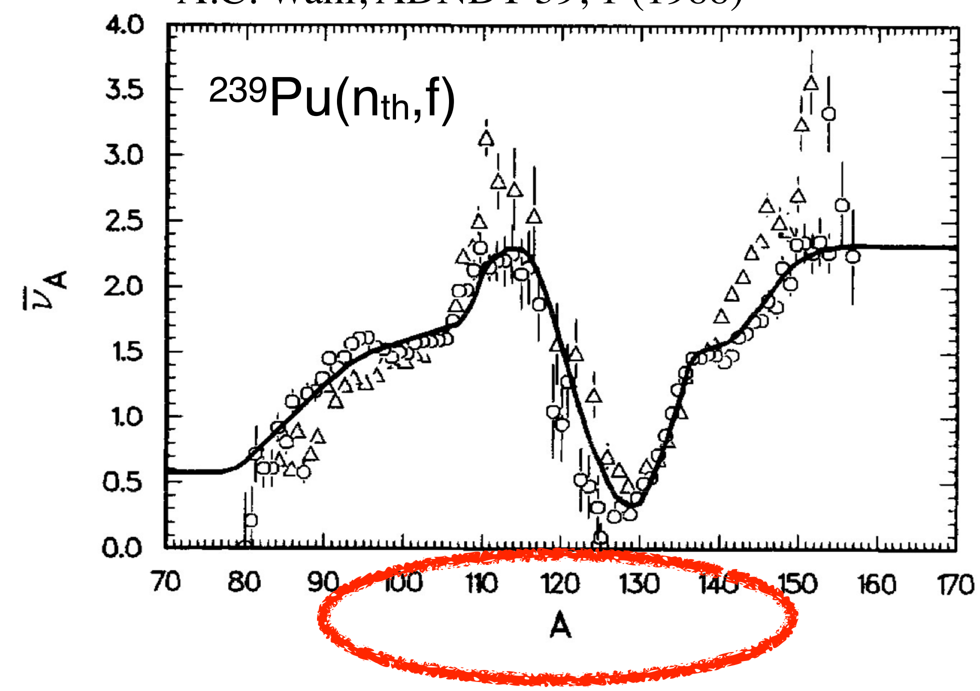
$$\nu \propto E^{def} + E^{int}$$

Fragment identification: All is Mass

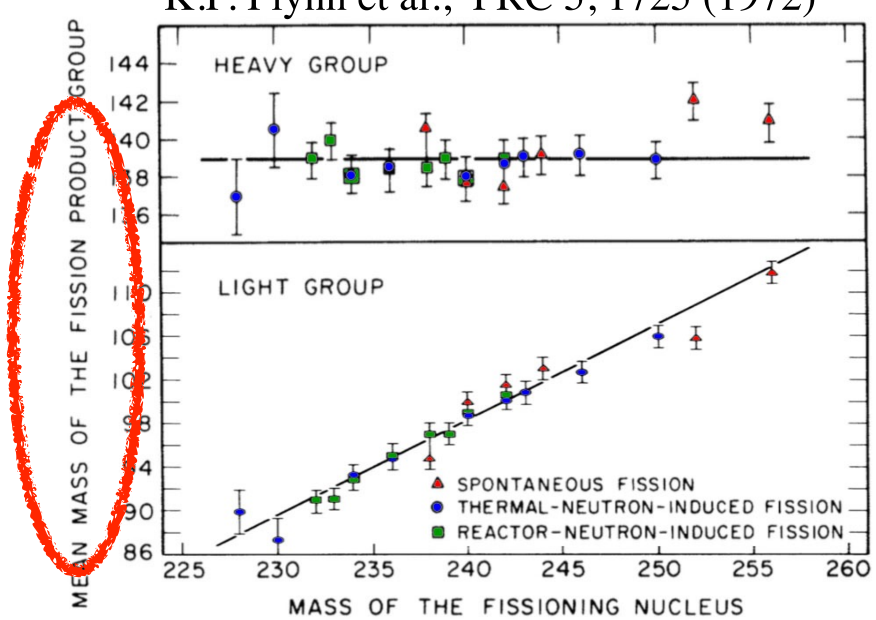
H.C. Britt et al., NIMA 24, 13 (1963)



A.C. Wahl, ADNDT 39, 1 (1988)



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



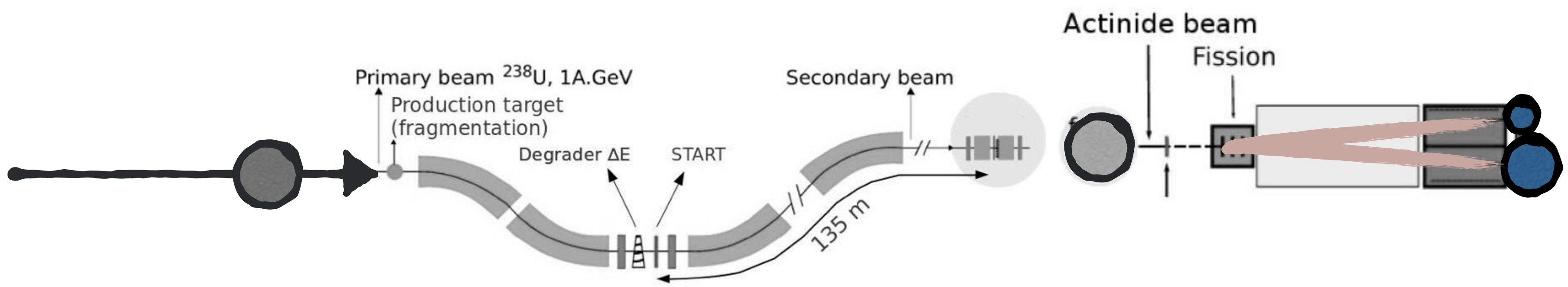
Most of the data is measured in terms of fragment masses.

But **shells, structure appear in Z and N.**

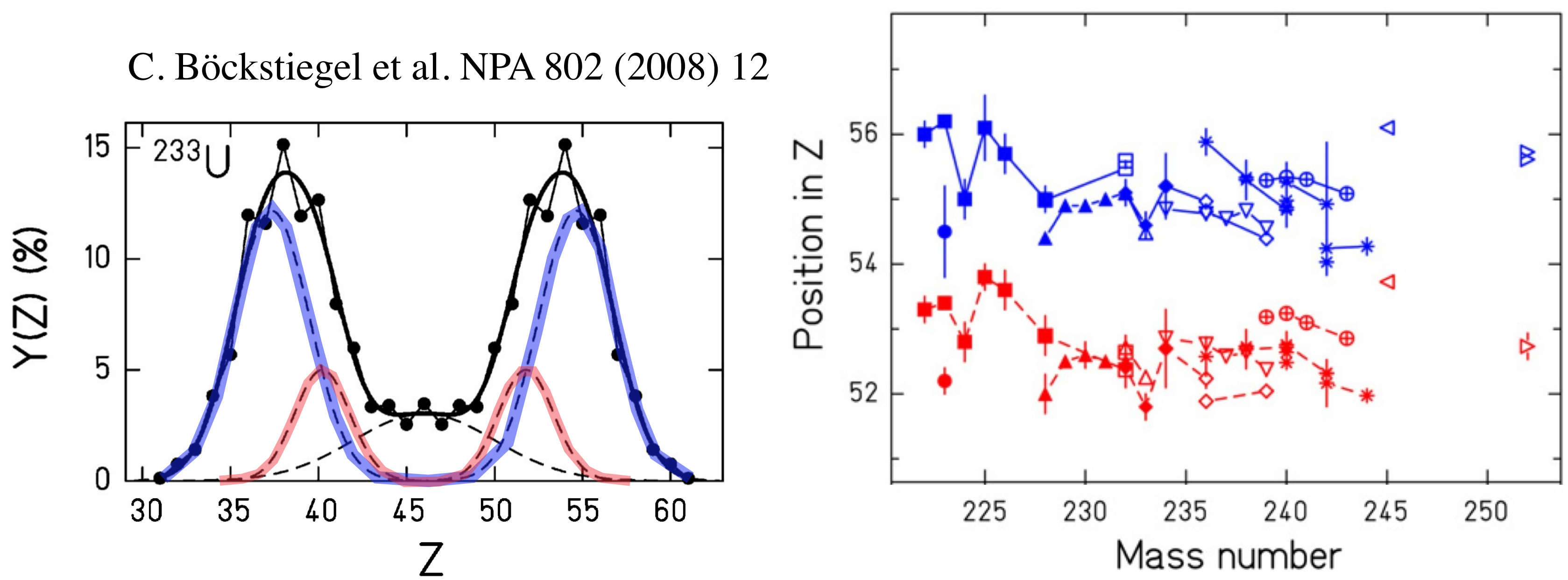
Inverse kinematics at GSI:

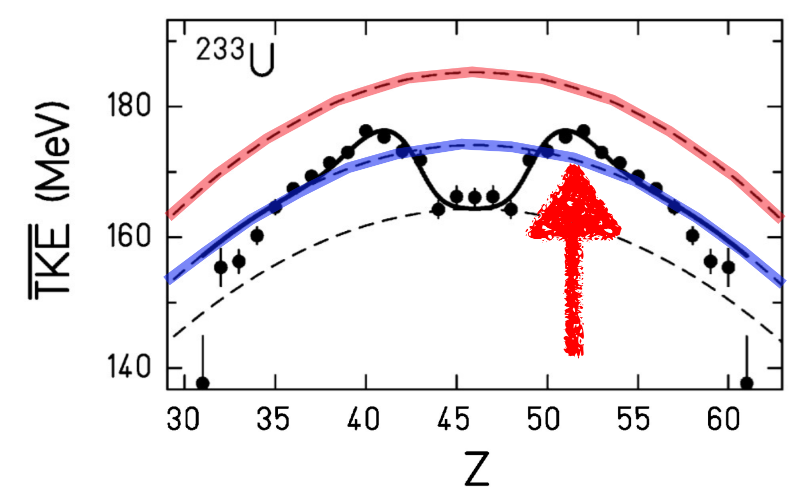
Production from fragmentation and e-m fission induced

K.-H. Schmidt et al.



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





Accurate access to components on the yield distribution

Compact scission around Z~52

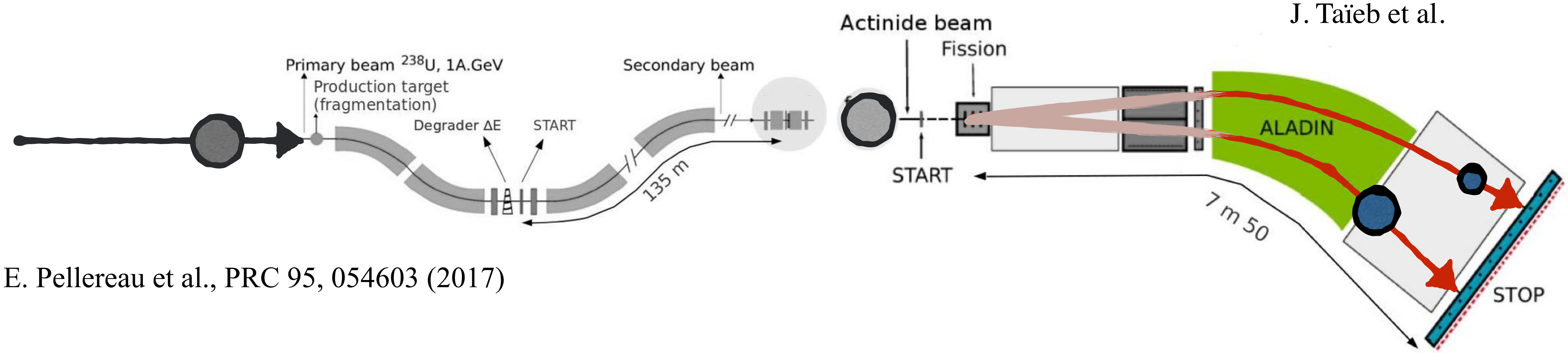
Inverse kinematics at GSI:

Production from fragmentation and e-m fission induced

K.-H. Schmidt et al.

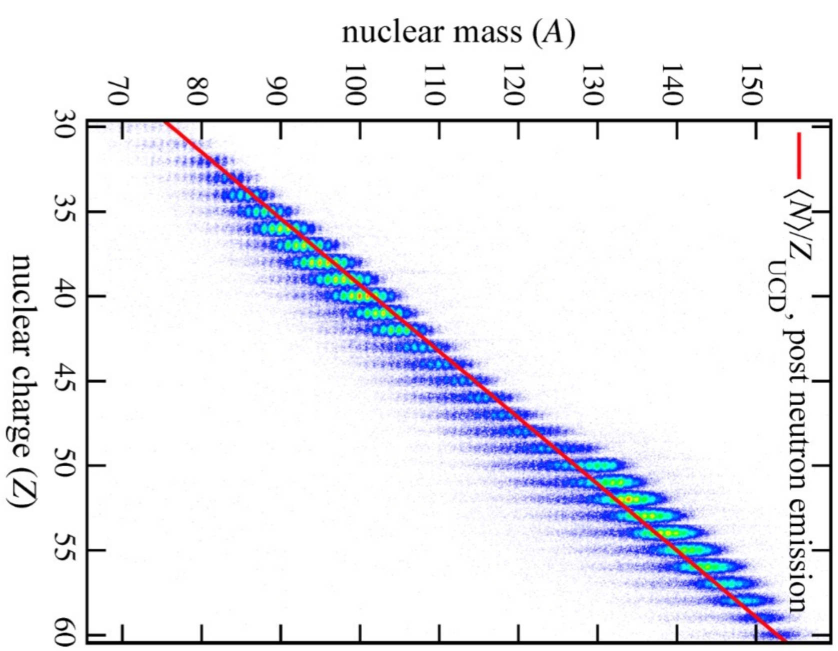
SOFIA @ GSI

J. Taïeb et al.

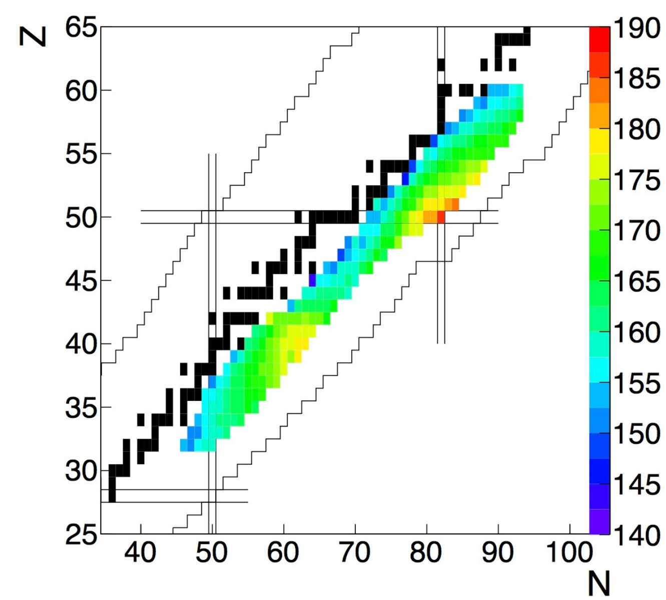


E. Pellereau et al., PRC 95, 054603 (2017)

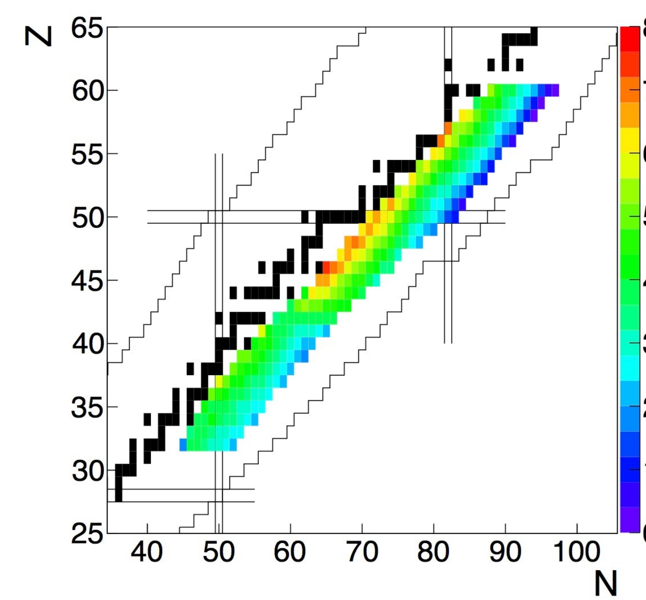
J.-F. Martin PhD, U. Paris-Sud (2015)



Accurate access to **Z and Mass**



TKE



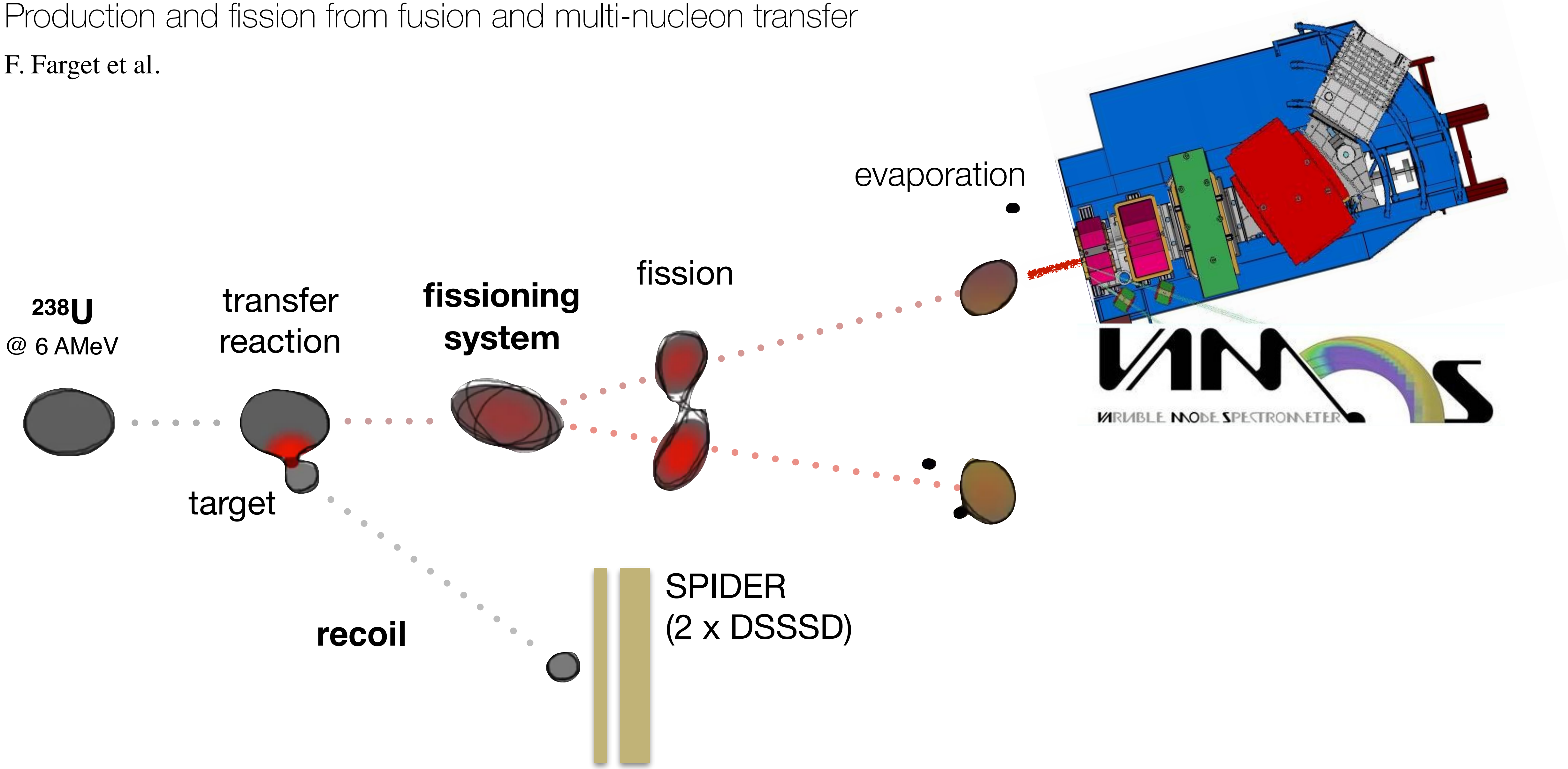
Neutron evaporation

MORE ABOUT THIS IN LAURENT'S TALK...

Inverse kinematics at VAMOS/GANIL:

Production and fission from fusion and multi-nucleon transfer

F. Farget et al.



Inverse kinematics at VAMOS/GANIL:

Production and fission from fusion and multi-nucleon transfer

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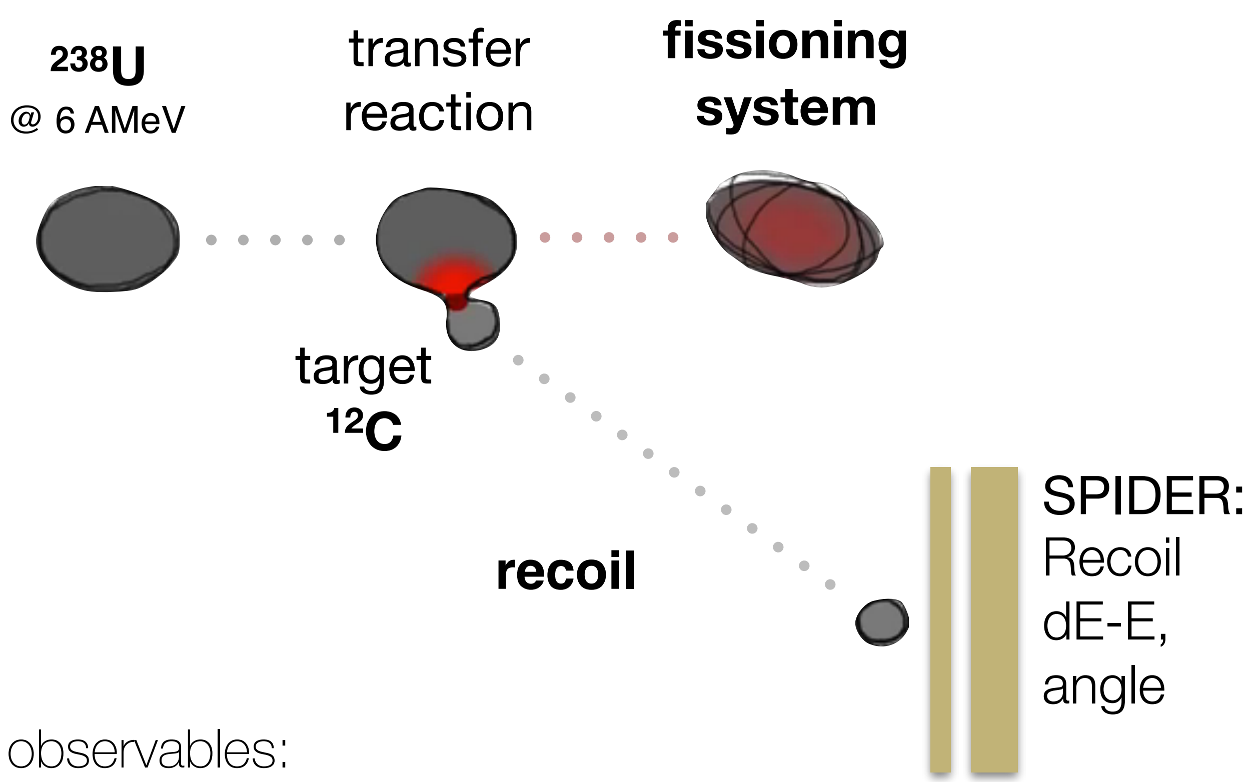
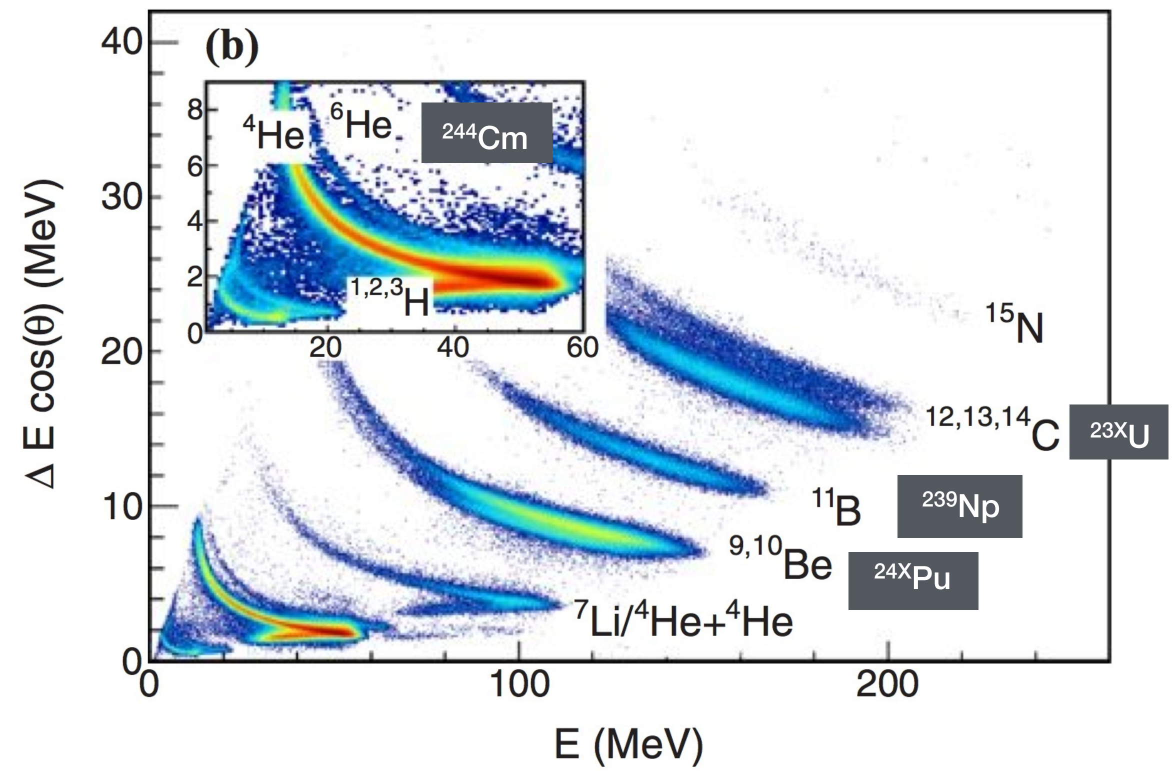
C. Rodríguez. Tajes et al., PRC 89 (2014) 024614



recoil / fissioning system ID



observables:

Fissioning System:

- A, Z, E*, angle, velocity

The **reconstruction** of the binary reaction gives **kinematical information** and the **identification of the fissioning system**

Inverse kinematics at VAMOS/GANIL:

Production and fission from fusion and multi-nucleon transfer

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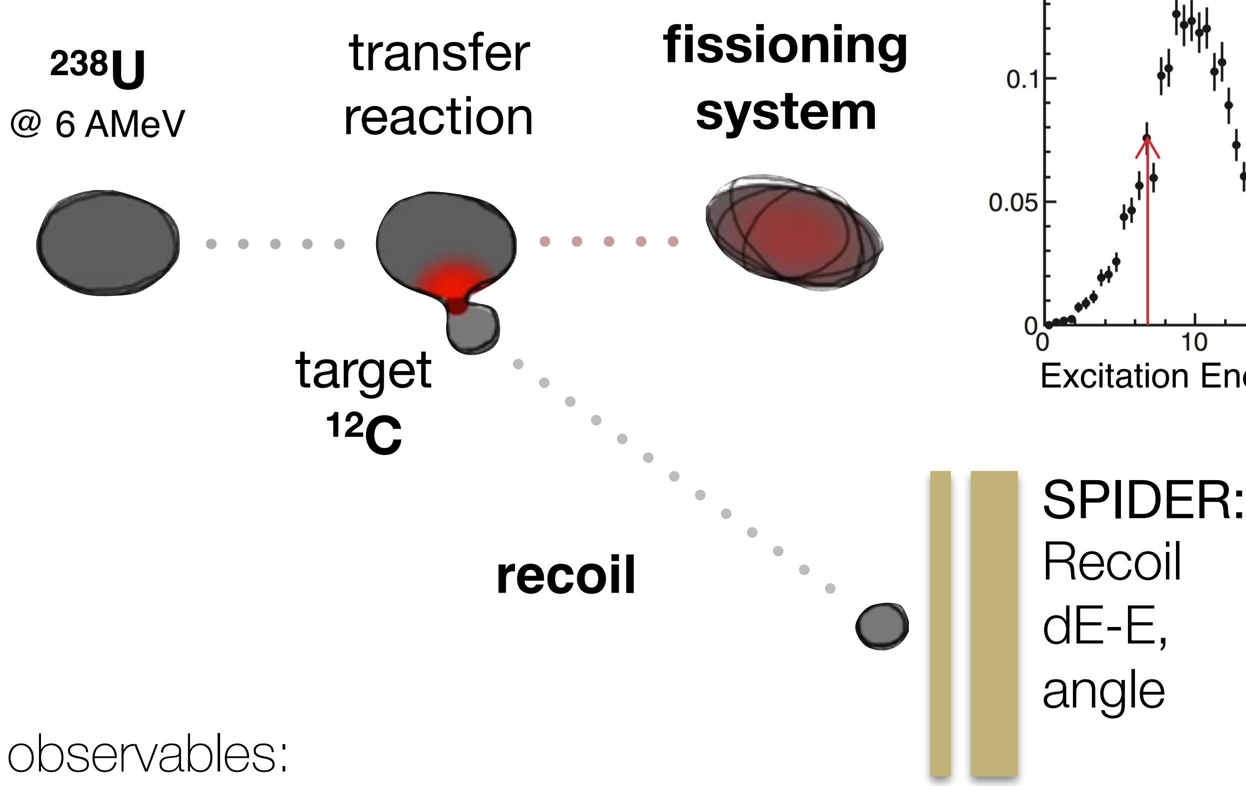
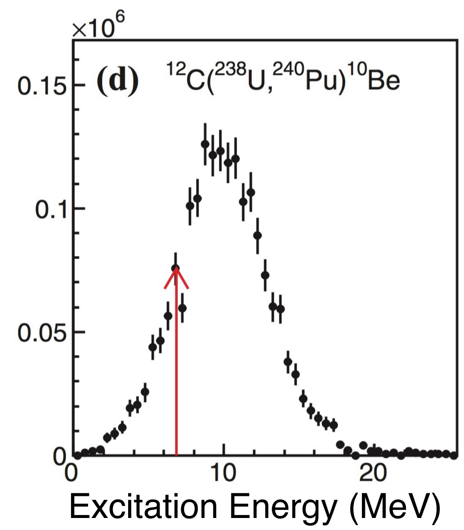
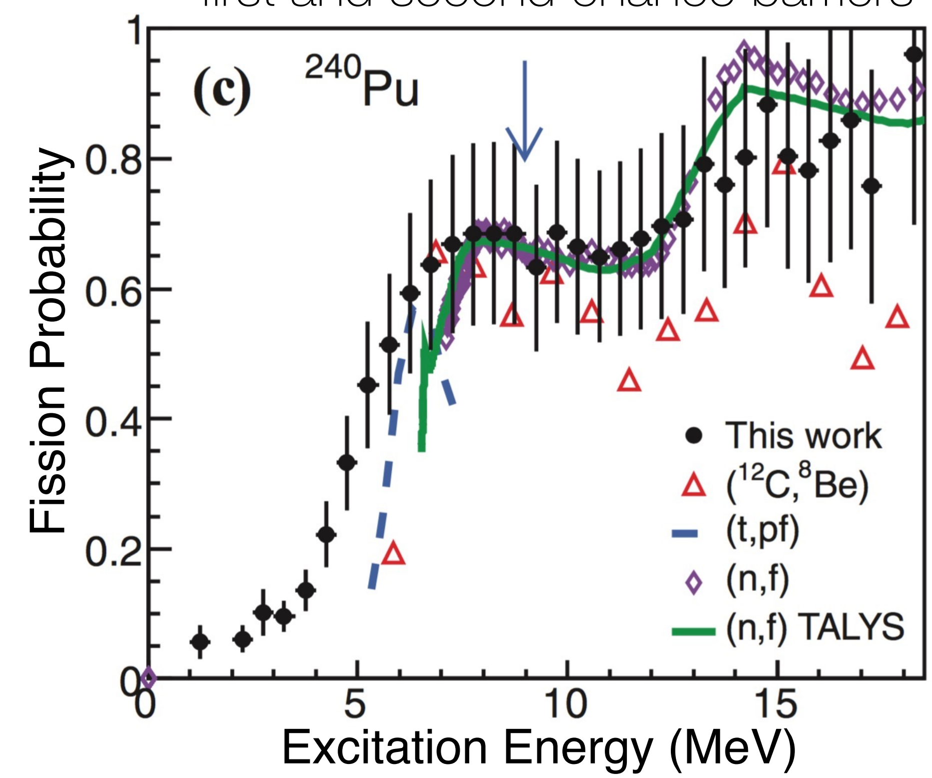




first and second chance barriers



observables:

Fissioning System:

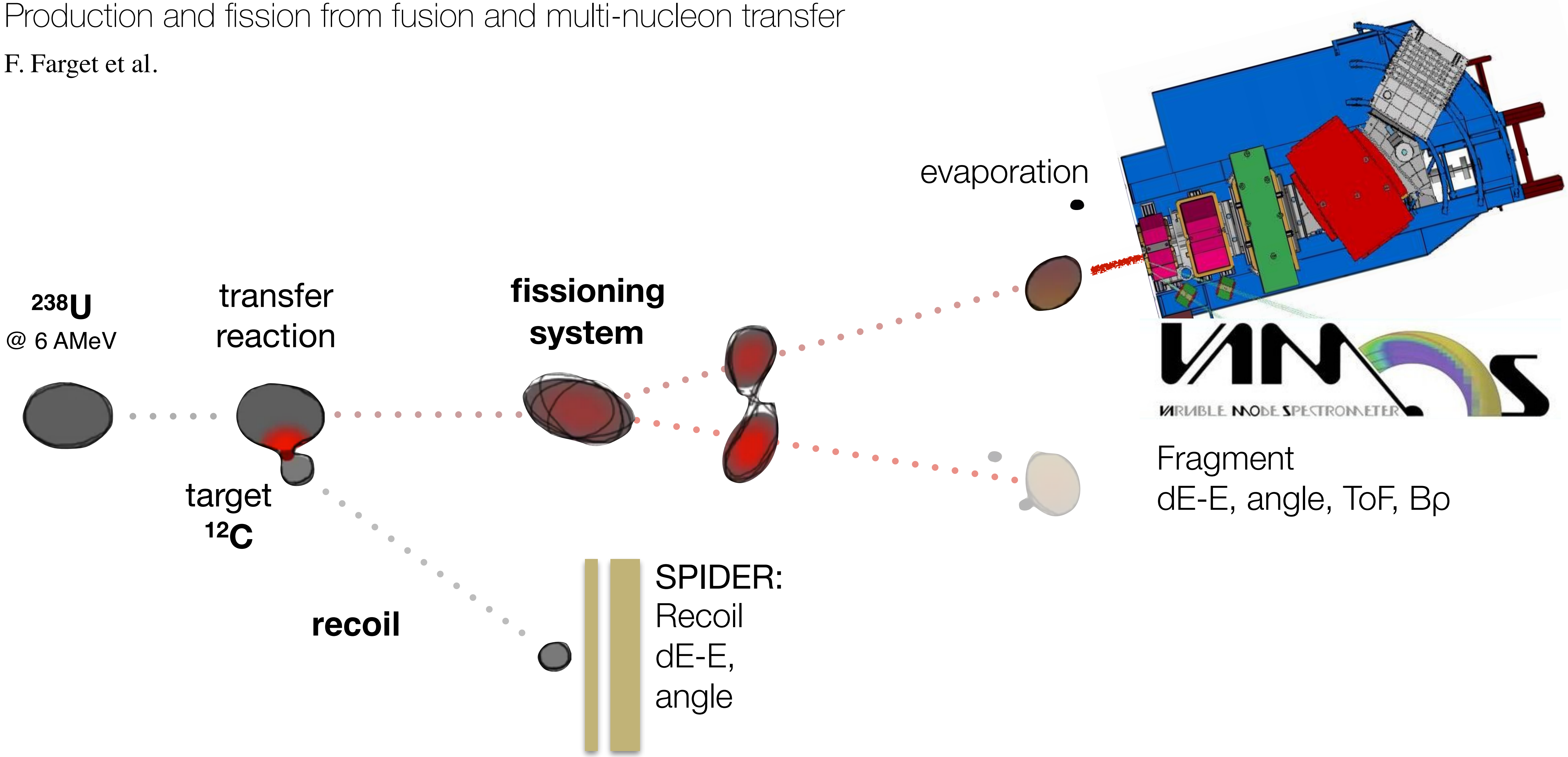
- A, Z, E*, angle, velocity

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

Inverse kinematics at VAMOS/GANIL:

Production and fission from fusion and multi-nucleon transfer

F. Farget et al.

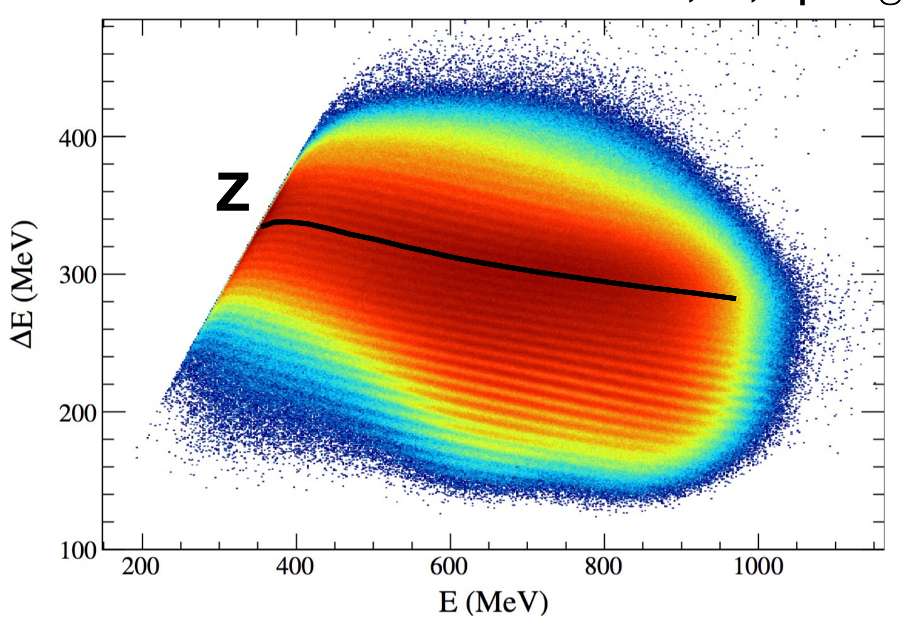


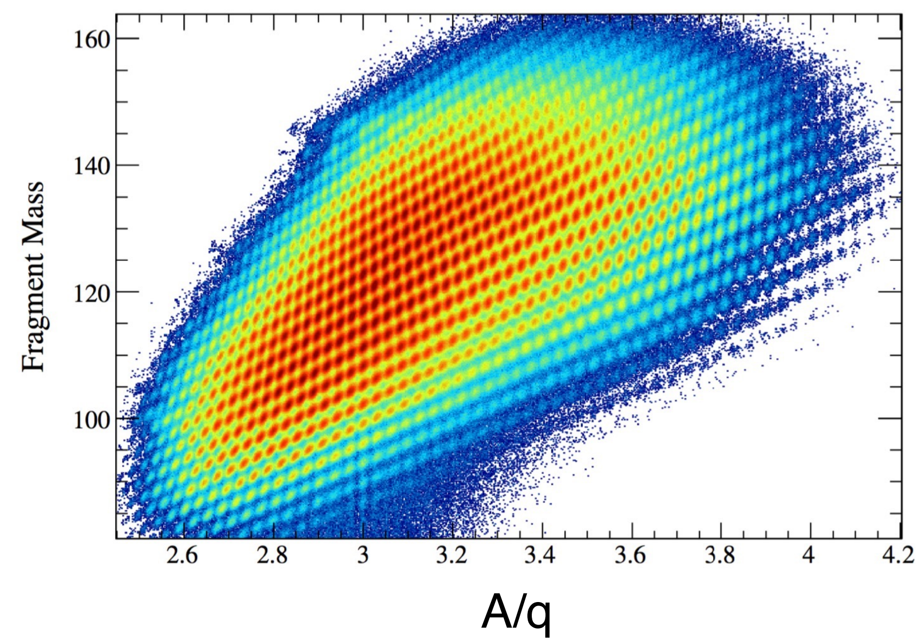
Inverse kinematics at VAMOS/GANIL:

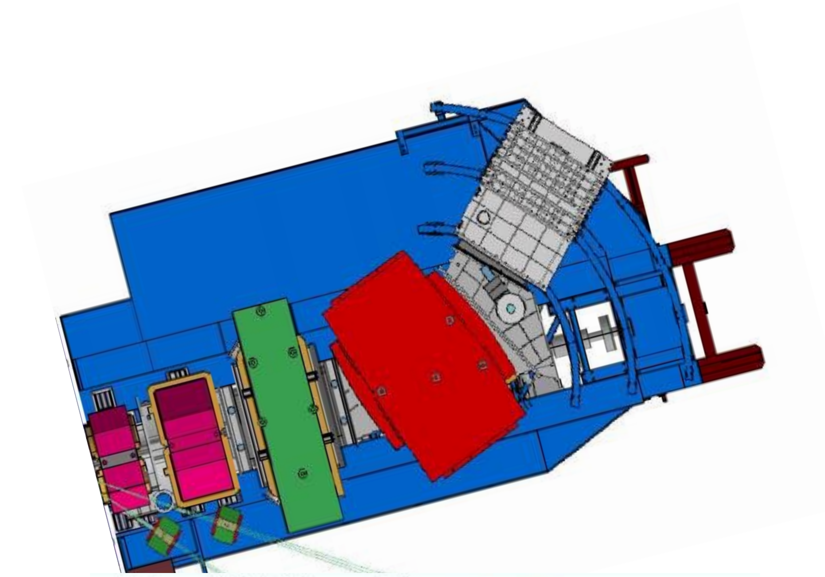
Production and fission from fusion and multi-nucleon transfer

F. Farget et al.

A, Z, q fragment identification





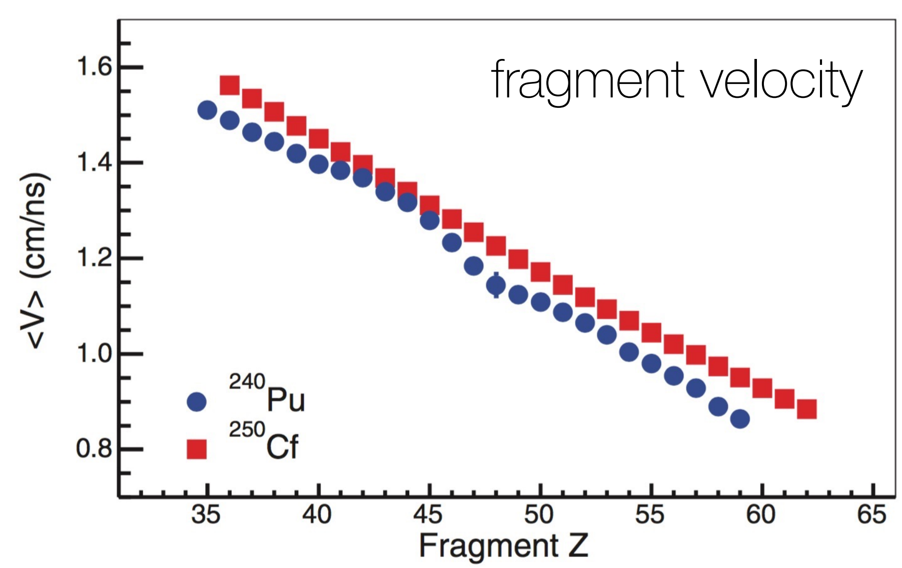


Fragment
dE-E, angle, ToF, Bρ

observables:

Fissioning System:
- A, Z, E*, angle, velocity

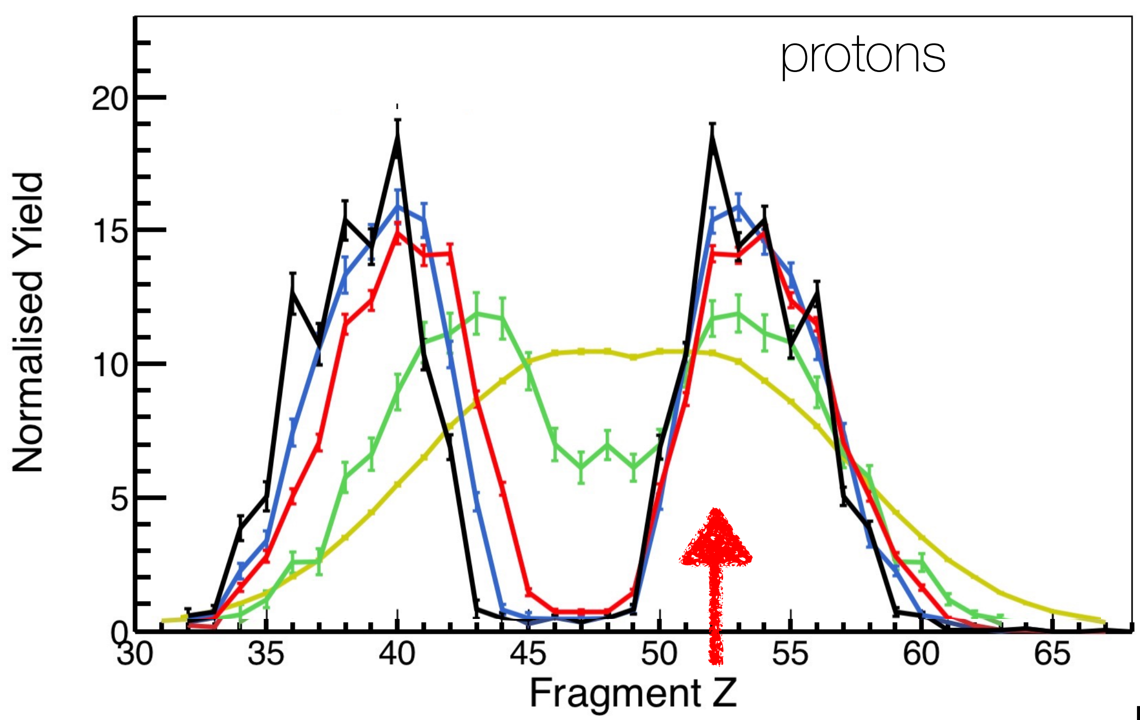
Fission Fragments:
- A^{post}, Z, q, angle, velocity

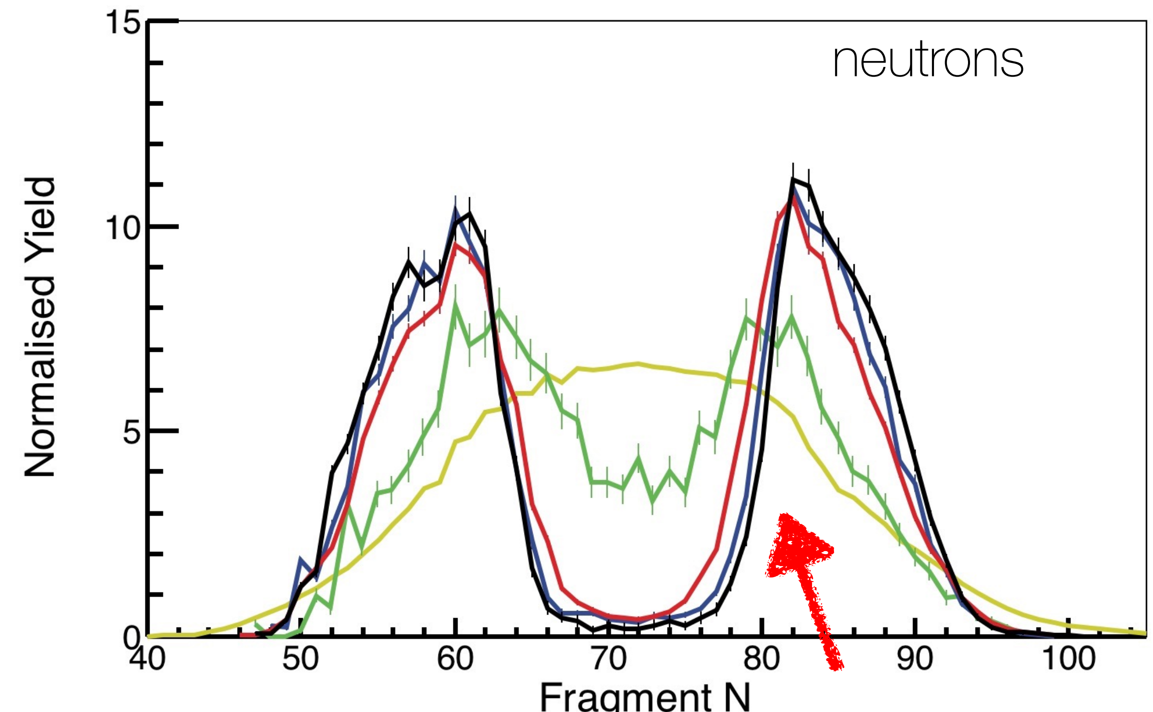


A set of revisited and new observables

Fragment Z, N distributions

D. Ramos, PhD USC (2016), PRC (2018) 97, 054612 (2018).





FS (<E*>)

- ^{250}Cf (46 MeV)
- ^{244}Cm (23 MeV)
- ^{240}Pu (10.7 MeV)
- ^{239}Np (7.5 MeV)
- ^{238}U (7.4 MeV)

The effect of the heavy group lasts until very high excitation energy.

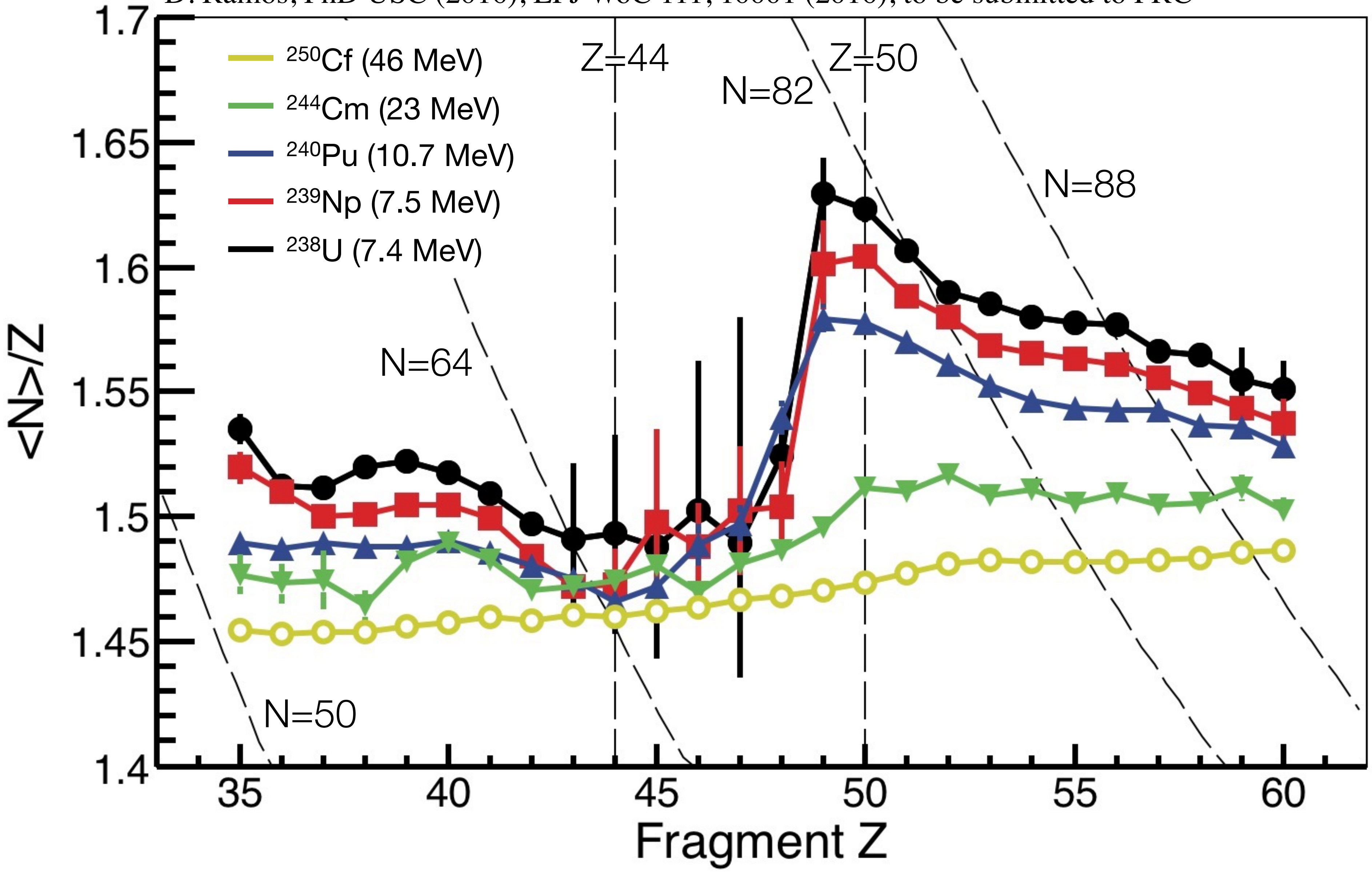
At ~46 MeV the distribution is not yet fully LD.

The measured neutron distribution is affected by post-scission evaporation.

A set of revisited and new observables

Fragment N excess (N/Z)

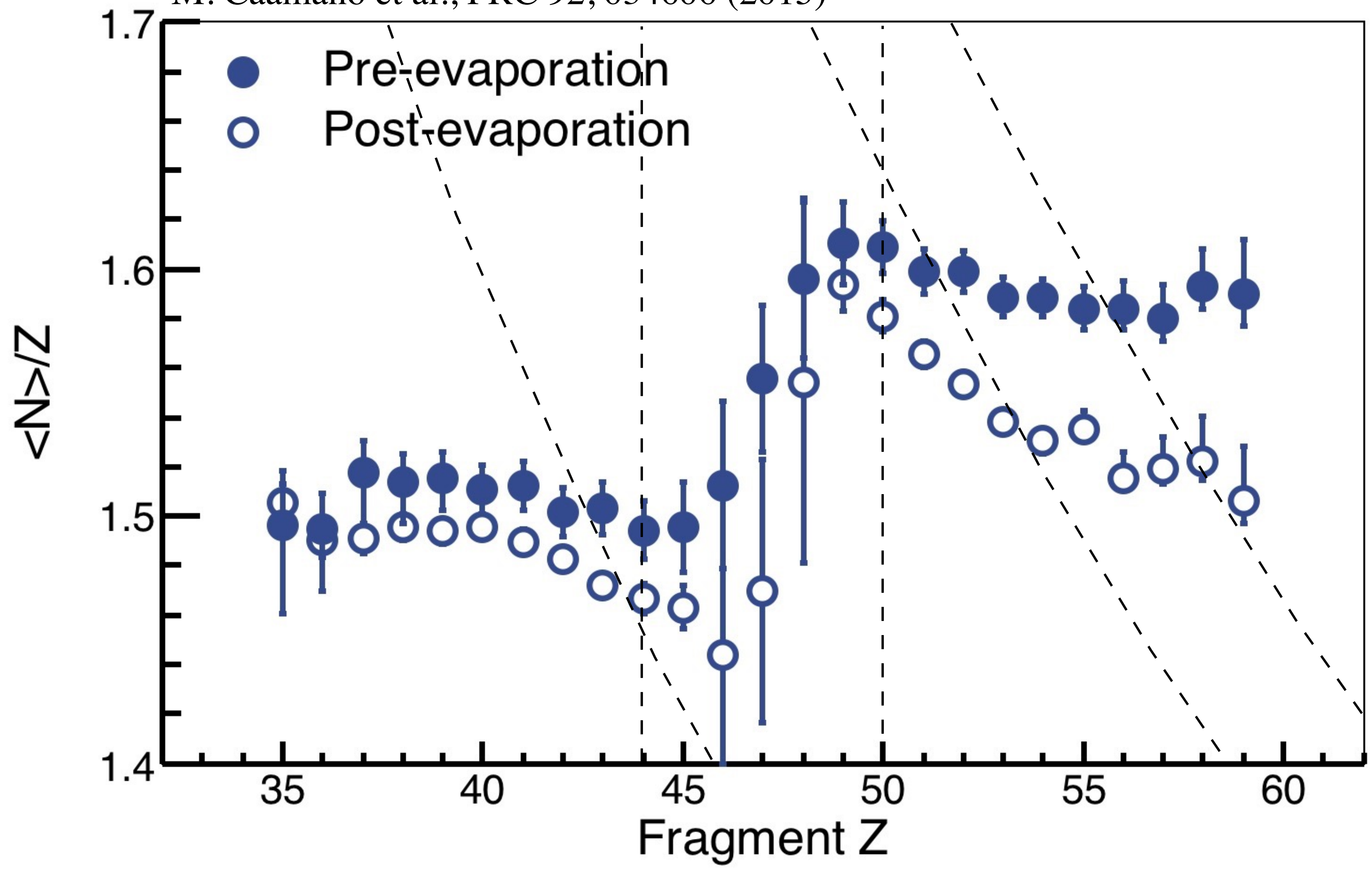
D. Ramos, PhD USC (2016), EPJ WoC 111, 10001 (2016), to be submitted to PRC



New access to scission; the case of ^{240}Pu (9 MeV)

Fragment N excess (N/Z)

M. Caamaño et al., PRC 92, 034606 (2015)

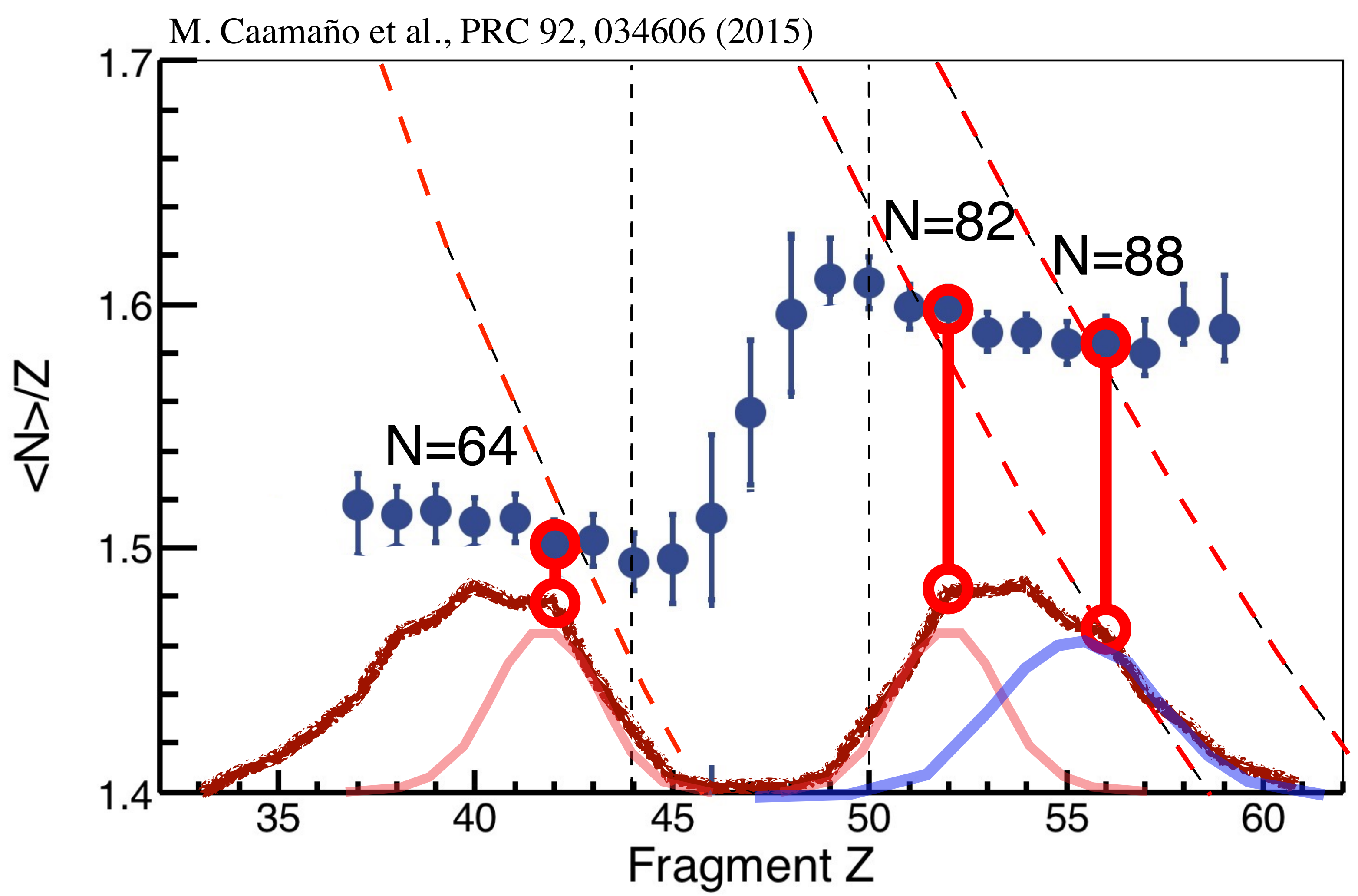


measured velocities and momentum conservation:

$$\langle A_1^* \rangle = A_{FS} \frac{\langle V_2 \gamma_2 \rangle}{\langle V_1 \gamma_1 \rangle + \langle V_2 \gamma_2 \rangle}, \quad \langle A_2^* \rangle = A_{FS} - \langle A_1^* \rangle.$$

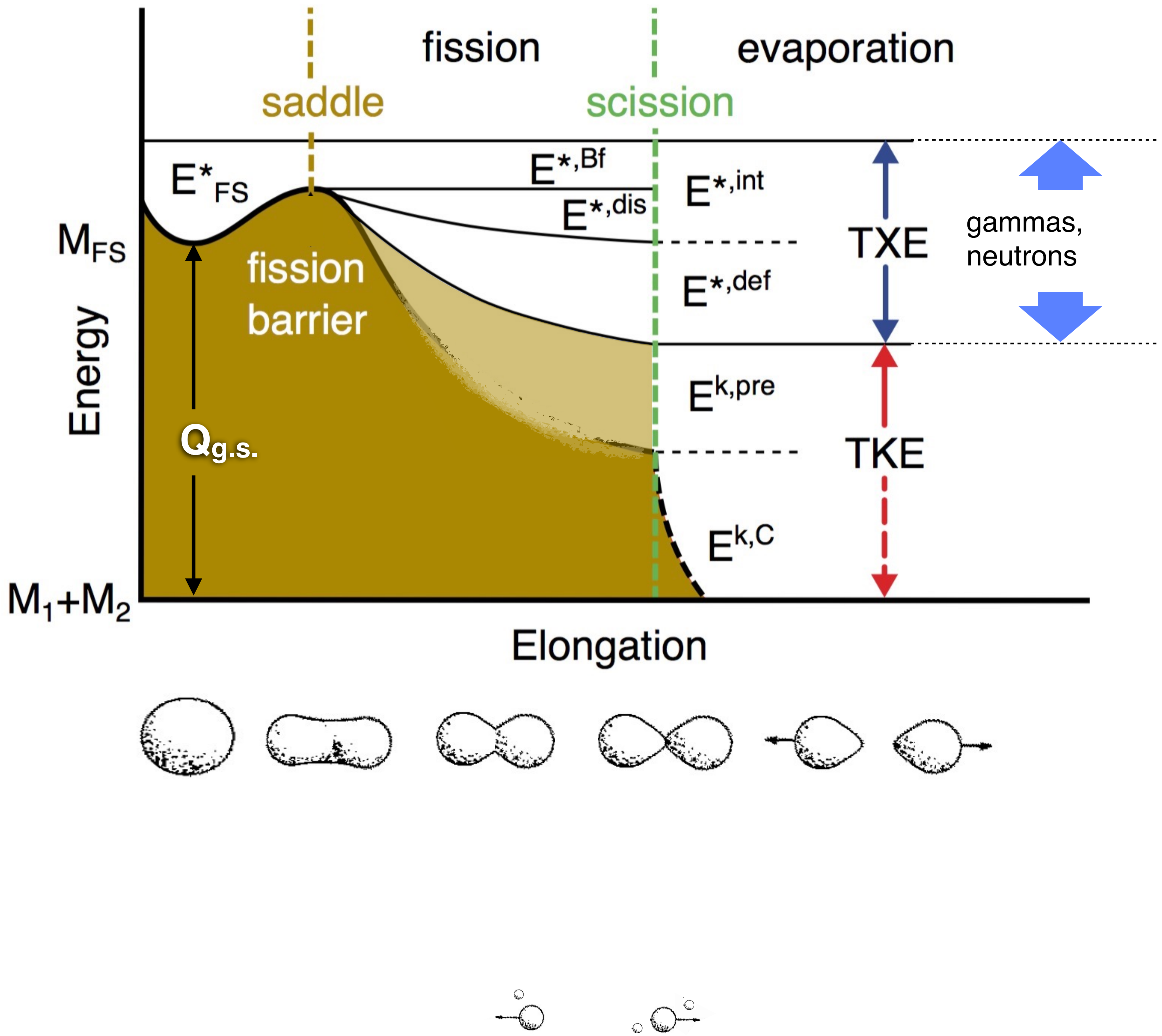
New access to scission; the case of ^{240}Pu (9 MeV)

Fragment N excess (N/Z)

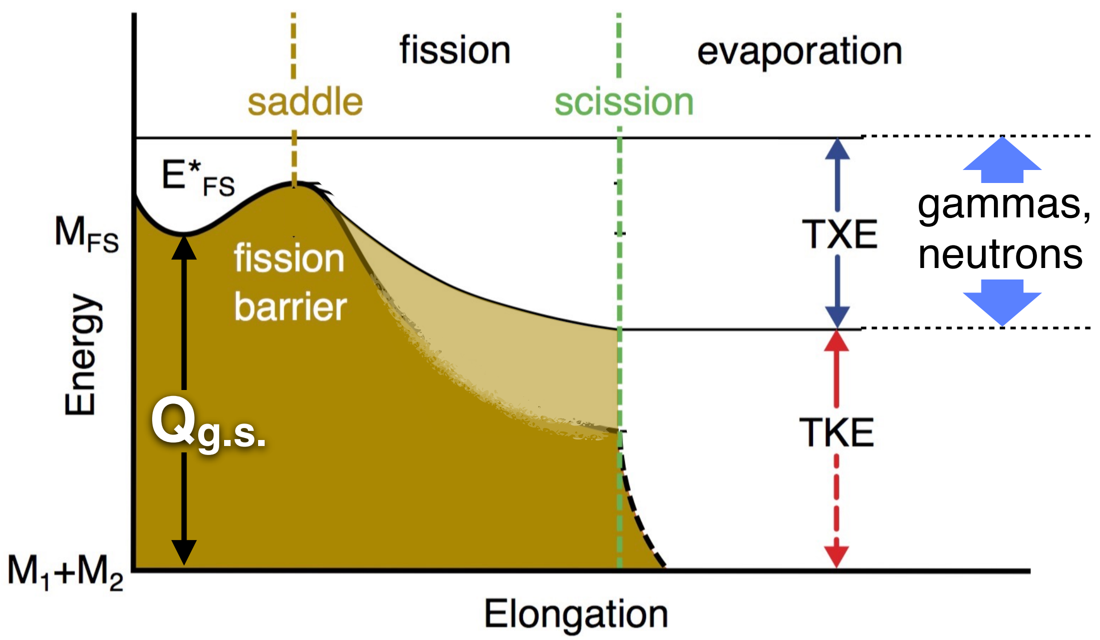


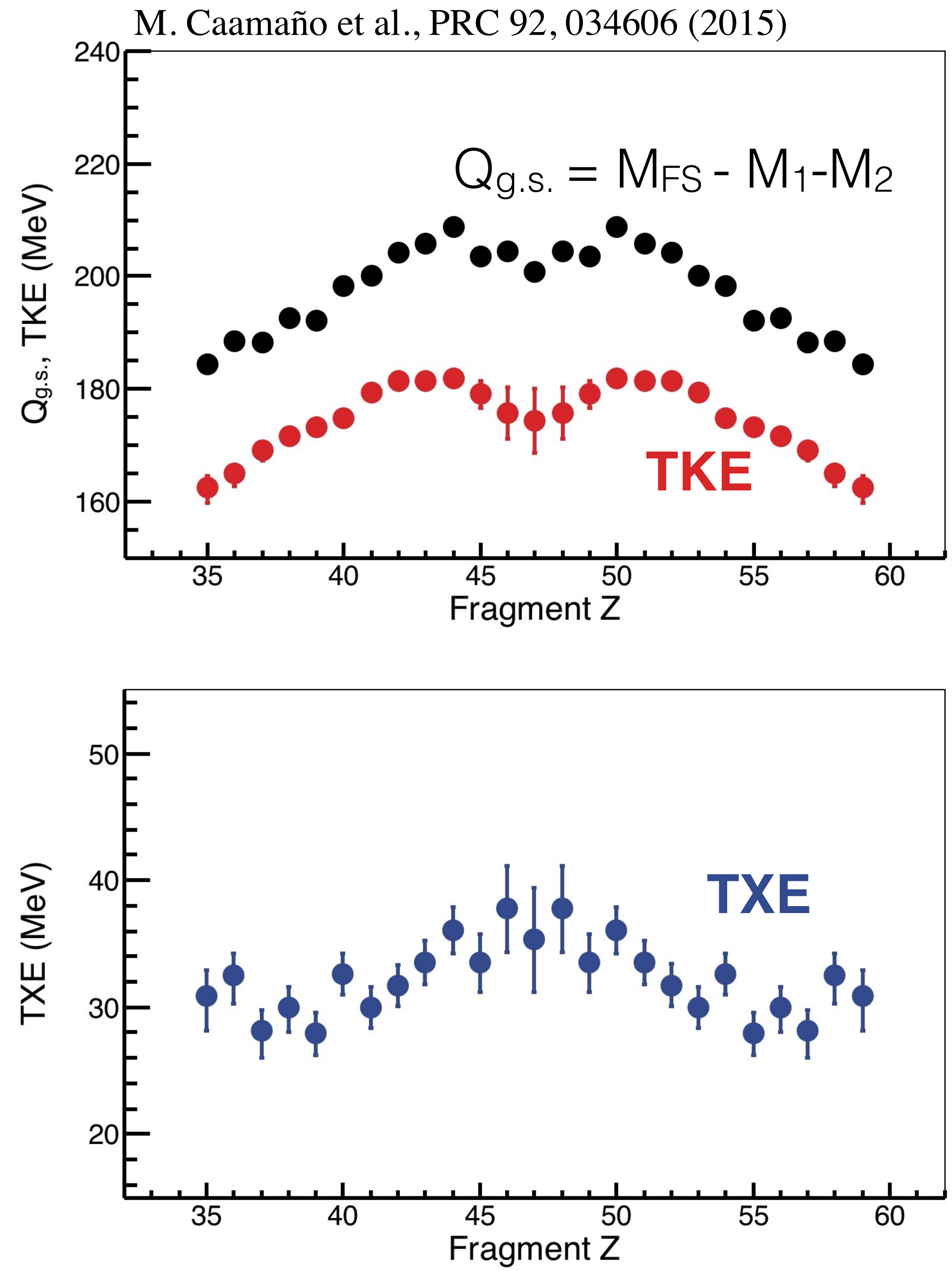
Neutron shells seem to drive the final splits

A more detailed energy balance



Total Kinetic Energy and Total eXcitation Energy

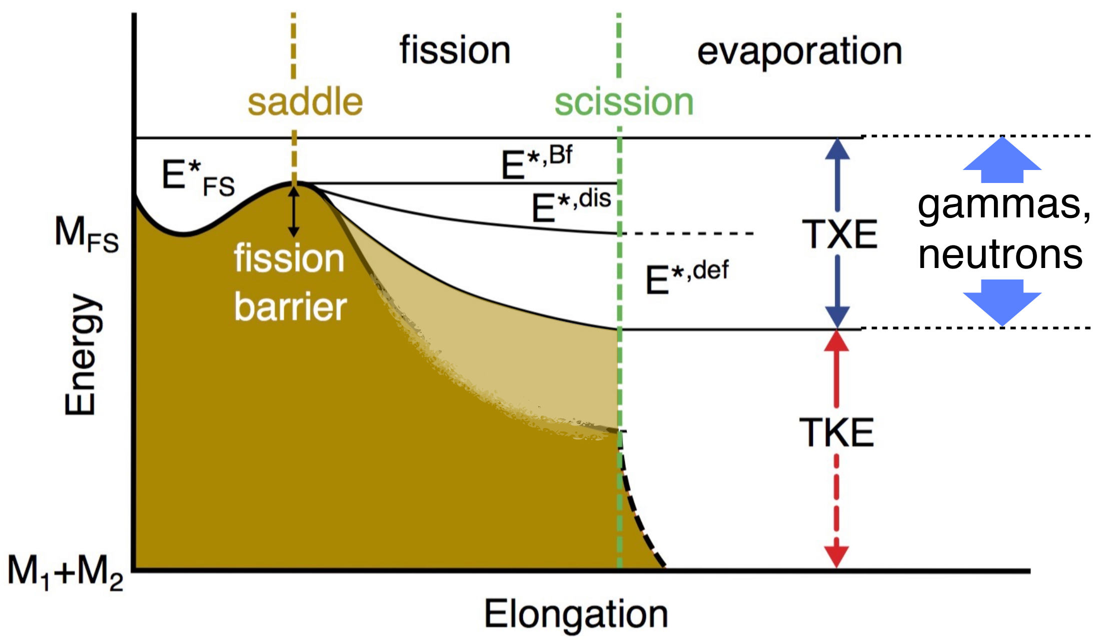




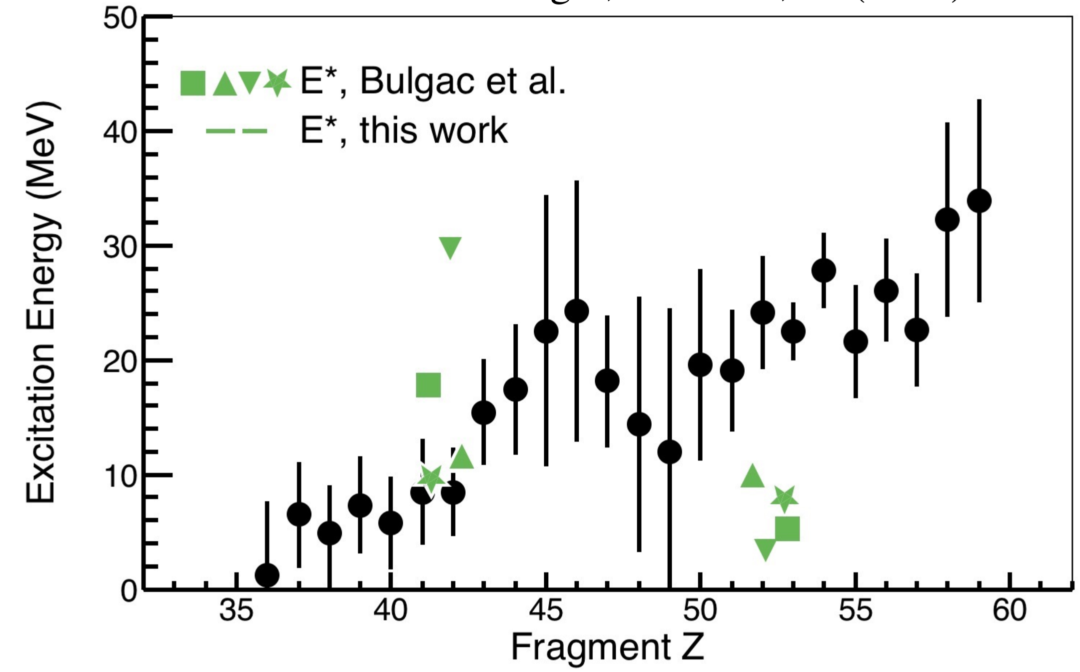
$$M_{FS} + E^*_{FS} = \mathbf{TXE} + \mathbf{TKE} + M_1 + M_2$$

These are all **measured** quantities

Intrinsic energy: statistical equilibrium



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

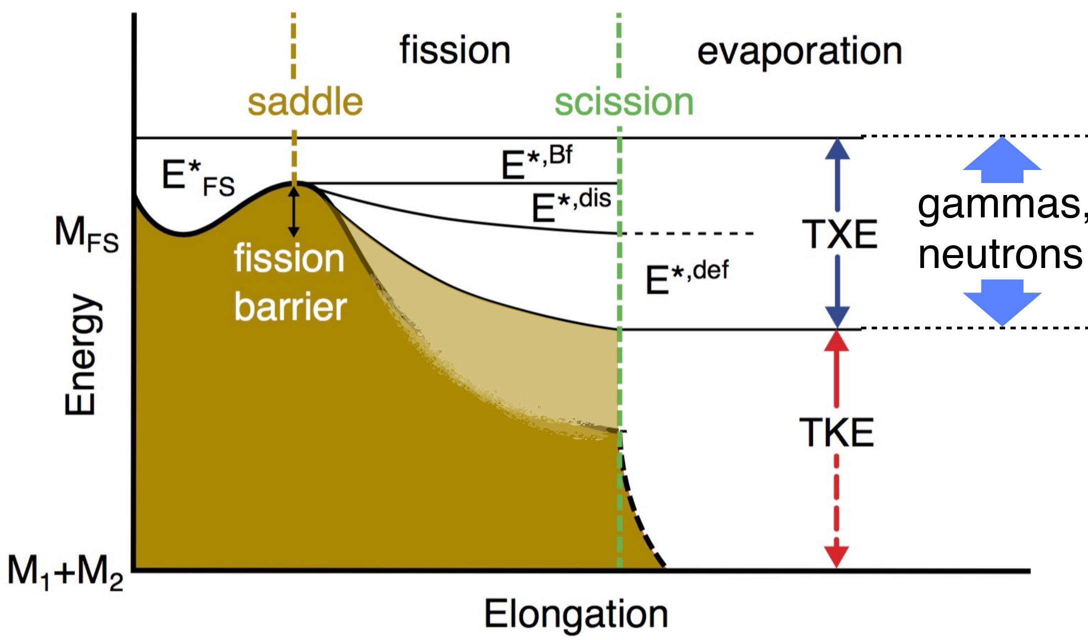


$$M_{FS} + E^*_{FS} = \mathbf{TXE} + \mathbf{TKE} + M_1 + M_2$$

$$\mathbf{TXE} = \sum (E^{*,Bf} + E^{*,dis} + E^{*,def})$$
$$= \sum (\nu \cdot (Q_n + \varepsilon) + E^{\gamma})$$

The **total E*** is shared between the fragments following the neutron evaporation.
It can be used to assess theoretical descriptions

Intrinsic and deformation energy

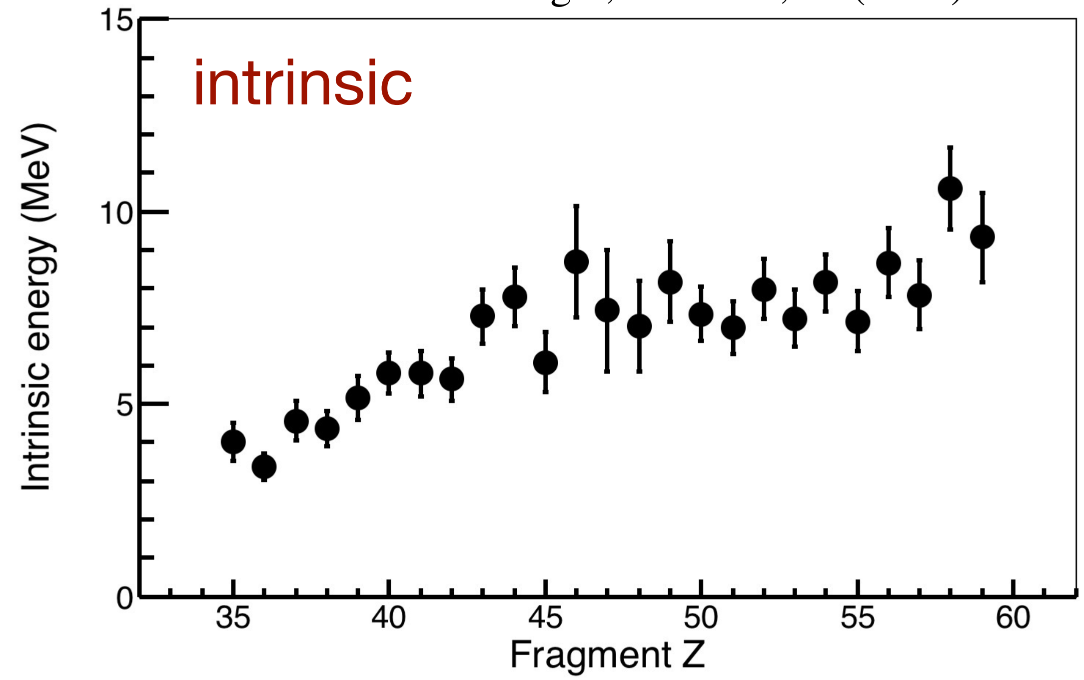


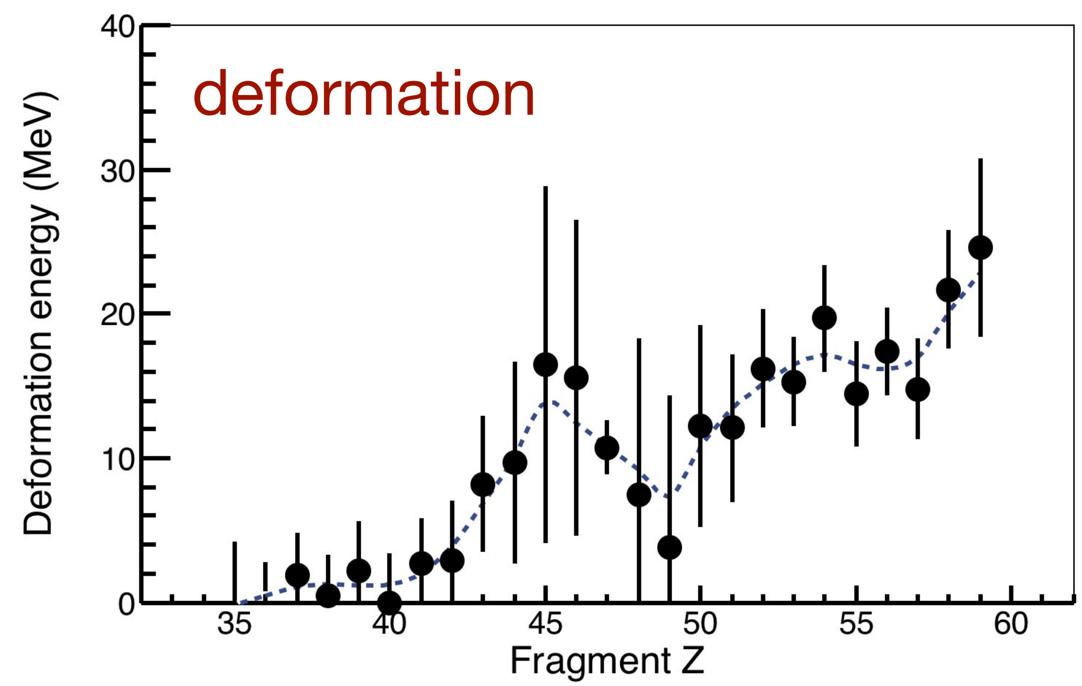
$M_{FS} + E^{*}_{FS} =$ **TXE** + **TKE** $+ M_1 + M_2$

TXE $= \sum (E^{*,Bf} + E^{*,dis} + E^{*,def})$

We can also access **intrinsic energy** and **deformation energy**

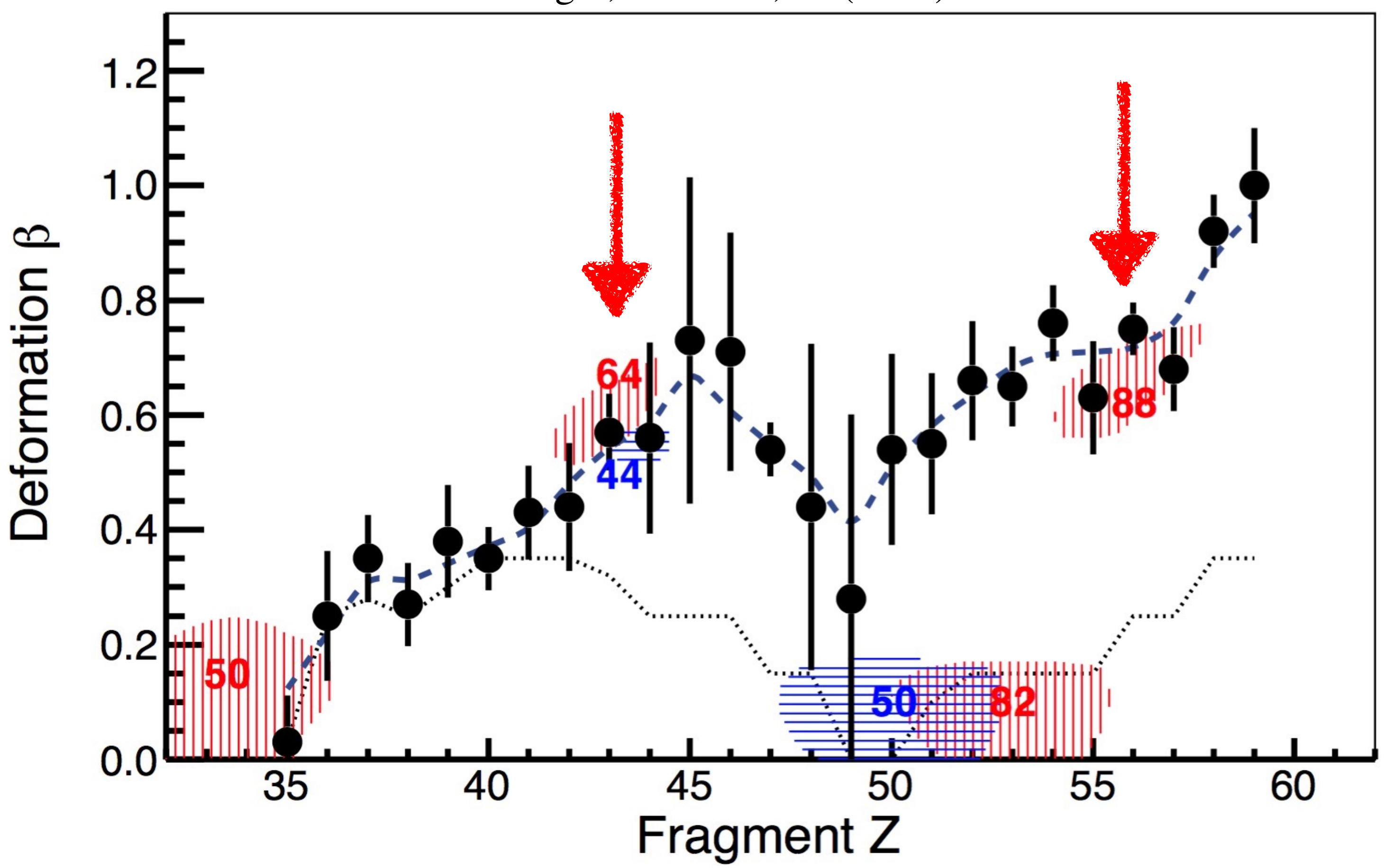
M. Caamaño and F. Farget, PLB 770, 72 (2017)



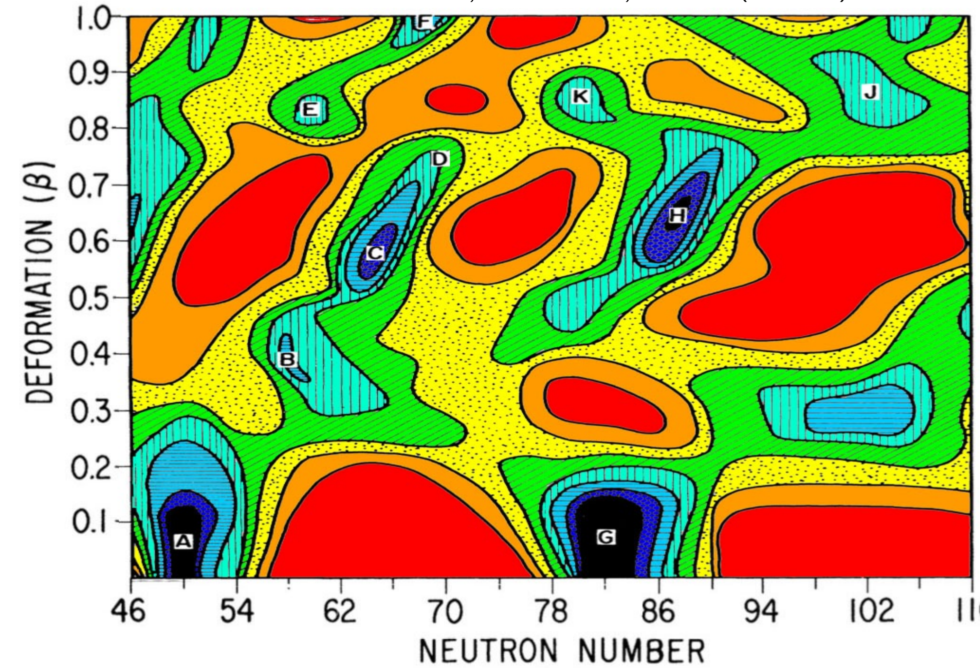


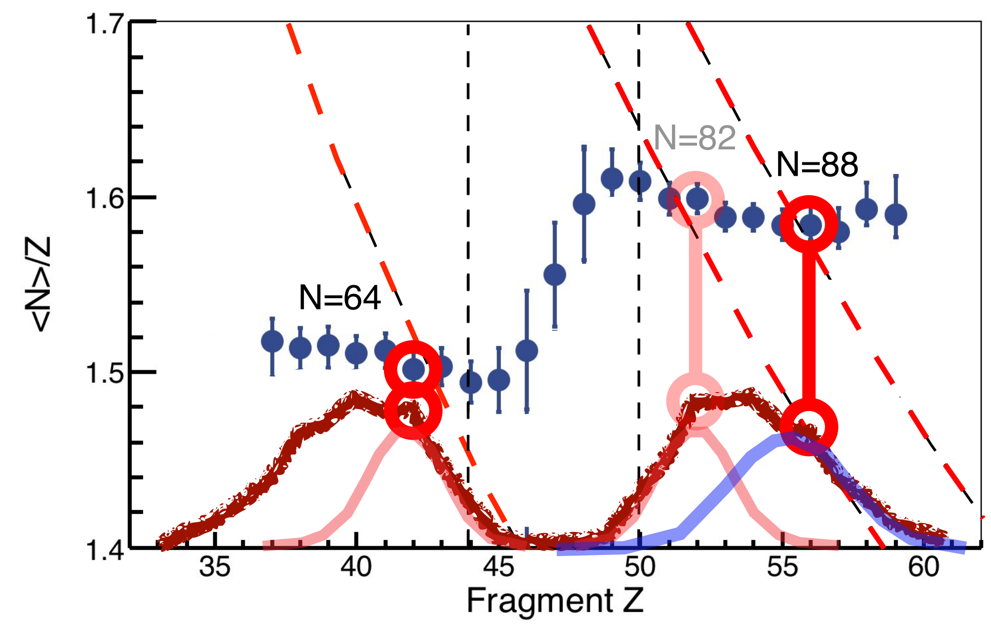
Deformed shells

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



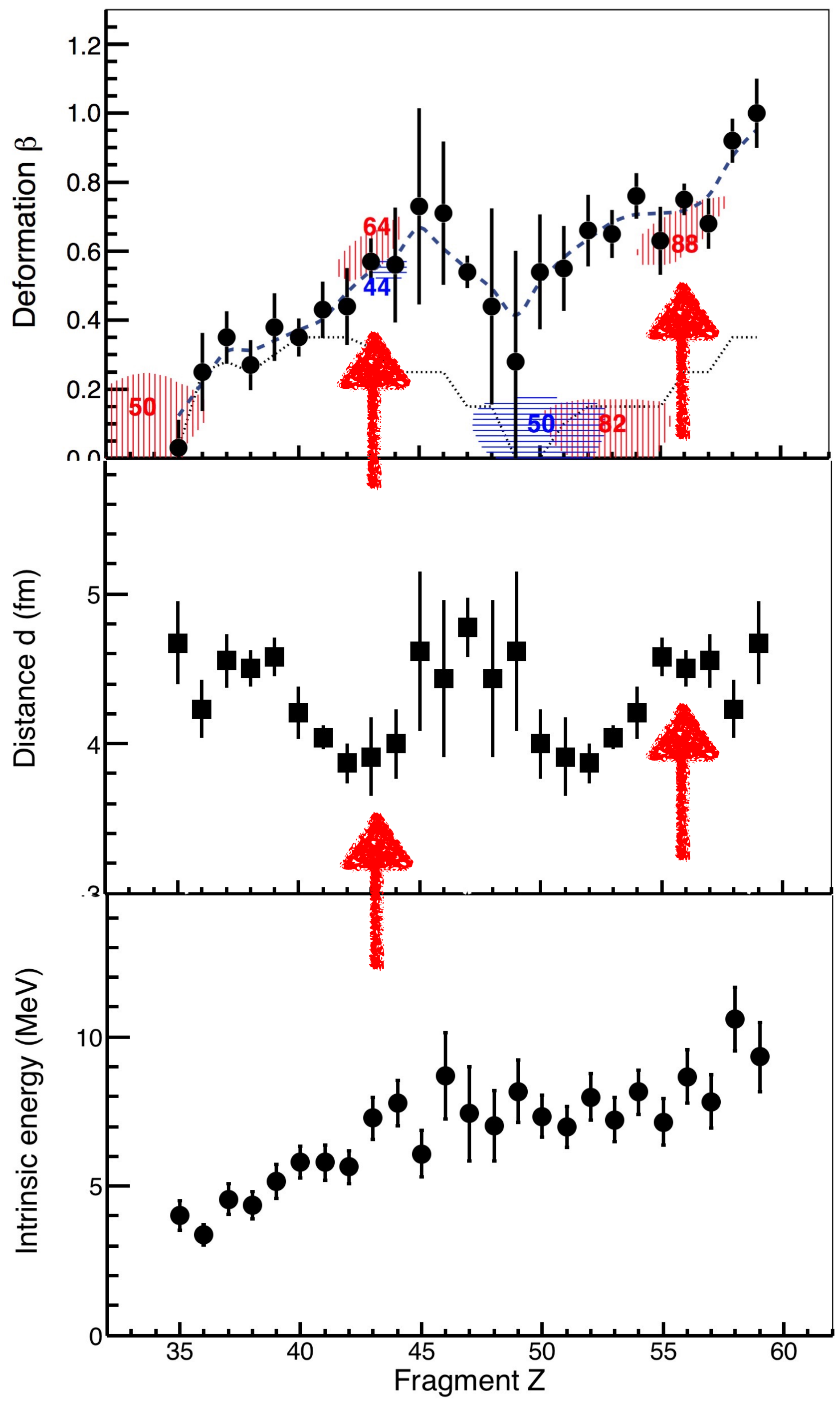
B.D. Wilkins et al., PRC 14, 1832 (1976)



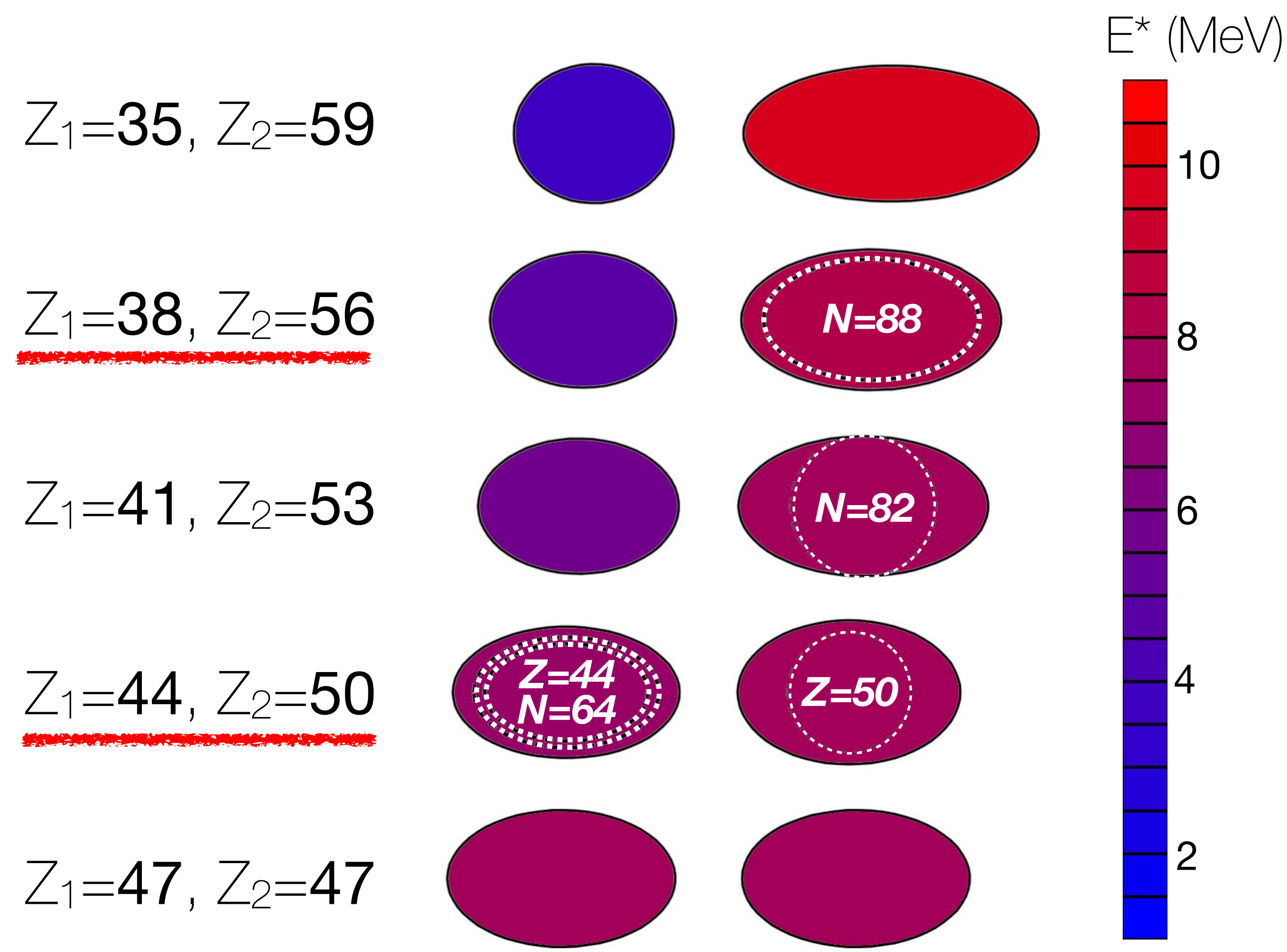


The deformation distribution crosses
N=64, N=88 shells to produce **Z~43, Z=56**

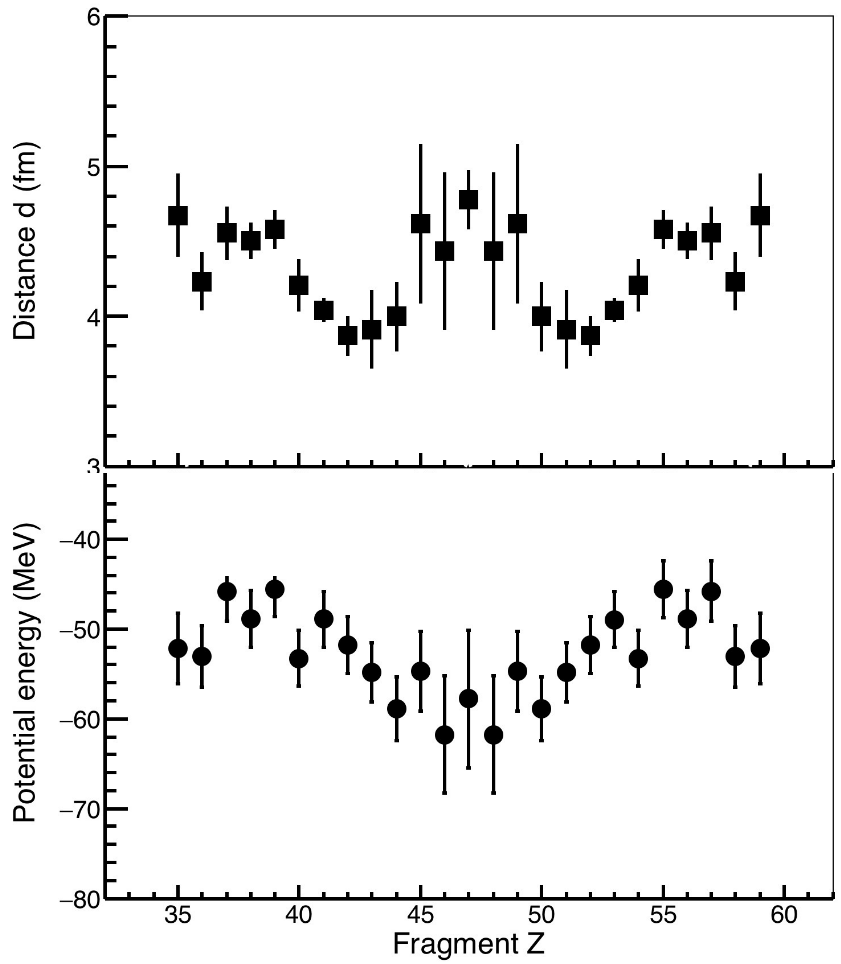
A picture of scission: shapes and energy



a collective picture of scission:

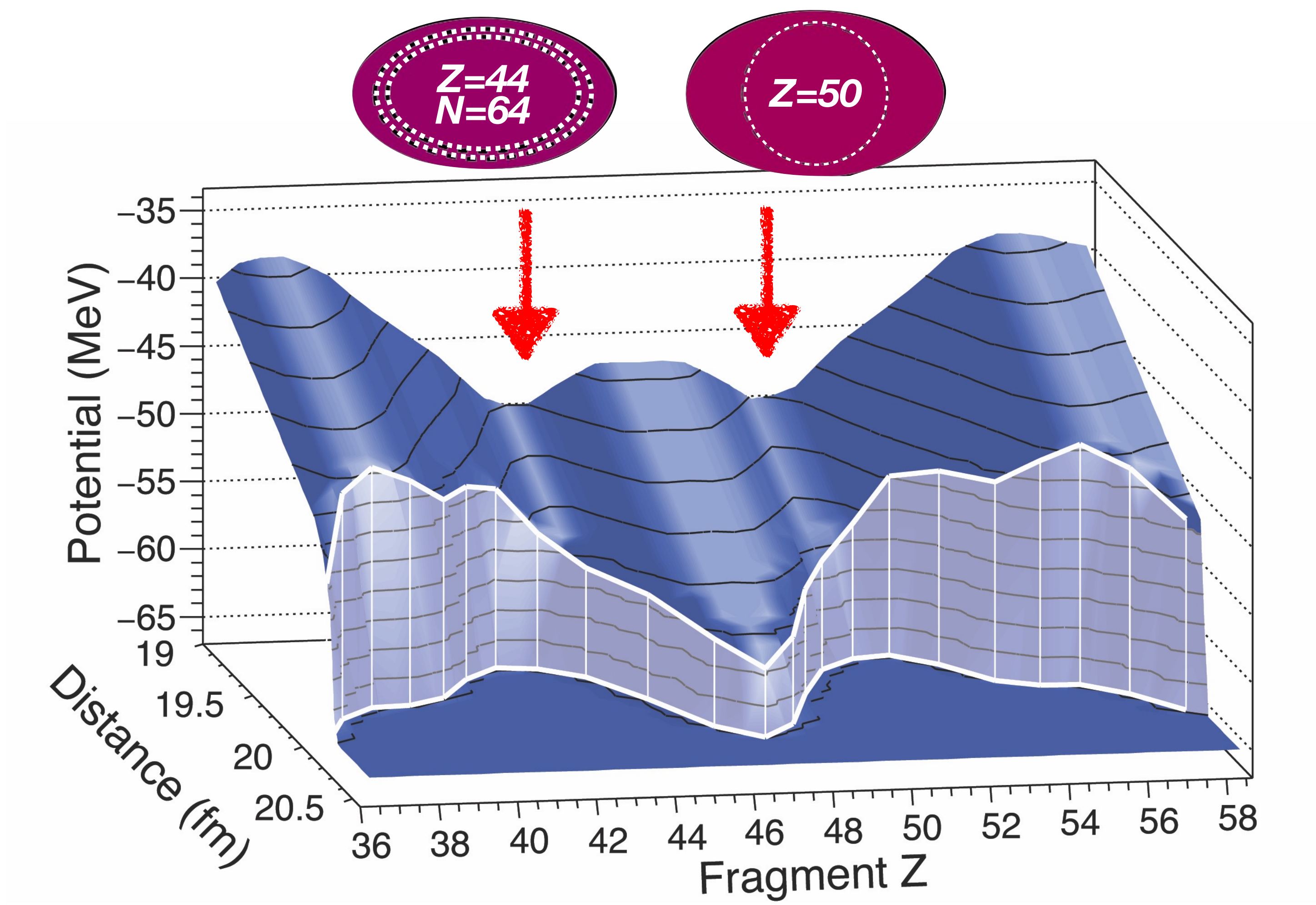


A picture of scission: potential energy landscape



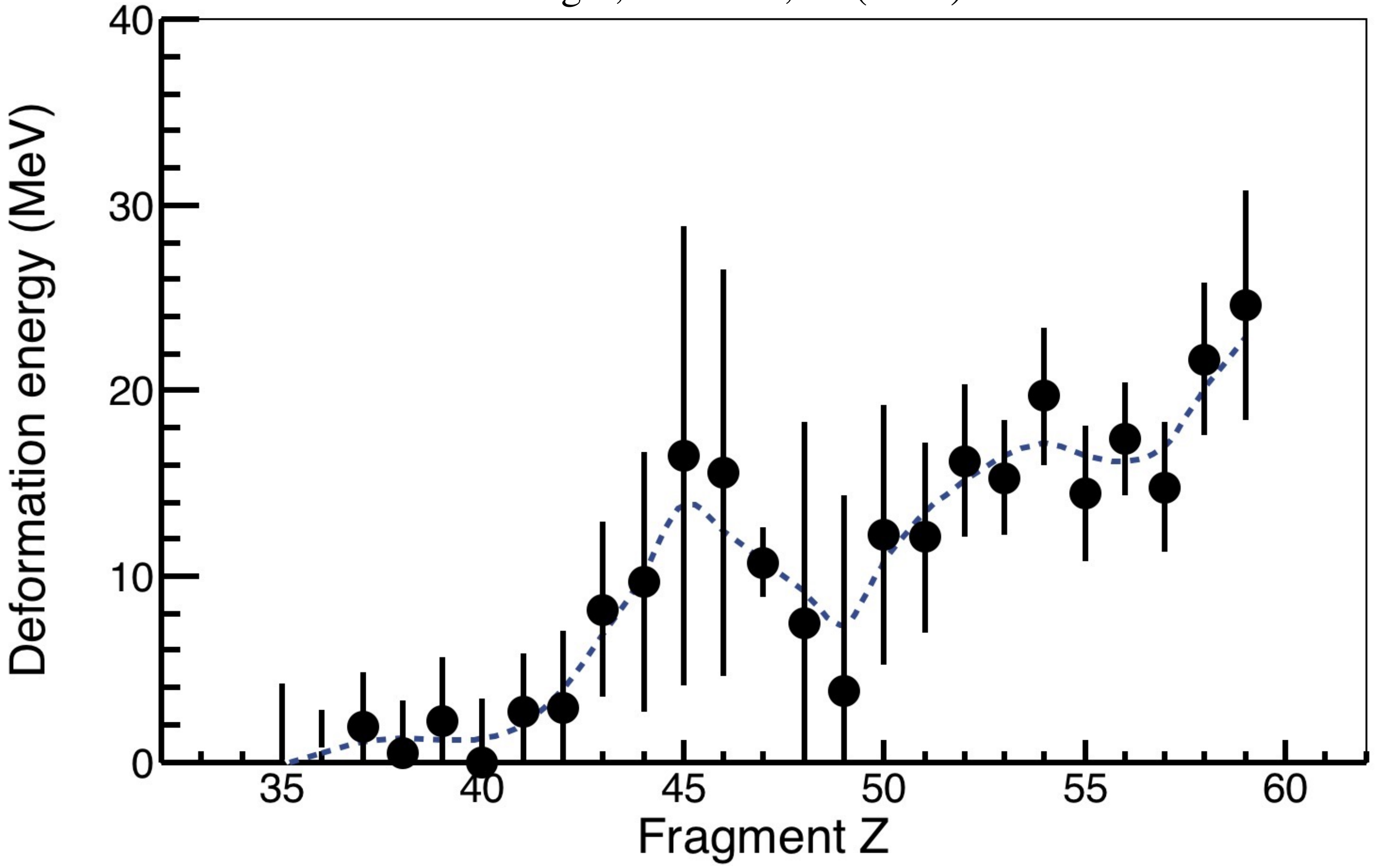
$$PE = -TXE + E^{*,def}$$

and a sneak peek of the potential landscape:

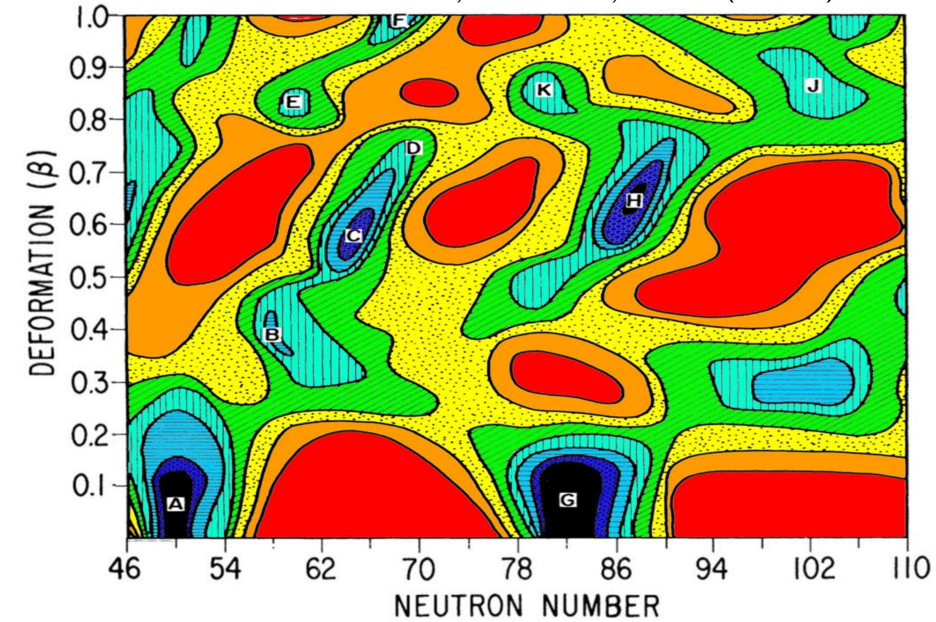


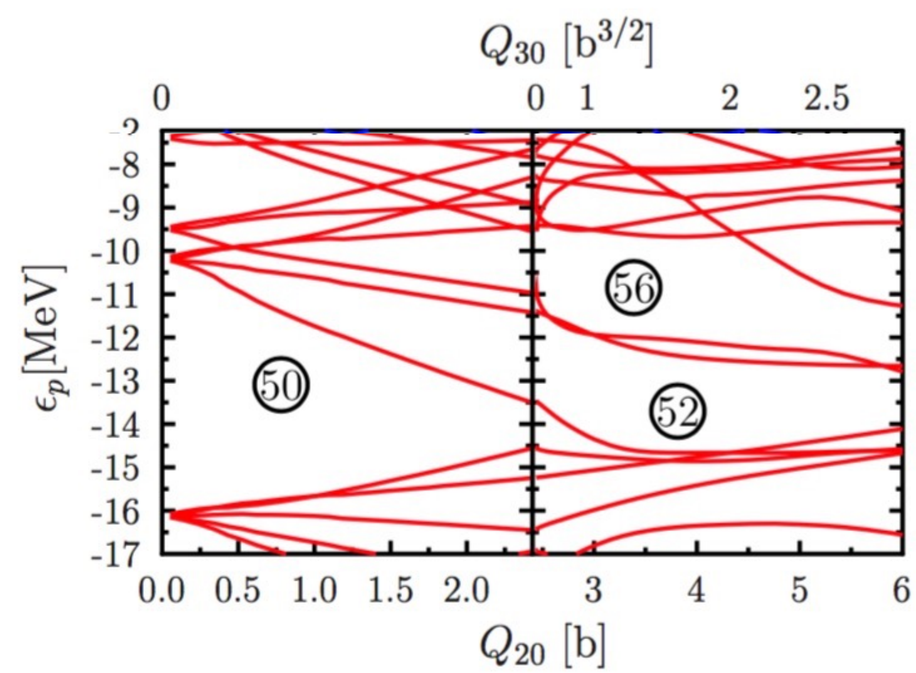
Except that… Quadrupolar or octupolar?

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



B.D. Wilkins et al., PRC 14, 1832 (1976)

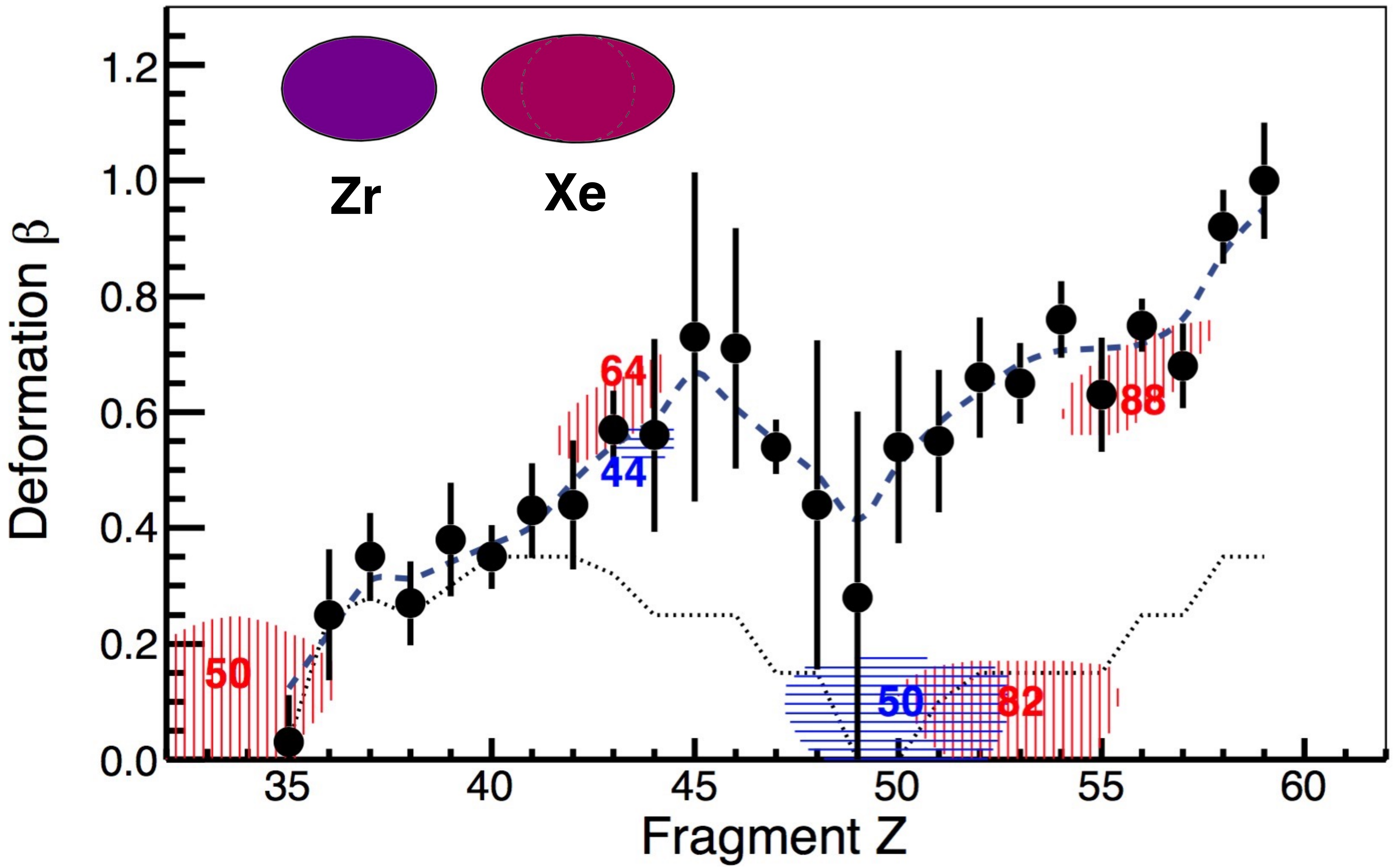




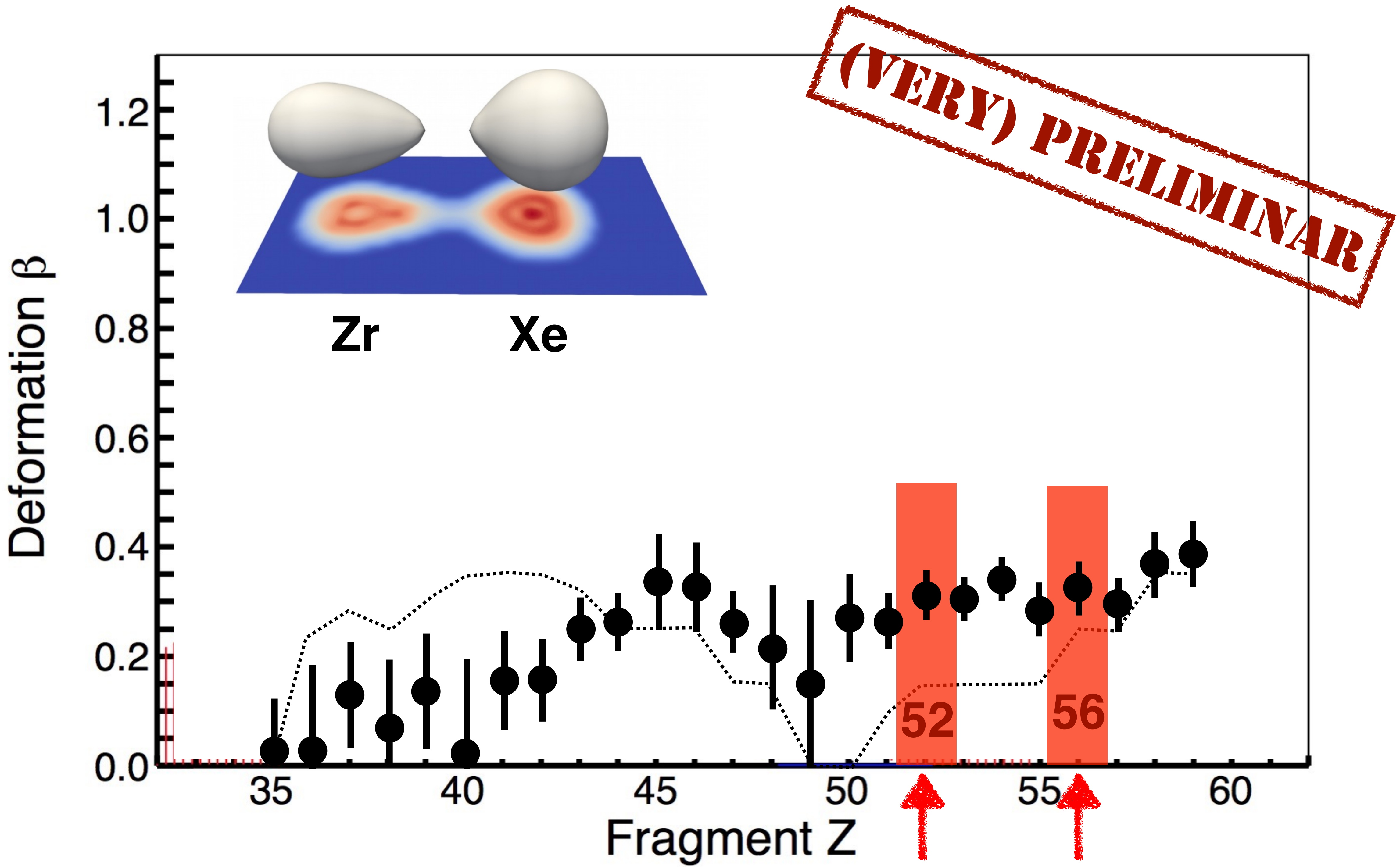
G. Scamps, C. Simenel, arXiV 1804.03337v1 (2018)

How do the fragments use their **deformation energy**?

Quadrupolar or Octupolar?

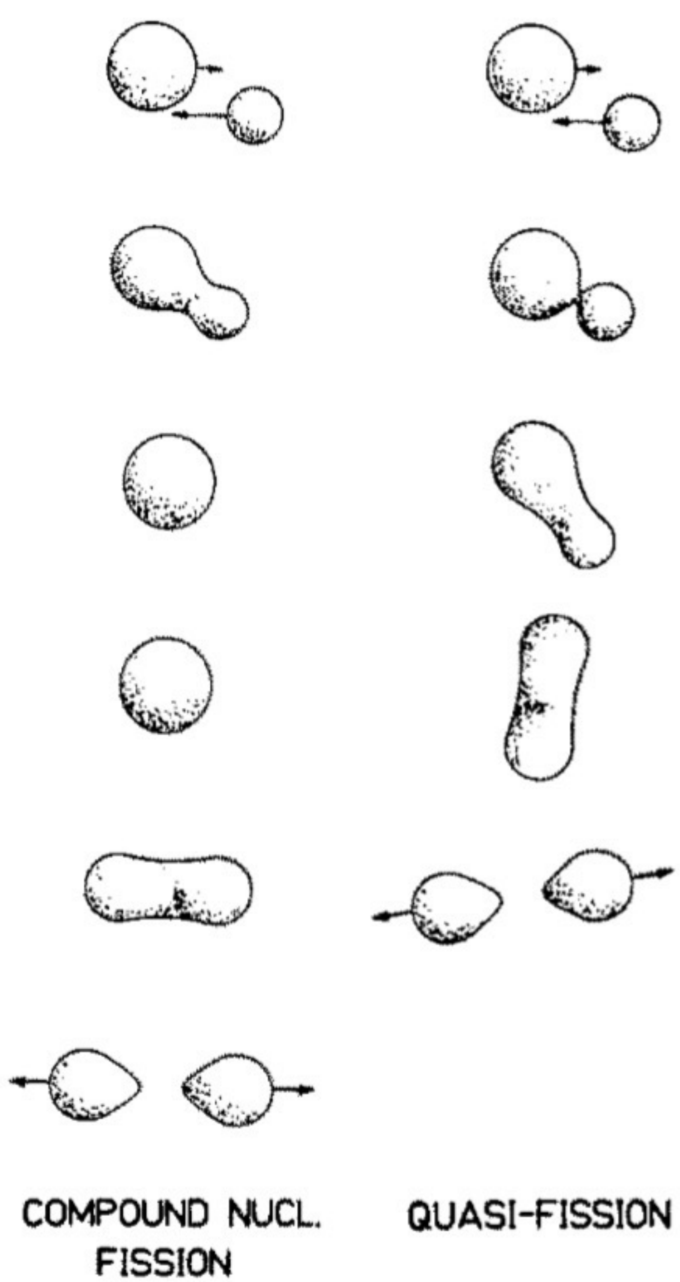


Quadrupolar or **Octupolar**?



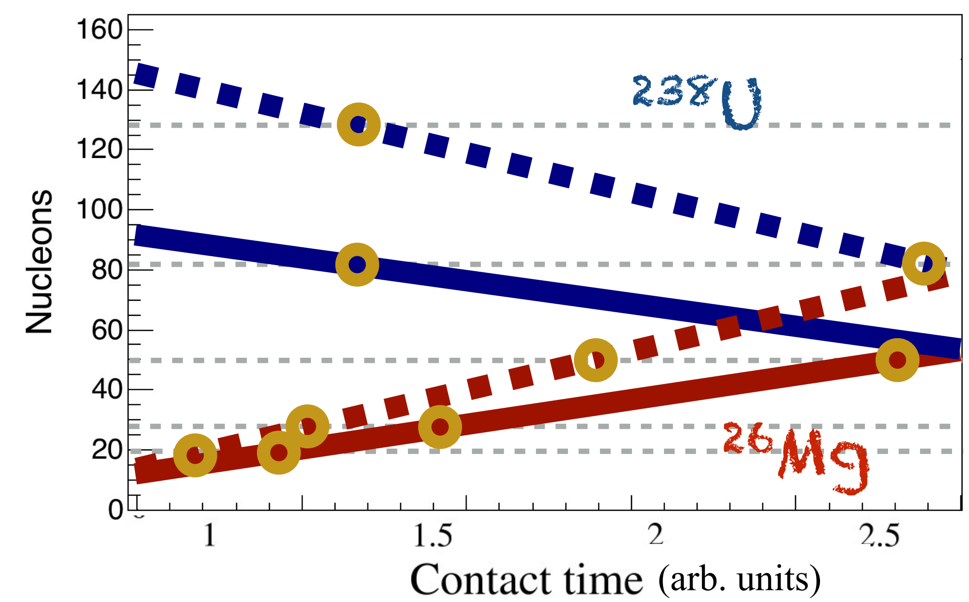
What else?

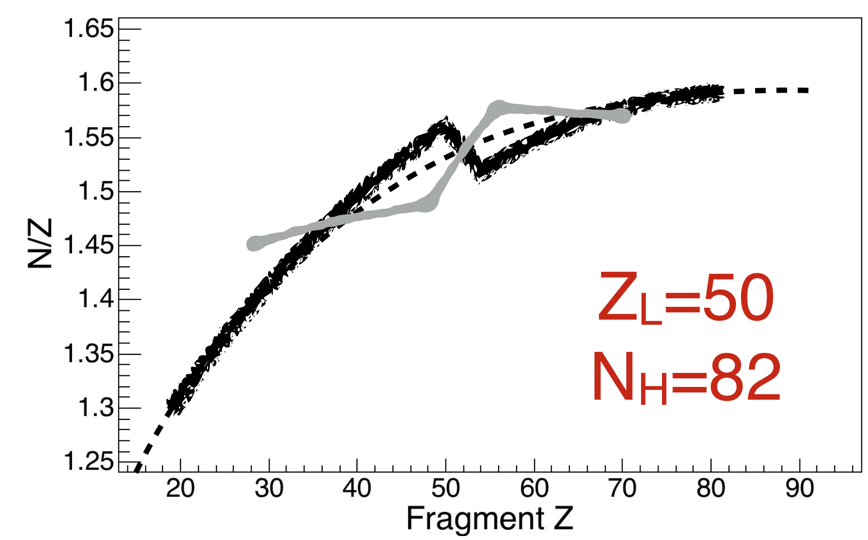
J. Töke et al., NPA 440, 327 (1985)



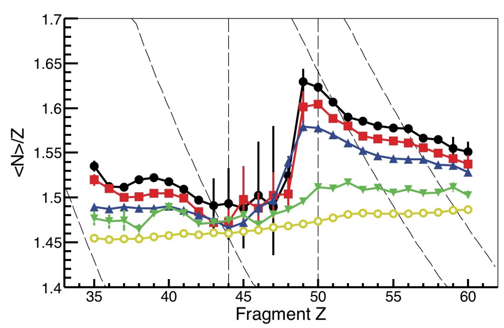
The case of **high-energy** and **quasi-fission**

^{238}U @ 5.9 AMeV + [^{26}Mg, ^{27}Al, ^{11}B, ^{9}Be] at **VAMOS/GANIL**

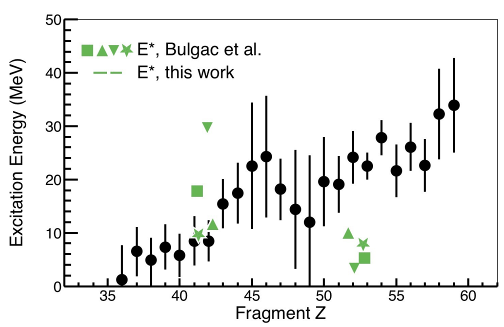




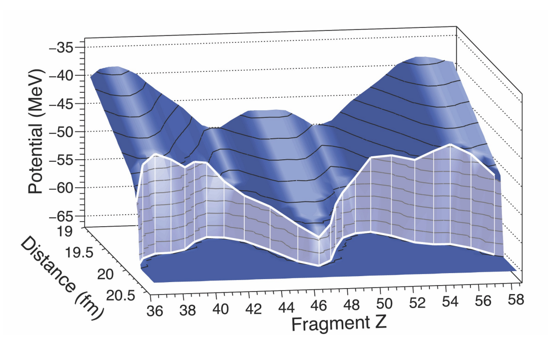
In summary, inverse kinematics brings



New and revisited fission observables (nuclear databases)



Stringent checking and comparisons with models

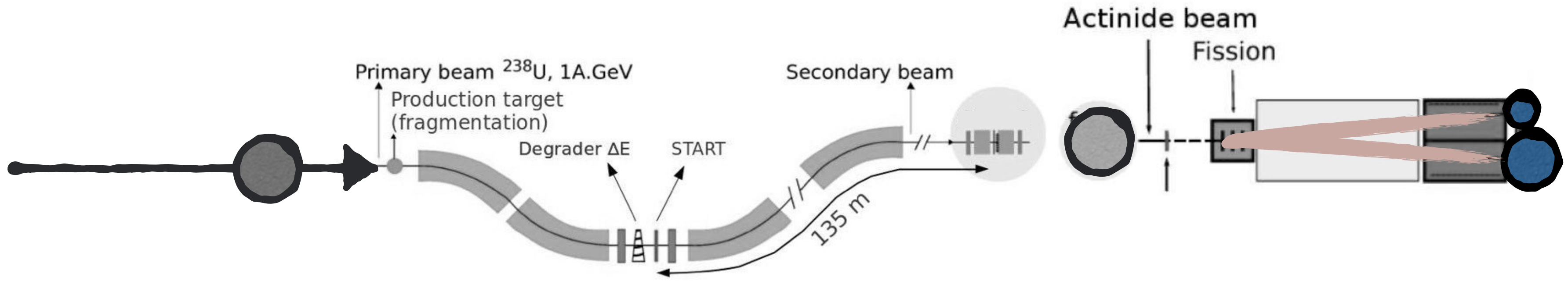


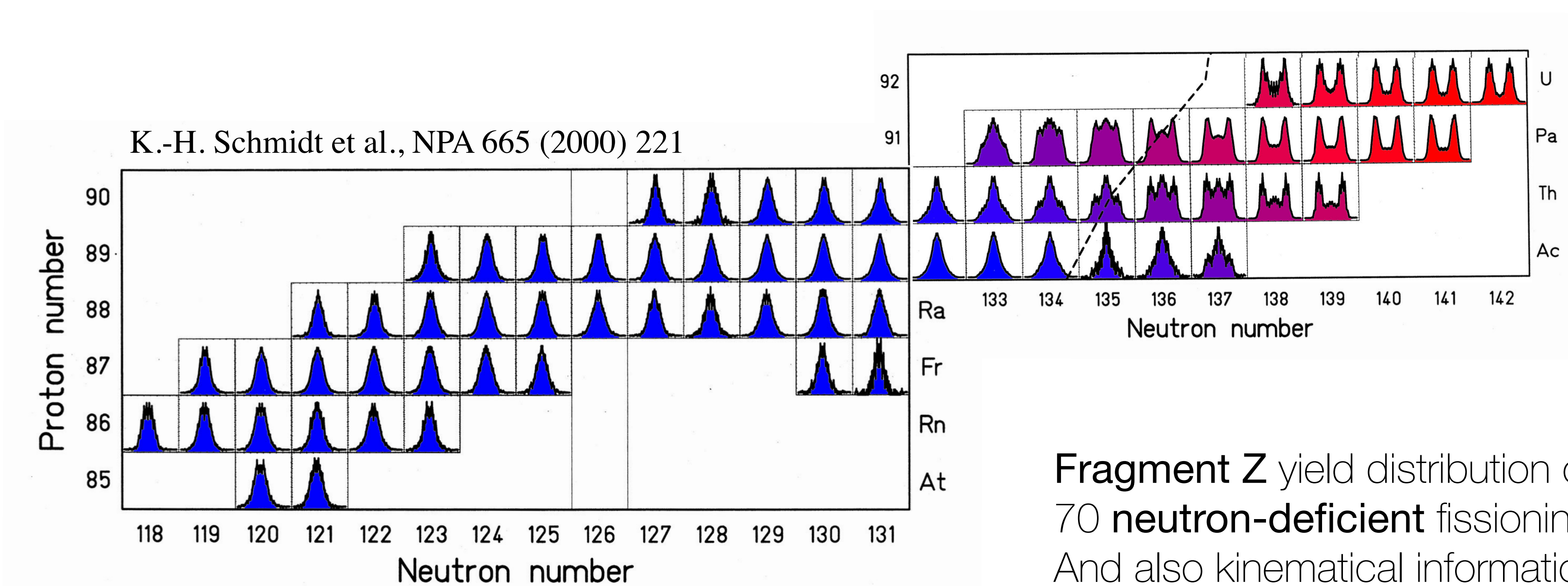
Access to the scission configuration (shells and dynamics)

Inverse kinematics at GSI:

Production from fragmentation and e-m fission induced

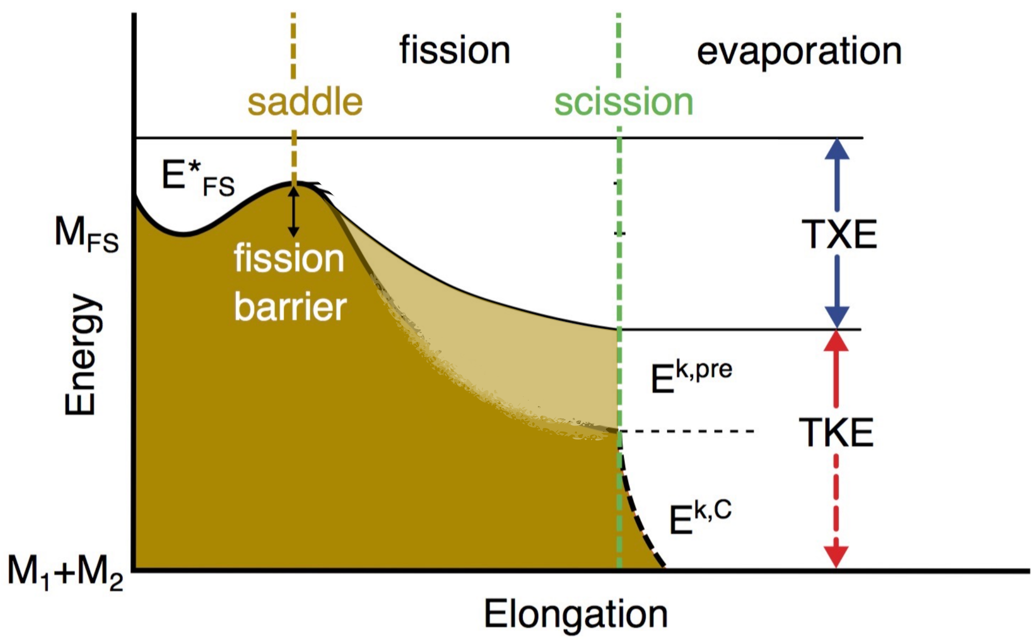
K.-H. Schmidt et al.

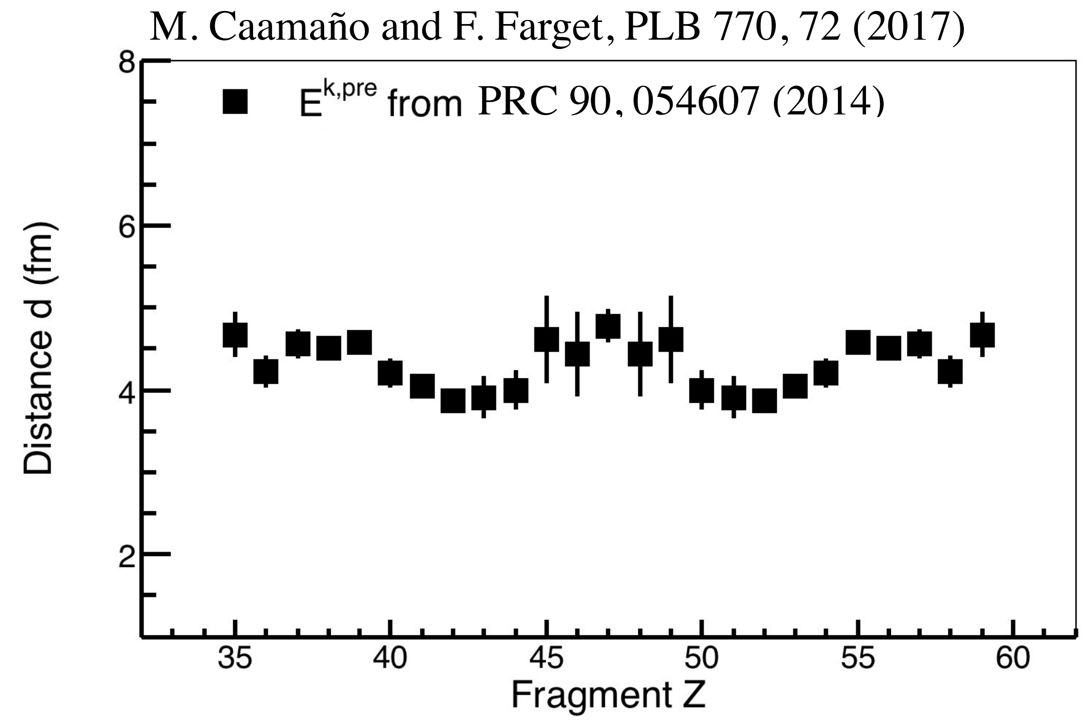




Fragment Z yield distribution of more than 70 **neutron-deficient** fissioning systems.
And also kinematical information…

TKE and fragment distance

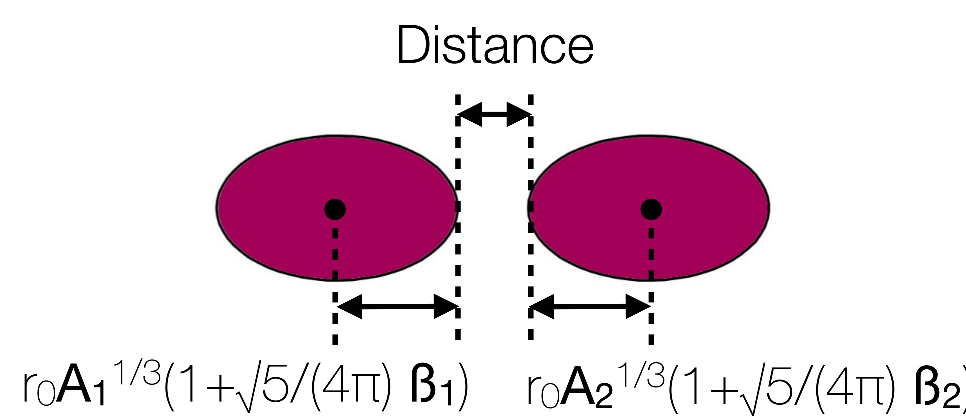




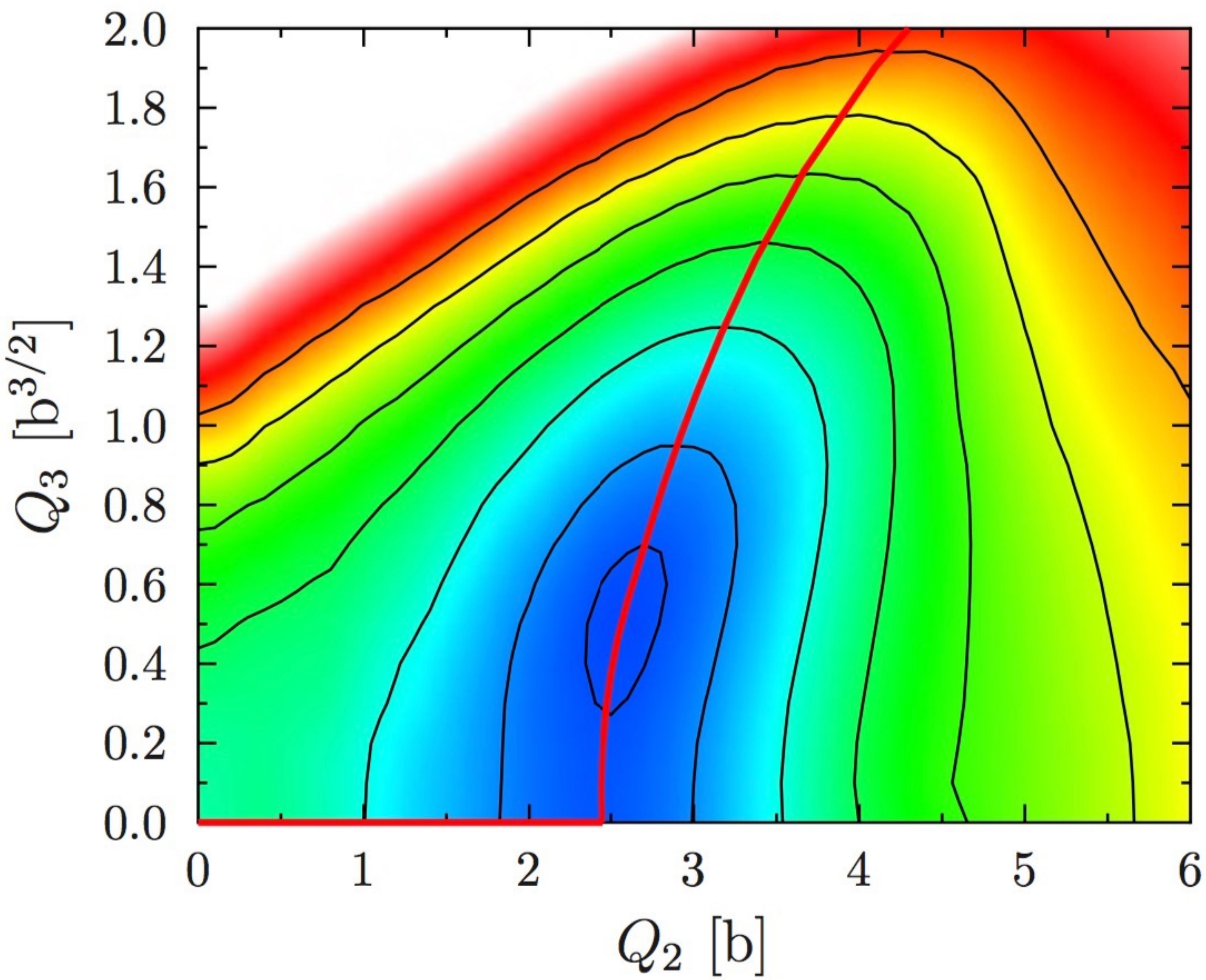
$$M_{FS} + E^*_{FS} = \mathbf{TXE} + \mathbf{TKE} + M_1 + M_2$$

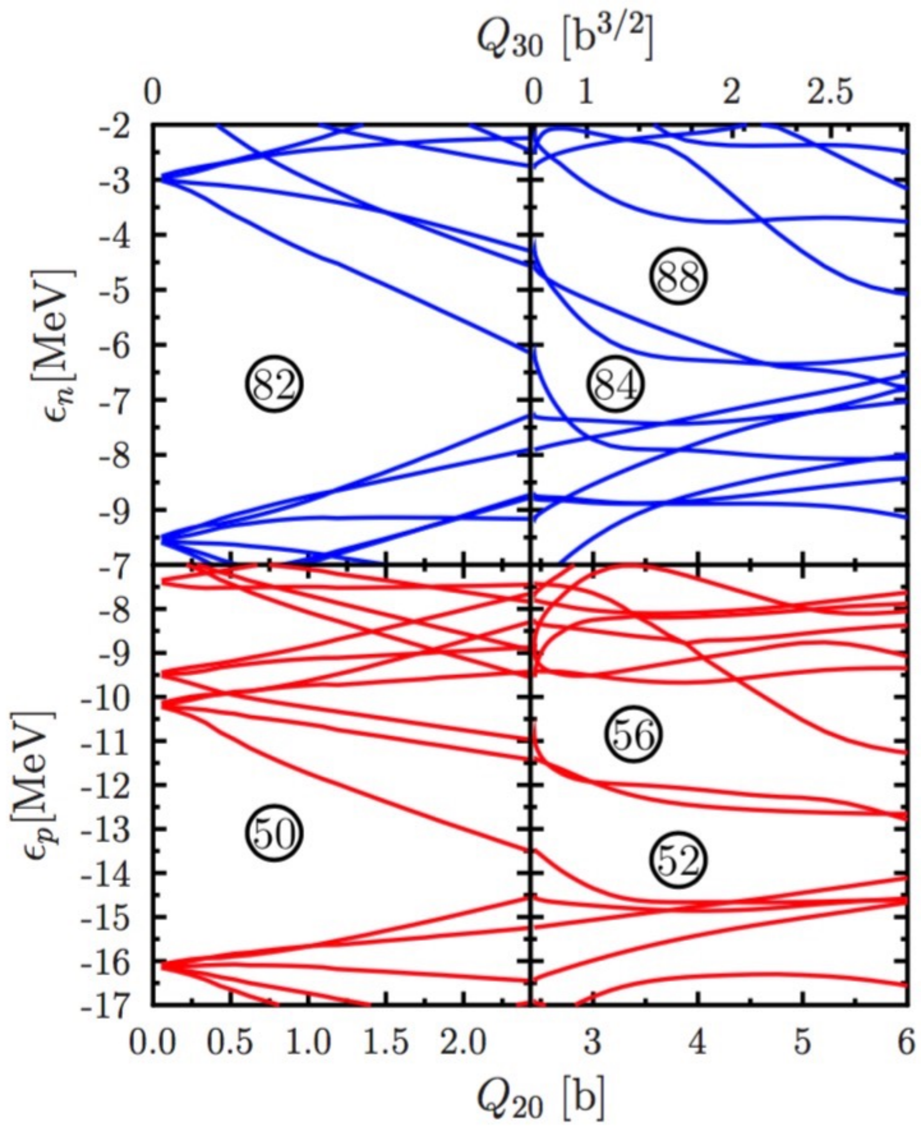
$$\mathbf{TKE} = E^{k,pre} + E^{k,C}$$

$$= E^{k,pre} + 1.44 \cdot Z_1 \cdot Z_2 / D(\beta, d)$$



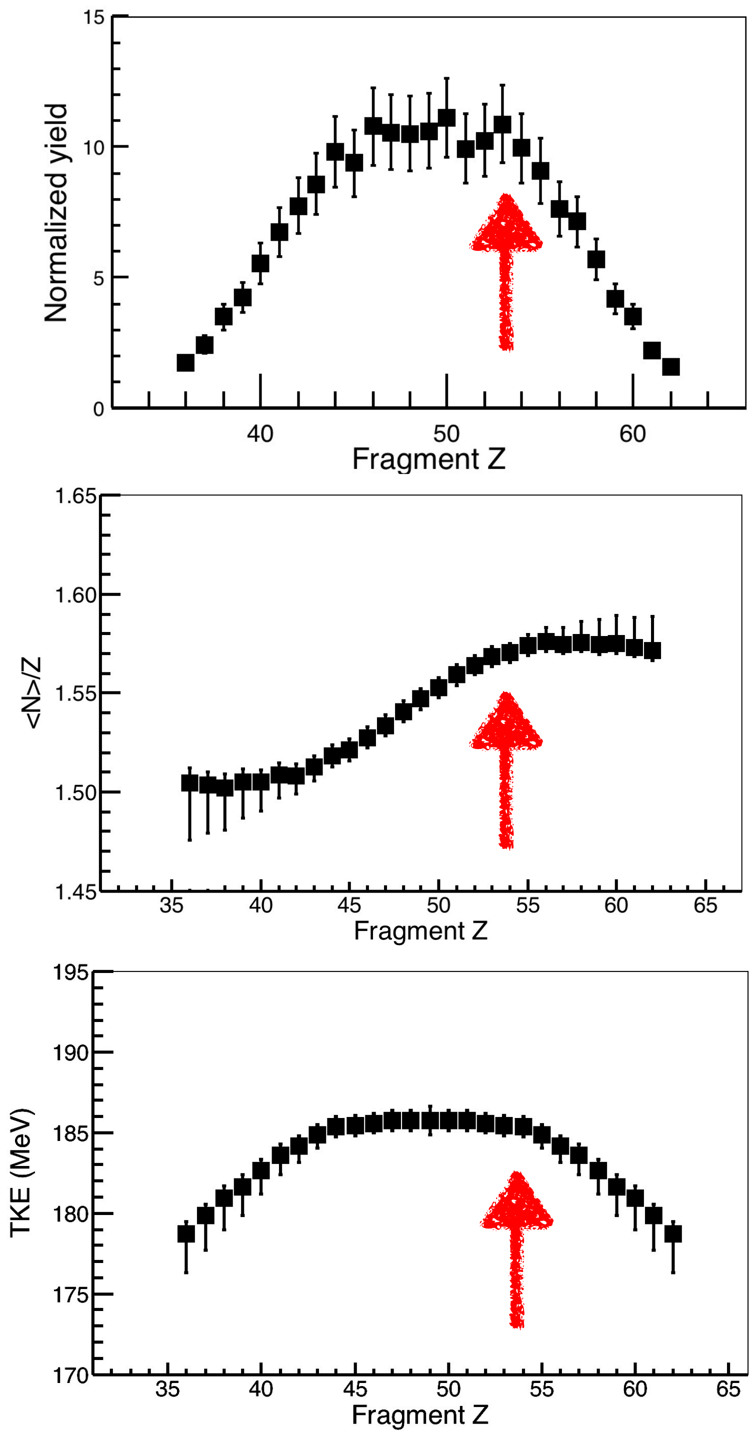
access to the distance between fragments

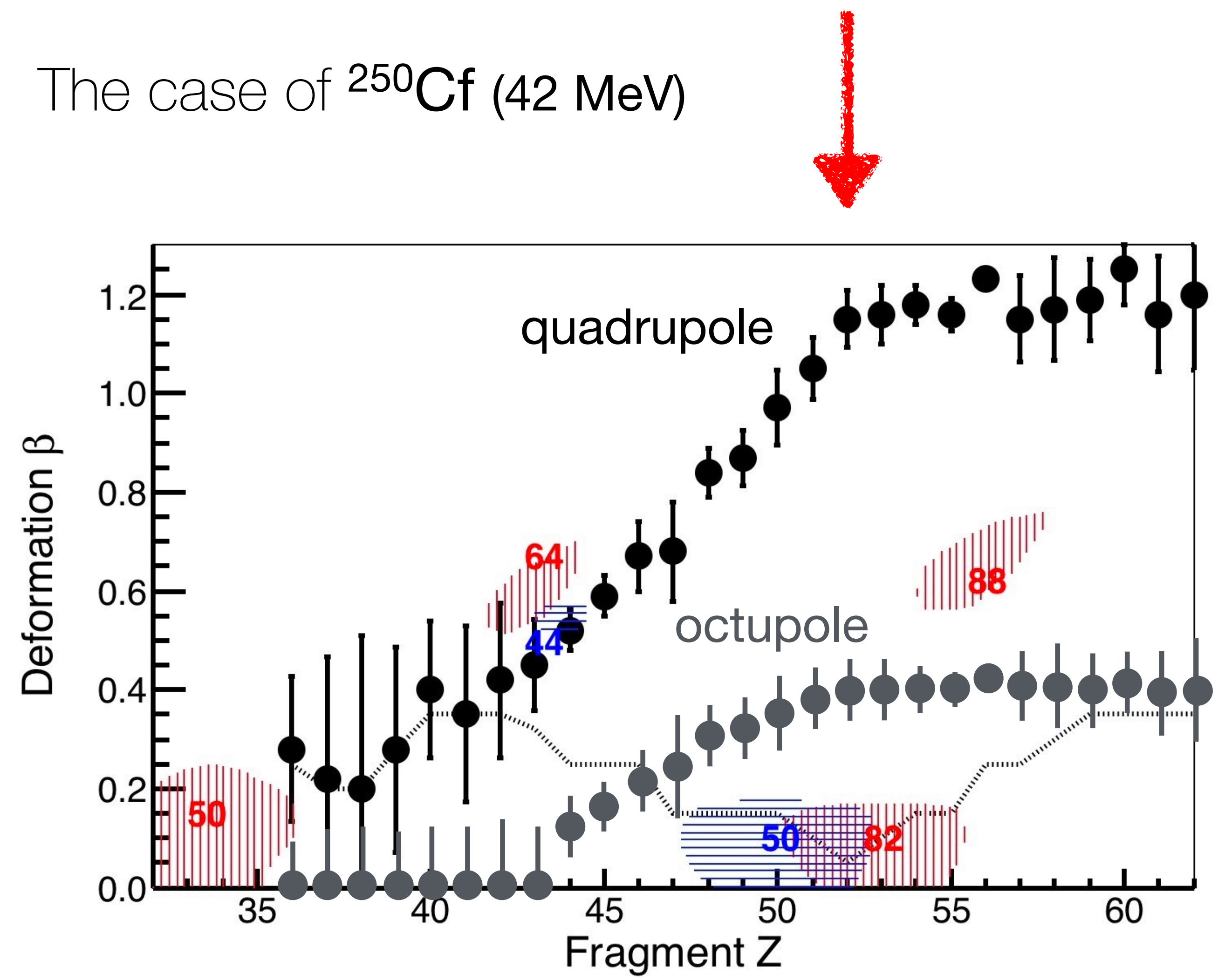

2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Q_3 [$b^{3/2}$]
0
1
2
3
4
5
6
Q_2 [b]


Q_{30} [$b^{3/2}$]
0
0
1
2
2.5
-2
-3
-4
-5
-6
-7
-8
-9
ϵ_n[MeV]
82
84
88
-7
-8
-9
-10
-11
-12
-13
-14
-15
-16
-17
ϵ_p[MeV]
50
52
56
0.0
0.5
1.0
1.5
2.0
3
4
5
6
Q_{20} [b]

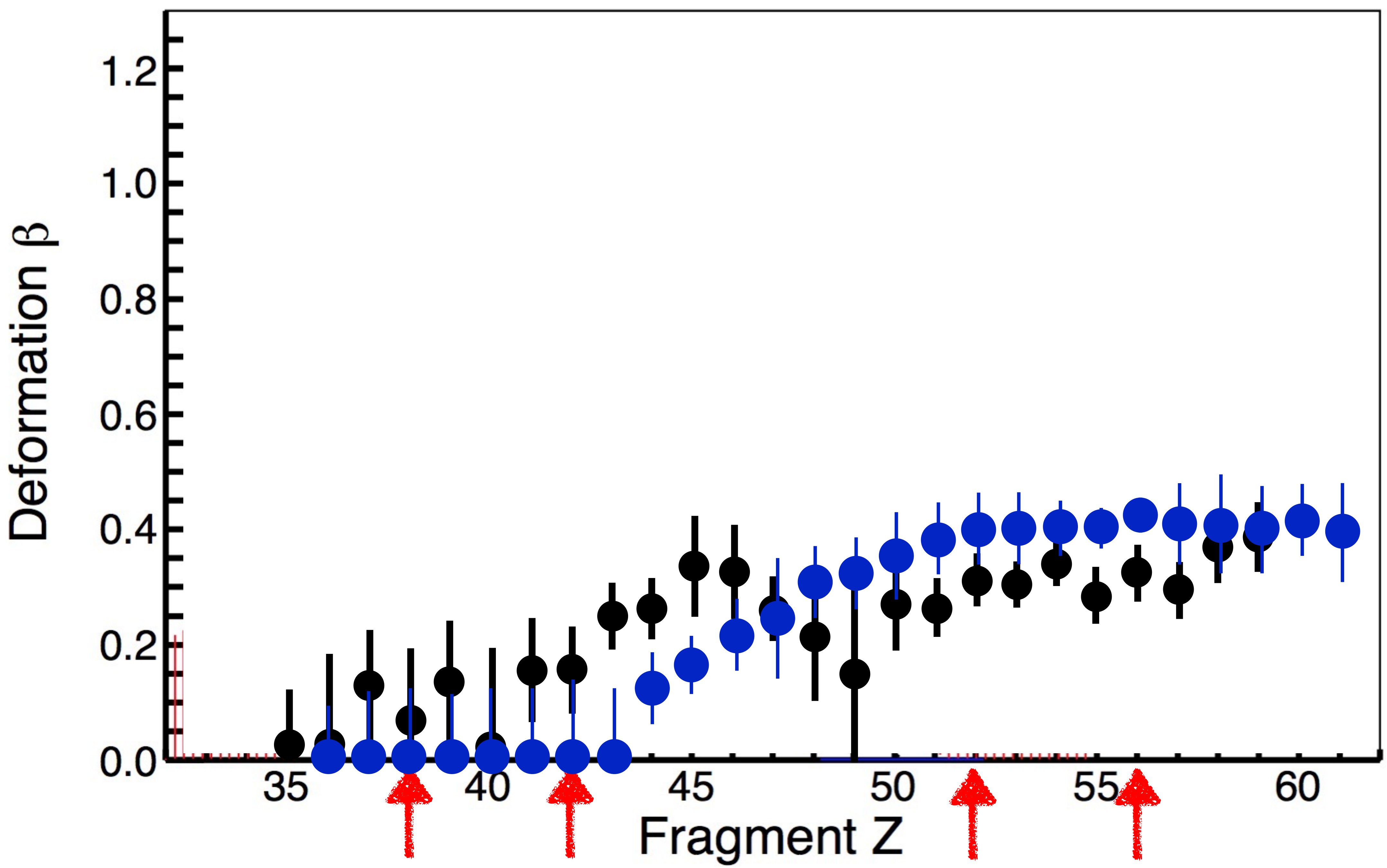
What else?

The case of ^{250}Cf (42 MeV)

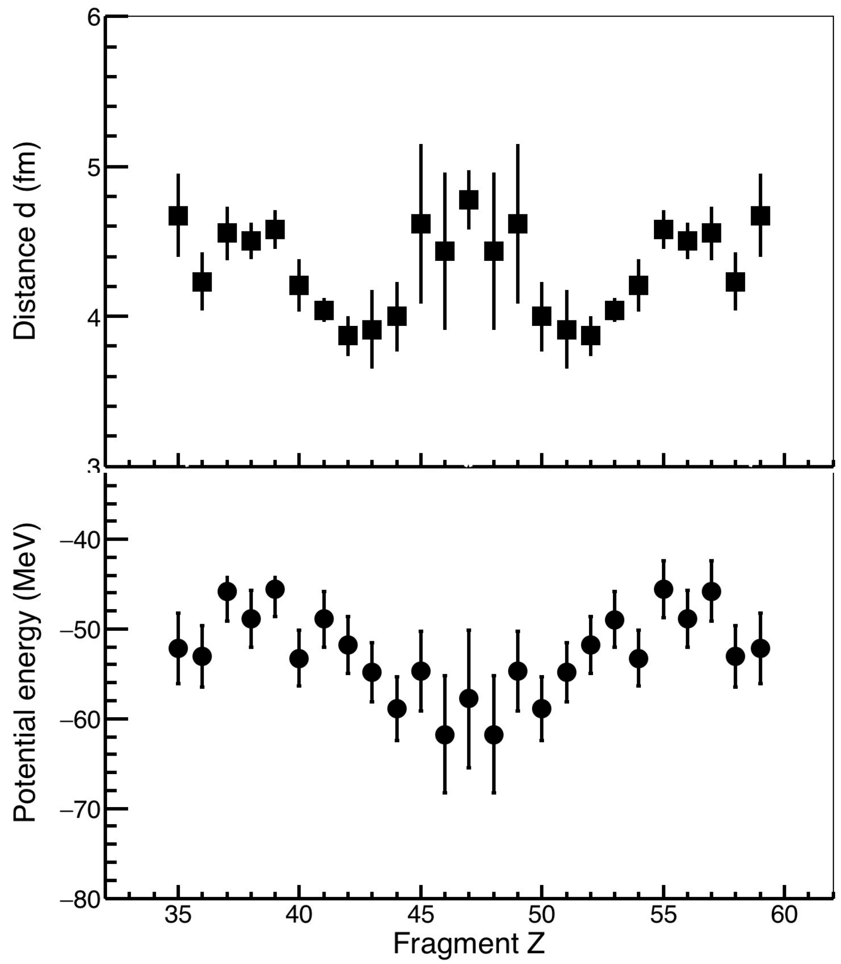




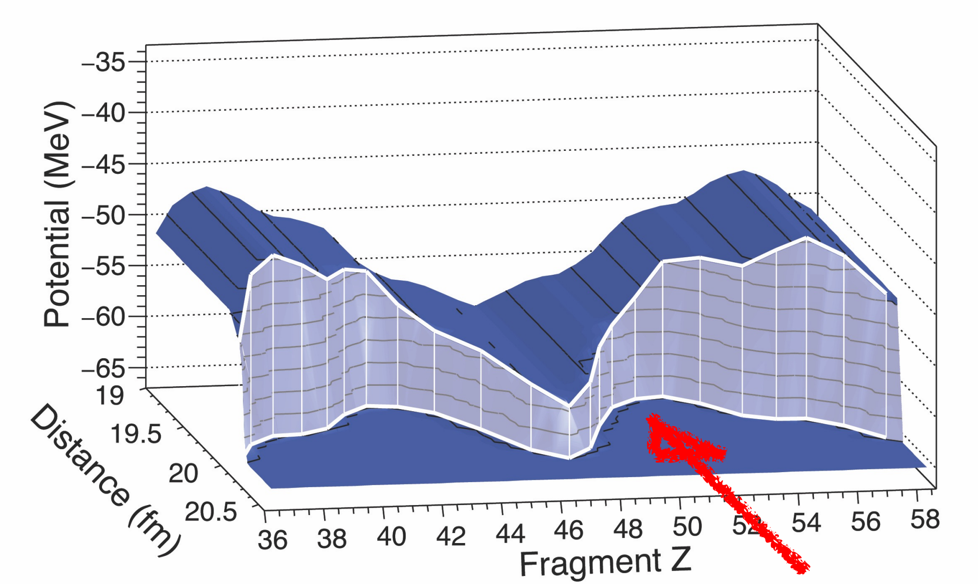
- Pre-saddle emission?
- No dissipation?
- Still shells?

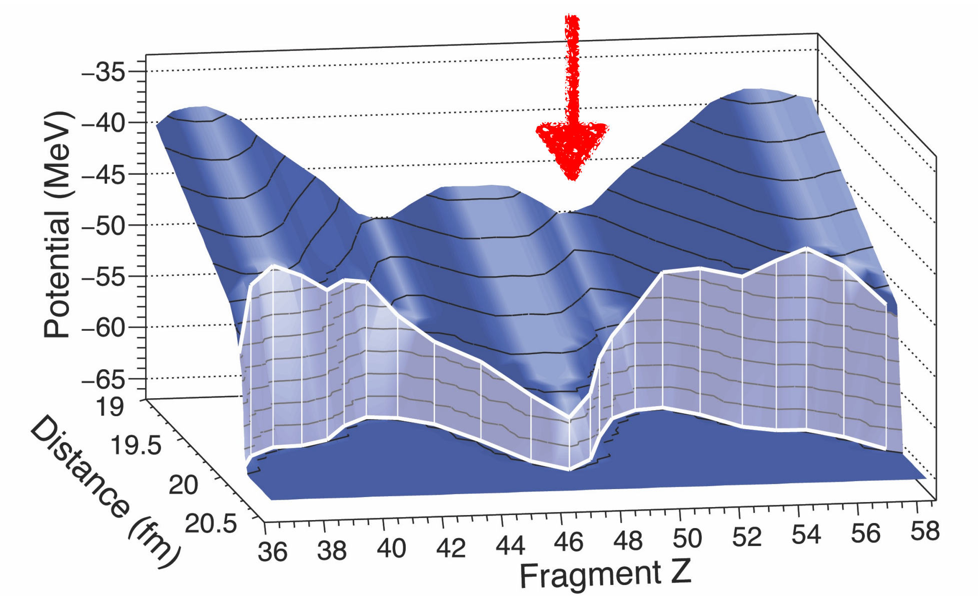

Deformation β
1.2
1.0
0.8
0.6
0.4
0.2
0.0
35
40
45
50
55
60
Fragment Z

New access to scission; the case of ^{240}Pu (9 MeV)



and a sneak peak of the potential landscape:



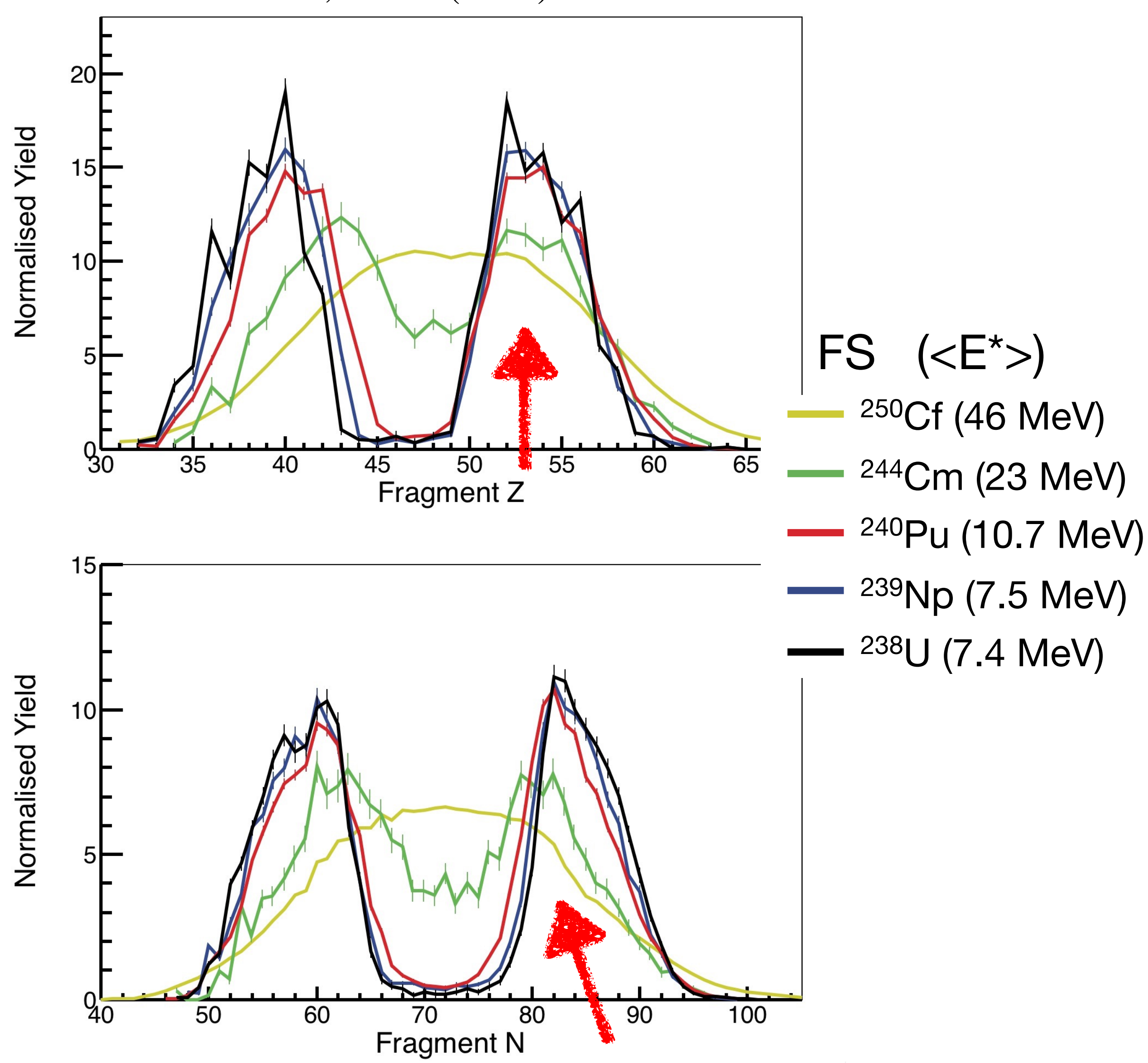


$$PE = -TXE + E^{*,def}$$

A set of revisited and new observables

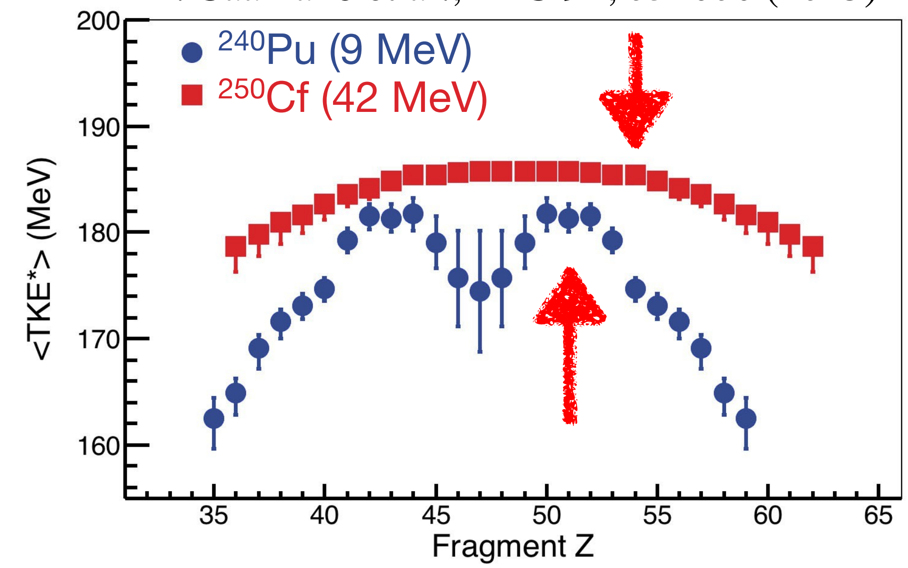
Fragment Z, N distributions

D. Ramos, PhD USdC (2016),
EPJ WoC 111, 10001 (2016)

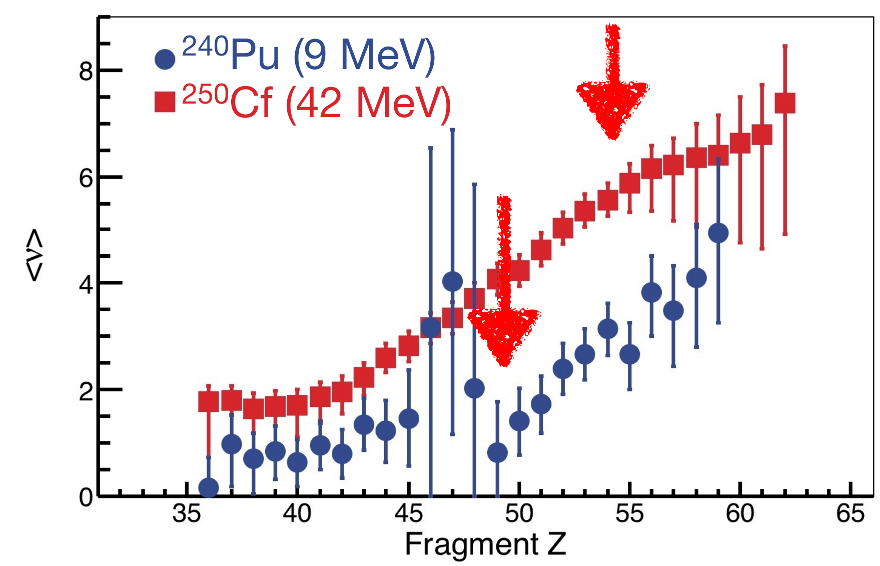


Total kinetic energy (TKE)

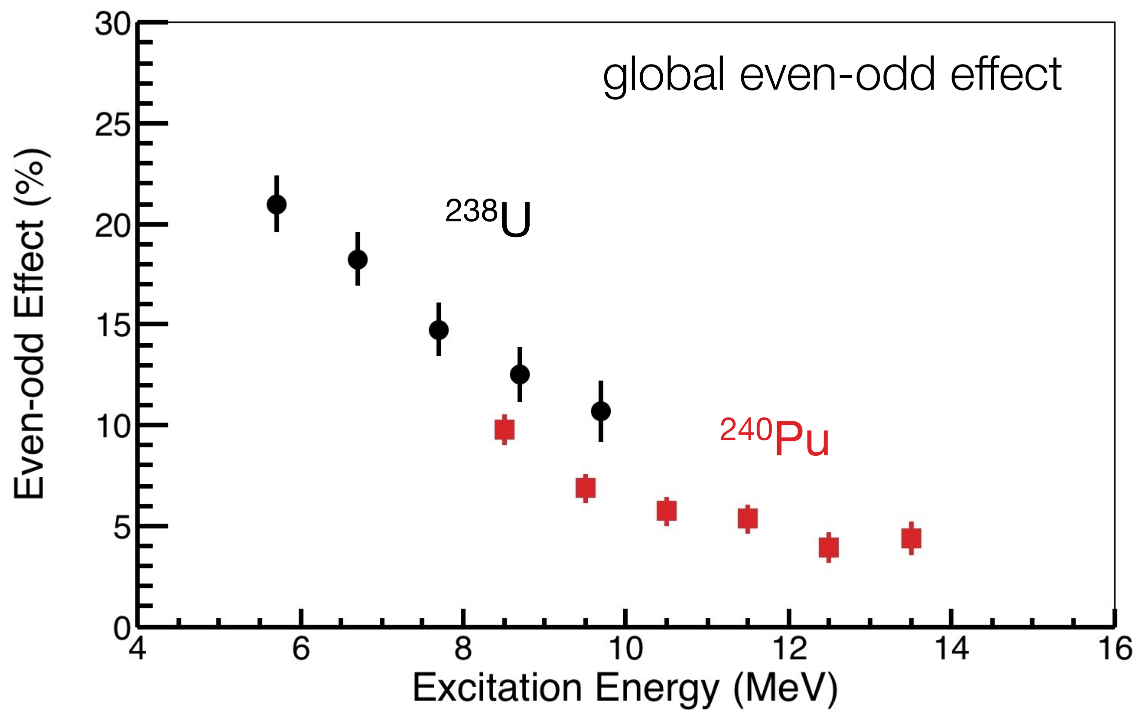
M. Caamaño et al., PRC 92, 034606 (2015)



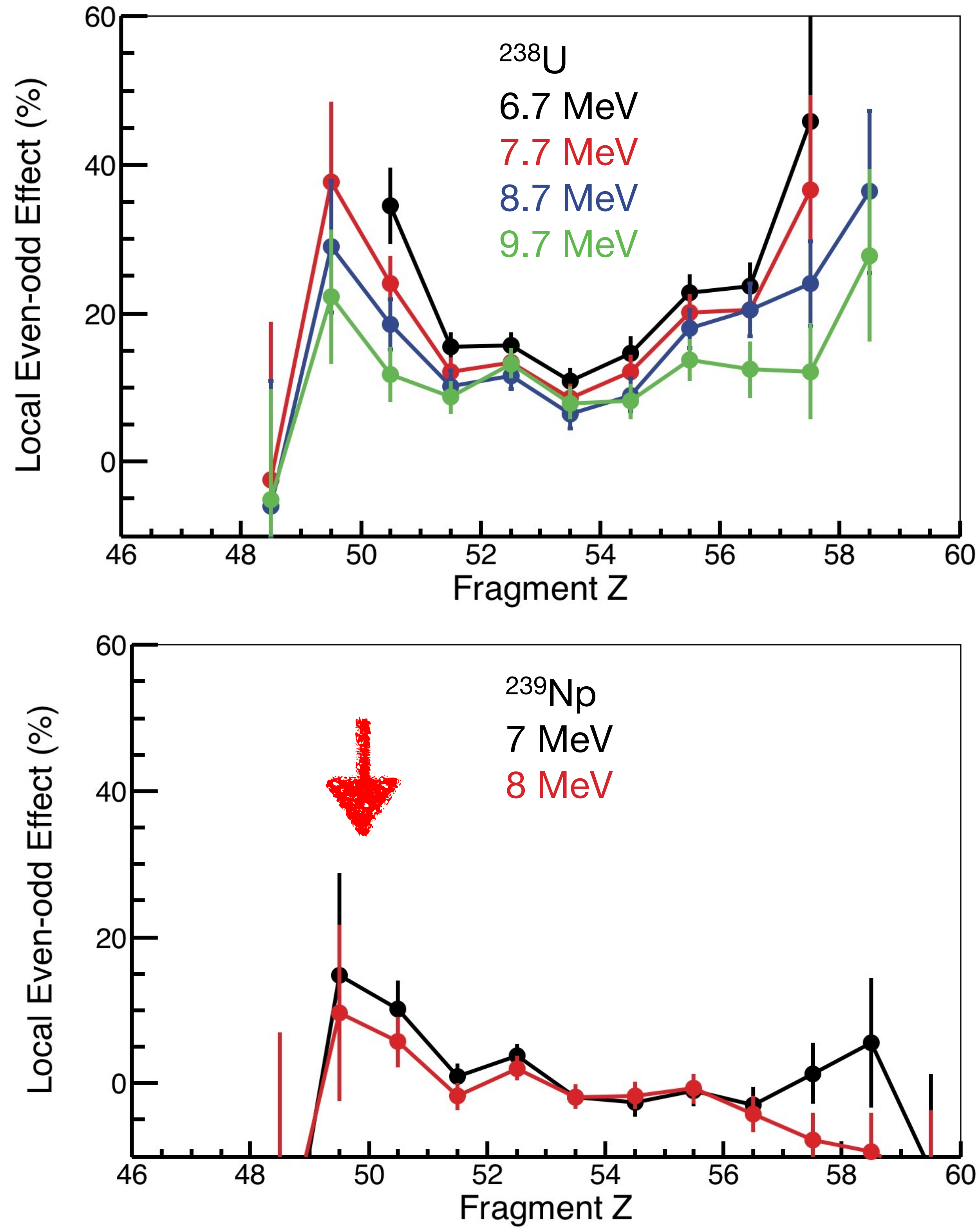
Neutron evaporation



Inverse kinematics: A window to new observables in fission.



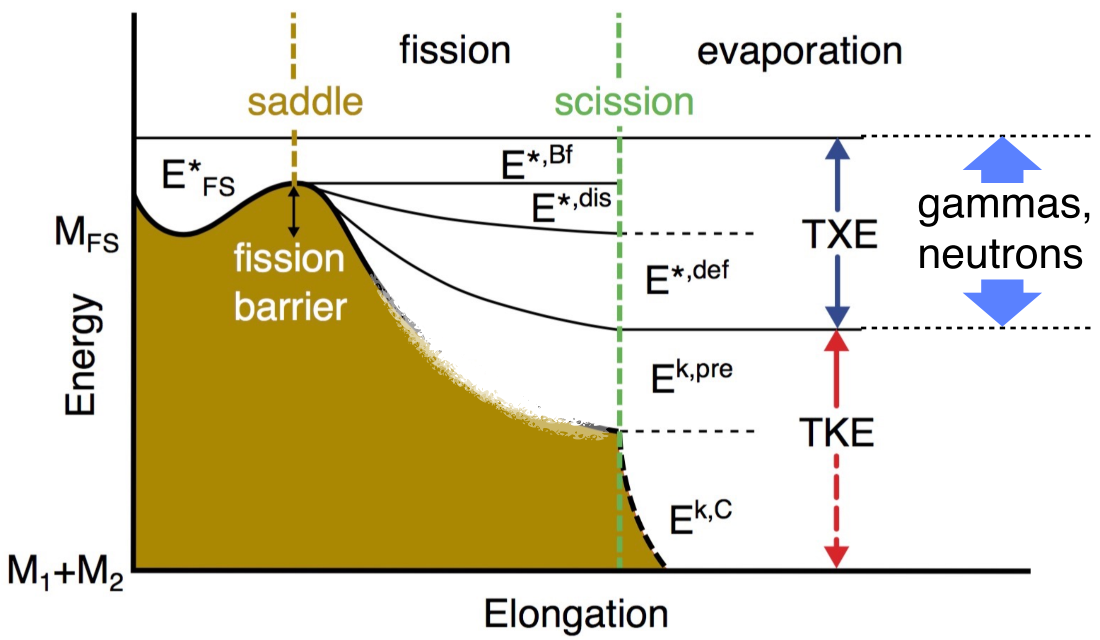
D. Ramos, PhD USdC (2016), EPJ WoC 111, 10001 (2016)



M. Caamaño (USC)

Inverse kinematics: A window to new observables in fission.

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



$$E^*_{FS} + M_{FS} = M_1 + M_2 + TKE + TXE,$$

$$E_i^{*,def} = B(A_i, Z_i, \beta_i) - B(A_i, Z_i, \beta_i^{g.s.})$$

$$TKE = E^{k,C}(Z_1, Z_2, \beta_1, \beta_2, d) + E^{k,pre}$$

PRC 90, 054607 (2014)

$$TXE = E^{*,Bf} + E^{*,dis} + \sum_{i=1}^{2} E_i^{*,def}$$

$$E^{*,dis} = F^{dis}\left(TXE - E^{*,Bf}\right)$$

$$\sum_{i=1}^{2} E_i^{*,int} = E^{*,Bf} + E^{*,dis}$$

shared according statistical eq.

$$TXE = \sum_{i=1}^{2} Q_i^n + \nu_i \varepsilon_i + E_i^\gamma$$

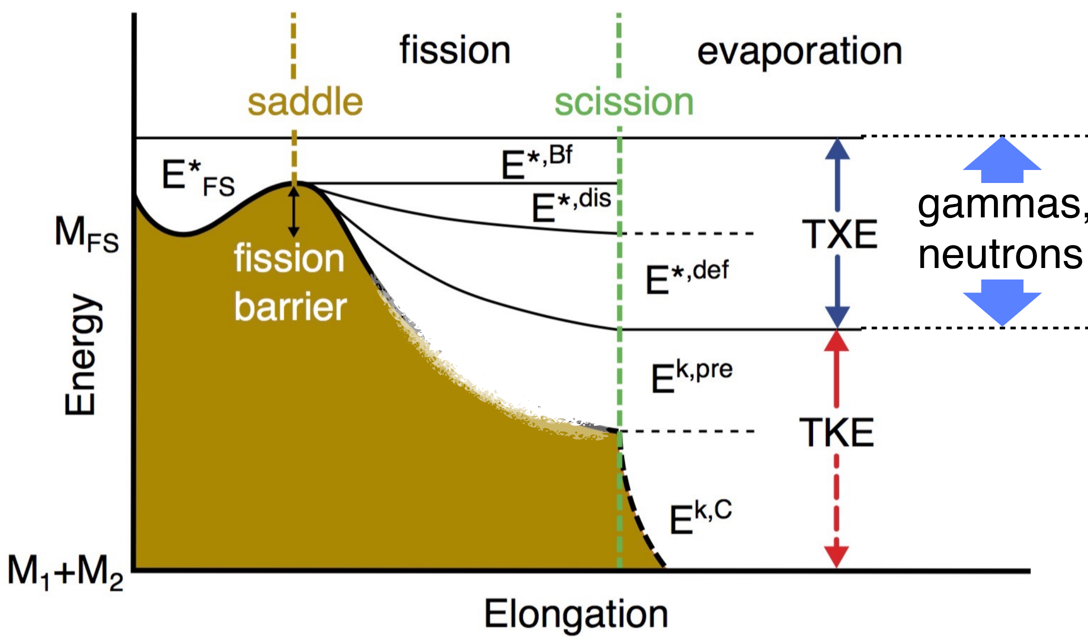
$$E_i^\gamma = Sn_i^{post} \frac{\nu_i}{\nu_1 + \nu_2}$$

$$E_i^* = Q_i^n + \nu_i \varepsilon + E_i^\gamma$$

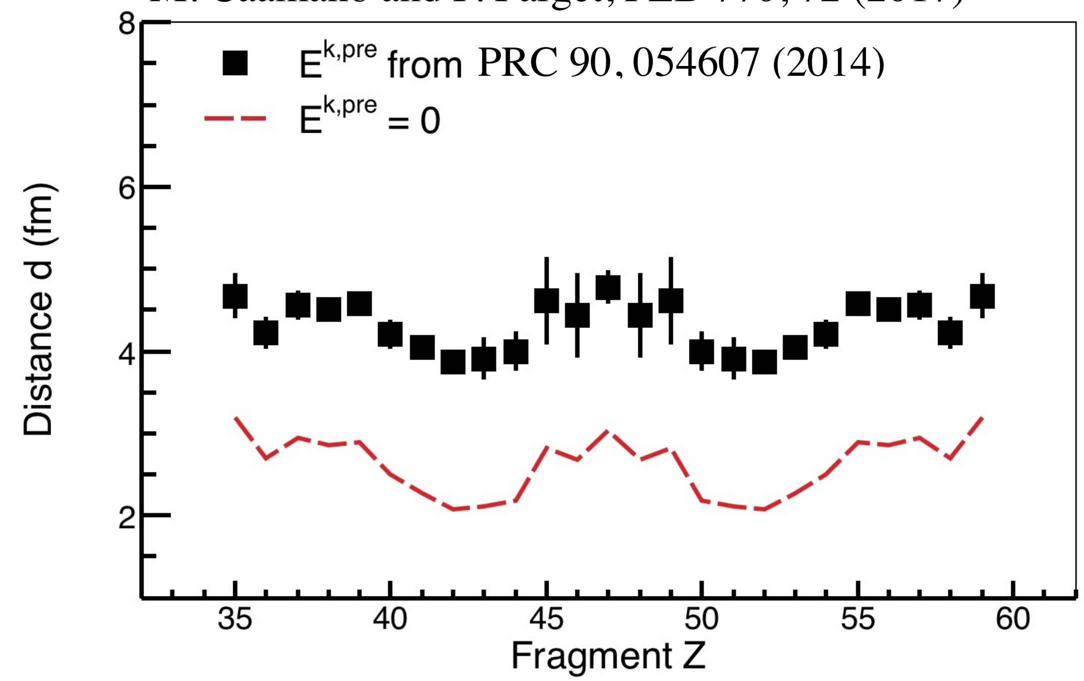
$$E_i^{*,def} = E_i^* - E_i^{*,int}$$

M. Caamaño (USC)

New access to scission; the case of ^{240}Pu (9 MeV)

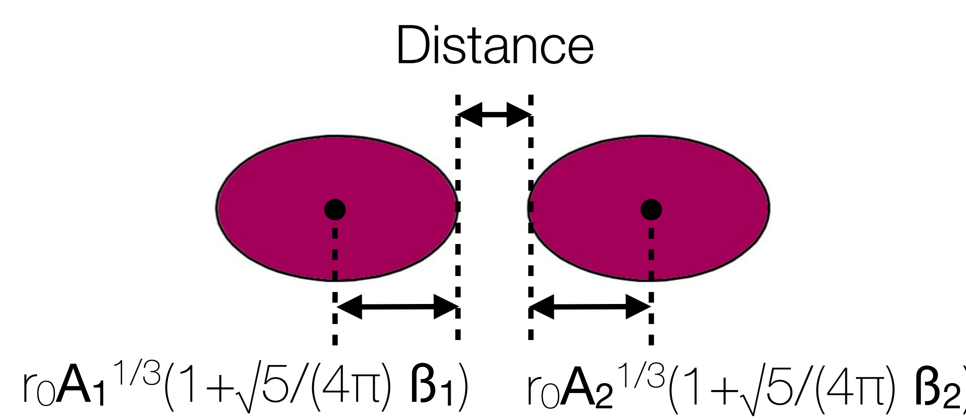


M. Caamaño and F. Farget, PLB 770, 72 (2017)



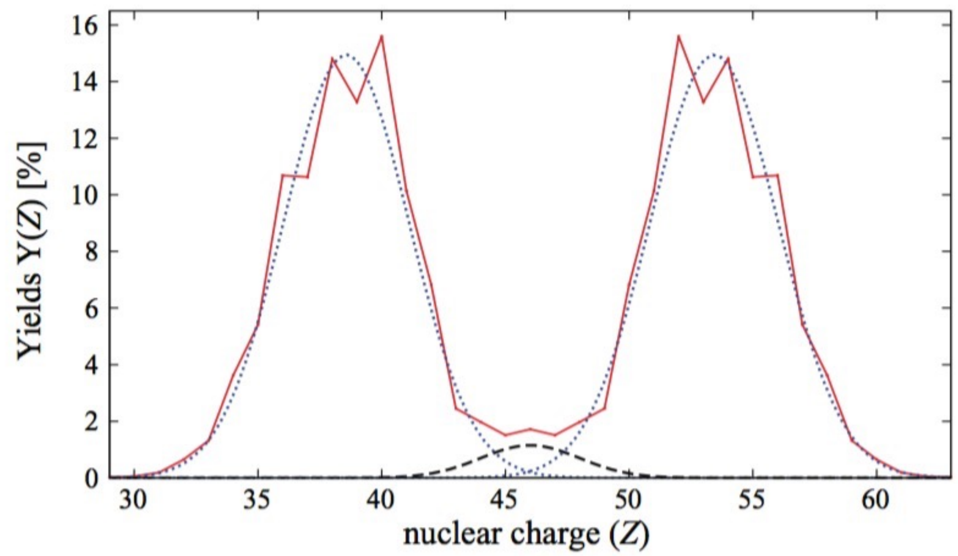
$$M_{FS} + E^*_{FS} = \text{TXE} + \text{TKE} + M_1 + M_2$$

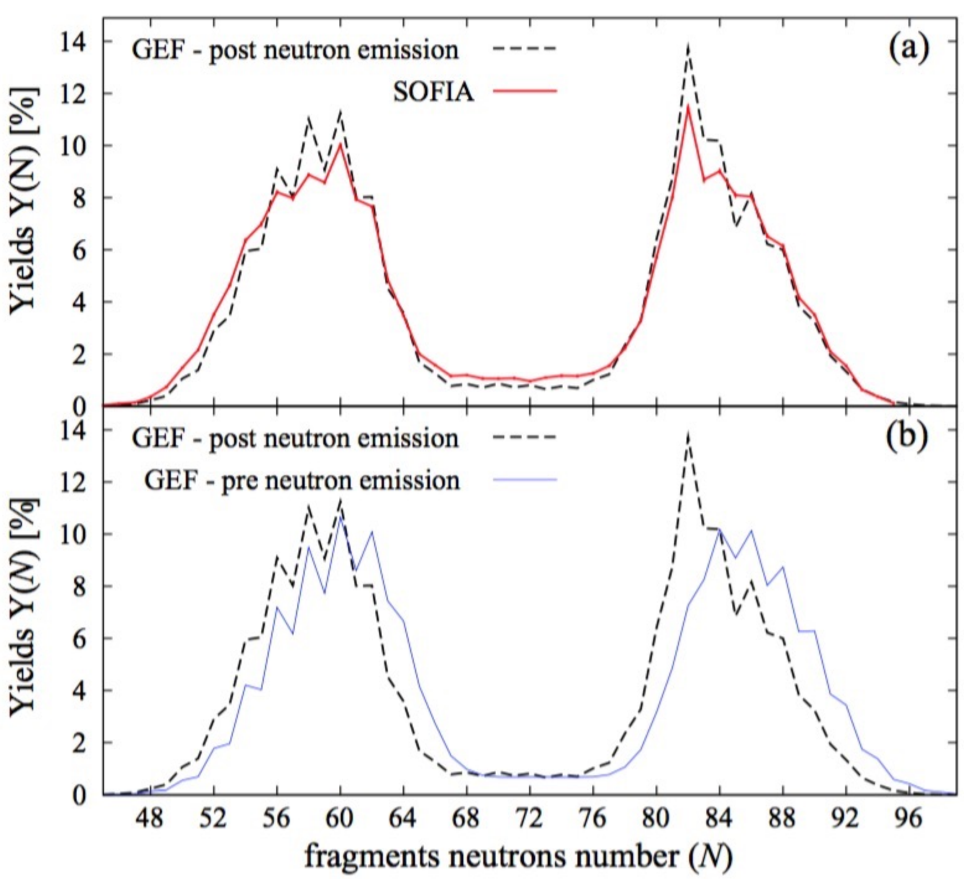
$$\text{TKE} = E^{k,pre} + E^{k,C}$$

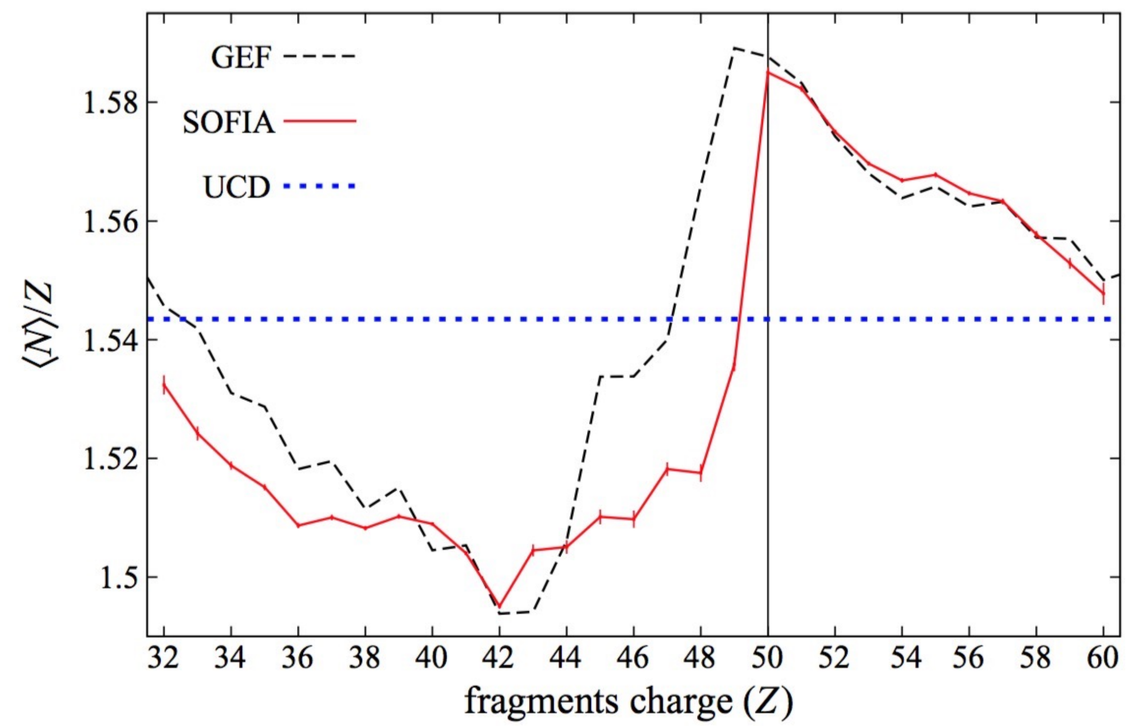


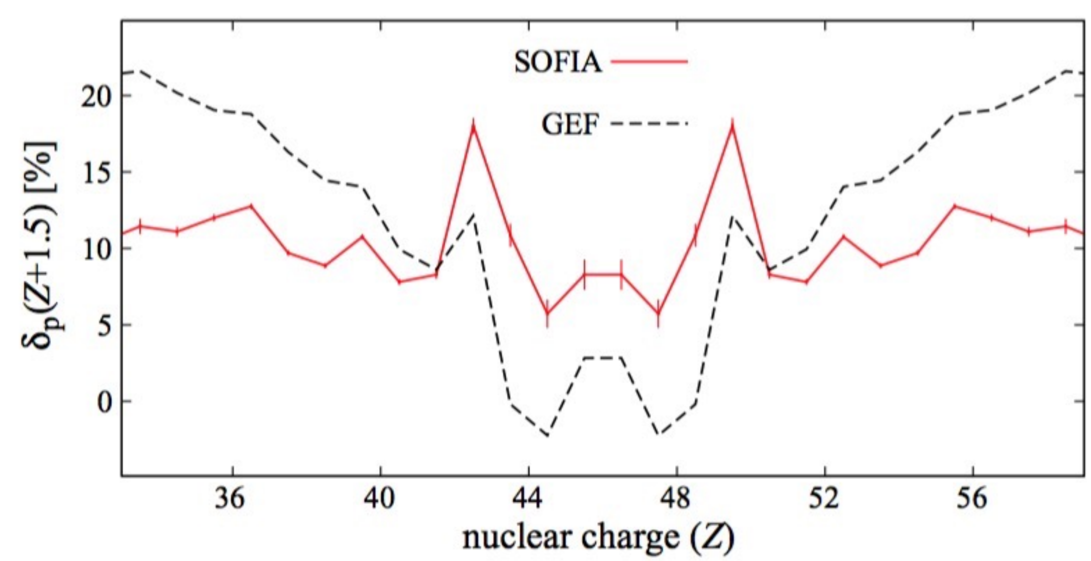
SOFIA @ GSI

^{238}U (*em*,f) @ 650AMeV





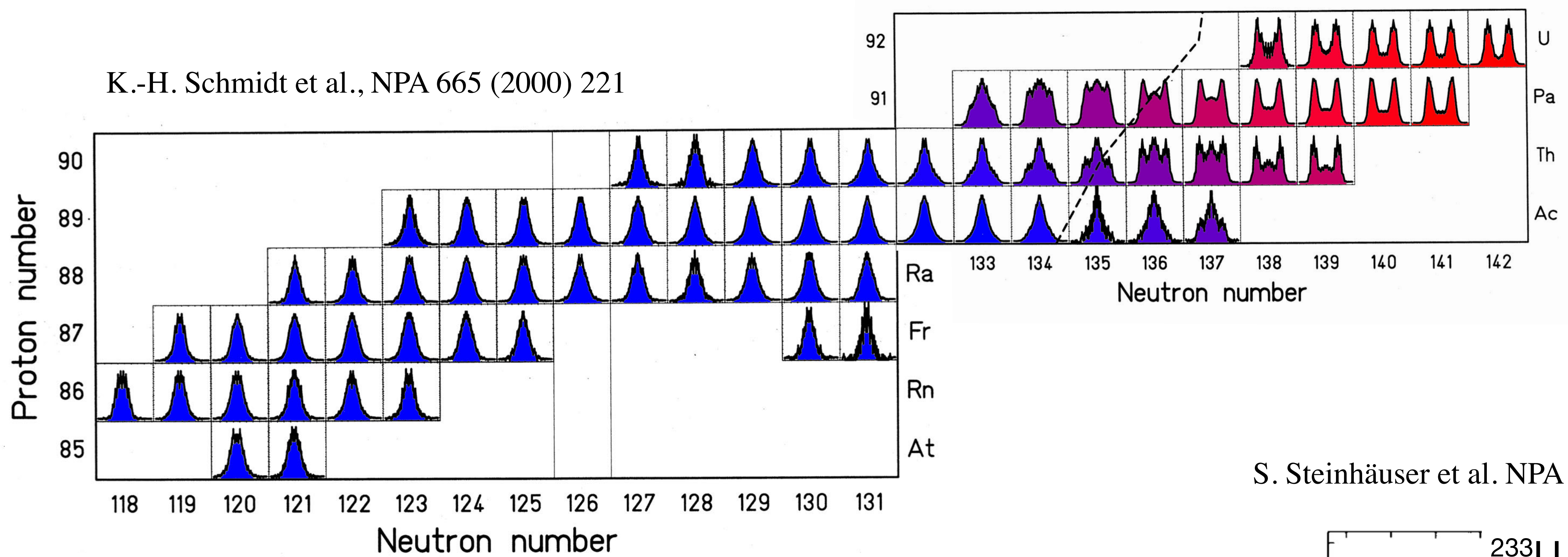


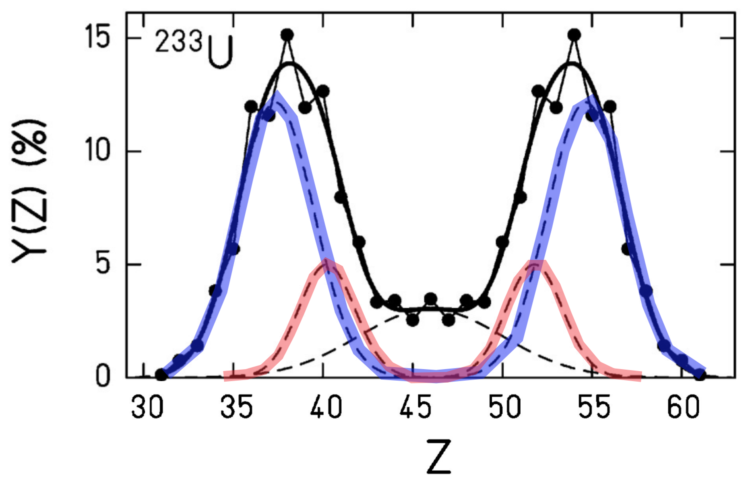


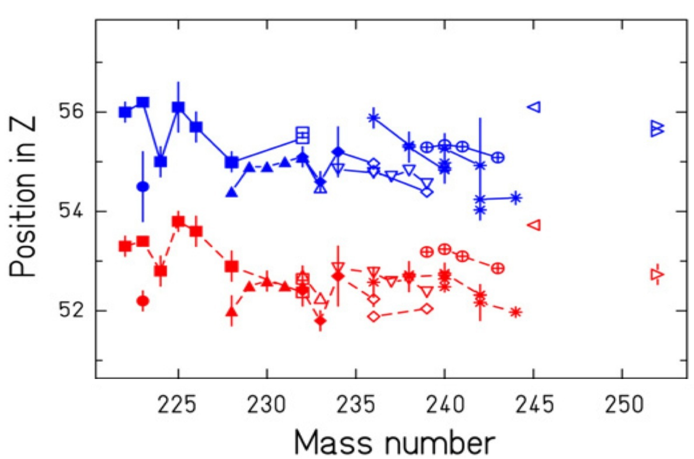
E. Pellereau et al., PRC 95, 054603 (2017)

FRS campaign @ GSI

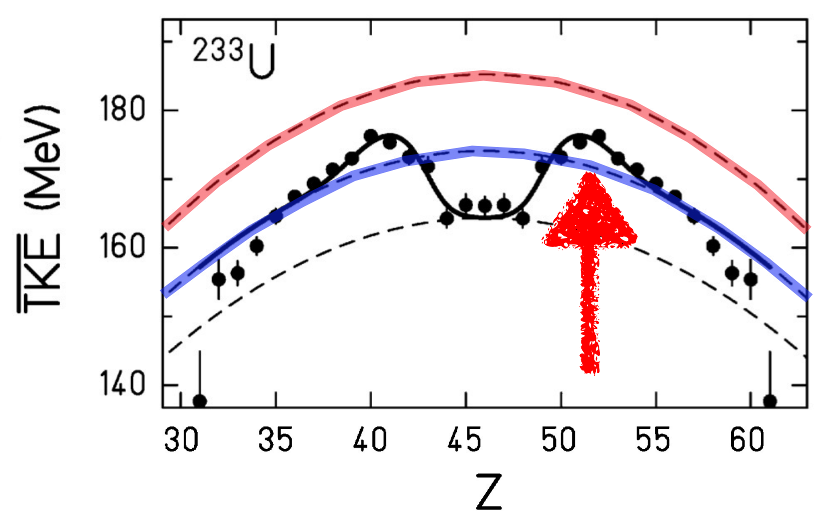
K.-H. Schmidt et al., NPA 665 (2000) 221



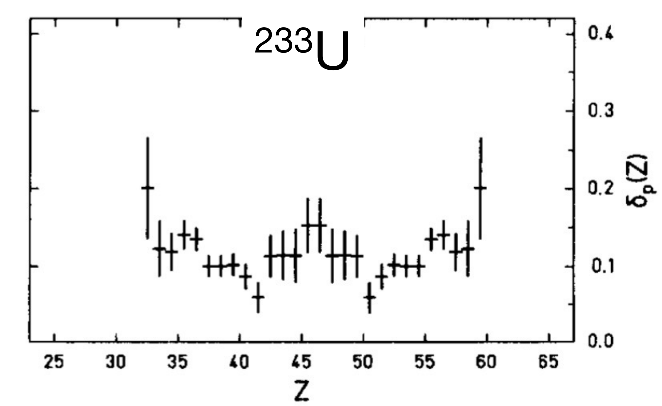


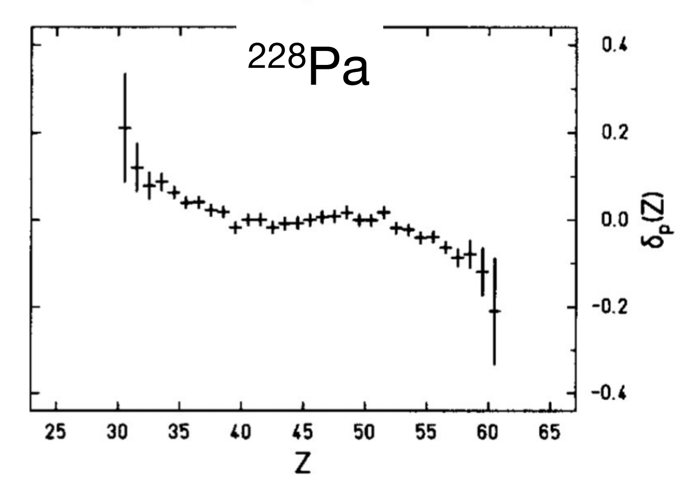


C. Böckstiegel et al. NPA 802 (2008) 12

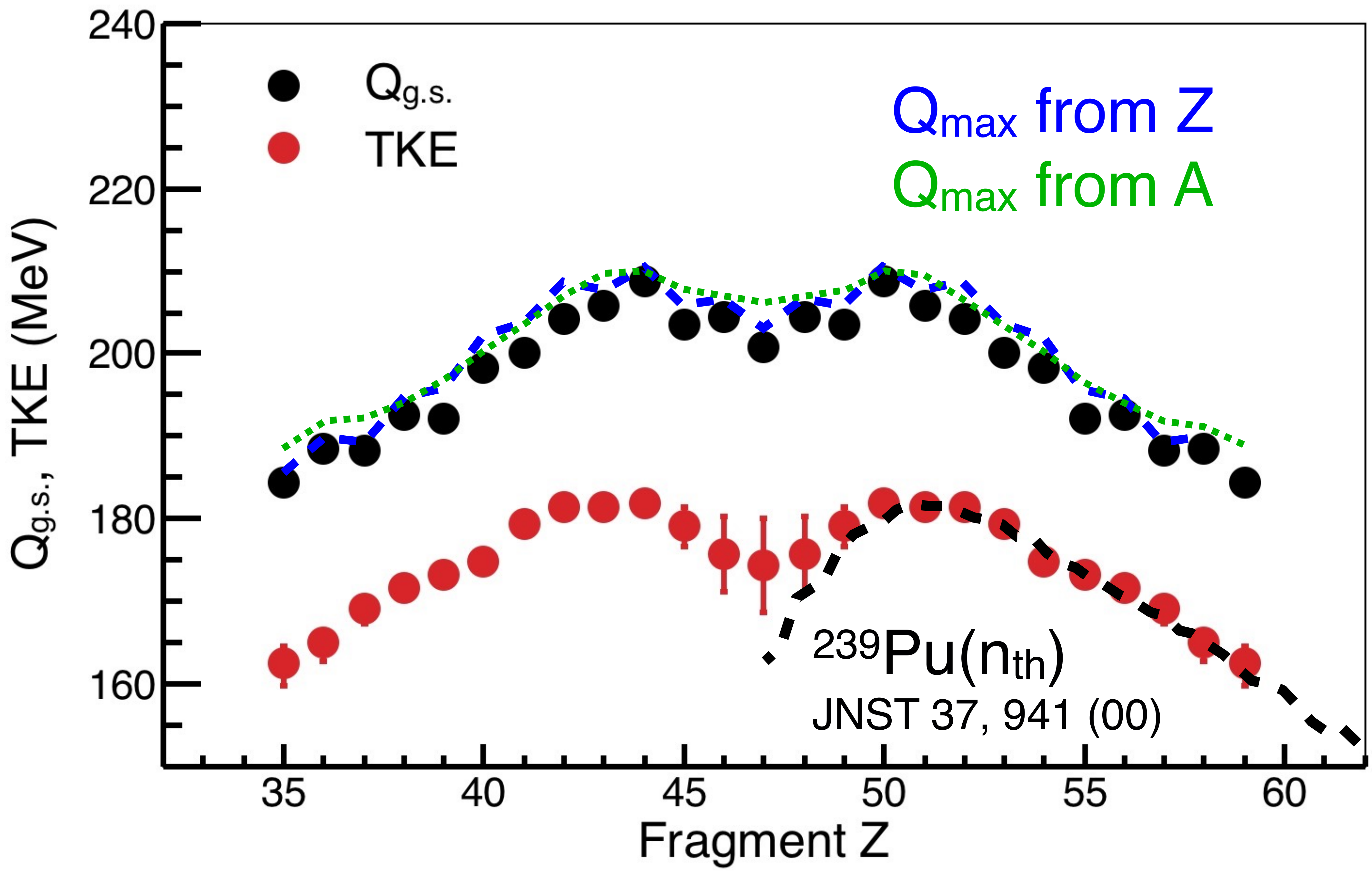


S. Steinhäuser et al. NPA 634 (1998) 89

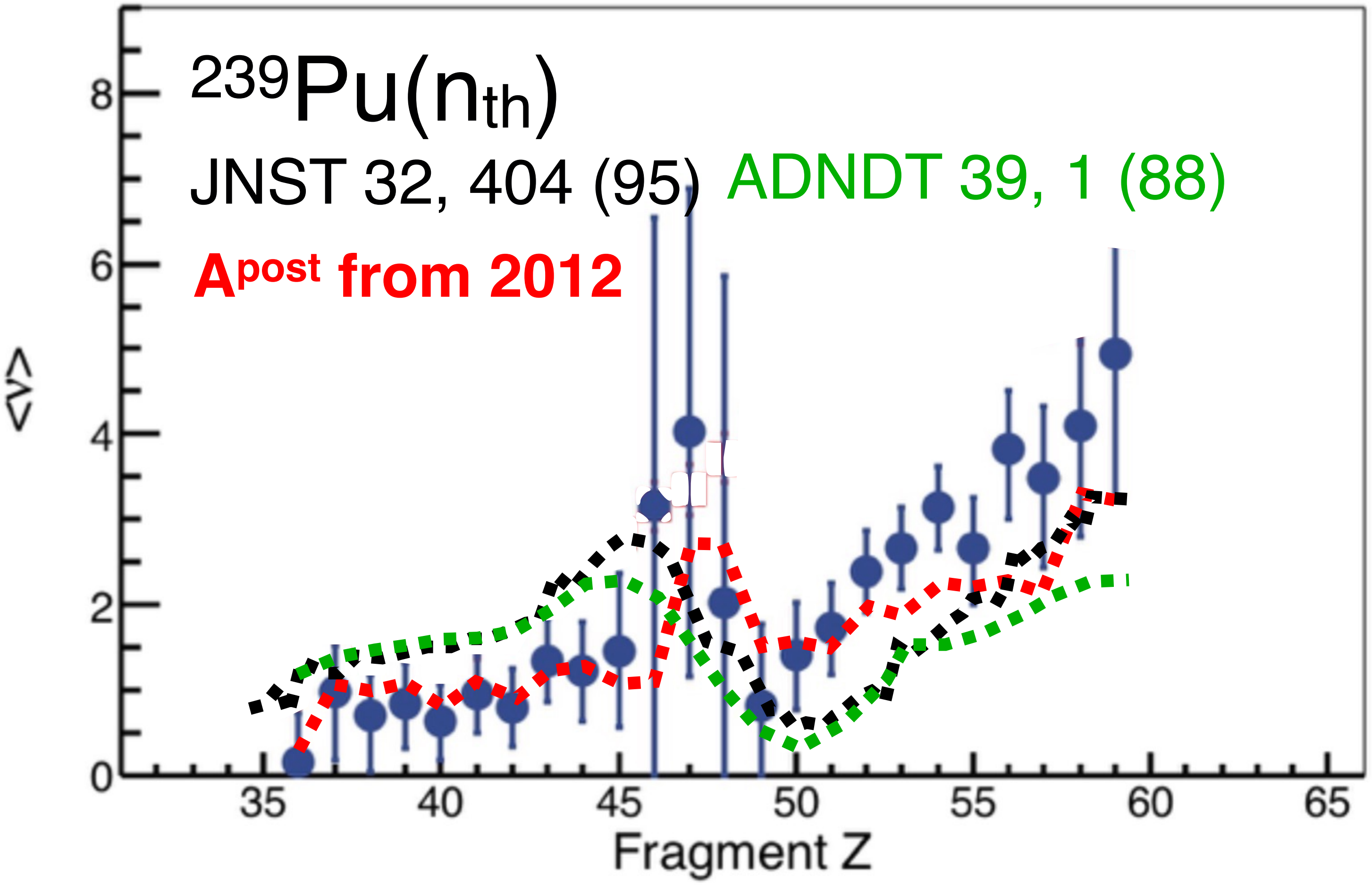




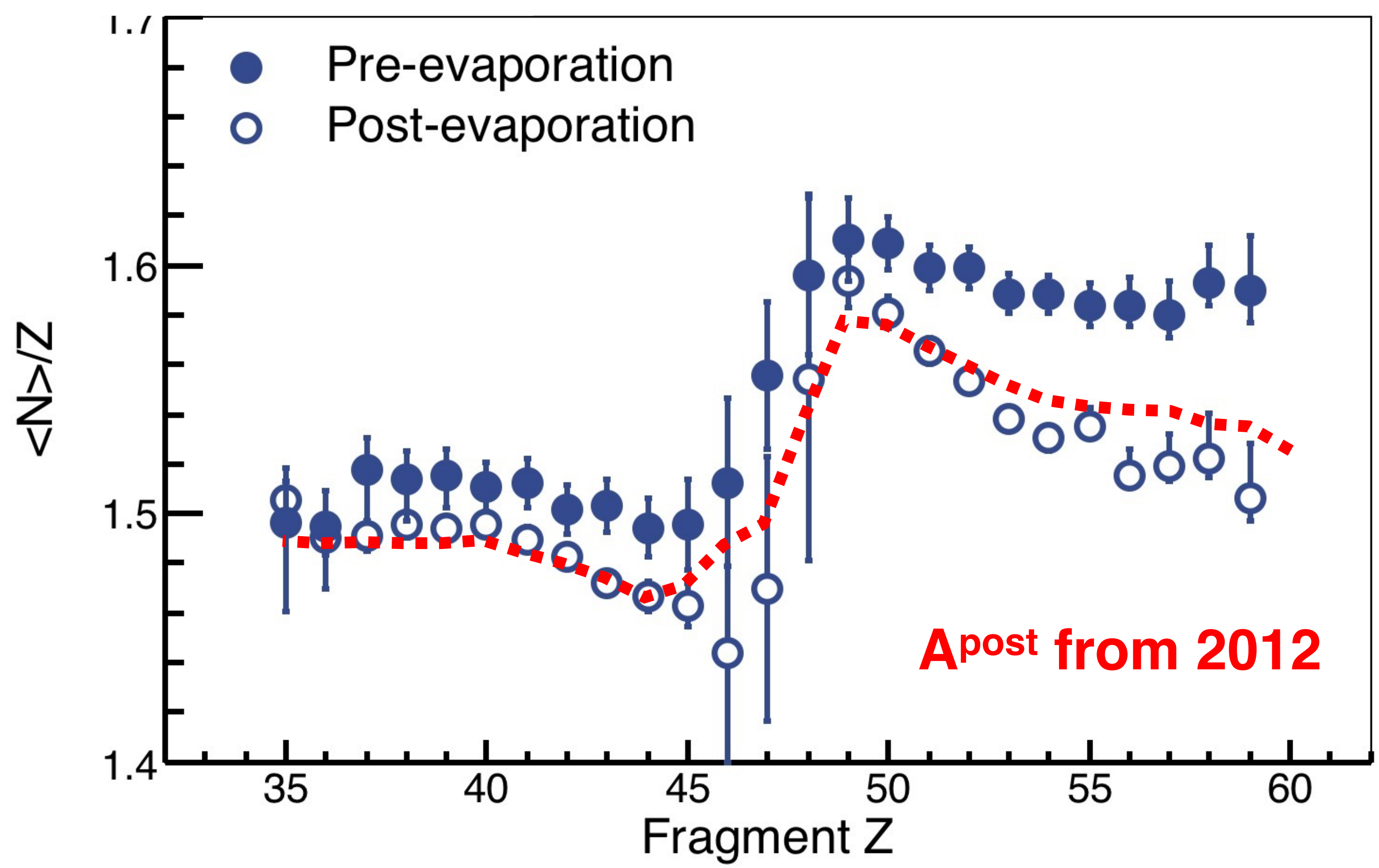
M. Caamaño (USC)

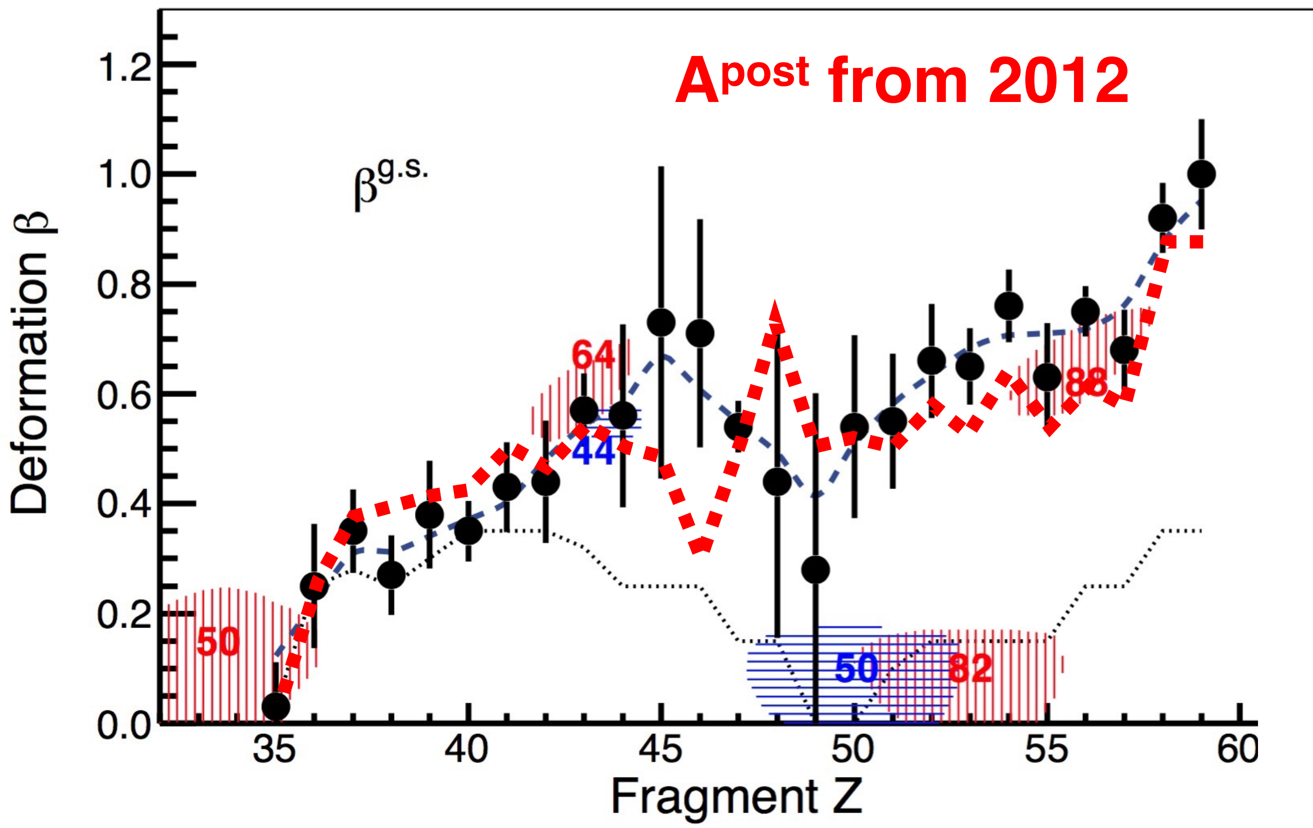


$Q_{g.s.}$
TKE
Q_{max} from Z
Q_{max} from A
$^{239}Pu(n_{th})$
JNST 37, 941 (00)
240
220
200
180
160
$Q_{g.s.}$, TKE (MeV)
35
40
45
50
55
60
Fragment Z

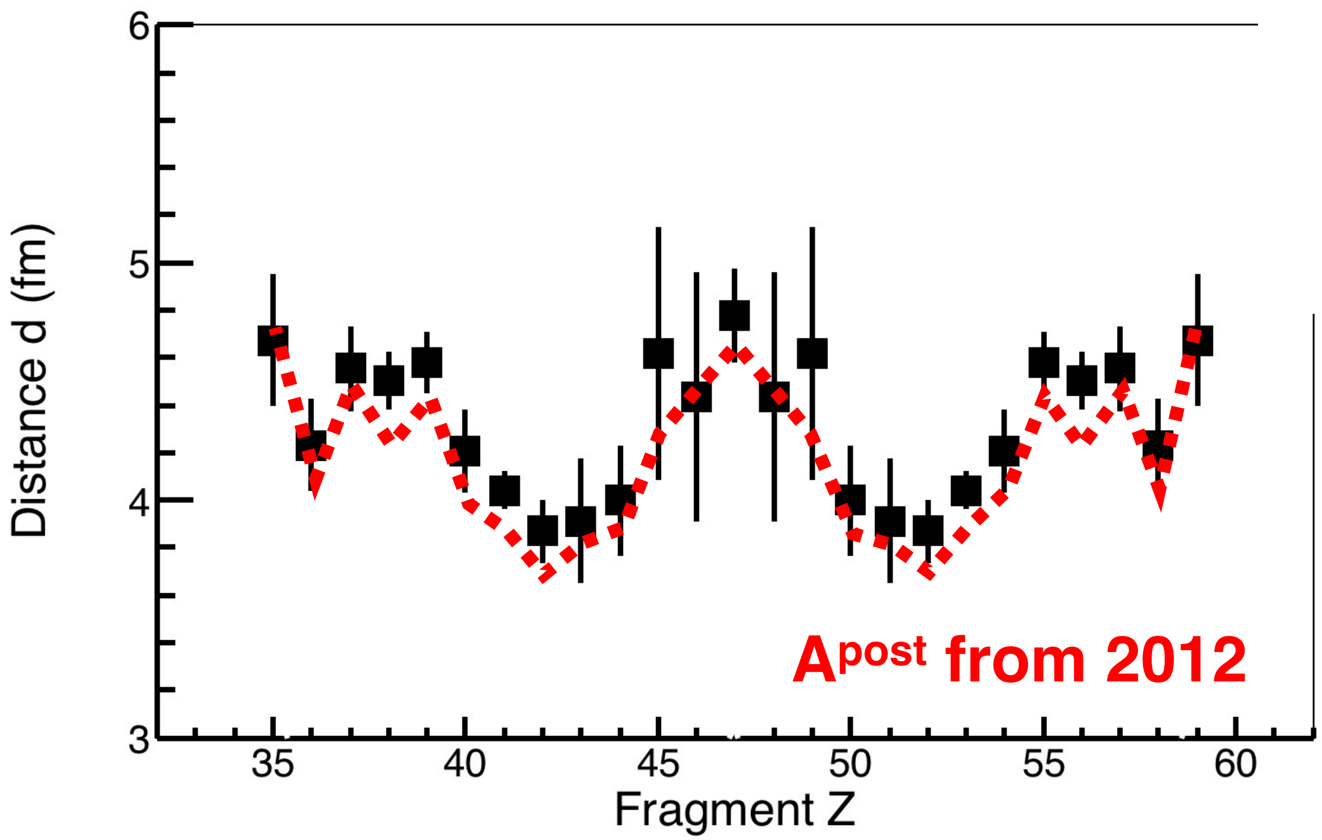


problems in mass measured around symmetry: low statistics

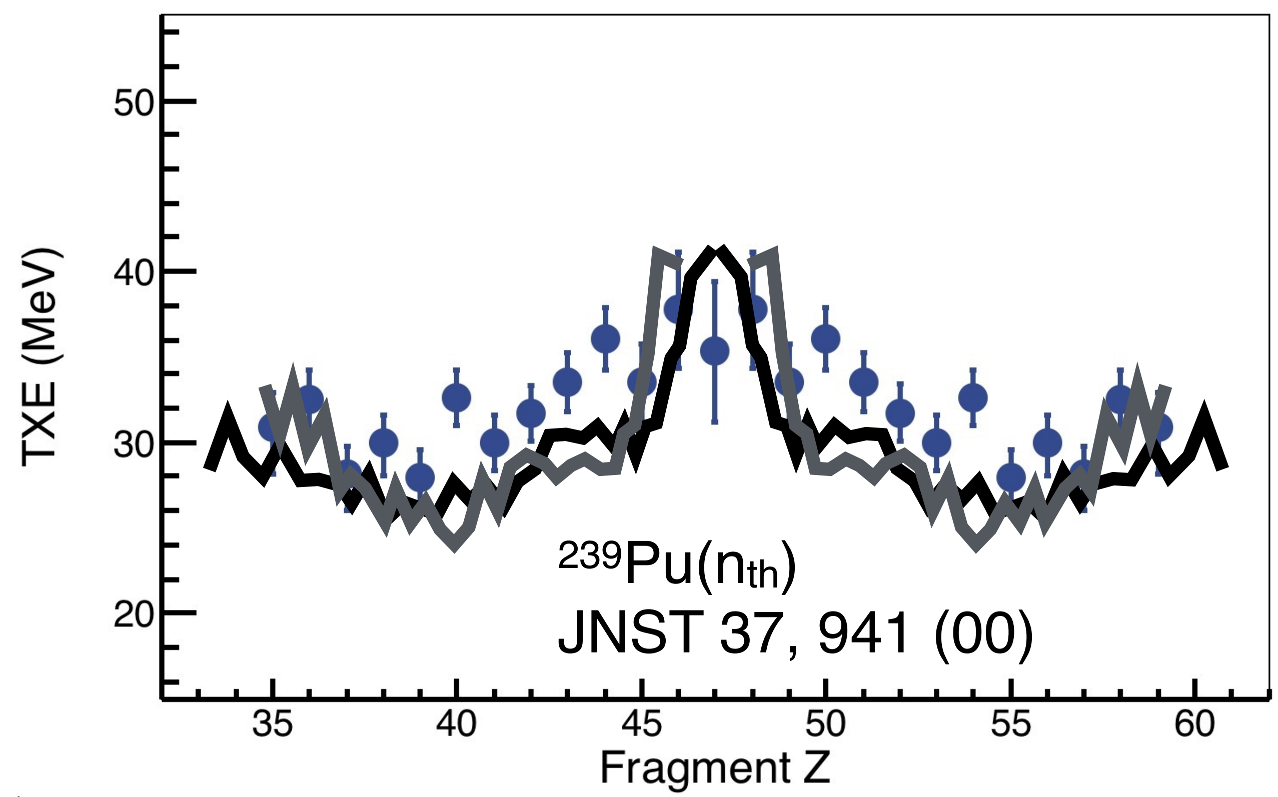




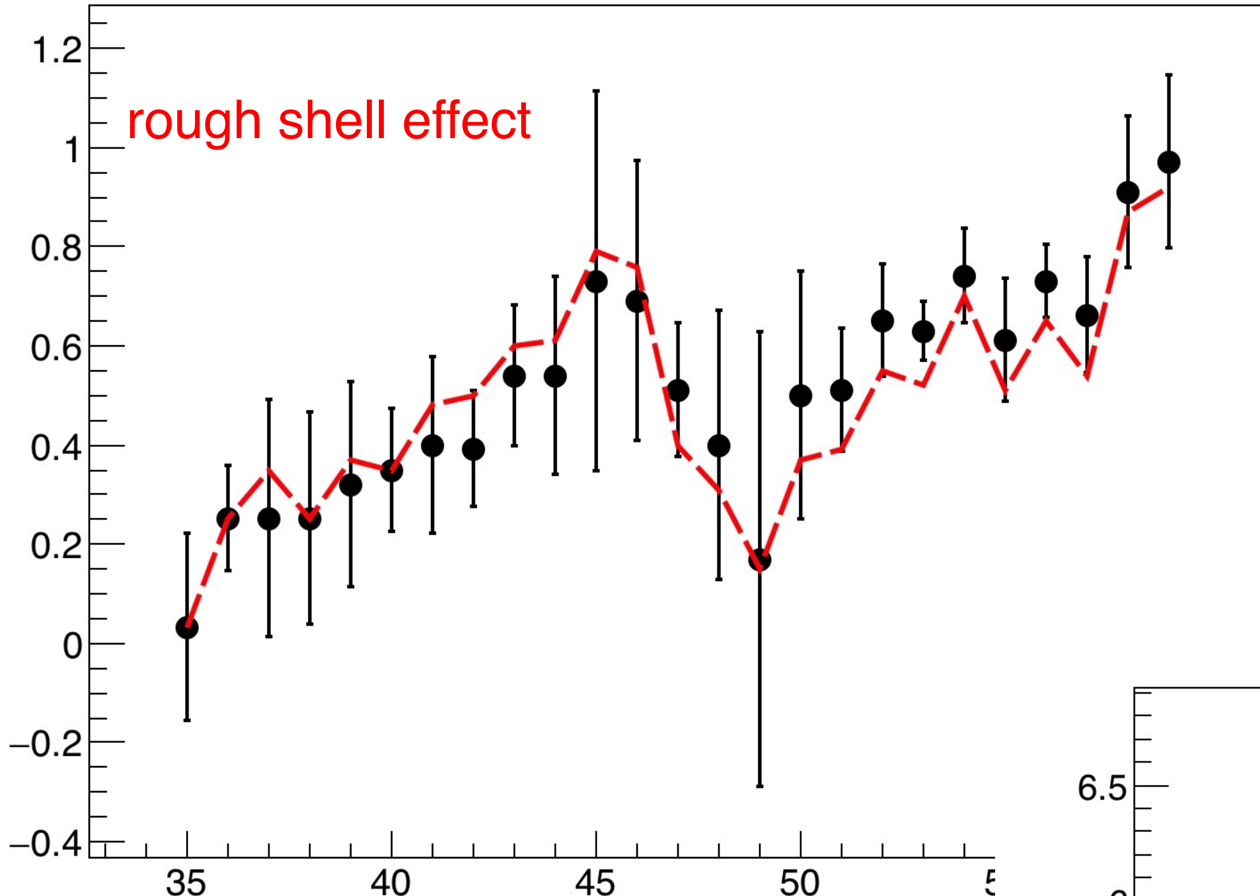
A^post from 2012
β^g.s.
Deformation β
1.2
1.0
0.8
0.6
0.4
0.2
0.0
64
44
50
50
82
88
35
40
45
50
55
60
Fragment Z



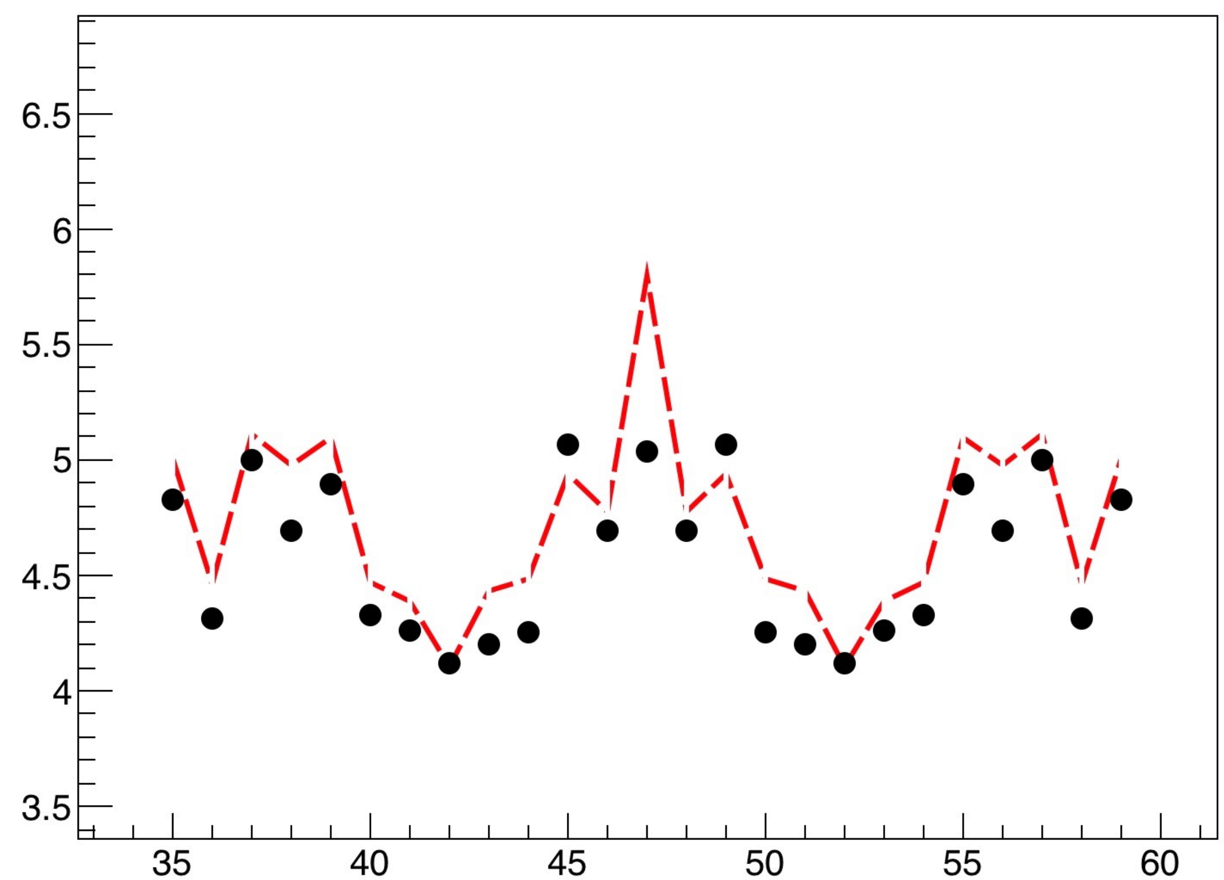
Distance d (fm)
6
5
4
3
A^post from 2012
35
40
45
50
55
60
Fragment Z



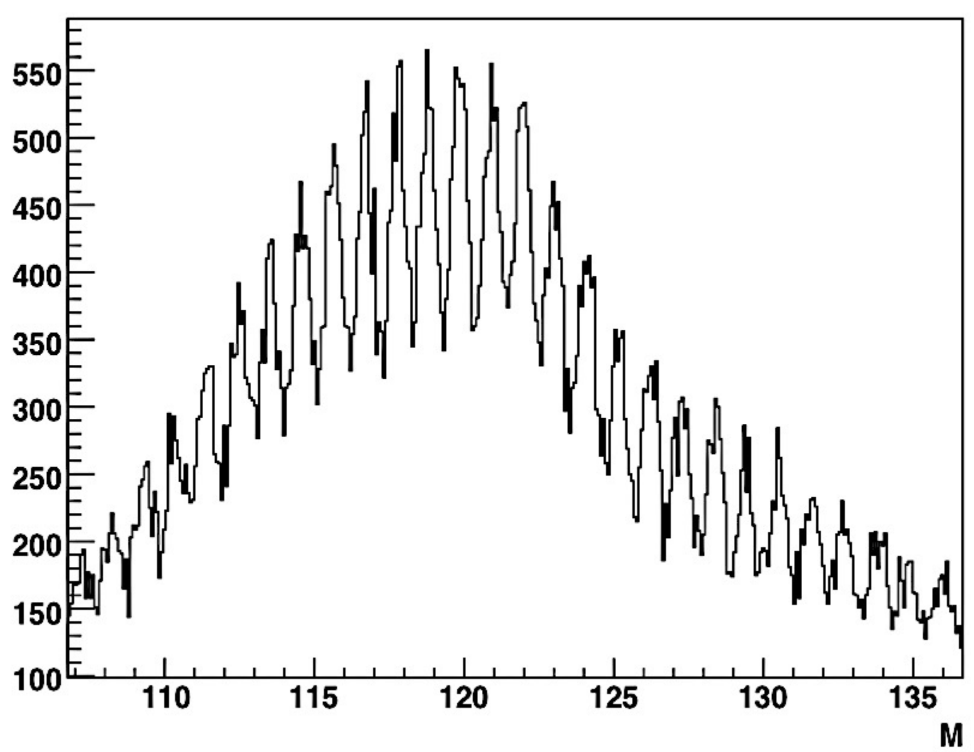
TXE (MeV)
50
40
30
20
239Pu(nth)
JNST 37, 941 (00)
35
40
45
50
55
60
Fragment Z

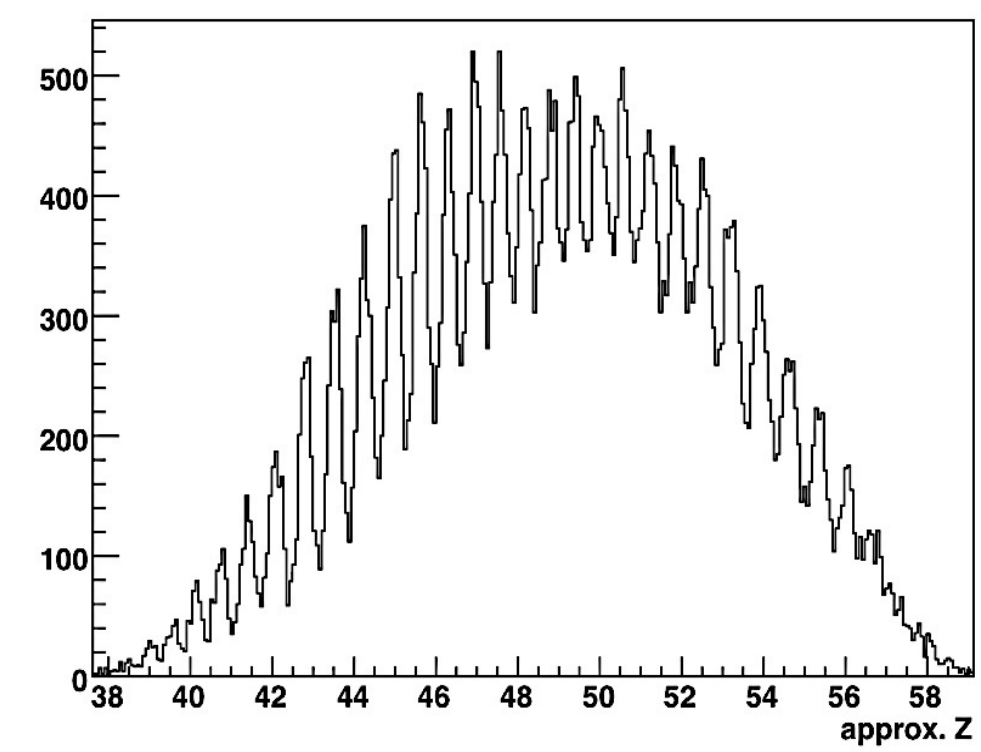


rough shell effect
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
35
40
45
50



6.5
6
5.5
5
4.5
4
3.5
35
40
45
50
55
60





$\Delta M/M \approx 0.6 \cdot 10^{-2}$

$\Delta Z/Z \approx 1.5 \cdot 10^{-2}$

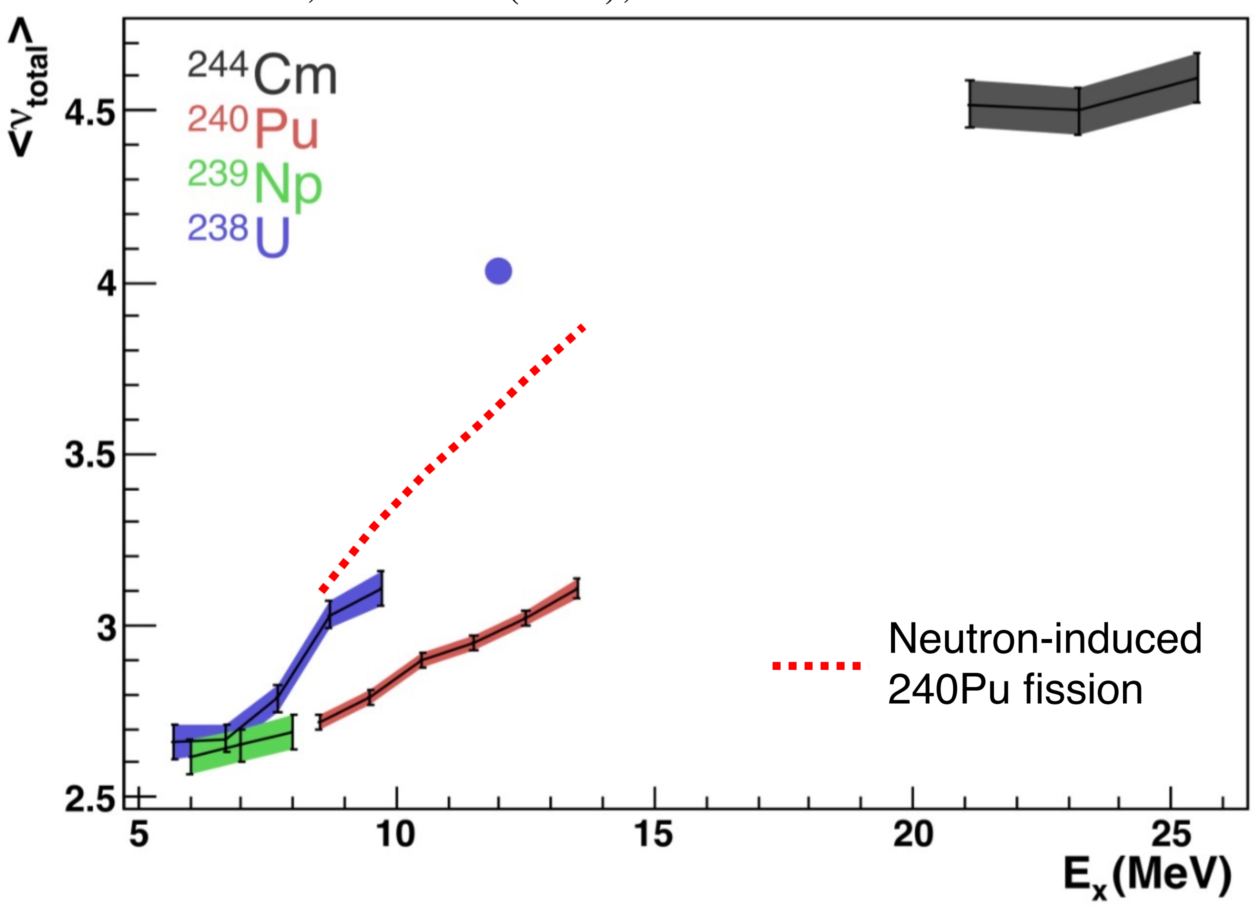
Fragments identified from **M** ≈ **90** to **M** ≈ **140**

Fragments identified from **Z** ≈ **36** to **Z** ≈ **59** in 600 MeV range

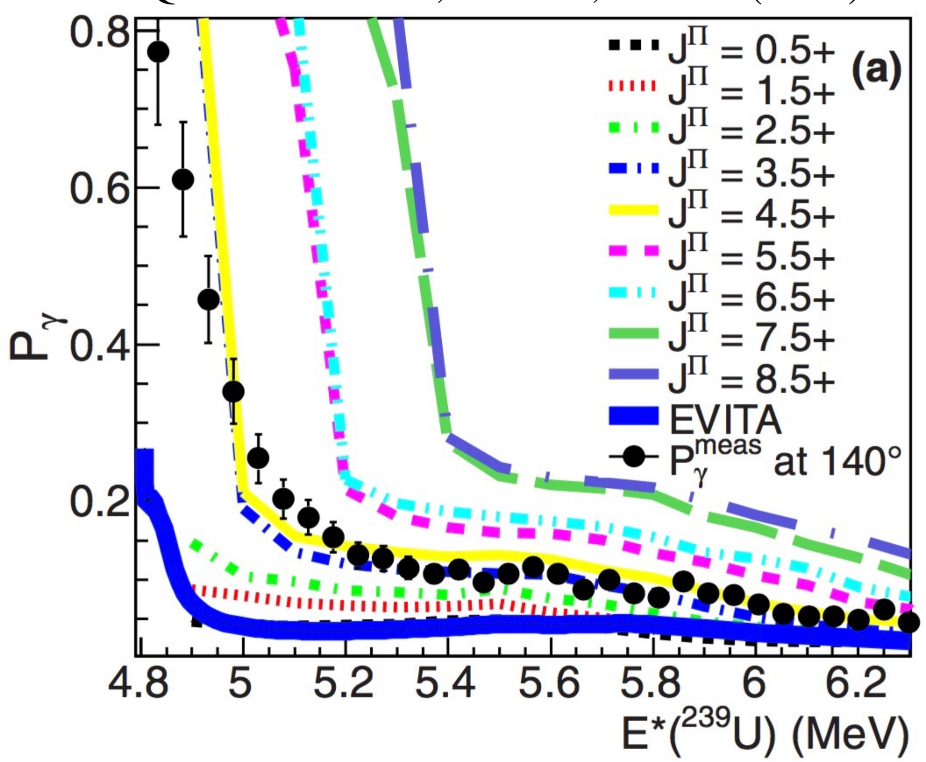
A set of revisited and new observables

Neutron evaporation

D. Ramos, PhD USC (2016), to be submitted to PRC



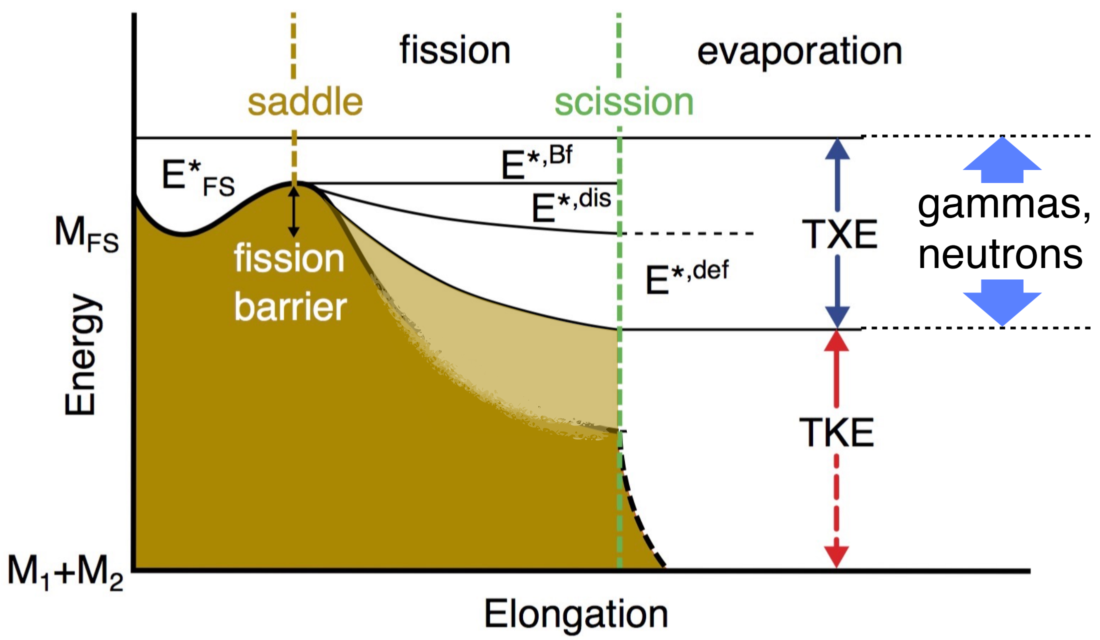
Q. Ducasse et al., PRC 94, 024614 (2016)



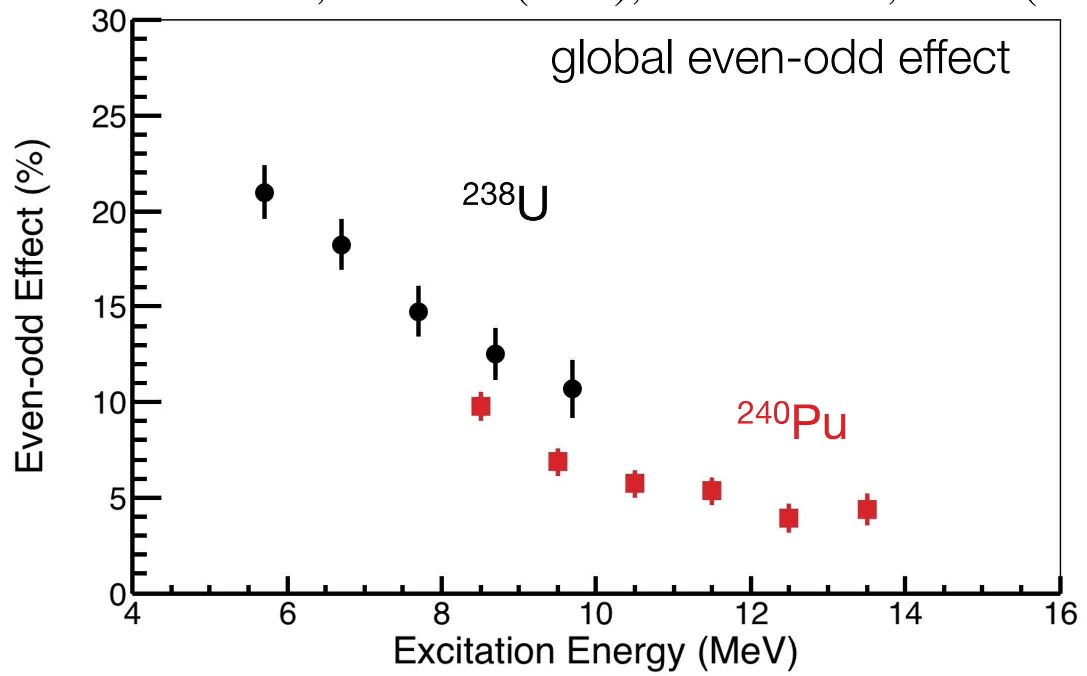
The evolution of the neutron evaporation with E* is slower for the case of transfer-fission than for neutron-induced.

An measurement of angular momentum?

Even-odd effect and dissipation



D. Ramos, PhD USC (2016), EPJ WoC 111, 10001 (2016)



$M_{FS} + E^*_{FS} =$ **TXE** + **TKE** $+ M_1 + M_2$

TXE $= \sum(E^{*,Bf} + E^{*,dis} + E^{*,def})$

There is a correlation between the **even-odd effect** and **dissipation**

from data:

$$\ln \delta_Z \propto -TXE$$

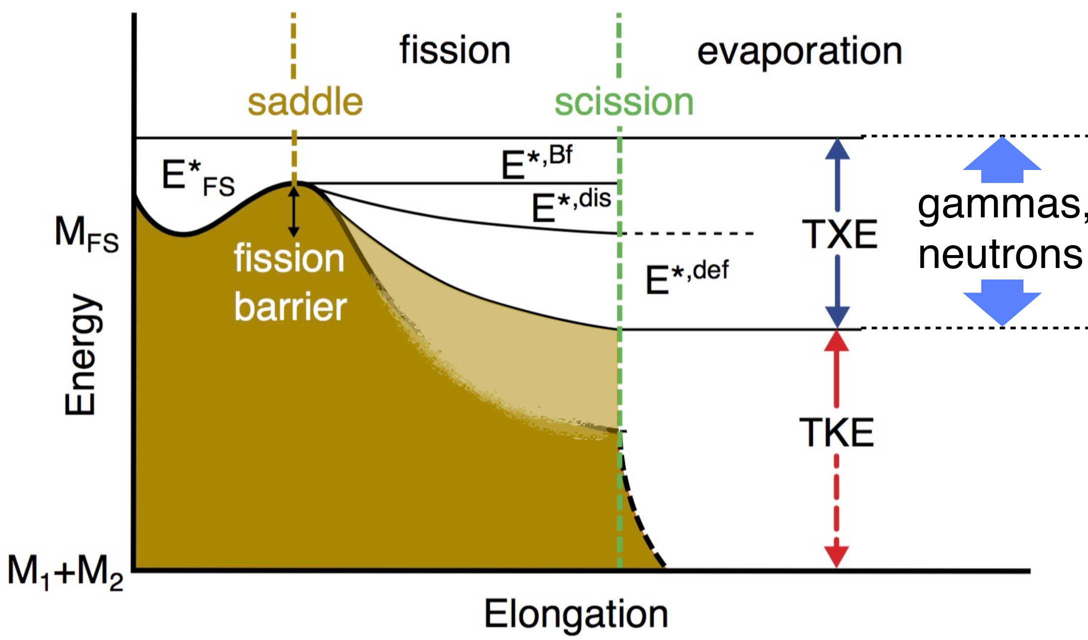
from theory:

$$E^{*,\mathrm{diss}} \propto -\ln \delta_Z$$

in the case of ^{240}Pu:

$$E^{*,\mathrm{diss}} \approx 0.35\ TXE$$

Even-odd effect and dissipation



$$M_{FS} + E^*_{FS} = \mathbf{TXE} + \mathbf{TKE} + M_1 + M_2$$

$$\mathbf{TXE} = \sum(E^{*,Bf} + \underline{E^{*,dis}} + E^{*,def})$$

There is a correlation between the **even-odd effect** and **dissipation**

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