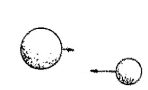
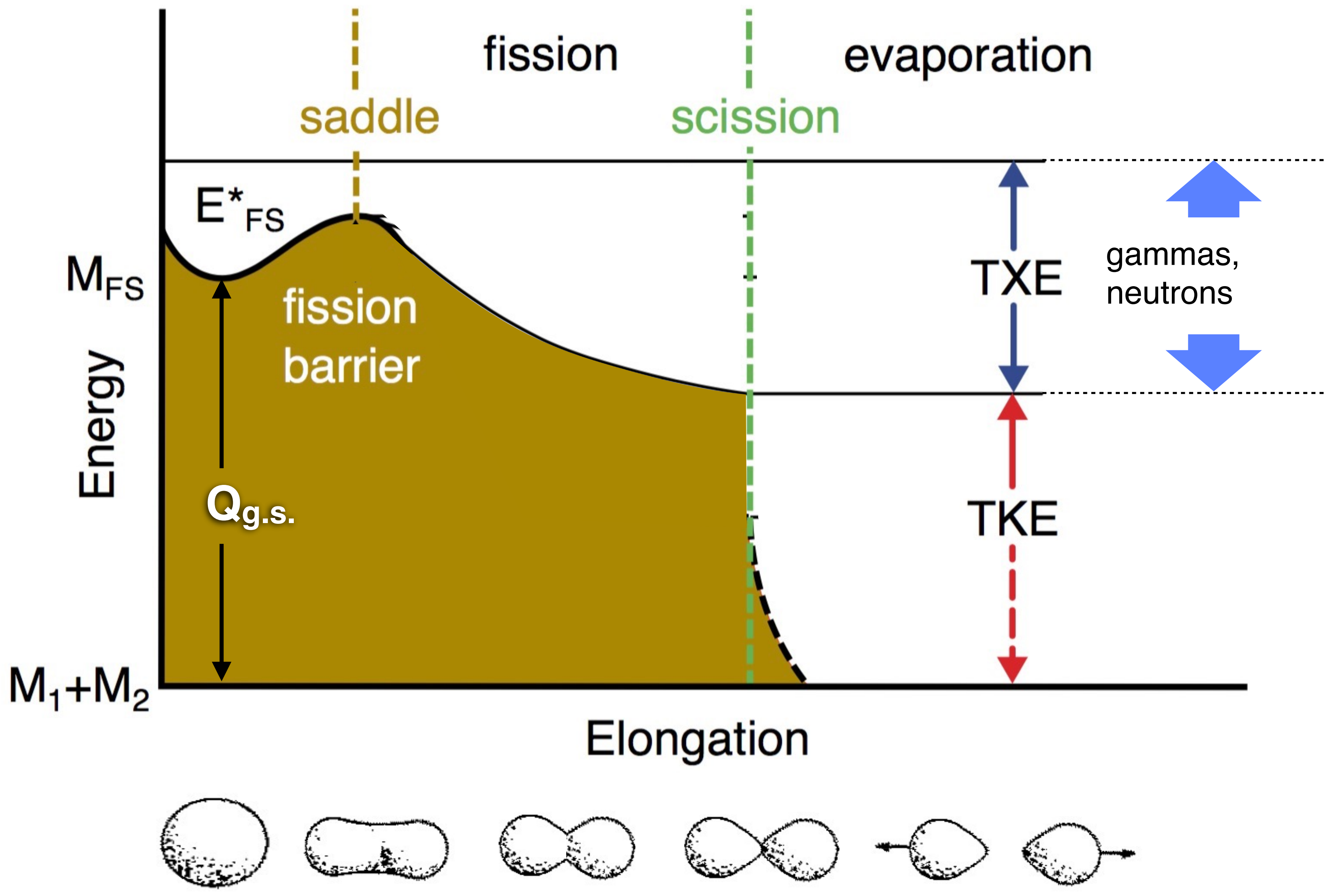
Fission dynamics and nuclear structure

A fission campaign at GANIL (France)

M. Caamaño



A macroscopic LD behaviour



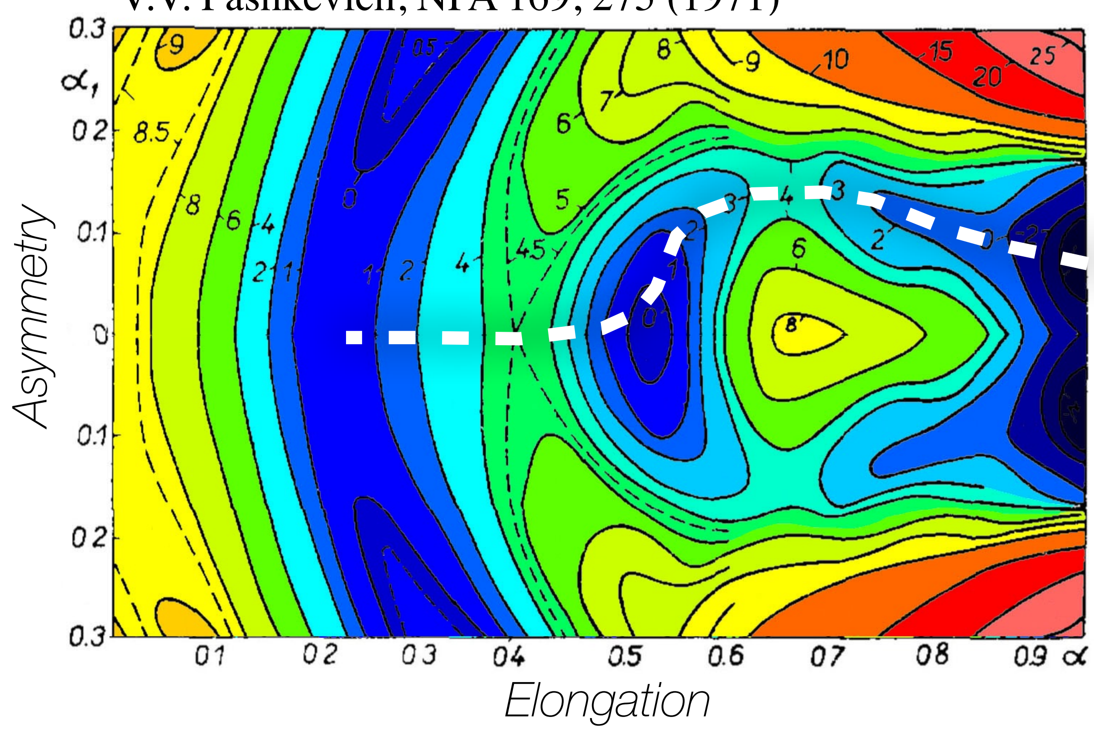
A macroscopic LD behaviour shaped by structure

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

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

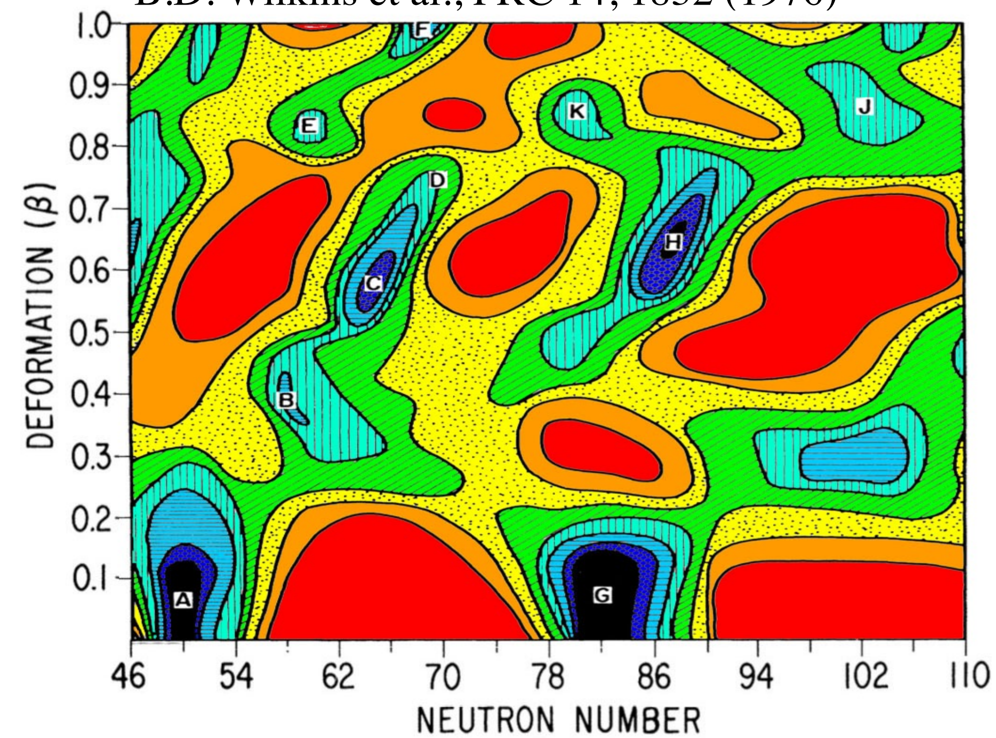
at the barrier

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



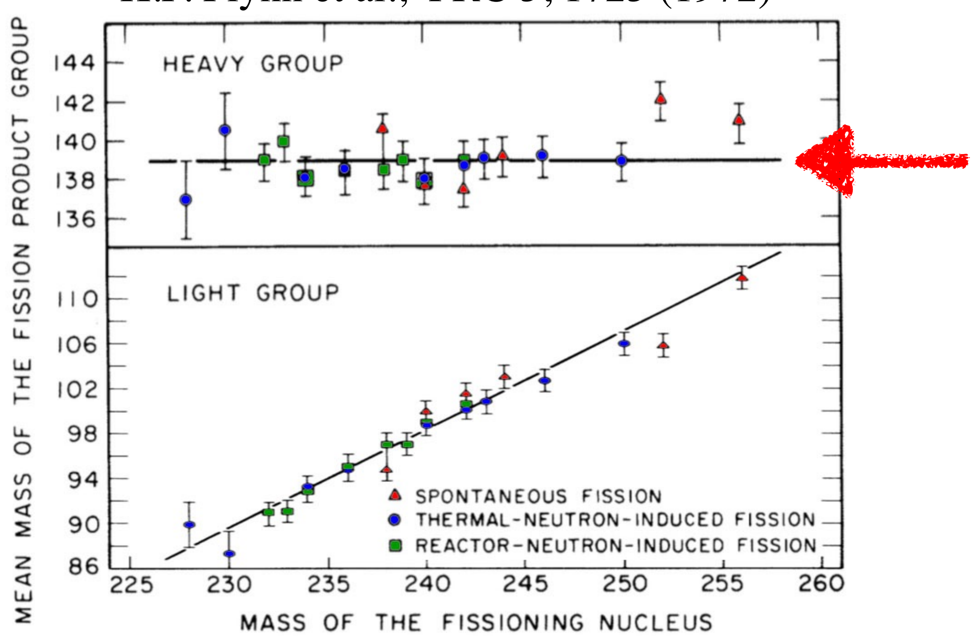
and at scission

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

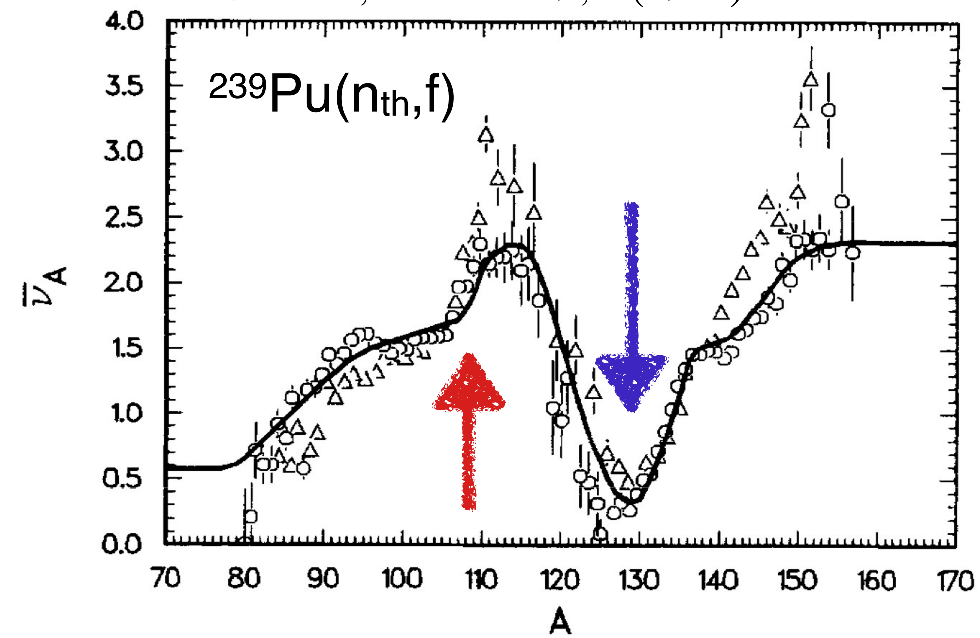


Consistent with a number of observables

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

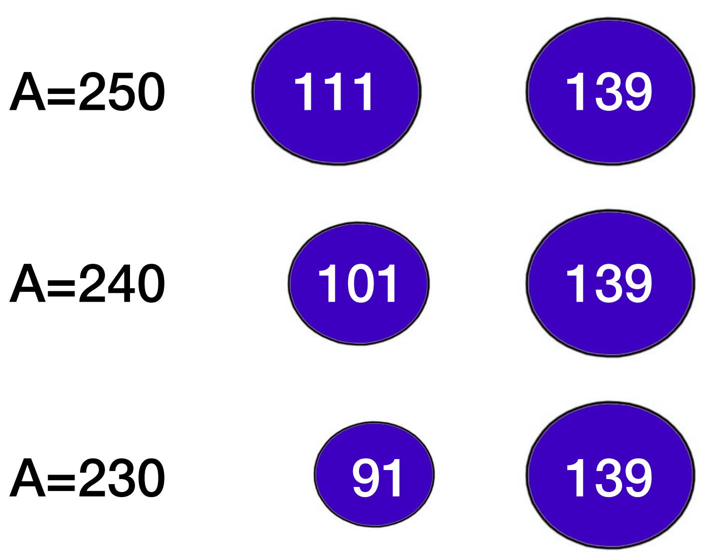


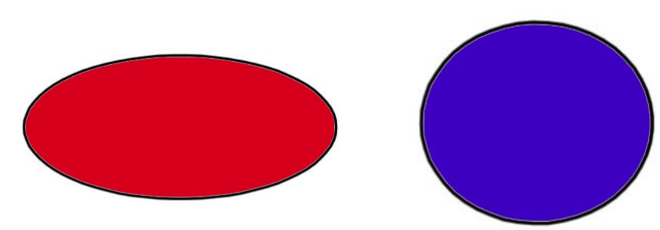
A.C. Wahl, ADNDT 39, 1 (1988)



Size of asymmetric fragments

Neutron evaporation

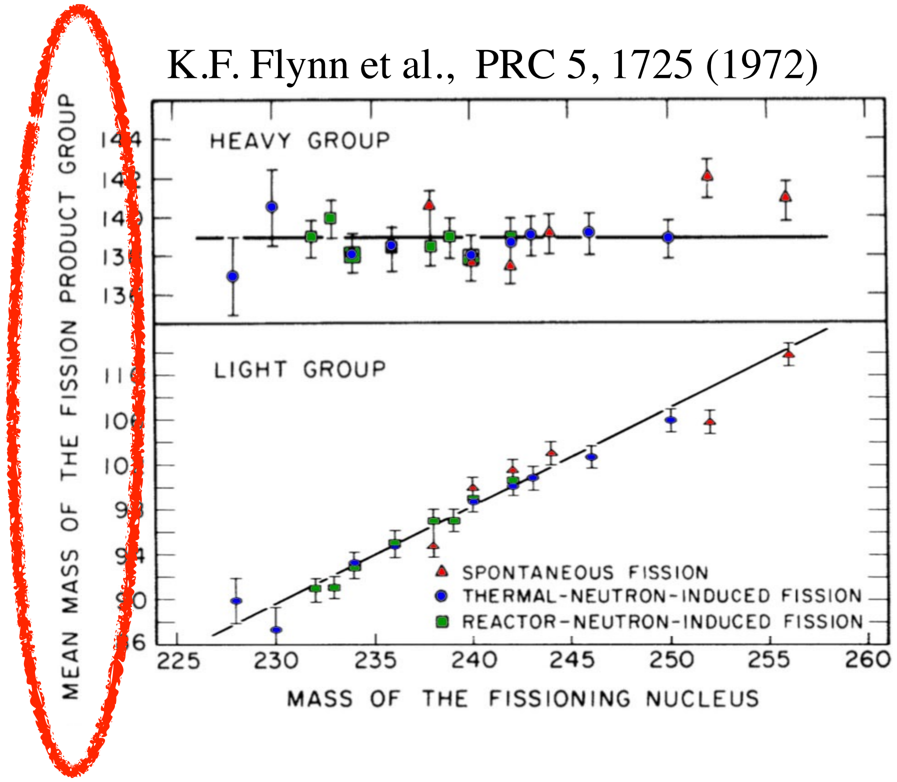




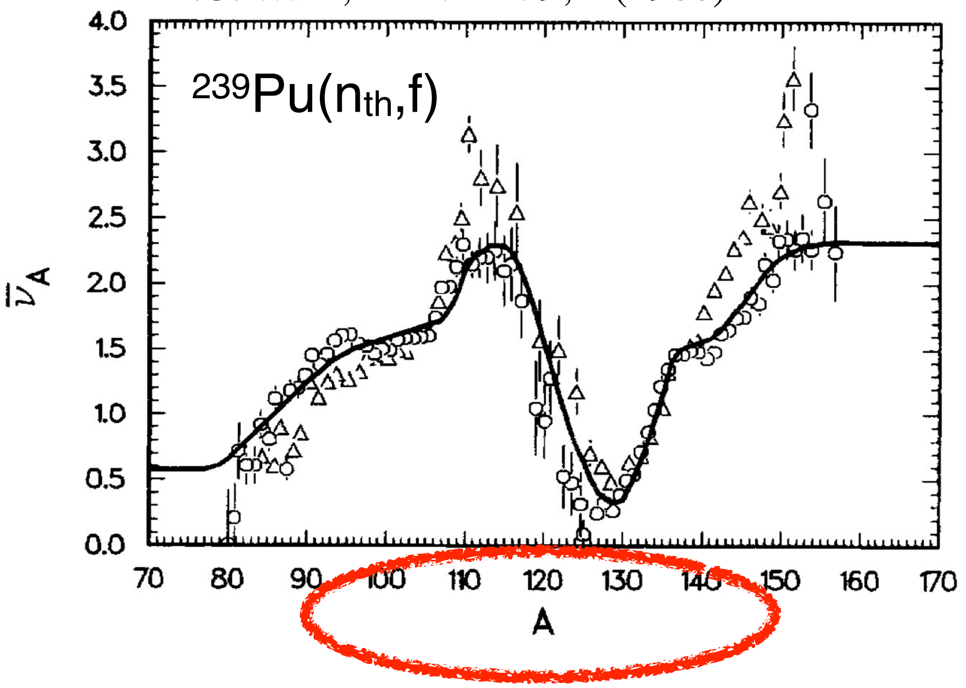
$$\nu \propto E^{def} + E^{int}$$

Fragment identification: All is Mass

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



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



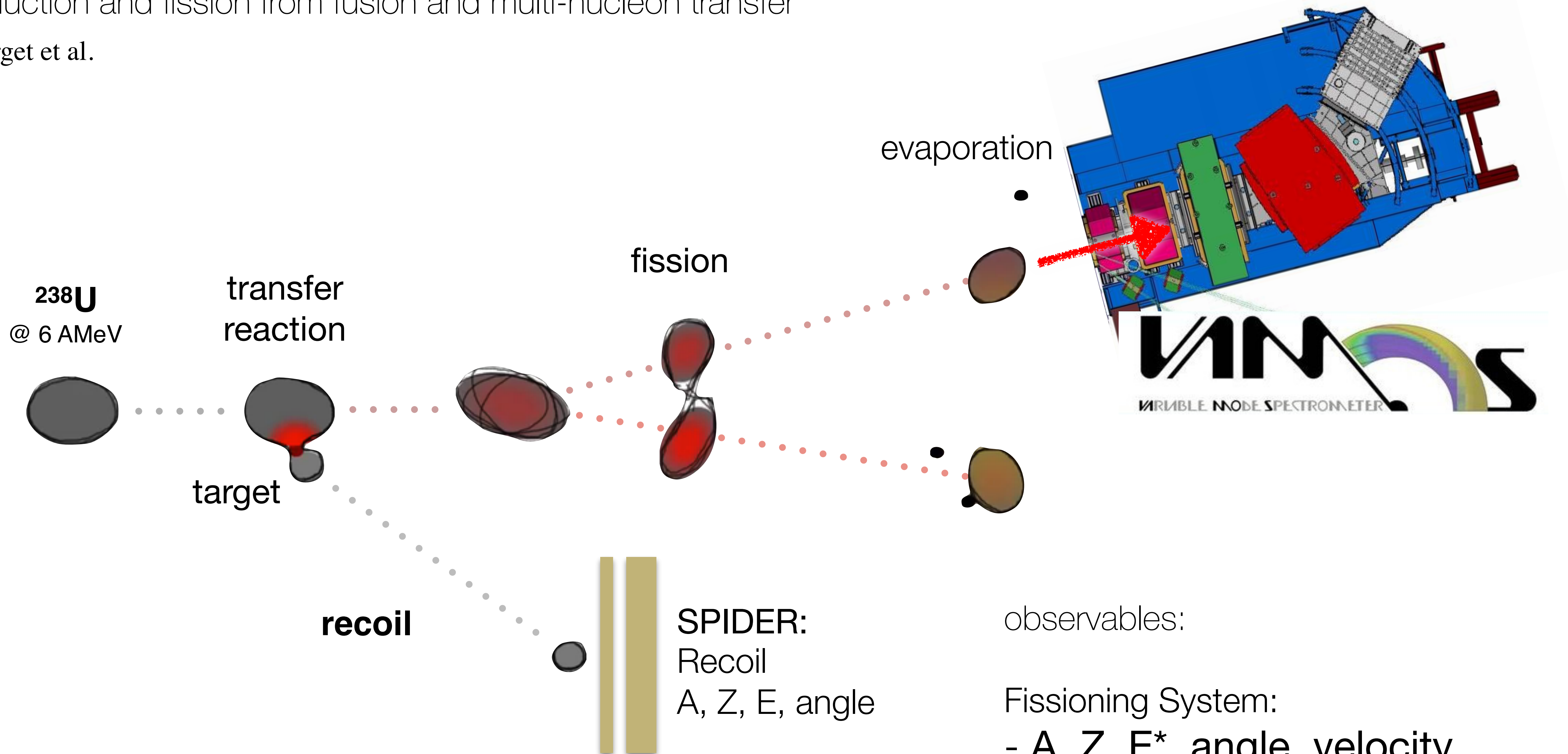
Most of the data is measured in terms of fragment masses.

But shells and structure appear in Z and N.

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

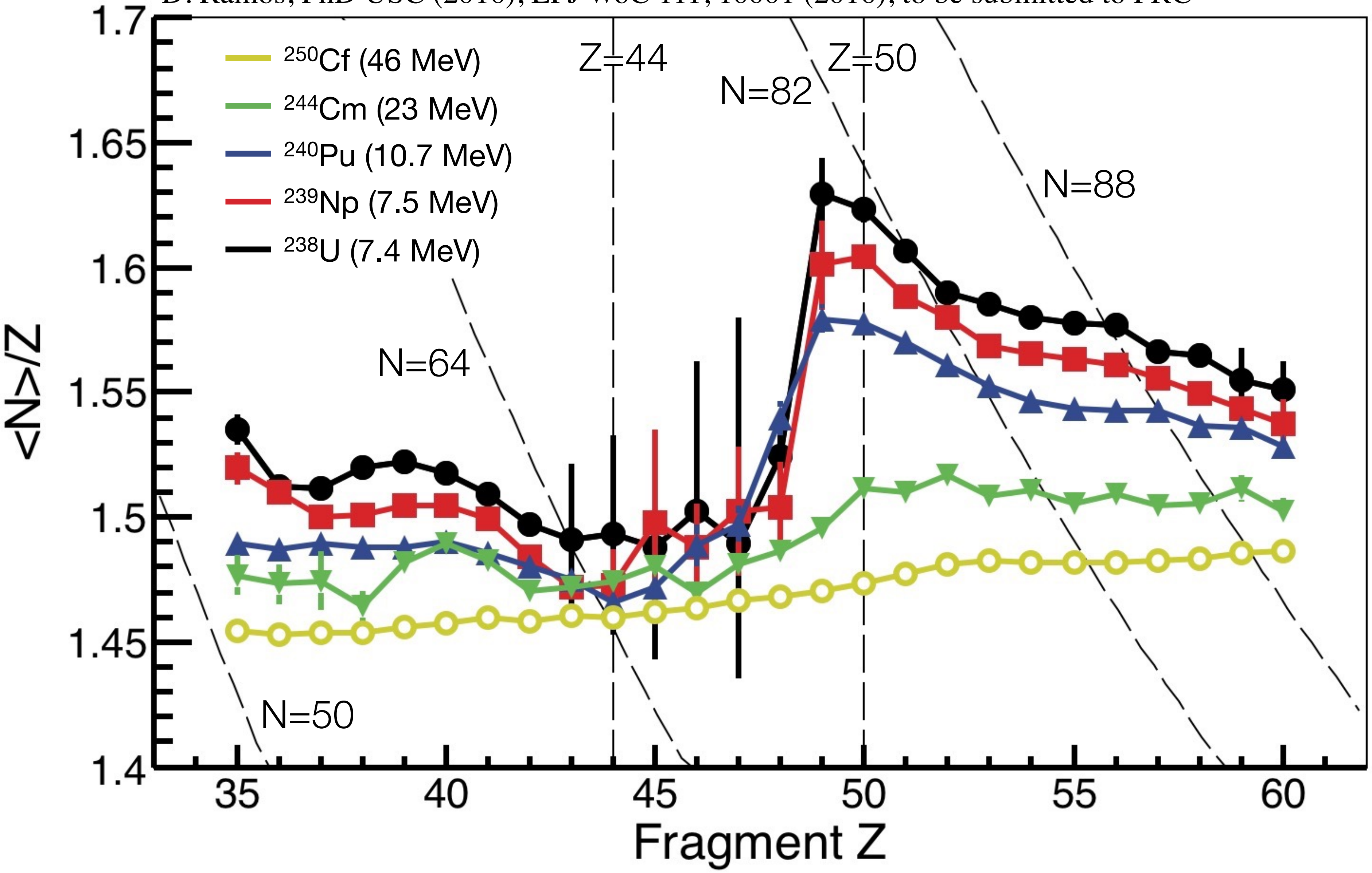
Fission Fragments:

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

A set of revisited and new observables

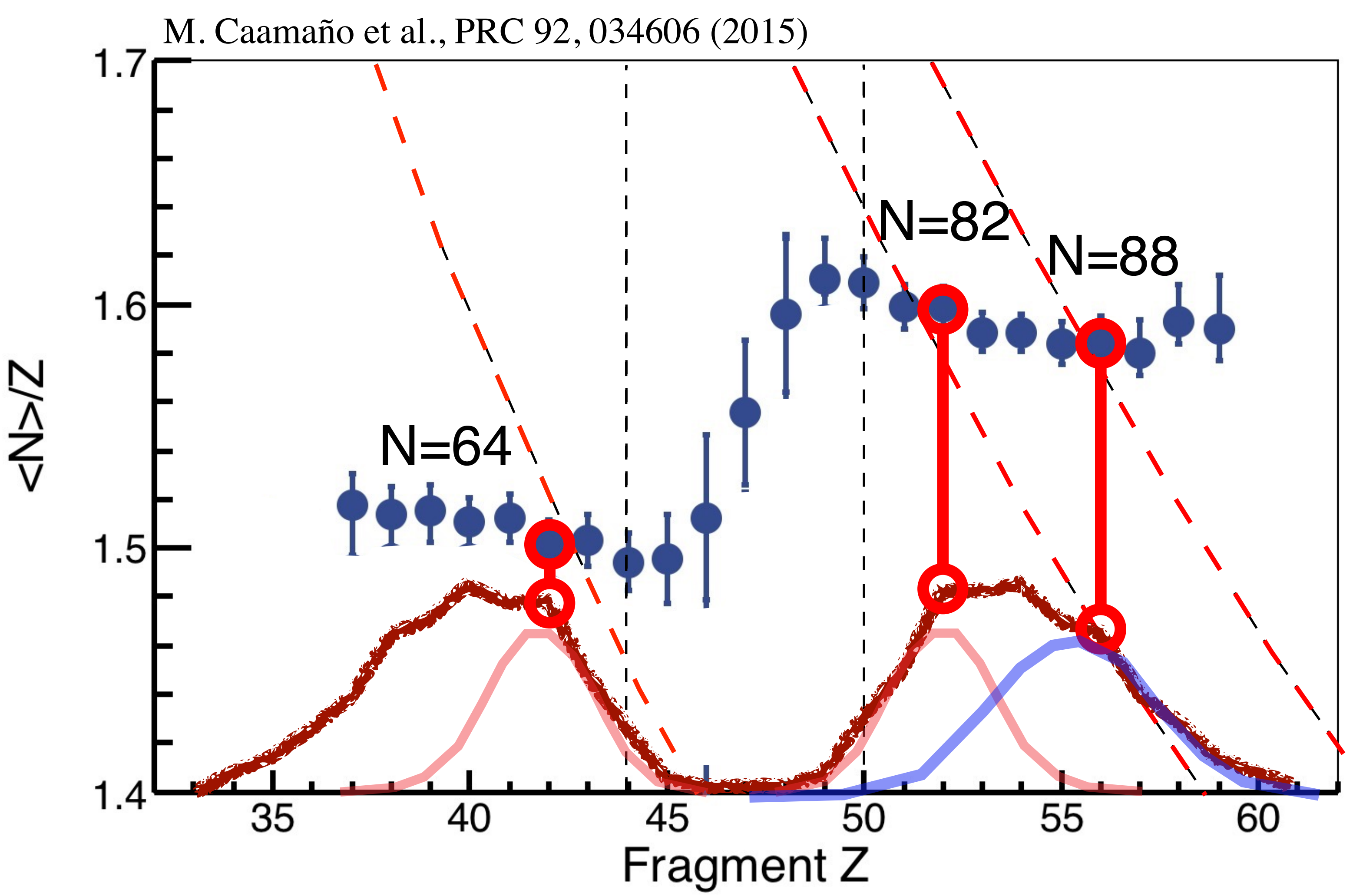
Fragment N excess (N/Z)

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)

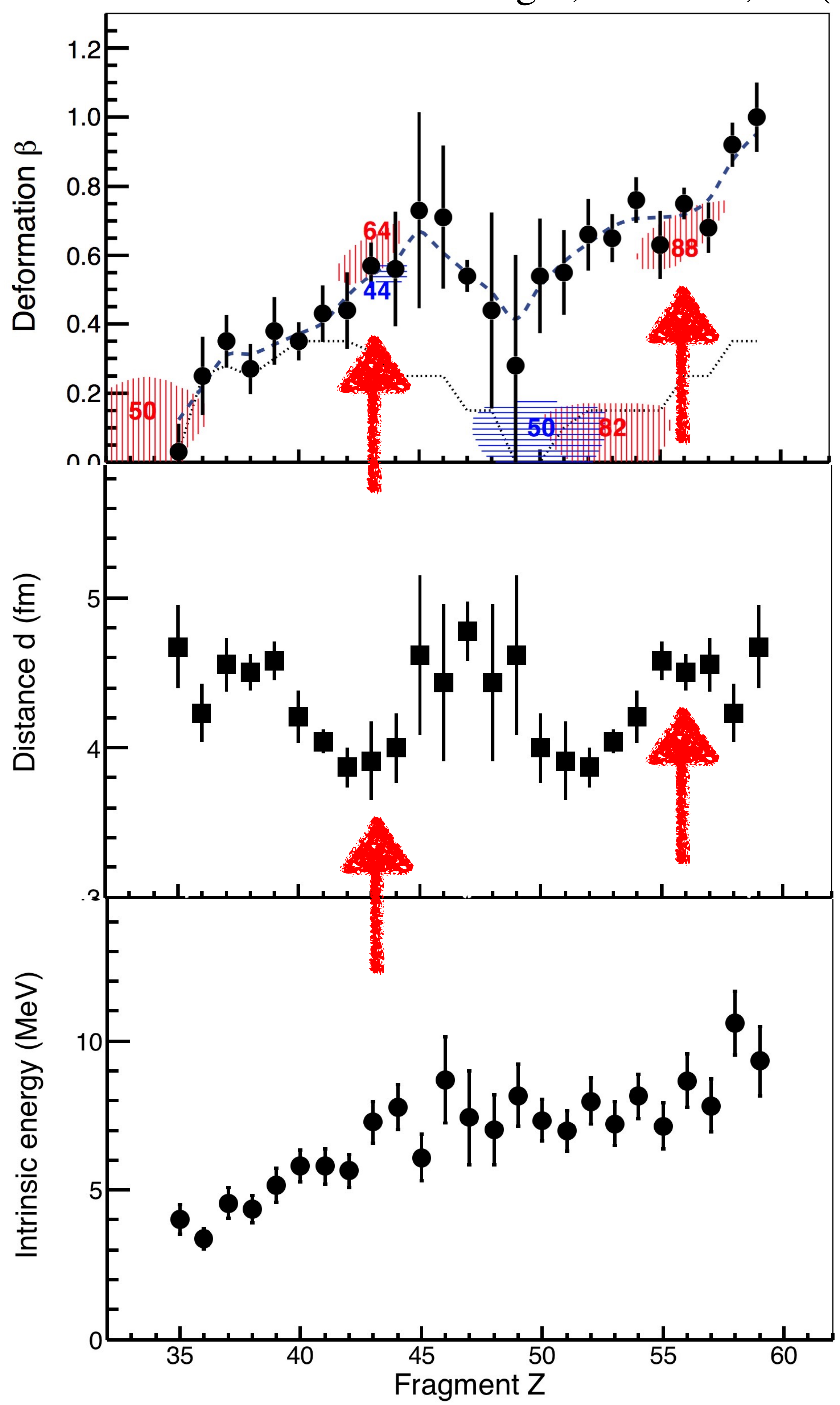
Fragment N excess (N/Z)



Neutron shells seem to drive the final splits

A picture of scission: shapes and energy

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



a collective picture of scission:

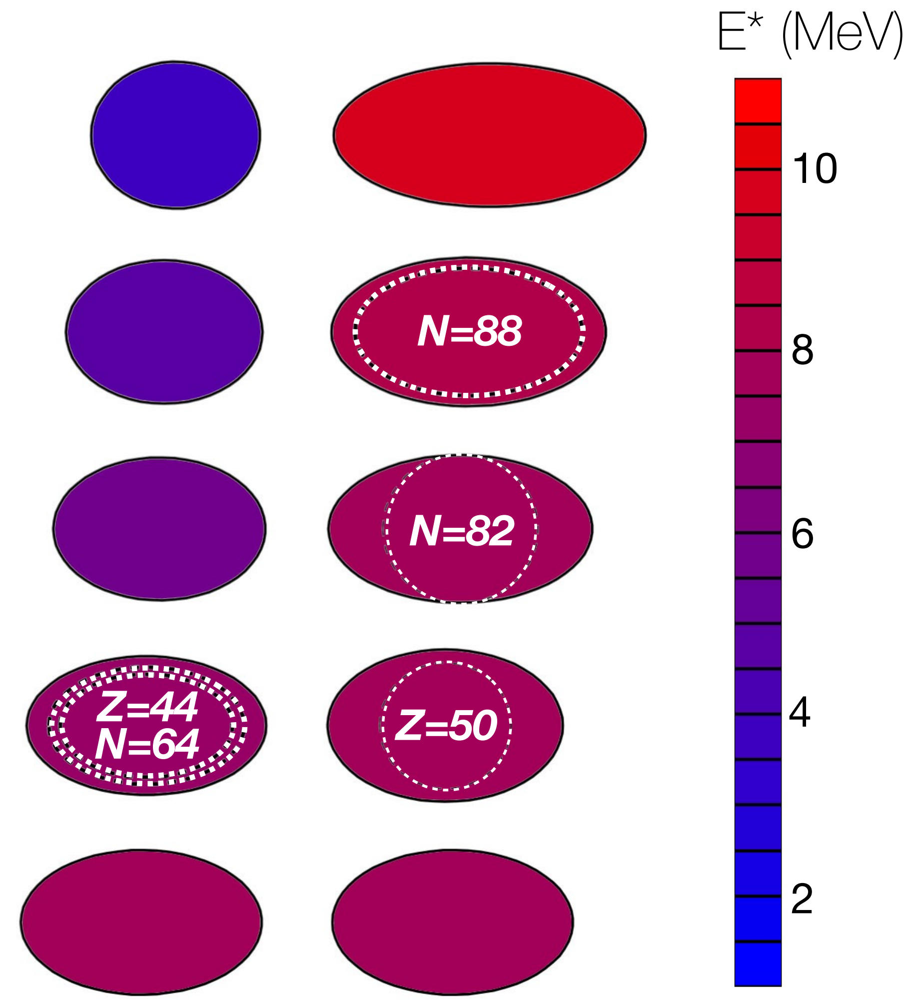
Z_1=35, Z_2=59

Z_1=38, Z_2=56

Z_1=41, Z_2=53

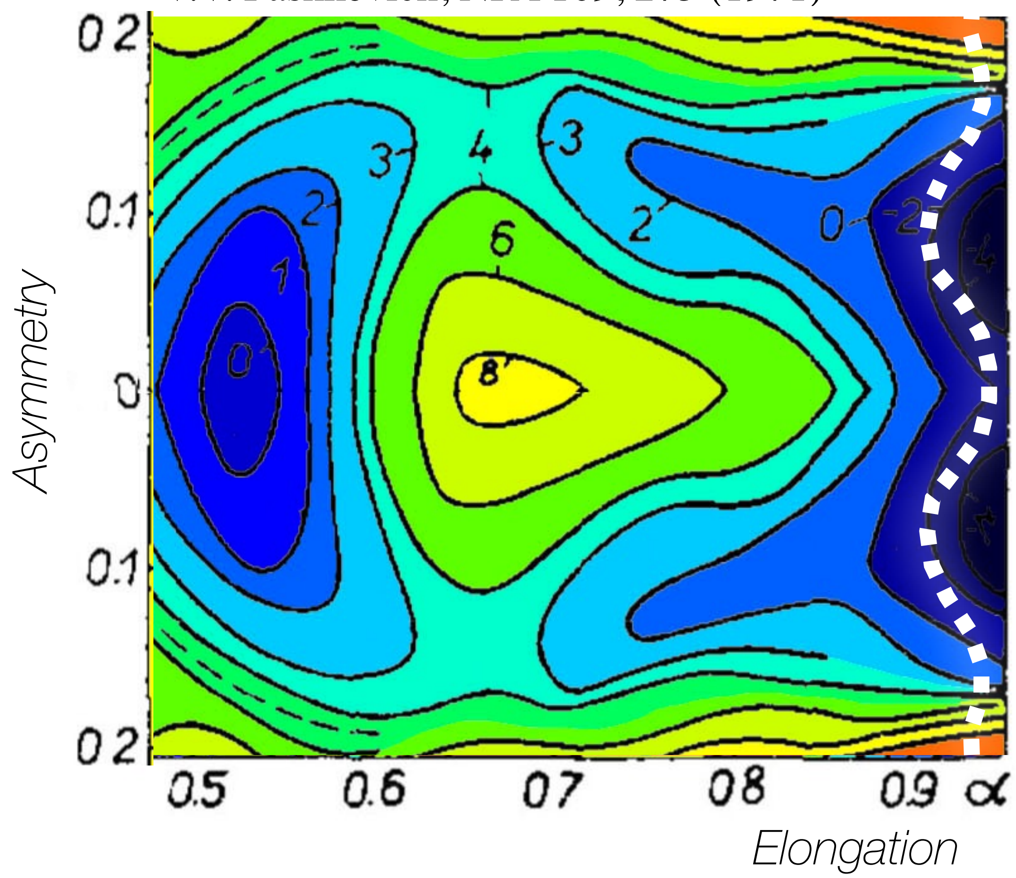
Z_1=44, Z_2=50

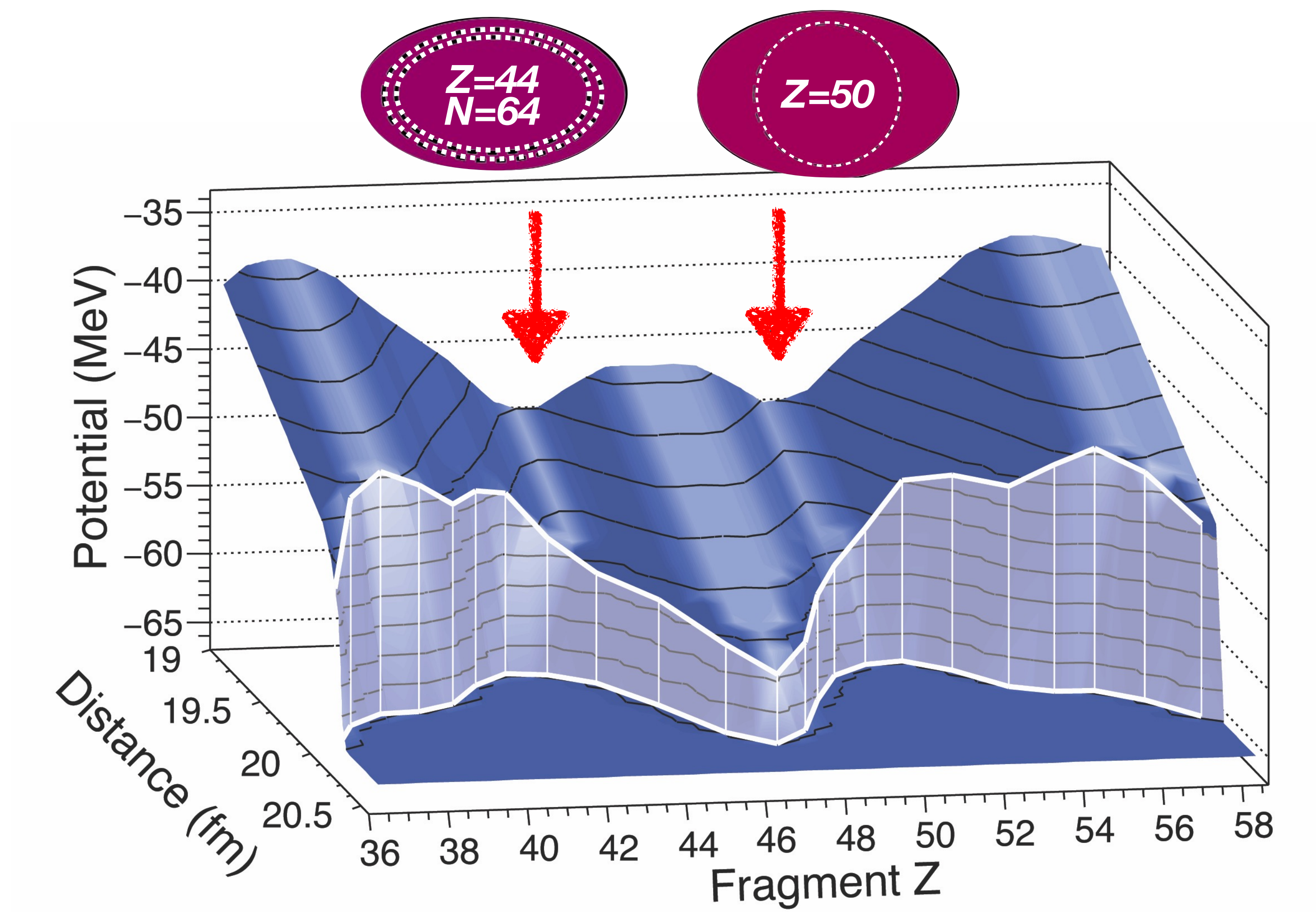
Z_1=47, Z_2=47



A picture of scission

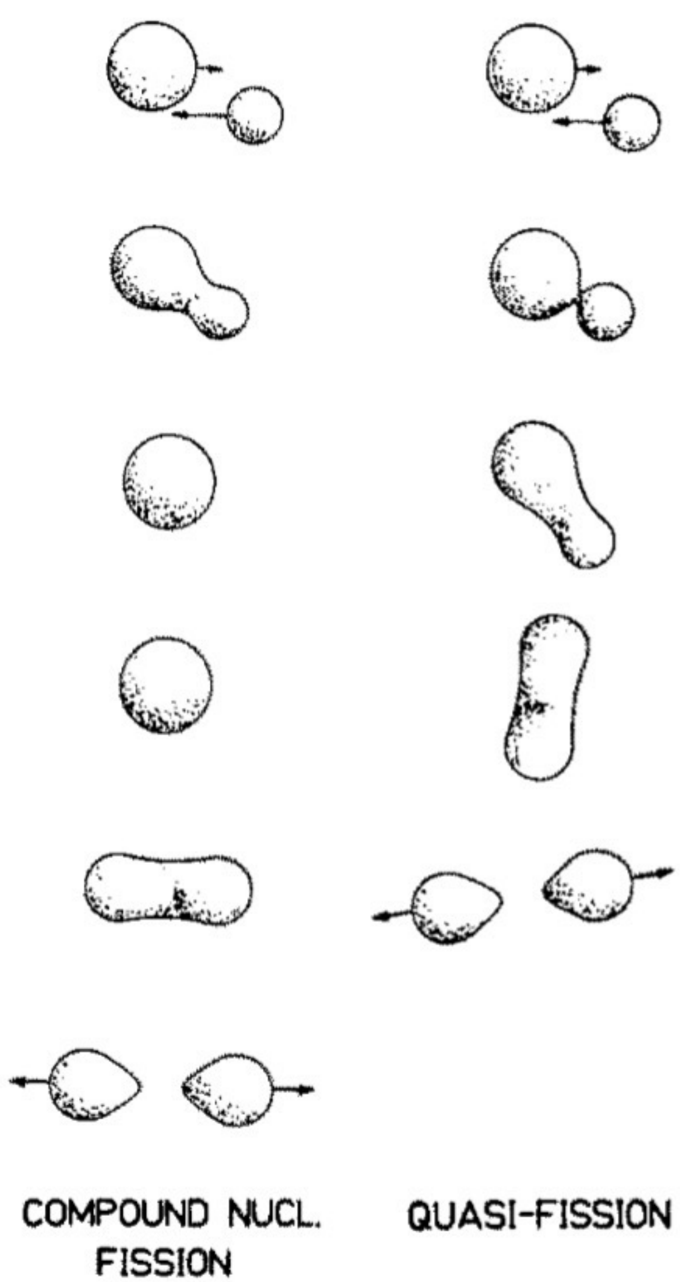
and a sneak peek of the potential landscape:



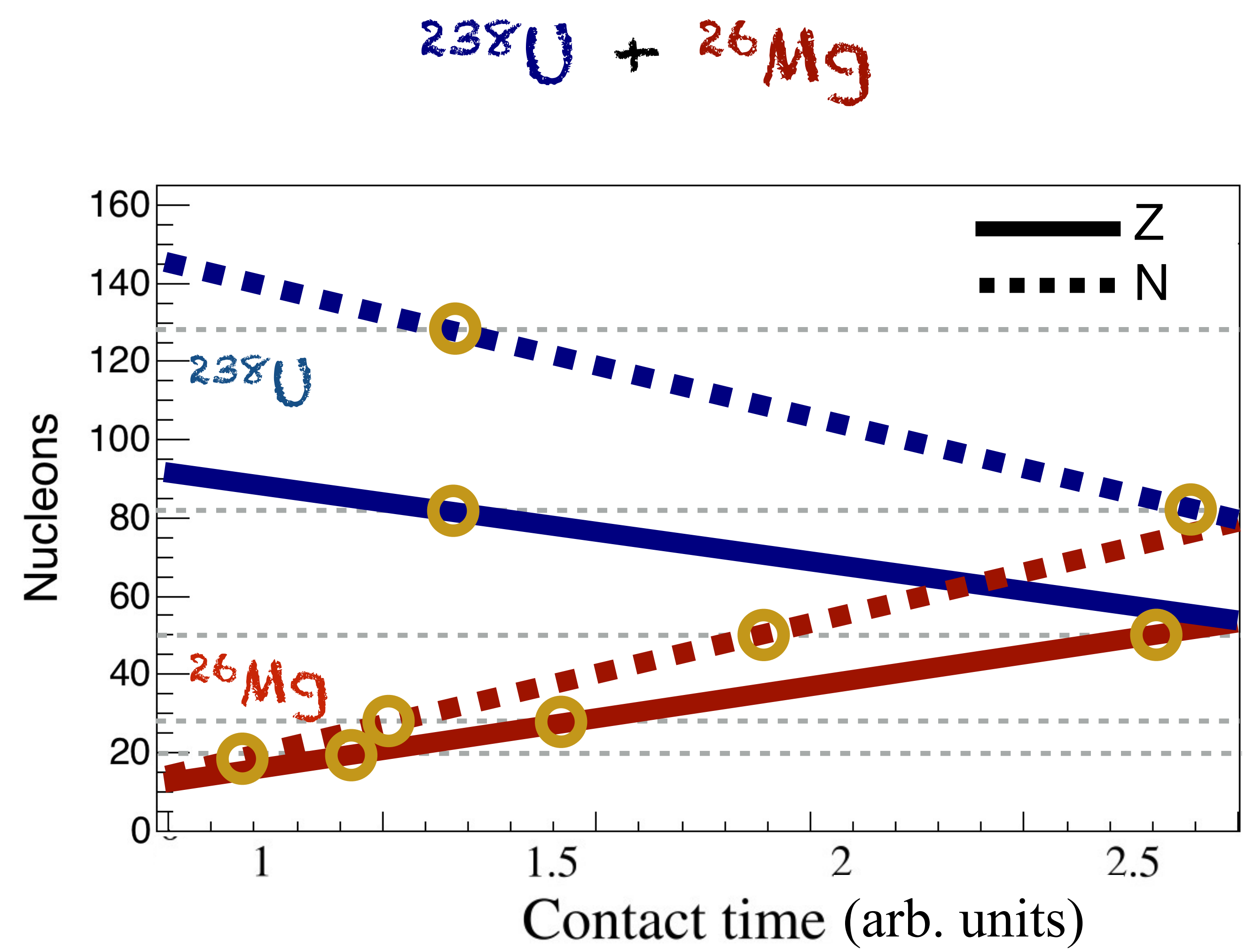


What else? quasi-fission!

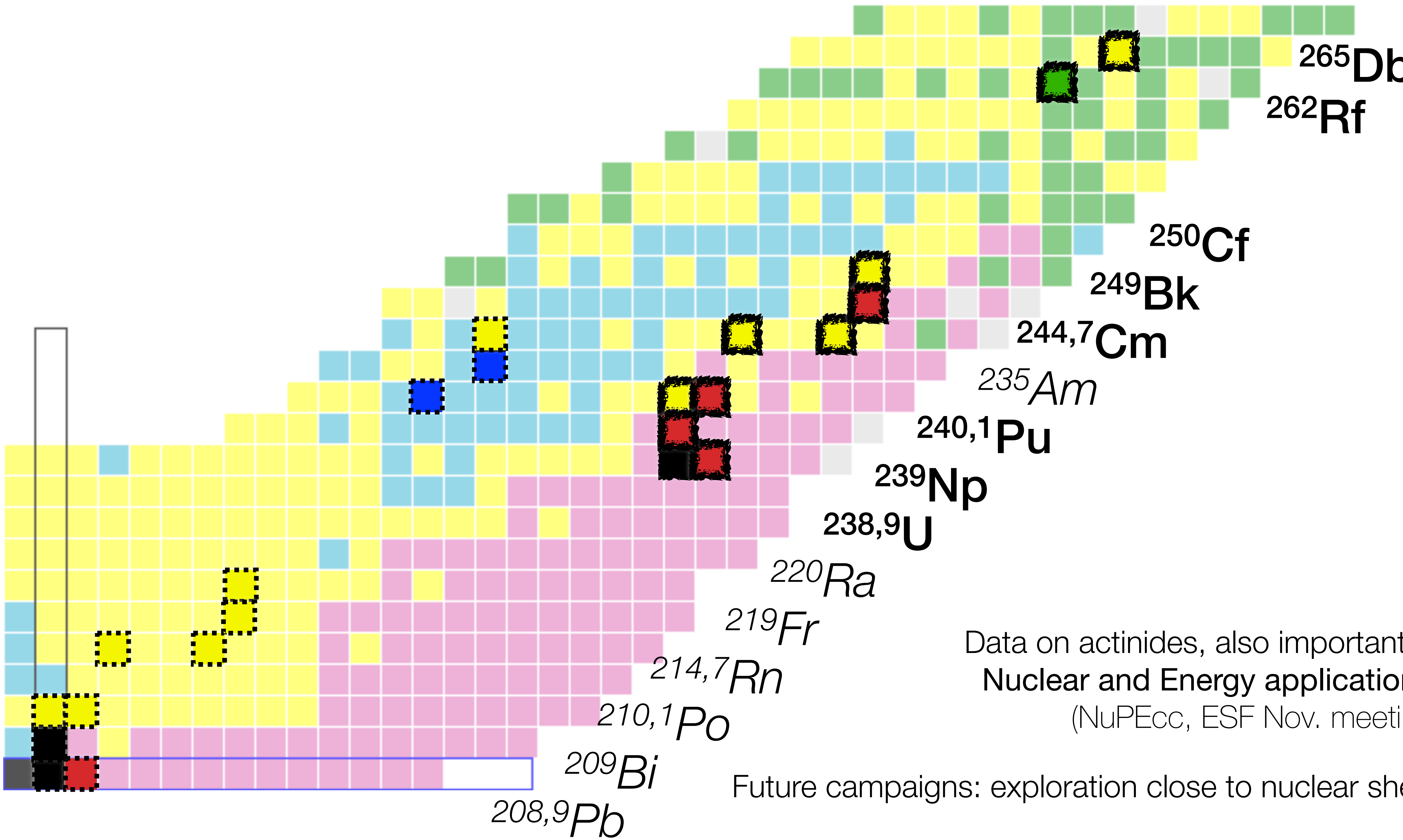
J. Töke et al., NPA 440, 327 (1985)



The measurement of the **fragments Z and N** gives information on **the time of the process**:



A picture of scission and quasi-fission for a collection of systems

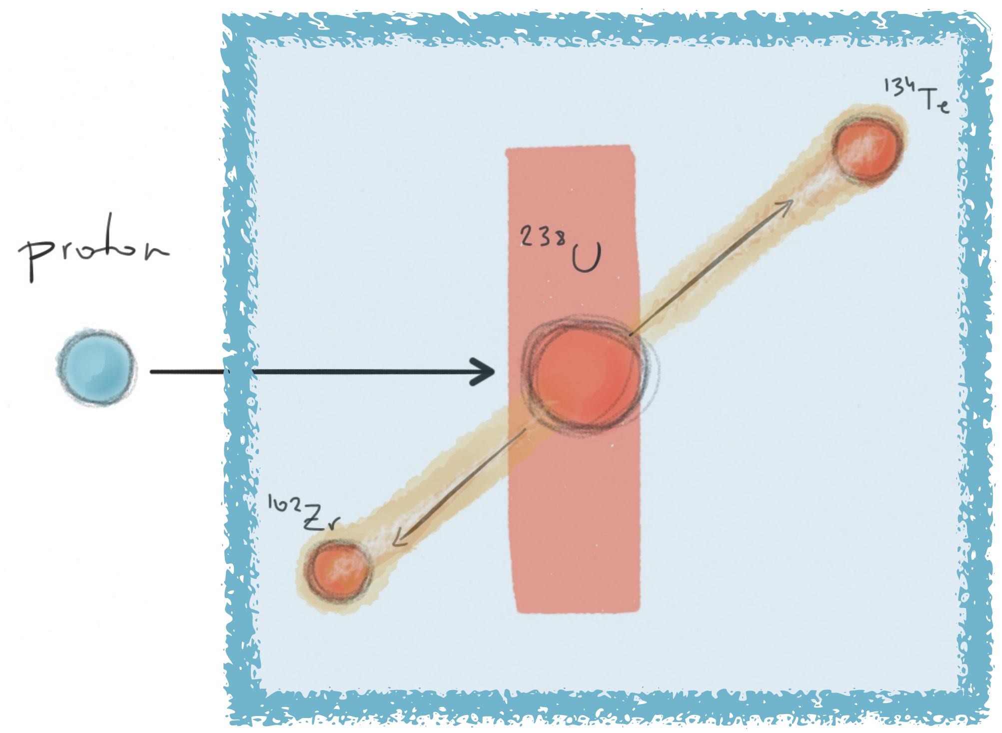


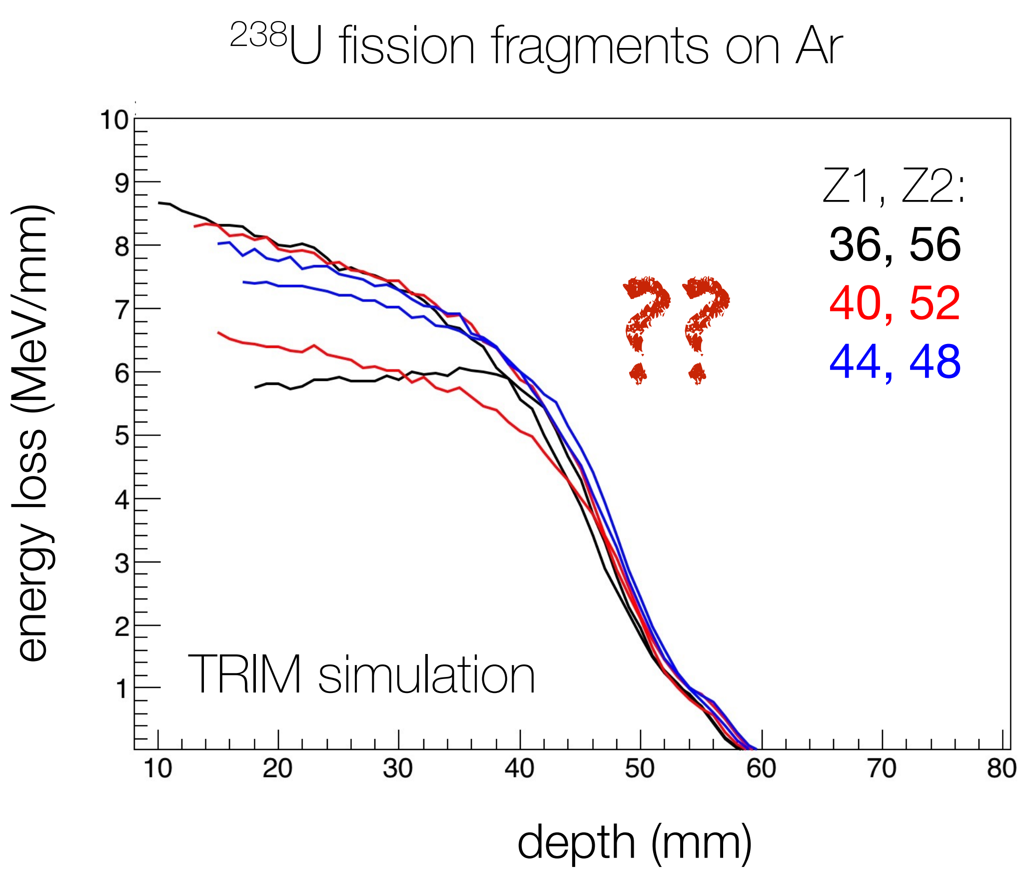
Data on actinides, also important to
Nuclear and Energy applications.
(NuPEcc, ESF Nov. meeting)

Future campaigns: exploration close to nuclear shells

M. Caamaño

A compact system for direct kinematics

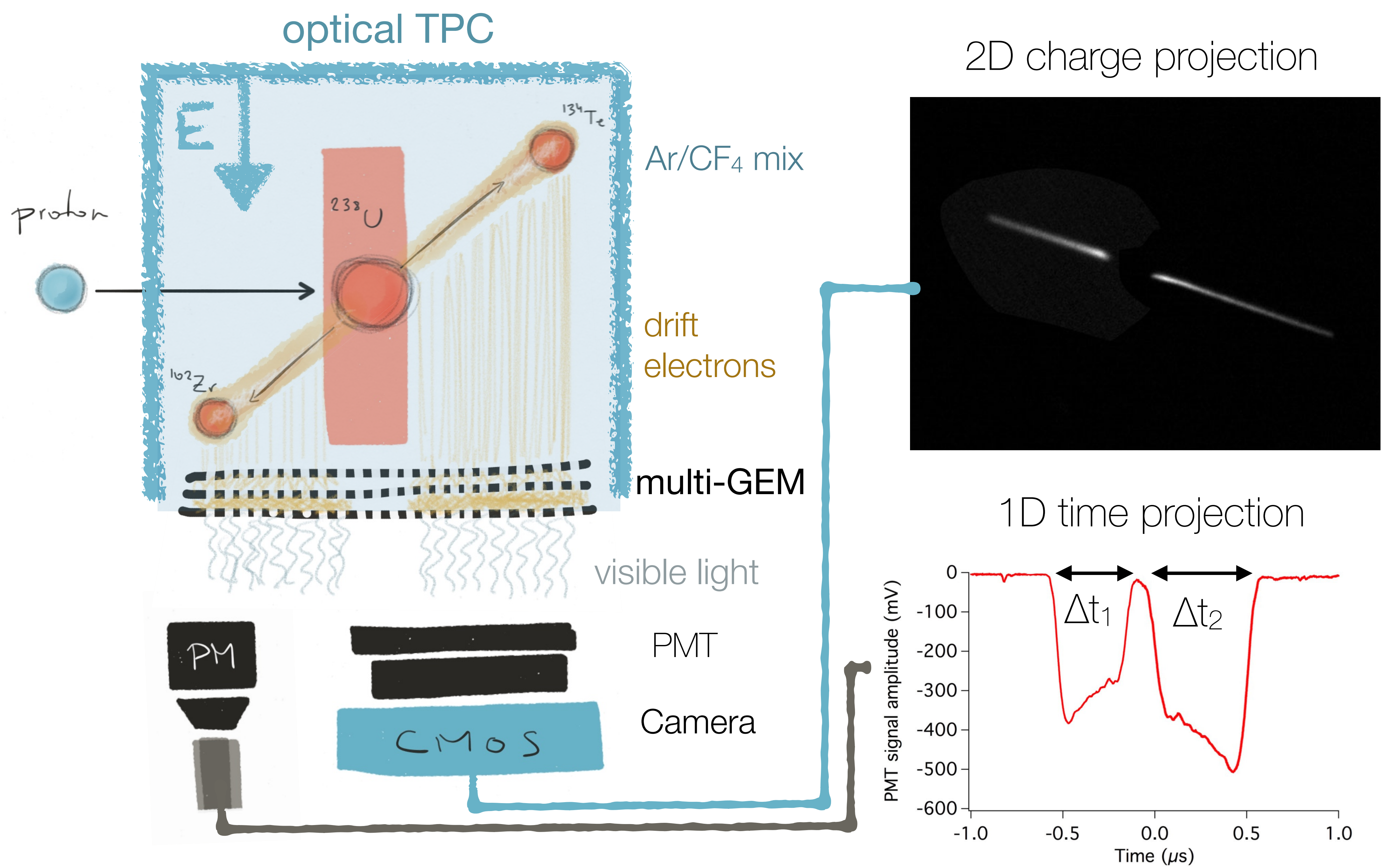




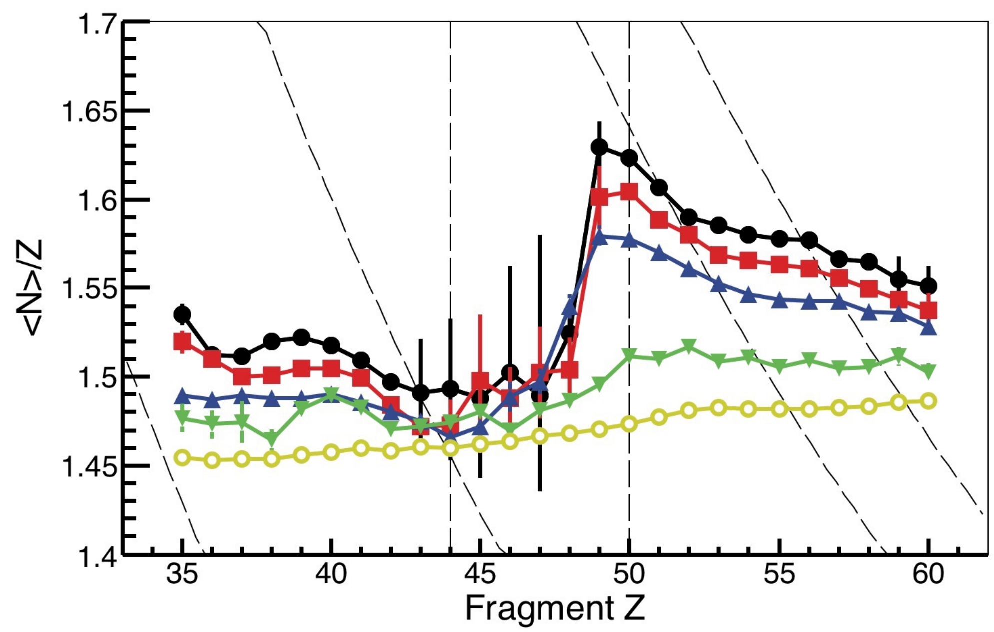
gas-filled detector:
total energy
angle
energy loss / range

M. Caamaño

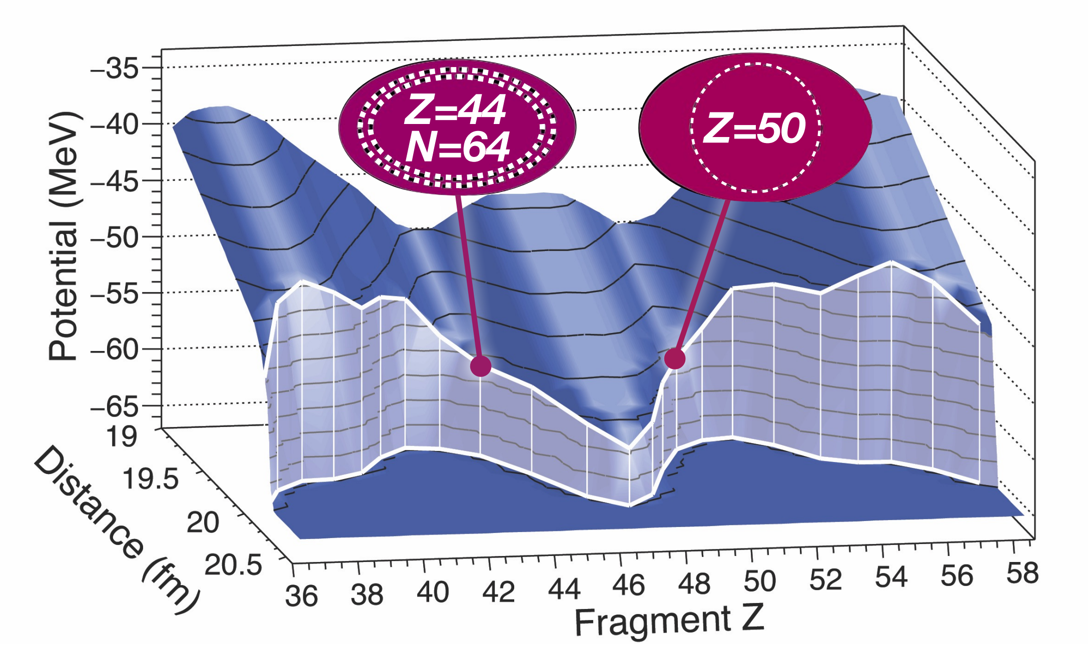
A compact system for direct kinematics



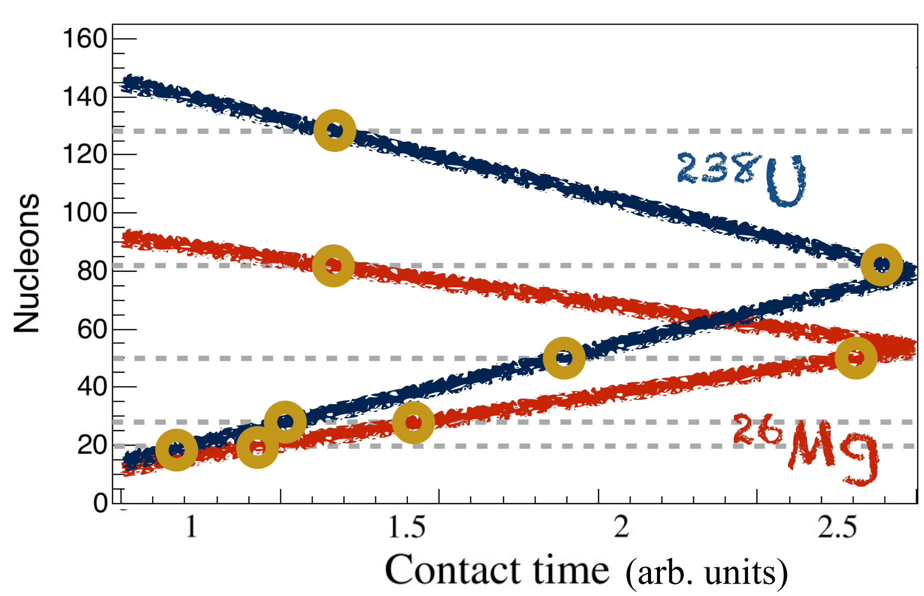
In summary…



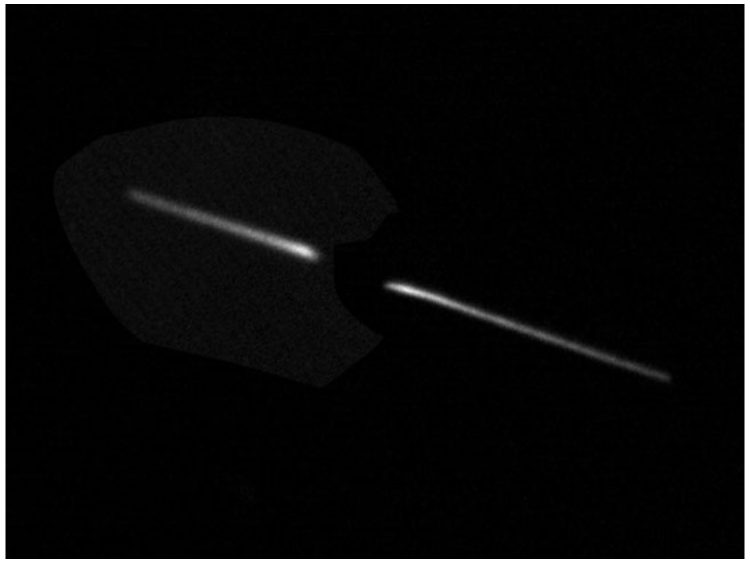
new and revisited fission observables



access to the scission configuration



next in line: quasi-fission



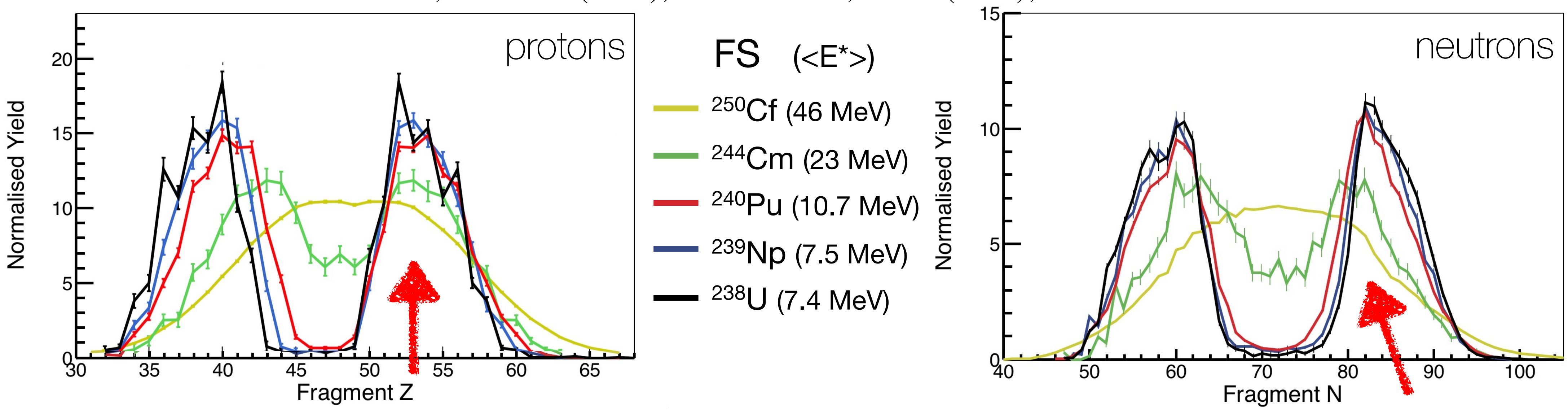
a new approach for fission detection

M. Caamaño

A set of revisited and new observables

Fragment Z, N distributions

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

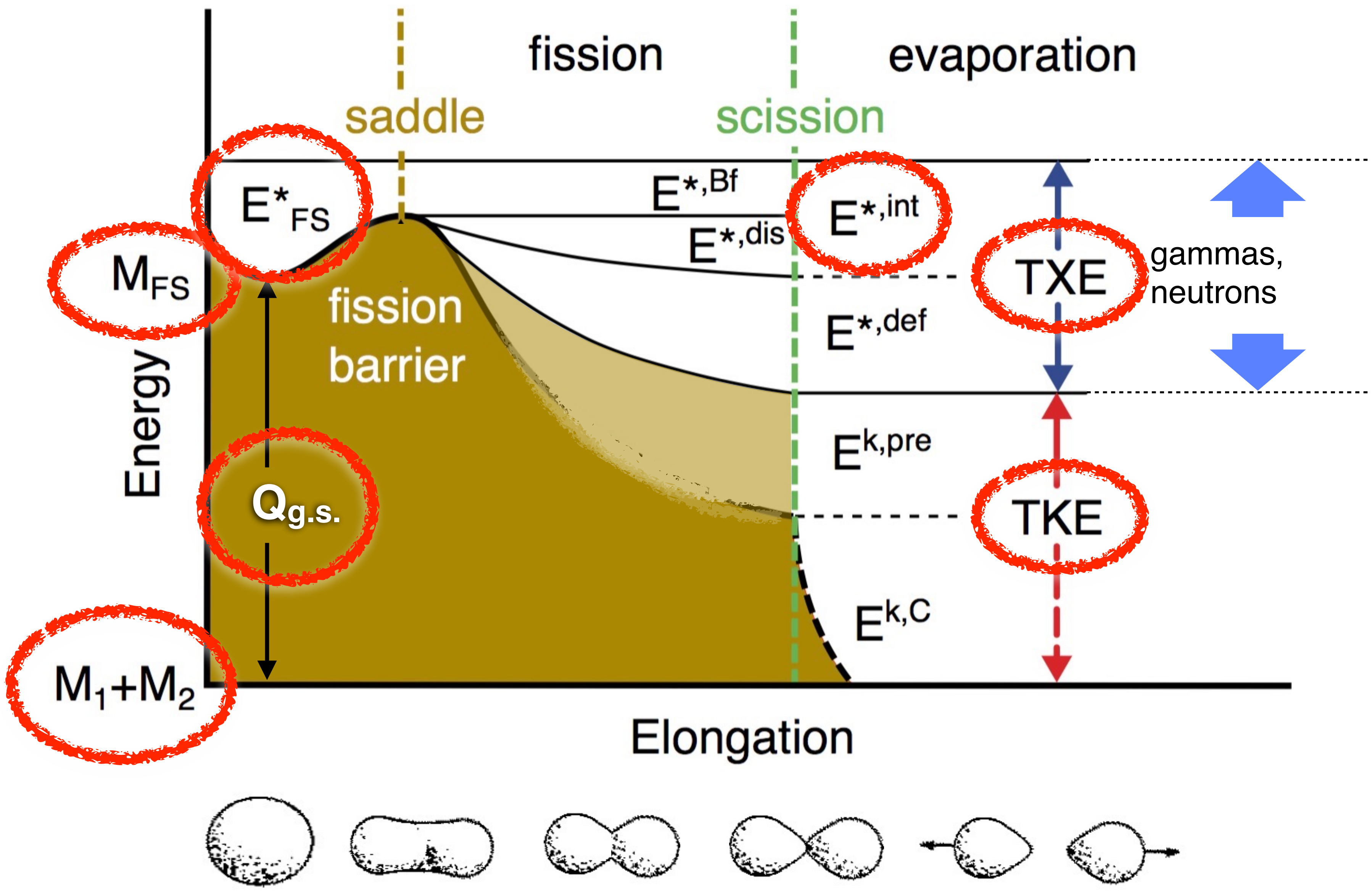


The dominance of the heavy group lasts until very high excitation energy.

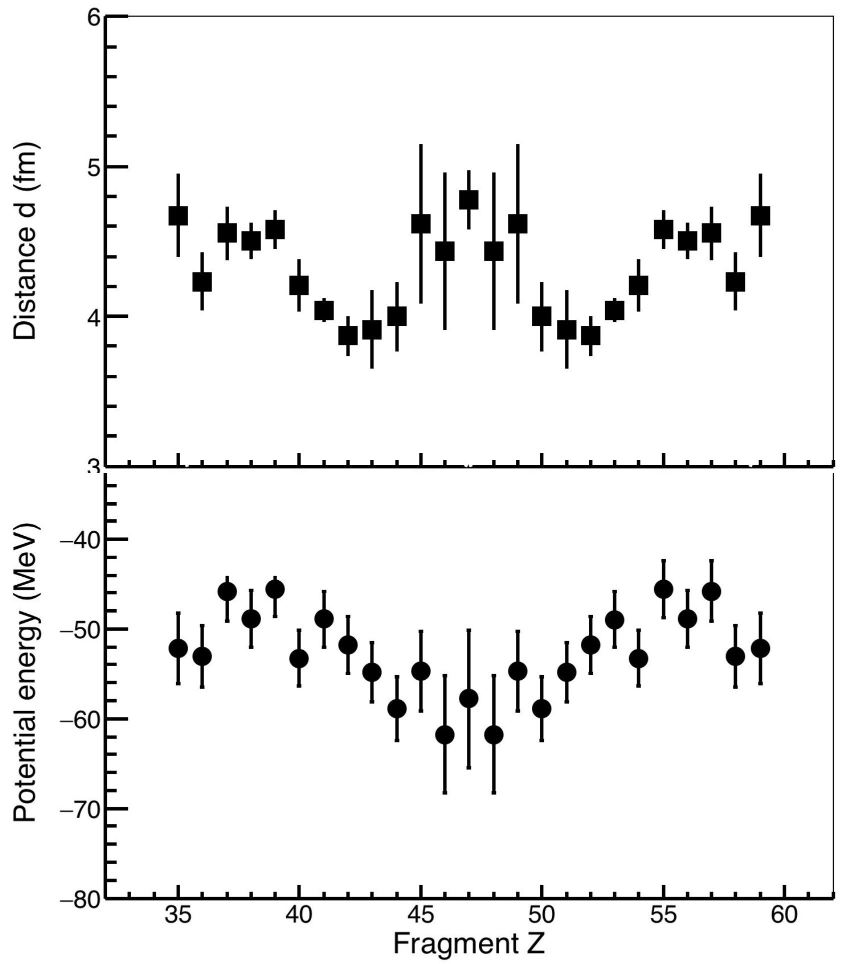
At ~46 MeV the distribution is not yet fully LD.

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

A more detailed energy balance

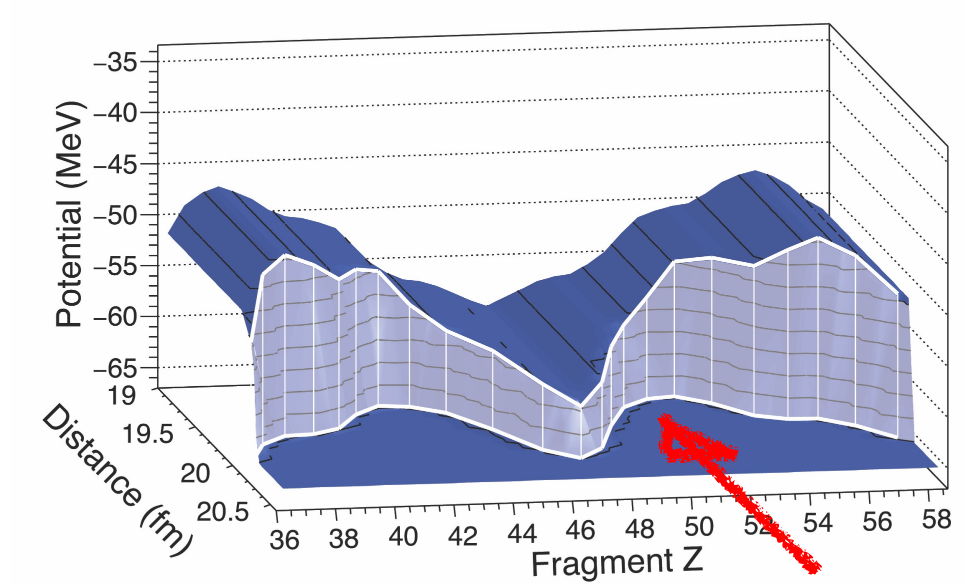


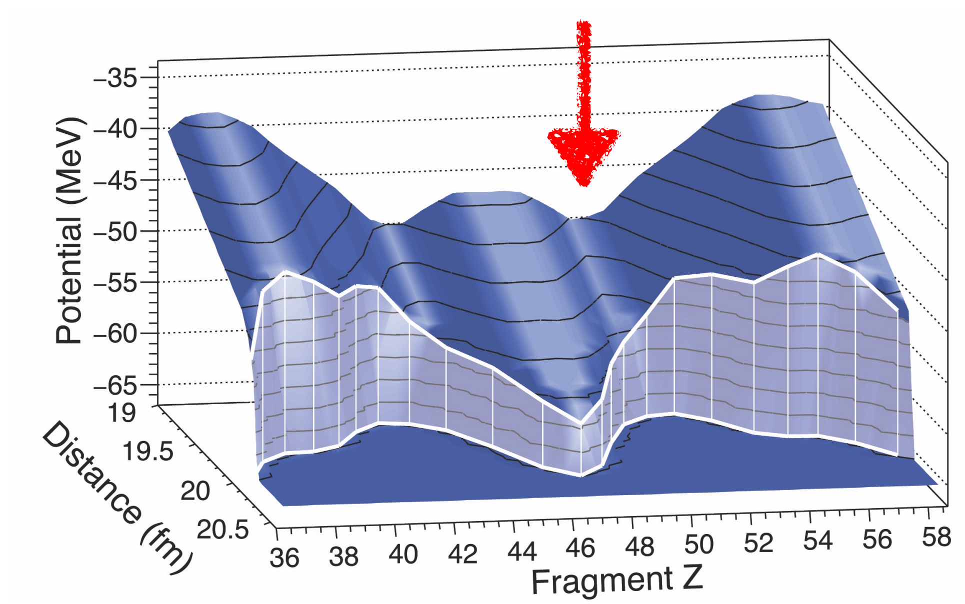
New access to scission; the case of ^{240}Pu (9 MeV)



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

and a sneak peak of the potential landscape:



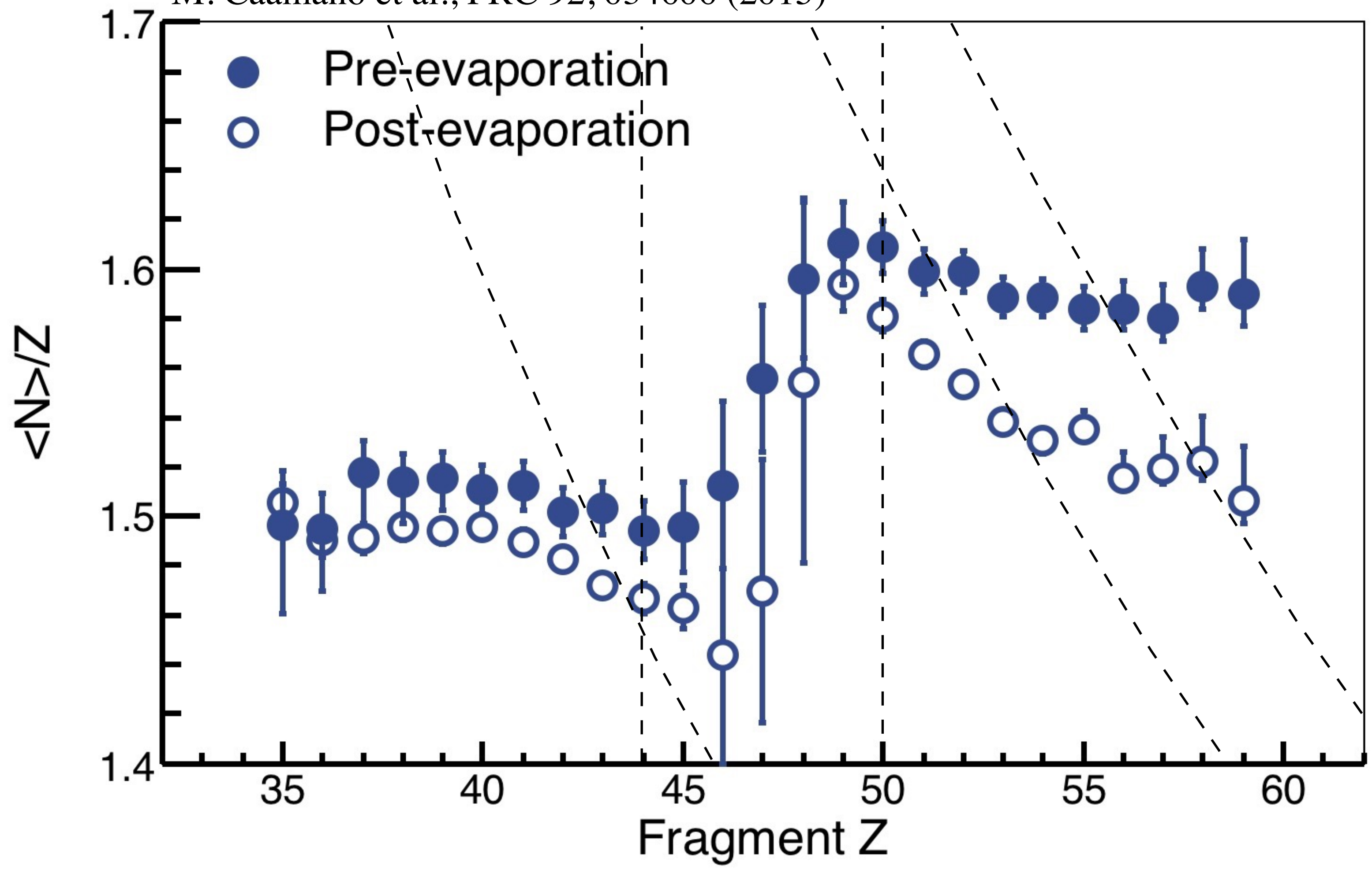


M. Caamaño (USC)

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

Fragment N excess (N/Z)

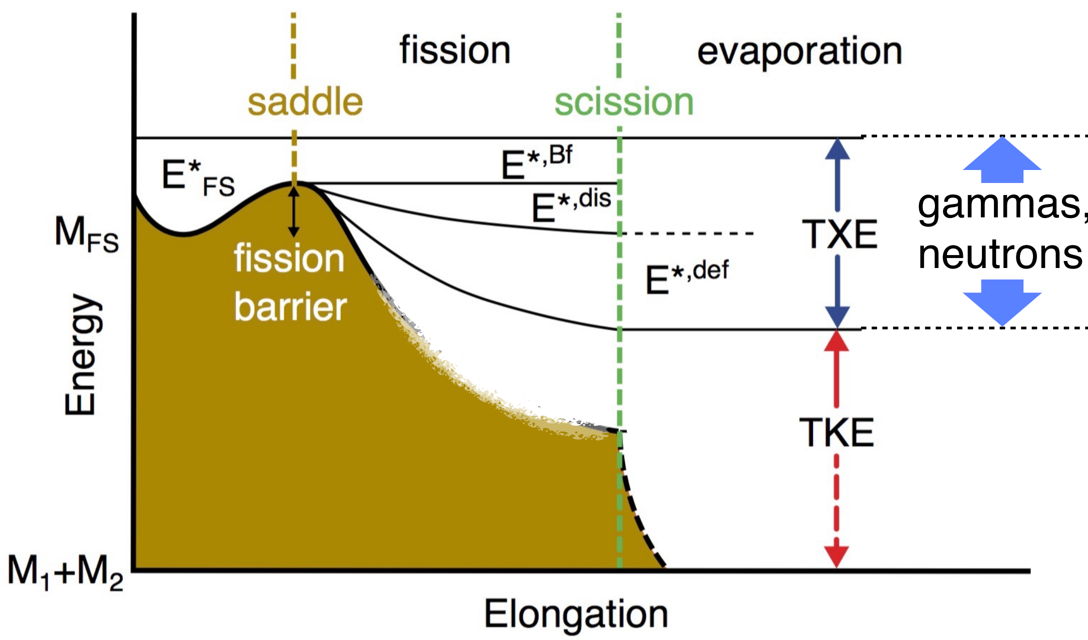
M. Caamaño et al., PRC 92, 034606 (2015)



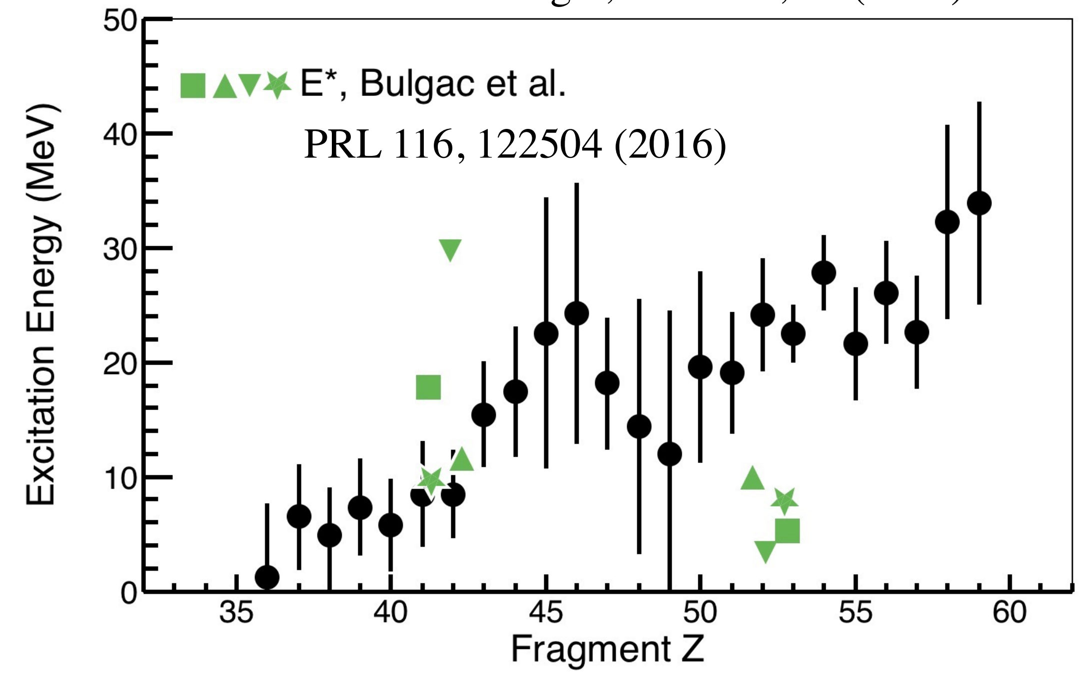
measured velocities and momentum conservation:

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

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



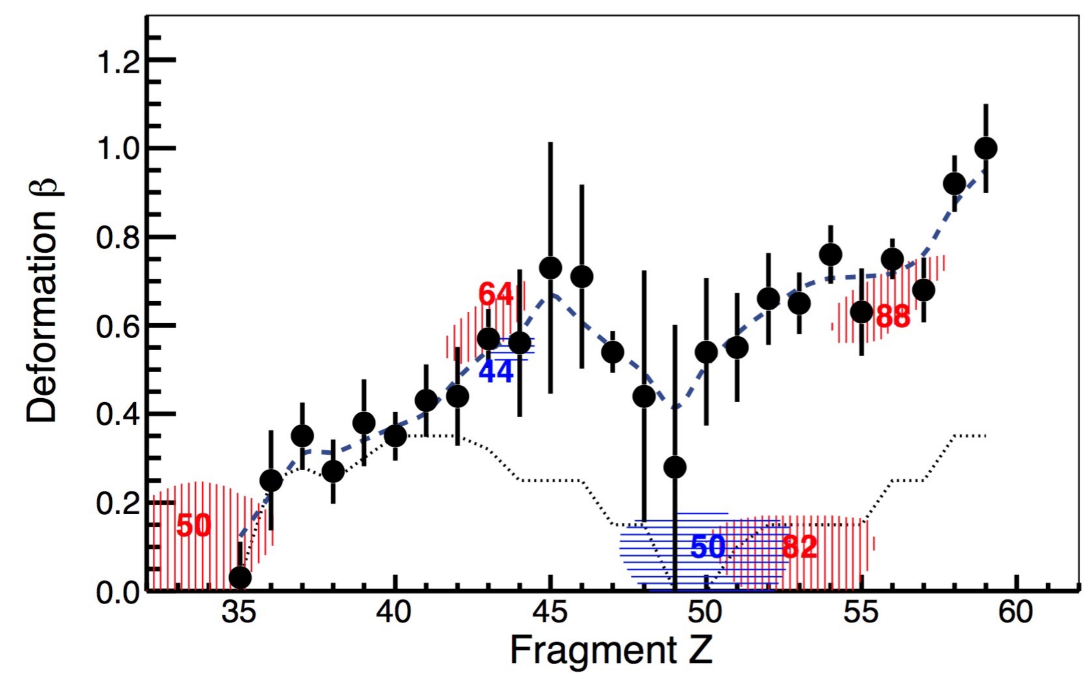
M. Caamaño and F. Farget, PLB 770, 72 (2017)



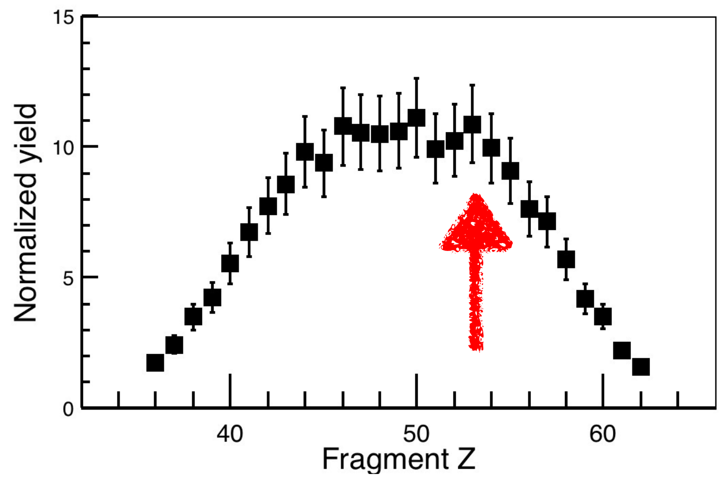
$$M_{FS} + E^{*}_{FS} = \text{TXE} + \text{TKE} + M_1 + M_2$$

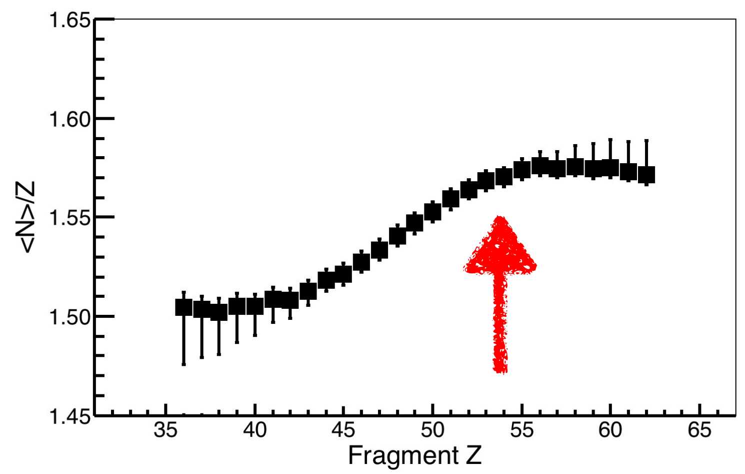
$$\text{TXE} = E^{*,Bf} + E^{*,dis} + E^{*,def}$$

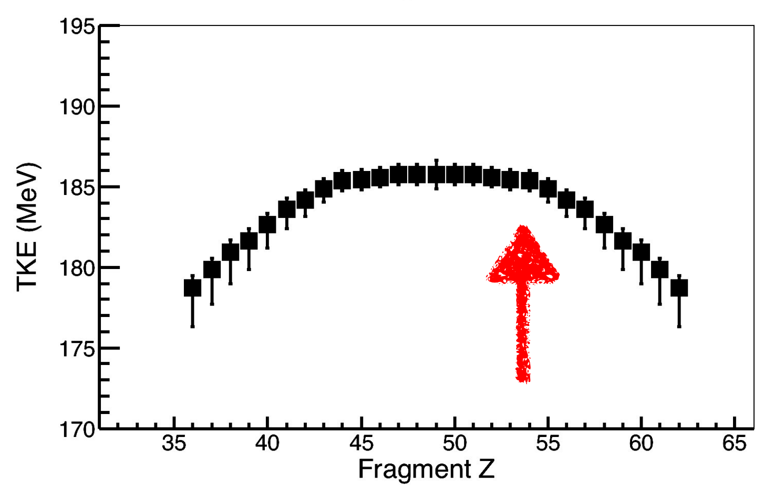
$$= \nu \cdot (Q_n + \varepsilon) + E^{\gamma}$$



access to the fragment deformations !!

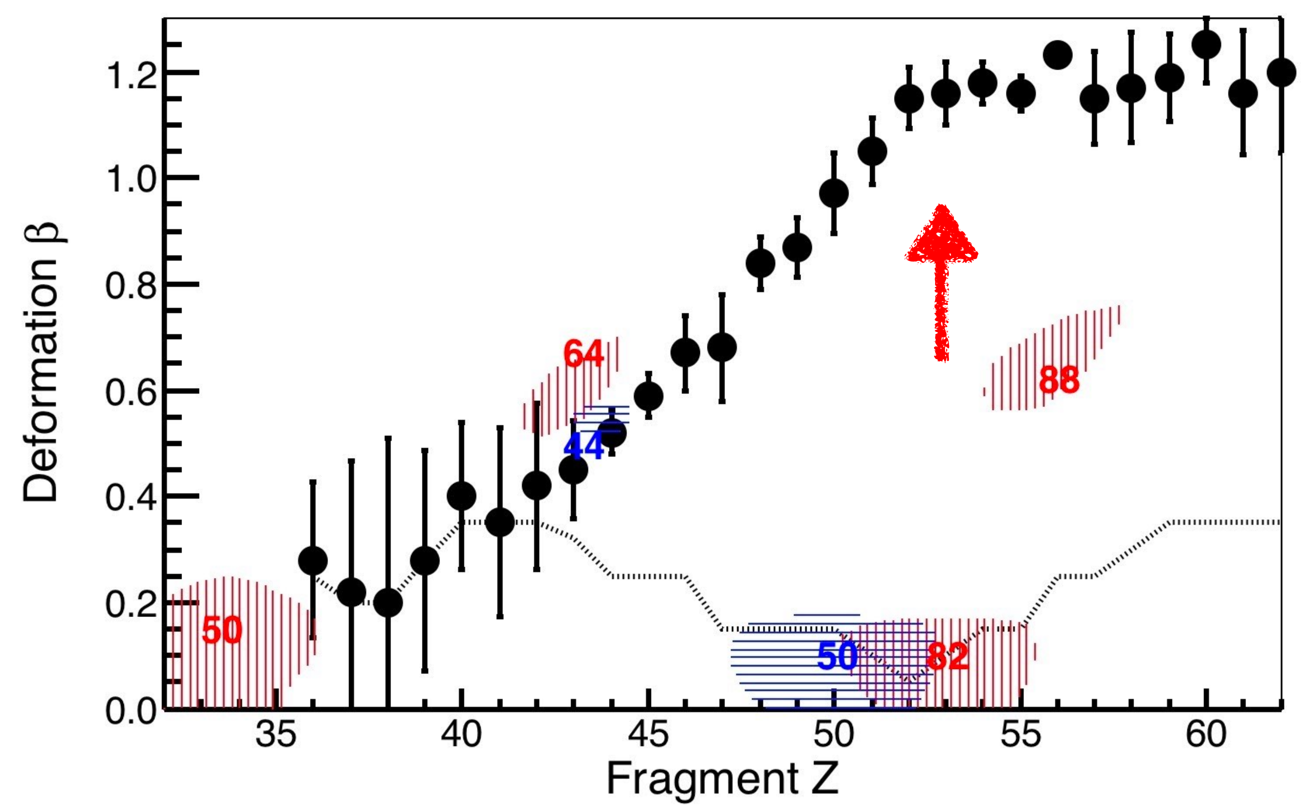






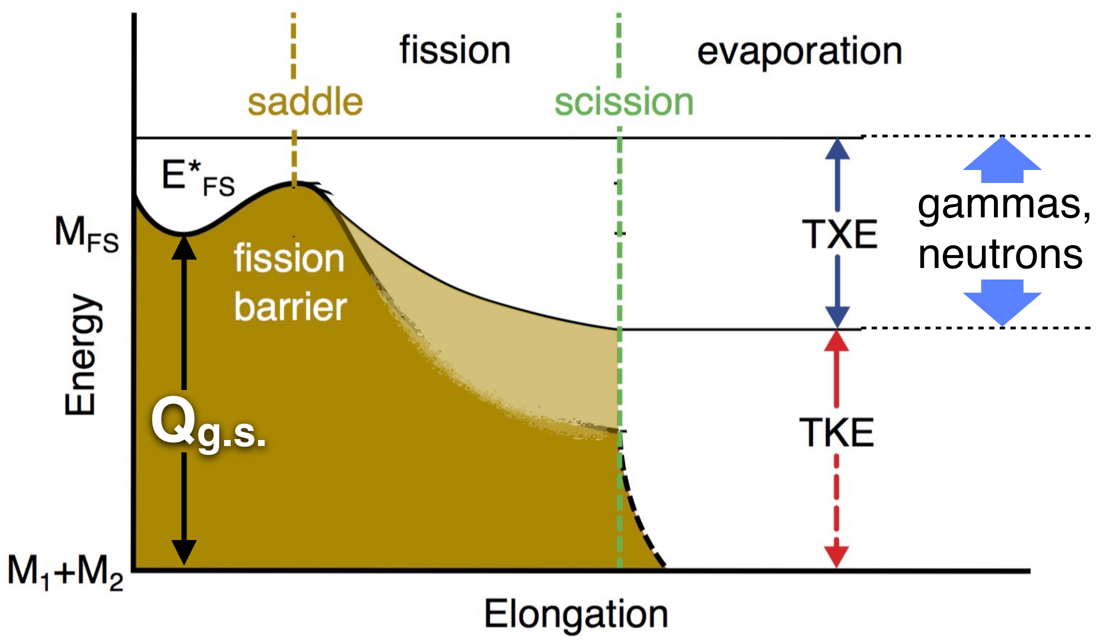
What else?

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

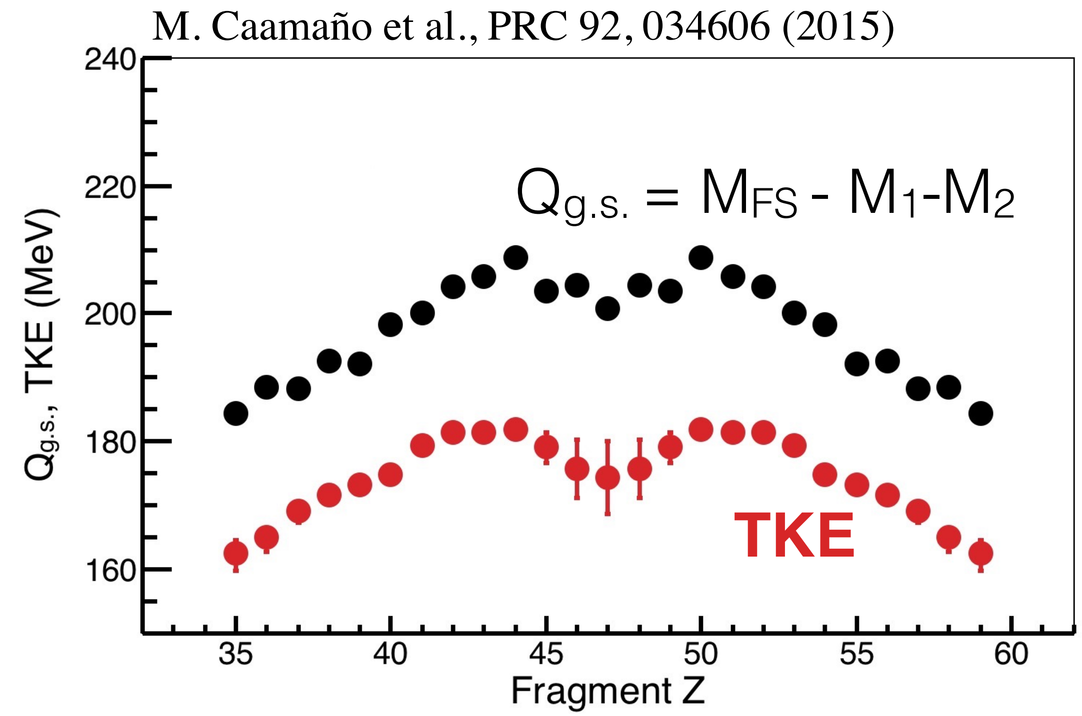


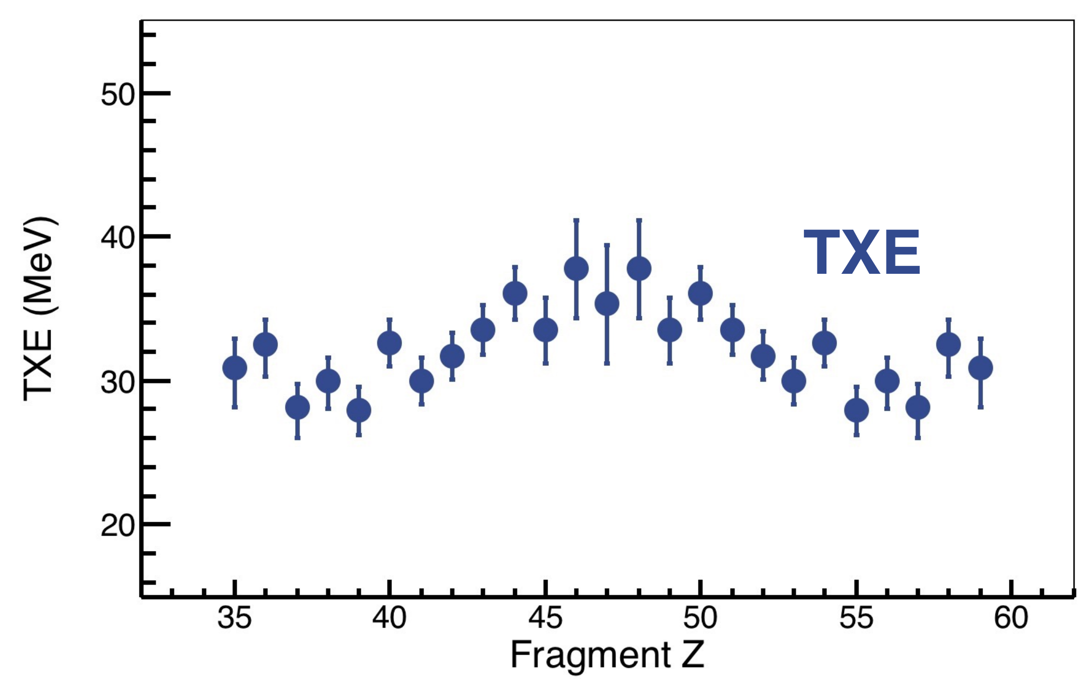
- Pre-saddle emission?
- No dissipation?
- Still shells?

Total Kinetic Energy and Total eXcitation Energy

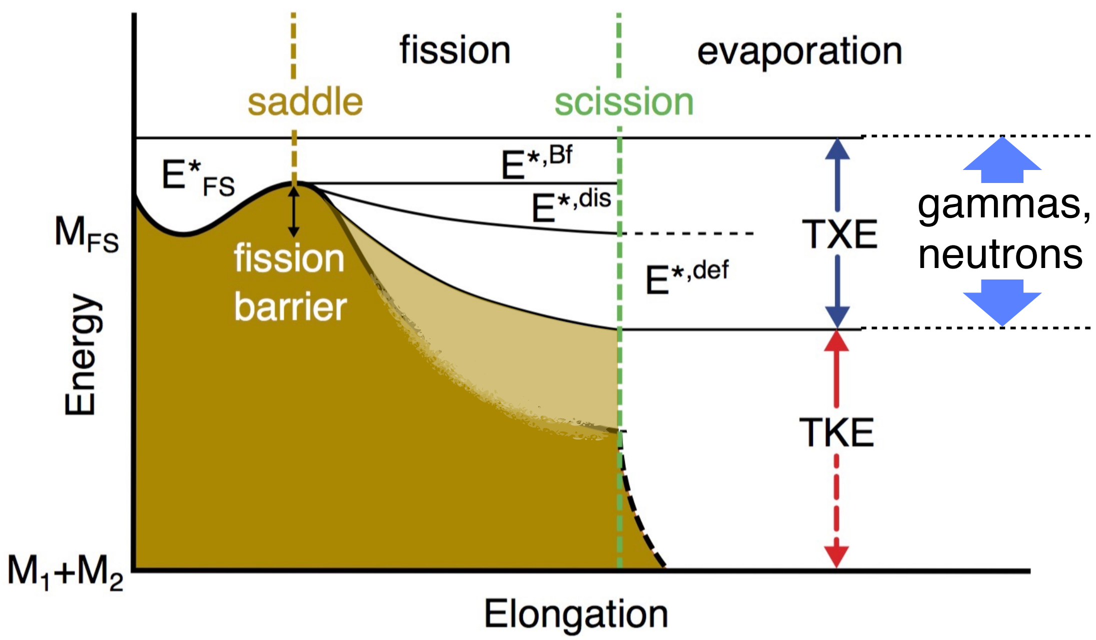


$M_{FS} + E^*_{FS} =$ **TXE** + **TKE** $+ M_1+M_2$





Intrinsic energy: statistical equilibrium



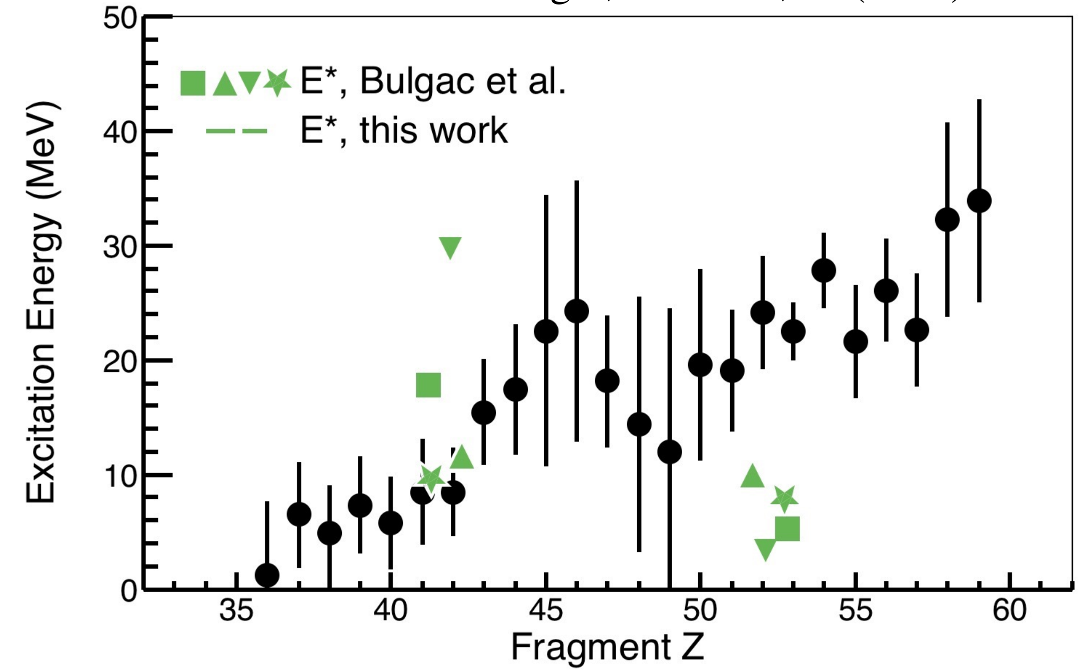
$$M_{FS} + E^{*}_{FS} = \mathbf{TXE} + \mathbf{TKE} + M_1 + M_2$$

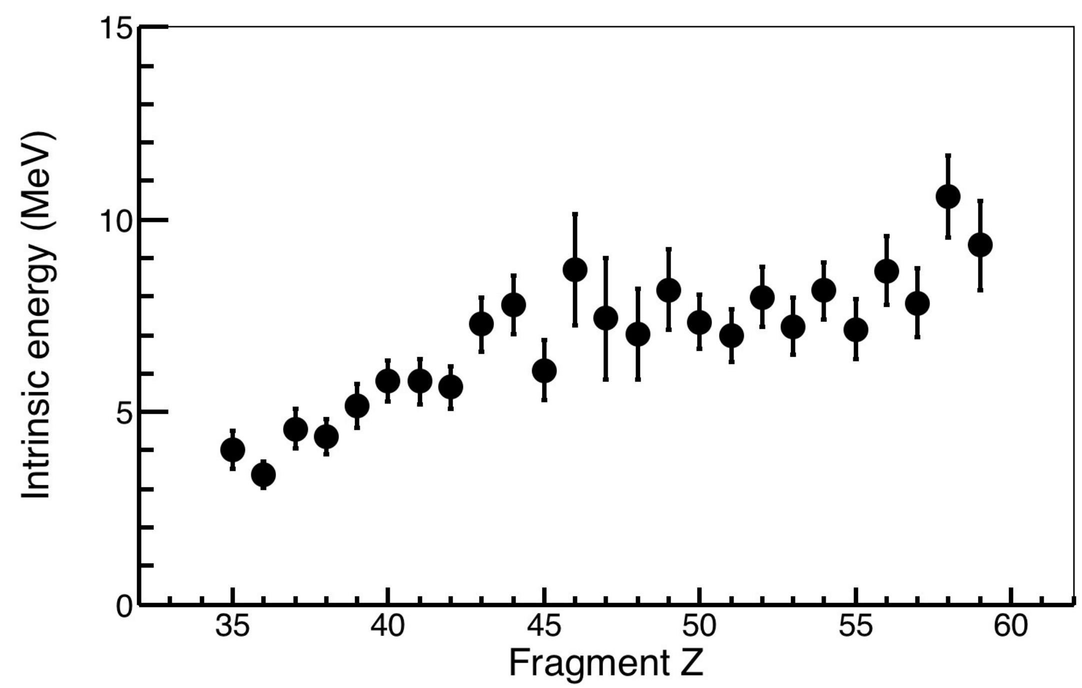
$$\mathbf{TXE} = \sum\left(E^{*,Bf} + E^{*,dis} + E^{*,def} \right)$$

$$= \sum\left(\nu\cdot(Q_n + \varepsilon) + E^{\gamma} \right)$$

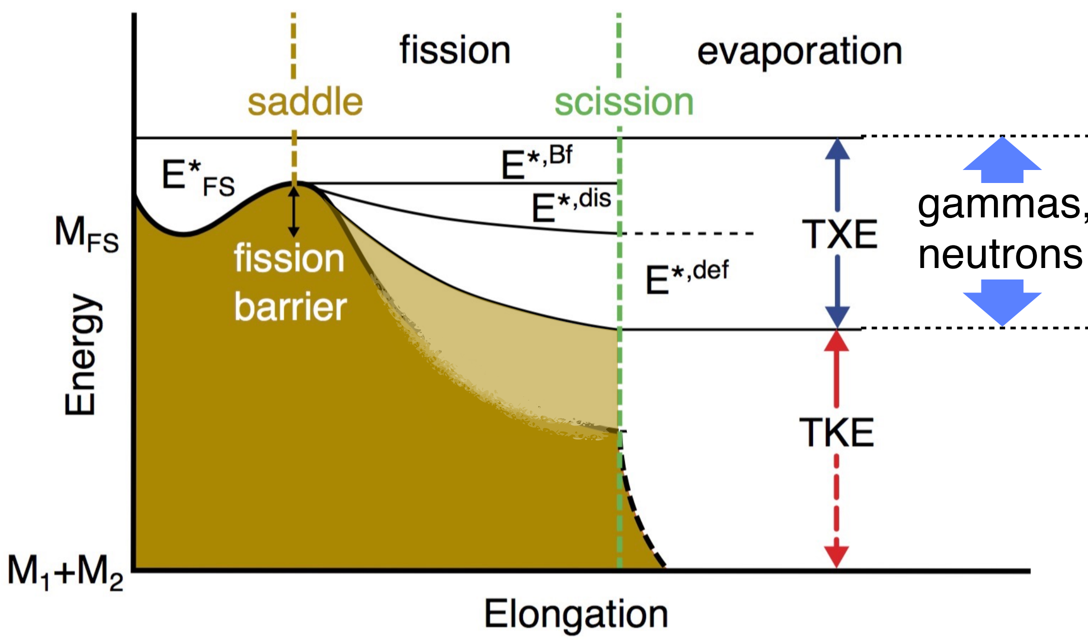
The **intrinsic E*** is shared following **statistical equilibrium** between the fragments

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





Fragment deformation and shells



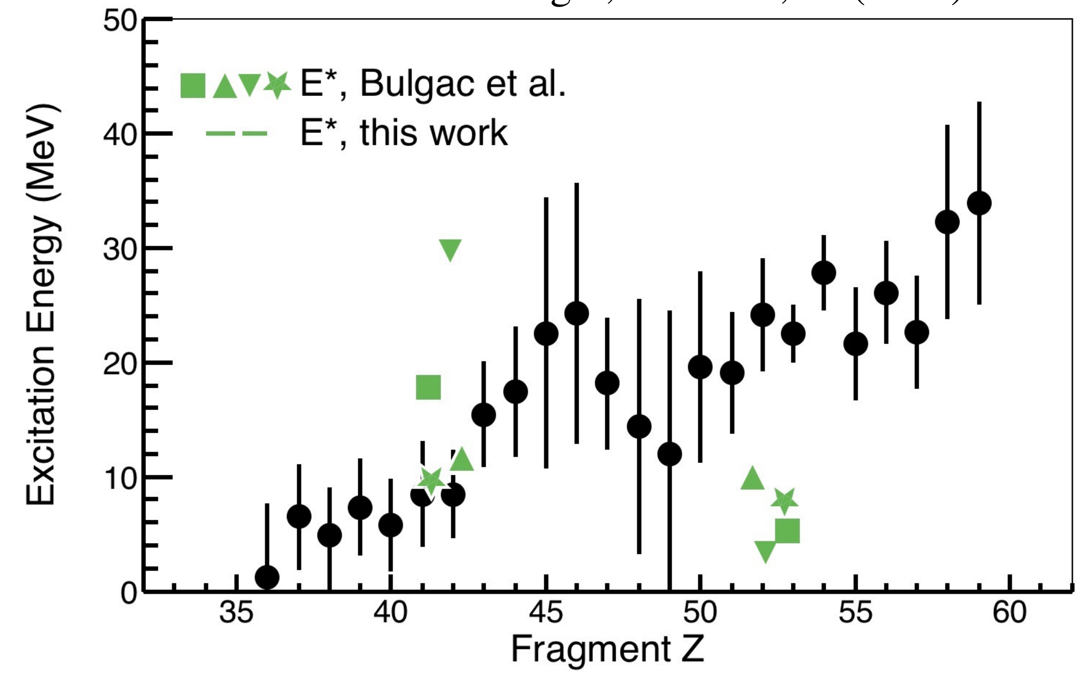
$$M_{FS} + E^*_{FS} = \mathbf{TXE} + \mathbf{TKE} + M_1+M_2$$

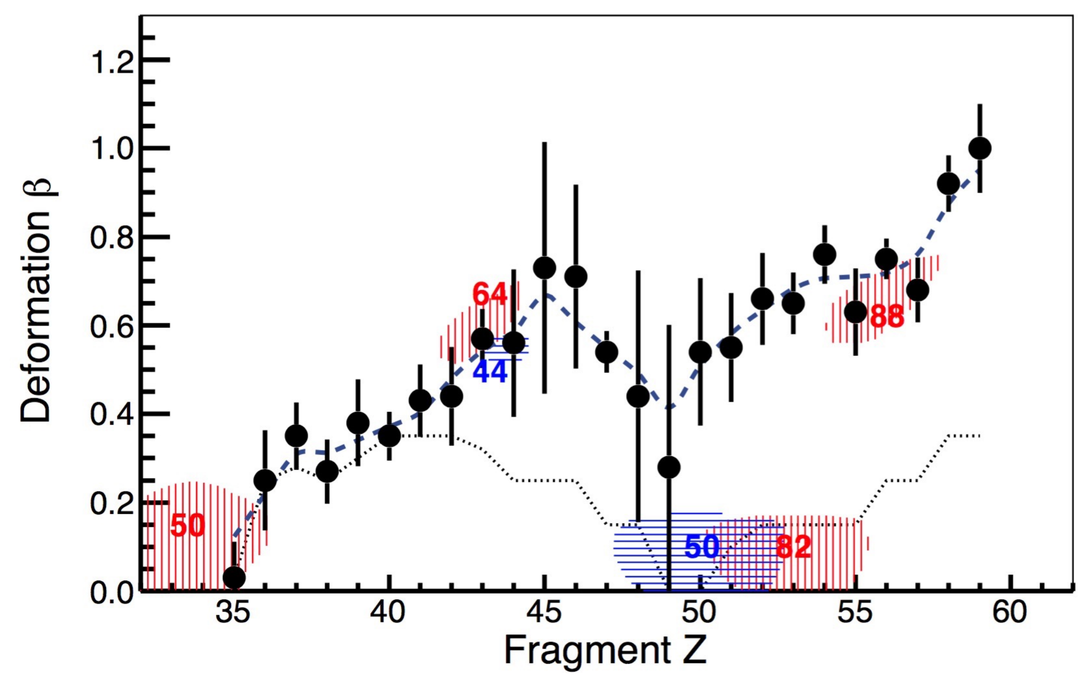
$$\mathbf{TXE} = \sum\left(E^{*,Bf} + E^{*,dis} + E^{*,def} \right)$$

$$= \sum\left(\nu\cdot(Q_n + \varepsilon) + E^{\gamma} \right)$$

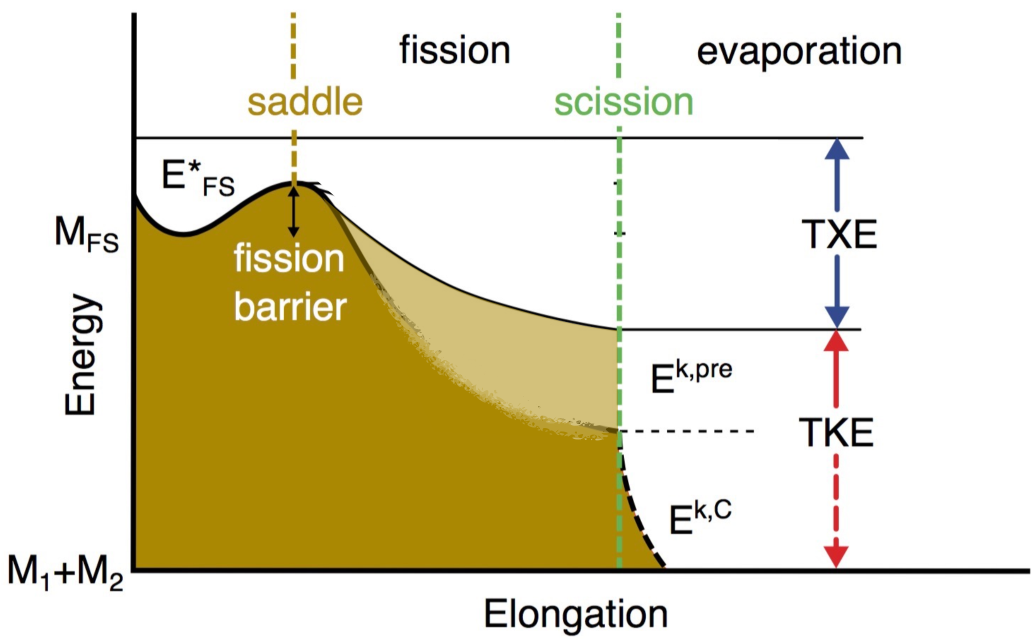
access to the fragment deformation

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

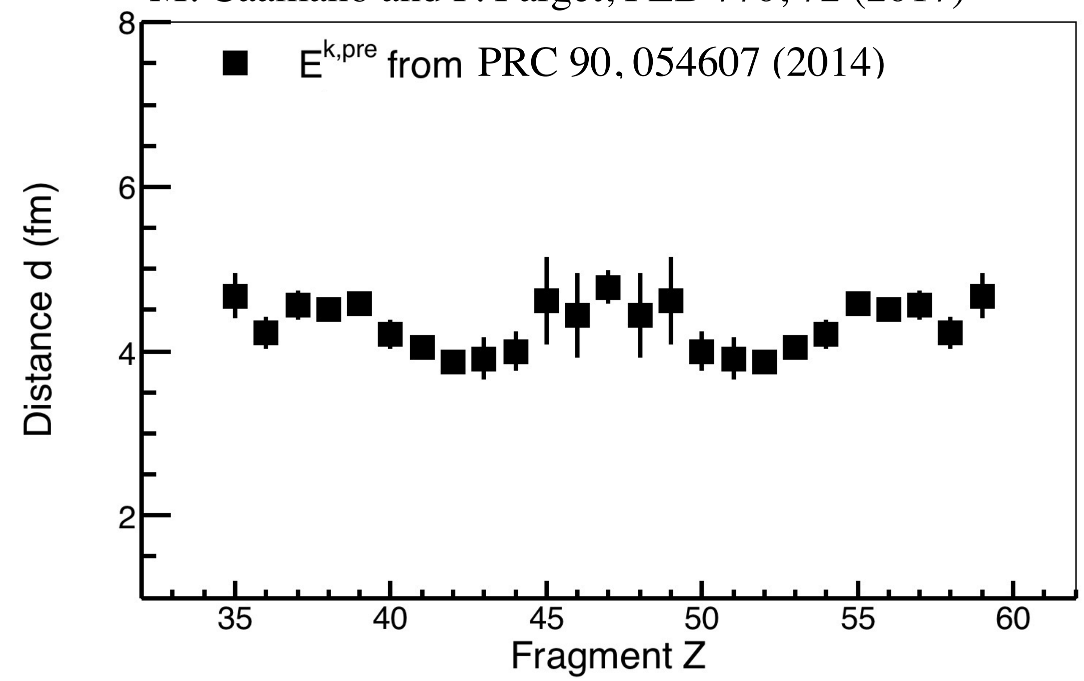




TKE and fragment distance



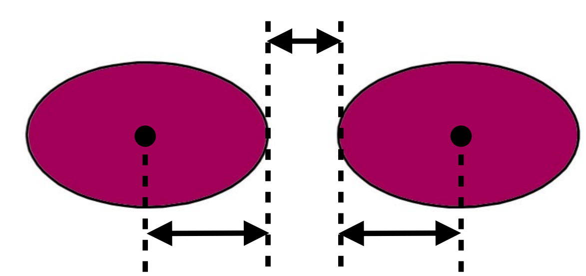
M. Caamaño and F. Farget, PLB 770, 72 (2017)



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

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

Distance



$r_0 A_1^{1/3}(1+\sqrt{5/(4\pi)}\ \beta_1)$ $r_0 A_2^{1/3}(1+\sqrt{5/(4\pi)}\ \beta_2)$

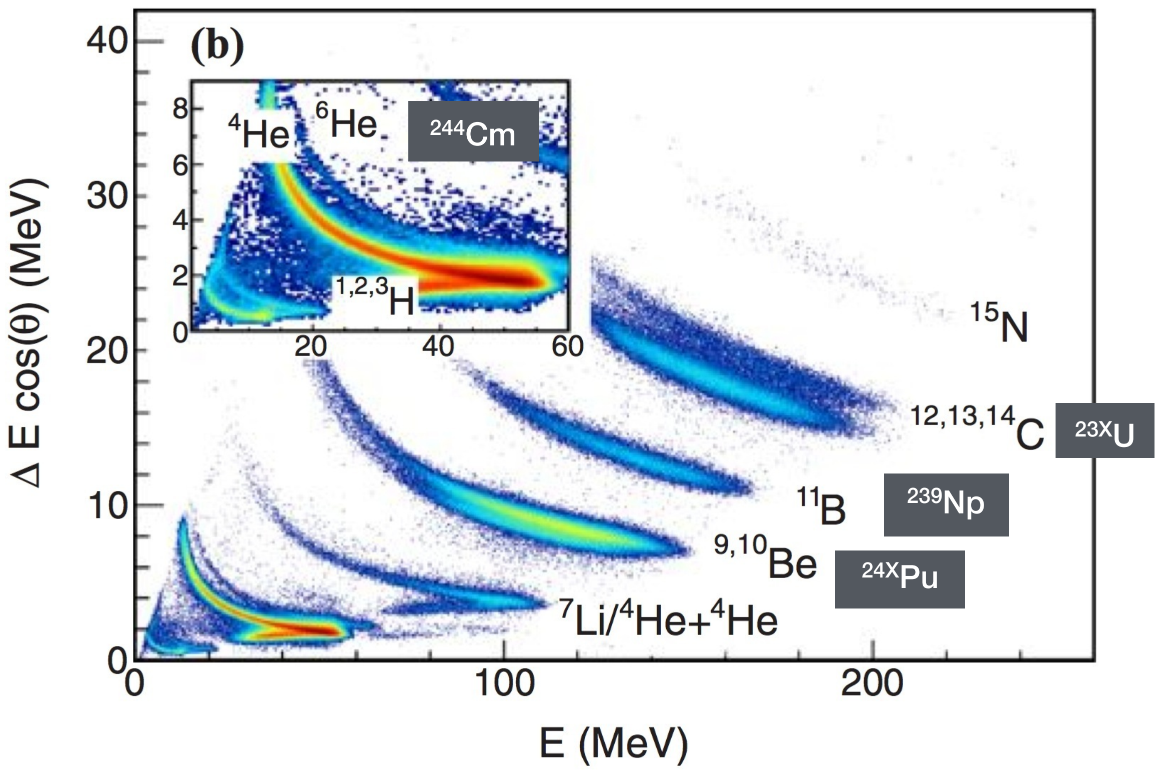
access to the distance between fragments

Inverse kinematics at VAMOS/GANIL:

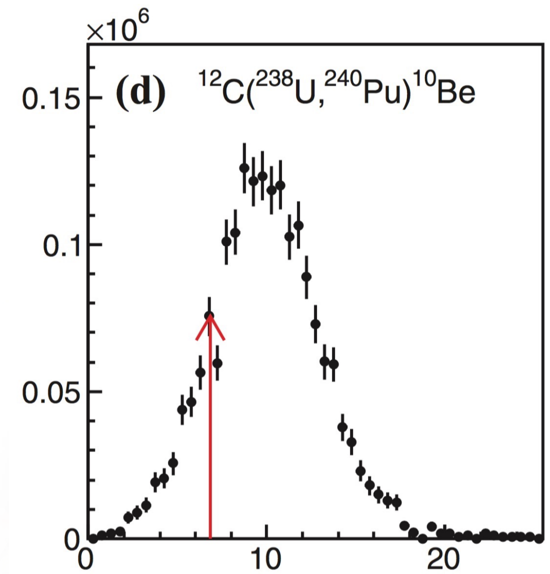
Production and fission from fusion and multi-nucleon transfer

F. Farget et al.

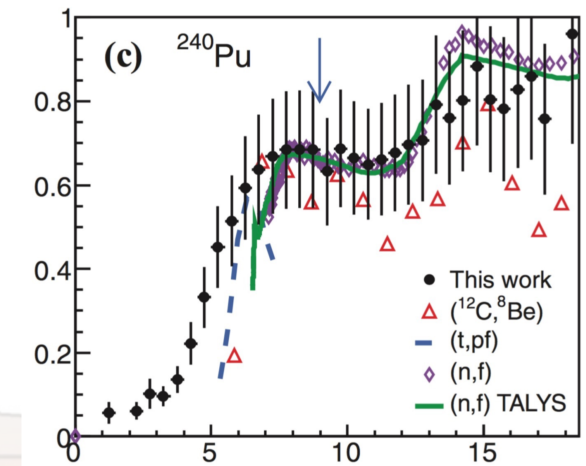
C. Rodríguez. Tajes et al., PRC 89 (2014) 024614



Excitation energy



Fission probability



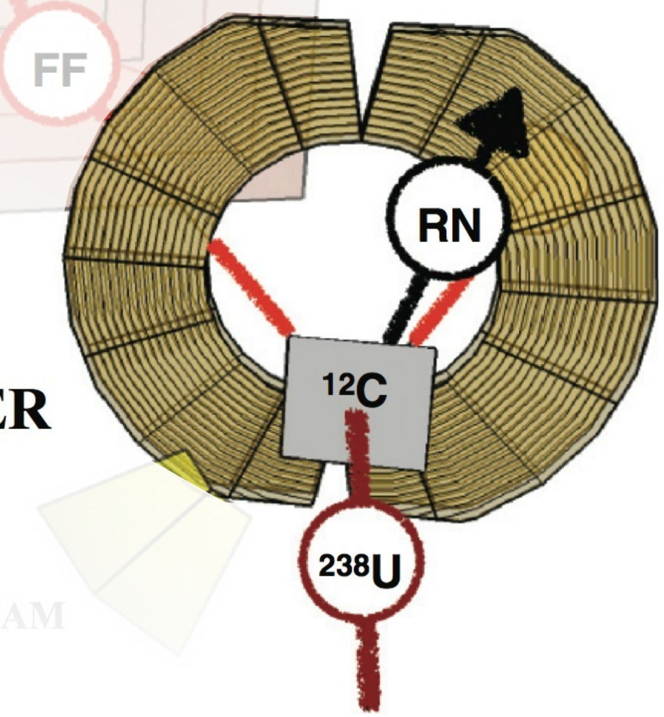
observables:

Fissioning System:

- A, Z, E*, angle, velocity

SPIDER

dE-E, angles



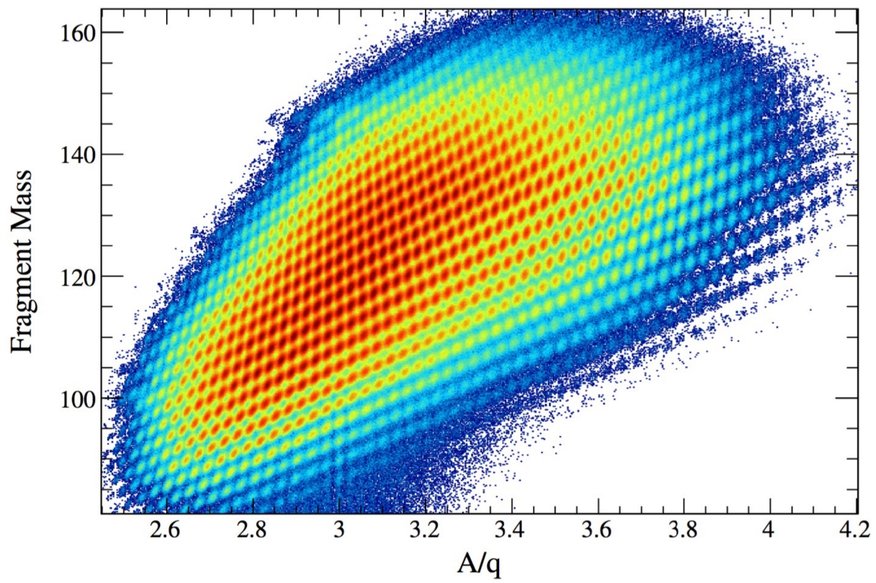
M. Caamaño (USC)

Inverse kinematics at VAMOS/GANIL:

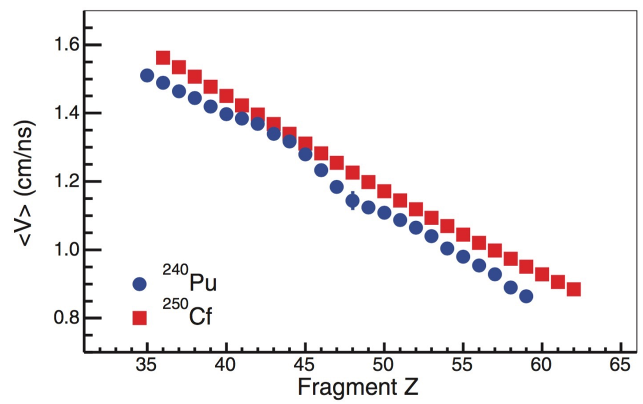
Production and fission from fusion and multi-nucleon transfer

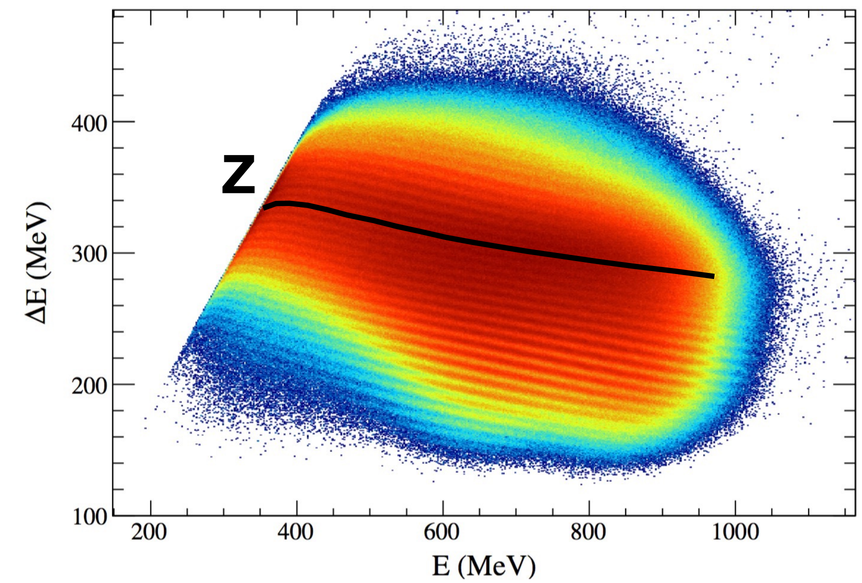
F. Farget et al.

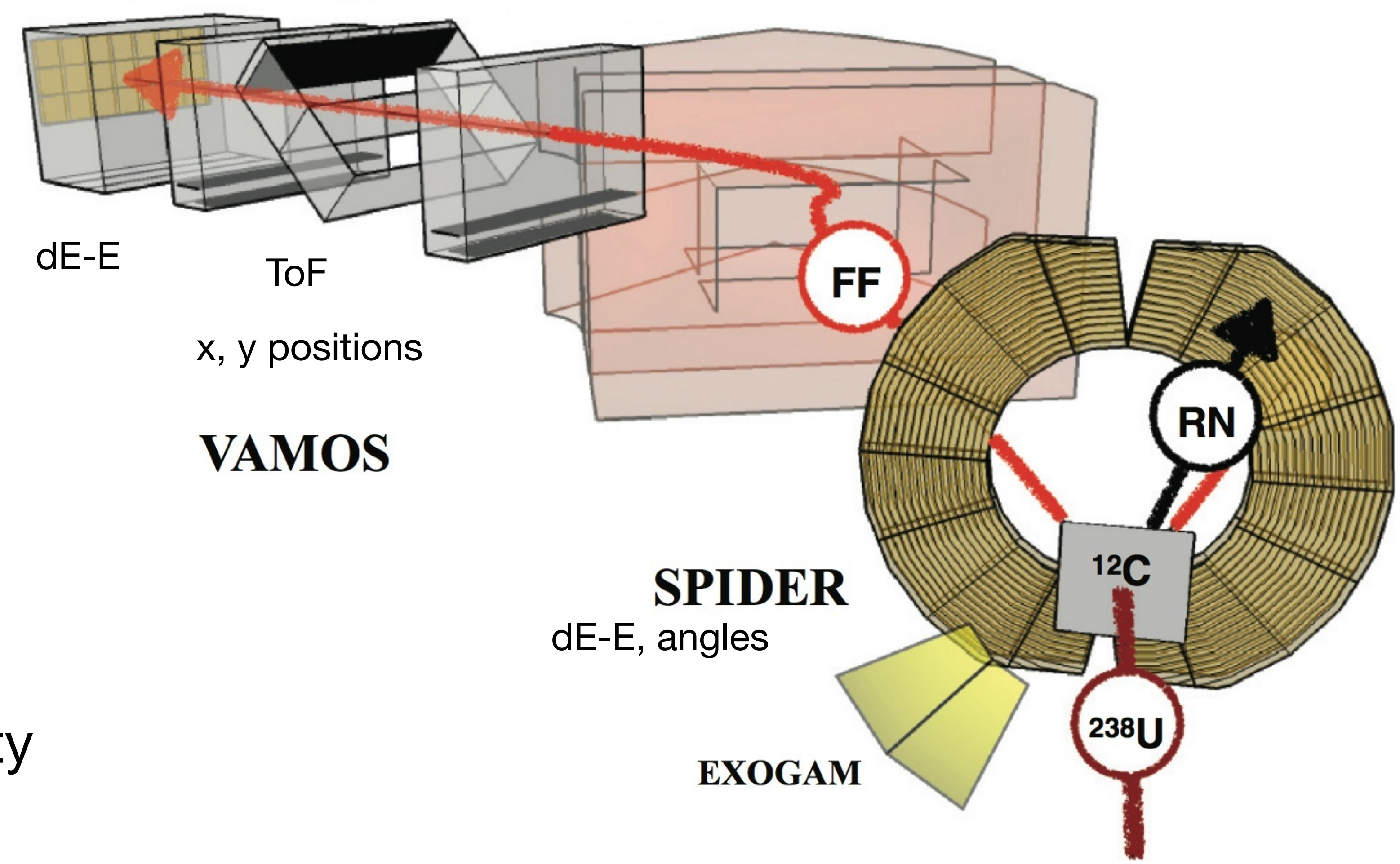
PRC 92, 034606 (2015)



D. Ramos, PhD USdC (2016)







observables:

Fissioning System:

- A, Z, E*, angle, velocity

Fission Fragments:

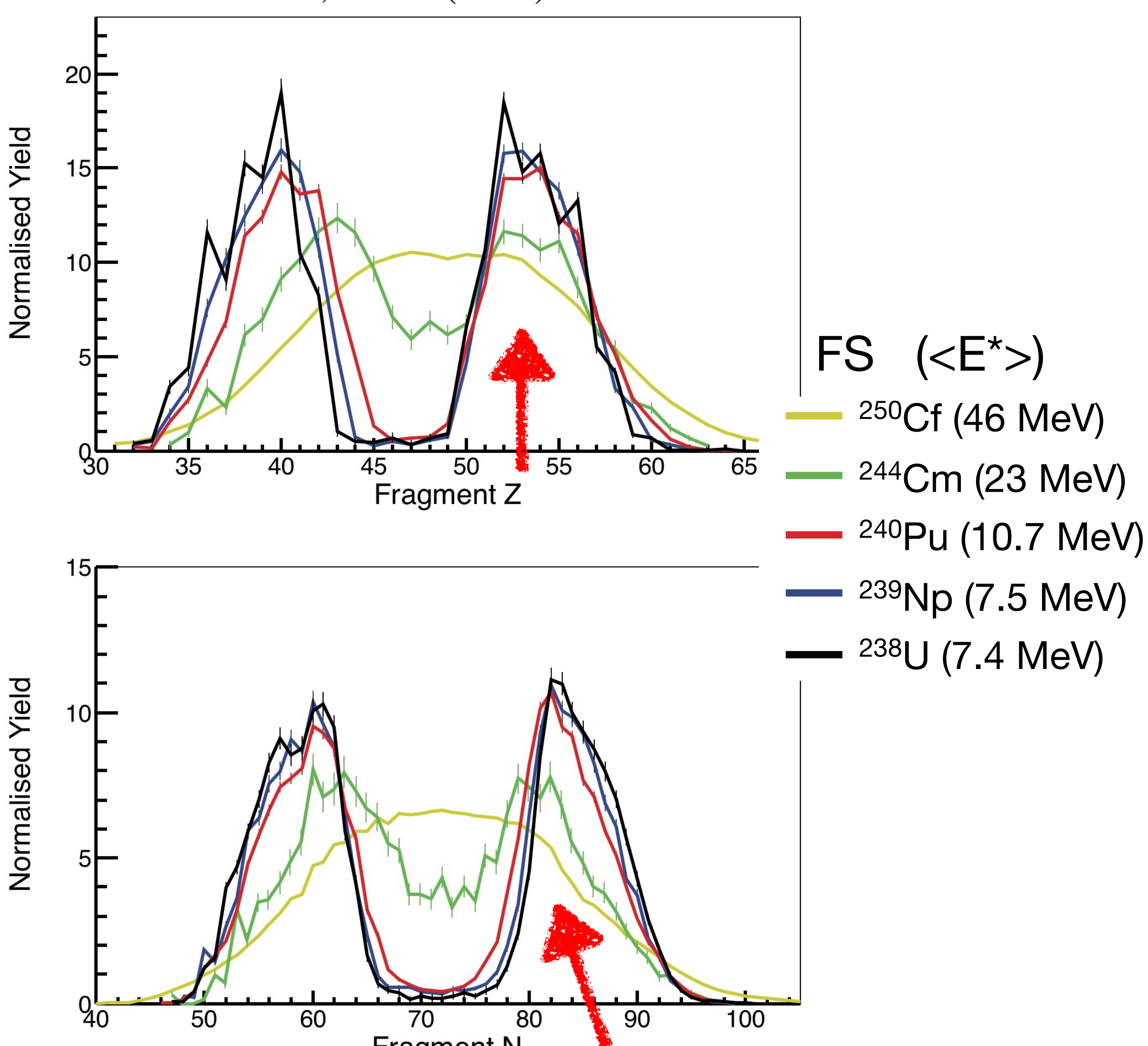
- A^{post}, Z, q, angle, velocity

M. Caamaño (USC)

A set of revisited and new observables

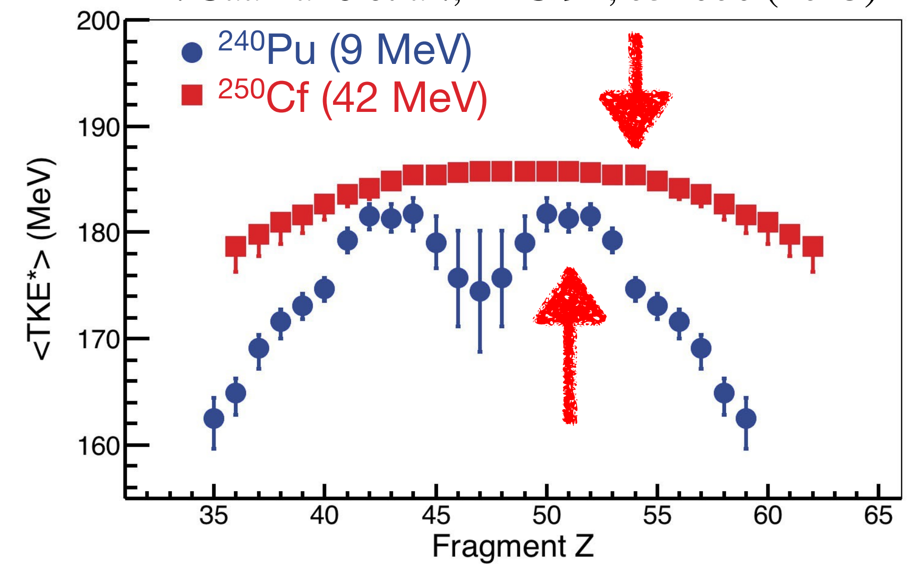
Fragment Z, N distributions

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

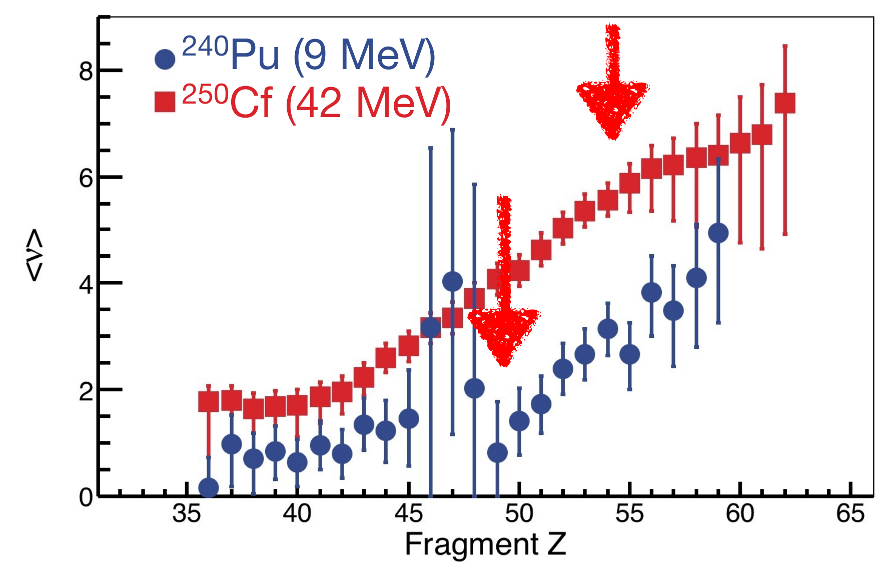


Total kinetic energy (TKE)

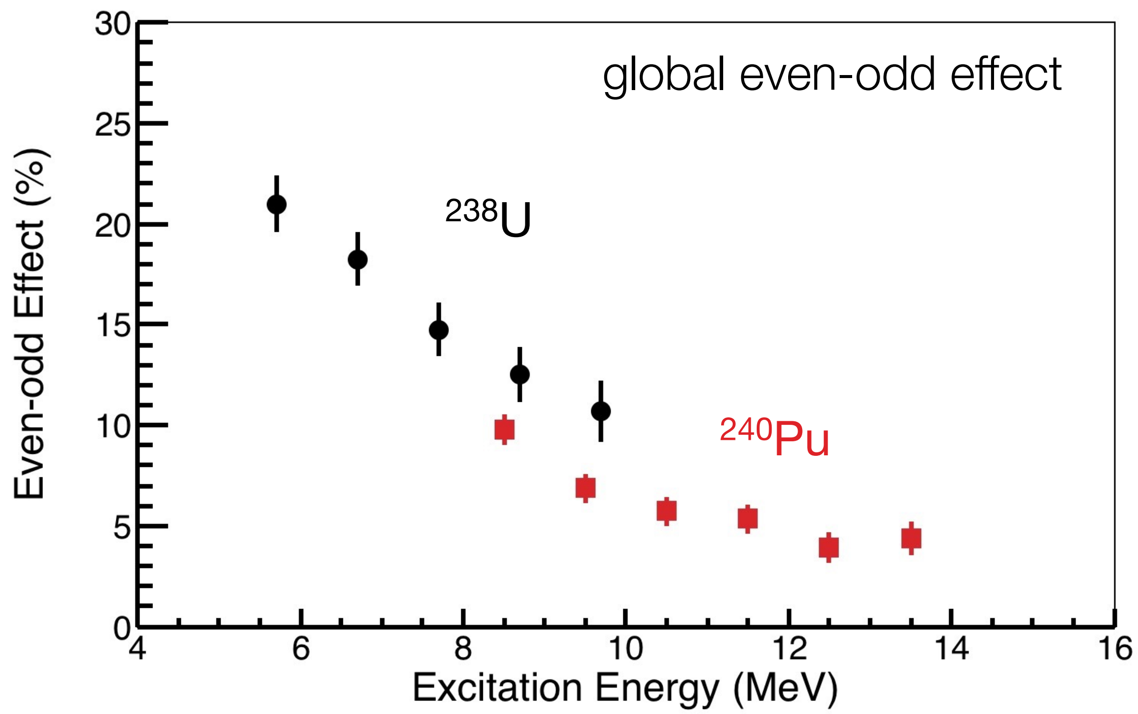
M. Caamaño et al., PRC 92, 034606 (2015)



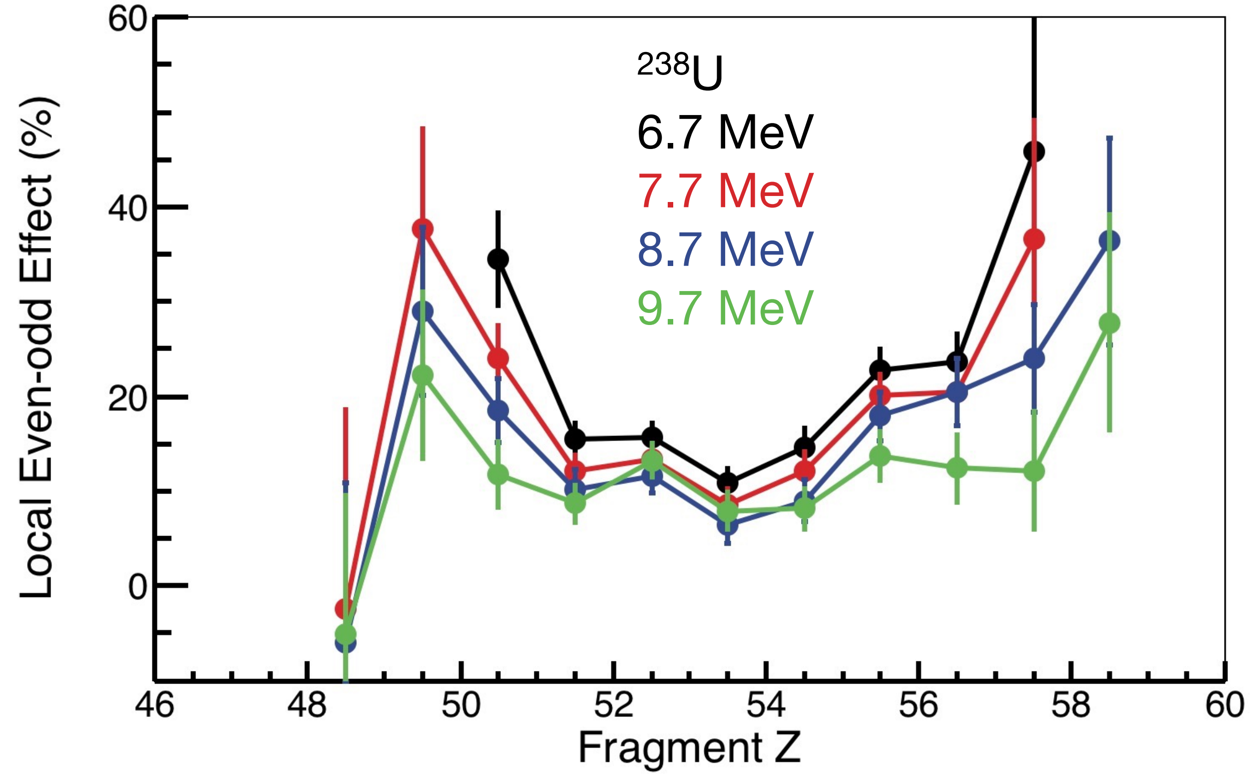
Neutron evaporation

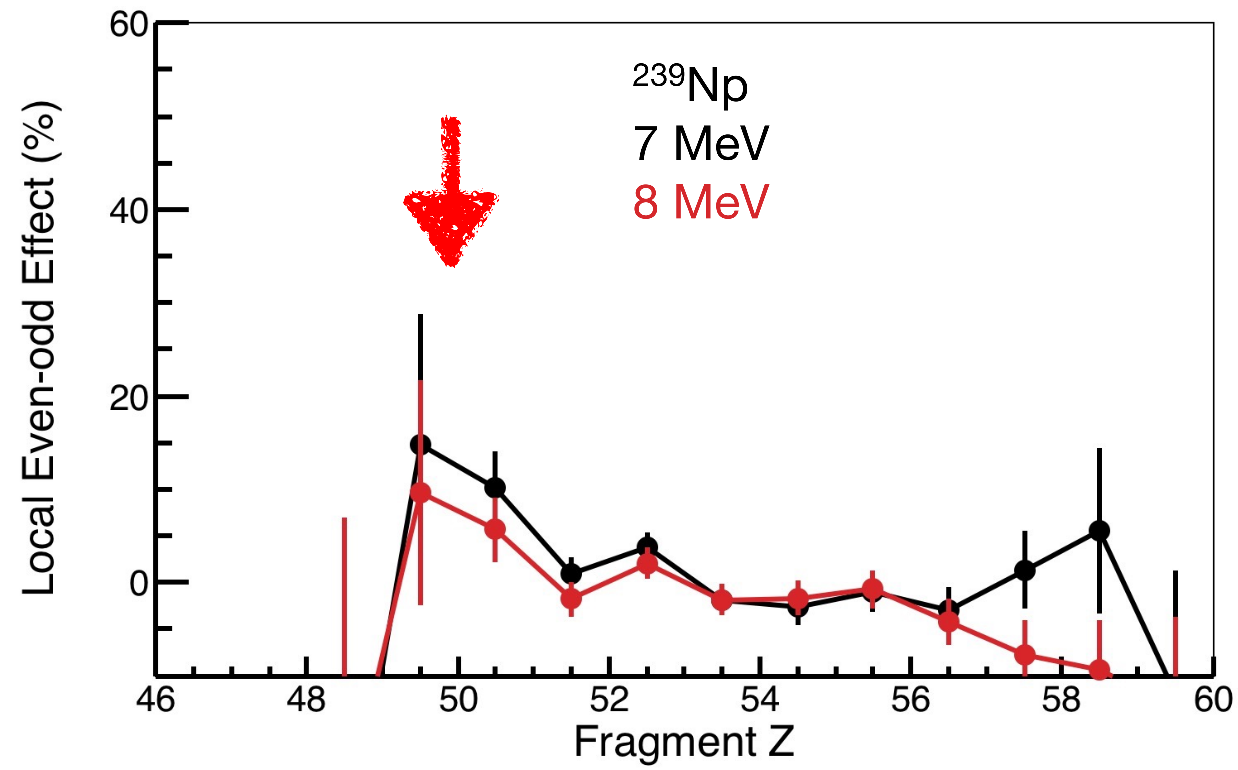


Inverse kinematics: A window to new observables in fission.



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

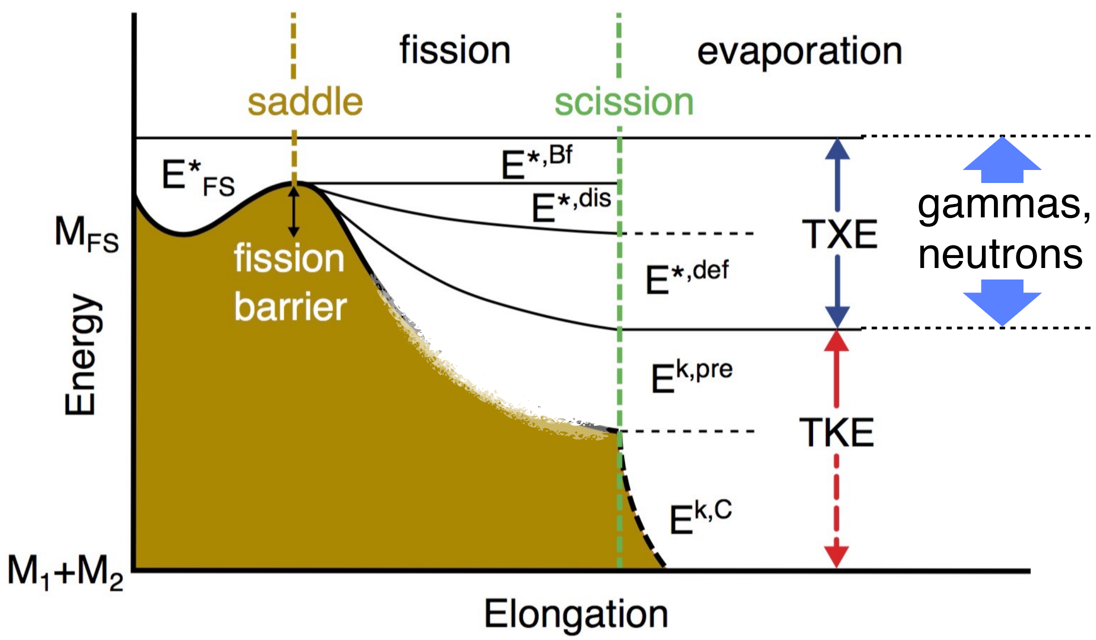




M. Caamaño (USC)

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.

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

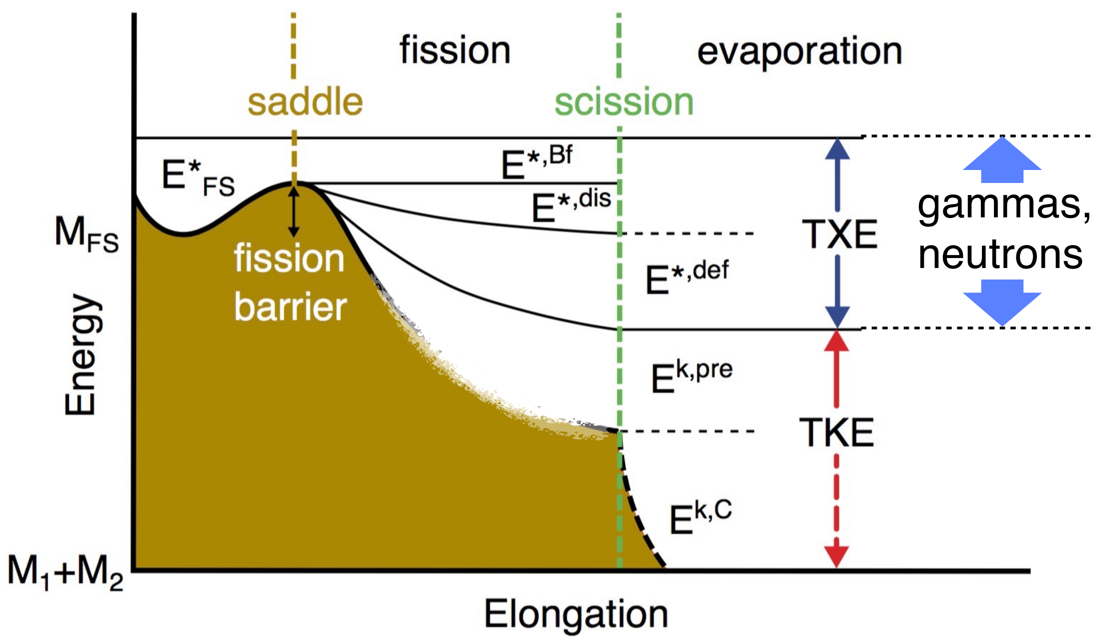
$$E_i^\gamma = Sn_i^{post} \frac{\nu_i}{\nu_1 + \nu_2}$$

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

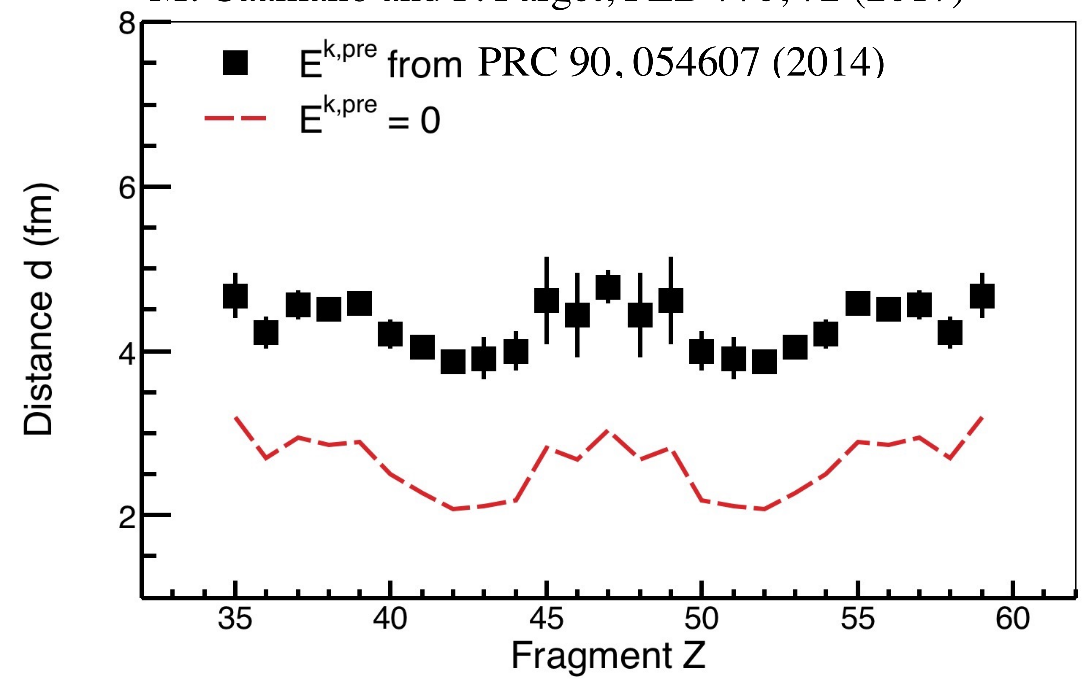
$$E_i^{*,def} = E_i^* - E_i^{*,int}$$

M. Caamaño (USC)

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

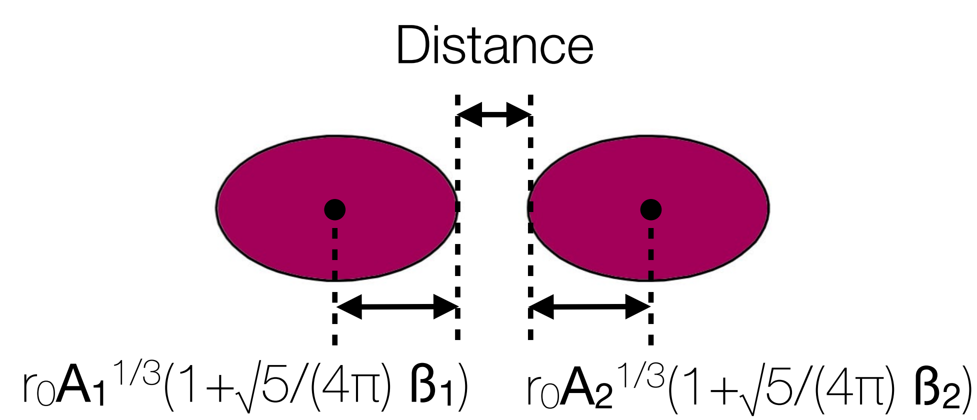


M. Caamaño and F. Farget, PLB 770, 72 (2017)

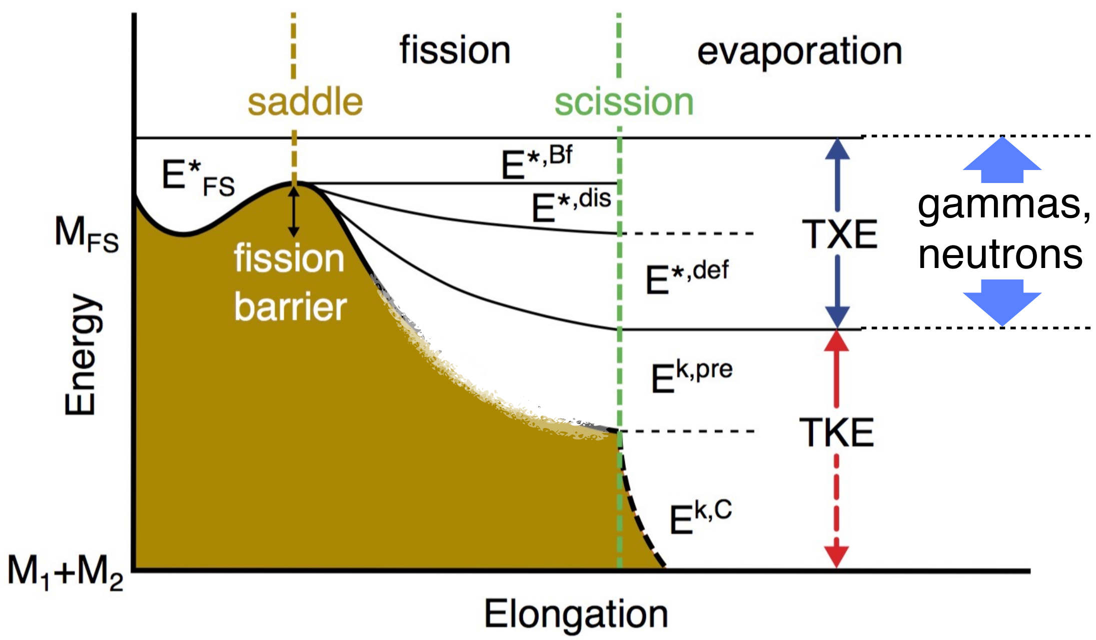


$$M_{FS} + E^*_{FS} = \text{TXE} + \text{TKE} + M_1 + M_2$$

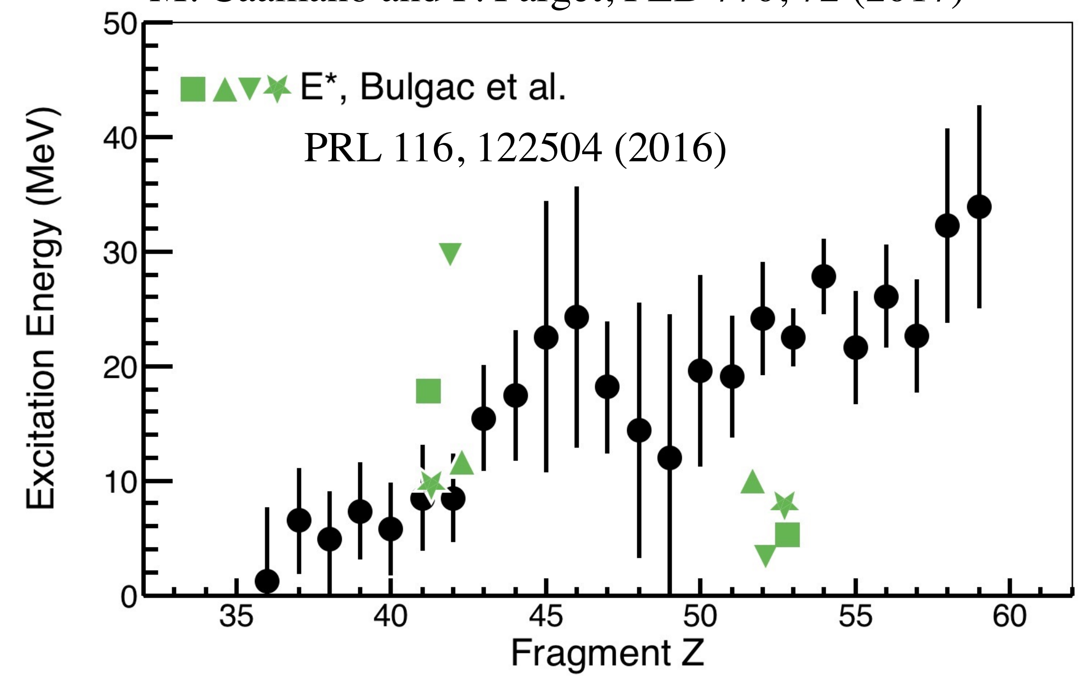
$$\text{TKE} = E^{k,pre} + E^{k,C}$$

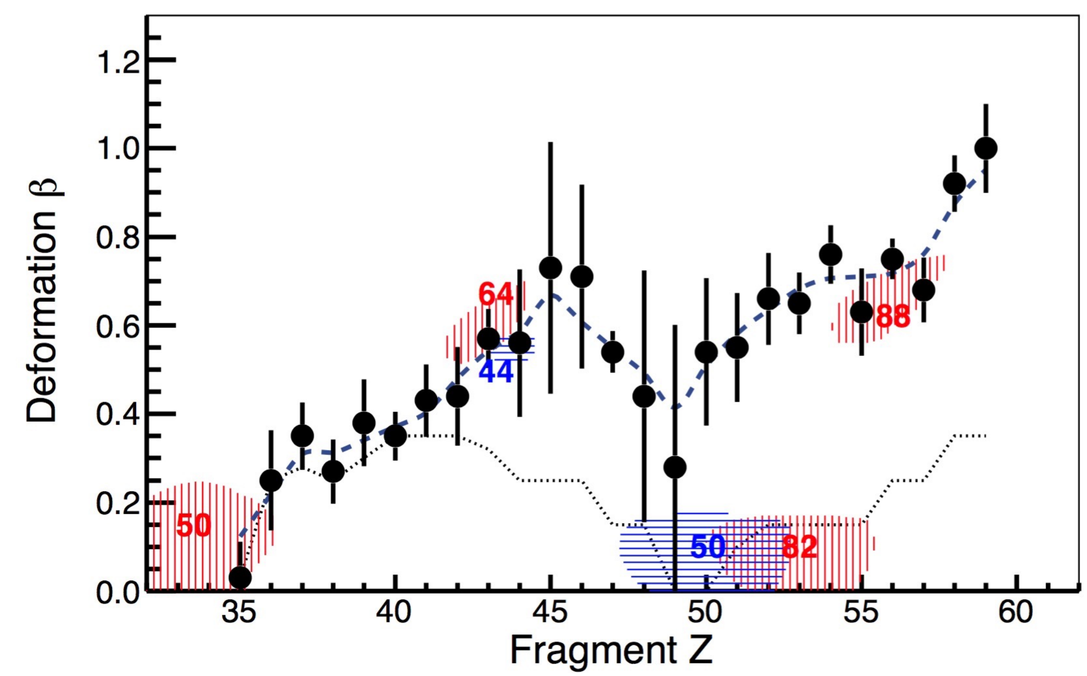


New access to scission; the case of ^{240}Pu (9 MeV)



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





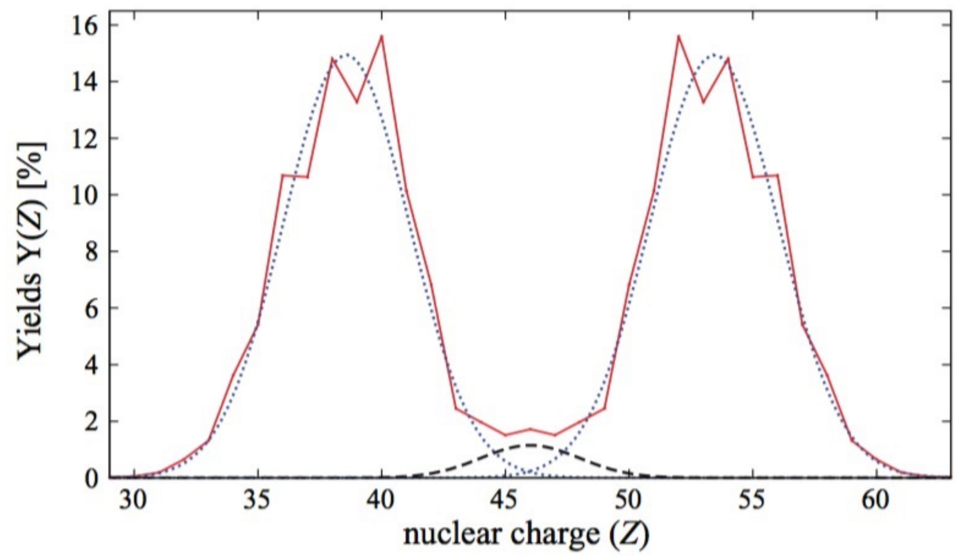
$$M_{FS} + E^*_{FS} = \text{TXE} + \text{TKE} + M_1 + M_2$$

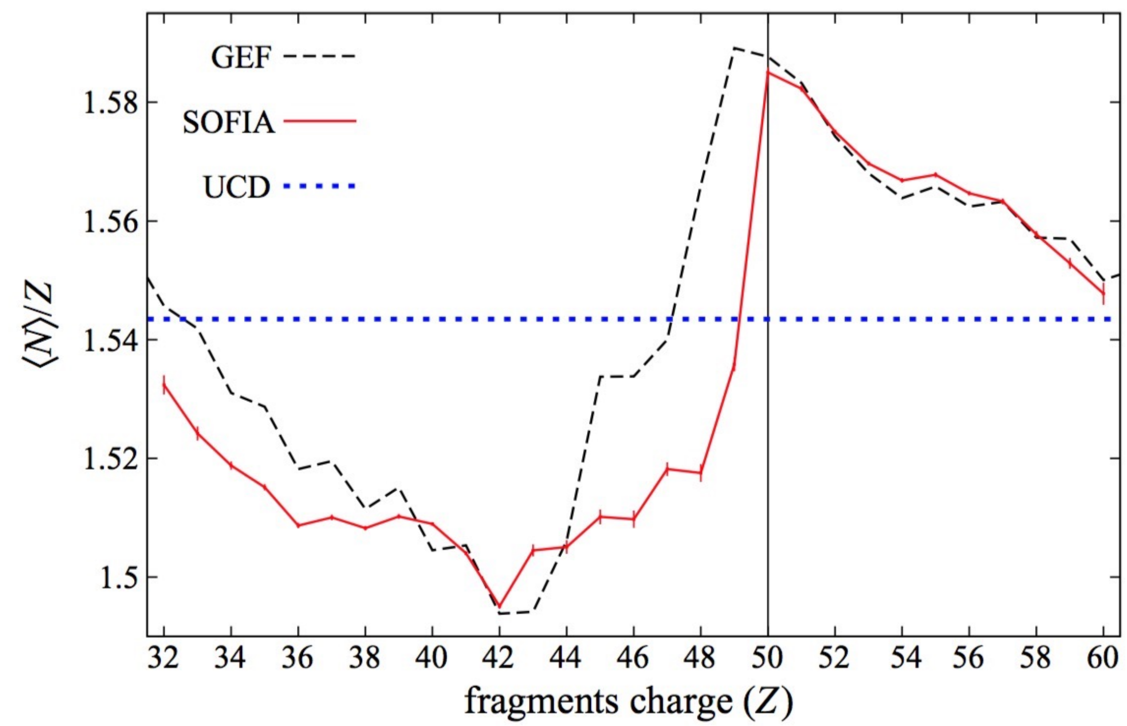
$$\text{TXE} = E^{*,Bf} + E^{*,dis} + E^{*,def}$$

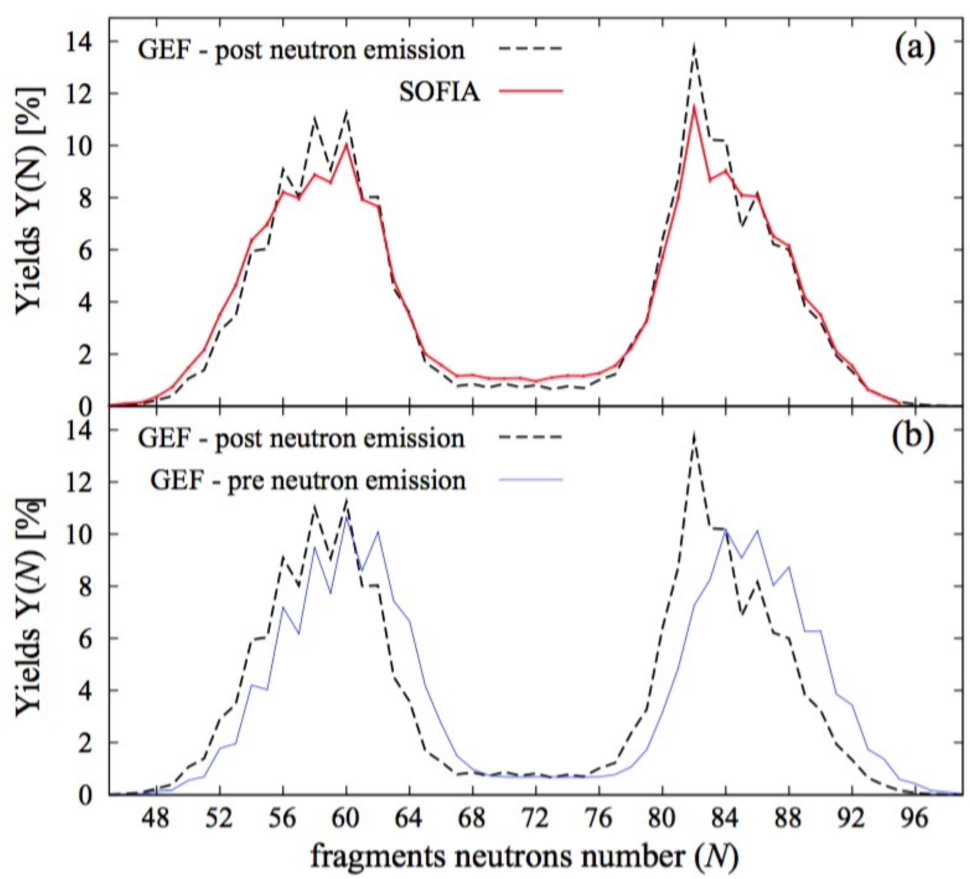
$$= \nu \cdot (Q_n + \varepsilon) + E^{\gamma}$$

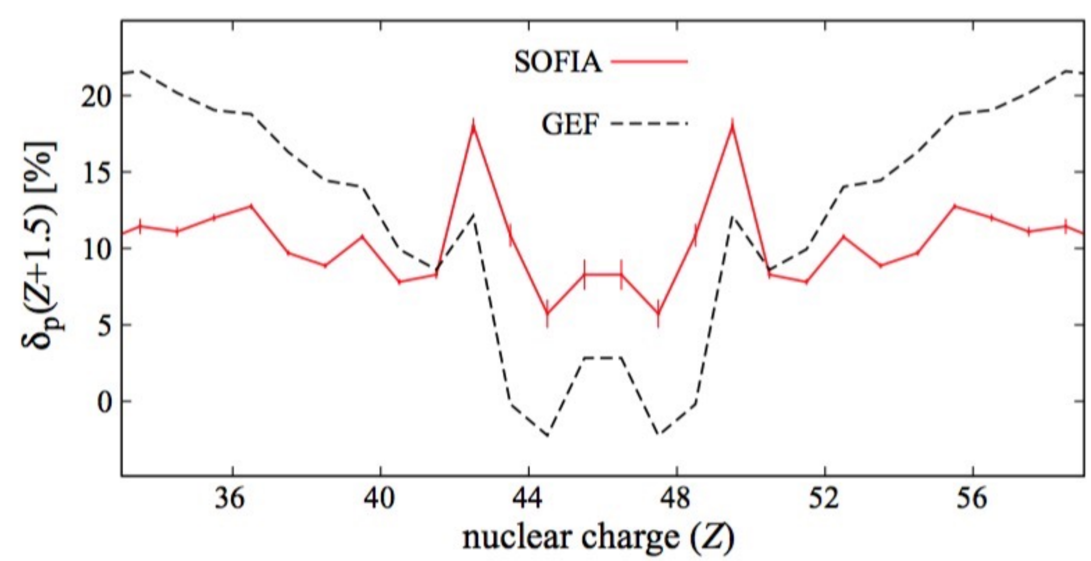
SOFIA @ GSI

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







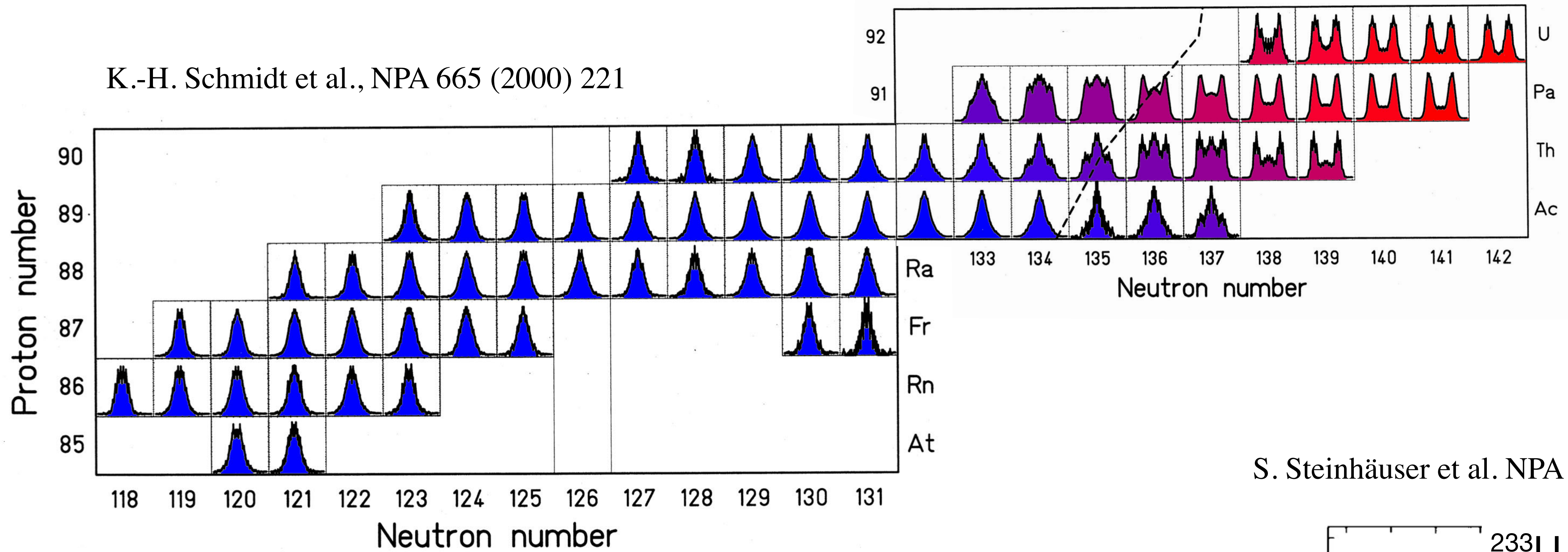


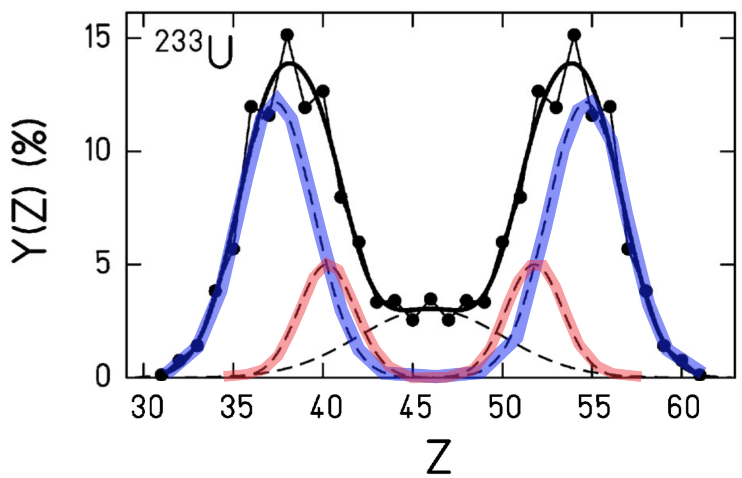
E. Pellereau et al., PRC 95, 054603 (2017)

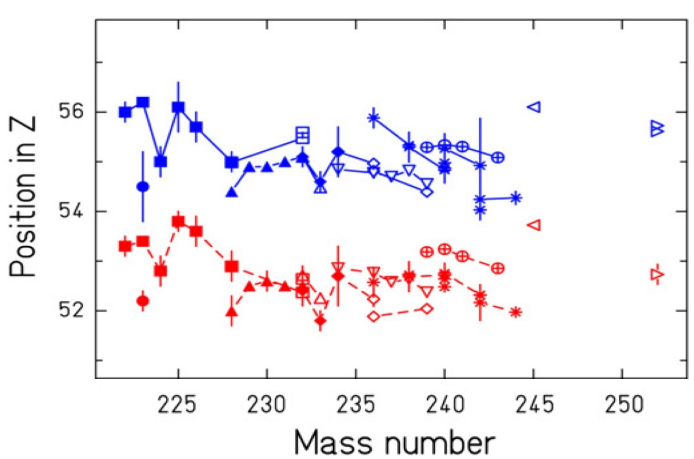
M. Caamaño (USC)

FRS campaign @ GSI

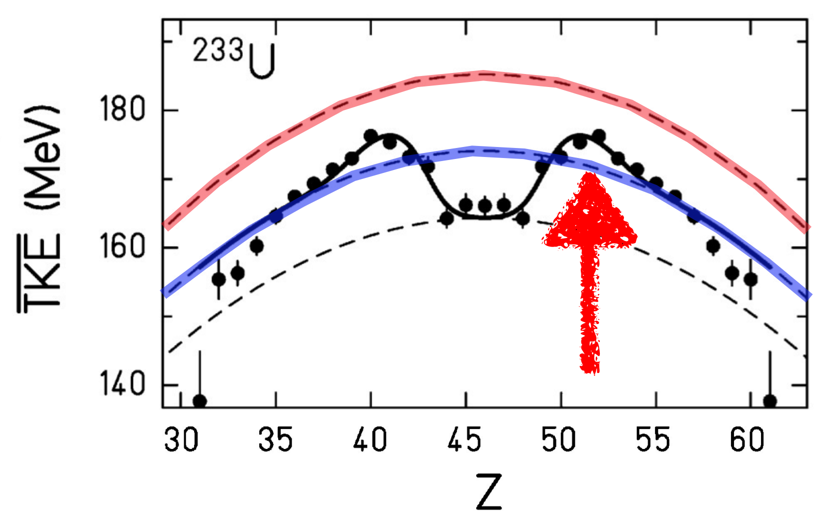
K.-H. Schmidt et al., NPA 665 (2000) 221



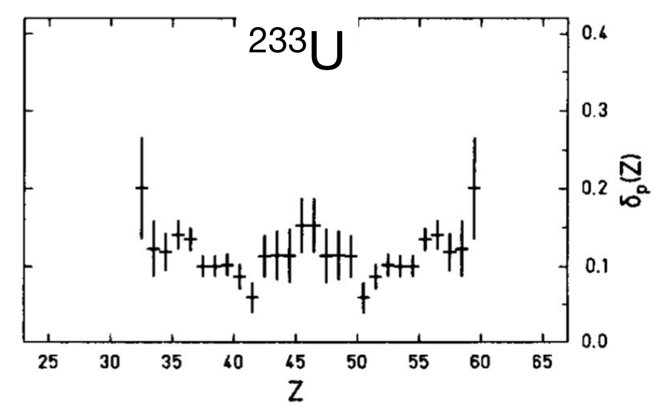


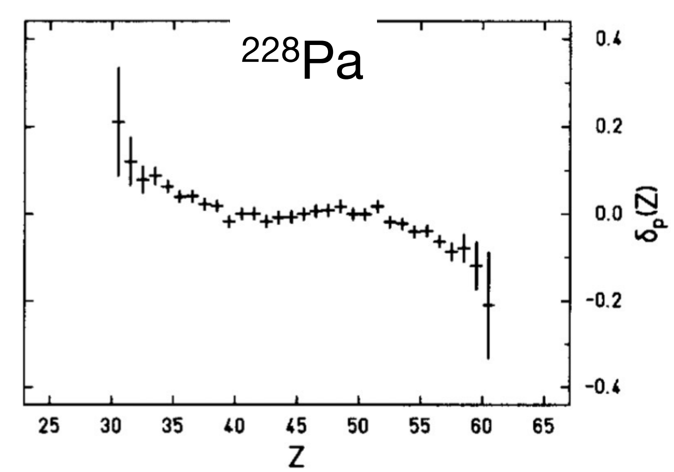


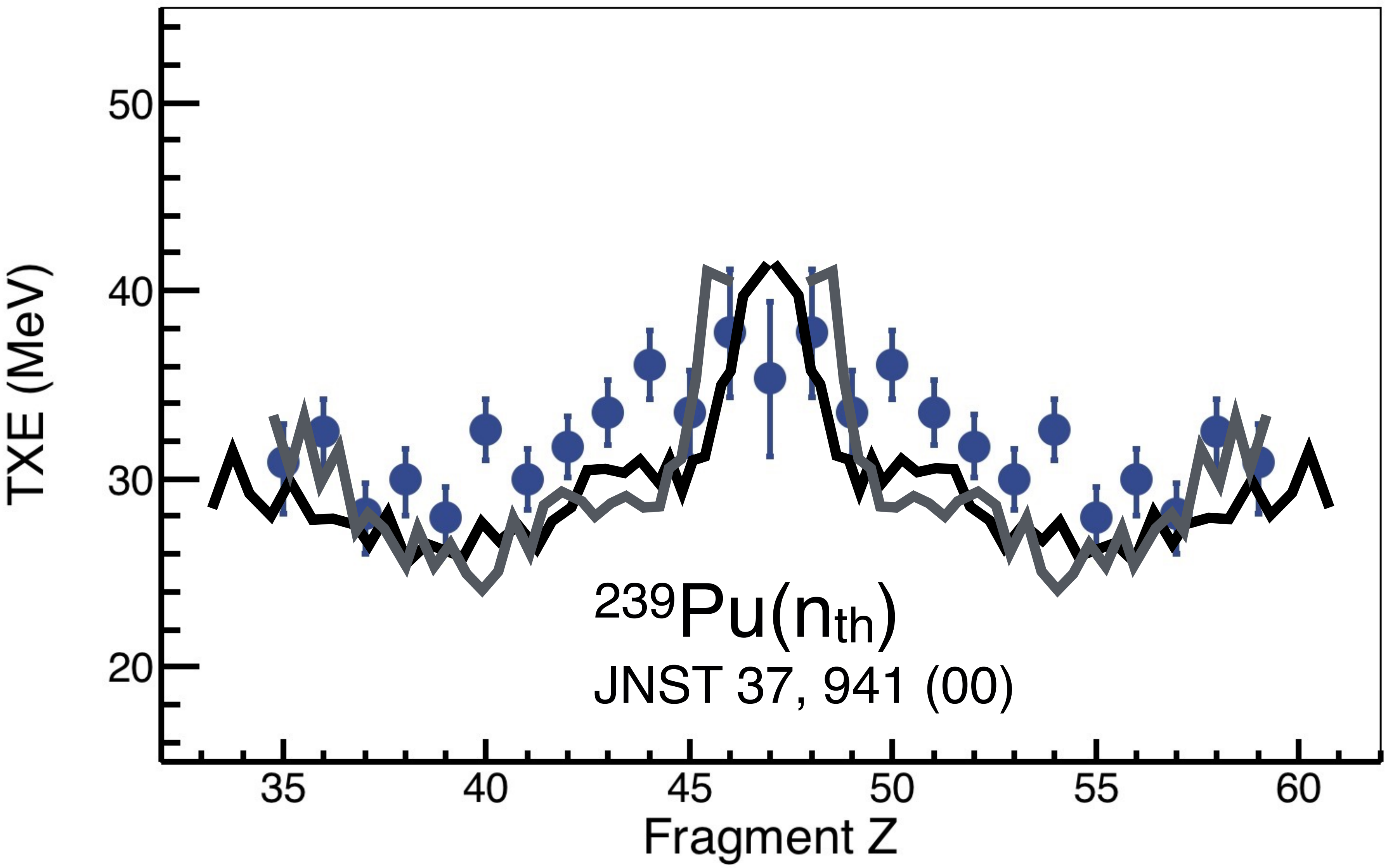
C. Böckstiegel et al. NPA 802 (2008) 12



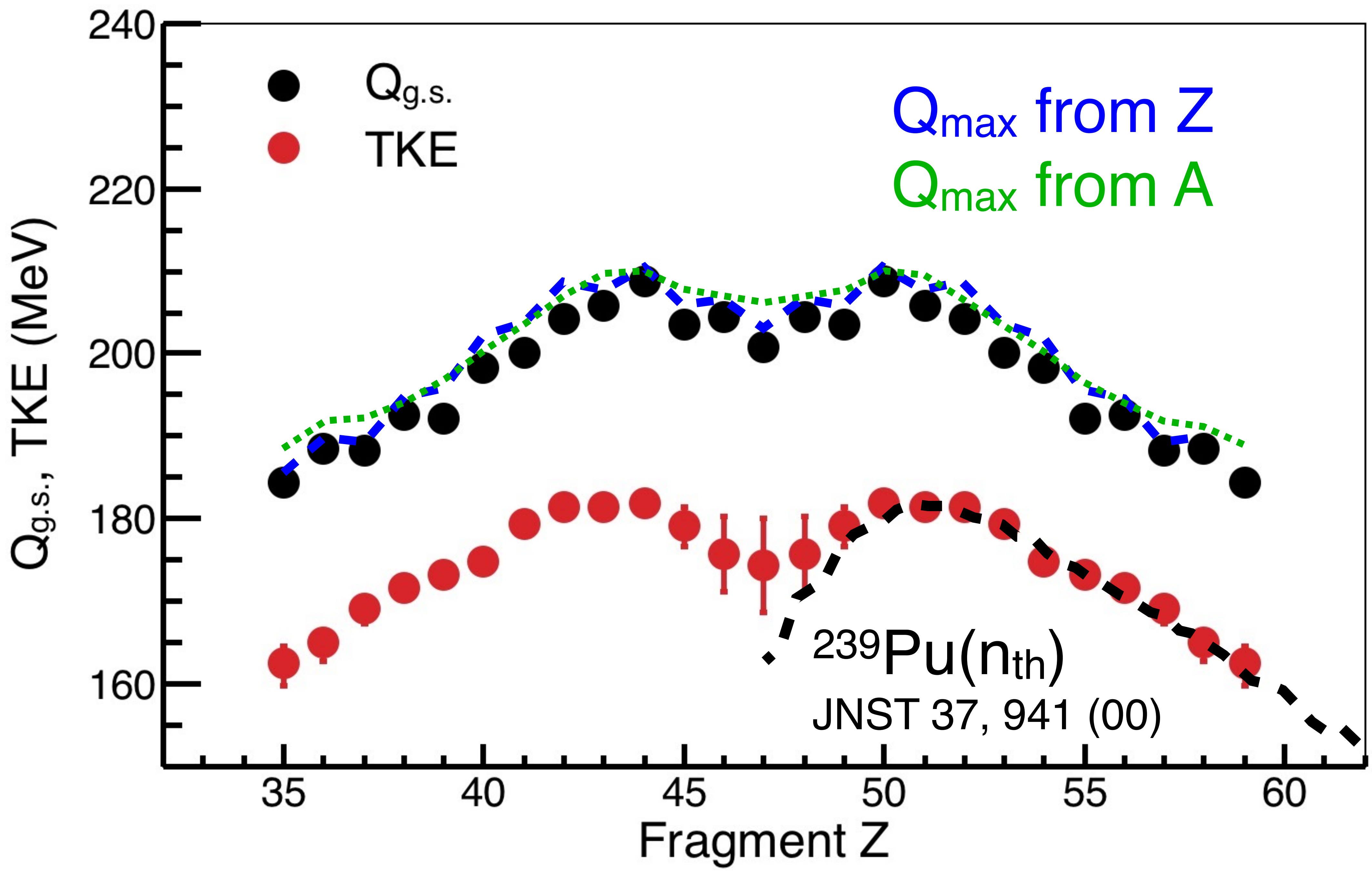
S. Steinhäuser et al. NPA 634 (1998) 89



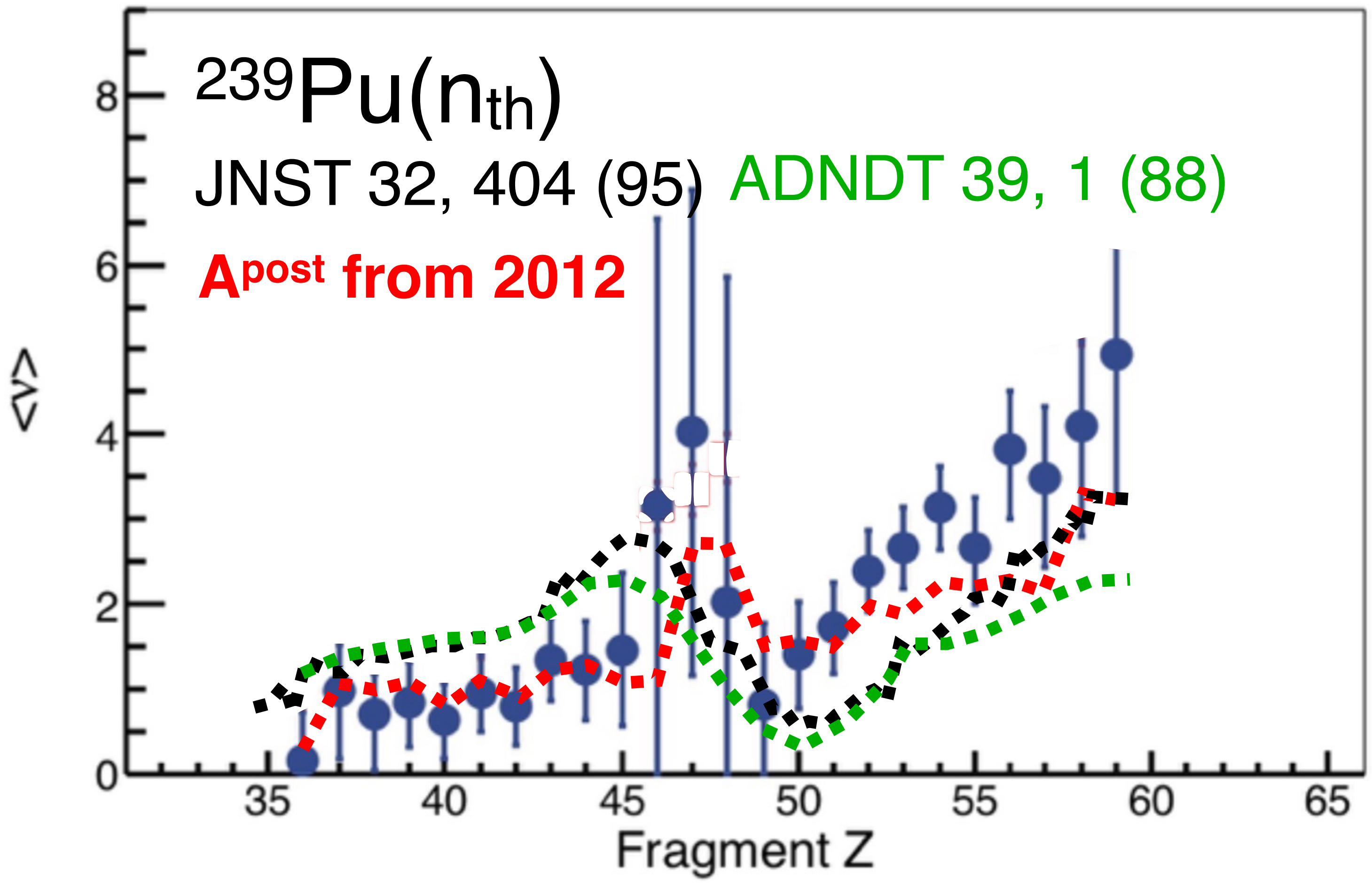




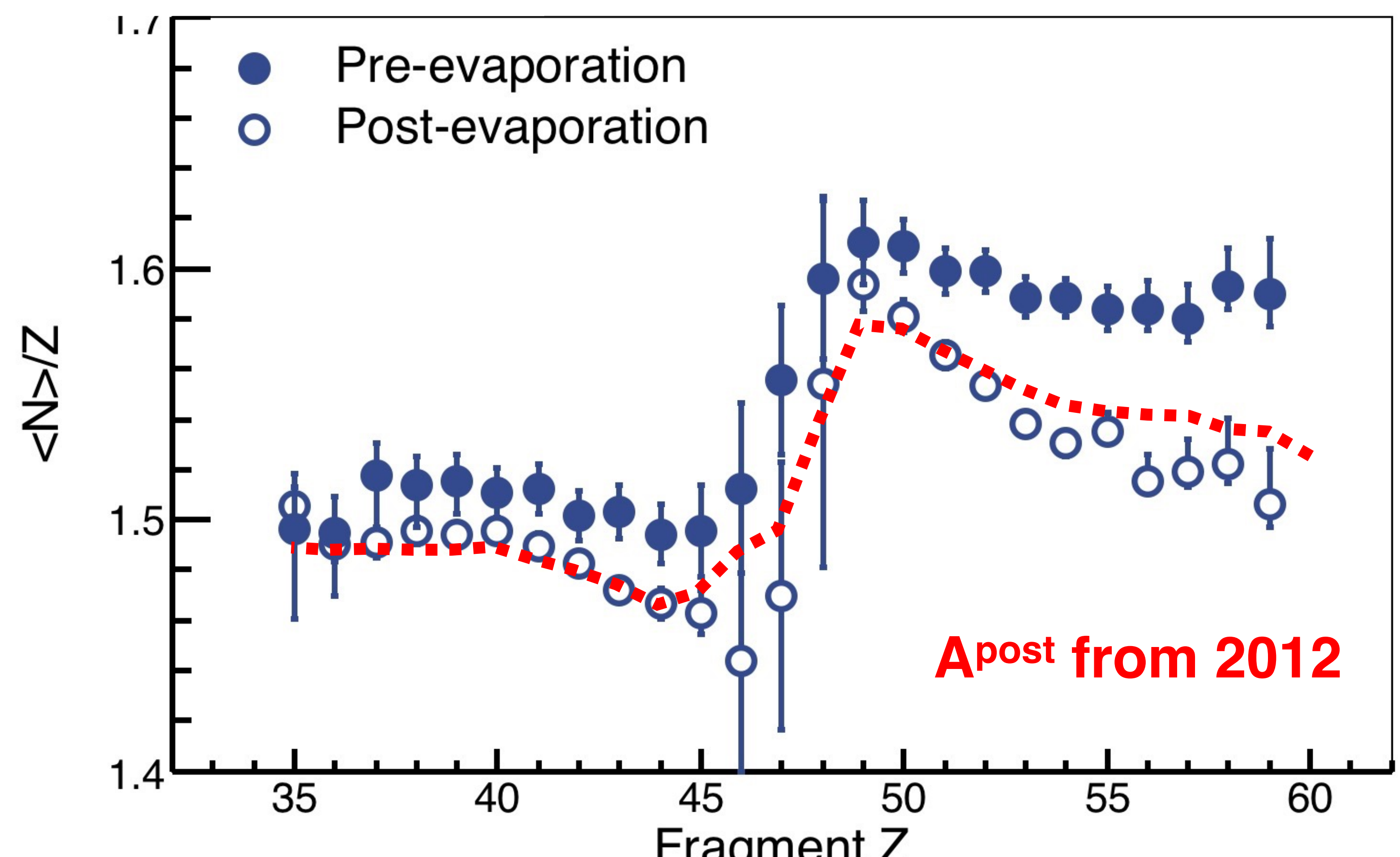
TXE (MeV)
20
30
40
50
35
40
45
50
55
60
Fragment Z
$^{239}Pu(n_{th})$
JNST 37, 941 (00)

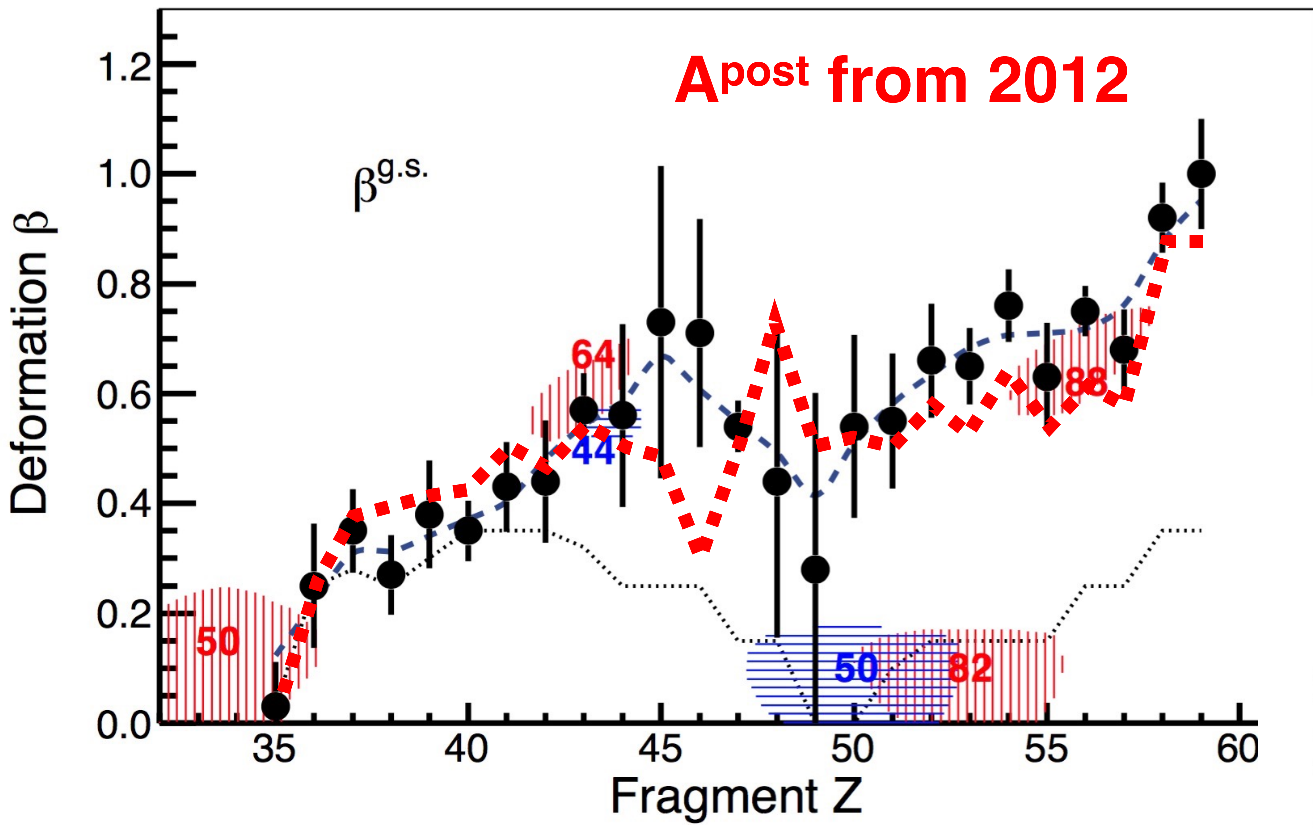


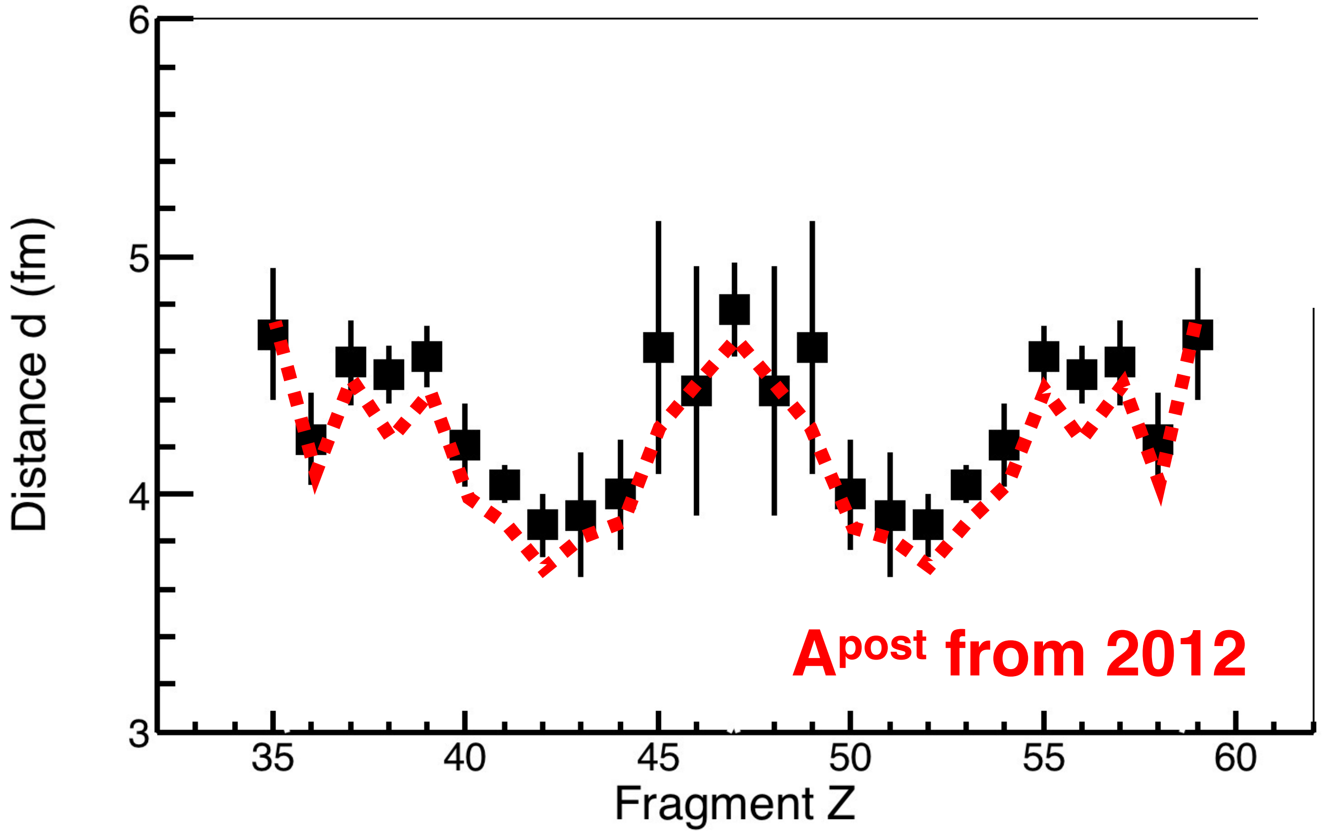
240
220
200
180
160
$Q_{g.s.}$, TKE (MeV)
$Q_{g.s.}$
TKE
Q_{max} from Z
Q_{max} from A
$^{239}Pu(n_{th})$
JNST 37, 941 (00)
35
40
45
50
55
60
Fragment Z

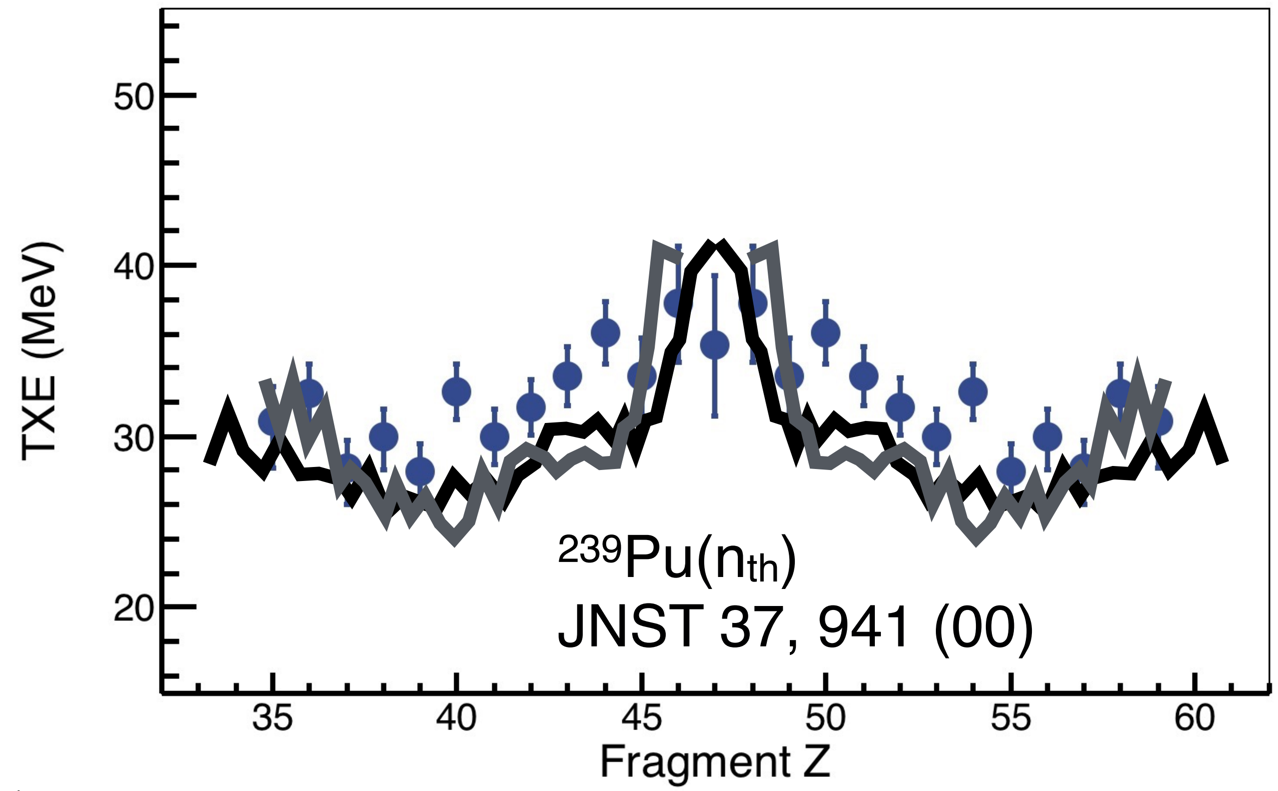


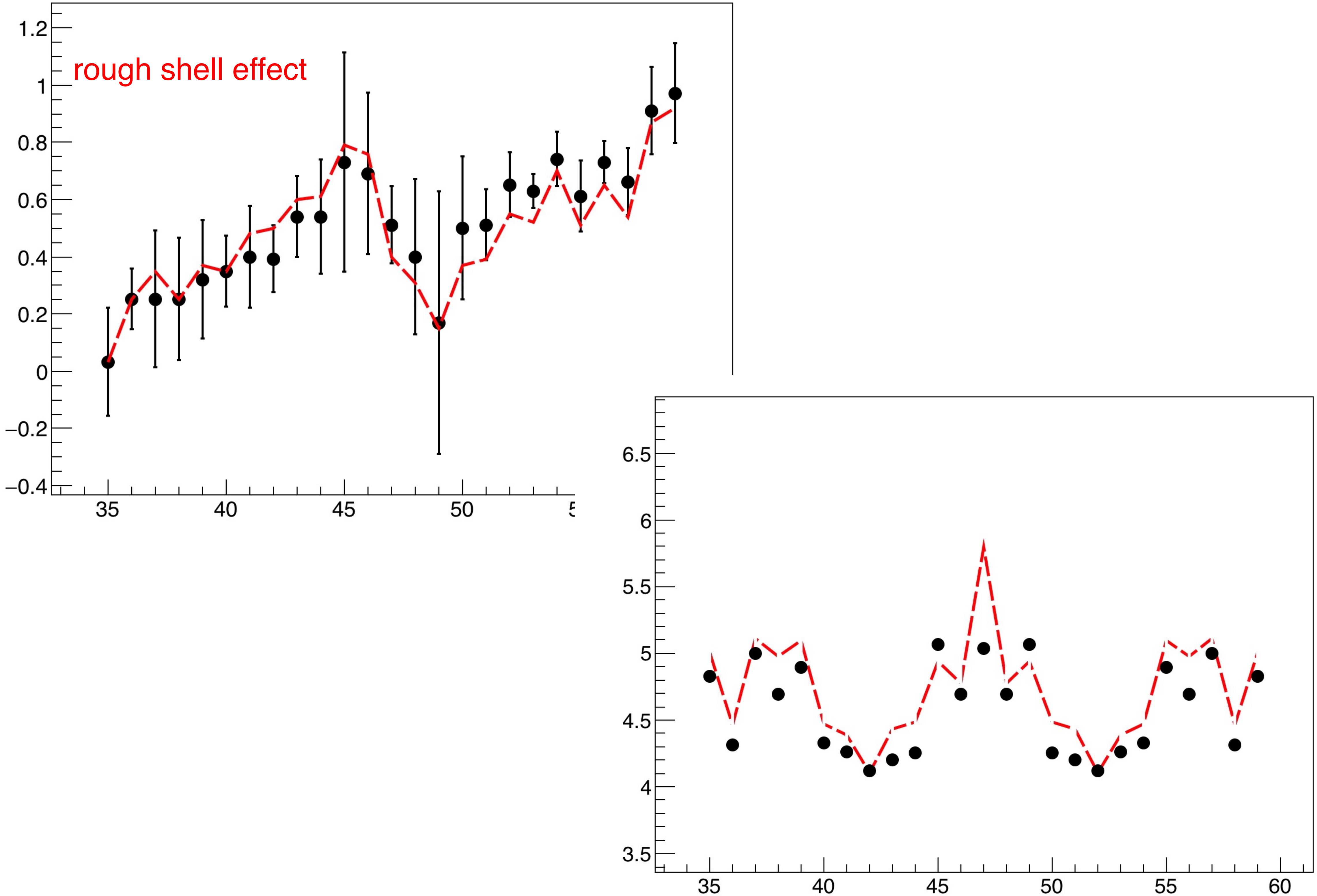
problems in mass measured around symmetry: low statistics

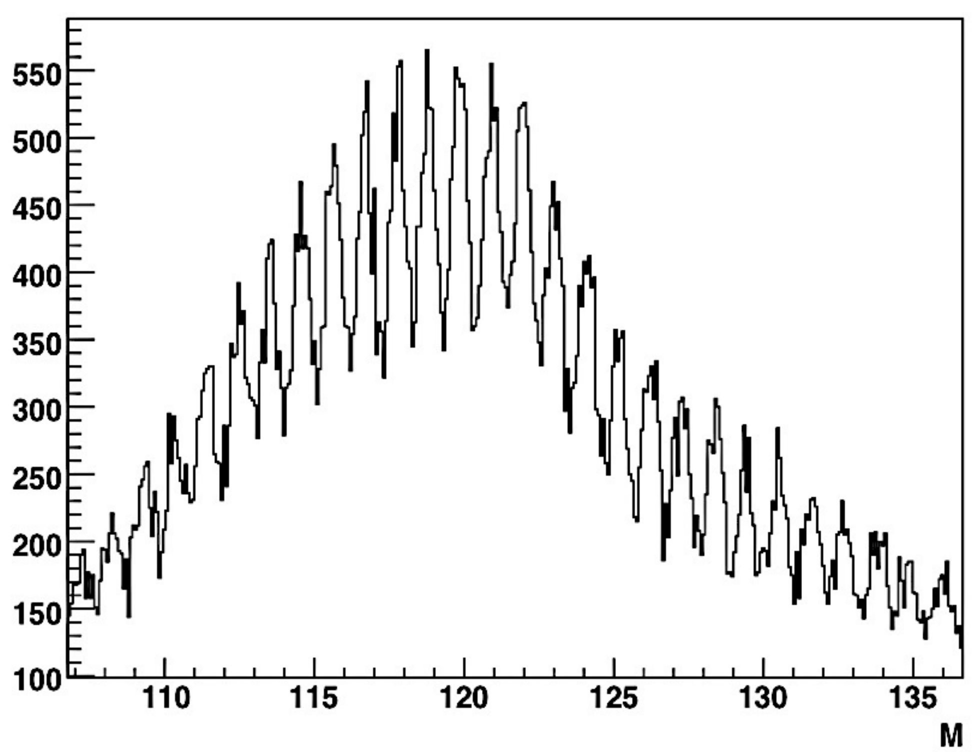


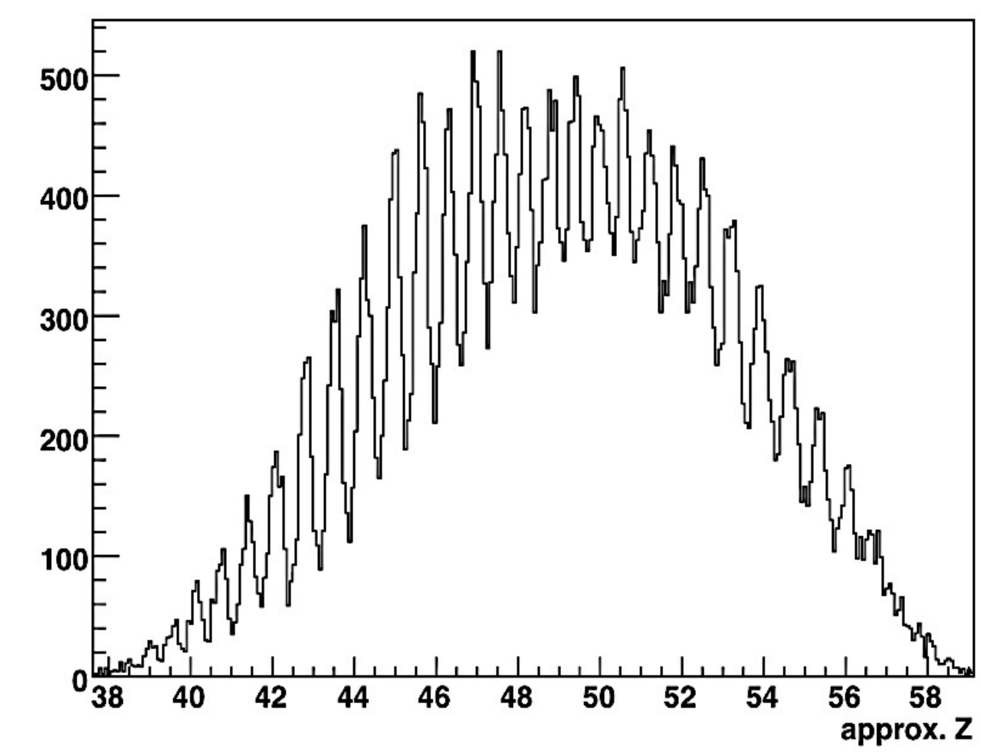

Apost from 2012
βg.s.
Deformation β
Fragment Z
64
44
50
50
82
88


Distance d (fm)
Apost from 2012
Fragment Z


TXE (MeV)
239Pu(nth)
JNST 37, 941 (00)
Fragment Z


rough shell effect





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

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

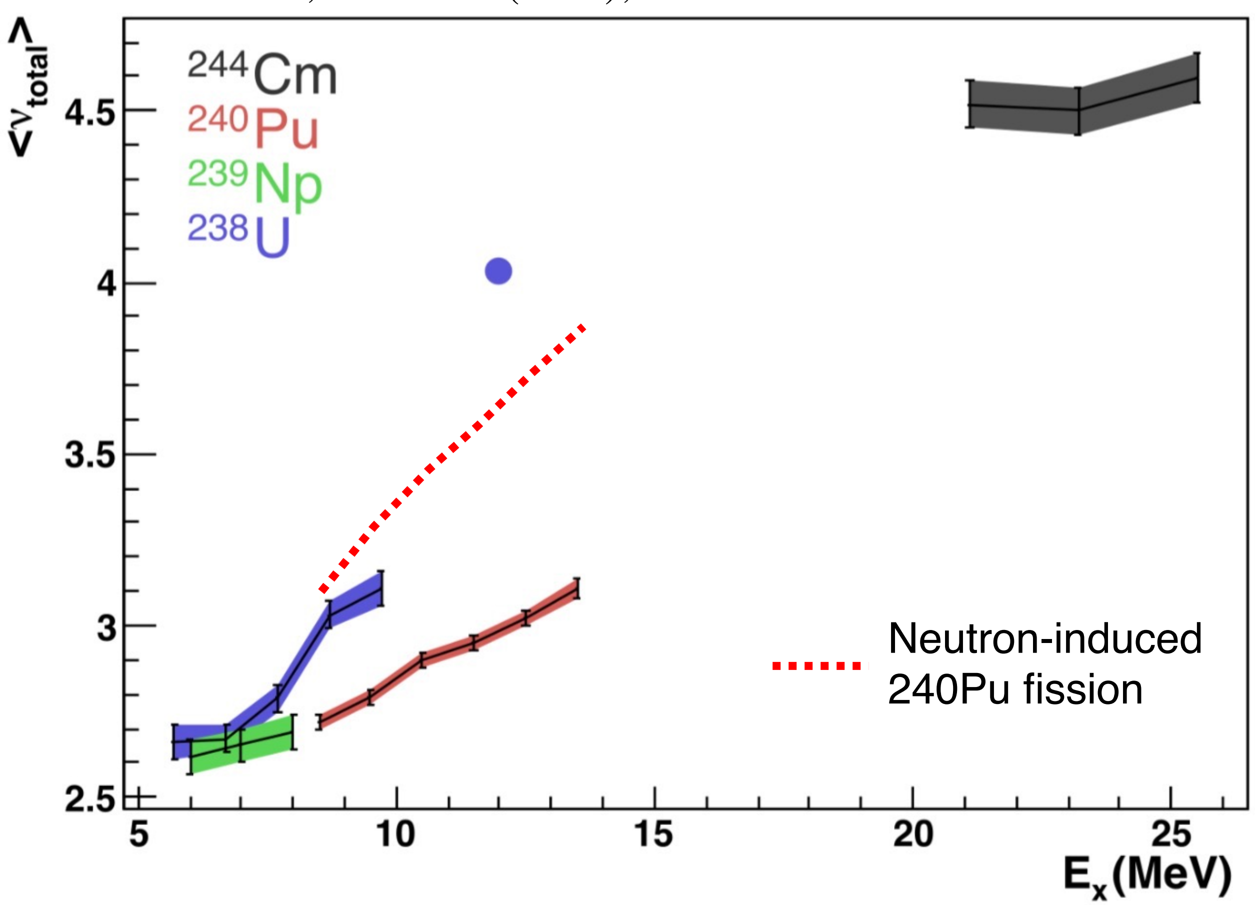
Fragments identified from **M** ≈ **90** to **M** ≈ **140**

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

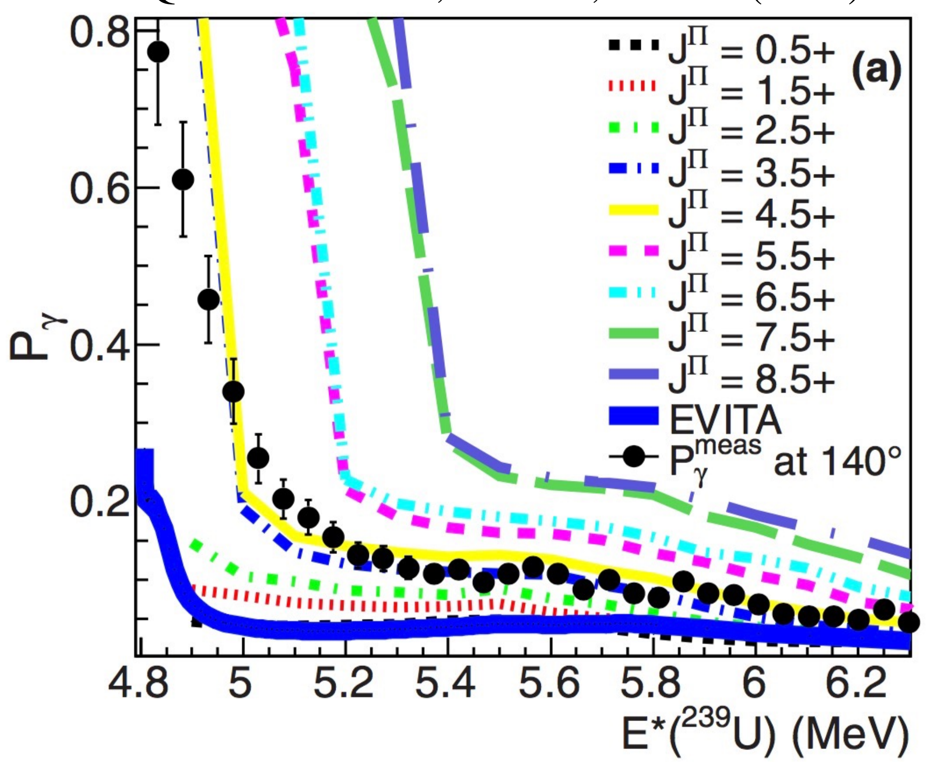
A set of revisited and new observables

Neutron evaporation

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



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

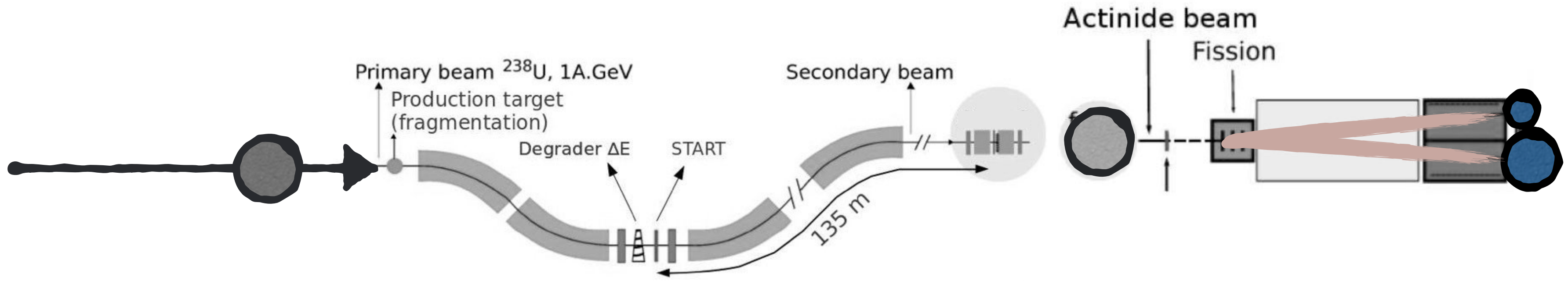


The evolution of the neutron evaporation with E* is slower for the case of transfer-fission than for neutron-induced.
An measurement of angular momentum?

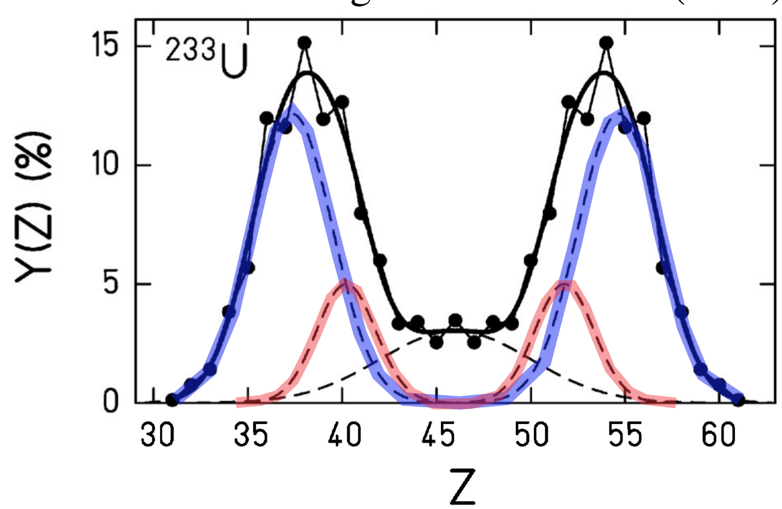
Inverse kinematics at GSI:

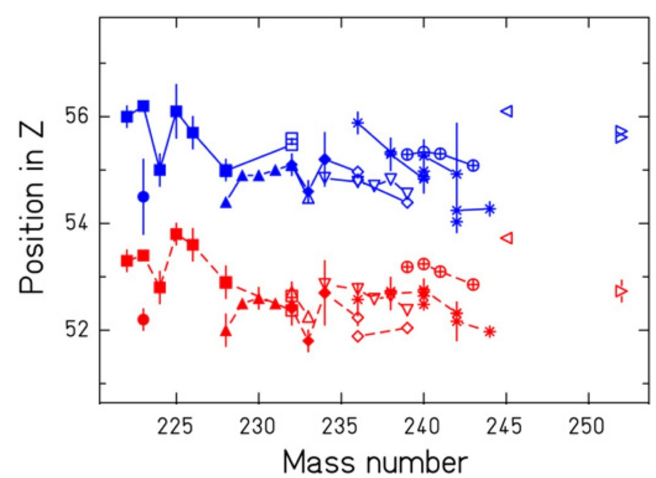
Production from fragmentation and e-m fission induced

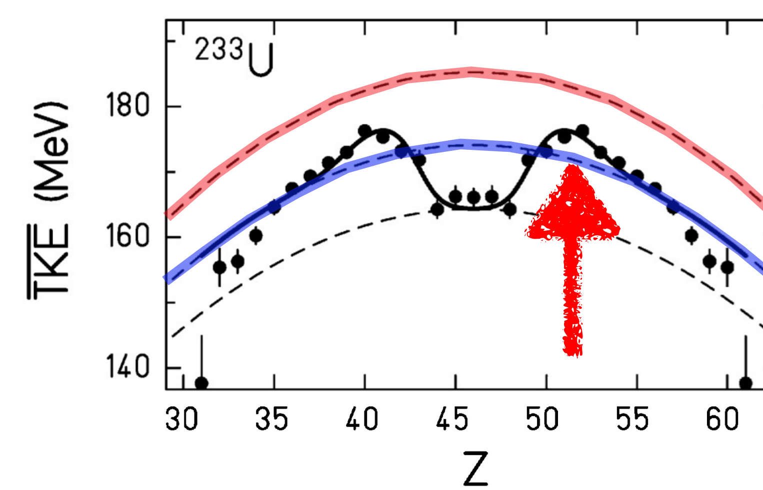
K.-H. Schmidt et al.



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



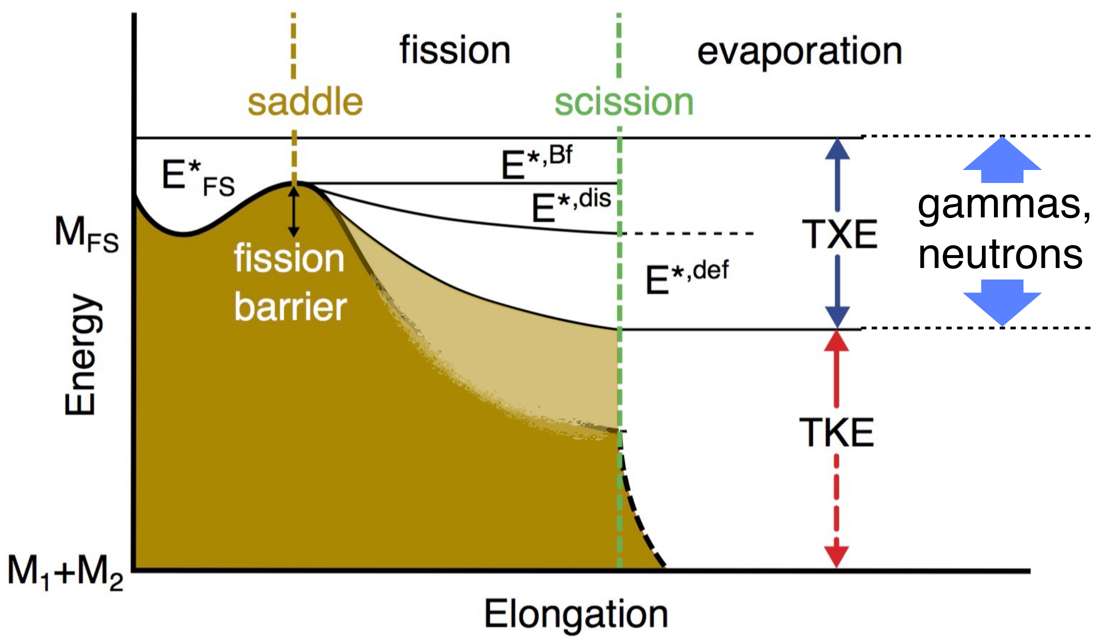


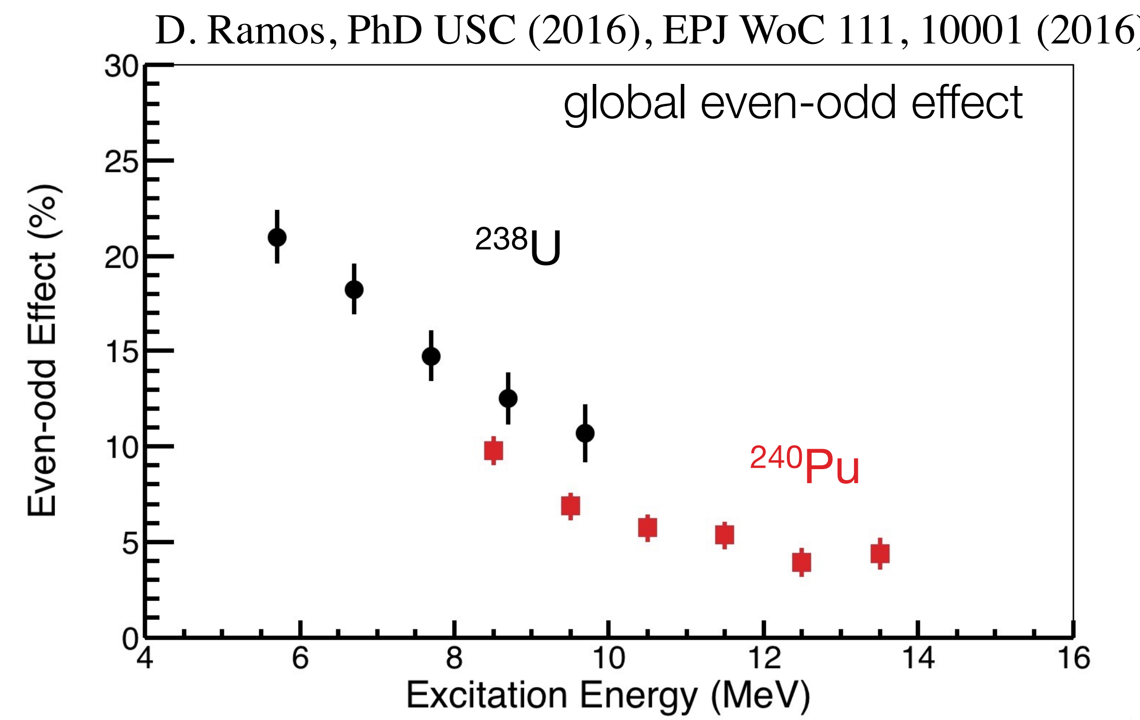


Accurate access to components on the yield distribution

Compact scission around Z~52

Even-odd effect and dissipation





$M_{FS} + E^*_{FS} =$ **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:

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

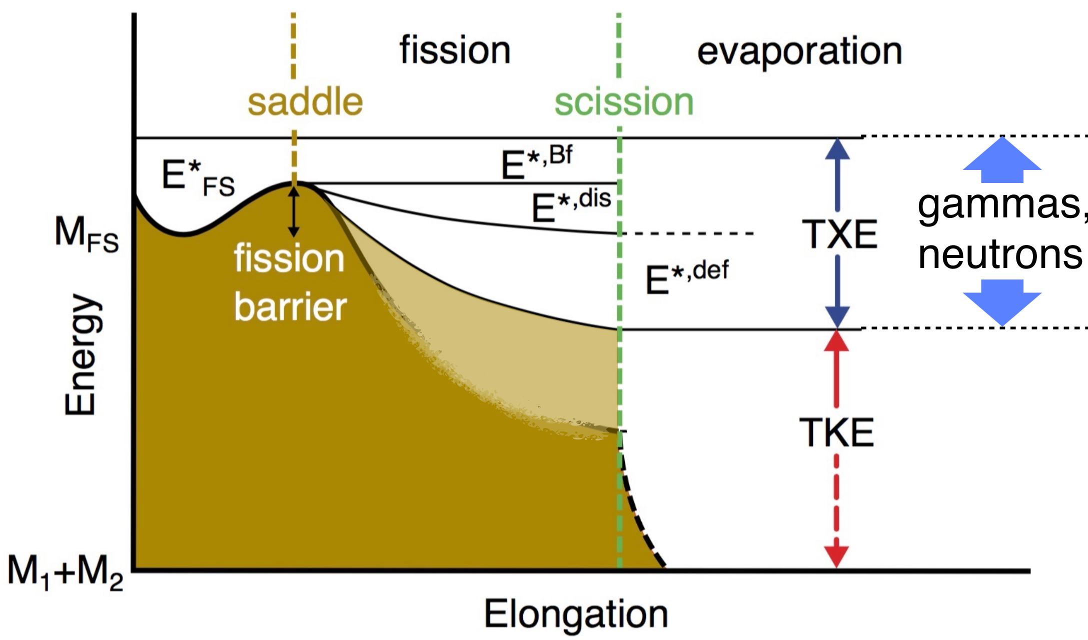
from theory:

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

in the case of ^{240}Pu:

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

Even-odd effect and dissipation



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

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

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

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