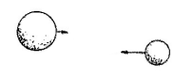
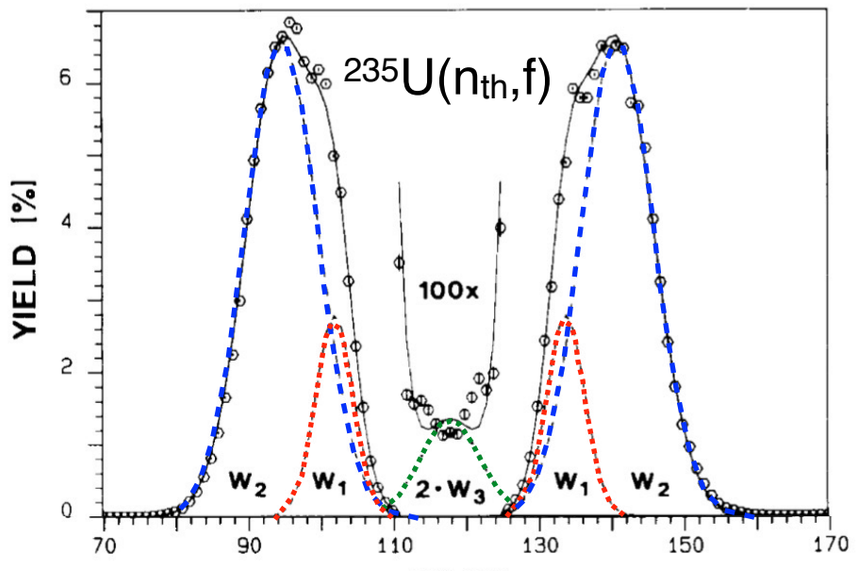
Fission in Inverse Kinematics at GANIL

M. Caamaño, F. Farget, D. Ramos, C. Rodríguez, O. Delaune, and many more…
(U. Santiago de Compostela, GANIL, etc.)

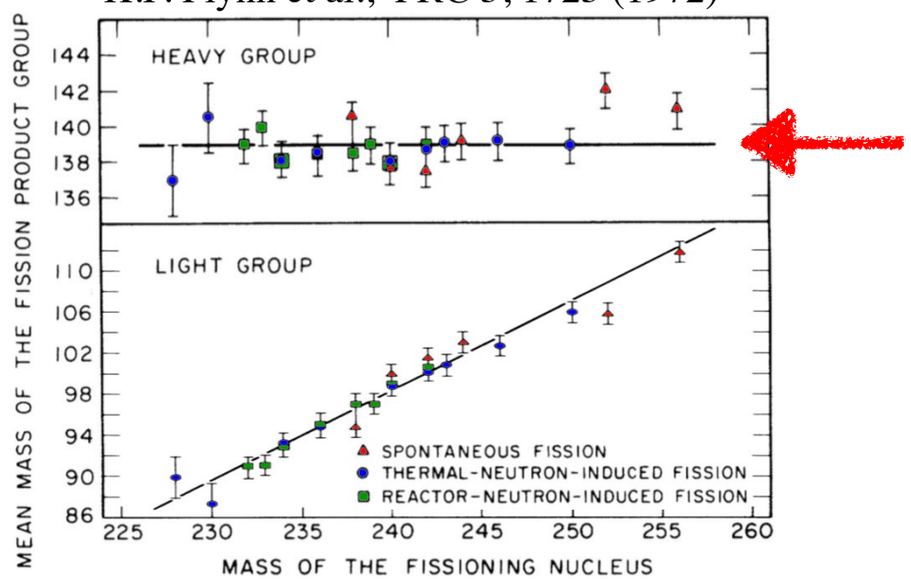


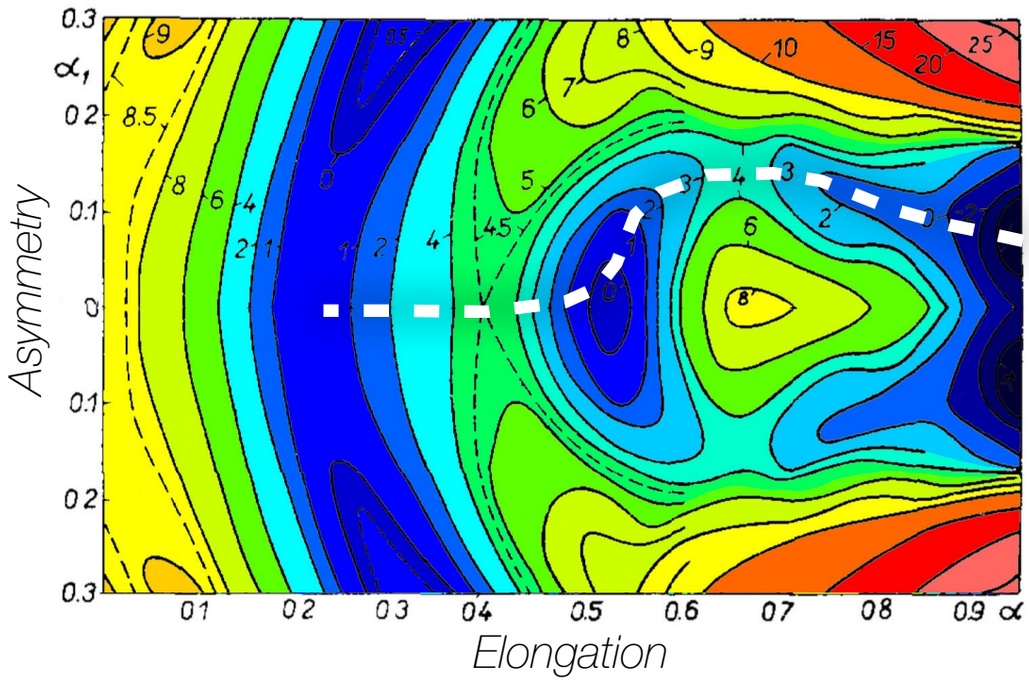
Shell effects shape the landscape

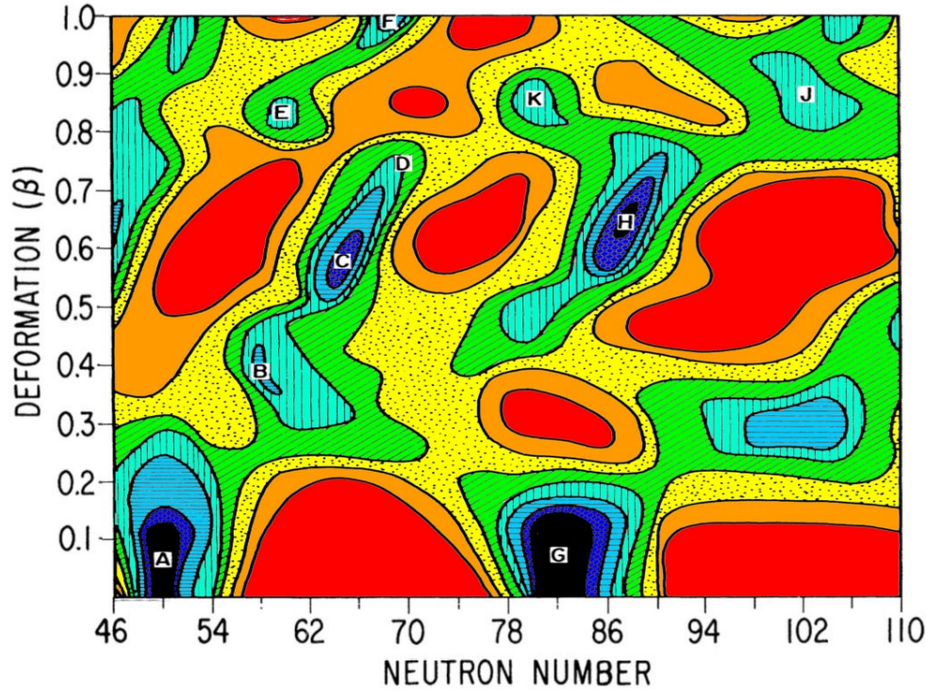
F.-J. Hambsch et al., NPA 491, 56 (1989)



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

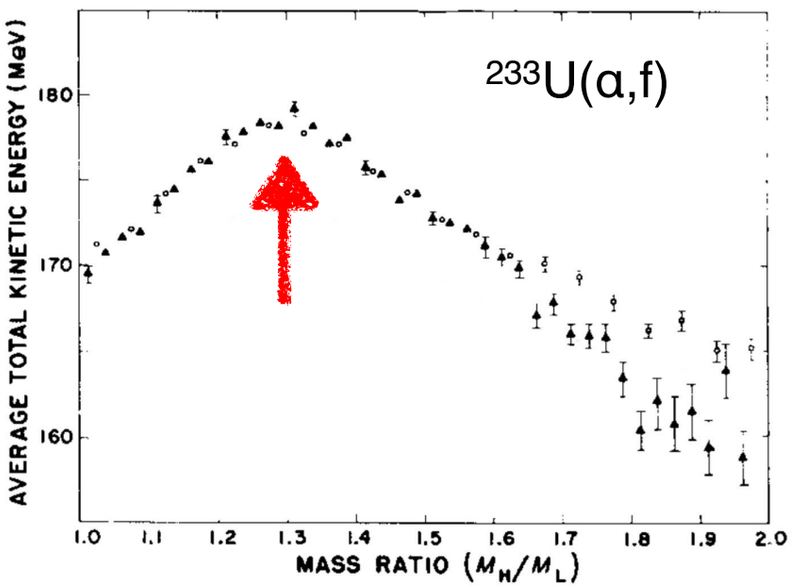




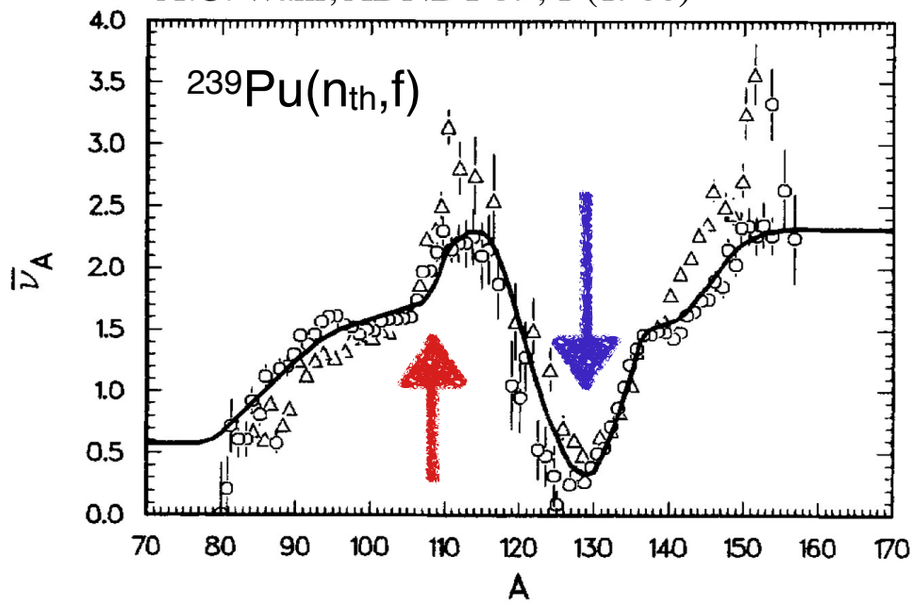


Confirmed/consistent with a number of observables

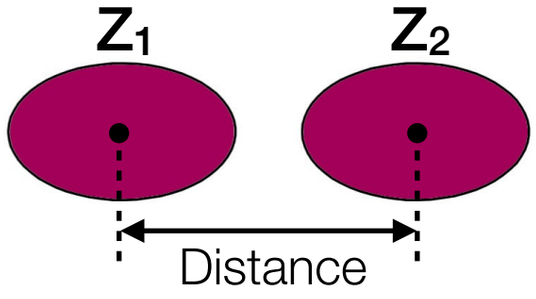
H.C. Britt et al., NIMA 24, 13 (1963)



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

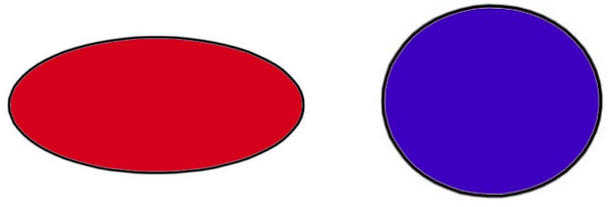


Total kinetic energy (TKE)



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

Neutron evaporation



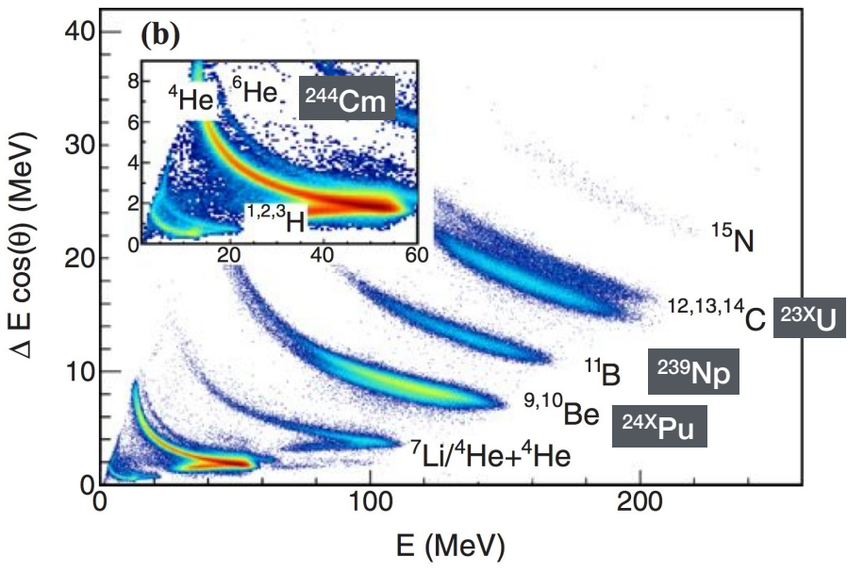
$$\nu \propto E^{def} + E^{int}$$

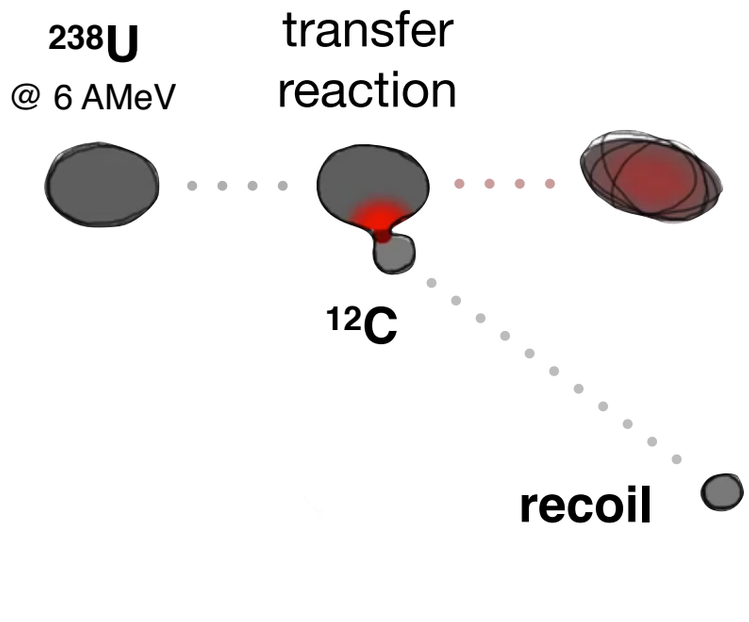
Inverse kinematics at VAMOS/GANIL:

Production and fission from fusion and multi-nucleon transfer

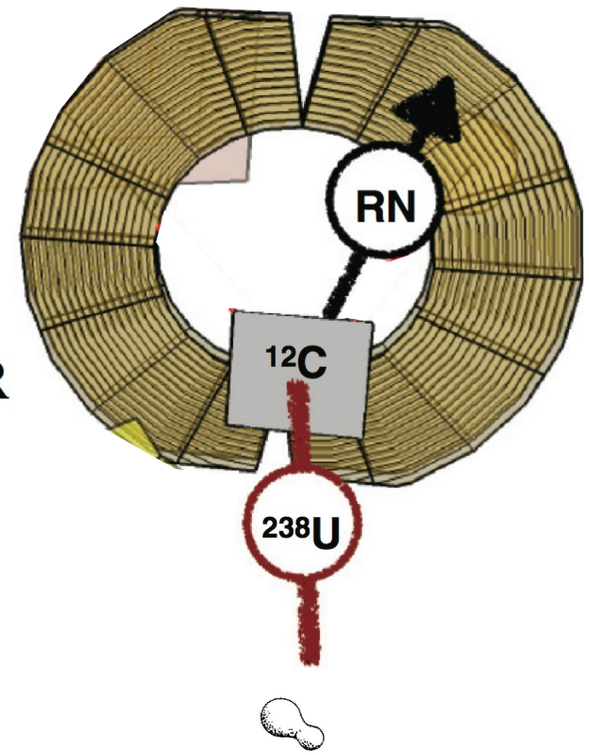
F. Farget et al.

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





SPIDER:
Recoil
A, Z, E, angle



SPIDER
dE-E, angles

observables:

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

M. Caamaño (USC)

Inverse kinematics at VAMOS/GANIL:

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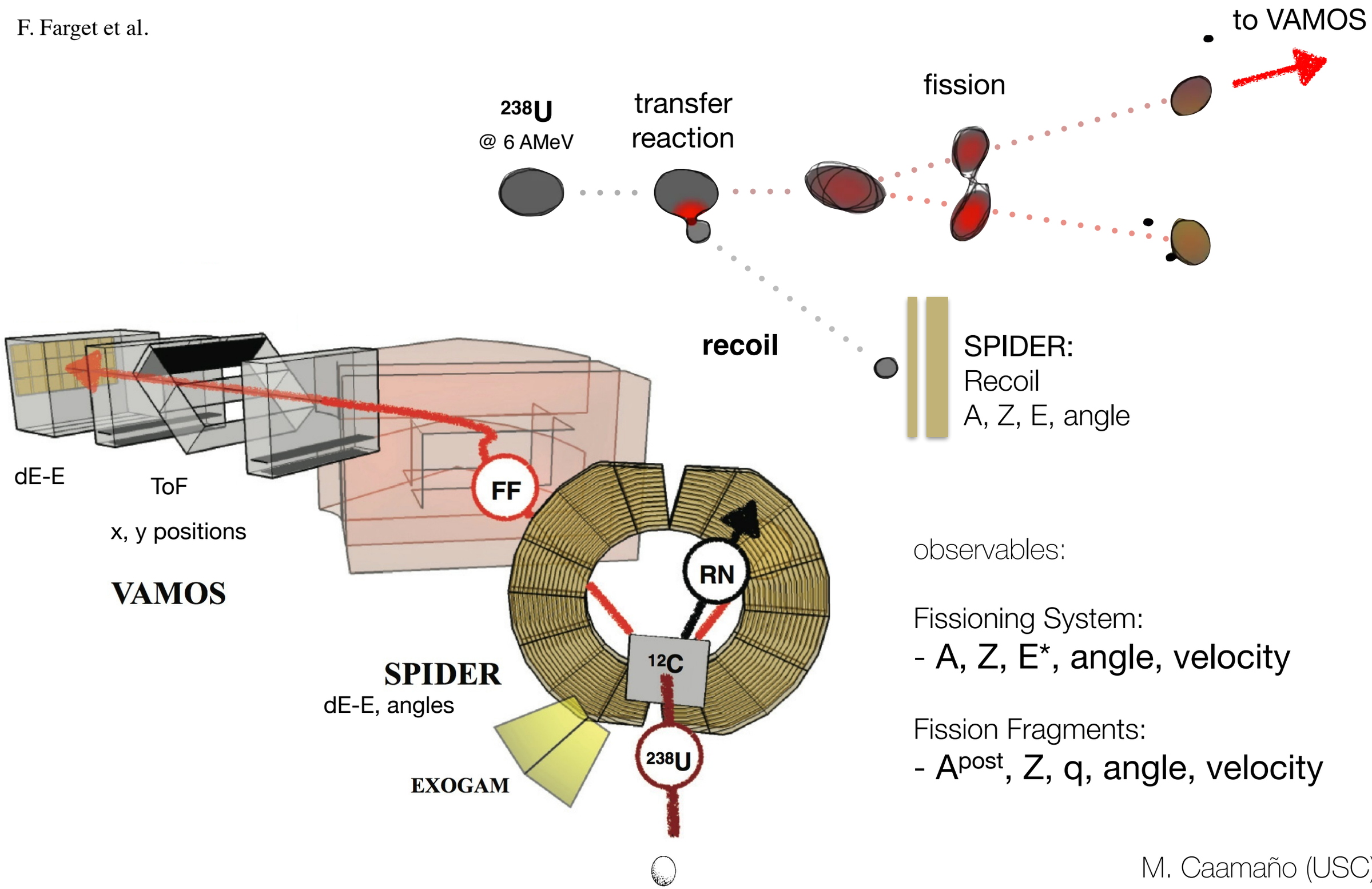

observables:

Fissioning System:

- A, Z, E*, angle, velocity

Fission Fragments:

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

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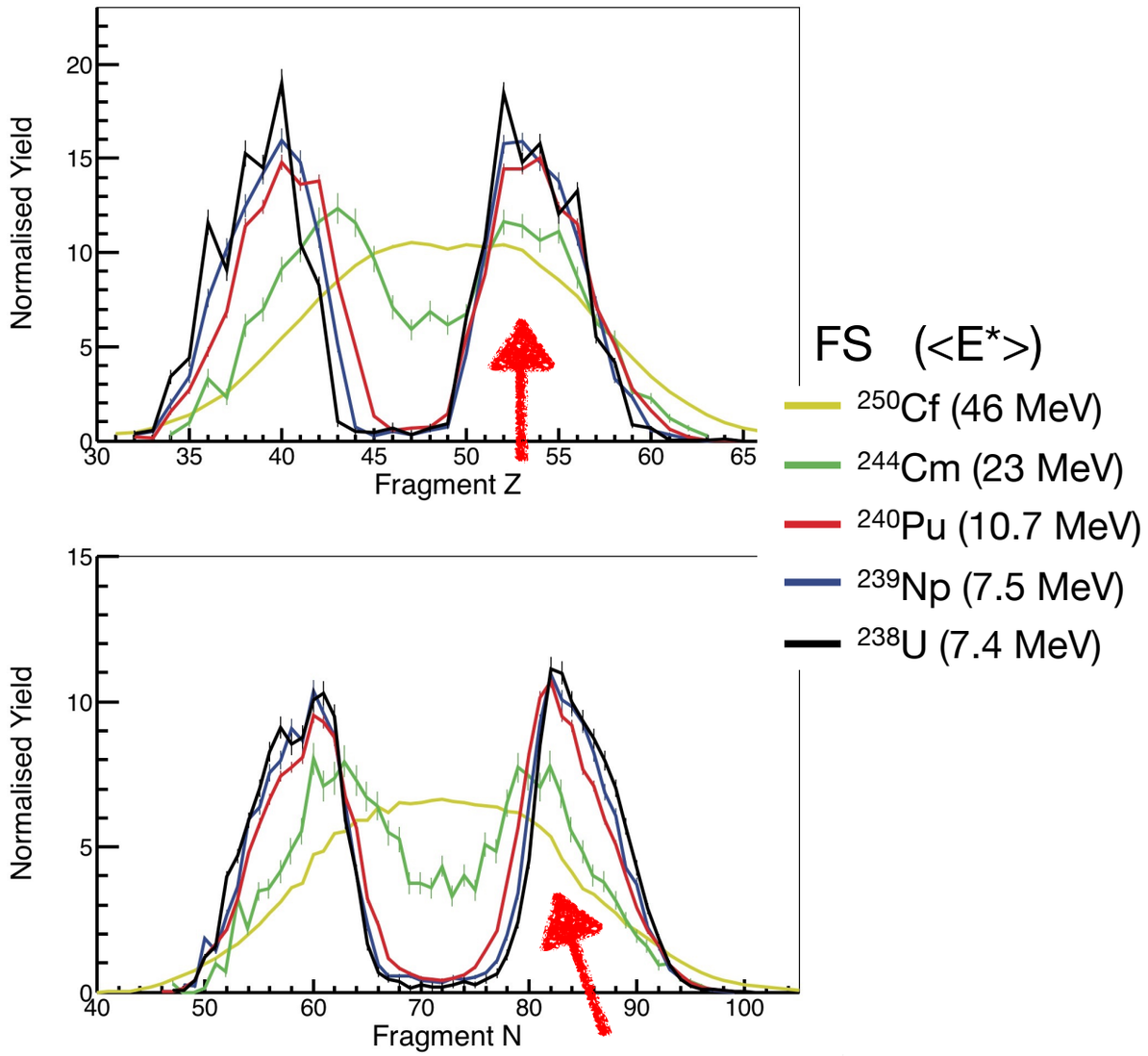
A set of revisited and new observables

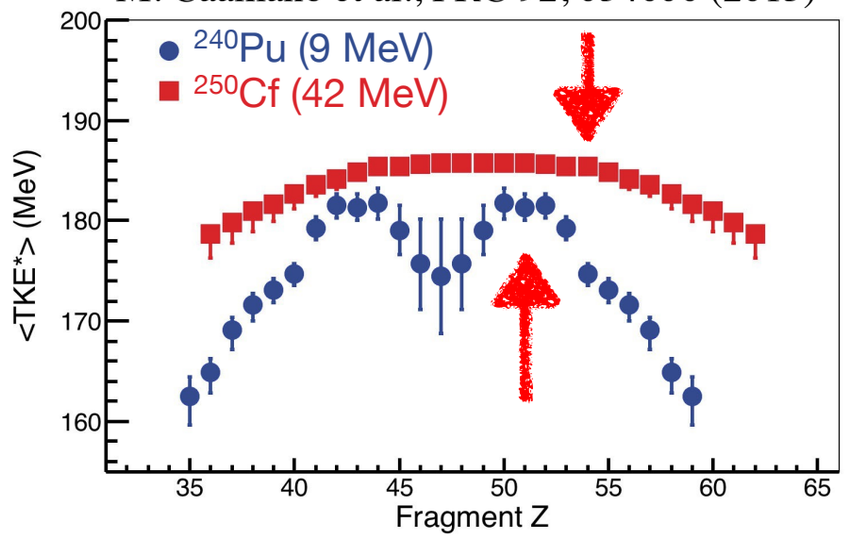
Fragment Z, N distributions

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

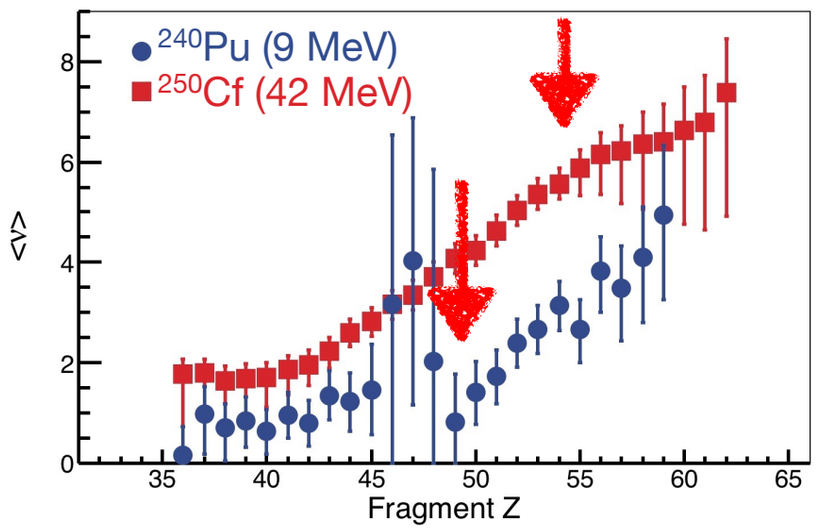


Total kinetic energy (TKE)

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

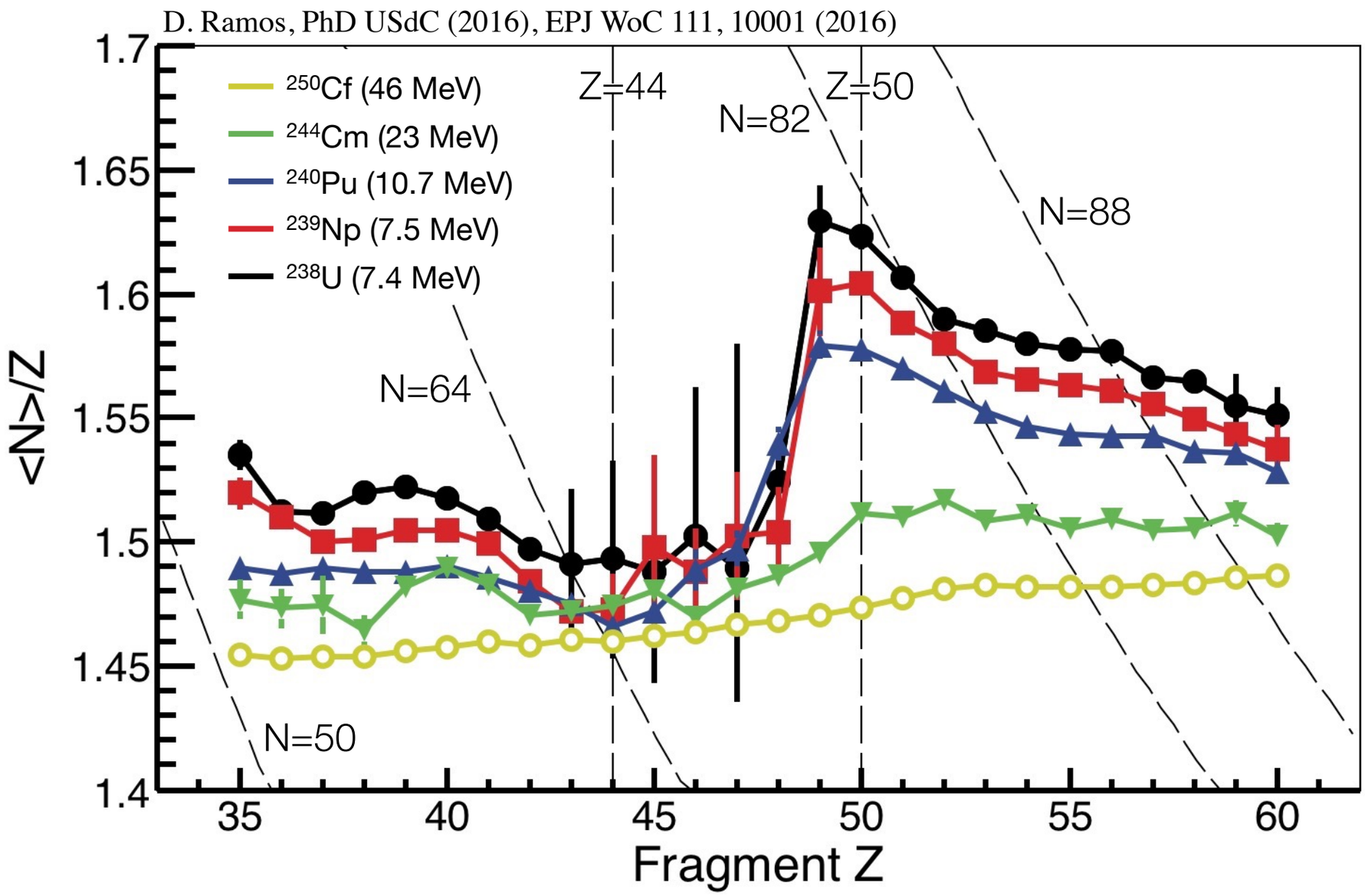


Neutron evaporation



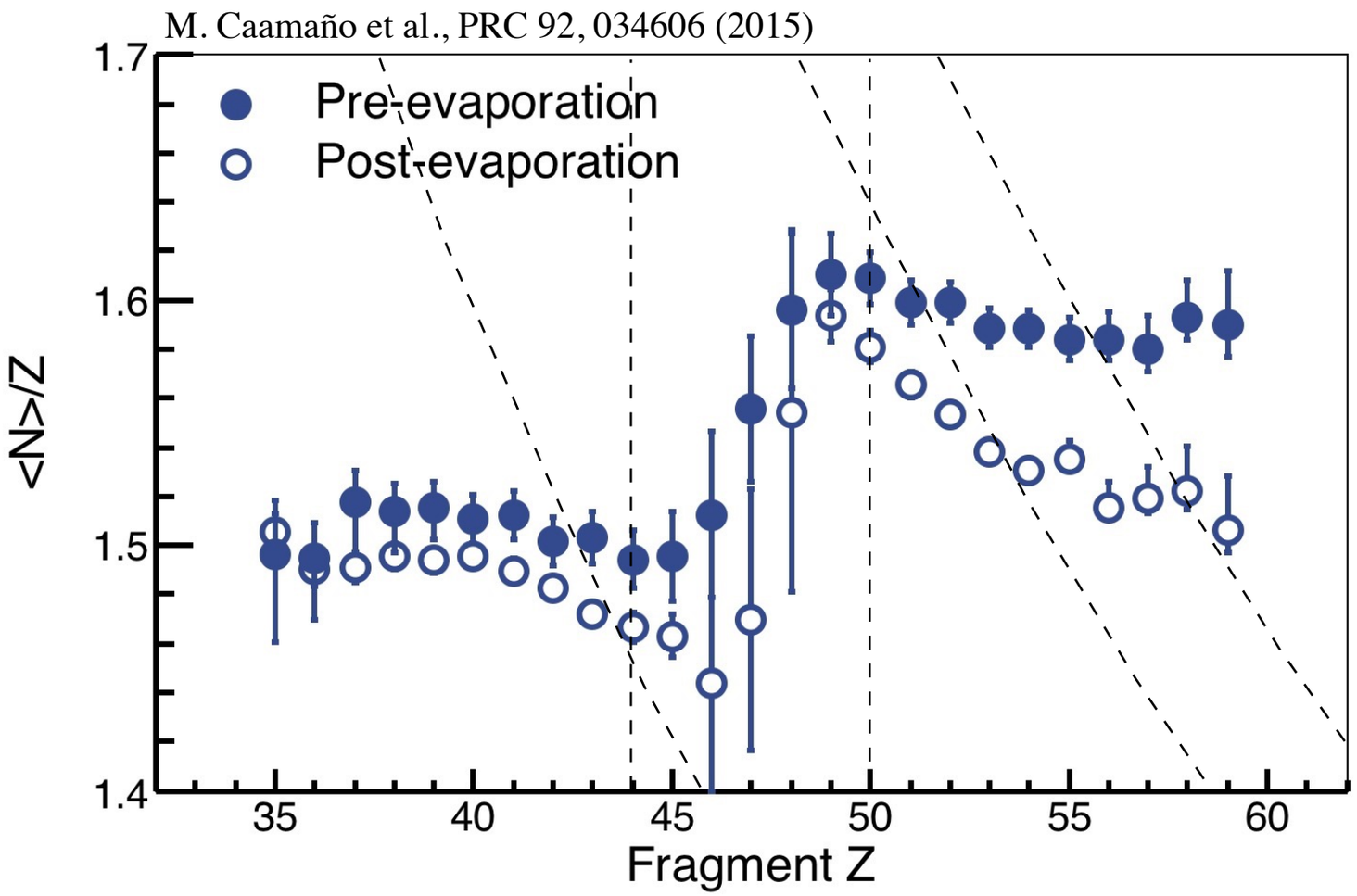
A set of revisited and new observables

Fragment N excess (N/Z)



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

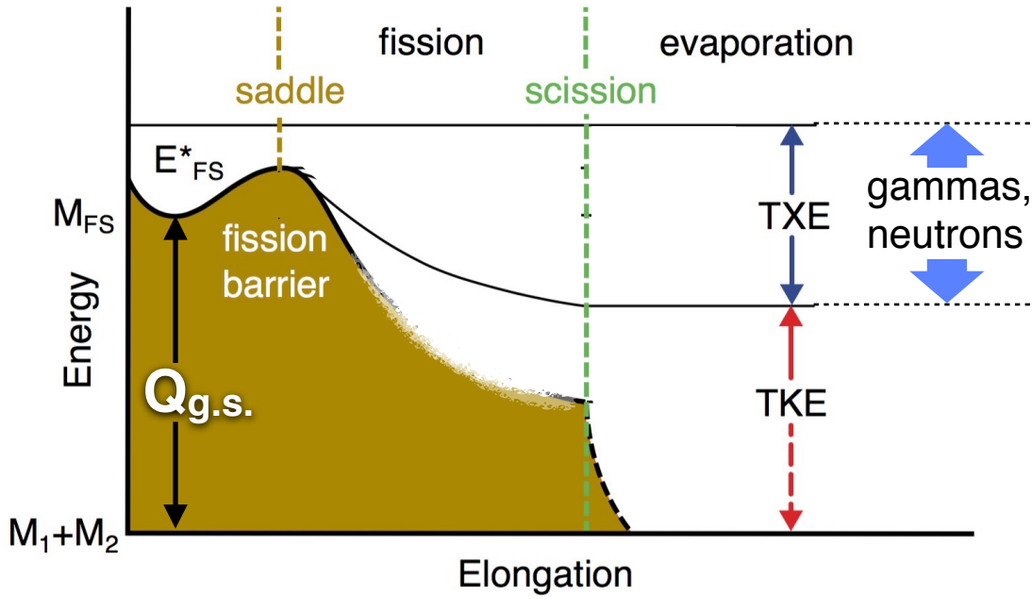
Fragment N excess (N/Z)



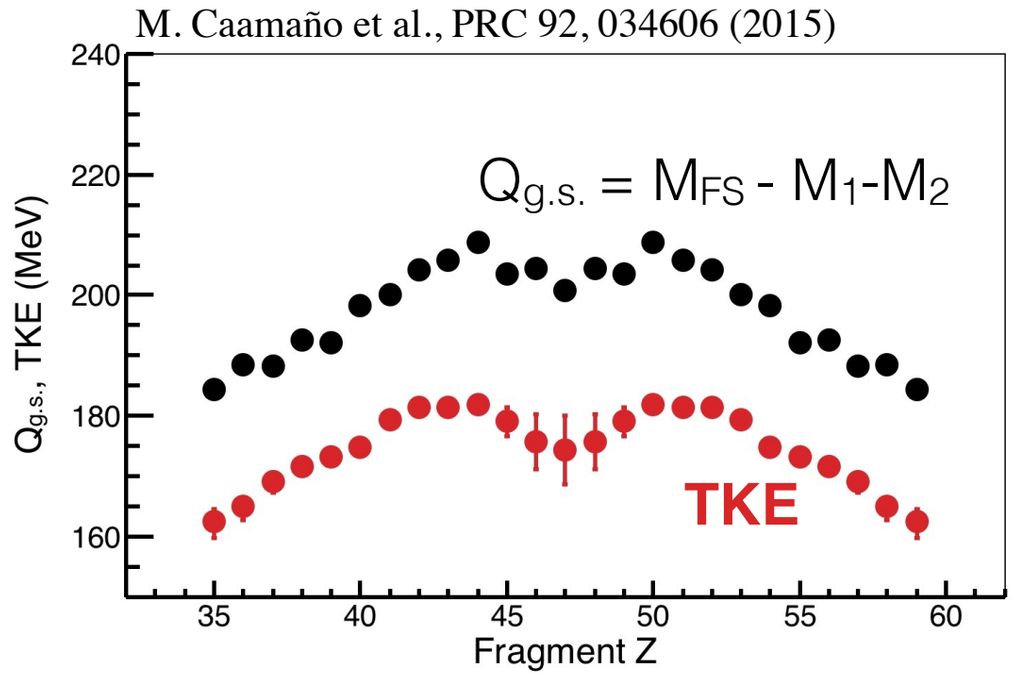
measured velocities and momentum conservation:

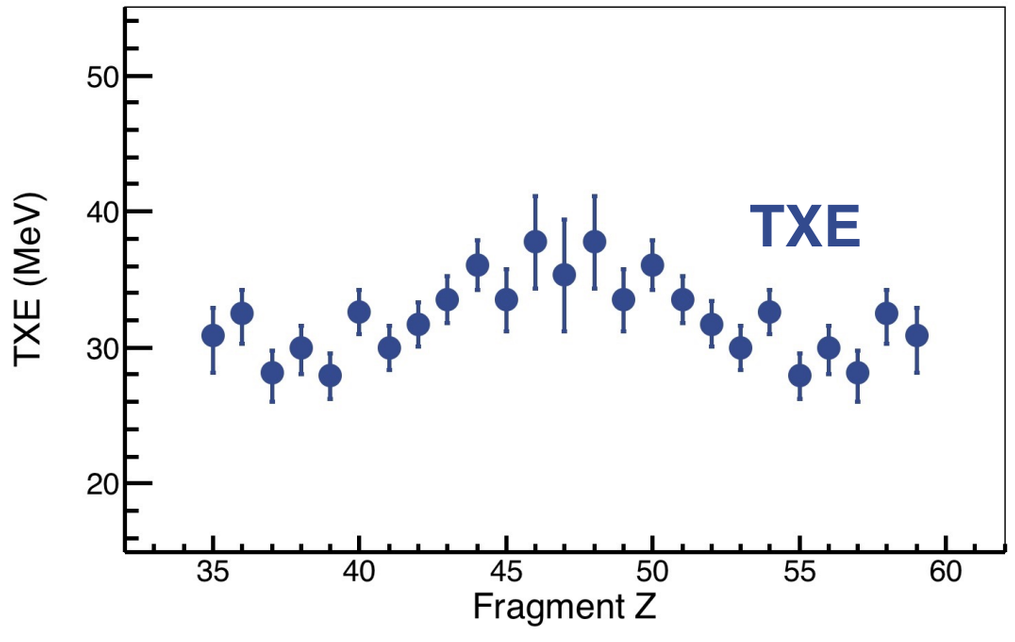
$$\langle A_1^* \rangle = A_{\rm FS} \frac{\langle V_2 \gamma_2 \rangle}{\langle V_1 \gamma_1 \rangle + \langle V_2 \gamma_2 \rangle}, \quad \langle A_2^* \rangle = A_{\rm FS} - \langle A_1^* \rangle.$$

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



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





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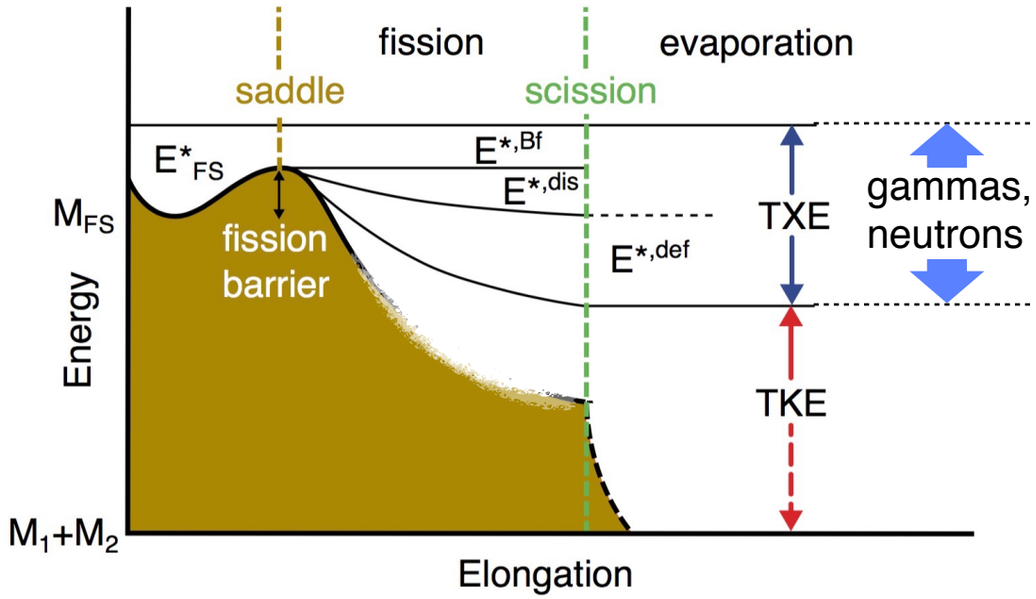


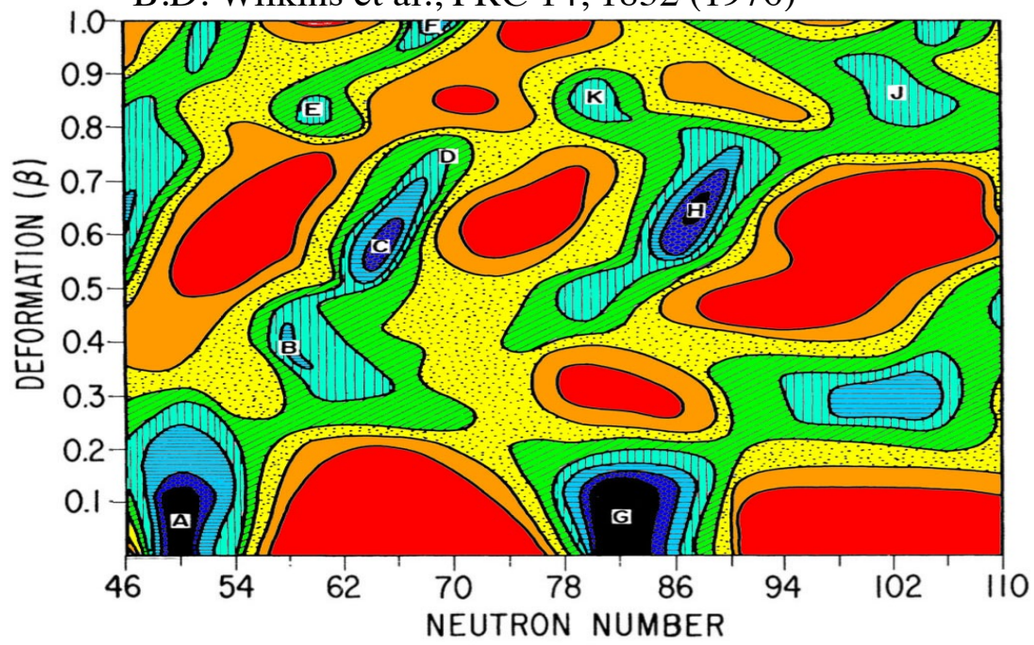
$$M_{FS} + E^*_{FS} = \mathbf{TXE} + \mathbf{TKE} + M_1 + M_2$$

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

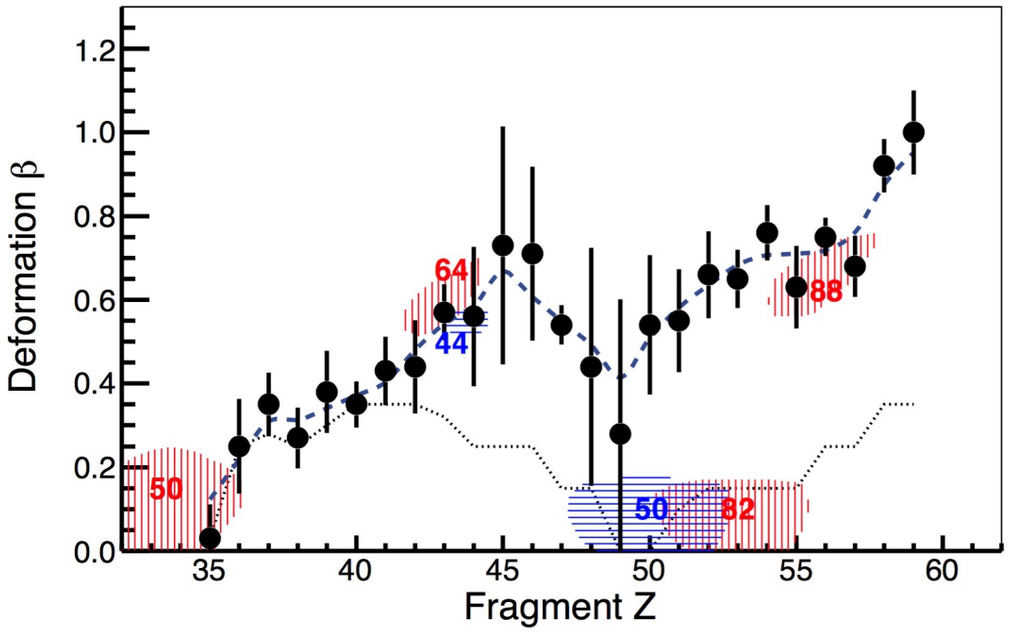
$$= \nu\cdot(Q_n + \varepsilon) + E^{\gamma}$$

access to the fragment deformations !!

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



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



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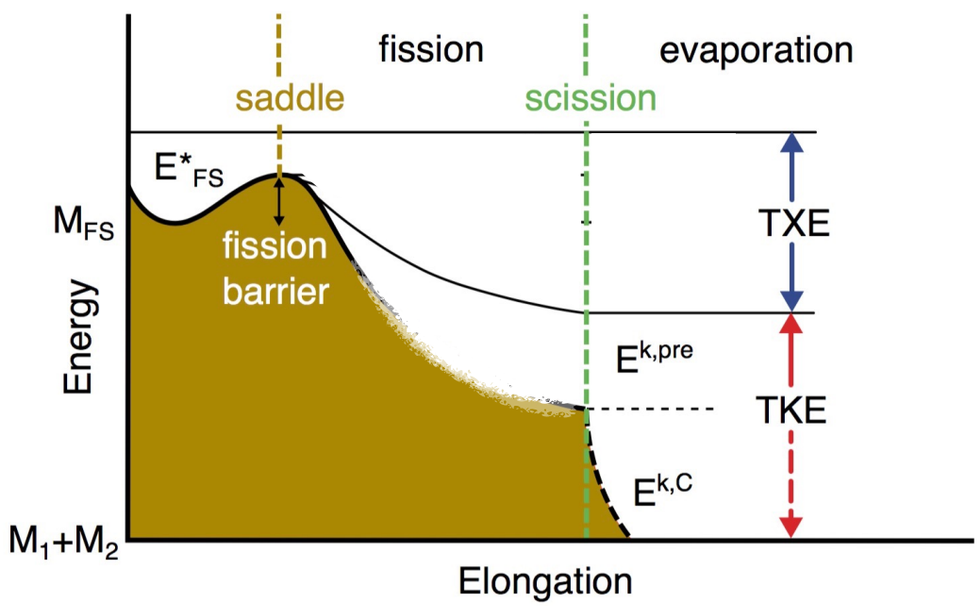
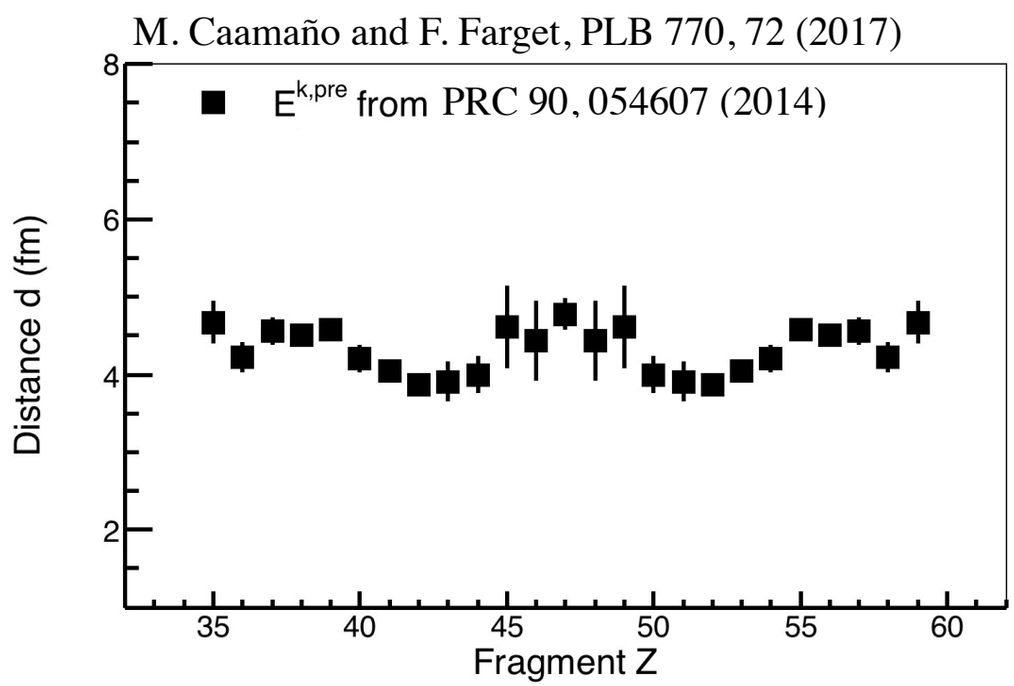
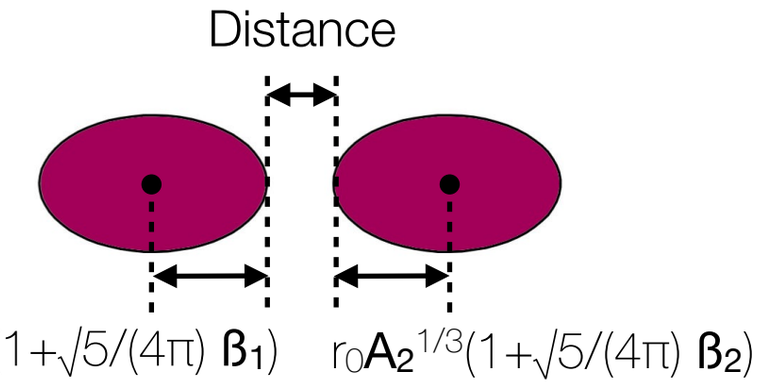




$$M_{FS} + E^*_{FS} = \mathbf{TXE} + \mathbf{TKE} + M_1+M_2$$

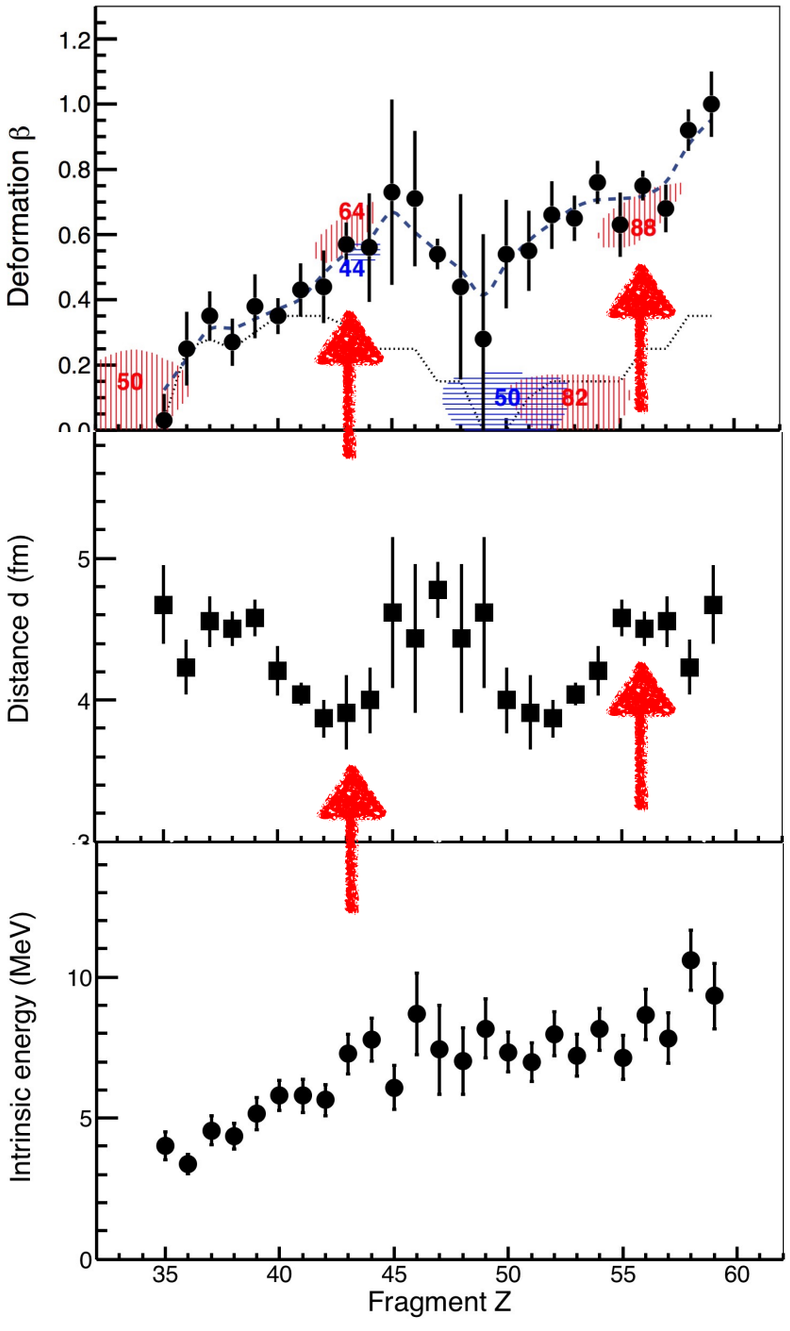
$$\mathbf{TKE} = E^{k,pre} + E^{k,C}$$

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



access to the distance between fragments !!

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



a collective picture of scission:

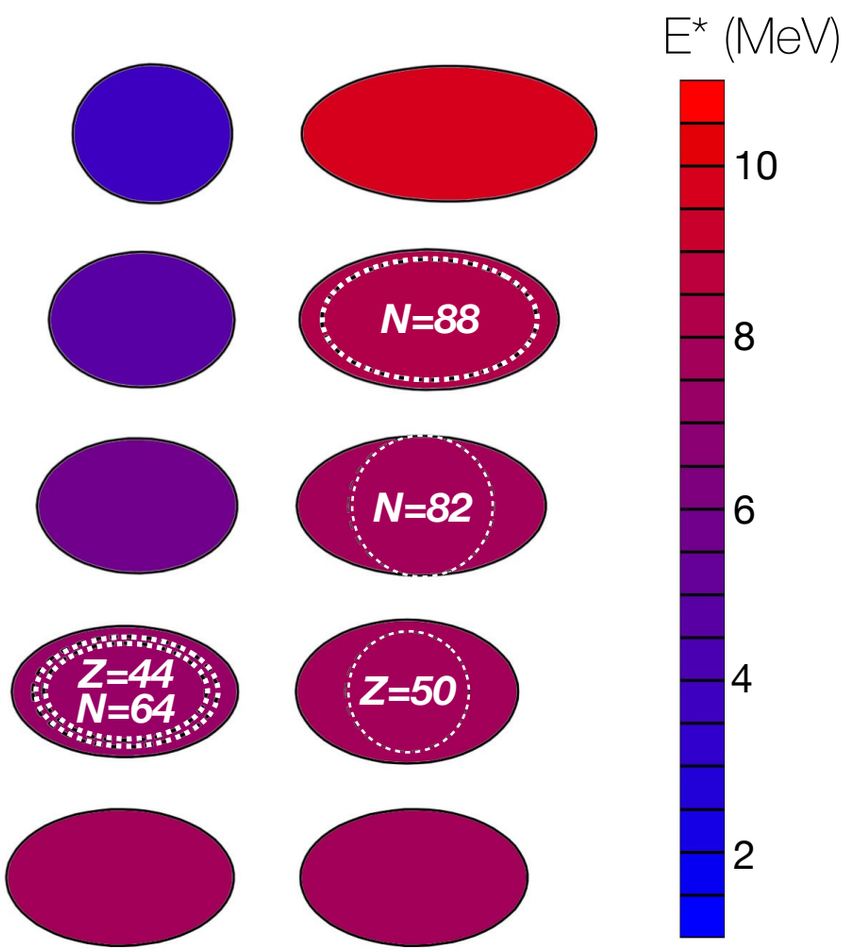
Z_1=35, Z_2=59

Z_1=38, Z_2=56

Z_1=41, Z_2=53

Z_1=44, Z_2=50

Z_1=47, Z_2=47



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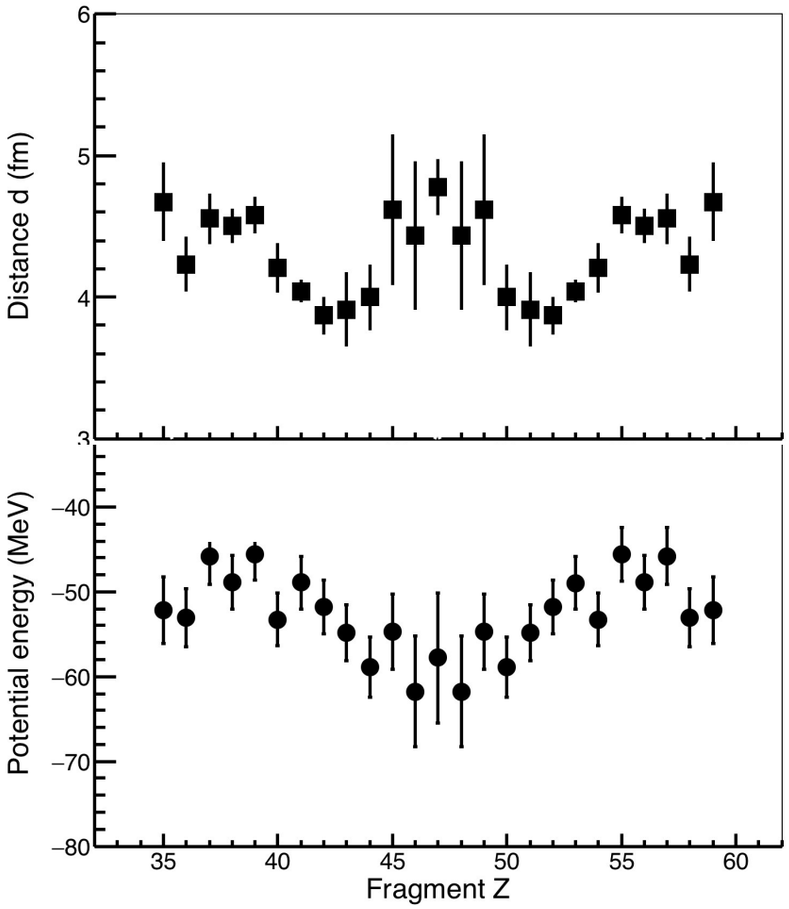
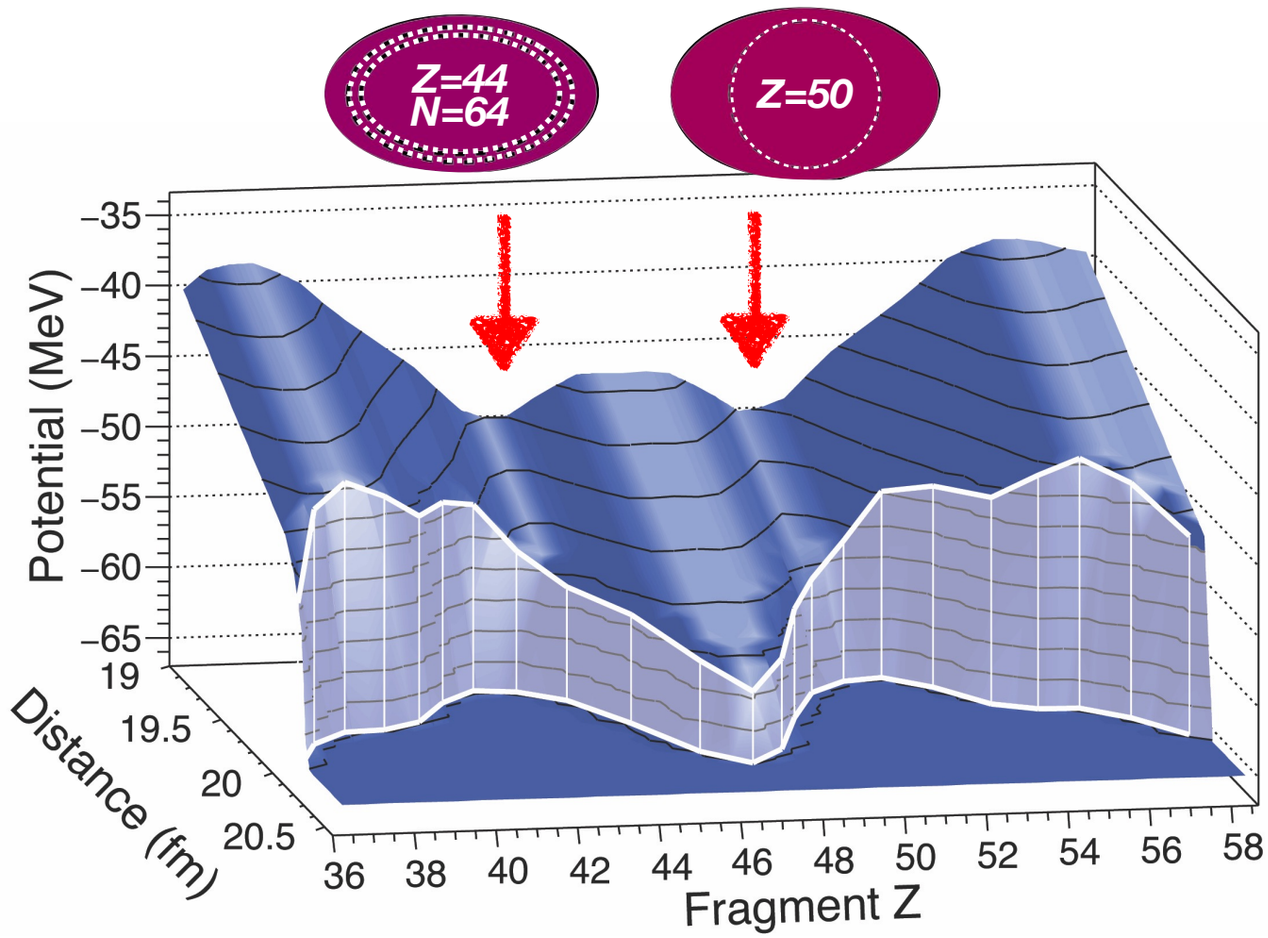
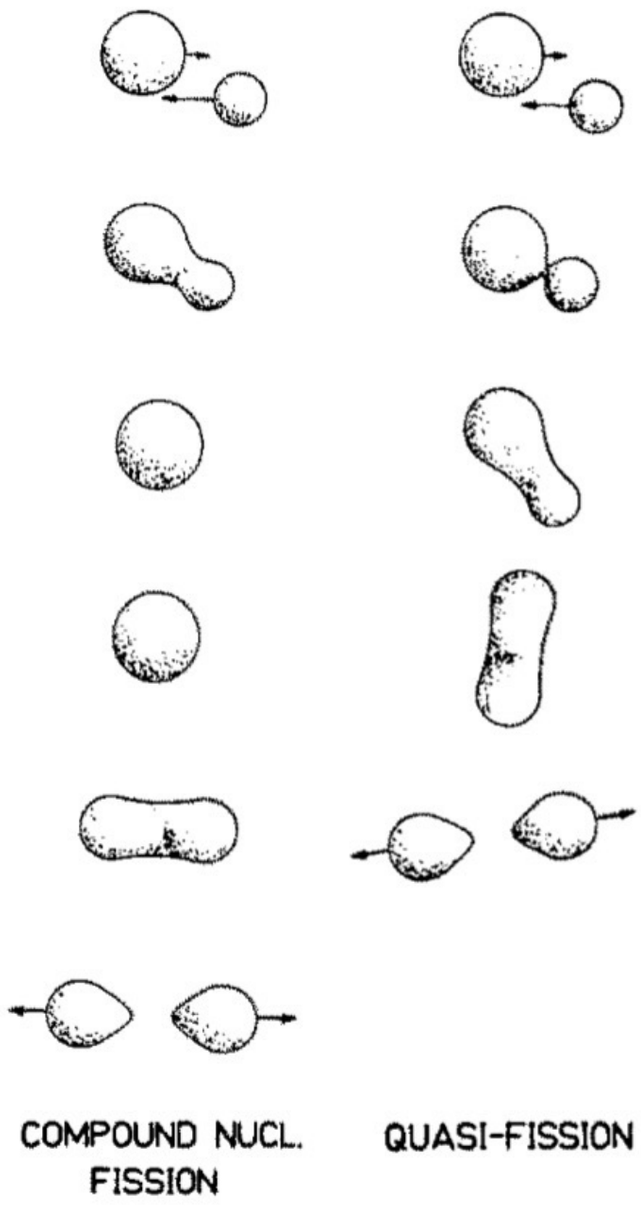


PE = -TXE + $E^{*,def}$

and a sneak peek of the potential landscape:



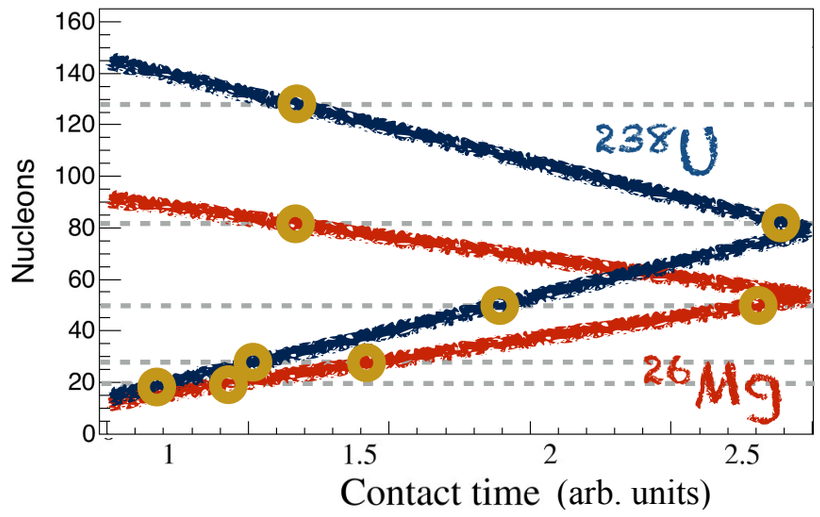
J. Töke et al., NPA 440, 327 (1985)

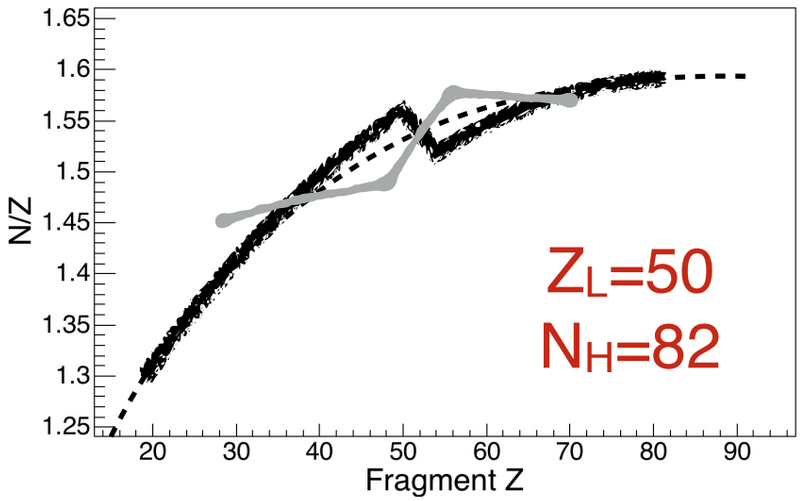


What else?

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

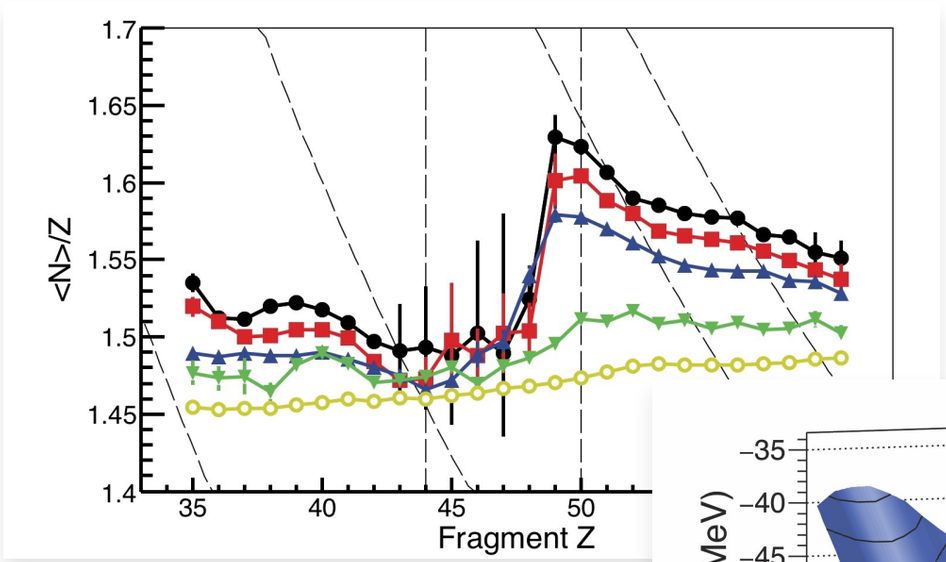
^{238}U @ 5.9 AMeV + [^{26}Mg, ^{27}Al, ^{11}B, ^{9}Be] at **VAMOS/GANIL**



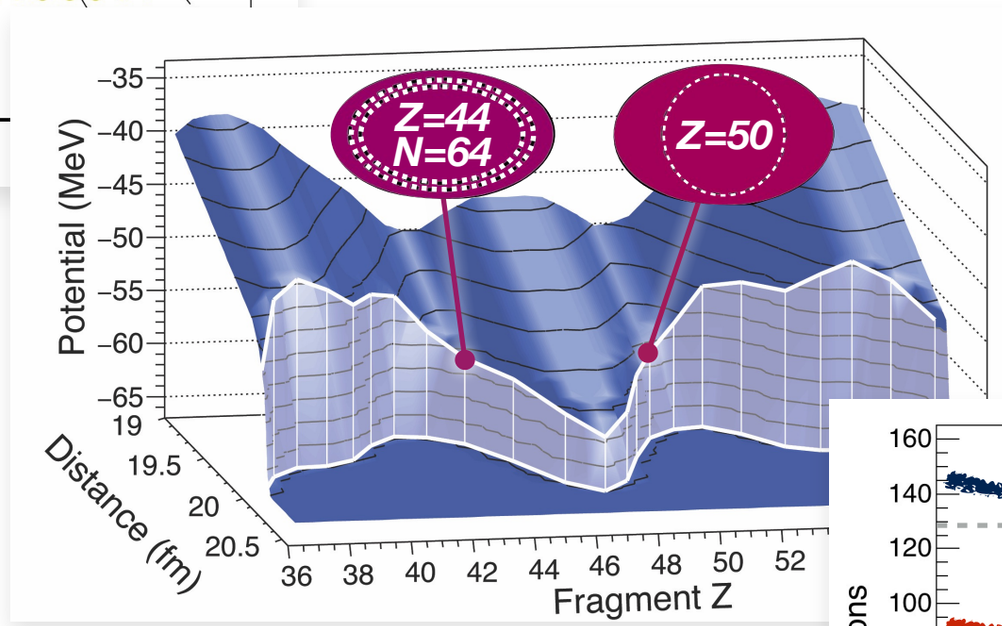


Fission in Inverse kinematics at GANIL.

In summary…

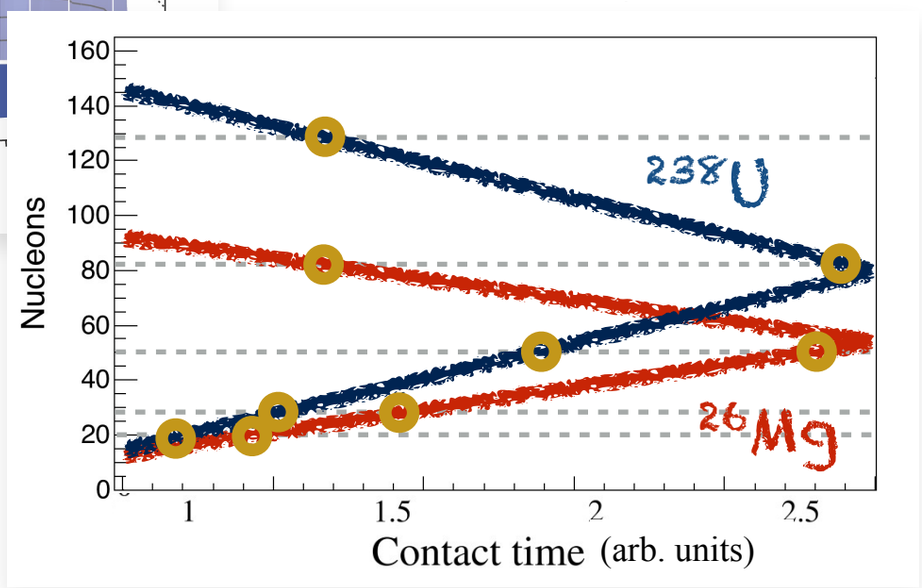


new and revisited
fission observables



access to the
scission configuration

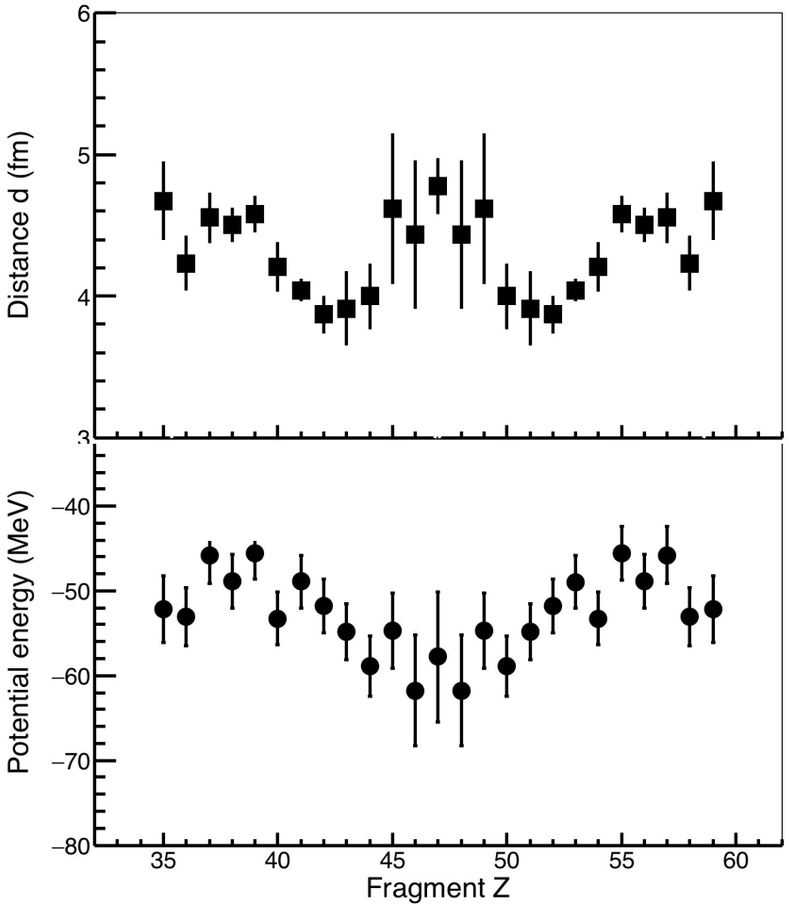
next in line:
quasi-fission



M. Caamaño (USC)

Inverse kinematics: A window to new observables in fission.

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



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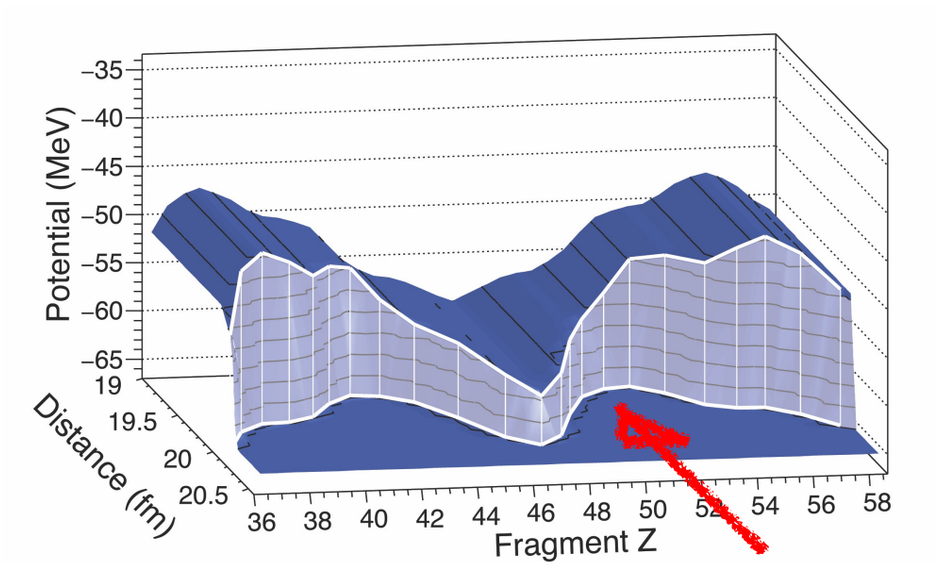
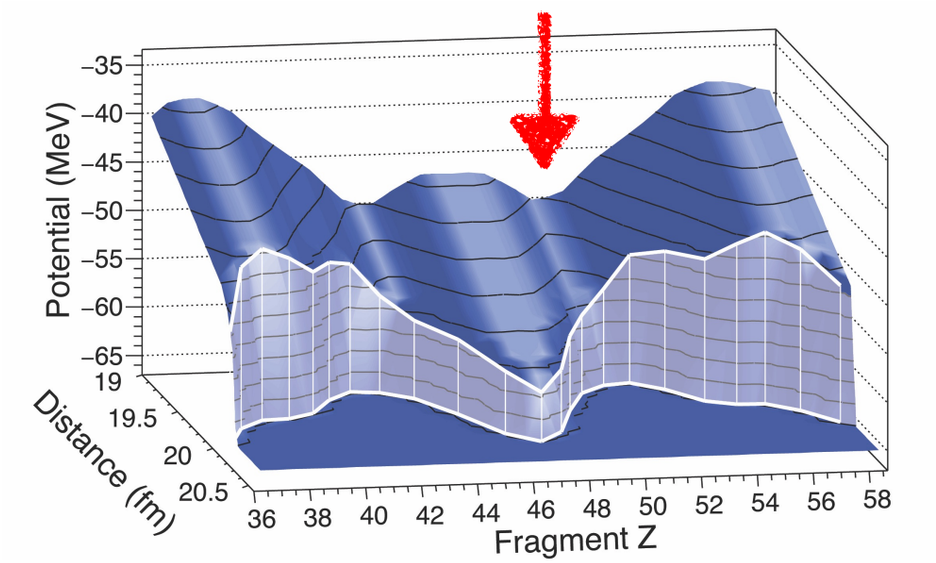
and a sneak peak of the potential landscape:





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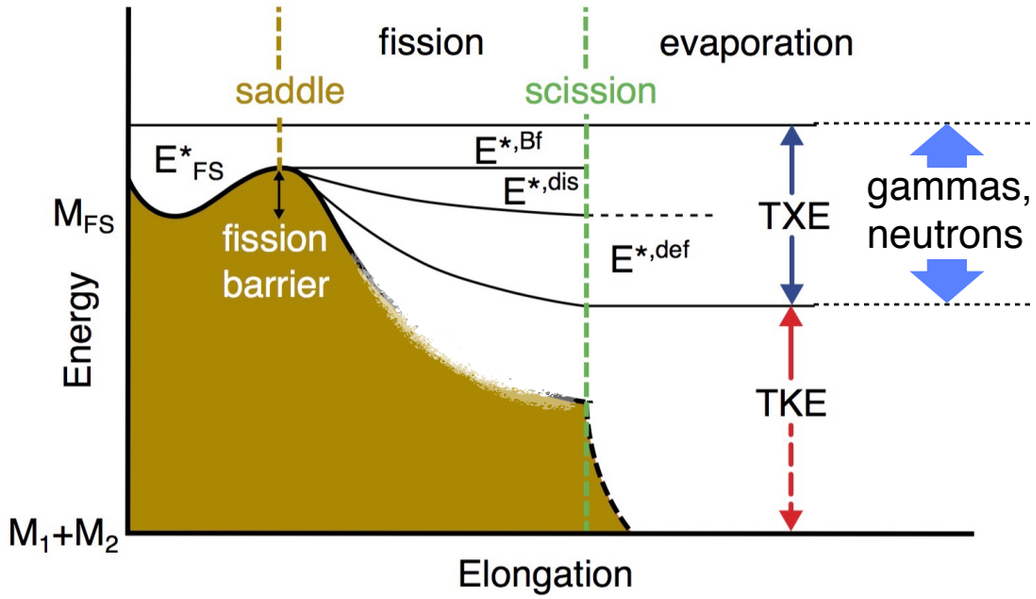

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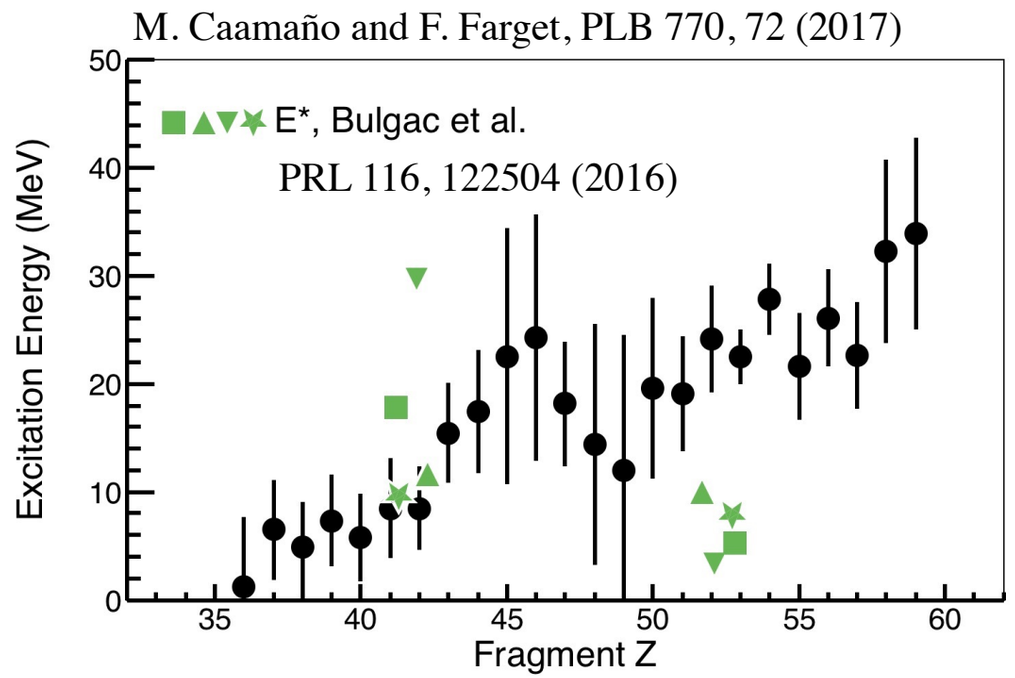
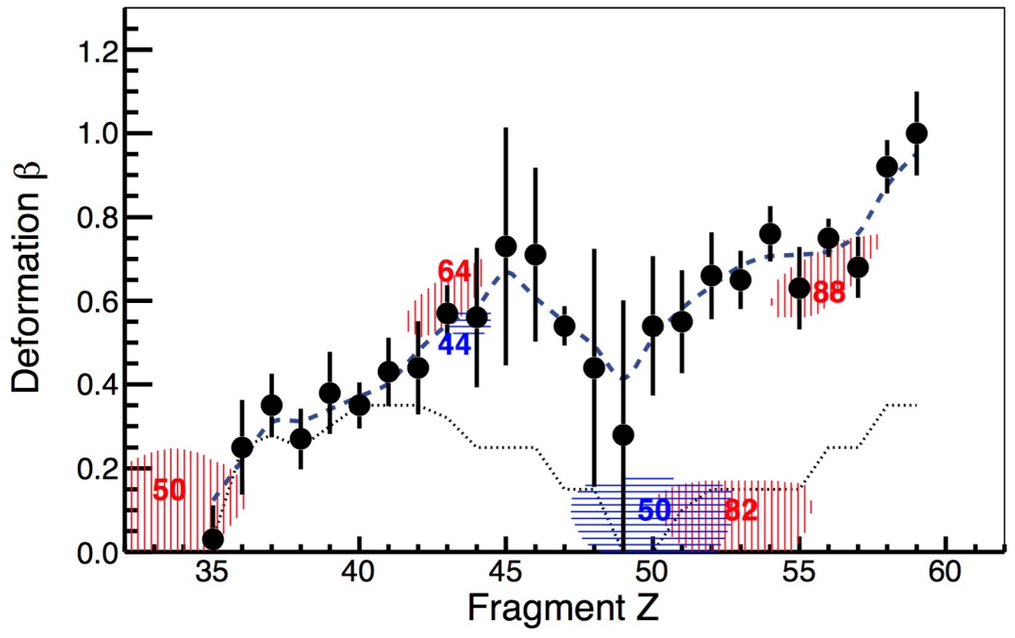
$$TXE = E^{*,Bf} + E^{*,dis} + E^{*,def}$$

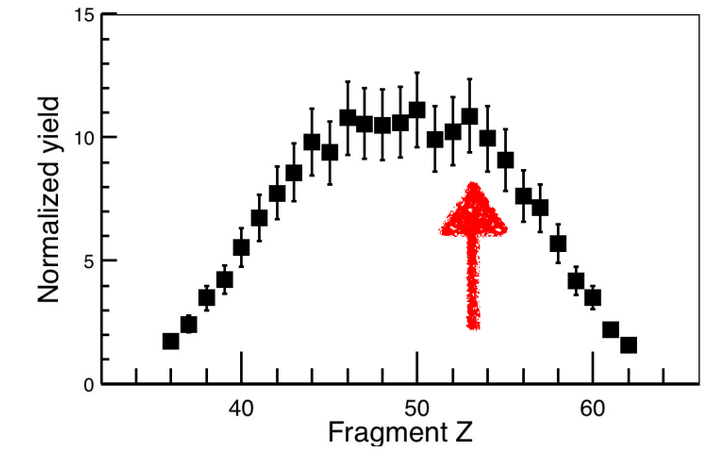
$$= \nu\cdot(Q_n + \varepsilon) + E^{\gamma}$$

access to the fragment deformations !!



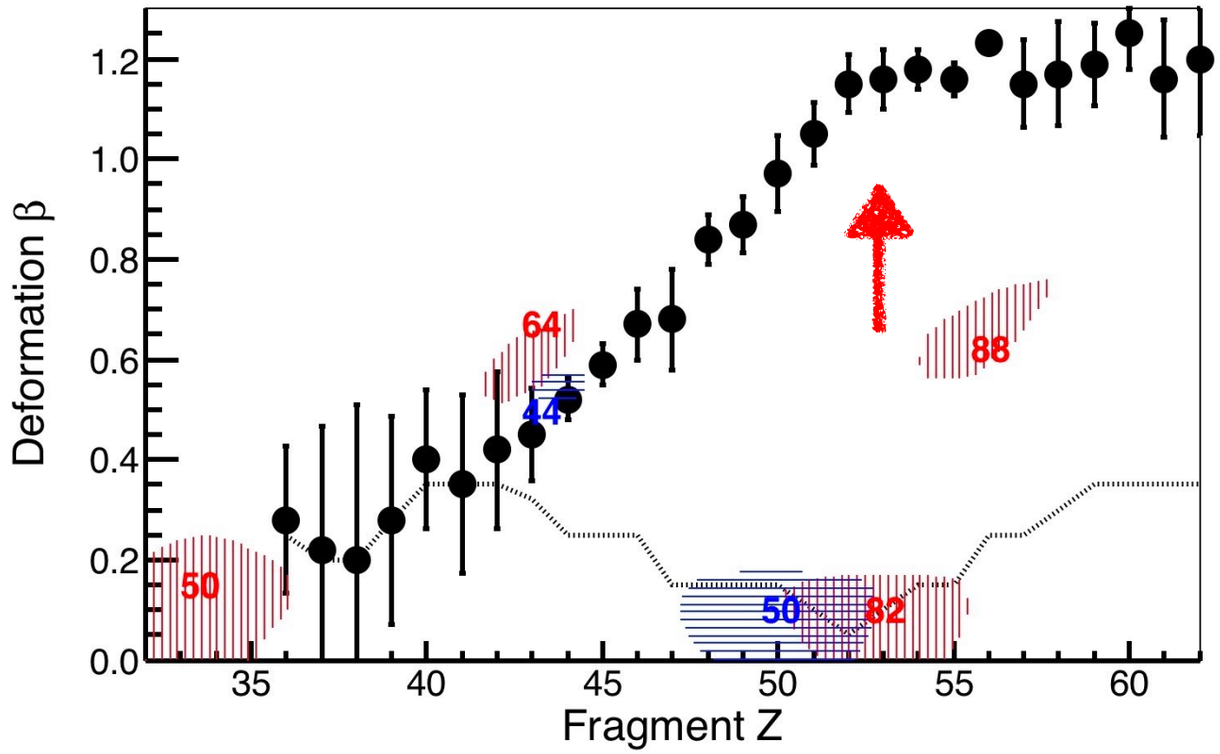


Inverse kinematics: A window to new observables in fission.



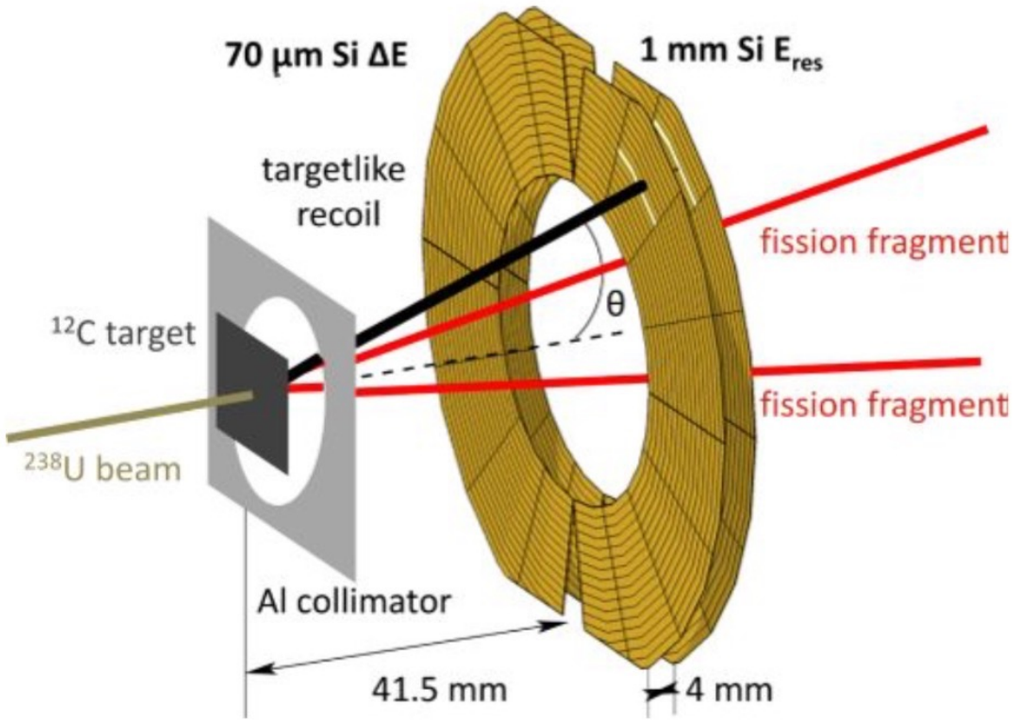
What else?

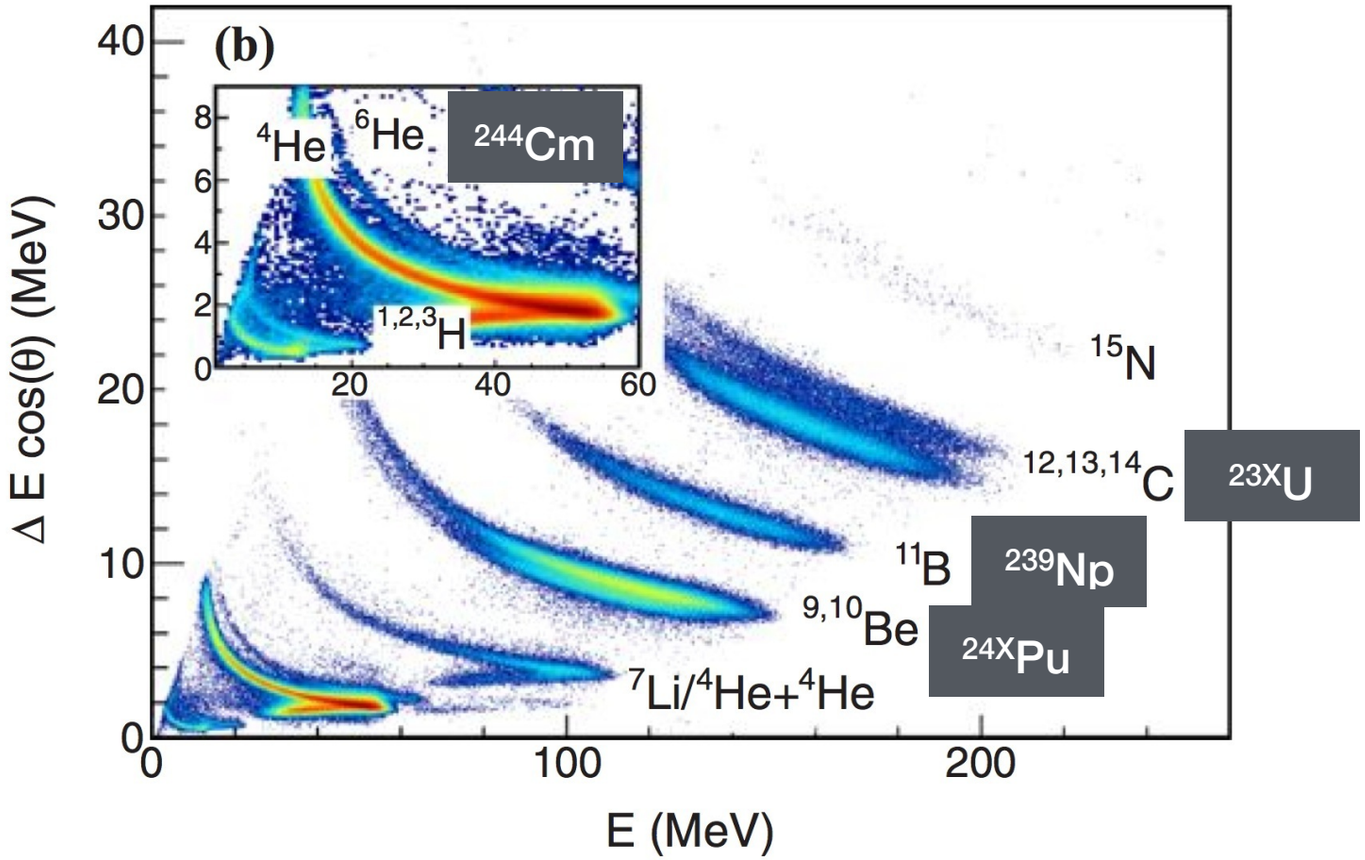
The case of ^{250}Cf (42 MeV)



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

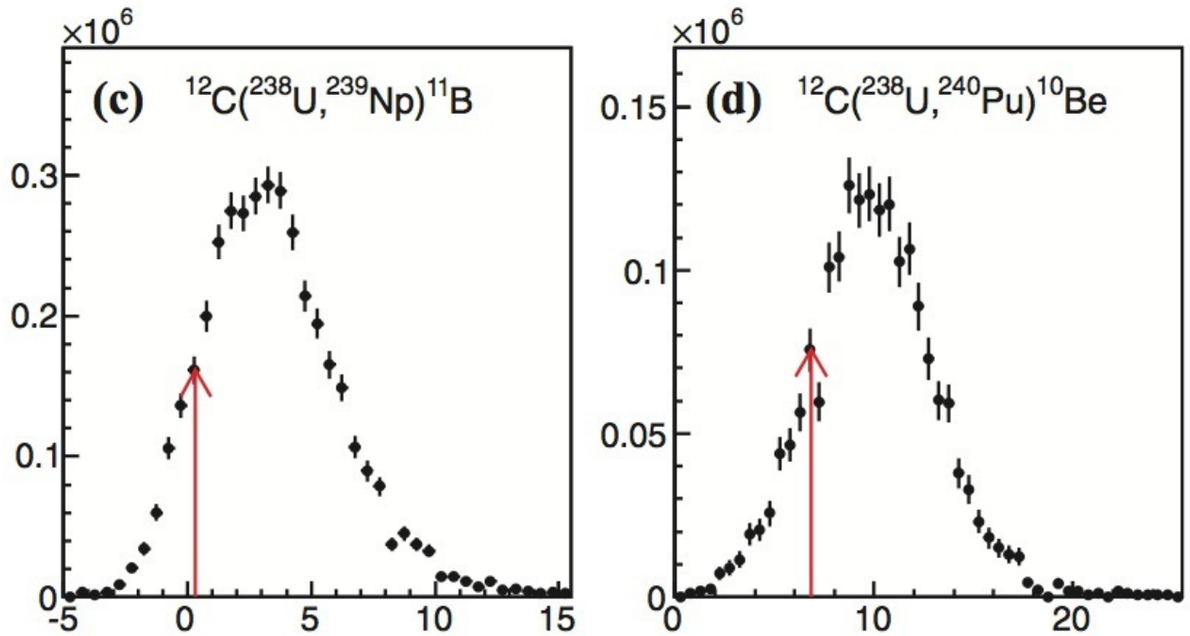
Inverse kinematics: A window to new observables in fission.





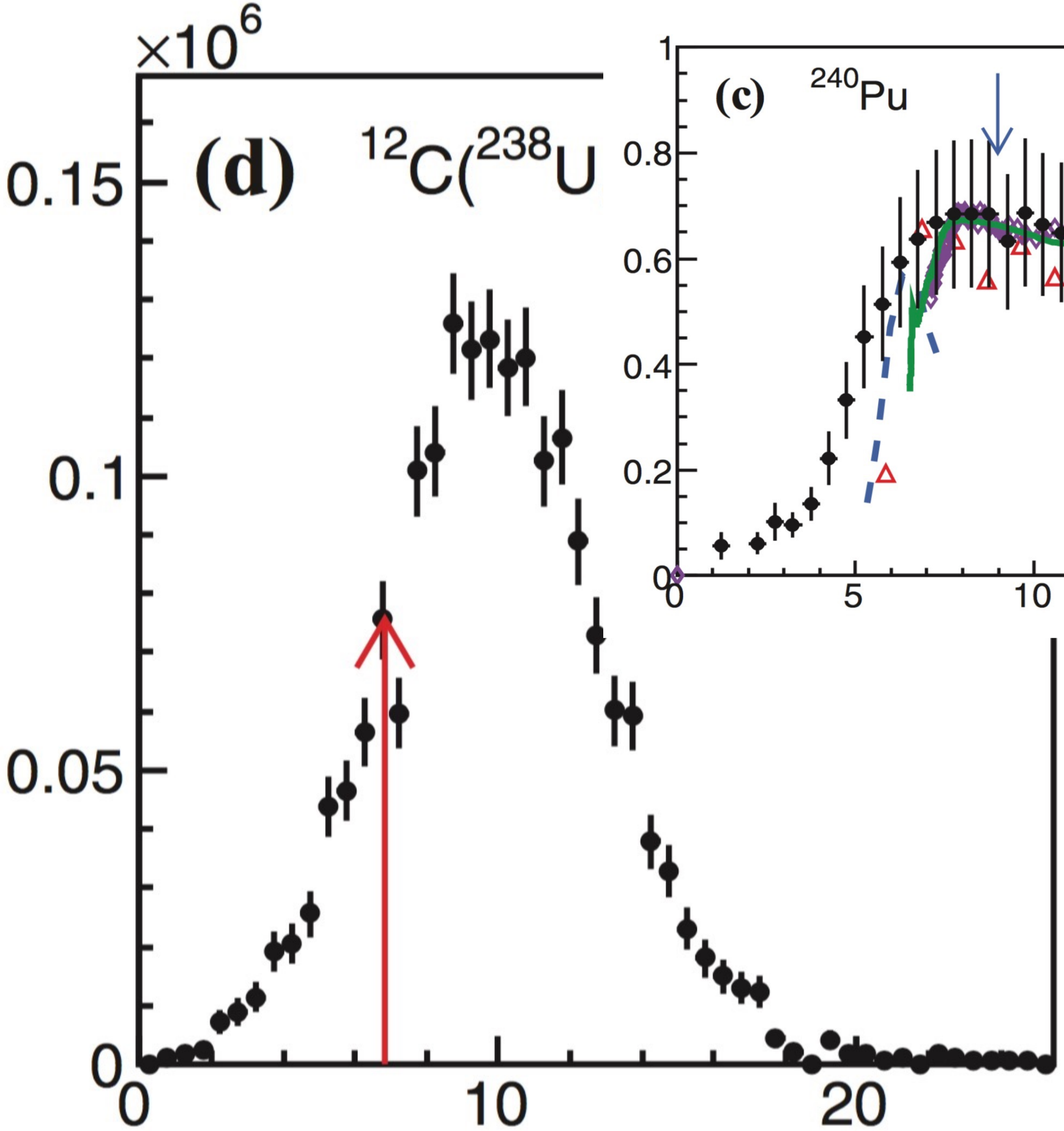
C. Rodríguez Tajes et al., PRC 89 (2014) 024614

Targetlike nucleus	E_γ (keV)	P_γ^{expt}
^{12}C	4439	0.14 ± 0.03
^{11}B	2125	0.12 ± 0.02
^{10}Be	3368	0.14 ± 0.04



M. Caamaño (USC)

Inverse kine



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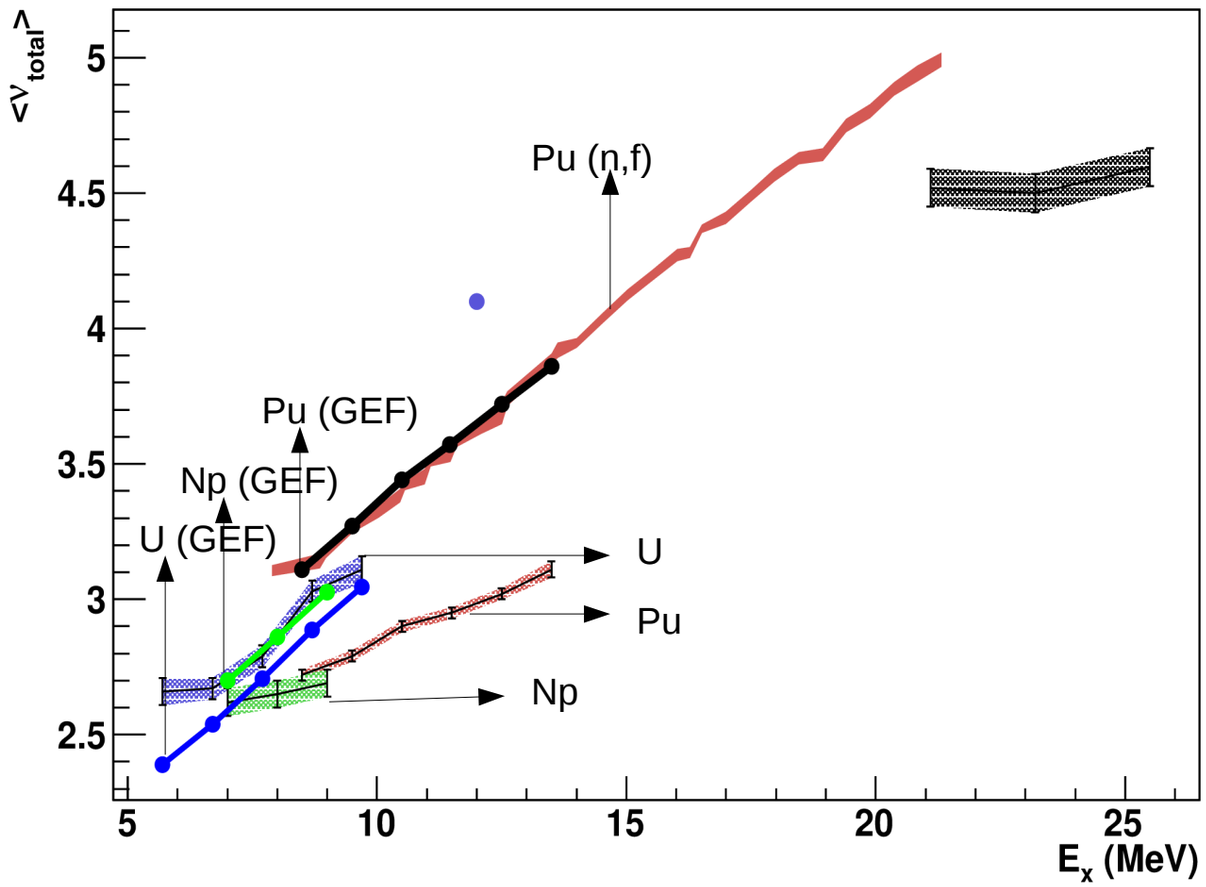
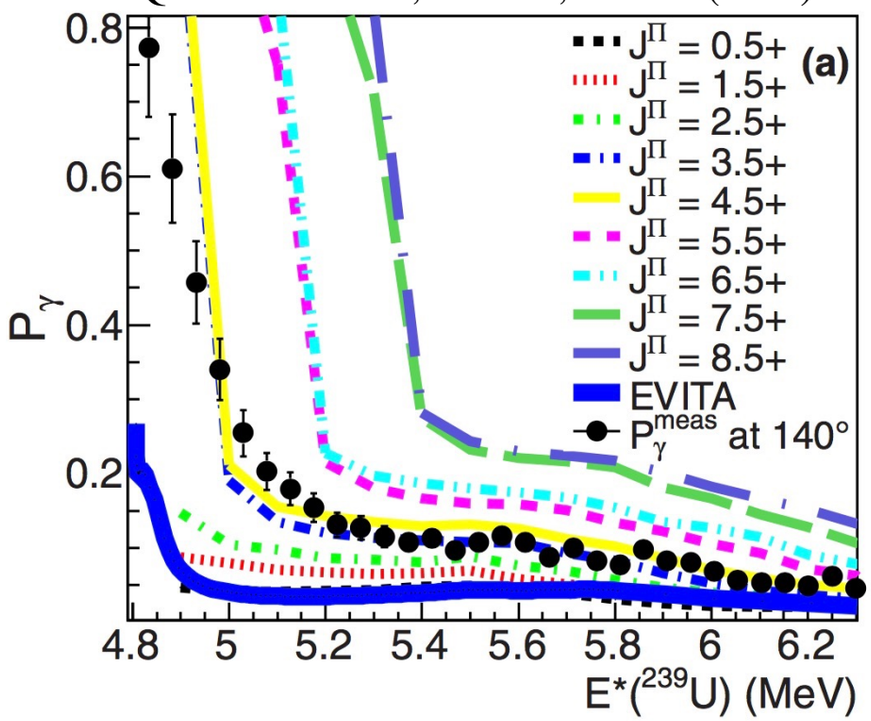
D. Ramos, PhD USdC (2016), EPJ WoC 111, 10001 (2016)

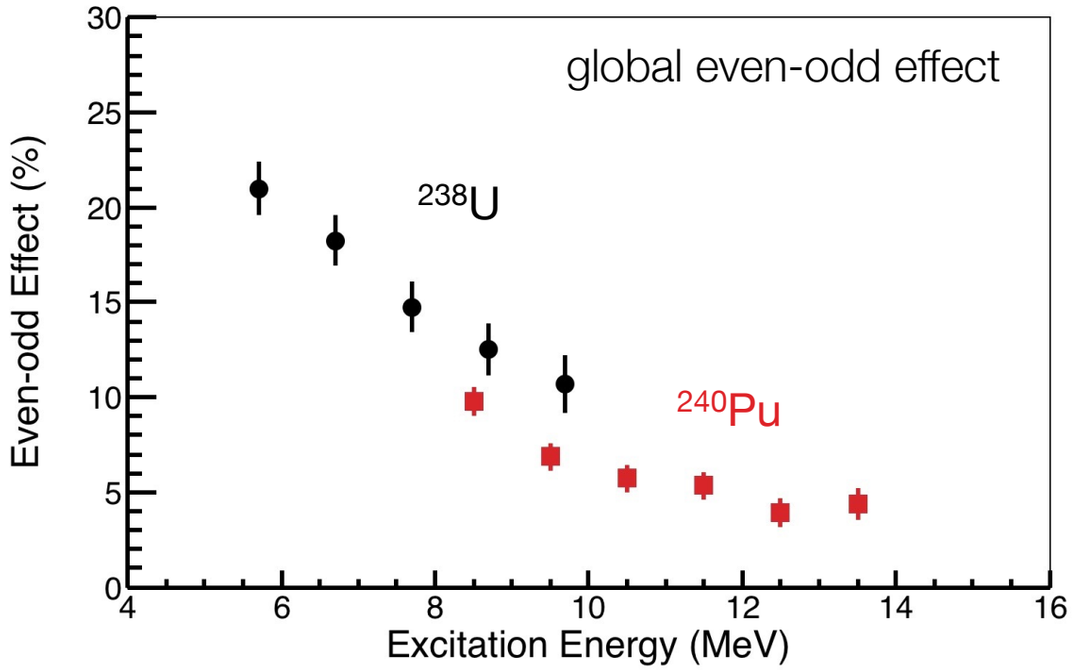


Q. Ducasse et al., PRC 94, 024614 (2016)

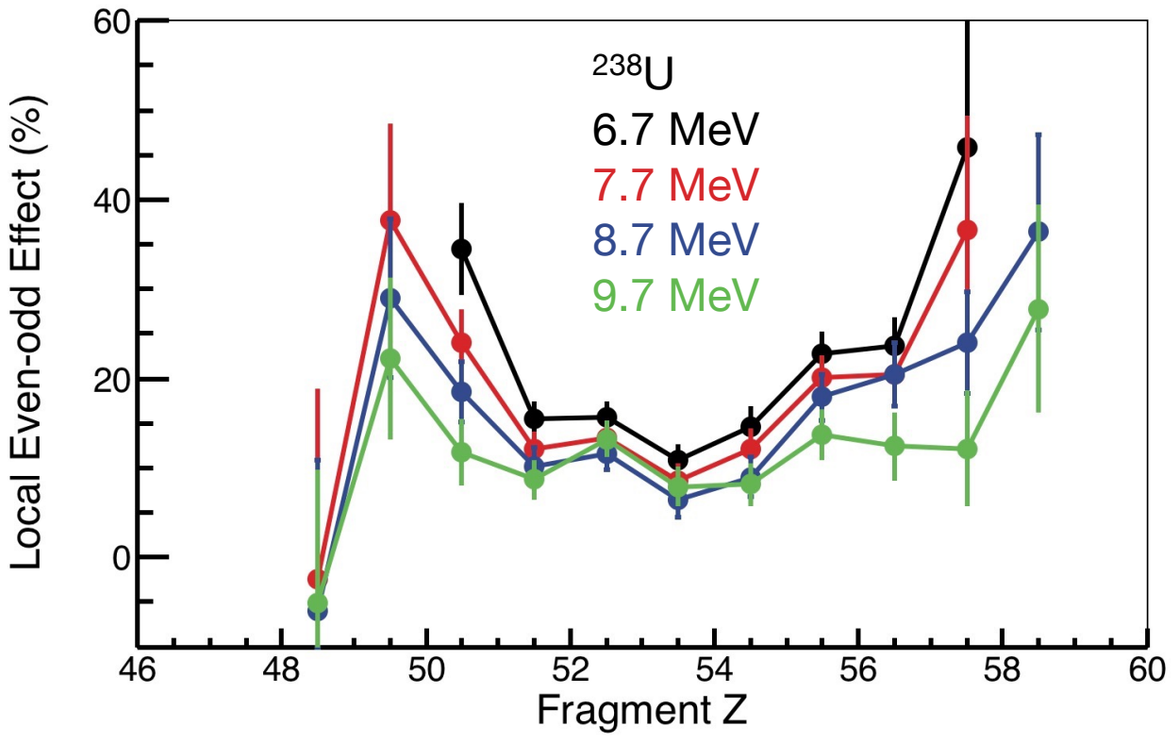


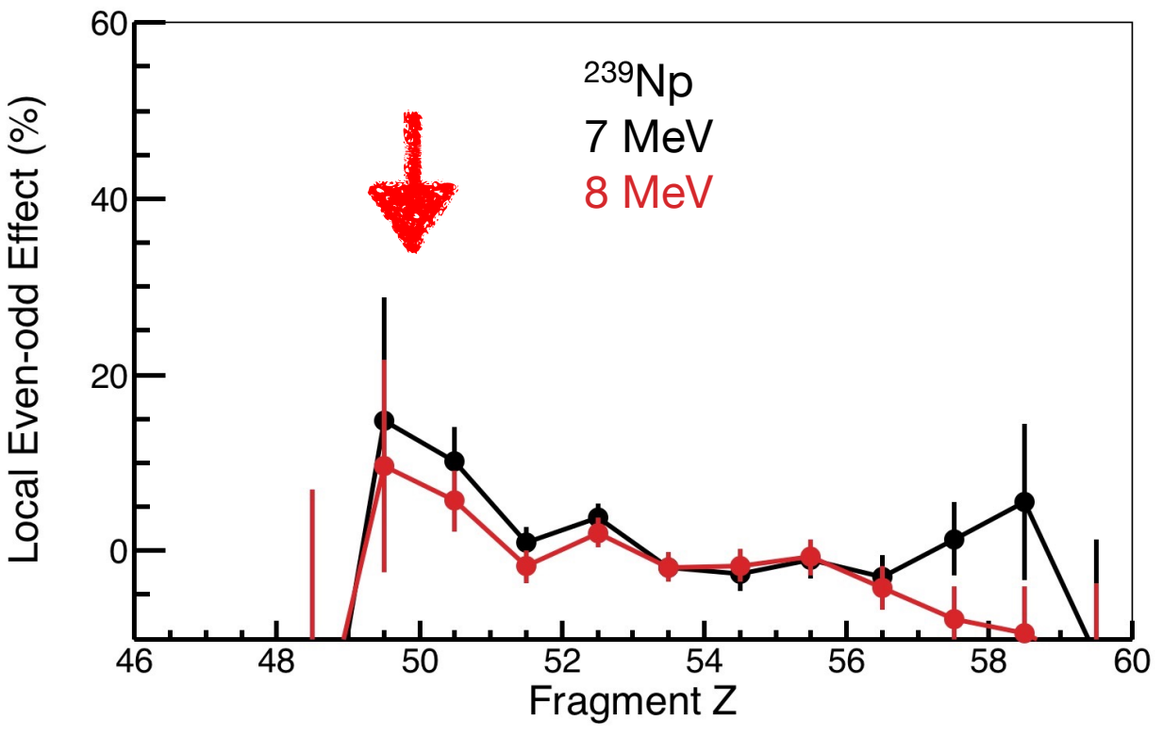
M. Caamaño (USC)

Inverse kinematics: A window to new observables in fission.



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

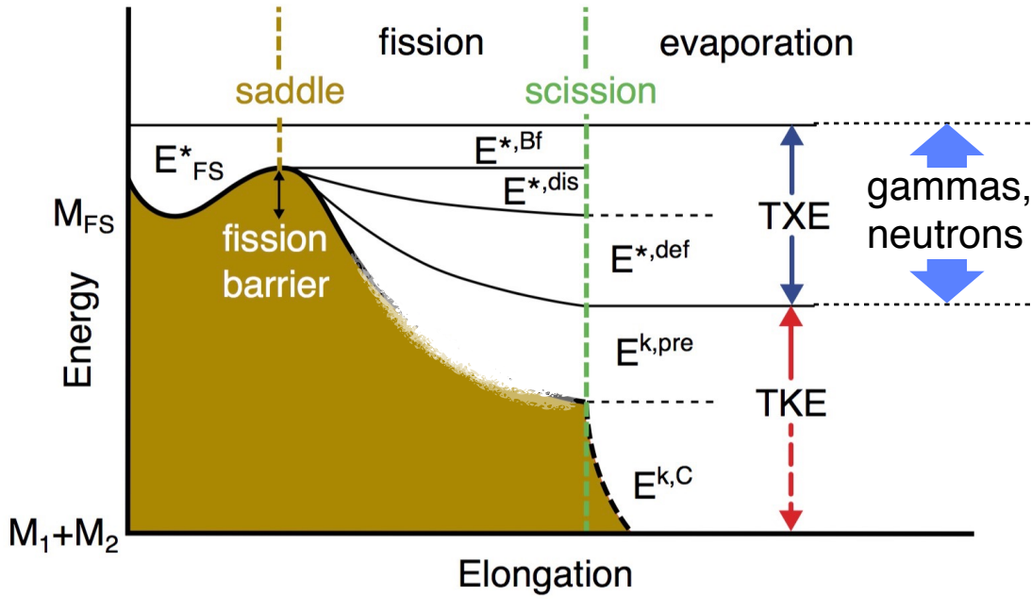




M. Caamaño (USC)

Inverse kinematics: A window to new observables in fission.

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



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

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

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

PRC 90, 054607 (2014)

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

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

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

shared according statistical eq.

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

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

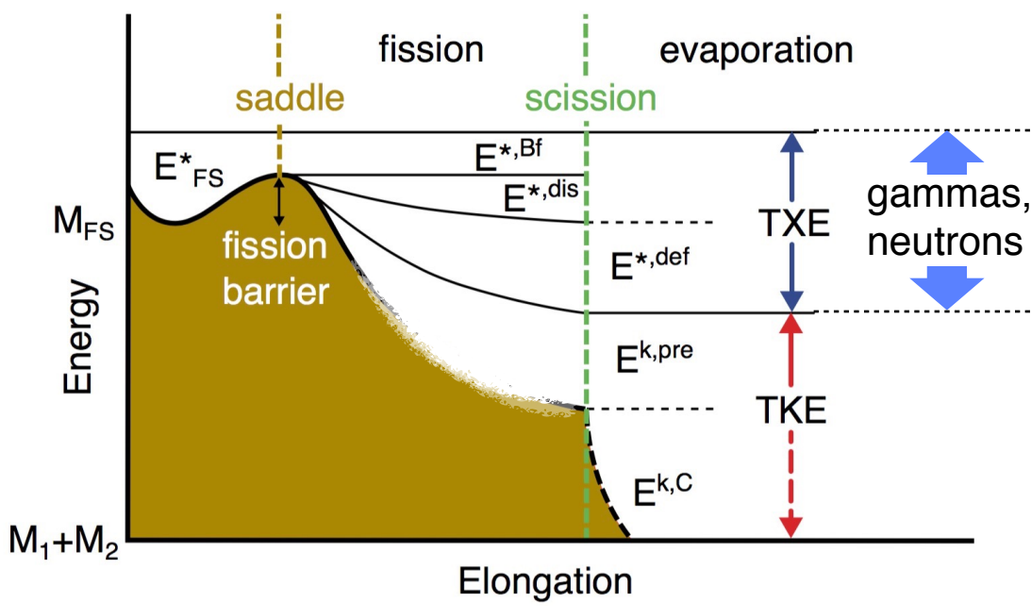
$$E_i^* = Q_i^n + \nu_i \varepsilon + E_i^{\gamma}$$

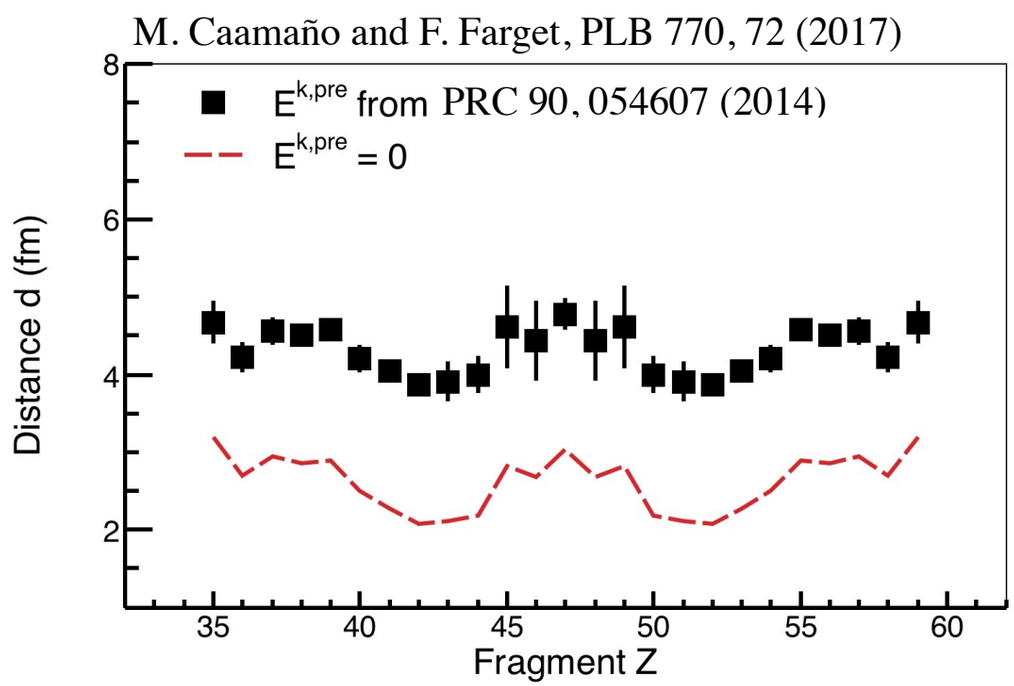
$$E_i^{*,\mathrm{def}} = E_i^* - E_i^{*,\mathrm{int}}$$

M. Caamaño (USC)

Inverse kinematics: A window to new observables in fission.

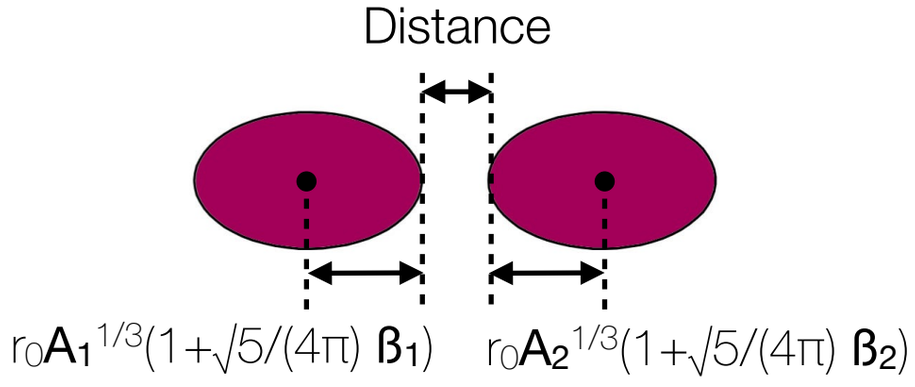
New access to scission; the case of ^{240}Pu (9 MeV)





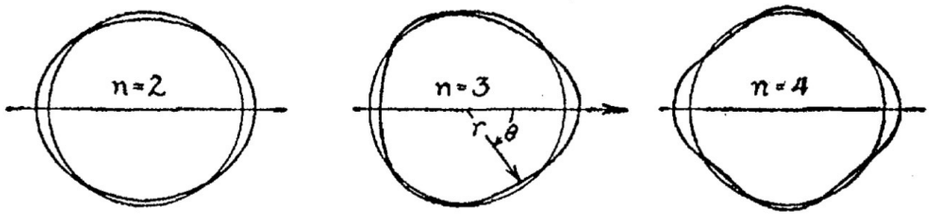
$$M_{FS} + E^*_{FS} = TXE + TKE + M_1 + M_2$$

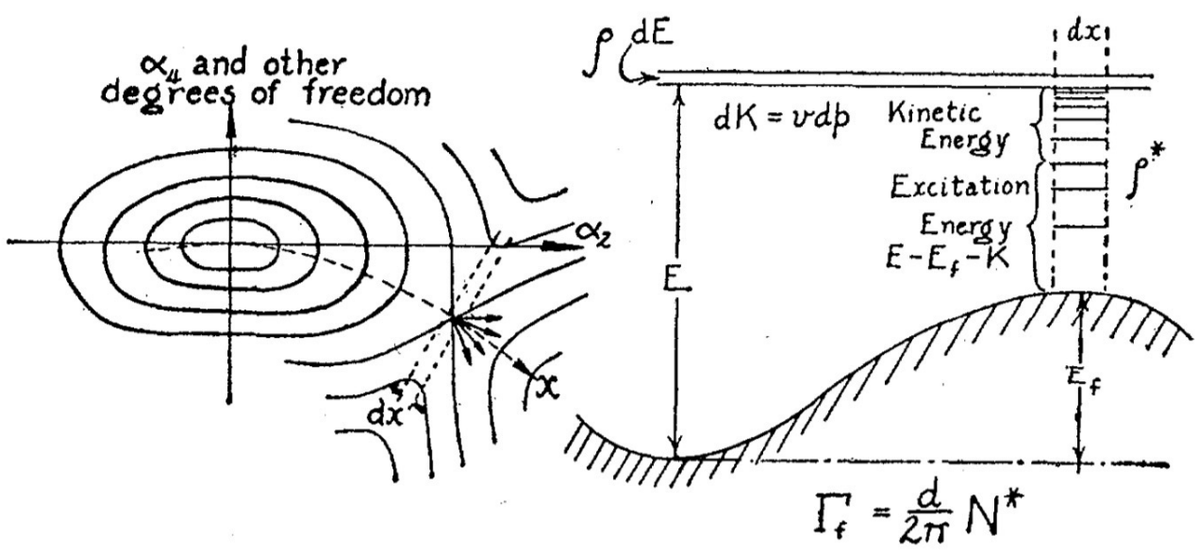
$$TKE = E^{k,pre} + E^{k,C}$$



access to the distance between fragments !!

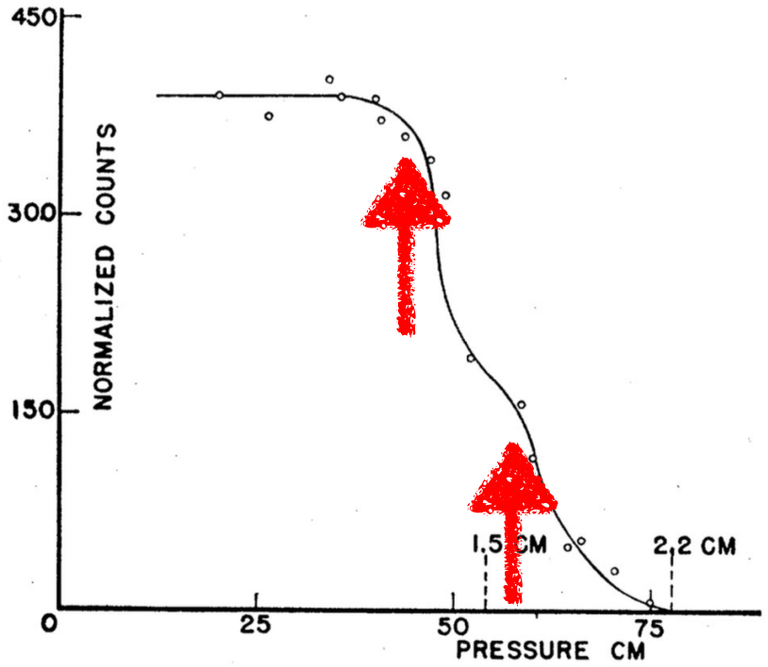
A liquid drop behaviour…





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

… with surprises



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

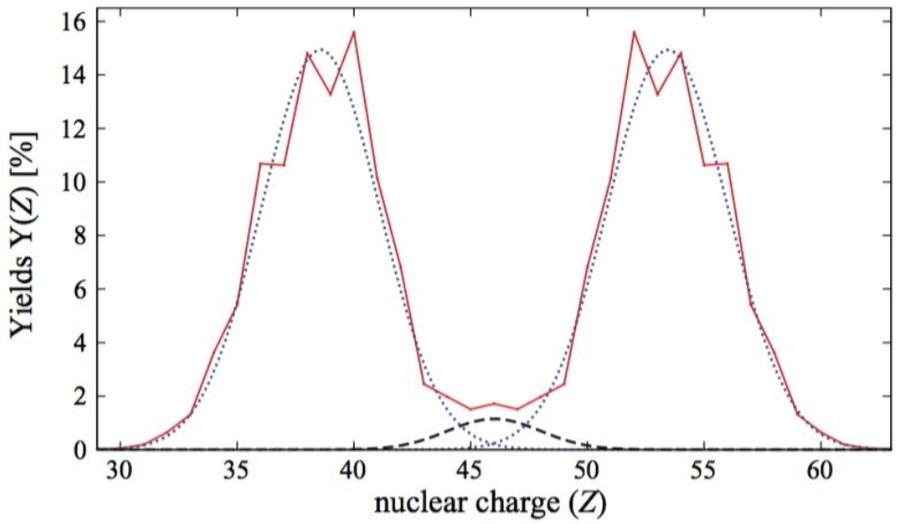
IX. ASYMMETRIC FISSION

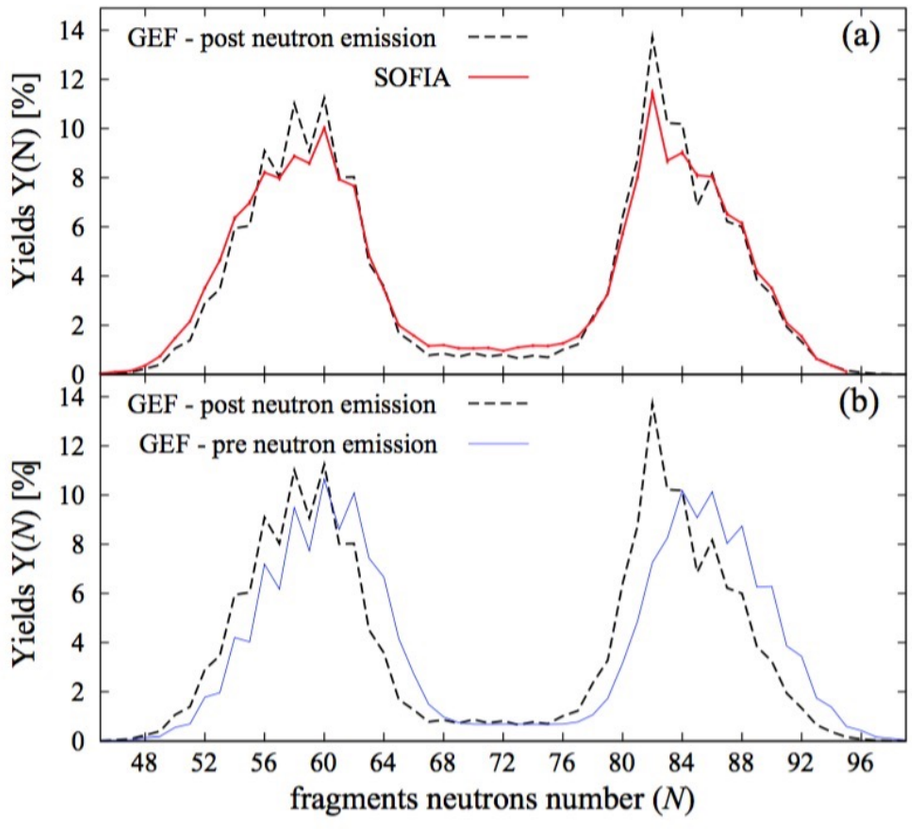
It is somewhat tempting to associate the existence of the closed shells of 50 and 82 neutrons with the dissymmetry of masses encountered in the fission process. U^{235} contains $143 = 82 + 50 + 11$

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

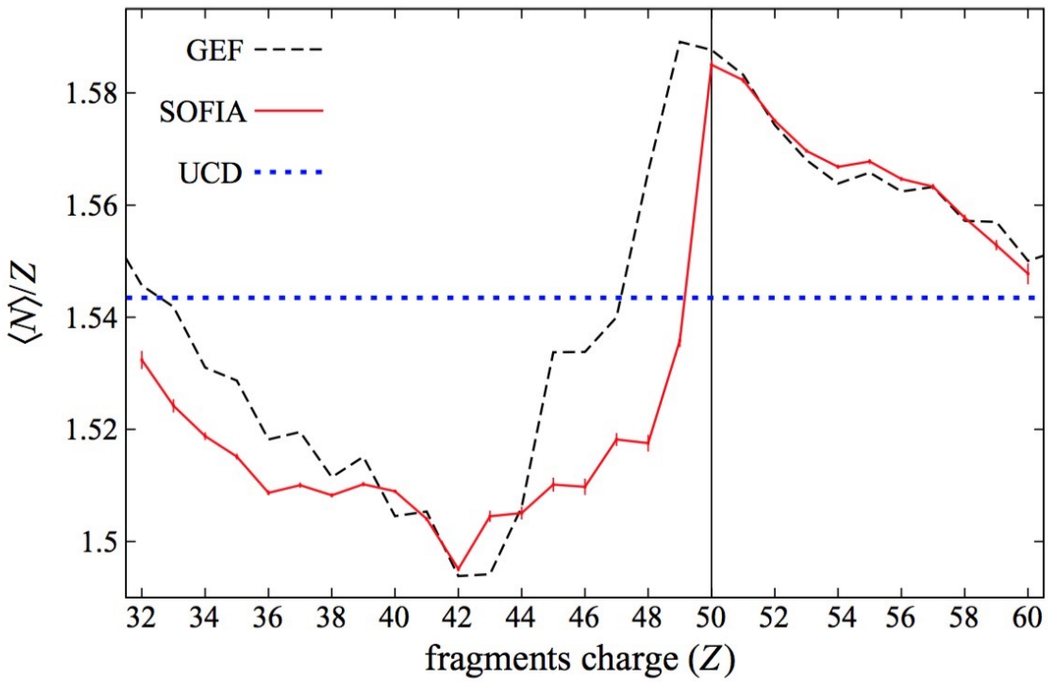
Inverse kinematics: A window to new observables in fission.

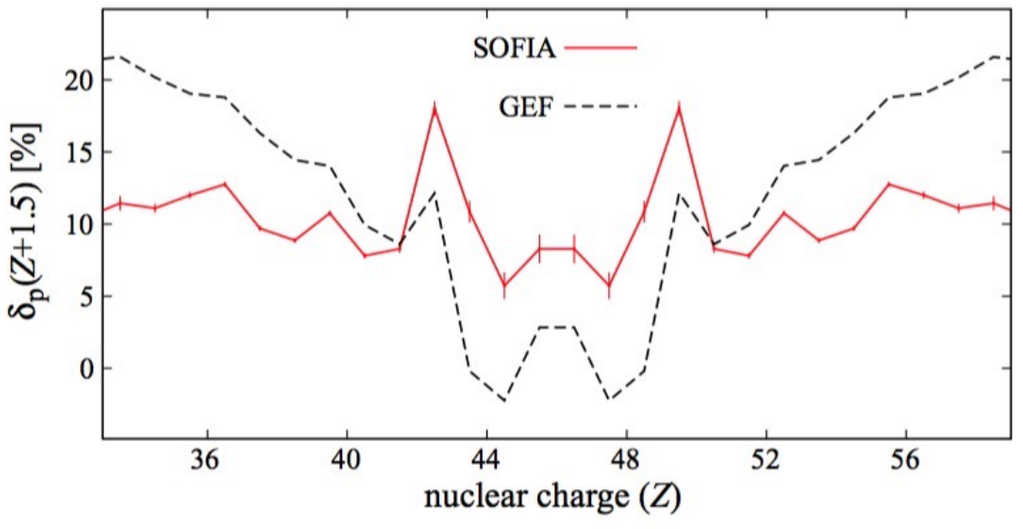
SOFIA @ GSI





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



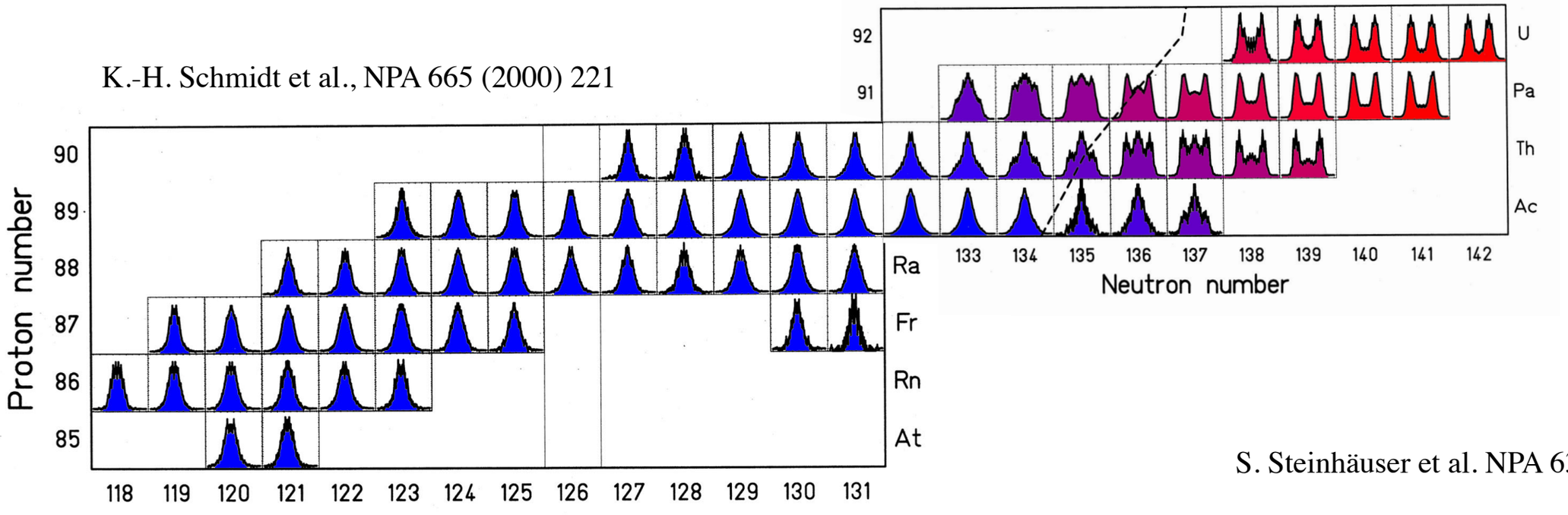


E. Pellereau et al., PRC 95, 054603 (2017)

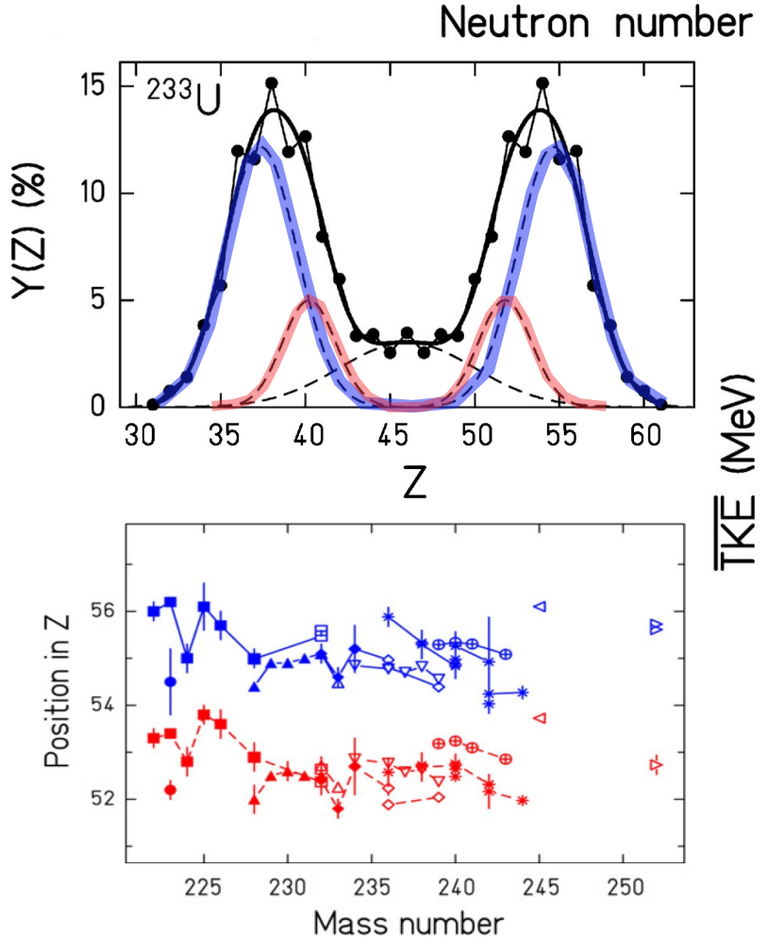
Inverse kinematics: A window to new observables in fission.

FRS campaign @ GSI

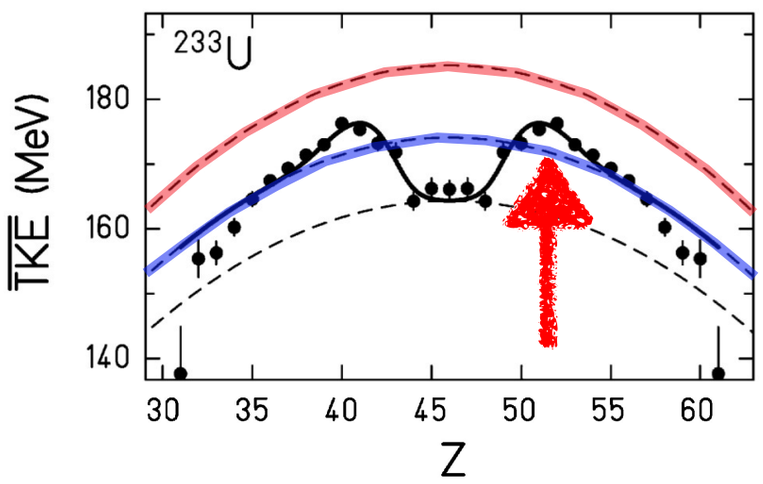
K.-H. Schmidt et al., NPA 665 (2000) 221

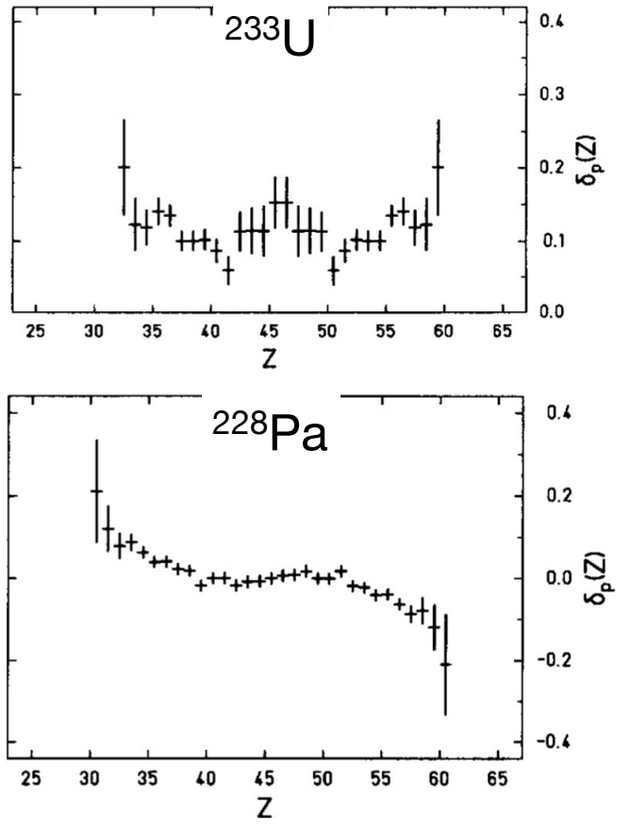


S. Steinhäuser et al. NPA 634 (1998) 89



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

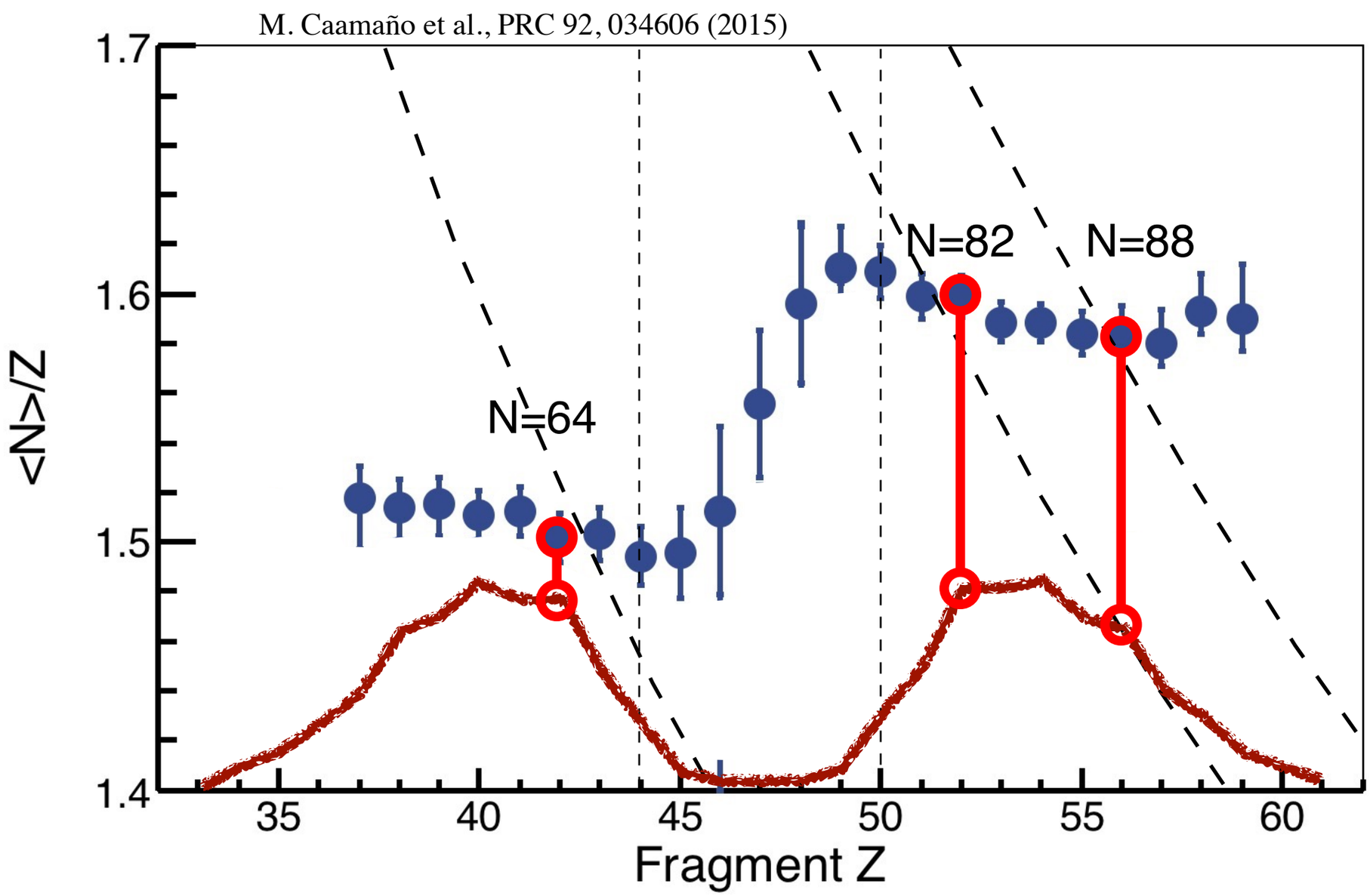




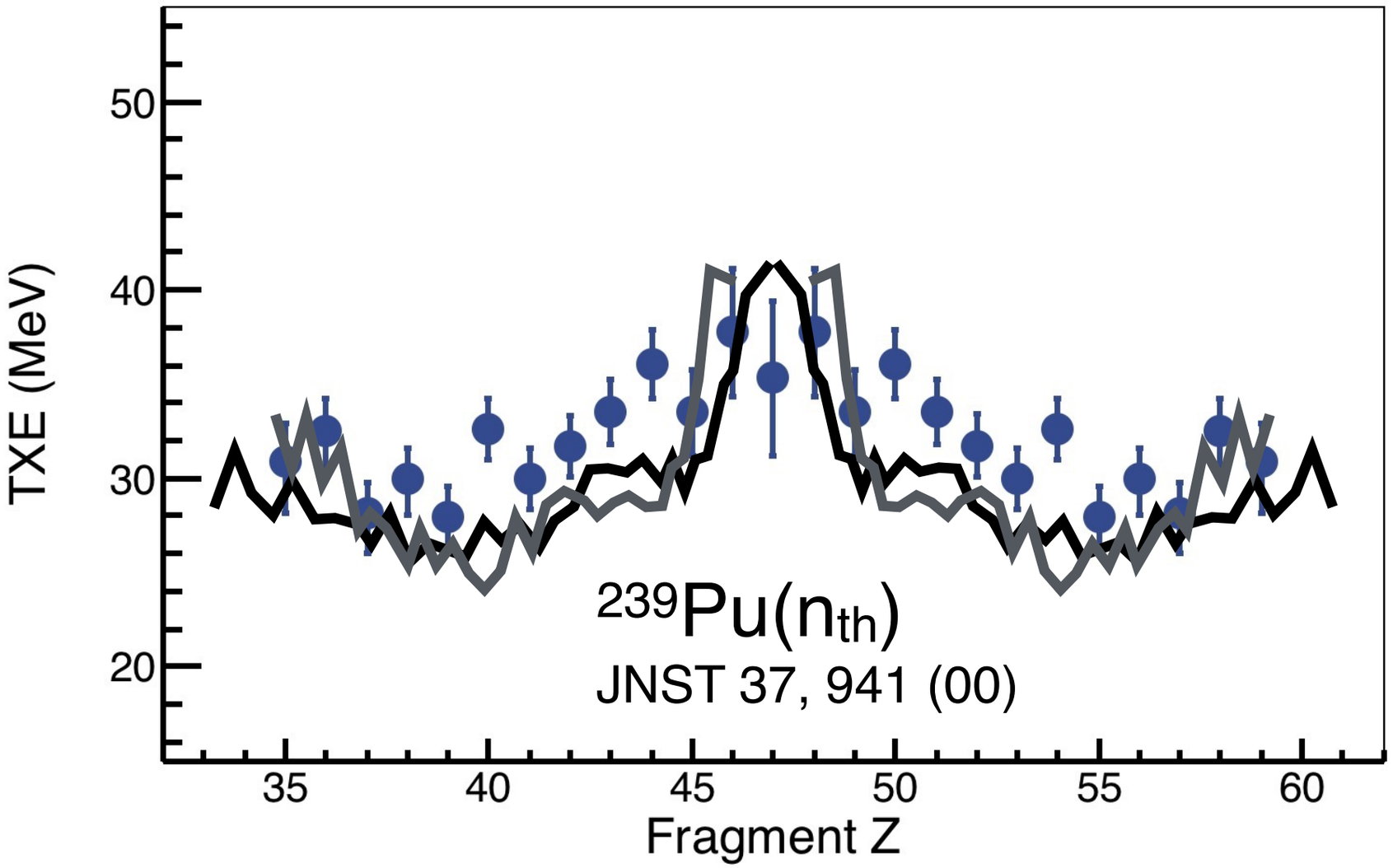
M. Caamaño (USC)

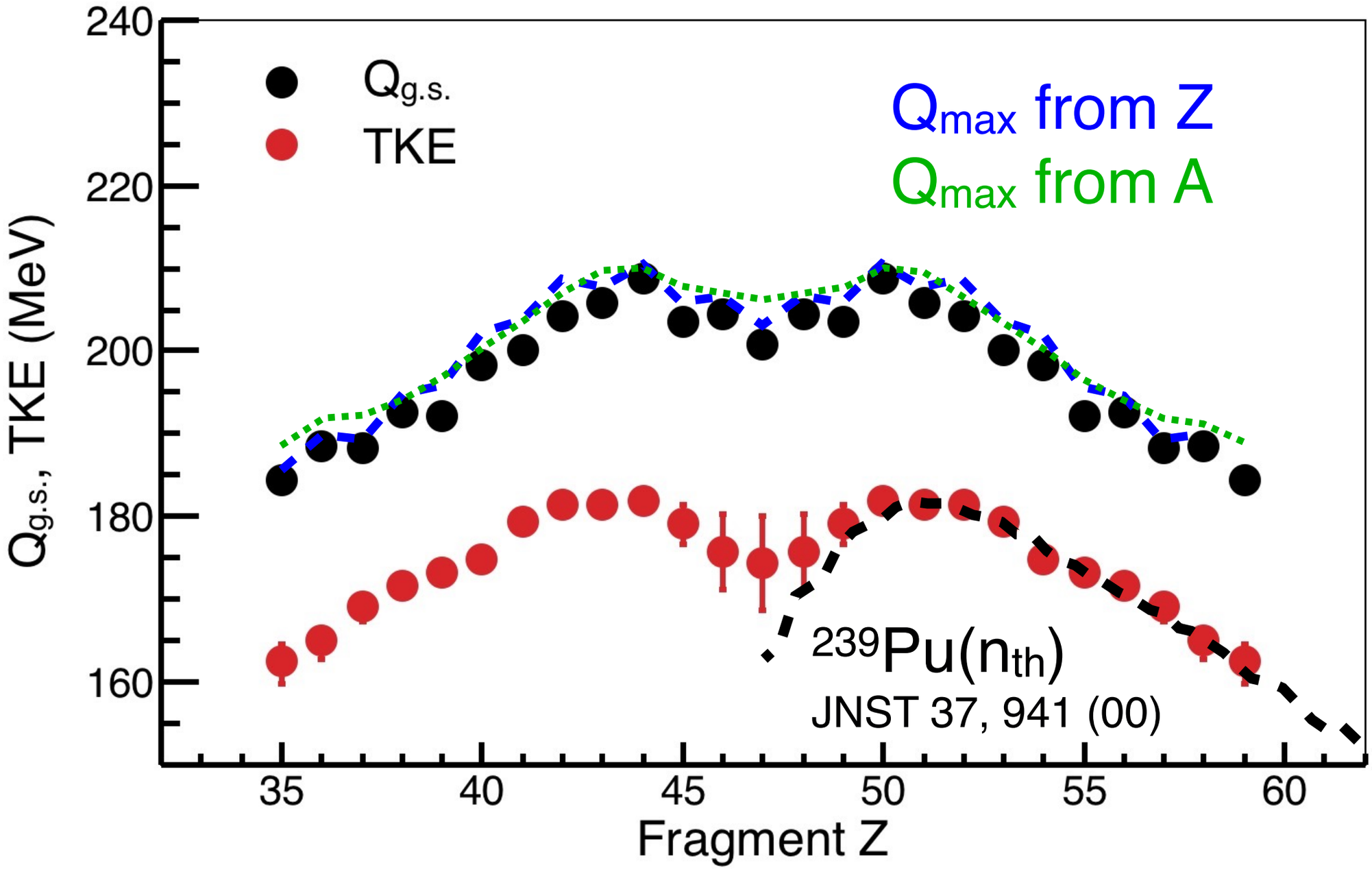
Inverse kinematics: A window to new observables in fission.

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

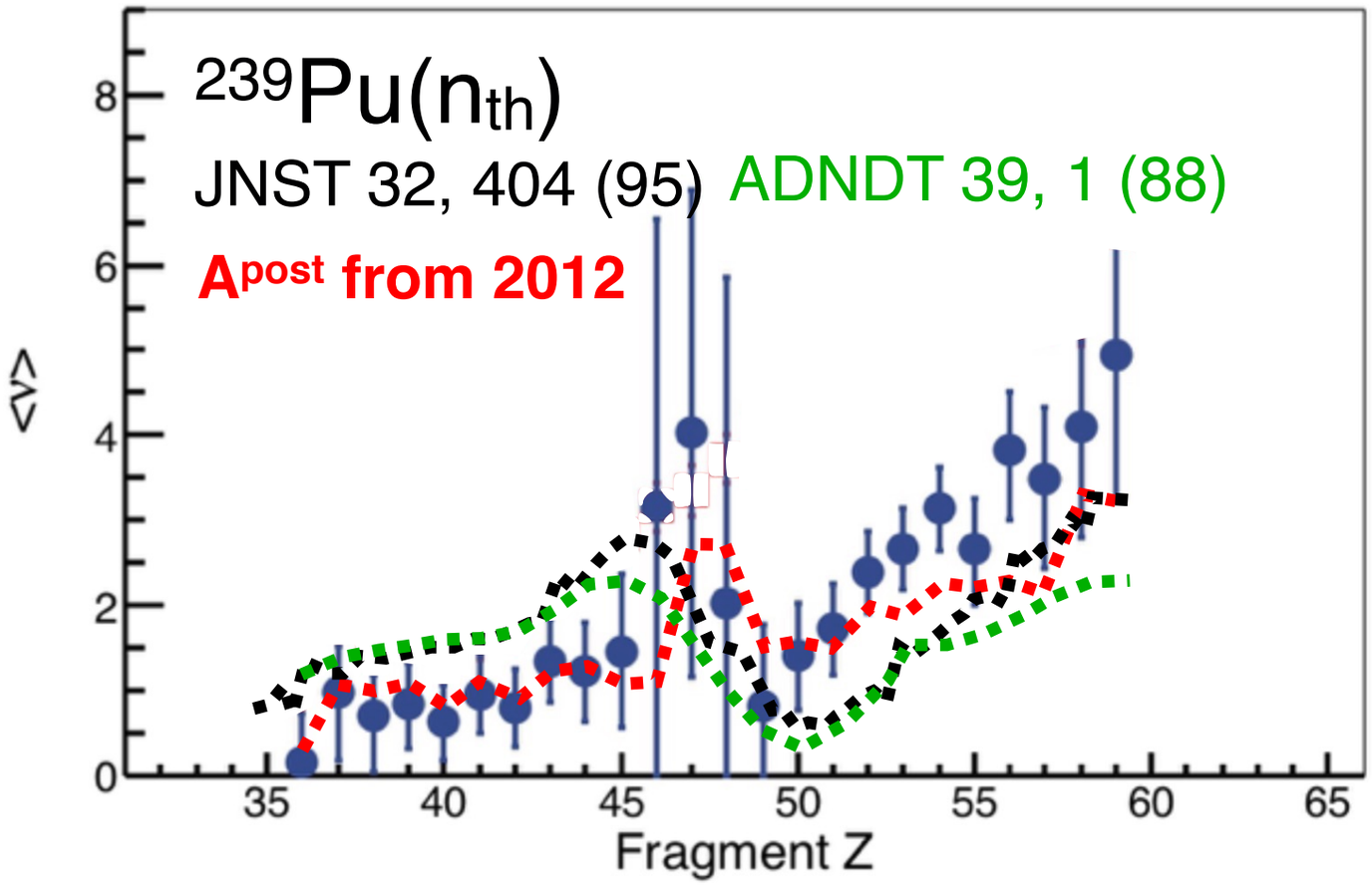


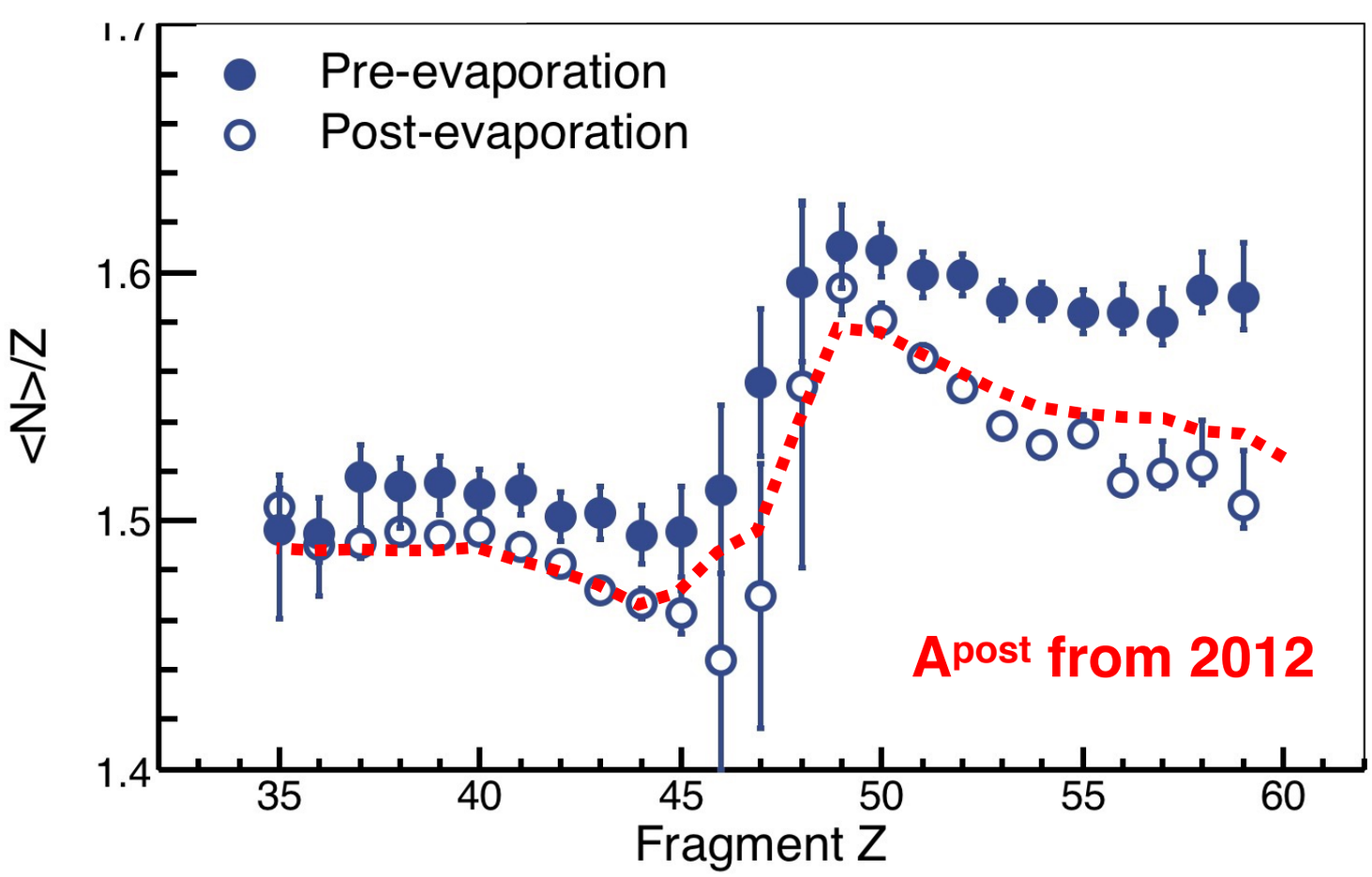
M. Caamaño (USC)

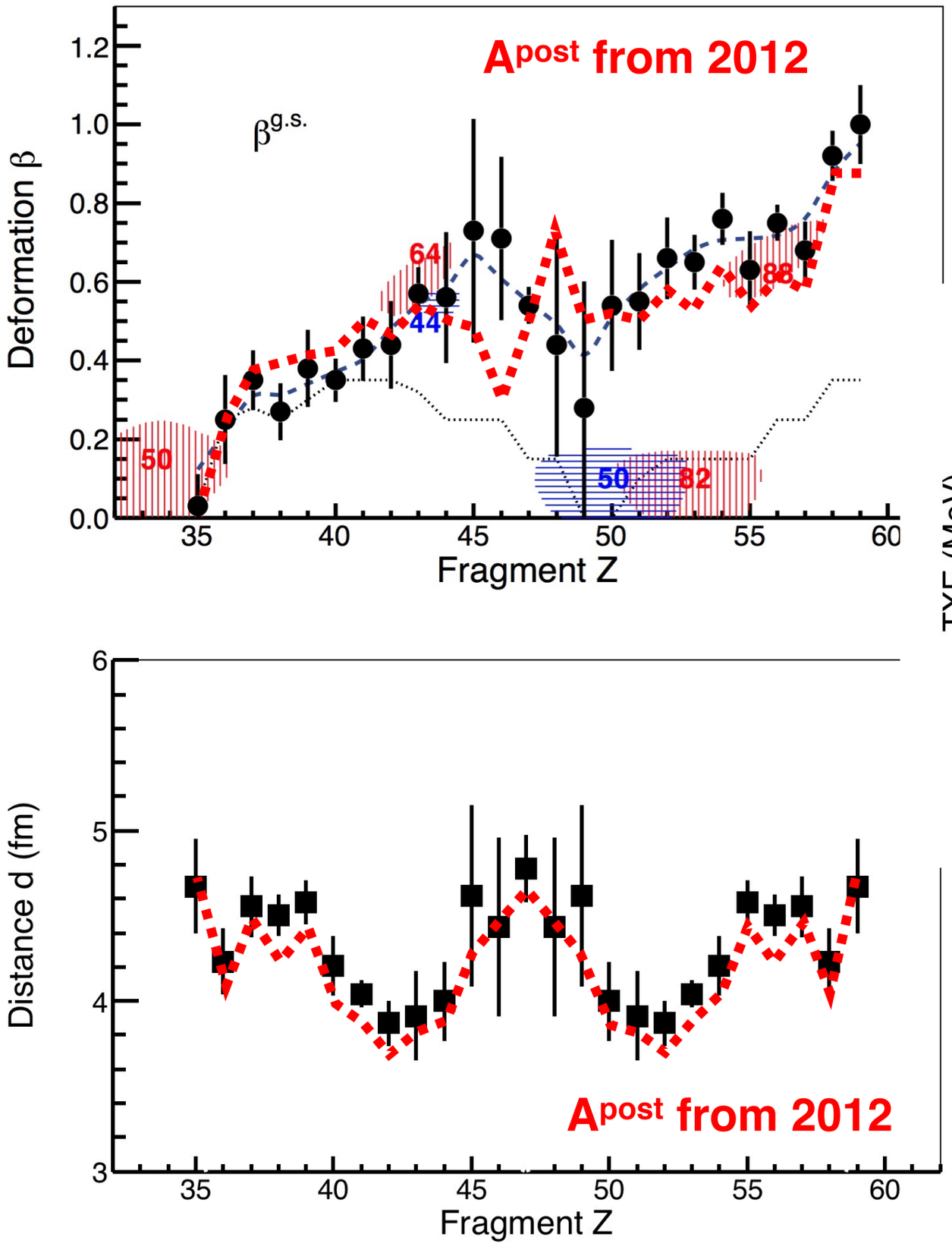

TXE (MeV)
50
40
30
20
35
40
45
50
55
60
Fragment Z
239Pu(nth)
JNST 37, 941 (00)

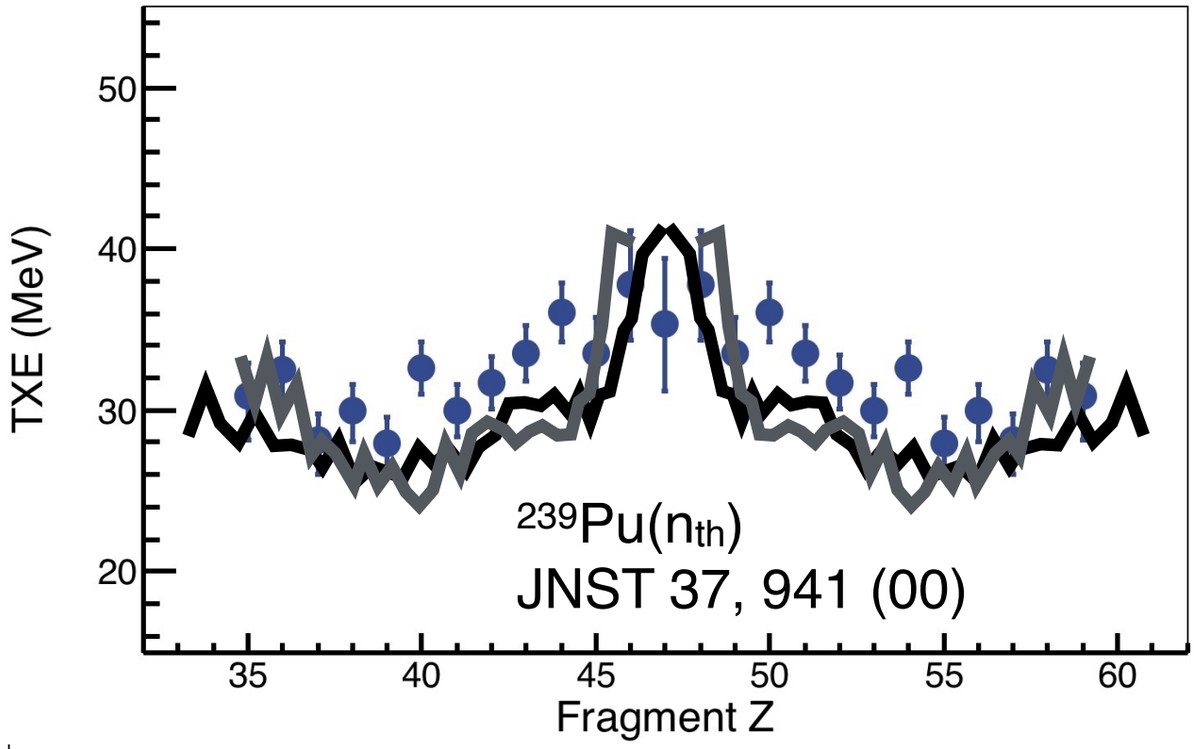

240
220
200
180
160
$Q_{g.s.}$, TKE (MeV)
$Q_{g.s.}$
TKE
Q_{max} from Z
Q_{max} from A
$^{239}Pu(n_{th})$
JNST 37, 941 (00)
35
40
45
50
55
60
Fragment Z

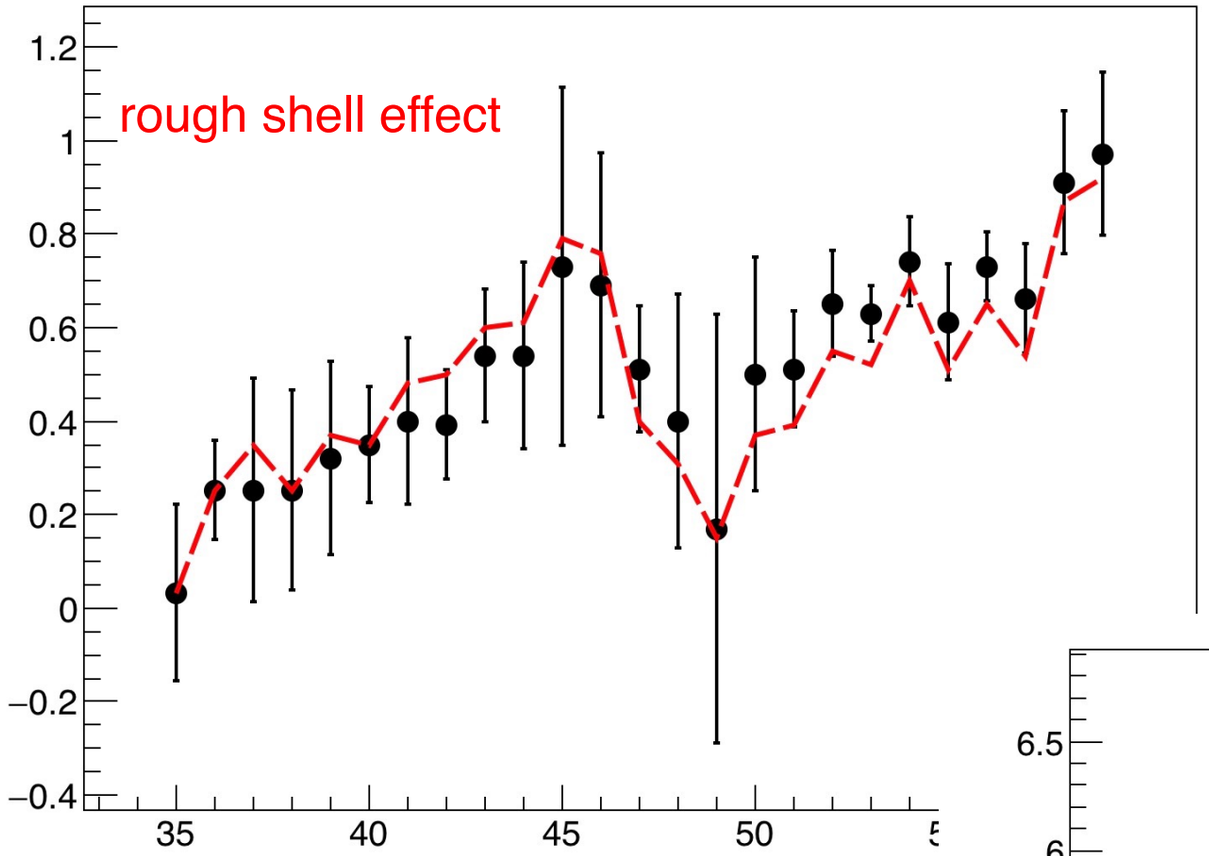
problems in mass measured around symmetry: low statistics

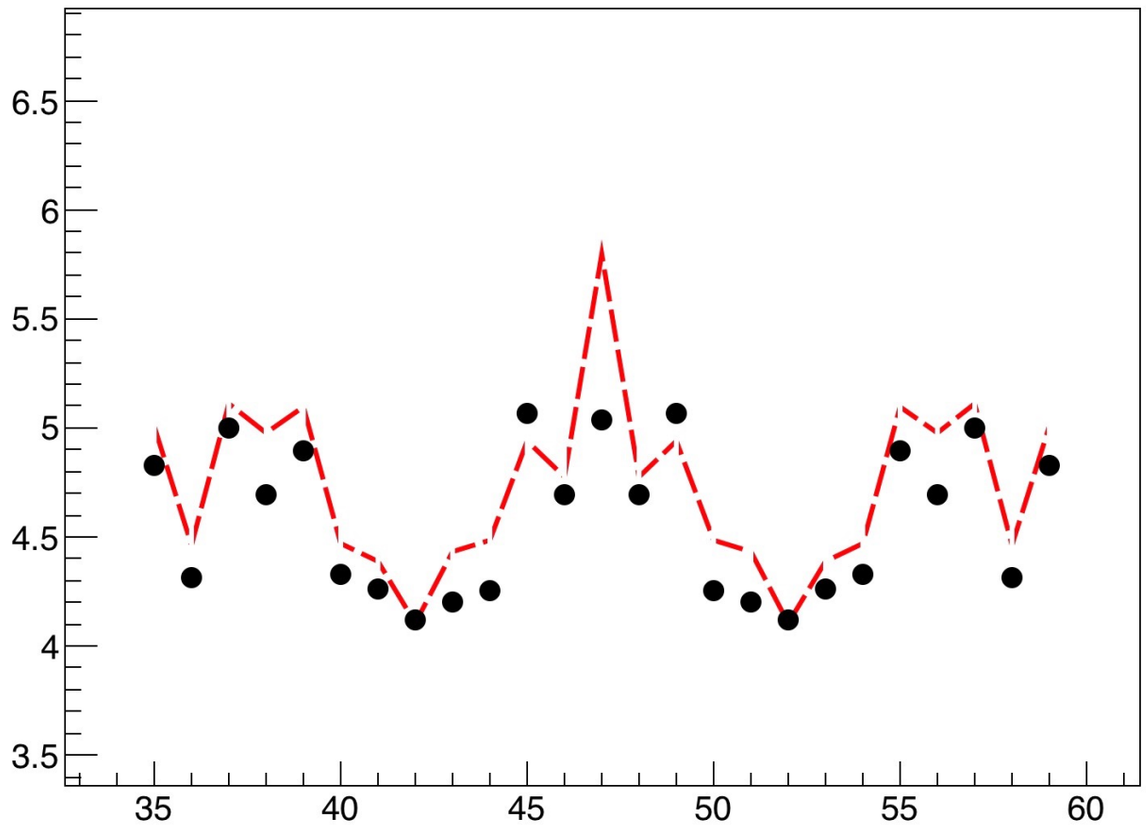


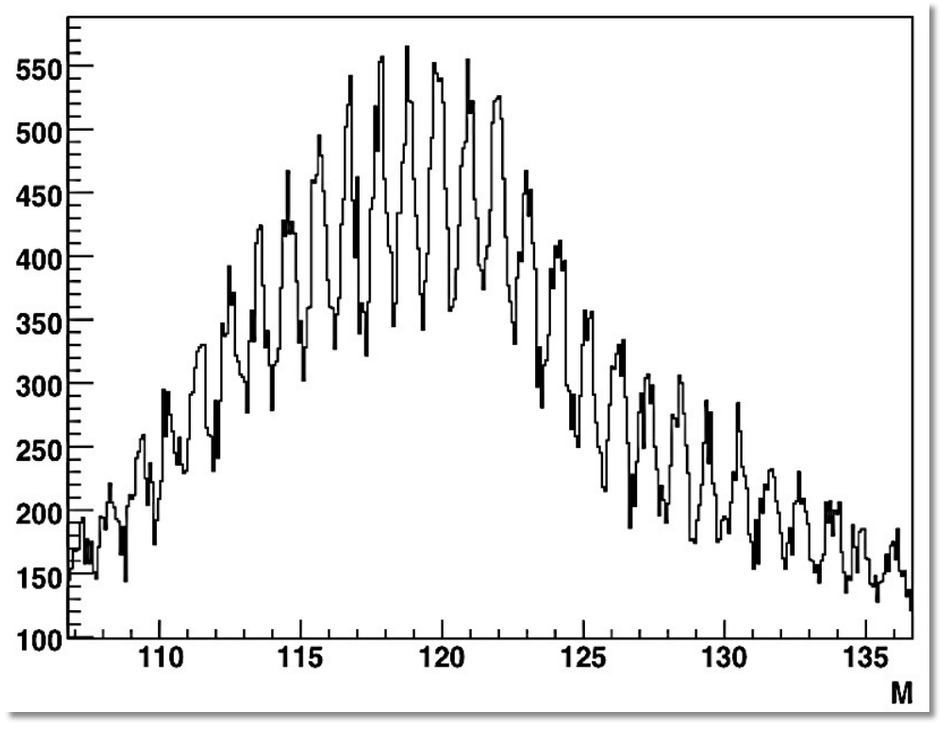



Apost from 2012
βg.s.
Deformation β
Fragment Z
64
44
88
50
50
82
Distance d (fm)
Apost from 2012


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

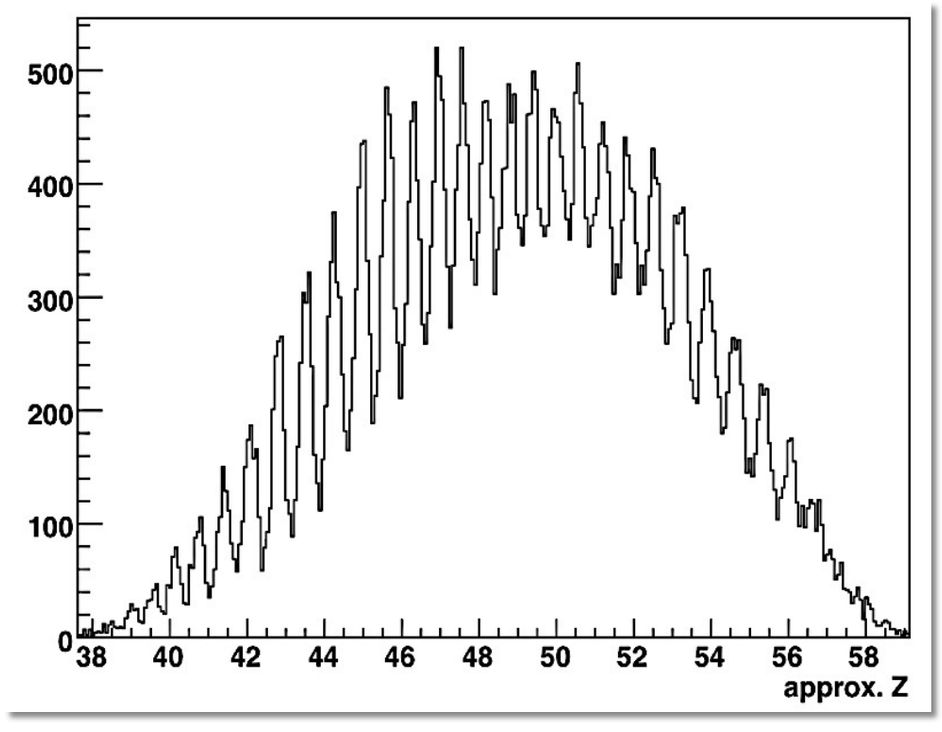

rough shell effect
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
35
40
45
50


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



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

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



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

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