Transfer-induced fission in inverse kinematics: Impact on experimental and evaluated nuclear data bases

F. Farget et al., GANIL

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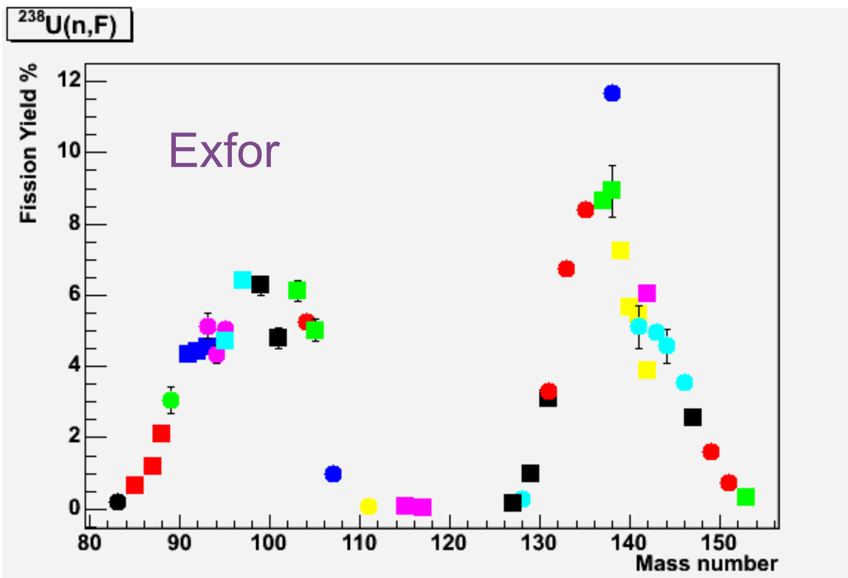
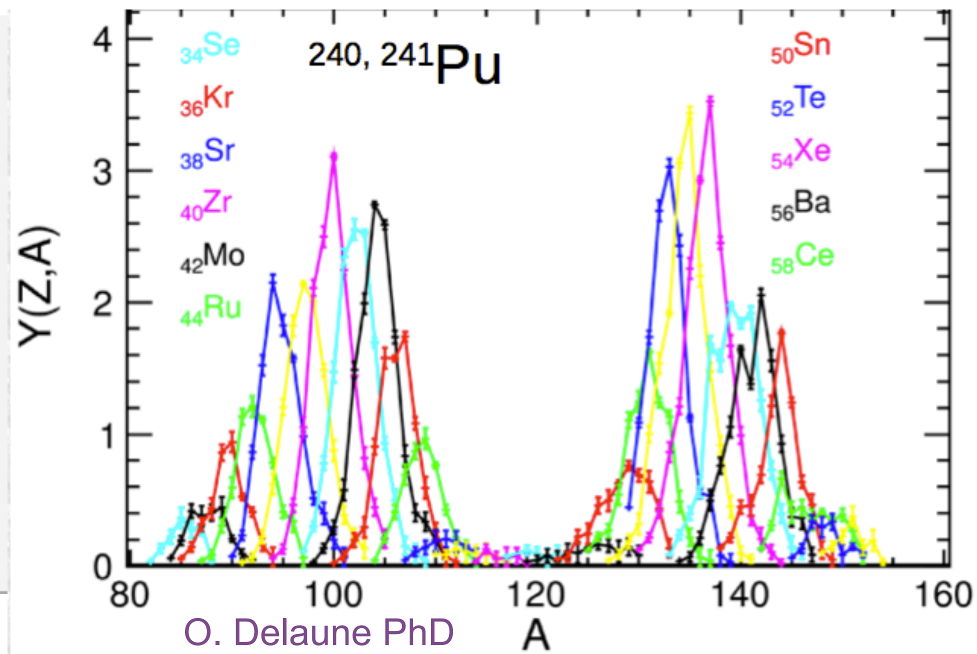
Why inverse kinematics for fission ?

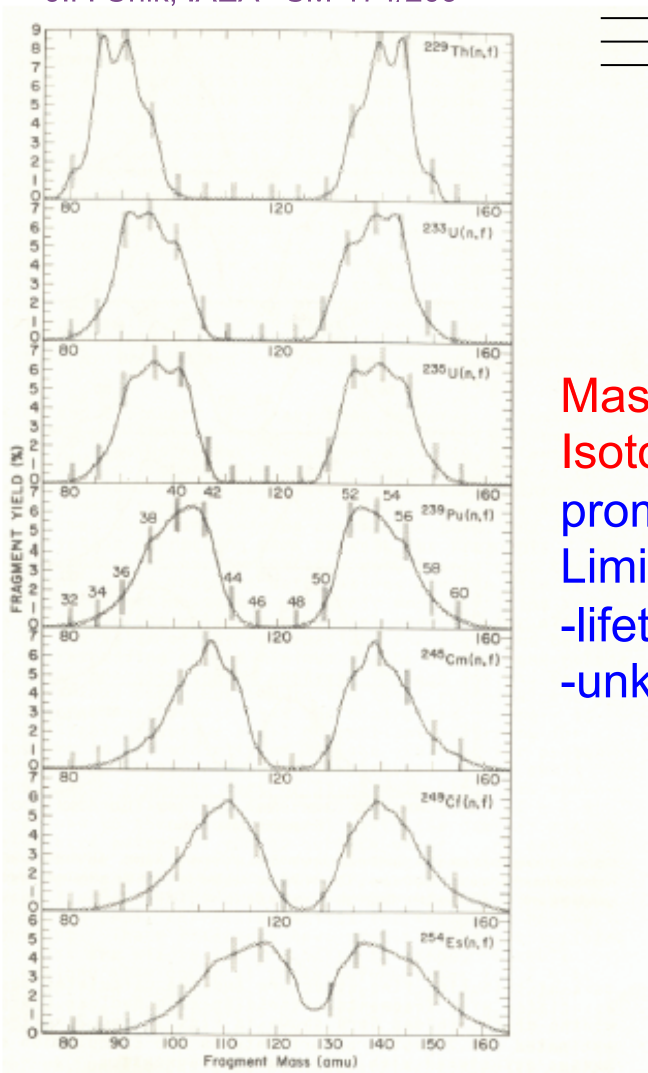
Isotopic fission yields

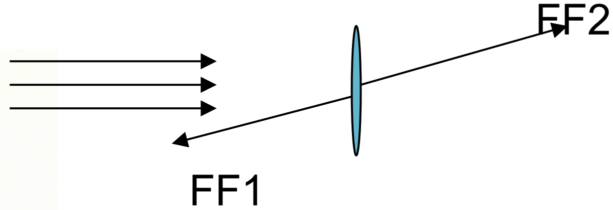




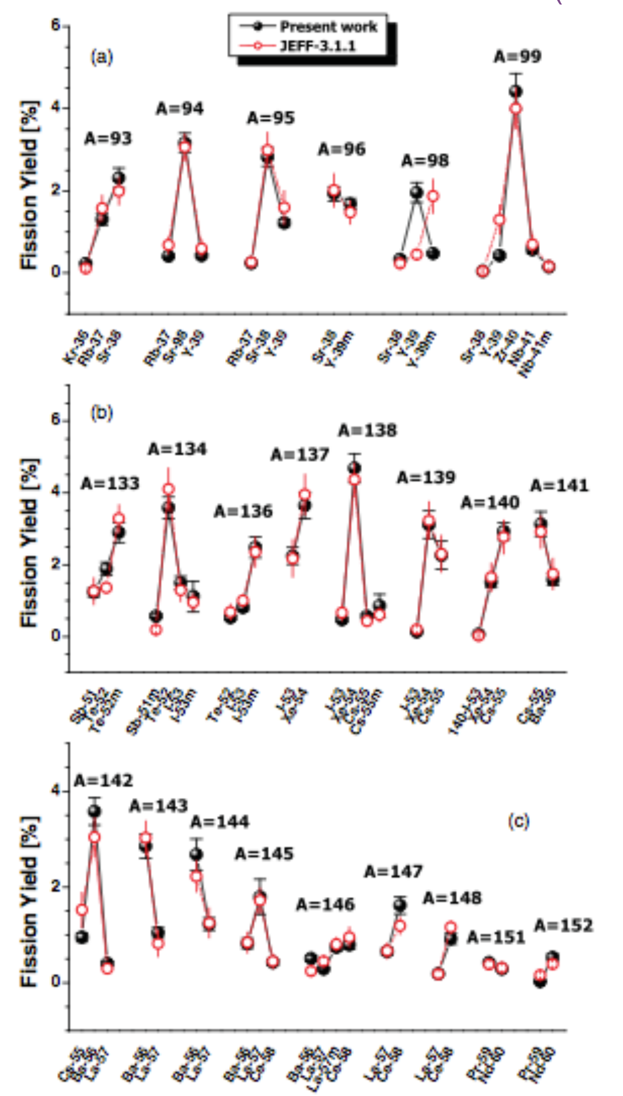
Fission yields in direct kinematics

J.P. Unik, IAEA –SM-174/209



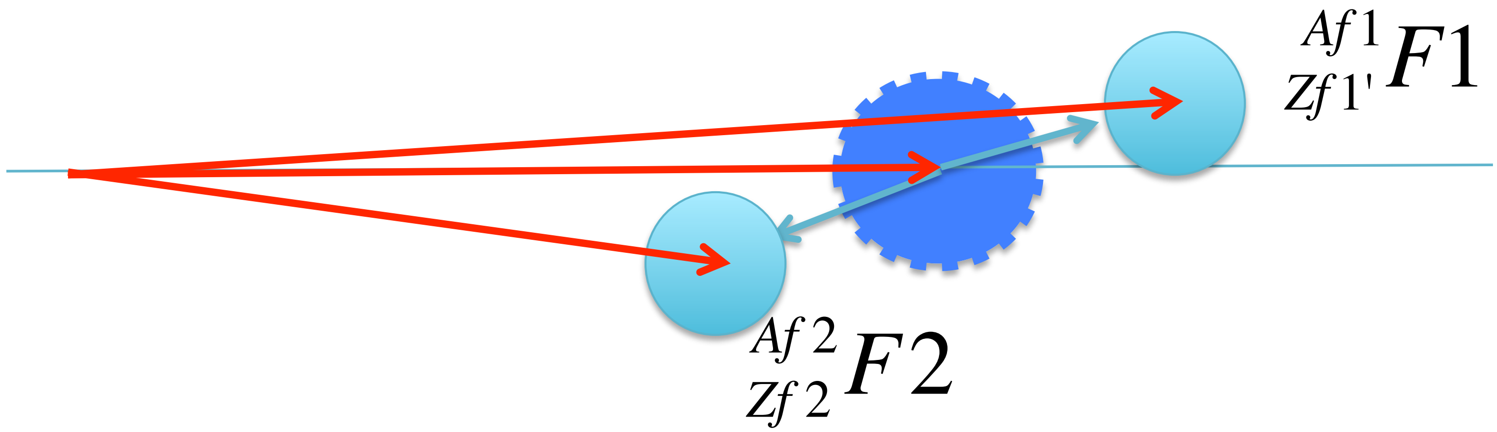


A. Bail PRC 84(2011)



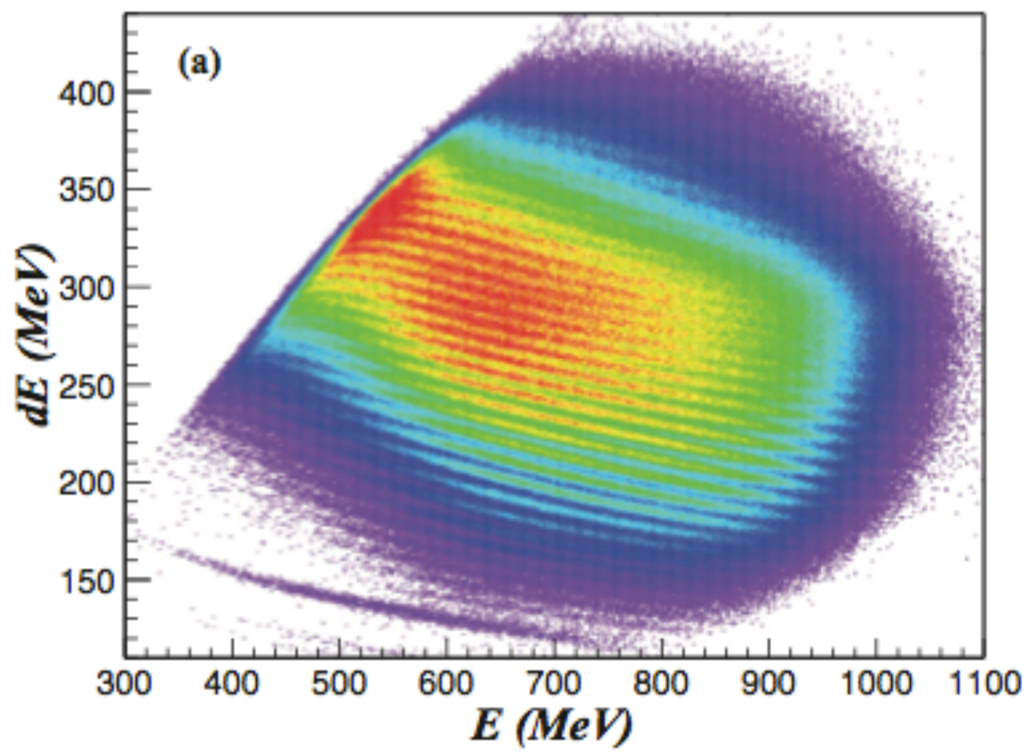
Mass distribution: OK
Isotopic distribution:
prompt or β-delayed spectroscopy
Limited by the
-lifetime of the FF
-unknown level scheme of FF

Fission in inverse kinematics: kinematical boost for a direct identification of the fission fragments



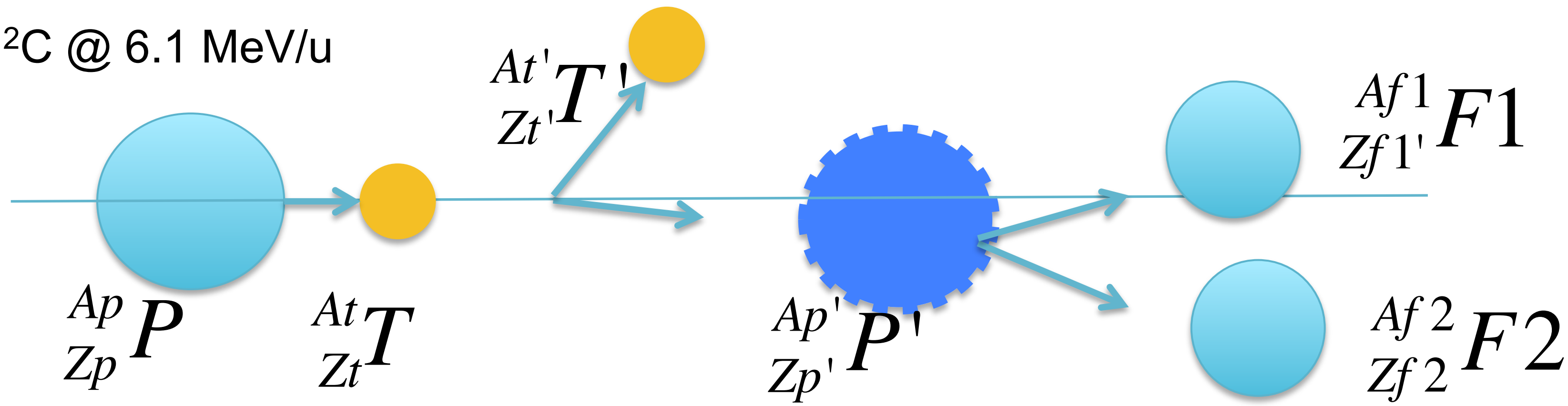
We will see in the following slides
That inverse kinematics
Bring more than isotopic distribution

With some price to pay



Transfer-induced fission in inverse kinematics @ GANIL

$^{238}U + ^{12}C$ @ 6.1 MeV/u

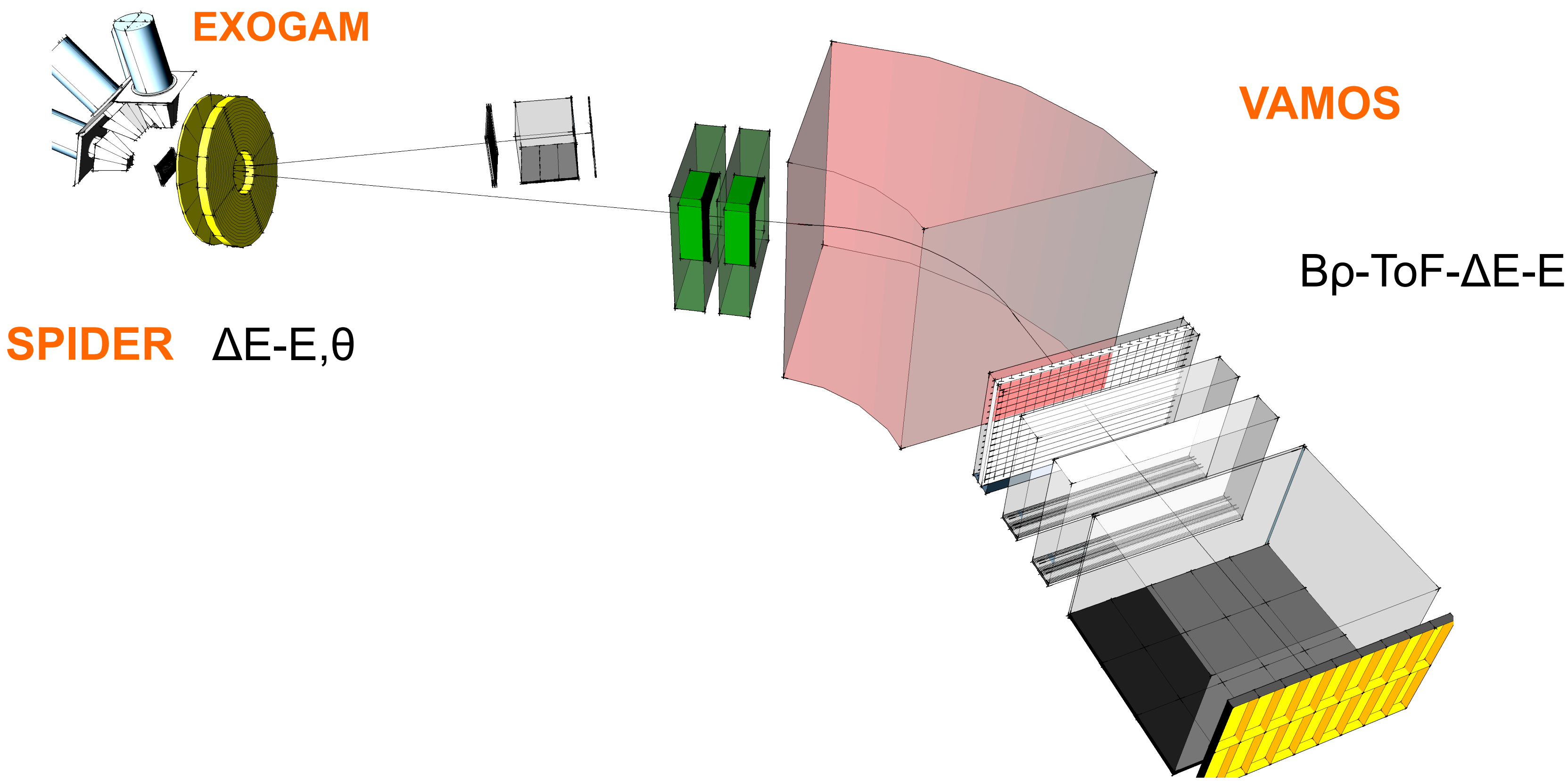


242 Cf	243 Cf	244 Cf	245 Cf	246 Cf	247 Cf	248 Cf	249 Cf	250 Cf	251 Cf	252 Cf
241 Bk	242 Bk	243 Bk	244 Bk	245 Bk	246 Bk	247 Bk	248 Bk	249 Bk	250 Bk	251 Bk
240 Cm	241 Cm	242 Cm	243 Cm	244 Cm	245 Cm	246 Cm	247 Cm	248 Cm	249 Cm	250 Cm
239 Am	240 Am	241 Am	242 Am	243 Am	244 Am	245 Am	246 Am	247 Am	248 Am	249 Am
238 Pu	239 Pu	240 Pu	241 Pu	242 Pu	243 Pu	244 Pu	245 Pu	246 Pu	247 Pu	
237 Np	238 Np	239 Np	240 Np	241 Np	242 Np	243 Np	244 Np			
236 U	237 U	238 U	239 U	240 U	241 U	242 U				

- 10 actinides produced
- E* distribution
- Full resolution in (Z,A) of fragments
- TKE
- Détermination of scission fragments

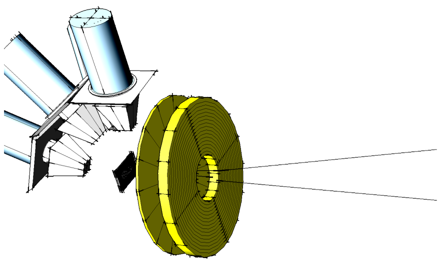
Can't choose your actinide
Can't choose your E*

Transfer-induced fission in inverse kinematics



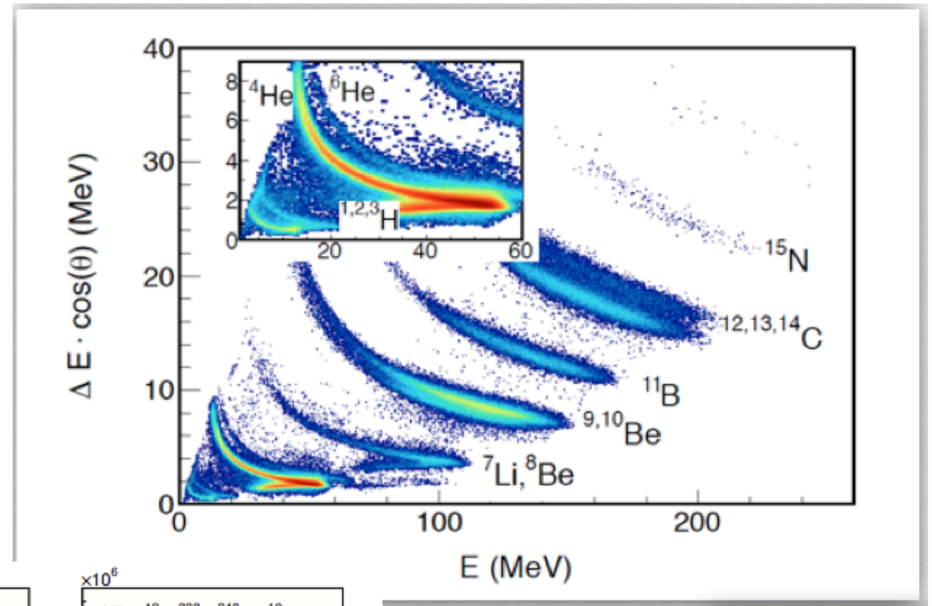
S. Pullanhiotan et al., NIM 593 (2008) 343
M. Rejmund et al., NIMA 646 (2011) 184

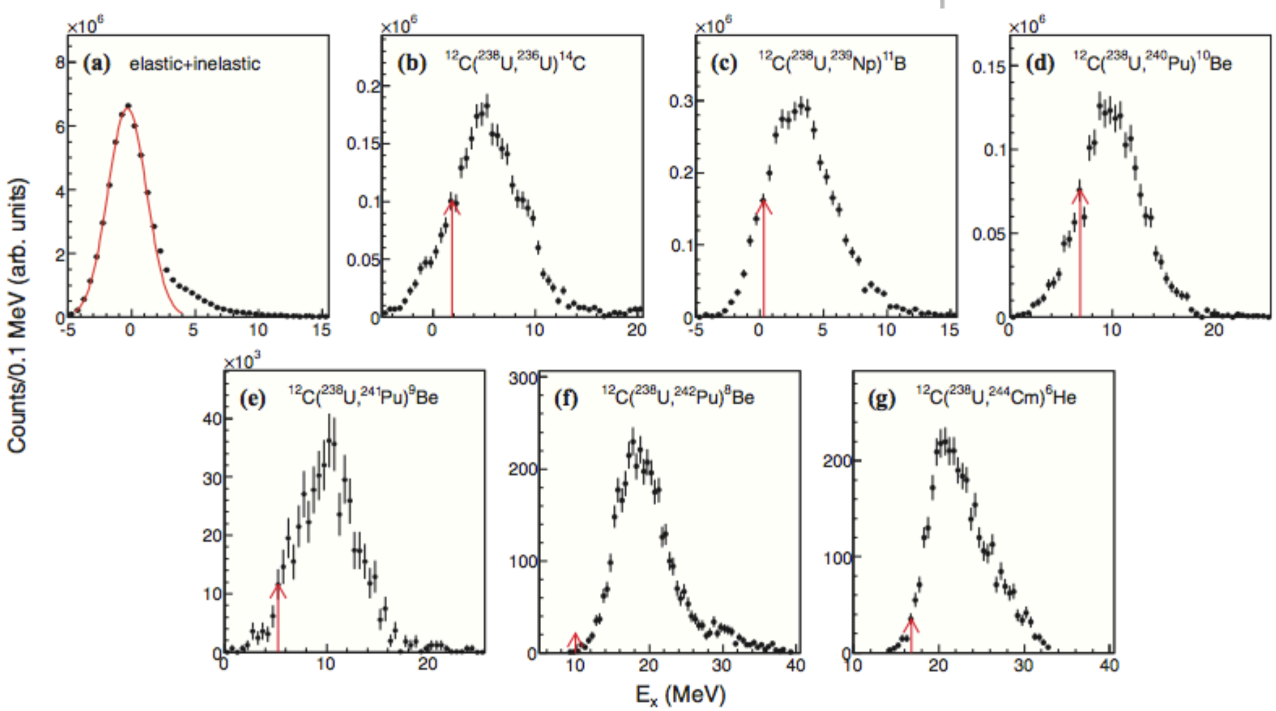
Transfer-induced fission in inverse kinematics



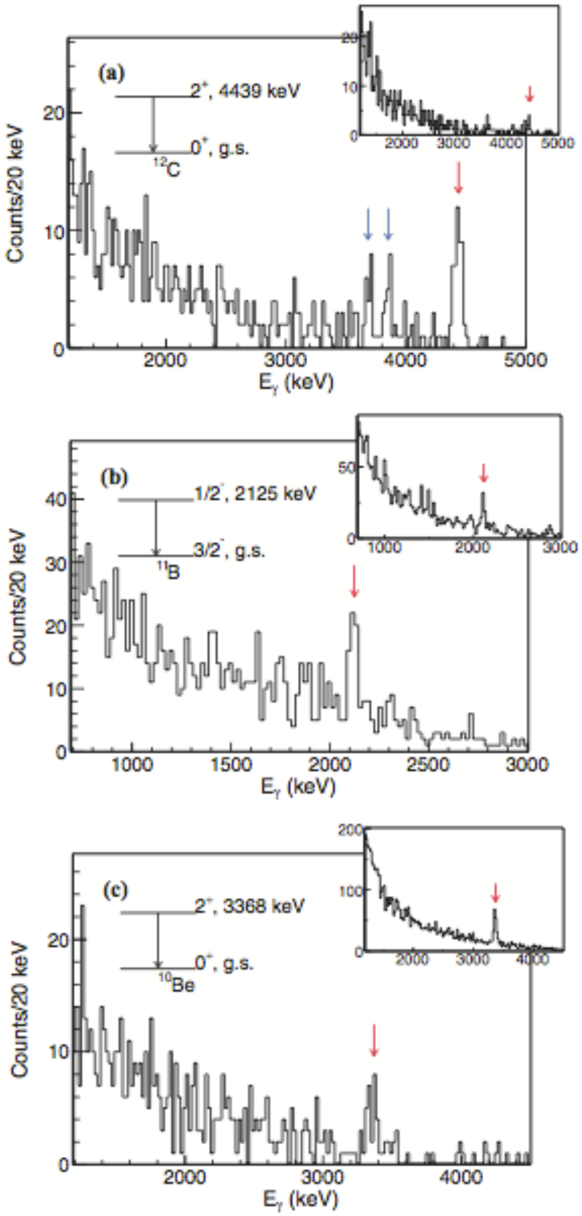
SPIDER ΔE-E,θ

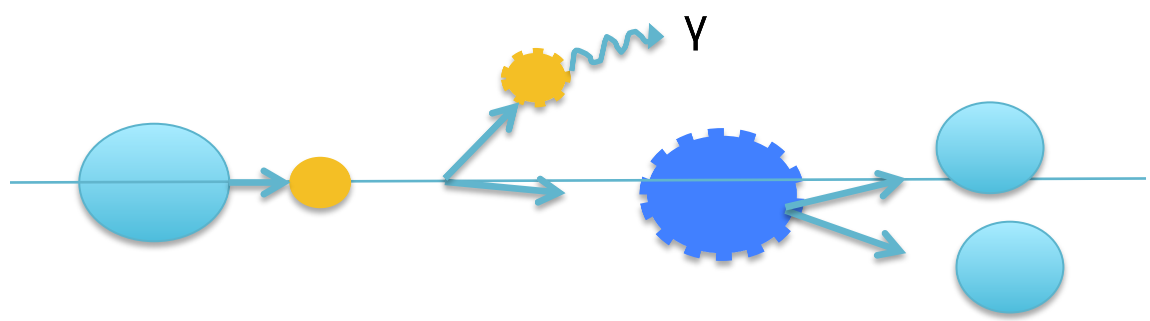
C. Rodriguez-Tajes et al., PRC (2014) 024614





Towards an extended use of surrogate reactions : excitation of the outgoing particle needs to be considered

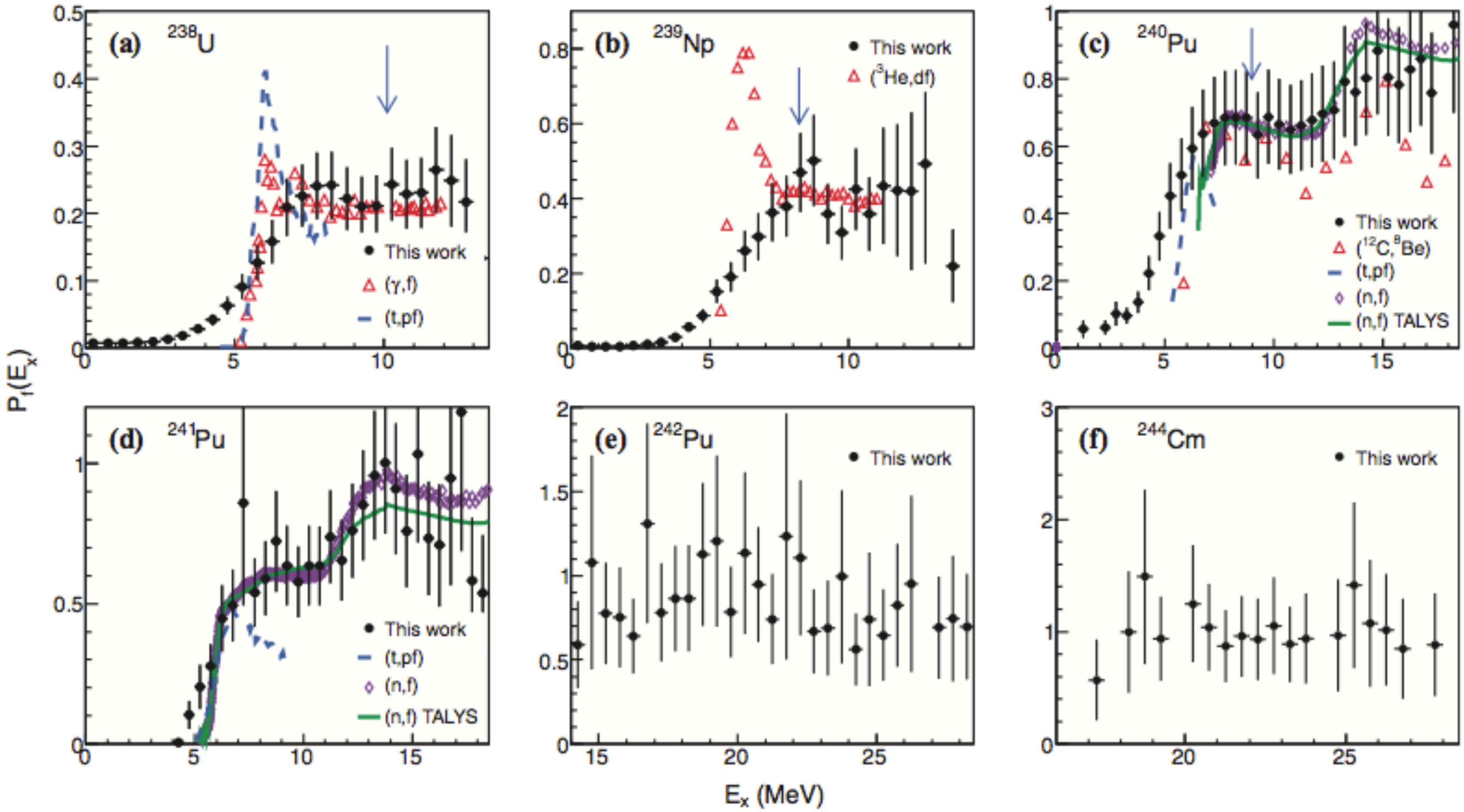




In 10-15% of the transfer reactions,
few MeV of E*
are taken away by the transfer partner
(Only first states have been observed)

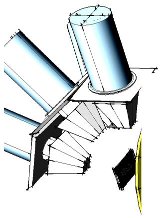
C. Rodriguez-Tajes et al., PRC (2014) 024614

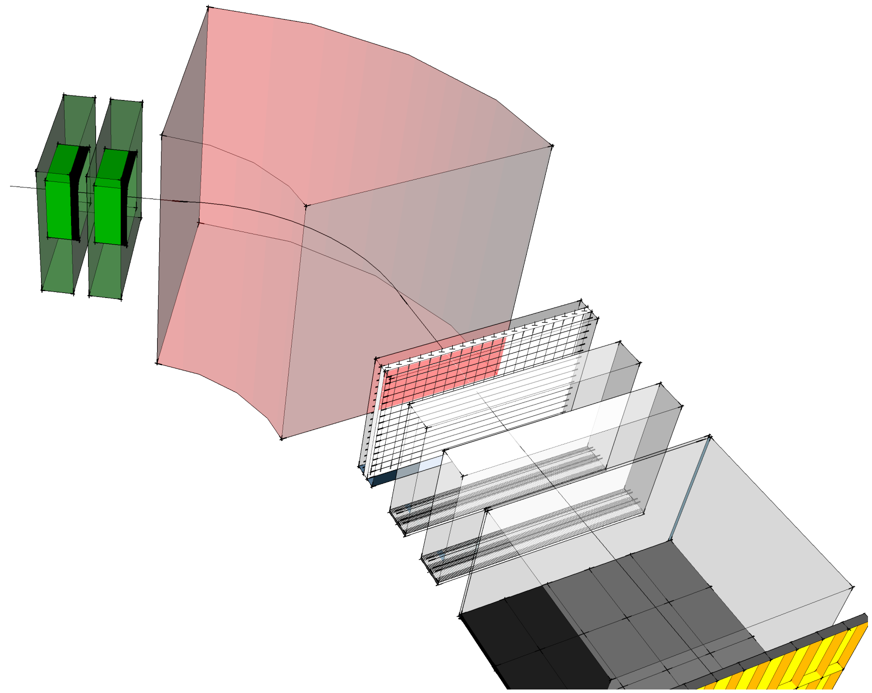
Fission probabilities

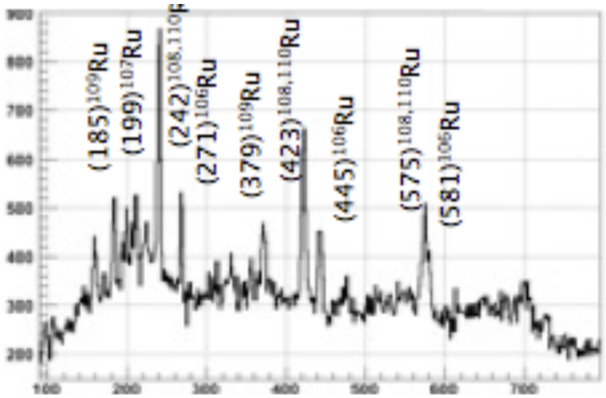


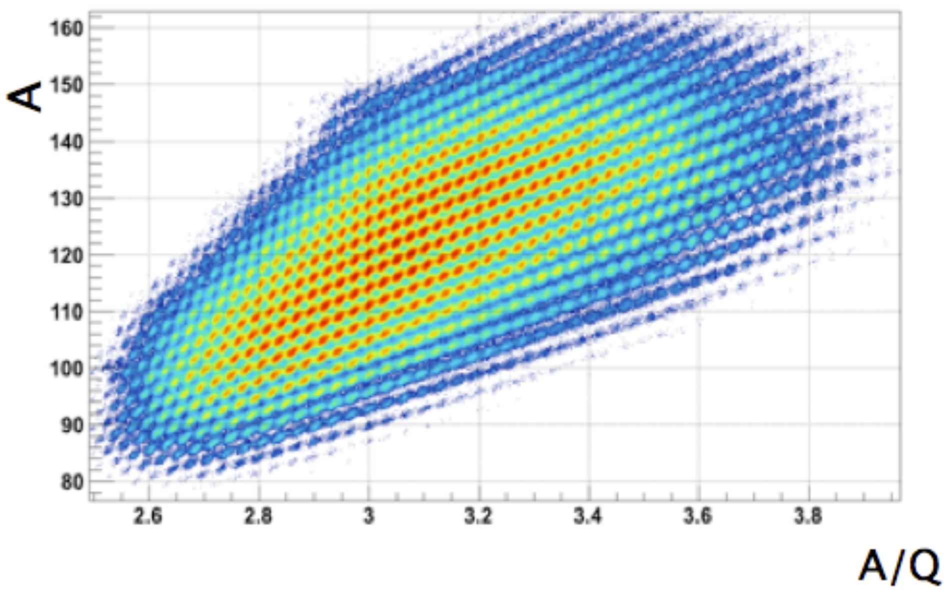
Agreement with previous data : plateau and positions of the thresholds
Difference in slope and structure at the threshold (reaction mechanism)

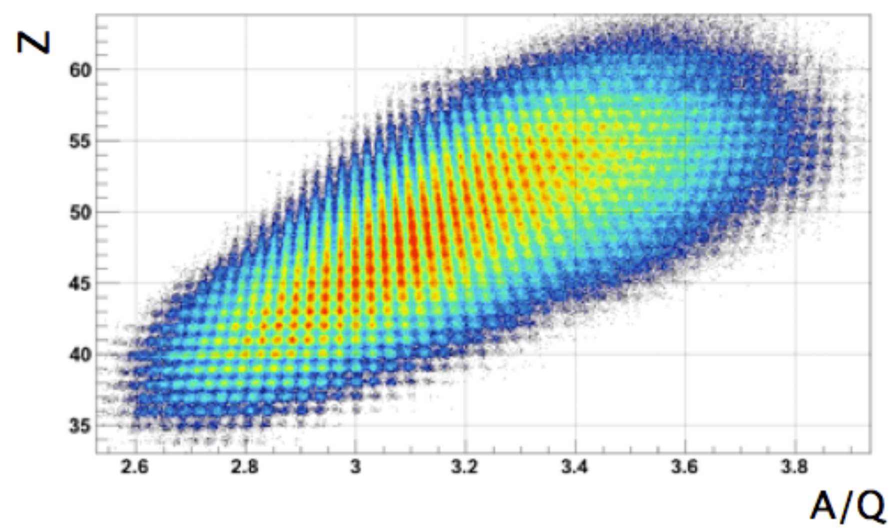
Transfer-induced fission in inverse kinematics



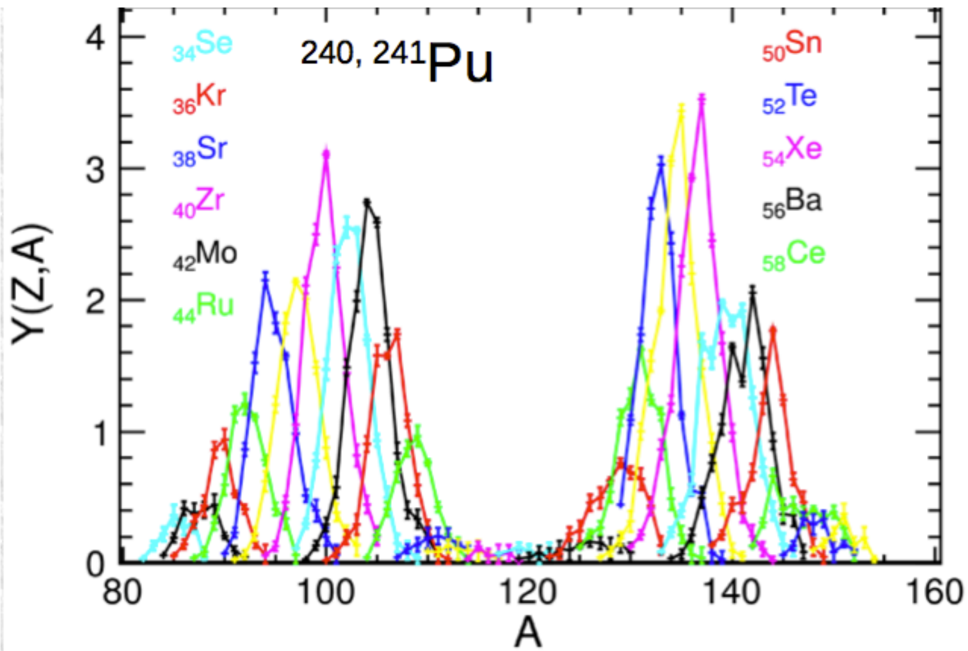




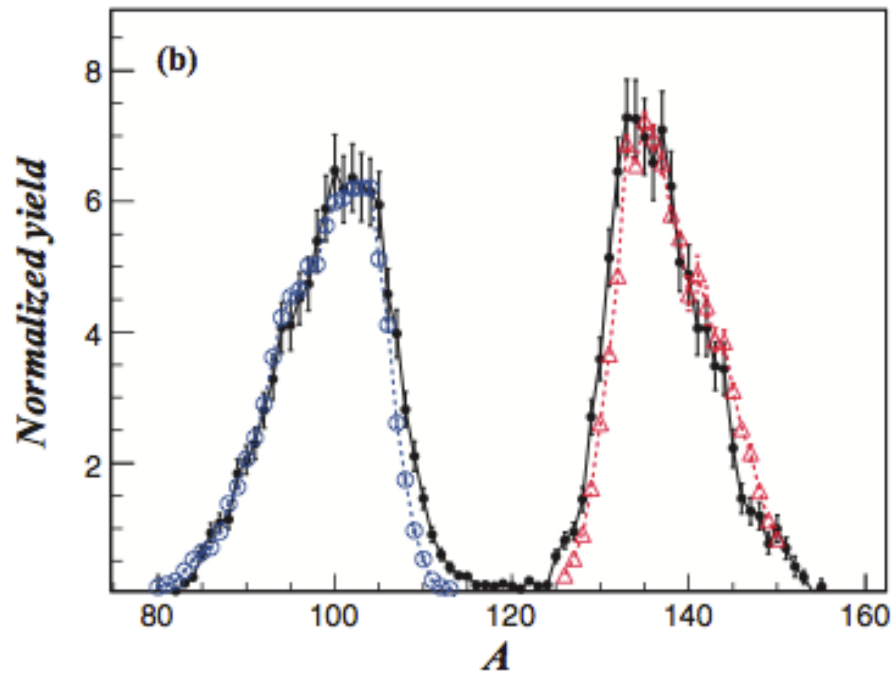




Isotopic distribution of fission fragments



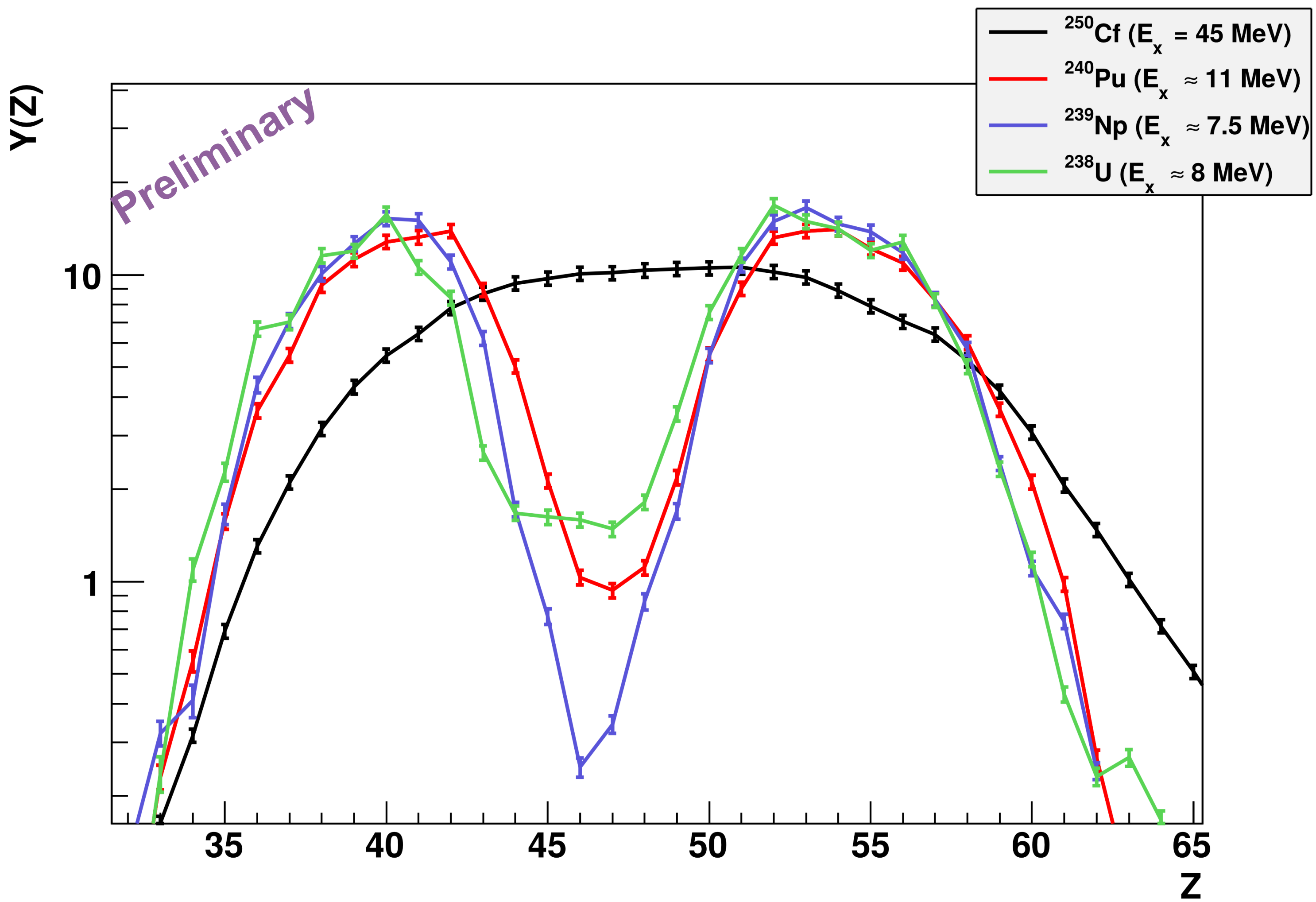
M. Caamaño et al., PRC 88 (2013) 024605



C. Schmitt et al, NPA430 (1984) A. Bail, PRC84 (2011)

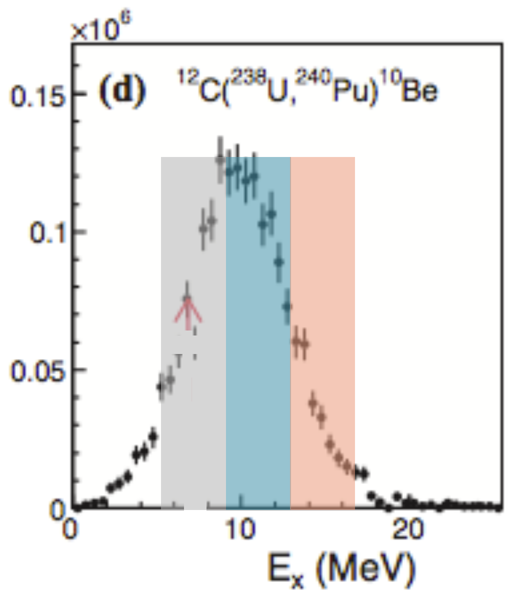
Excellent control of the spectrometer transmission

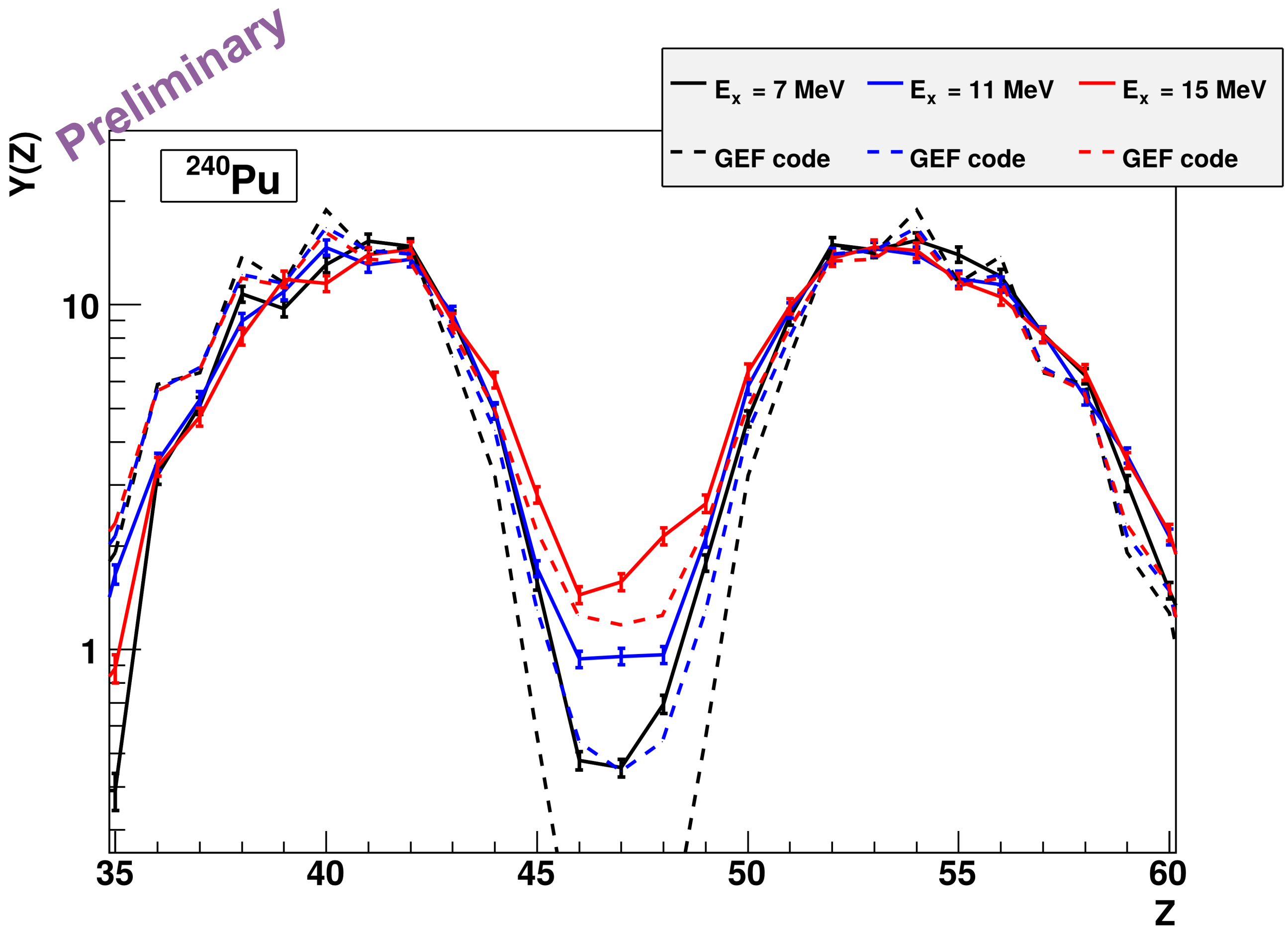
Evolution of yields with fissioning system



D. Ramos, USC PhD

Evolution of yields with E*



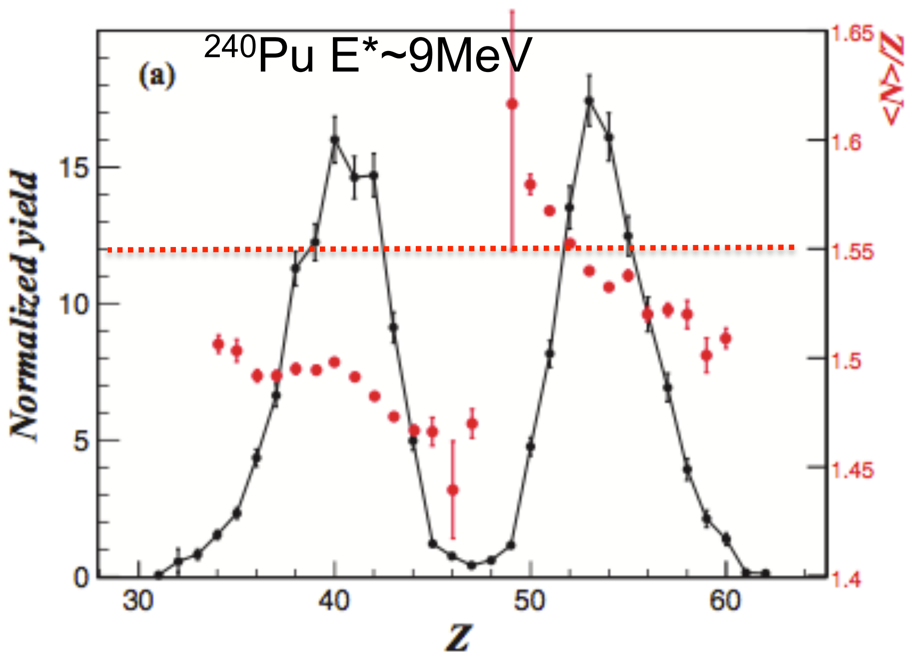


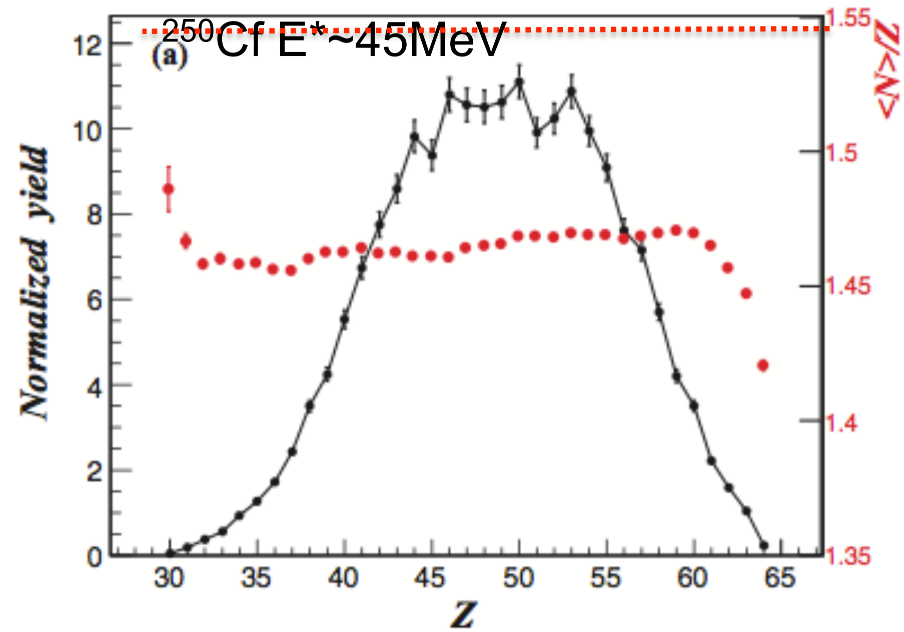
D. Ramos, USC PhD

Neutron excess of fission fragments

Charge polarization

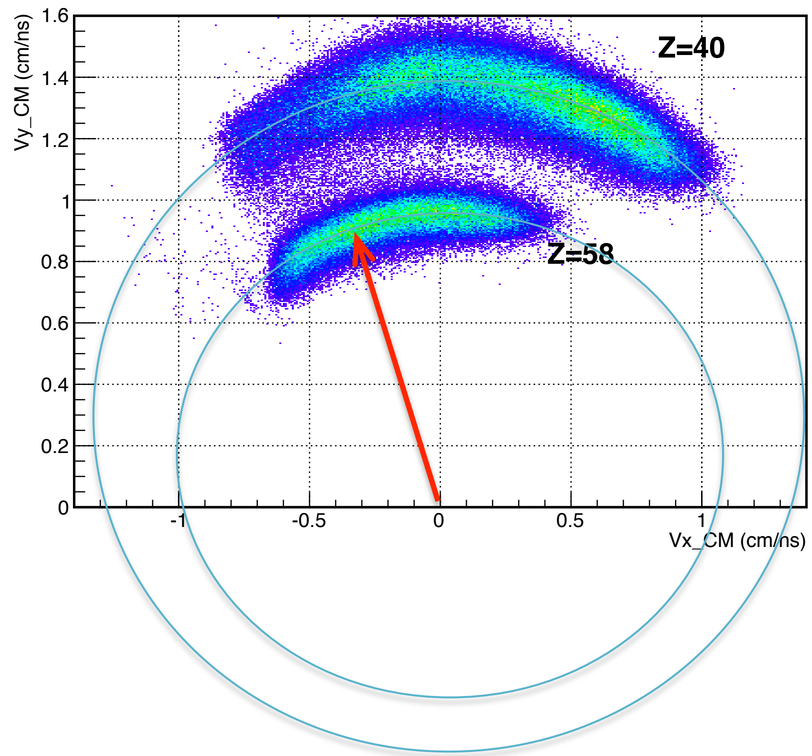
M. Caamaño et al.,
PRC 88 (2013) 024605





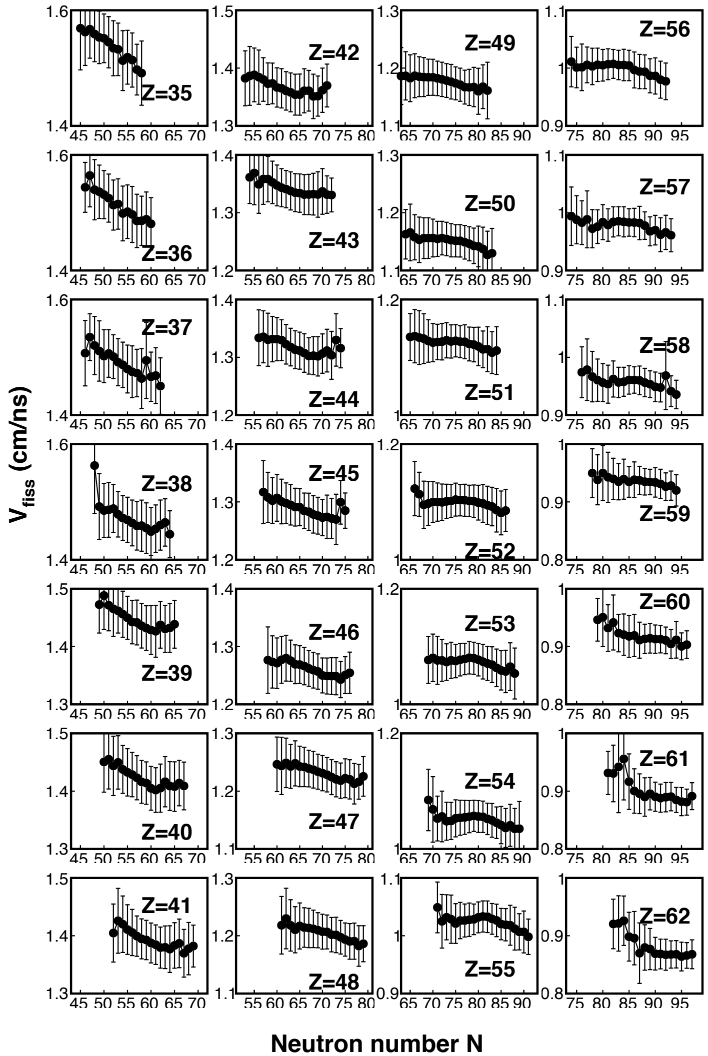
Kinematics properties of fission fragments

^{250}Cf (θ=φ=0) V_{FS}= reaction kinematics
^{240}Pu(θ,φV_{FS}) measured in SPIDER assuming a direct (two-body) reaction.

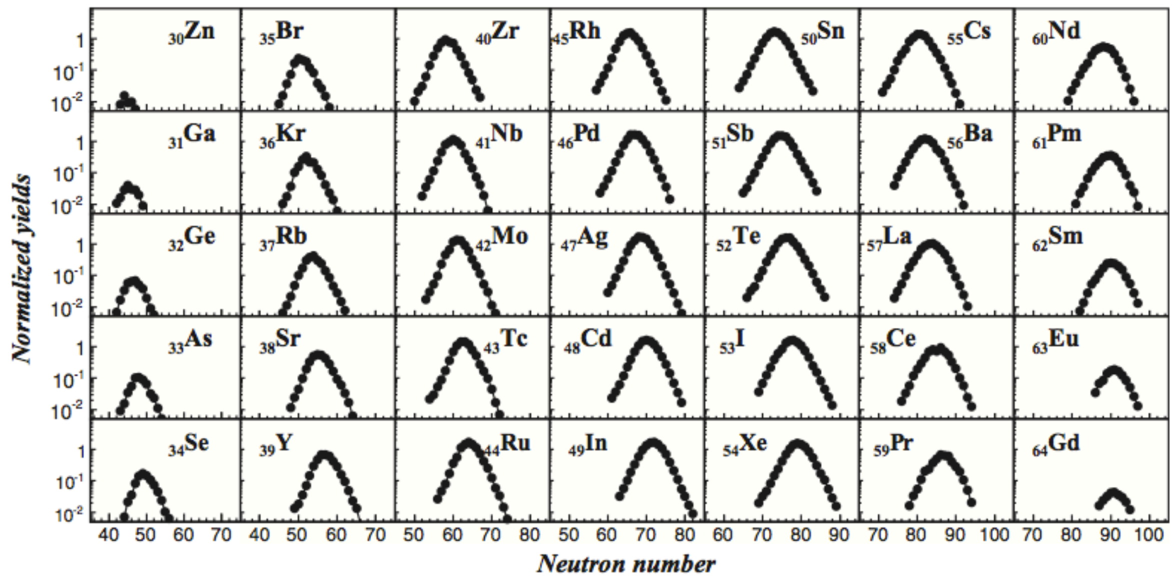


Reconstruction of the vecolity vector in the reference frame of the fissioning system

V(Z,A)

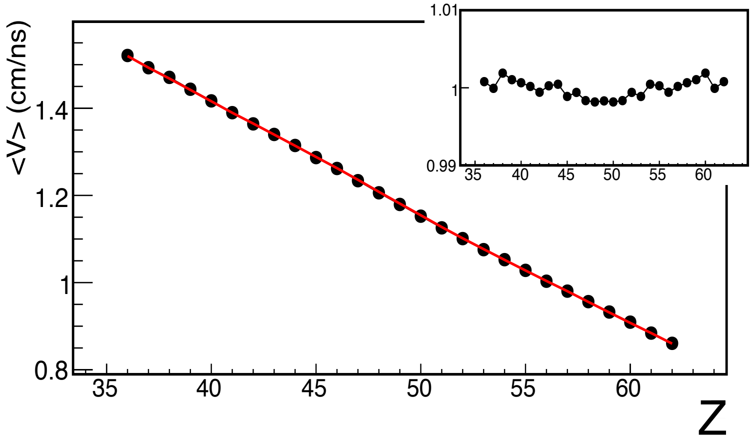


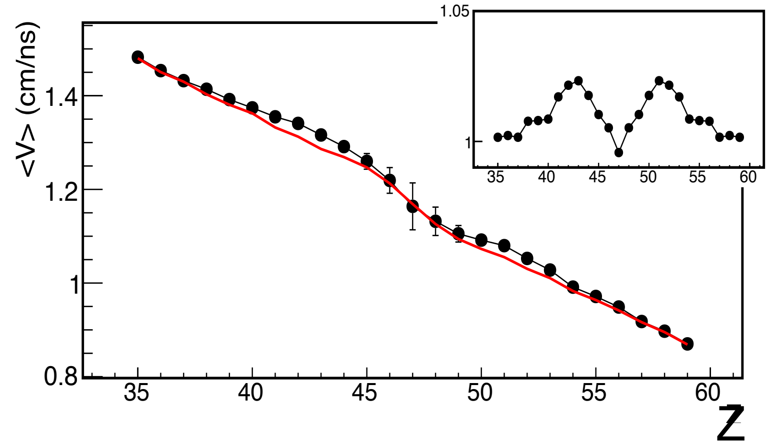
Y(Z,A)



$$< V > (Z) = \frac{\sum_A Y(A,Z) V(Z,A)}{\sum_A Y(A,Z)}$$

Average fission velocities <V>(Z)





$$TKE = 1.44\frac{Z_1 Z_2}{D}$$

$$D = r_0(A_1^{*1/3}(1+\frac{2}{3}\beta_1) + A_2^{*1/3}(1+\frac{2}{3}\beta_2)) + d,$$

d=2.5 fm for ^{240}Pu (2p transfer, E*=9 MeV)

d=2.7 fm for ^{250}Cf (fusion, E*=45 MeV)

$B_1=\beta_2=0.6$

Scission fragment neutron excess !!

Average velocity not modified by post-scission evaporation

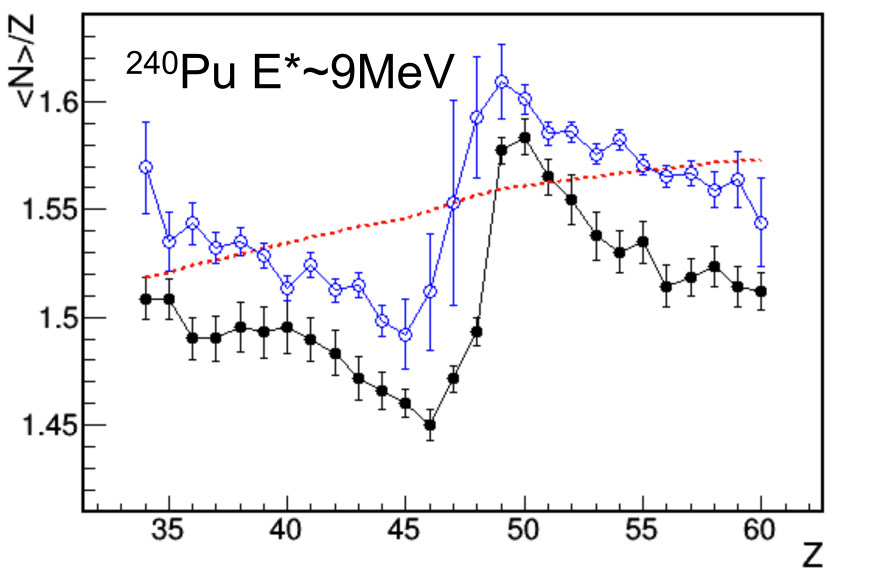
Momentum conservation

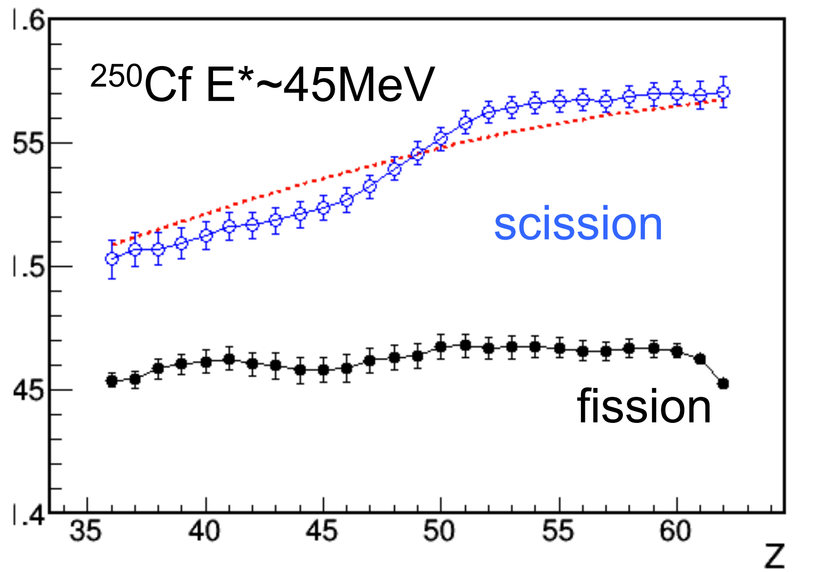
$$\frac{V_1}{V_2} = \frac{A_2^*}{A_1^*}$$

Charge and mass conservation

$$Z_2 = Z_{FS} - Z_1$$

$$< A_1^* > = A_{FS}\frac{<V_2>}{<V_1>}$$
$$< A_2^* > = A_{FS} - < A_1^* >$$





M. Caamaño, F. Farget et al.,

Scission configuration investigation: ^{240}Pu E*=9MeV

Scission point model: minimisation of the total energy

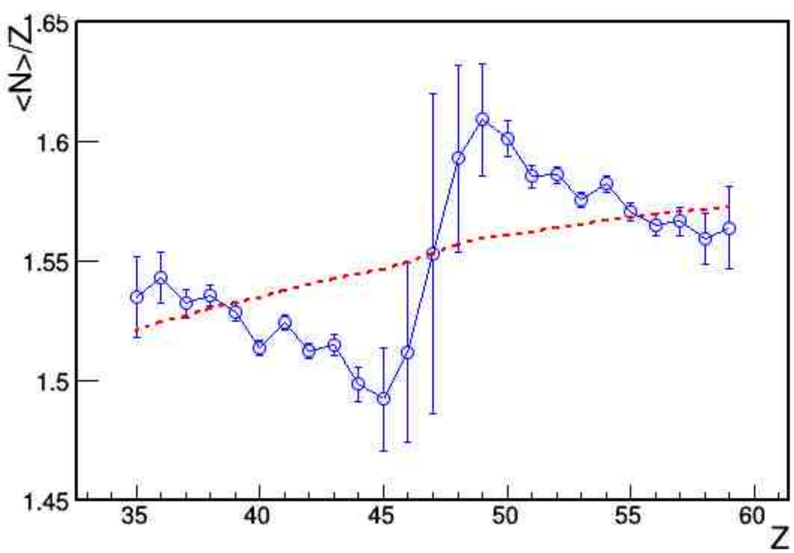
$$E_{tot} = E_{LD_1} + S_1(Z_1, N_1, \tau) + E_{LD_2} + S_2(Z_2, N_2, \tau) + V_{Cb}(Z_1, N_1, \beta_1, Z_2, N_2, \beta_2, d) + V_n(Z_1, N_1, \beta_1, Z_2, N_2, \beta_2, d)$$

Liquid-drop energy

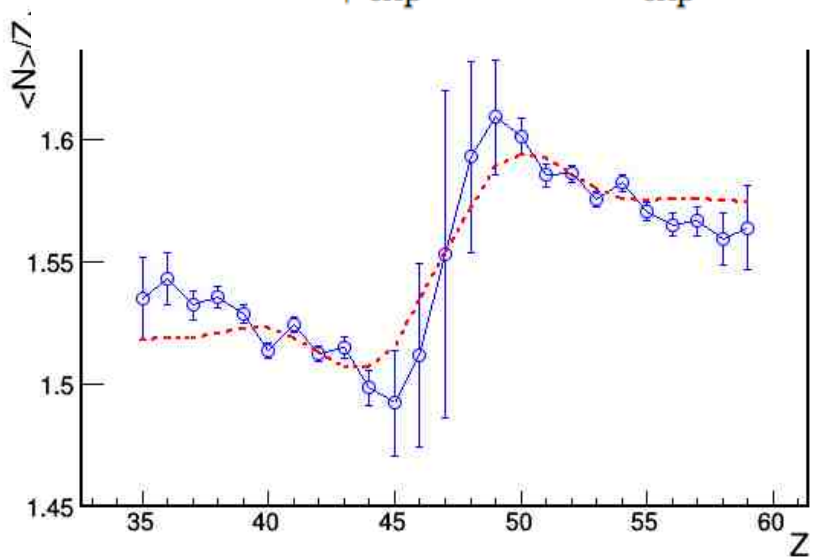
Myers & Swiatecki, Lysekil, Ark. Phys. 36 (1967) 343

$$E(Z,N,\beta) = a_a A - a_s A^{2/3}(1+0.4\alpha^2) - 1.78 I^2 (a_a A - a_s A^{2/3}(1+0.4\alpha^2)) + Z^2\left(\frac{0.705}{A^{1/3}}(1-0.2\alpha^2) - \frac{1.15}{A}\right) - SE(Z,N)$$

$$SE(Z,N) = 0$$



$$SE(Z,N,\beta) = \exp^{(-(N-82)^2/\sigma_N^2)} \exp^{(-(Z-50)^2/\sigma_Z^2)} + \exp^{(-(N-90)^2/\sigma_N^2)} \exp^{(-(Z-54)^2/\sigma_Z^2)}$$



Scission configuration investigation: ^{250}Cf E*=45MeV

Scission point model: minimisation of the total energy

$$E_{tot} = E_{LD_1} + S_1(Z_1, N_1, \tau) + E_{LD_2} + S_2(Z_2, N_2, \tau) + V_{Cb}(Z_1, N_1, \beta_1, Z_2, N_2, \beta_2, d) + V_n(Z_1, N_1, \beta_1, Z_2, N_2, \beta_2, d)$$

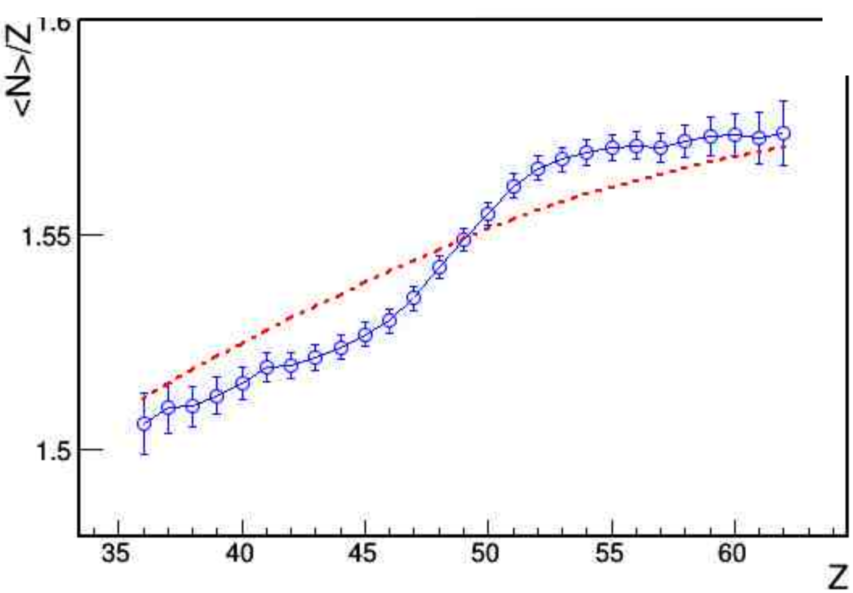
Liquid-drop energy

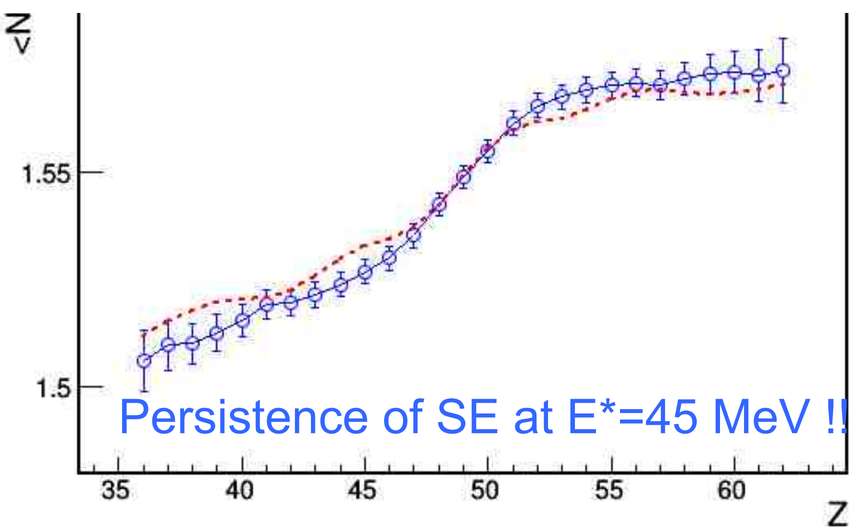
Myers & Swiatecki, Lysekil, Ark. Phys. 36 (1967) 343

$$E(Z,N,\beta) = a_a A - a_s A^{2/3}(1+0.4\alpha^2) - 1.78 I^2 (a_a A - a_s A^{2/3}(1+0.4\alpha^2)) + Z^2\left(\frac{0.705}{A^{1/3}}(1-0.2\alpha^2) - \frac{1.15}{A}\right) - SE(Z,N)$$

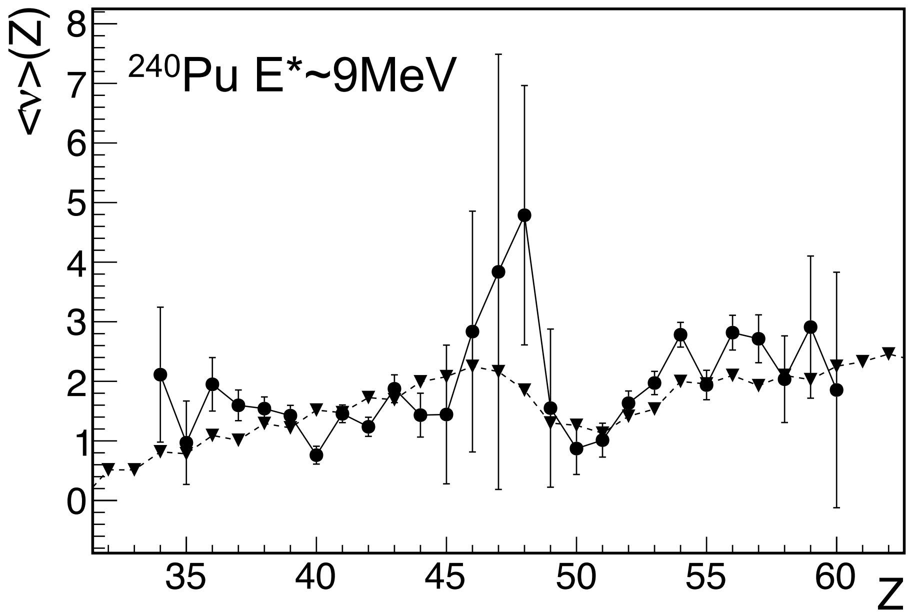
$$SE(Z,N) = 0$$

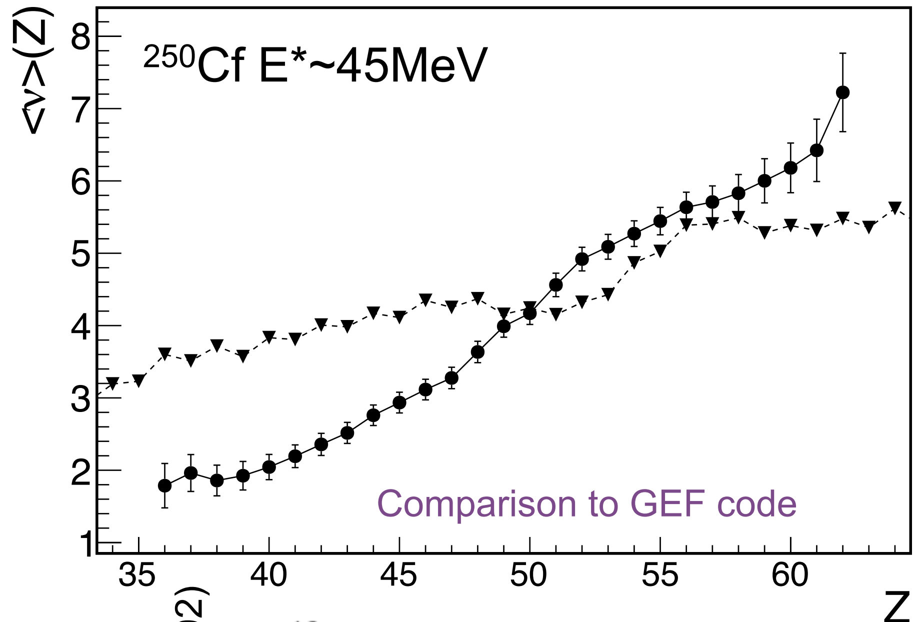
$$SE(Z,N,\beta) = \exp^{(-(N-82)^2/\sigma_N^2)} \exp^{(-(Z-50)^2/\sigma_Z^2)} * 0.4 + \exp^{(-(N-90)^2/\sigma_N^2)} \exp^{(-(Z-54)^2/\sigma_Z^2)} * 0.95$$

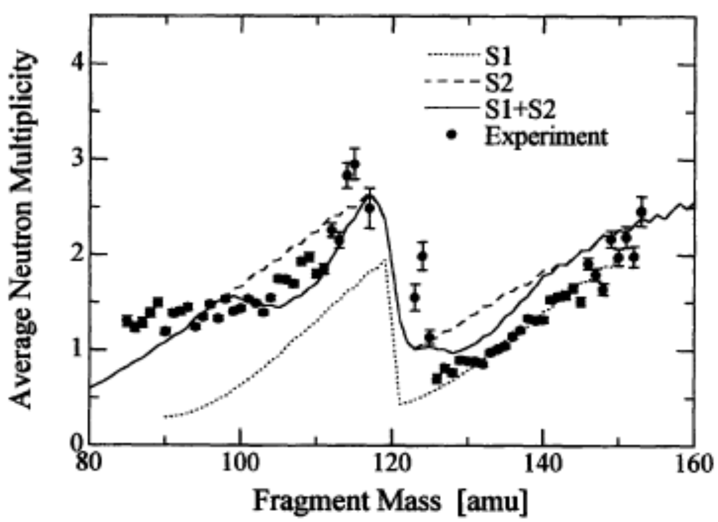




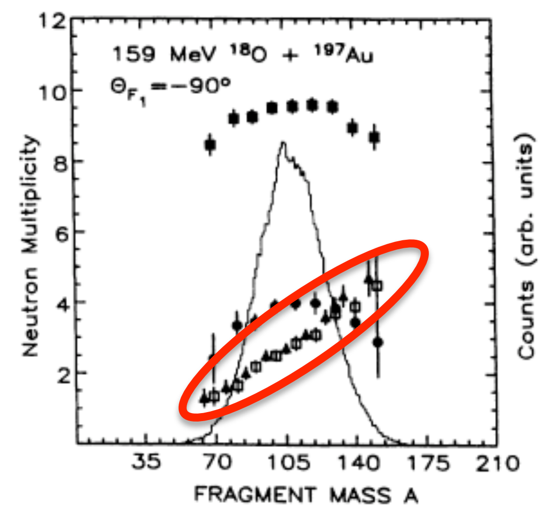
Post-scission neutron evaporation







D. Hinde et al, PRC45(1992)



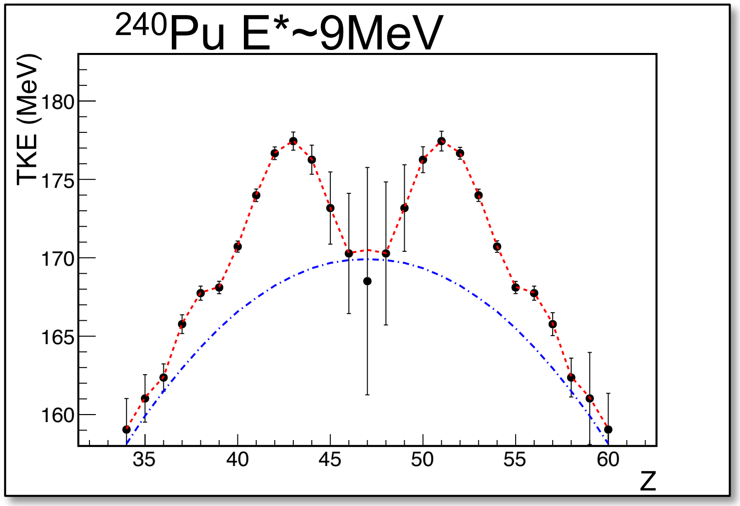
Total Kinetic Energy

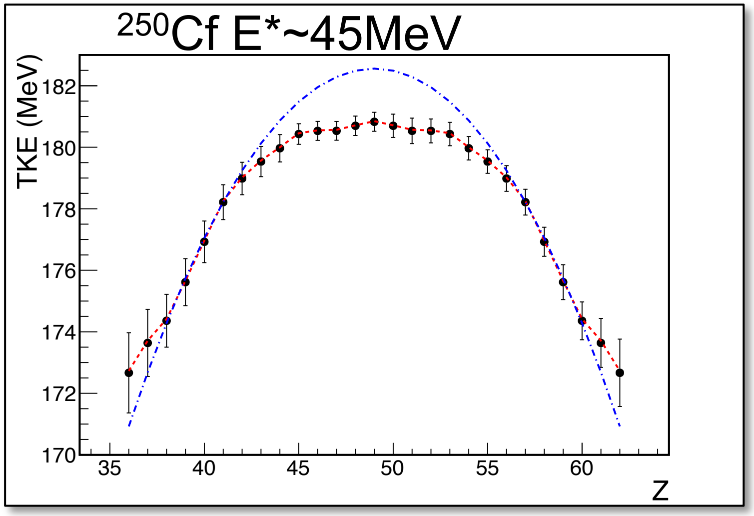
$V(Z_1) \Leftrightarrow V(Z_2) = V(Z_{FS}-Z_1)$

$$TKE = \frac{1}{2}m_0A_1V_1^2 + \frac{1}{2}m_0A_2V_2^2 +$$

$$TKE = 1.44\frac{Z_1Z_2}{D}$$

$$D = r_0(A_1^{*1/3}(1+\frac{2}{3}\beta_1) + A_2^{*1/3}(1+\frac{2}{3}\beta_2)) + d,$$





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Deformation at scission !!

Summary and outlook

Transfer-induced fission in inverse kinematics coupled to the spectrometer VAMOS allows to

- Investigate a ten of fissioning actinides, heavier than 238U
- With E* ranging from few MeV above the fission barrier to 45 MeV
- Isotopic fission-fragment distributions are available for each system
- With kinematics properties of the fission fragments it is possible to reconstruct the properties of the fragments at scission
  - Their TKE
  - Their average neutron excess <N>/Z
  - Deduce the prompt neutron multiplicity <ν>(Z)

- The present results show the importance to consider polarisation in the emergence of the fragments
- Further developments in the description of the scission fragments (evolution of binding energy with E* and deformation, sharing of E*) are needed !!
- Impact on evaluated fission yield will be decisive in the next decade

Message to the data-evaluation community

- These type of experiments are held in laboratories meant for « fundamental nuclear physics »

- They rely on the use of expensive state-of-the art spectrometers and heavy-ion beam facilities

- It is difficult for us (experimentalists) to defend our goals
  - Too much applied (not interesting)
  - Not really applied (Fission Yields not in the HPRL, actinides not the good ones for applications, energy range not adapted…)

- If there exists an interest in this type of data it is important to find a way to defend at a high level of strategy and funding decision
  - The sustainability of U beams
  - The adequate human resources to pursue these programmes