FUSTIPEN Topical Meeting

«Fission at FUSTIPEN II: recent observables and their modeling »

From fission yields to scission properties

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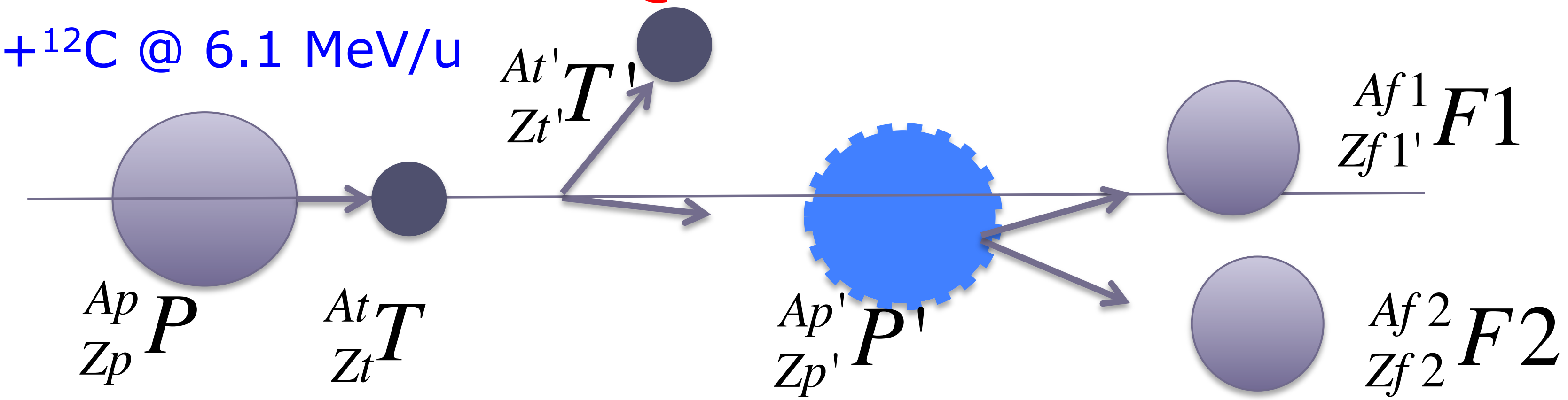
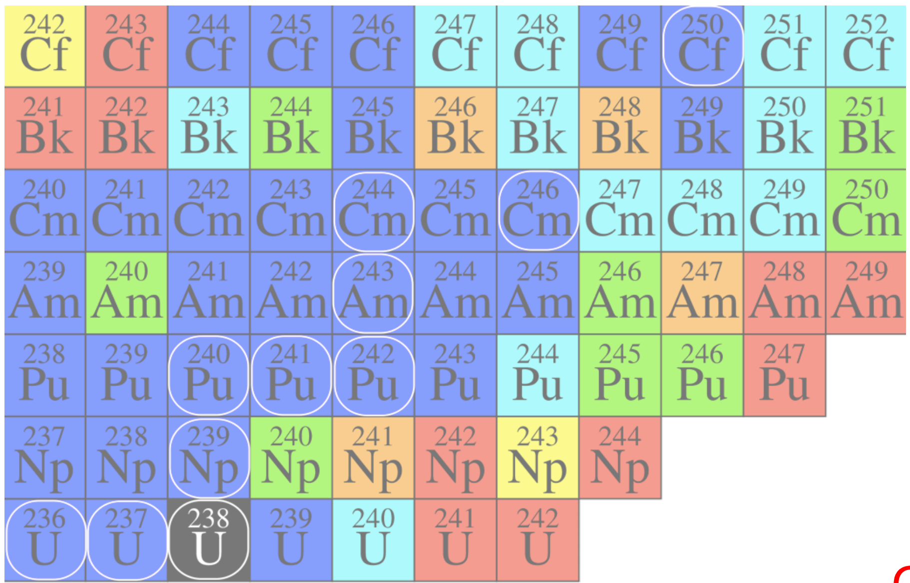
GANIL

May 4th, 2016

Transfer-induced fission in inverse kinematics @ GANIL

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





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

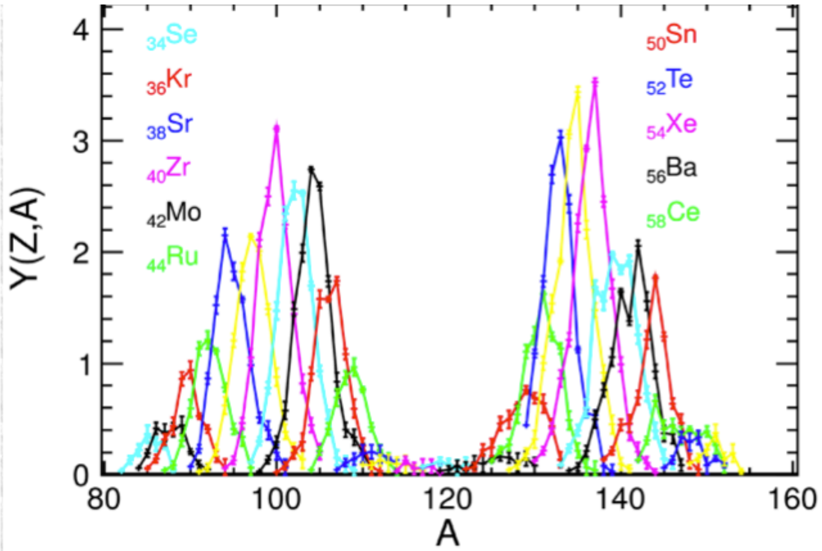
Can't choose your actinide

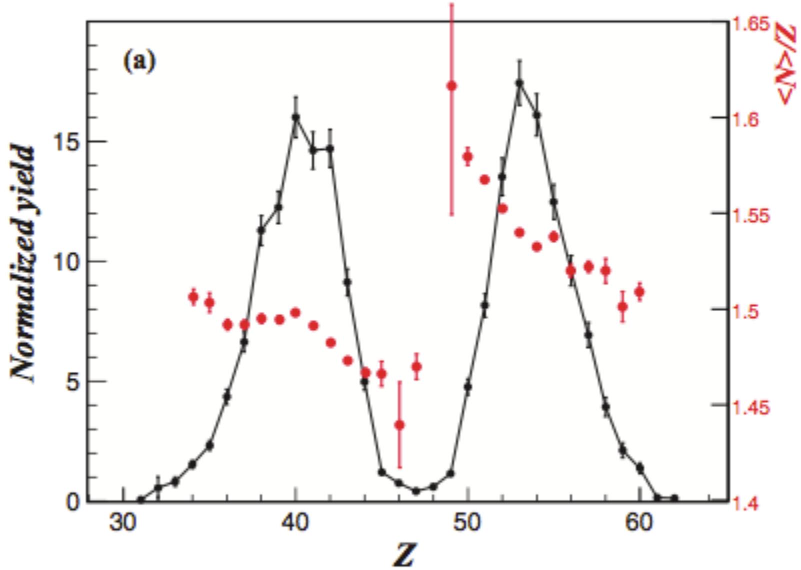
Can't choose your E*

See talk of D. Ramos

The strength of inverse kinematics for fission

Isotopic fission yields





^{240}Pu E*~10MeV

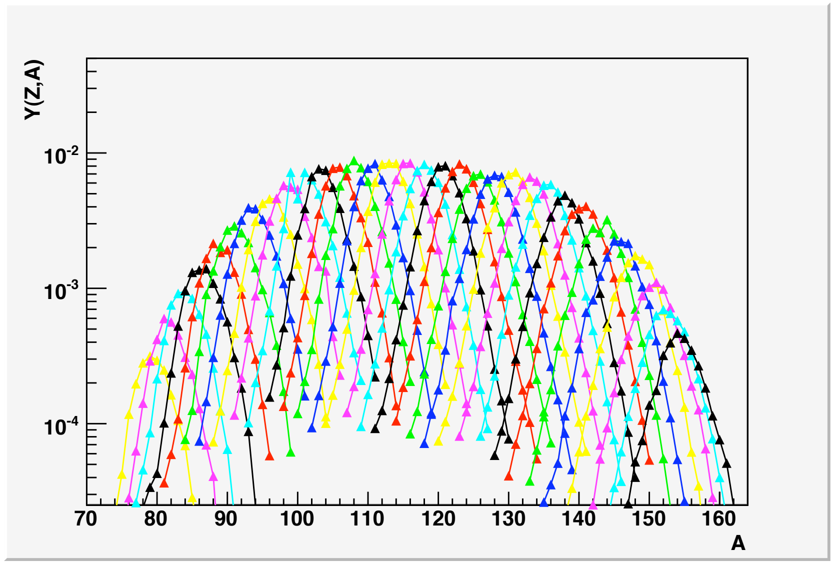
M. Caamaño et al., PRC 88 (2013) 024605

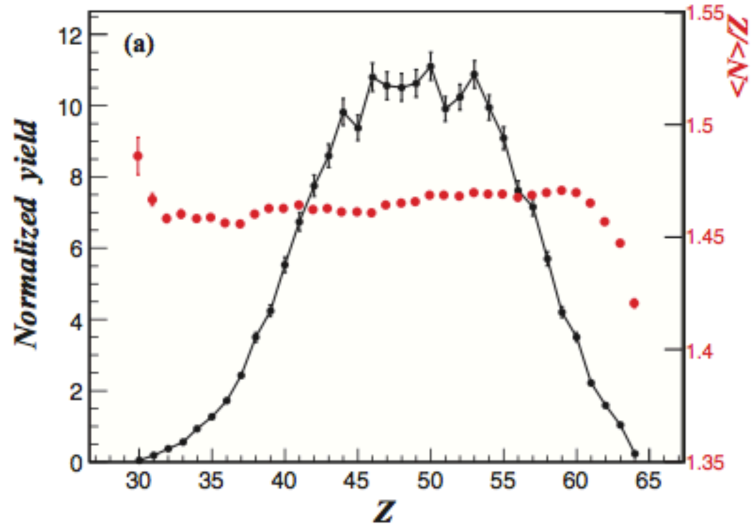
Neutron excess

$$\langle N\rangle(Z) = \frac{\sum_A A\, Y(Z,A)}{\sum_A Y(Z,A)} - Z.$$

The strength of inverse kinematics for fission

Isotopic fission yields





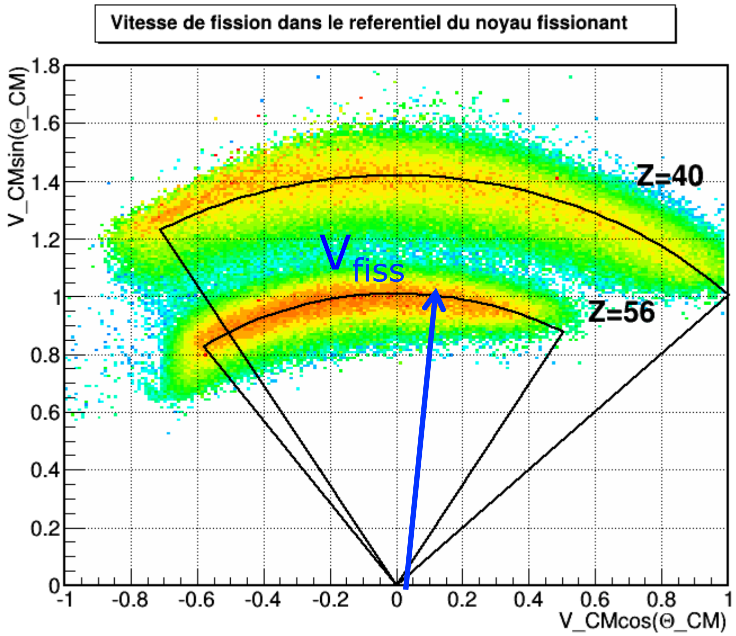
^{250}Cf E*~45MeV

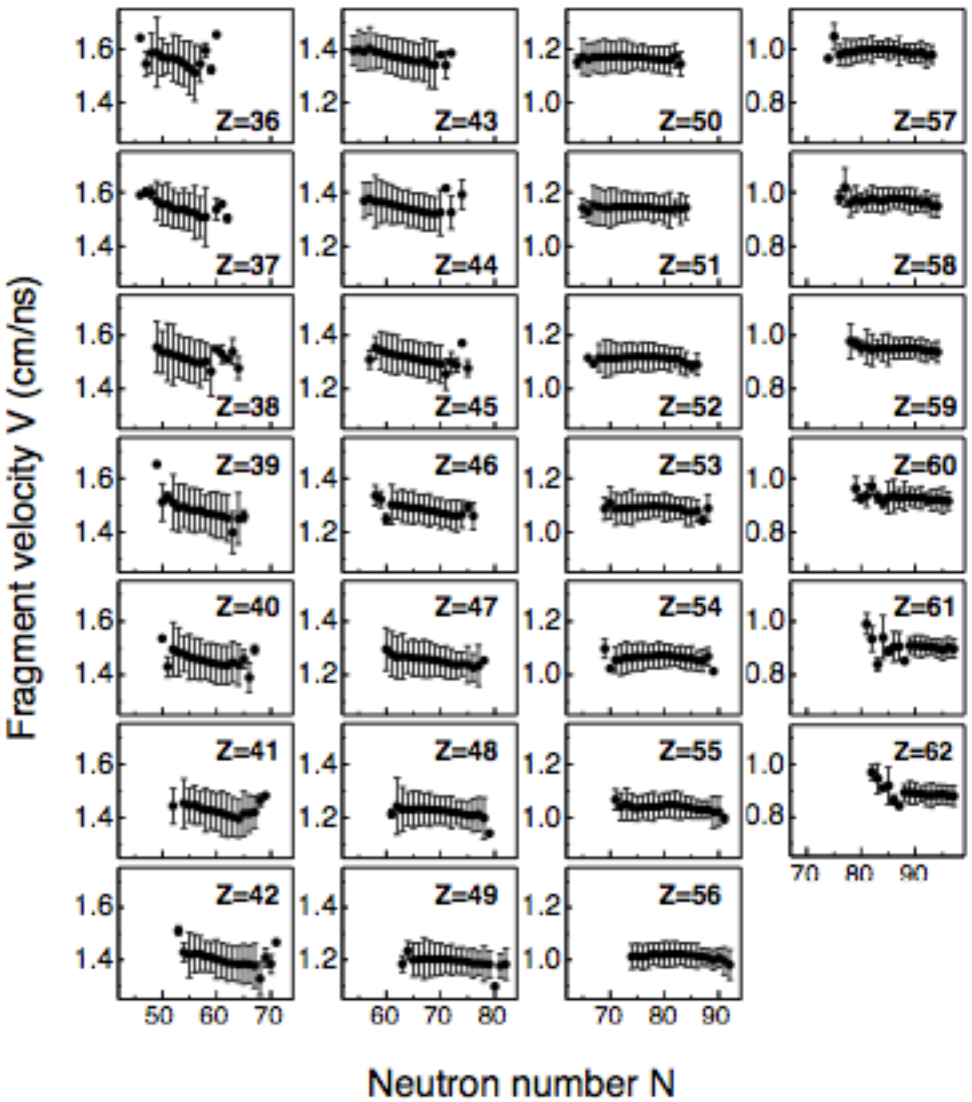
M. Caamaño et al., PRC 88 (2013) 024605

Neutron excess

$$\langle N \rangle(Z) = \frac{\sum_A A\, Y(Z,A)}{\sum_A Y(Z,A)} - Z.$$

Assets of the experimental set-up: Reconstruction of kinematical properties

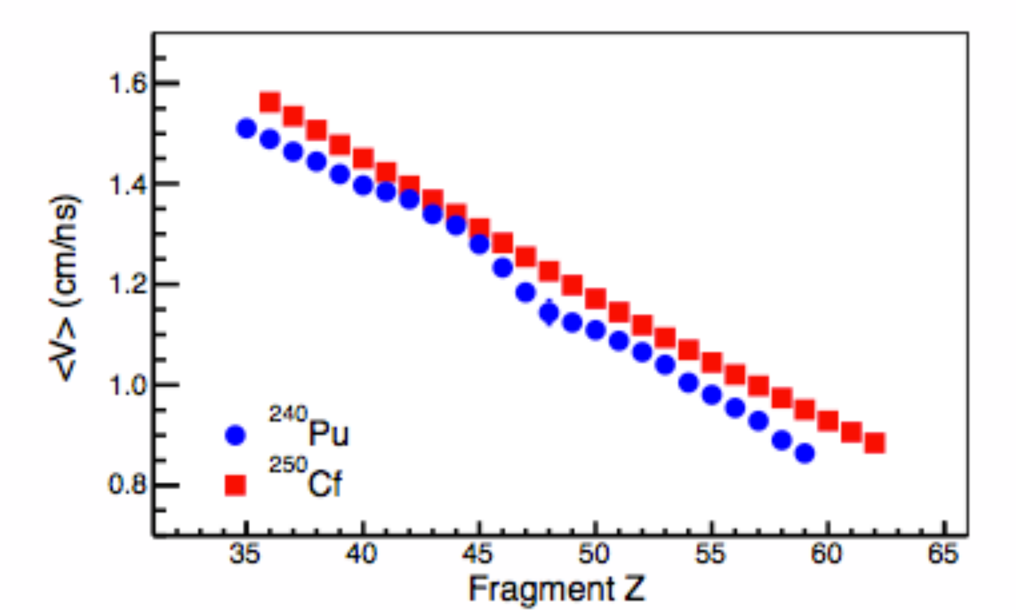




M. Caamaño, F. Farget et al**. PRC 92, 034606 (2015)**

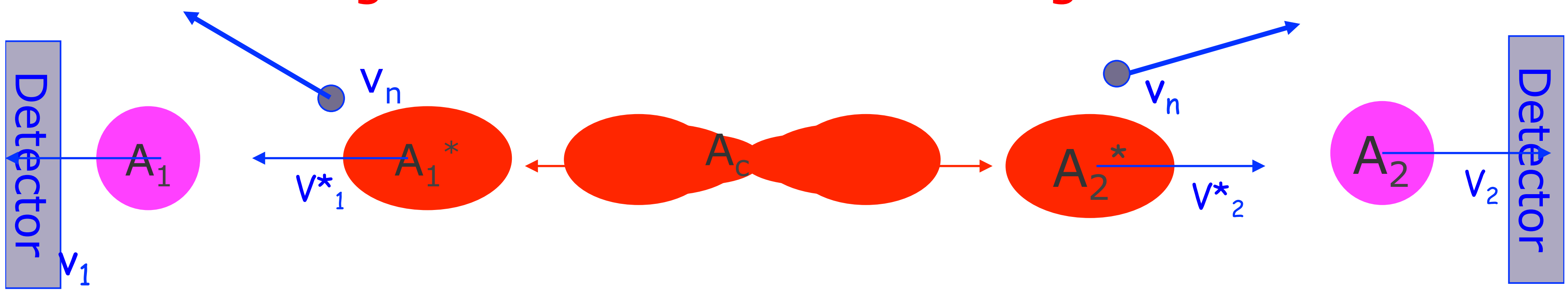
Average velocity of fission fragments

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



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

Recovering scission masses from fragment velocities



$A^*_1\, v^*_1 = A^*_2\, v^*_2$ — Momentum conservation

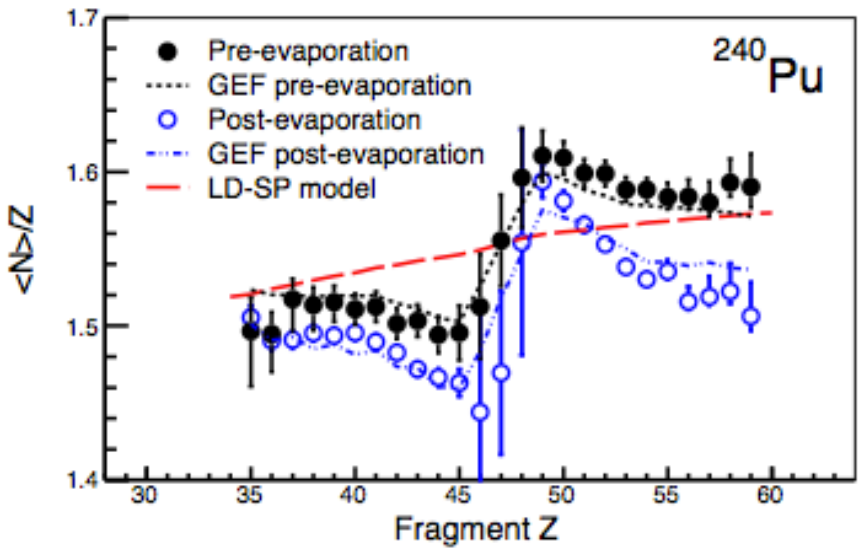
$< A^*_1>+ <A^*_2> = A_c$ — Mass conservation

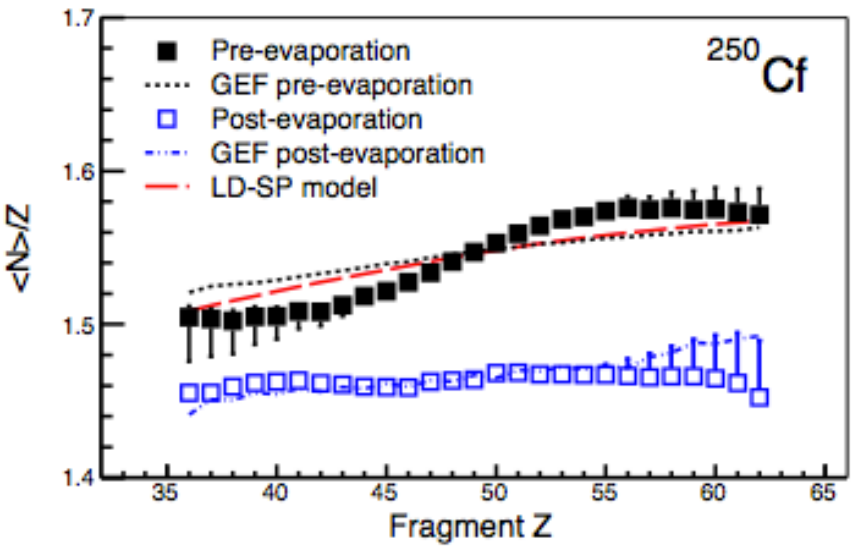
$<v^*_{1,2}> = <v_{1,2}>$ — Isotropic evaporation

$<v_1>/<v_2> = <A^*_2> / <A^*_1>$

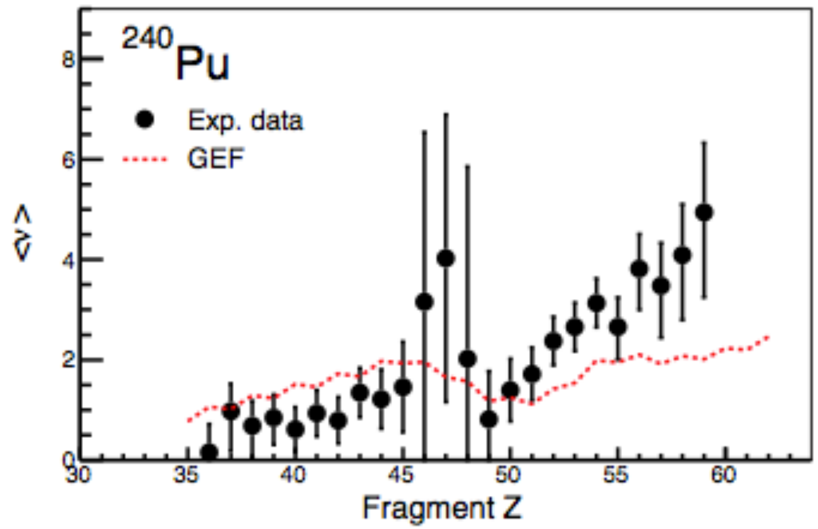
$$\boxed{\begin{aligned} <A^*_1> &= A_c\,(<v_1>/(<v_1>+ <v_2>)) \\ <A^*_2> &= A_c- <A^*_1> \end{aligned}}$$

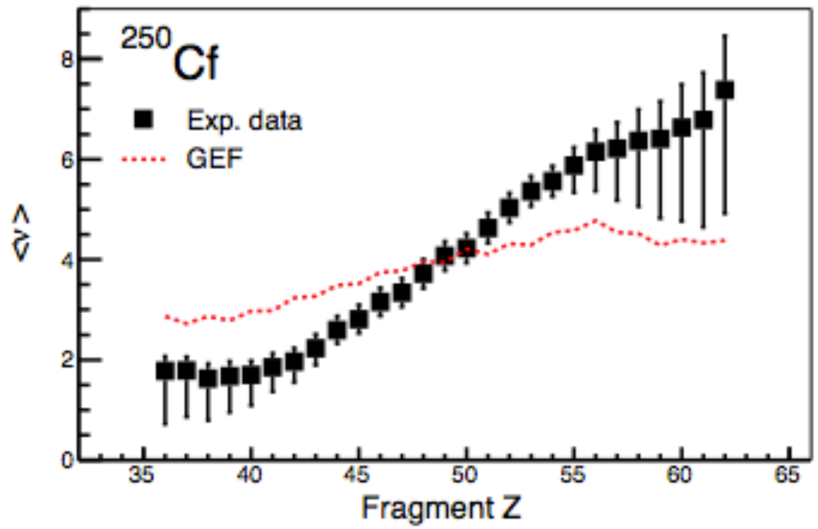
Average neutron excess @ scission



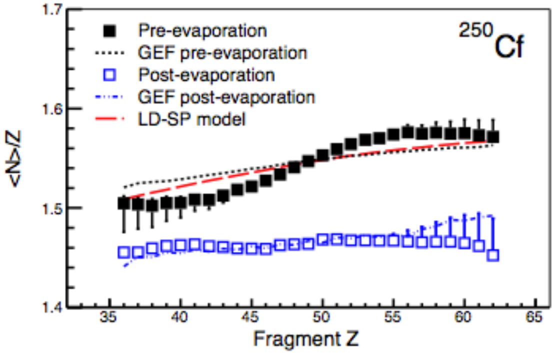


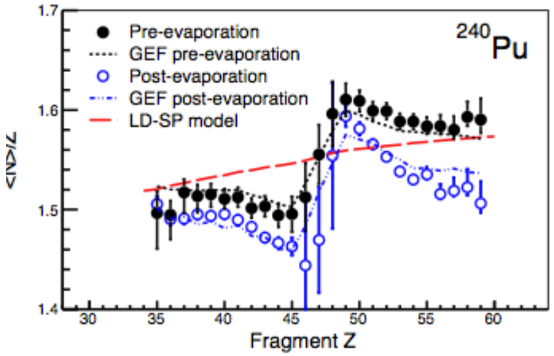
Average neutron multiplicities @ scission

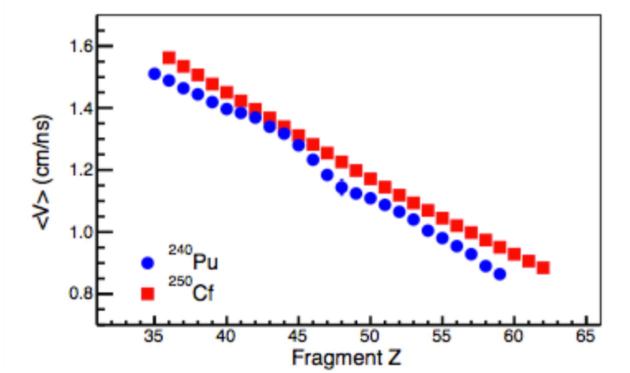




Determination of TKE(Z)

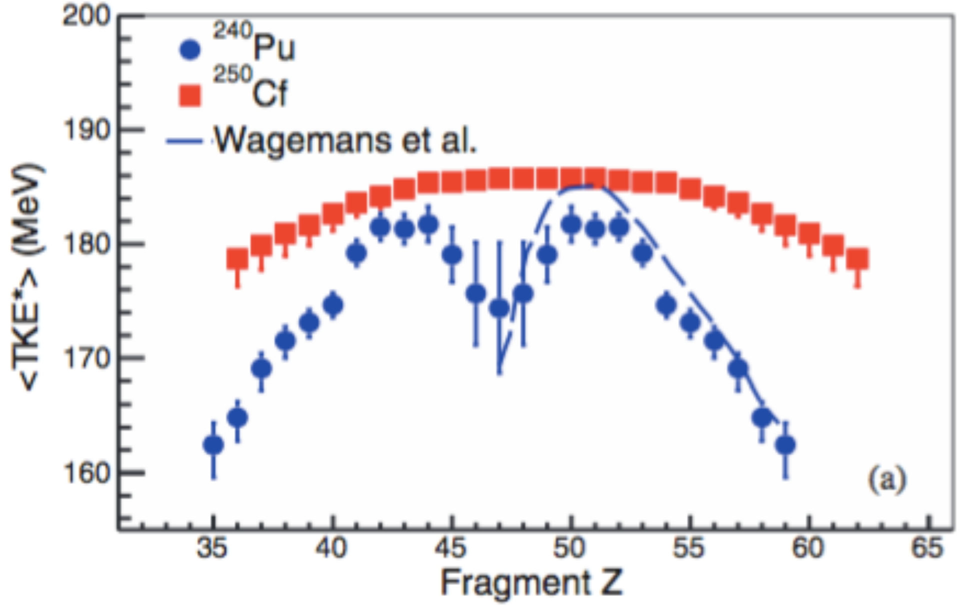






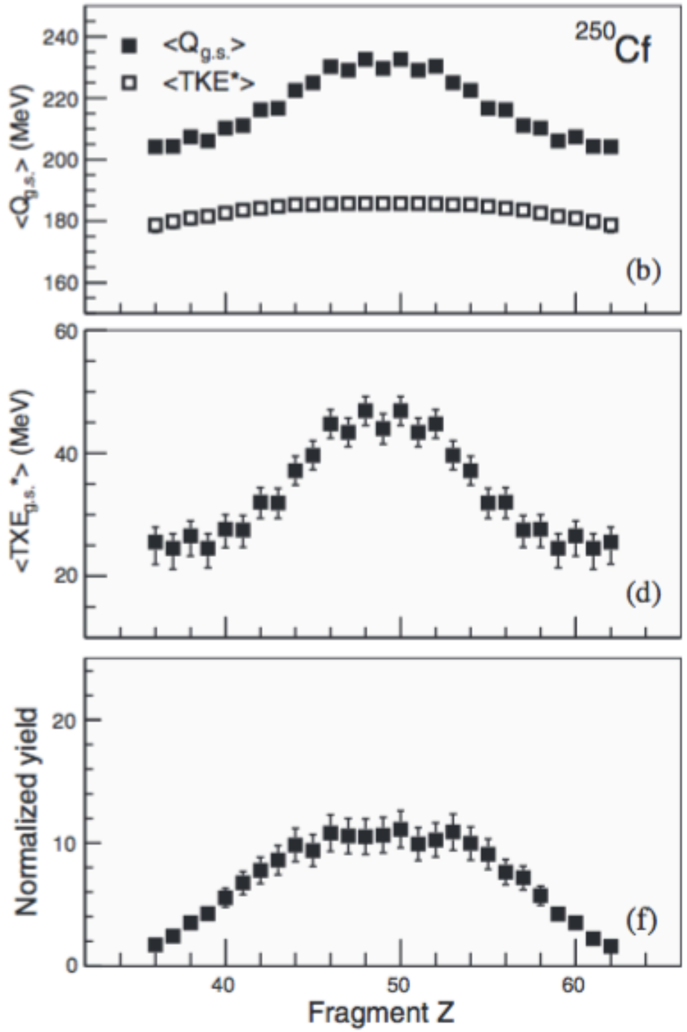
$$KE(Z_1) = 1/2\langle A_1{}^{*}\rangle(Z_1)\langle V_1\rangle^2$$

$$TKE(Z_1) = KE(Z_1) + KE(Z_c - Z_1)$$



Determination of TXE

$$\langle TXE^*_{\mathrm{g.s.}} \rangle = M_{\mathrm{FS}} - \langle M^*_1 \rangle - \langle M^*_2 \rangle - \langle TKE^* \rangle$$
$$= \langle Q_{\mathrm{g.s.}} \rangle - \langle TKE^* \rangle,$$



Sharing of TXE

Considering statistical equilibrium at scission

$$\bar{E}_1 = \frac{\int_0^E E_1 \rho_1(E_1) \rho_2(E - E_1) \, \mathrm{d}E_1}{\int_0^E \rho_1(E_1) \rho_2(E - E_1) \, \mathrm{d}E_1}$$

And the Fermi level density $\rho(E_i^*) \sim e^{2\sqrt{a_i E_i^*}}$

TXE shares following the level density parameters

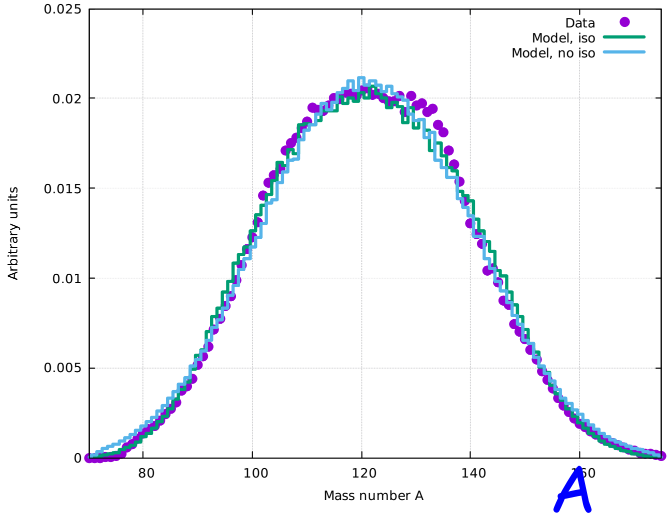
$$E_i^* = \frac{a_i E^*}{a_1 + a_2}$$

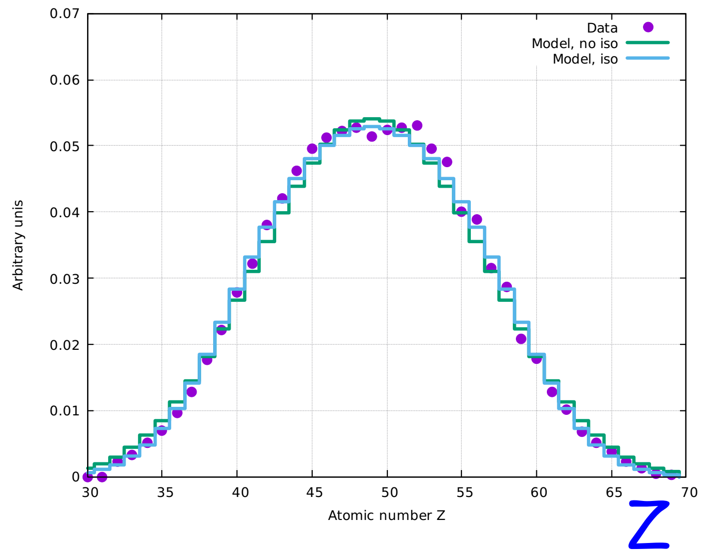
The statistical weight of each fission channel :

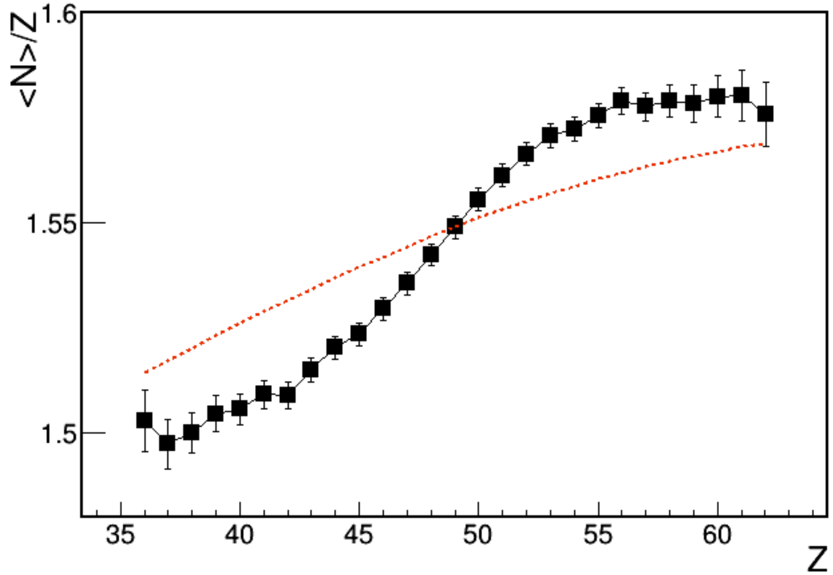
$$W_{12} = \rho_1(E_1^*) \rho_2(E_2^*)$$

Standard level density parameter

a_0=A/8







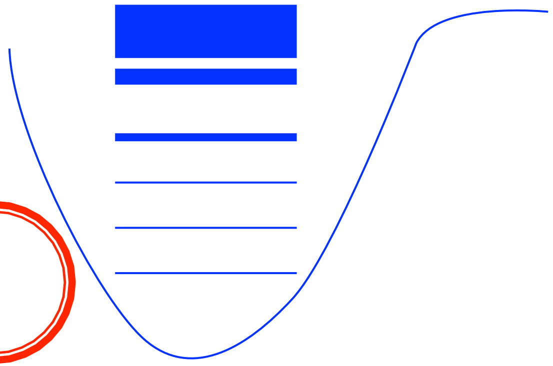
Evolution of level density parameter with isospin ?

$$a_i = \frac{A_i^\gamma}{a_0}\phi(I_i - I_\beta)$$

S. I. Al-Quraishi et al., PRC 63, 065803

2 arguments :

1



Approaching the drip-line,
the quasi-continuum is reached at much lower energy :
Life-time of states is smaller than the time to reach an equilibrium :
Fermi gas is expression is not valid anymore

2

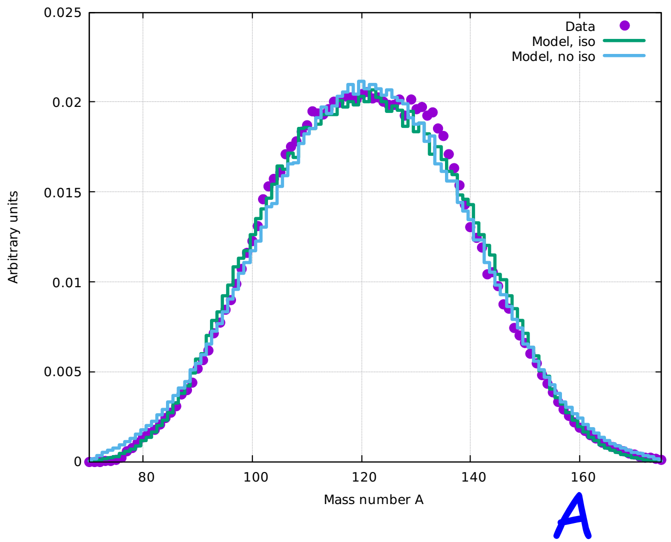
Number of accessible states must obey the Isospin conservation and scales from |N-Z| to |N+Z|
If N>>Z, number of states is reduced

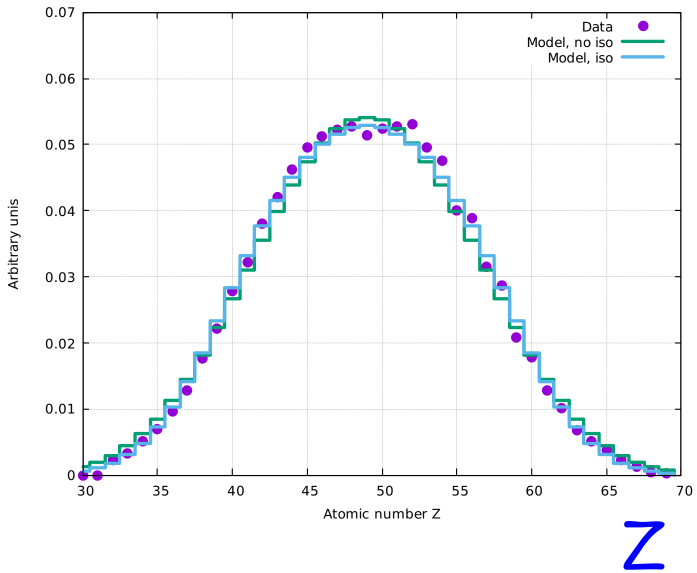
Evolution of level density parameter with isospin ?

$$a_i = \frac{A_i^\gamma}{a_0}\phi(I_i - I_\beta)$$

D. Durand, in preparation, 2016

$$\phi(I_i - I_\beta) = e^{-C_0(I_i - I_\beta)^2} = e^{-\frac{C_0(Z_i - Z_\beta)^2}{A_i^2}}$$





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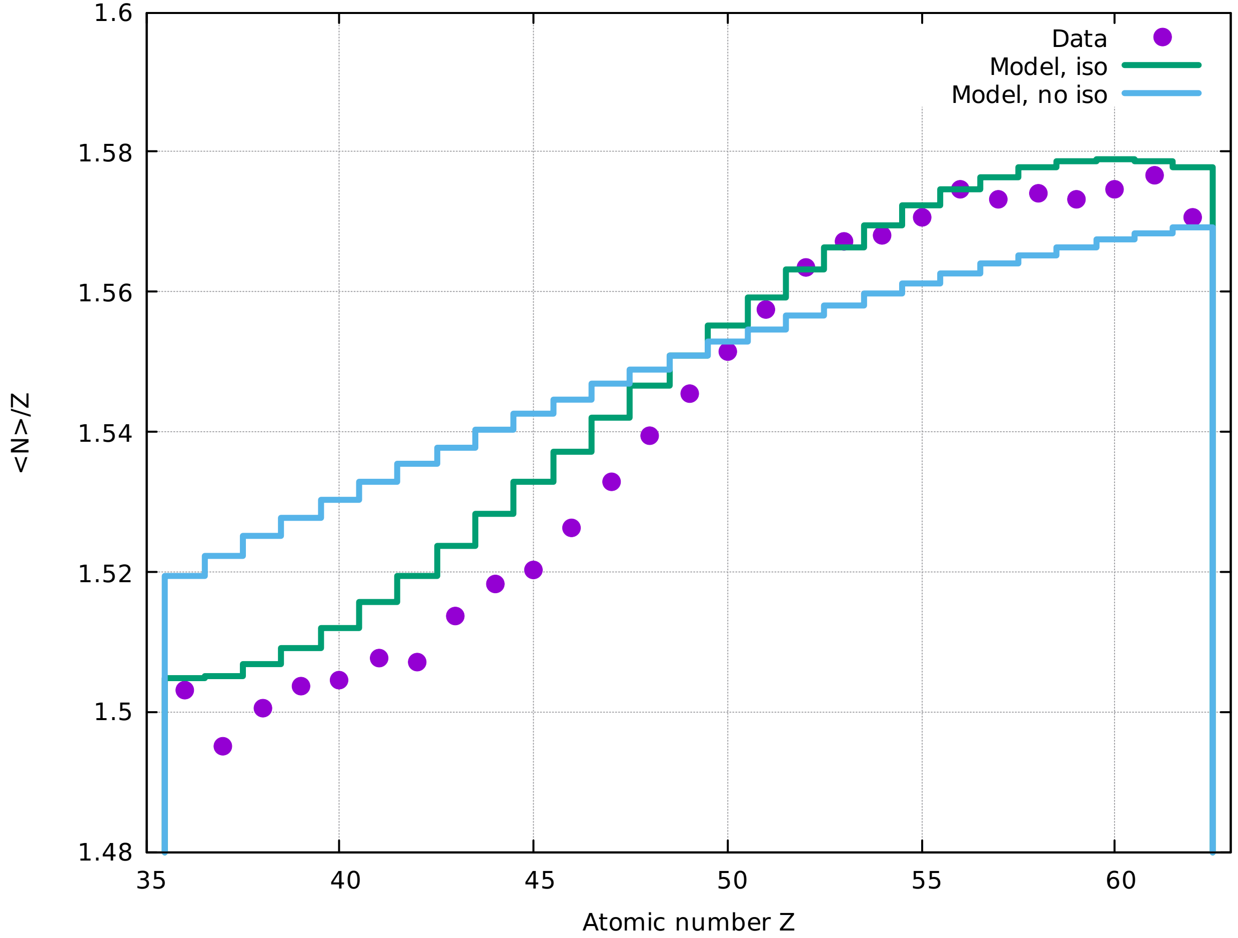
D. Durand, in preparation, 2016



CONCLUSIONS

- Inverse kinematics is a powerful method
  - Broad range of actinides produced
  - Isotopic distribution
  - Kinematical properties
  - Access to the scission point !!
    - Neutron evaporation multiplicity
    - Neutron and proton sharing

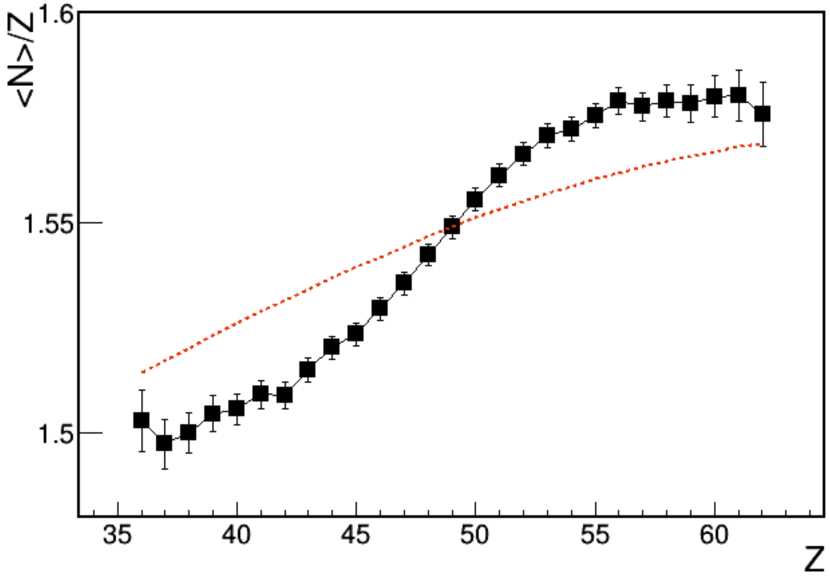
  - Evidence for (strong) charge polarisation at scission, even at moderate (high) excitation energy
  - Polarisation is a new and very sensitive observable to the description of fission
    - Effect of isospin on level density
    - Other property of the deformed scission nuclei ?

Scission point model:
minimization of the total potential energy

$$
\begin{aligned}
V(N_1, Z_1, \beta_1, N_2, Z_2, \beta_2, \tau, d) = {} & V_{\mathrm{LD}_1}(N_1, Z_1, \beta_1) + V_{\mathrm{LD}_2}(N_2, Z_2, \beta_2) \\
& \cancel{+ S_1(N_1, \beta_1, \tau) + S_1(Z_1, \beta_1, \tau) + S_2(N_2, \beta_2, \tau) + S_2(Z_2, \beta_2, \tau)} \\
& \cancel{+ P_1(N_1, \beta_1, \tau) + P_1(Z_1, \beta_1, \tau) + P_2(N_2, \beta_2, \tau) + P_2(Z_2, \beta_2, \tau)} \\
& + V_C(N_1, Z_1, \beta_1, N_2, Z_2, \beta_2, d) \cancel{+ V_n(N_1, Z_1, \beta_1, N_2, Z_2, \beta_2, d),}
\end{aligned}
$$

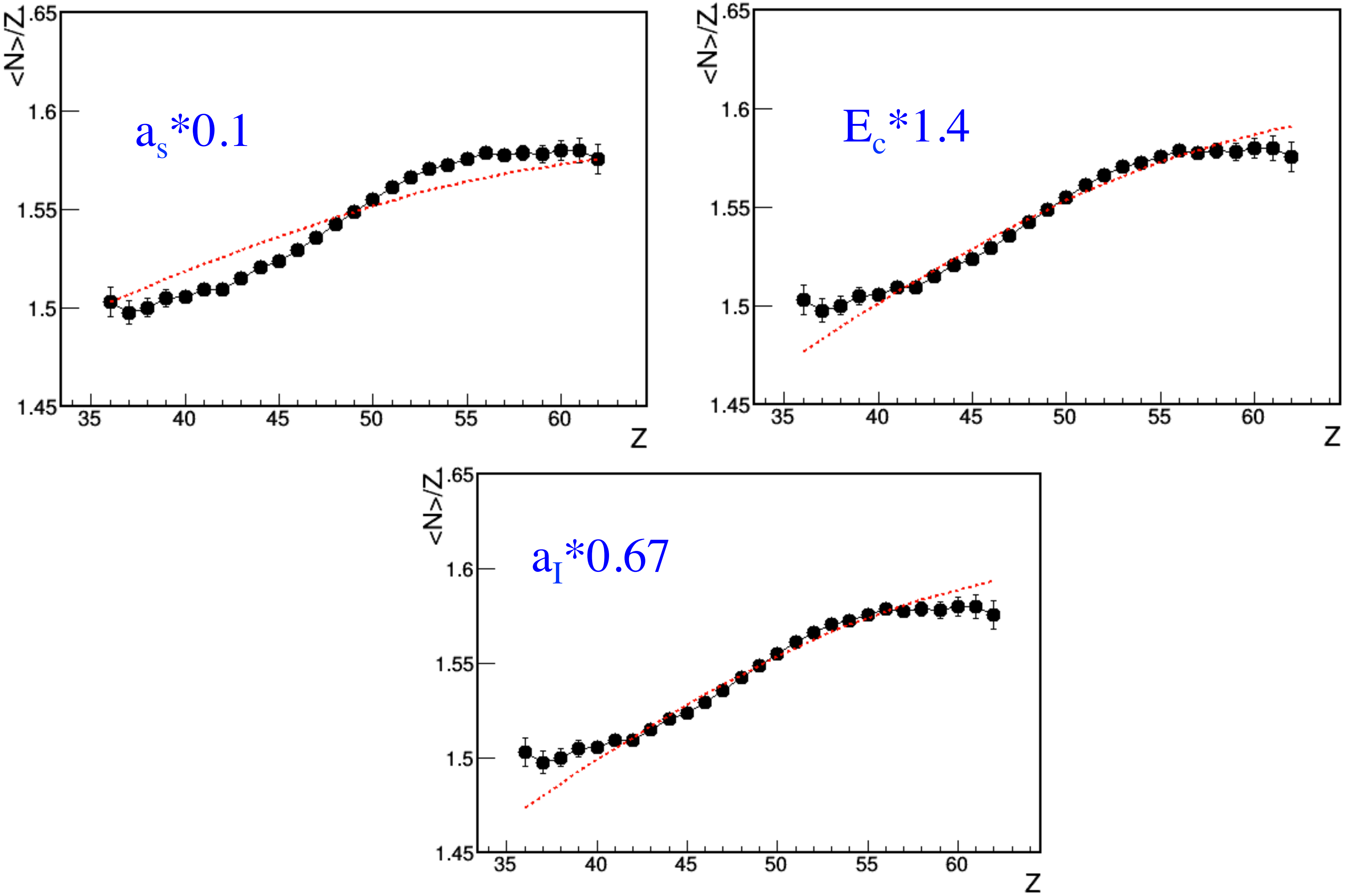
^{250}Cf E*=45 MeV :
only liquid-drop terms play a role (shell effects disapeared)

$$
\begin{aligned}
V_{LD}(Z, N, \beta) = {} & a_a A - a_s A^{2/3}(1 + 0.4\,\alpha^2) \\
& - 1.78\, I^2(a_a A - a_s A^{2/3}(1 + 0.4\,\alpha^2)) \\
& + Z^2((0.705/A^{1/3})(1 - 0.2\,\alpha^2) - 1.15/A)
\end{aligned}
$$

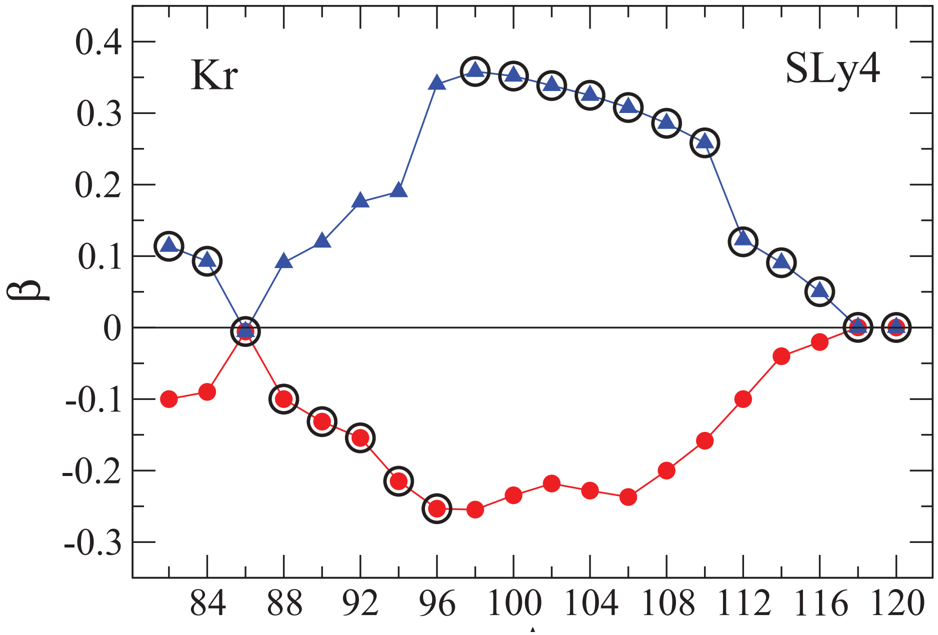


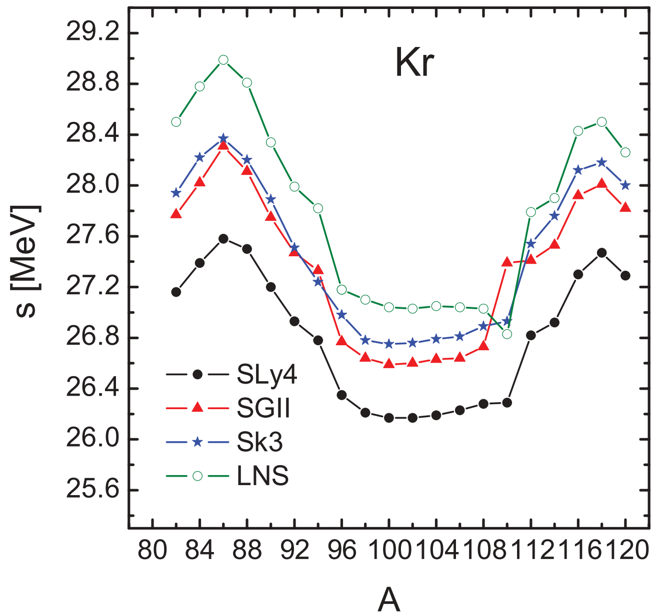
W.D. Myers, and W.J. Swiatecki, Ark. Fys., 36, 343, (1967)

Scission point model: influence of different mass terms



Diminution of symmetry energy with deformation ?





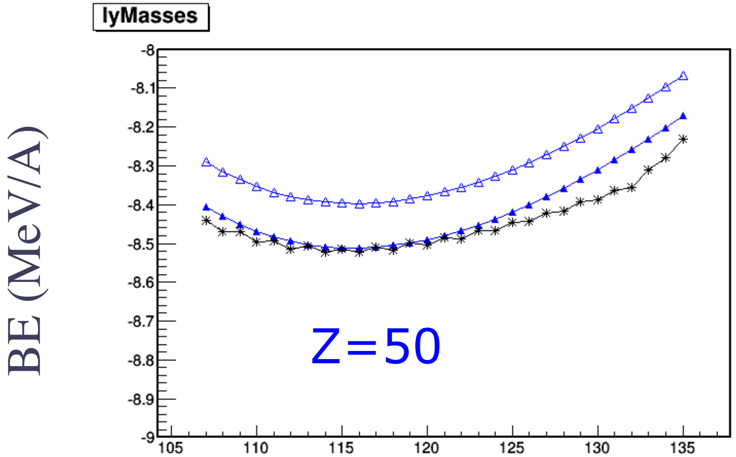
Gaidarov et al., PRC 85 (2012) 064319

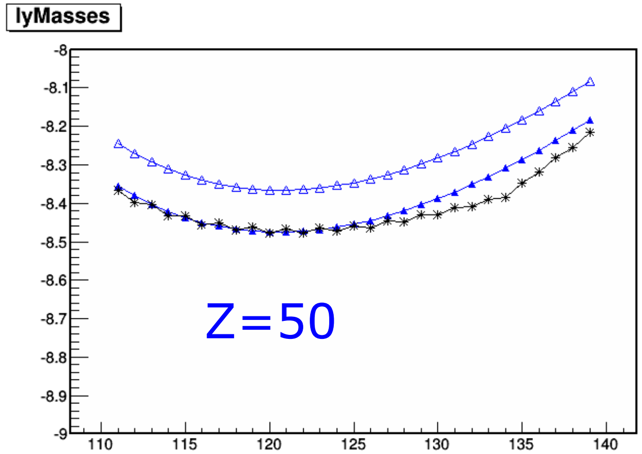
A diminution of 10% is predicted when deformation increases
From 0 to 0.4

⇒ What happens at scission deformation ??

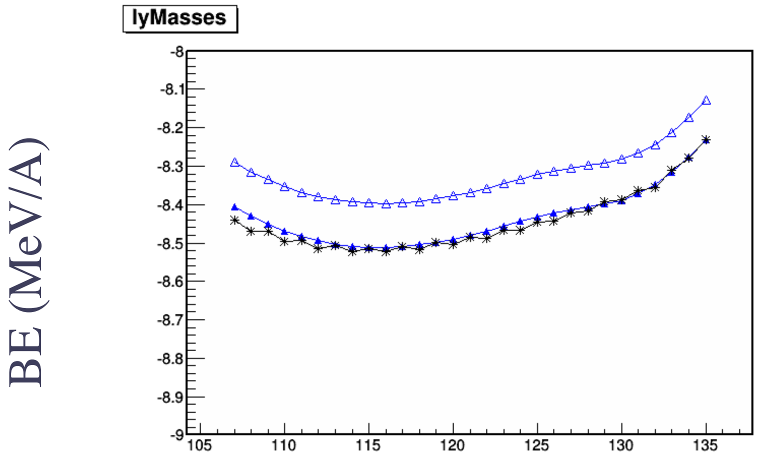
⇒ Effect of density ??

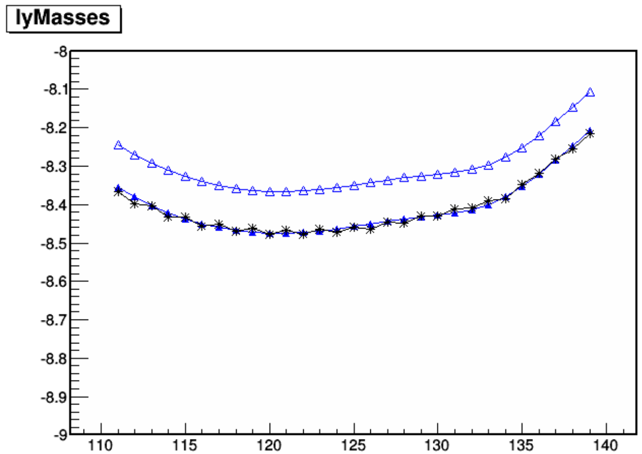
Other explanation: Remaining of shell effects in BE



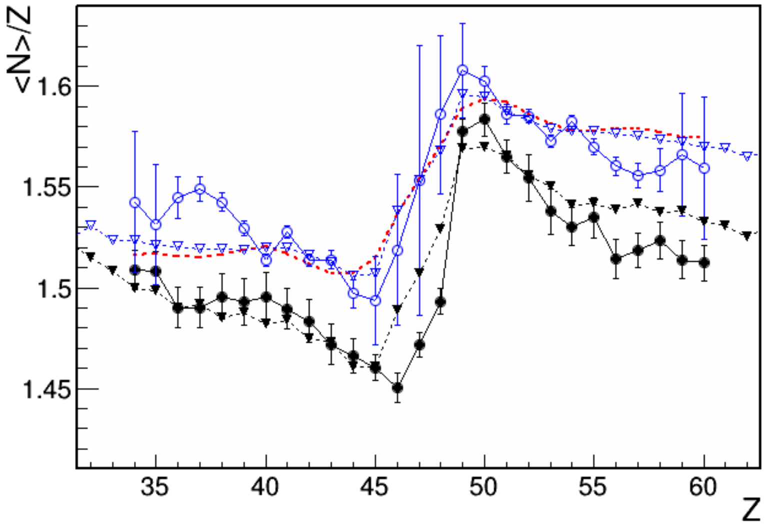


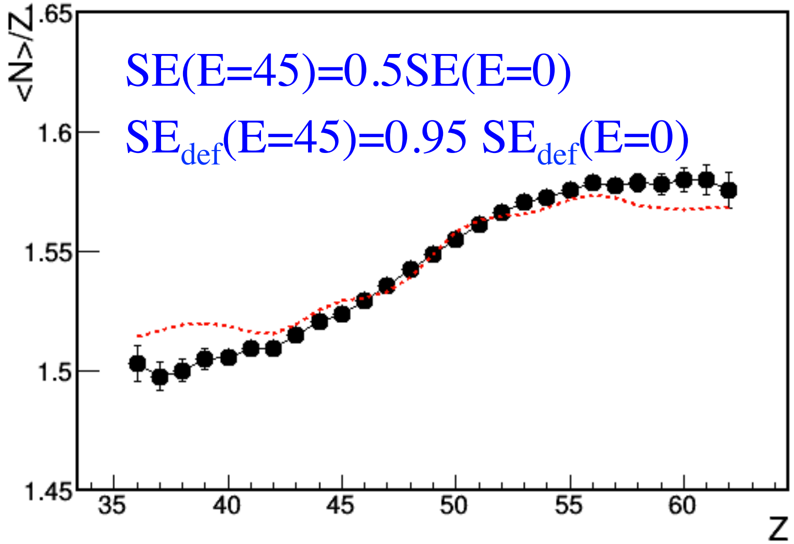
$$BE = BE + SE + SE_{def}$$
$$SE = 3*\exp(-(Z-50)^2/(2*3^2))*4*\exp(-(N-82)^2/(2*3.5^2))$$
$$SE_{def} = 3*\exp(-(Z-54)^2/(2*3^2))*4*\exp(-(N-90)^2/(2*3.5^2))$$





Scission-point model with shell effects





Shell effects remain quite strong, even at E*=45 MeV ??