Isotopic Fission-Fragment Distributions as a Deep Probe to Fusion-Fission Dynamics

Fanny Farget, Manuel Caamaño

Universidade de Santiago de Compostela (Spain)

O. Delaune, **X. Derkx**, **C. Rodríguez**, C. Golabek, A. Navin, M. Rejmund, T. Roger, M.G. Saint-Laurent, H. Savajols, C. Schmitt, C. Stodel, J.C. Thomas, A.C. Villari — GANIL (France)

D. Ramos, J. Benlliure, D. Cortina, B. Fernández — USC (Spain)

O. Tarasov, D. Bazin, W. Mittig, D.J. Morrisey, J. Pereira, B.M. Sherrill — NSCL (USA)

K.-H. Schmidt, B. Blank, S. Grévy, B. Jurado — CENBG (France)

E. Casarejos — U. de Vigo (Spain)

L. Audouin, C-O Bacri, L. Perrot — IPNO (France)

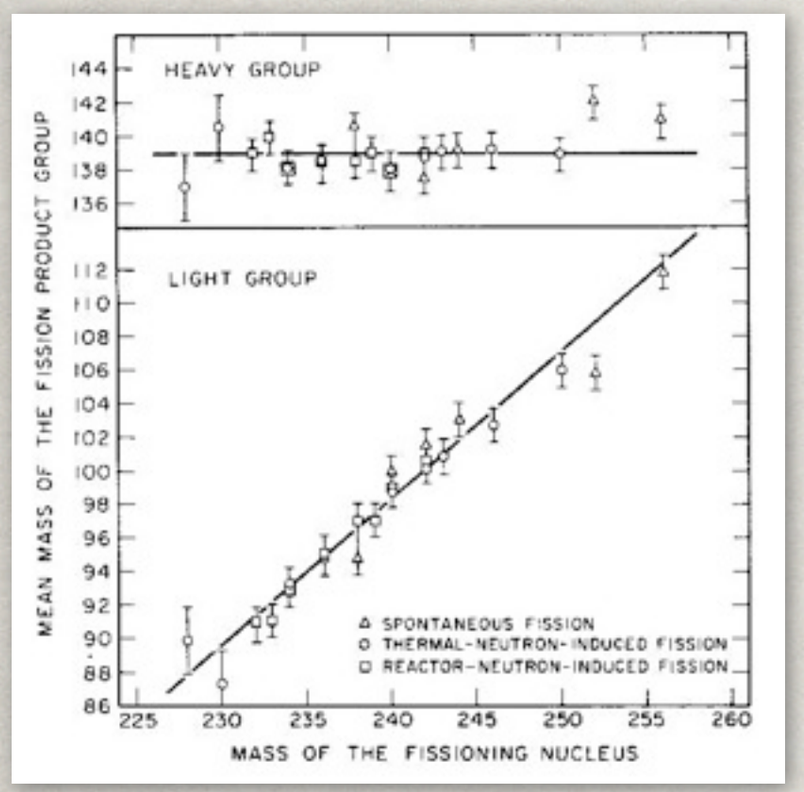
A. Heinz — U. of Chalmers (Sweden)

D. Doré, M. Delphine de Salsac — SPhN (France)

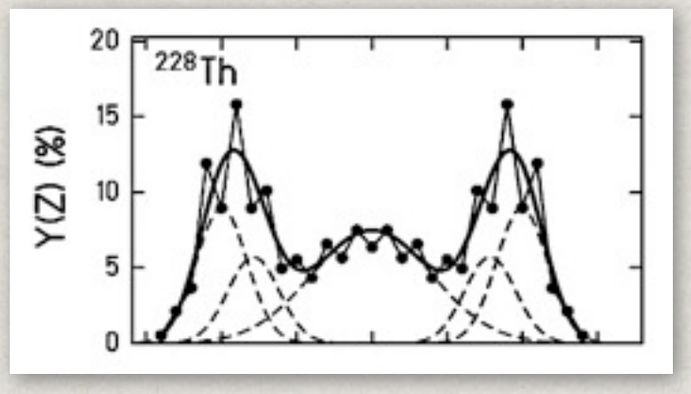
S. Lukyanov — FNLR (Russia)

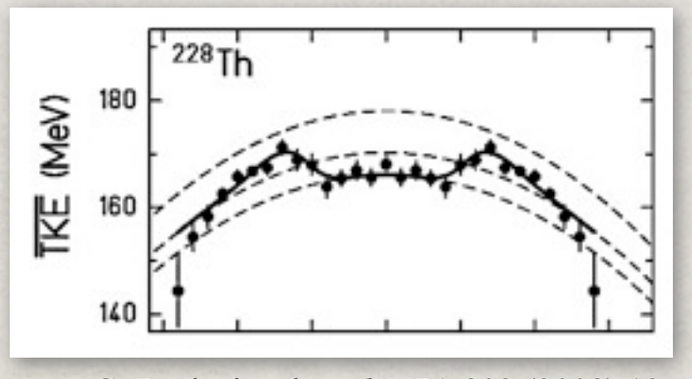
L. Gaudefroy — CEA DIF (France)

Experimental observables



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



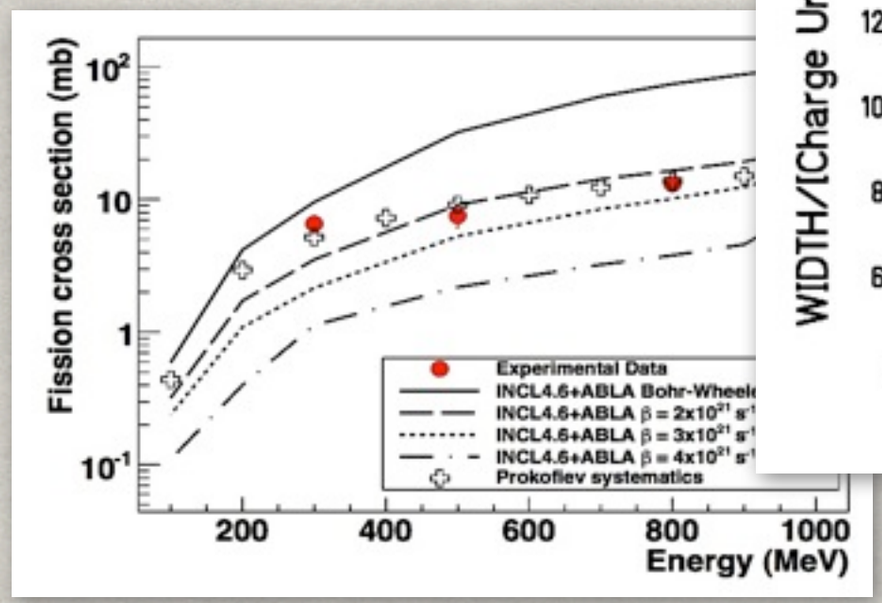


C. Böckstiegel *et al.* NPA 802 (2008) 12

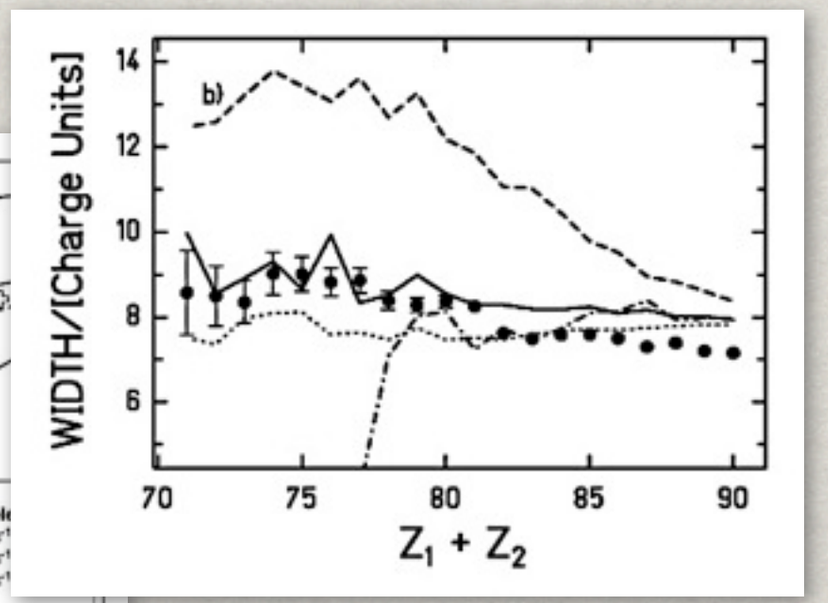
Mass, **Z**, and **TKE** showed that shell effects come into play

Measurements of **fragment distributions** and **yields** hints on the dynamics of fission

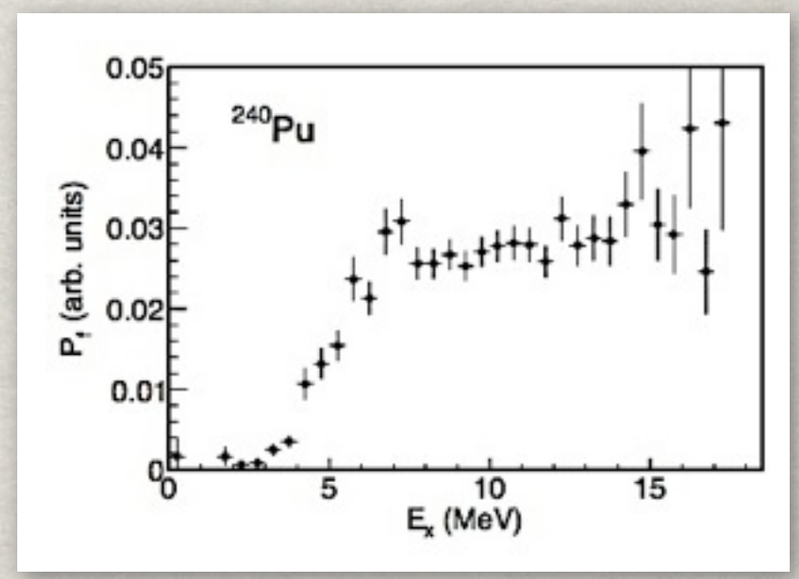
Fission probabilities reveal barrier's features



Y. Ayyad, PhD U. Santiago C (2012)



B. Jurado *et al.* PRL 93 (2004) 072501



C. Rodríguez-Tajes *et al.*, to be published

Experimental observables

Different reactions grant the access to
different observables and conditions

Direct kinematics

Inverse kinematics

neutron - induced fission:

- control of E*
- no high L

- limited to stable targets
- no access to Z

spallation/EM - induced fission:

- inverse kinematics (A, Z of fragments)
- access to unstable FS
- no high L

- no control of E*
- reduced control on FS

fusion - induced fission:

- control of E*
- access to unstable FS

- high L
- quasi-fusion

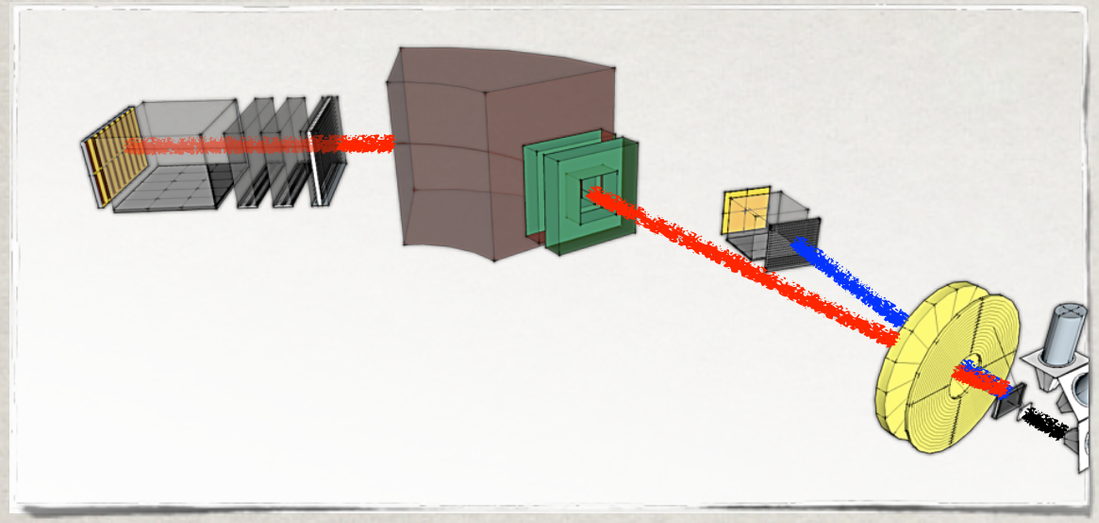
transfer - induced fission:

- control of E*
- inverse kinematics (A, Z of fragments)
- access to unstable FS
- includes fusion for free

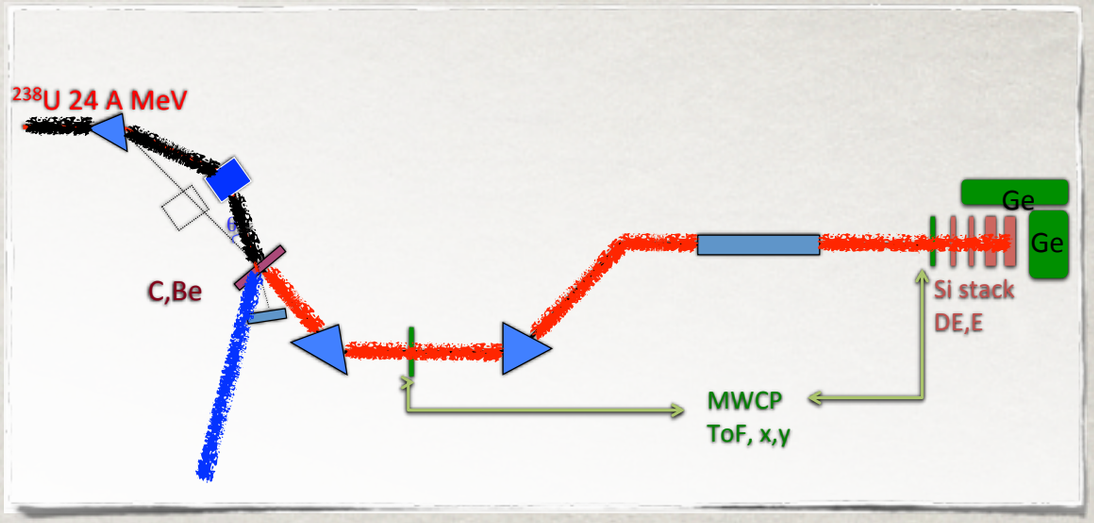
- high L
- quasi-fusion

Transfer/fusion-induced fission: three flavors

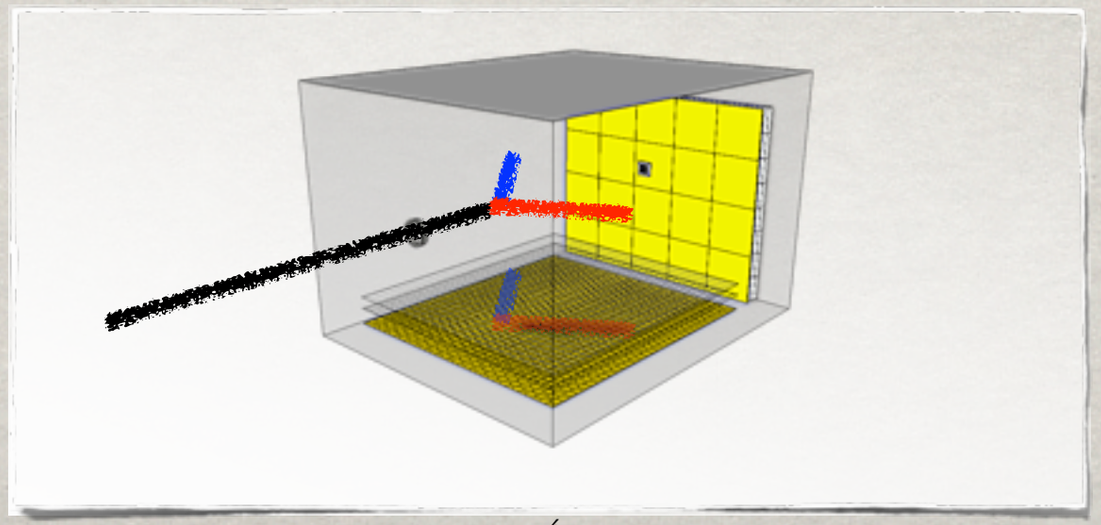
^{238}U (6.1 AMeV) + ^{12}C at VAMOS



^{238}U (24 AMeV) + ^{12}C/^{9}Be at LISE

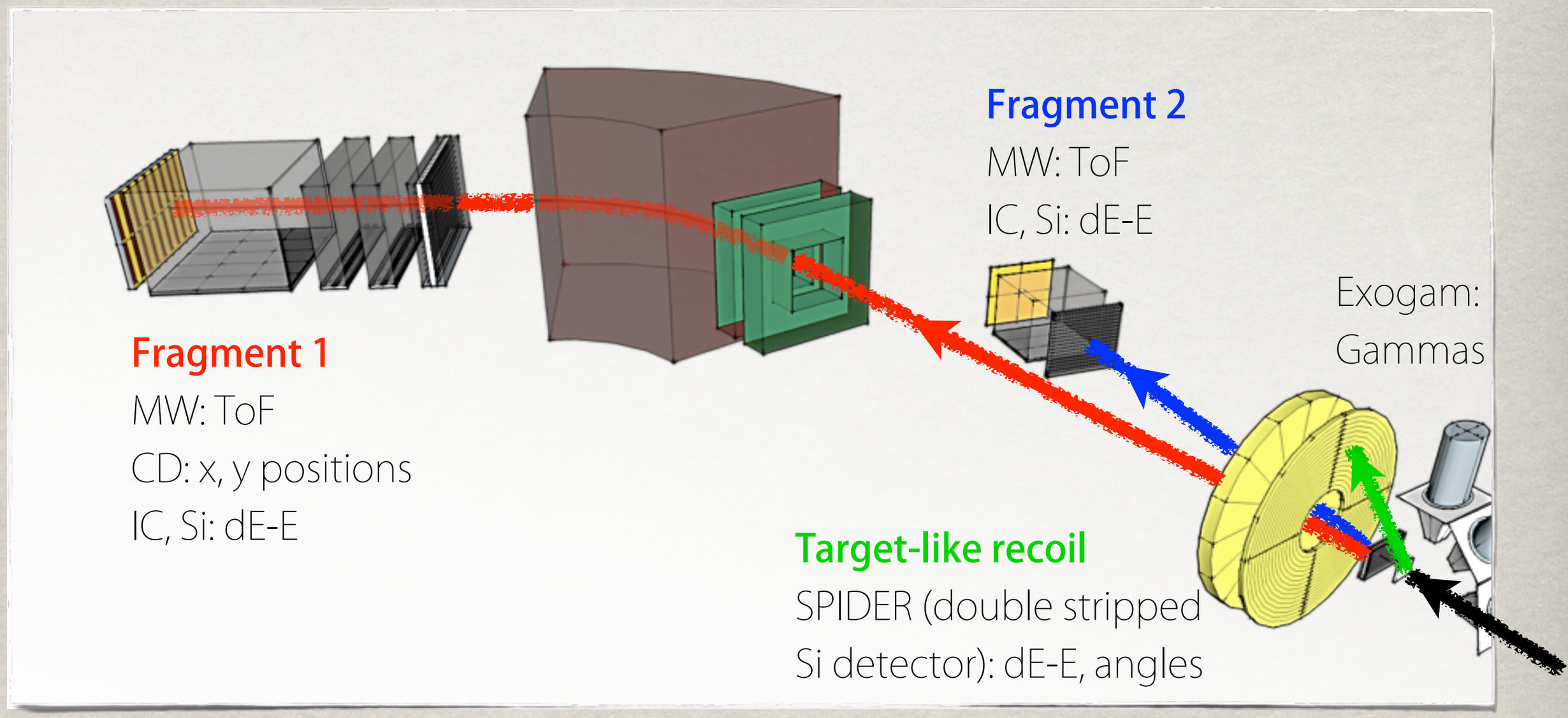


^{238}U (6 AMeV) + ^{12}C/^{2}H/^{1}H with MAYA



^{238}U (6.1 AMeV) + ^{12}C at VAMOS

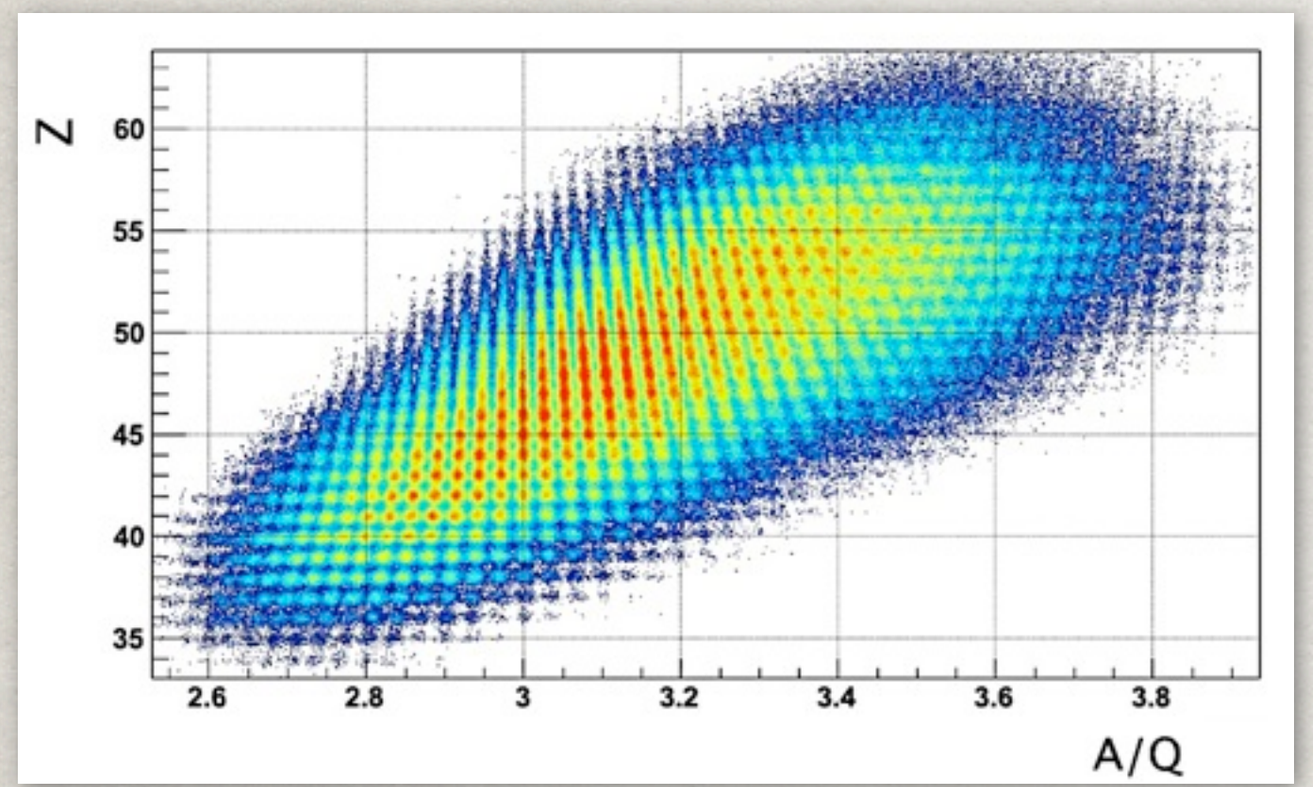
- Setup based on **inverse kinematics**
- Transfer reactions produce unstable species, induce fission.



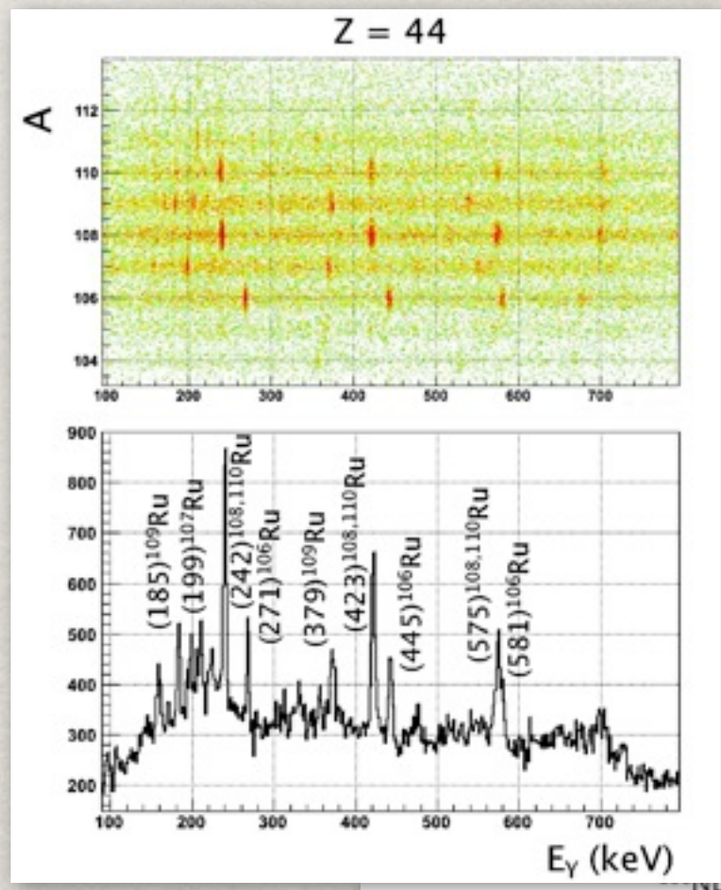
FS's observables: **Z, A, E***.

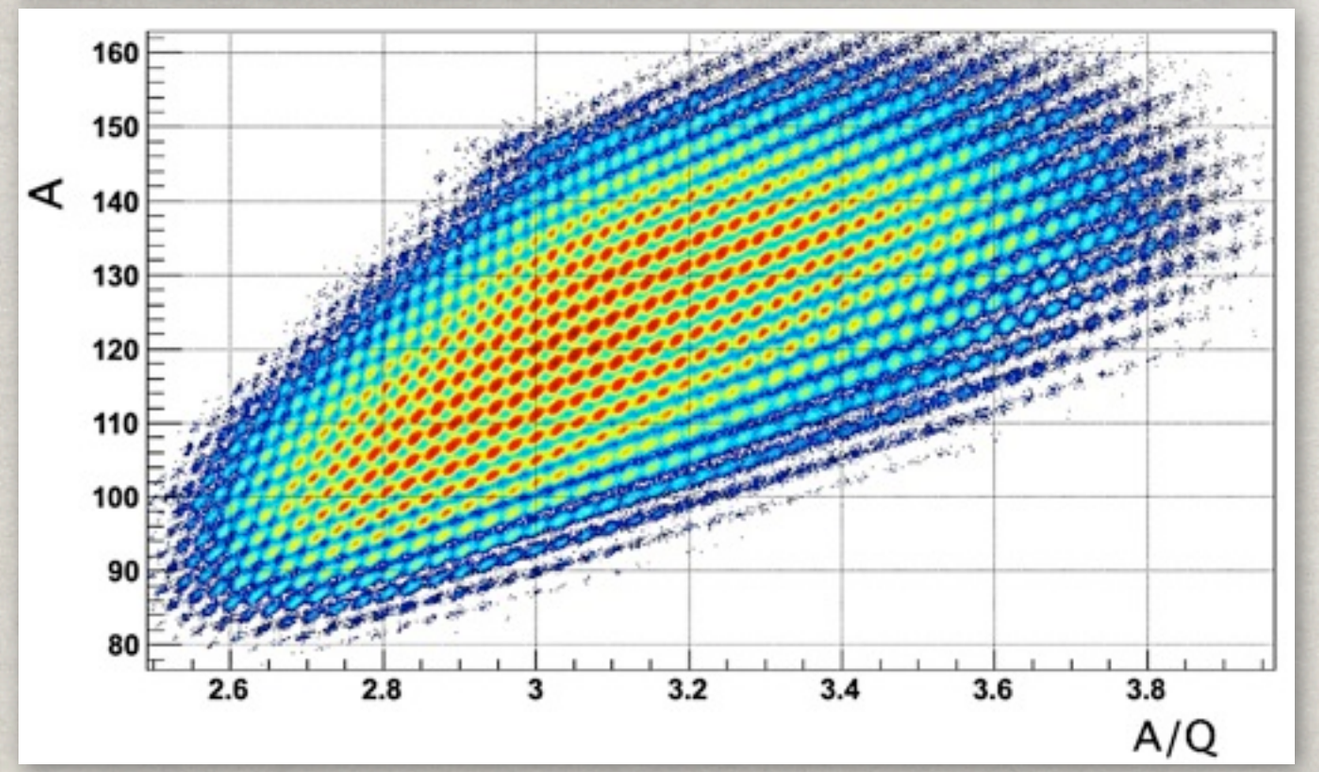
Fragments' observables: **Z, A, q, angles, velocity**, gammas.

^{238}U (6.1 AMeV) + ^{12}C at VAMOS

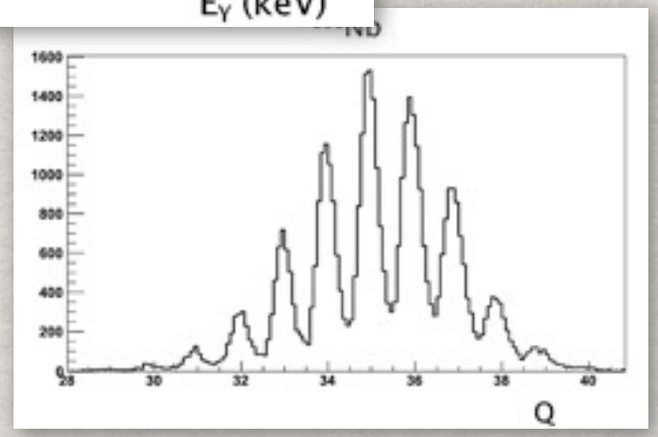


A from 80 to 160 (σ/A~0.3 %)
and Z from 30 to 70 (σ/Z~0.9 %)
confirmed by gamma identification.



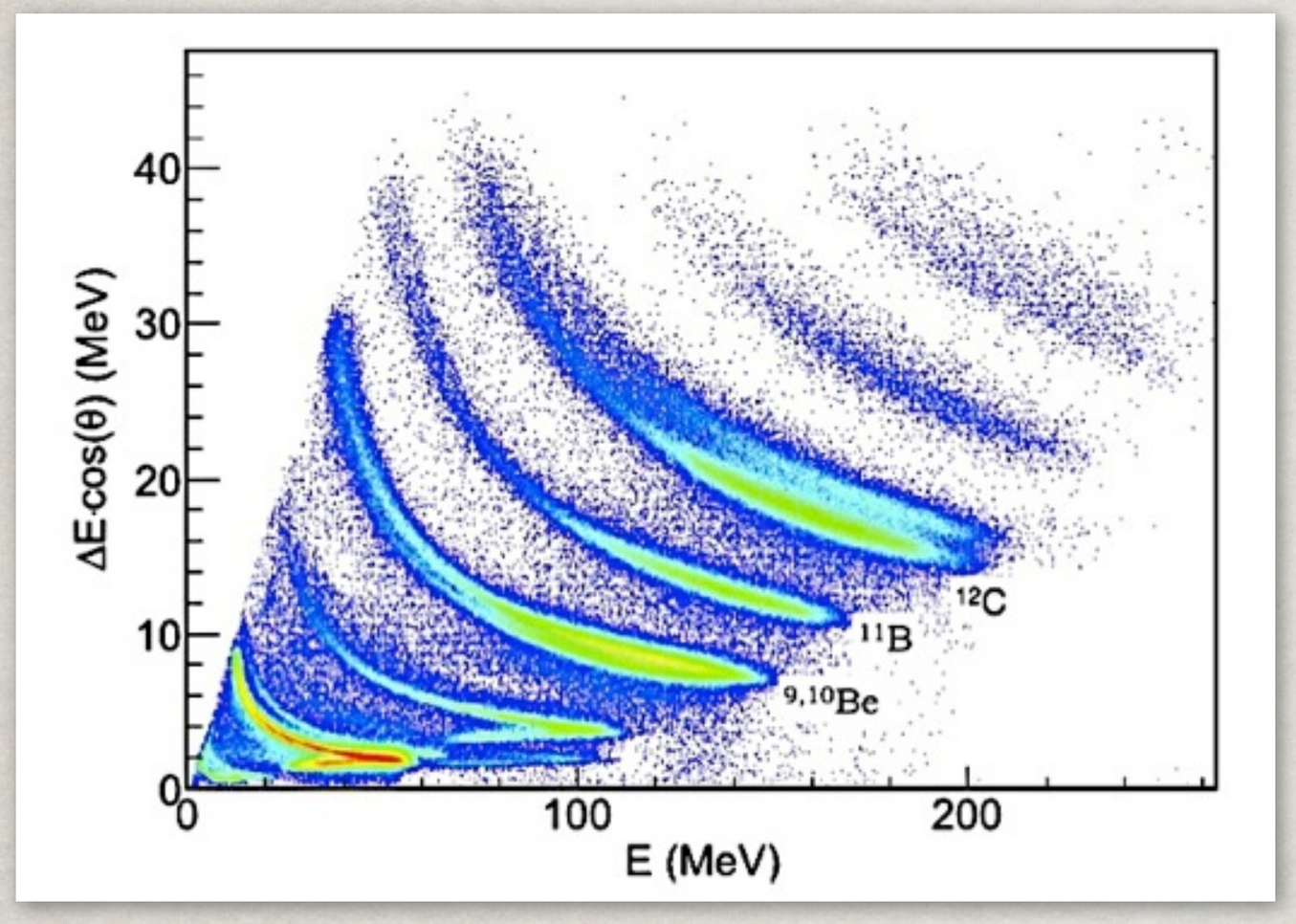


~10 q states
per isotope



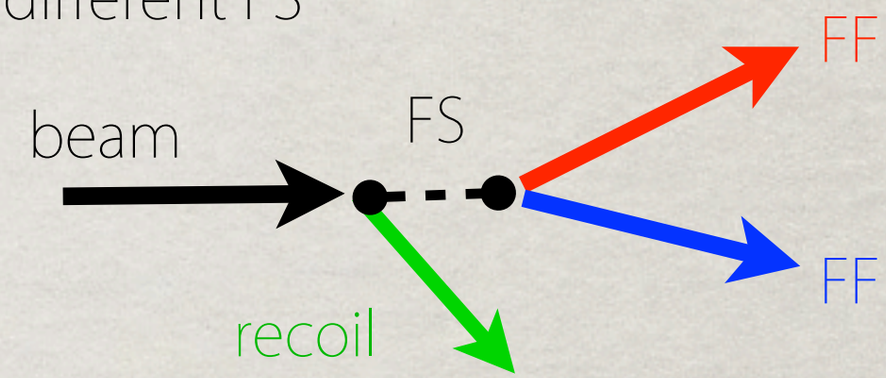
D. Ramos, PhD at U. Santiago de Compostela

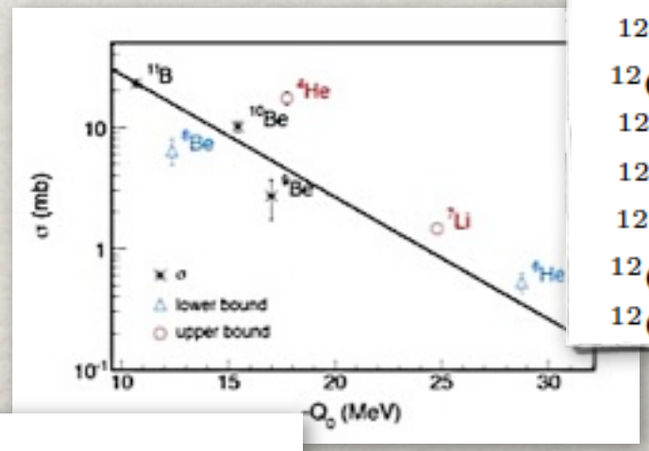
^{238}U (6.1 AMeV) + ^{12}C at VAMOS



C. Rodríguez-Tajes *et al.*, to be published

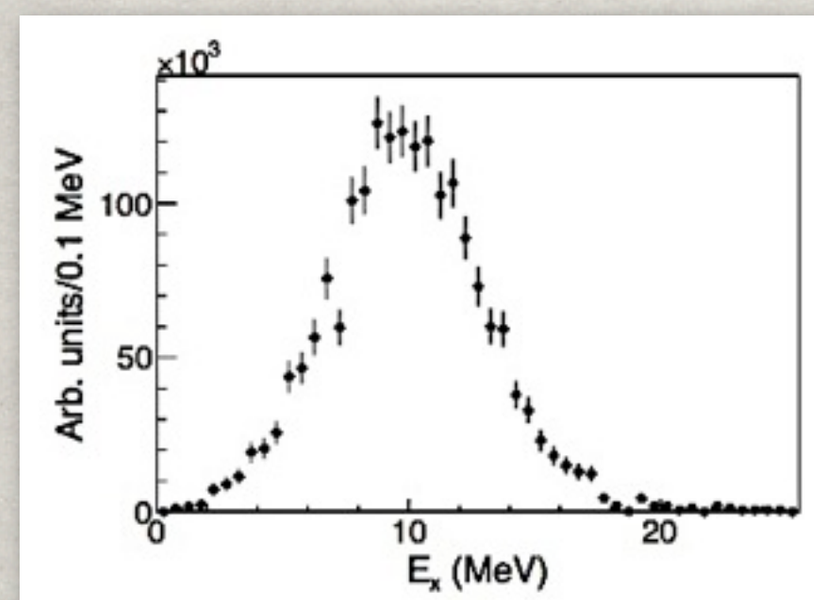
The target-like recoil tags the different FS

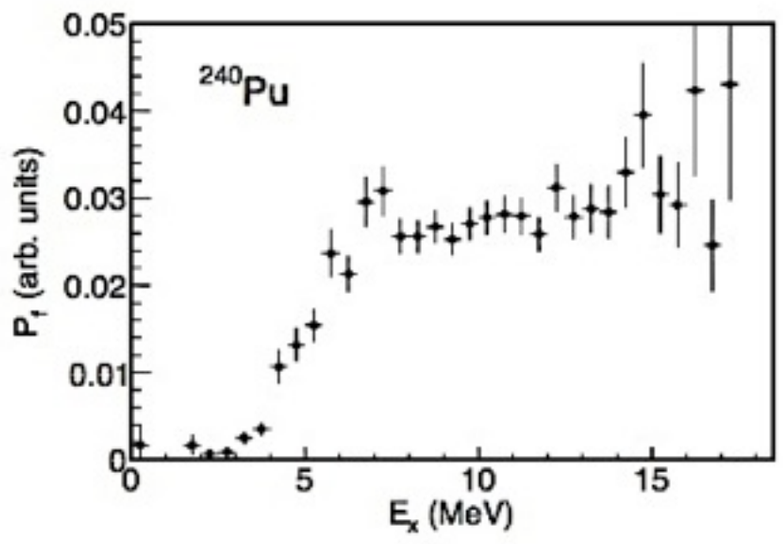




Inelastic, E_x >4 MeV

^{12}C(^{238}U,^{236}U)^{14}C
^{12}C(^{238}U,^{239}Np)^{11}B
^{12}C(^{238}U,^{240}Pu)^{10}Be
^{12}C(^{238}U,^{241}Pu)^{9}Be
^{12}C(^{238}U,^{242}Pu)^{8}Be
^{12}C(^{238}U,^{243}Am)^{7}Li
^{12}C(^{238}U,^{244}Cm)^{6}He
^{12}C(^{238}U,^{246}Cm)^{4}He

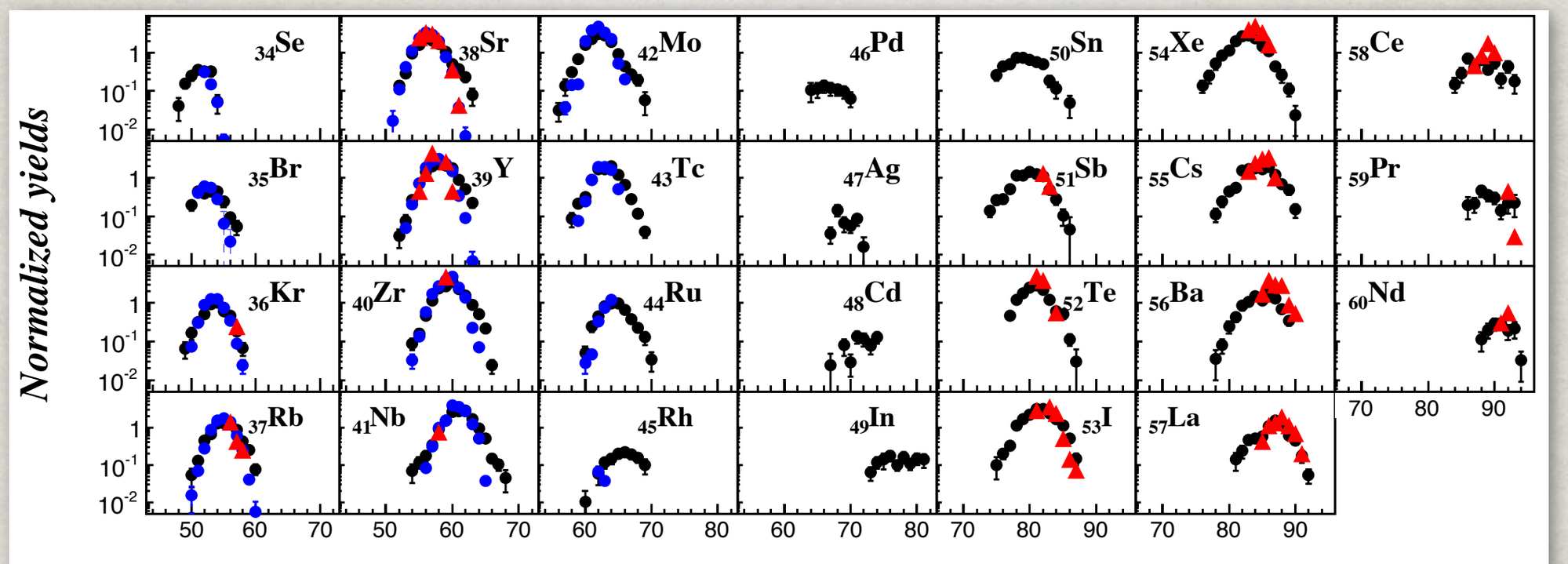




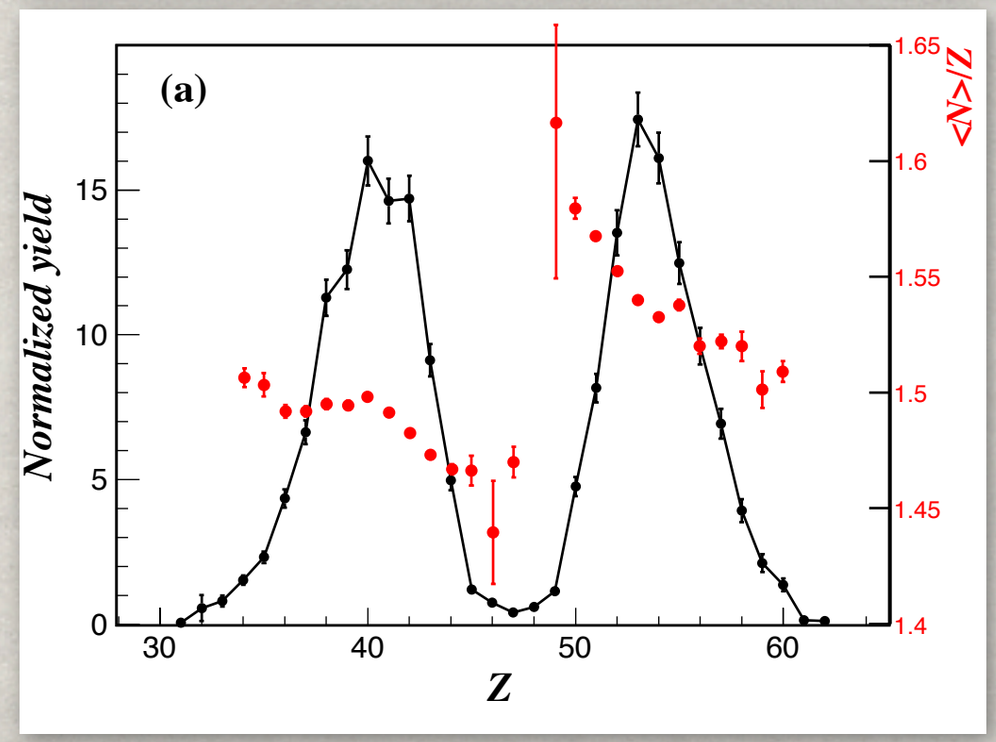
the E* (σ ~1 MeV) is deduced from kinematics.
Fission probability shows barrier's features

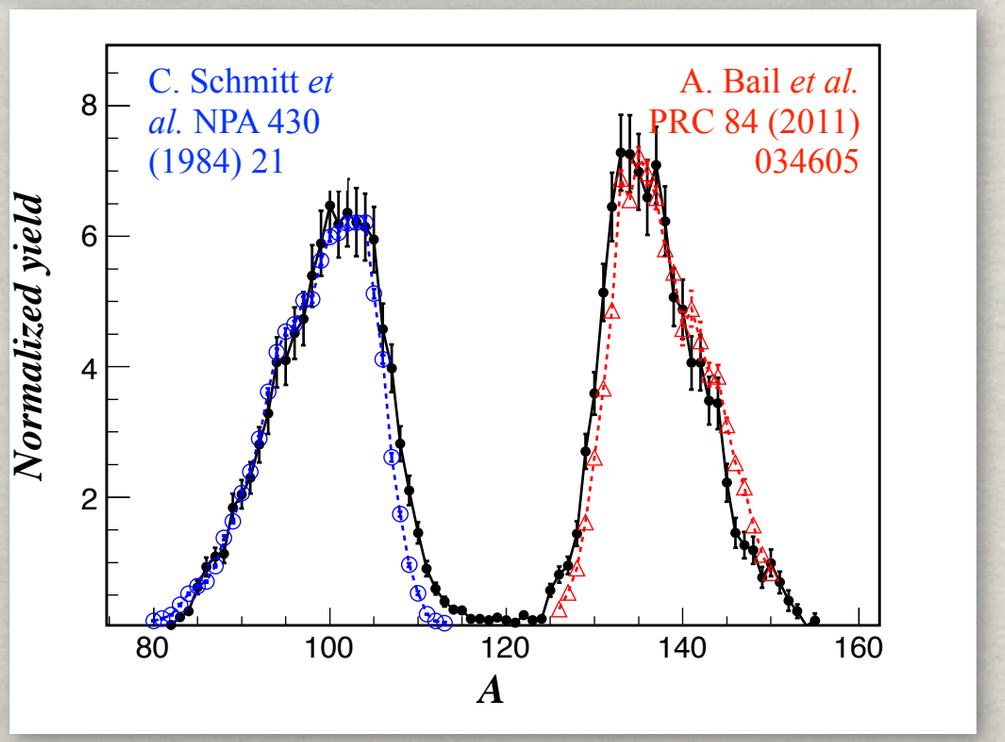
^{238}U (6.1 AMeV) + ^{12}C at VAMOS

^{12}C (^{238}U , **^{240}Pu** (E*~9 MeV)) ^{10}Be



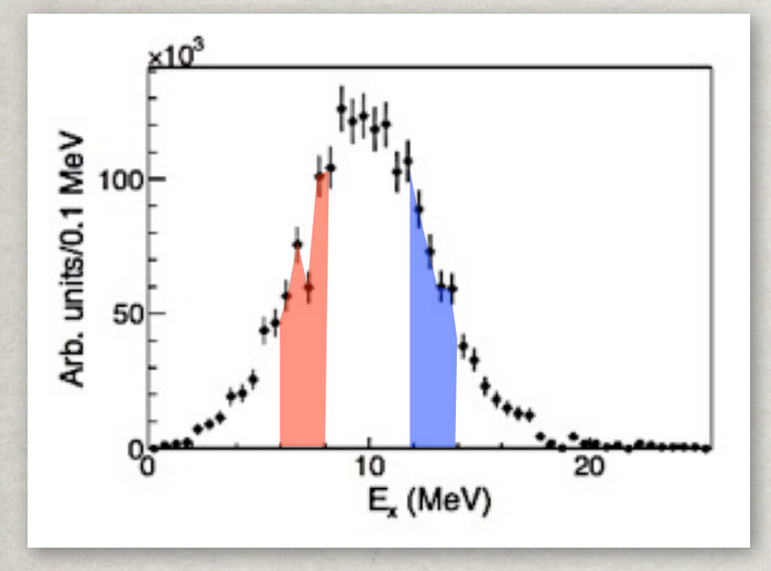
M. Caamaño *et al.* PRC 88 (2013) 024605





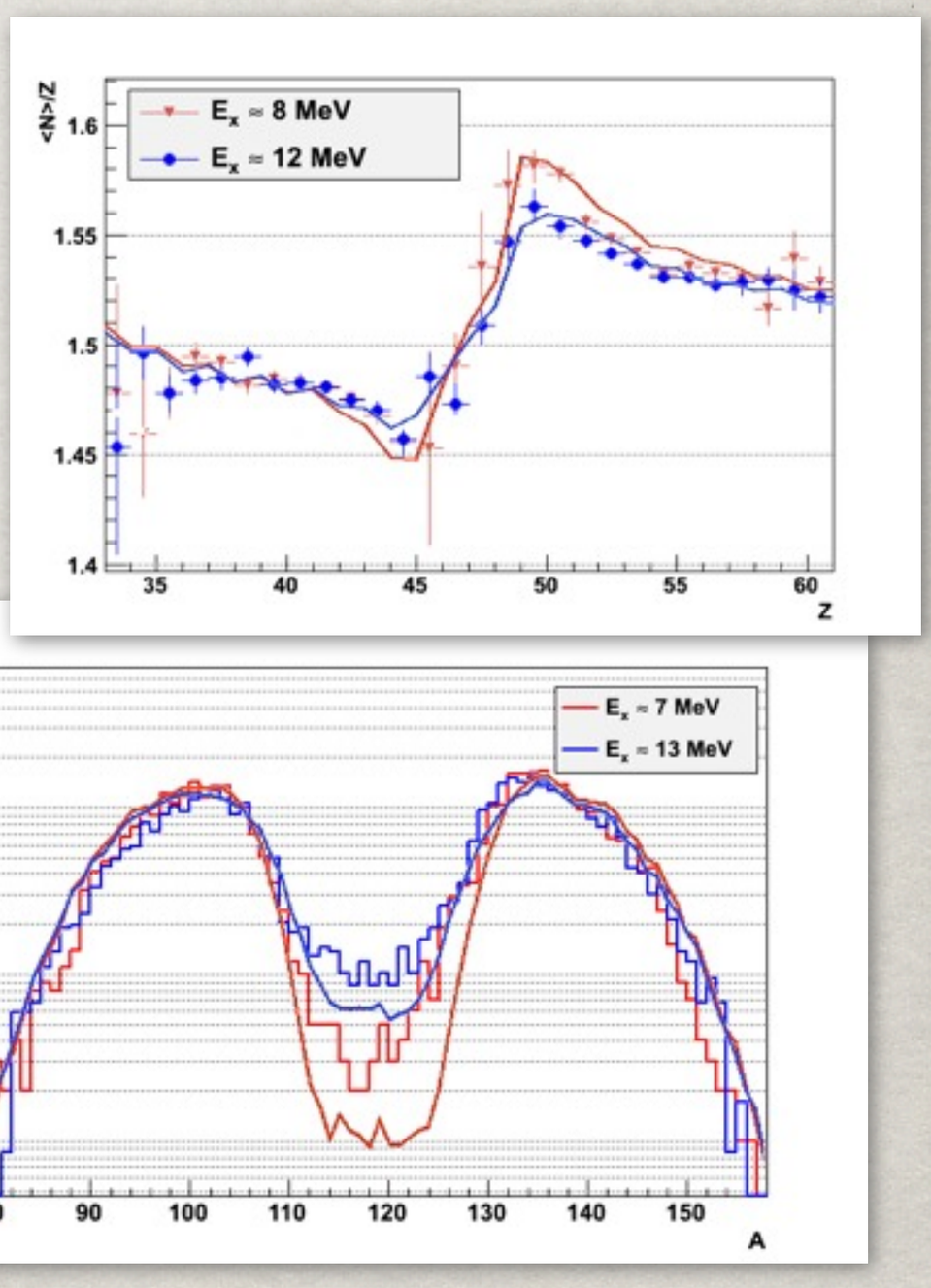
^{238}U (6.1 AMeV) + ^{12}C at VAMOS

^{240}Pu (E*~9 MeV)

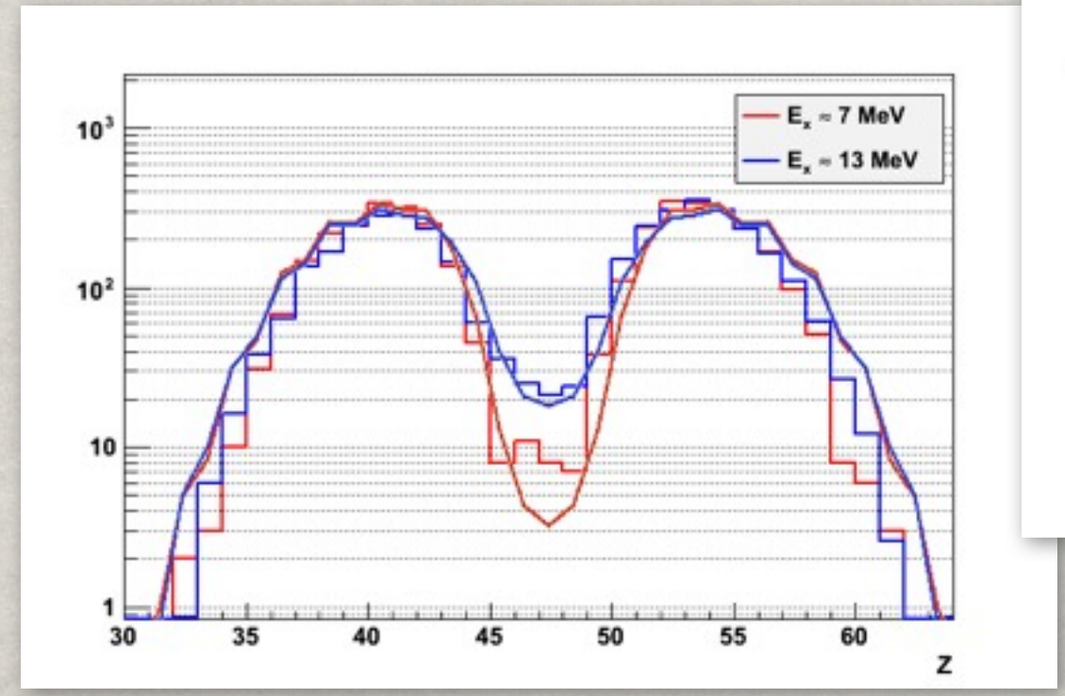


- evolution of A, Z, <N>/Z distributions with E*

- gradual disappearance of shell effects



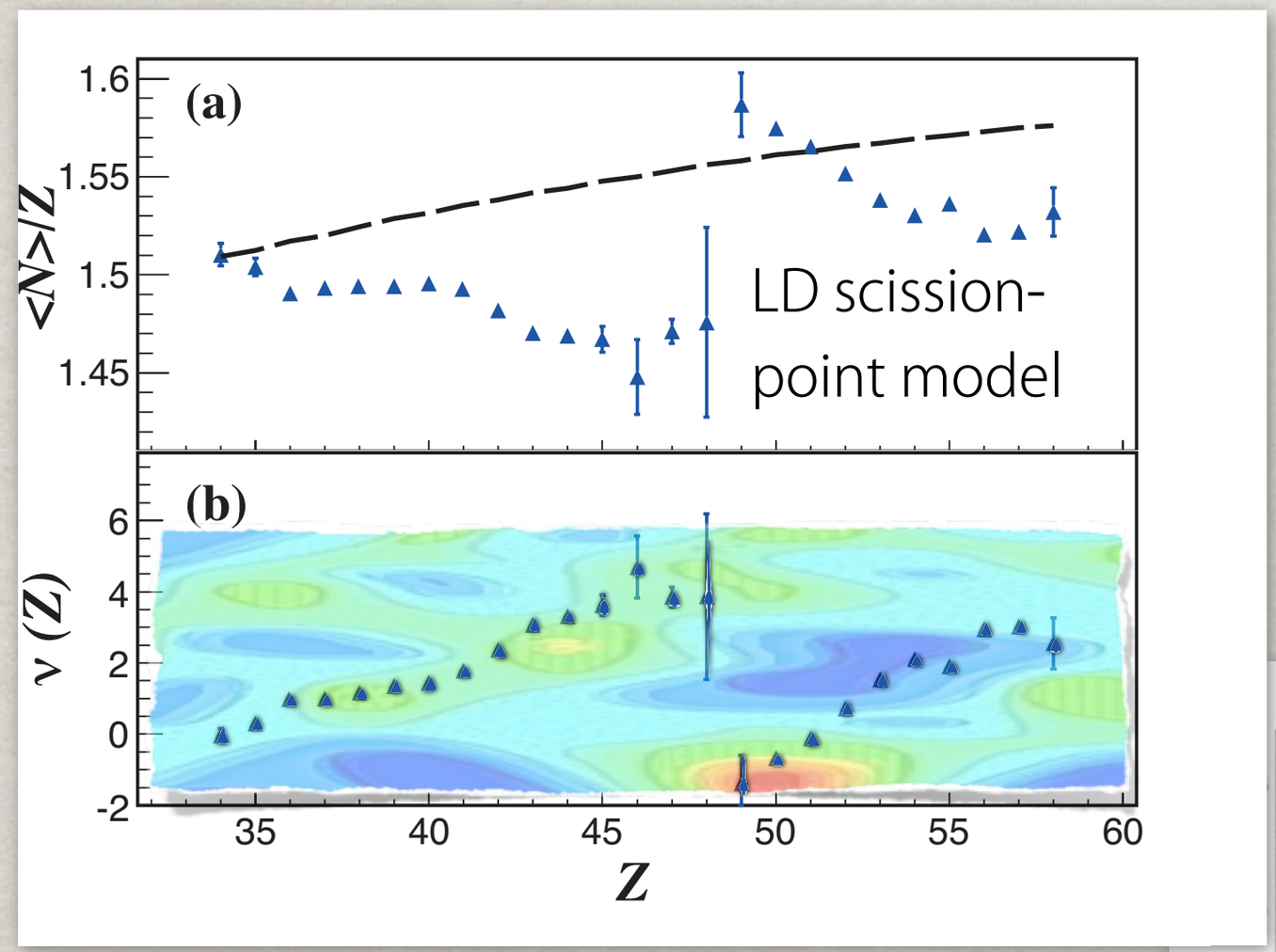
– – GEF (K.-H. Schmidt & B. Jurado)



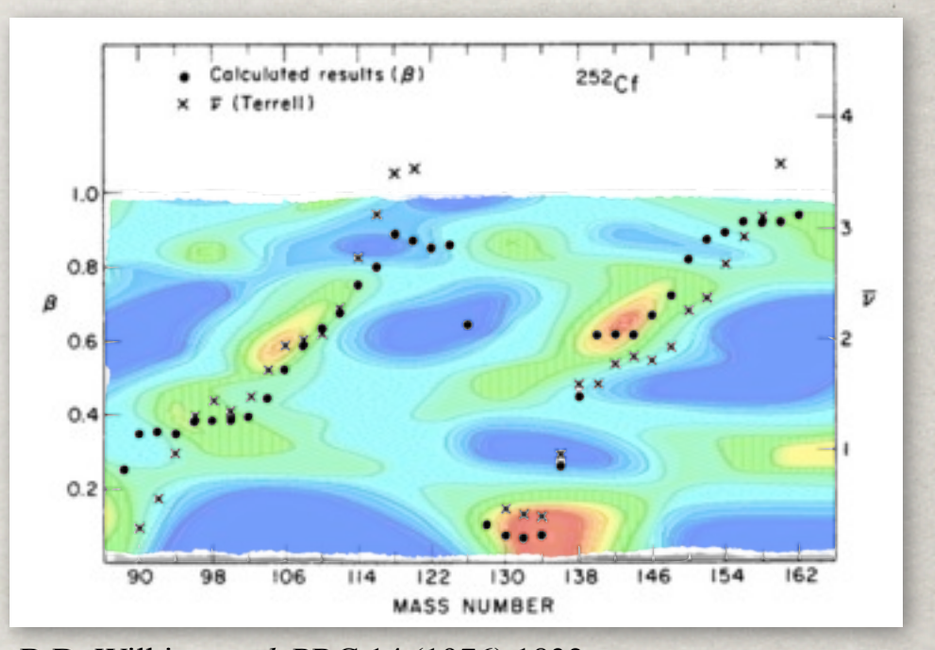
D. Ramos, PhD at U. Santiago de Compostela

^{238}U (6.1 AMeV) + ^{12}C at VAMOS

^{240}Pu (E*~9 MeV)



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

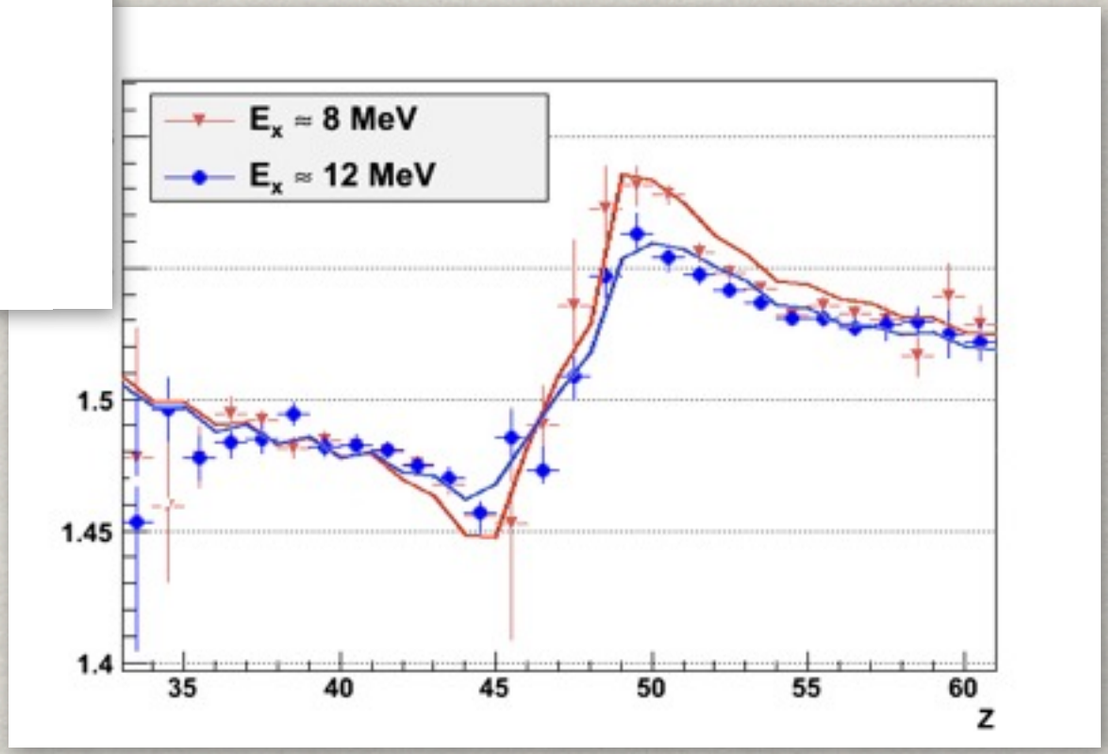


B.D. Wilkins *et al.* PRC 14 (1976) 1832

LD scission-point model

$E_{tot} = E_{LD}(Z_1,A_1) + E_{LD}(Z_2,A_2)$

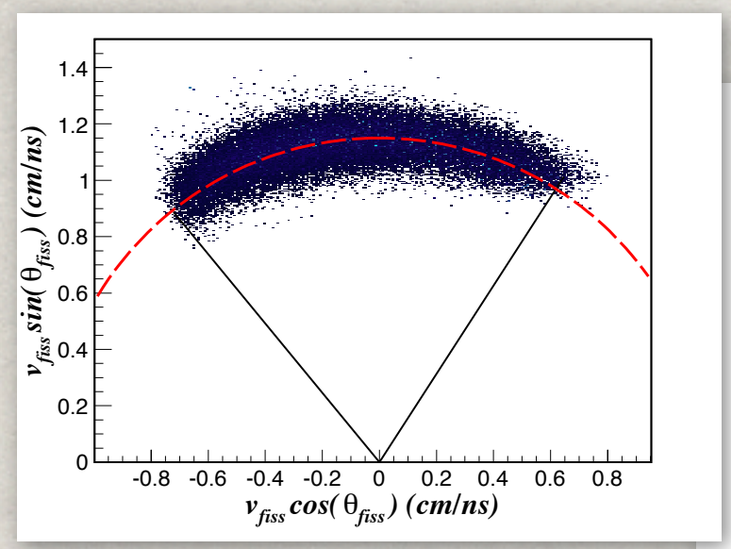
the obtained results can be linked to deformed shell effects

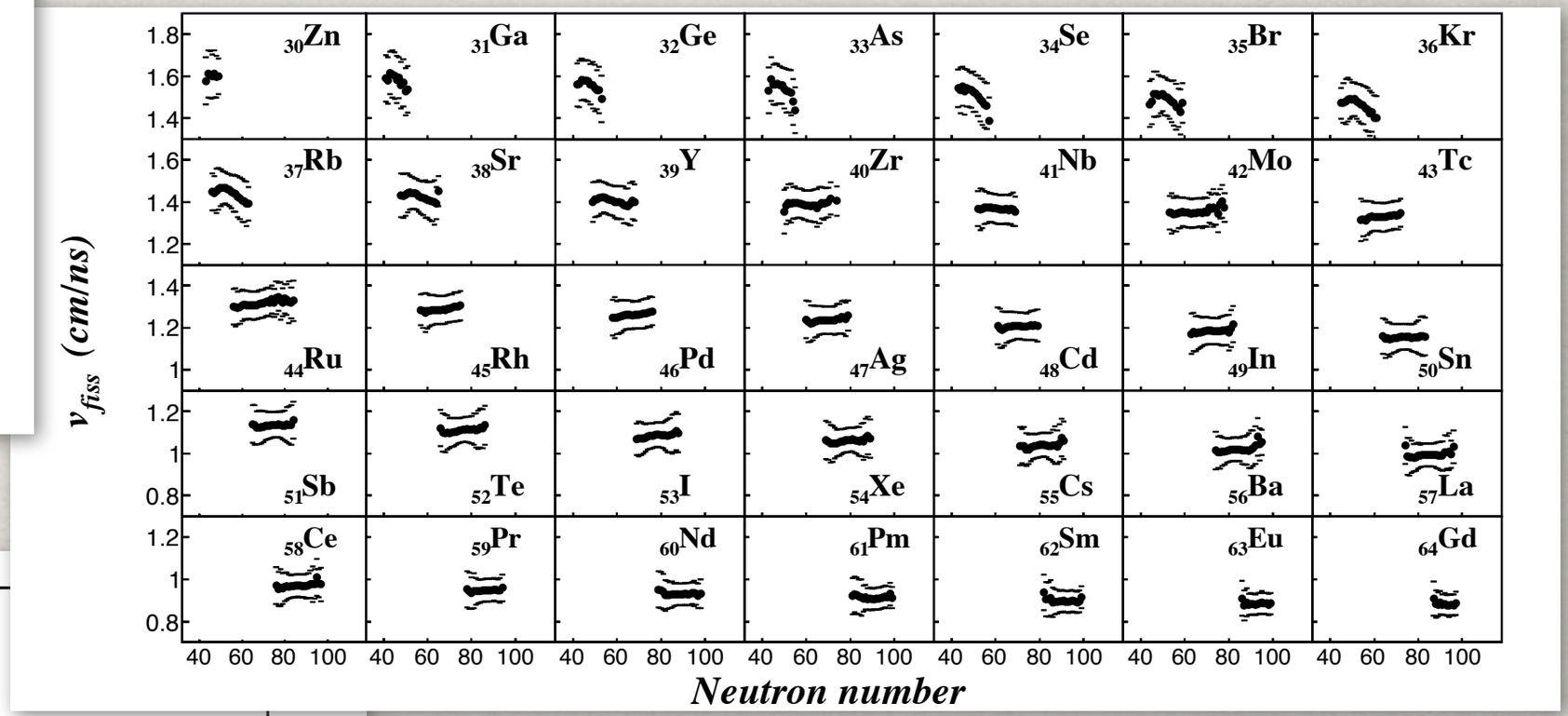


D. Ramos, PhD at U. Santiago de Compostela

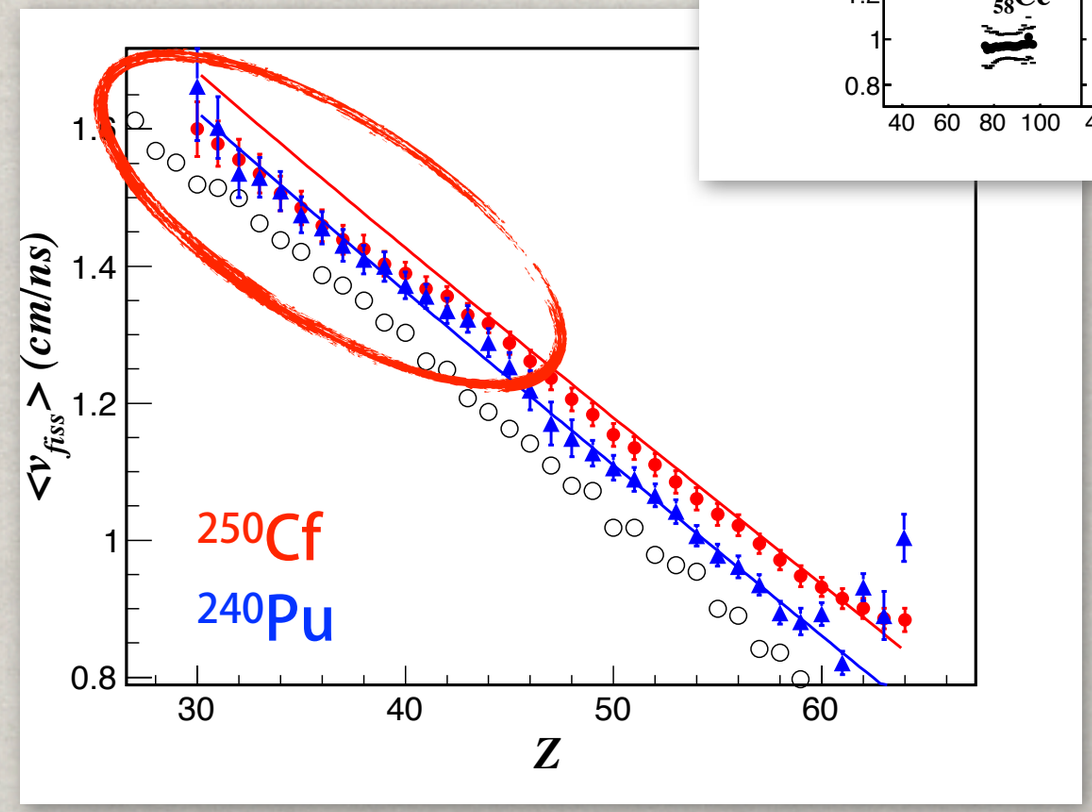
^{238}U (6.1 AMeV) + ^{12}C at VAMOS

^{240}Pu (E*~9 MeV)





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



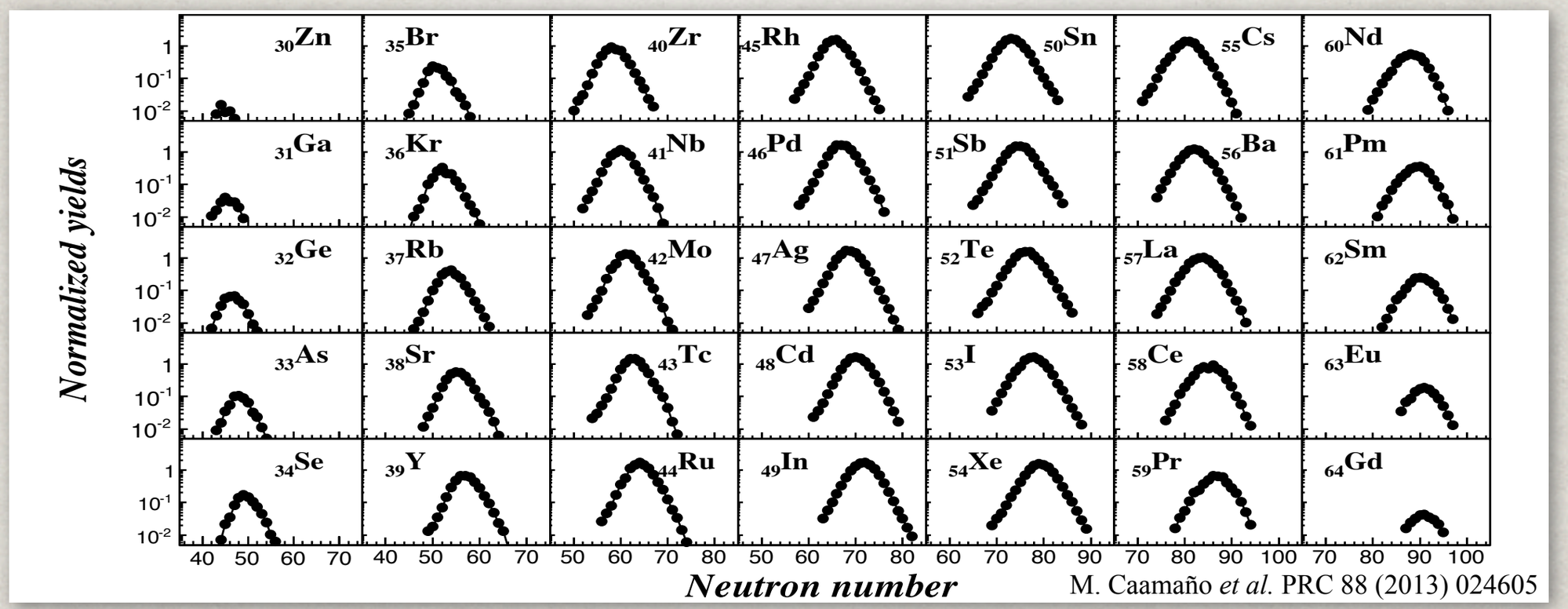
The fragments' velocities are also available.

^{240}Pu follows the systematics of Wilkins.

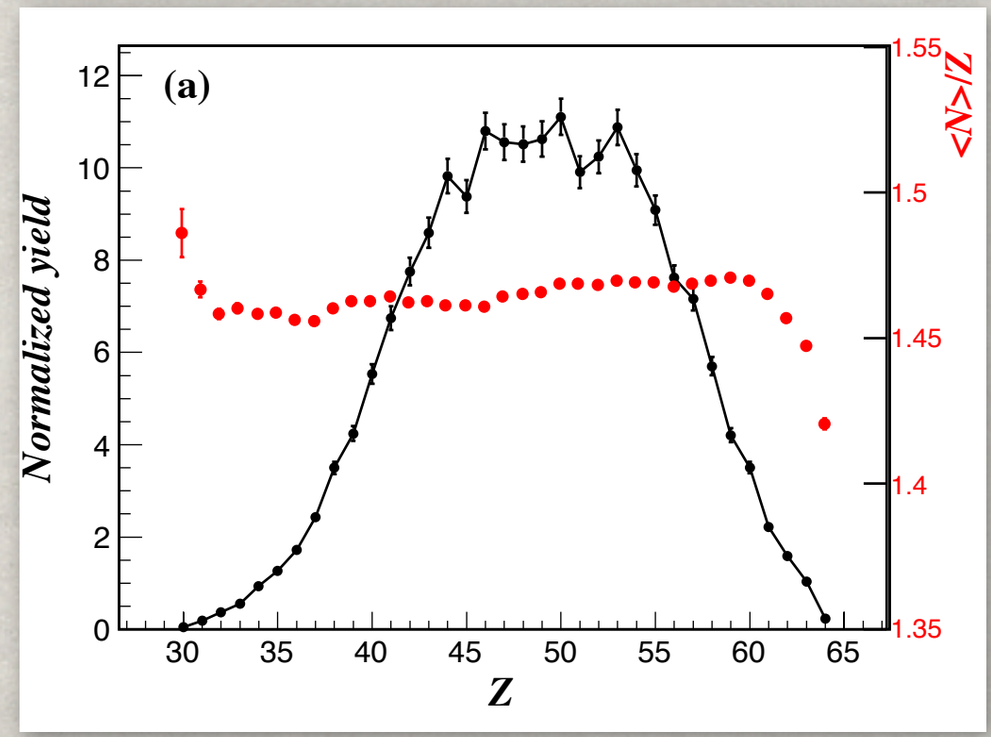
^{250}Cf deviates at light fragments.

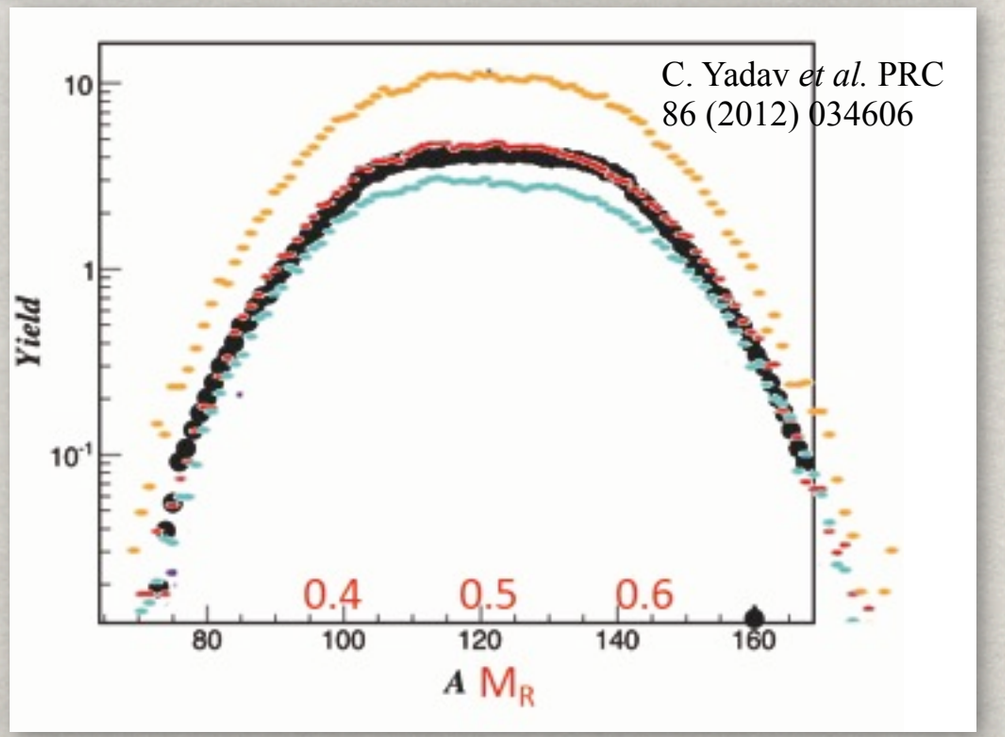
^{238}U (6.1 AMeV) + ^{12}C at VAMOS

^{12}C (^{238}U , **^{250}Cf** (E*~45 MeV))



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



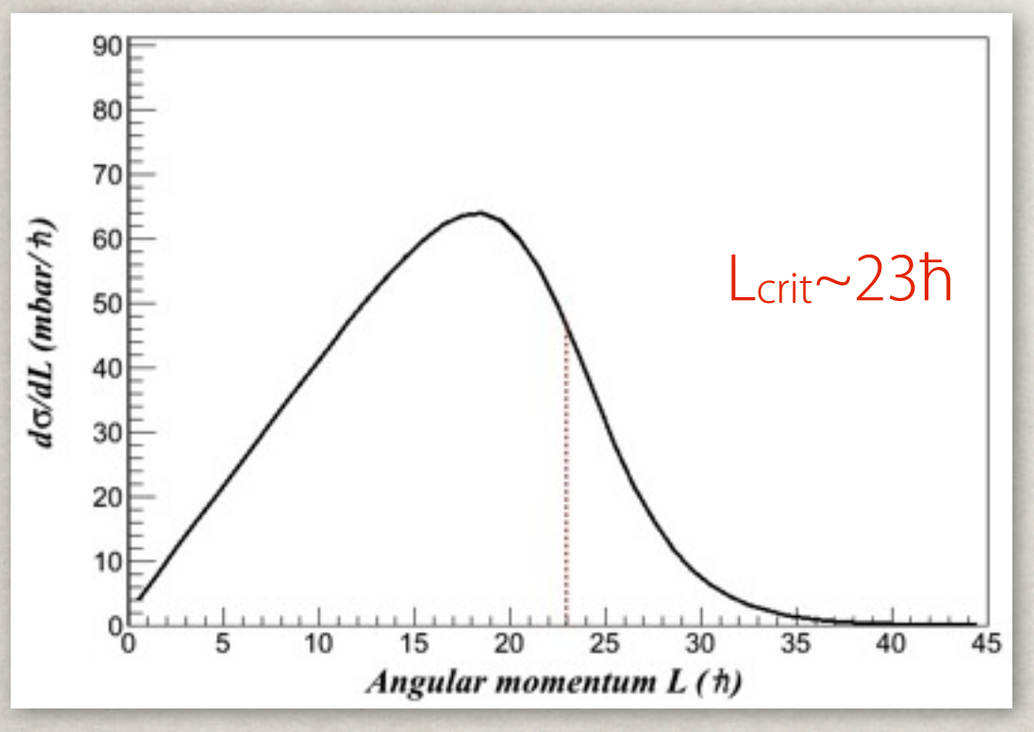


C. Yadav *et al.* PRC 86 (2012) 034606

^{238}U (6.1 AMeV) + ^{12}C at VAMOS

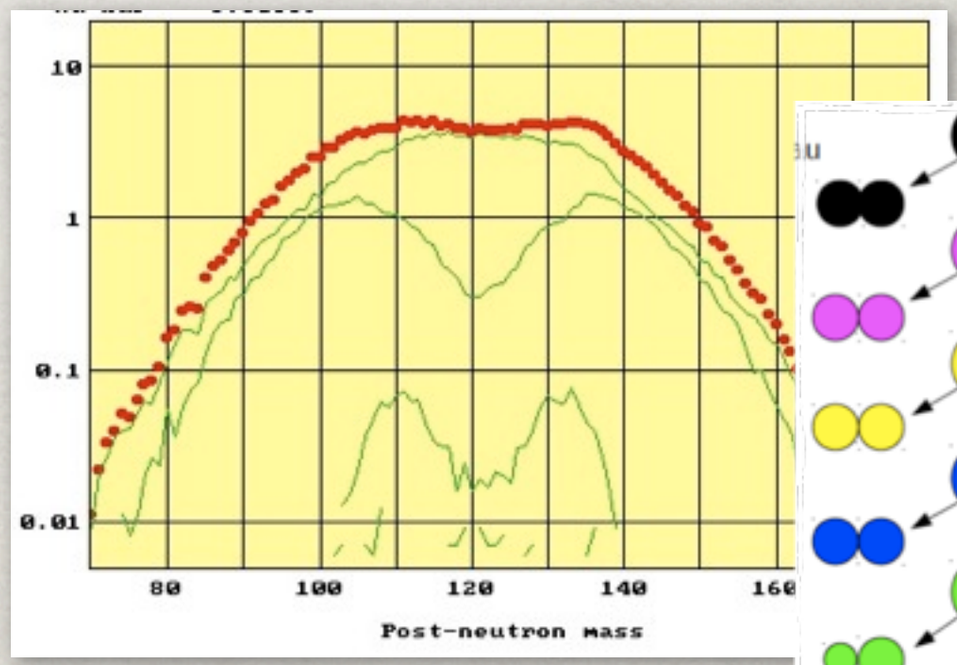
^{250}Cf (E*~45 MeV)

Fusion-fission reaction:
angular momentum distribution

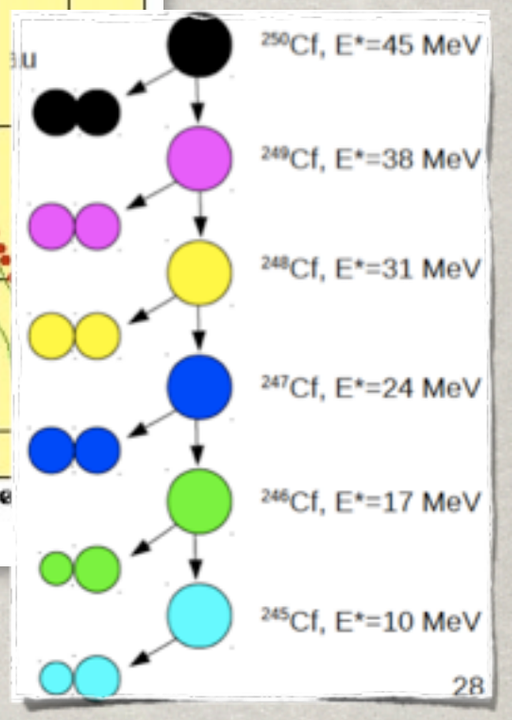


L_{crit}~23ħ

High excitation energy:
multi-chance fission

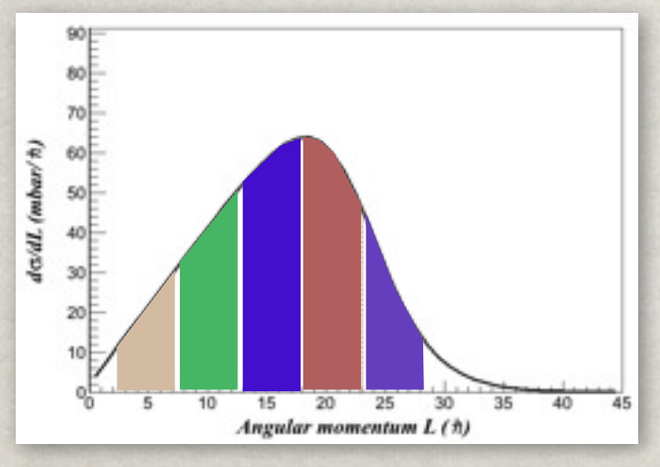


GEF output for E*=45 L=16

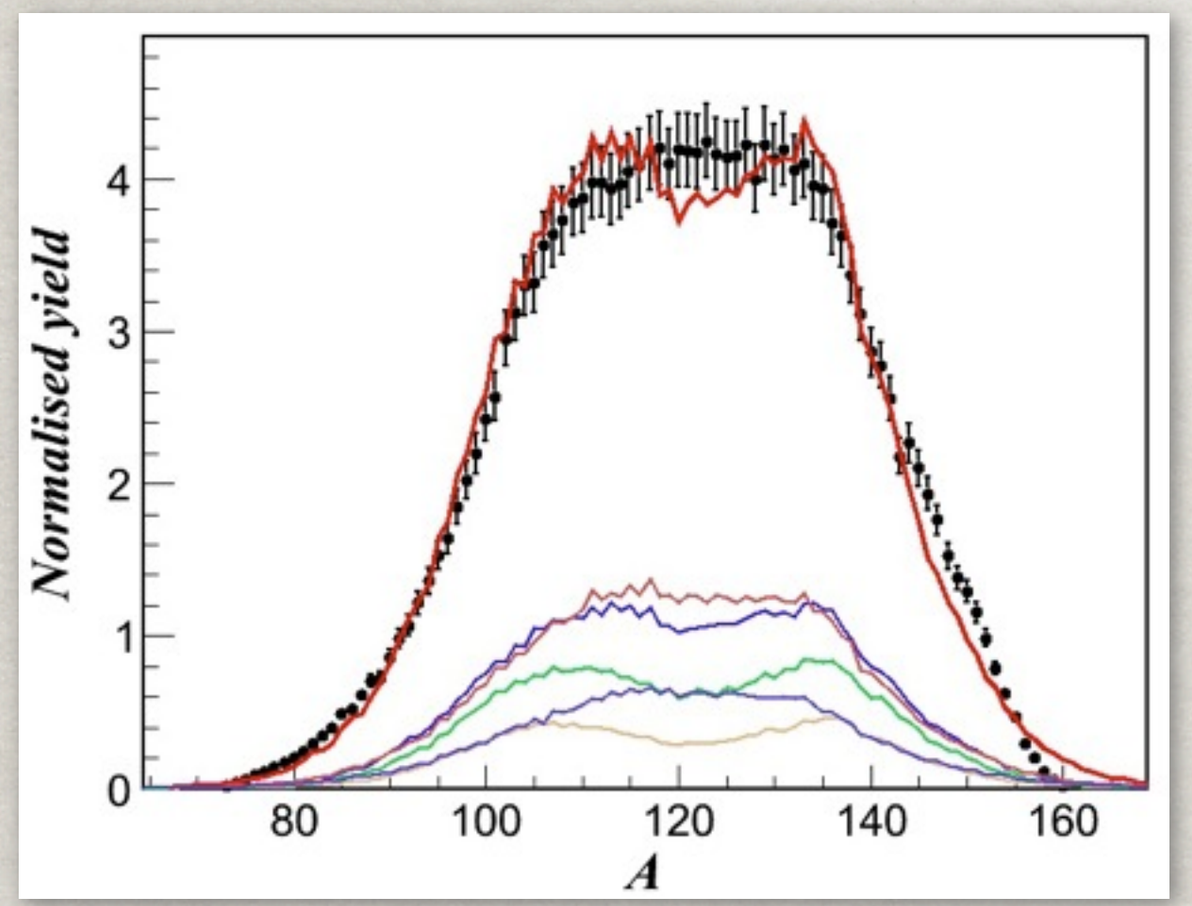


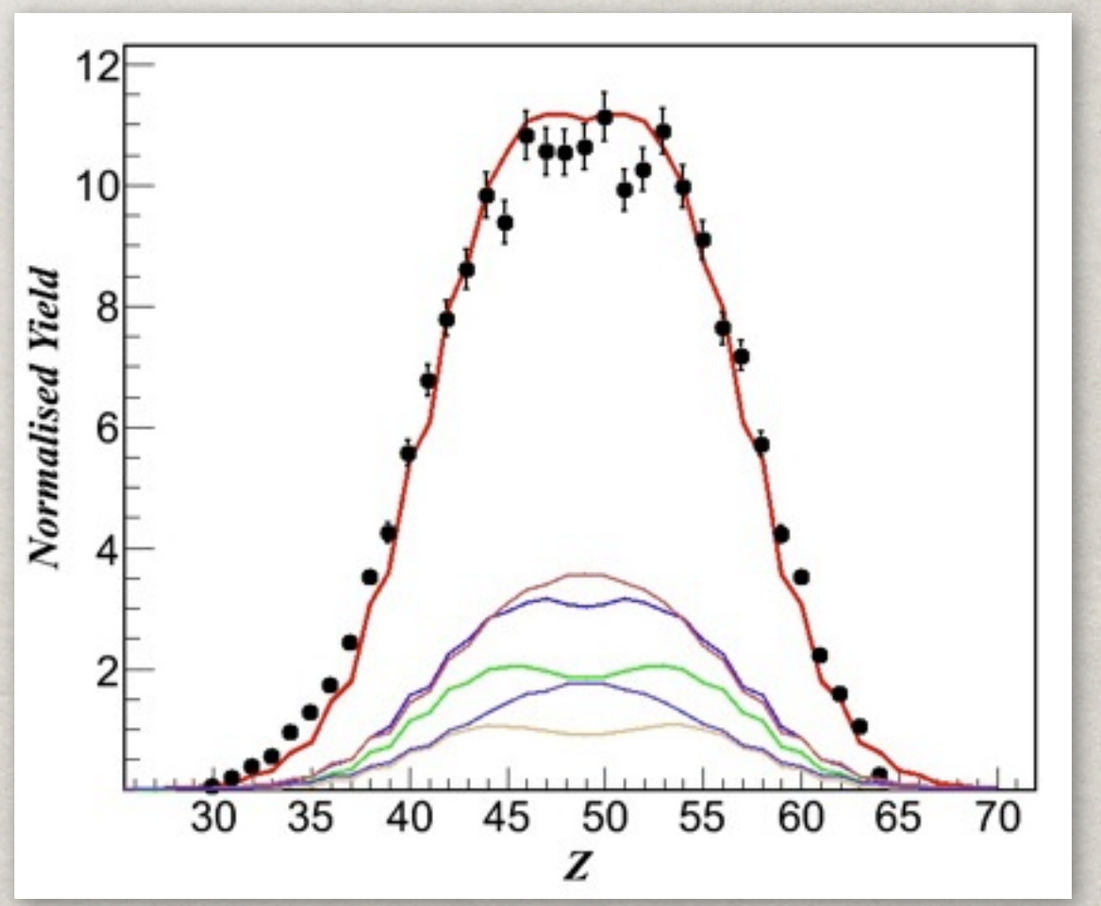
^{238}U (6.1 AMeV) + ^{12}C at VAMOS

^{250}Cf (E*~45 MeV)



Widths and shapes behave as expected
with small differences.
<L> marks the transition to symmetric fission

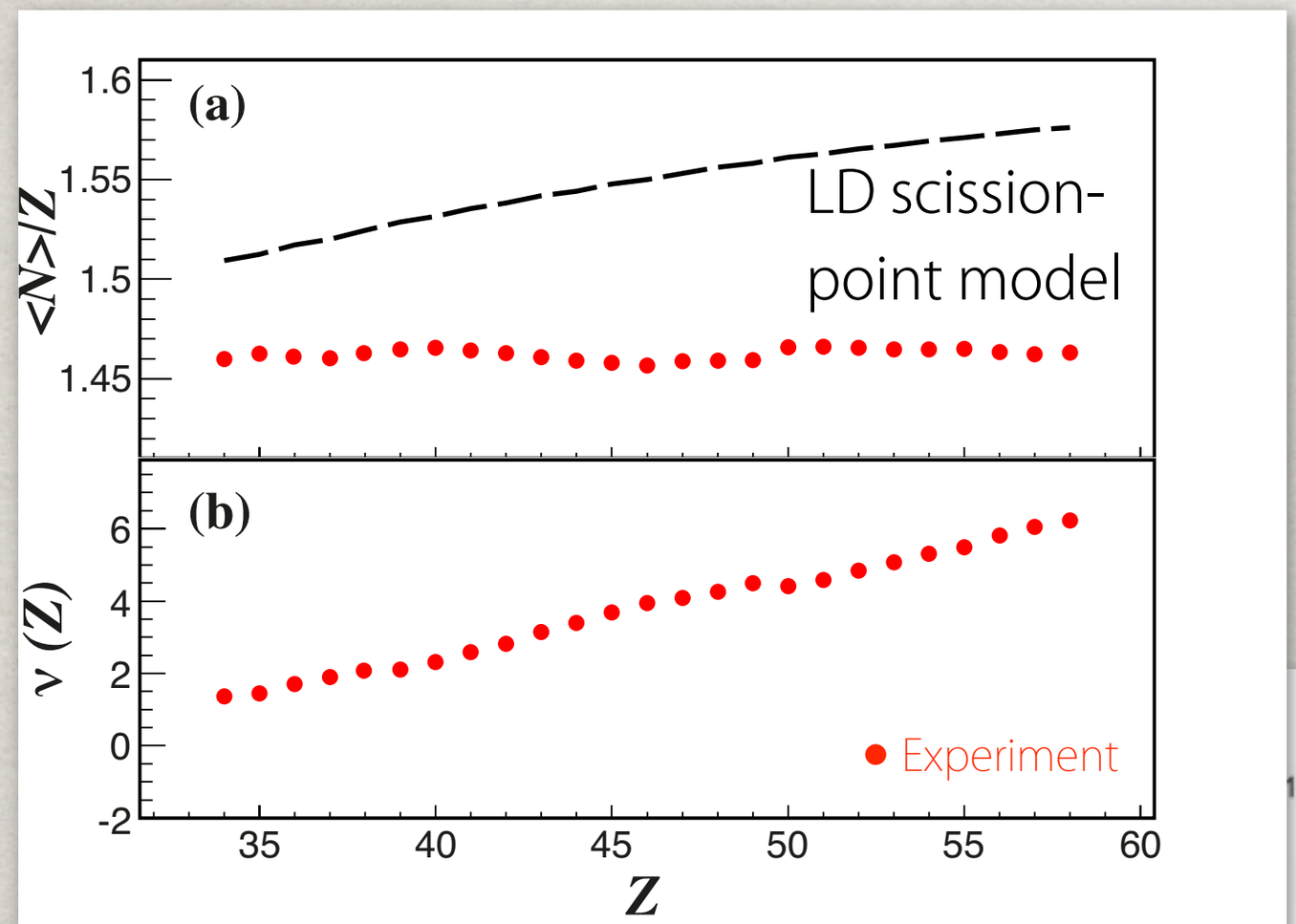




solid lines: Code GEF (K.-H. Schmidt & B. Jurado)

^{238}U (6.1 AMeV) + ^{12}C at VAMOS

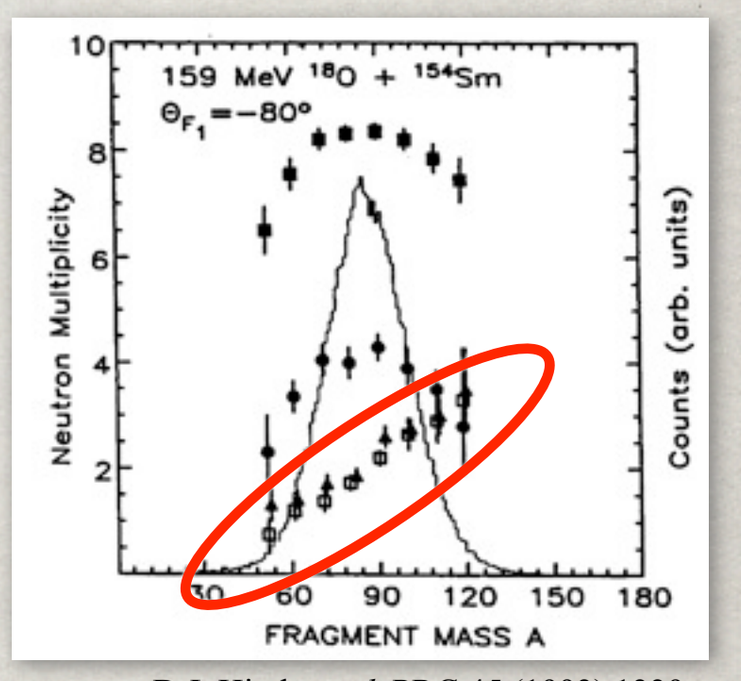
^{250}Cf (E*~45 MeV)



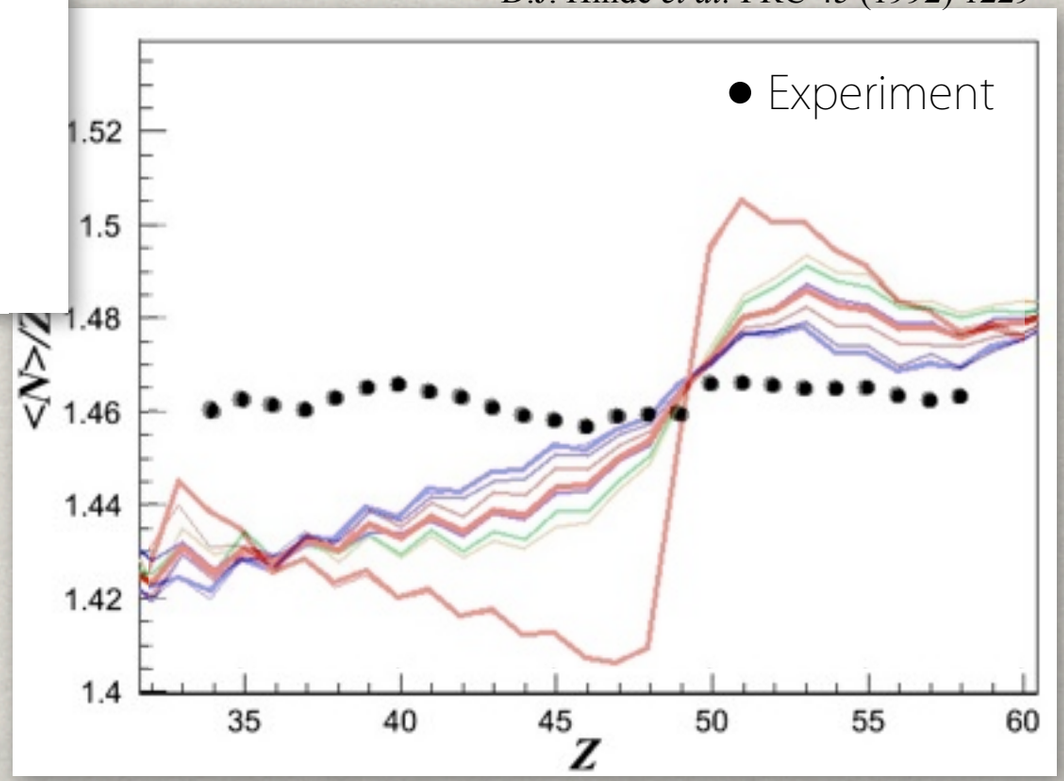
LD scission-point model

$E_{tot} = E_{LD}(Z_1,A_1) + E_{LD}(Z_2,A_2)$

- **no polarization** at high E*
- cannot be reproduced with multi-chance fission and/or <L> influence.



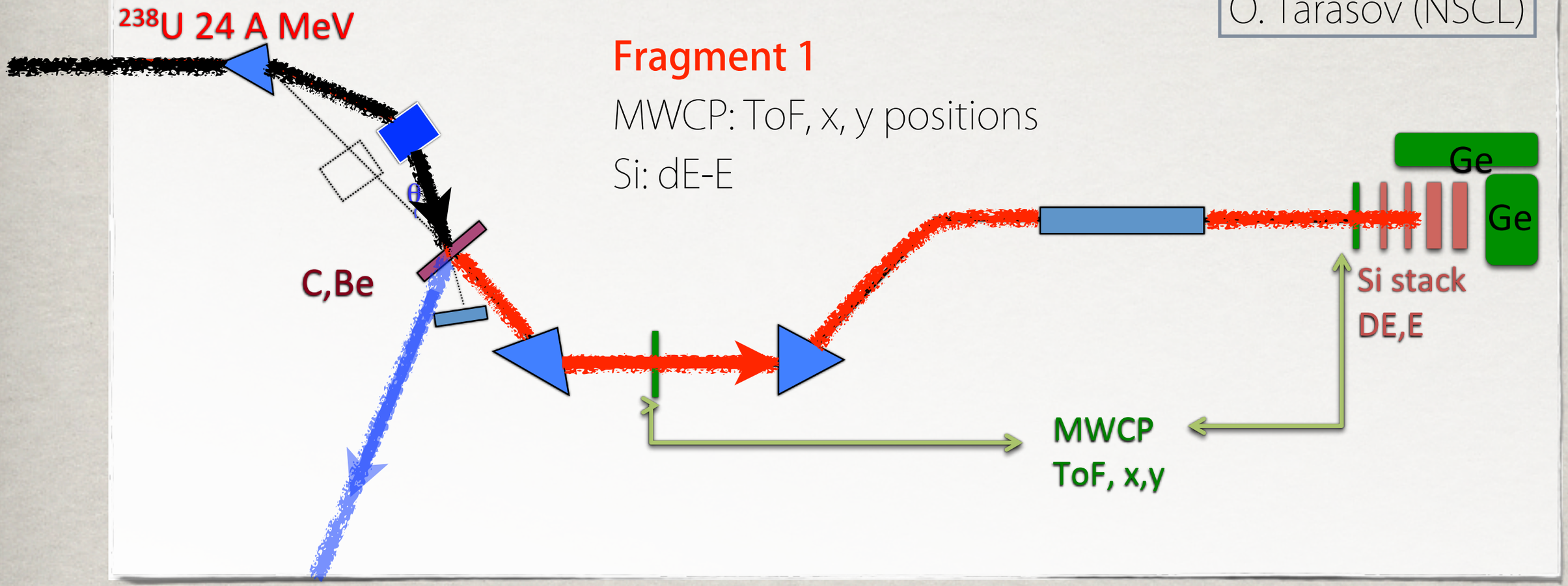
D.J. Hinde *et al.* PRC 45 (1992) 1229



^{238}U (24 AMeV) + ^{12}C/^{9}Be at LISE

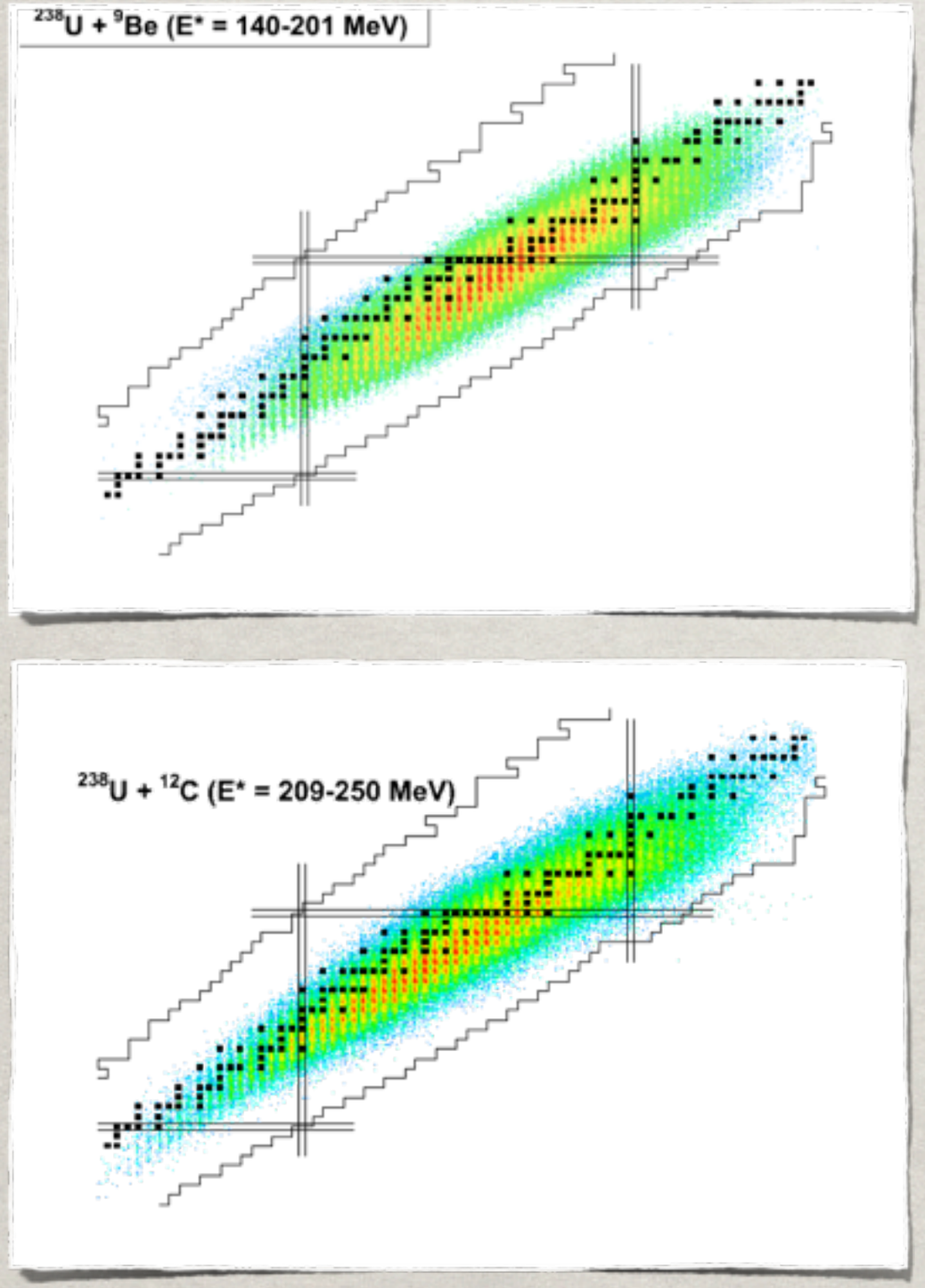
- Setup based on inverse kinematics
- Fusion-fission at different E*

Spokesperson:
O. Tarasov (NSCL)

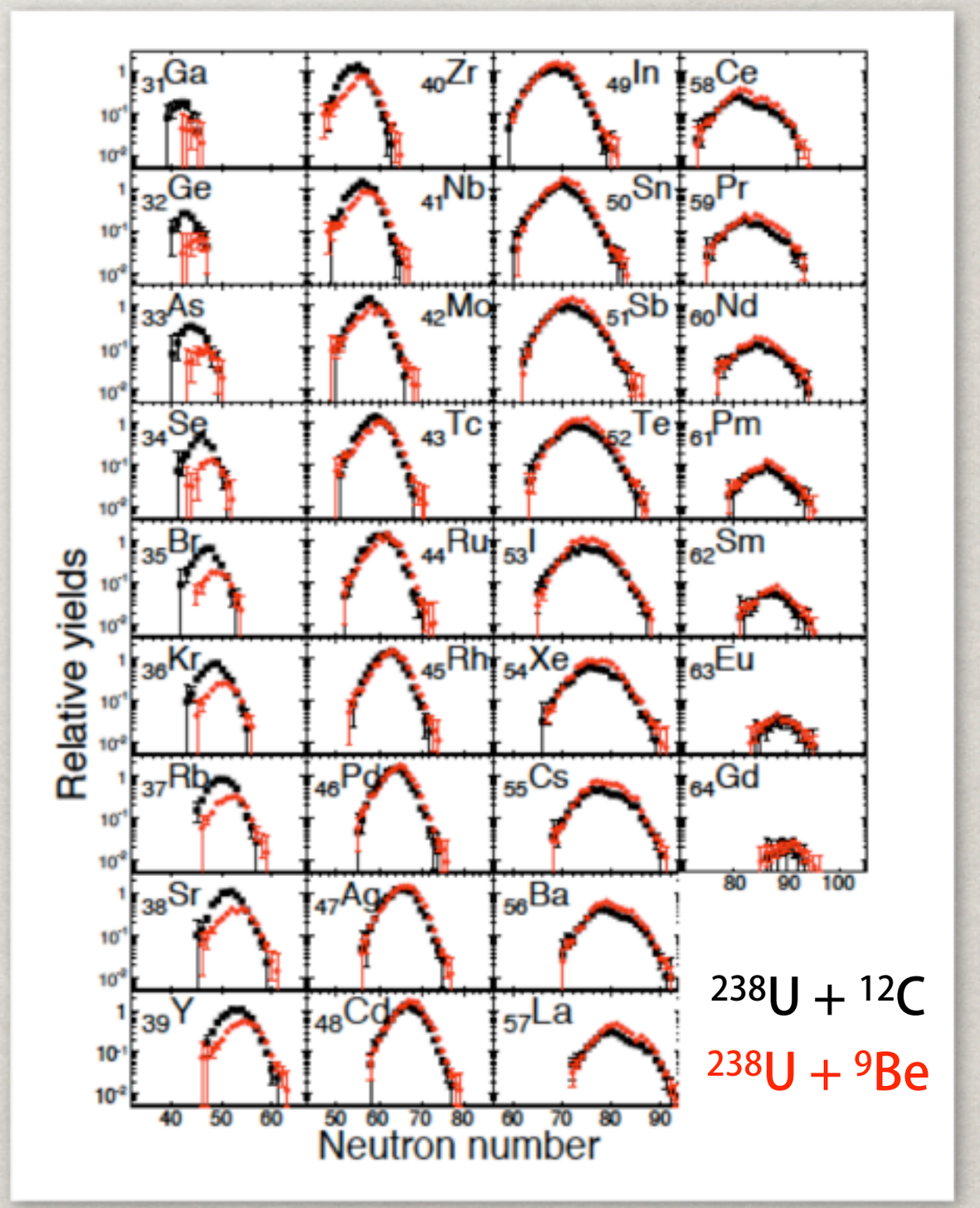


Fragment's observables: Z, A, q, angles, **velocity**, gammas.

^{238}U (24 AMeV) + ^{12}C/^{9}Be at LISE



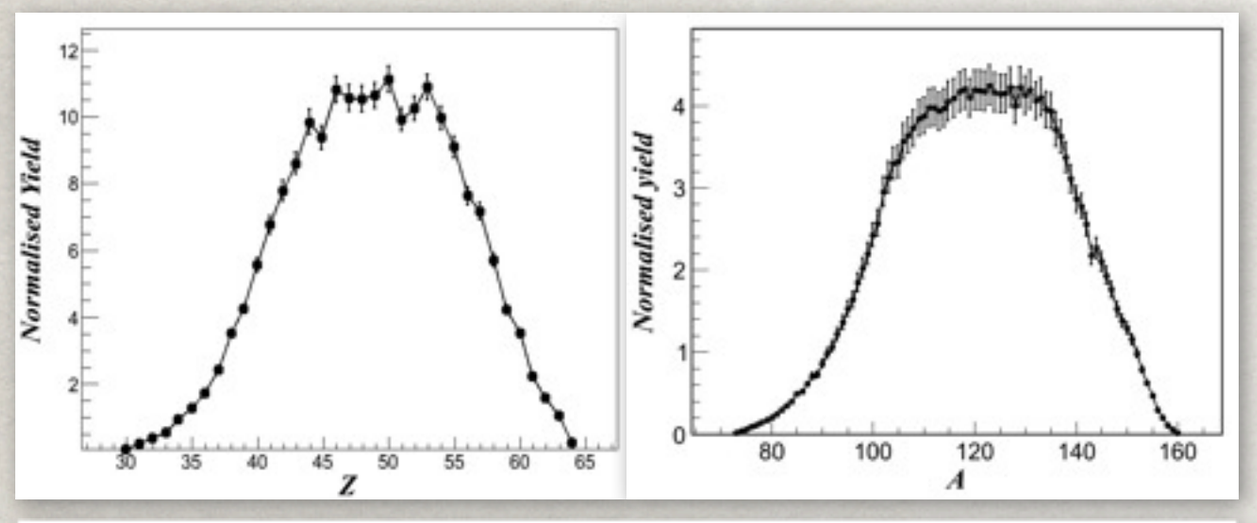
^{132}Sn ~10 pps

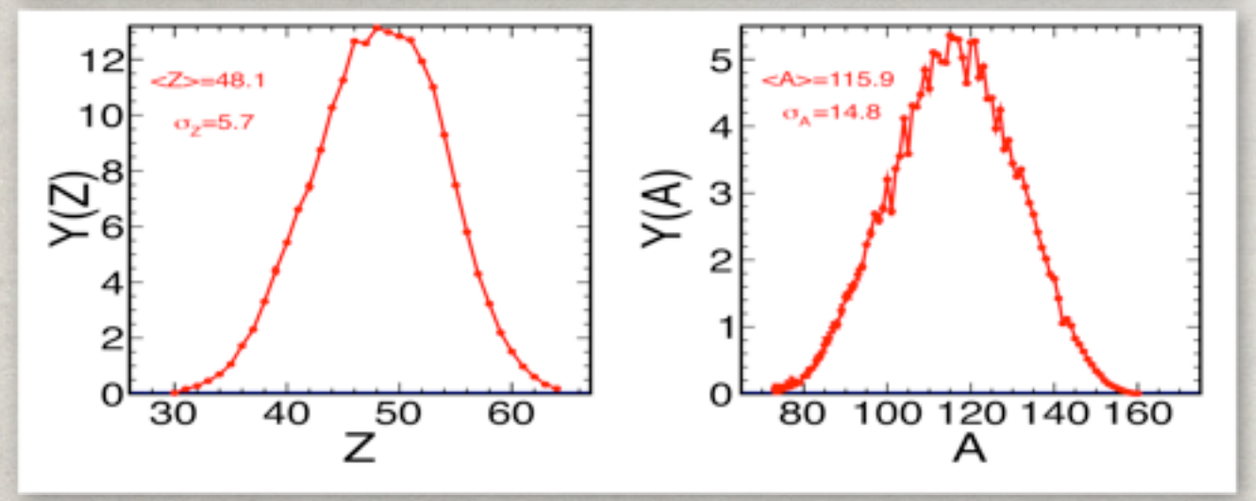


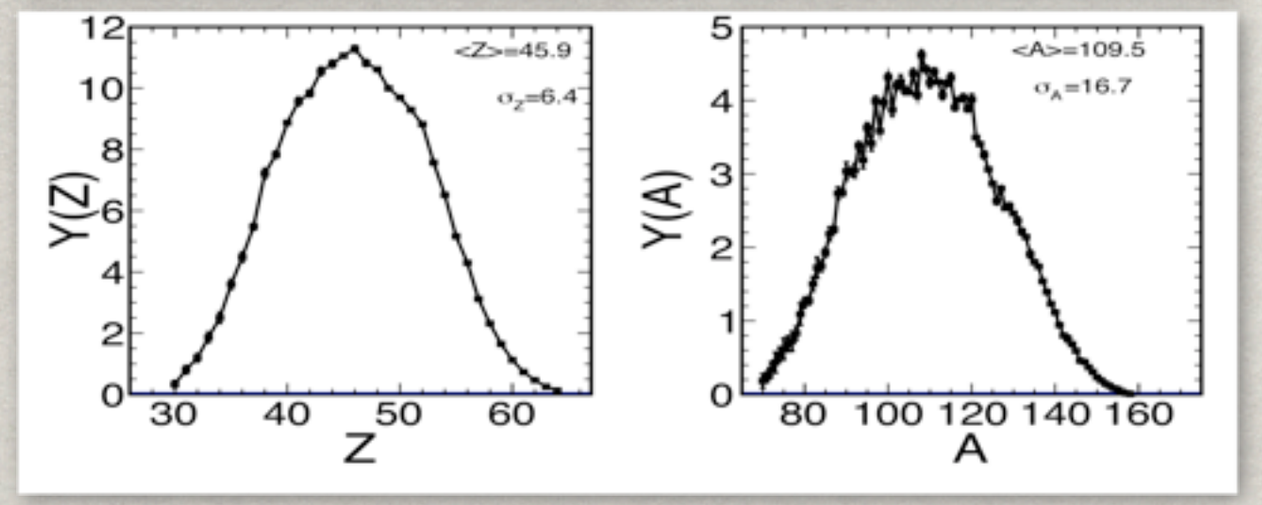
O. Delaune *et al.*, to be published

$^{238}U + ^{12}C/^{9}Be$

Fusion-fission summary







O. Delaune *et al.*, to be published

^{250}Cf ^{238}U (6.1 AMeV) + ^{12}C

E* = 45 MeV

<L>~15

2*<Z>=98 2*<A>=243 (ν ~7)

^{247}Cm ^{238}U (24 AMeV) + ^{9}Be

E* = 200 - 150 MeV

<L>~75

2*<Z>=96 2*<A>=232 (ν ~15)

~~^{250}Cf~~ ? ^{238}U (24 AMeV) + ^{12}C

E* = 250 - 200 MeV

<L>~95

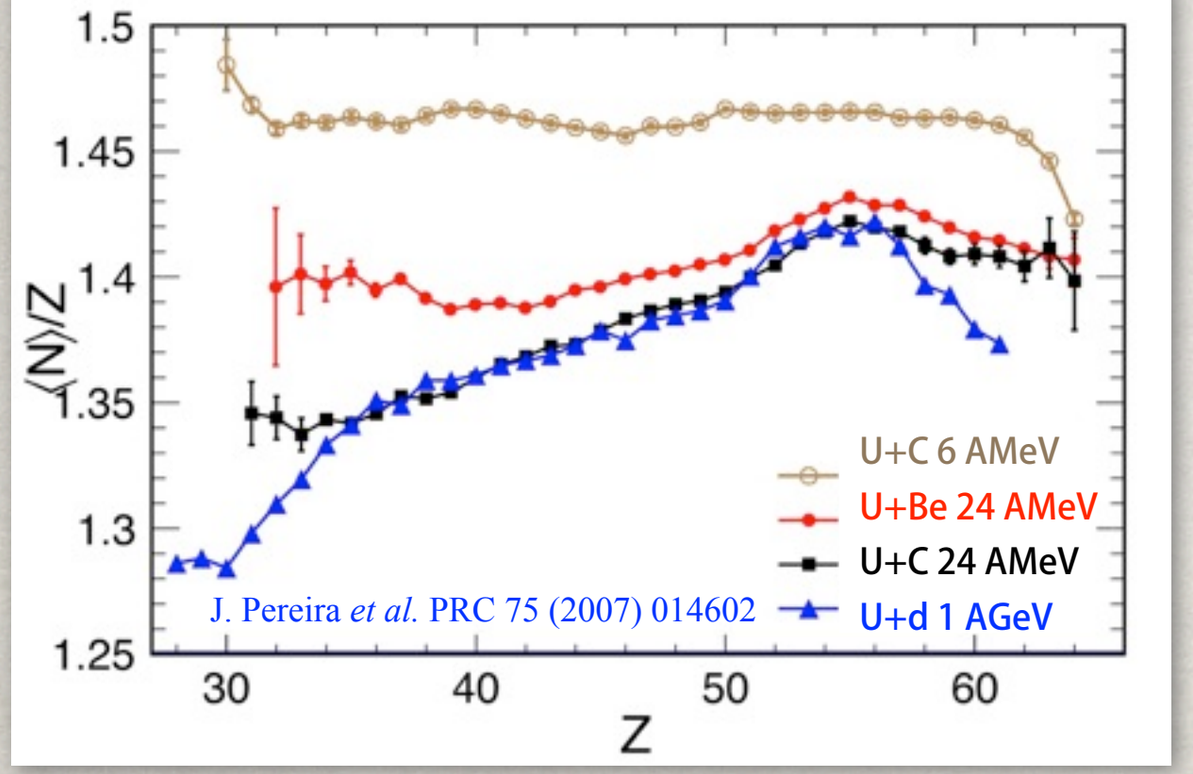
2*<Z>=92 2*<A>=219 (ν ~?)

no fusion occurs

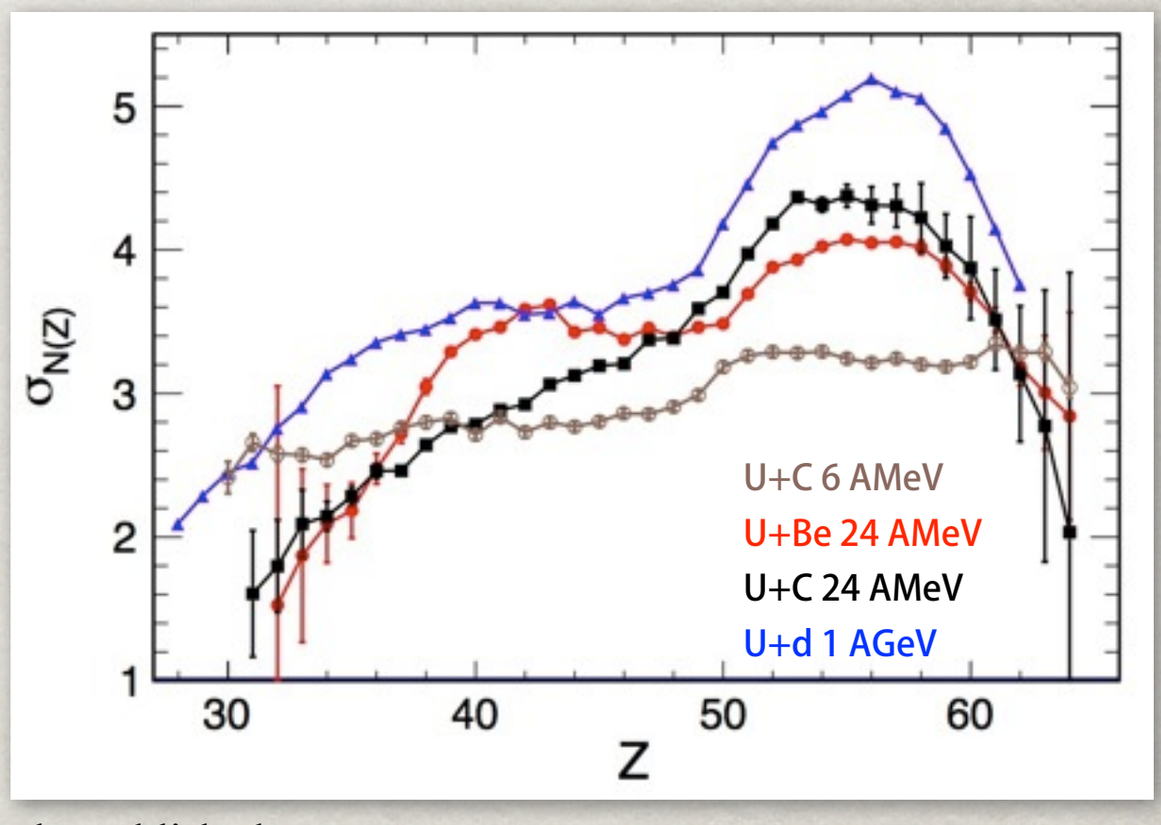
$^{238}U + {}^{12}C/{}^{9}Be$

Fusion-fission summary

polarisation



width of isotopic distribution



O. Delaune *et al.*, to be published

- As E* diminishes, <N>/Z becomes flat in U+C @ 6 AMeV (!!)
- U+Be recovers some shell influence (maybe due to evaporation)
- U+C @ 24 AMeV is remarkably similar to spallation reactions

Summary and conclusions

- The study of transfer- and fusion-induced fission in inverse kinematics allows the **access to observables not available so far**.
- We have shown **A**, **Z**, **<N>/Z**, and **velocity** distributions for ^{250}Cf, ^{247}Cm, and ^{240}Pu, and their evolution with **E*** and the reaction mechanism.

- The ^{240}Pu measured distributions are in agreement with their expected behaviour.
- ^{250}Cf with E*=45 MeV shows **unexpected features** in <N>/Z, velocity, and isotopic distributions.

- The results on ^{250}Cf reveal the **need for a better understanding** of the fission process, post-saddle.
- The study of the isotopic distributions of fission fragments proves to be a valid tool to extract **new information on the fission dynamics**.