Dependence of Fission-Fragment Properties on Excitation Energy for N-rich Actinides

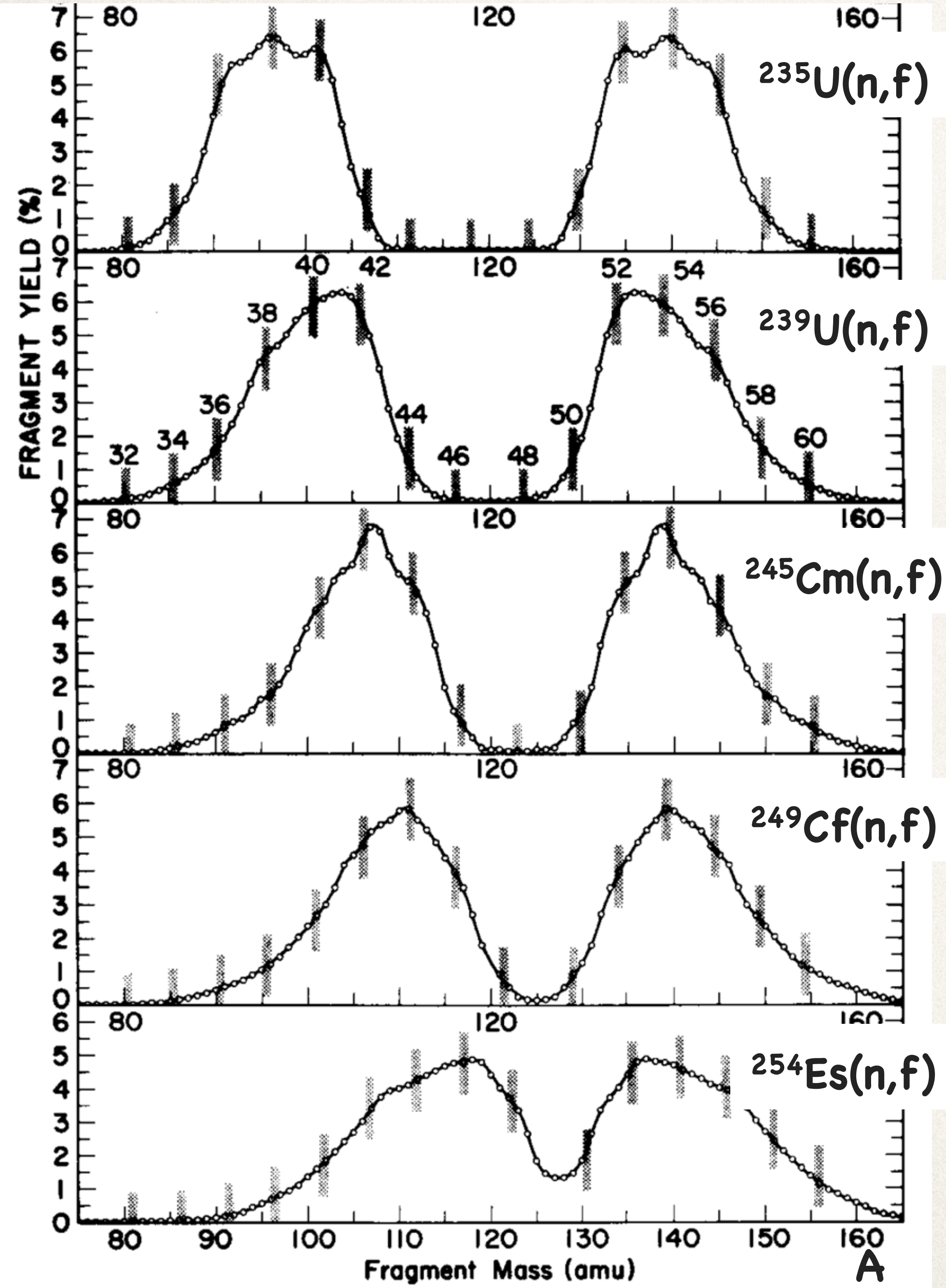
D. Ramos[1], C. Rodríguez-Tajes[2], M. Caamaño[1], F. Farget[2], L. Audouin[3], J. Benlliure[1], E. Casarejos[4], E. Clement[2], D. Cortina[1], O. Delaune[2], X. Derkx[5,*], A. Dijon[2], D. Doré[6], B. Fernández-Domínguez[1], G. de France[2], A. Heinz[7], B. Jacquot[2], A. Navin[2], C. Paradela[1], M. Rejmund[2], T. Roger[2], M.-D. Salsac[6], C. Schmitt[2]

(1) Dpto. Física de Partículas, USC, Santiago de Compostela, Spain. (2) GANIL, CEA/DMS - CNRS/IN2P3, Caen, France. (3) IPN Orsay, Université de Paris-Sud XI - CNRS/IN2P3, Orsay, France. (4) CIMA, Escuela Técnica Superior de Ingenieros Industriales, UVigo, Vigo, Spain. (5) LPC Caen, Université de Caen Basse-Normandie – ENSICAEN - CNRS/IN2P3, Caen, France. (6) CEA Saclay, DSM/IRFU/SPhN, Saclay, France. (7) Chalmes University of Technology, Göteborg, Sweden.

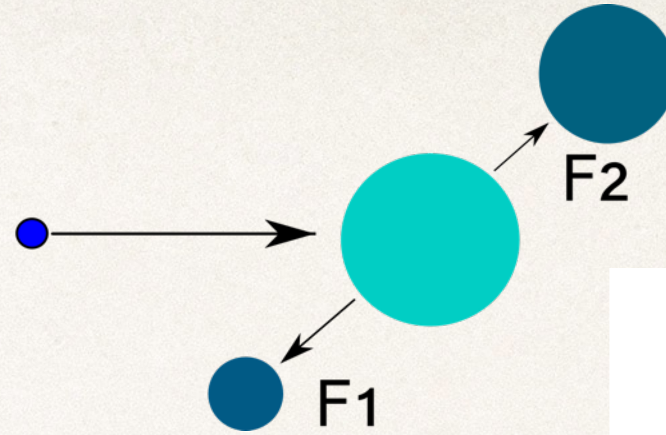
FUSTIPEN Fission Workshop , Caen, France 22/10/2015

Limitations of Direct Kinematics

Good measurement of **mass distribution**



J.P. Unik, IAEA –SM-174/209



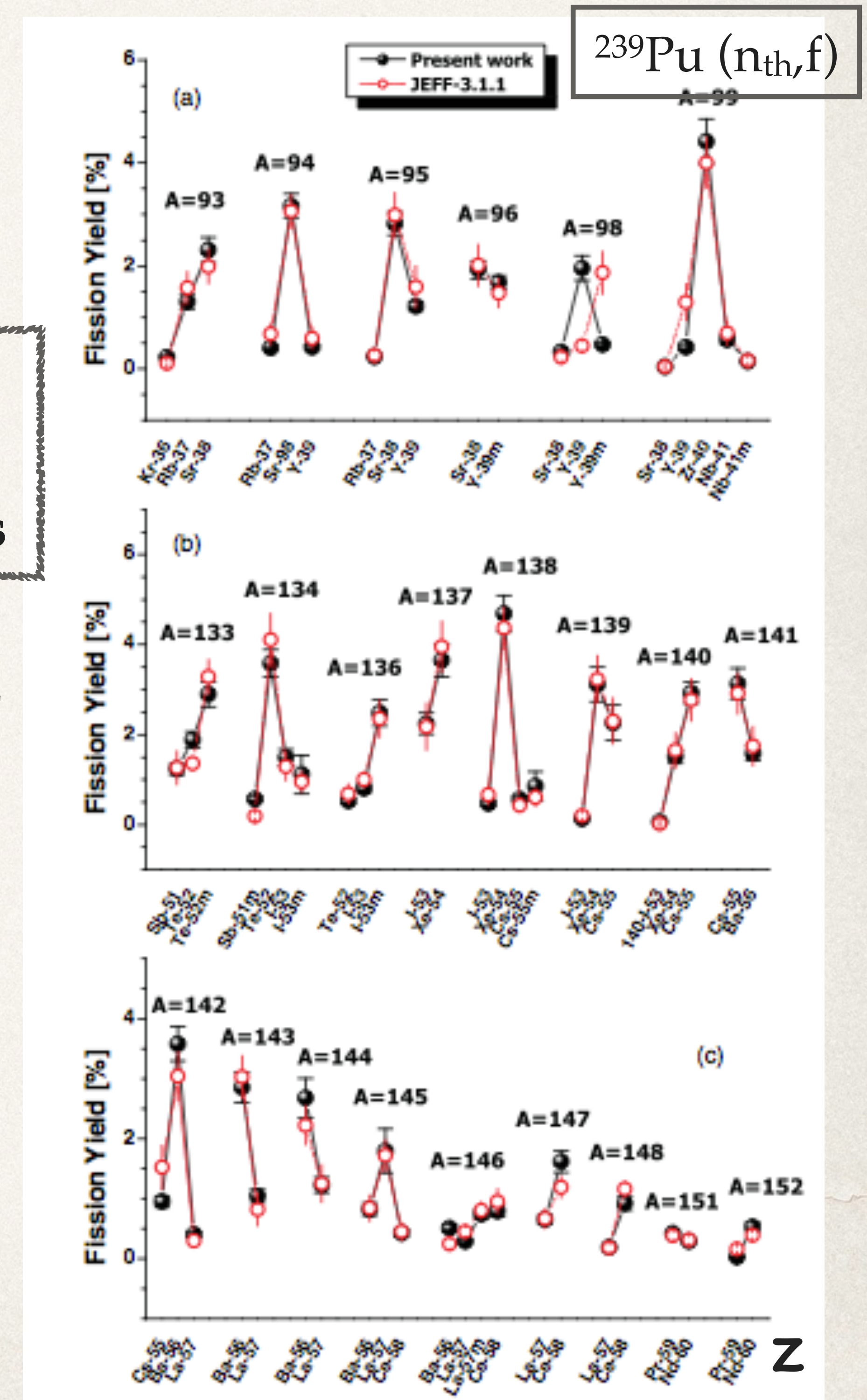
Incomplete Measurements of Isotopic distributions

limitations for heavy ff

- lifetimes

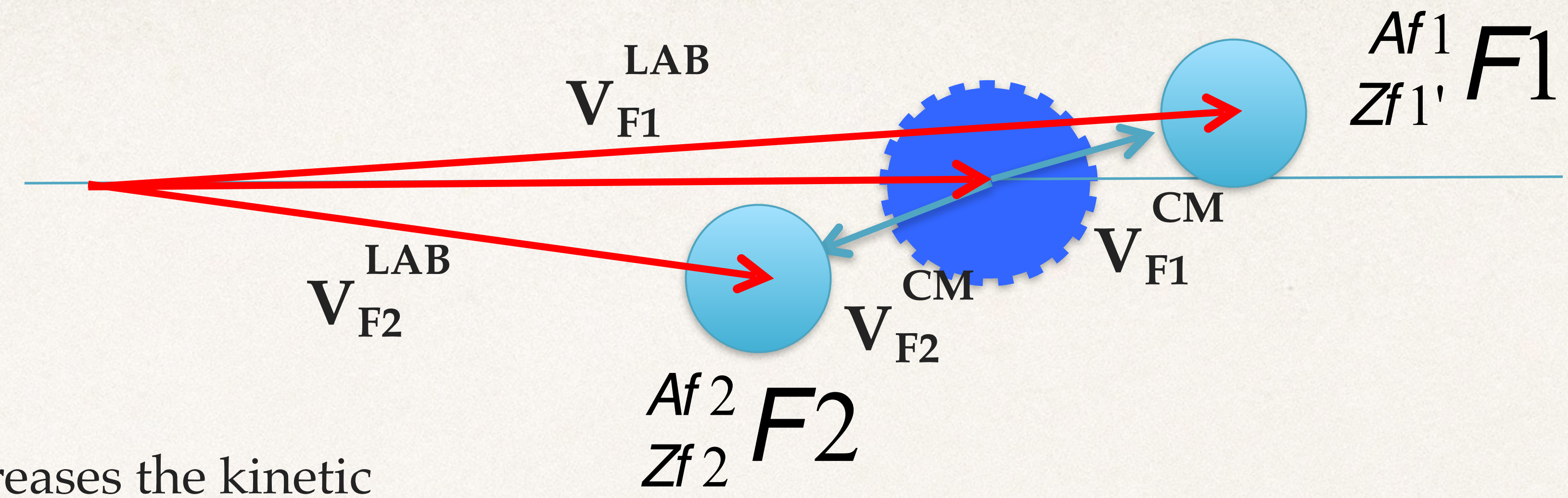
-unknown level schemes

Isotopic distribution by ɣ-spectroscopy



A. Bail PRC 84(2011)

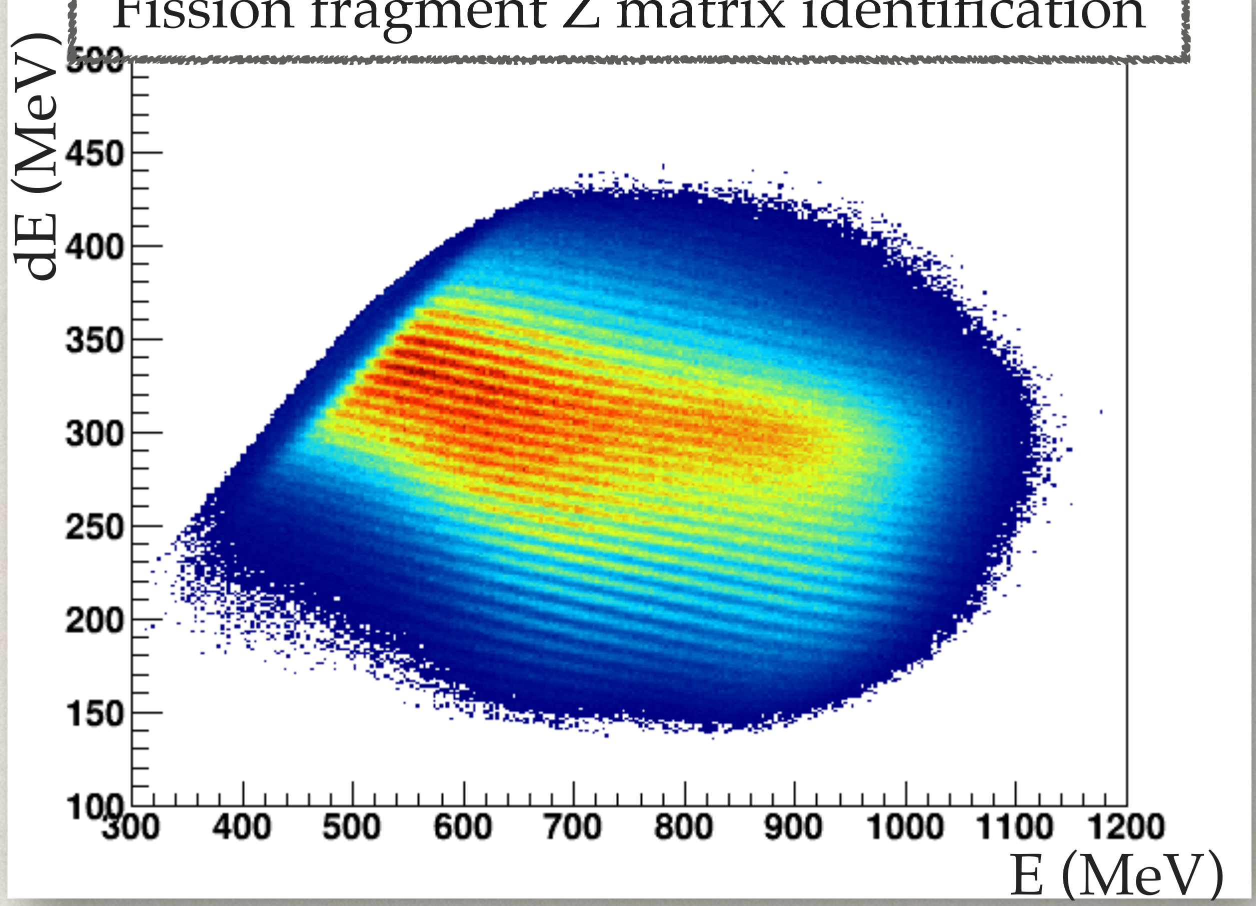
Goals of Inverse kinematics

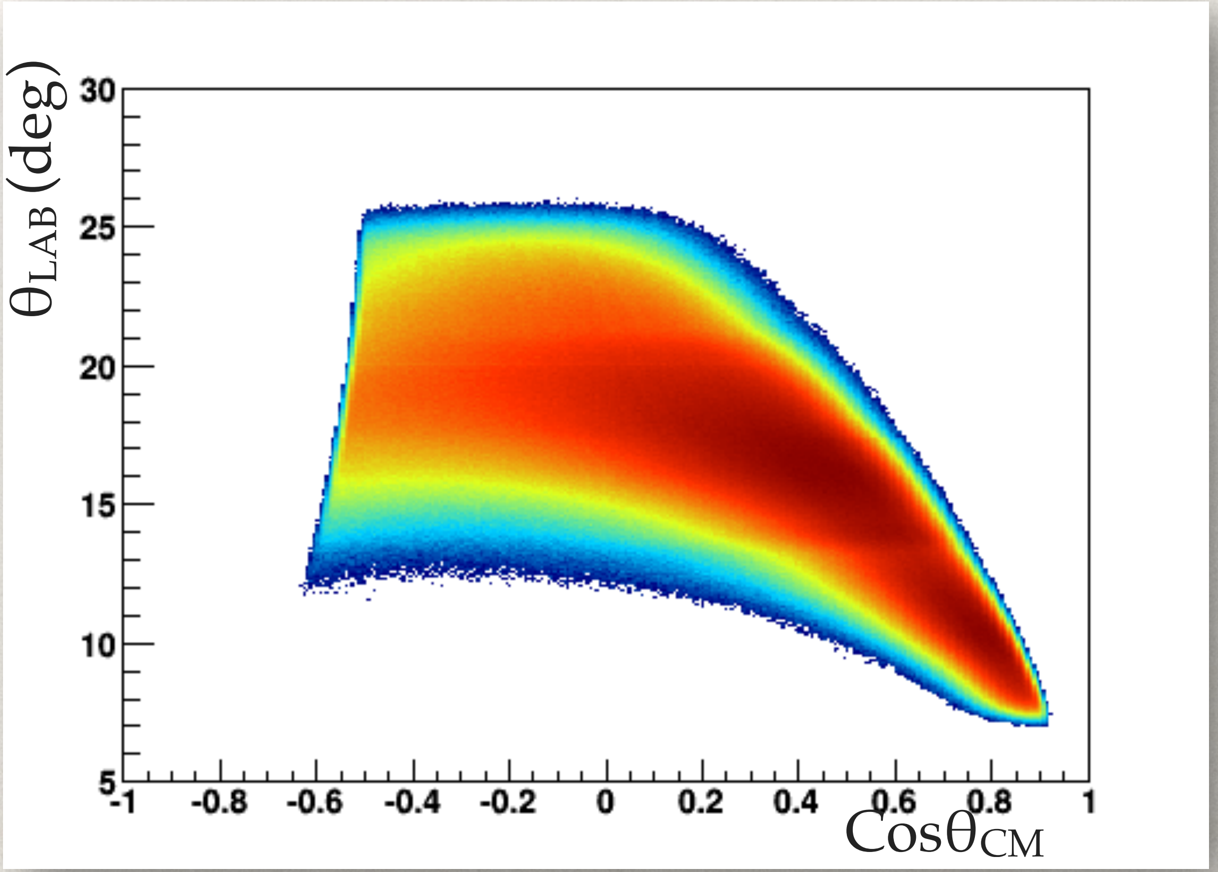


Kinematical boost increases the kinetic energy of the fission fragments providing **the capability of a direct identification**

Kinematical boost allows to keep a wide angular coverage in the CM frame when the size of the detectors is limited

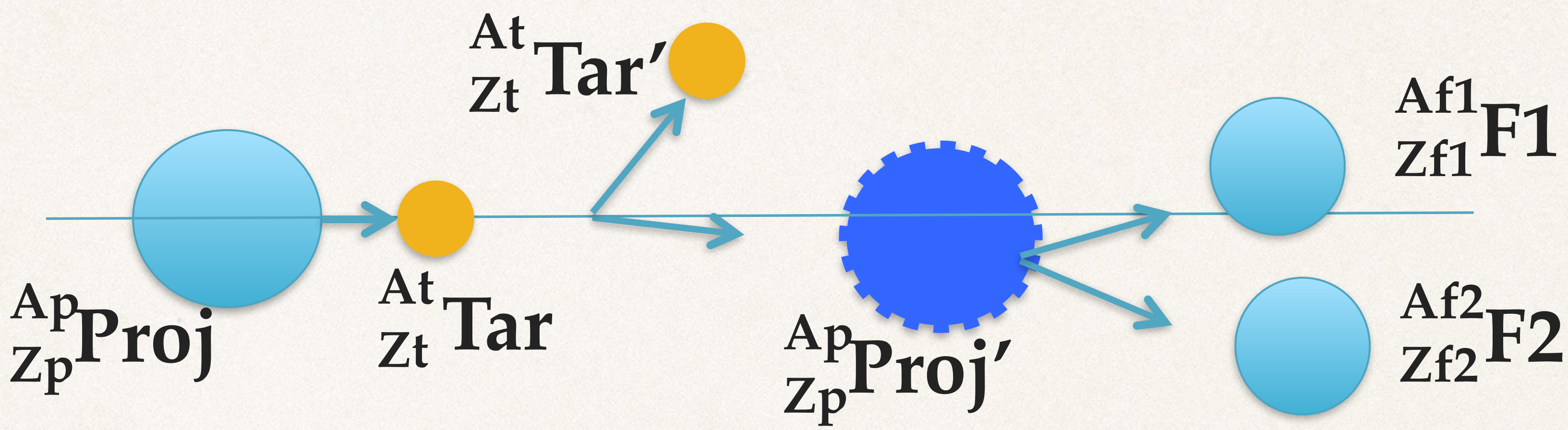
Fission fragment Z matrix identification





Reaction Mechanism

$^{238}U + ^{12}C$ @ 6.14 AMeV



Fissioning Systems

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				

Fissioning systems not accessible from any other mechanism

10% above Coulomb barrier

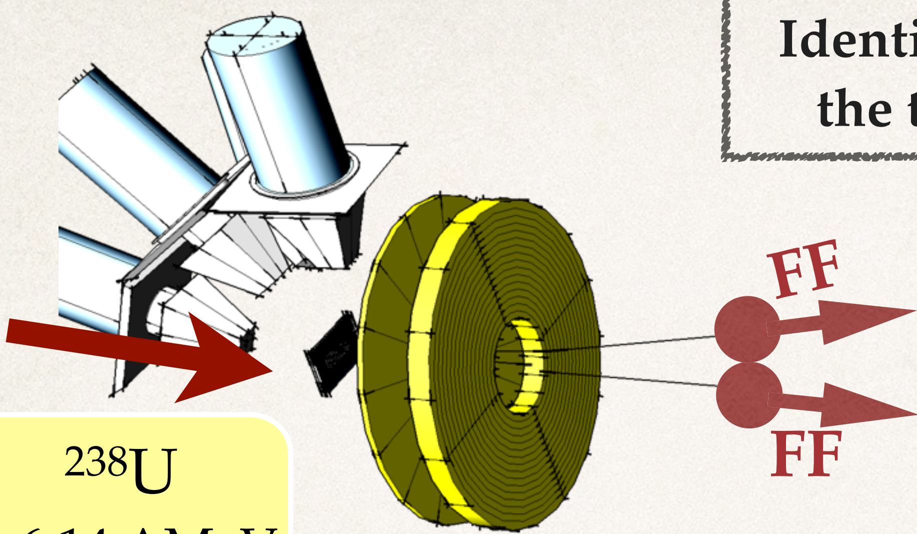
Transfer-Fission:

10 n-rich actinides produced with a distribution of E_X below 30 MeV

Fusion-Fission:

production of ^{250}Cf with $E_X = 46$ MeV 10 times more likely than any transfer channel

Transfer Reaction and Excitation Energy

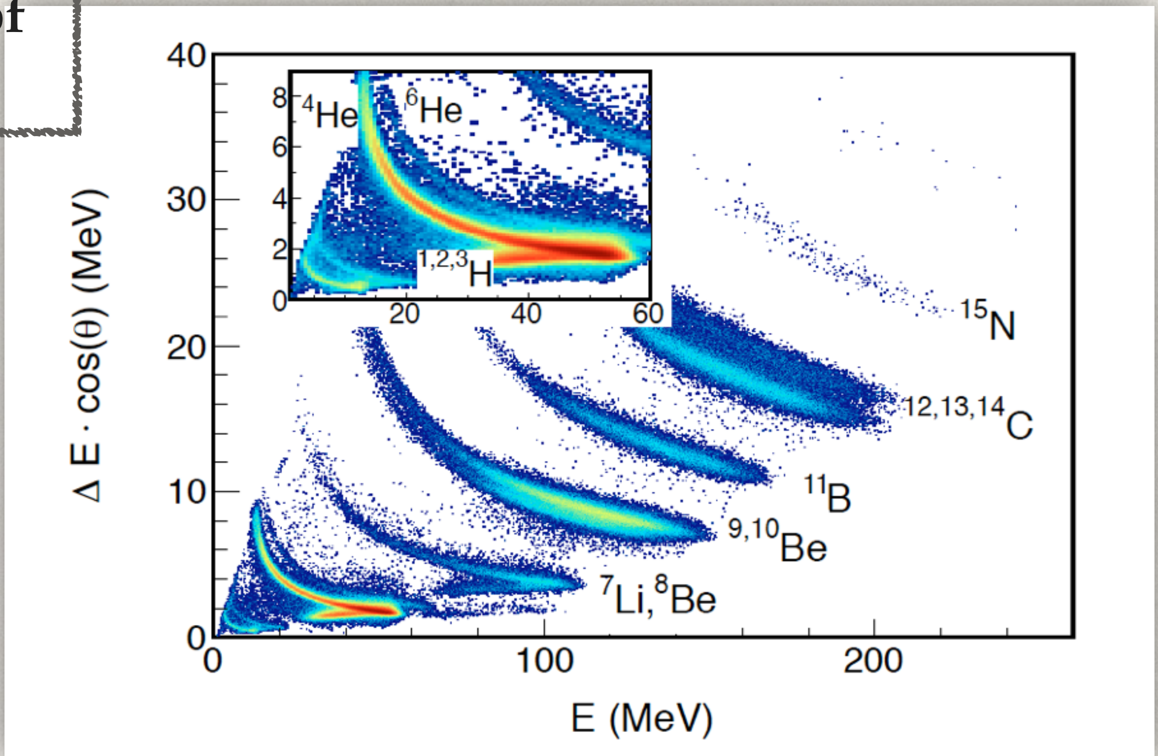


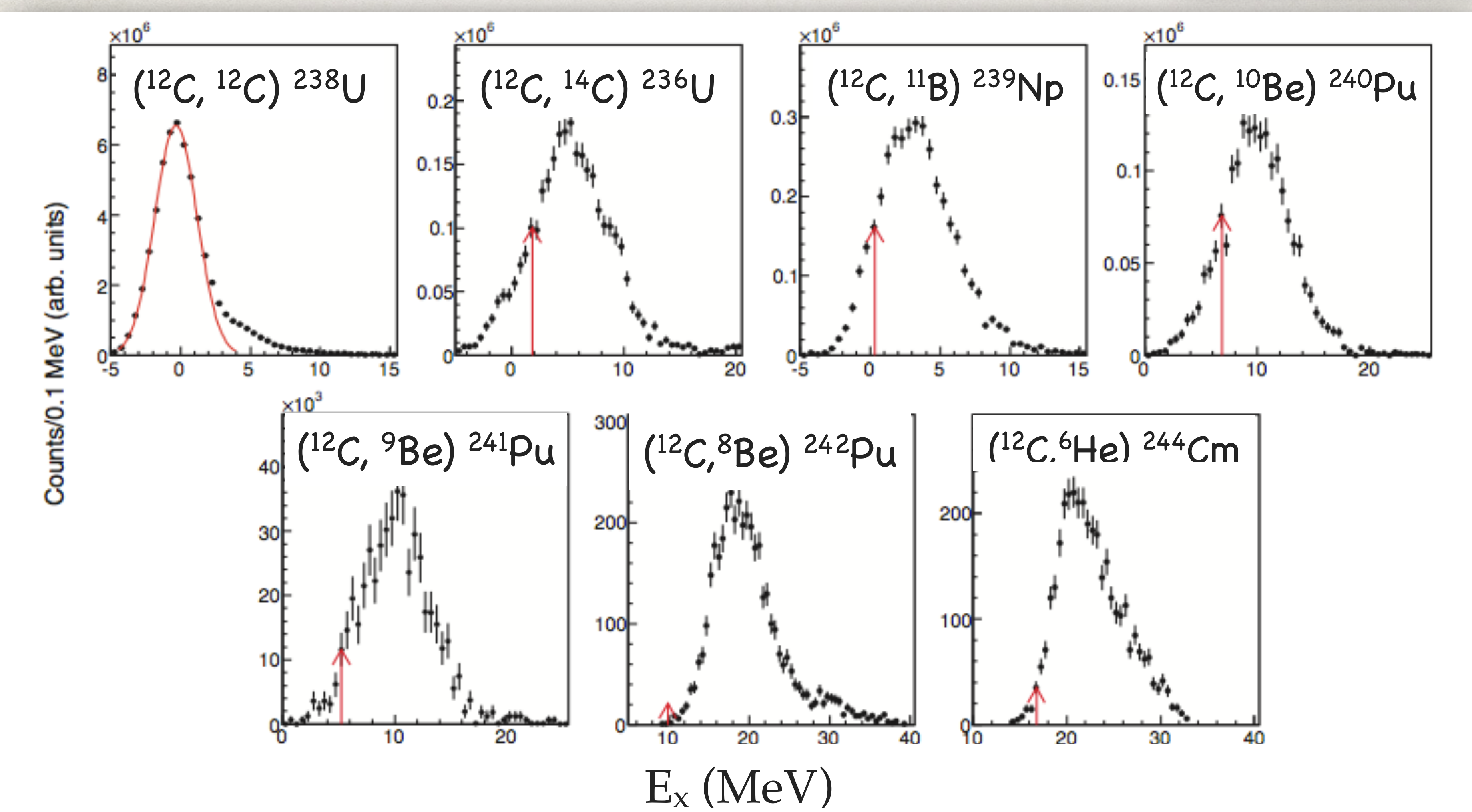
^{238}U
@ 6.14 AMeV

E-ΔE and θ,φ of the recoil

Identification Matrix of the target-like recoil

reconstruction of the transfer reaction & E*





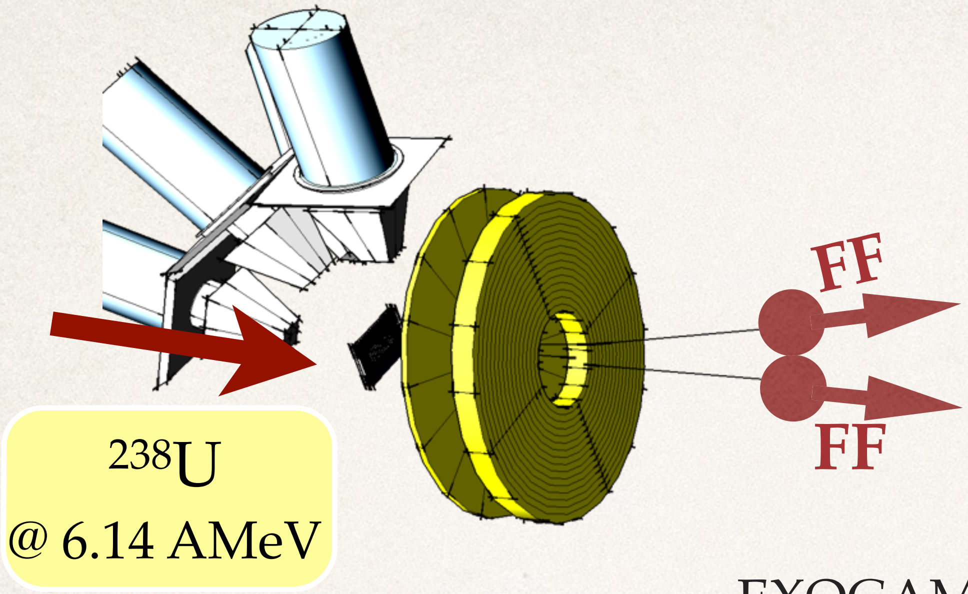
Distribution of E_x for the different fissioning systems from reconstruction of the binary reaction

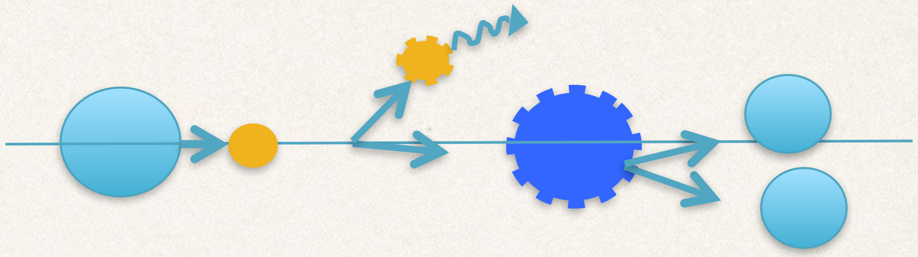
Higher E_x for higher number of transferred nucleons

E_x ~ 8 MeV is comparable with fast-neutron fission

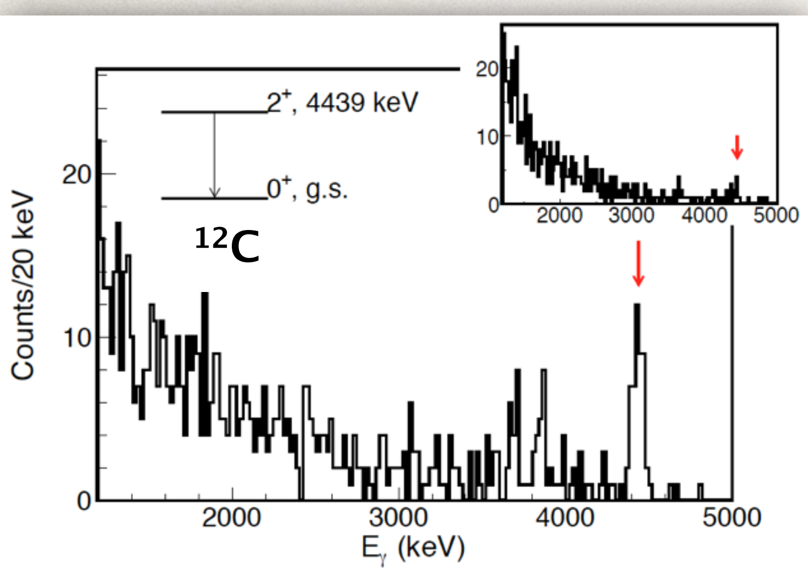
C. Rodriguez-Tajes et *al.*, PRC (2014) 024614

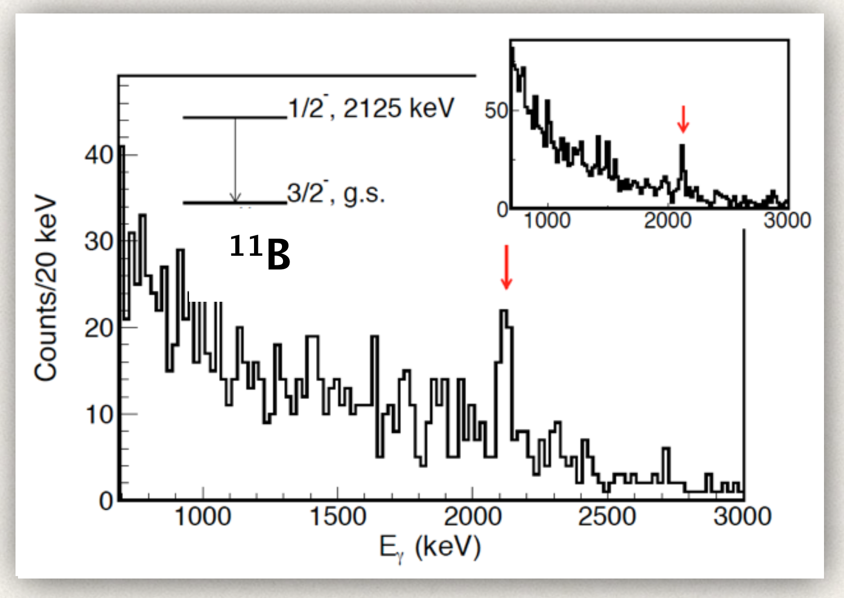
Excitation of Target-like Recoil

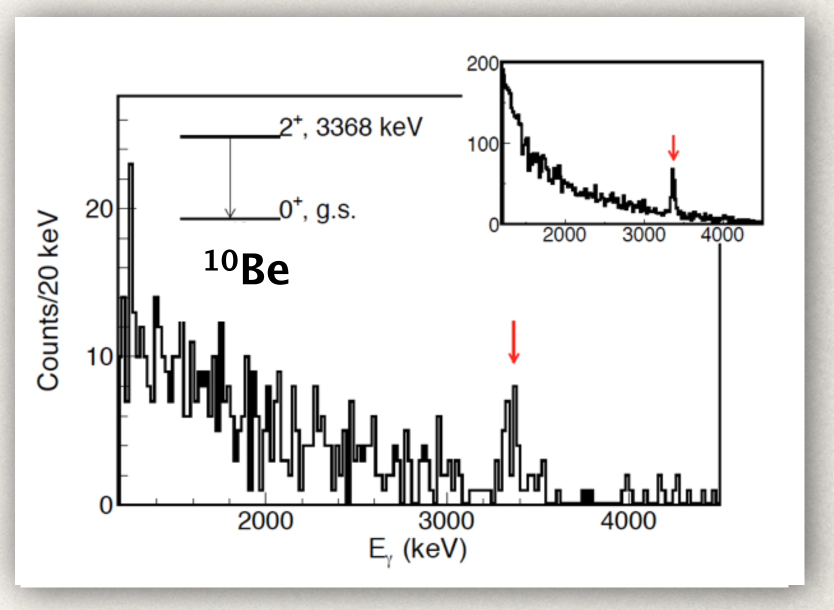




EXOGAM detector allow us to evaluate the excitation probability of the target-like nuclei



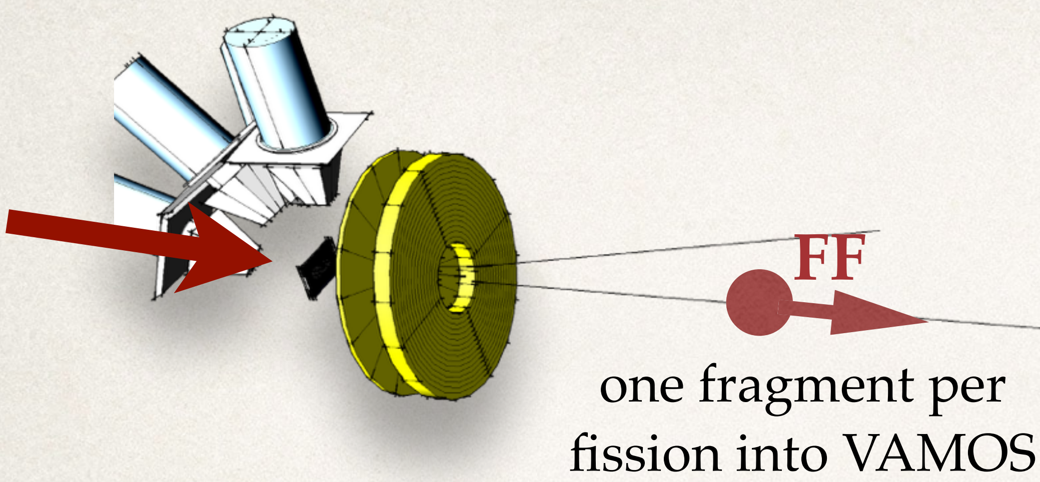


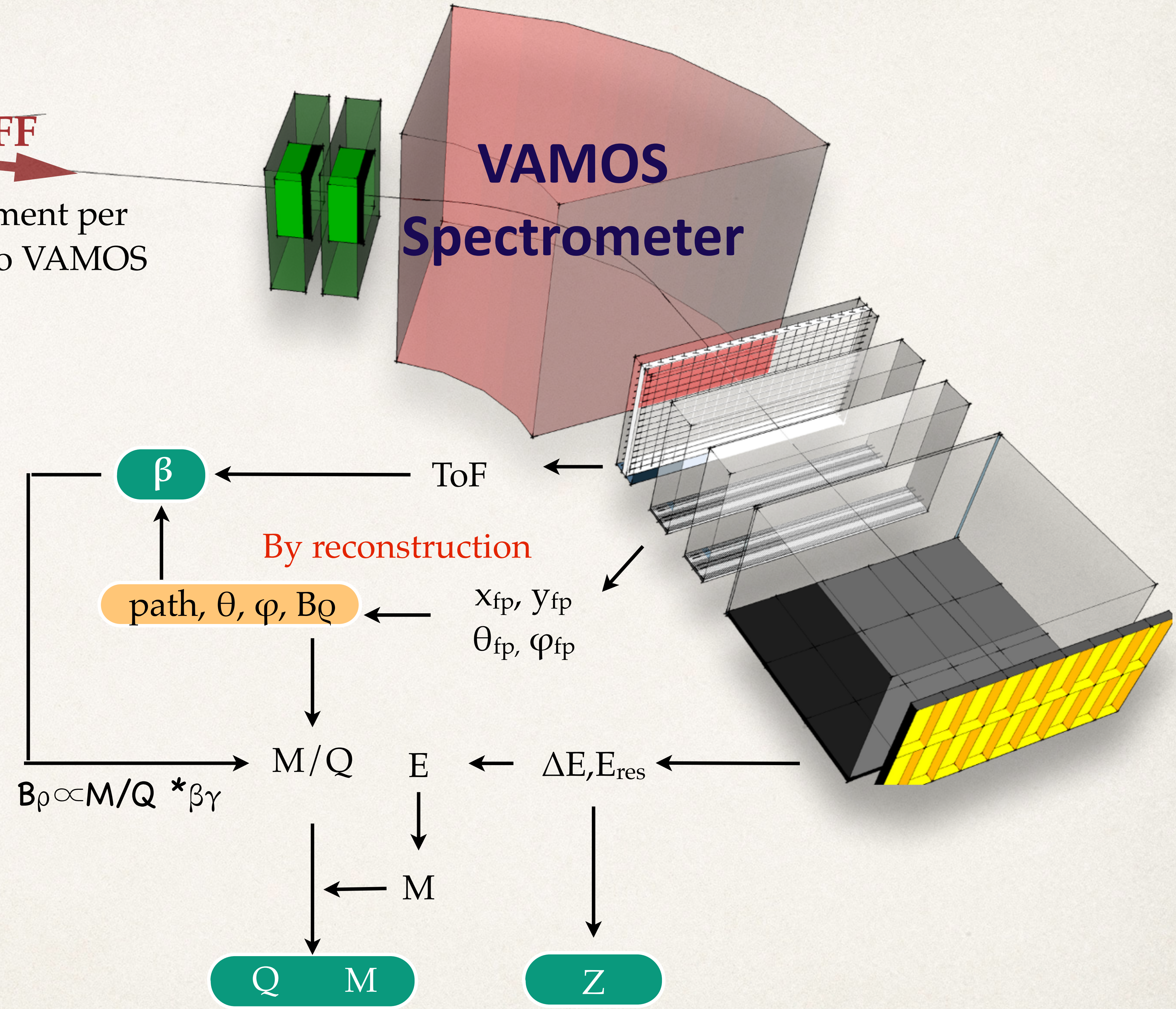


γ-rays measurements show excited states in ^{12}C, ^{11}B and ^{10}Be **in coincidence with fission with P_γ = 0.12-0.14**

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

Fission Fragments Detection





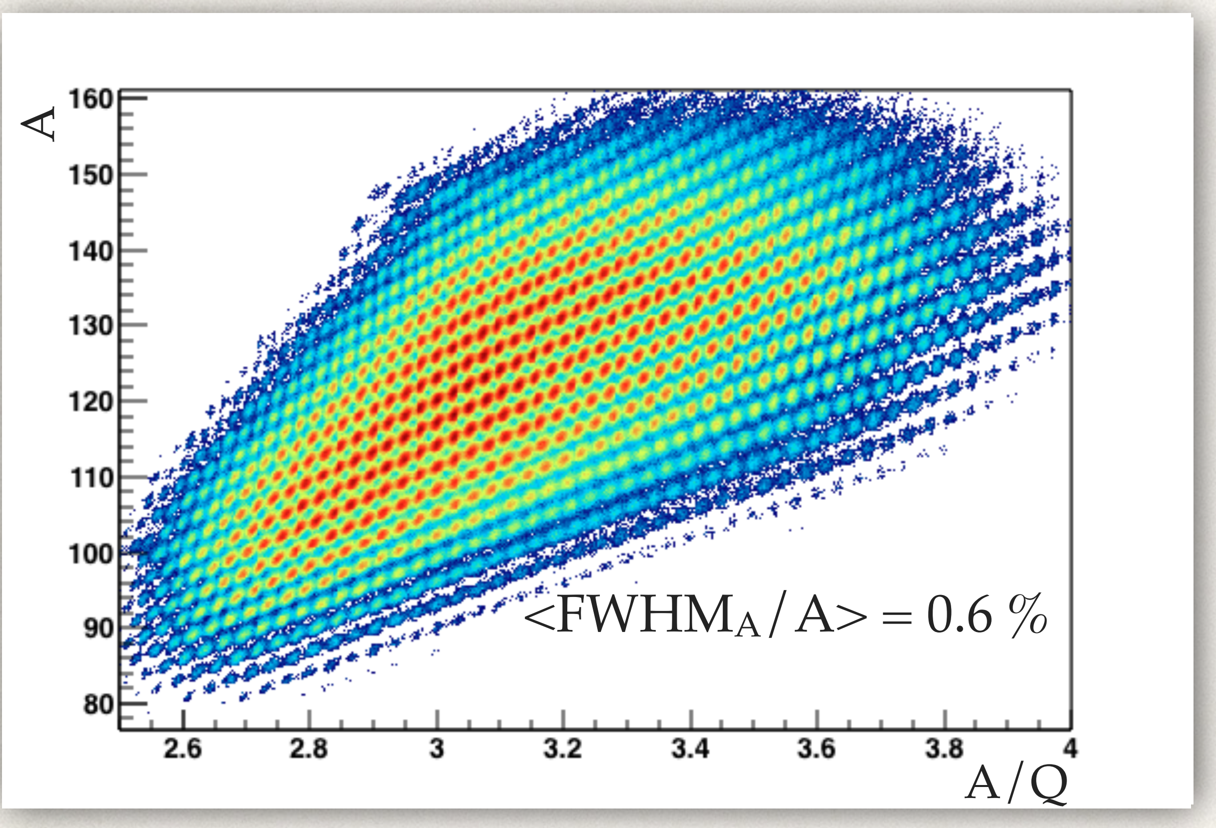
VAMOS Acceptance:
$\Delta\theta \sim 13$ deg
$\Delta\phi \sim 30$ deg
$\Delta B\rho \sim 10$ %

Large acceptance increased by using different settings in central Bρ and in central θ

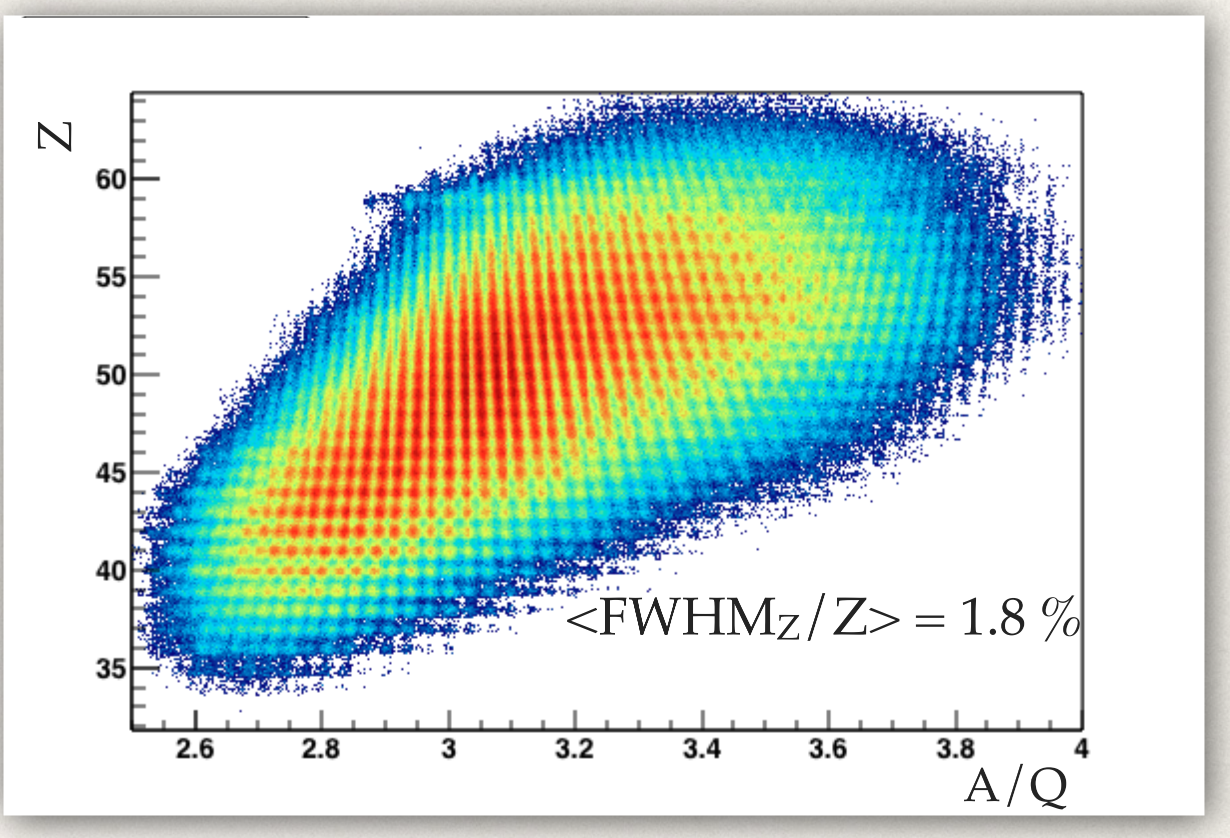
M. Rejmund et al., NIM A 646 (2011) 184
S. Pullanhiotan et al., NIM A 593 (2008) 343

Fission Fragments Identification

Mass Identification

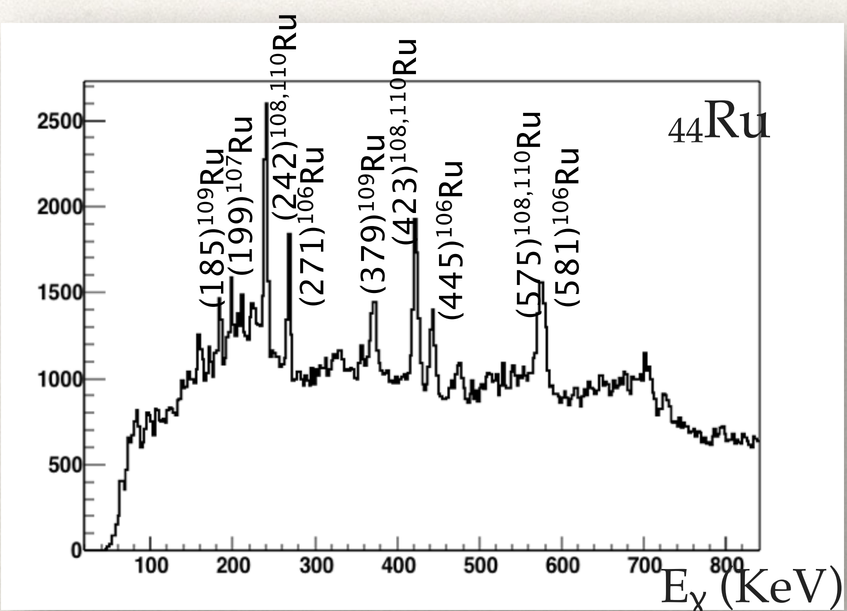


Proton Number Identification



A/Q provides the Q separation and contributes to a better A resolution

More than 300 isotopes identified

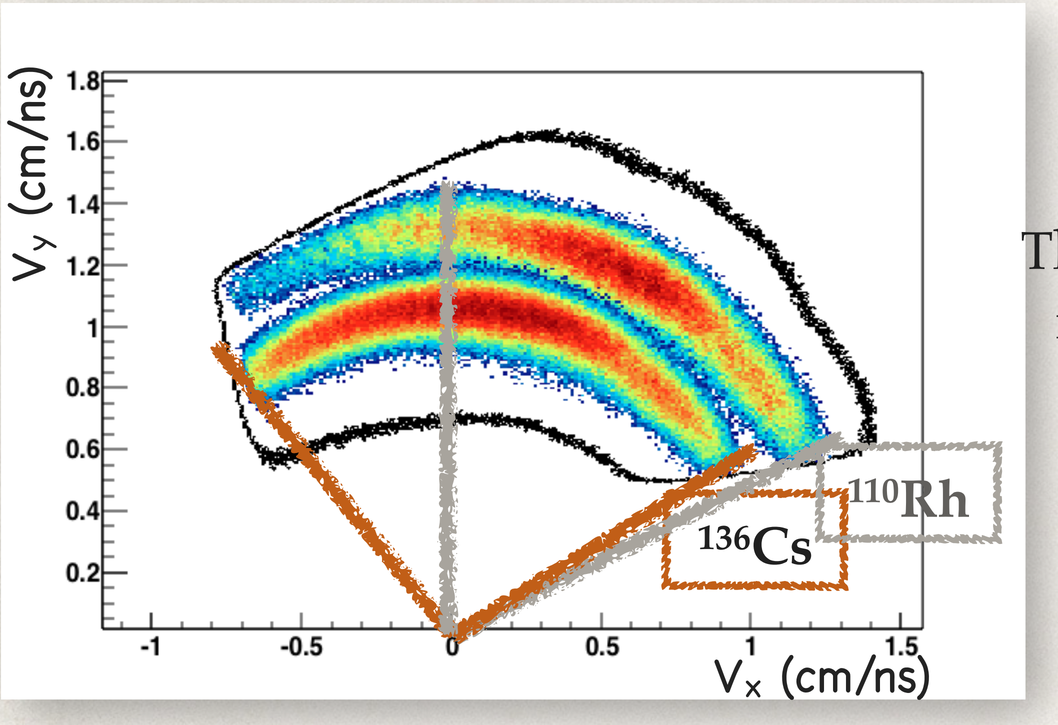


γ-rays in coincidence with fission fragments provide a cross check for the Z and A identification

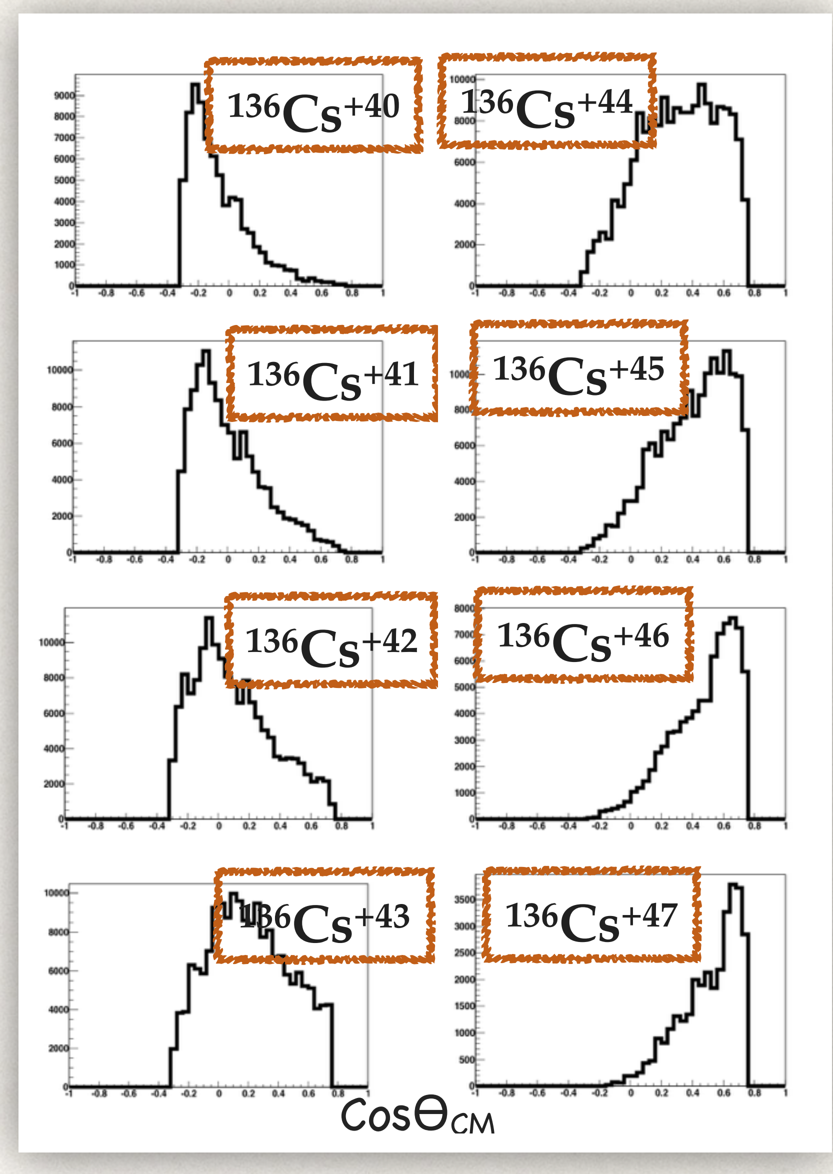
A. Shrivastava et al. PRC 80 (2009) 051305

Transmission through VAMOS

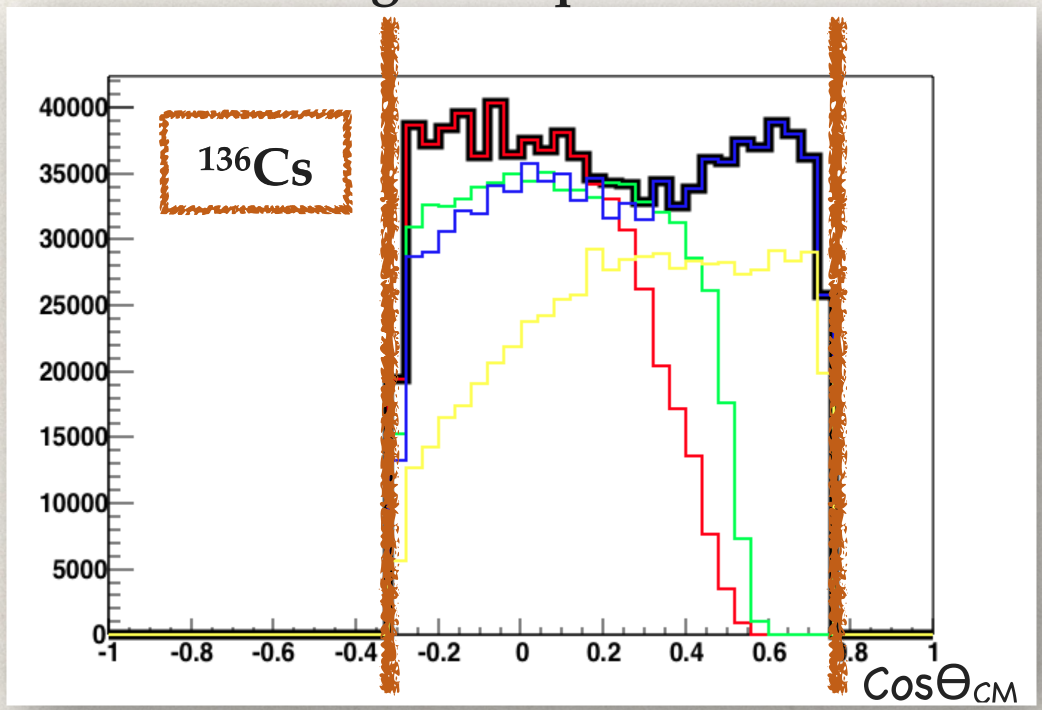
The detection is limited by the transmission



The transmission is different for different isotopes



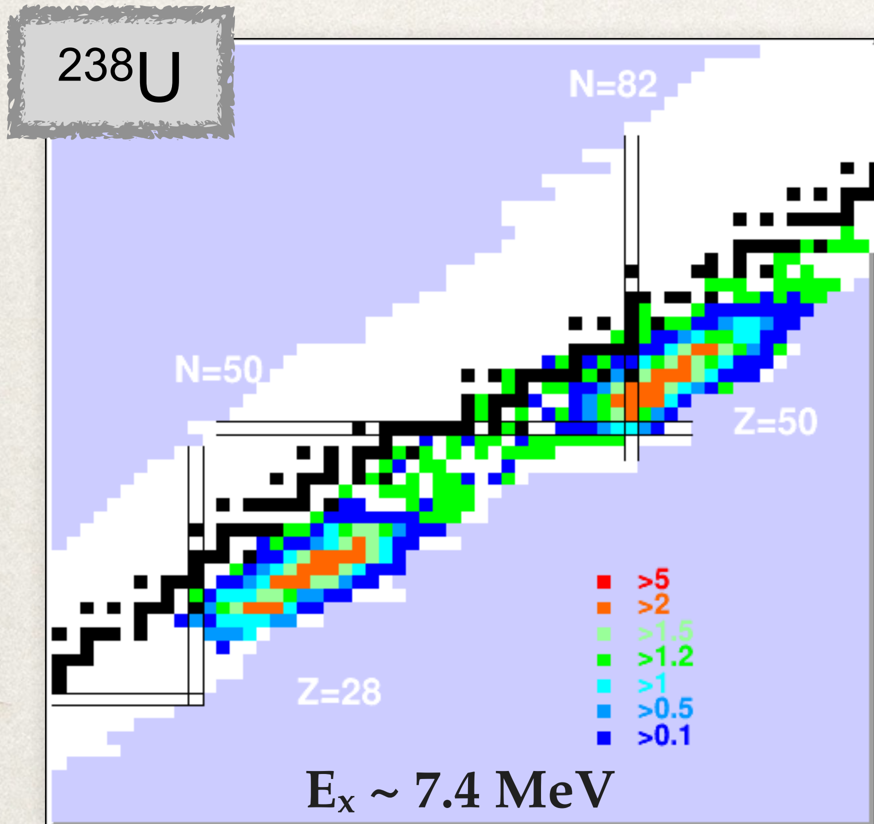
Beam normalization for different settings is required as well

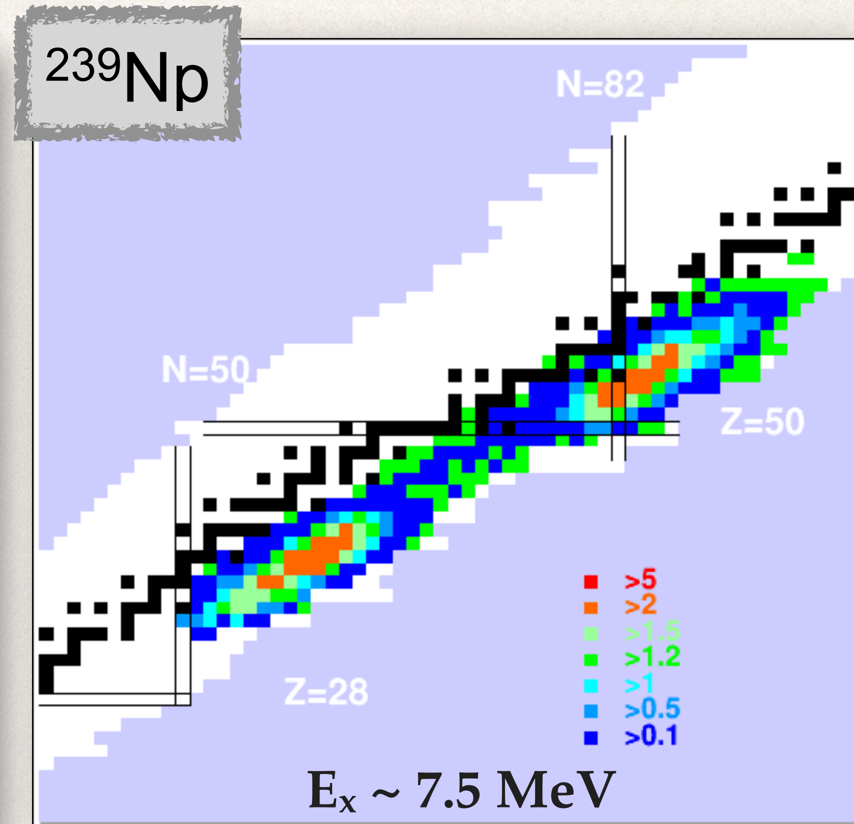


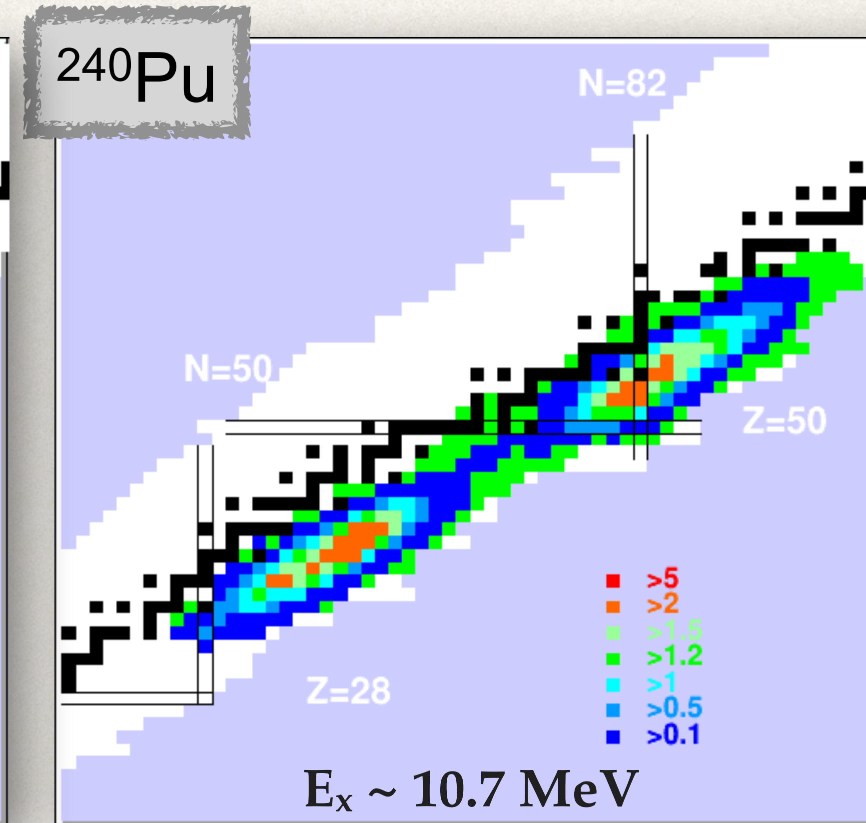
We need to recover all the charge states per isotope and compensate the acceptance in the azimuthal and polar angles

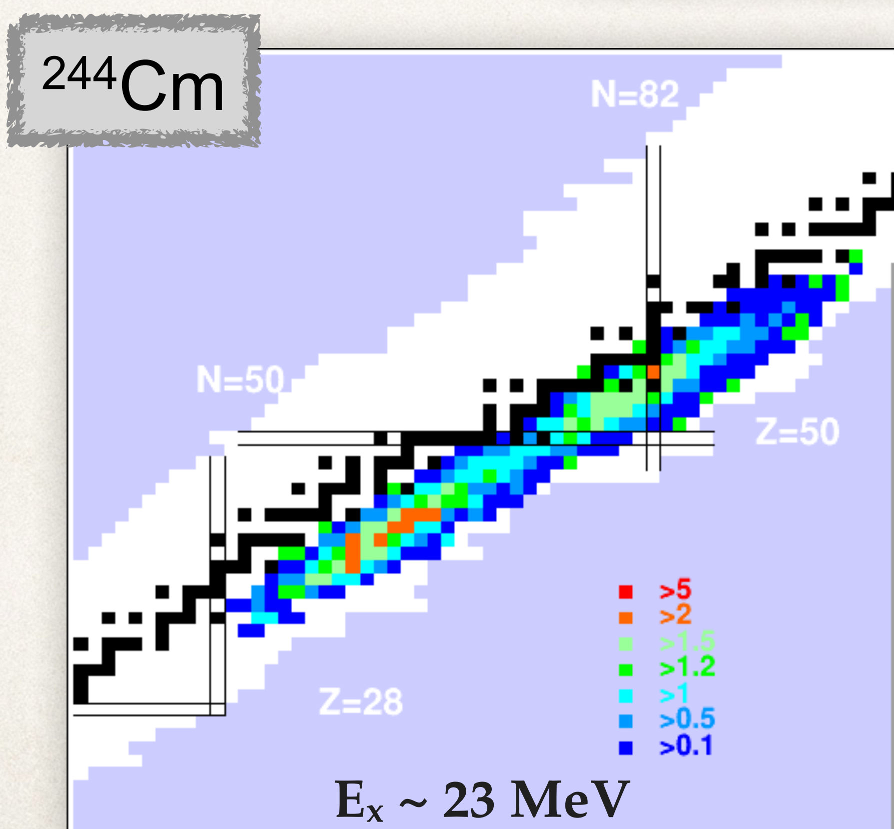
$$Y(Z,A) = I(Z,A)\frac{2}{Range(Z,A)}$$

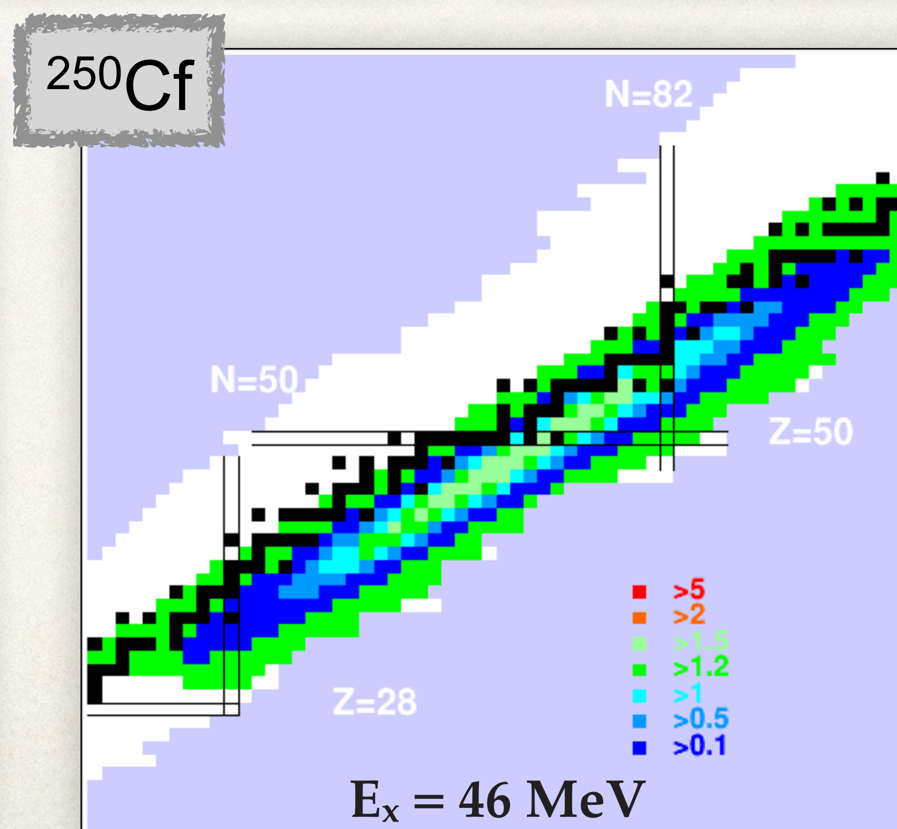
Isotopic Fission-Fragment Distribution





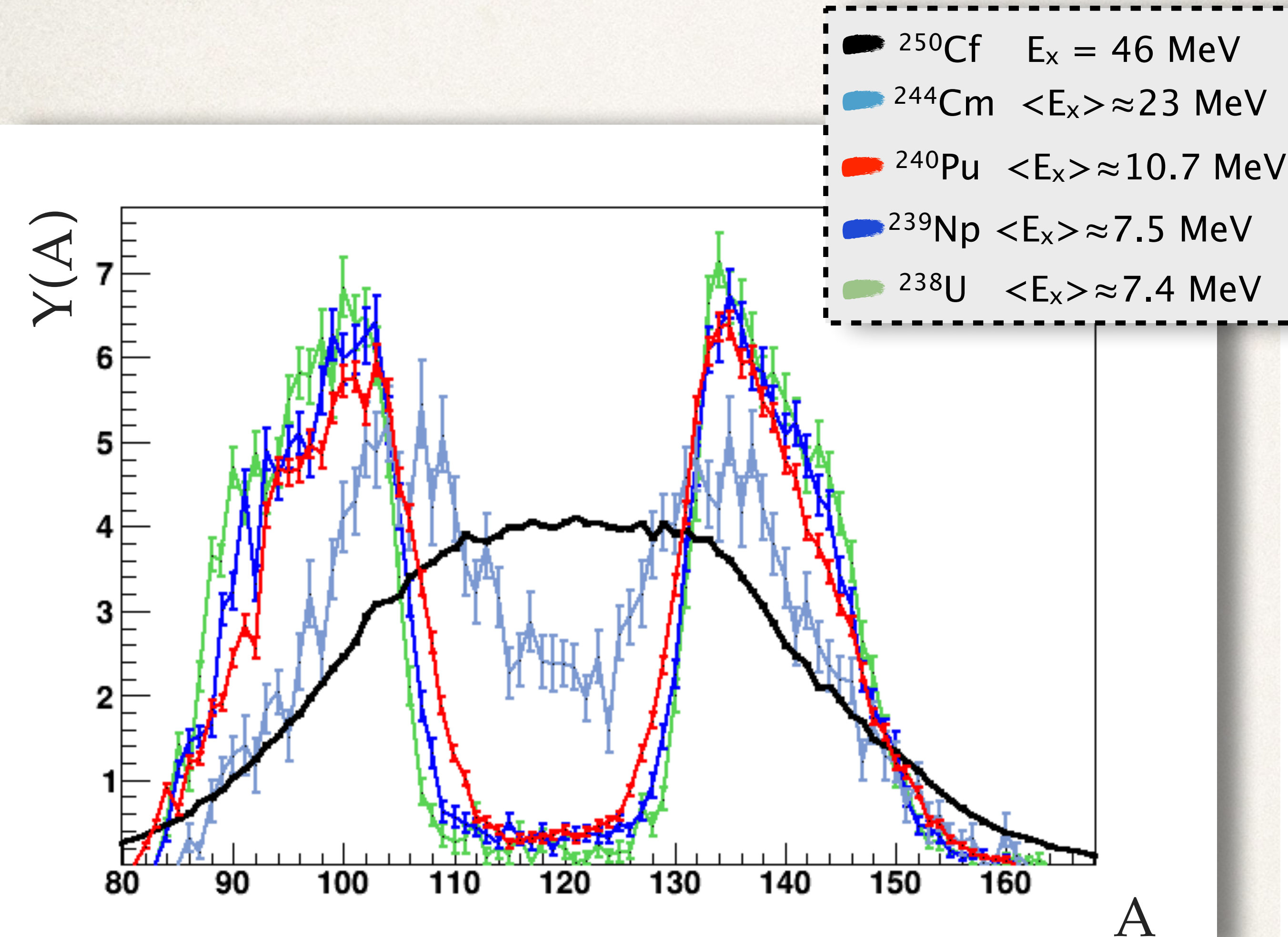


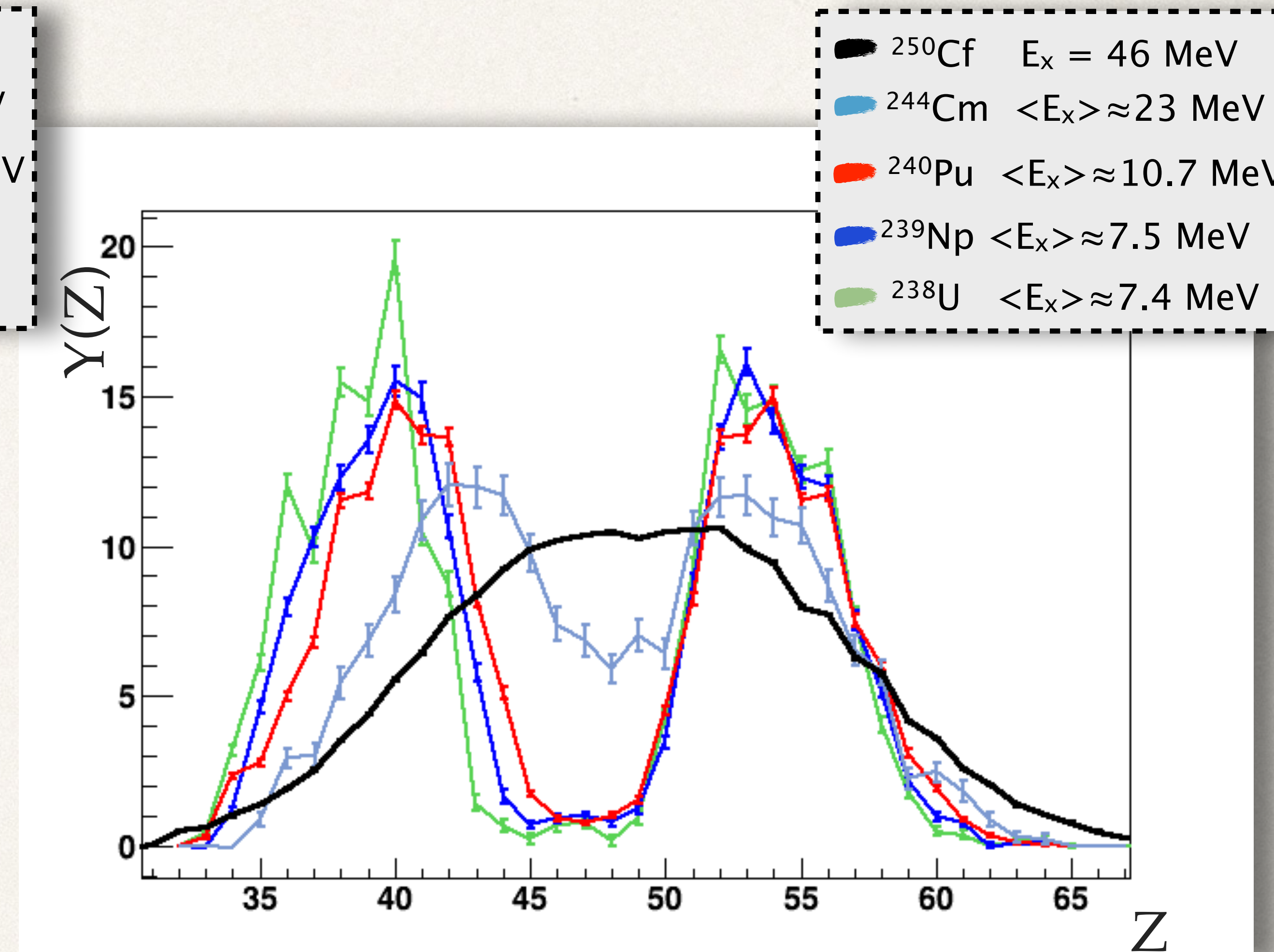




Fission Yields

Mass-yields and Z-yields distribution of 5 different fissioning systems, most of them exotic nuclei





New complete measurements, difficult to produce by n-capture

Measurements of fragment distributions of ^{239}Np is scarce ($T_{1/2}$ (^{238}Np) = 2.1 d)

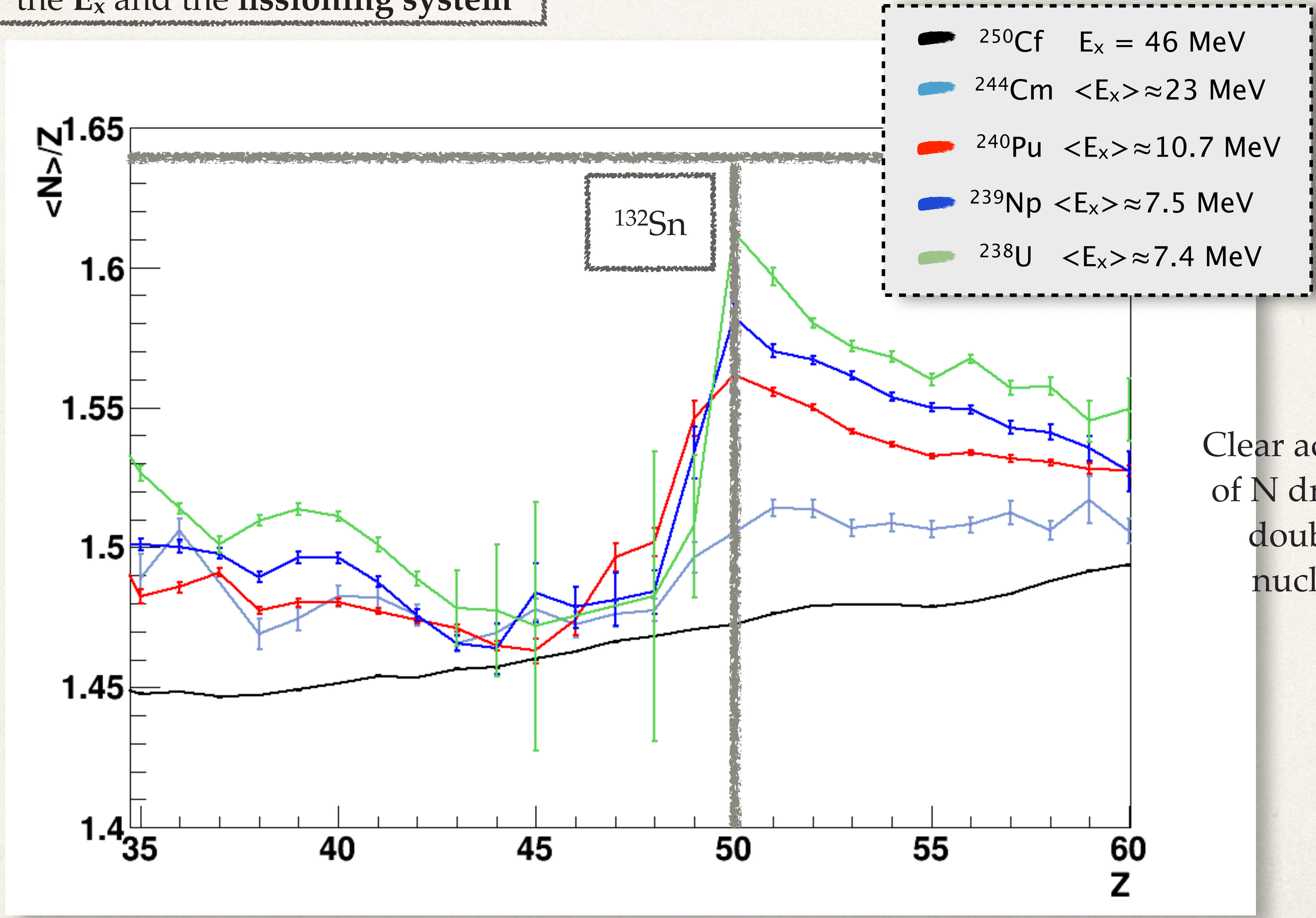
There is no direct measurements of fragment distributions of ^{244}Cm

The contribution of the symmetric mode disappears for the systems at low excitation energy

The shift in Z of the light fragments reflects the atomic number of the fissioning system

Neutron Excess

Evolution of the polarization with the E_x and the **fissioning system**

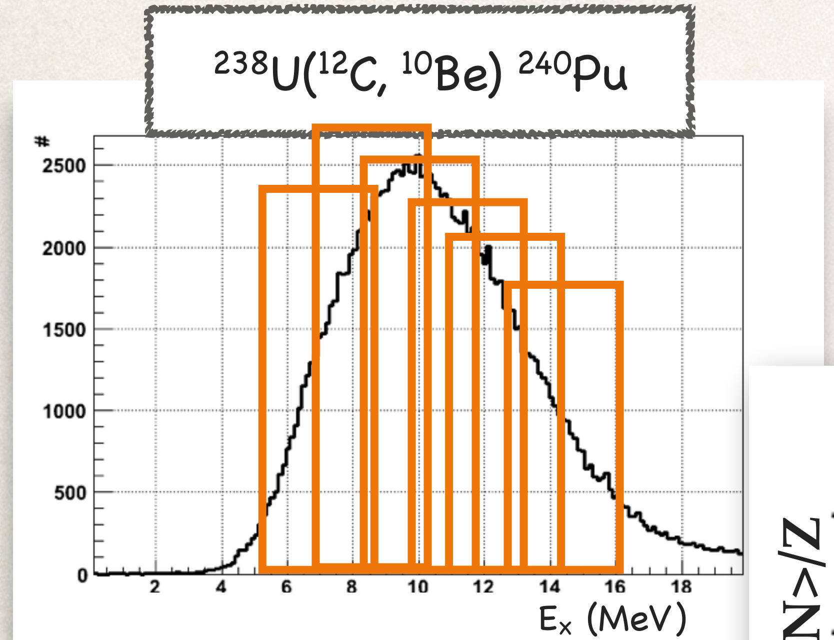


Clear accumulation of N driven by the double magic nucleus ^{132}Sn

Charge Polarization present in all the systems

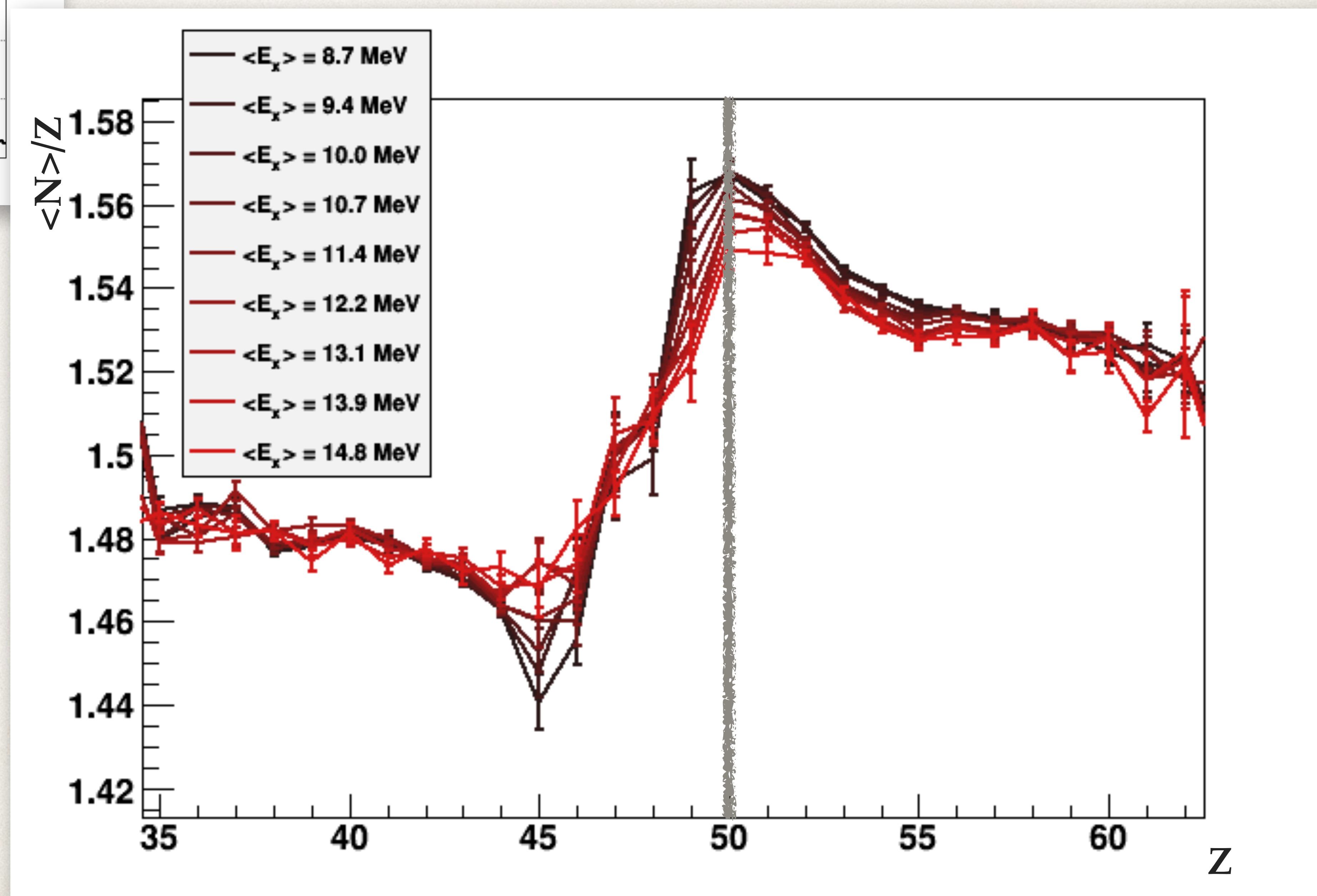
Neutron Excess

^{240}Pu



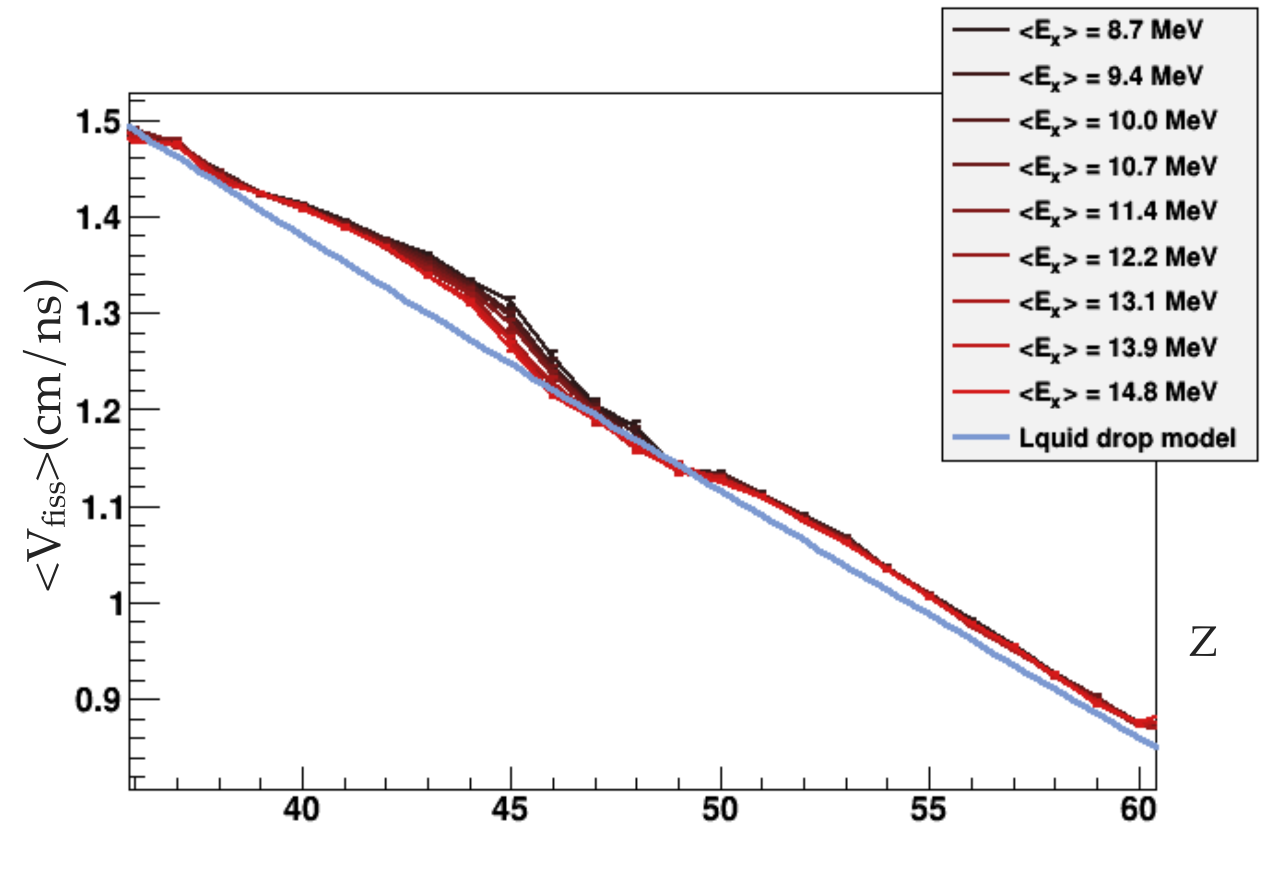
Different positions of gate along the E_x distribution

The <N>/Z ratio gets reduced around Z ≈ 50 by increasing E_x, signature of a closed shell which effect is smaller for higher E_x.



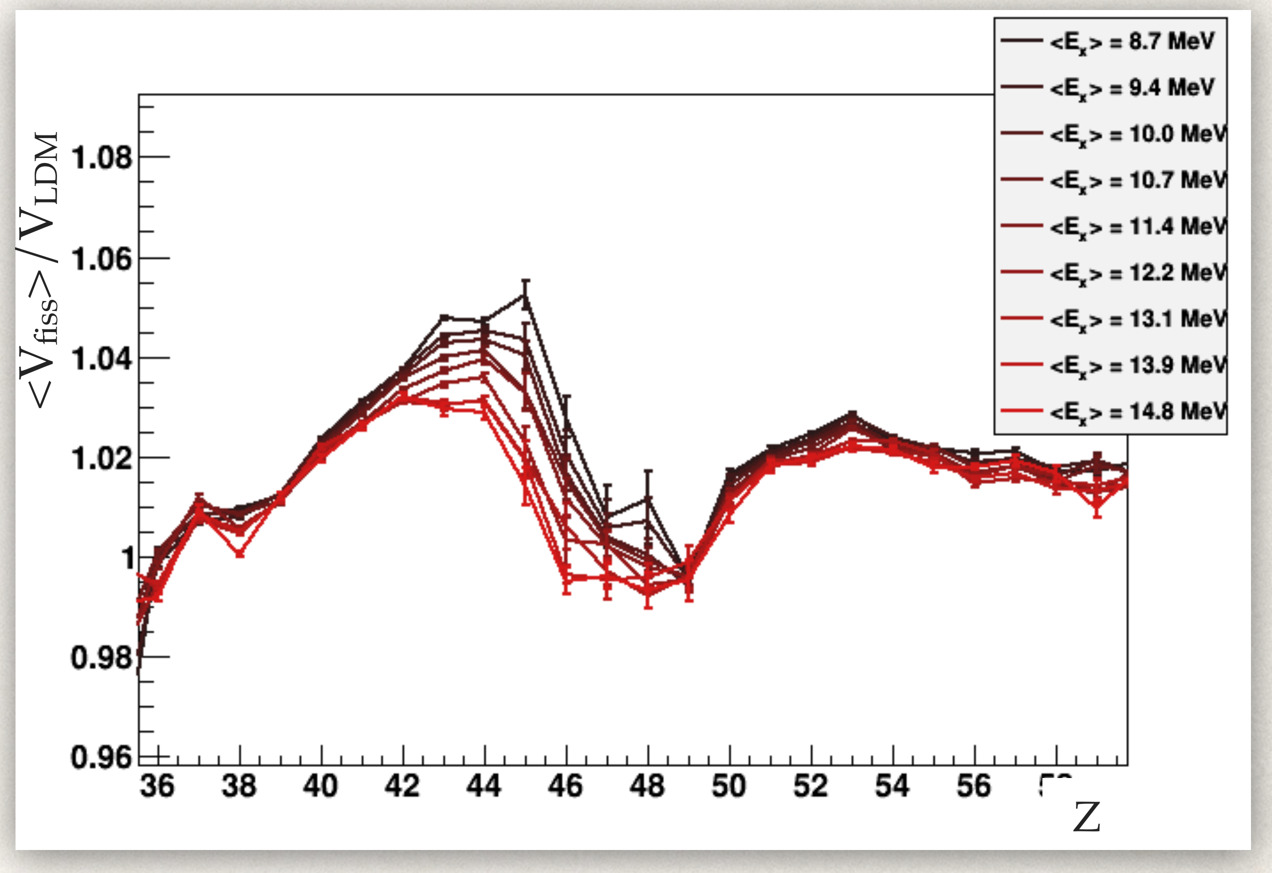
Average Velocity

PRELIMINARY



$$< V_{fiss} >= \frac{\sum_A V_{fiss}(Z,A) \cdot Y(Z,A)}{\sum_A Y(Z,A)}$$

In the asymmetric region, the light fragment is emitted with a higher velocity compared with the LDM



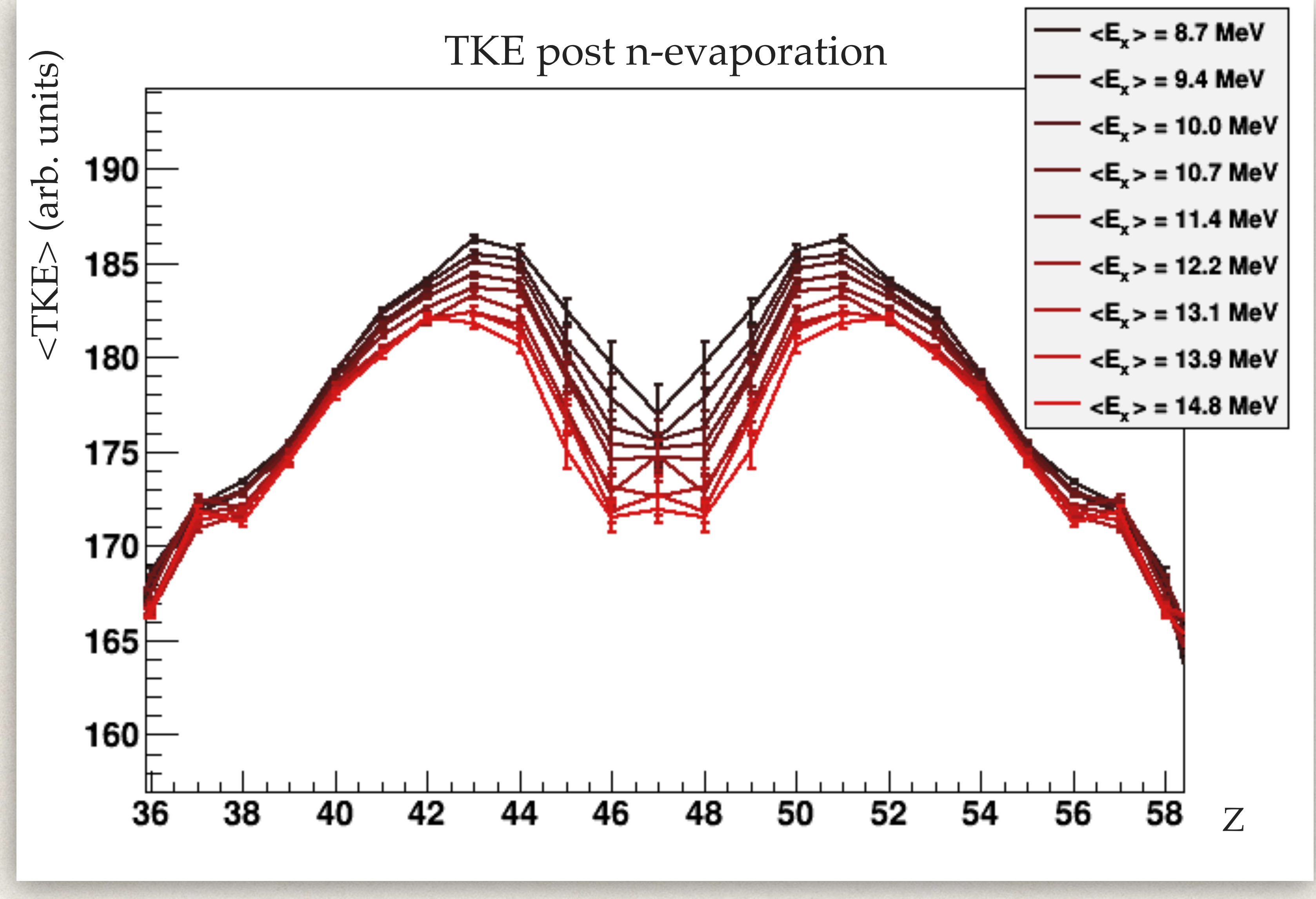
Velocity decrease with higher E_x
The distance between both fragments at the scission point is larger with higher E_x

^{240}Pu

Average Total Kinetic Energy

PRELIMINARY

$$TKE = u \cdot < A >_Z \cdot (< \gamma >_Z - 1) + u \cdot < A >_{Z_{Act} - Z} \cdot (< \gamma >_{Z_{Act} - Z} - 1)$$

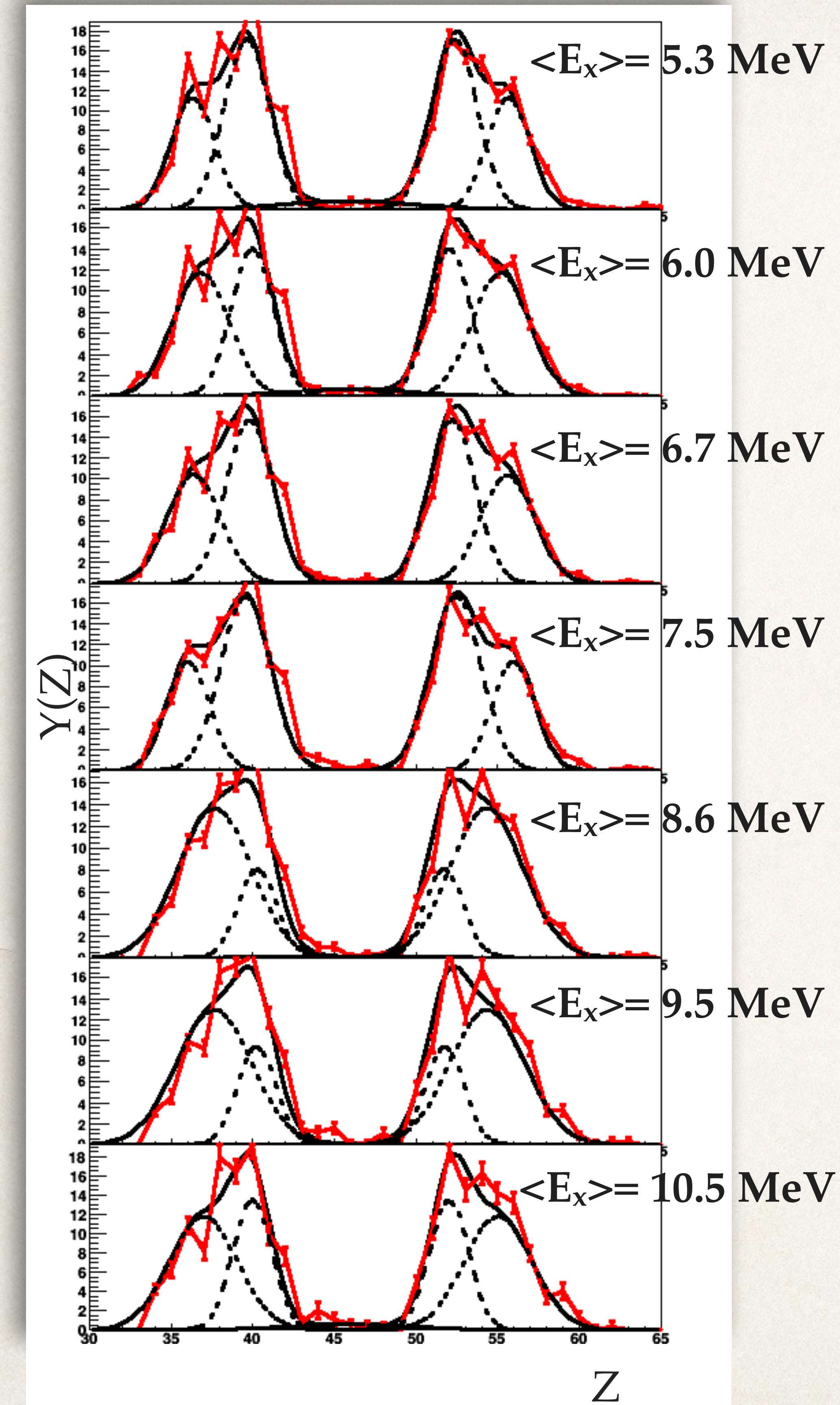


TKE values decrease with higher E_x

- Larger distance at scission point
- Larger neutron evaporation

^{238}U

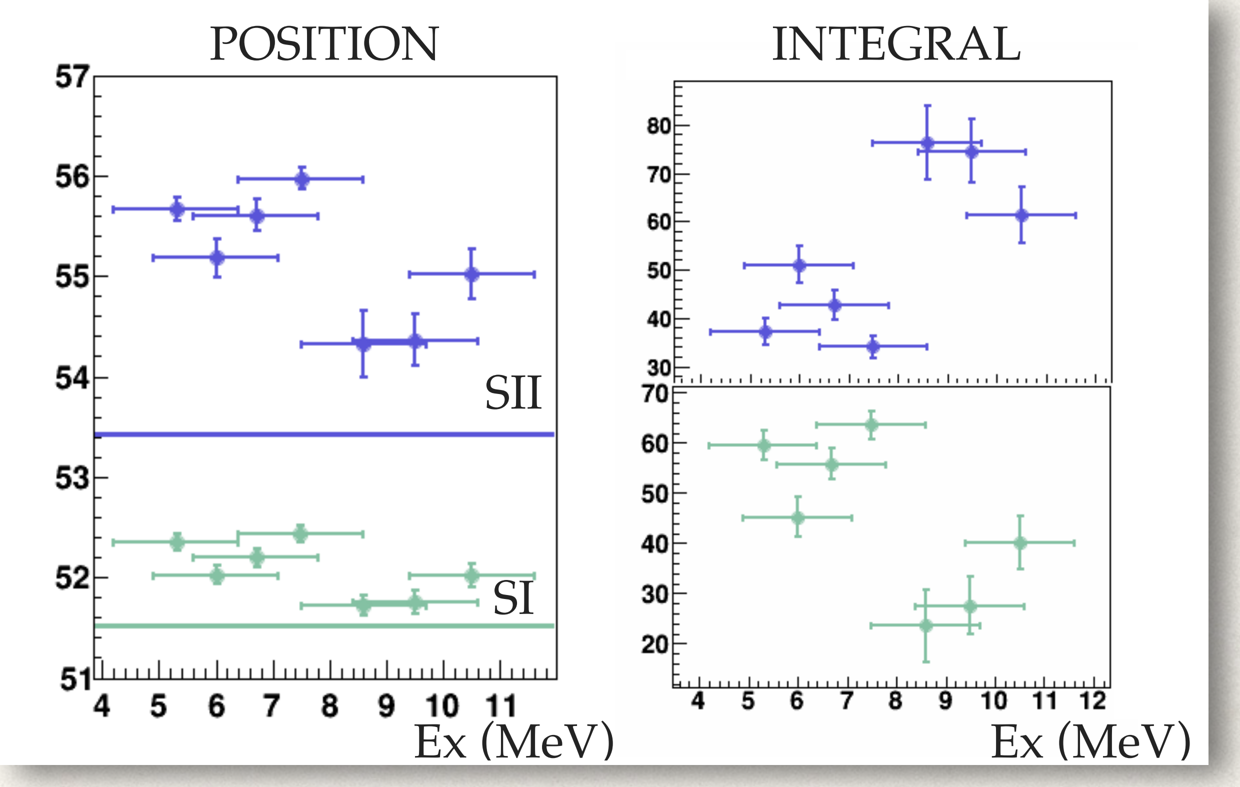
Excitation Energy Dependence



- Super Long (A, μ and σ fixed)
- Standard I
- Standar II

Both Standard positions appear above the K.-H. Schmidt prescription

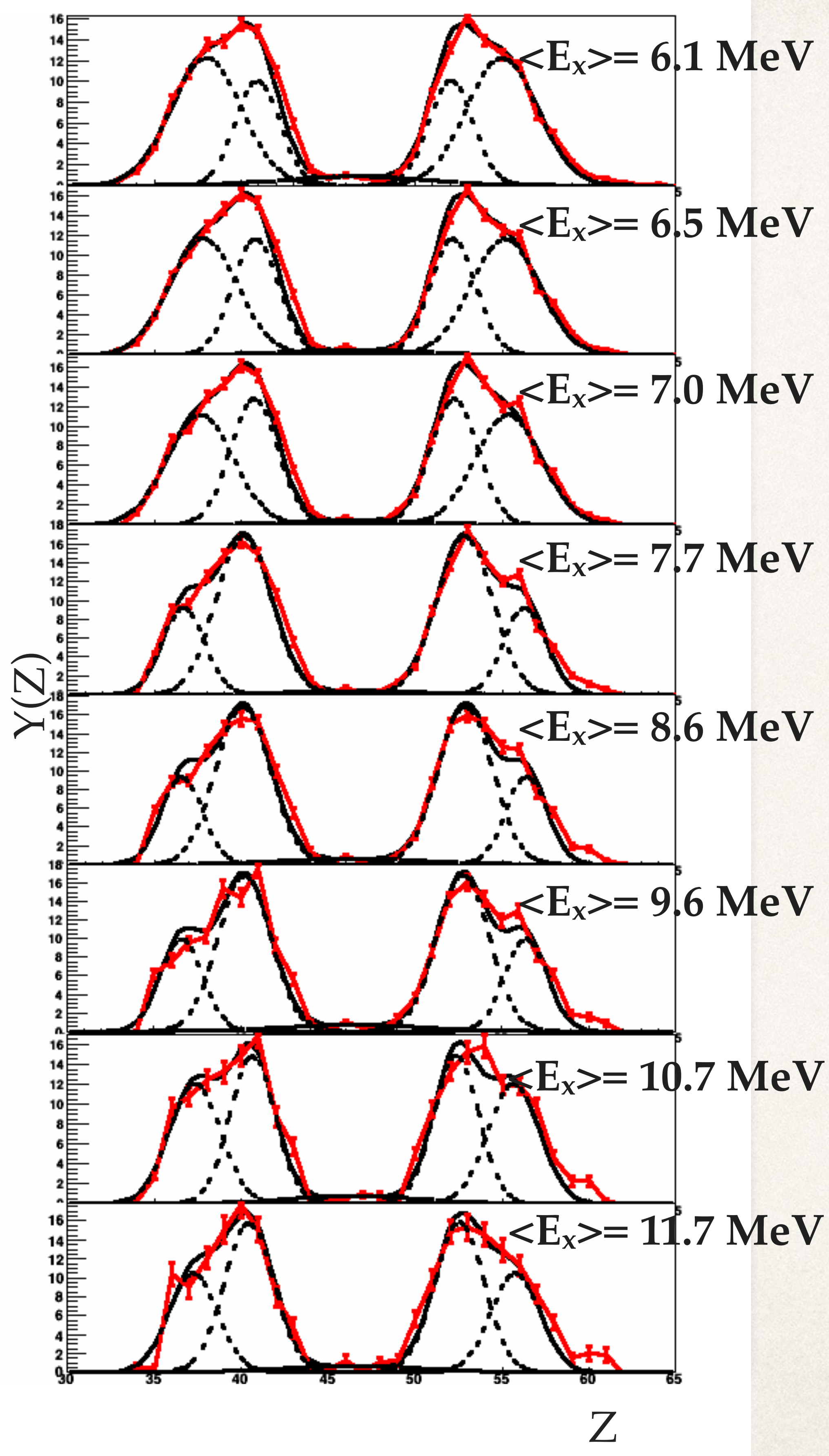
K.-H. Schmidt et *al.*, Nucl. Phys. A 665, 221 (2000)

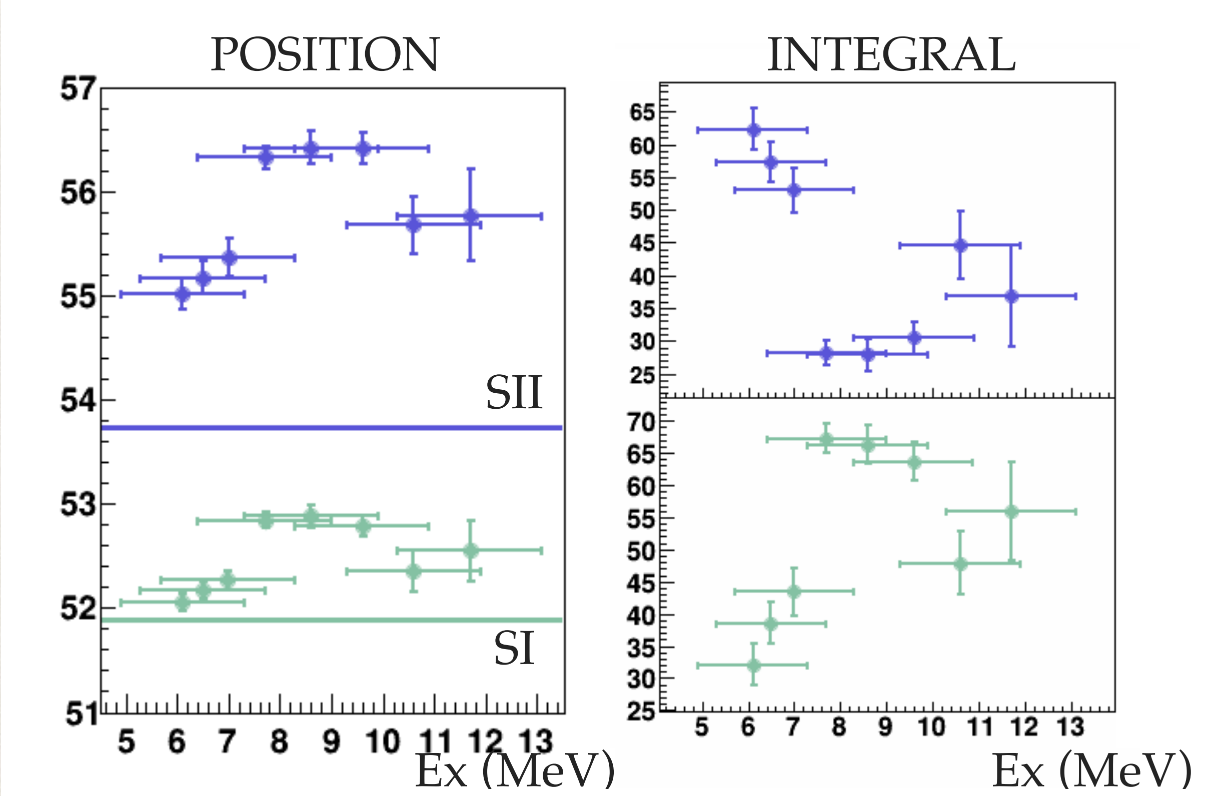


We observe an evolution of the position and the integrals of the asymmetric modes Standard I and Standard II

^{239}Np

Excitation Energy Dependence

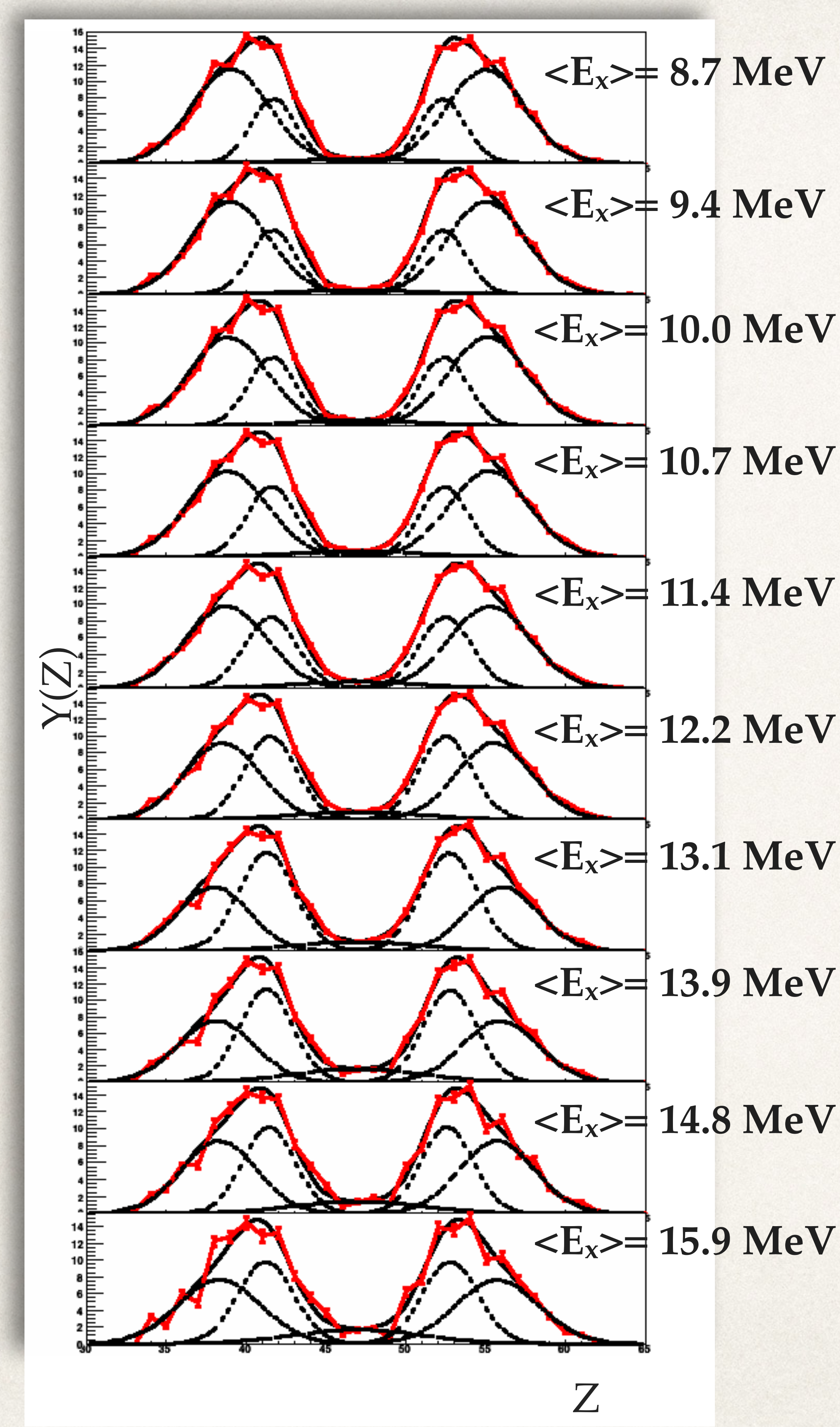




The evolution of the fission channels becomes more clear in this case

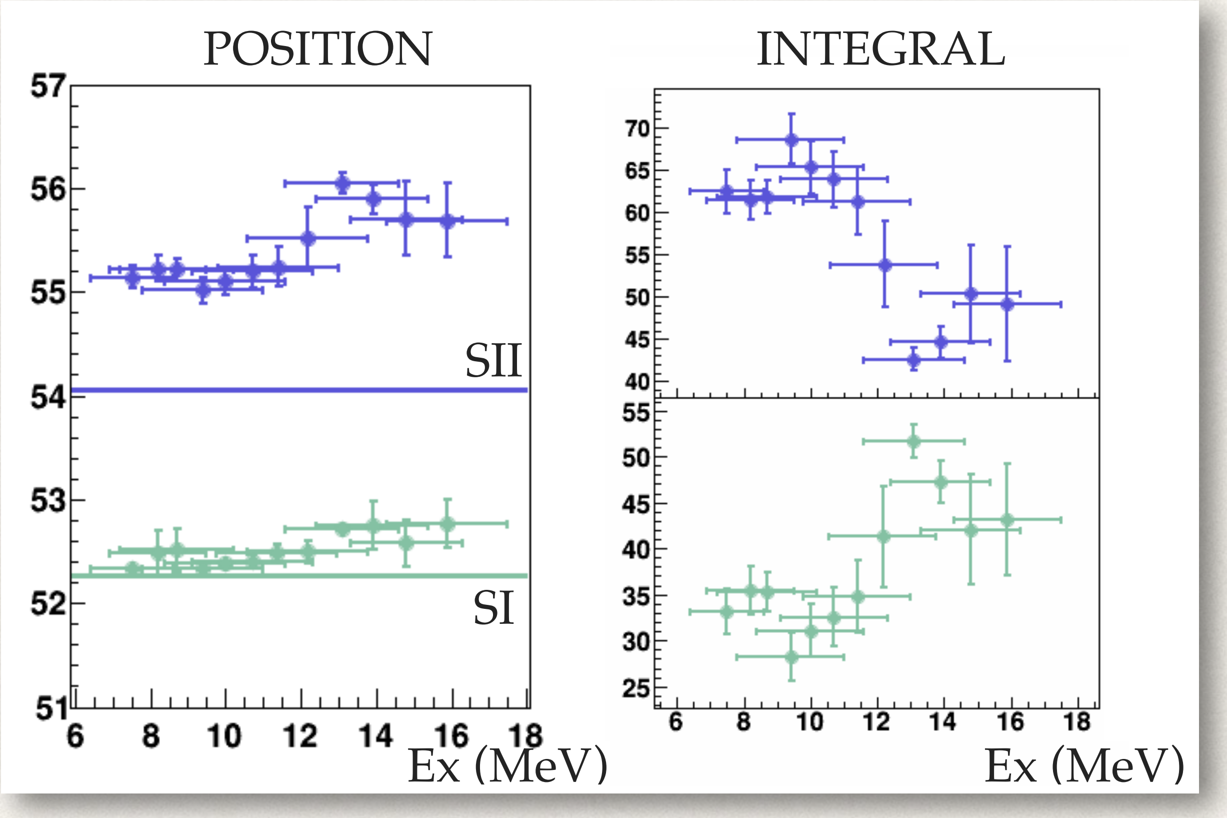
^{240}Pu

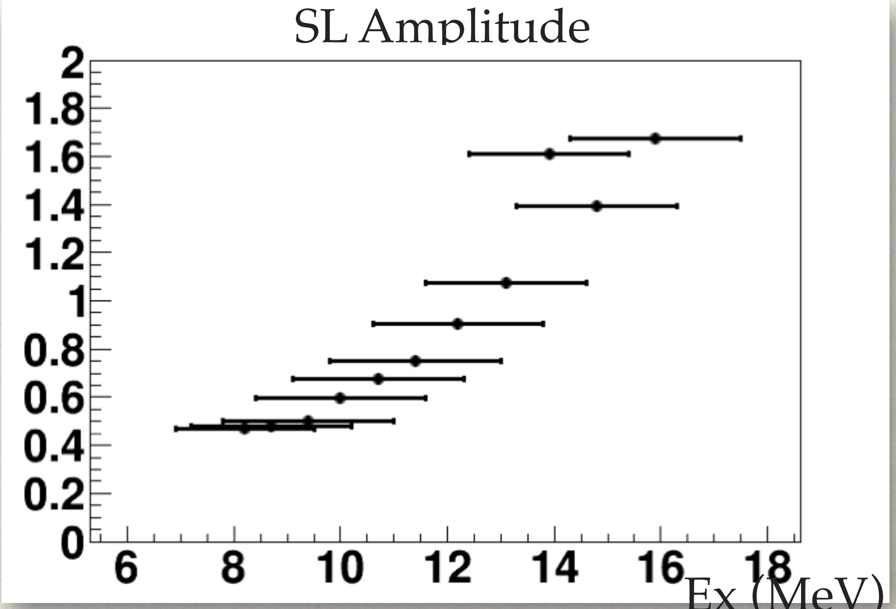
Excitation Energy Dependence



Fissioning system with higher statistics

Both positions increase with the Ex for SI and SII. The evolution of the integrals is also clear

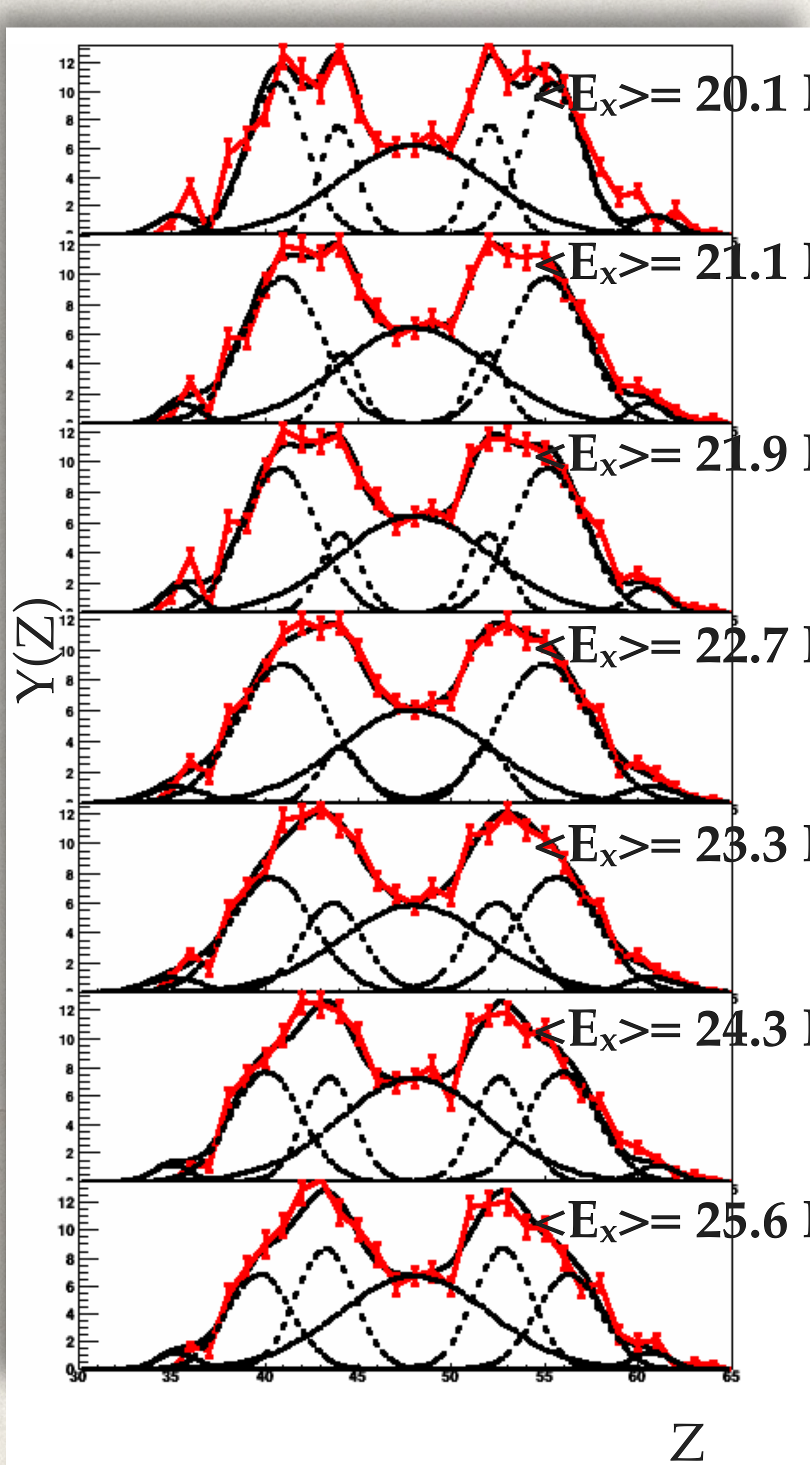




The SuperLong channel becomes more important for higher excitation energy

Excitation Energy Dependence

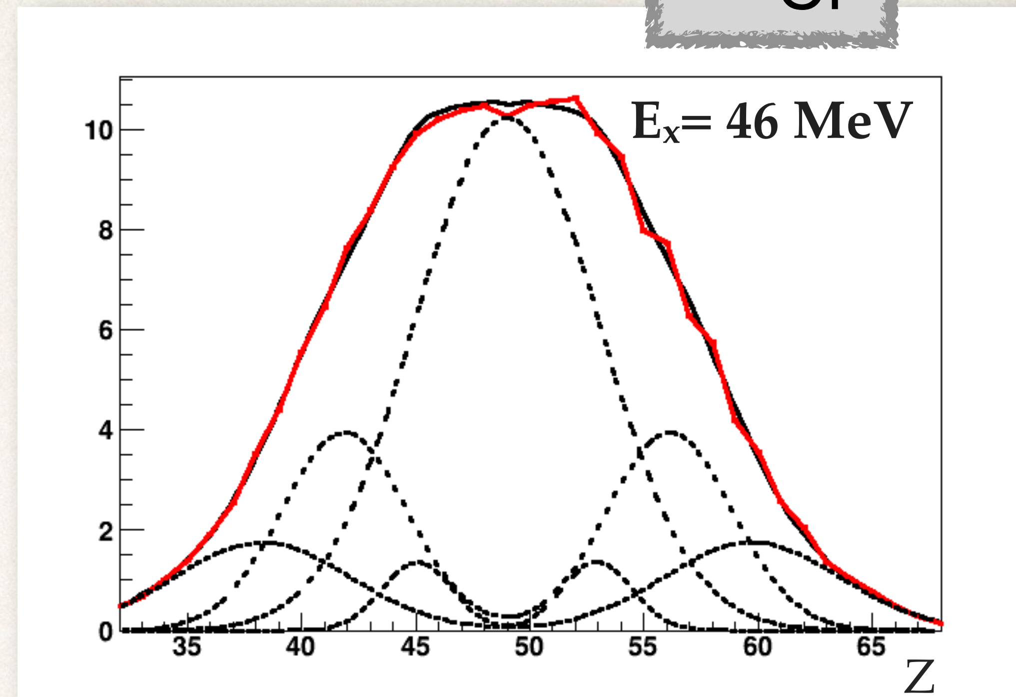
^{244}Cm



The Standard III is needed to explain the shape of the distribution of ^{244}Cm and ^{250}Cf

SuperLong Channel becomes relevant for these ranges of Ex

^{250}Cf

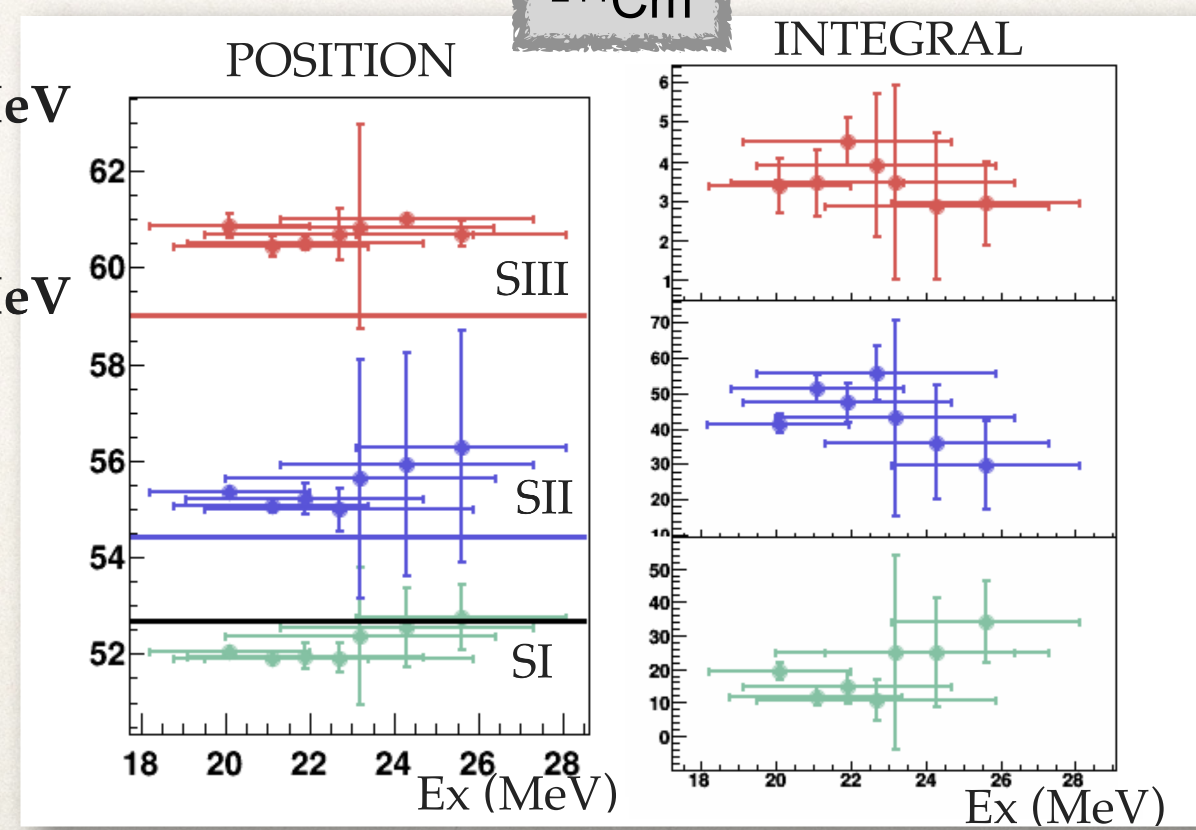


SI : $\overline{Z} = 52.9$ I=5.22

SII : $\overline{Z} = 56.1$ I=27.13

SIII : $\overline{Z} = 59.7$ I=16.80

^{244}Cm



Conclusions

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

- The study the fission of different fissioning systems (^{238}U, ^{239}Np, ^{240}Pu, ^{244}Cm and ^{250}Cf).
- The excitation energy measurement distribution through the transfer reaction kinematics.
- The full isotopic identification of fission fragments using the VAMOS spectrometer.

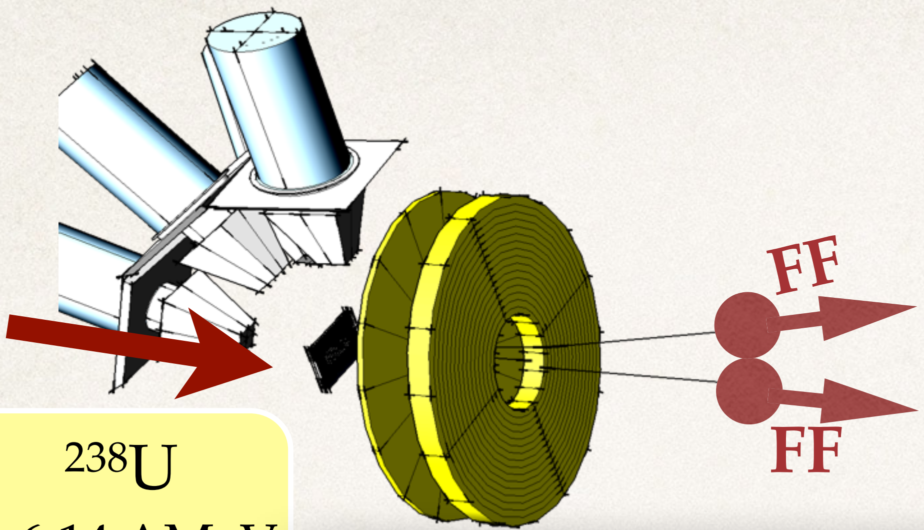
The effect of shell structure was observed as a function of the excitation energy.

- The evolution of the fission fragments from asymmetric to symmetric distributions.
- The $\langle N \rangle /Z$ ratio at $Z \approx 50$ decreases by increasing the excitation energy.
- The TKE decreases by increasing the excitation energy.

Fission Fragment Distribution were investigated in terms of Fission Channels Interpretation

- The SI, SII and SIII are needed to reproduce the almost gaussian shape of ^{250}Cf
- Observed an evolution of the position and the integral of SI and SII with the excitation energy depending on the fissioning system

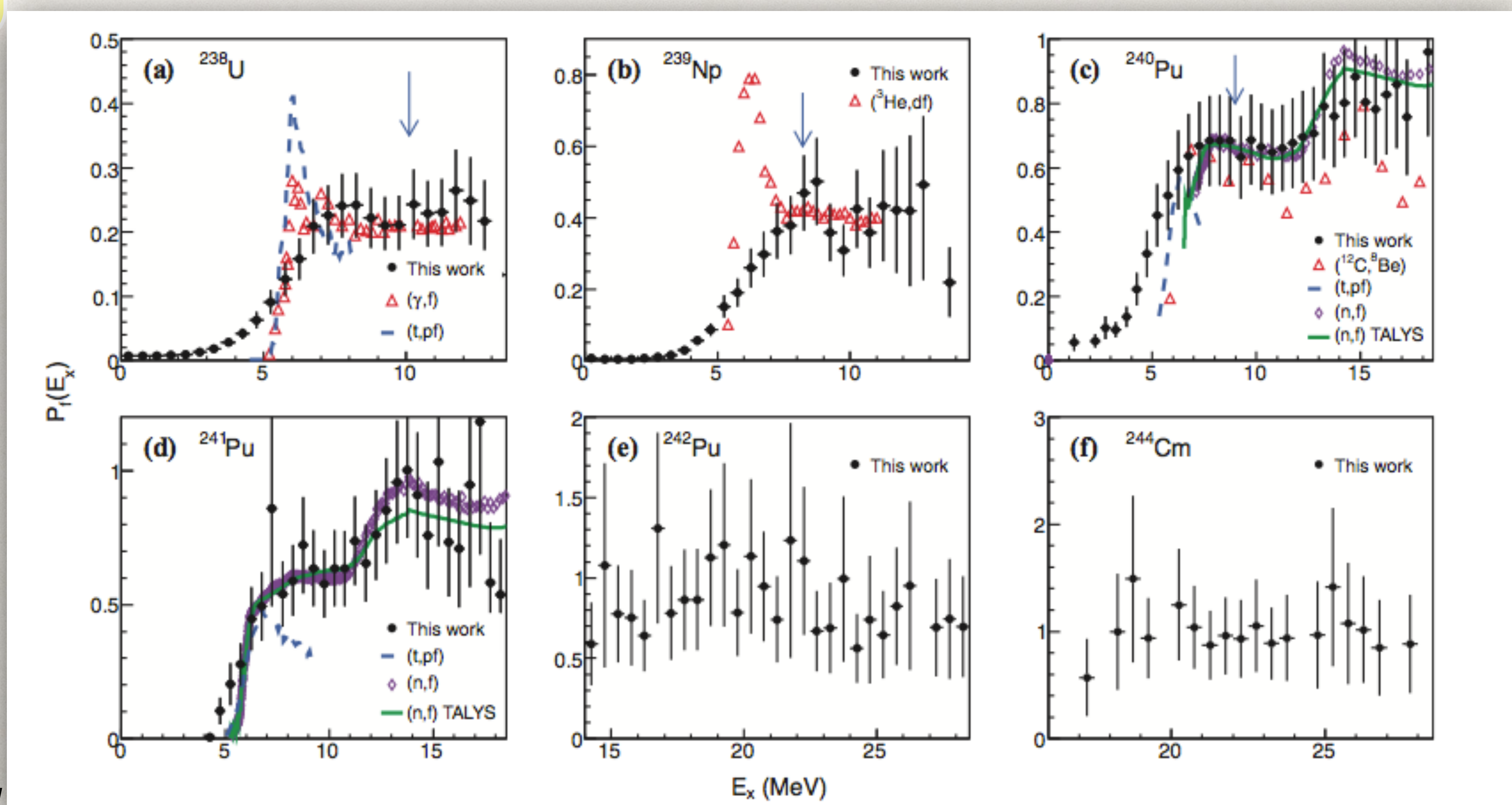
Fission Barriers



^{238}U
@ 6.14 AMeV

We observe a general agreement with previous data
with small discrepancies

First and second chance are measured in ^{240}Pu and ^{241}Pu



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