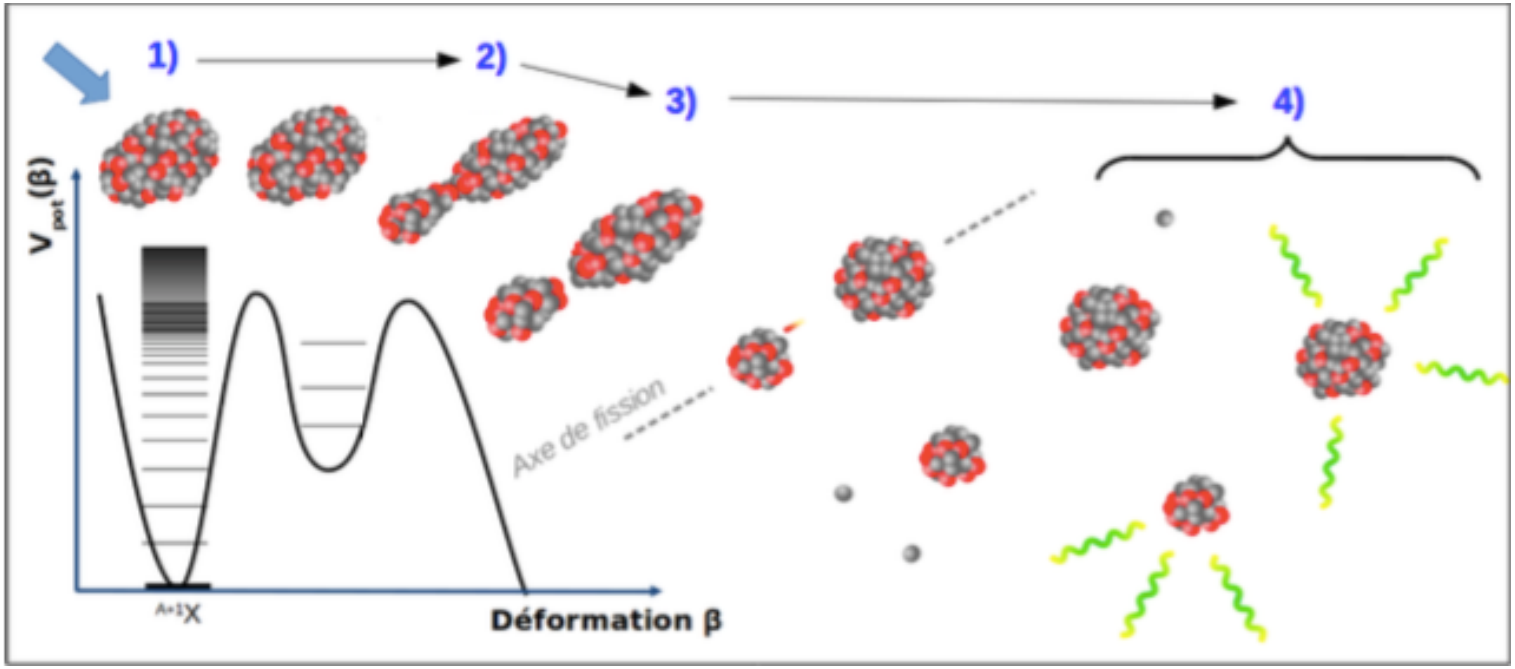
Experimental Description of Fission Fragment yields

1. Fission process and Fission Yields
    1. Kinetic properties of Fission Fragment
    2. Fission Fragment population of excited states
2. Measurement based on kinematic properties
        1. Energy and time-of-flight based experiments
        2. Rigidity-based experiments
3. Atomic number identification
4. Gamma-spectroscopy techniques
5. Inverse kinematics
    5.1 SOFIA experiment
    5.2 Multi-nucleon induced fission in inverse kinematics
6. Surrogate reactions
7. Fission yields, systematic uncertainties and errors
8. Conclusions

1. Fission Process and Fission Yields

1. Compound Nucleus Formation
2. De-excitation via deformation
3. Saddle point : no-return
4. scission point : formation of fission fragments



Fission **fragments** defined at scission A*, Z*, E*

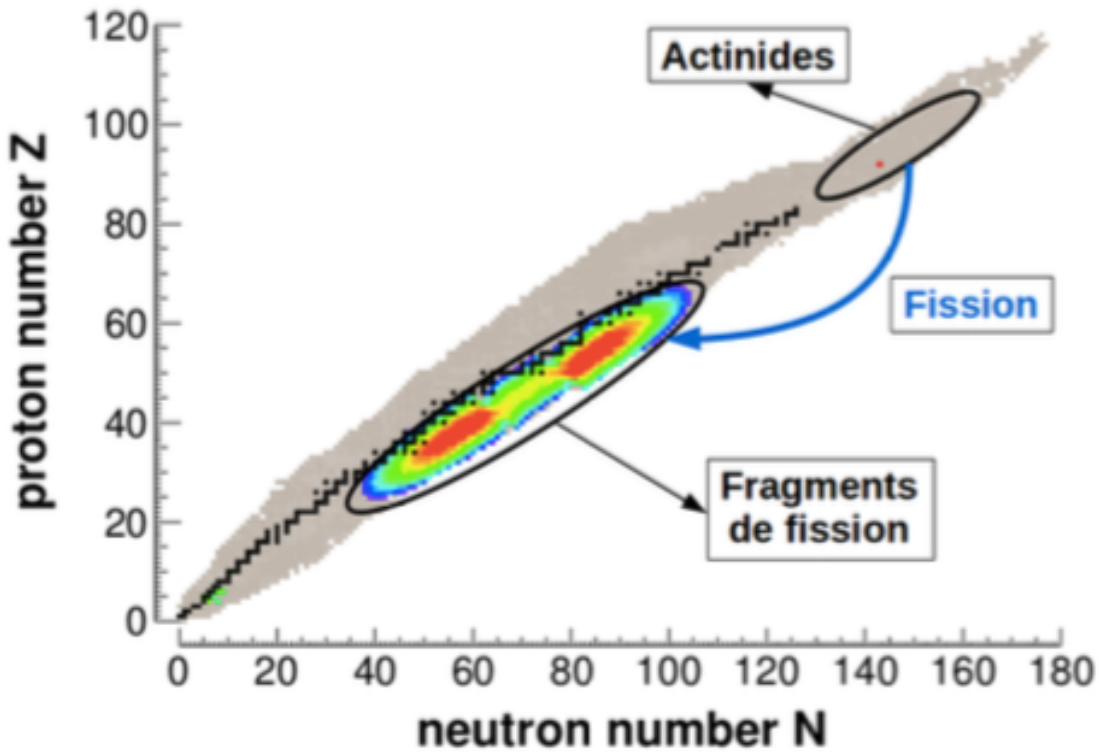
E* is released : Fission **product** A, Z

1. Fission Process and Fission Yields

Scission point defines the fission fragment properties :

- proton and neutron numbers
- kinetic energy
- excitation energy, angular momentum
  —>(neutron evaporation, gamma emission)

Fission Products are radioactive



Independent yields : **before** beta decay

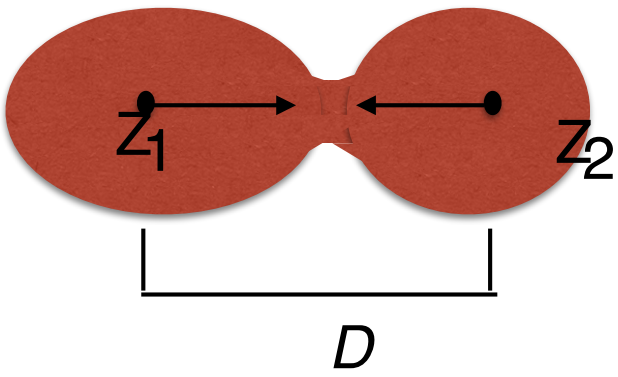
Cumulative yields : **after** beta decay

1.1 Kinetic properties of fission products

Fission-Fragment kinetic energy defined at scission

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

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



(1)

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

(2)

$$E_1 = \frac{A_2}{A_1}E_2$$

(3)

$$E_1 + E_2 = TKE$$

1.1 Kinematic properties of fission products

Assumptions :
UCD
D ~constant
no n evaporation

$$\frac{Z_1}{A_1} = \frac{Z_2}{A_2} = \frac{Z_f}{A_f} = \alpha_f \quad (4)$$

(3;4)

$$E_2 \frac{Z_1 + Z_2}{Z_1} = TKE$$

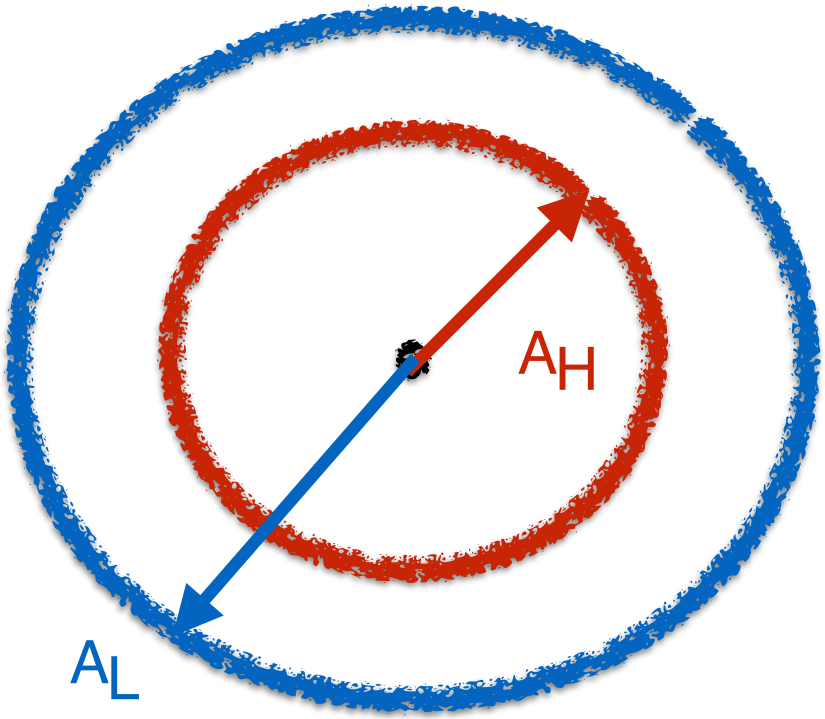
(2;3)

$$E_2 \frac{A_1 + A_2}{A_1} = TKE$$

1.1 Kinematic properties of fission products

$$E_2 \frac{Z_1 + Z_2}{Z_1} = \frac{1.44}{D} \frac{Z_1}{Z_1 + Z_2} Z_1 Z_2$$

$$E_1 \frac{Z_1 + Z_2}{Z_1} = \frac{1.44}{D} \frac{Z_2}{Z_1 + Z_2} Z_1 Z_2$$

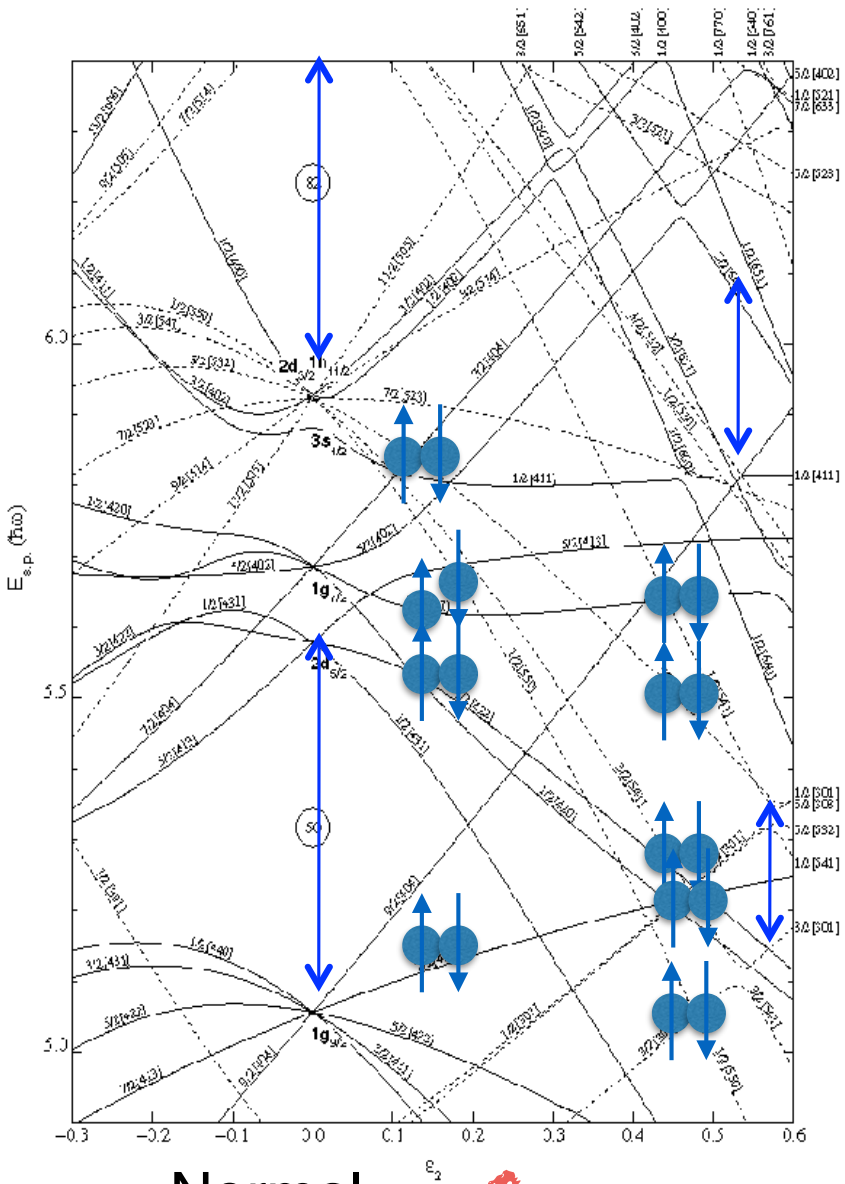


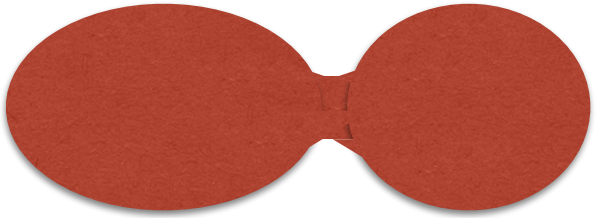
Light fragment is **faster**

Fission fragments are slow (typically 1 cm/ns <=>1 A MeV)

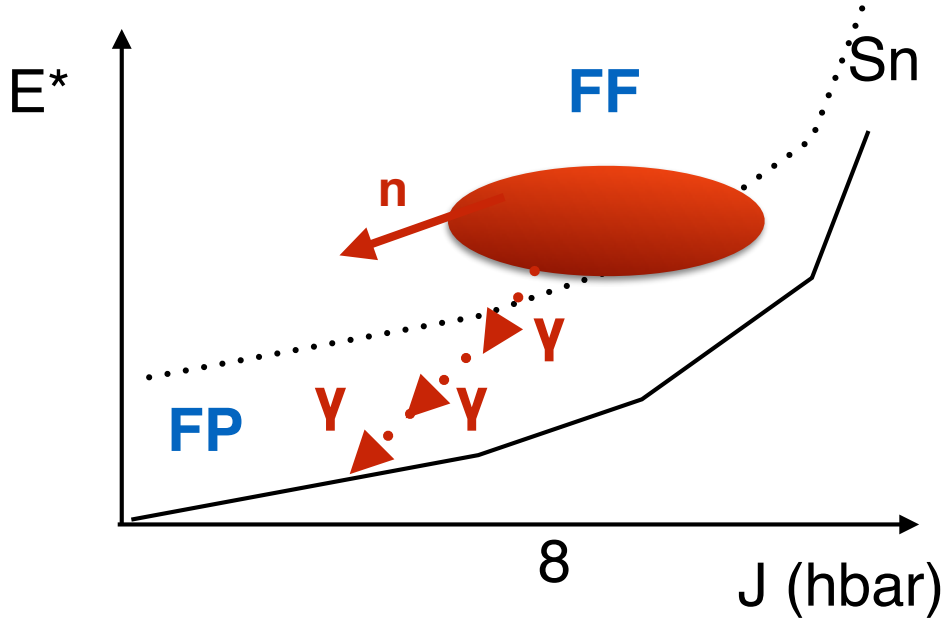
They are emitted in 4 π

1.2 fission products : population of excited states



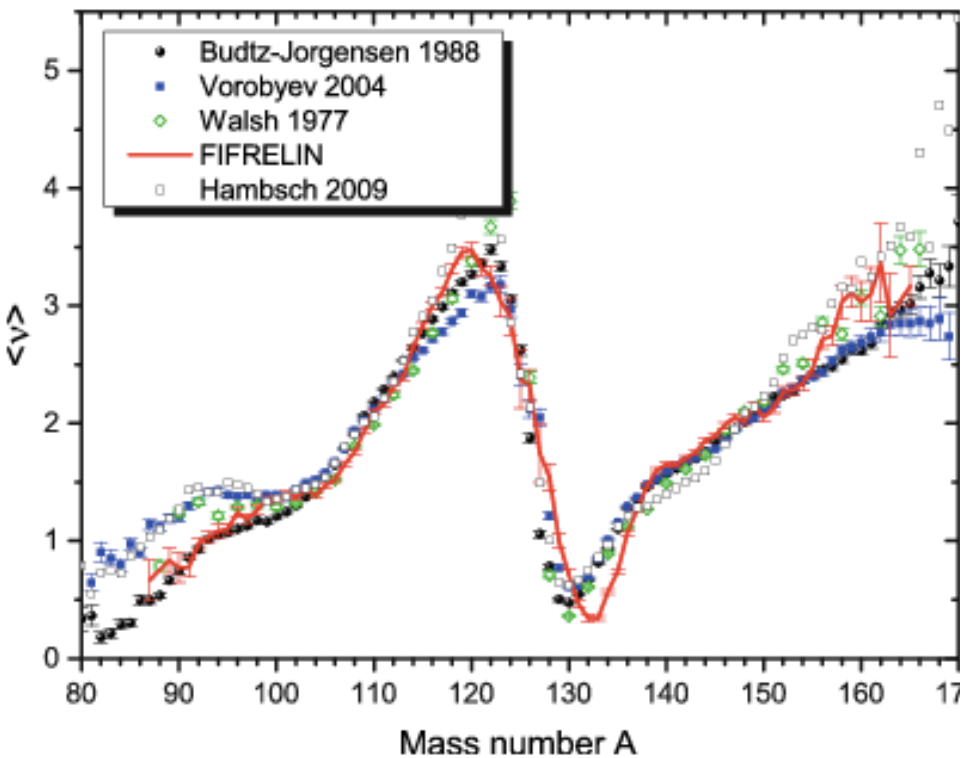


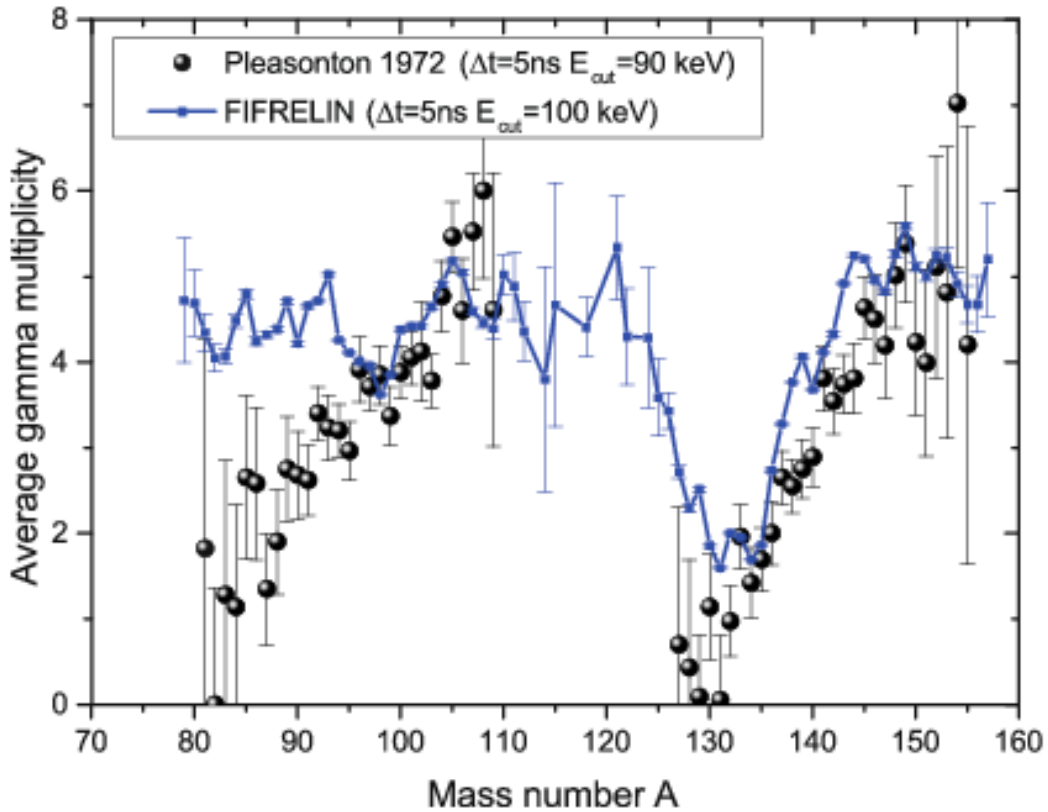
Deformed configuration of fragments at scission:
particle-hole excitation in the level states
Angular momentum and E*



1.2 fission products : population of excited states

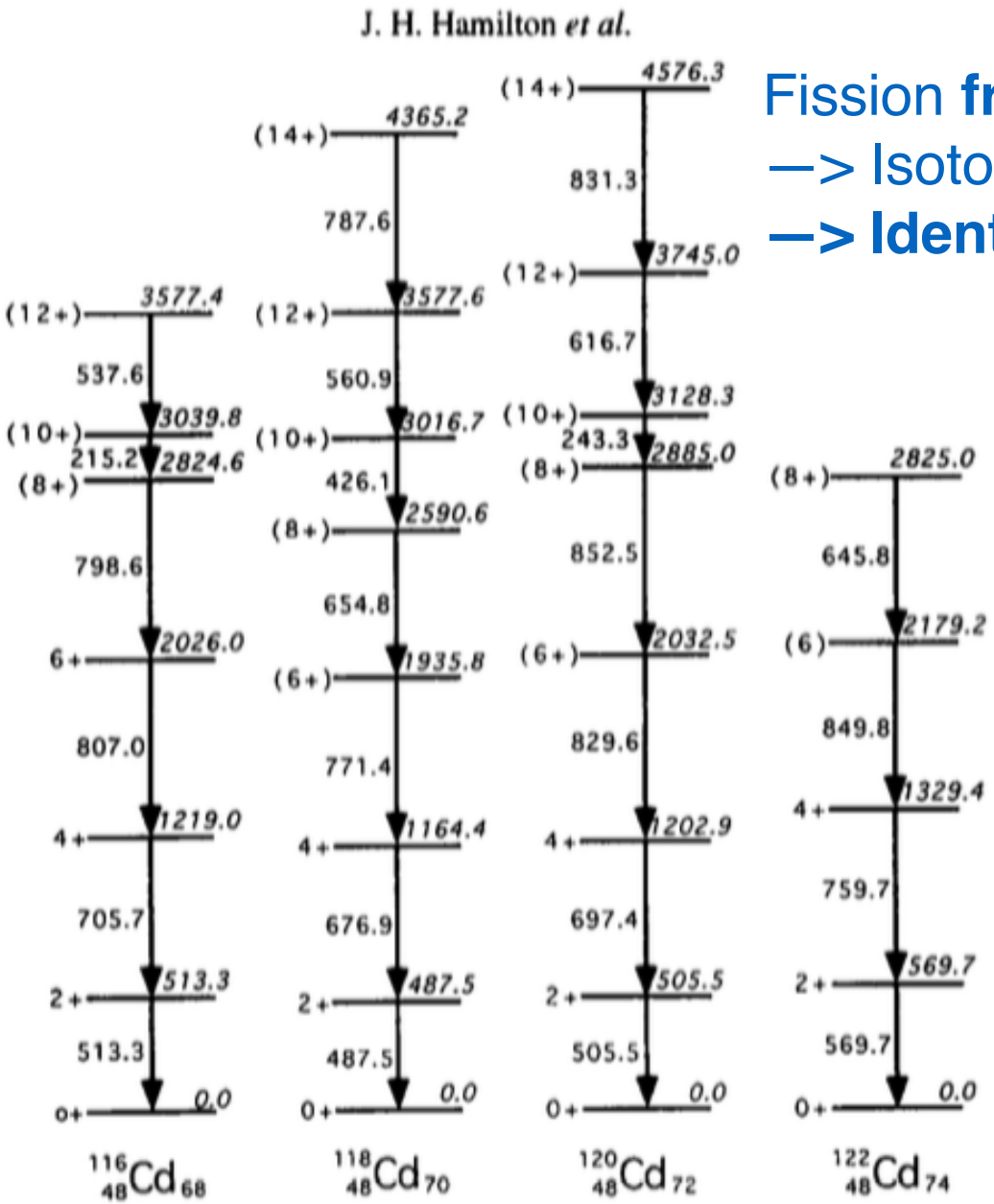
ν(A) and γ(A) :: excitation energy is depending on the sorting





From O. Litaize et al., EPJA 51(2015)

1.2 De-excitation properties of fission fragments



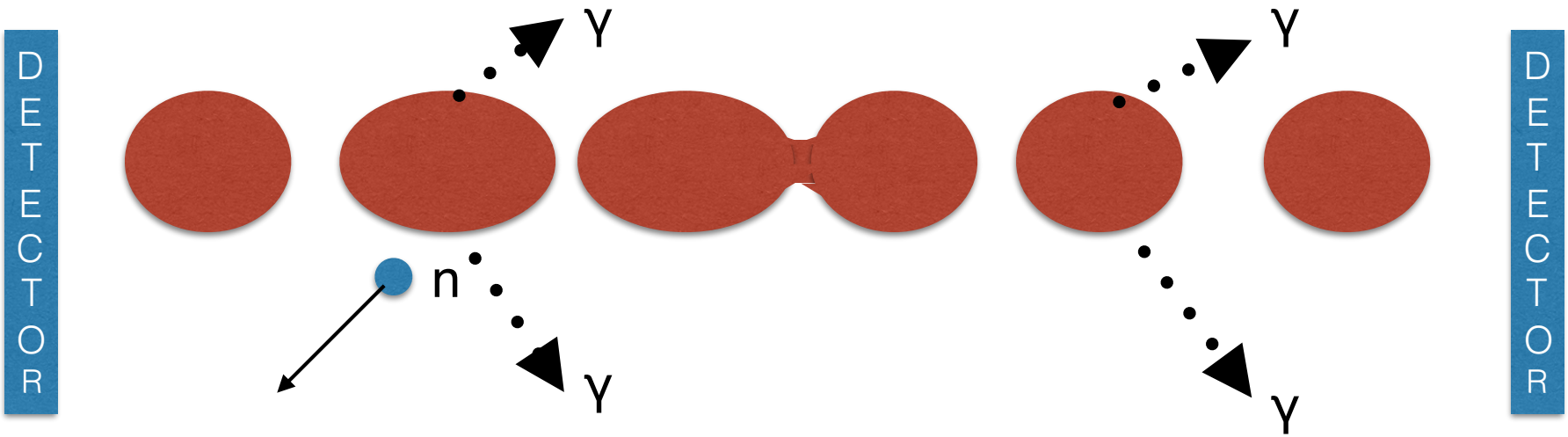
Fission **fragments** emit gamma rays

—> Isotopic identification of fission **products**

—> Identification of the fission products pair

mettre un petit schéma

2. Measurements based on kinematical properties



Fragment mass identification

$$A_1^* \beta_1^* c = A_2^* \beta_2^* c$$

Momentum and Mass conservation

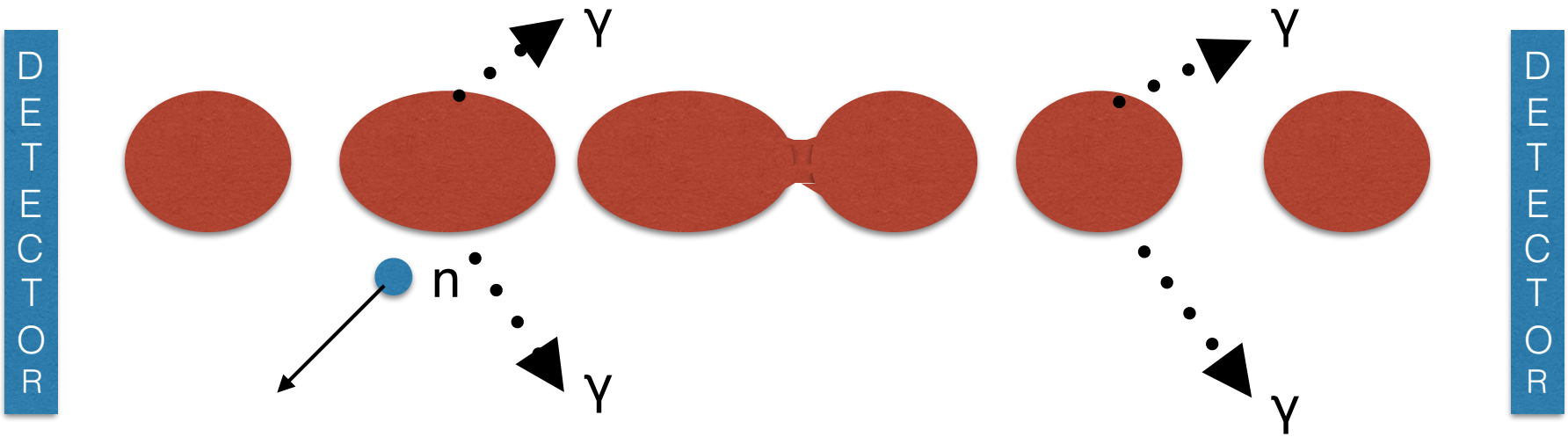
$$A_1^* + A_2^* = A_f$$

Isotropic emission of neutrons

$$< \beta_{1,2}^* > = < \beta_{1,2} >$$

$$A_1^* = A_f \frac{\beta_2}{\beta_1 + \beta_2}$$

2. Measurements based on kinematical properties



Product mass identification :

$$E_{1,2} = \frac{1}{2} A_{1,2} m_0 \beta_{1,2} c^2$$

Energy and velocity measurement

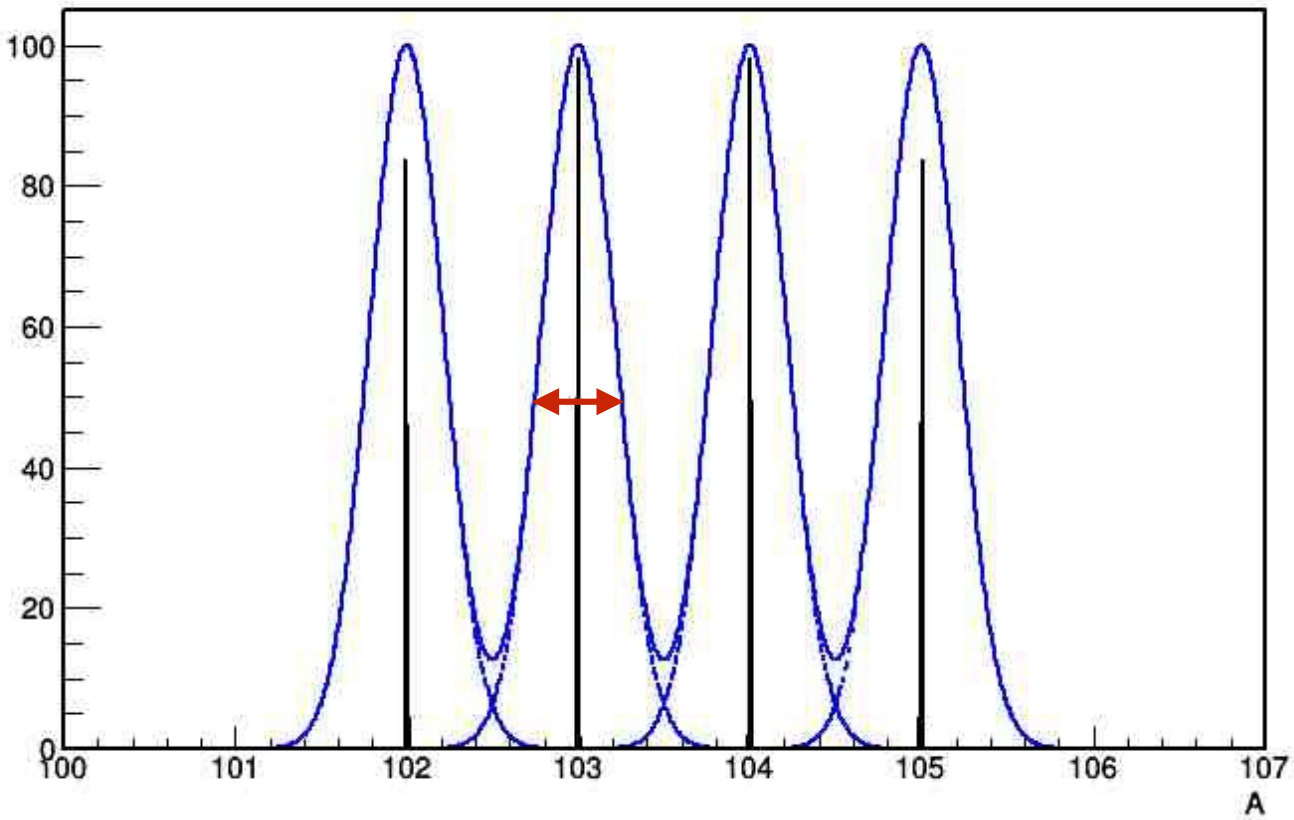
$$A_{1,2} = {2E_{1,2}}/{2A_{1,2} m_0 \beta_{1,2} c^2}$$

$$\nu_{1,2} = A_{1,2} - A^*_{1,2}$$

neutron multiplicity

which resolution ?

Resolution of 1uma does depends on the mass range :
Around A~100 : 2 adjacent masses are distant by 1%
Around A~50 : 2 adjacent masses are distant by 2 %
Around A~150 : 2 adjacent masses are distant by 0.7%



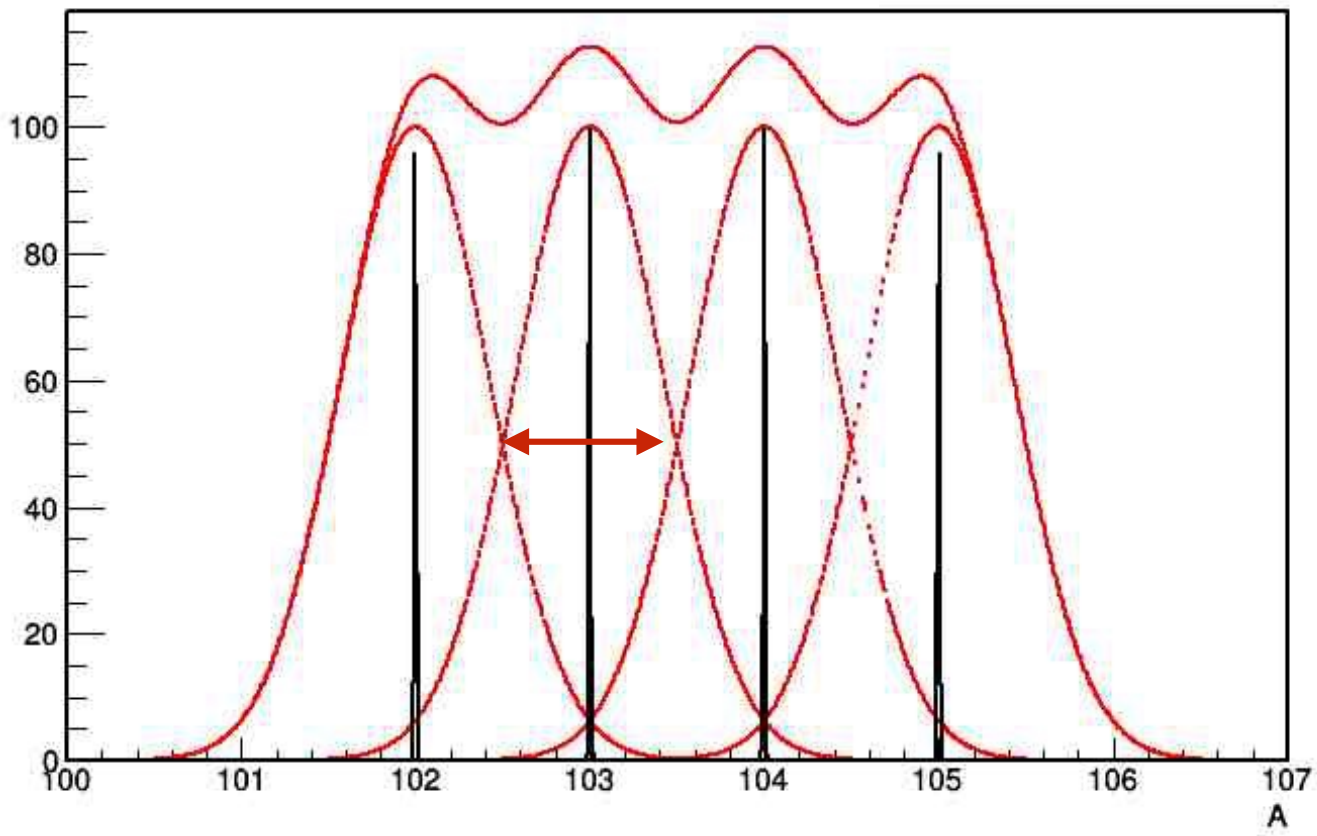
FWHM = 0.5

Resolution is important for a better counting

which resolution ?

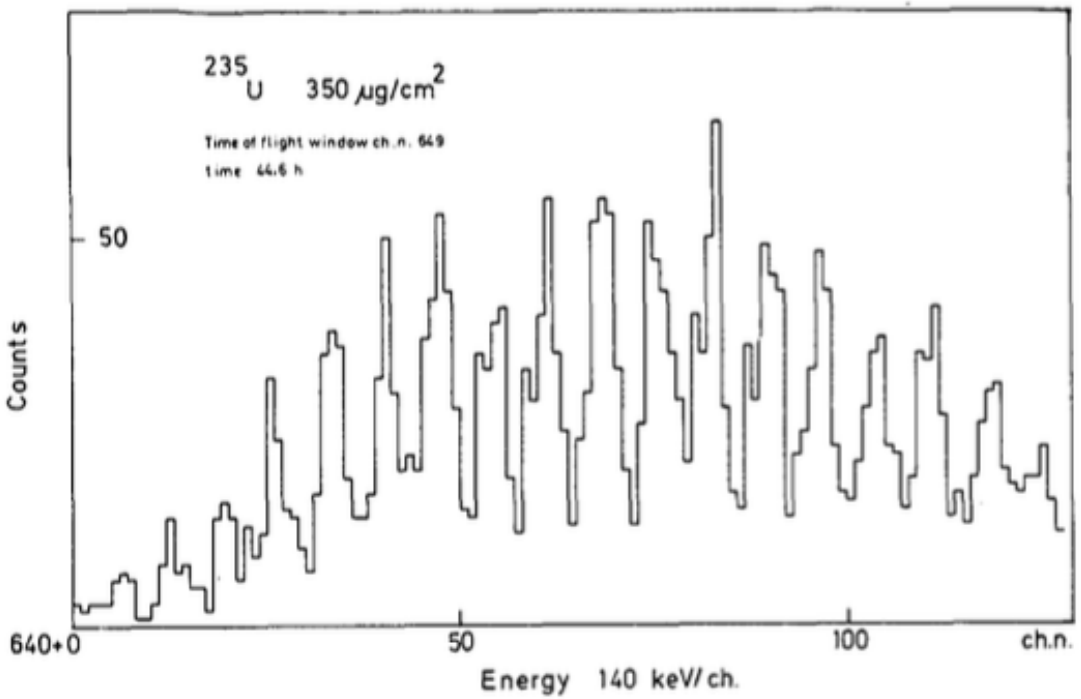
DA/A ~1 :: Resolve A ~ 100
DA/A ~0,5 :: Resolve A~200

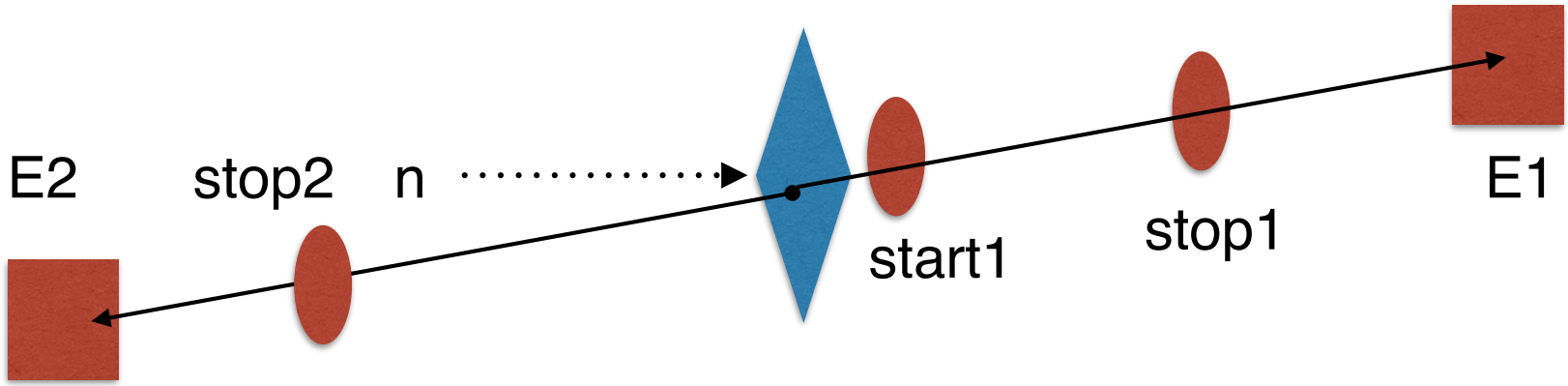
FWHM = 1



2.1 Energy and Time-of-Flight based experiments

$$\frac{\partial A}{A} = \sqrt{\frac{\partial E^2}{E} + 2\frac{\partial \beta^2}{\beta}}$$



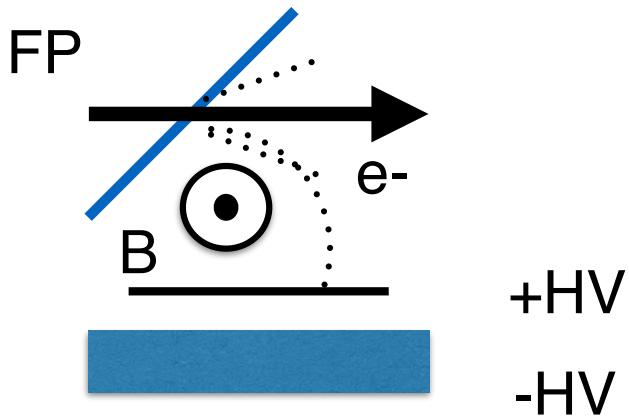


BEST : 0,6% in COSIFANTUTE, ILL, 1980

Time-of-Flight measurement

Minimum layer
Fast timing

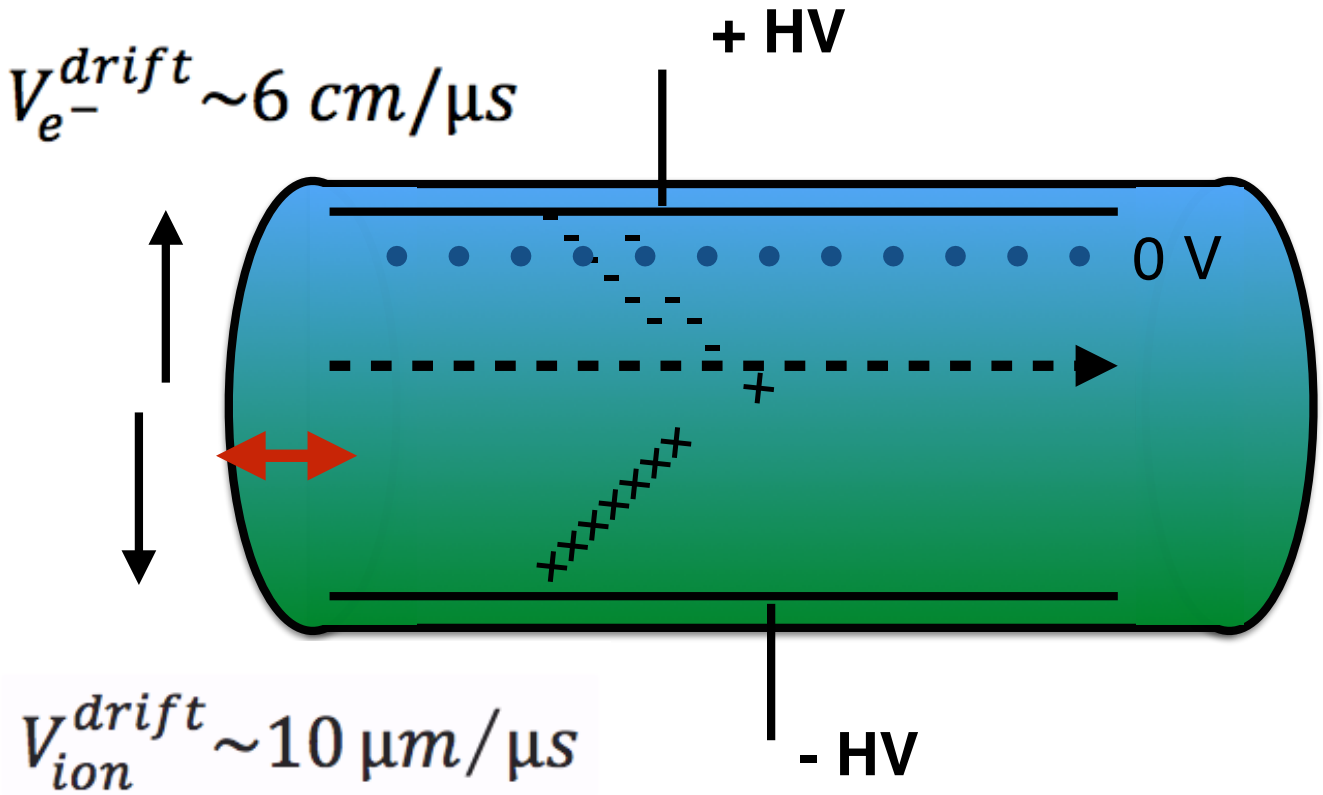
Secondary electron detectors



MICRO-CHANNEL PLATE

MULTI-WIRE PROPORTIONAL COUNTER

Energy measurement in Ionisation Chambers



$$N_e - W_e = \Delta E$$

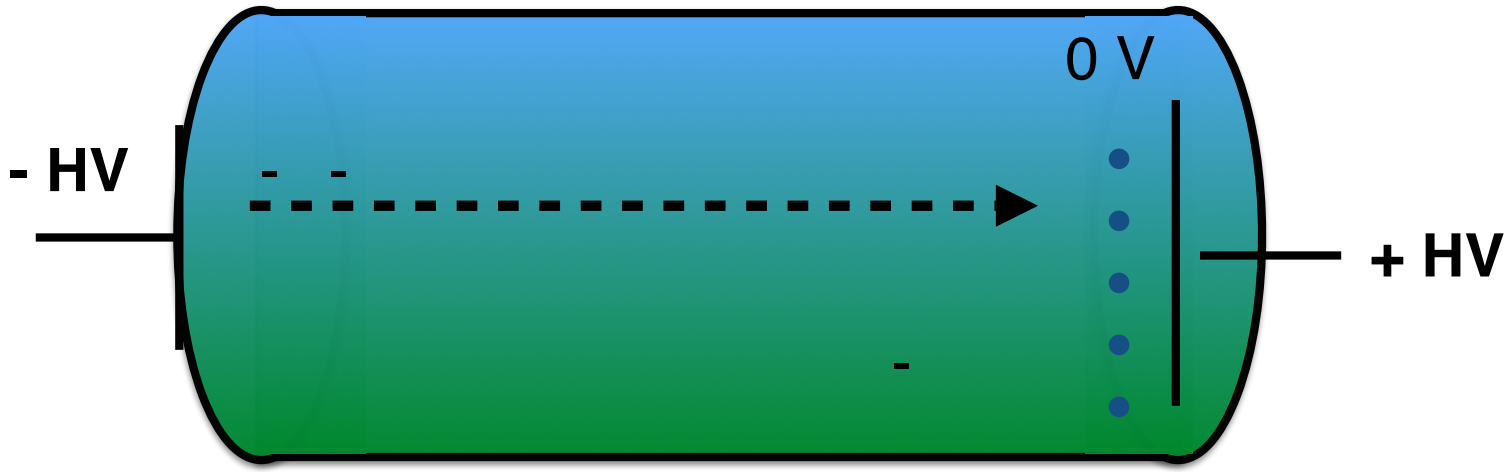
$$W_e \sim 15 eV$$

$$N_{e^-} \sim 10^7$$

Number of electrons is large —> good statistical resolution
Despite drift velocity of ions is slow, they may disturb the apparent total charge collected on the anode —> Frisch Grid (0V) to isolate the anode from the positive current

↔ Zone of electric field distortion and energy-loss uncertainty that decreases significantly the resolution

Energy measurement in Ionisation Chambers

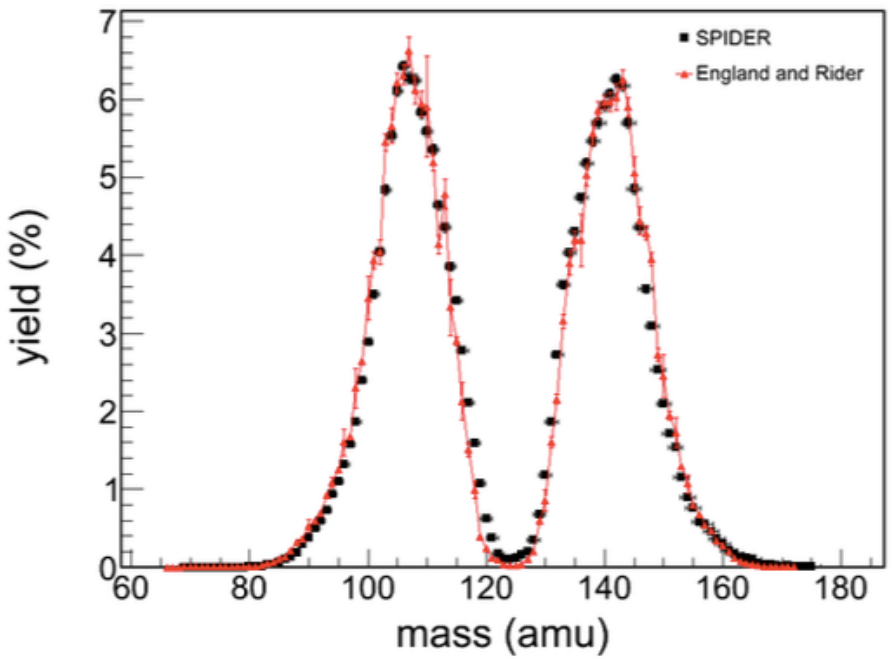


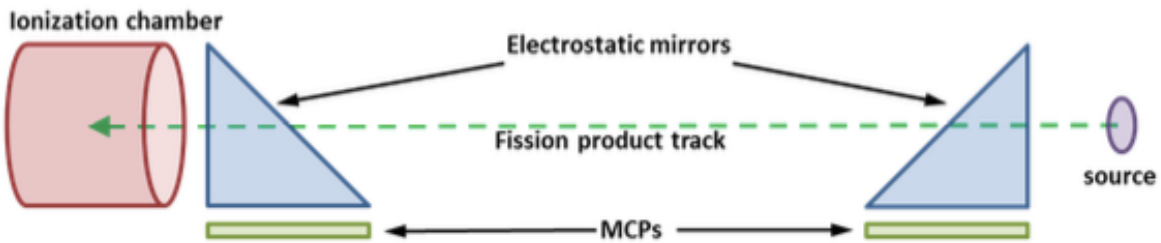
In axial chamber, all electrons are collected on the anode
Energy-loss collection with 1‰ percision
Electronics (noise and amplification) limits to the percentage limit

Fission-fragment distributions : experimental challenges

Improvement of technology :
thin layers
SED : amplification in gaz : large surfaces
Digital electronics : energy-loss profile

Physical limits to the resolution :
Energy-loss straggling in materials (stochastic process)



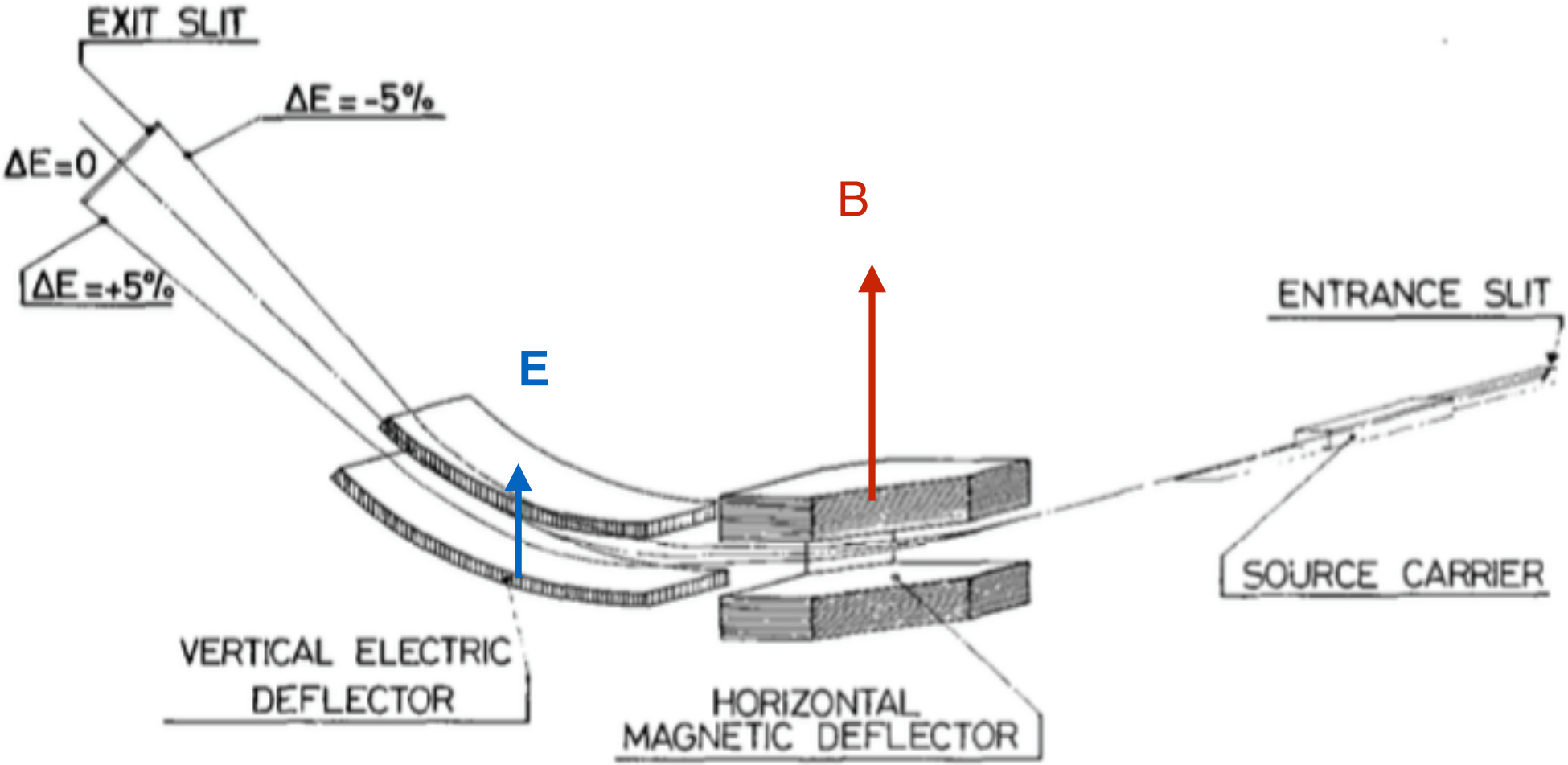


K. C. Meierbachtol, F.K.E Tovesson et al. LA-UR-15-20101

Rigidity-based experiment

LOHENGRIN spectrometer

No ToF measurement !



Rigidity measurement

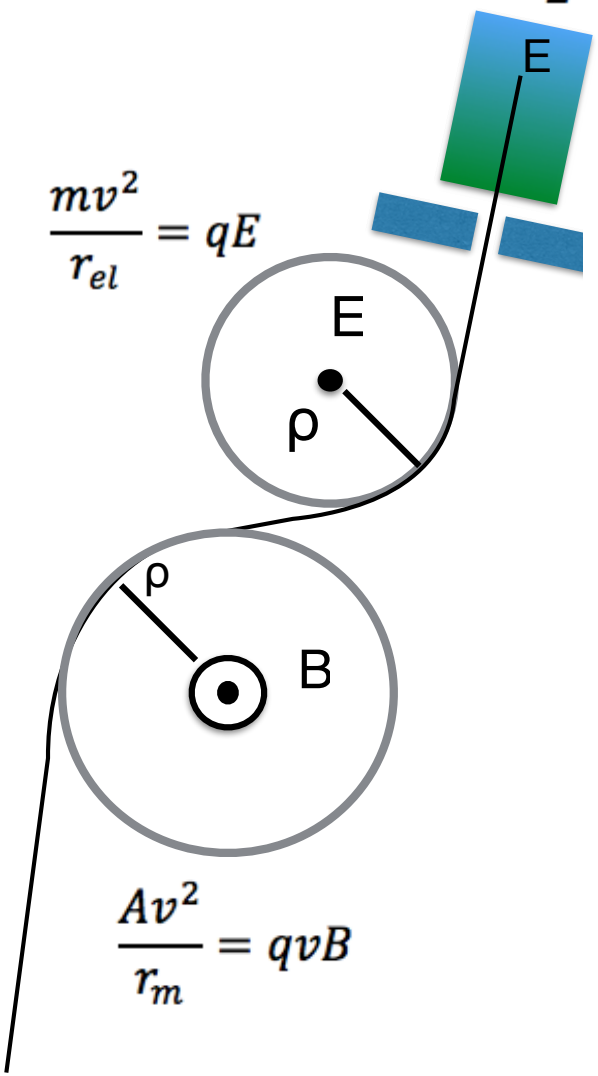
$$E_k = \frac{1}{2} m v^2$$

$$\frac{A}{q}\frac{Av^2}{q} = {r_m}^2 B^2$$

$$\frac{A}{q} = \frac{{r_m}^2 B^2}{r_{el} E}$$

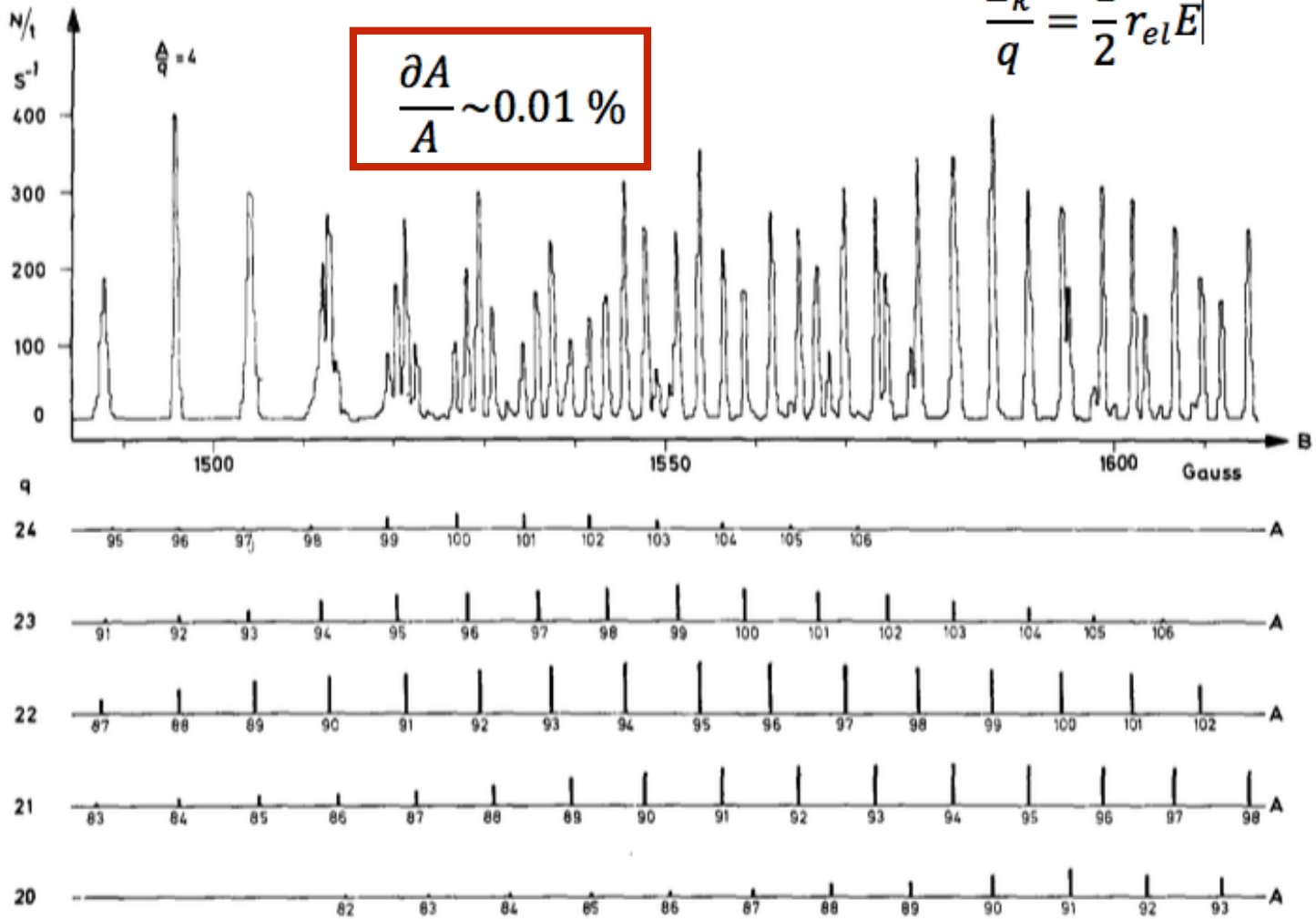
$$\frac{E_k}{q} = \frac{1}{2} r_{el} E$$

$$\frac{mv^2}{r_{el}} = qE$$



$$\frac{Av^2}{r_m} = qvB$$

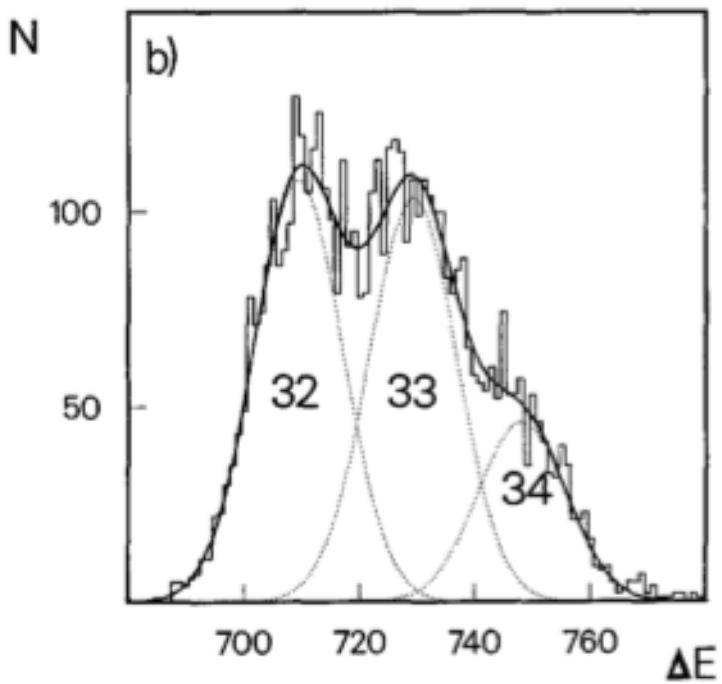
$$\frac{\partial A}{A} \sim 0.01\ \%$$



3. Atomic Number identification

Energy loss in ionisation chamber

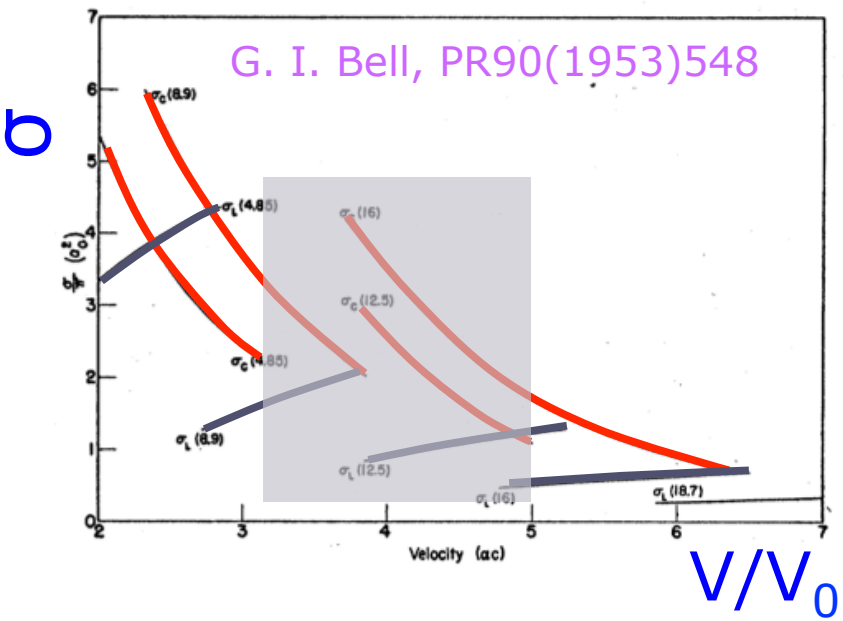
$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{q^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$

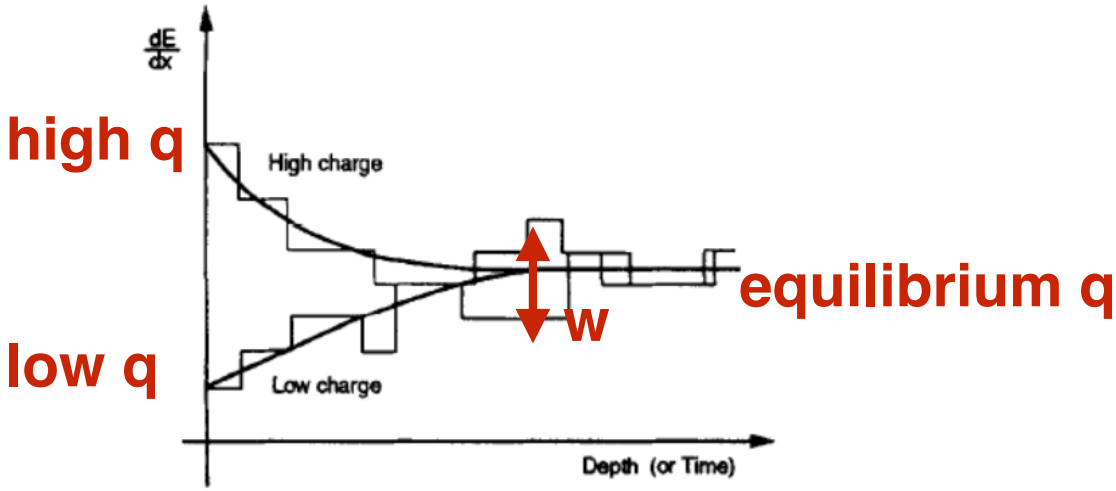


FF have a large q-state distribution
—> energy-loss resolution limited

Energy-loss of ion in material

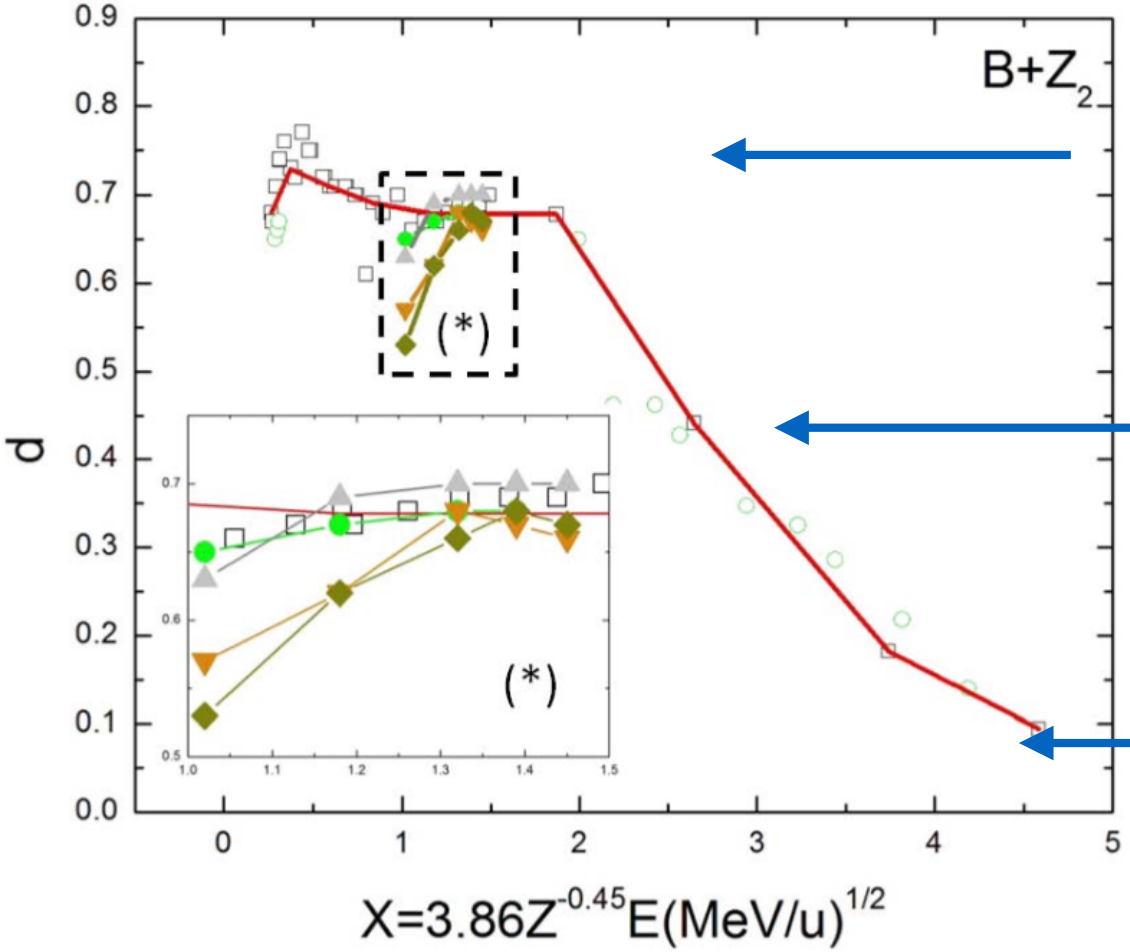
Energy-loss prop. to ionic charge state
Electron loss and capture cross sections depend on ion energy :





ionic charge dispersion diminishes with energy

w



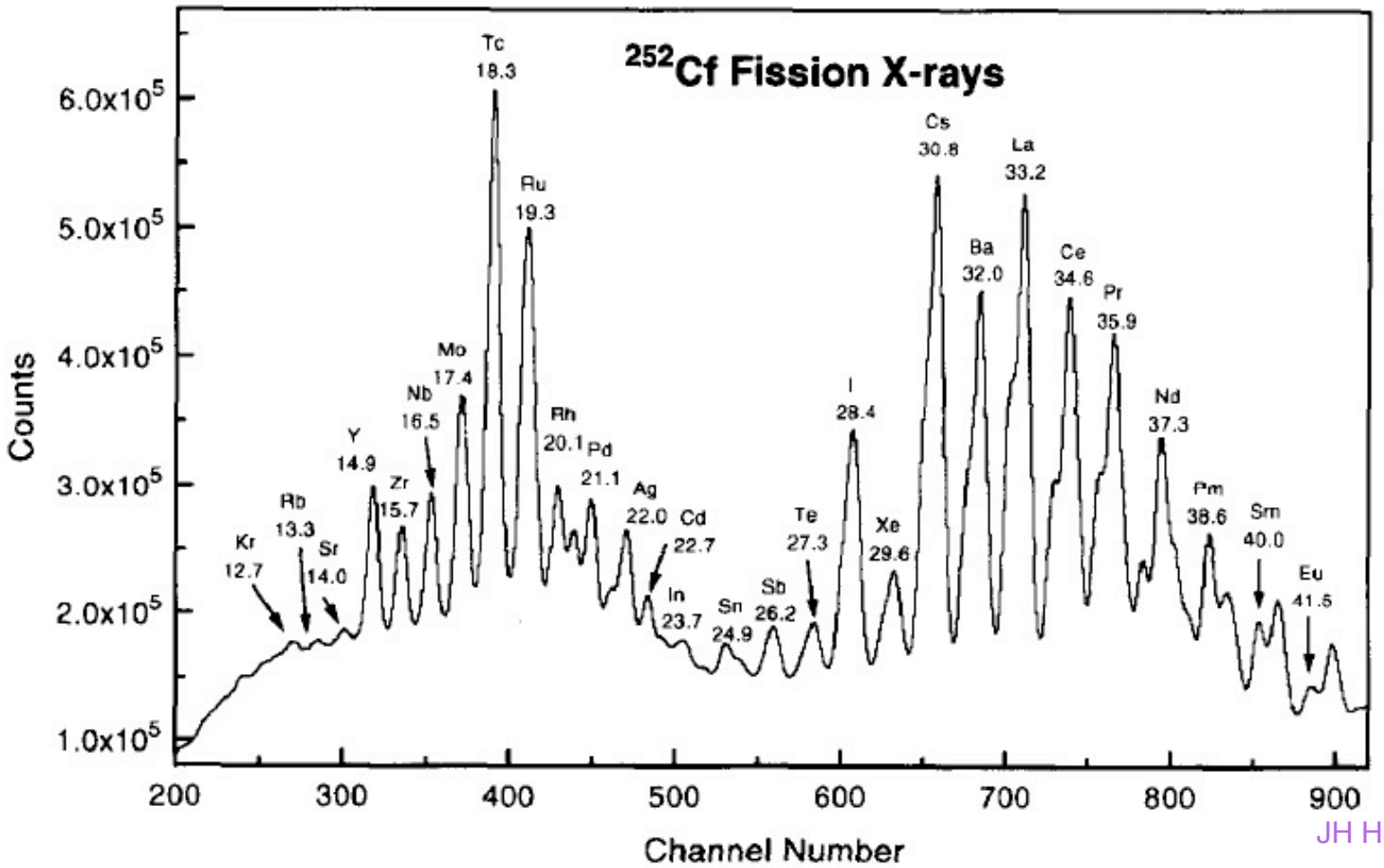
Z= 50 E = 1MeV/u

Z= 50 E = 10 MeV/u

Z= 50 E = 100 MeV/u

Atomic Number identification

Detection of X-rays



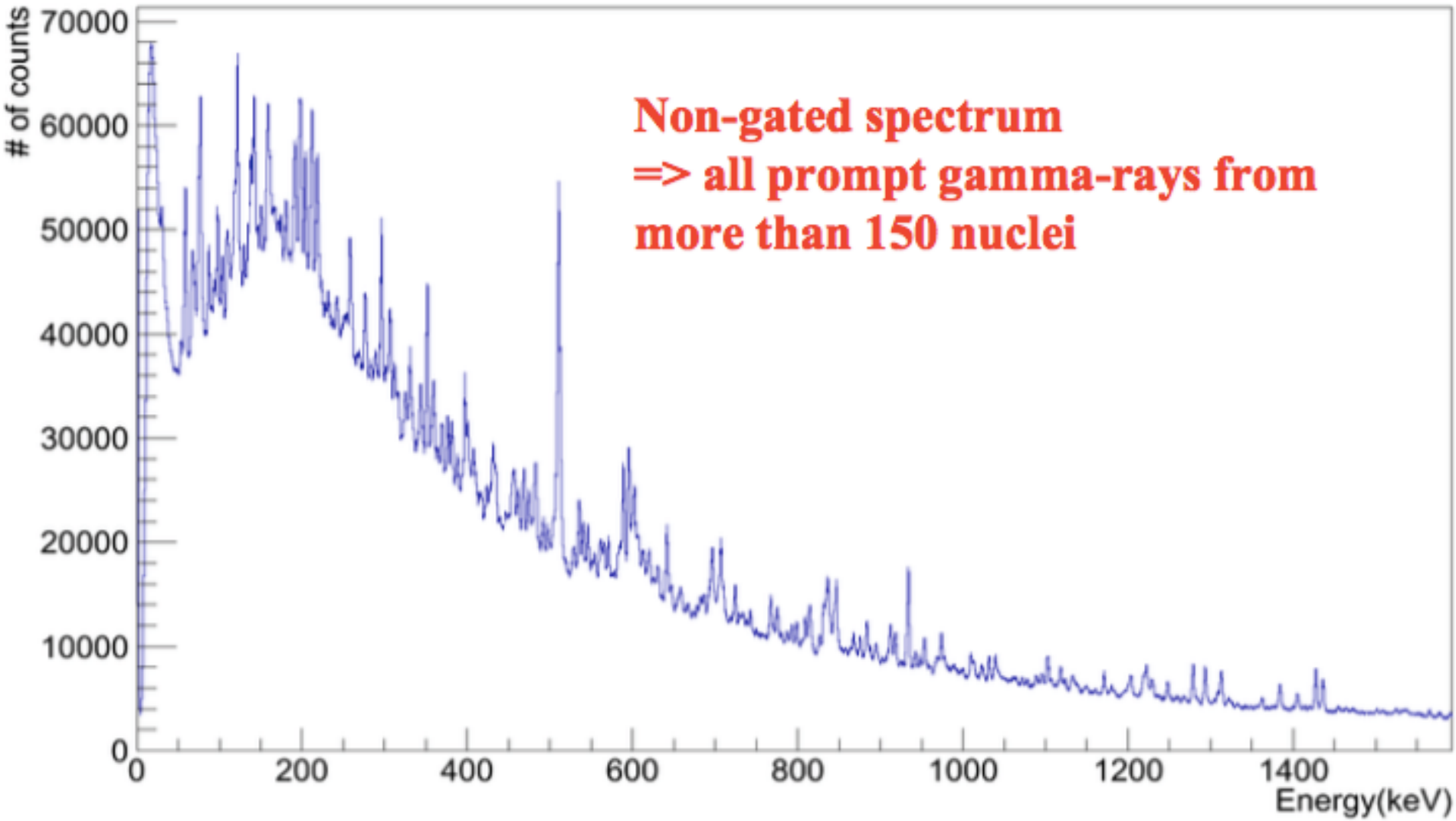
JH Hamilton Prog. Part. Nucl. Phys. 35

small detection efficiency —> Difficulty to connect with mass distribution

4. Isotopic identification from gamma spectroscopy

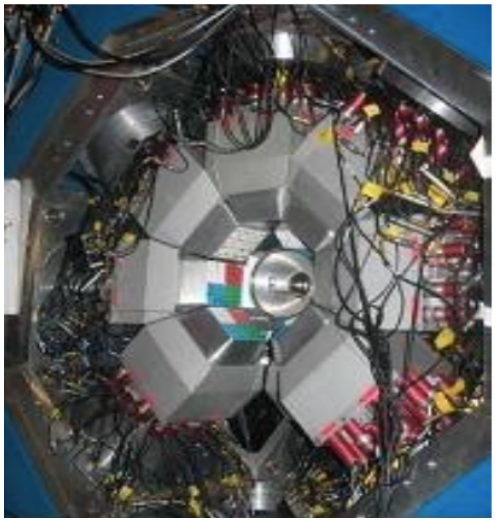
Fission products may be identified unambiguously from their γ-ray emission

Large background from beta decay

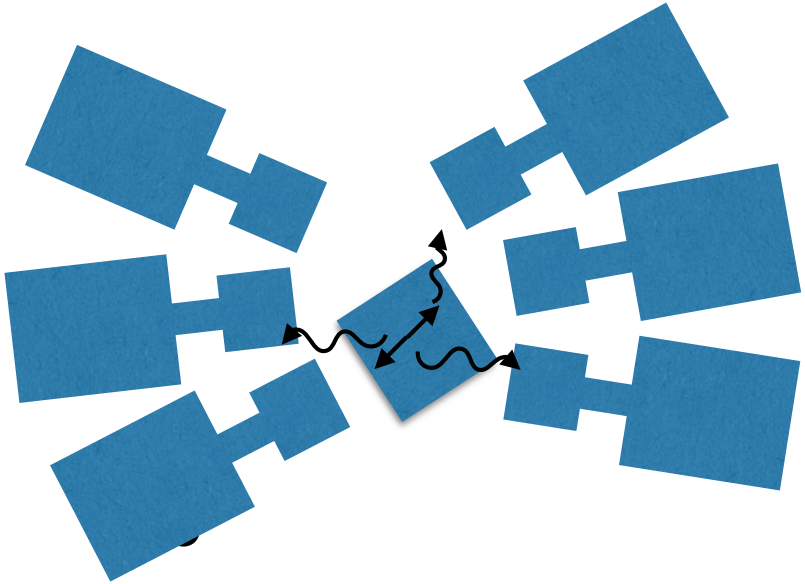


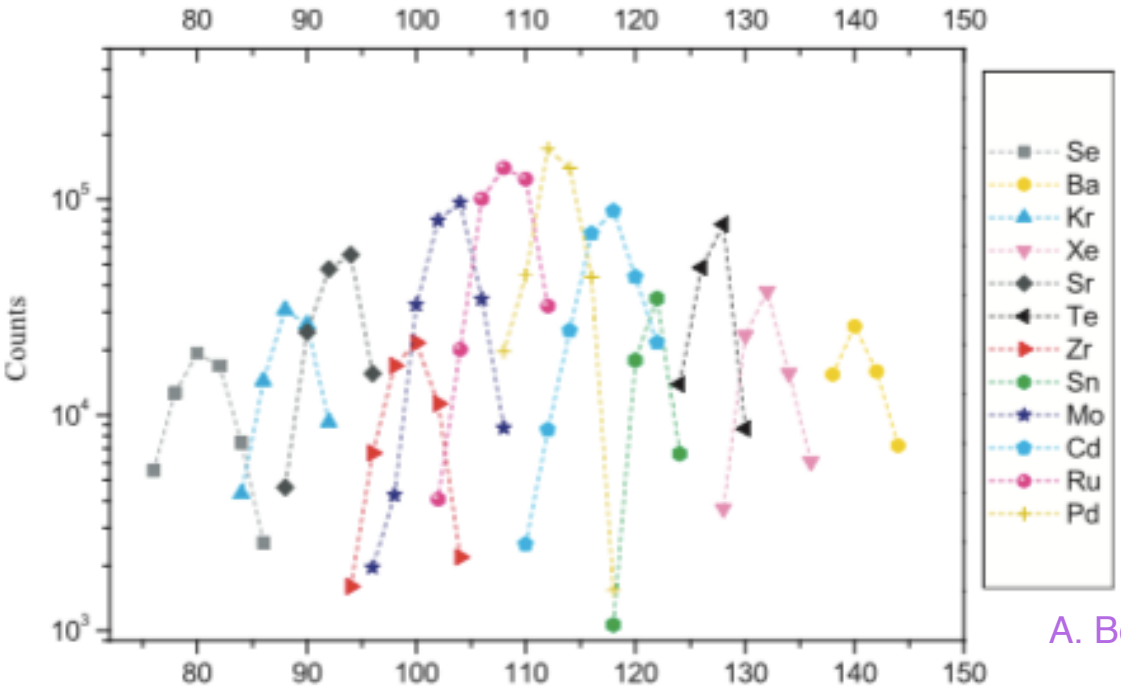
Isotopic identification from gamma spectroscopy

γ-γ technique :



EXILL, ILL



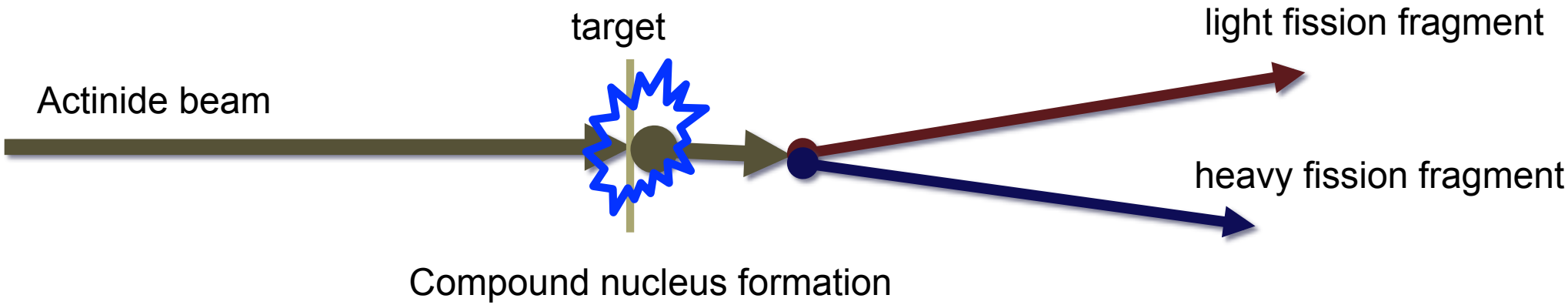


A. Bogachev et al. EPJA 34(2007)

4. Isotopic identification from gamma spectroscopy

External trigger experiment
+ : no (less) background due to beta-decay

Inverse kinematics : need for accelerator complexe



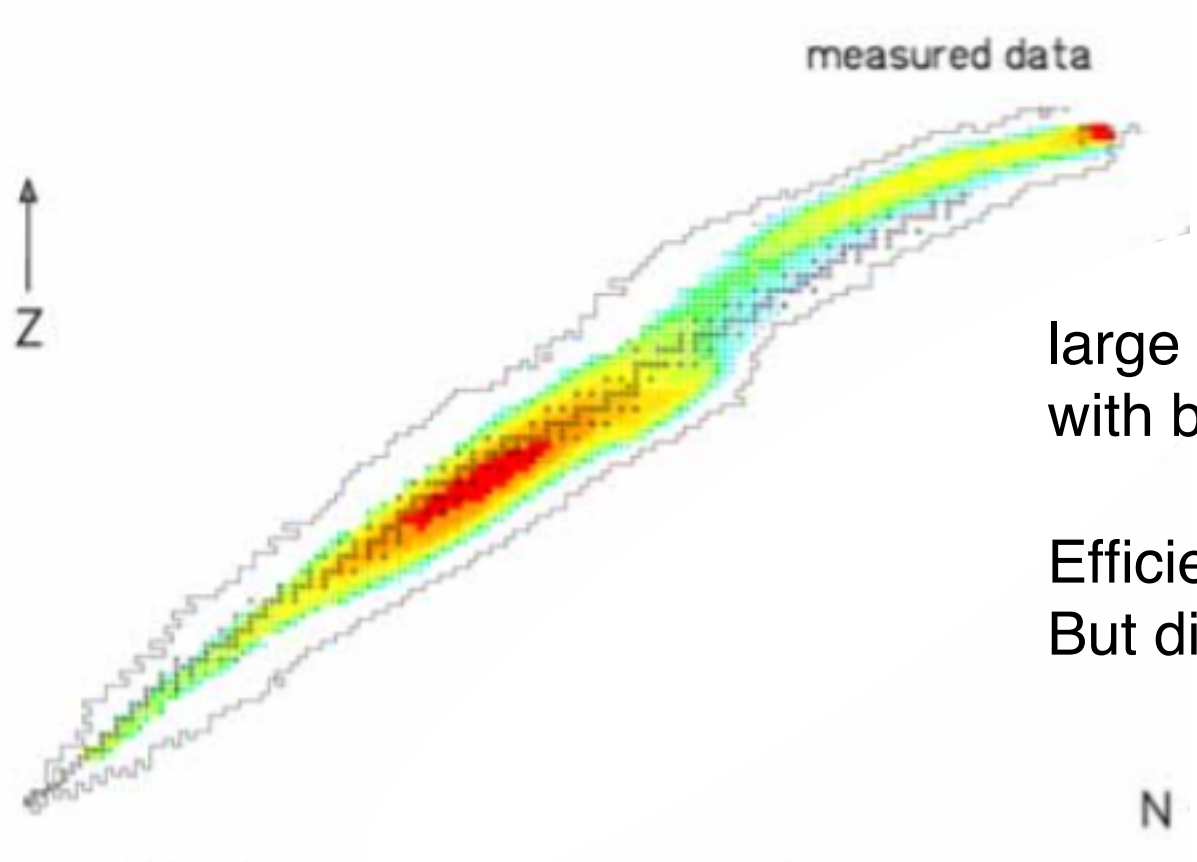
Increasing fission-fragment velocity for a better resolution

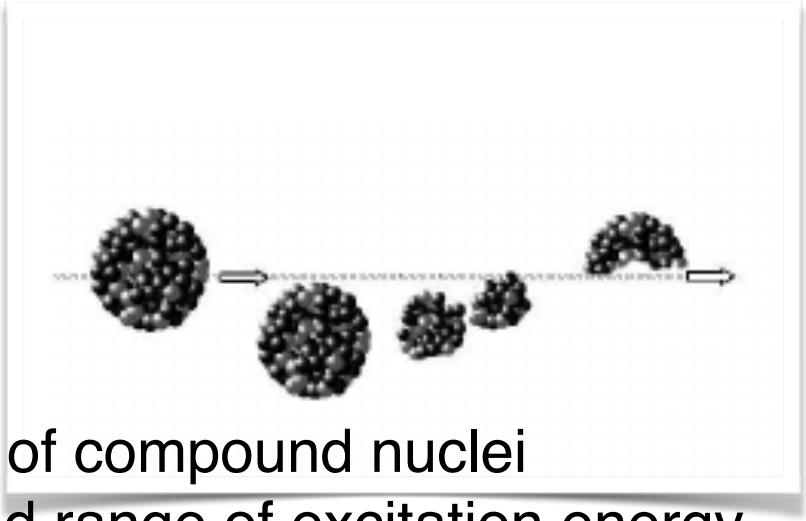
+ forward focusing for a better detector acceptance
- time-of-flight resolution decreased

Inverse kinematics : nuclear-reaction -induced fission

Different regimes : relativistic energy
Coulomb barrier energy

Relativistic energy : fragmentation or spallation



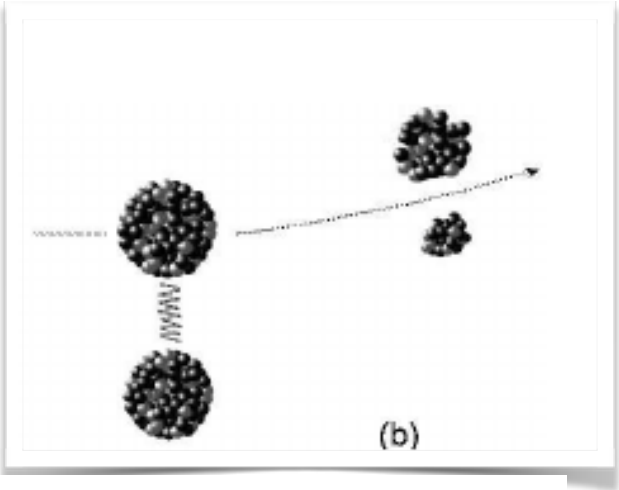


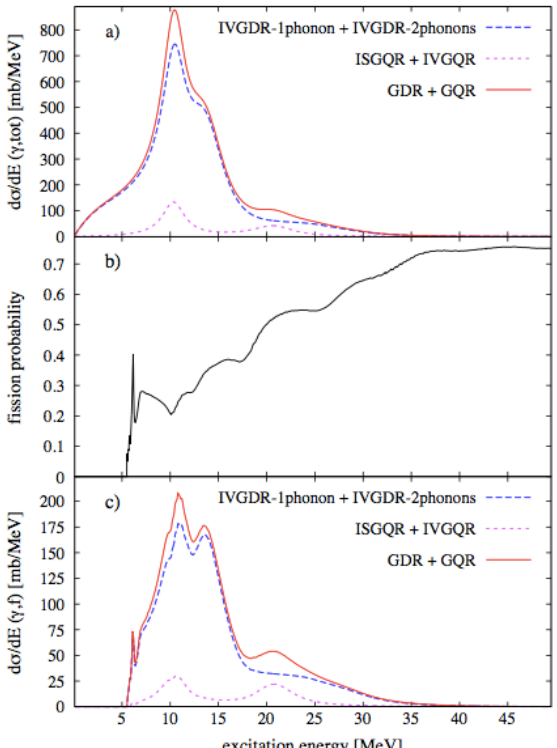
large set of compound nuclei
with broad range of excitation energy

Efficient to produce RIB
But difficult to study fission process !

Inverse kinematics : Coulomb -induced fission

Relativistic energy : Coulomb excitation





To select Cb excitation events :
-large-Z target
-Z1+Z2 = Zbeam
-substraction of low-Z target induced fission

Inverse kinematics : Coulomb -induced fission

How to produce actinide beams ?
Natural U allows to extract 238U, but 235
Th is possible …
But actinides are very radioactive and it becomes very costly to decontaminate an accelerator !!

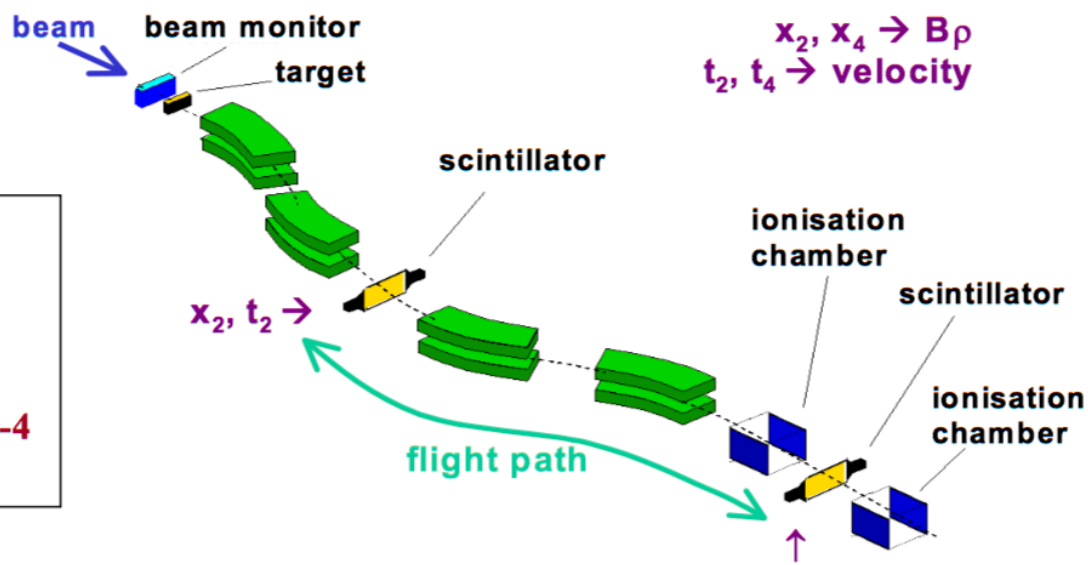
Two steps experiments :

1) production of actinides
2) induce fission and detect fission fragments

In-flight production of actinides

1) Fragmentation of U beam on target
2) Use of separator

$$\frac{A\beta\gamma}{q} = Br_m$$



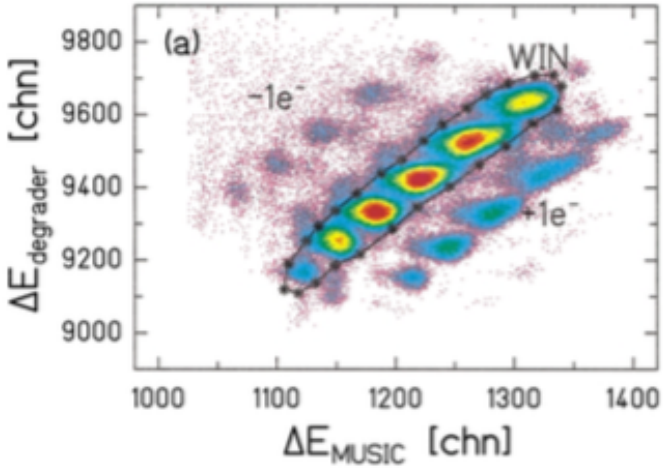
$A / \Delta A \approx 400$

$Z / \Delta Z \approx 200$

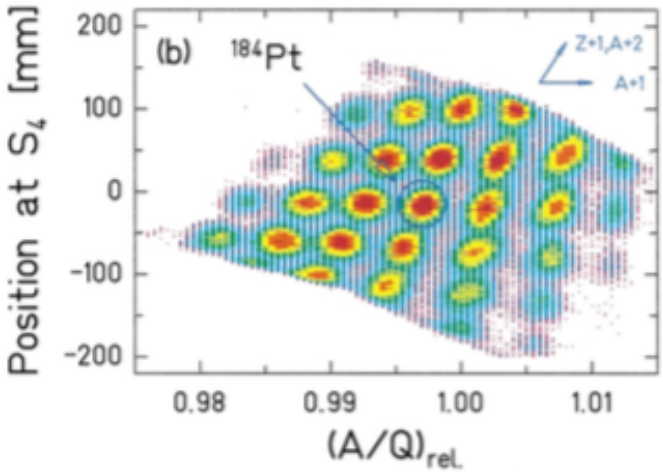
$\Delta(\beta\gamma)/\beta\gamma \approx 5 \cdot 10^{-4}$

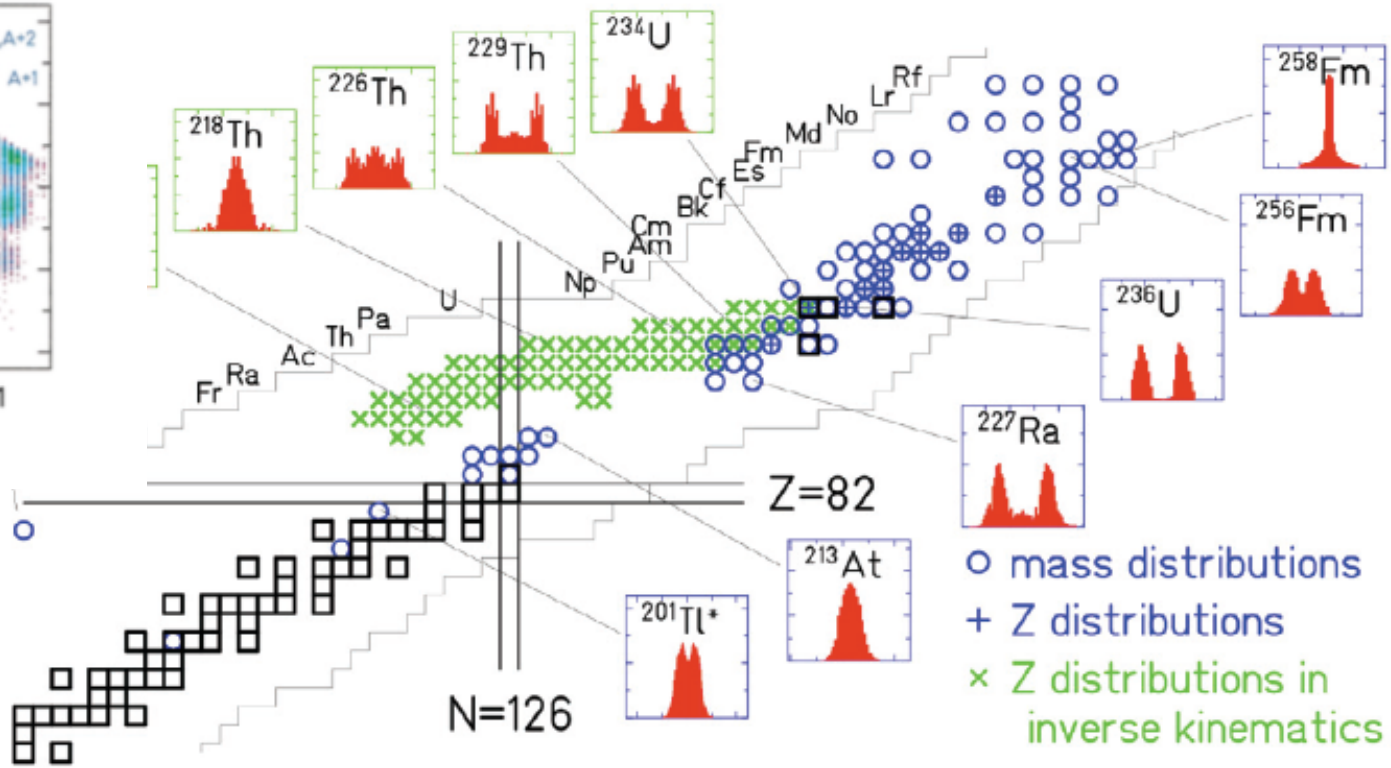
High velocity :
q = Z !!

In-flight production of actinides

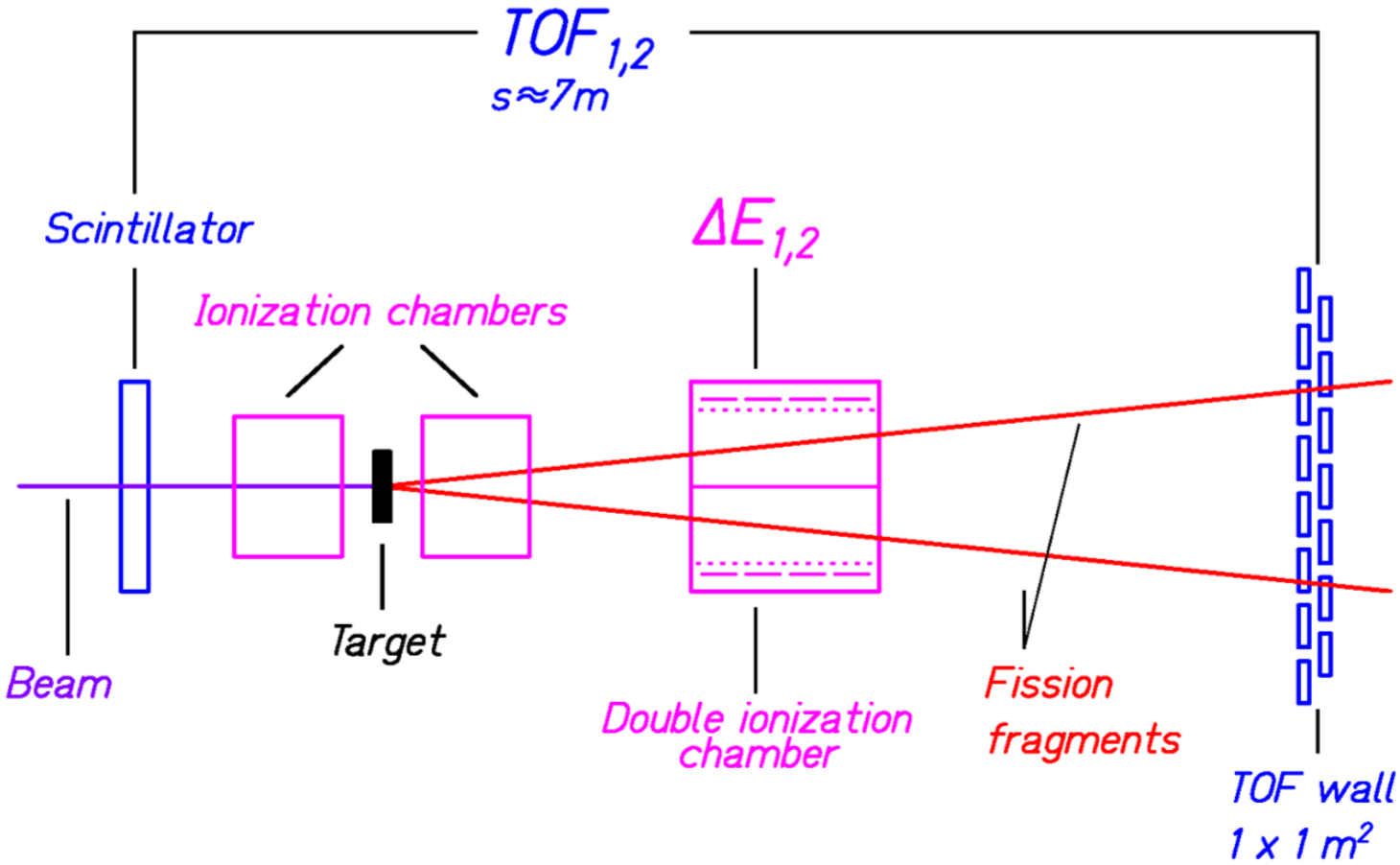


Large number of fissioning systems !

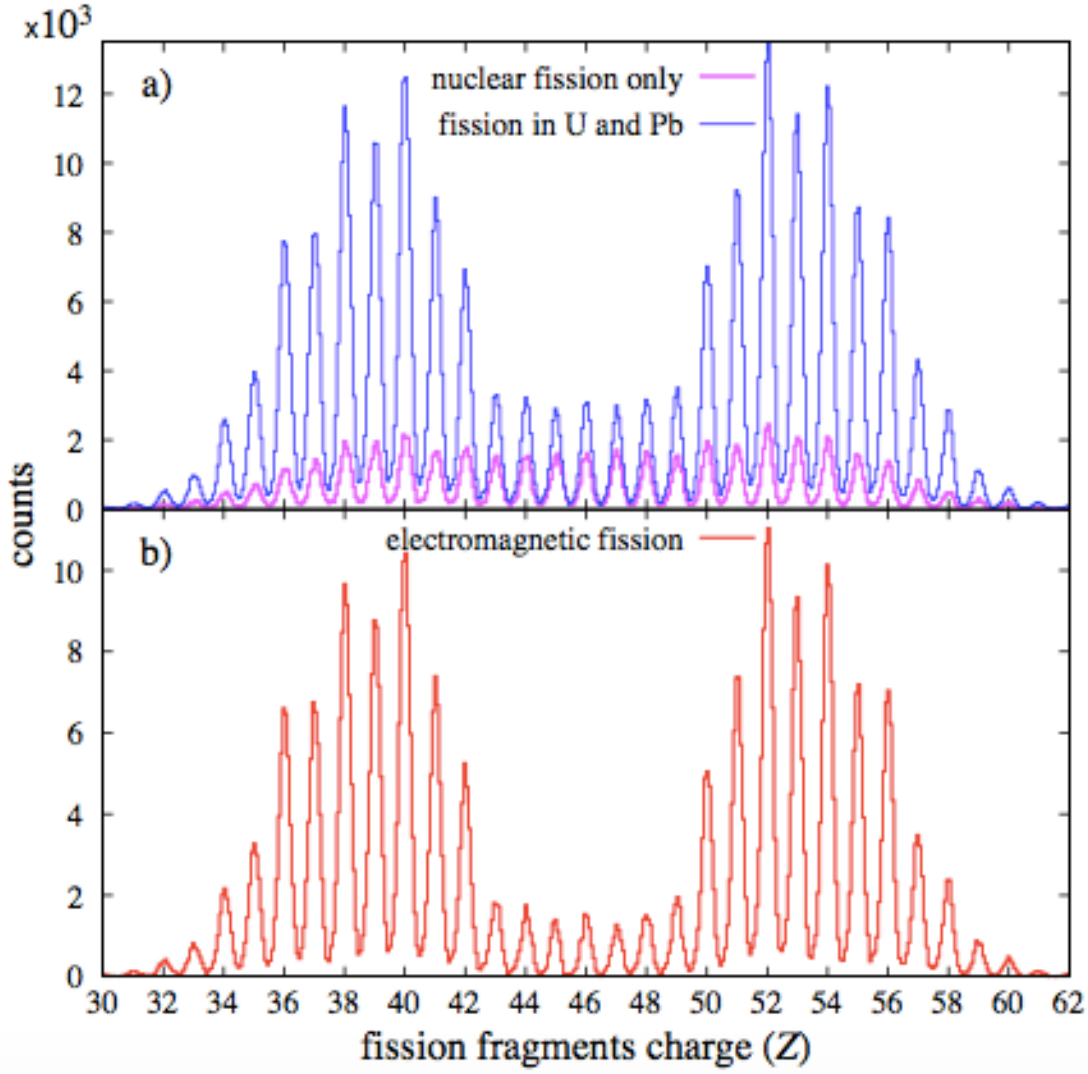




In-flight fission of actinides

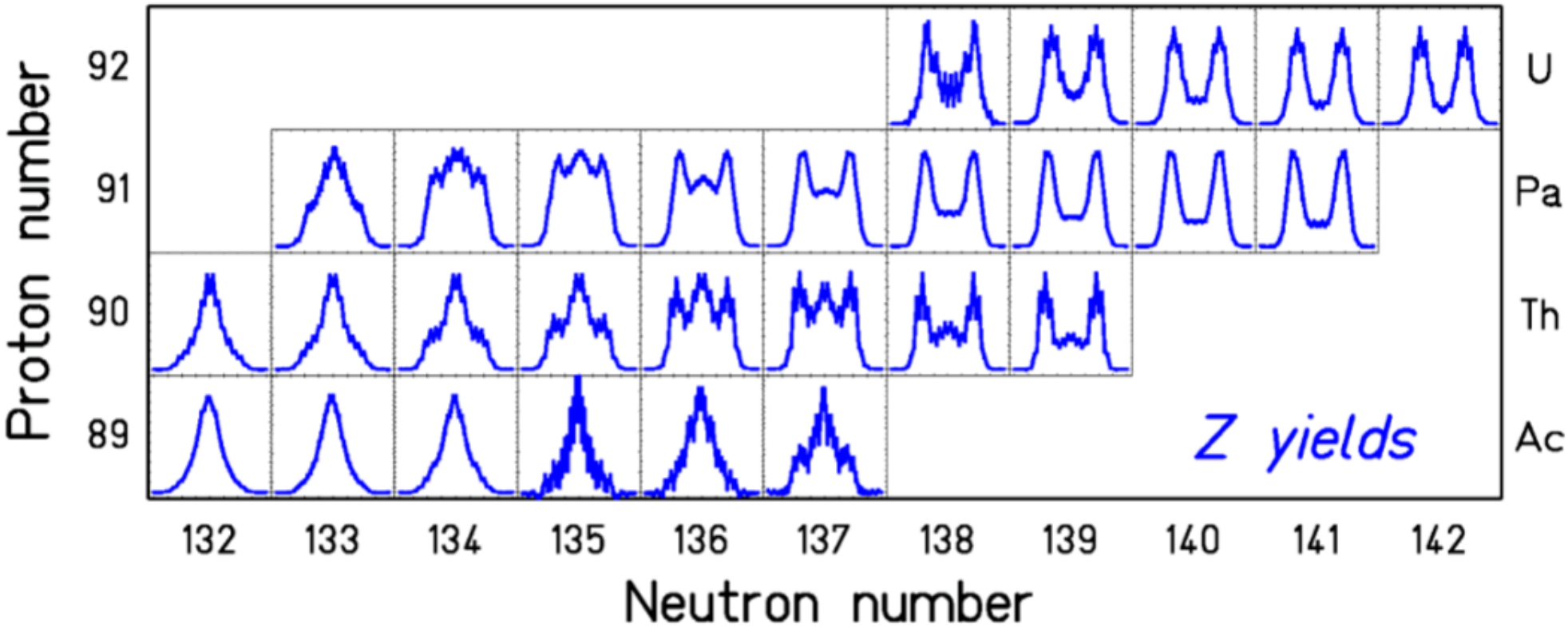


Improved Z resolution at high kinetic energy



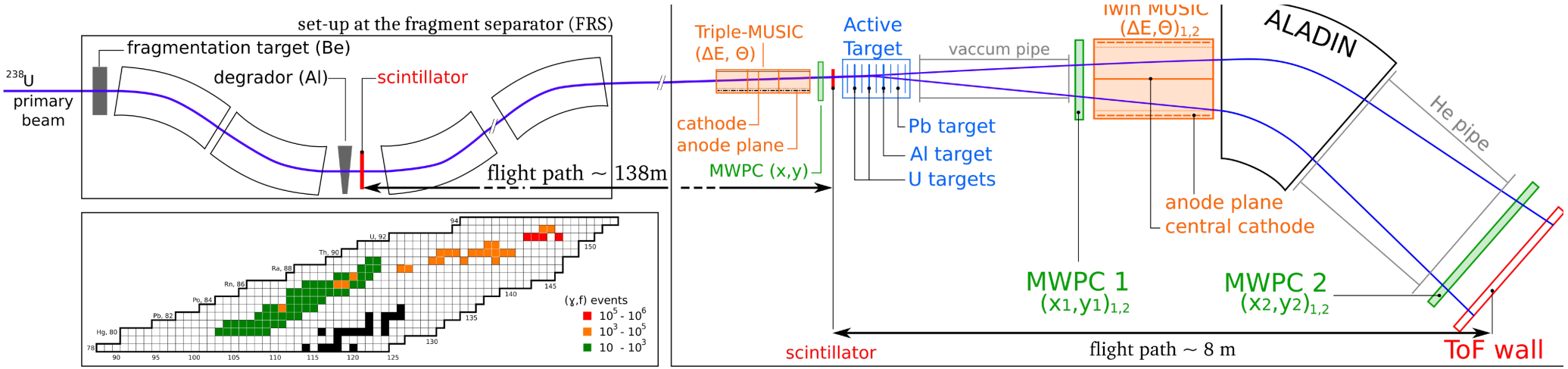
$$\frac{\partial Z}{Z} \sim 0.2\%$$

Complete distribution of Z yields in many systems



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

Isotopic identification at relativistic energy



Fragment separator to produce and select actinides

ALADIN magnet to identify both fission fragments

Measure of Bρ, ΔE, ToF

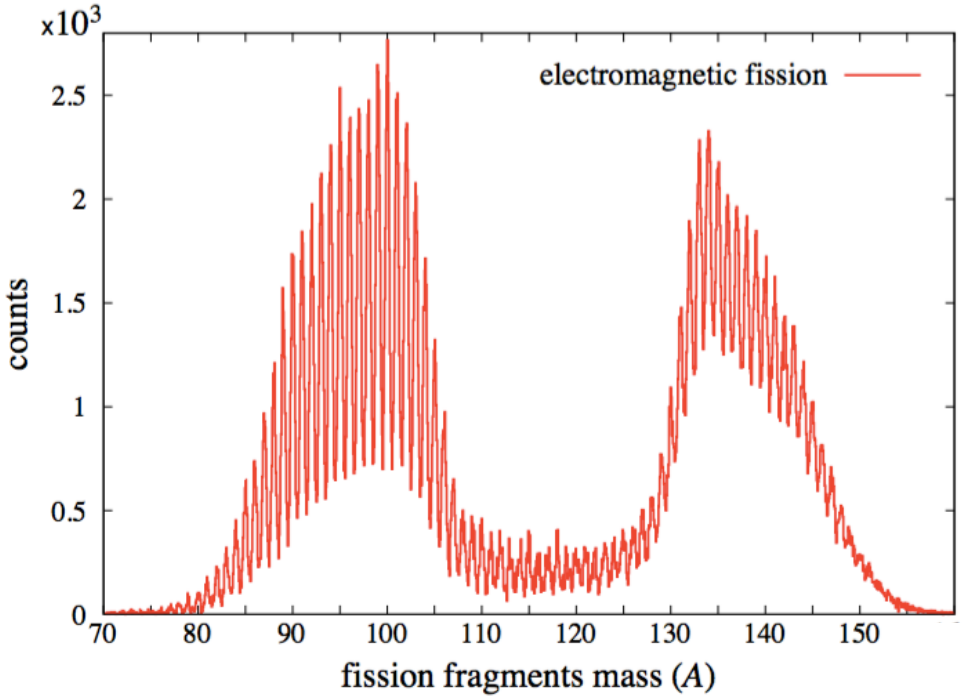
$$\frac{\partial A}{A} \sim 0.5\ \%$$

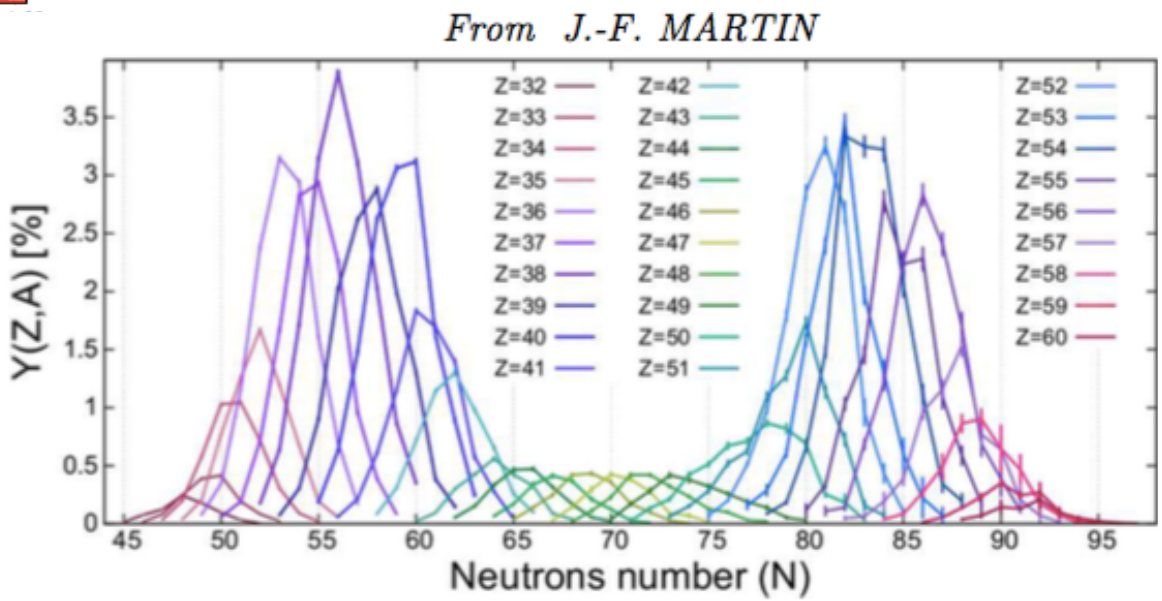
8 m ToF : Absolute challenge to get ToF resolution

Scintillators with 50ps FWHM resolution

A. Ebran, et al.Nucl. Instr. Meth. A 728 (2013)

Isotopic identification at relativistic energy



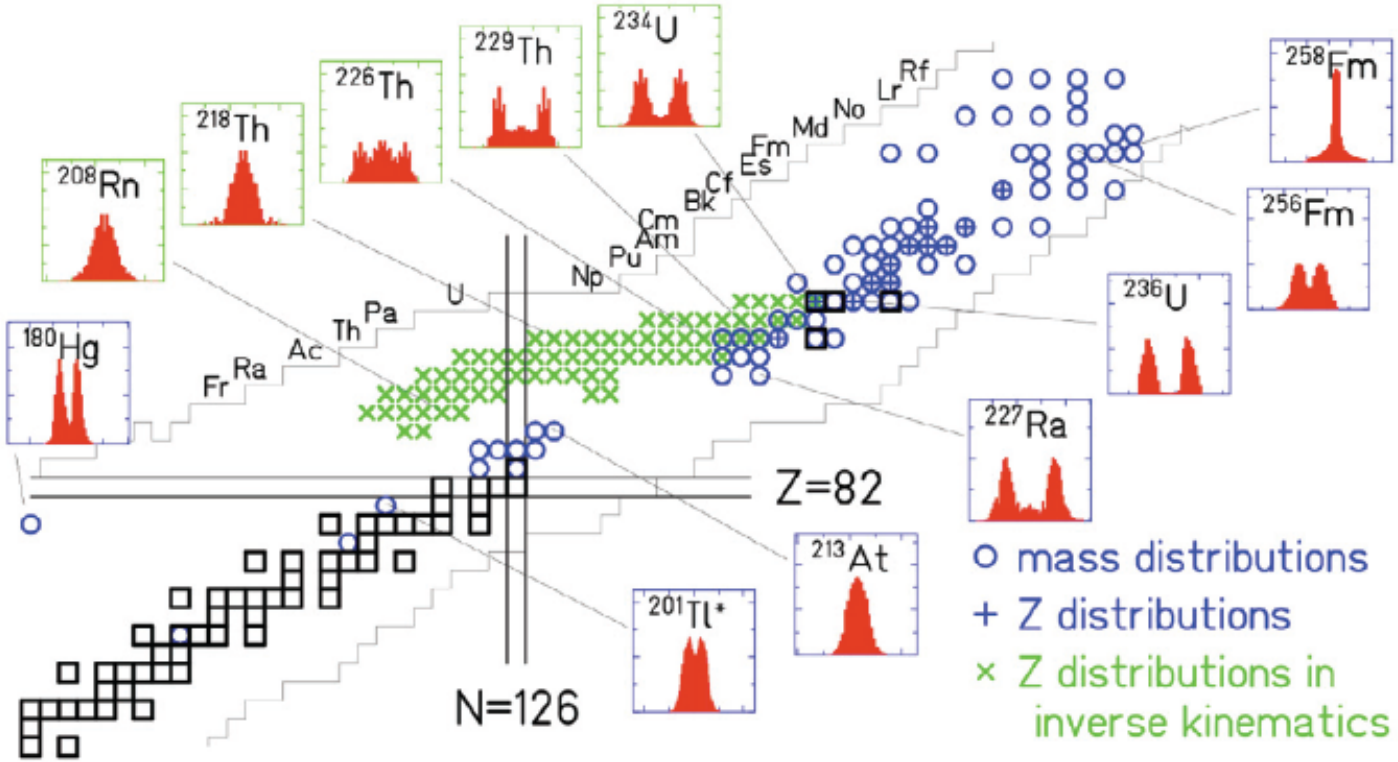


Impresive se of data !!
Compete isotopic yields
Very constraning to modelisation !

E. Pellereau et al. Phys. Rev. C 2017

Secondary beams

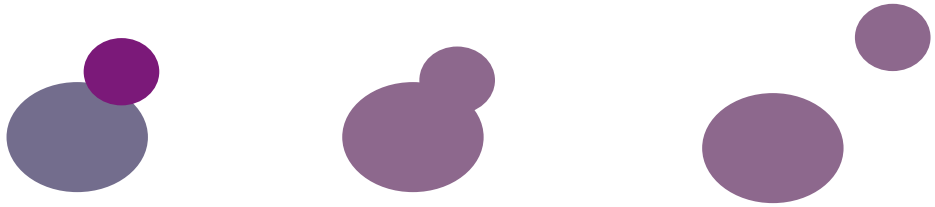
Fission in inverse kinematics
high resolution in Z,A
Complete identification
Both fission-fragments —> total neutron multiplicity !
Large number of fissioning systems but light systems

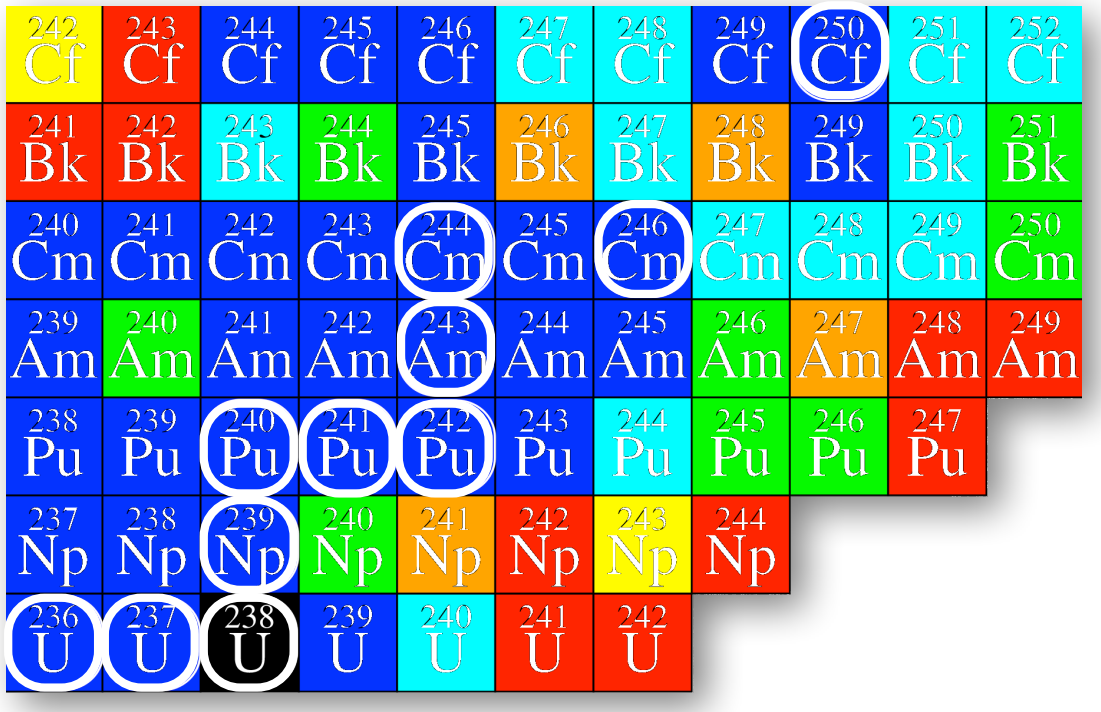


Multi-nucleon transfer induced fission

Coulomb barrier energy

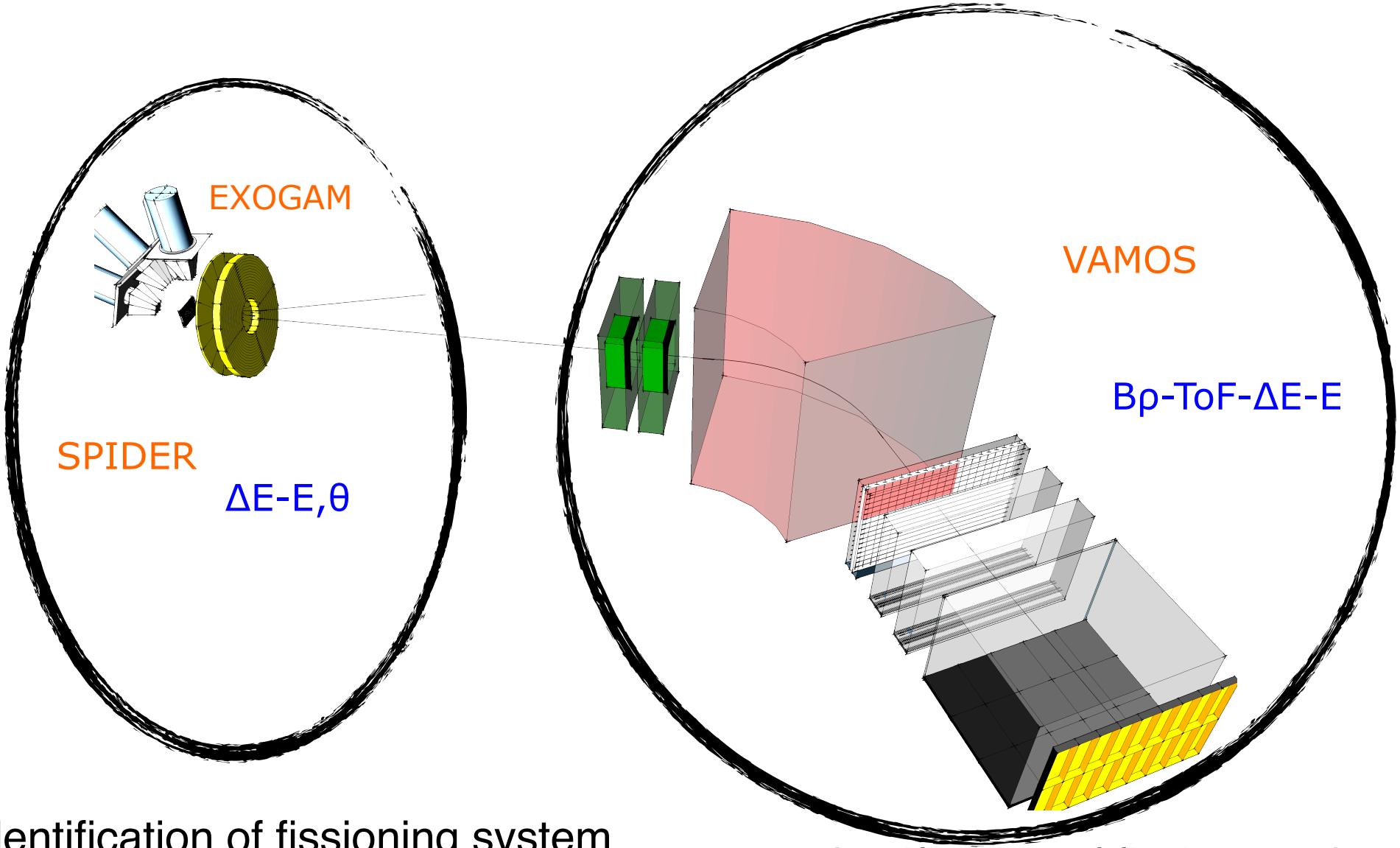
Very asymmetric reaction :
Nucleon exchange from light to heavy nucleus
Direct reaction





238U+12C :
Production of almost 10 neutron-rich actinides

Multi-nucleon transfer induced fission

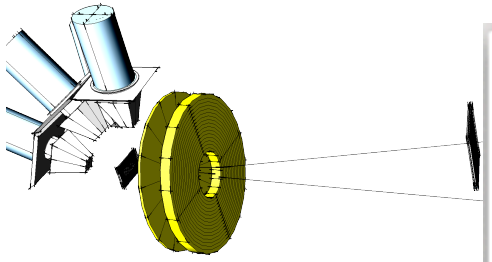


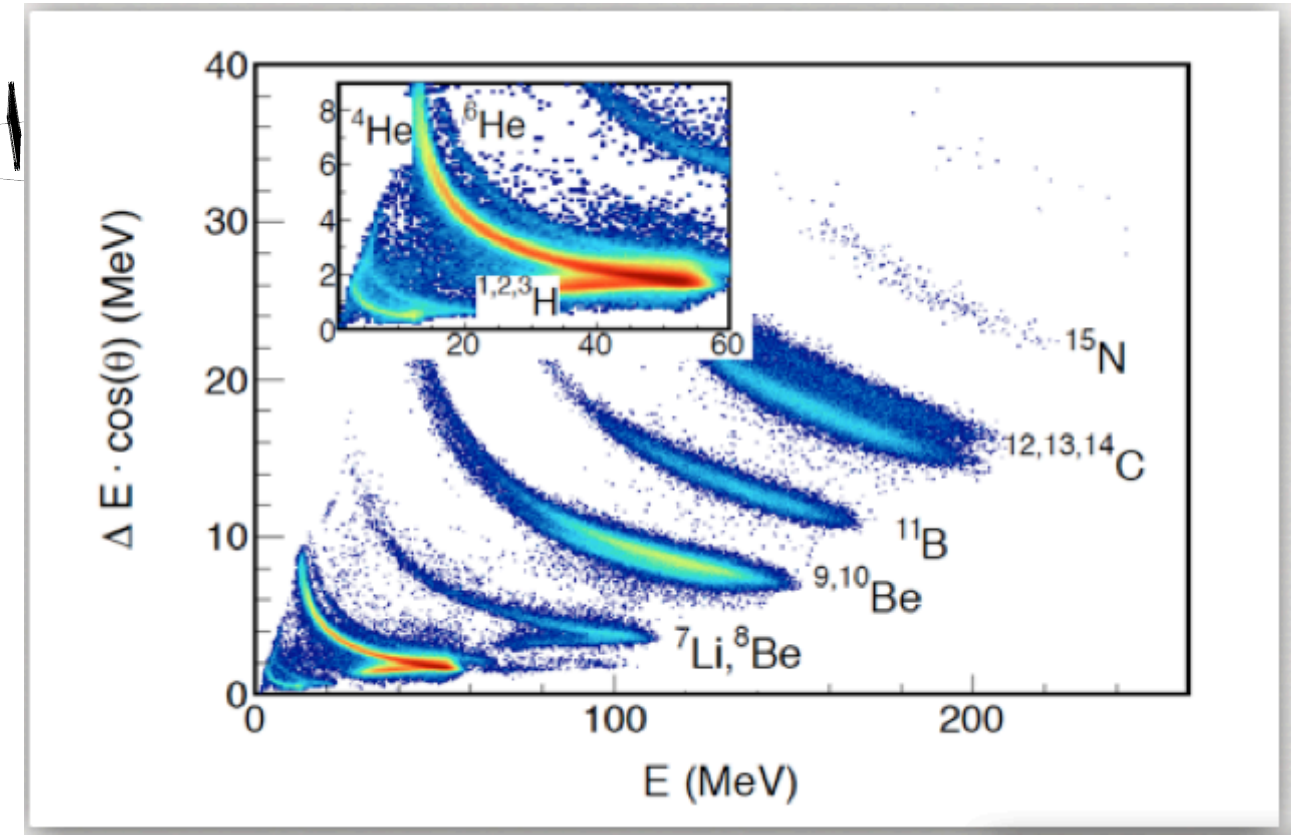
Identification of fissioning system

Identification of fission product

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

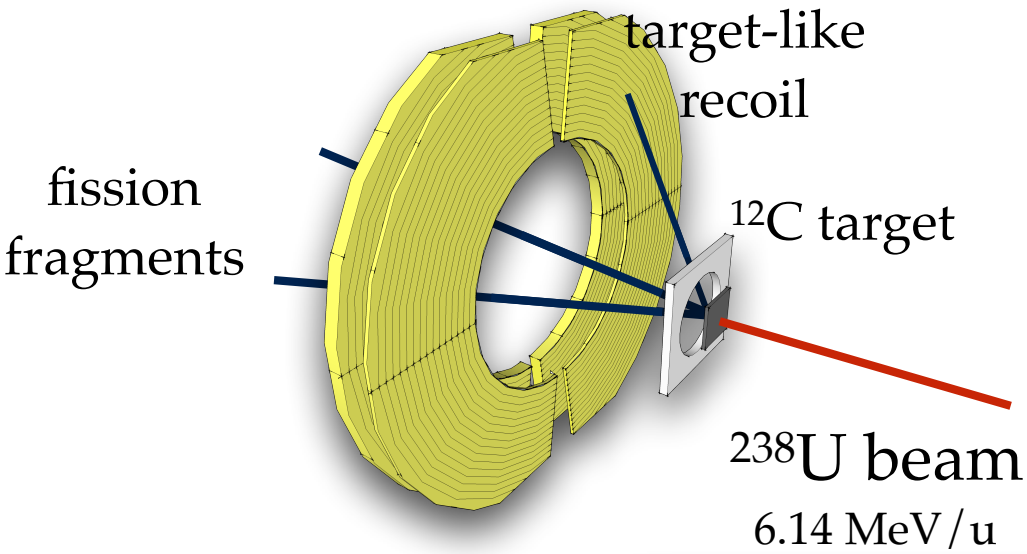
Identification of the transfer channels





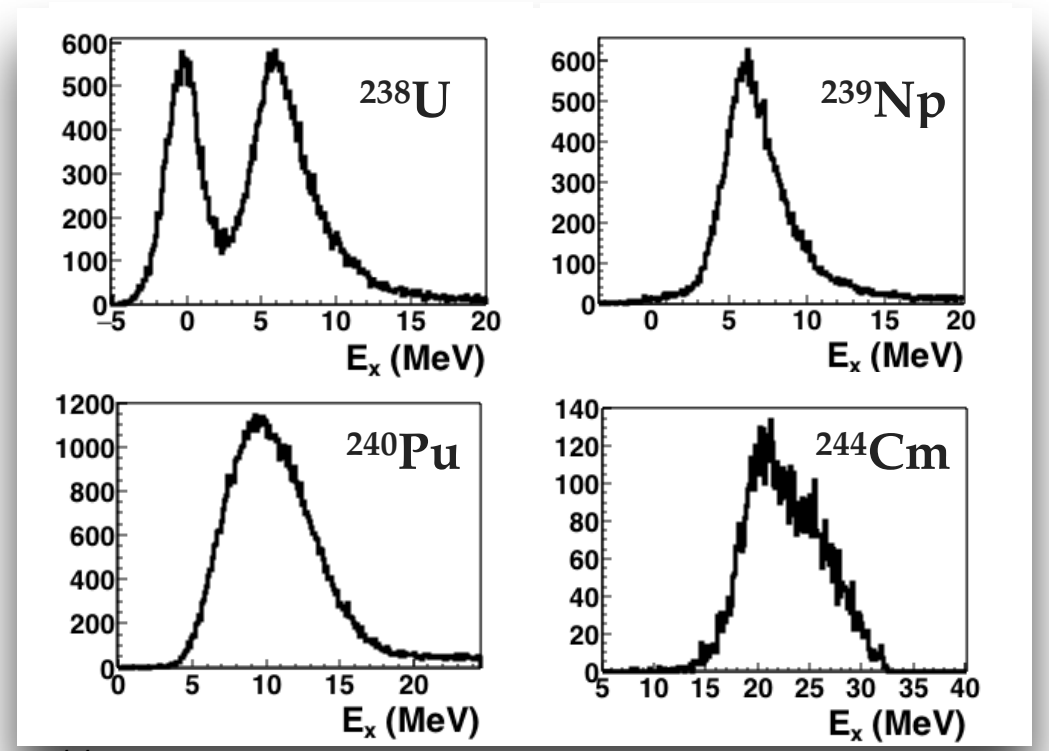
C. Rodriguez-Tajes et al.,
PRC89 (2014) 024614

Identification of the transfer channels

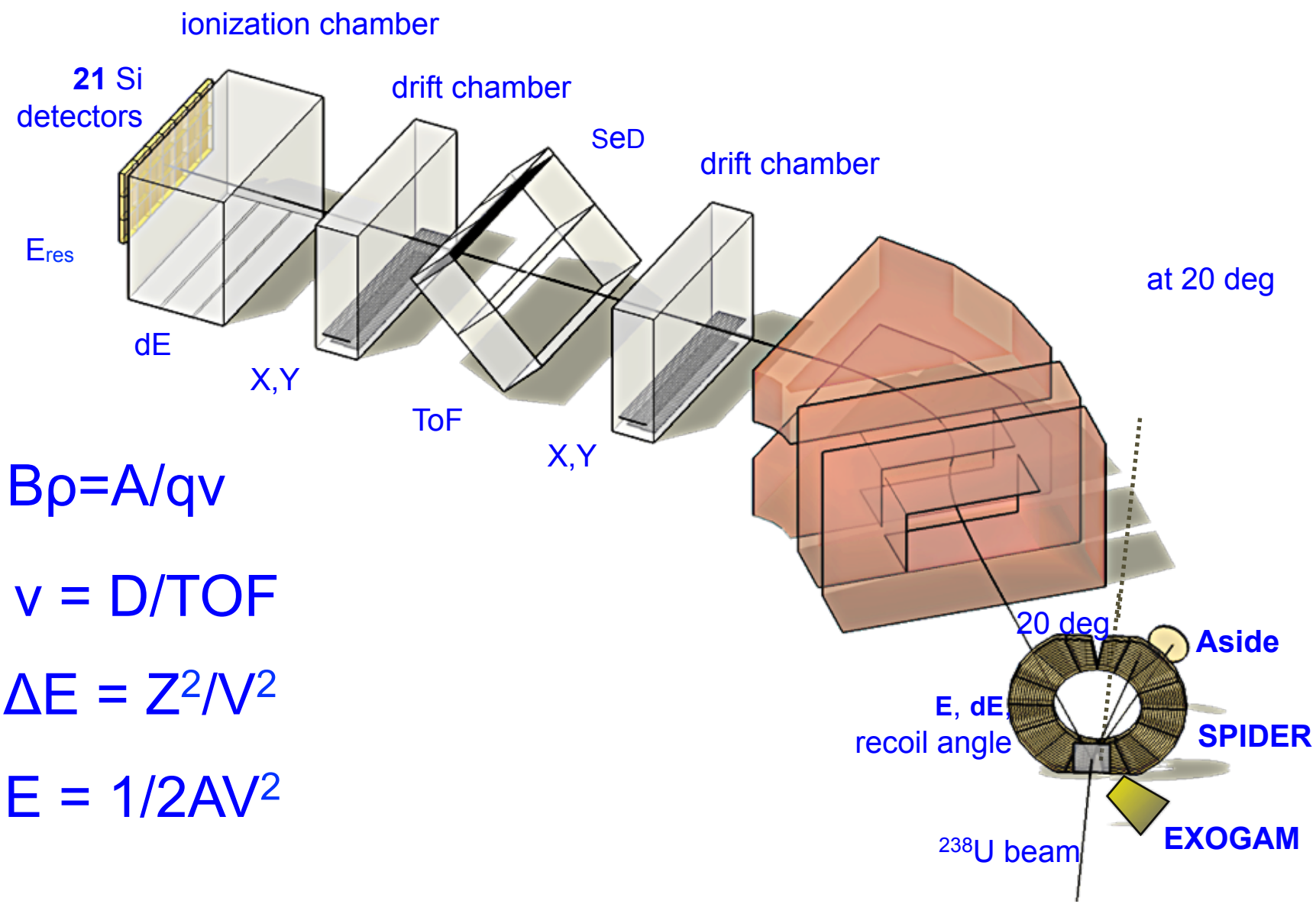


^{238}U (^{12}C, ^{12}C) ^{238}U
^{238}U (^{12}C, ^{11}B) ^{239}Np
^{238}U (^{12}C, ^{10}Be) ^{240}Pu
^{238}U (^{12}C, ^{6}He) ^{244}Cm

- Isotopic identification
- Reconstruction of binary reaction
- E_x reconstruction

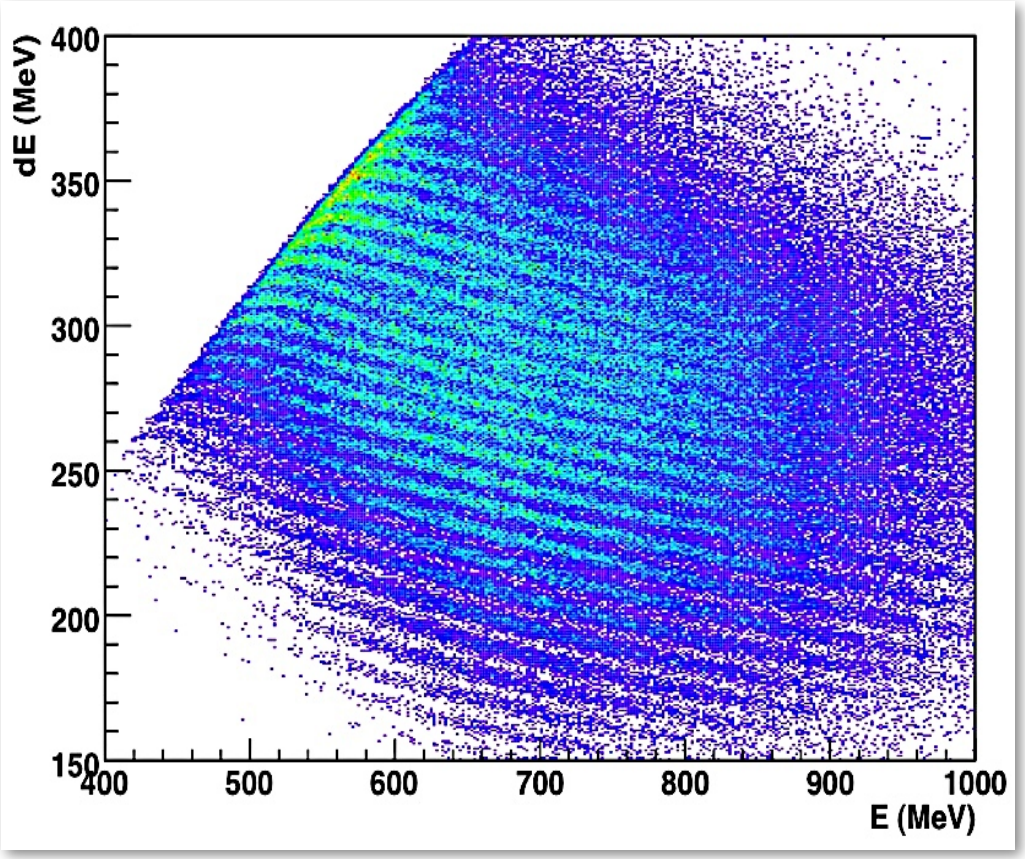


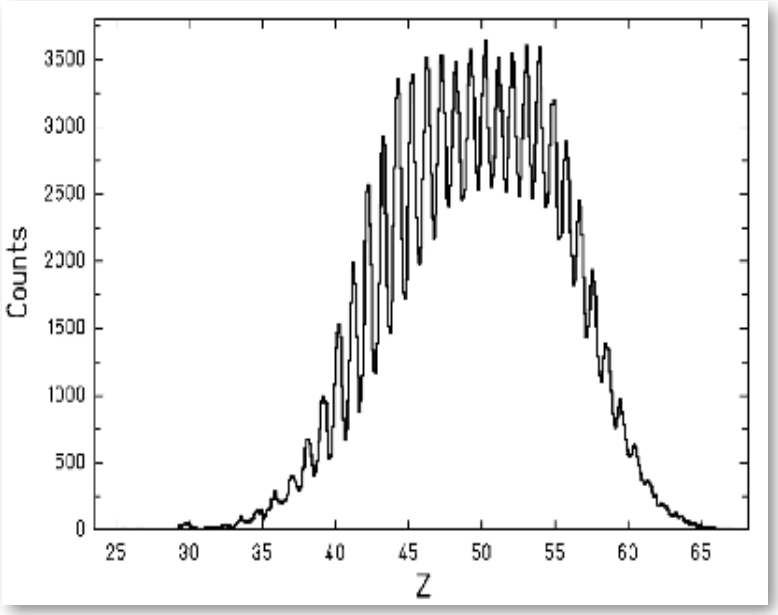
Identification of fission products



- $B\rho = A/qv$
- $v = D/TOF$
- $\Delta E = Z^2/V^2$
- $E = 1/2AV^2$

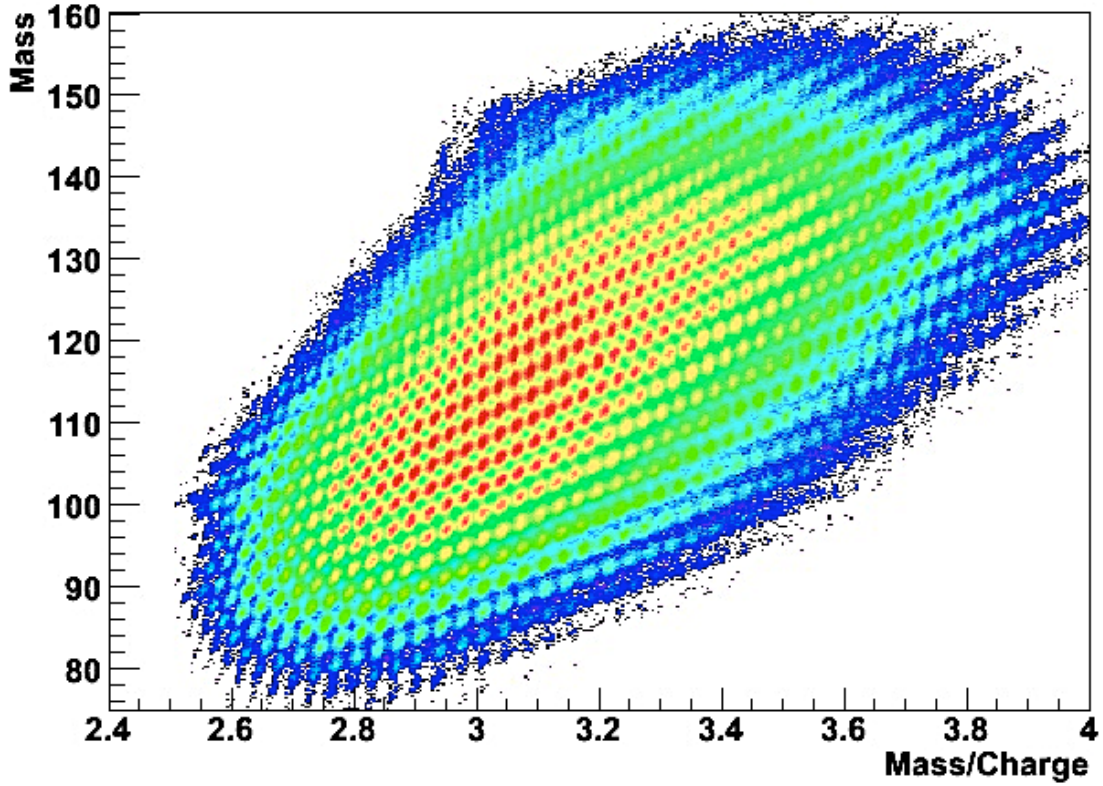
Improved atomic number resolution

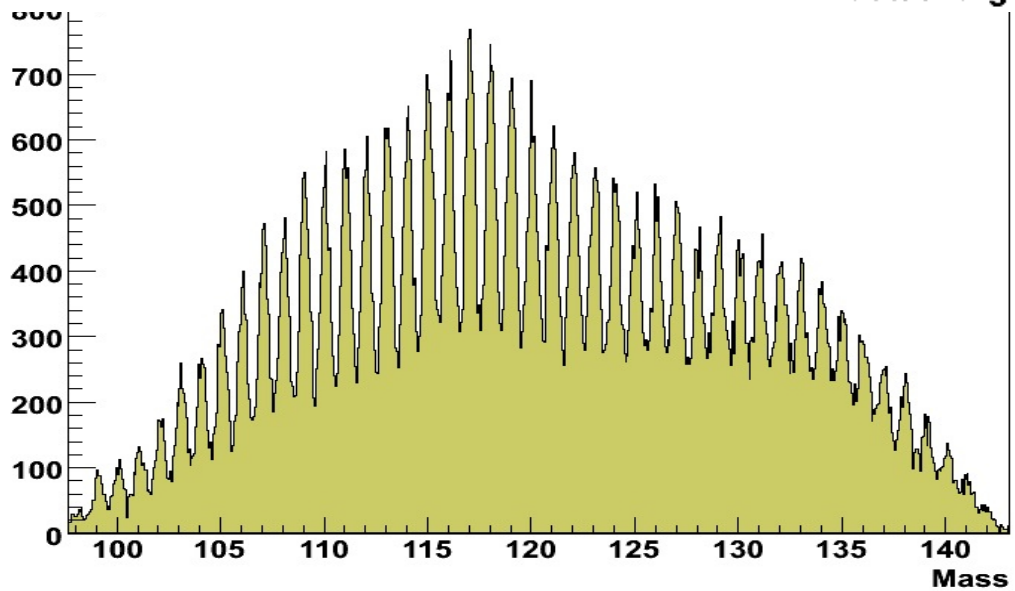




$\Delta Z/Z \approx 1.5 \cdot 10^{-2}$

Mass resolution through magnetic rigidity resolution

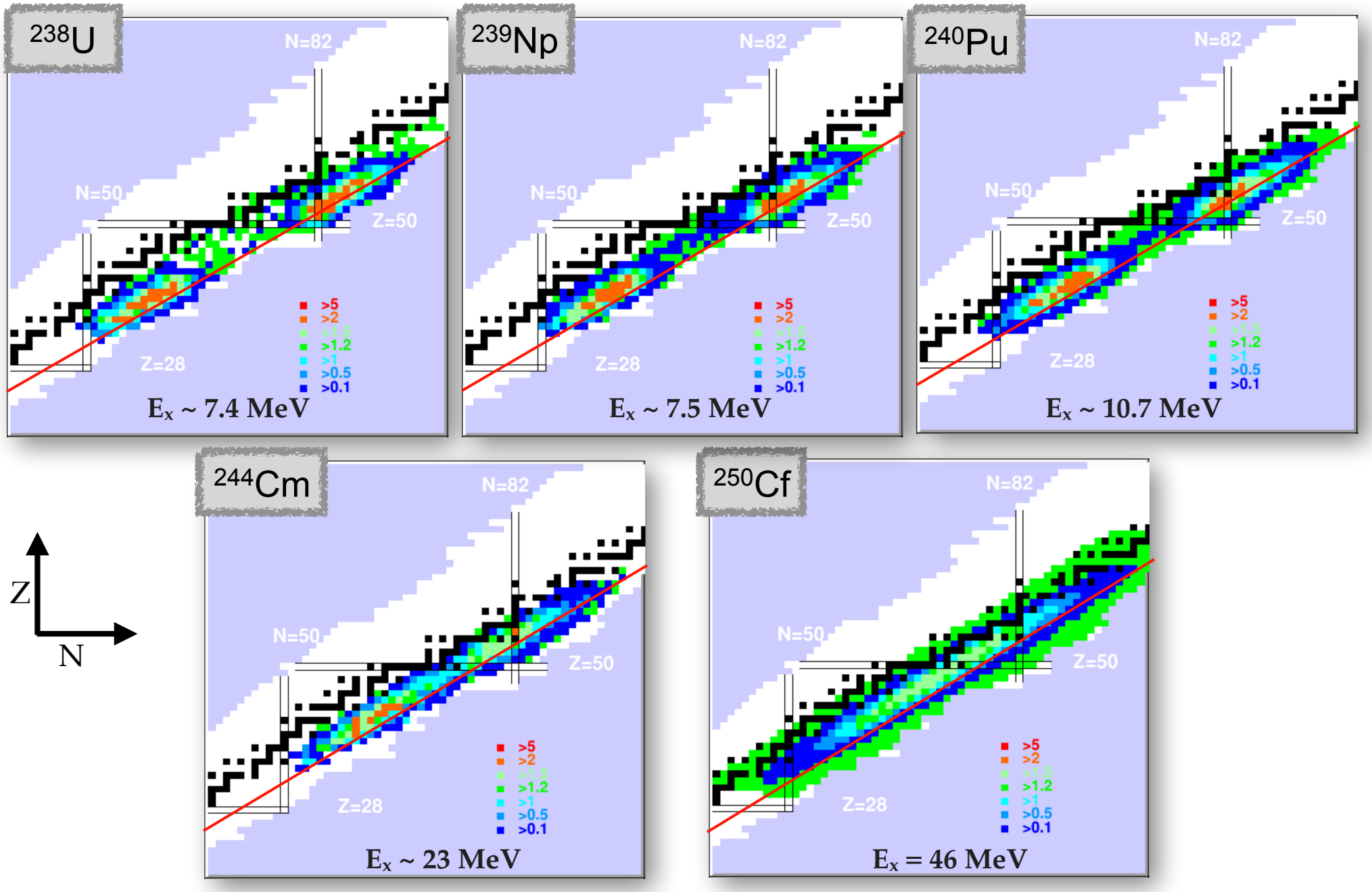




$$A = E/(\gamma - 1)$$

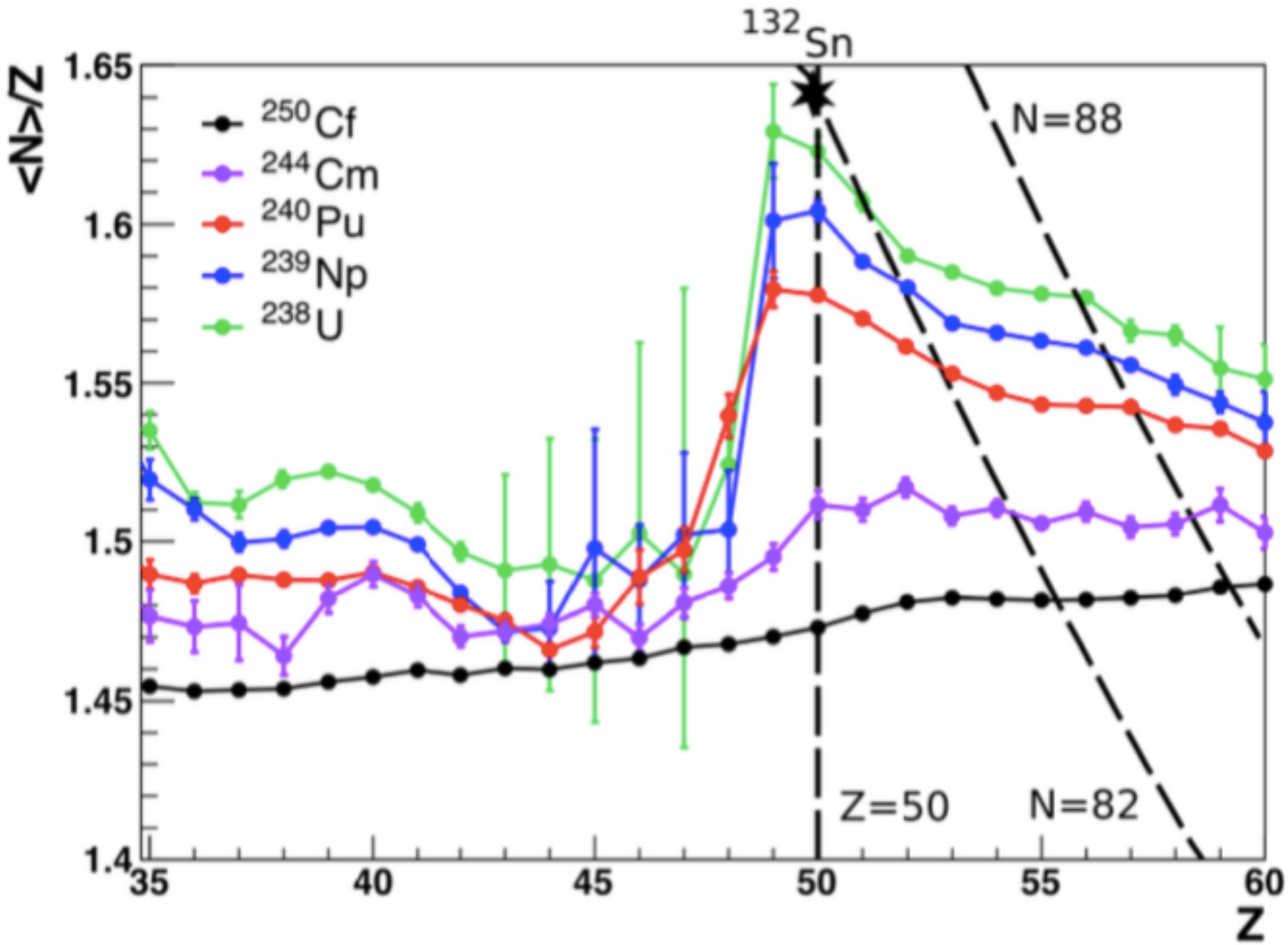
$$A/q = B\rho/(\beta\gamma)$$

Results: Isotopic Fission Yields



Mass resolution through magnetic rigidity resolution

New data : new type of observables : Charge polarisation



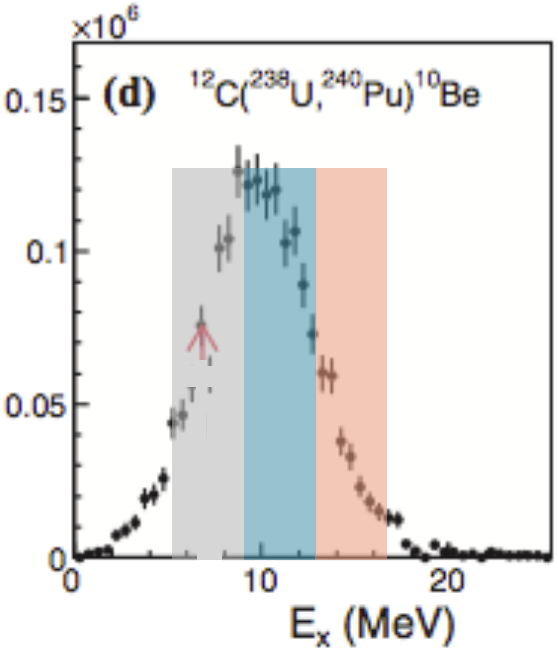
Mass resolution through magnetic rigidity resolution

New techniques allow for improved resolution for the identification of fission fragments

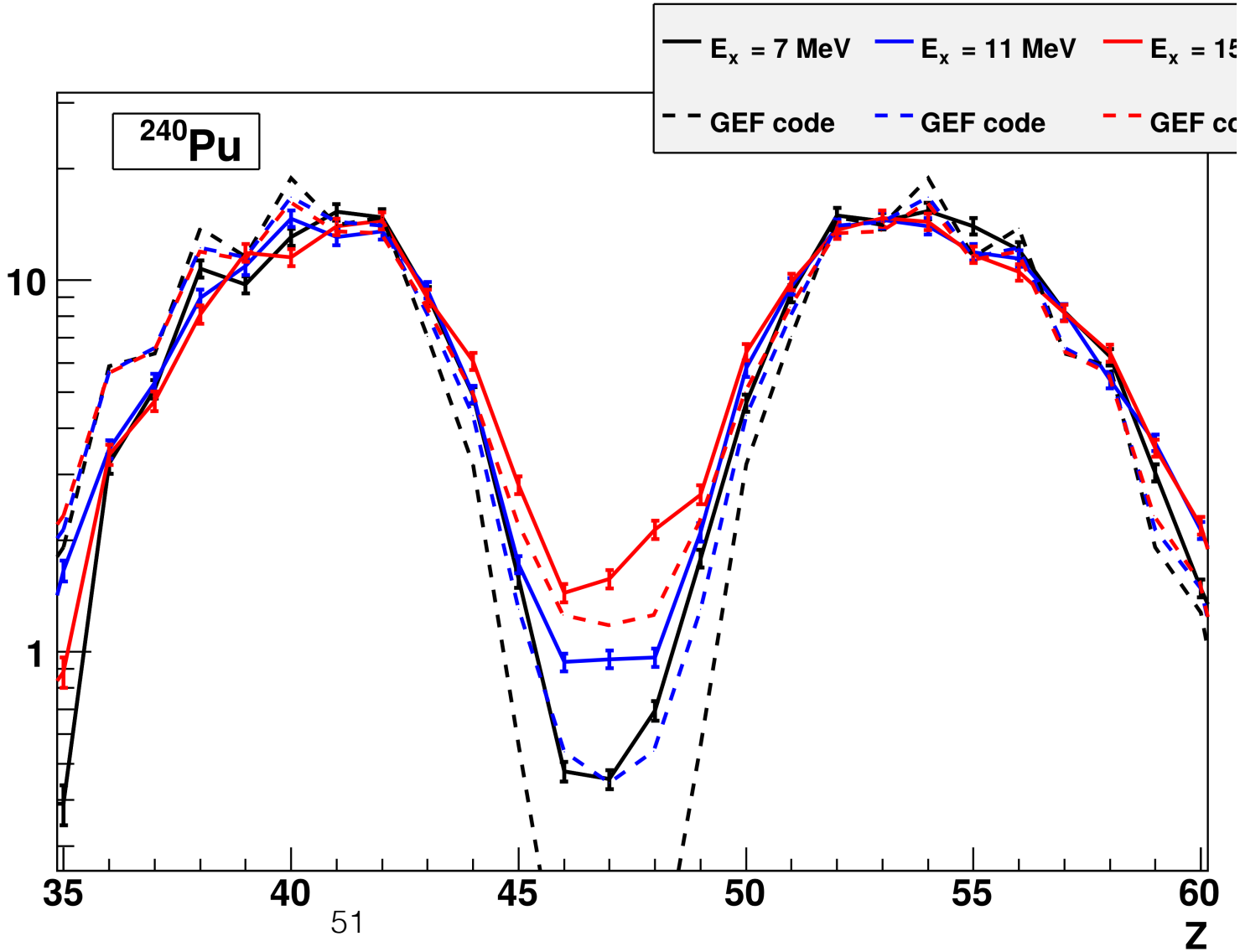
In addition they allow for :

- **2D-map of the fission fragments**
- **study the evolution with excitation energy**
- **improving the number of fissioning actinides due to nuclear reactions**

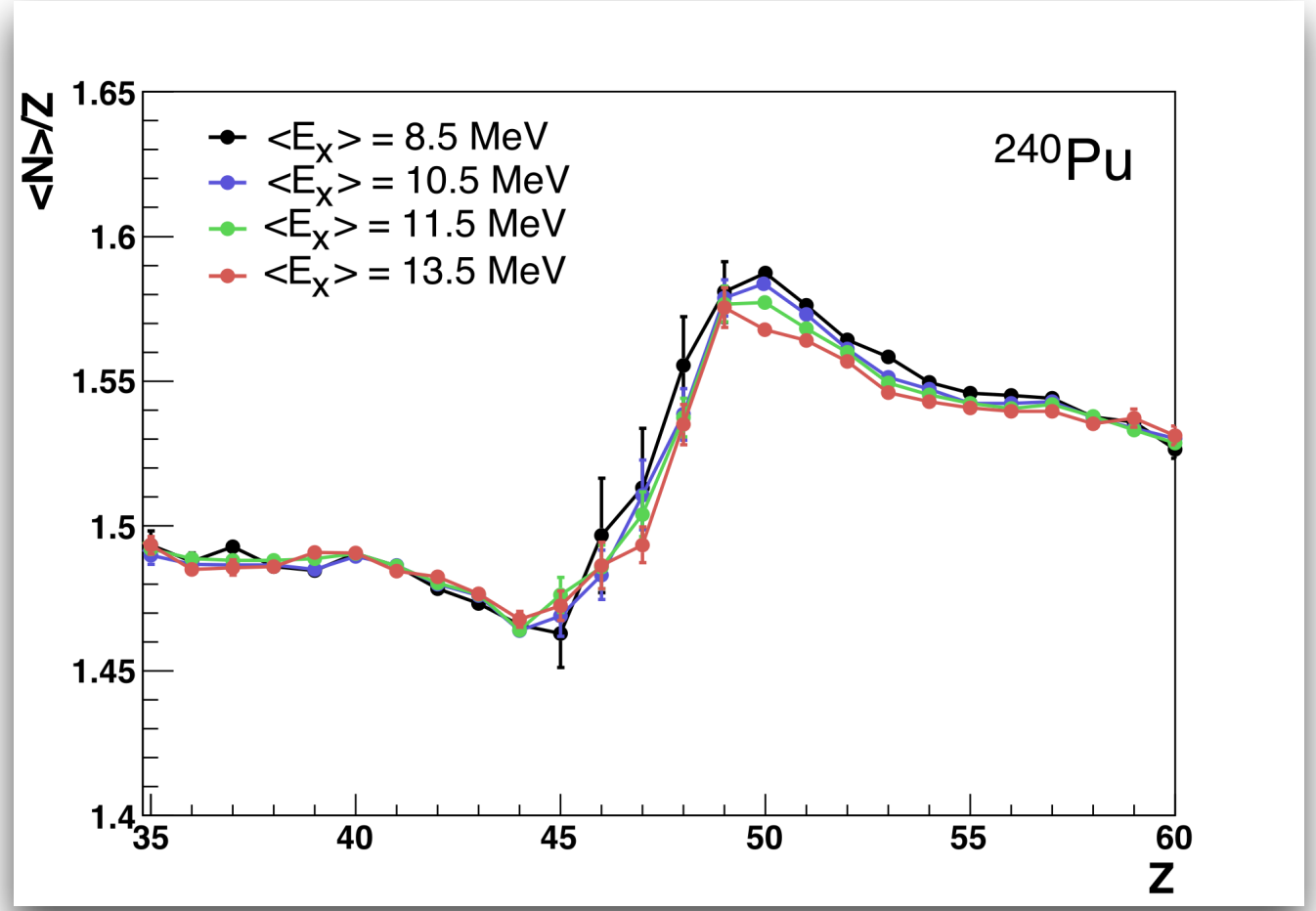
Evolution of mass distribution with Excitation energy

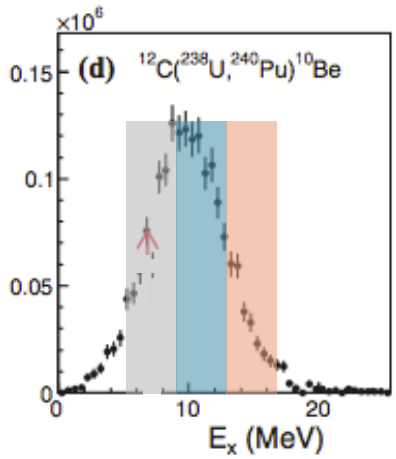


From transfer kinematics



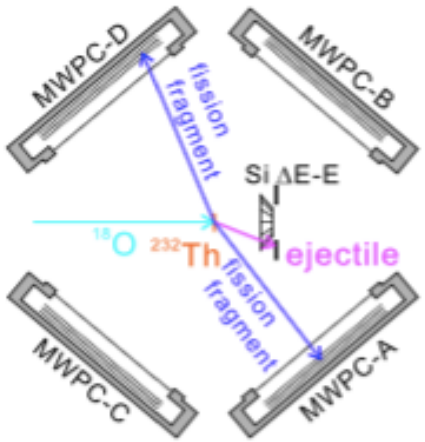
Evolution of charge polarisation with Excitation energy

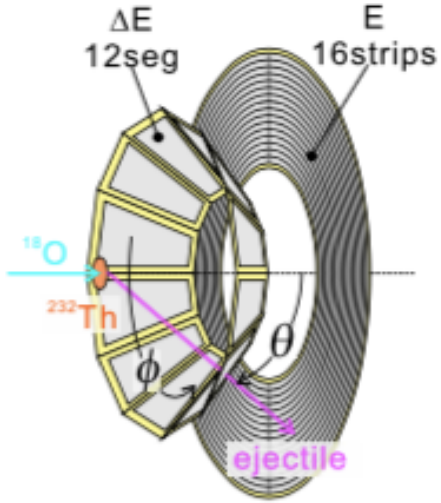


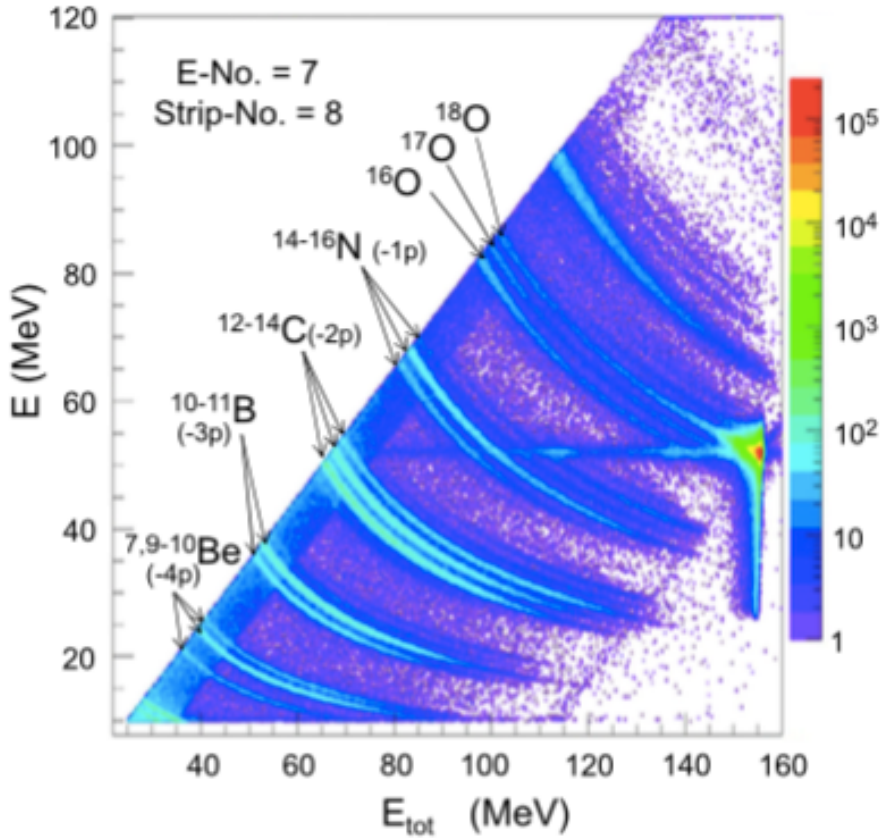


Only heavy fragments evaporate neutrons !!

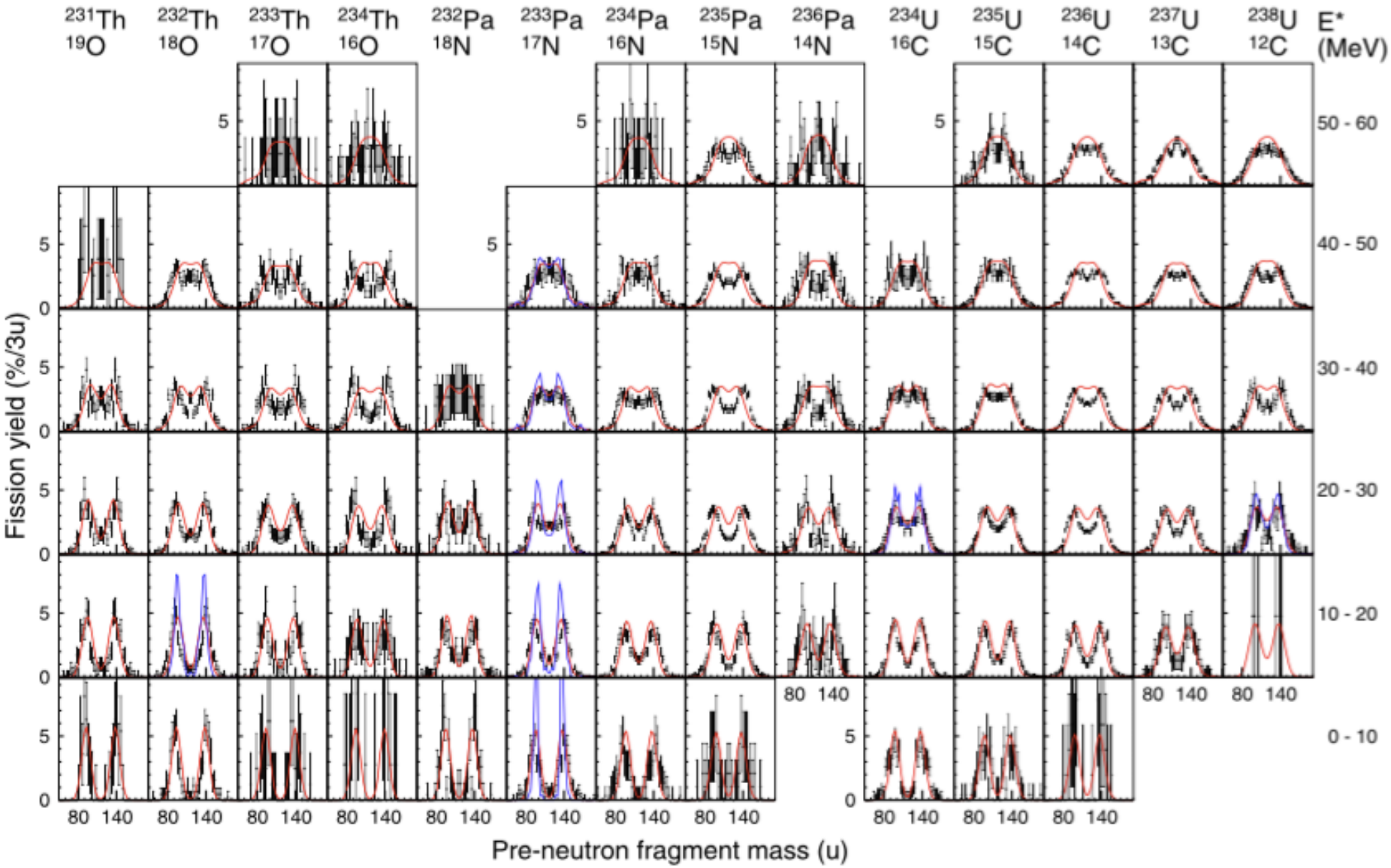
Multi-nucleon reaction used in direct kinematics







Multi-nucleon reaction used in direct kinematics



R. Léguillon et al., PLB 761(2016) 125

7. Fission Yields : systematic uncertainties and errors

Fission yields : number of fragment per fission event

$$\sum Y(Z,A) = 200$$

2 fission fragments/ fission

$$Y(Z,A) = \frac{\partial N_f}{\partial Z \partial A}$$

isotopic identification
gamma spectroscopy,
energy-loss, energy and time-of flight

$$Y(A) = \sum_Z Y(Z,A) = \frac{\partial N_f}{\partial A}$$

mass identification
energy, time-of-flight measurements

$$Y(Z) = \sum_A Y(Z,A) = \frac{\partial N_f}{\partial Z}$$

atomic number identification
energy-loss, X-ray

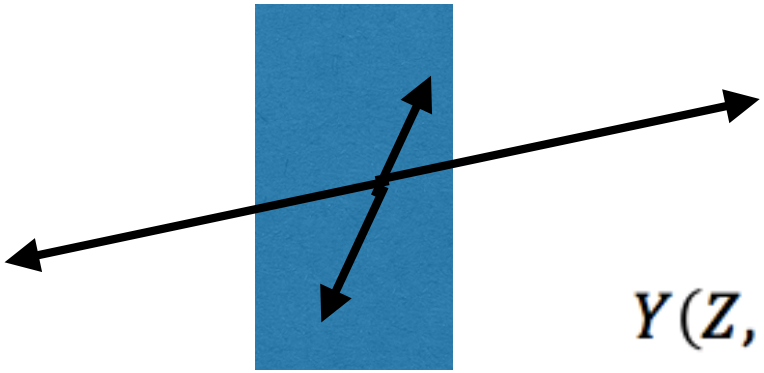
7. Fission Yields : systematic uncertainties and errors

Relative yields : beam intensity, target thickness, .. are not key parameters

Detection relative efficiency :

— —-from Z~ 30 to Z~60, energy-loss varies with a factor 4

— — target release efficiency : depends on Z, and angle



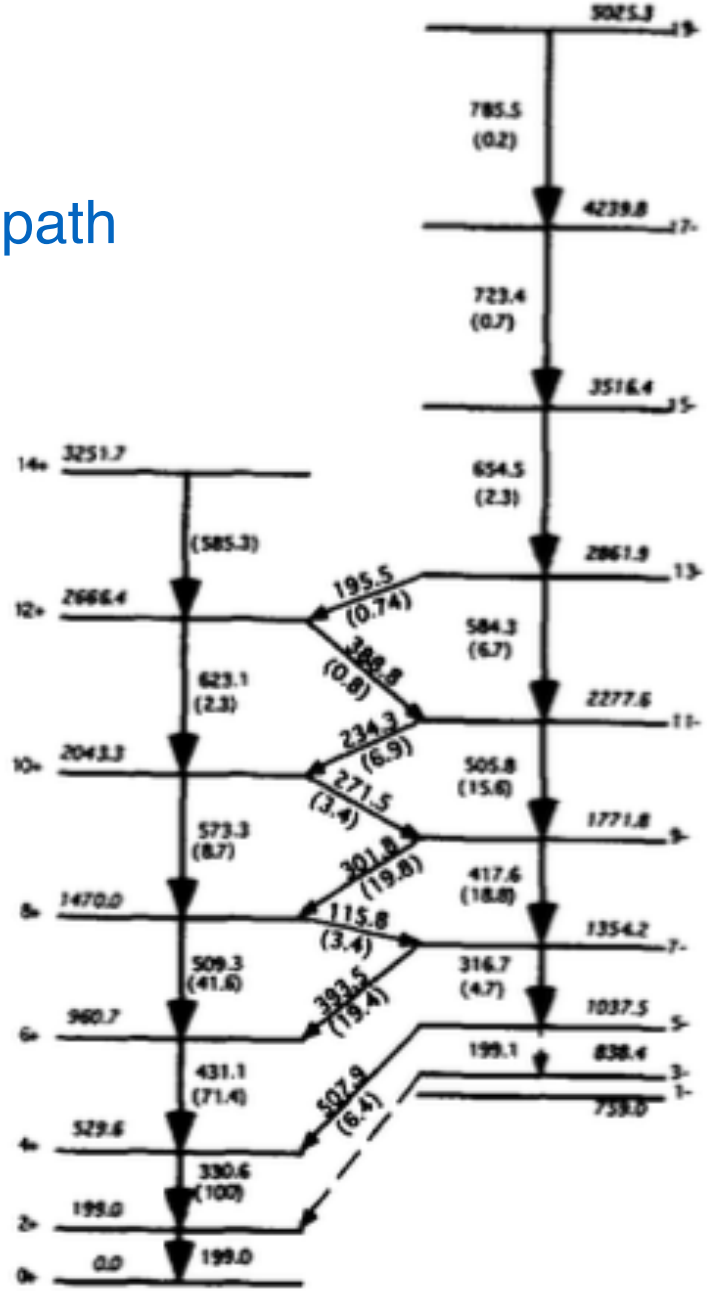
$$Y(Z,A) = \frac{\partial N_f}{\partial Z \partial A} \frac{1}{\xi(Z,A,E)}$$

Need a precise simulation of the detection set-up

7. Fission Yields : systematic uncertainties and errors

Uncertainty on level scheme:
isomeric states ; fragmentation of the decay path

$^{142}_{56}Ba_{86}$

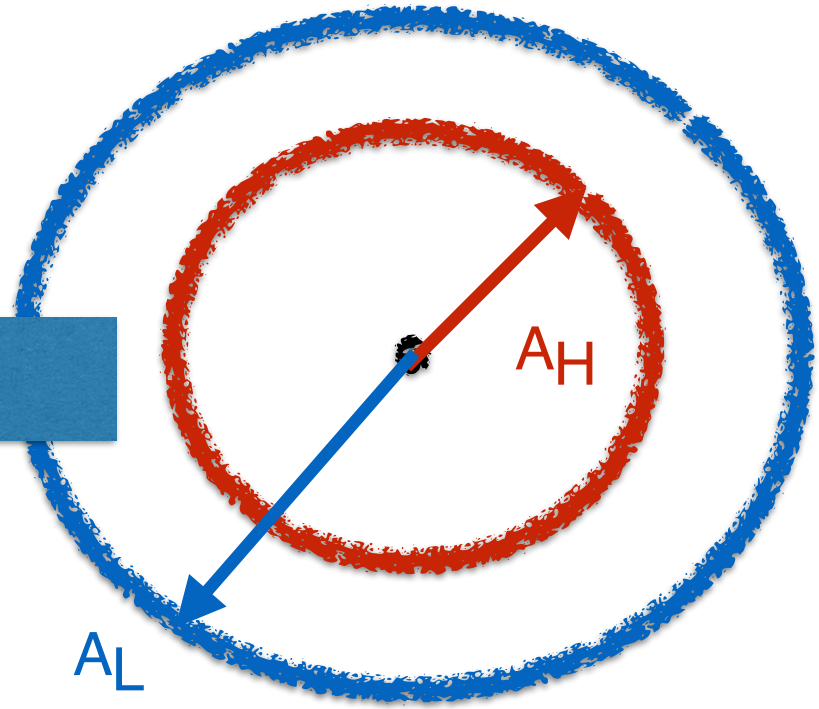


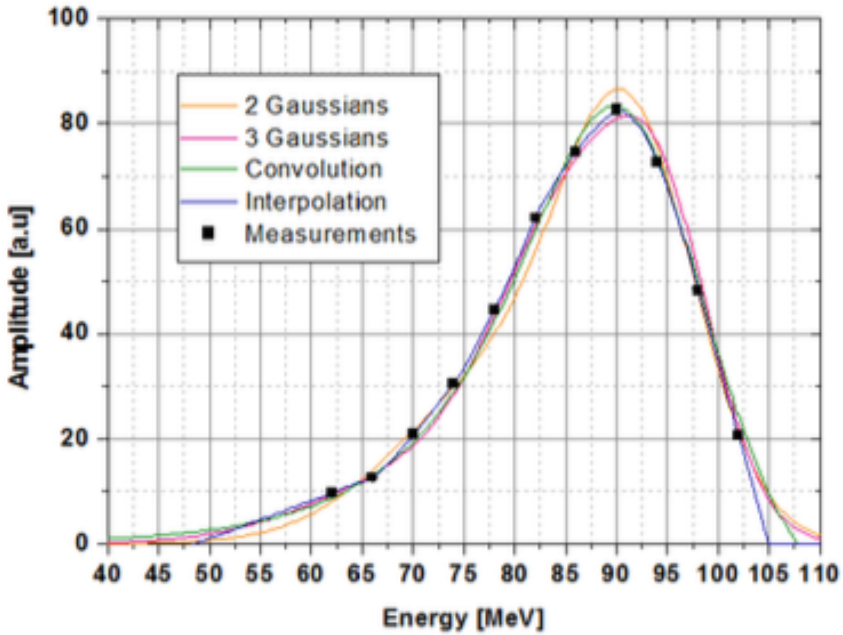
$^{144}_{56}Ba_{88}$

7. Fission Yields : systematic uncertainties and errors

$$Y(Z,A) = \frac{\partial N_f}{\partial Z \partial A} \frac{1}{\xi(Z,A,E)} \int dE \int d\theta$$

Detection system





full phase space measurement :

— correction for angular anisotropy
— correction for q-state distribution

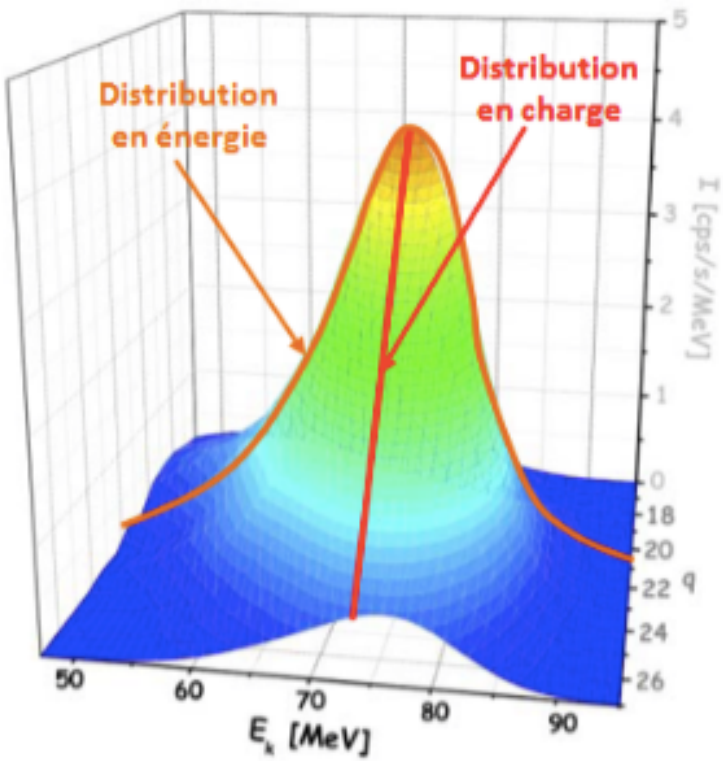
C. Amouroux PhD

7. Fission Yields : systematic uncertainties and errors

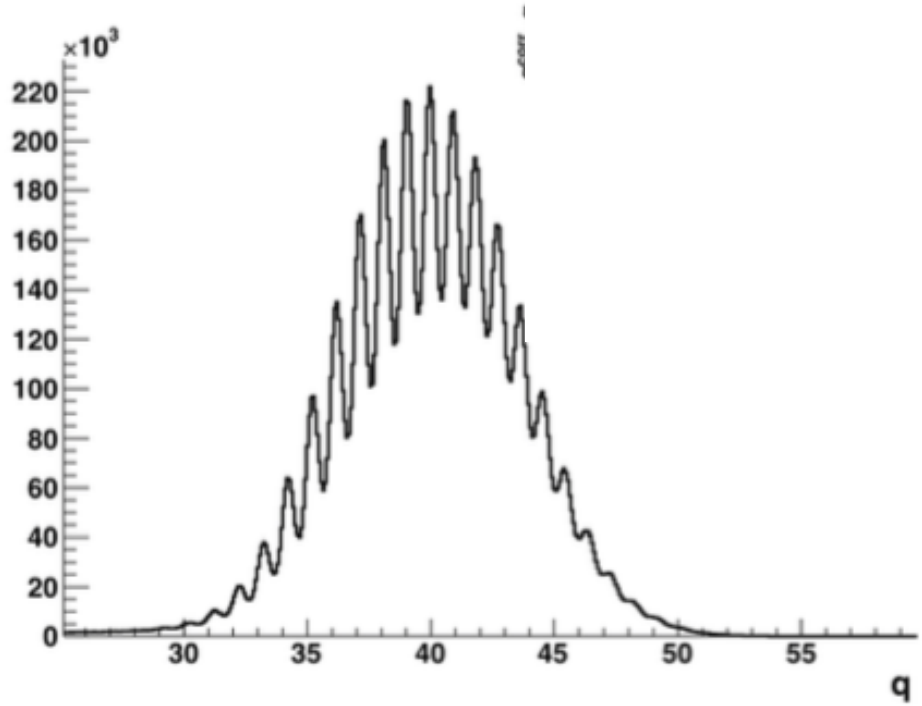
In case of magnetic spectrometer : correction for q-state distribution

$$Y(Z,A) = \sum_q \frac{\partial N_f}{\partial Z \partial A}(q) \frac{1}{\xi(Z,A,E,q)} \int dE \int d\theta$$

Lohengrin : estimated



VAMOS : (large acceptance)
measured



8. Conclusions

Measurement of fission yields is challenging

Standard techniques based on 2E-2v measurements pursue challenging programmes in mass distributions and neutron multiplicities

gamma spectroscopy is a powerful tool for isotopic identification

New innovative techniques based on nuclear-induced fission using spectrometers allow for new-generation data on a wide range (and new range) of actinides

This ensemble of data is challenging and constraining for the development of nuclear fission models