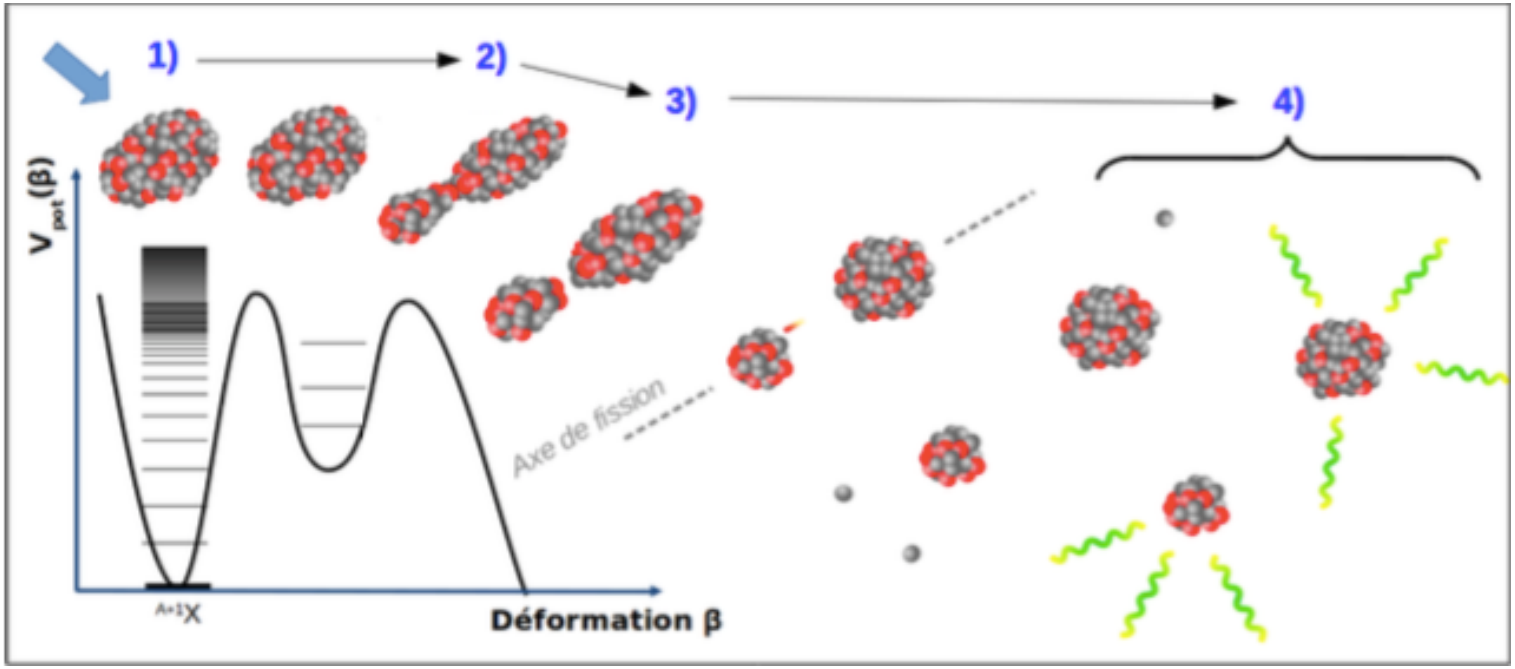
# Experimental Description of Fission Fragment yields

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

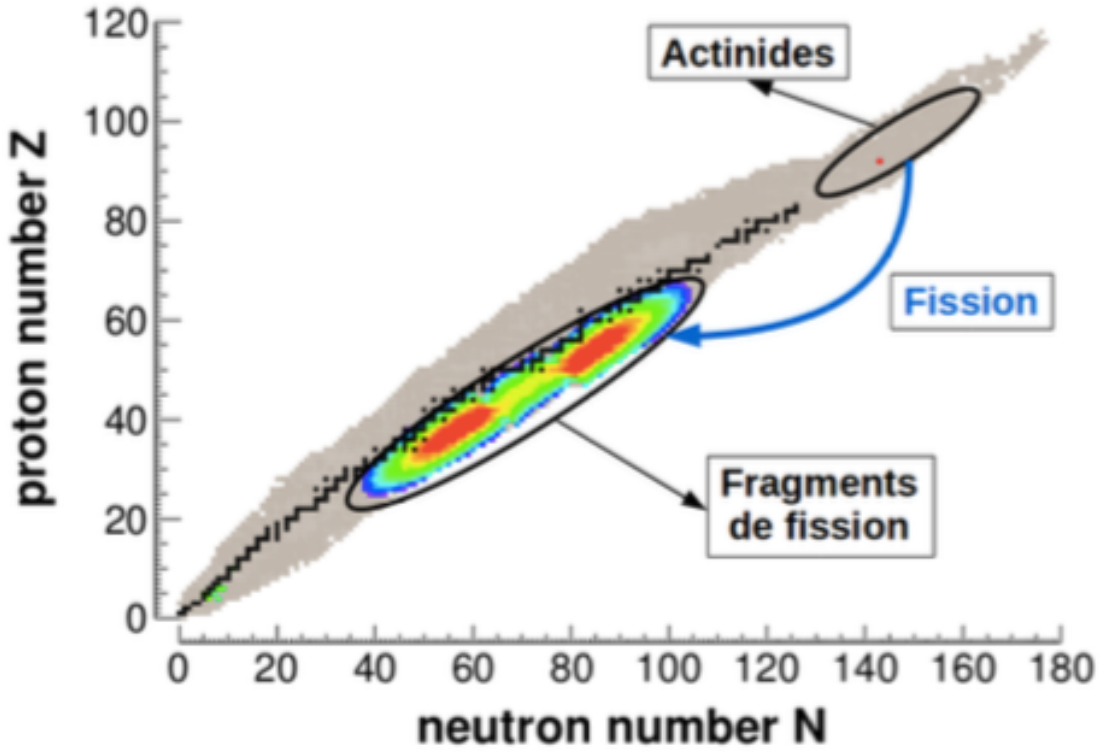
# 1. Fission Process and Fission Yields

Scission point defines the fission fragment properties :

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

# 1. Fission Process and Fission Yields

## Fission Products are radioactive




Independent yields : **before** beta decay

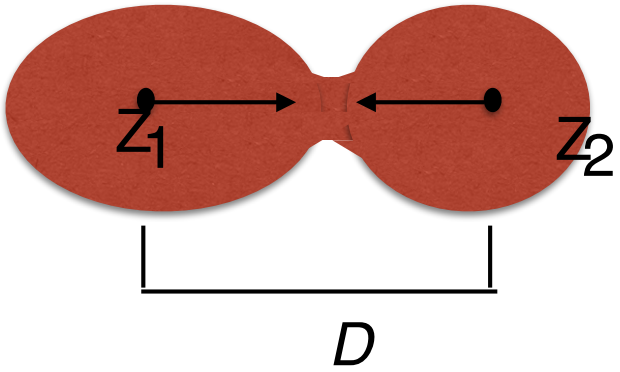
Cumulative yields : **after** beta decay

# 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**

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

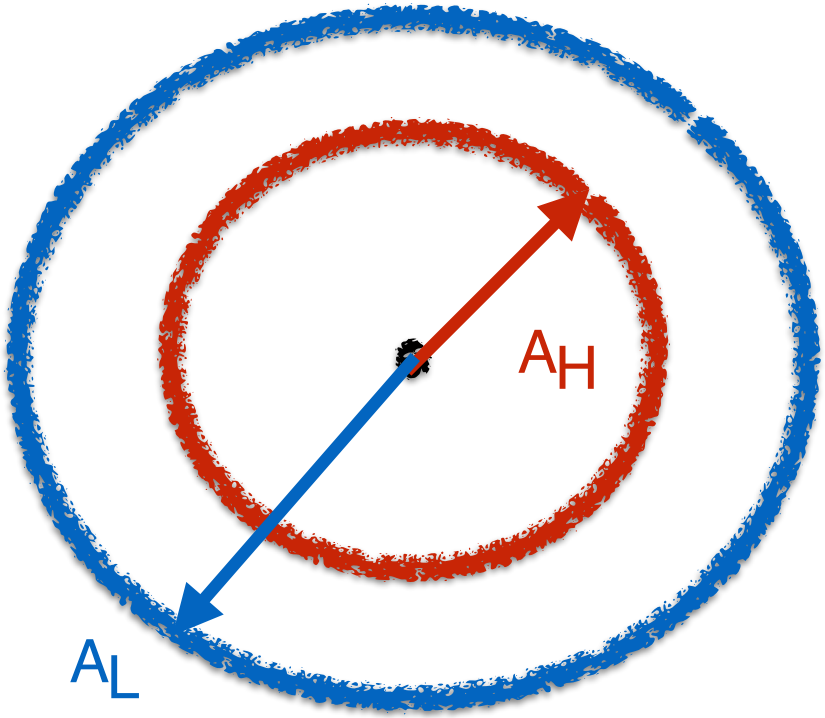
(2;3)
$$E_2 \frac{A_1 + A_2}{A_1} = TKE$$

(3;4)
$$E_2 \frac{Z_1 + Z_2}{Z_1} = TKE$$

# 1.1 Kinematic properties of fission products

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

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

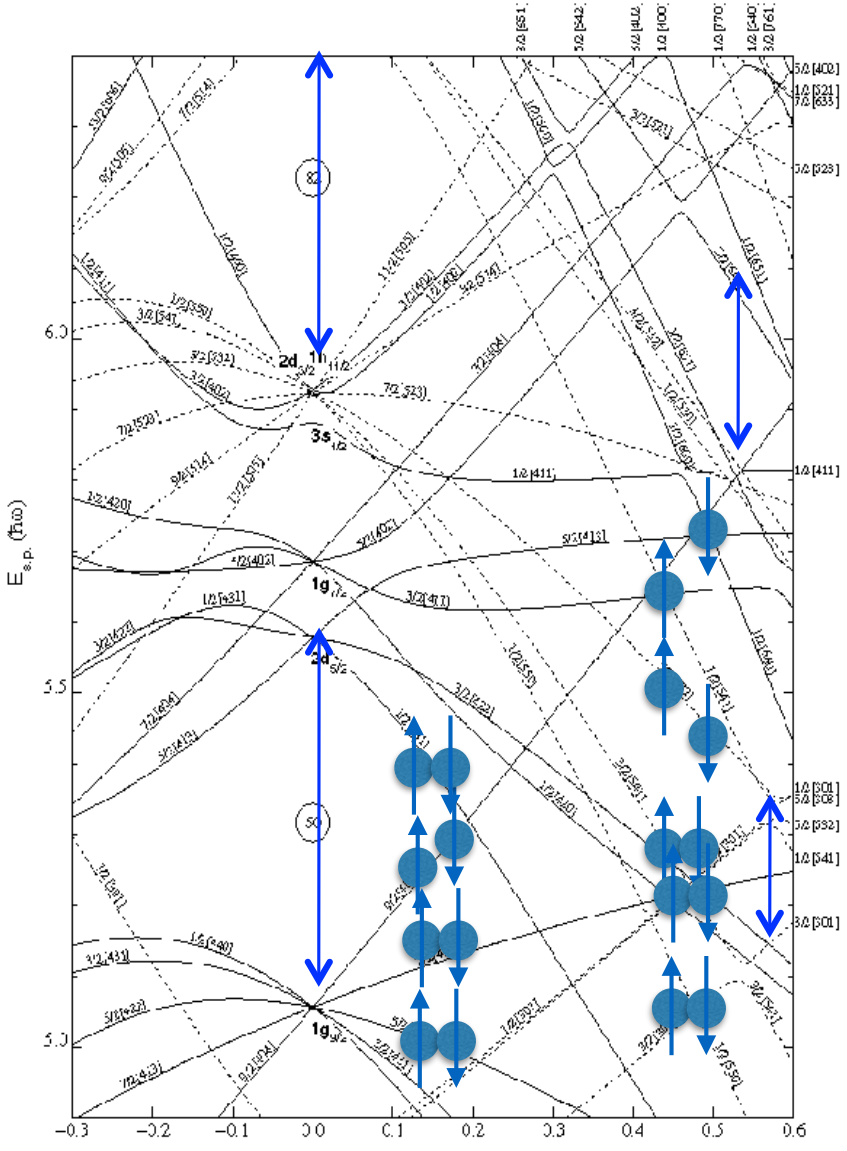


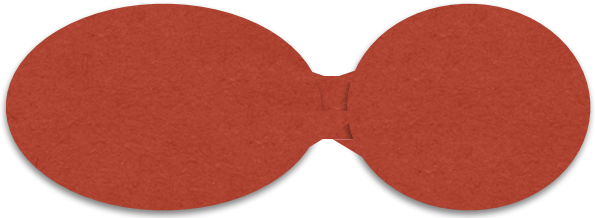

**Light** fragment is **faster**

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

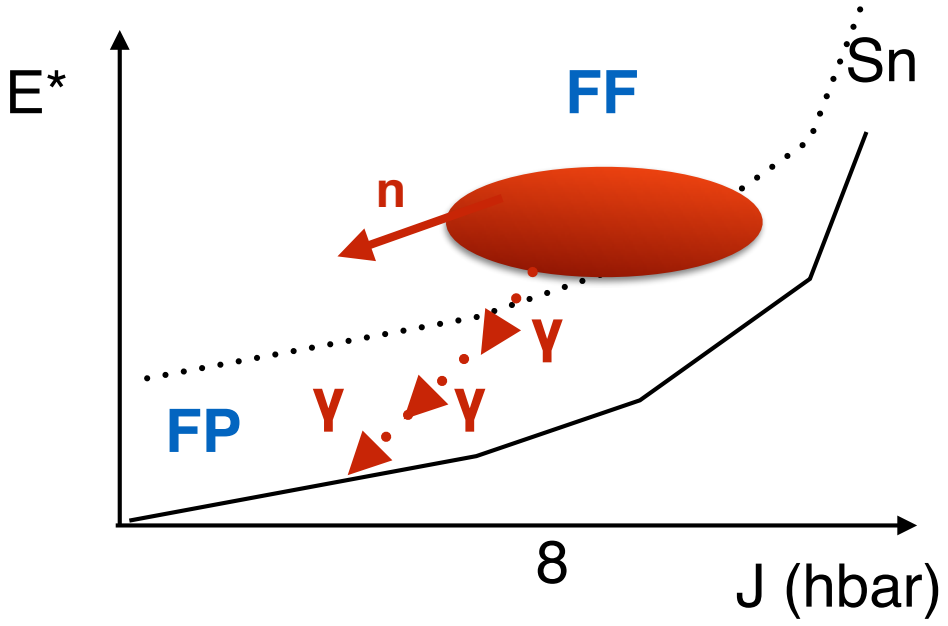
They are emitted in 4 π

# 1.2 fission products : population of excited states



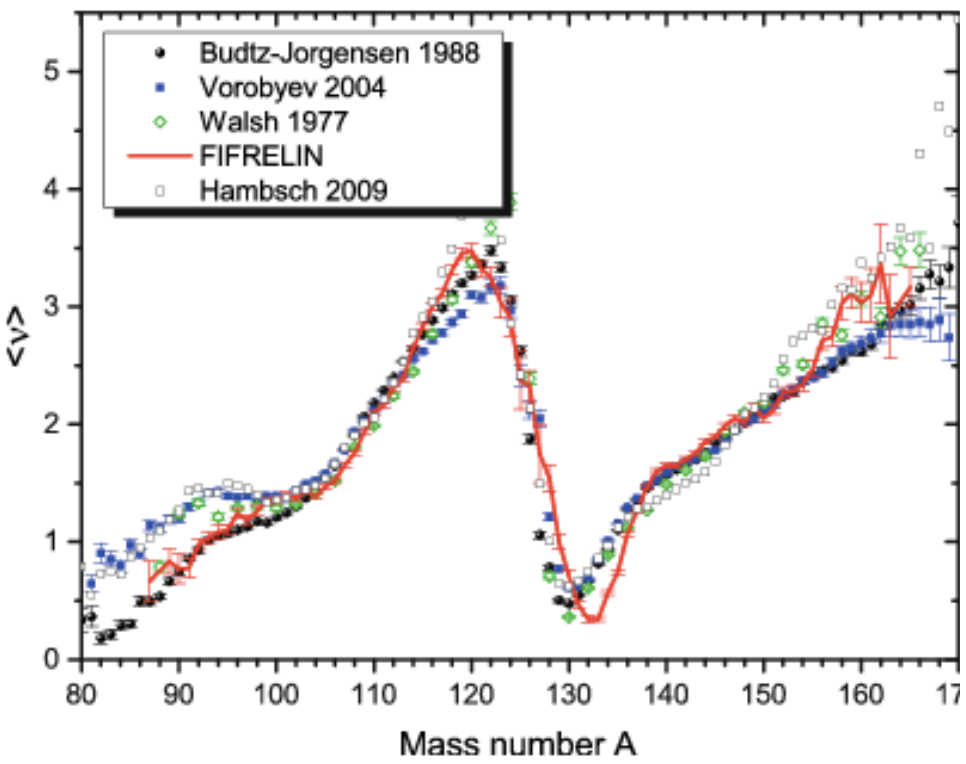



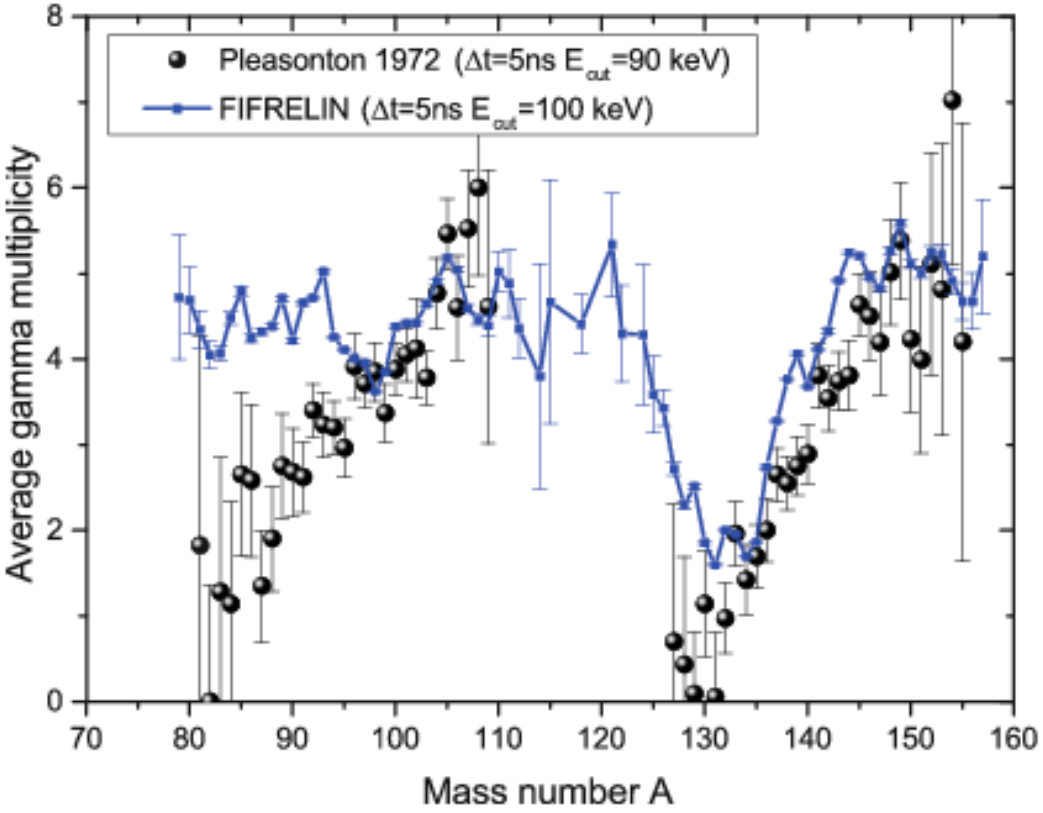
Deformed configuration of fragments at scission:
particle-hole excitation in the level states
Angular momentum and E*



# 1.2 fission products : population of excited states

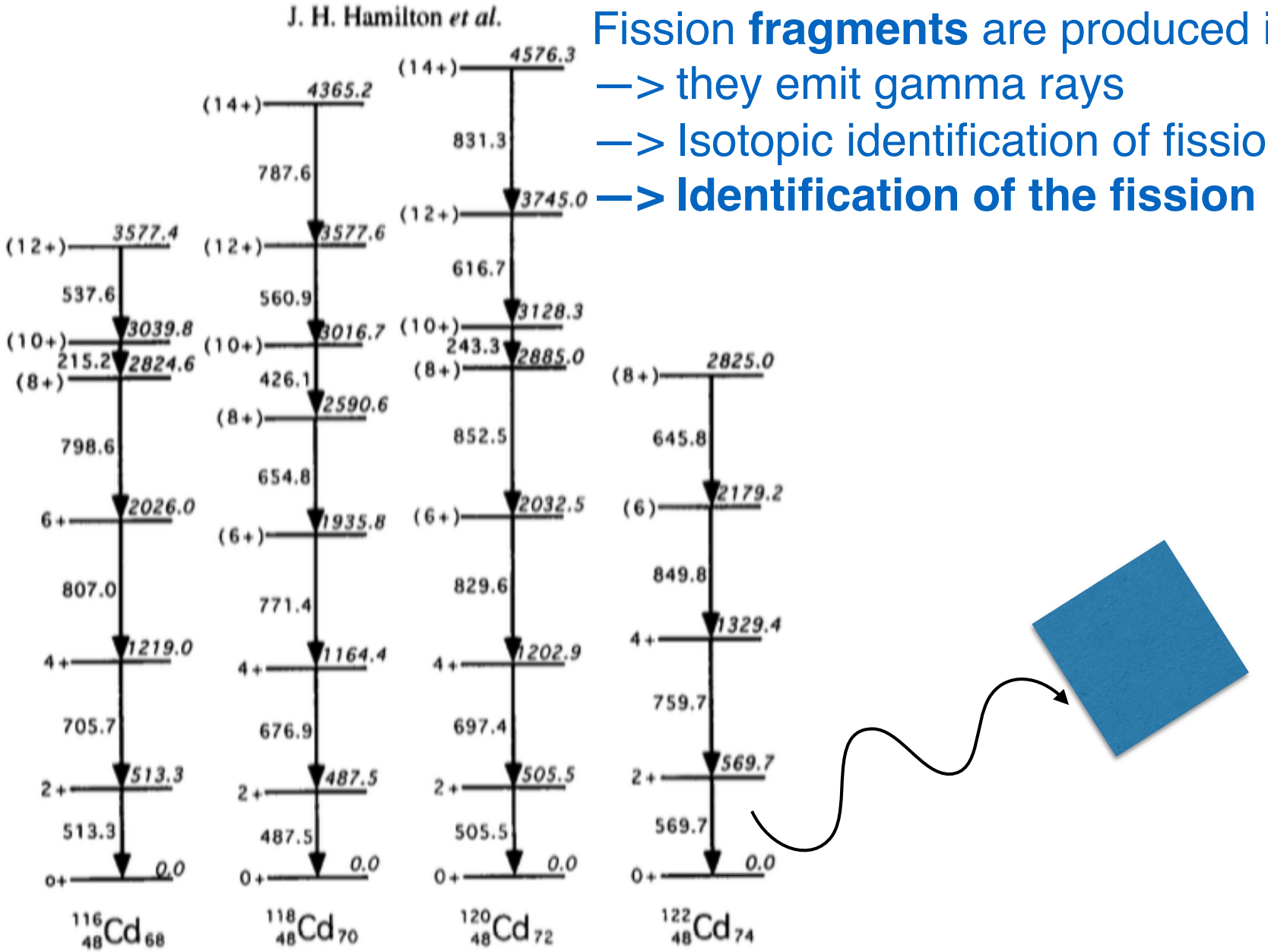
ν(A) and γ(A) :: excitation energy is depending on the sorting




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

# 1.2 De-excitation properties of fission fragments



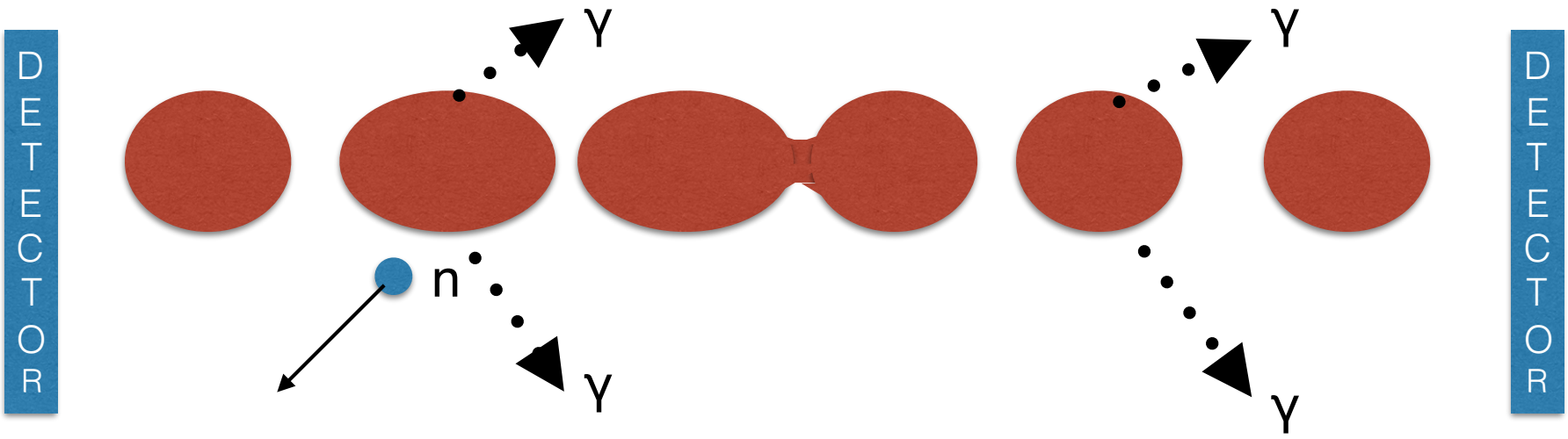

Fission **fragments** are produced in excited states

—> they emit gamma rays

—> Isotopic identification of fission **products**

**—> Identification of the fission products pair**

# 2. Measurements based on kinematical properties




**Fragment** mass identification

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

Momentum and Mass conservation

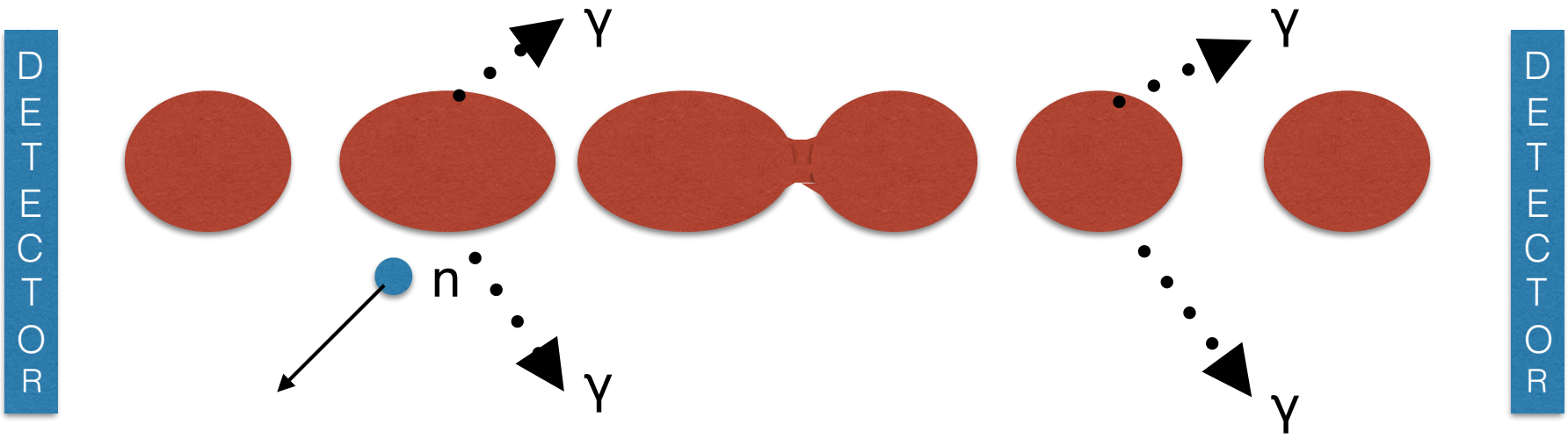
$$A_1^* + A_2^* = A_f$$

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

Isotropic emission of neutrons

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

# 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

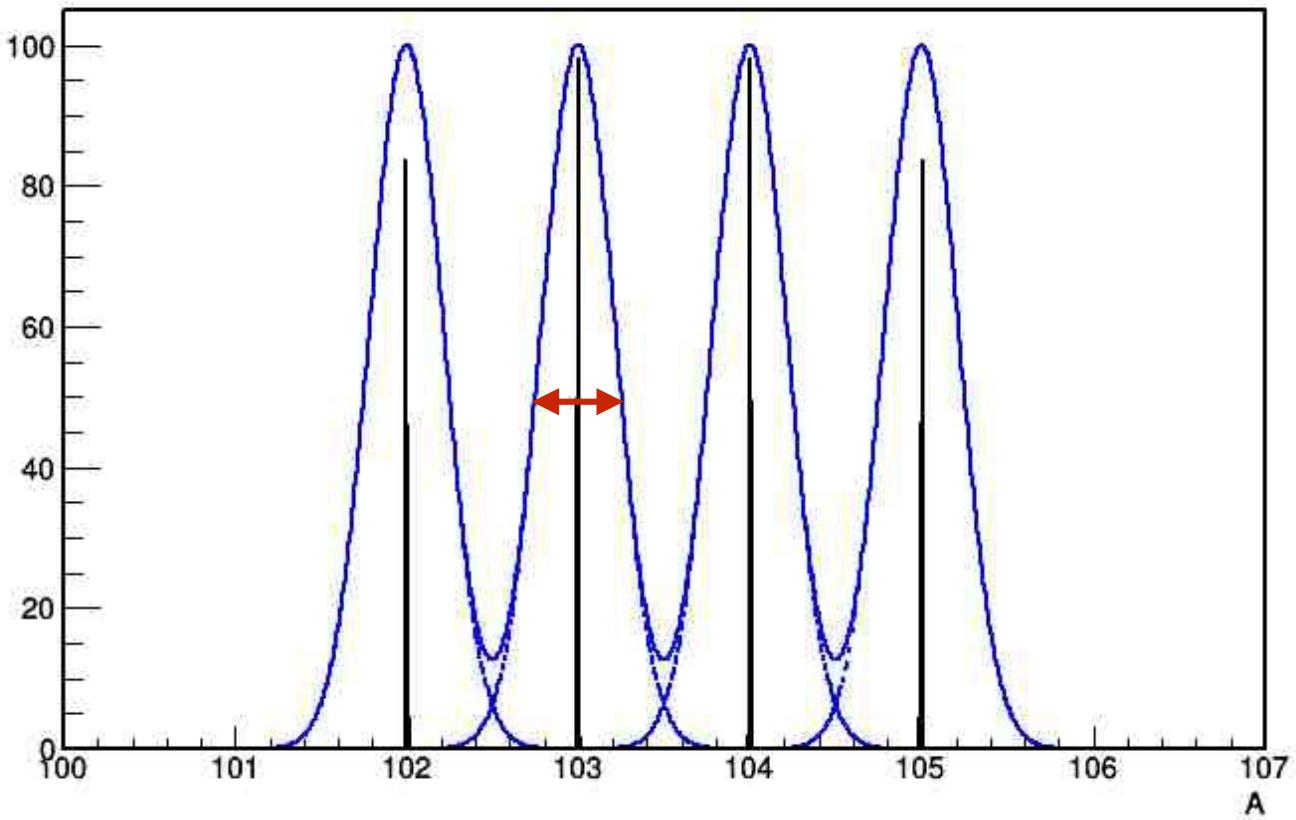
$$A_{1,2} = {}^{2E_{1,2}}\Big/_{2A_{1,2} m_0 \beta_{1,2} c^2}$$

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

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%



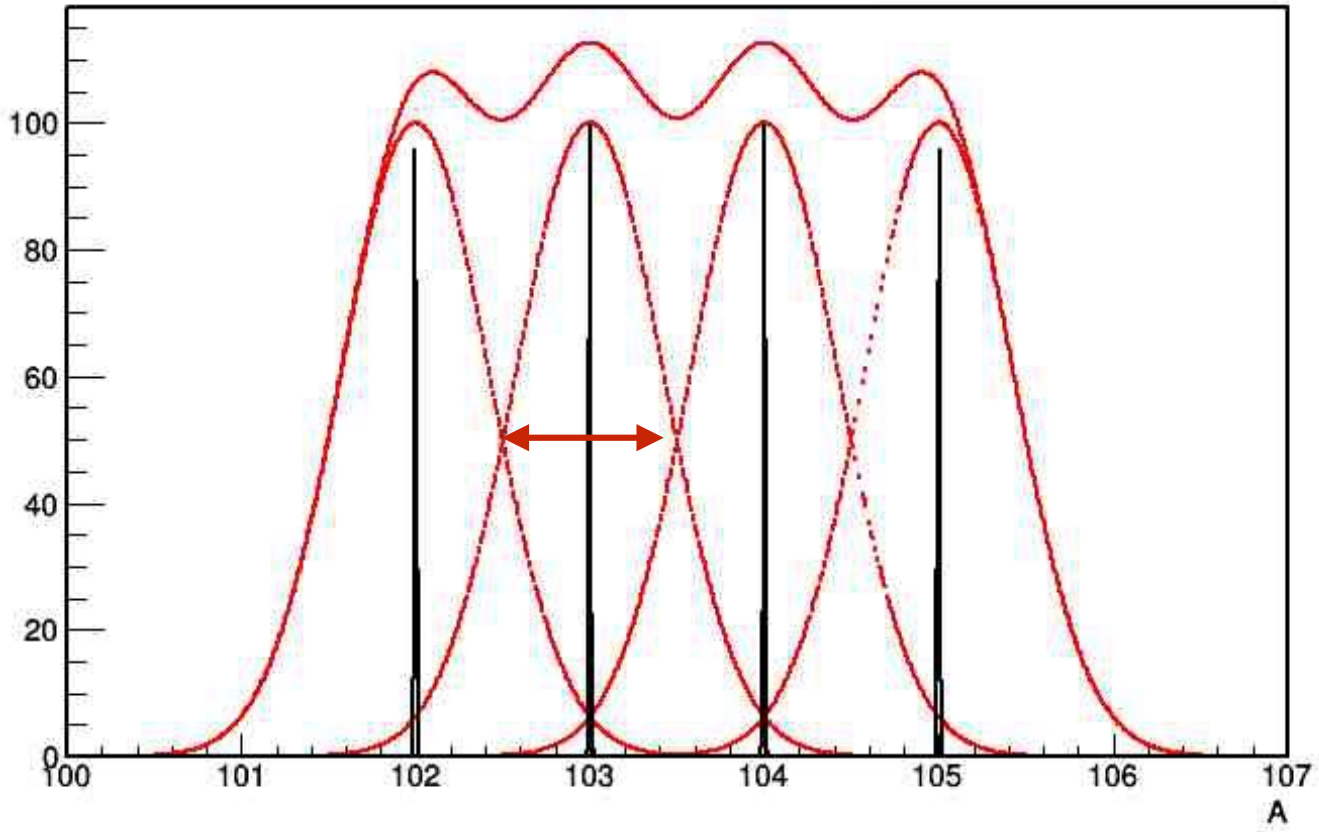

FWHM = 0.5 %

Resolution is important for a better counting

# which resolution ?

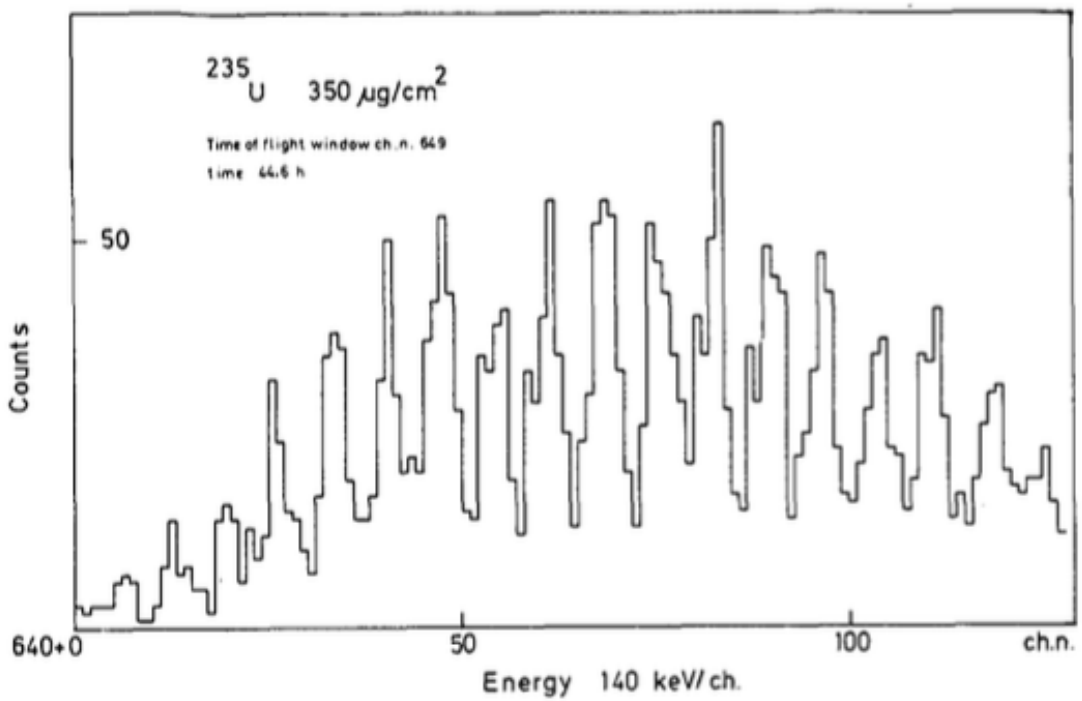
DA/A ~1 :: Resolve A ~ 100
DA/A ~0,5 :: Resolve A~200

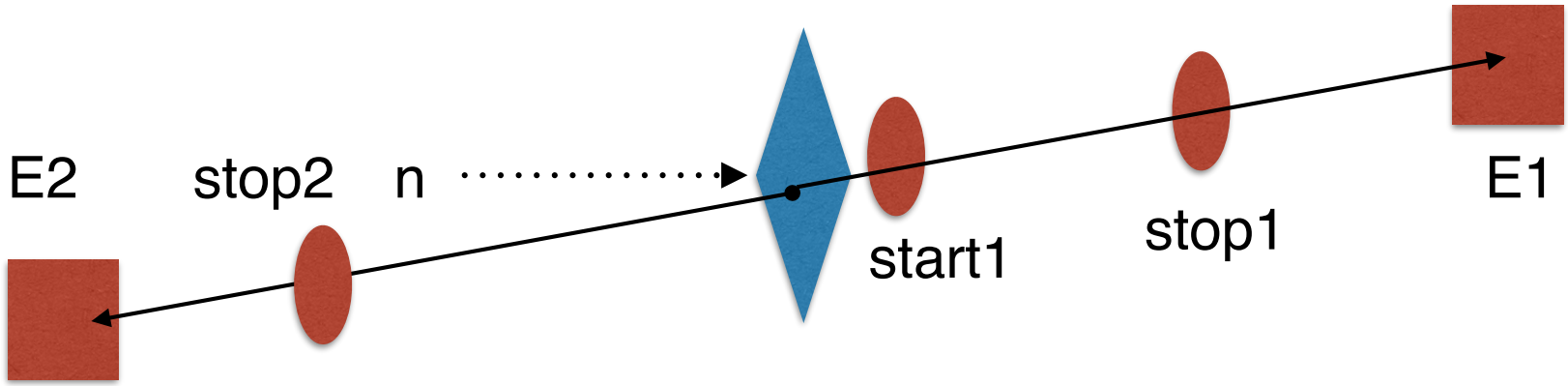
FWHM = 1 %



# 2.1 Energy and Time-of-Flight based experiments

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



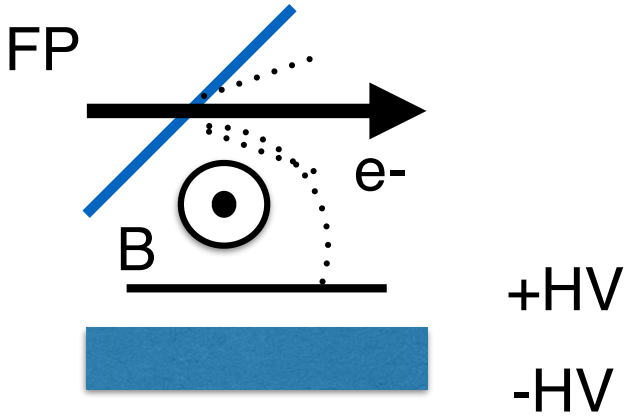




BEST : 0,6% in COSIFANTUTE, ILL, 1980

# Time-of-Flight measurement

Minimum layer
Fast timing

Secondary electron detectors

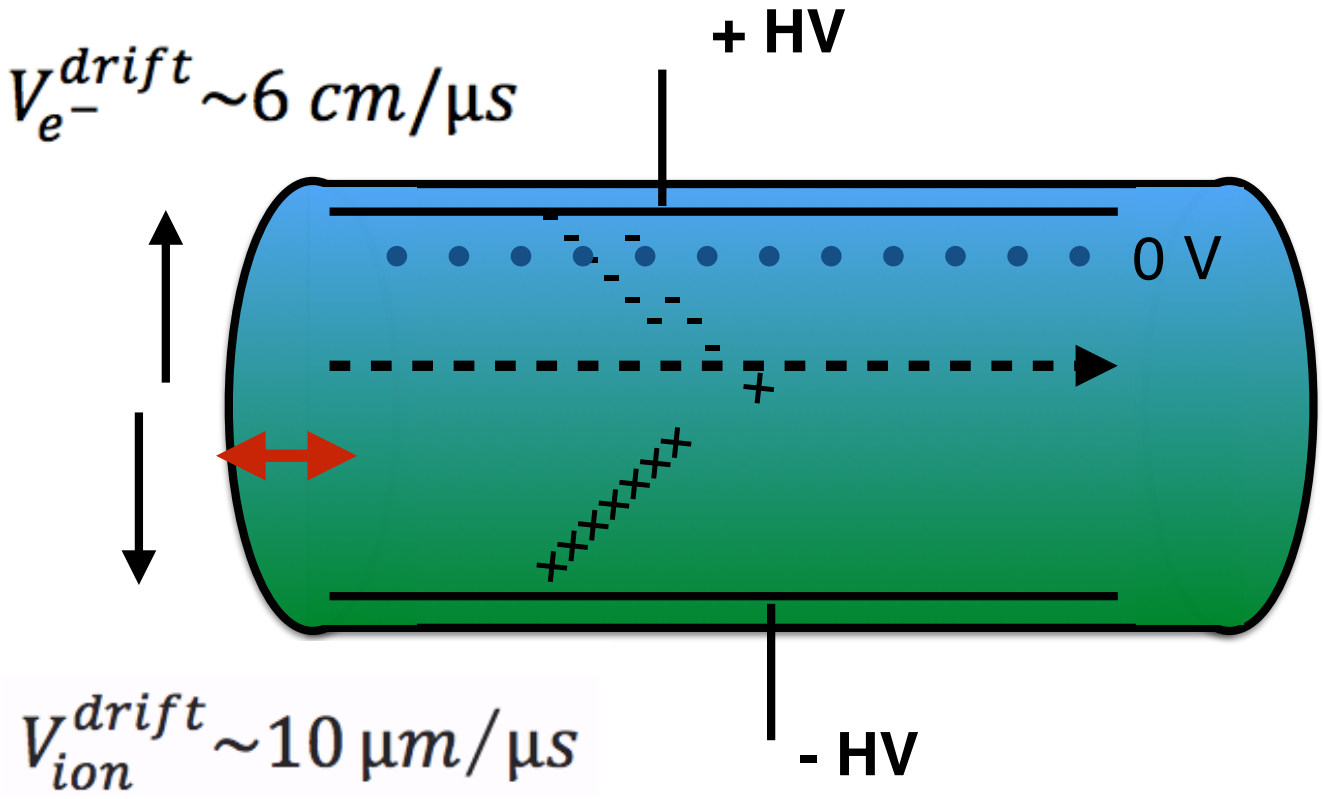



MICRO-CHANNEL PLATE

MULTI-WIRE PROPORTIONAL COUNTER

Typical resolution 150ps to 200ps; Typical flight path 50ns dT/T ~4‰

# Energy measurement in Ionisation Chambers




$$N_e\text{-}W_e = \Delta E$$

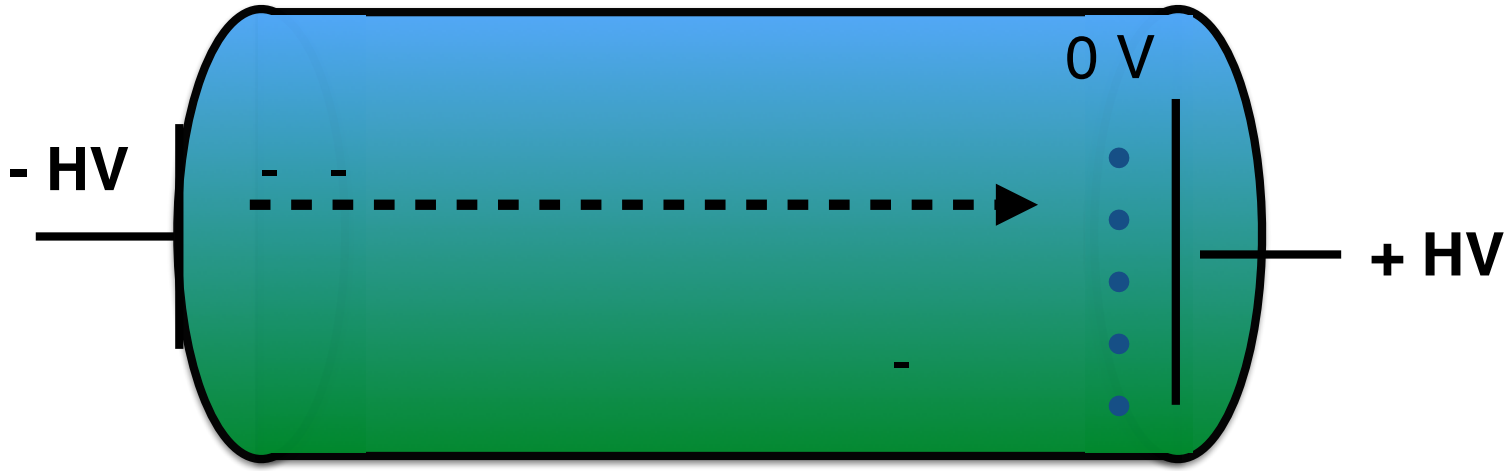
$$W_e \sim 15eV$$

$$N_e\text{-} \sim 10^7$$

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

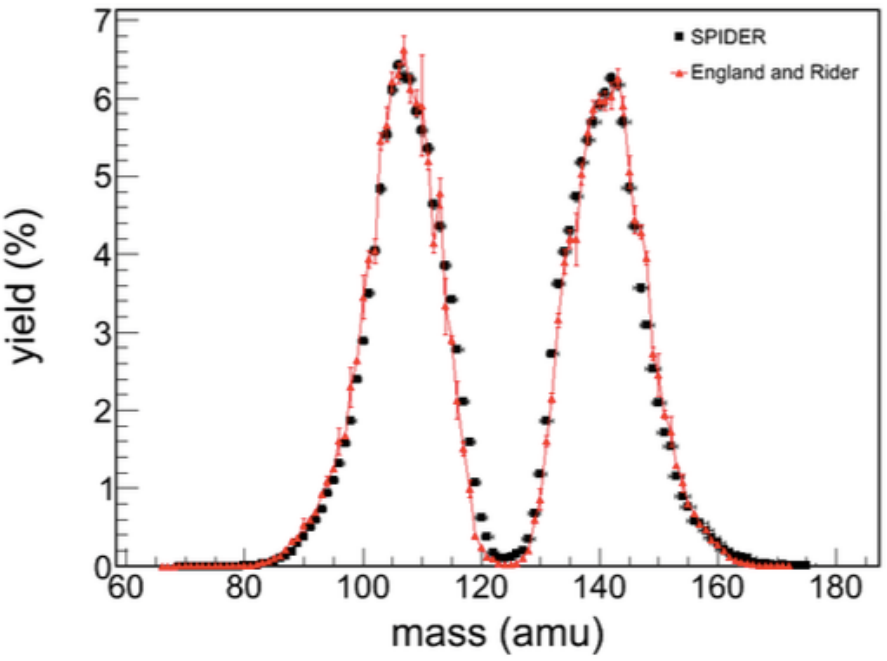


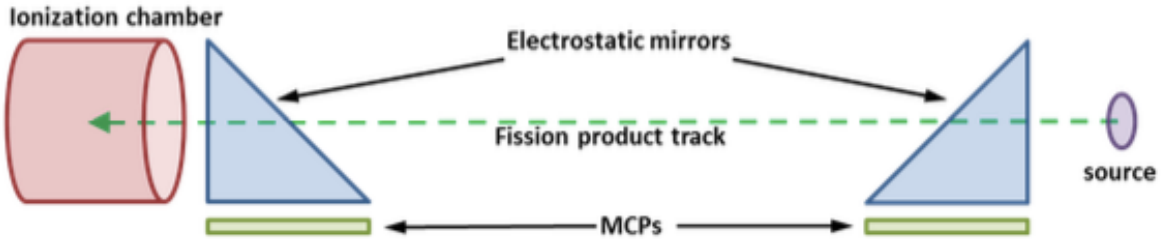

In axial chamber, all electrons are collected on the anode
Energy-loss collection with 1‰ precision
Electronics (noise and amplification) limits to the percentage limit

# 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)



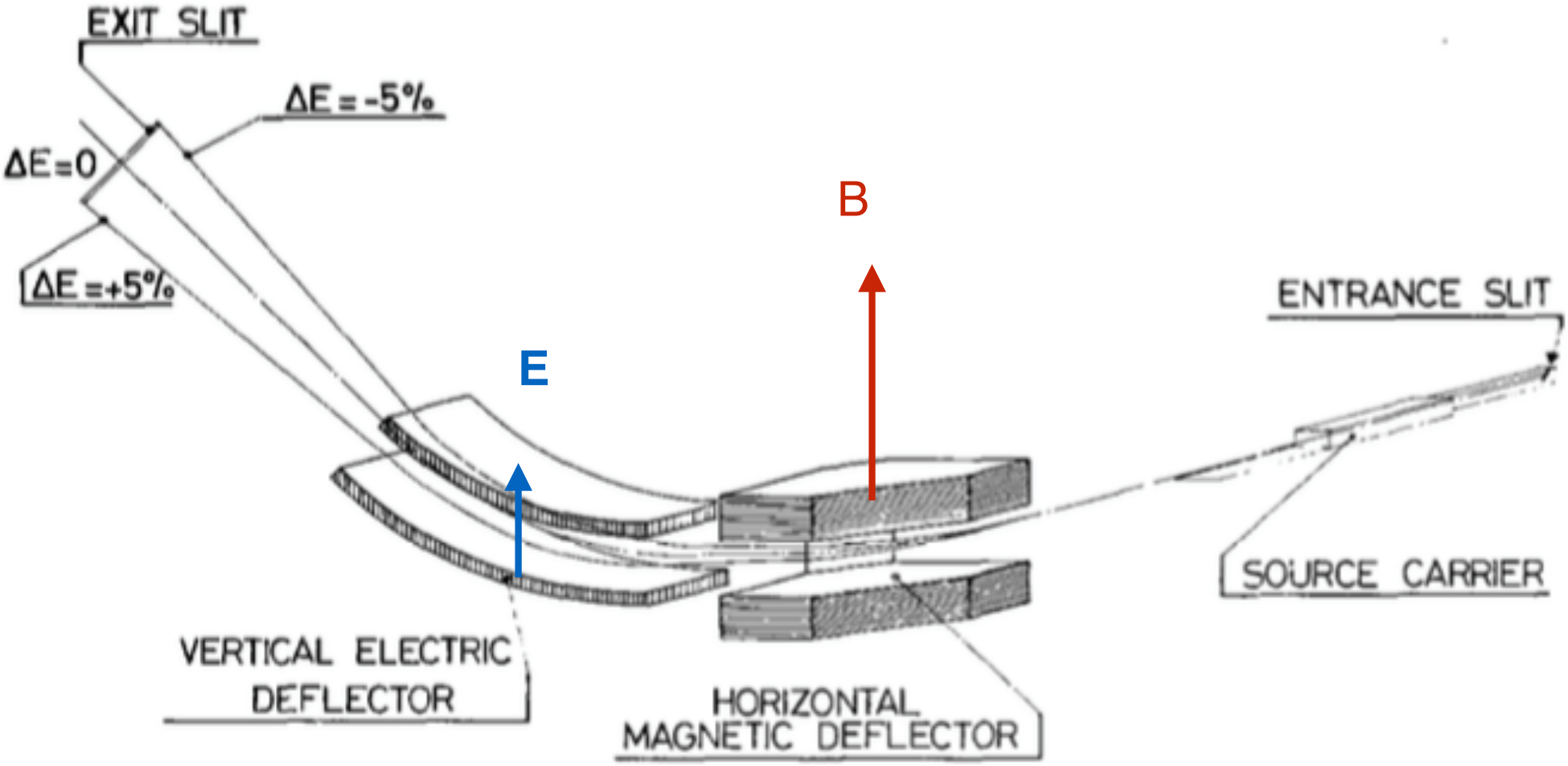




K. C. Meierbachtol, F.K.E Tovesson et al. LA-UR-15-20101

# Rigidity-based experiment

## LOHENGRIN spectrometer

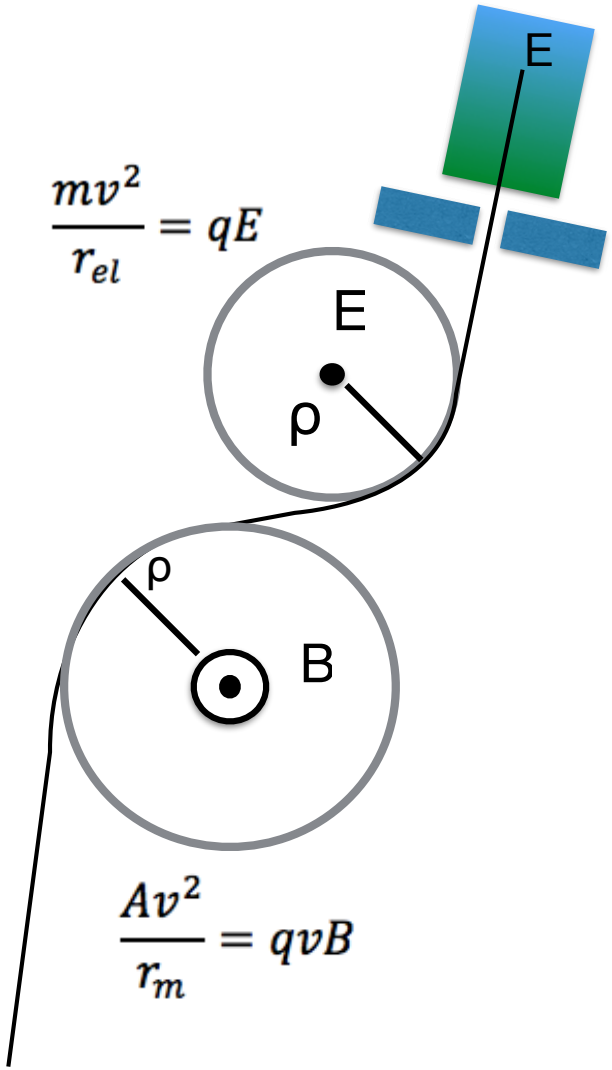
No ToF measurement !



# Rigidity measurement : Lohengrin

$$E_k = \frac{1}{2}mv^2$$

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



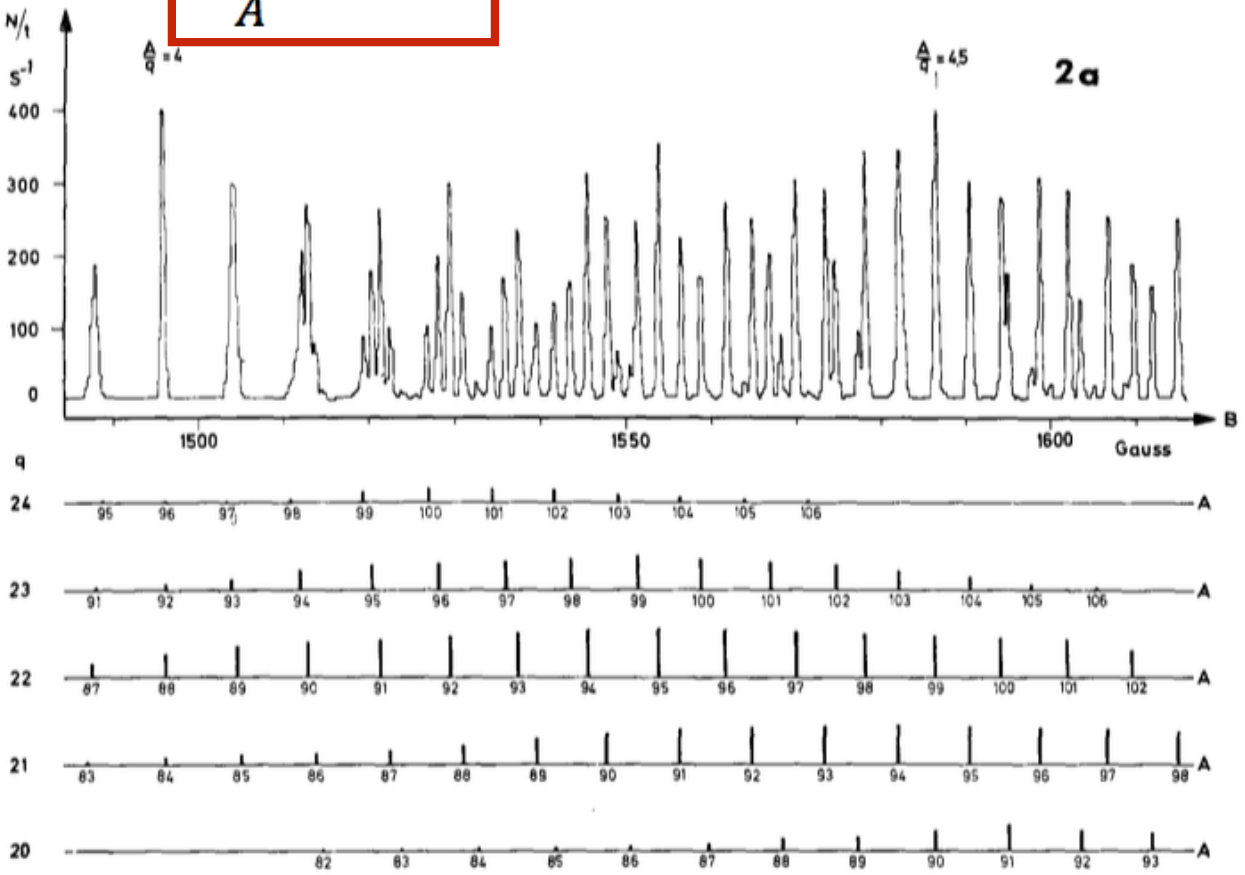

$$\frac{Av^2}{r_m} = qvB$$

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

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

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

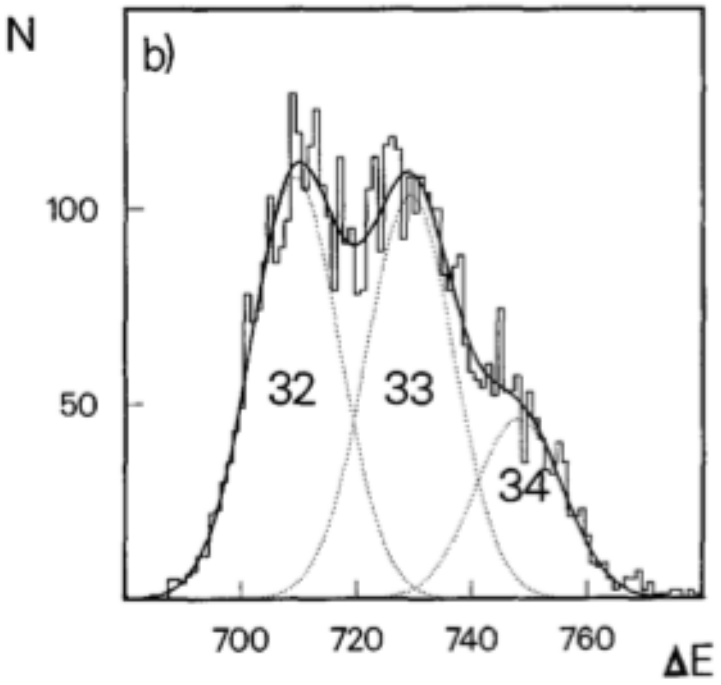
$$\frac{\partial A}{A} \sim 0.01\ \%$$



# 3. Atomic Number identification

## Energy loss in ionisation chamber

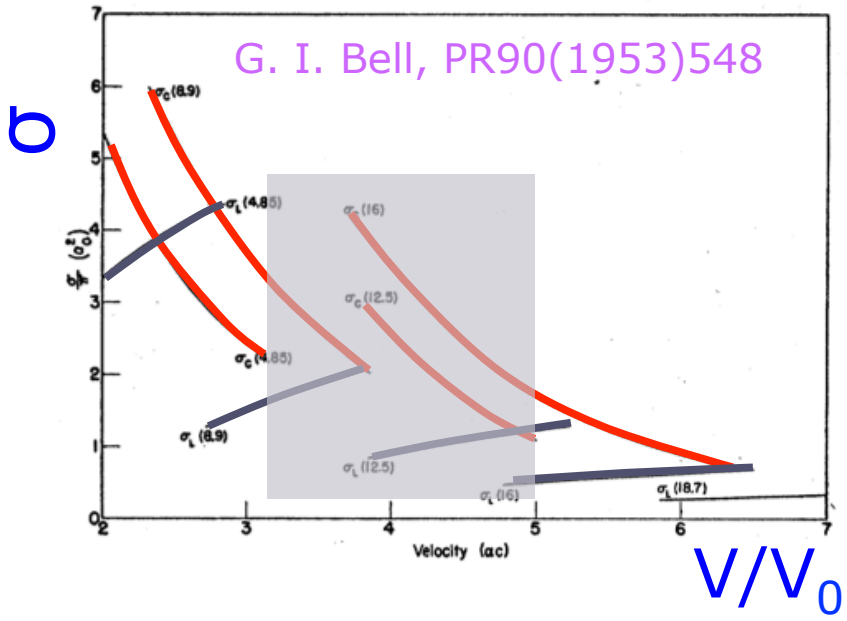
$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{q^2}{\beta^2}\left[\ln\left(\frac{2m_e\gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right]$$

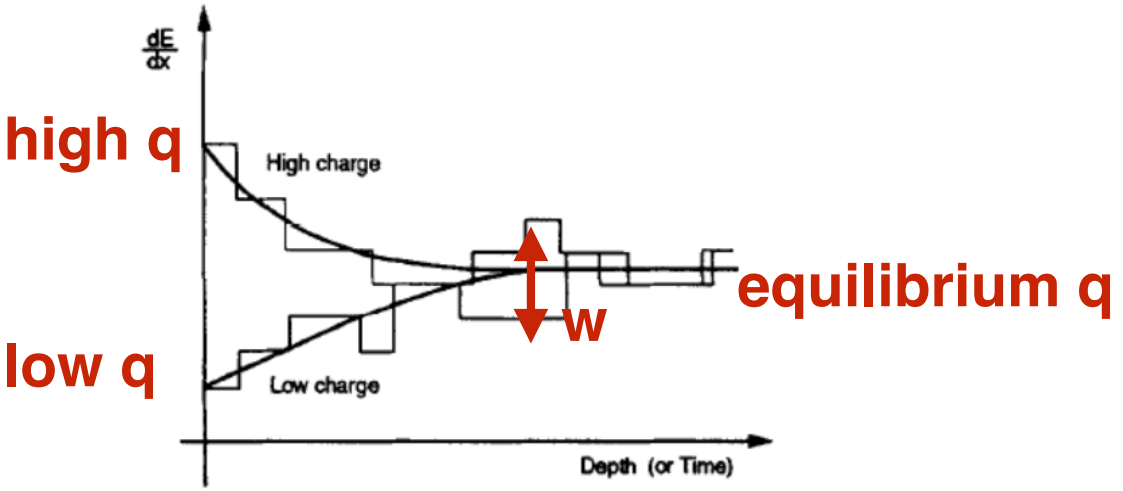



Fission products
have a broad q-state distribution
—> energy-loss resolution is limited

## Energy-loss of ion in material

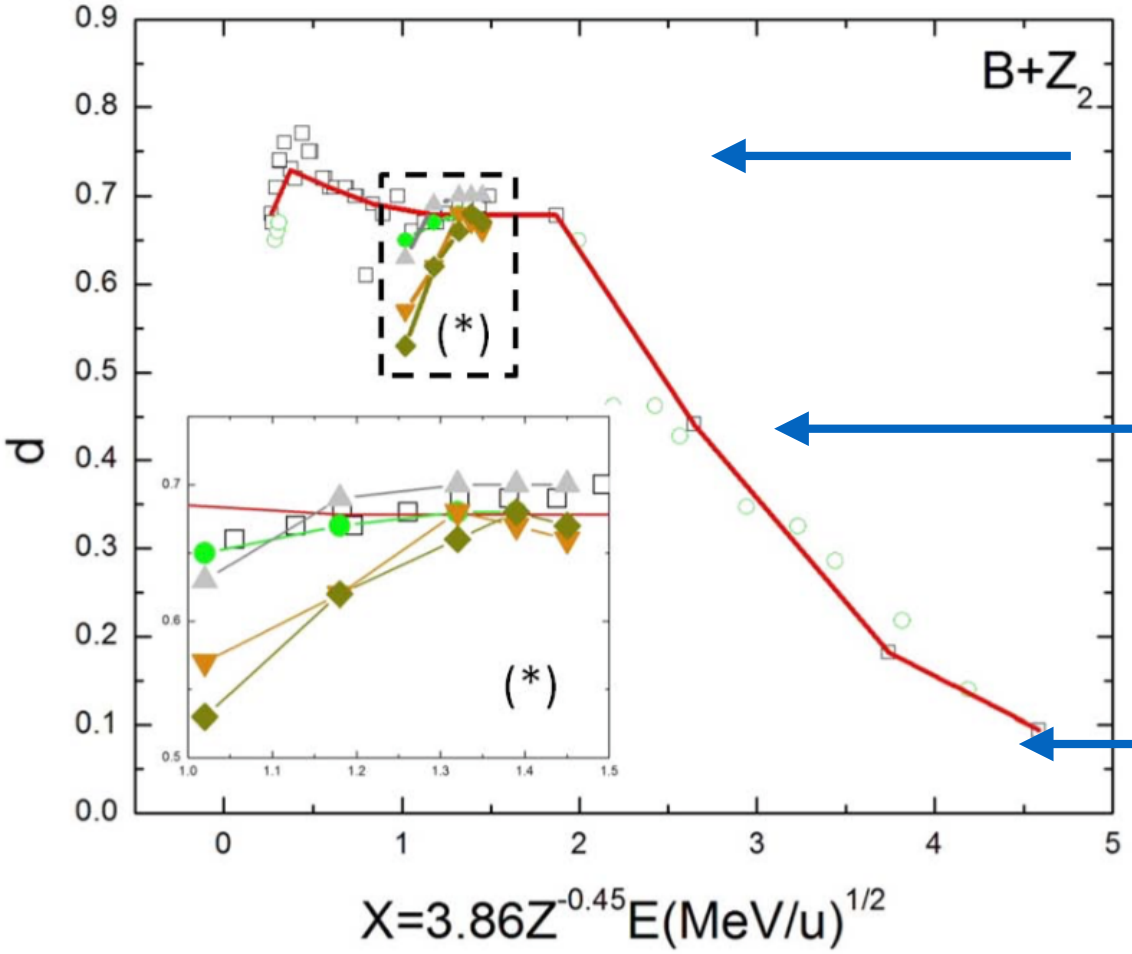
Energy-loss prop. to ionic charge state
Electron loss and capture cross sections depend on ion energy :



# ionic charge dispersion diminishes with energy

w



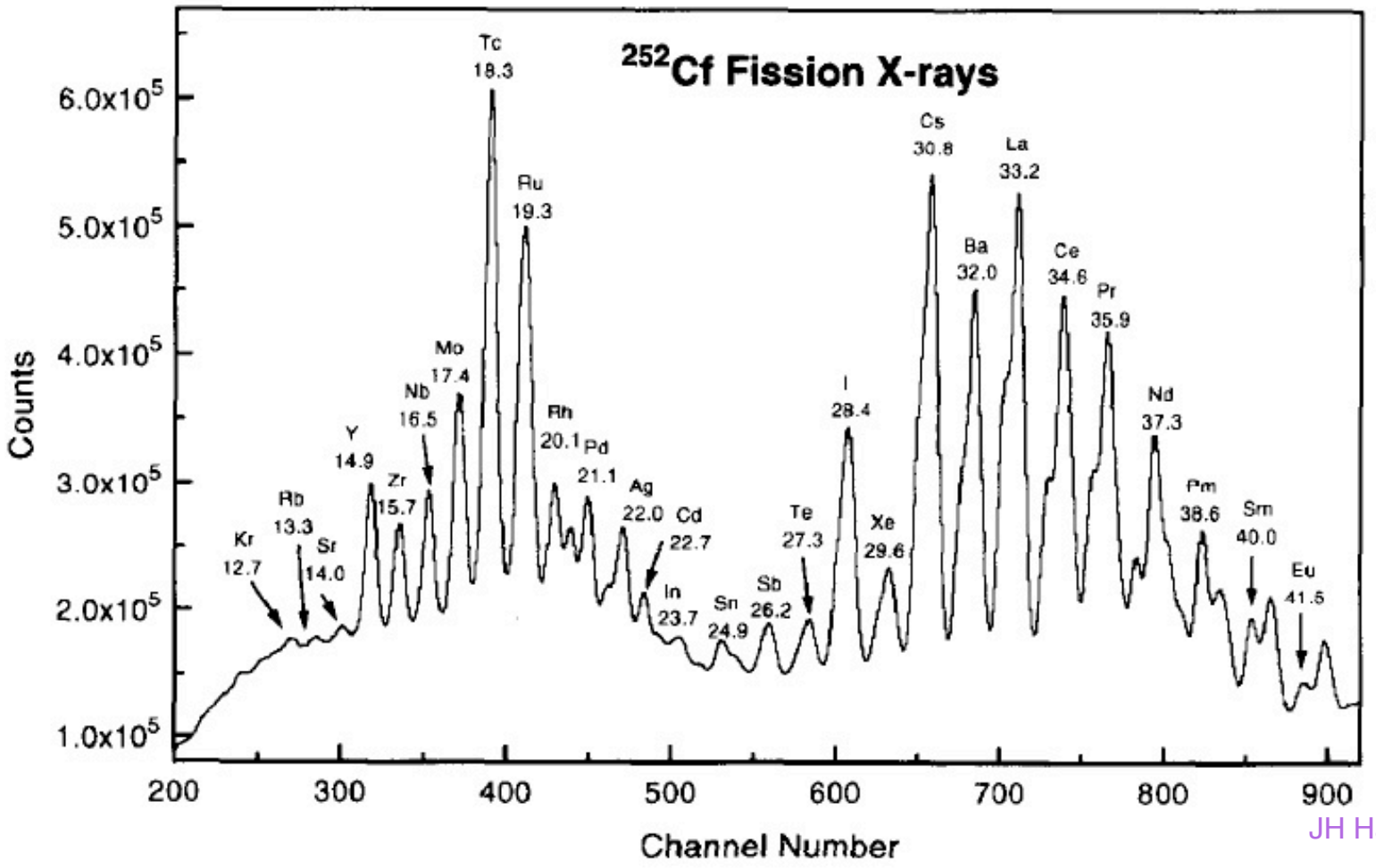

Z= 50 E = 1MeV/u

Z= 50 E = 10 MeV/u

Z= 50 E = 100 MeV/u

# Atomic Number identification

## Detection of X-rays



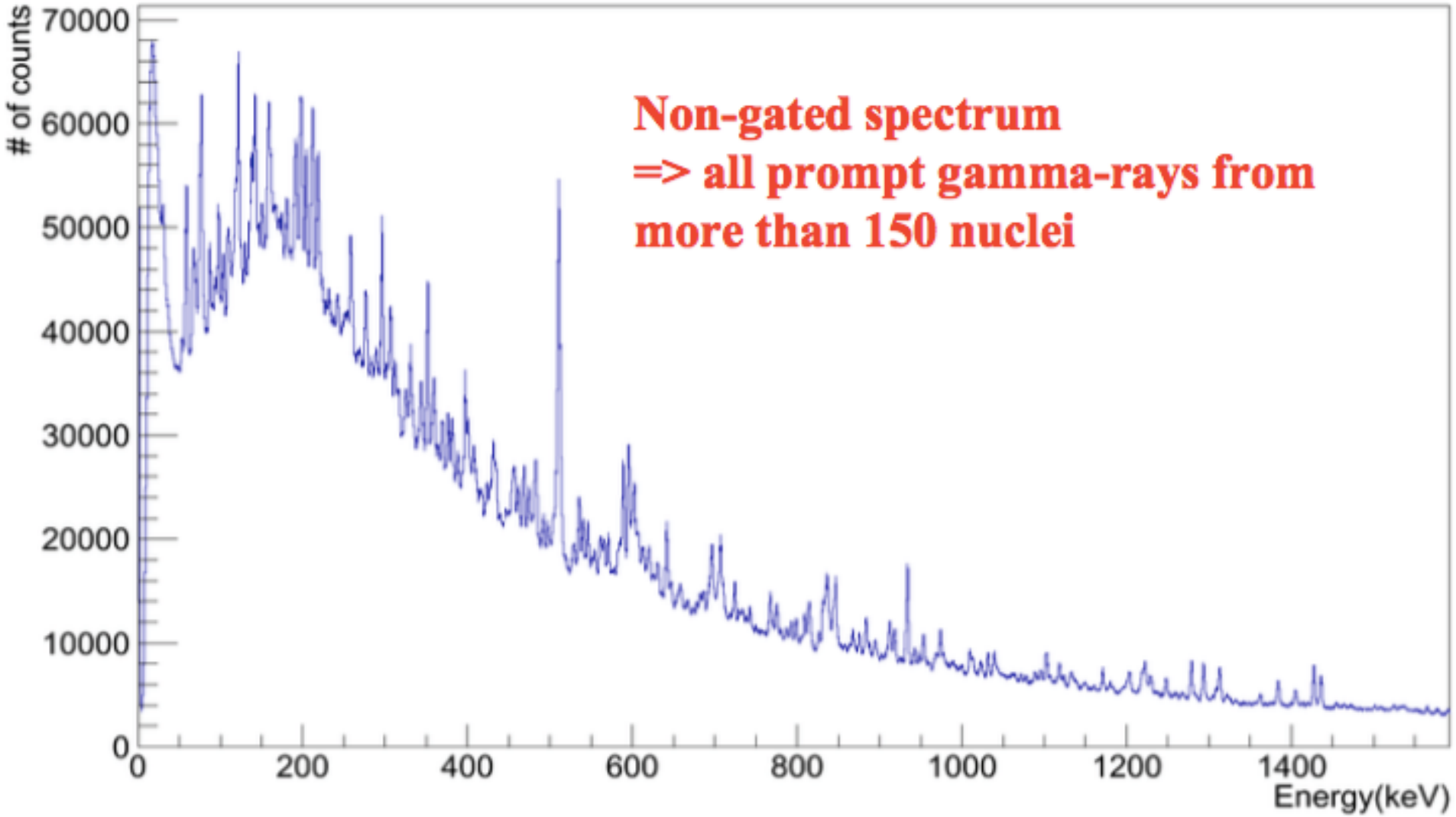

JH Hamilton Prog. Part. Nucl. Phys. 35

small detection efficiency —> Difficulty to connect with mass distribution

# 4. Isotopic identification from gamma spectroscopy

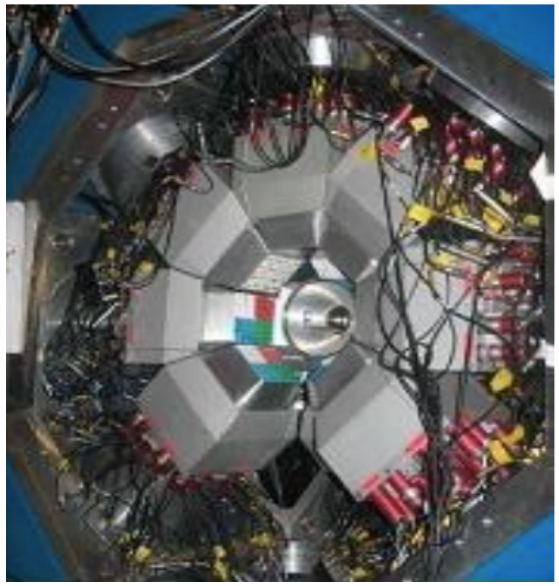
Fission products may be identified unambiguously from their γ-ray emission

Difficulties : Large background from beta decay

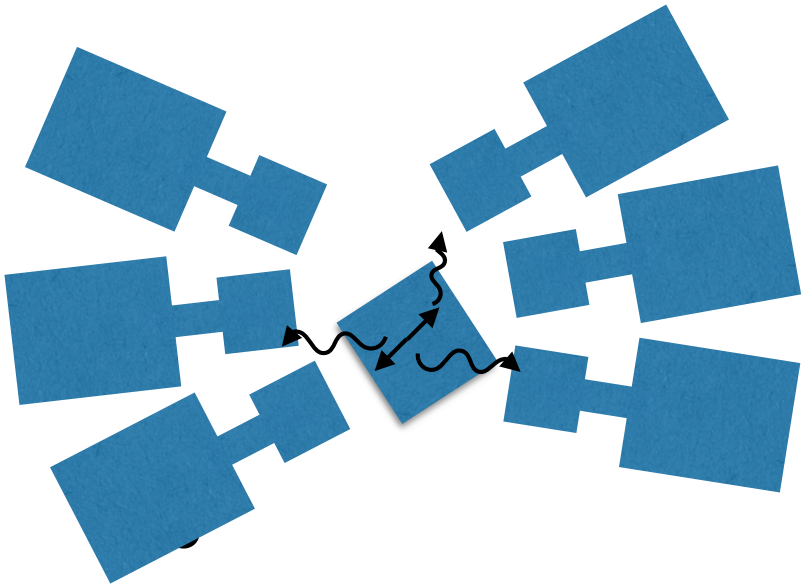


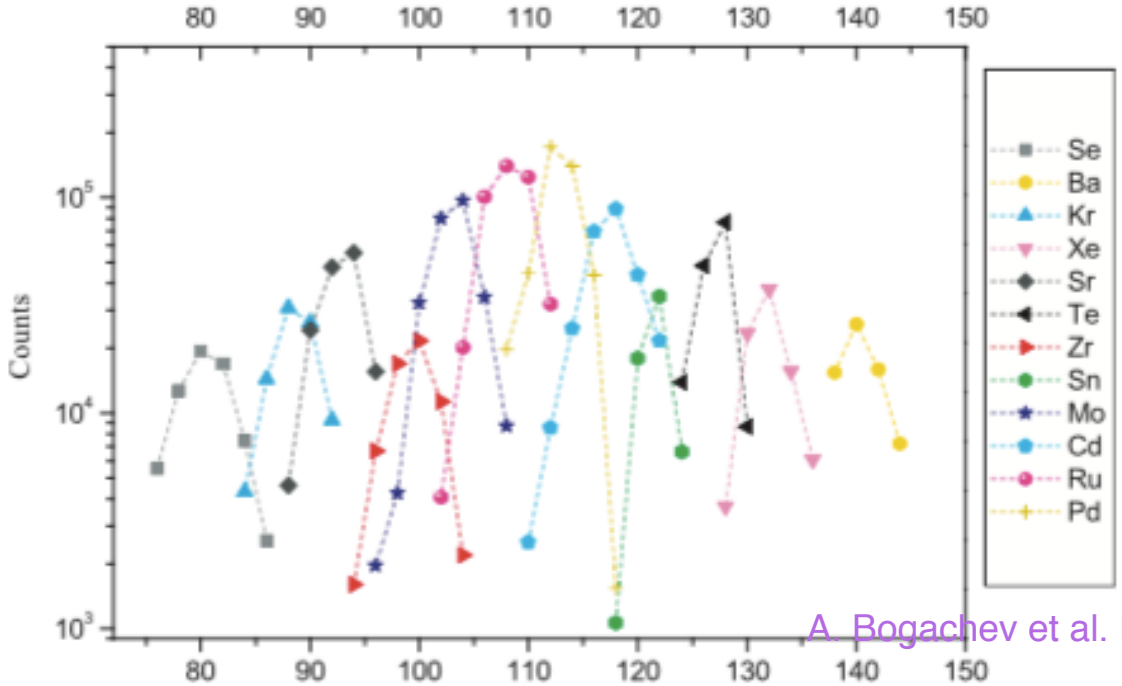
# Isotopic identification from gamma spectroscopy

γ-γ technique :



EXILL, ILL





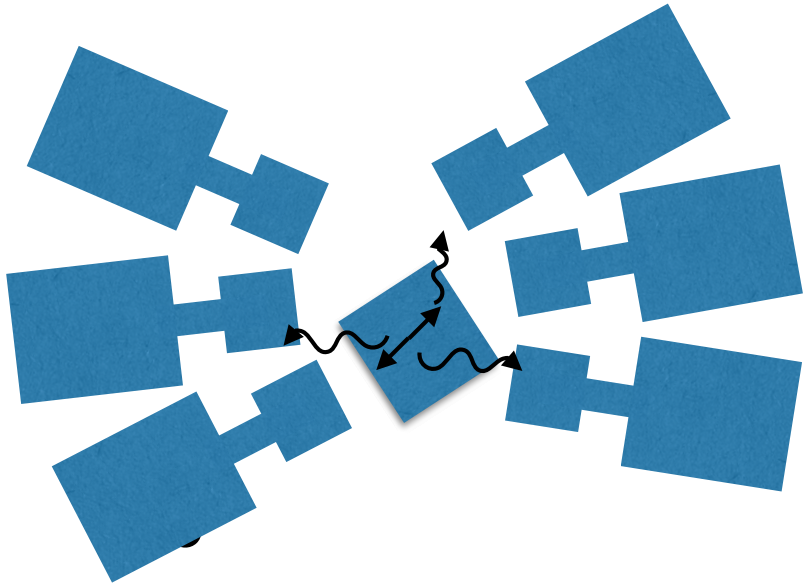

A. Bogachev et al. EPJA 34(2007)

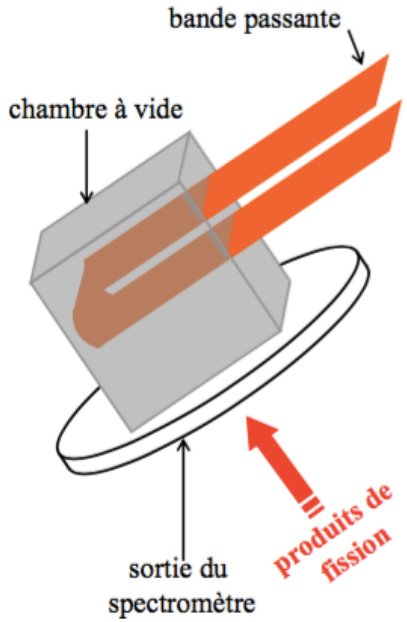
# 4. Isotopic identification from gamma spectroscopy

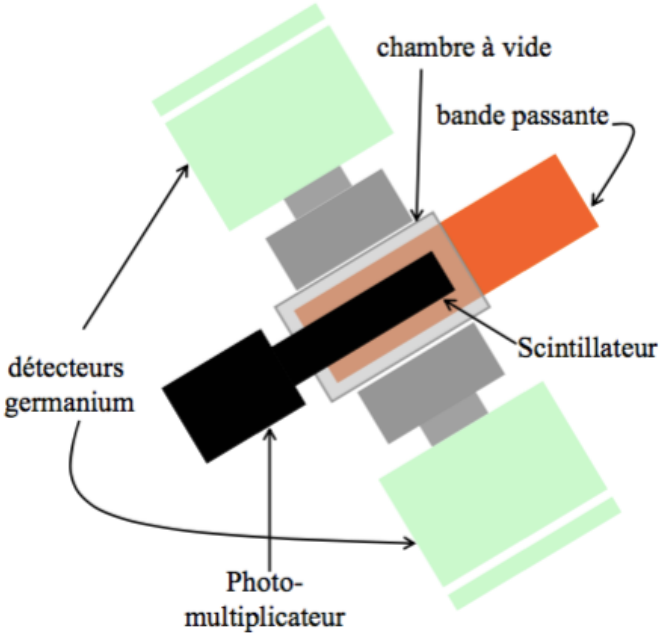
## To fight against background :

— larger number of detectors (γγγ technique)
— external trigger experiment
(fast ionisation chamber —> thin target)

— βγ coincidence experiment
( access to cumulative yields)





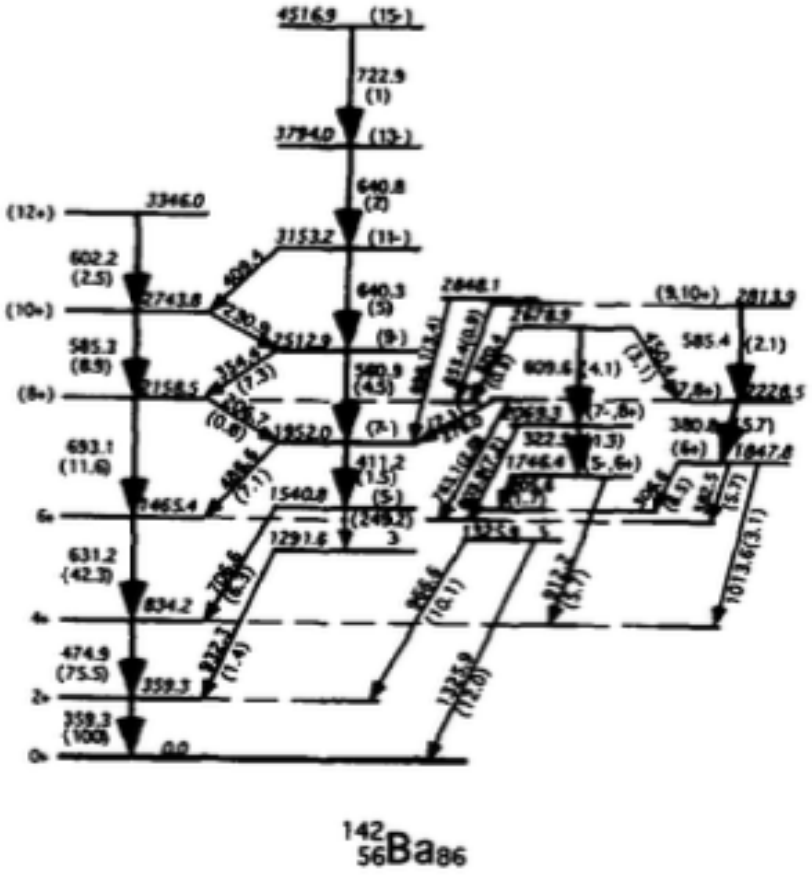



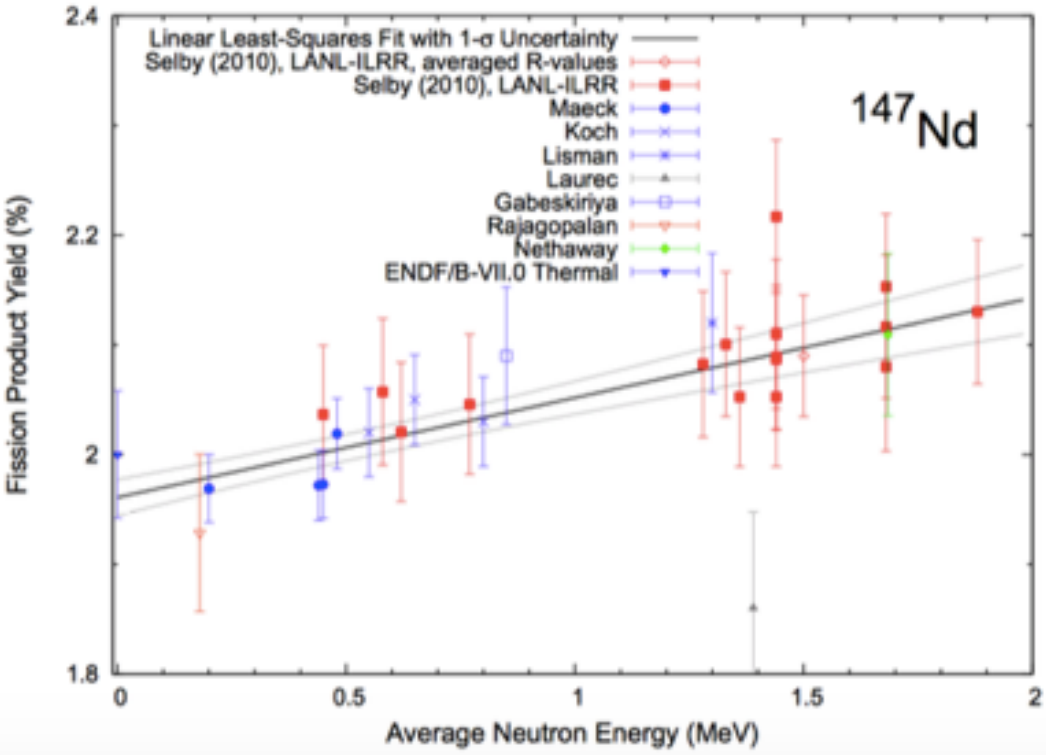

A. Bail PhD, 2009

# 4. Isotopic identification from gamma spectroscopy

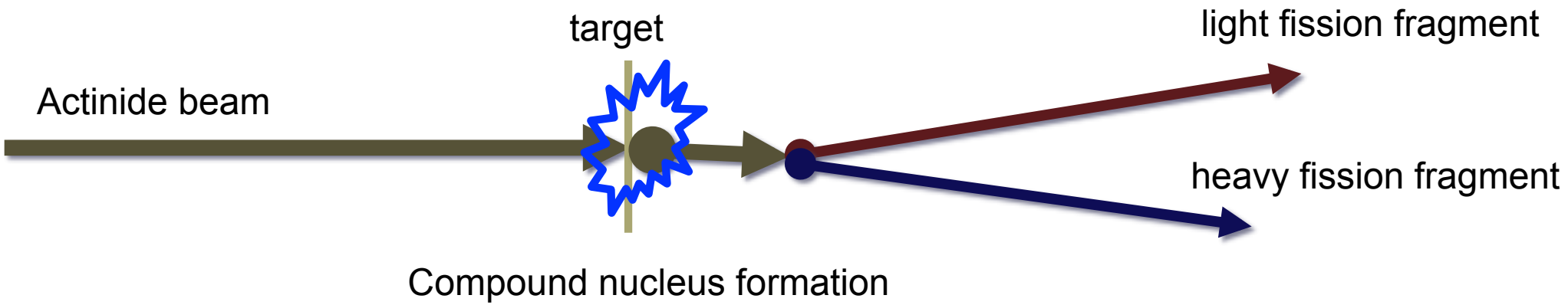
Difficulties to deduce yields : strong fragmentation of the decay path

==> Difficult measures !!



# Inverse kinematics : need for accelerator complexe



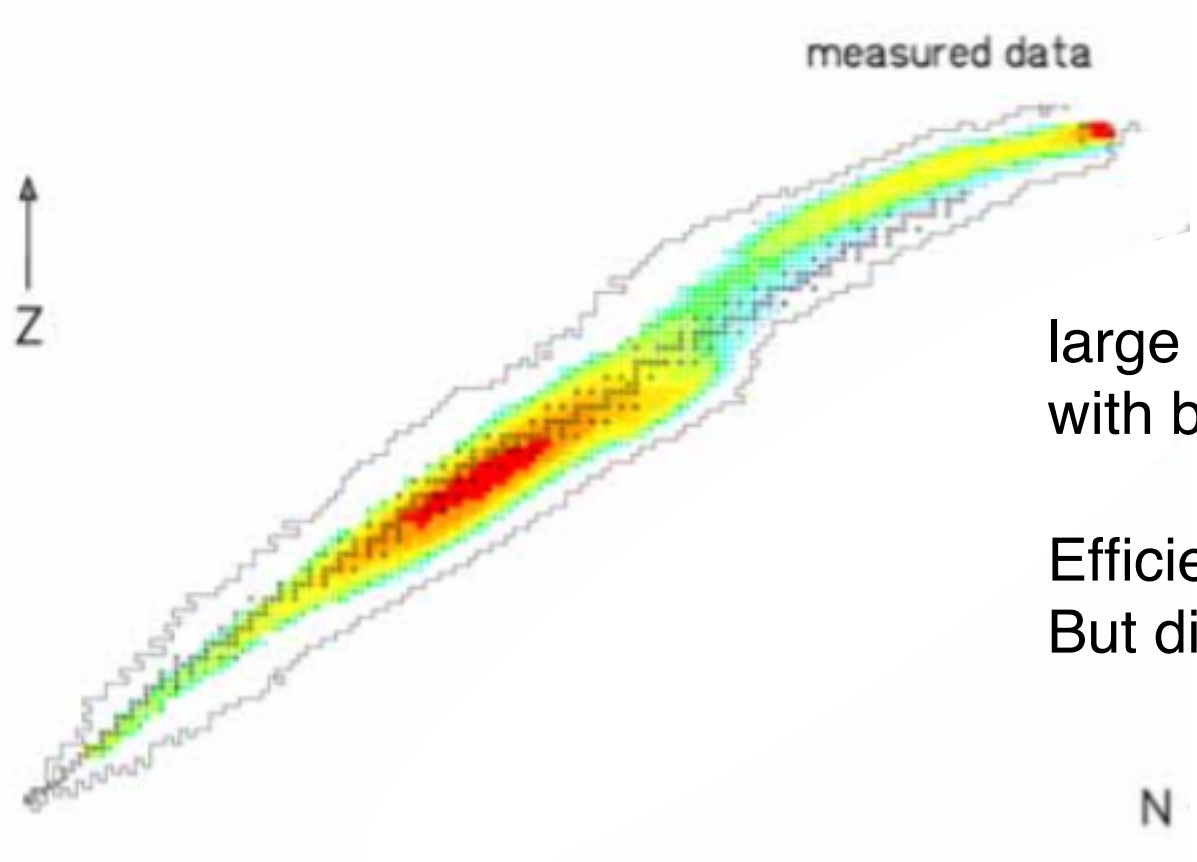

**Increasing fission-fragment velocity for a better resolution**

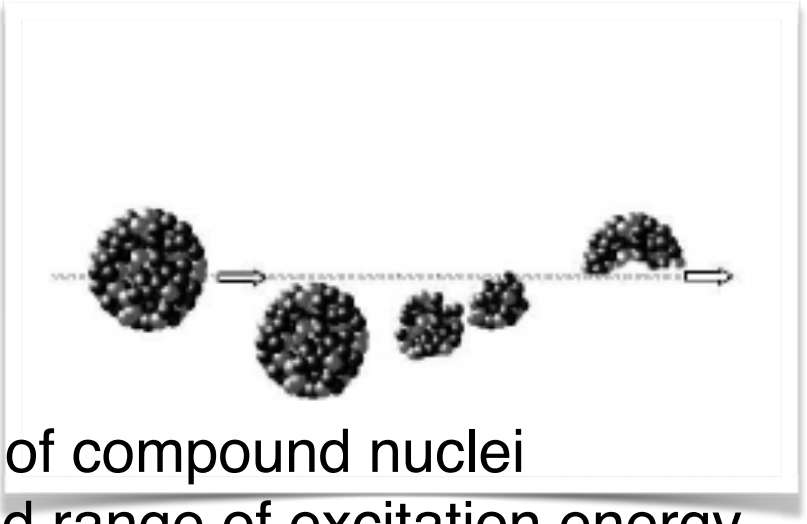
\+ forward focusing for a better detector acceptance
\- time-of-flight resolution decreased

# Inverse kinematics : nuclear-reaction -induced fission

Different regimes : relativistic energy
Coulomb barrier energy

Relativistic energy : fragmentation or spallation



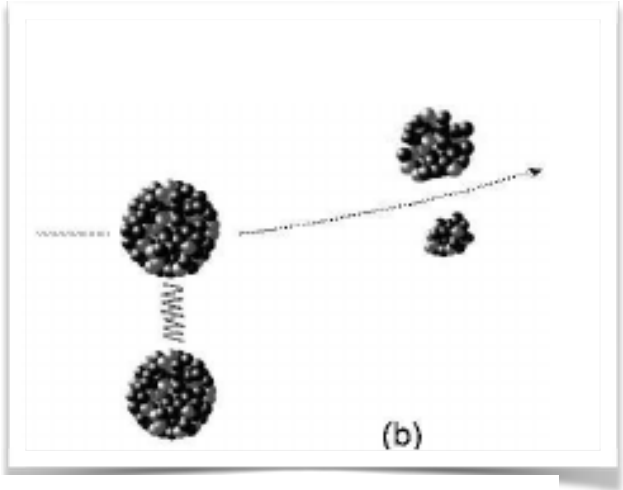



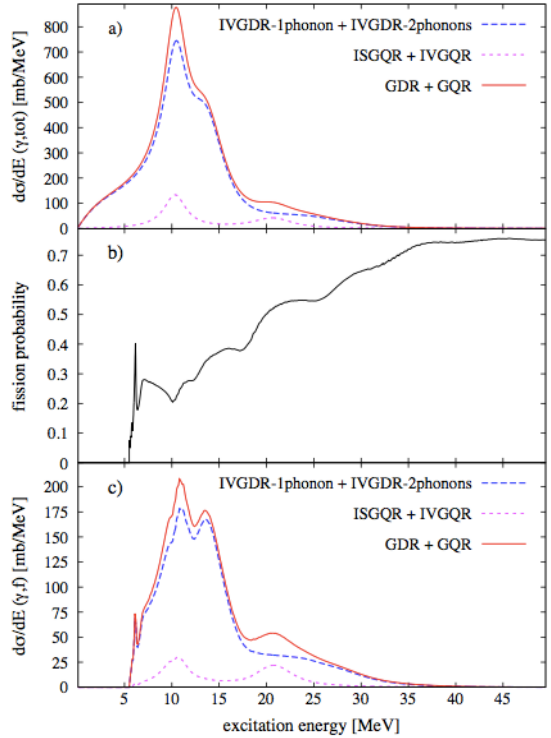
large set of compound nuclei
with broad range of excitation energy

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

Relativistic kinetic energy
Moderate excitation energy !

# Inverse kinematics : Coulomb -induced fission

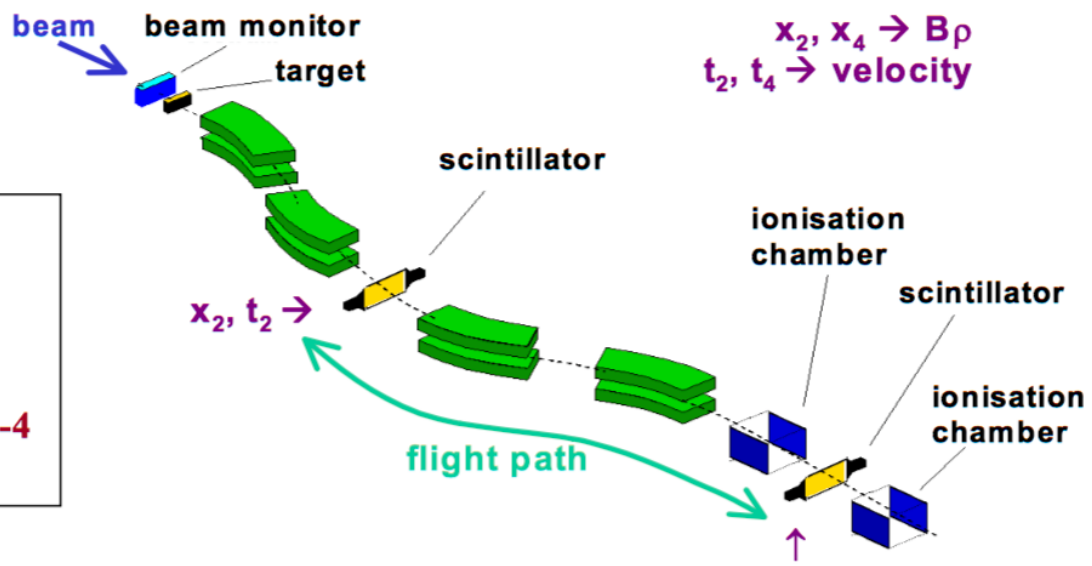
How to produce actinide beams ?
Natural U allows to extract 238U, but 235
Th is possible …
But actinides are very radioactive and it becomes very costly to decontaminate an accelerator !!

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




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

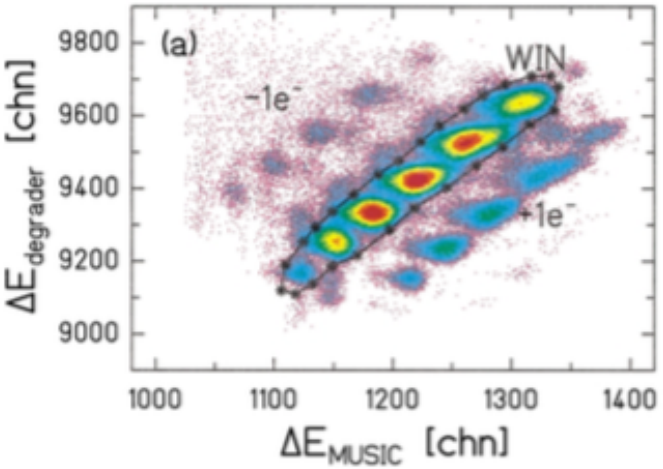
$A / \Delta A \approx 400$

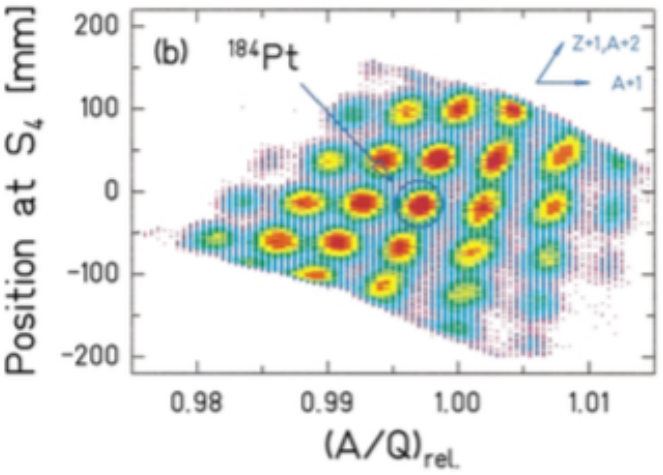
$Z / \Delta Z \approx 200$

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

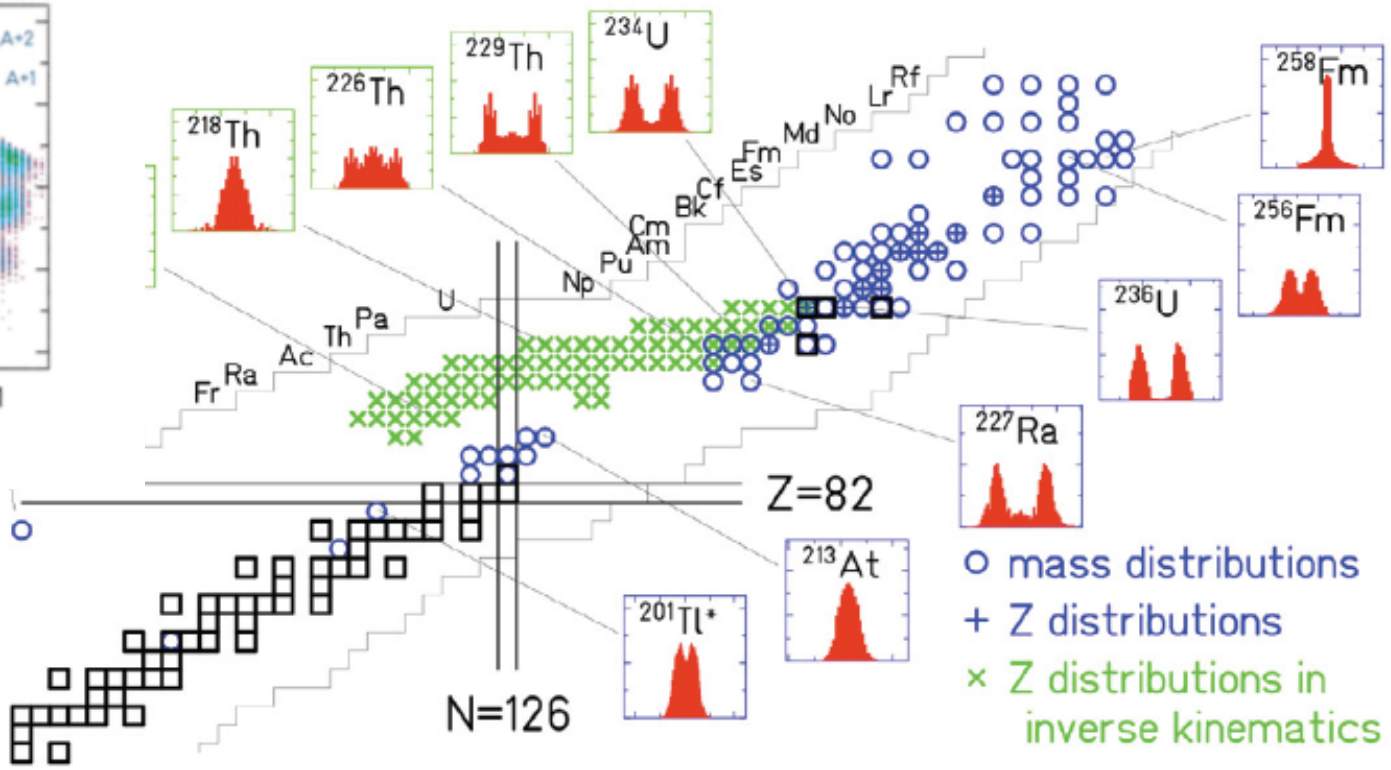
High velocity :
q = Z !!

# In-flight production of actinides

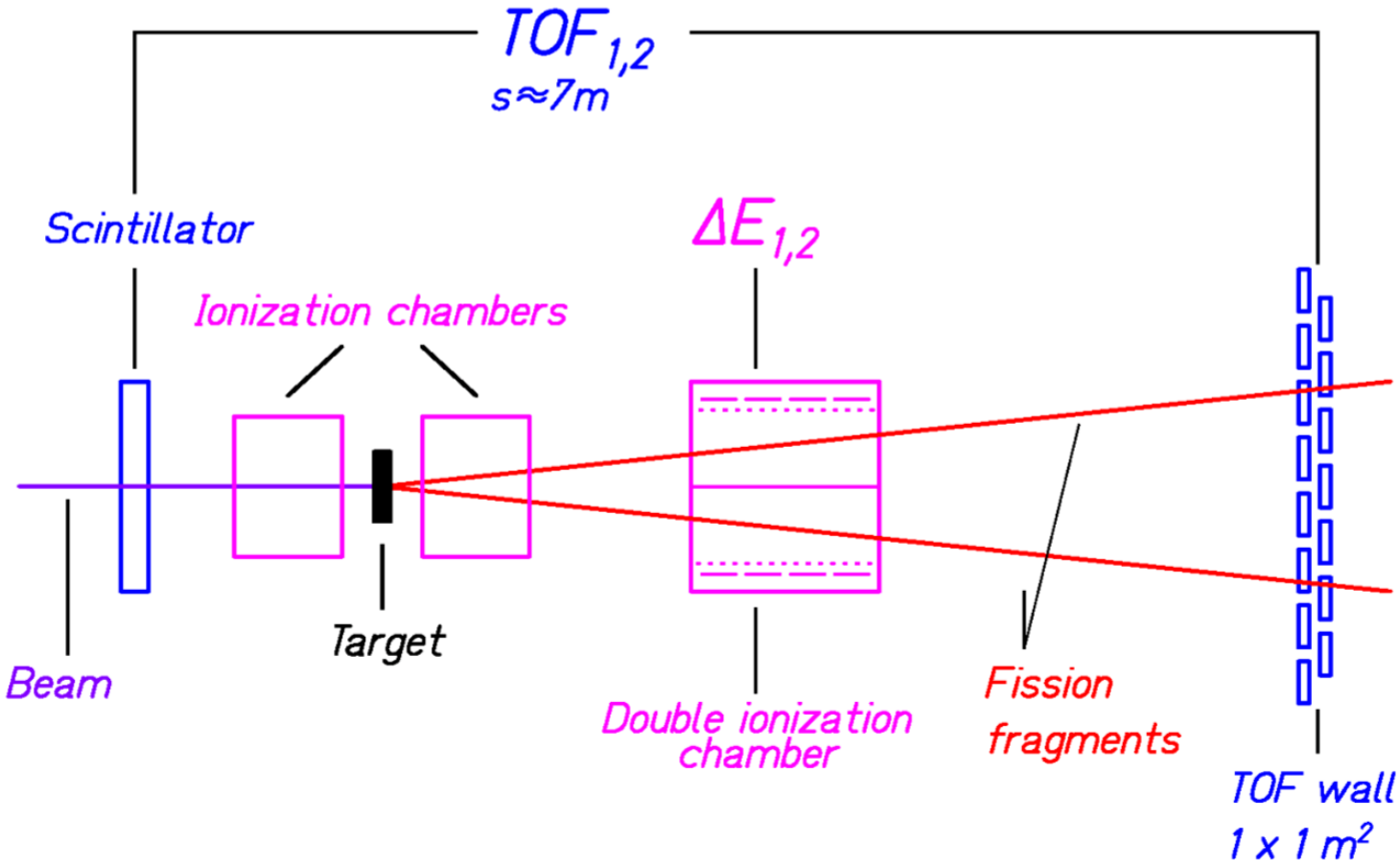


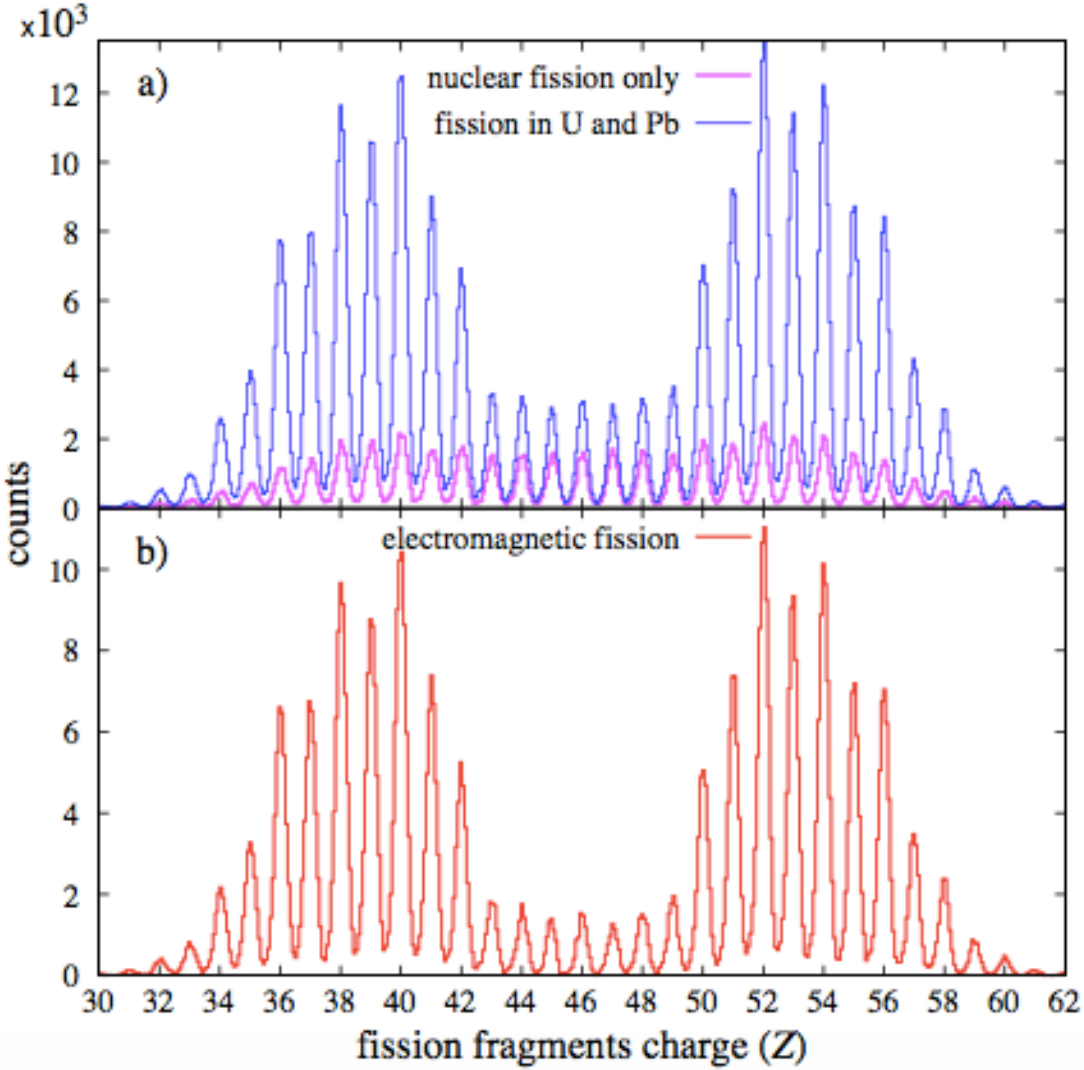

Large number of fissioning systems !



# In-flight fission of actinides

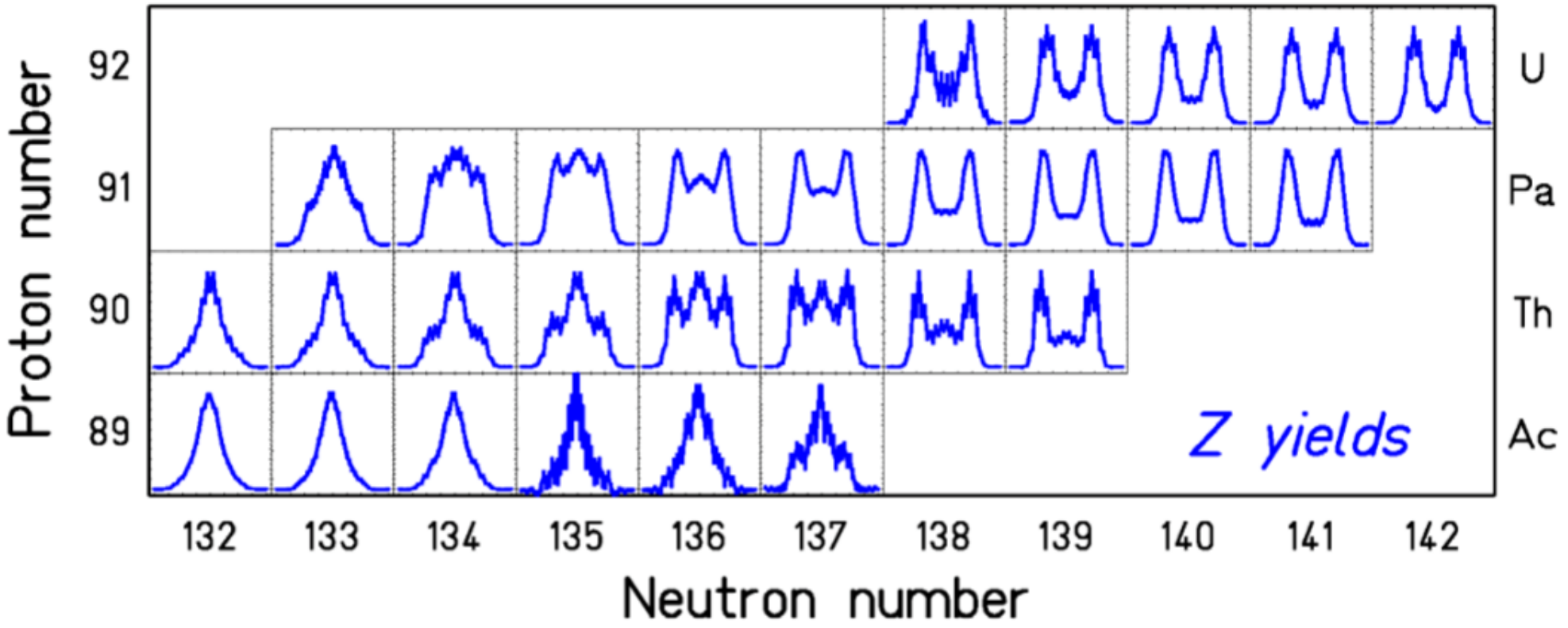


# Improved Z resolution at high kinetic energy



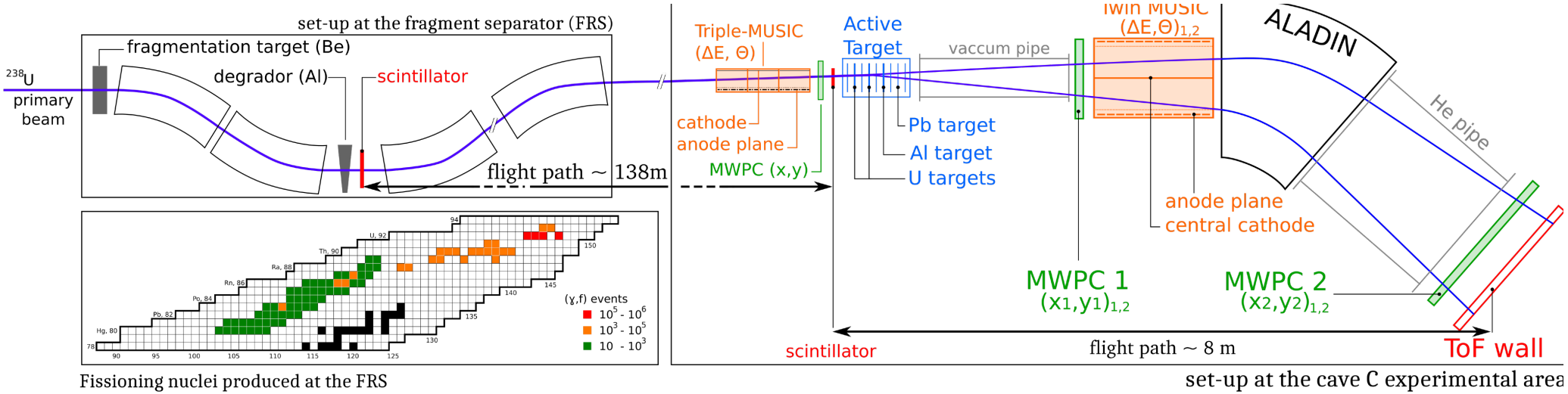

$$\frac{\partial Z}{Z} \sim 0.2\%$$

# 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

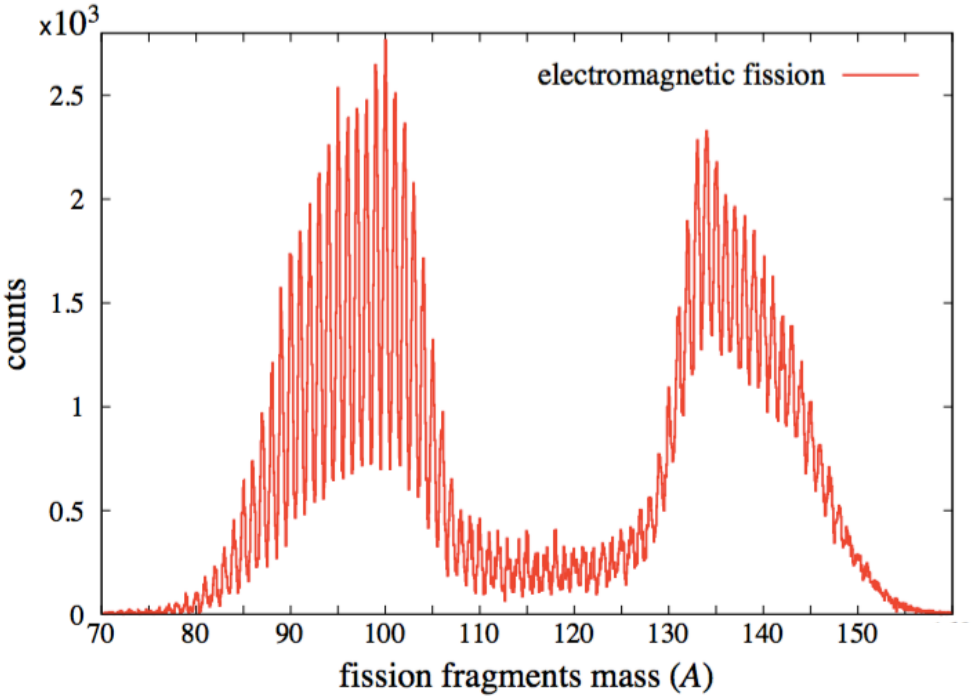
Measure of Bρ, ΔE, ToF

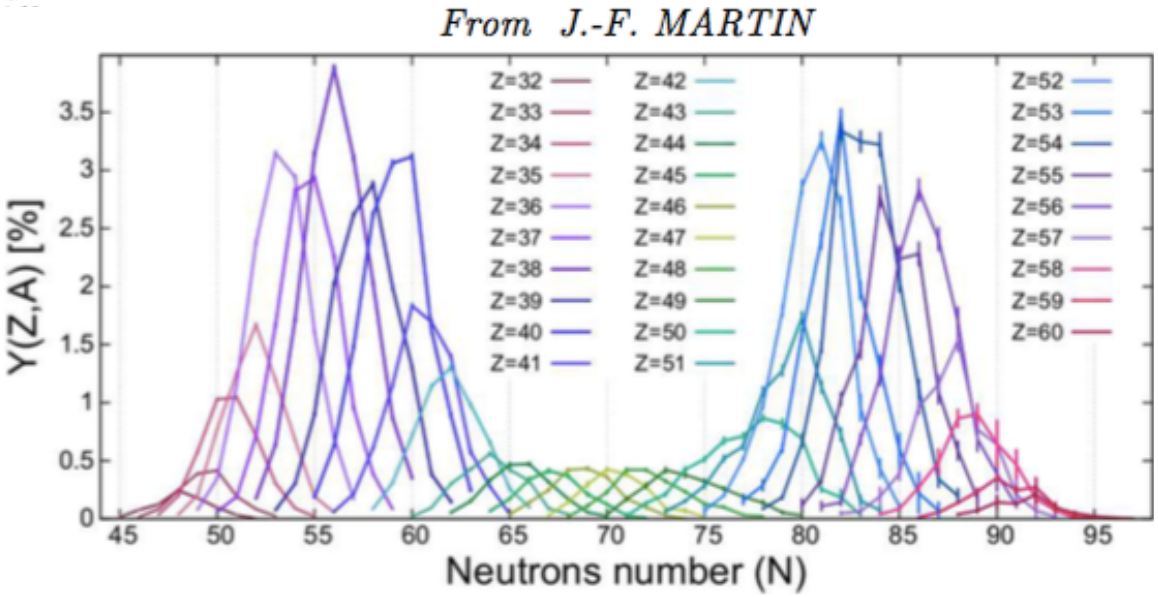
$$\frac{\partial A}{A} \sim 0.5\ \%$$

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



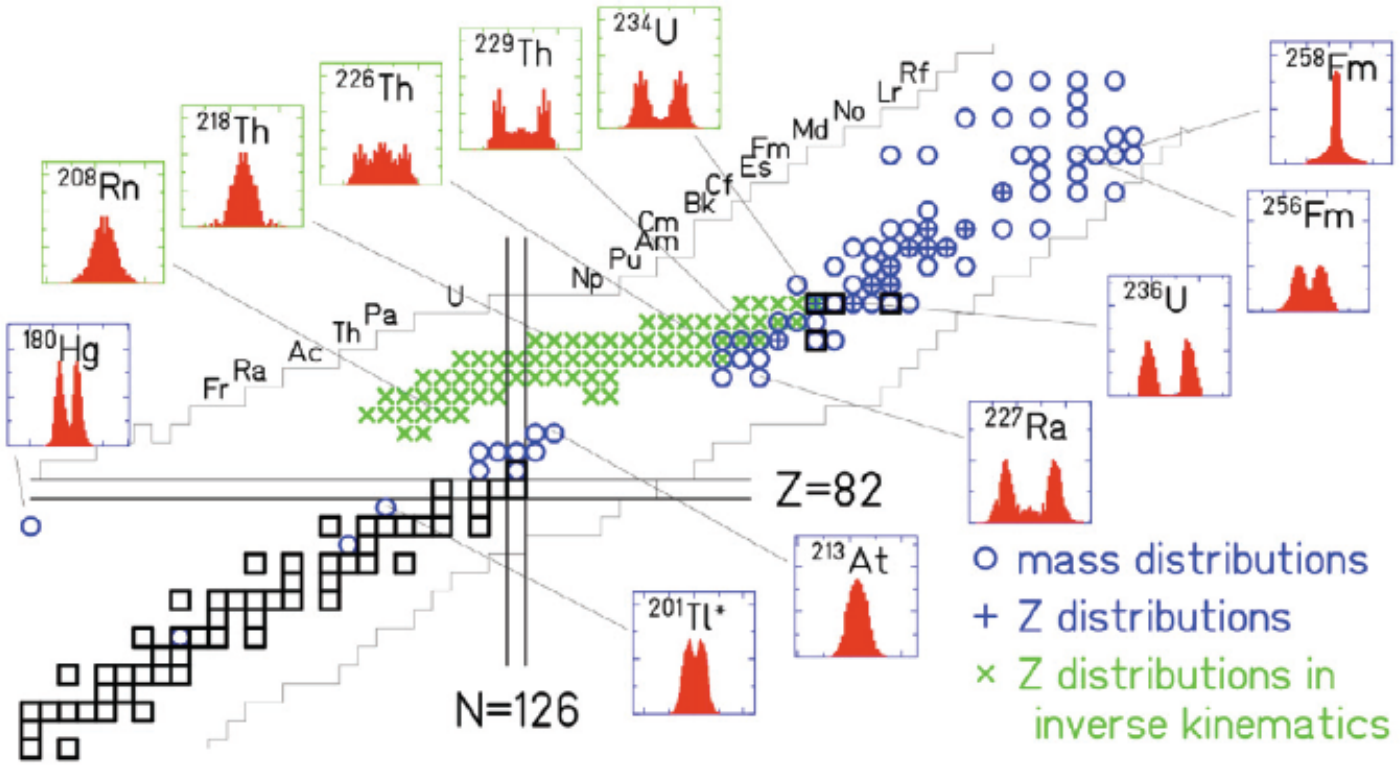

Impressive set of data !!
Compete isotopic yields
Very constraining to modelisation !



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

# Secondary beams

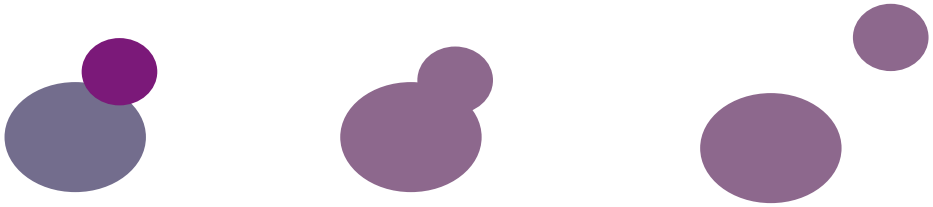
Fission in inverse kinematics
high resolution in Z,A
Complete identification
Both fission-fragments —> total neutron multiplicity !
Large number of fissioning systems but light systems

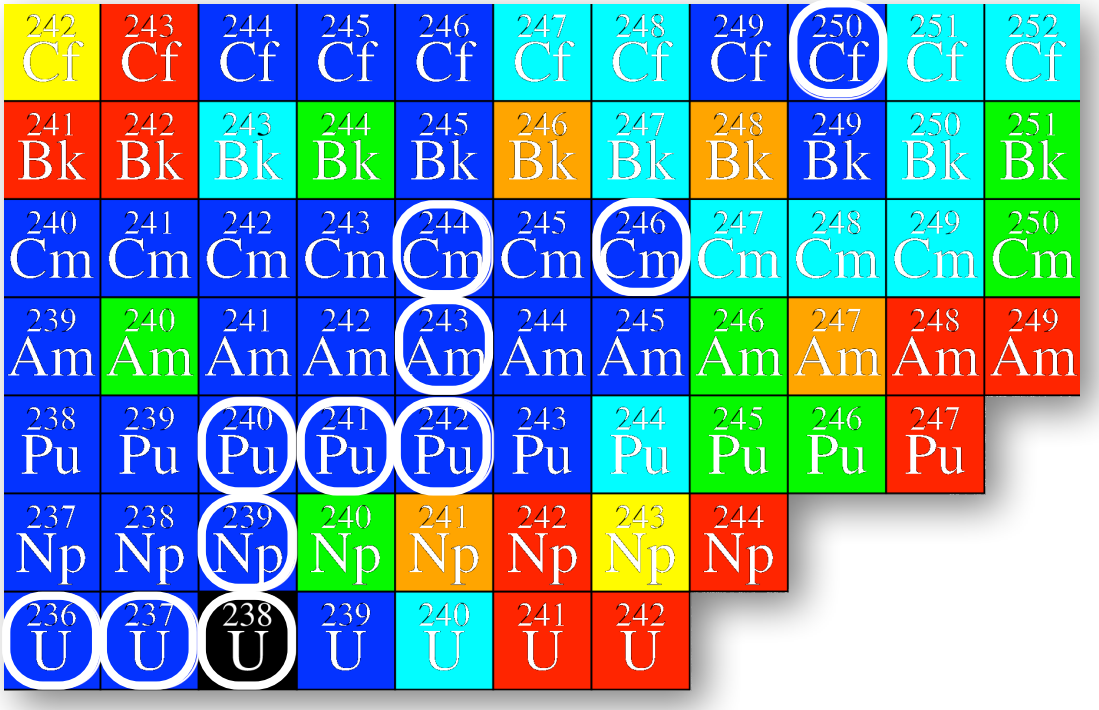


# Multi-nucleon transfer induced fission

Coulomb barrier energy

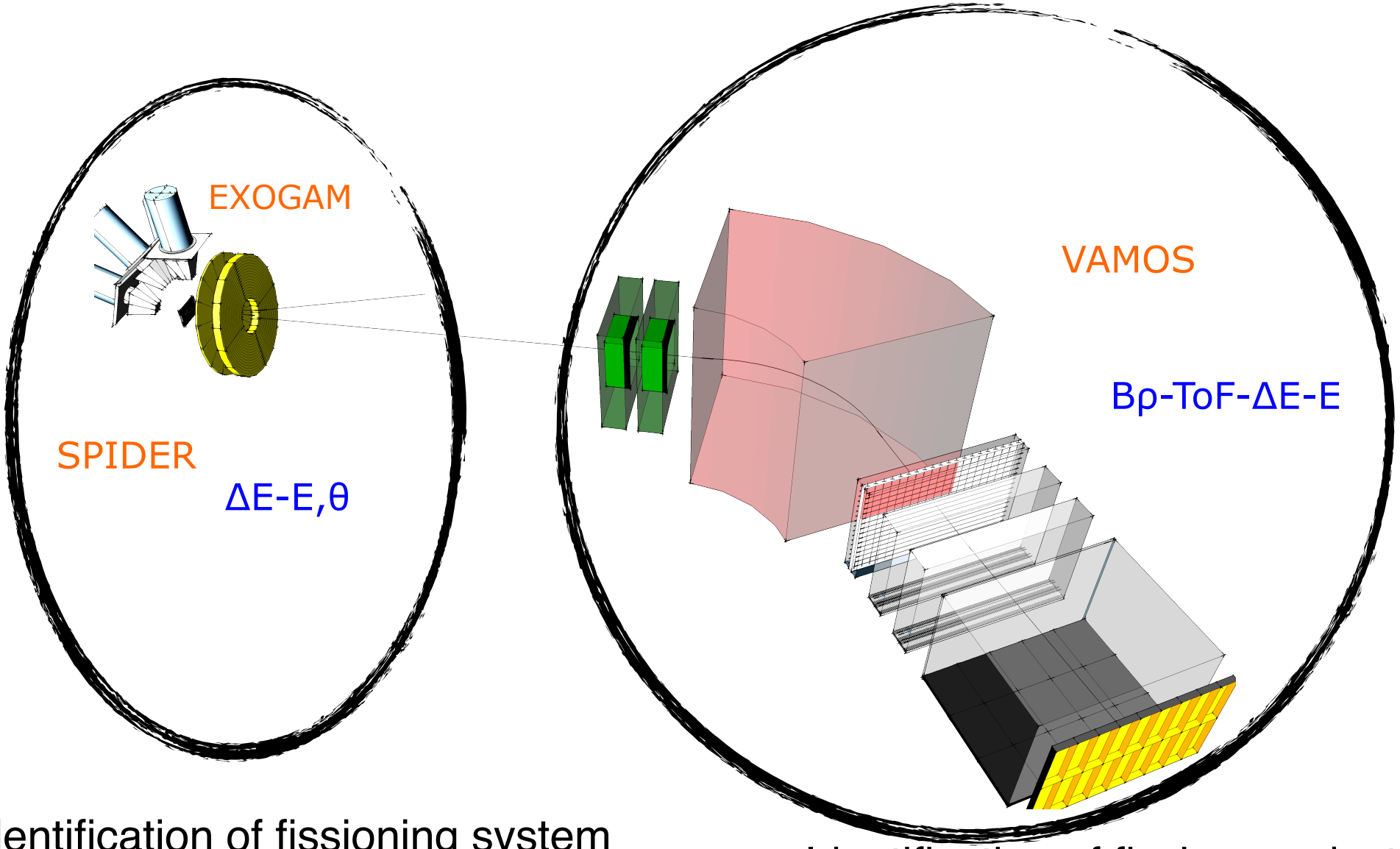
Very asymmetric reaction :
Nucleon exchange from light to heavy nucleus
Direct reaction






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

# Multi-nucleon transfer induced fission

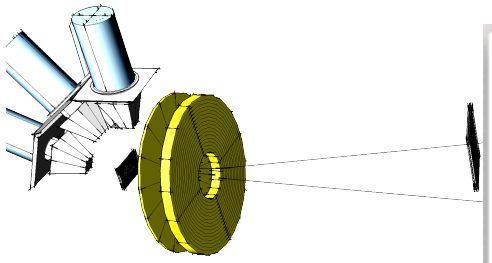


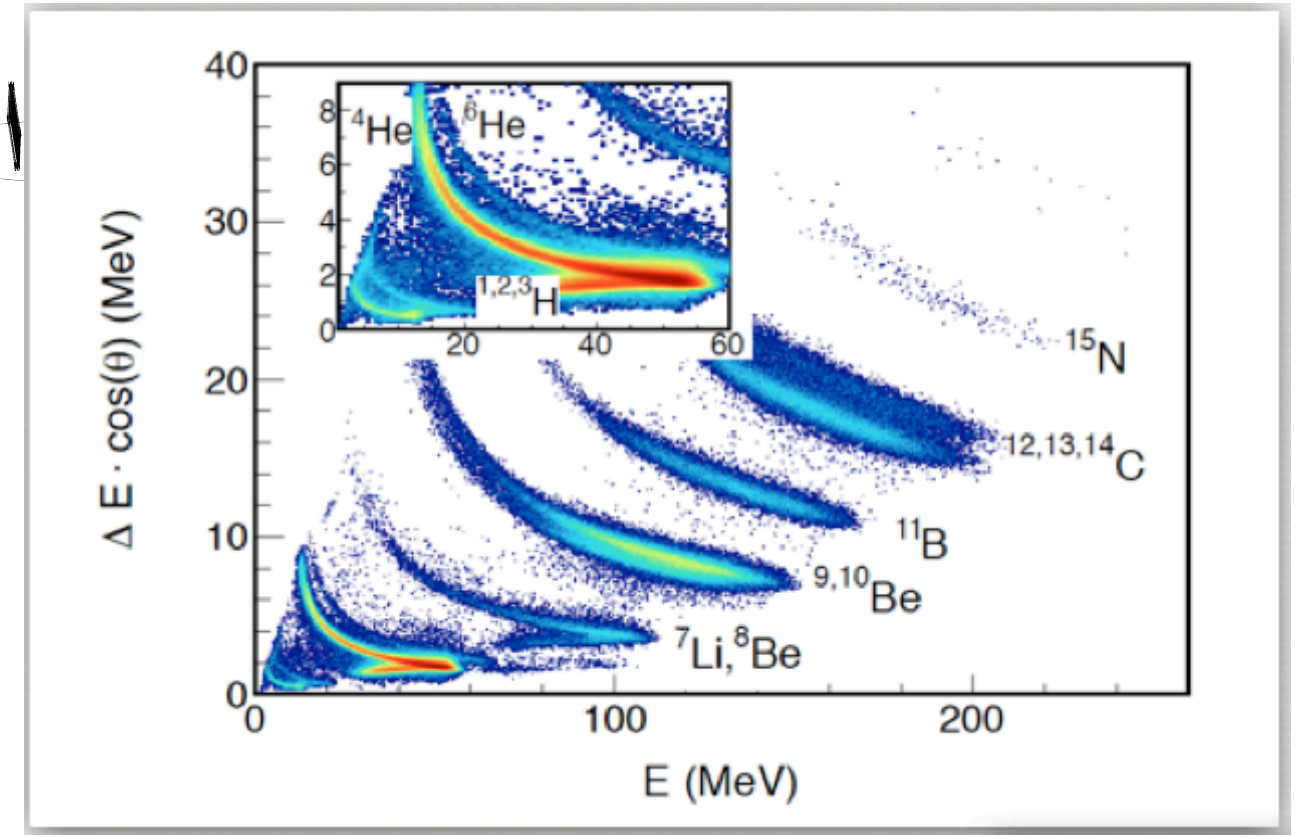

Identification of fissioning system

Identification of fission product

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

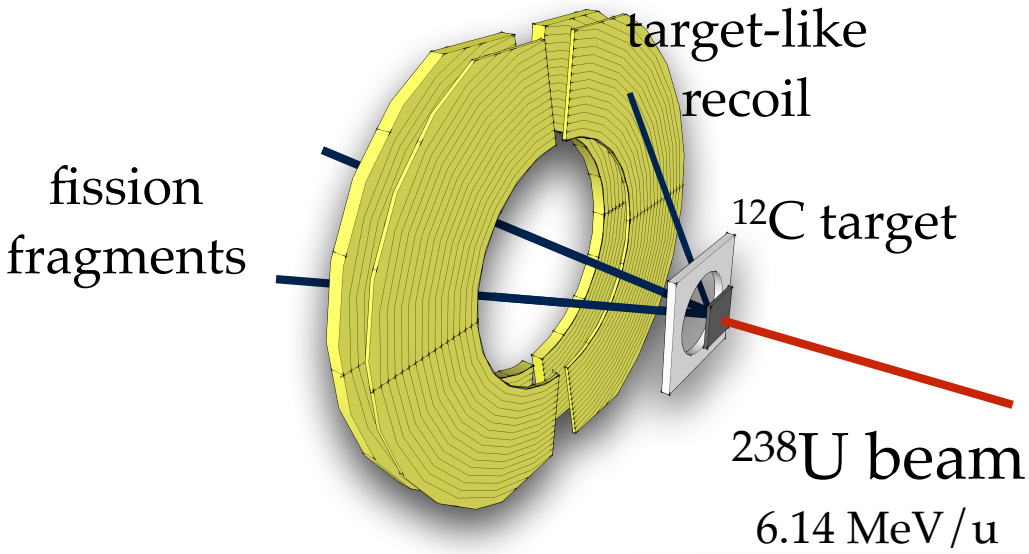
# Identification of the transfer channels





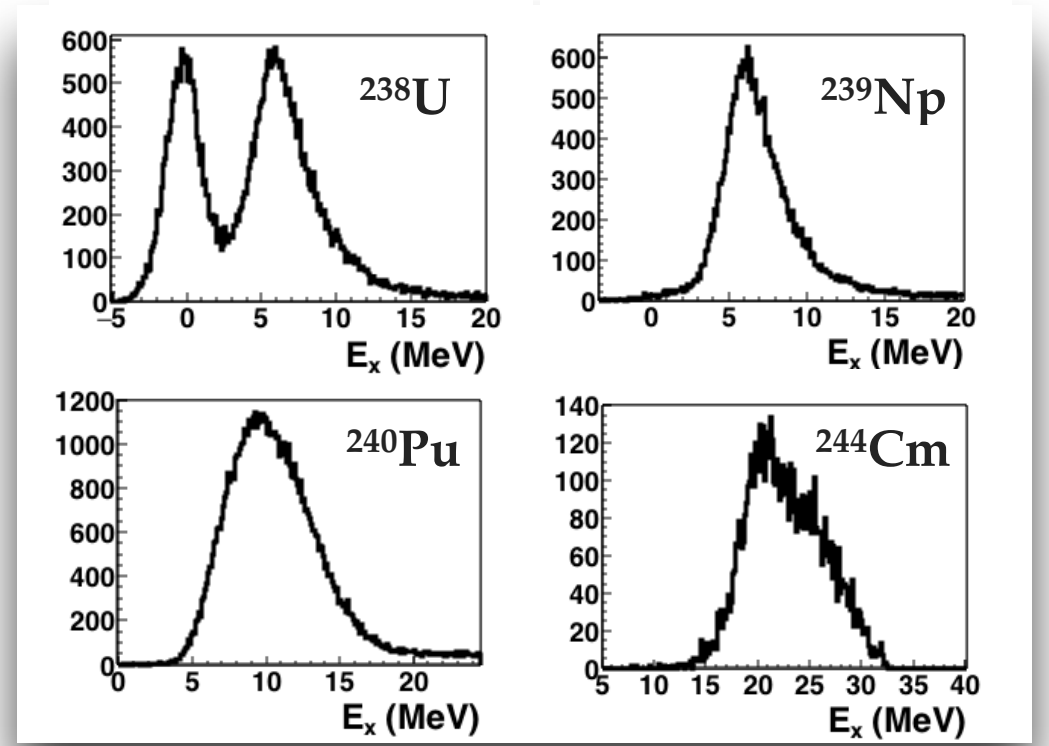

C. Rodriguez-Tajes et al.,
PRC89 (2014) 024614

# Identification of the transfer channels

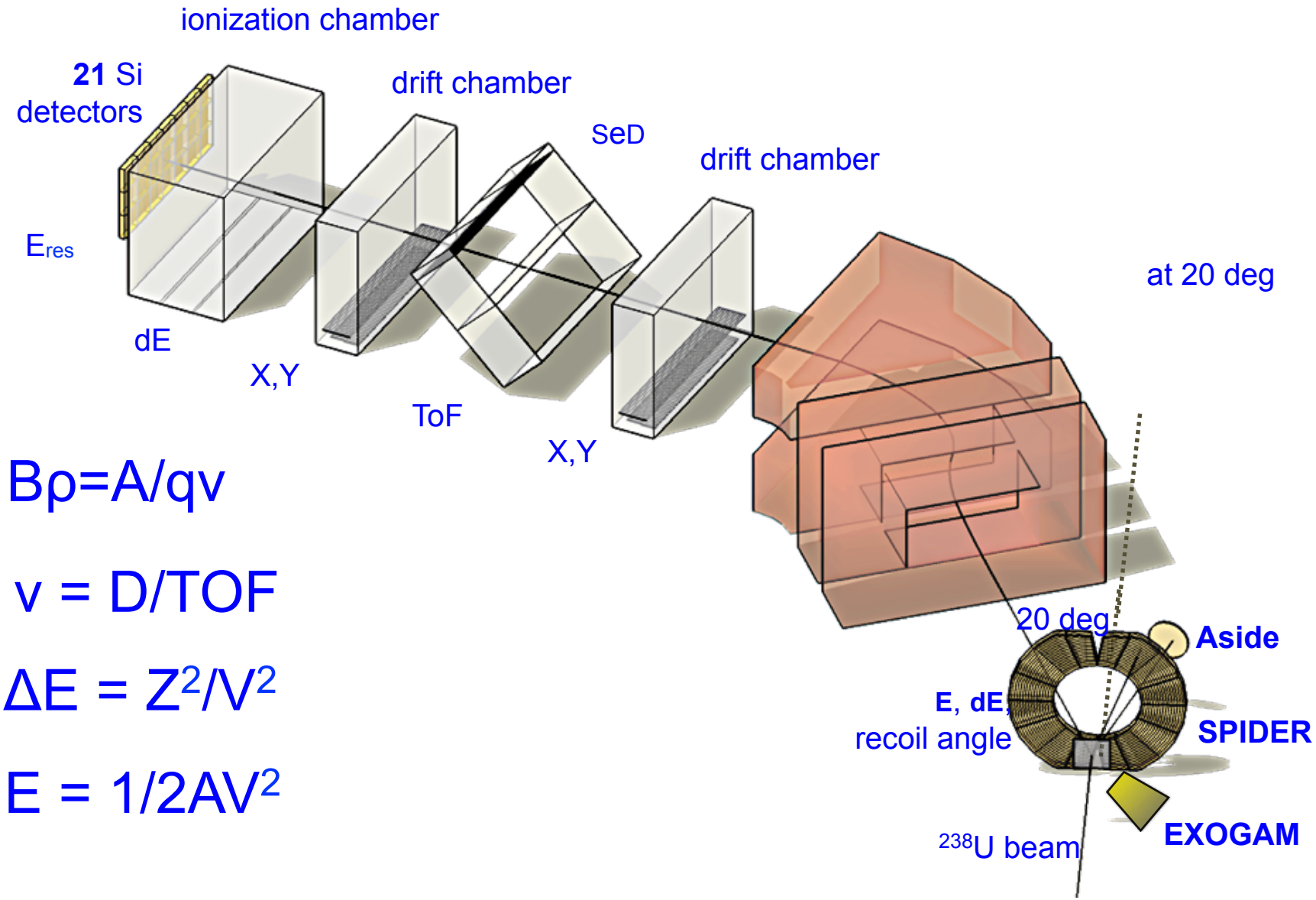



$^{238}$U ($^{12}$C, $^{12}$C) $^{238}$U
$^{238}$U ($^{12}$C, $^{11}$B) $^{239}$Np
$^{238}$U ($^{12}$C, $^{10}$Be) $^{240}$Pu
$^{238}$U ($^{12}$C, $^{6}$He) $^{244}$Cm

- Isotopic identification
- Reconstruction of binary reaction
- $E_x$ reconstruction

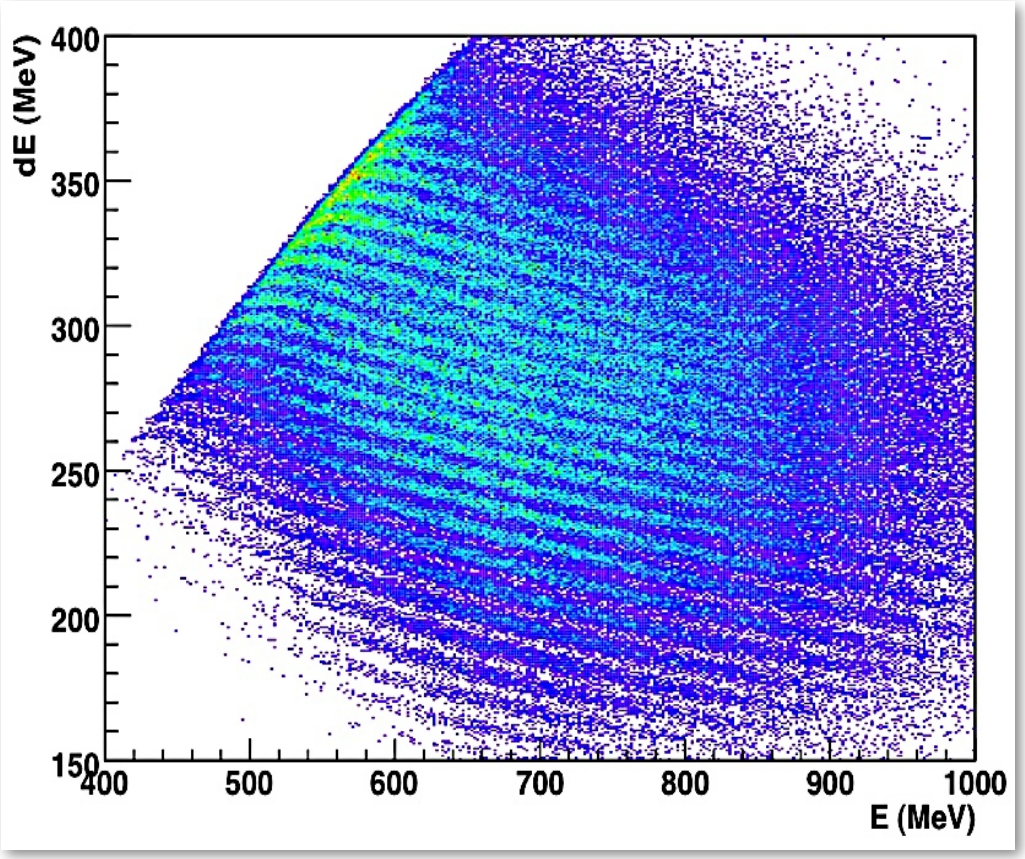


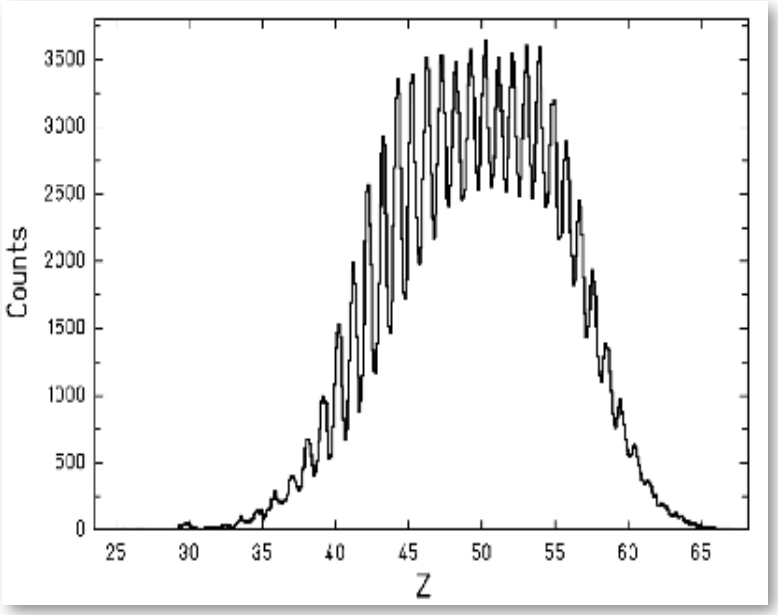
# Identification of fission products




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

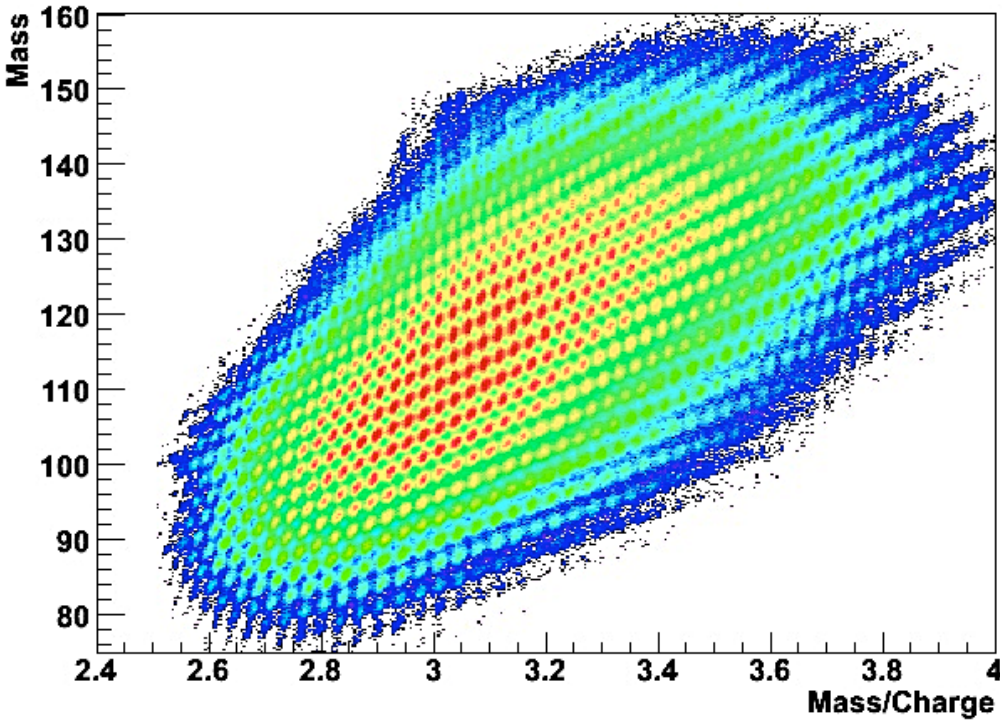
# Improved atomic number resolution

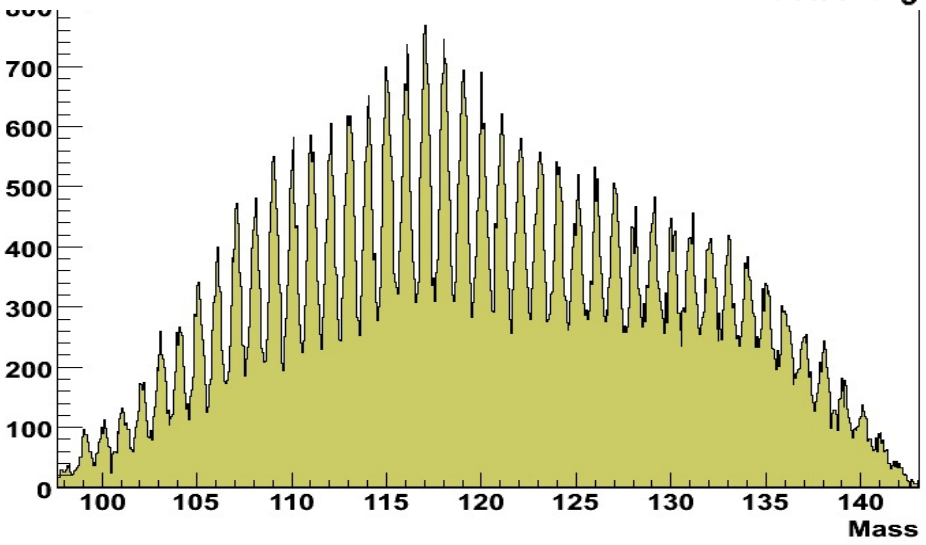



$\Delta Z/Z \approx 1.5 \cdot 10^{-2}$

# Mass resolution through magnetic rigidity resolution



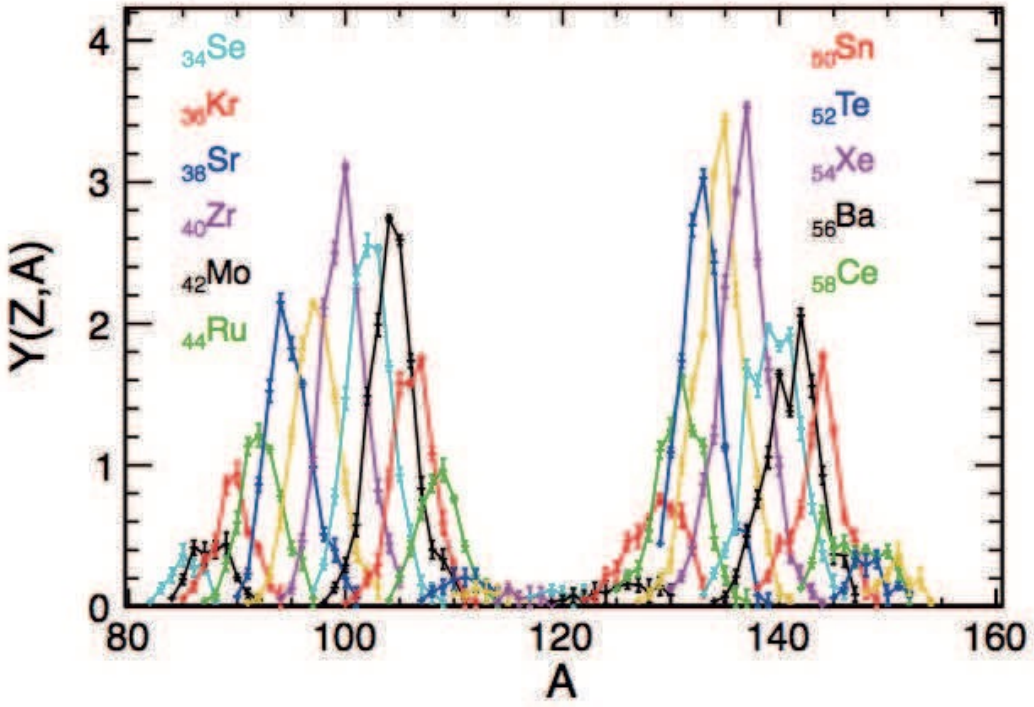




$A = E/(\gamma - 1)$

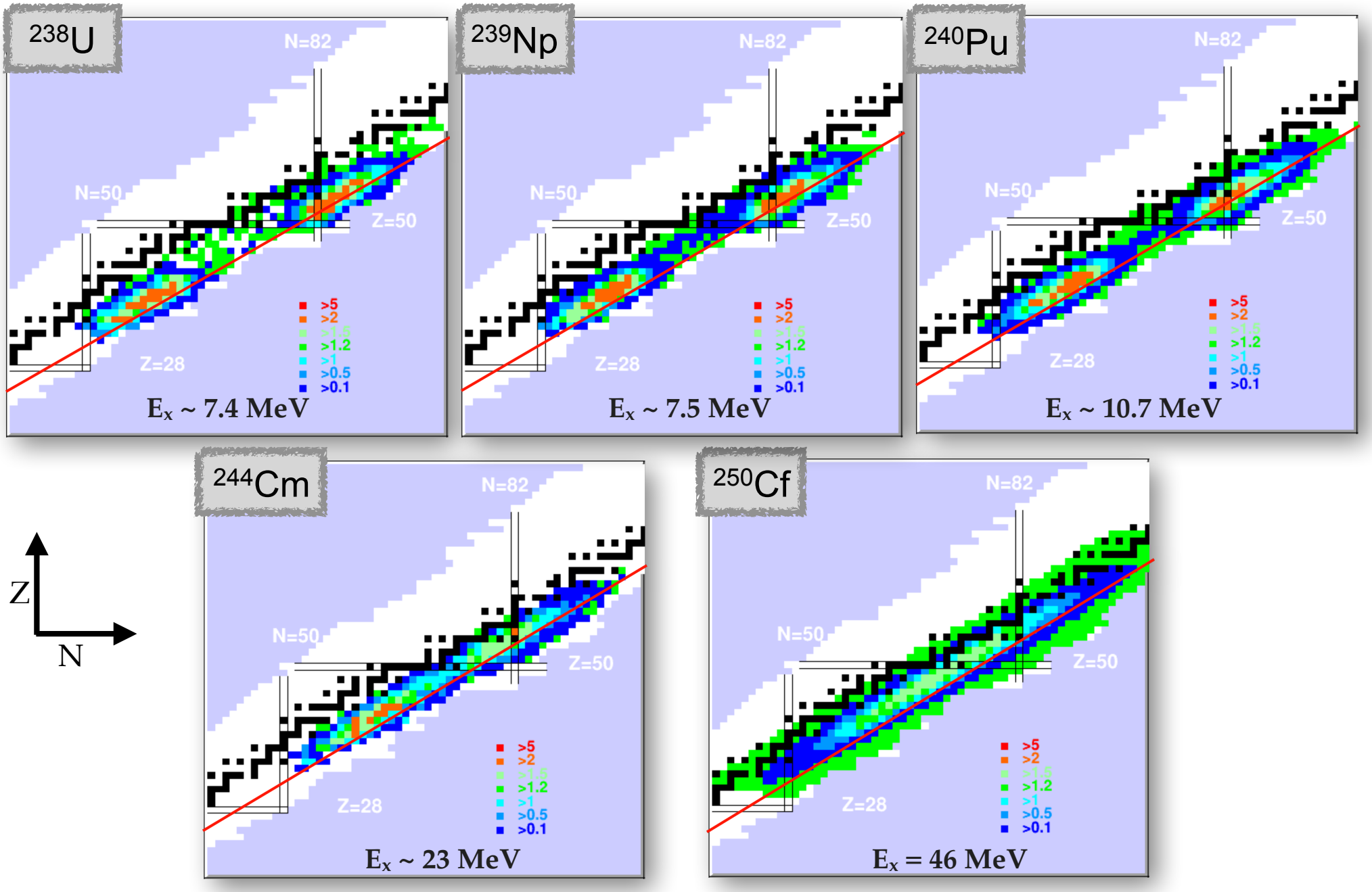
$A/q = B\rho/(\beta\gamma)$

dq/q ~ 1.5 %

dA/A ~0.6 %

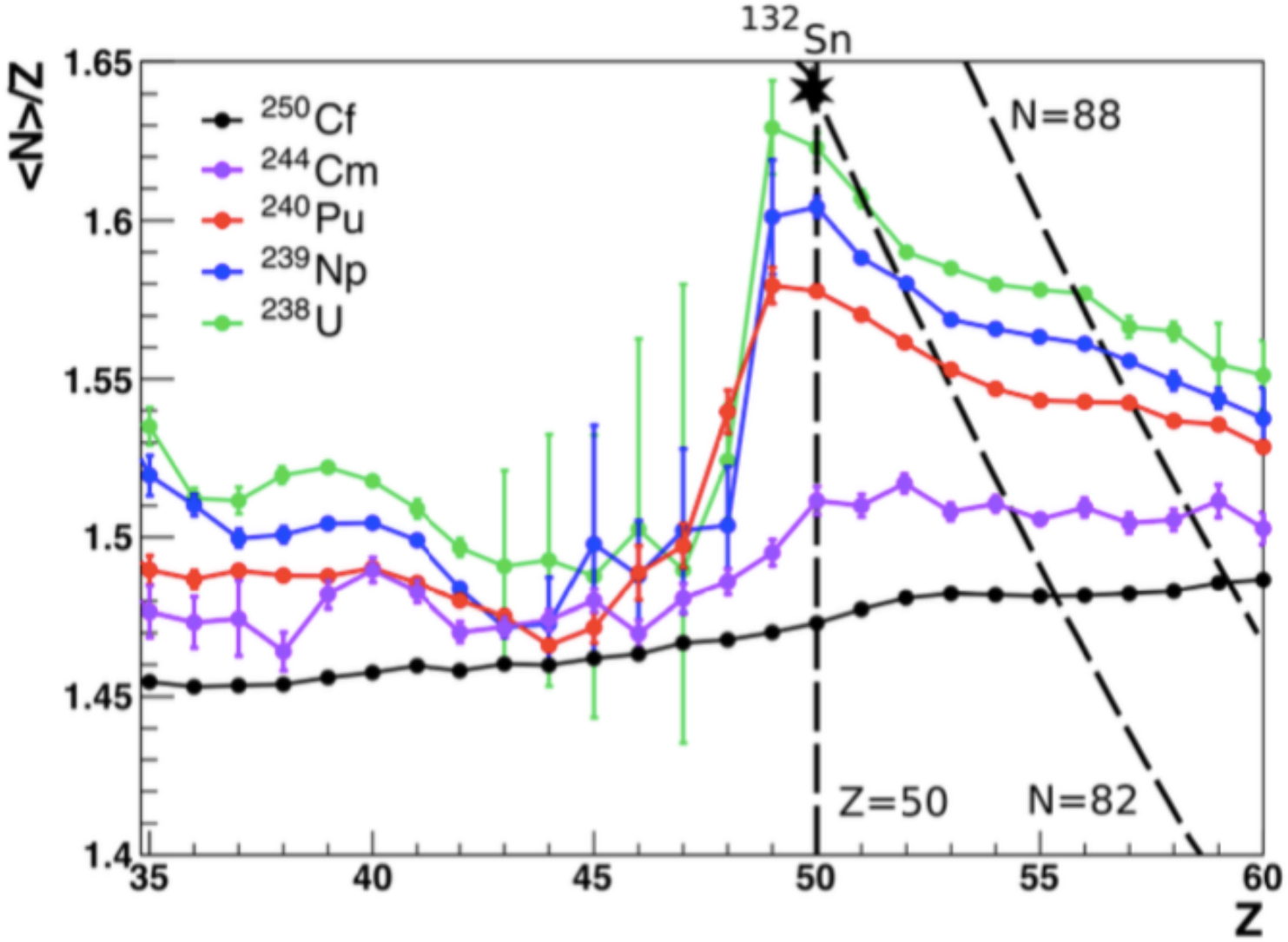


# Results: Isotopic Fission Yields



# Mass resolution through magnetic rigidity resolution

## New data : new type of observables : Charge polarisation



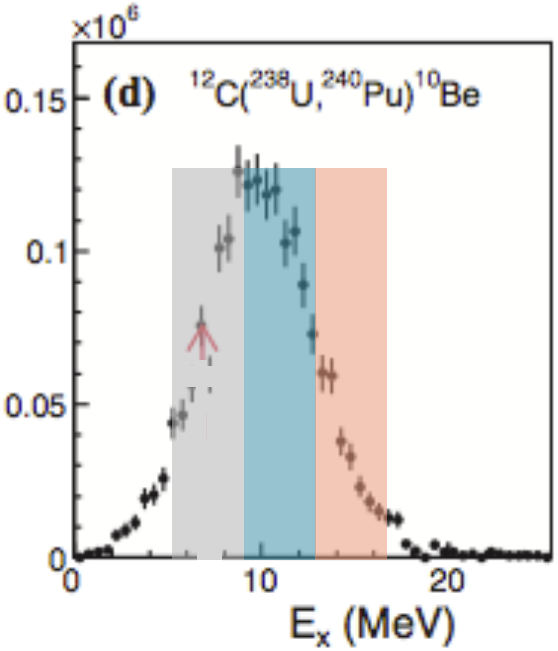
# Mass resolution through magnetic rigidity resolution

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

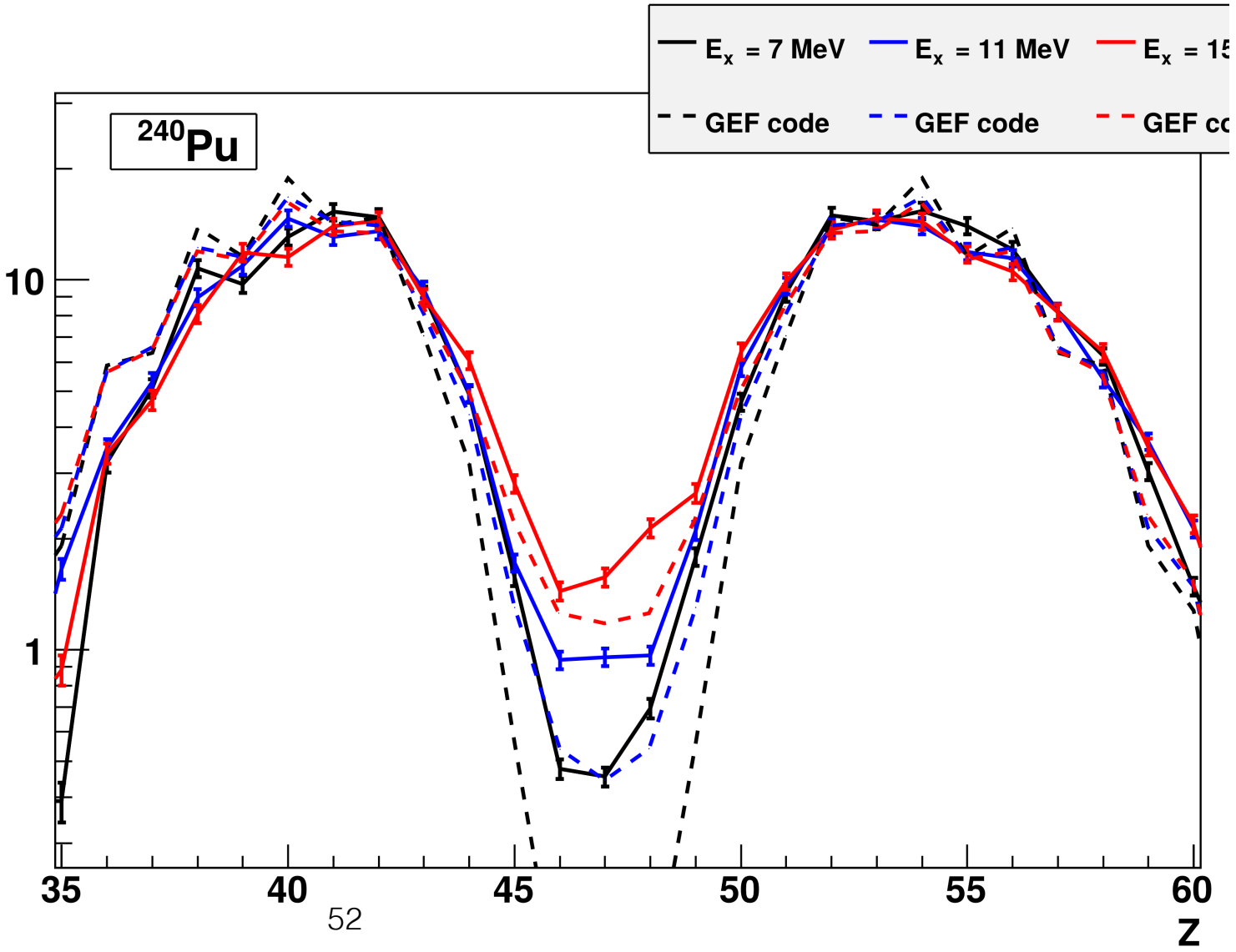
**In addition they allow for :**

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

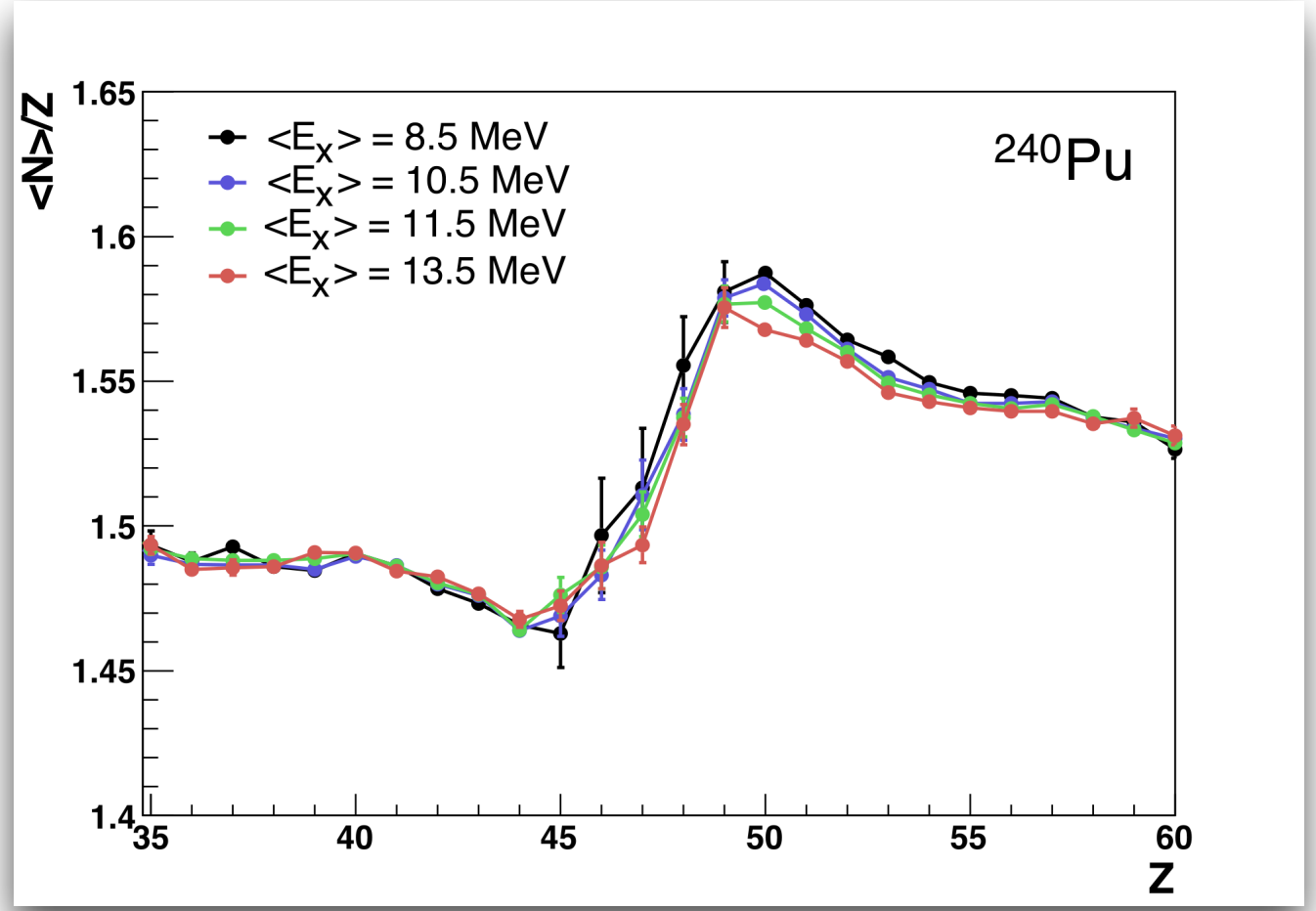
# Evolution of mass distribution with Excitation energy

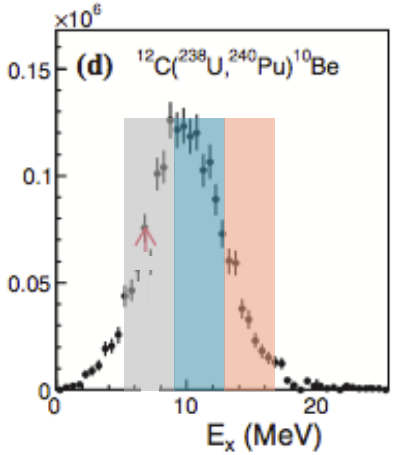



From transfer kinematics



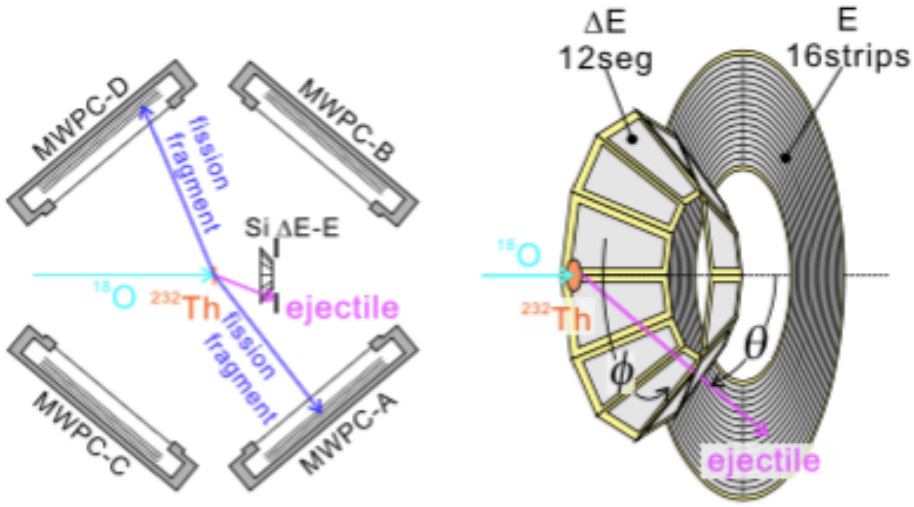
# Evolution of charge polarisation with Excitation energy

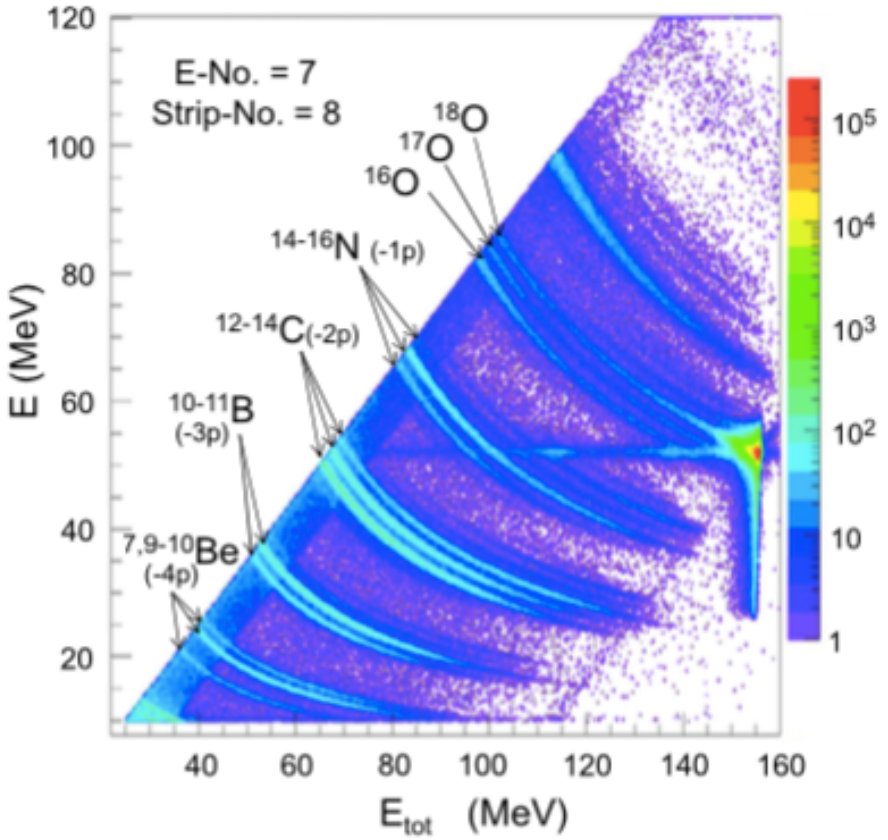



Only heavy fragments evaporate neutrons !!

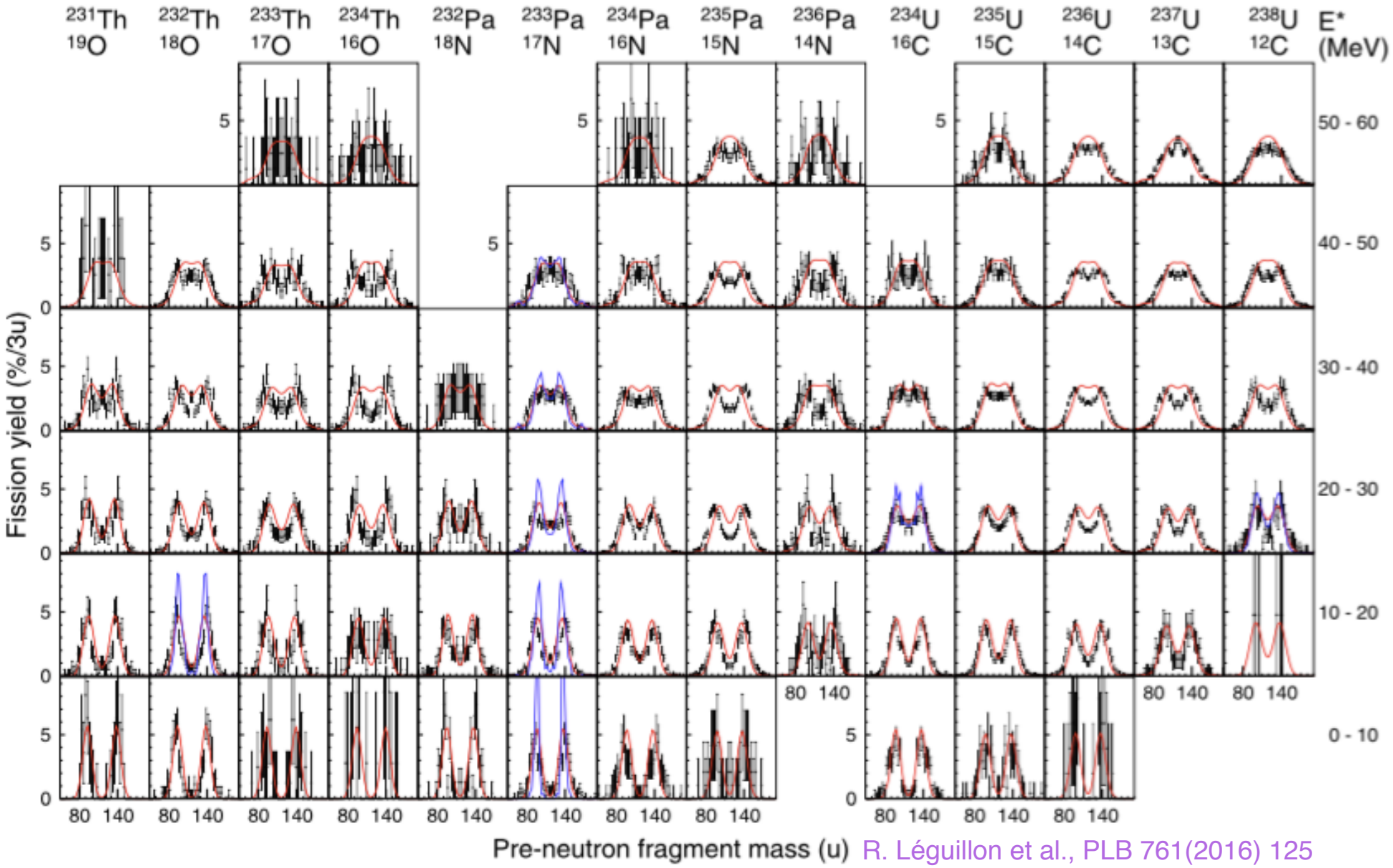
# Multi-nucleon reaction used in direct kinematics




K. Nishio,, JAEA Tandem

# 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

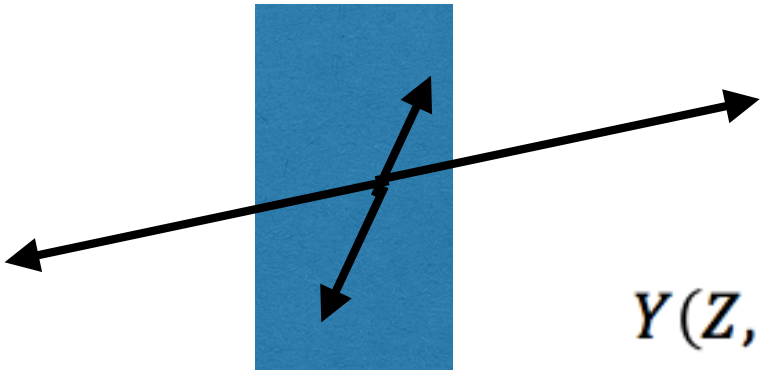
# 7. Fission Yields : systematic uncertainties and errors

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

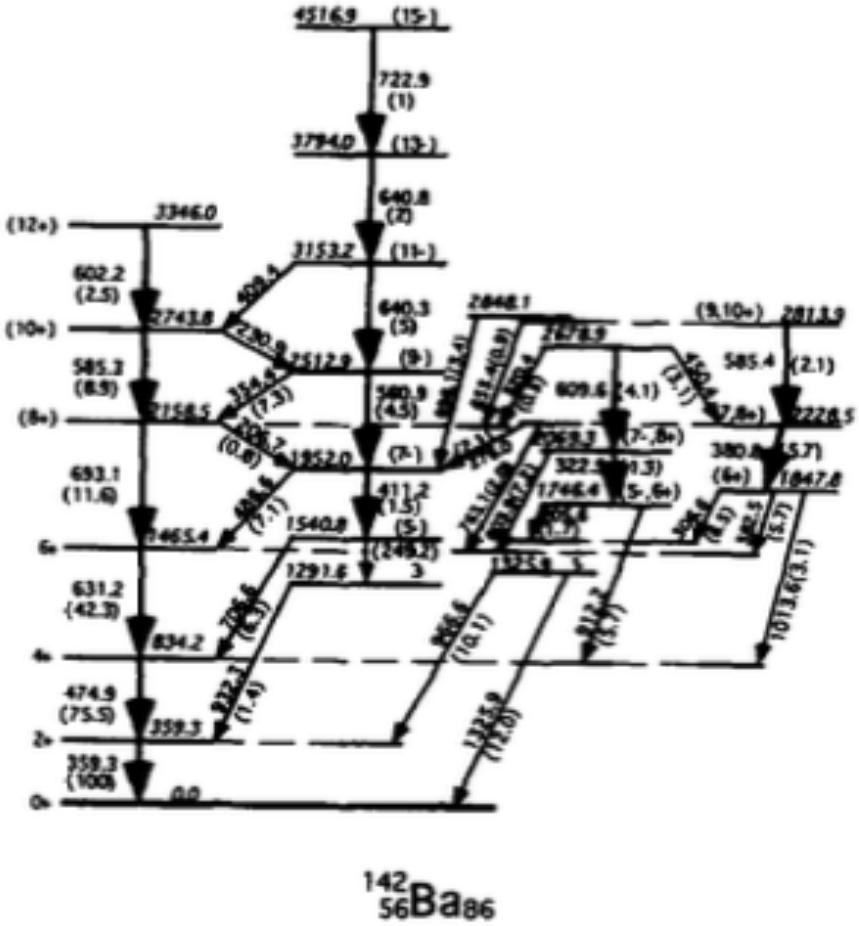


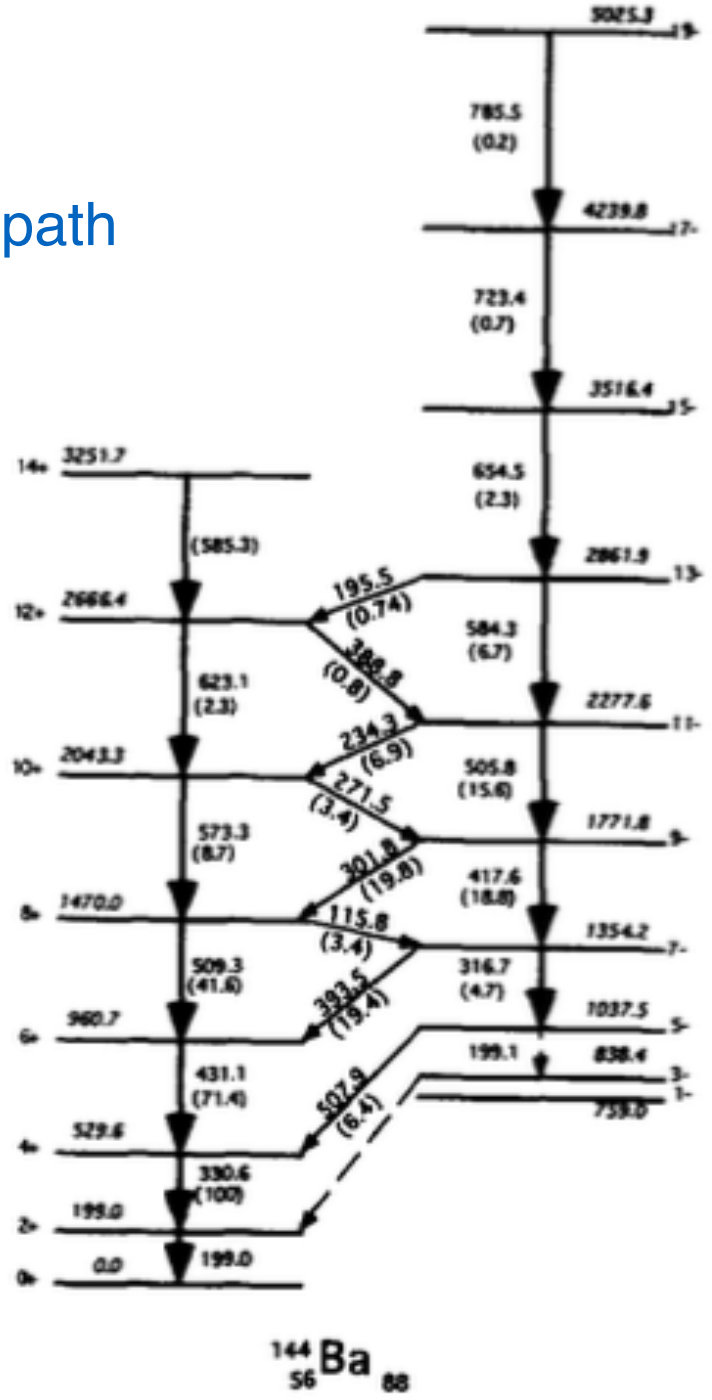
$$Y(Z,A) = \frac{\partial N_f}{\partial Z \partial A} \frac{1}{\xi(Z,A,E)}$$

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

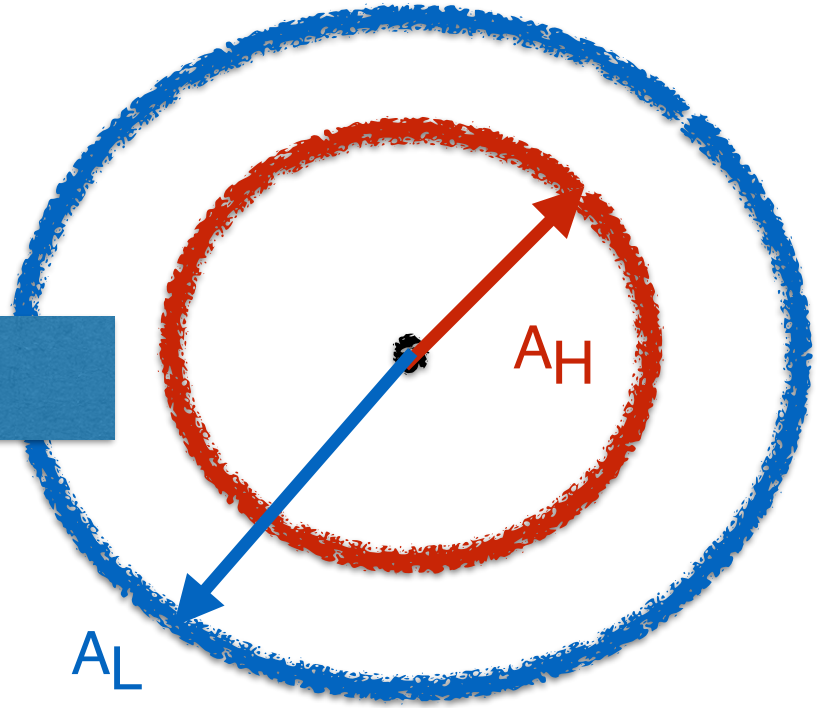


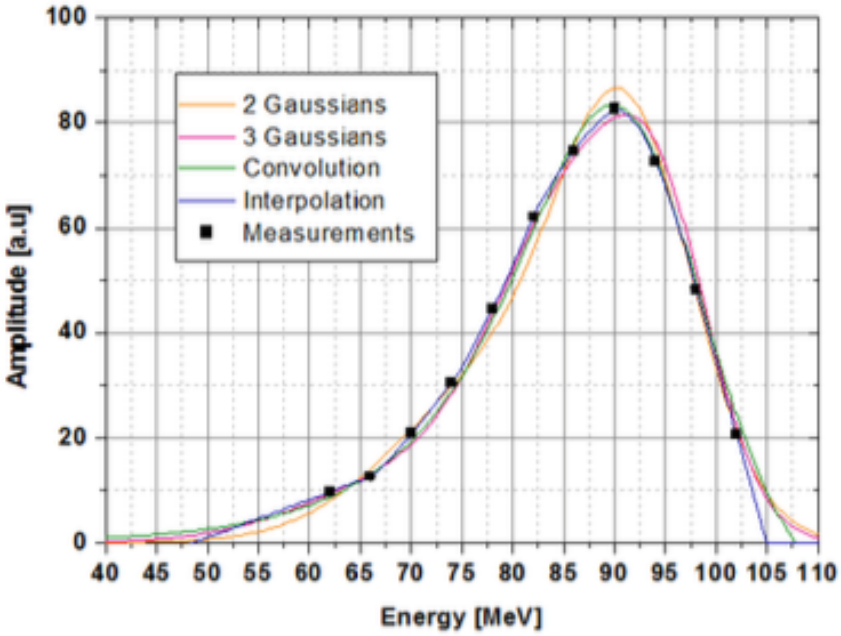



# 7. Fission Yields : systematic uncertainties and errors

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

Detection system




full phase space measurement :

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

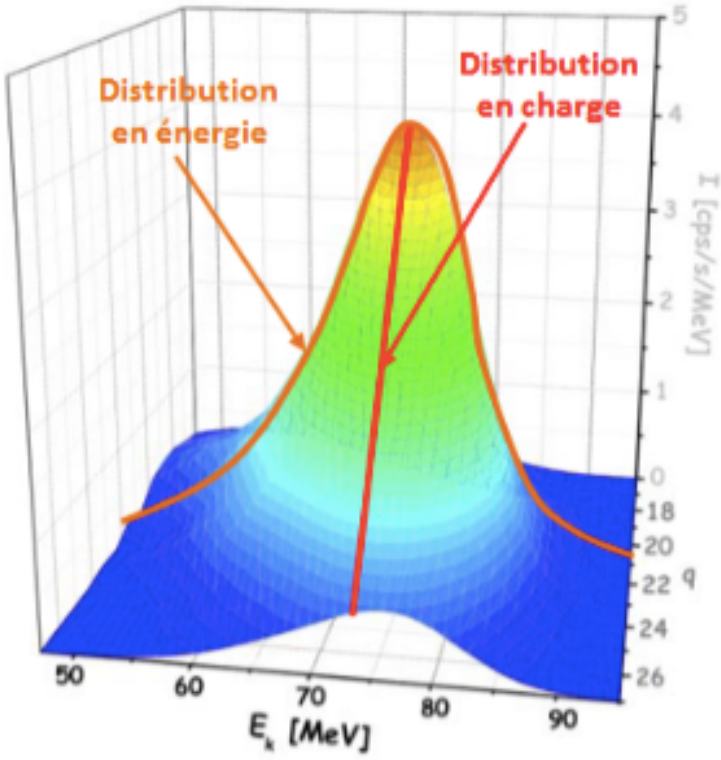
C. Amouroux PhD

# 7. Fission Yields : systematic uncertainties and errors

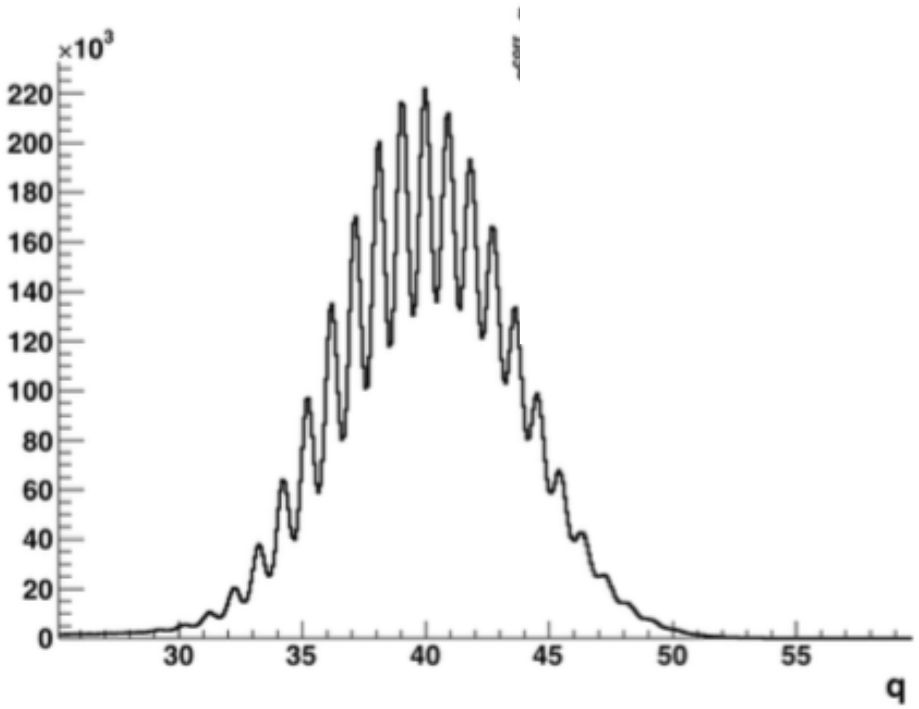
In case of magnetic spectrometer : correction for q-state distribution

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

Lohengrin : estimated




VAMOS : (large acceptance)
measured

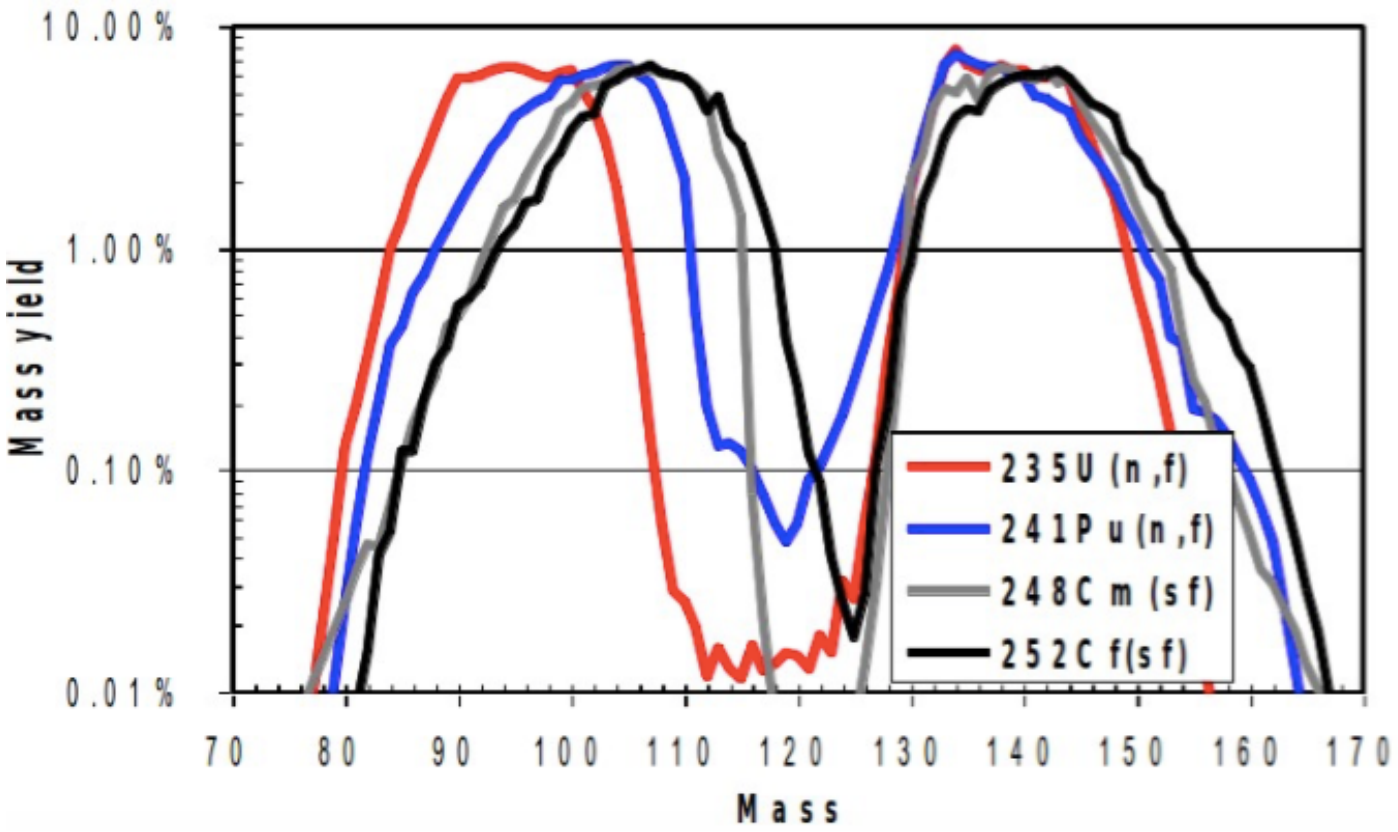


# 7. Fission Yields : systematic uncertainties and errors

Target composition :
Typical actinide target contains several other actinides

$^{235}$U: 93.27% ($^{234}$U: 1.05%, $^{238}$U: 5.68%)

$^{239}$Pu: 98.41 (40)%, $^{240}$Pu: 1.58(40)%




Need a carefull analysis !!

# 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 and fission pair 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