EuNPC

2025

Investigation of Shell Effect Damping in Nuclear Fission of ^{242}Pu using VAMOS and PISTA

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and all the Fission@VAMOS collaboration …

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université PARIS-SACLAY GANIL LMCE LABORATOIRE MATIERE EN CONDITIONS EXTREMES

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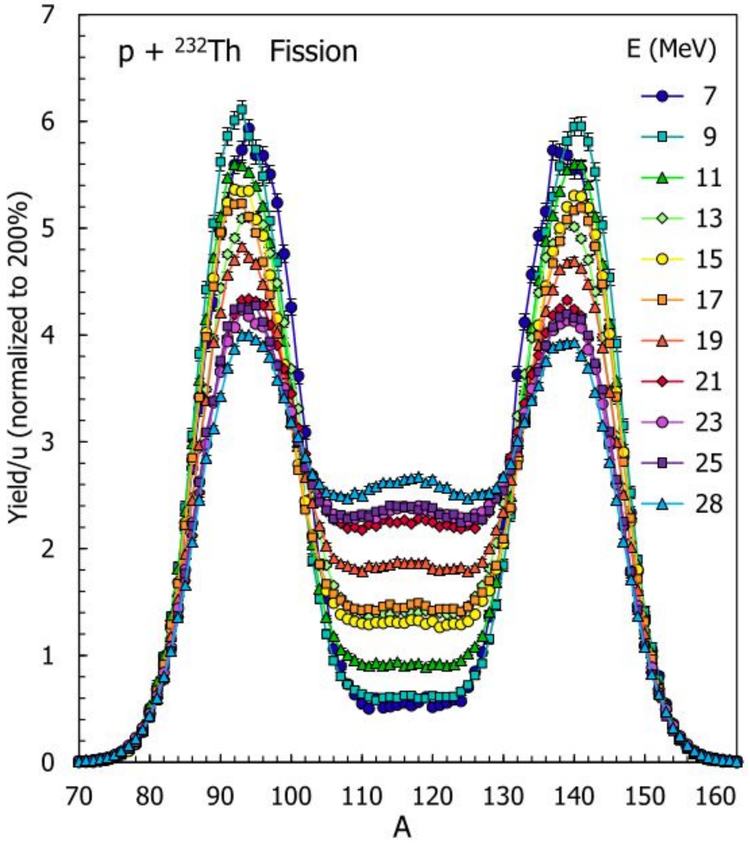
1. Experiment motivations



A.C. Berriman et al. Phys.Rev.C 105 (2022)

Shell effects damping

- Asymmetric fission for actinide driven by deformed magicity at Z = 52 and 56

Increase of the excitation energy of the fissioning system

- Lose shell structure impact
- Dampen the asymmetric yield in fission
- Highten symmetric yield

The goal is to quantify this effect

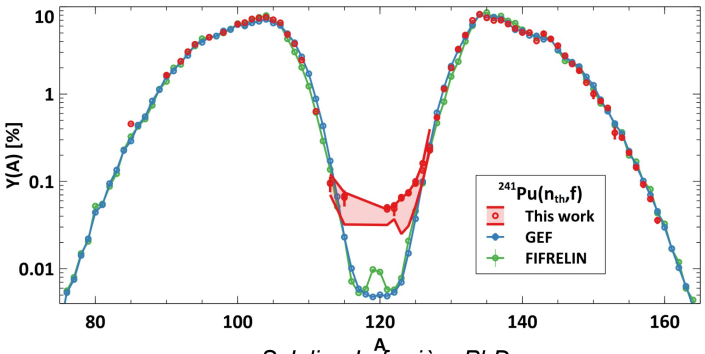
Plutonium 242 fissioning system

Main channel for this work

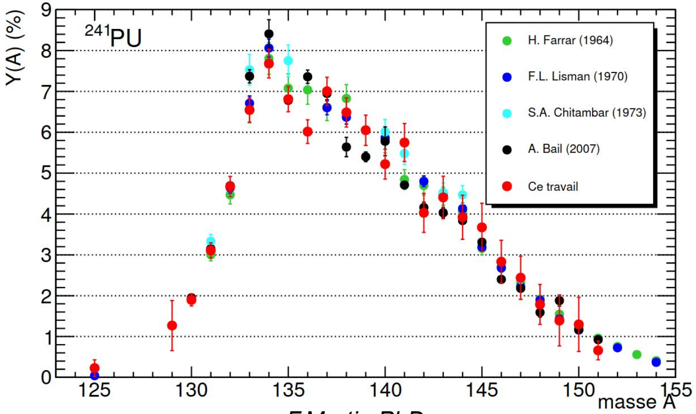
$$^{12}\mathrm{C}(^{238}\mathrm{U},^{242}\mathrm{Pu})^{8}\mathrm{Be} \rightarrow 2\alpha$$

- Equivalent to ^{241}Pu+n → **Useful for gen IV reactors**
- ^{241}Pu is **~17.6% of fissile Pu in MOX**
- ^{241}Pu has a **~ 14 years half-life** → hard to make a target
- Previous exp at ILL cannot measure all Z>40 and are thermal neutron induced

Plutonium 242 fissioning system



S.Julien-Laferrière PhD



F.Martin PhD

Previous experiment at ILL

$$^{241}\mathrm{Pu} + \mathrm{n}$$

- Thermal neutron induced
- Yields in A and Z
  - Gamma spectroscopy → heavy peak
  - Ionisation Chamber → light peak
- If half life of FF ≲2µs → cannot be measured

2. The setup

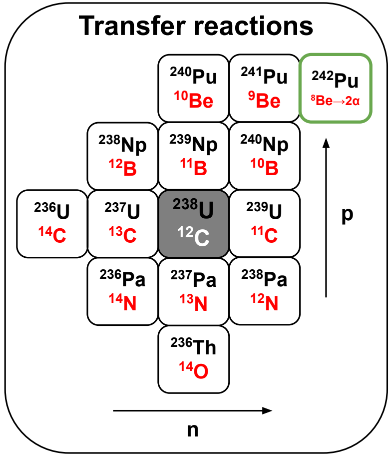
Experiment goals

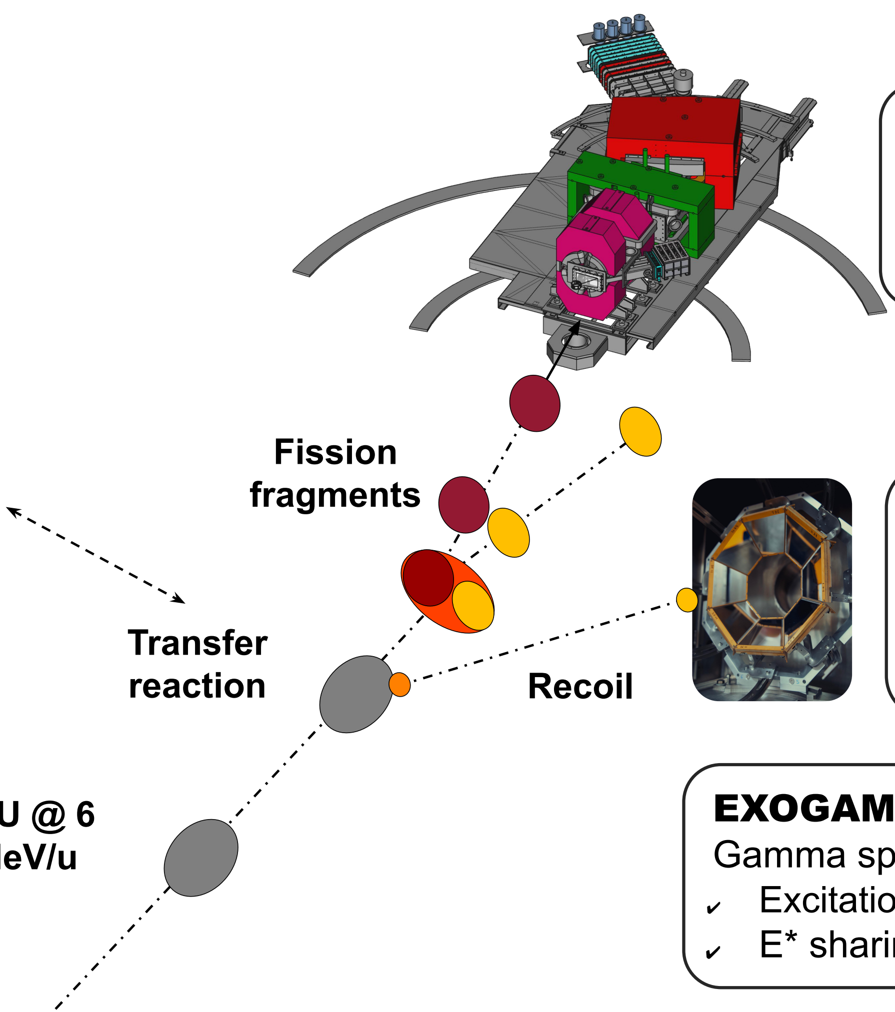
- Isotopic fission yields as a function of the excitation energy of the fissioning system $\left({}^{\mathbf{A}}\mathrm{Z}_{\mathbf{Parent}}\right)$ post neutron evaporation : **Y(A,Z,E*).**

The ingredients

1. Produce the ${}^{\mathbf{A}}\mathrm{Z}_{\mathbf{Parent}}$
2. Characterize the ${}^{\mathbf{A}}\mathrm{Z}_{\mathbf{Parent}}$ in **A Z and E***
3. Identify one of the **fission fragment in A and Z**

The setup





VAMOS
- ✔ Yield in mass and charge of fission fragments Y(A,Z)

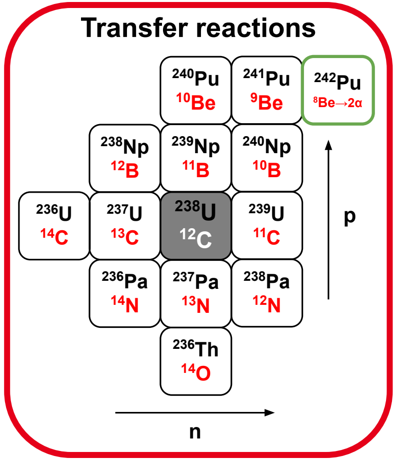
PISTA
Fissioning system
- ✔ A
- ✔ Z
- ✔ $(E_{lab},\theta_{lab}) \rightarrow E^*$

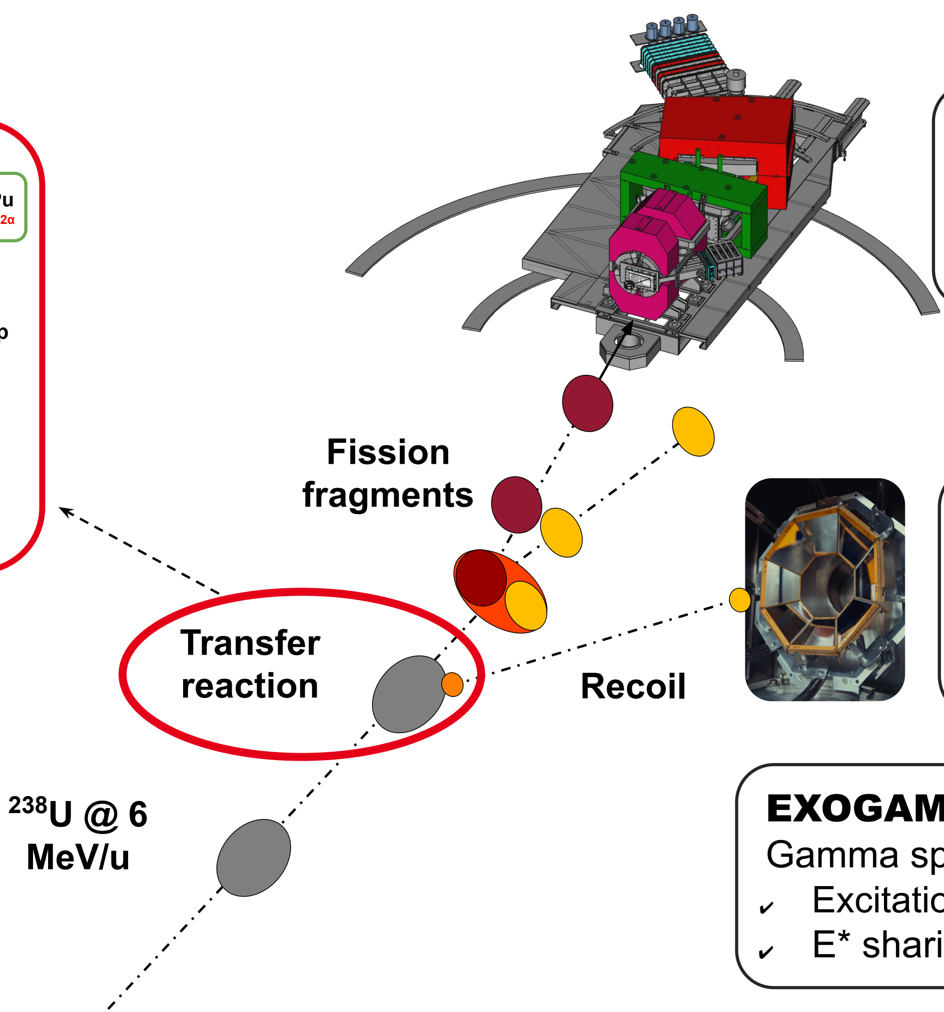
EXOGAM
Gamma spectrometer
- ✔ Excitation probability of recoil
- ✔ E* sharing between FF

First use of this setup (e850 exp)

June 2023

The setup





VAMOS

- Yield in mass and charge of fission fragments Y(A,Z)

PISTA

Fissioning system

- A
- Z
- $(E_{lab}, \theta_{lab}) \rightarrow E^*$

EXOGAM

Gamma spectrometer

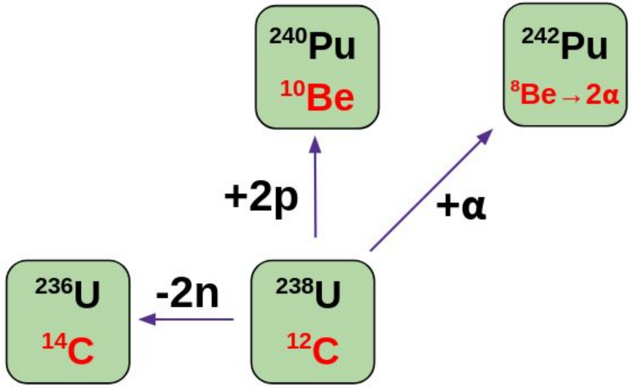
- Excitation probability of recoil
- E* sharing between FF

Inverse kinematics and surrogate reaction

- Some of our fissioning systems of interest are short-lived → Inverse kinematic enable their study (^{241}Pu ~ 14 years)
- FF will be boosted allowing charge identification for the full distribution
- Access desired system through transfer reaction

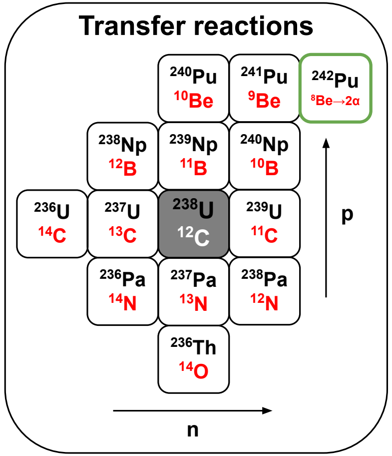
^{236}U(n+^{235}U), ^{240}Pu (n+^{239}Pu), ^{242}Pu(n+^{241}Pu)

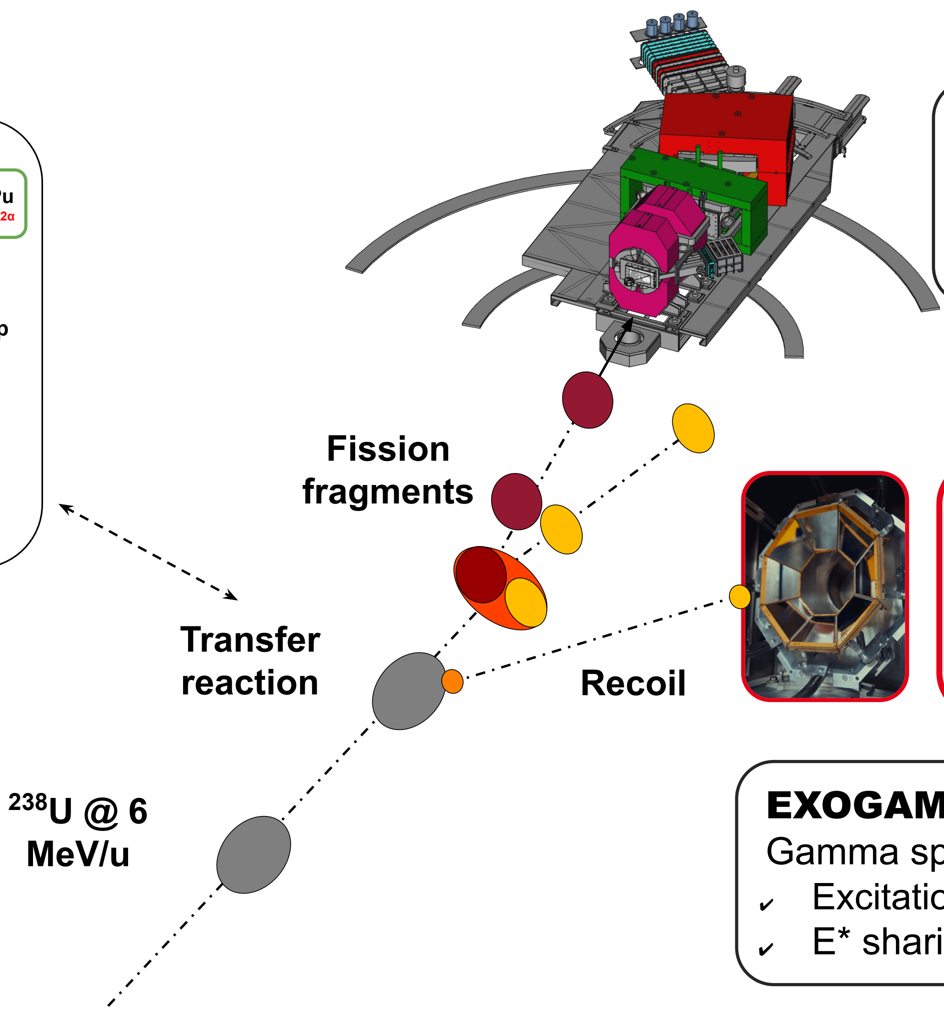
- Identification of the light recoil → characterize the fissioning system **A and Z**
- Angle and kinetic energy of the light recoil → missing mass → **E*** of the fissioning system



$$^{238}U + {}^{12}C \longrightarrow {}^{A}Z_{fiss} + {}^{A}Z_{recoil}$$

The setup





VAMOS
- ✓ Yield in mass and charge of fission fragments Y(A,Z)

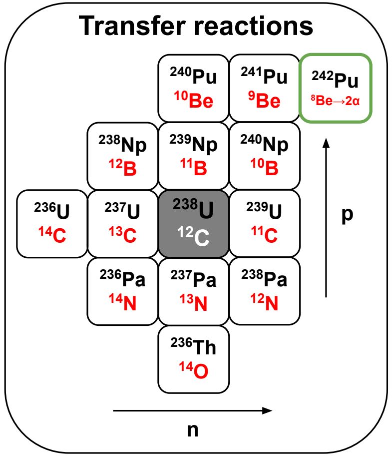
PISTA

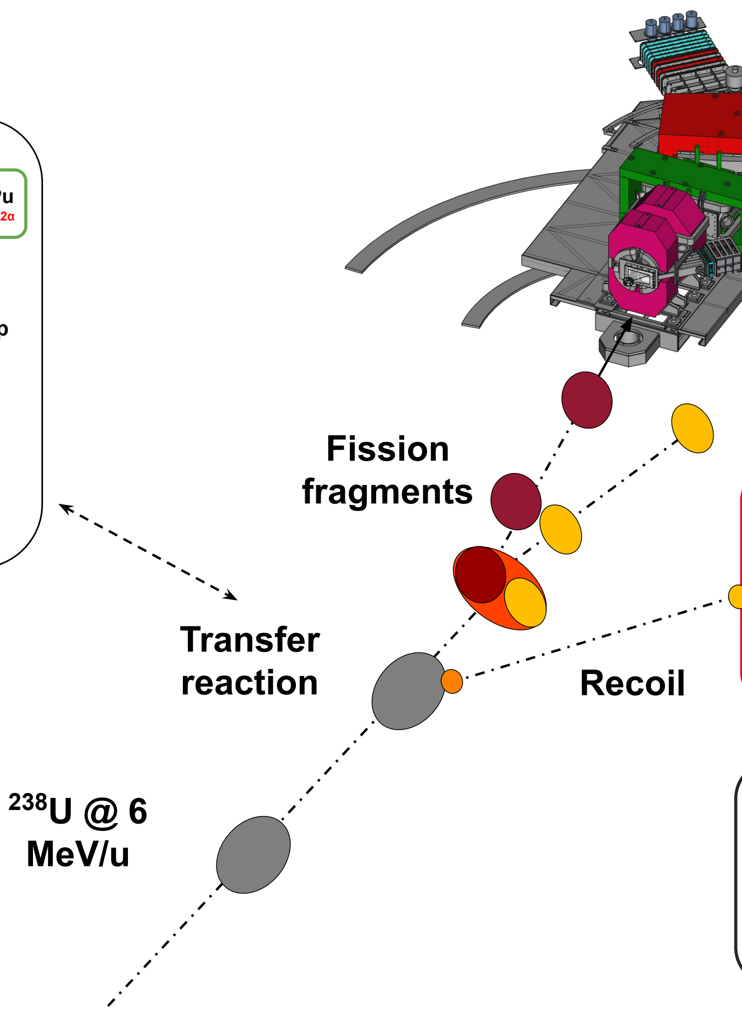
Fissioning system
- ✓ A
- ✓ Z
- ✓ $(E_{lab},\theta_{lab}) \rightarrow E^*$

EXOGAM

Gamma spectrometer
- ✓ Excitation probability of recoil
- ✓ E* sharing between FF

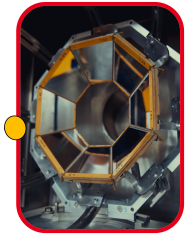
The setup





VAMOS
- ✔ Yield in mass and

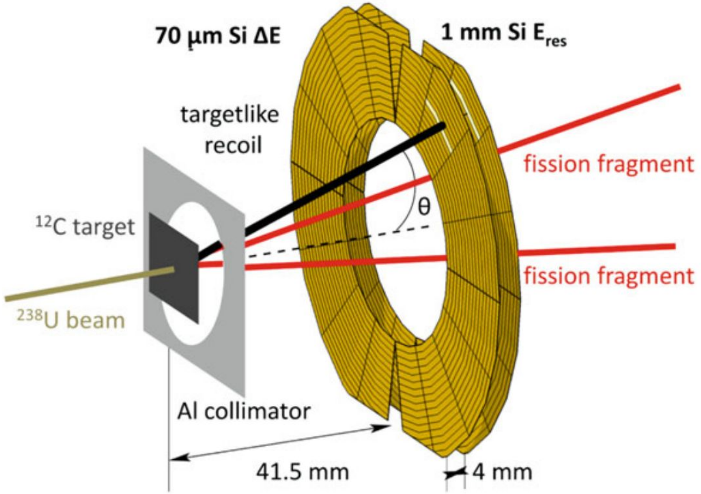
For more information see **L.Bégué-Guillou** presentation !



PISTA
Fissioning system
- ✔ A
- ✔ Z
- ✔ $(E_{lab},\theta_{lab}) \rightarrow E^*$

EXOGAM
Gamma spectrometer
- ✔ Excitation probability of recoil
- ✔ E* sharing between FF

Previous experiment



Rodríguez-Tajes, C., F. Farget, X. Derkx, M. Caamaño, O. Delaune, K.-H. Schmidt, E. Clément, et al. « Transfer reactions in inverse kinematics: An experimental approach for fission investigations ». *Physical Review C* 89, nº 2 (24 février 2014): 024614. https://doi.org/10.1103/PhysRevC.89.024614

Spider

GANIL Caen France

- Annular detector covering 30 to 47°
- E* resolution ~ 2.7 Mev (FWHM)
- 16 rings of 1.5 mm
- 16 sectors of 11° azimuthal range
- Angular resolution of about 1°
- Lots of result [1,2,3]

[1] M. Caamano et al. Phys. Rev. C 88 24605 (2013)
[2] C. Rodriguez-Tajes et al. Phys. Rev. C 89 024614 (2014)
[3] D.Ramos et al. Phys. Rev. C 97 054612 (2018)

Shortcoming

- E* resolution
- Some light recoil are ill-identified
- Counting rate too low for nuclear data

PISTA

A CEA-DAM + GANIL collaboration

Particle Identification Silicon Telescope Array

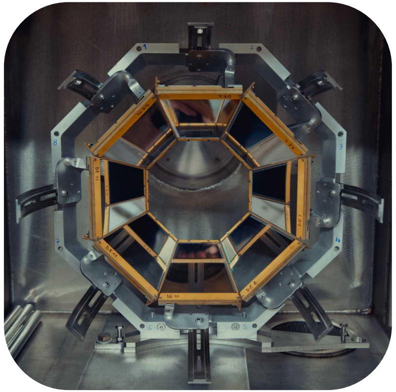
- Silicon semiconductor
- 8 Highly segmented ΔE-E telescope.
- E* resolution ~ 750 keV(FWHM)
- High count rate
- 30-60° coverage

ΔE First stage

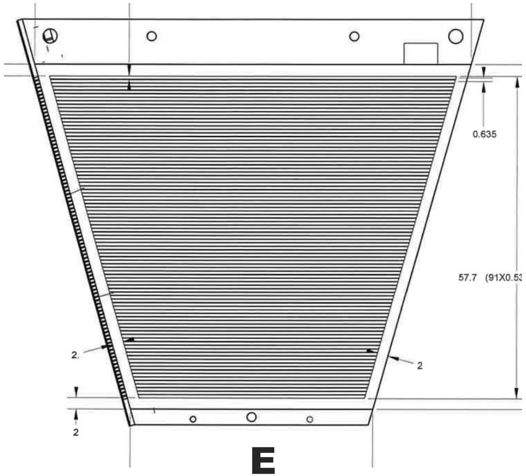
- 100 micrometer thick
- Stripped front
- 91 horizontal strips
- range : 0-60 MeV

E Second stage

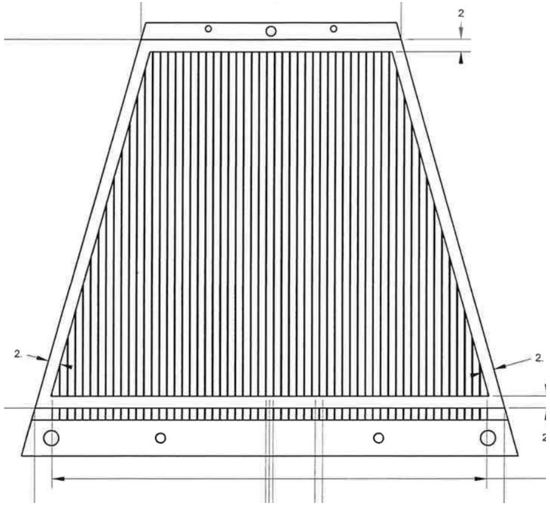
- 1mm thick
- Stripped front
- 57 vertical strips
- range : 0-200 MeV



ΔE

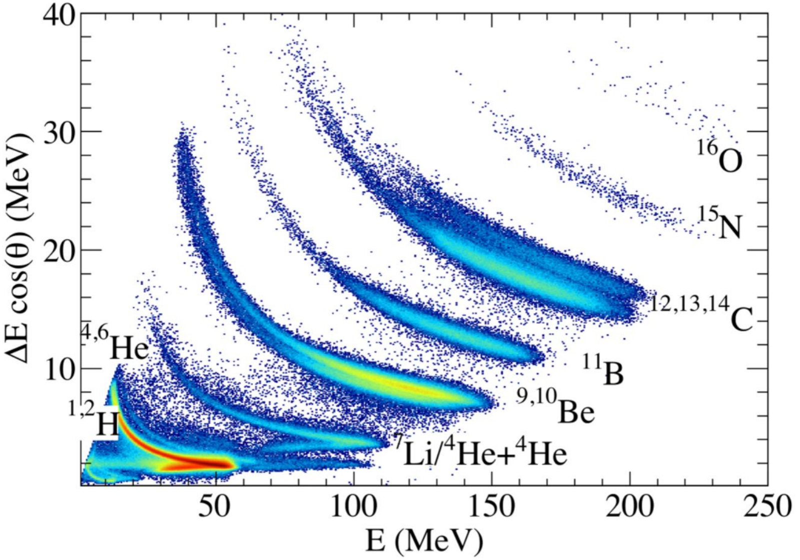


E



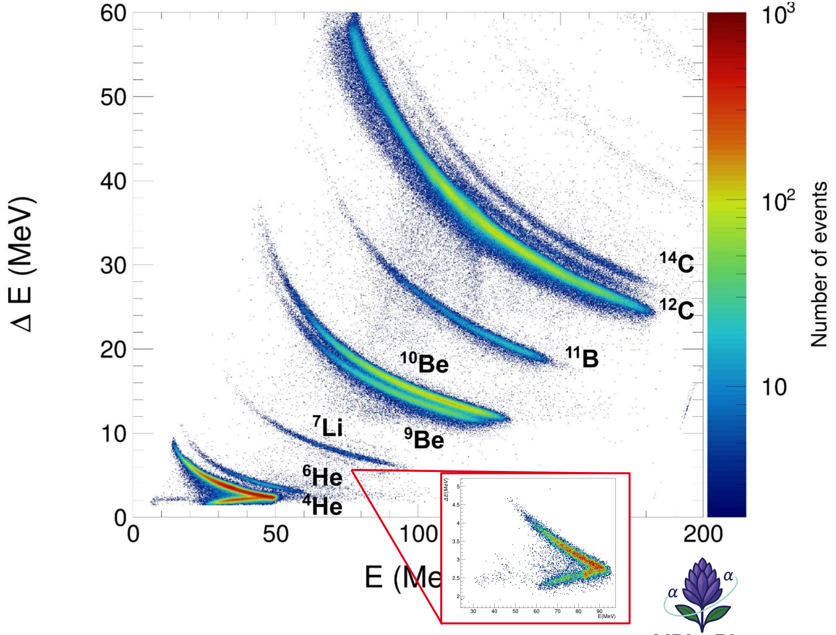
PID Comparison

Spider
(Previous generation)

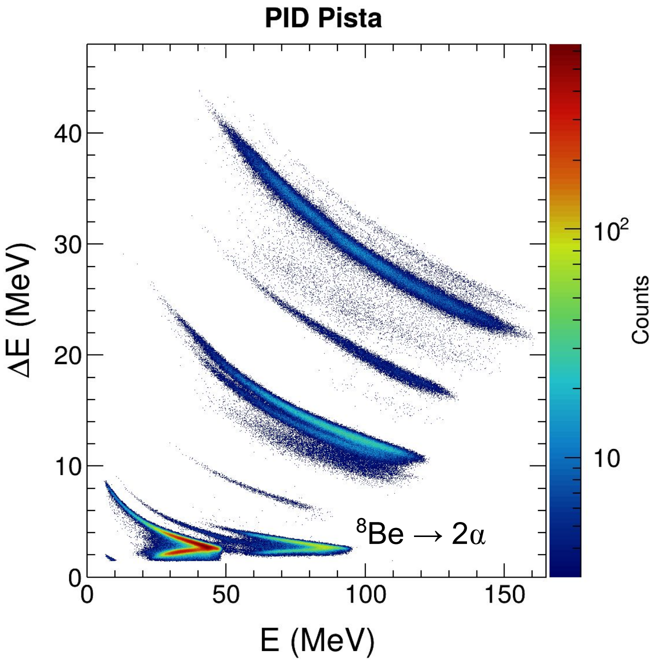


Ramos, D., M. Caamaño, F. Farget, C. Rodríguez-Tajes, L. Audouin, J. Benlliure, E. Casarejos, et al. « Isotopic Fission-Fragment Distributions of U 238 , Np 239 , Pu 240 , Cm 244 , and Cf 250

PISTA



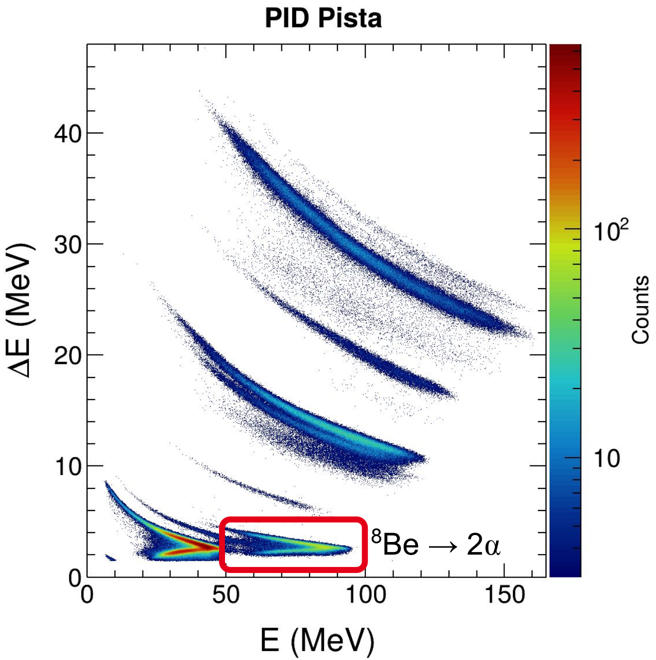
PID PISTA



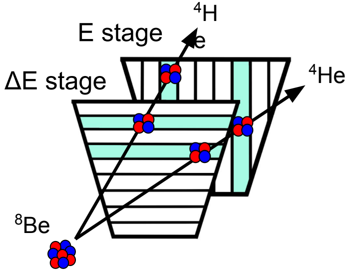
PID Pista
ΔE (MeV)
E (MeV)
Counts
$^{8}Be \rightarrow 2\alpha$
0
10
20
30
40
50
100
150
10^2

PID PISTA

PISTA highly efficient in this channel due to high granularity



AlPhaPha
^{8}Be → 2α



$$\begin{matrix} E_1 & E_2 \\ \theta_1 & \theta_2 \end{matrix} \rightarrow \begin{matrix} E_{lab} \\ \theta_{lab} \end{matrix}$$

PID PISTA

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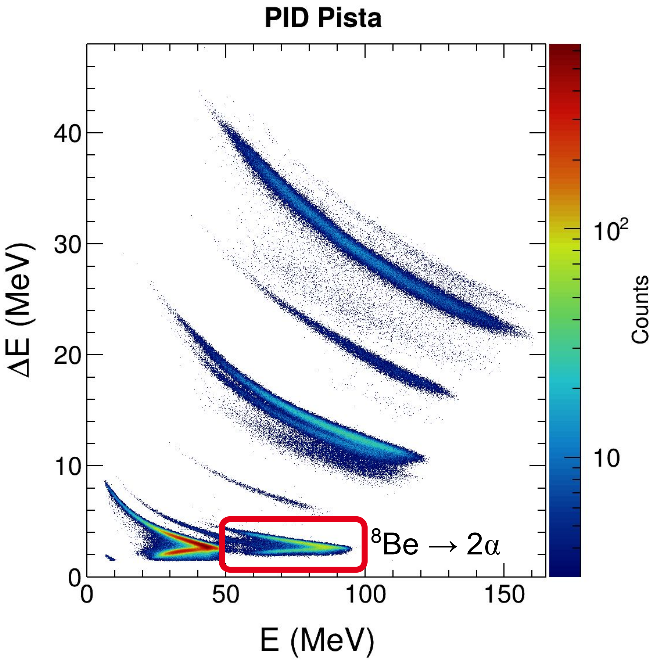

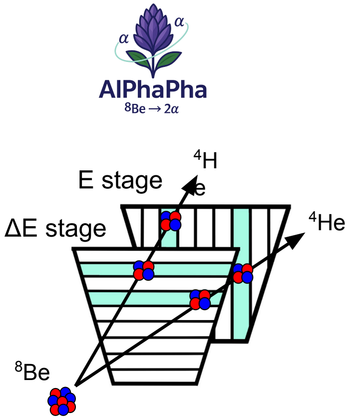

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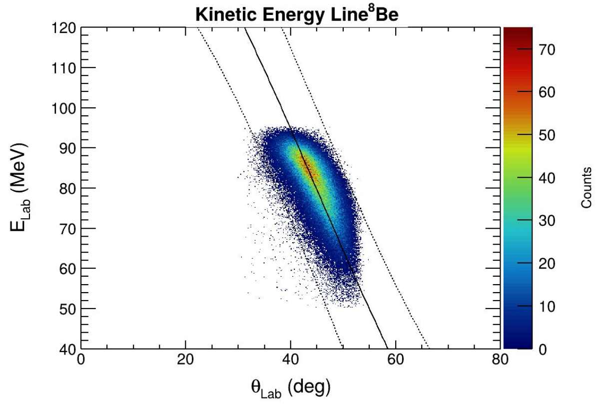

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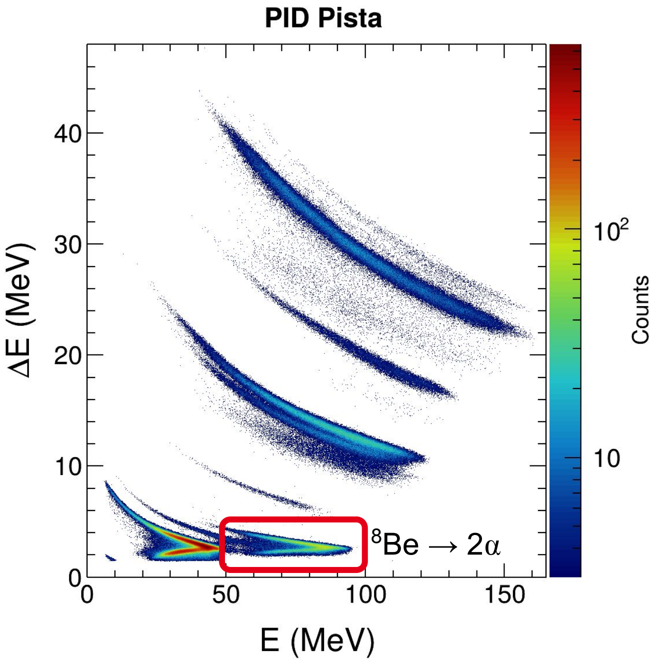

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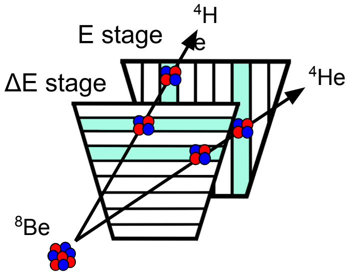
$^8Be \rightarrow 2\alpha$



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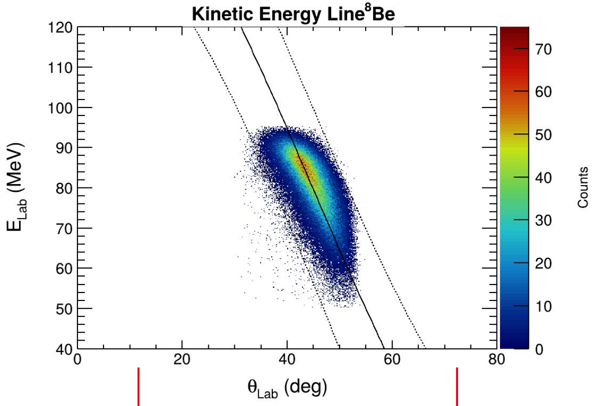
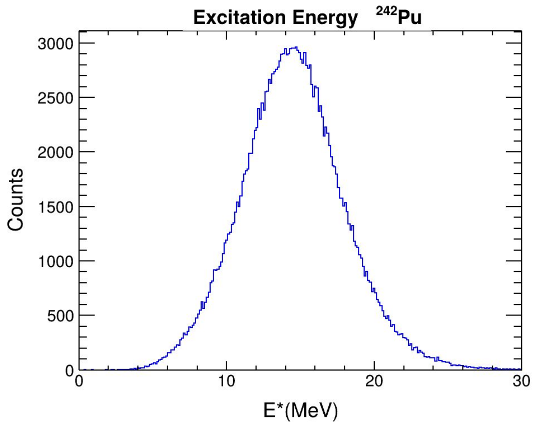
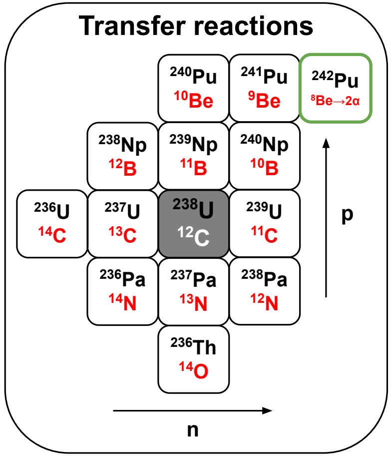
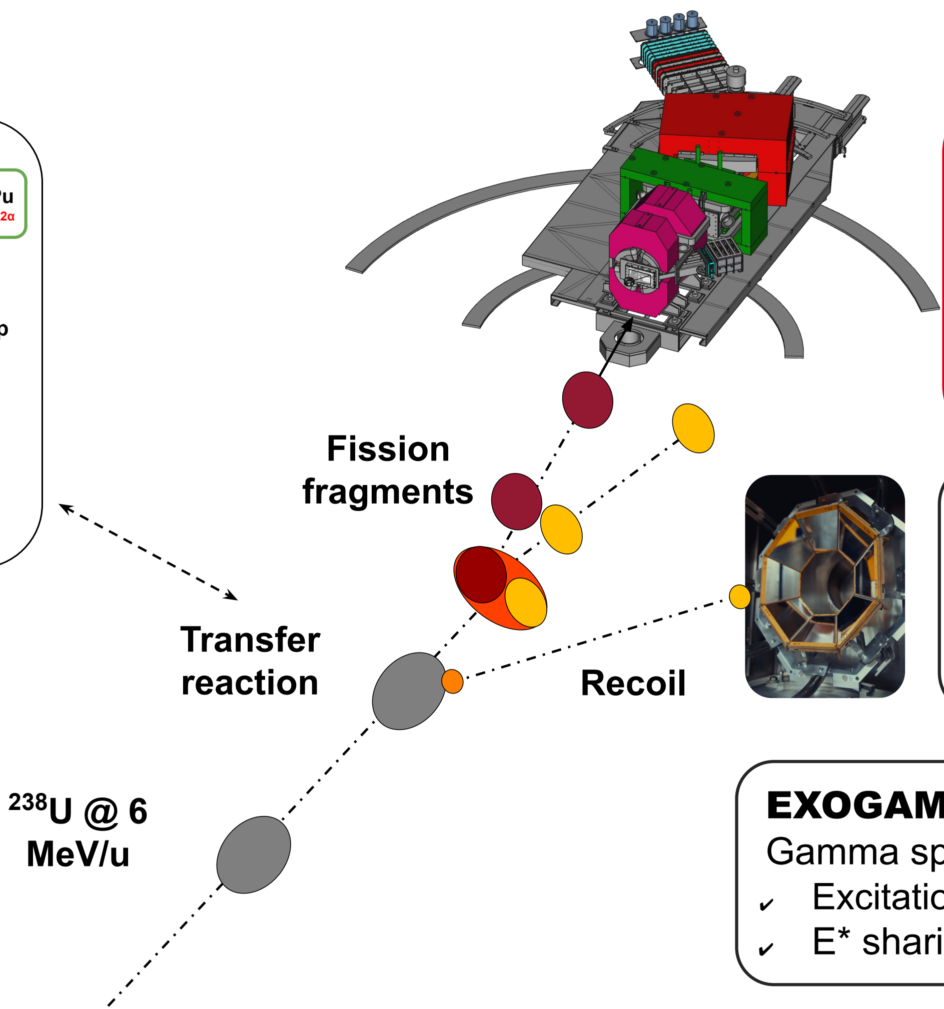




The setup





VAMOS

- Yield in mass and charge of fission fragments **Y(A,Z)**

~150-300 ns after fission
→**post neutron FF**

PISTA
Fissioning system
- A
- Z
- $(E_{lab},\theta_{lab}) \rightarrow E^*$

EXOGAM
Gamma spectrometer
- Excitation probability of recoil
- E* sharing between FF

VAMOS++
VAriable MOde Spectrometer

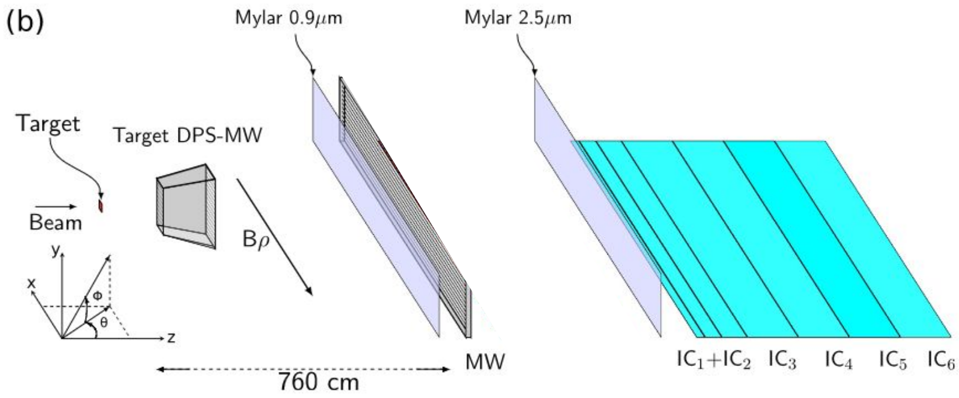
Observable

- Magnetic rigidity Bρ
- Velocity vector
- Trajectory length
- ΔE-E

Detector

- **IC** : ΔE-E → Z
- **MWPC + IC** : ToF + Bρ + ΔE-E → A

We get total identification of one of the fission fragment from those observables.



Fast trajectory reconstruction techniques for the large acceptance magnetic spectrometer VAMOS++ A. Lemasson ∗, M. Rejmund

VAMOS++

VAriable MOde Spectrometer

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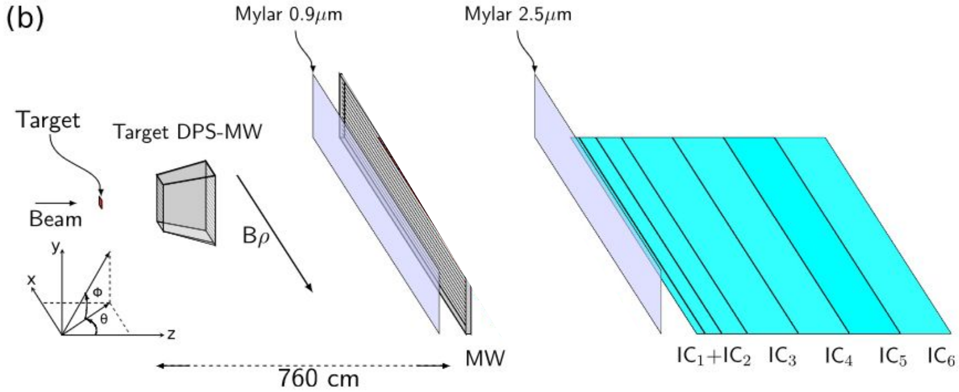
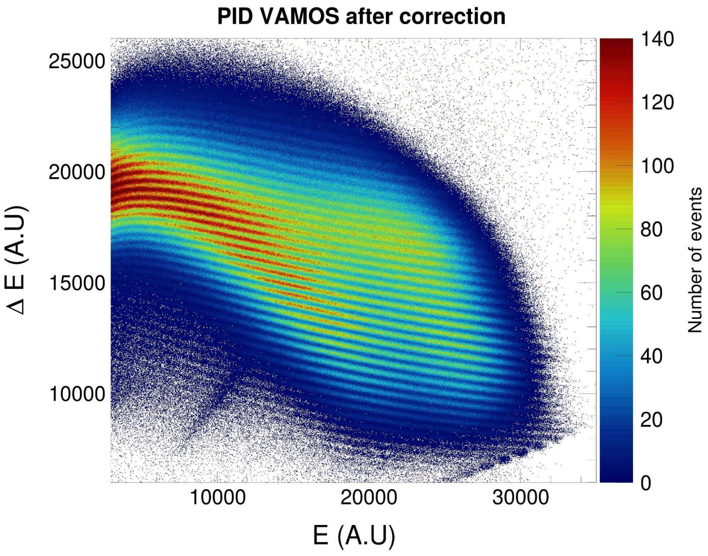


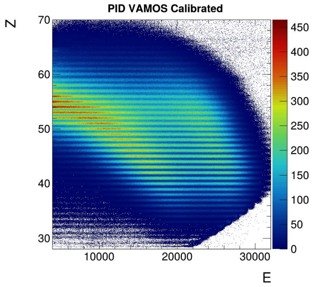
Fast trajectory reconstruction techniques for the large acceptance magnetic spectrometer VAMOS++ A. Lemasson ∗, M. Rejmund

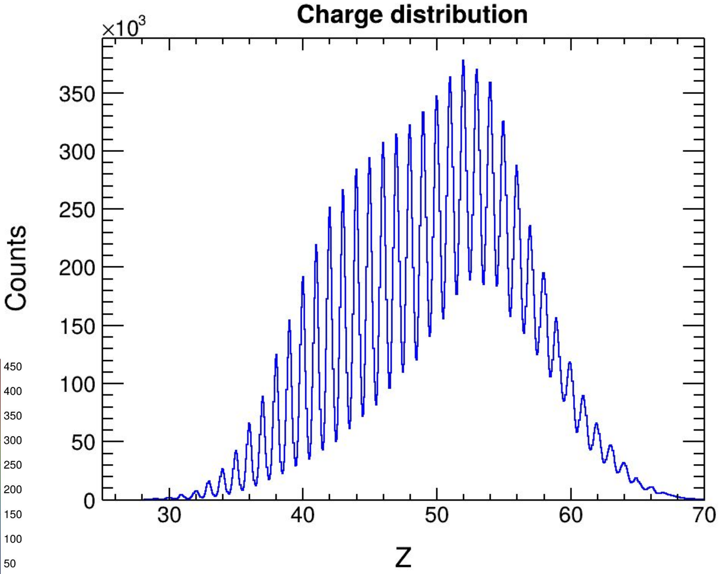
VAMOS++

Charge distribution

- ΔE-E in IC of VAMOS
- Resolution ΔZ/Z = 1.31







VAMOS++
VAriable MOde Spectrometer

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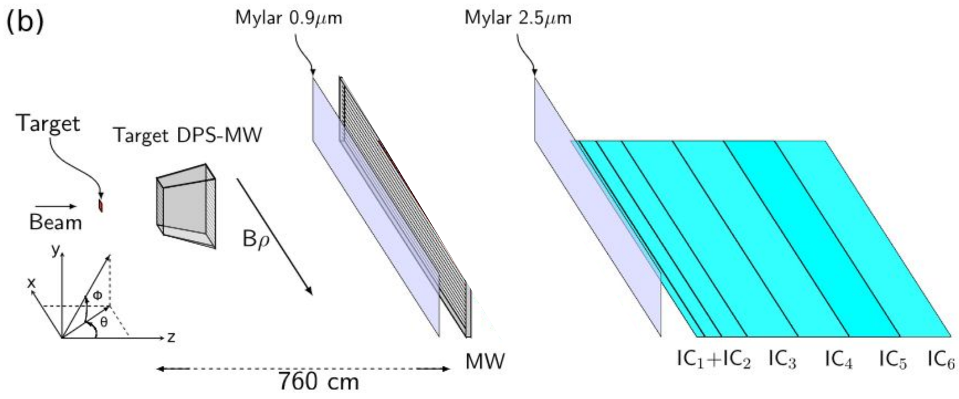
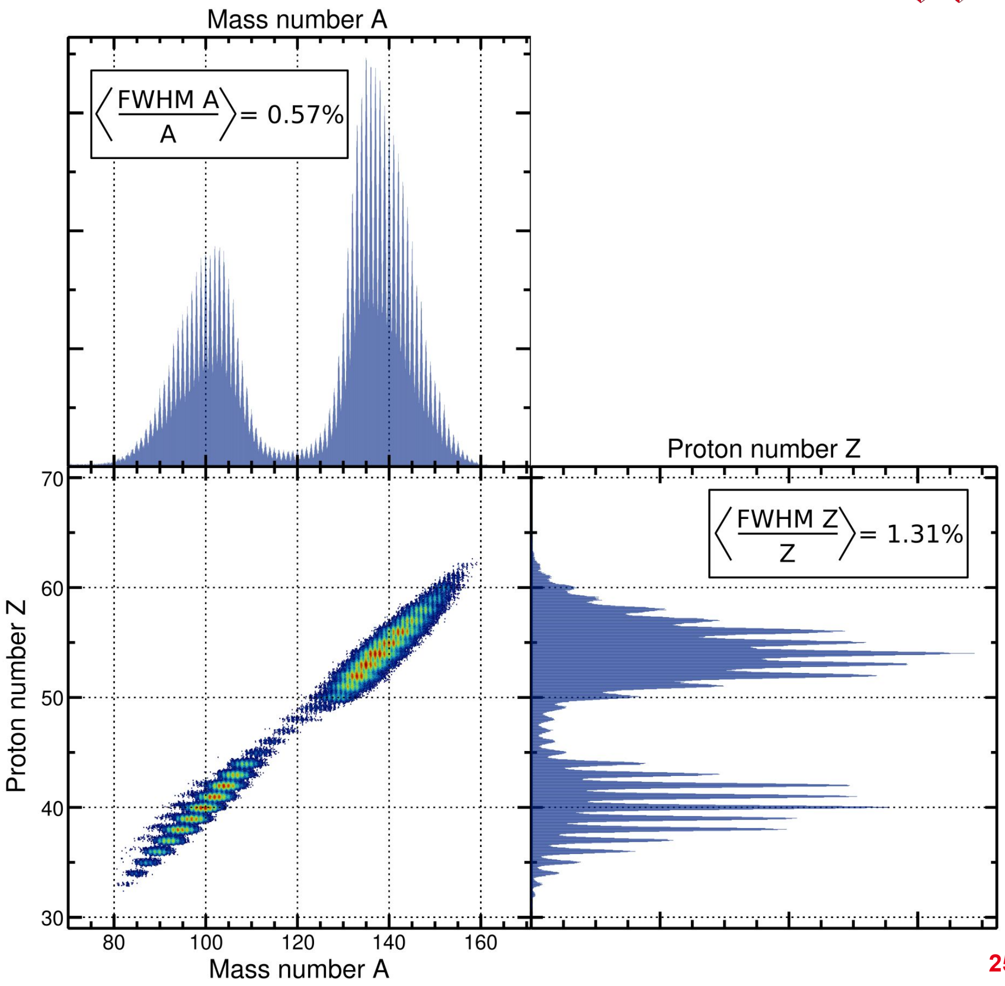


Fast trajectory reconstruction techniques for the large acceptance magnetic spectrometer VAMOS++ A. Lemasson ∗, M. Rejmund

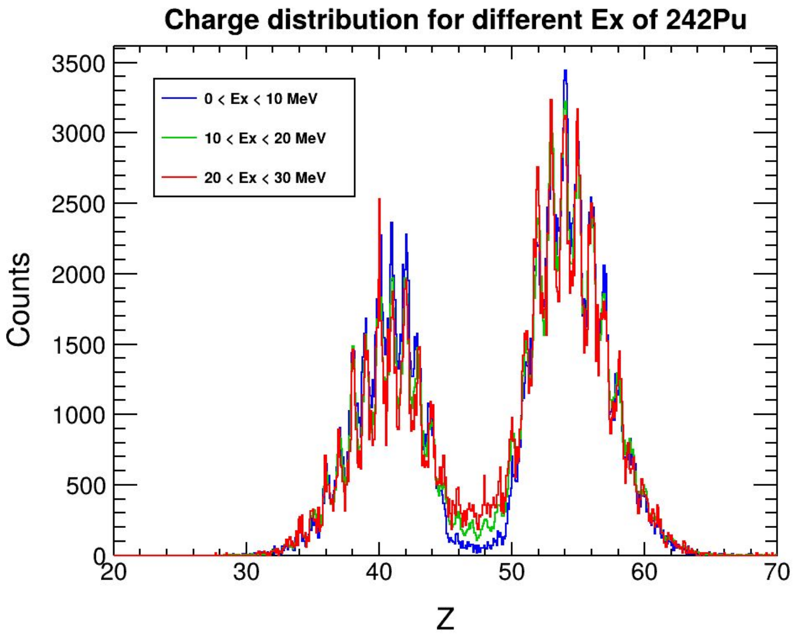
VAMOS++
VAriable MOde Spectrometer

We measure the mass using the following set of formulae

$$\begin{cases} \dfrac{A}{q} = \dfrac{B\rho}{3.107 \cdot \beta \cdot \gamma} \\[2ex] M_{inv} = \dfrac{E}{931.494(\gamma - 1)} \\[2ex] q_{int} = \dfrac{M_{inv}}{\frac{A}{q}} \\[2ex] A = \dfrac{A}{q} \cdot q_{int} \end{cases}$$



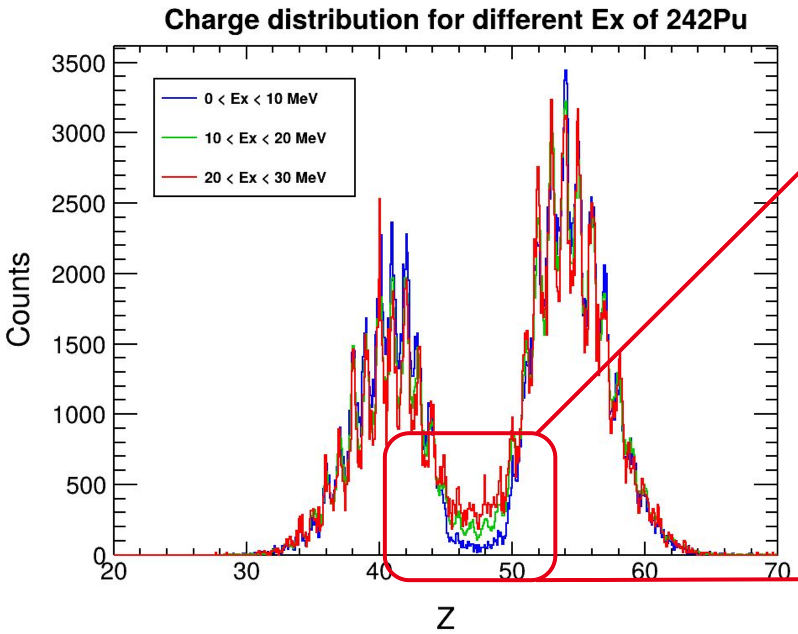
Preliminary result

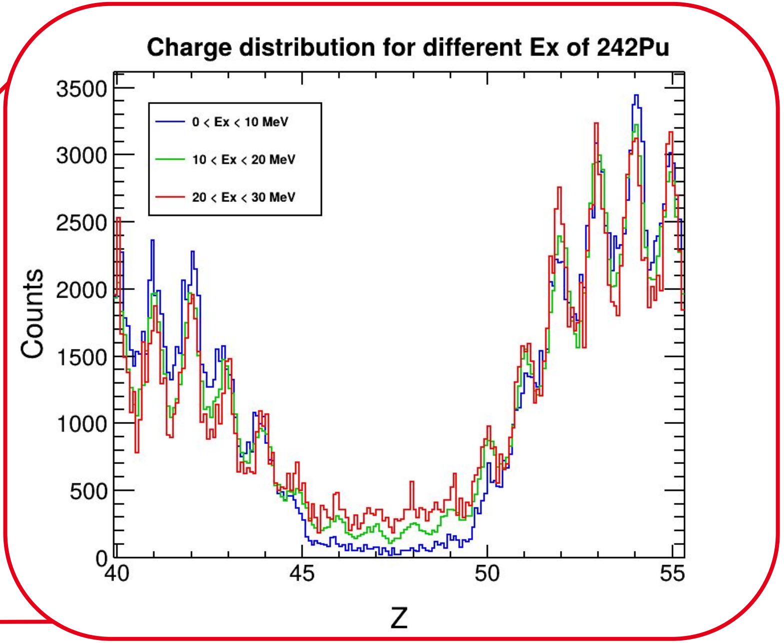


Charge distribution depending on E*

- Not corrected by VAMOS acceptance
- Symmetric yield rise with E*
- Preliminary result encouraging

Preliminary result





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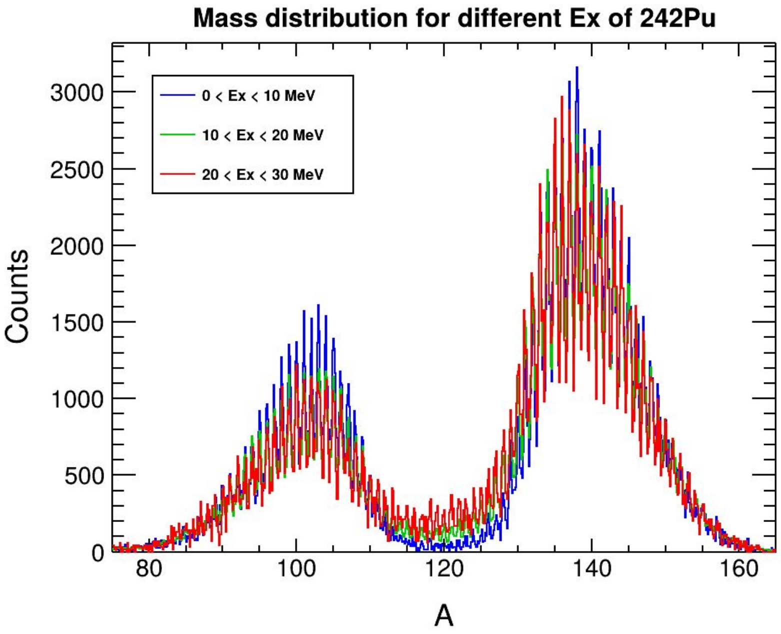

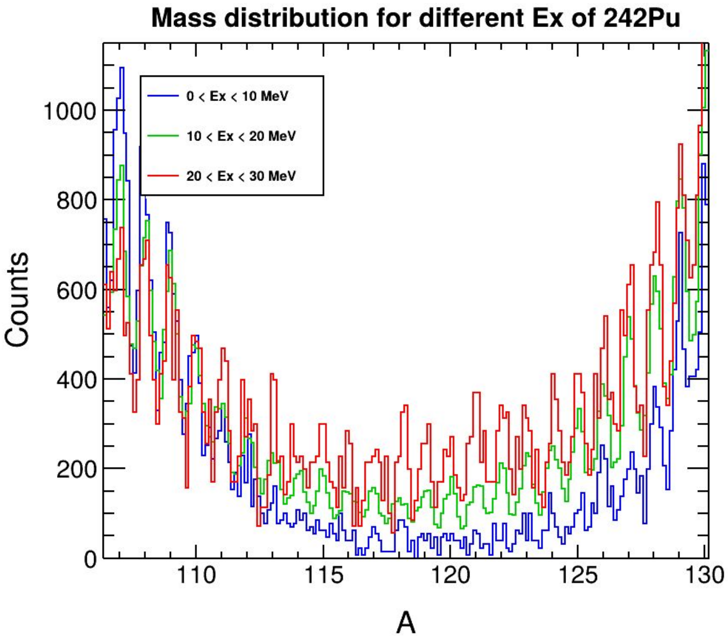

3. Conclusion

Conclusion and perspective

- Encouraging preliminary results on this experiment
- Identification of fissioning system is finalised
- Identification of the fission fragment in A and Z is finalised
- Now the acceptance of VAMOS needs to be evaluated in order to get to the final yields.
- “first” data for non-thermal yield for ^{242}Pu

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Thanks for your attention !
Feel free to ask questions.

T.Efremov[1,2], A.Chatillon[1,2], A.Graña González[1,2], C.Lenain[1,2], B.Mauss[1,2], P.Morfouace[1,2], J.Taieb[1,2], L.Bégué-Guillou[3], A.Cobo[3], A.Francheteau[3], A.Lemasson[3], D.Ramos[3], M.Rejmund[3]
and all the Fission@VAMOS collaboration …

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Contact : theodore.efremov@cea.fr

4. BACKUP

PID Interpretation

Beam of 238U at ~6 Mev/A
→ **1428 Mev**

KE max of Be 8 : **200 Mev**

$$\beta = \frac{\vec{P}}{E} = \frac{\sqrt{T^2 + 2mT}}{T + m}$$

β ~ 0.22 , βγ ~ 0.23

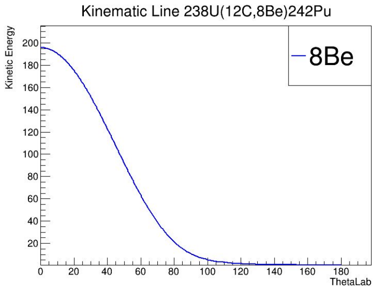
Bethe simplify

$$-\frac{1}{\rho}\left\langle \frac{dE}{dx} \right\rangle = \frac{2\pi z^2 e^4}{m_e v^2} \frac{Z}{A} N_A \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right]$$

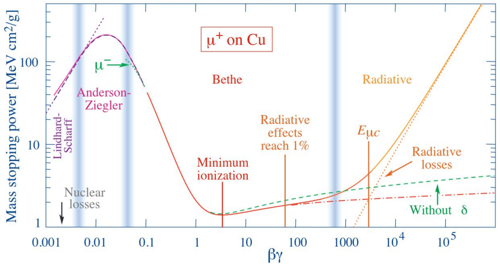
Source : Matthew Charles detector courses

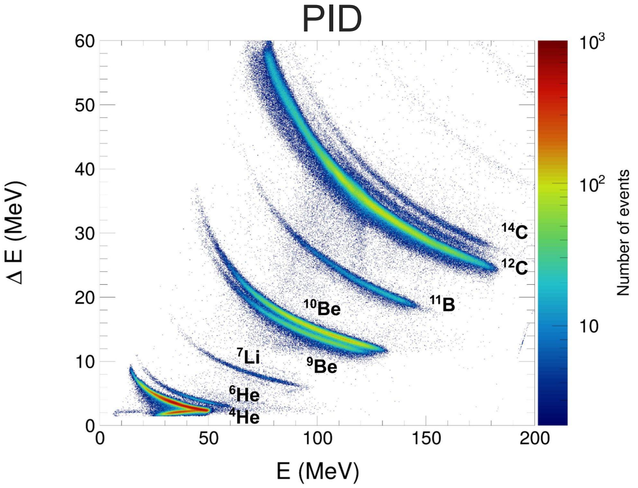
$$\frac{dE}{dx} \propto \frac{z^2}{v^2} \propto \frac{z^2 M}{T}$$

$$\boxed{\Delta E = \frac{Z^2 A u}{E}}$$



Source : PDG



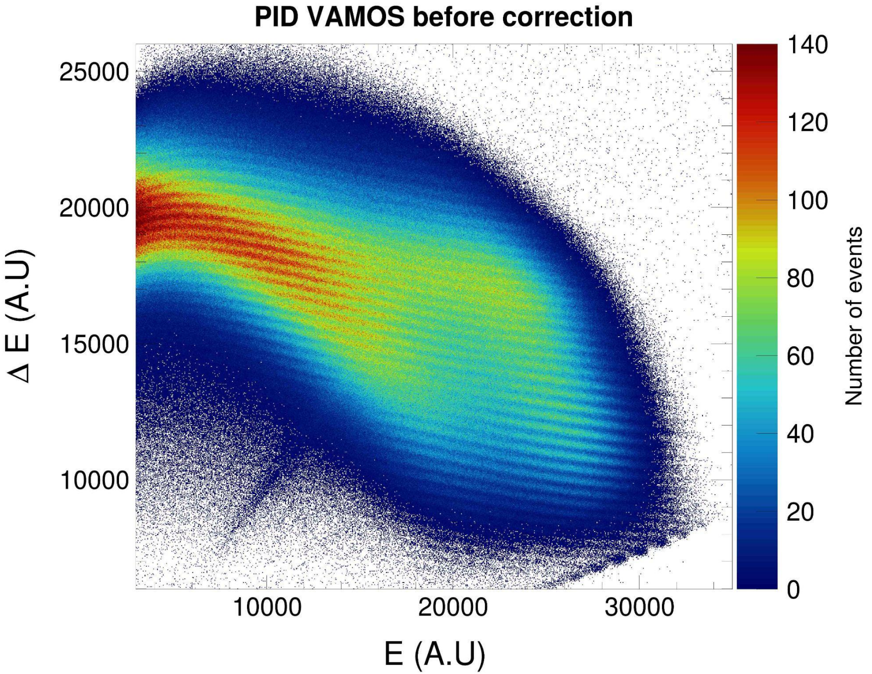


Work done on VAMOS

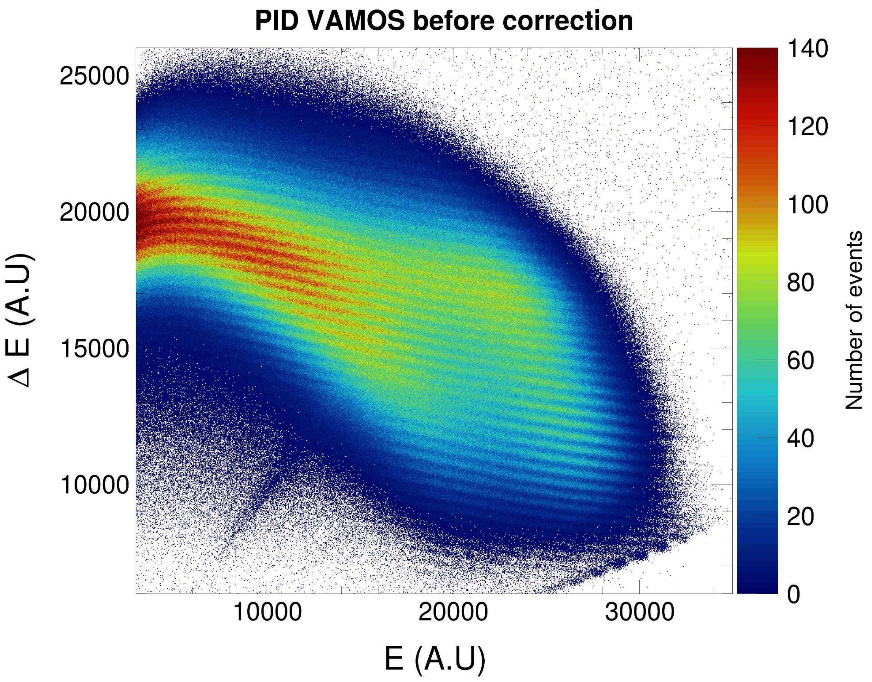
Enhancement of Z Resolution

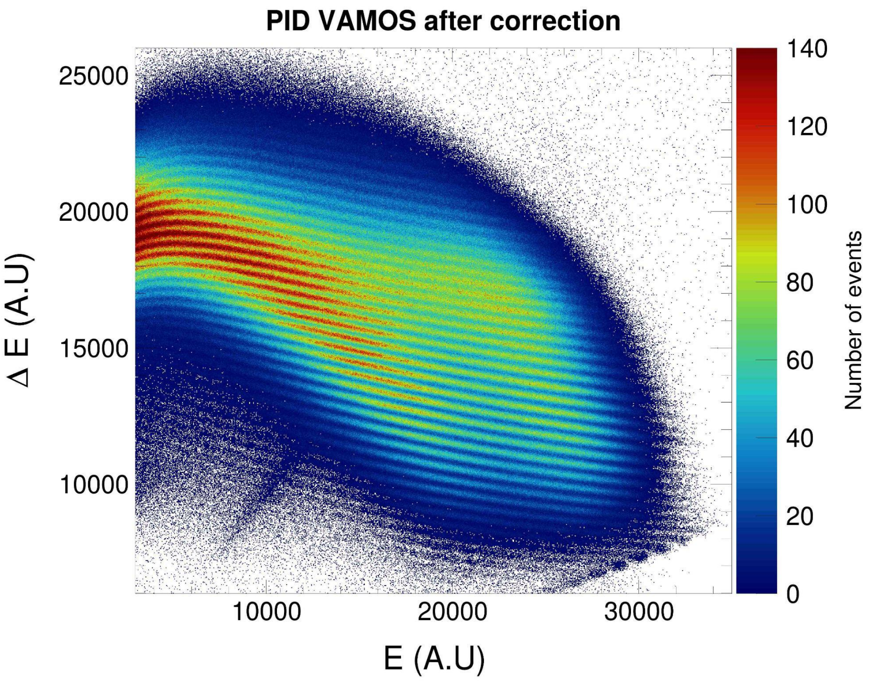
Corrections on IC output :

- As a function of Xf and Yf for the two first layer of the IC
- As a function of Yf for the later IC layer
- As a function of Θ_f



Work done on VAMOS
Enhancement of Z Resolution





Work done on VAMOS

Mass calibration

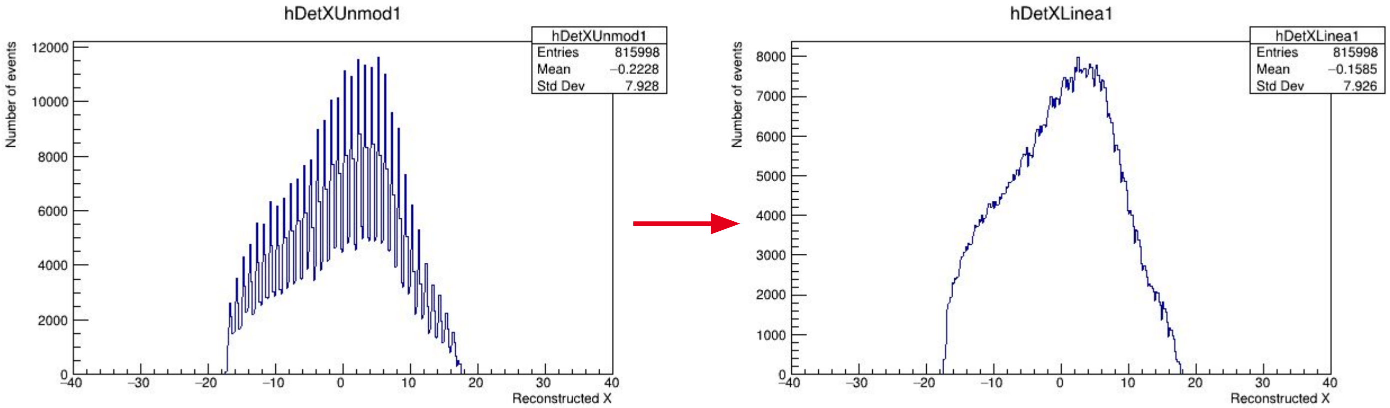
The mass distribution in VAMOS is reconstructed by using

- The position on the focal plane
- The Time of flight of the fission fragment(FF)
- The Q of the FF
- The Brho and Path of the FF

Each of these aspects have been calibrated to recover the mass of the FF.

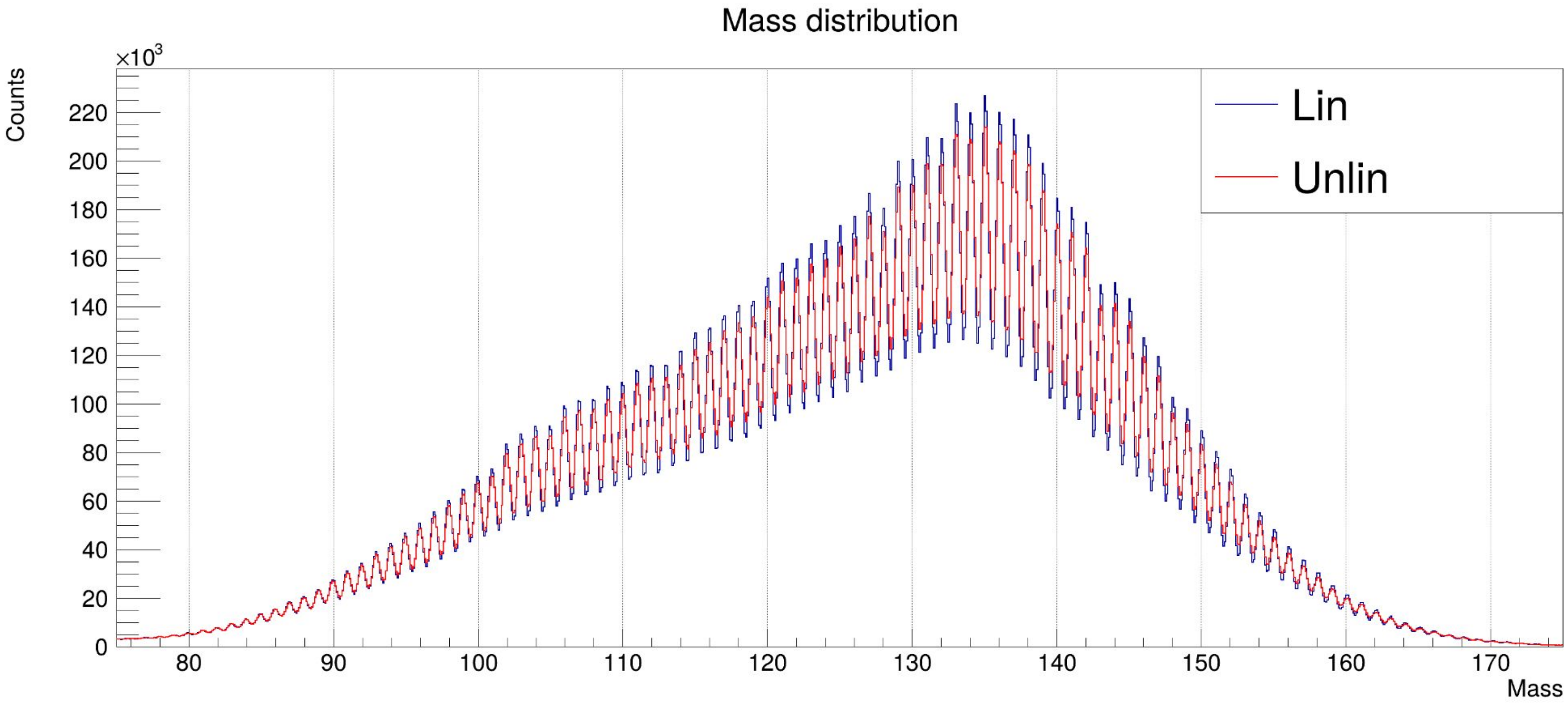
Work done on VAMOS
MWPC Linearisation

- The MWPC Output is peaked around each wire
- Resolution is then half of the wire distance
- We can improve that !



Work done on VAMOS

MWPC Linearisation

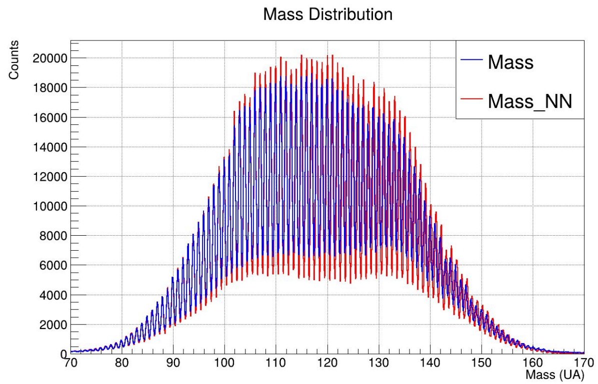


Work done on VAMOS

NN for Brho and Path

- The **Brho and the Trajectory length** are reconstructed using the **electric and magnetic field map of VAMOS**.
- There is a compromise between the **size of those maps** and the **accuracy of our Brho and Path reconstruction.**
- A new method using **multi layer perceptron** has been developed to alleviate this issue.

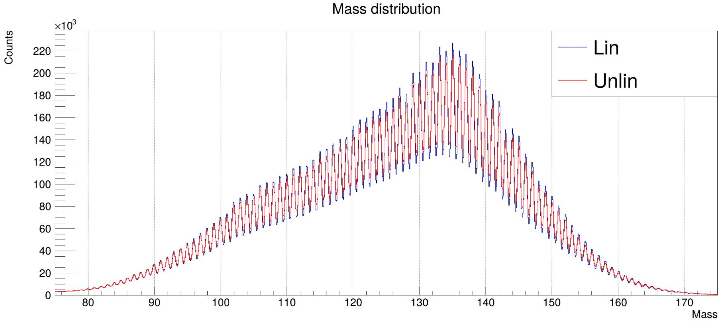
frugally-**deep**



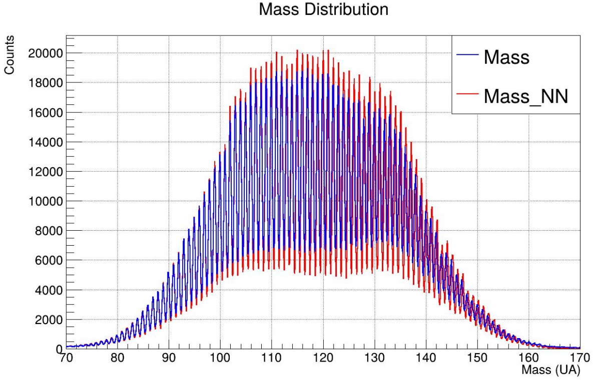
Work done on VAMOS

Mass calibration

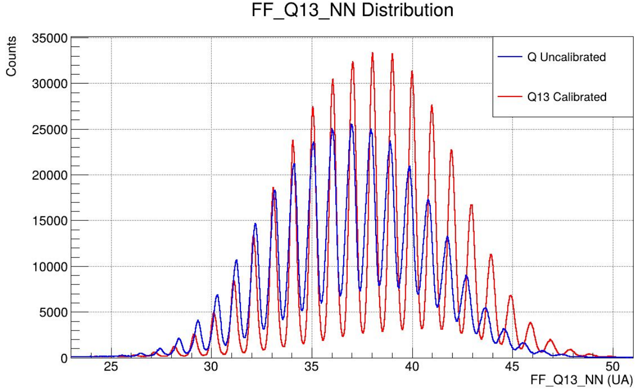
MWPC Linearisation



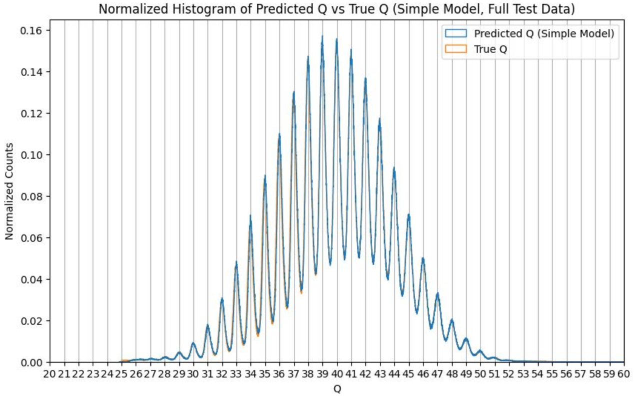
NN for Brho and Path



Calibration of Q

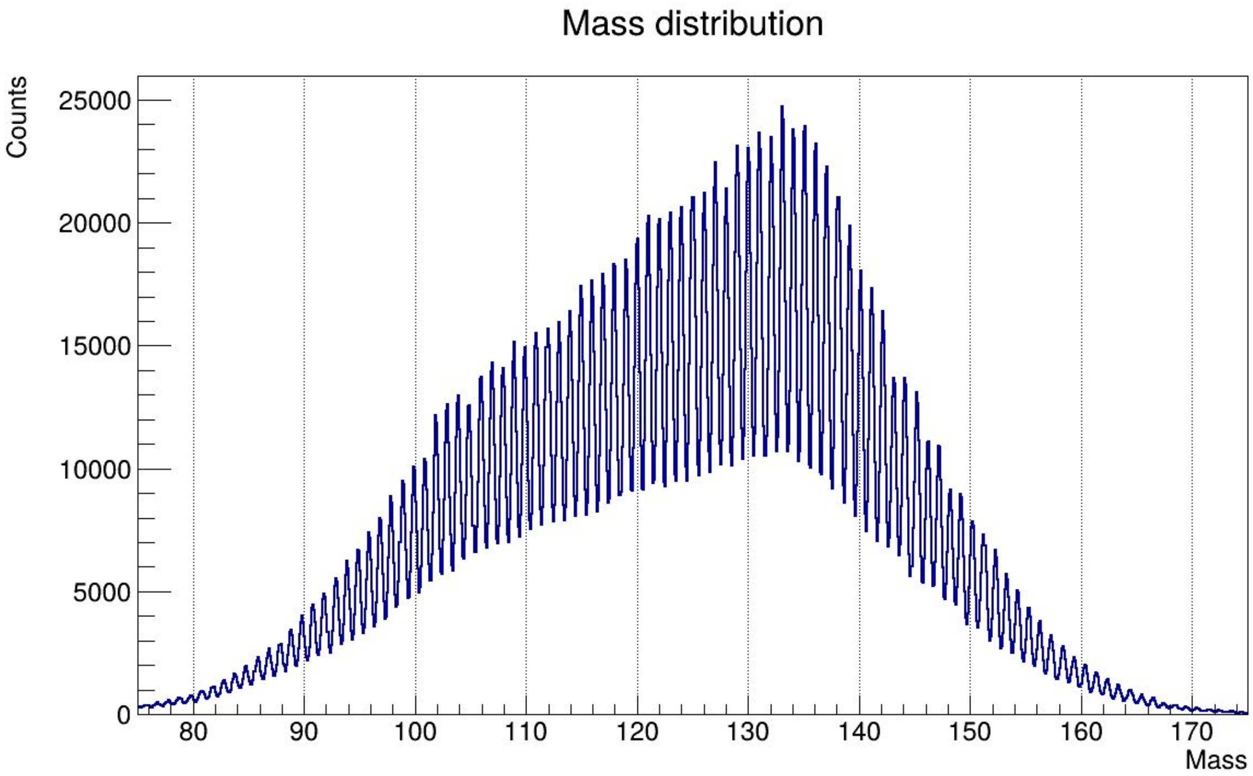


NN for Q



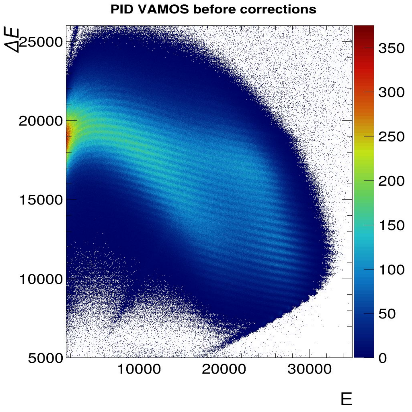
Work done on VAMOS

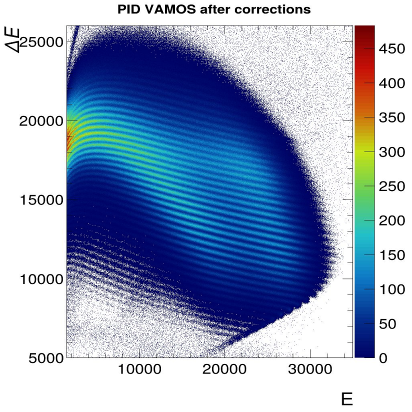
Mass calibration



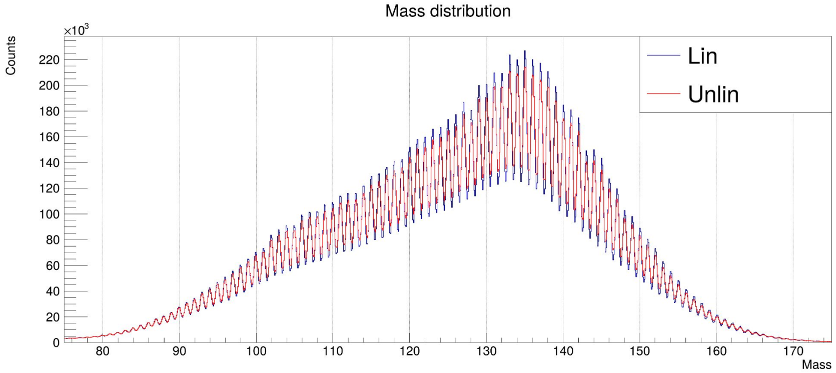
Conclusion

- **Charge calibration**
  - Correction of IC output position dependency
  - Check remaining correlation with trajectory of FF and correct the one in theta





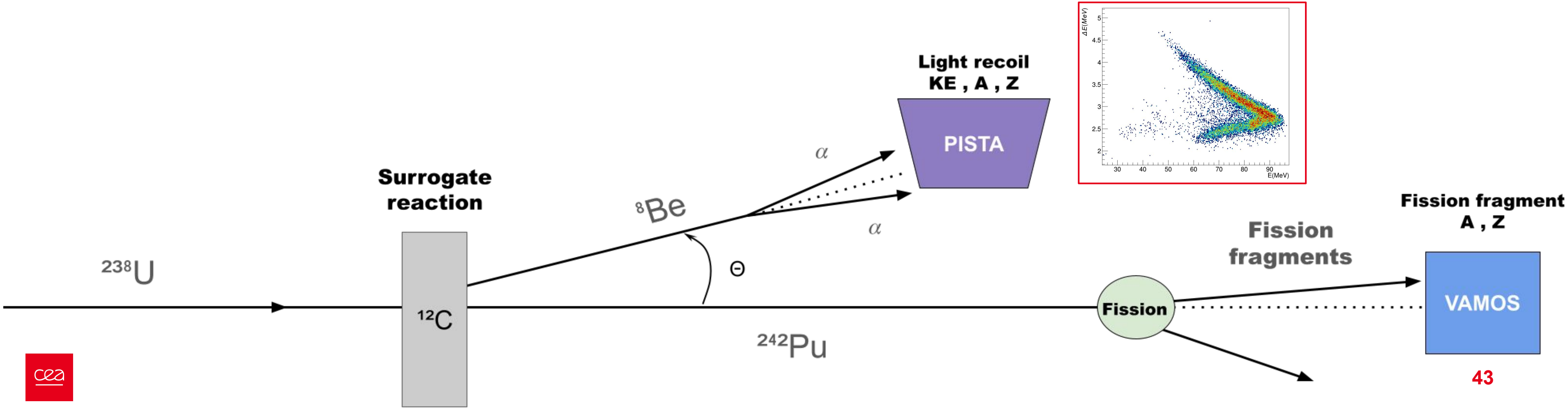
- **Mass calibration**
  - Linearisation of MWPC readout
  - Time offset for each MWPC
  - Implementation of NN for Brho and Path reconstruction
  - Automatic procedure for charge state calibration



^{242}Pu channel

$$^{238}U(^{12}C,^{8}Be \rightarrow 2\alpha)^{242}Pu$$

- Multiplicity 2 in PISTA tag the event
- High count rate
- Better excitation resolution (500 keV)
- Punch through energy can be reconstructed

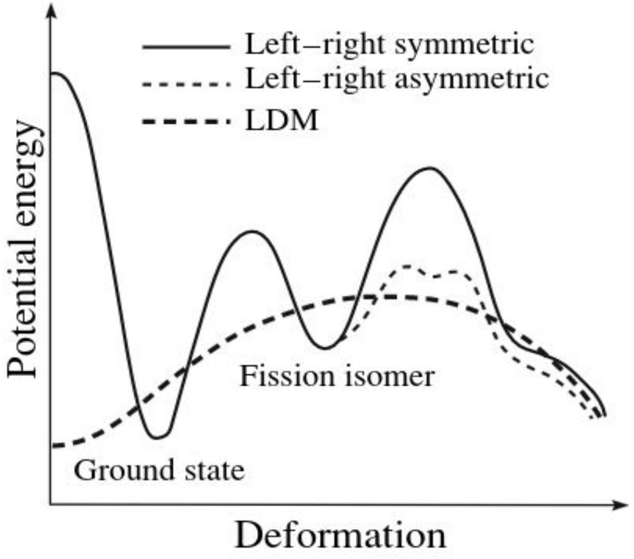


Nuclear Fission

- One of the most extreme reaction a nucleus can endure
- Deformation of the nucleus until it splits

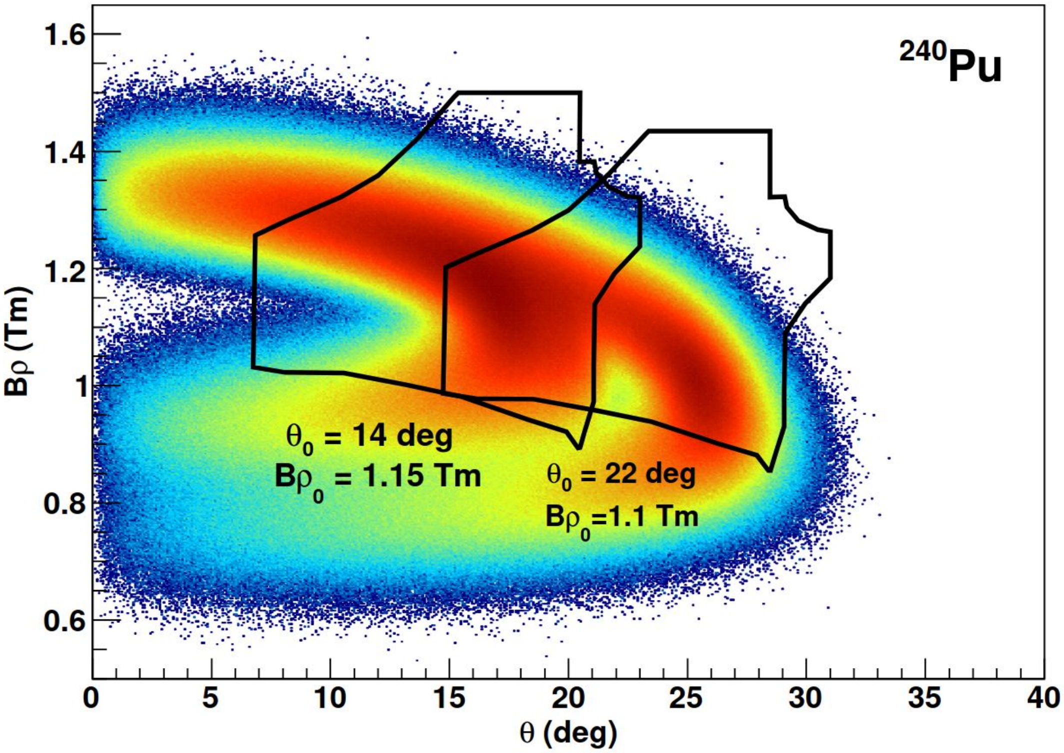
Microscopic / Macroscopic

- Shell effect → double humped fission barrier
- Asymmetric deformation → lower fission barrier



A. G. Magner et al. "Shell structure and orbit bifurcations in finite fermion systems". In: Physics of Atomic Nuclei 74.10 (Oct. 2011), pp. 1445–1477.

VAMOS Phase space



VAMOS

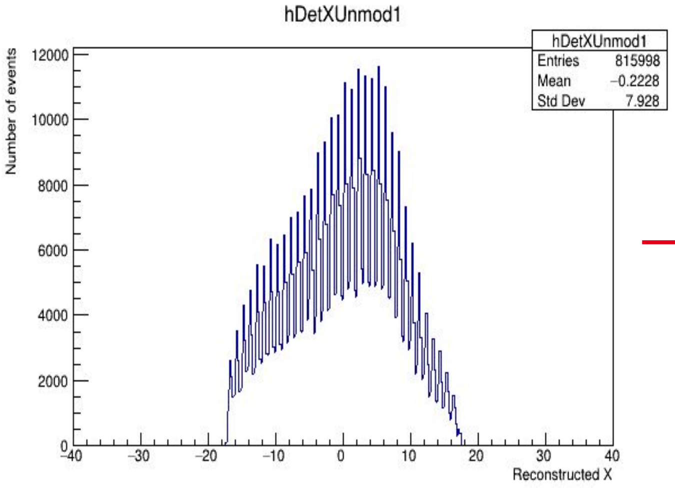
Linearisation of FPMW

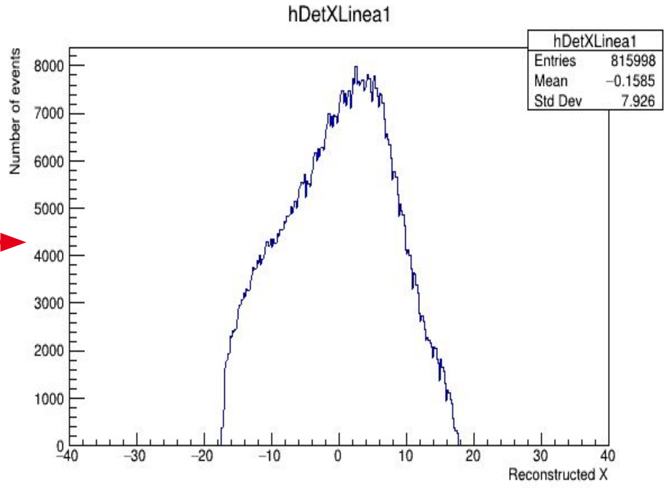
What we know

- Number of event near a wire is overestimated
- The distribution should be smooth

Method

- Change the size of the bin to reach a smooth distribution
- Gather the new edge of bin position
- Apply a transformation to each event to map them in the new linearised histogram

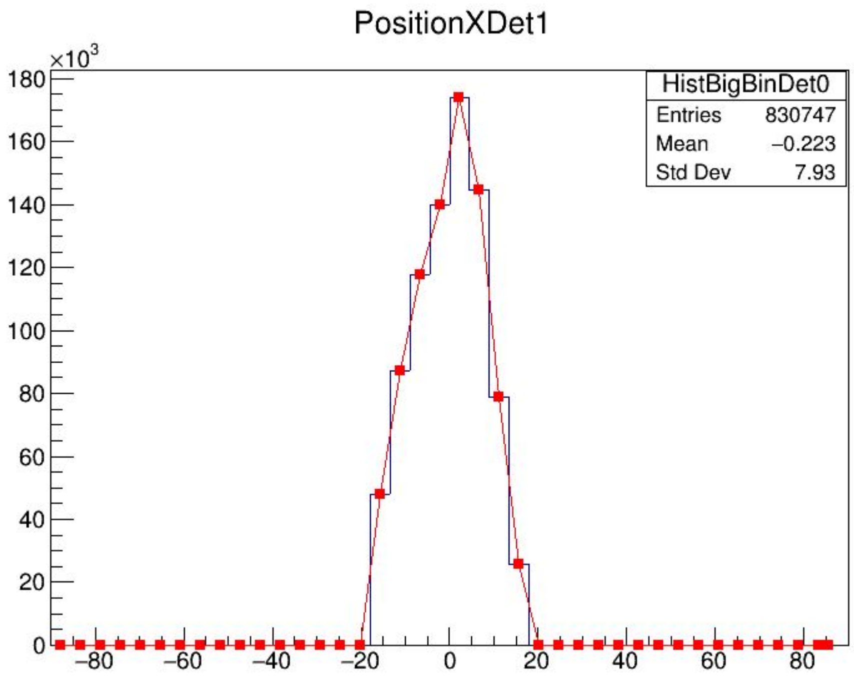




VAMOS

Linearisation of FPMW

1. Fetch unlinearised histogram
2. Rebin it with coarser binning
3. Link each bin center with a line



This is our starting point. We want the final distribution to look like the linked points.

1. Rescale the linked point to the unmodified histogram scale
2. Use this as the optimal number of event for each bin.

VAMOS

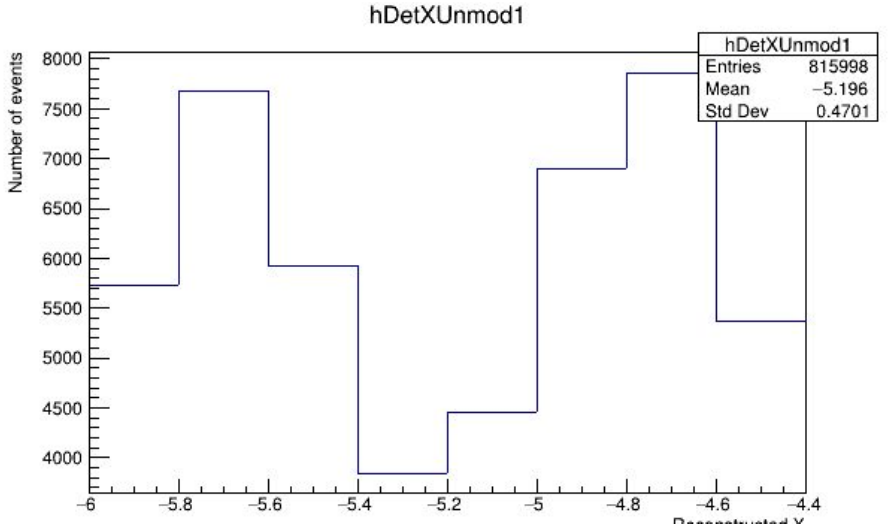
Linearisation of FPMW

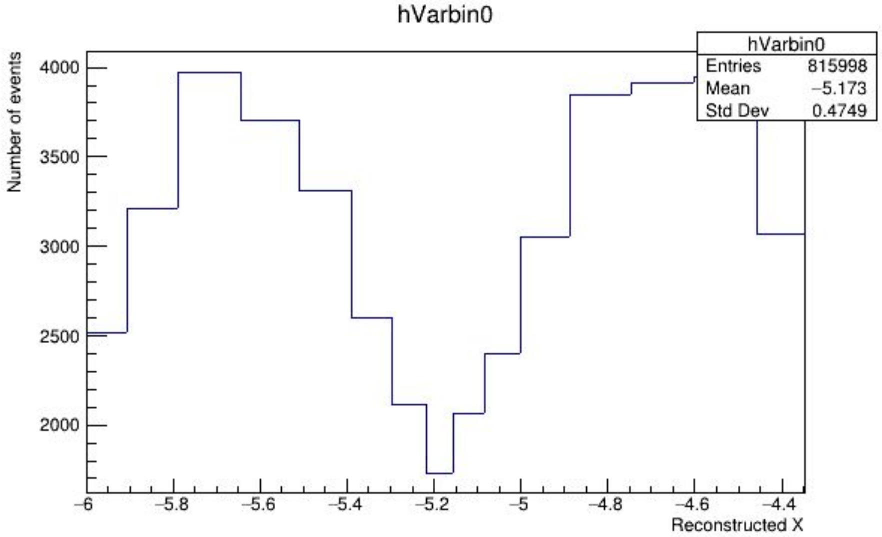
- Then modify the bin width of each bin as following :

$$NewWidth = \frac{N_{Bin}}{N_{Opt}}$$

- Normalise the bin as to make sur the number of event is conserved.
- Transform this modification of the bin with as a modification of the bin edge
- Make sure the edge of bin that fall exactly on a wire are not transformed
- Store the new bin edges in a file

Do a event per event transformation that do a mapping between the old bin and the new one

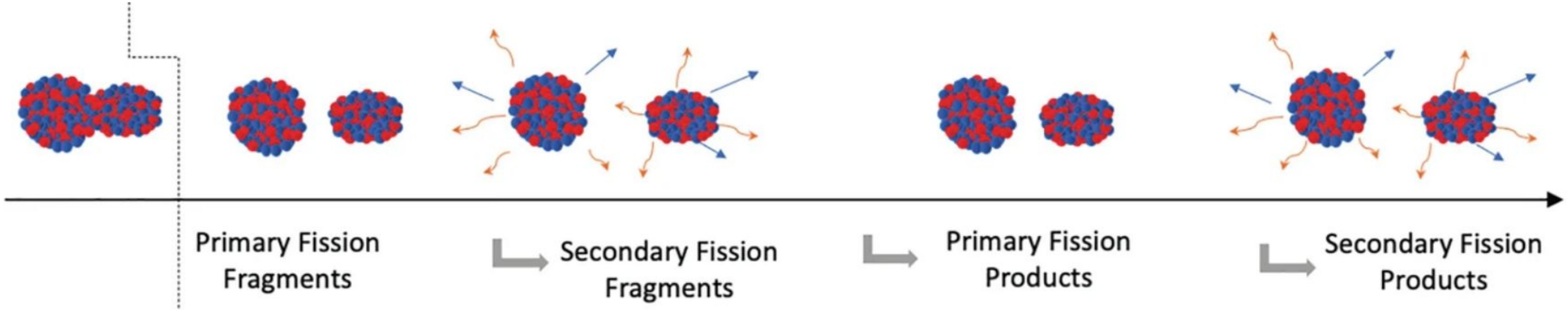




Basic definitions

Fragment stage after fission:

1. Before any emission
2. **Prompt neutron and gamma emission**
3. Beta decay
4. Delayed neutron and gamma



Patrick Talou and Ramona Vogt. Nuclear fission: theories, experiments and applications. Cham:Springer, 2023. isbn: 978-3-031-14545-2

Why study ^{242}Pu ?

Shell damping exist for numerous nucleus.

Applications

^{242}Pu fission is equivalent to ^{241}Pu+n.

- ^{241}Pu produced in reactor is recycled in MOX fuel
  → Fissile of MOX is ~17.6% ^{241}Pu

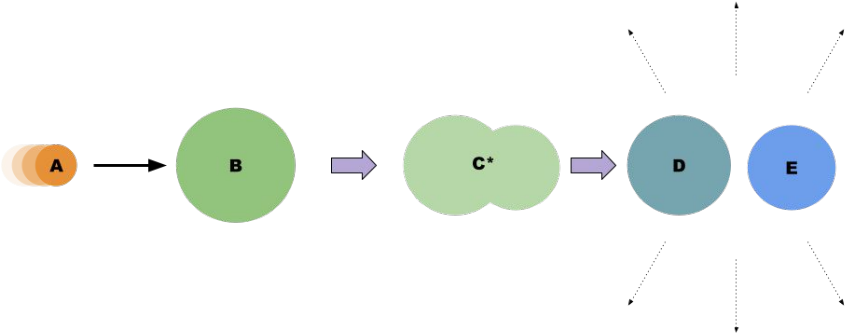
- Gen-IV reactor of fast neutron type → E* dependency in fission

- ^{241}Pu is unstable by β^- → ^{241}Am non-fissile and α emitter → Radioactivity of nuclear waste

Experimental methods

Direct kinematics

- Actinide at rest
- Only long-lived nuclei
- Low velocity in lab frame



Inverse kinematics

- Accelerated actinide
- Exotic nuclei
- Surrogate reaction to access desired channel