Fission Program in Inverse Kinematics at VAMOS/GANIL

Fission-Fragments Even-Odd Staggering as a New Fission Dynamics Observable

Diego Ramos
On behalf of the Fission@VAMOS collaboration

Inverse Kinematics Fission @VAMOS

- **Fusion Reactions**

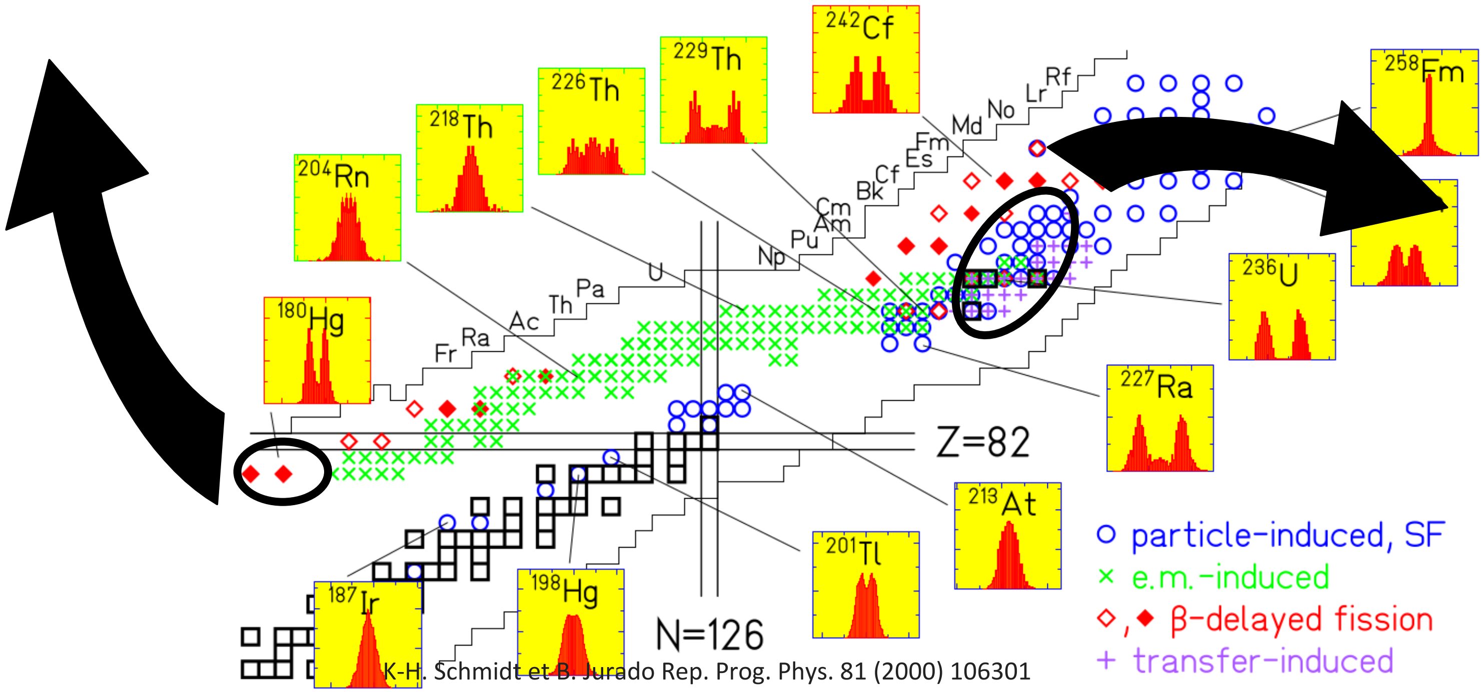
^{124}Xe + ^{54}Fe $\rightarrow$ ^{178}Hg
^{124}Xe + ^{60}Ni $\rightarrow$ ^{184}Pb

◆**FISSION@VAMOS**
- Heavy ion Beams (Xe,Th,U, Pb)
- Inverse-Kinematics Surrogate-Induced Fission

- **MultiNucleon Transfer Reactions**

^{238}U + ^{12}C $\rightarrow$
^{236}U + ^{14}C
^{238}U + ^{12}C
^{240}Pu + ^{10}Be
^{241}Pu + ^{9}Be
^{242}Pu + 2α
^{243}Am + ^{7}Li
^{244}Cm + ^{6}He

^{232}Th + ^{12}C $\rightarrow$
^{232}Th + ^{12}C
^{230}Th + ^{14}C
^{233}Pa + ^{11}B
^{234}U + ^{10}Be
^{235}U + ^{9}Be
^{237}Np + ^{7}Li
^{238}Pu + ^{6}He

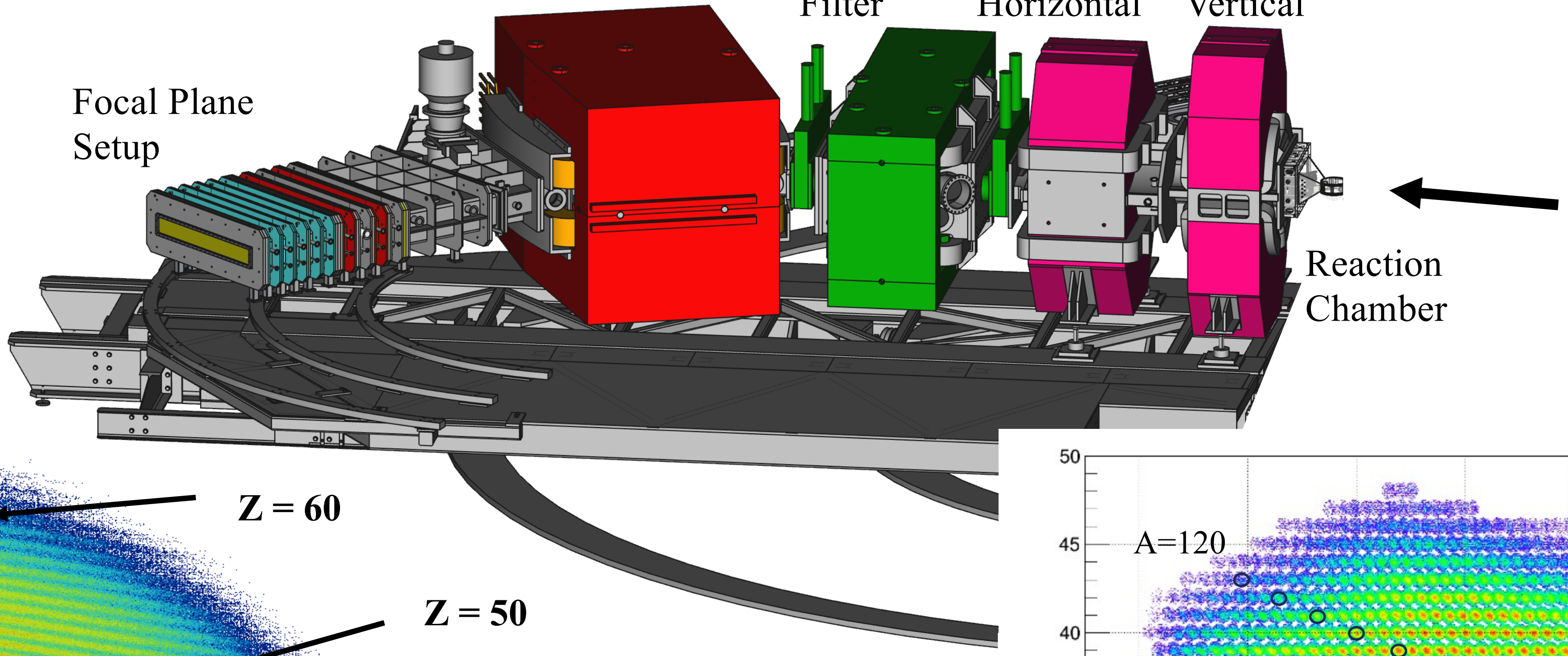


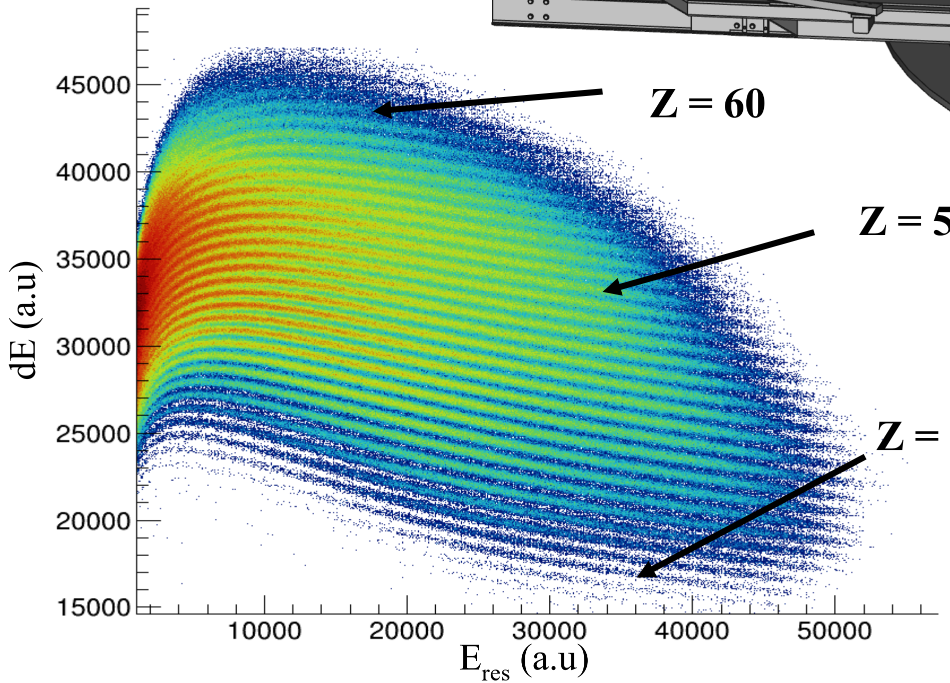
K-H. Schmidt et B. Jurado Rep. Prog. Phys. 81 (2000) 106301

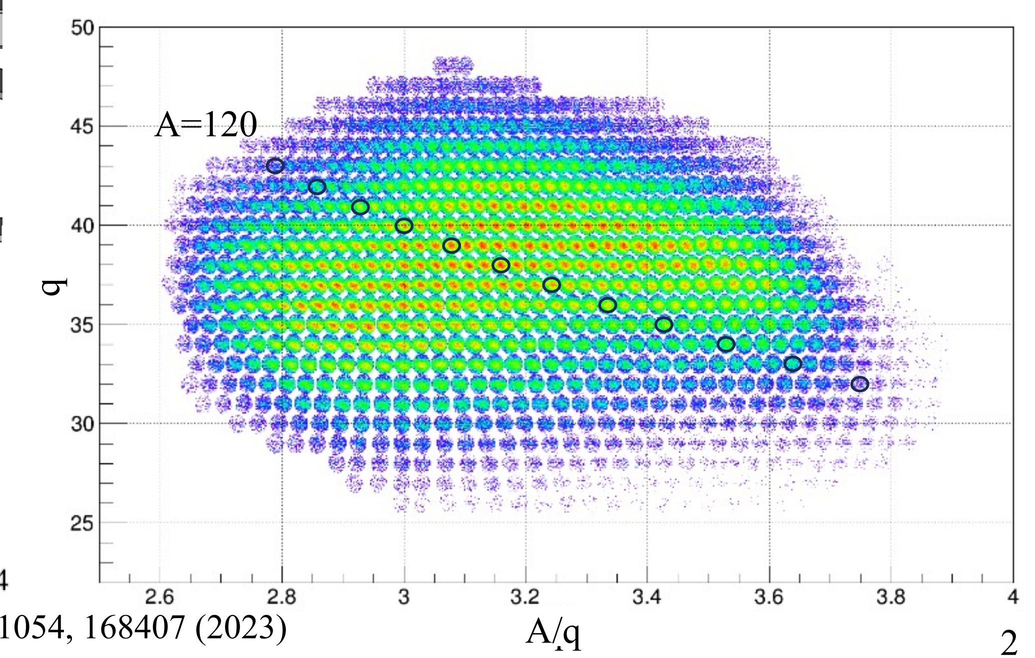
Complete Isotopic-distribution of fission-fragments Yields

The VAMOS Spectrometer

Isotopic Identification of Heavy Ions





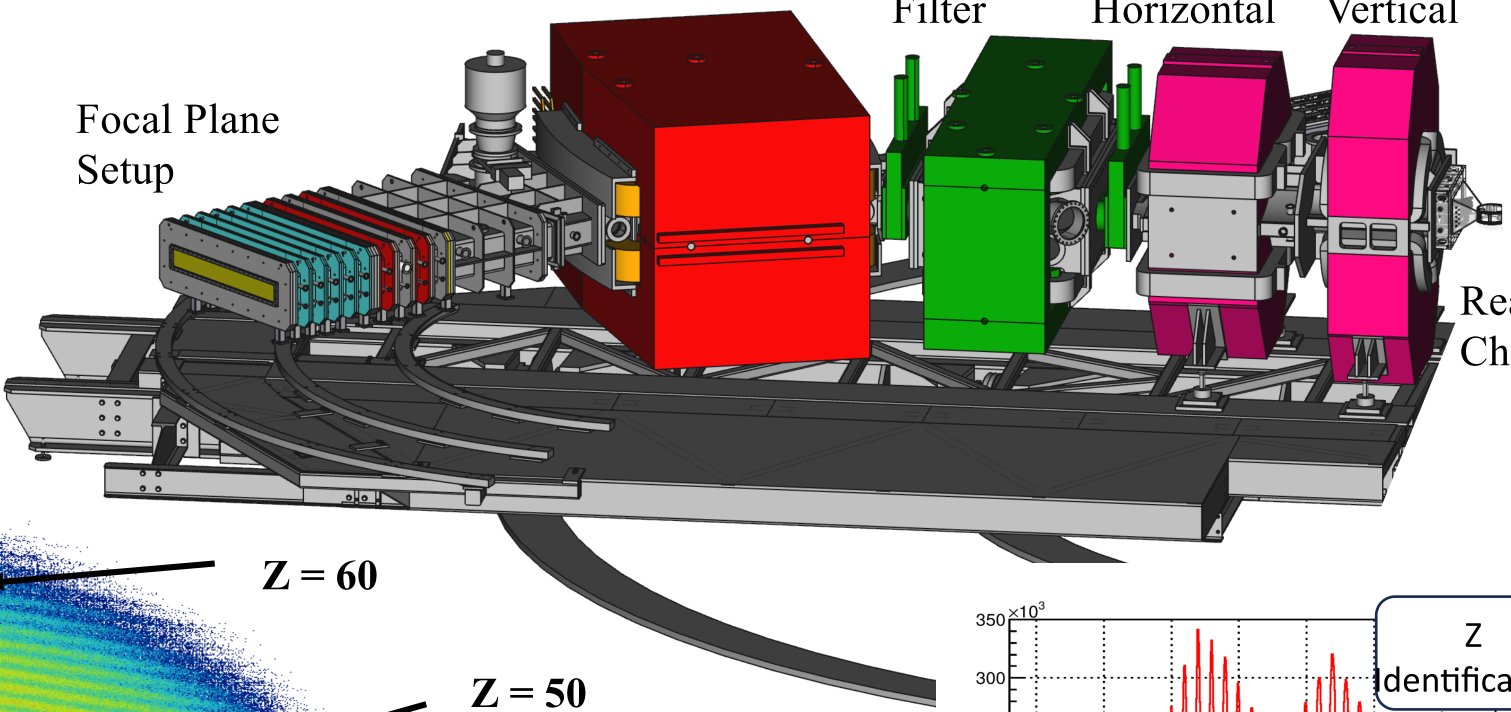


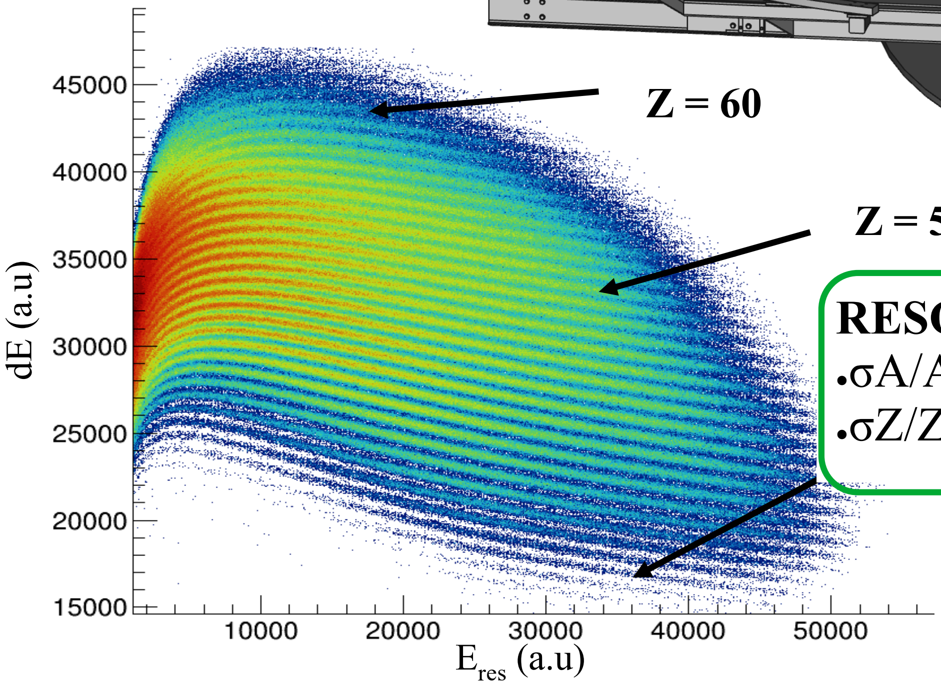
M. Rejmund et al., NIM A 646 (2011) 184

A. Lemasson & M. Rejmund ,NIM A 1054, 168407 (2023)

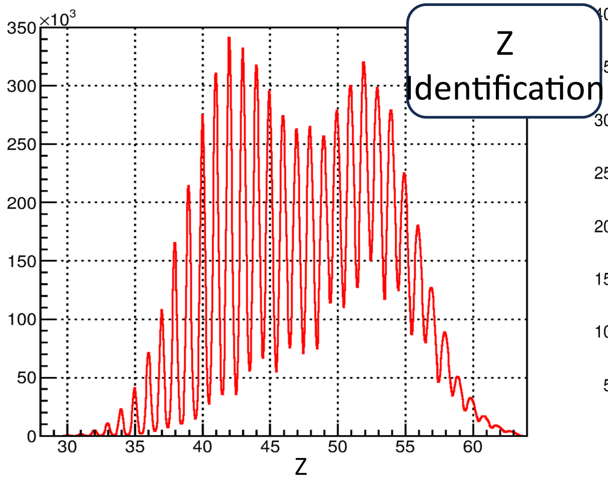
The VAMOS Spectrometer

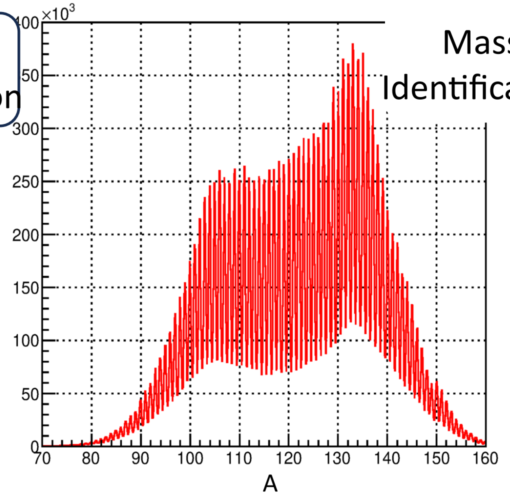
Isotopic Identification of Heavy Ions





RESOLUTIONS:
- $\sigma A/A \sim 3\times10^{-3}$ (FWHM)
- $\sigma Z/Z \sim 1.3$ % (FWHM)

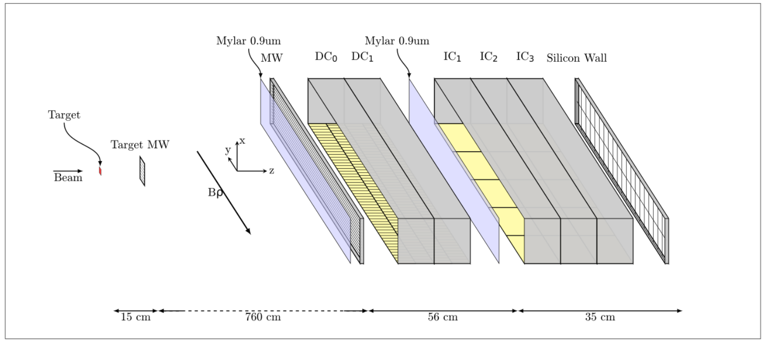


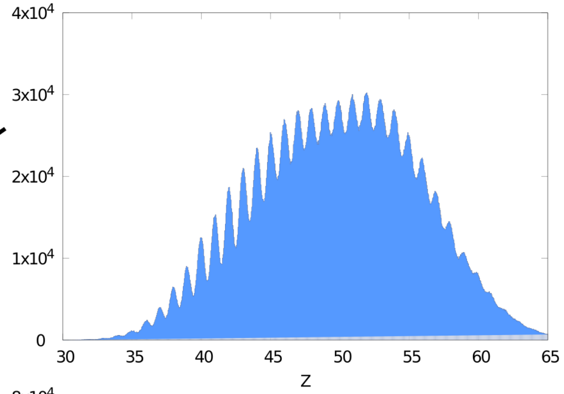


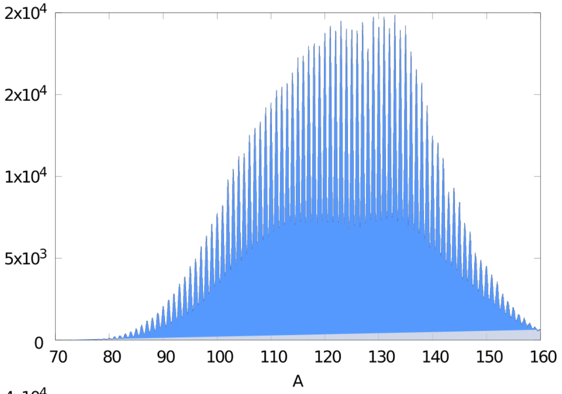
Evolution of the VAMOS Identification

Focal Plane Configuration | Charge(Z) | Mass(A)

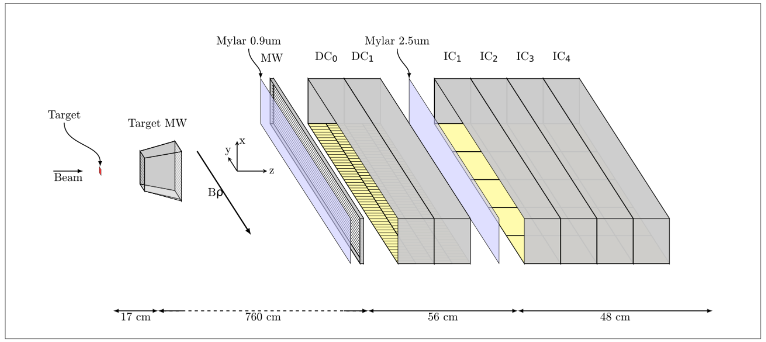
2011

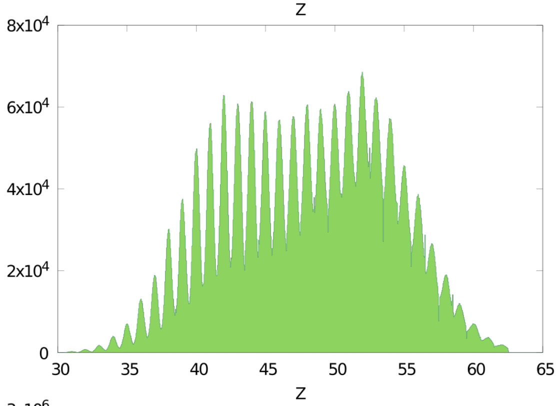


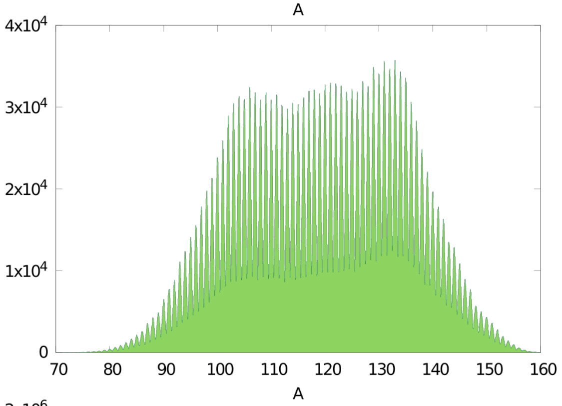




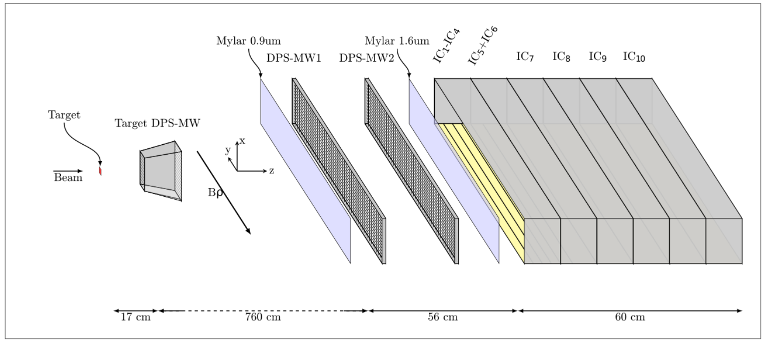
2016

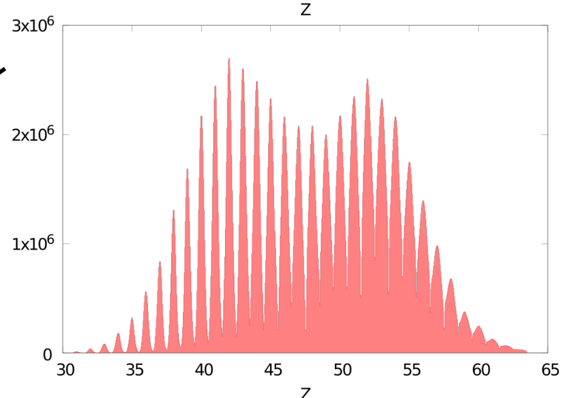


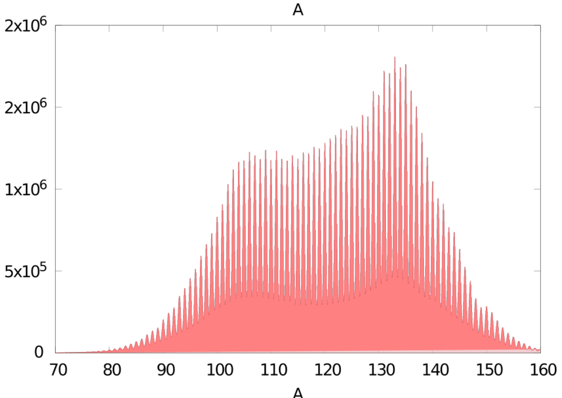




2022





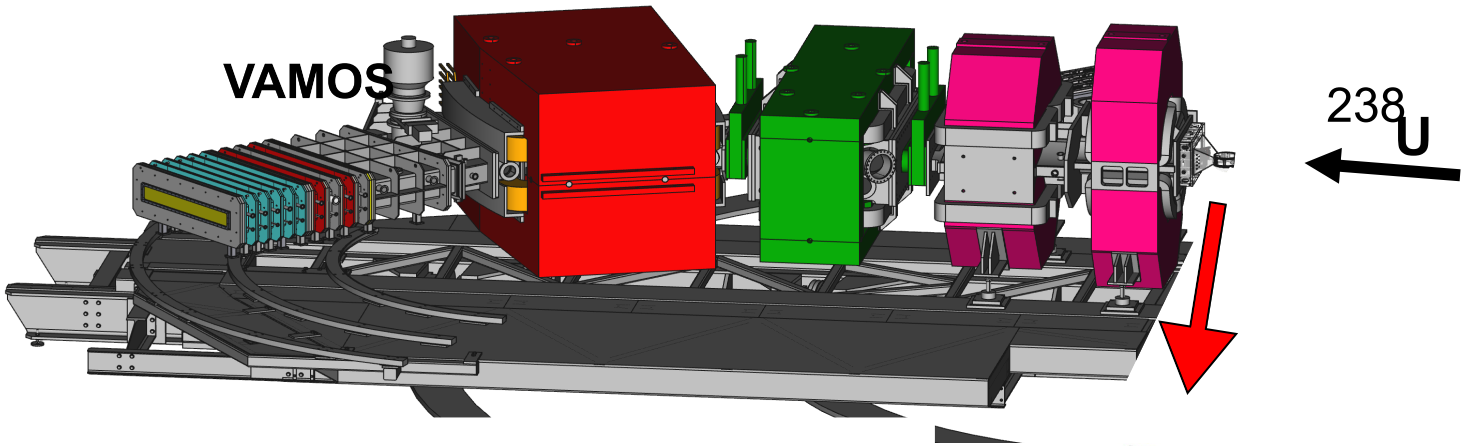


Multi-nucleon Transfer Reactions

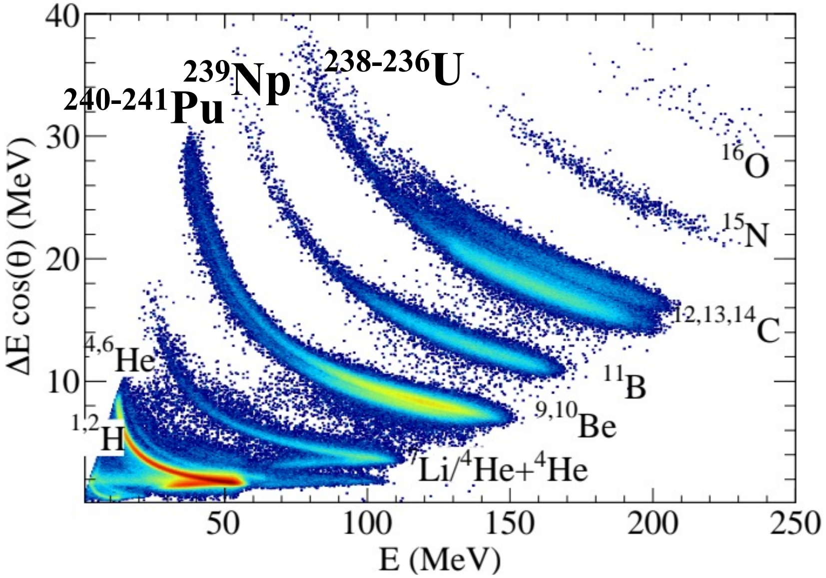
Access to Actinides

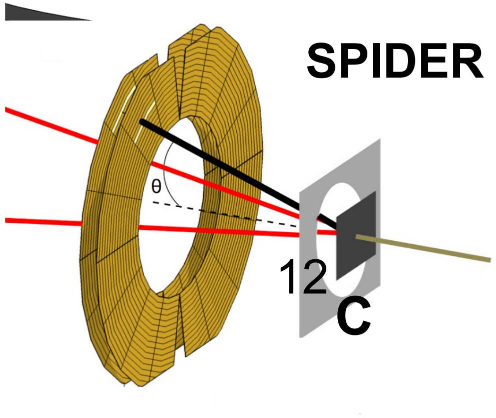
Fissioning System Identification

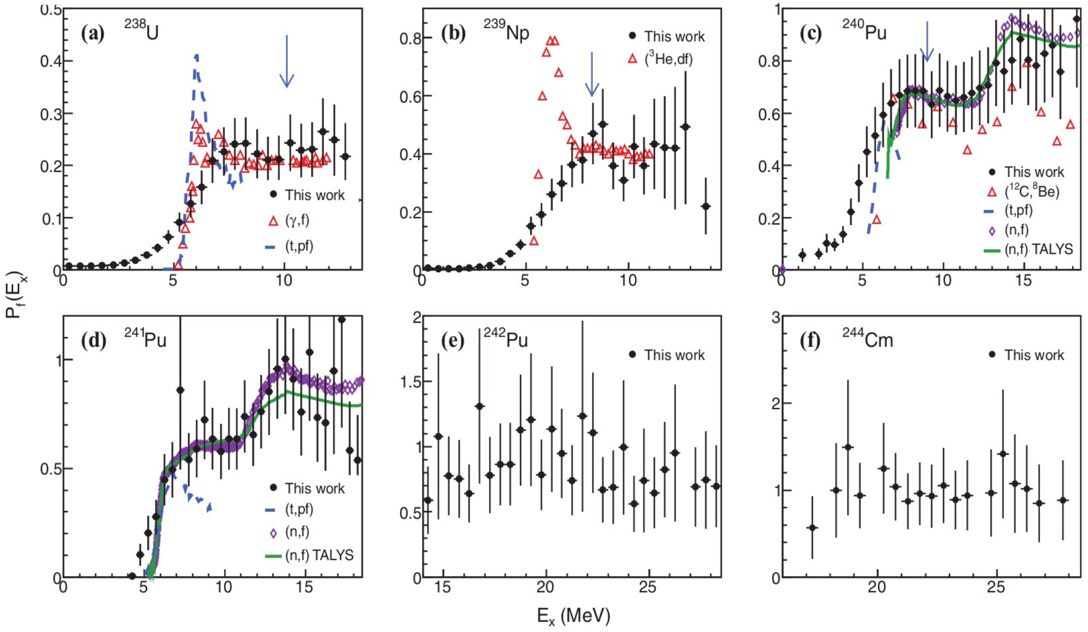
- ^{238}**U/** ^{232}**Th beam at ~6 MeV/u** (Coulomb energies)



- **STRIP SILICON TELESCOPE**
  - Identification of the fissioning system by detection of the target-like recoil
  - Measurement of the Excitation Energy by reconstruction the binary reaction
  - Measurement to fission probabilites by detection of fission fragments



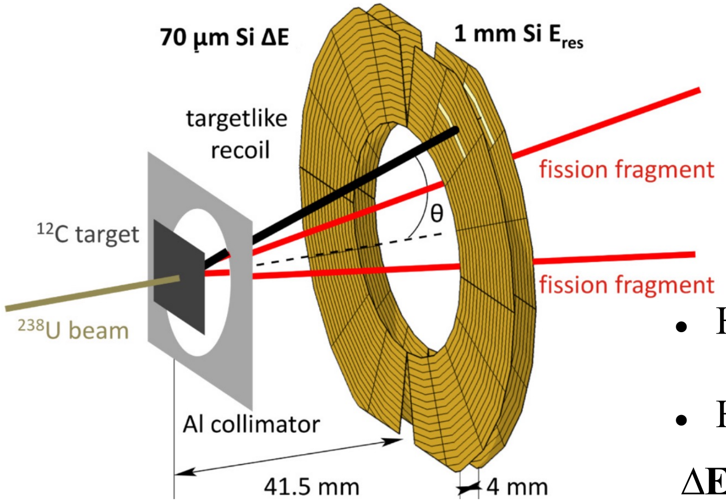




C. Rodríguez-Tajes et al., PRC 89, 024614 (2014)

Fissioning System Identification

- **SPIDER**

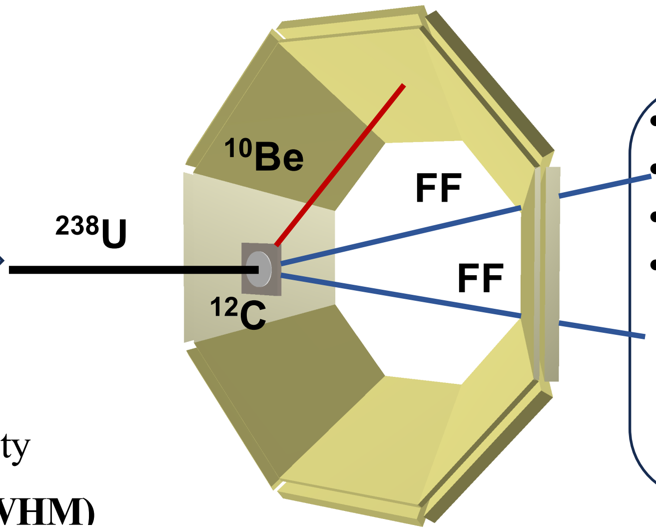


2023

- High granularity (0.5 mm strips)
- High homogeneity

ΔE_x~700 keV (FWHM)

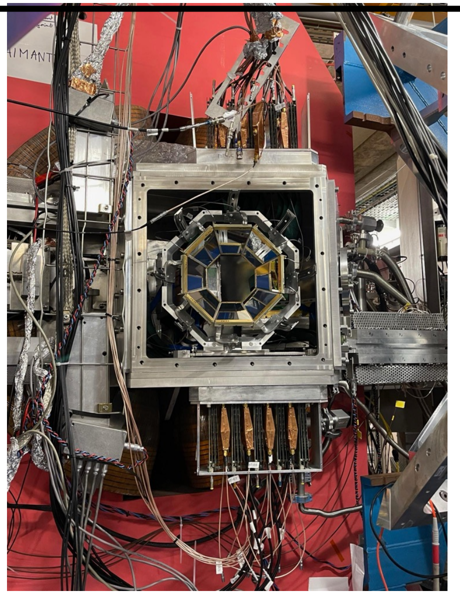
- **PISTA**

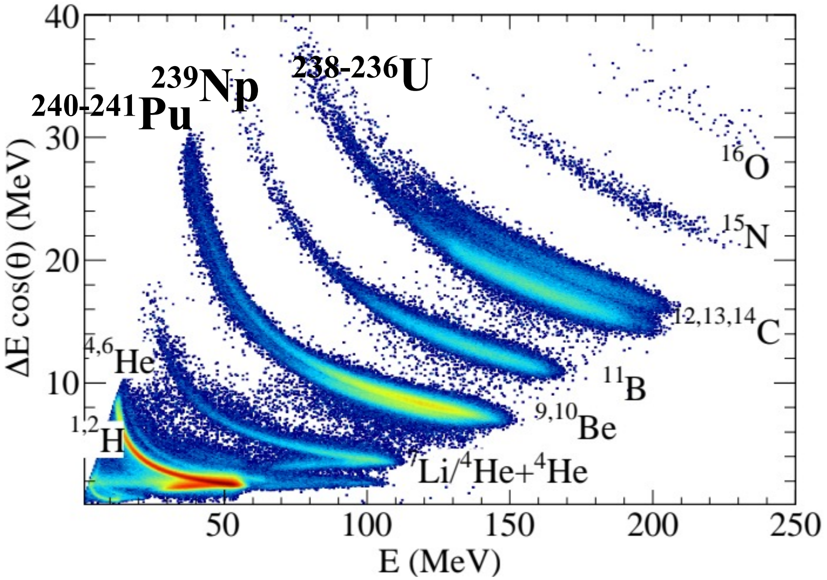


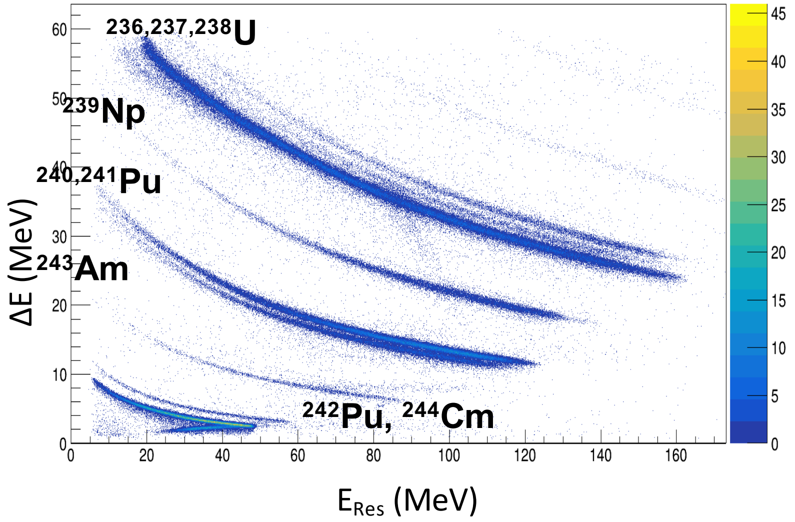
GANIL-CEA/DAM collaboration

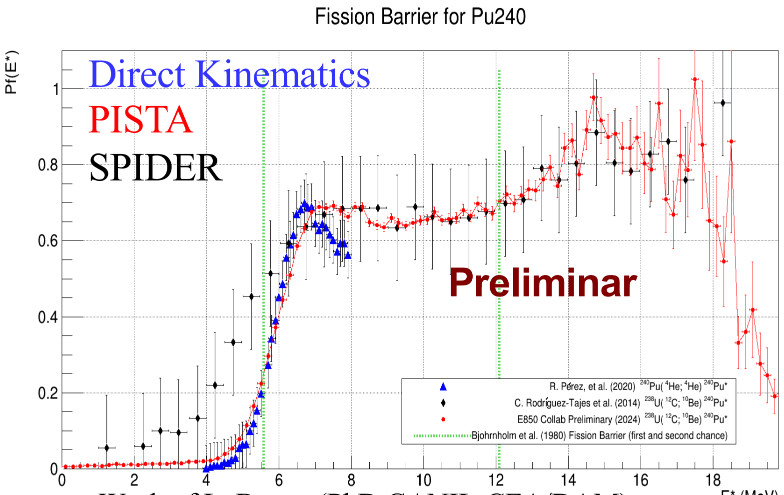
- **dE**
- 100 um thickness
- 0.5 mm strips (θ)
- 10 cm from target

- **E**
- 1 mm thickness
- 1.2 mm strips (ϕ)









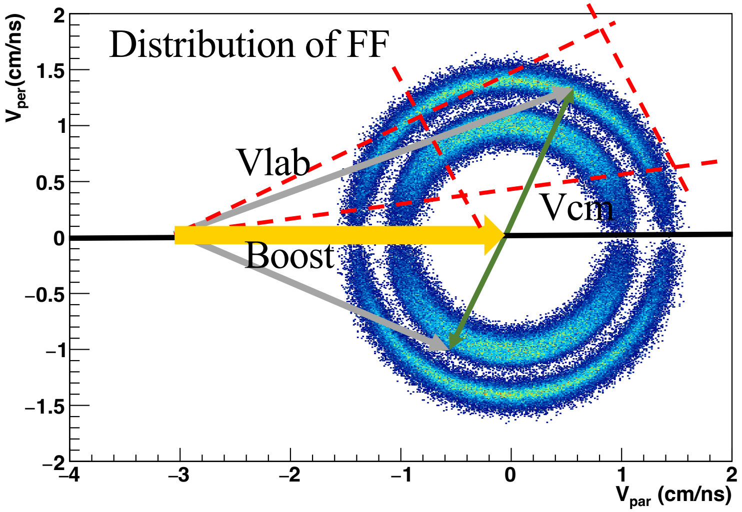
Work of L. Begue (PhD GANIL-CEA/DAM)

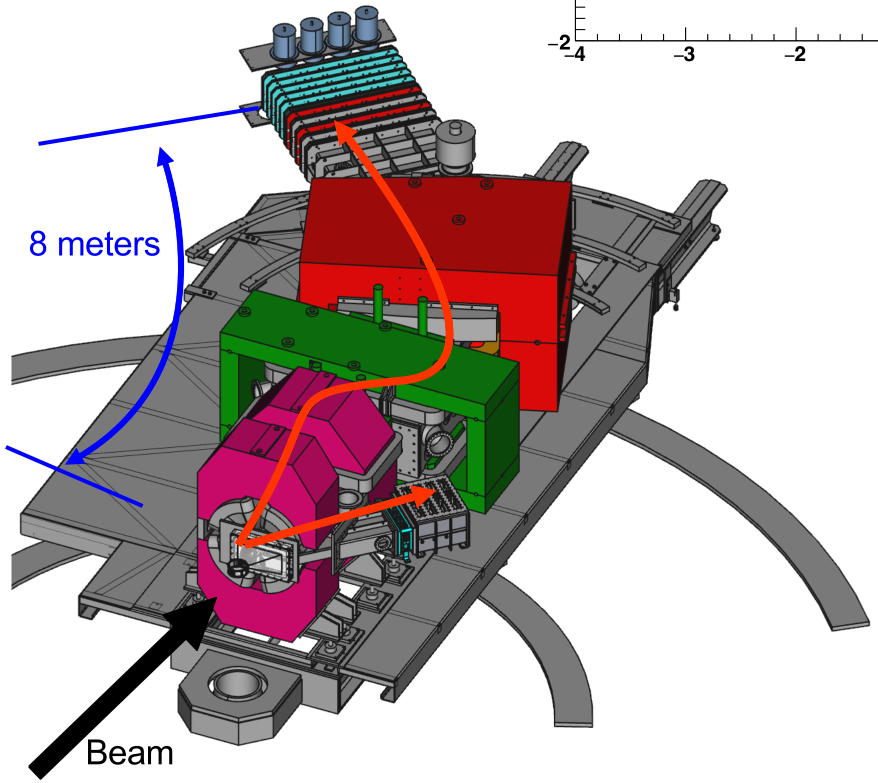
(Pierre Morfouace Talk)

Fission Fragments Detection

Fission Fragments:

- FF Z : 30 – 70
- FF A : 80 - 160
- FF angle: 0 - 30 deg
- FF Vlab: 1 - 5 cm/ns





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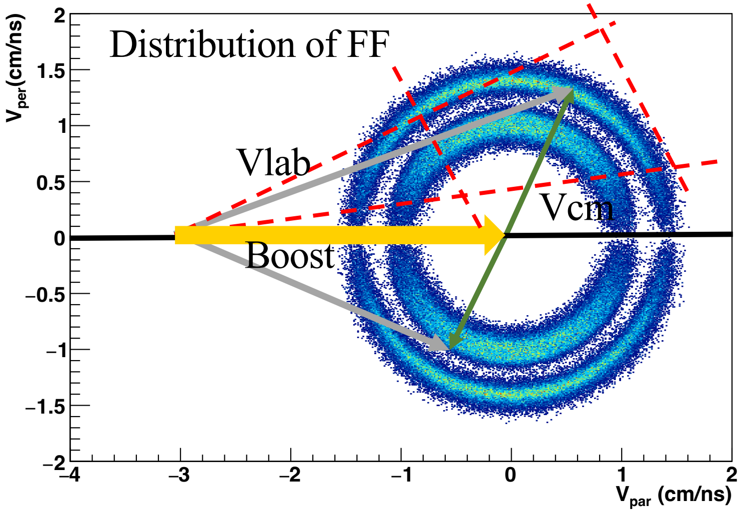
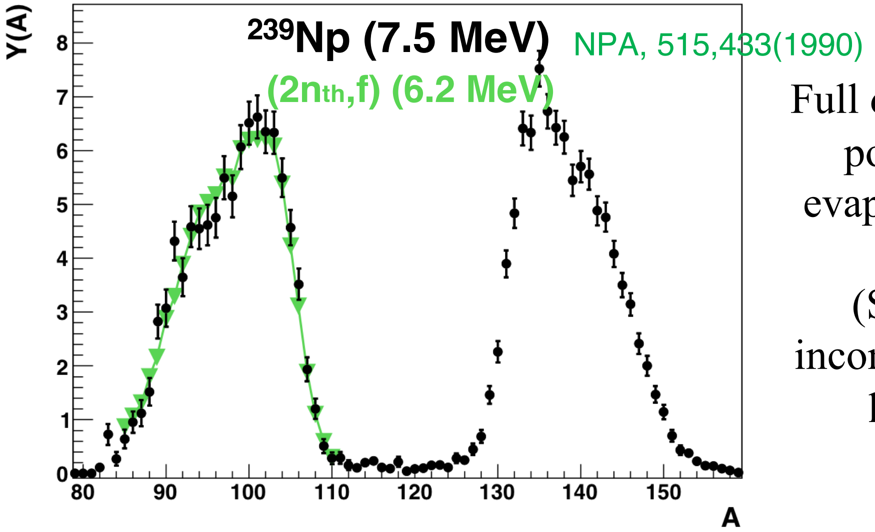
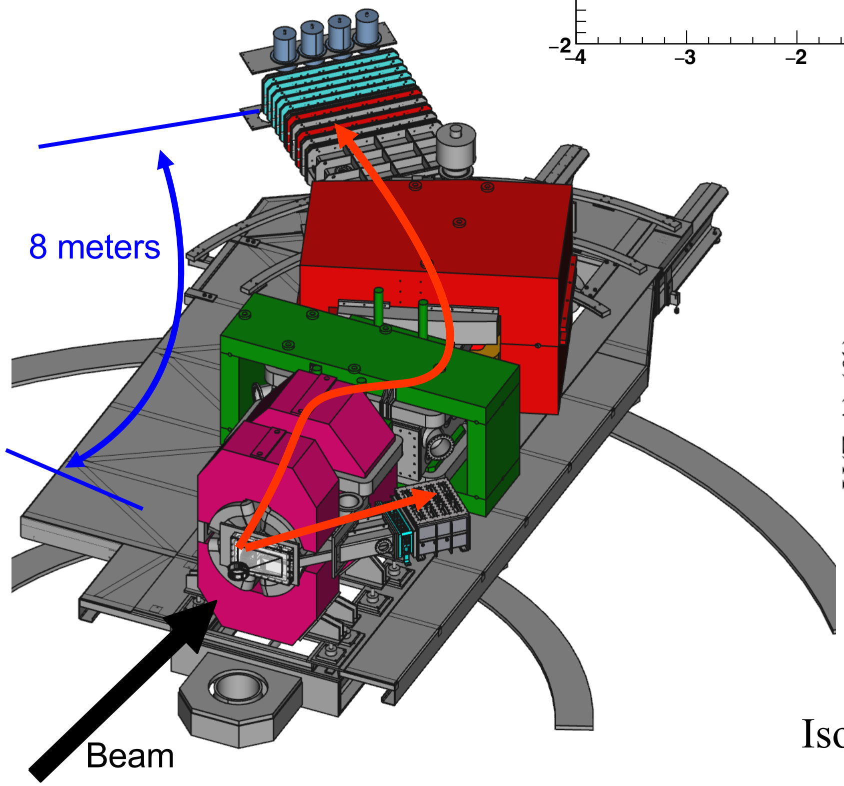
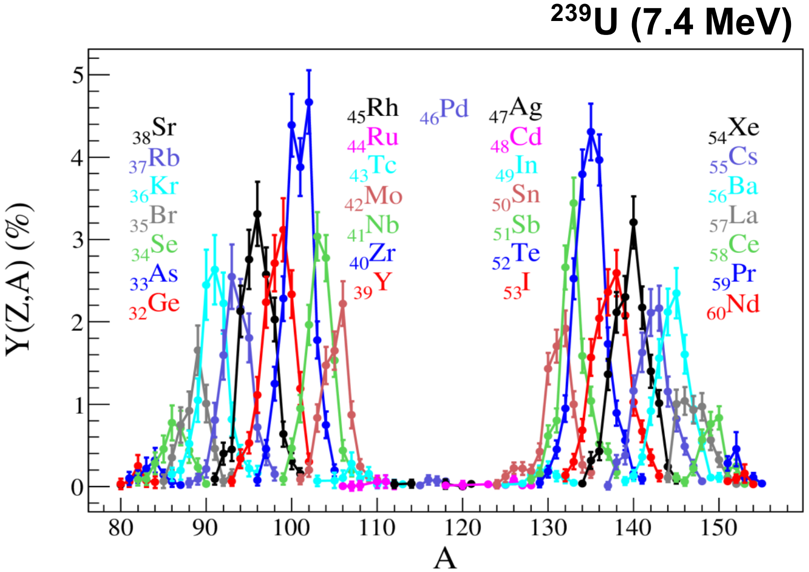
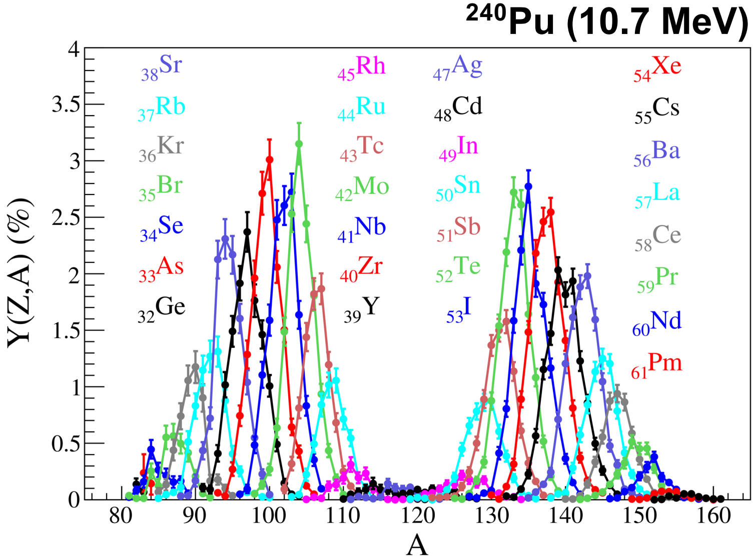




Full distribution of post-neutron evaporation mass yields (Scarce and incomplete data in literature)







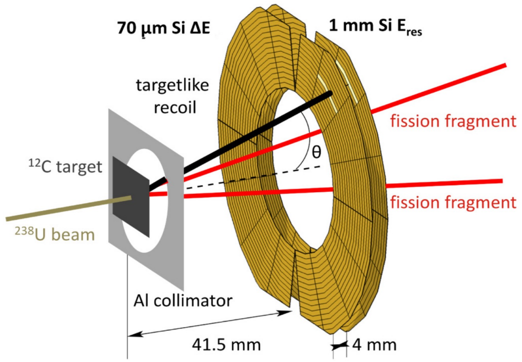
Isotopic distribution of post-n evaporation fission yields

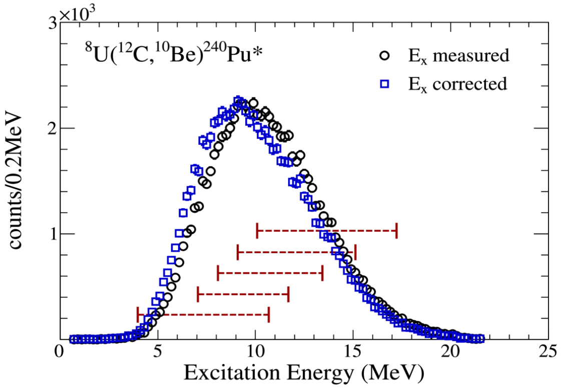
M. Caamaño et al., Phys. Rev. C 88, 024605 (2013)
D. Ramos et al., Phys. Rev. C 97, 054612 (2018)

Evolution with the Excitation Energy

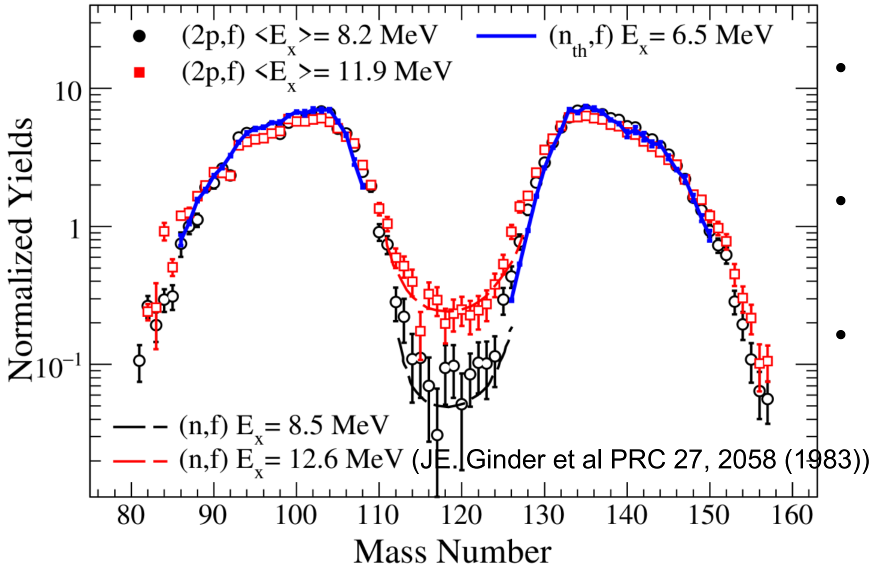
^{238}U + 2p -> ^{240}Pu

SPIDER





(A.Bail et al. PRC 84, 034605 (2011))

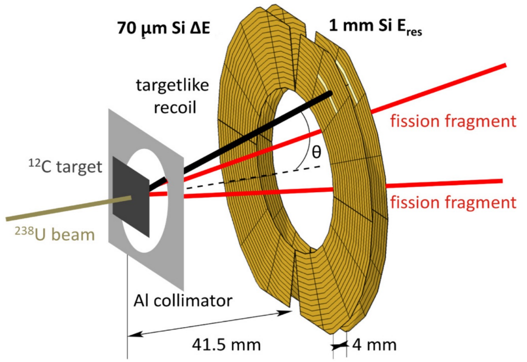


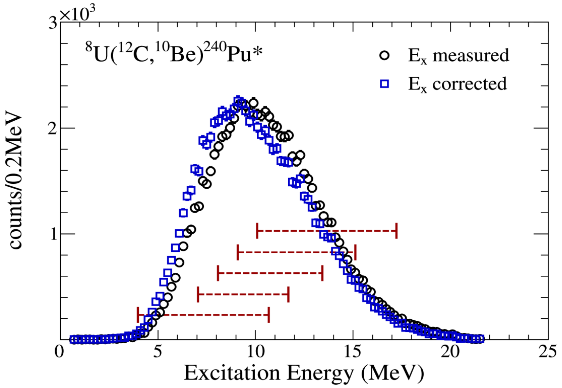
- Feeding of the valley by increasing Ex
- Very good agreement with n-induced fission
- Insensitivy to the entry channel

Effect of Prompt-Neutron evaporation

^{238}U + 2p -> ^{240}Pu

SPIDER





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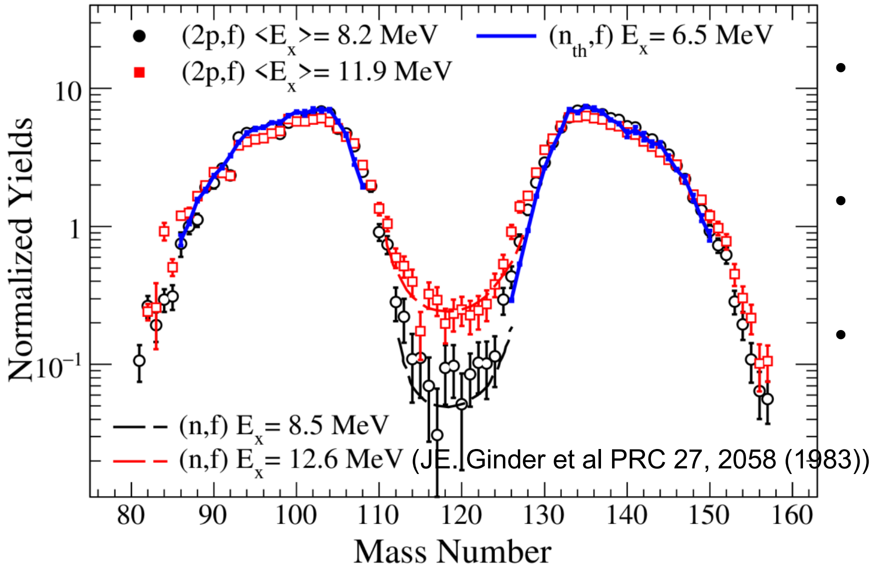

- Feeding of the valley by increasing Ex
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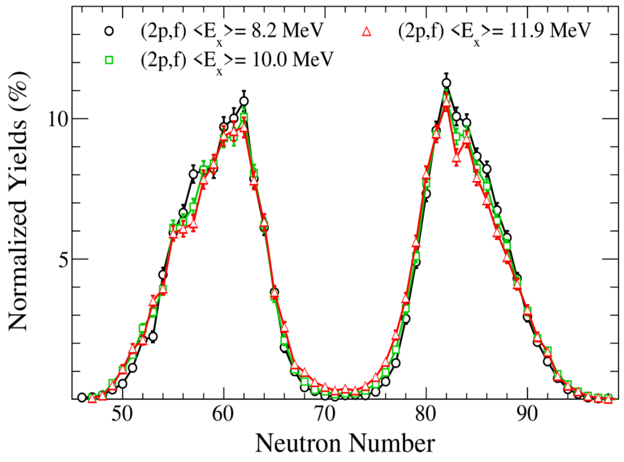
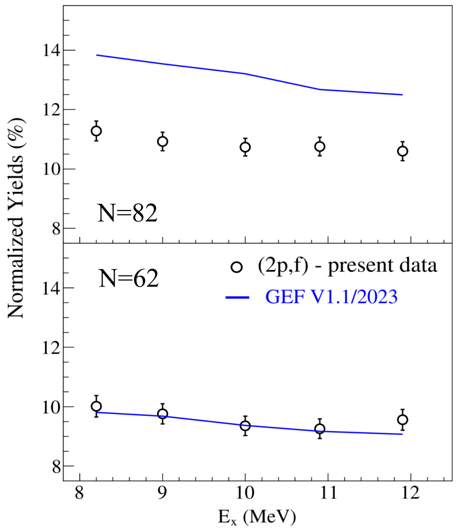
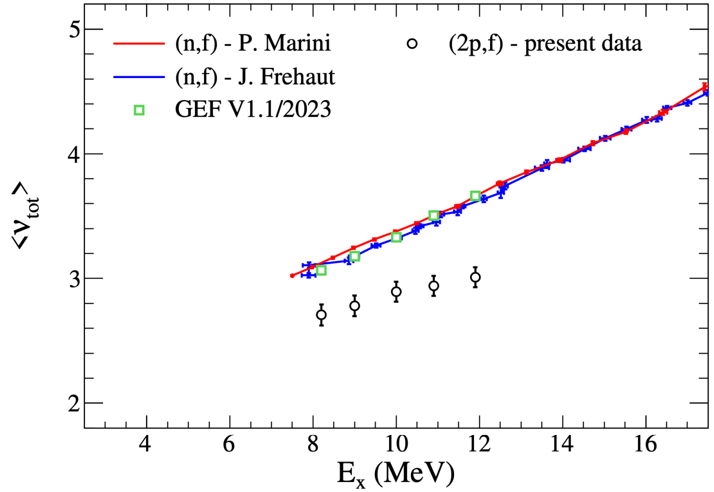
- Post-neutron evaporation **Isotonic fission yields**





- Constraints for the sharing of energy between the fragments (neutron evaporation)

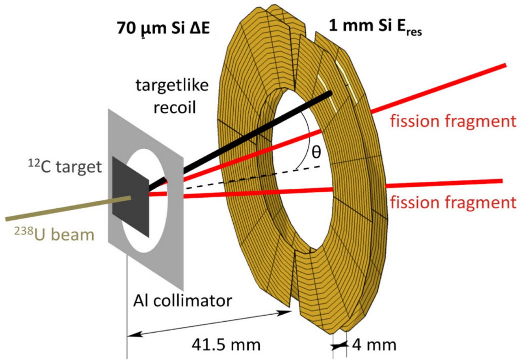
$$\langle \nu_{tot} \rangle = 146 - \frac{1}{200} \sum_{Z} (\langle N \rangle|_Z + \langle N \rangle|_{Z_{fis}-Z}) \times Y(Z)$$



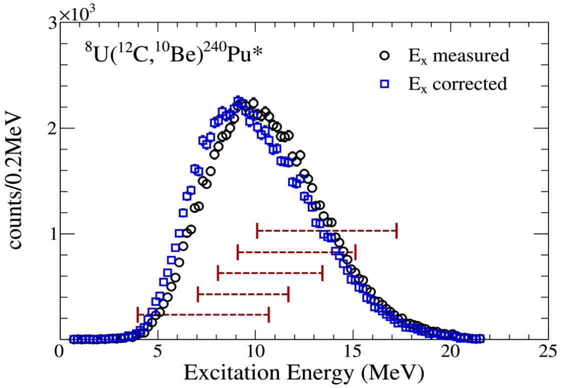
- **Lower neutron evaporation** observed in 2p-transfer reactions compared to n-capture

Effect of Prompt-Neutron evaporation

SPIDER



^{238}U + 2p -> ^{240}Pu



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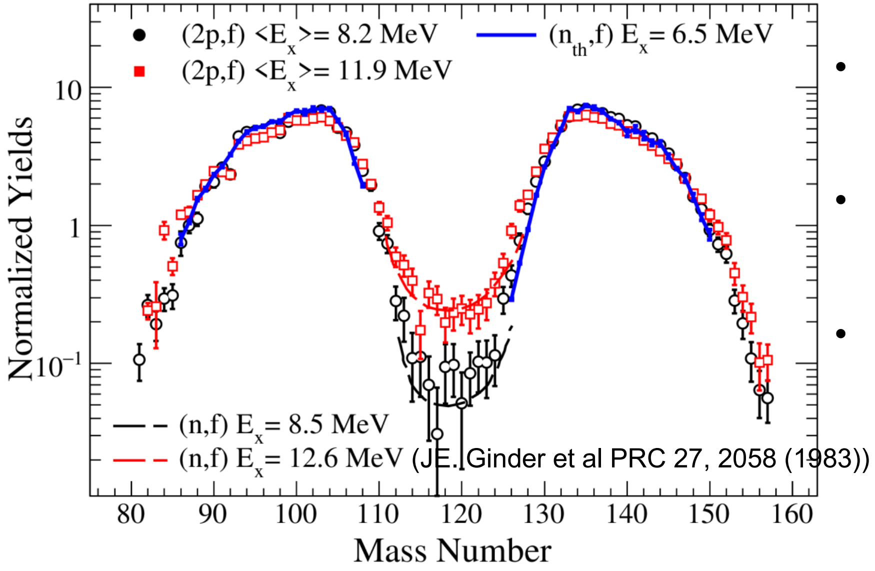

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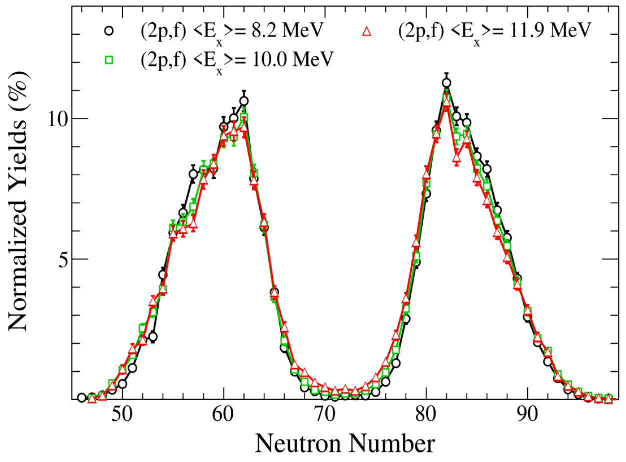

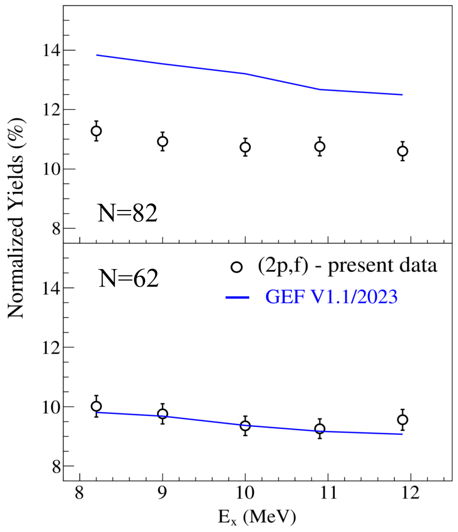

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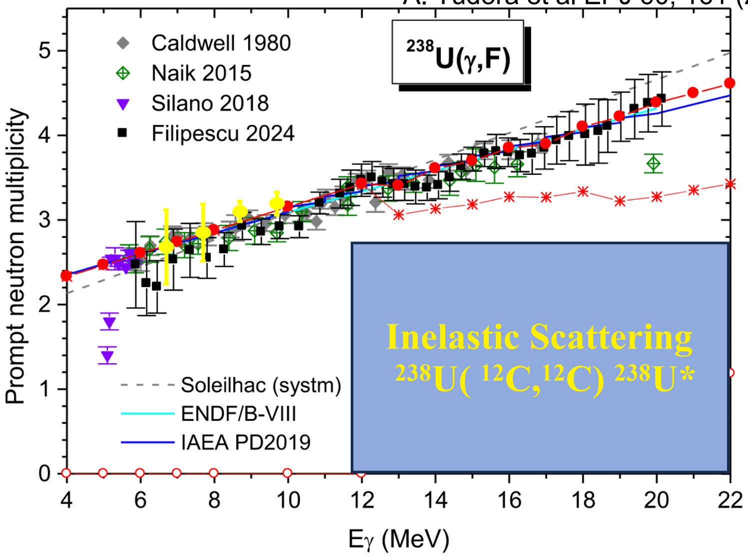
A. Tudora et al EPJ 60, 161 (2024)

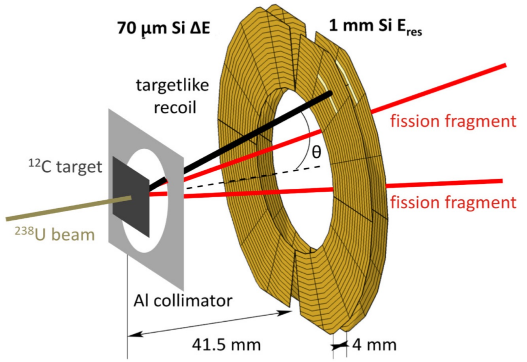


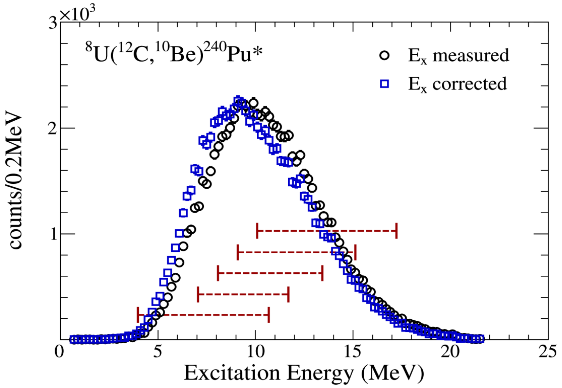
- **Lower neutron evaporation** observed in 2p-transfer reactions compared to n-capture
- **Incoming channel effect**

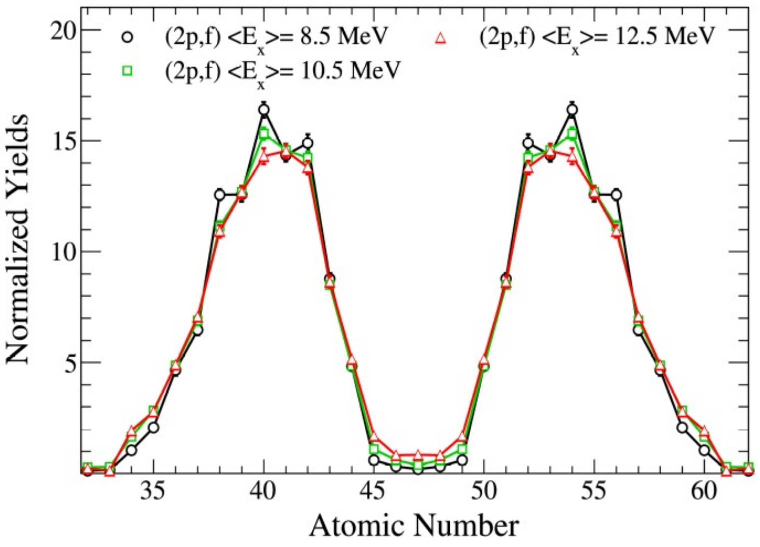
Even-Odd Stagering in Fission

$^{238}U + 2p \rightarrow {}^{240}Pu$

SPIDER





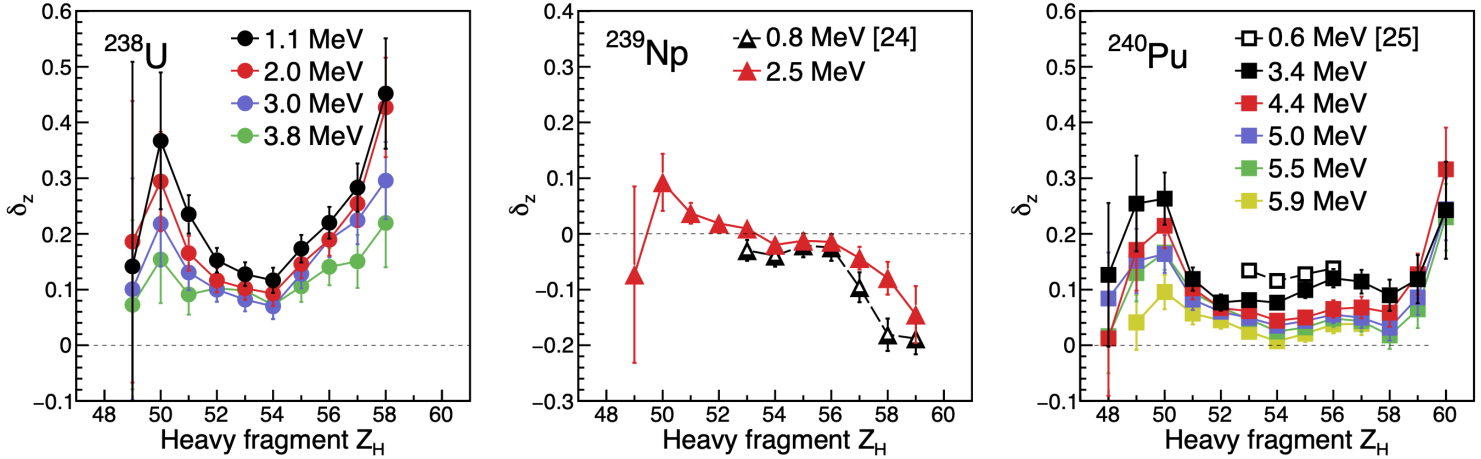


- **Proton even-odd effect decreasing for higher inital Intrinsic Excitation energy**

B.L.Tracy et al PRC 5, 222 (1972)

$$\delta_{\mathrm{Tracy}}(\mathrm{Z}+1.5)=\frac{(-1)^{\mathrm{Z}}}{8}\Big(\ln Y(\mathrm{Z})-\ln Y(\mathrm{Z}+3)+3\big[\ln Y(\mathrm{Z}+2)-\ln Y(\mathrm{Z}+1)\big]\Big).$$

Local Even-Odd Effect

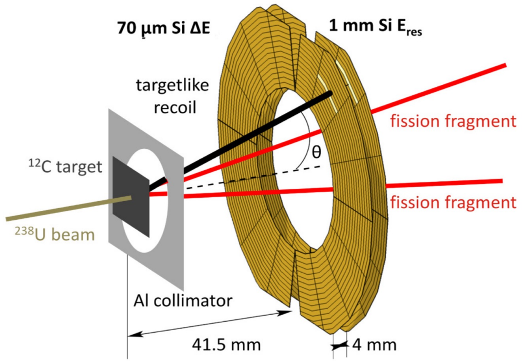


- Higher the even-odd effect for higher fission asymmetry
- Z-odd fissioning system show negative even-odd effect for high asymmetry: **unpair proton is mainly taken by the heavy fragment**

D. Ramos et al., Phys. Rev. C 107, L021601 (2023)

Even-Odd Stagering in Fission

SPIDER



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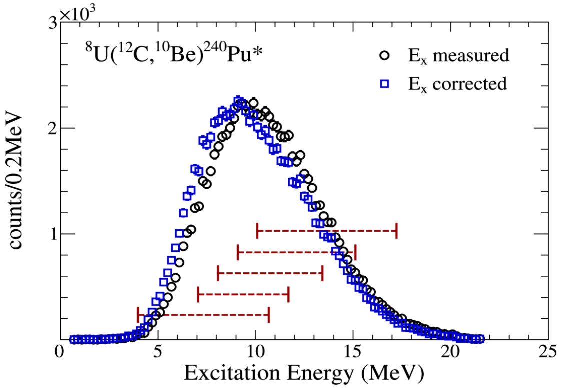

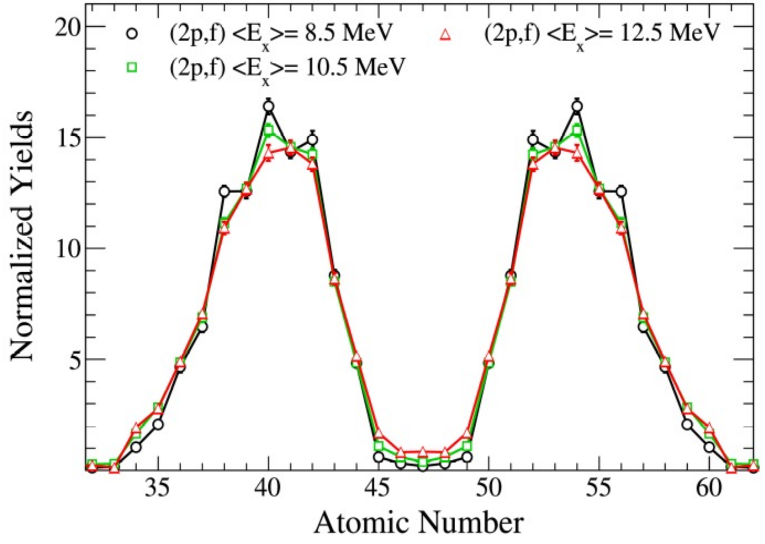

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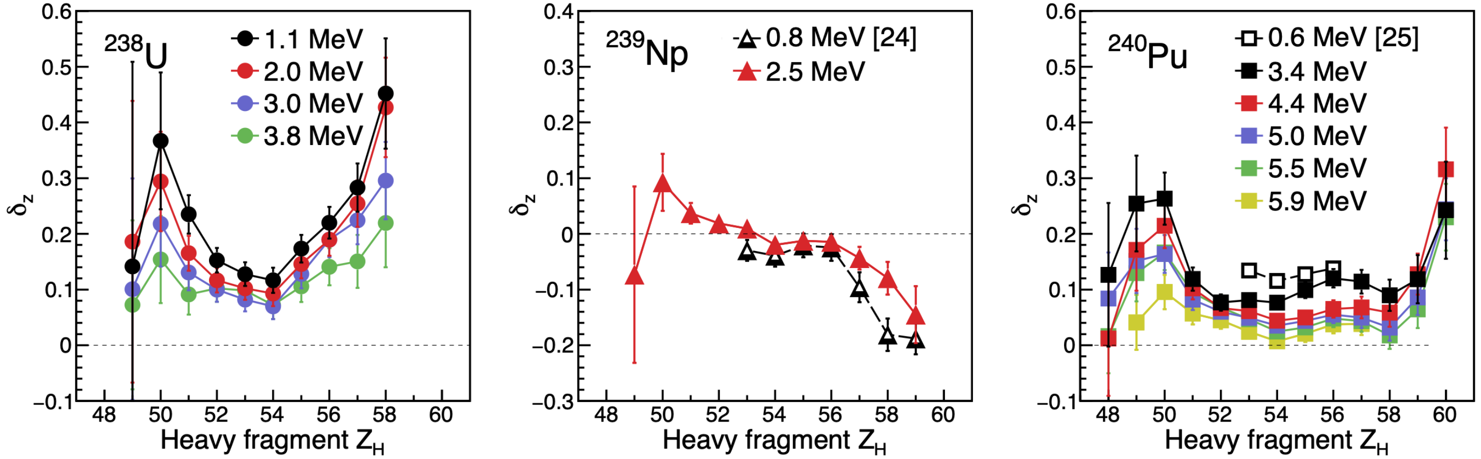
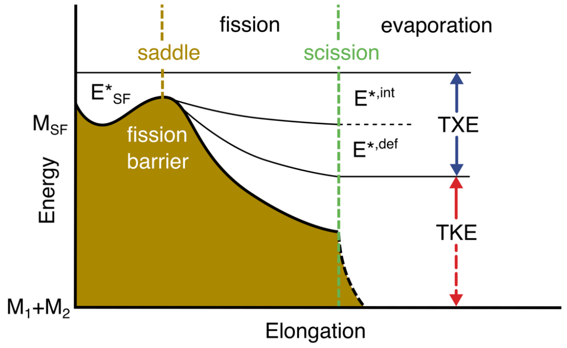




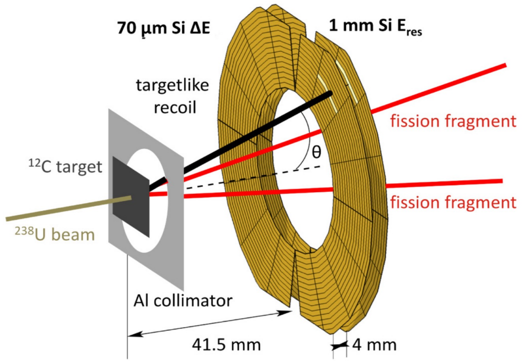
- Intrinsic Excitation energy is needed for breaking proton-pairs
  - **Excitation Energy above the Barrier**
  - **Dissipated energy (collective -> intrinsic excitations)**

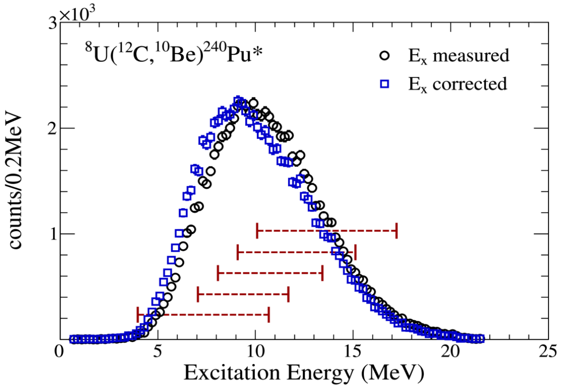
D. Ramos et al., Phys. Rev. C 107, L021601 (2023)

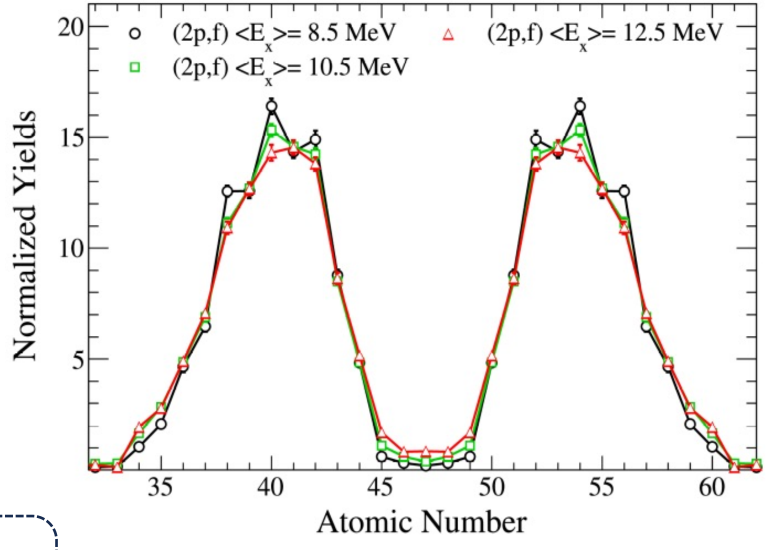
Dissipation in Fission

^{238}U + 2p -> ^{240}Pu

SPIDER





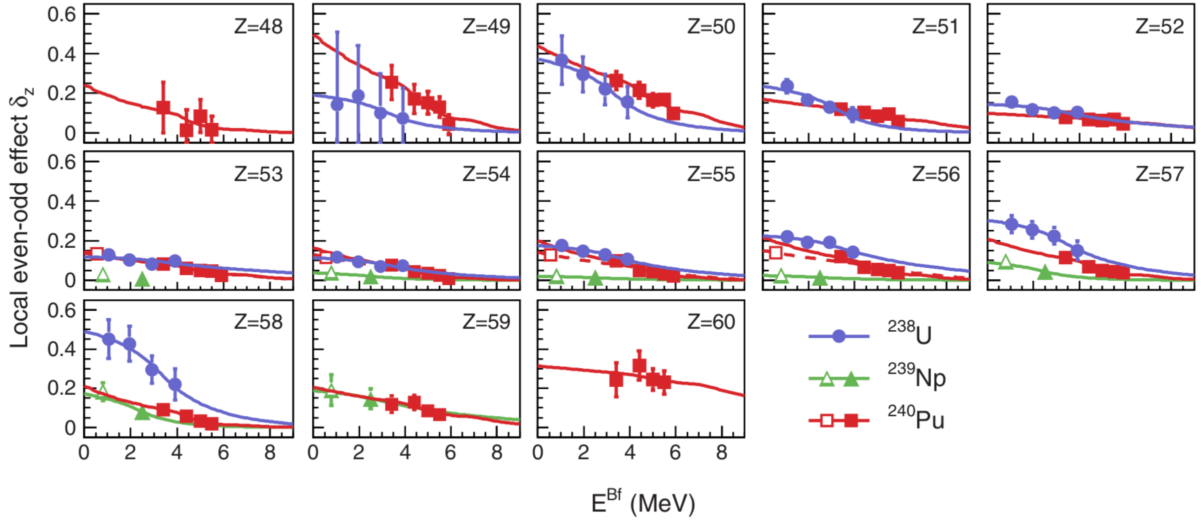


- **Proton even-odd effect decreasing for higher inital Intrinsic Excitation energy**

$$E^{\text{dis}}(Z) + [E^{Bf} - \Delta] = G(Z)\ln(|\delta_Z|) \quad E^{Bf} > \Delta,$$
$$E^{\text{dis}}(Z) = G(Z)\ln(|\delta_Z|) \quad E^{Bf} \leqslant \Delta.$$

$$E^{\text{dis}} + E^{Bf} \approx -4\ln(\delta).$$

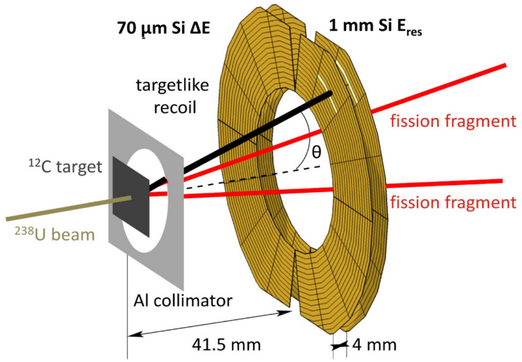
From Combinatorial analysis
(H. Nifenecker et al. Z.Phys.A 308,39(1982)



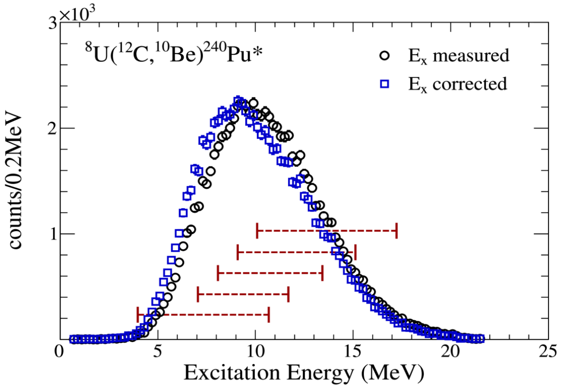
D. Ramos et al., Phys. Rev. C 107, L021601 (2023)

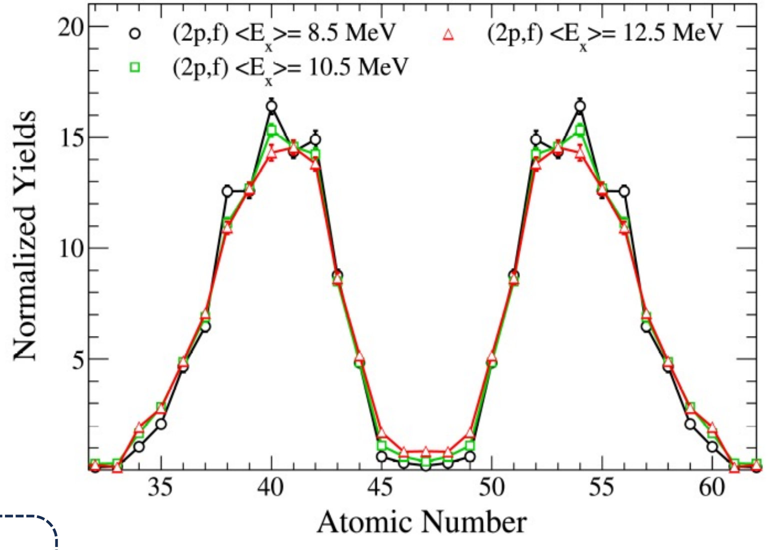
Dissipation in Fission

SPIDER



$^{238}U + 2p \rightarrow {}^{240}Pu$





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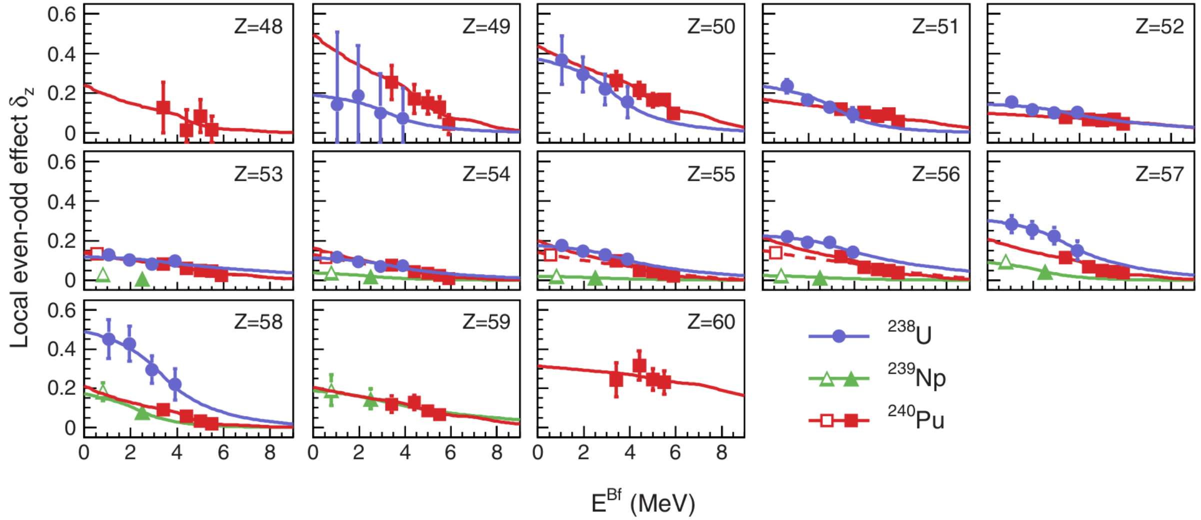
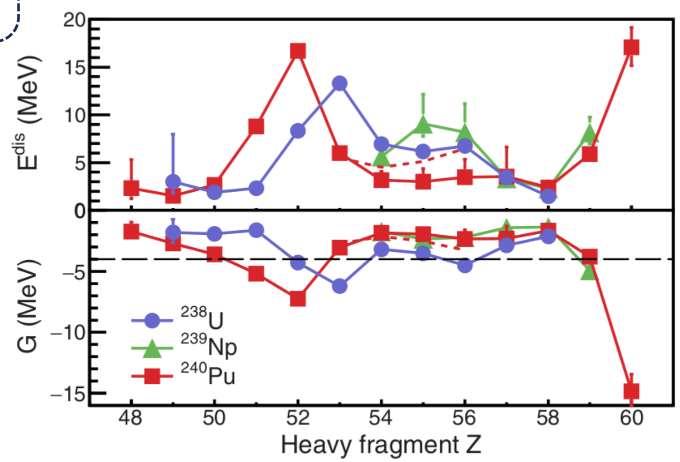
From Combinatorial analysis

(H. Nifenecker et al. Z.Phys.A 308,39(1982))





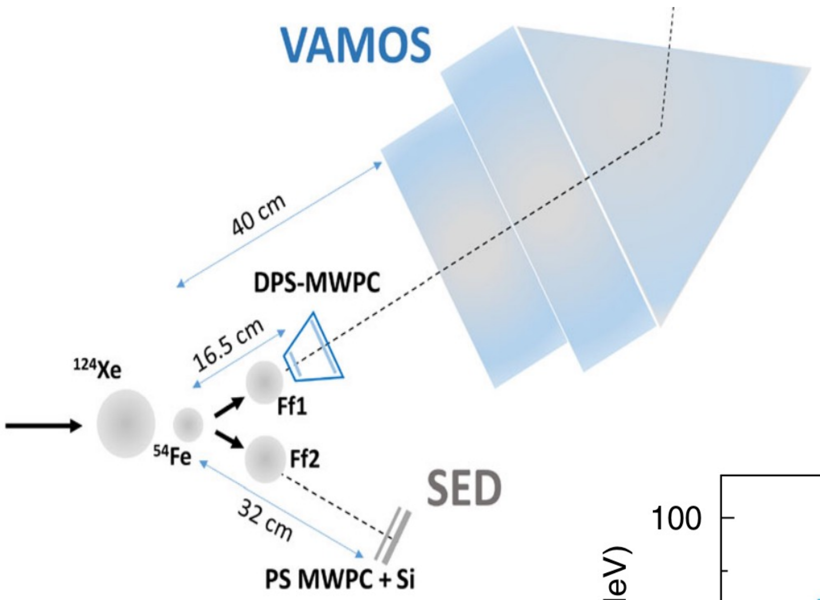
- Estimation of the Dissipation Energy from Sadle to Scission
- Higher Dissipation around deformed shell Z=52

D. Ramos et al., Phys. Rev. C 107, L021601 (2023)

Fusion Reactions

The n-defficient Pre-actinides Region

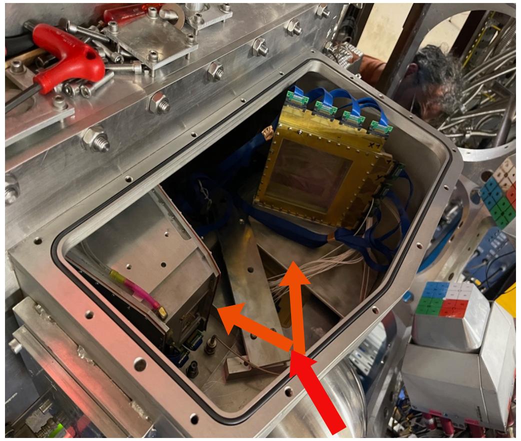
Fusion-Fission in n-defficient pre-Actinides

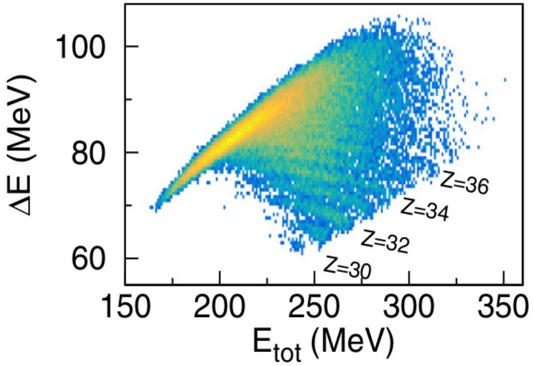


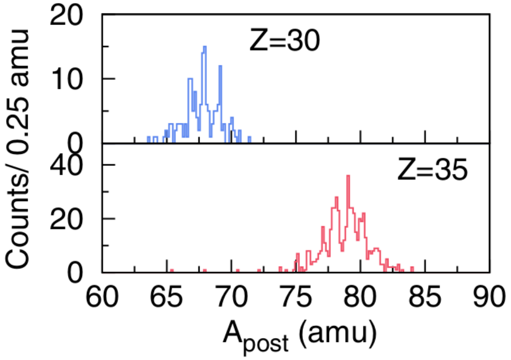
- **^{124}Xe (4.3 MeV/u) + ^{54}Fe → ^{178}Hg (E_x=34 MeV)**
- **2 arms at 64° (folding angle)**
- **Complete-Kinematics Measurement**

New Measurement (2024):

- **^{124}Xe beam (4MeV/u) + ^{60}Ni target → ^{184}Pb (E_x = 32.3, 29.5, 23.4 MeV)**

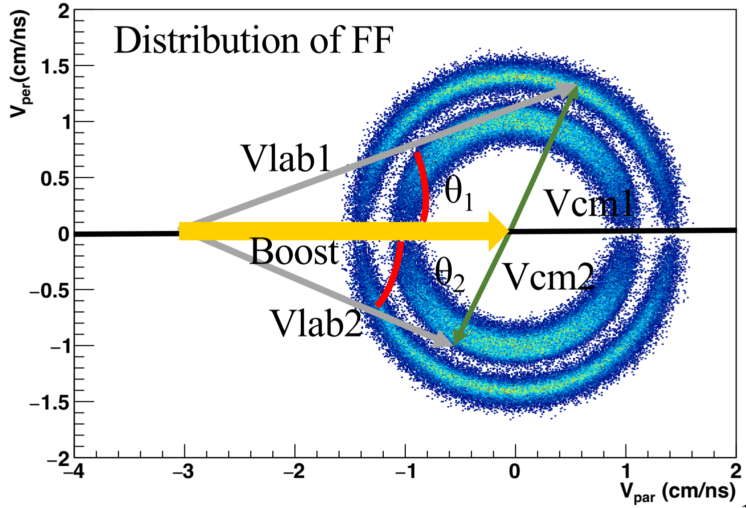






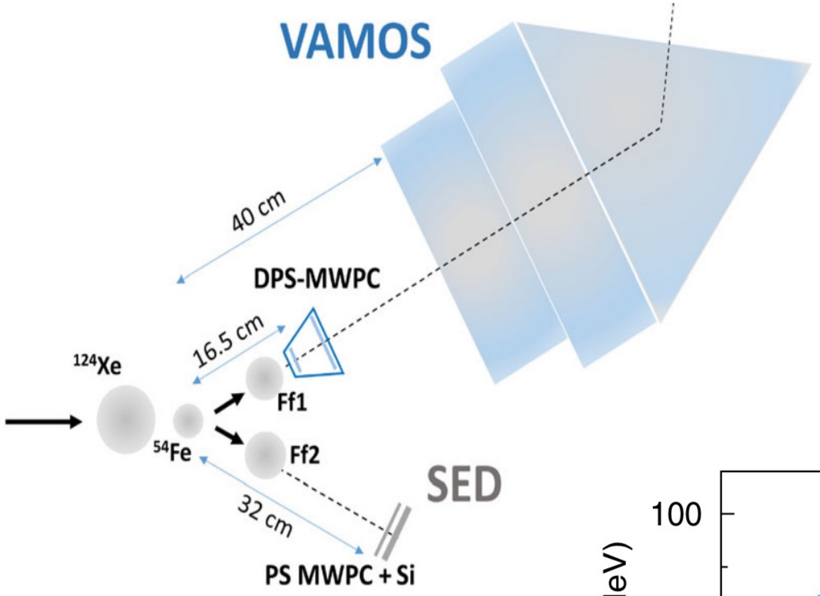
- First isotopic FF measurement in n-defficient pre-actinides

Low kinetical boost allows to recover the fission-fragment velocities in center-of-mass frame



C. Schmitt et al. PRL 126, 132502 (2021)

Fusion-Fission in n-defficient pre-Actinides



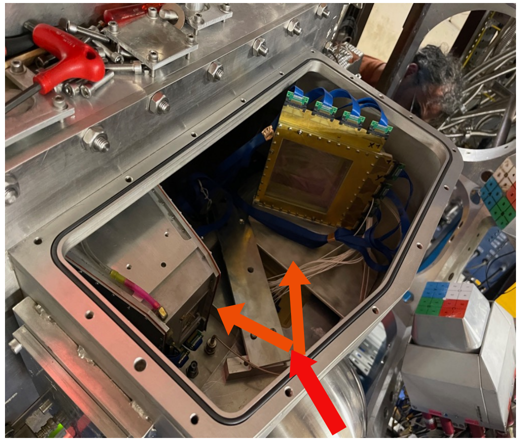
- ^{124}Xe (4.3 MeV/u) + ^{54}Fe → ^{178}Hg (E_x=34 MeV)
- 2 arms at 64° (folding angle)
- Complete-Kinematics Measurement

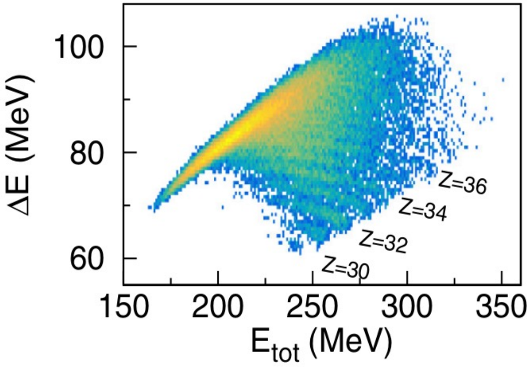
2V method

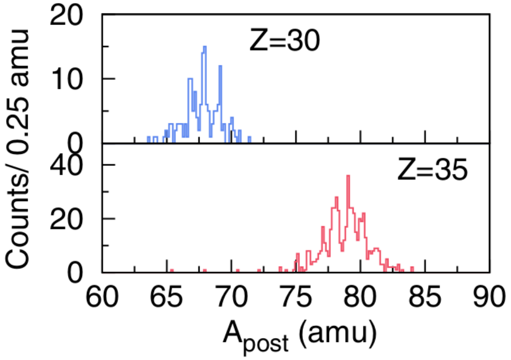
$$\frac{M_1^*}{M_2^*} = \frac{\gamma_{c.m._2} v_{c.m._2}}{\gamma_{c.m._1} v_{c.m._1}}$$

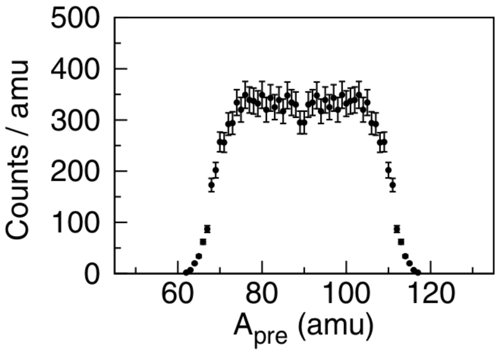
New Measurement (2024):

- **^{124}Xe beam (4MeV/u) + ^{60}Ni target → ^{184}Pb (E_x = 32.3, 29.5, 23.4 MeV)**

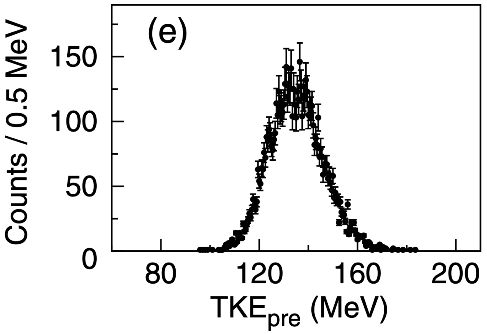


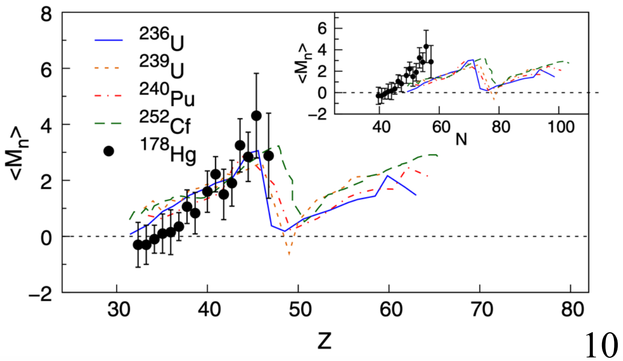






- First isotopic FF measurement in n-defficient pre-actinides
- **Confirmed presence of asymetric fission in ^{178}Hg**
  - **Pre-evaporation mass, TKE, neutron multiplicity**





C. Schmitt et al. PRL 126, 132502 (2021)

Current status

Towards High Resolution &
Highly Correlated Data

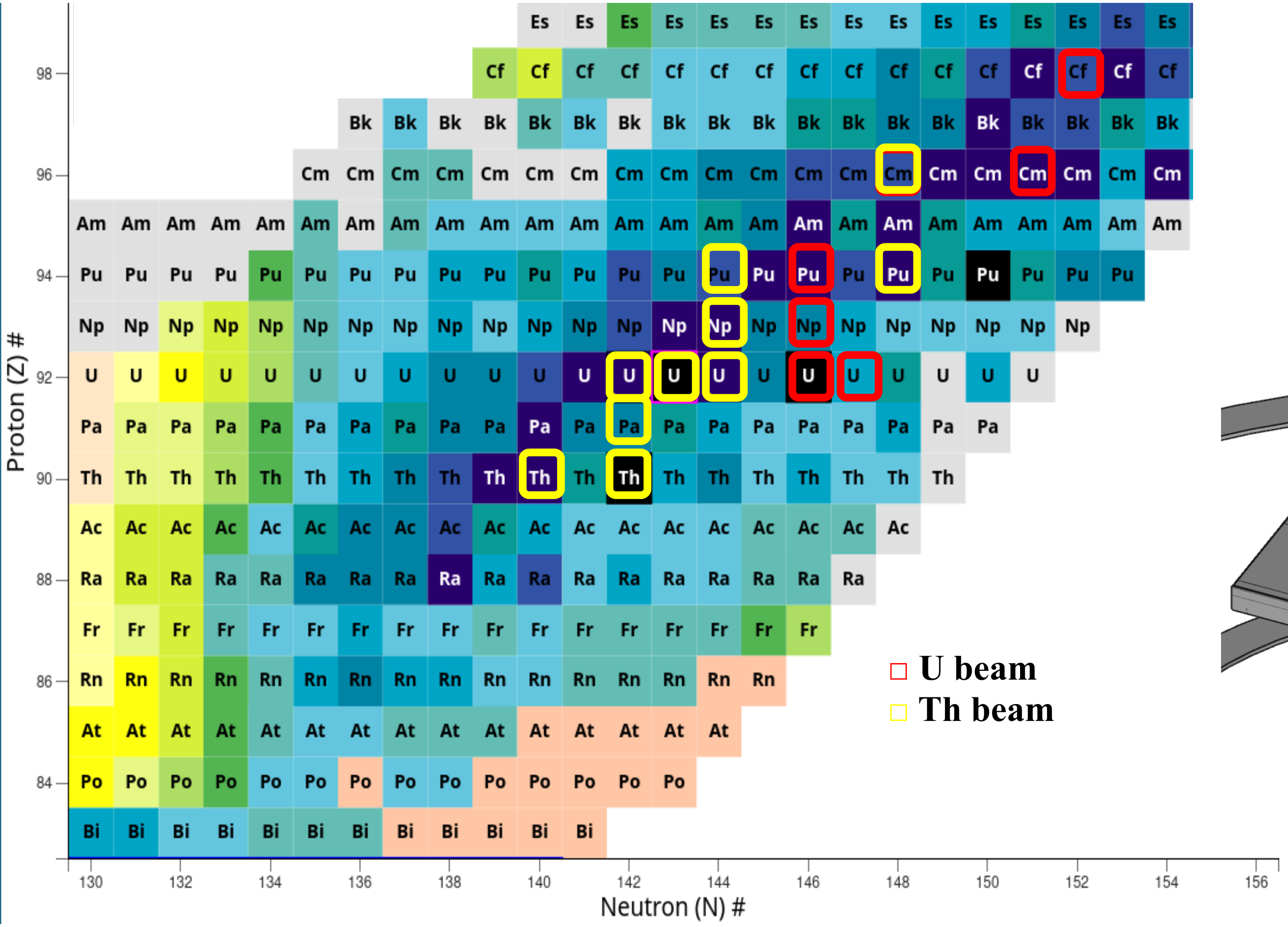
Present and Future of Fission@VAMOS

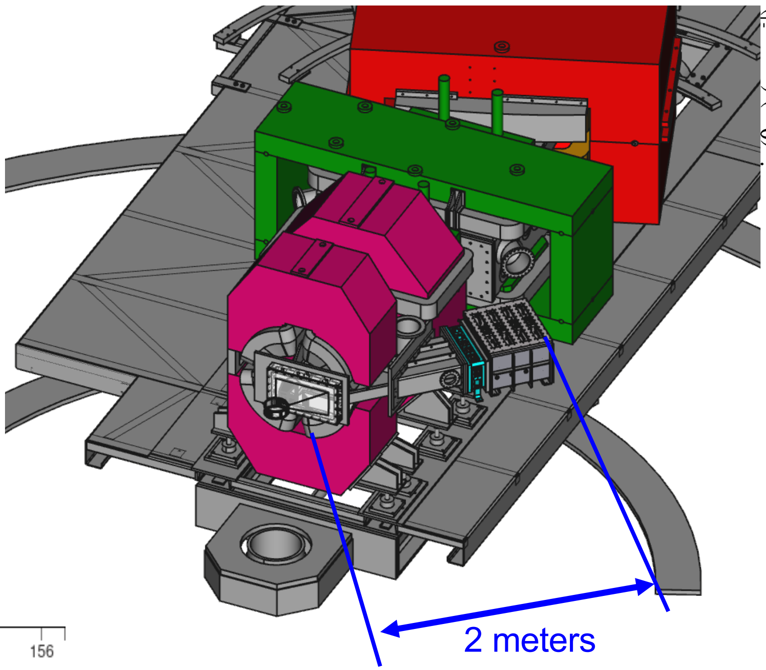
^{238}U beam + PISTA detector
New ^{232}Th beam accelerated at GANIL
Unprecedent resolution
Access to new region of actinides

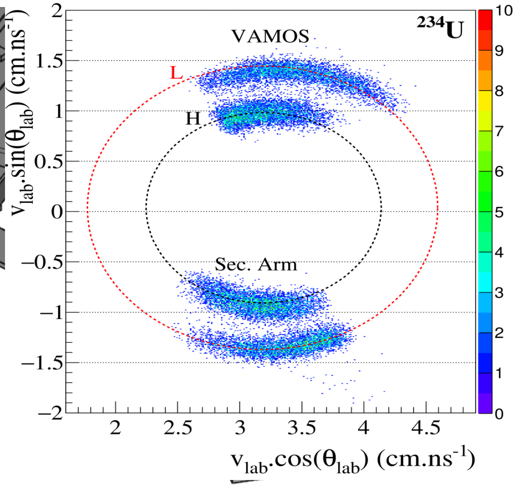
2024

HIGH RESOLUTION 2V detection
- **First measurement in beam**

- Pre-neutron evaporation fission yields
- Isotopic distribution of FF Kinetic Energy
- Isotopic neutron evaporation multiplicities





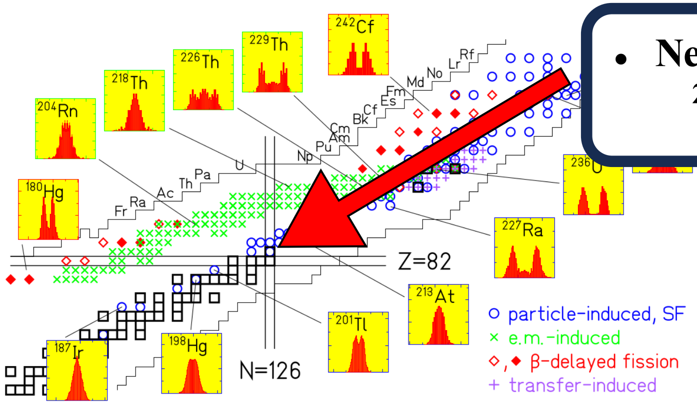


Present and Future of Fission@VAMOS

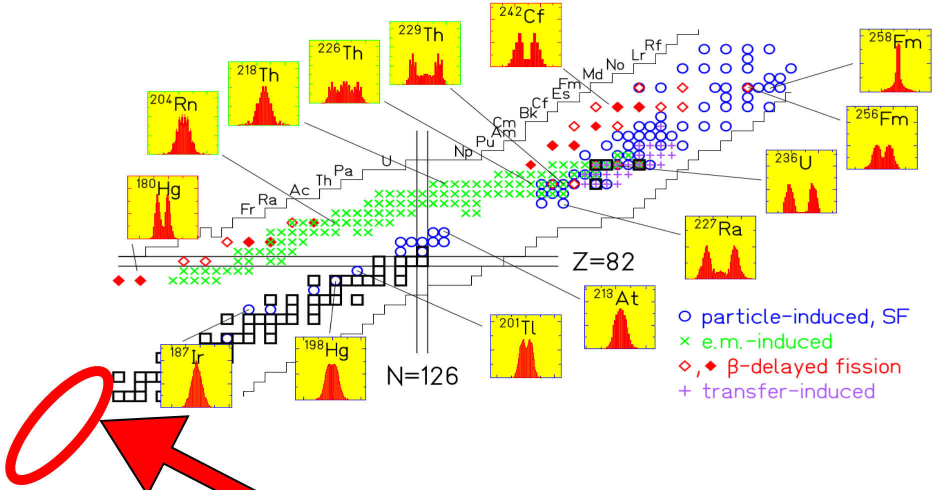
FUSION-FISSION at FISSION BARRIER ENERGIES
- **Heavy beams + light gaseous detectors**
- **Gas cell under development at GANIL**

2025

Fission in Light Systems (Z<=60)

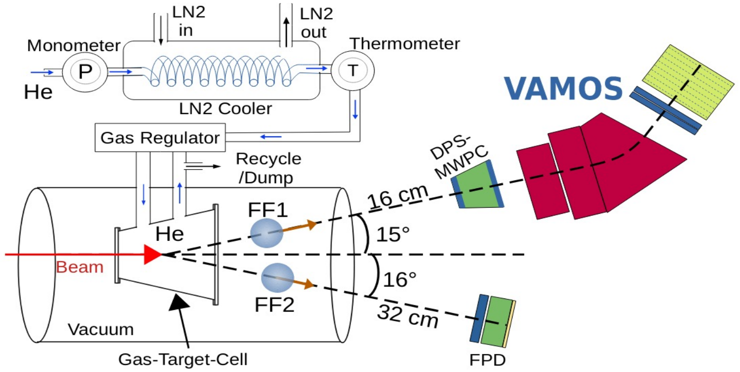


- **Next Experiment**
  ^{206}**Pb** + ^{4}**He** → ^{210}**Po**



- **Barely explored region:**
- ^{136}**Xe** + ^{12}**C** → ^{148}**Nd**
- ^{136}**Xe** + ^{9}**Be** → ^{145}**Ce**

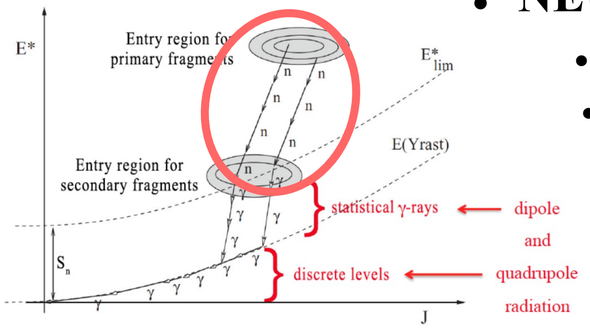
- **GAS CELL**



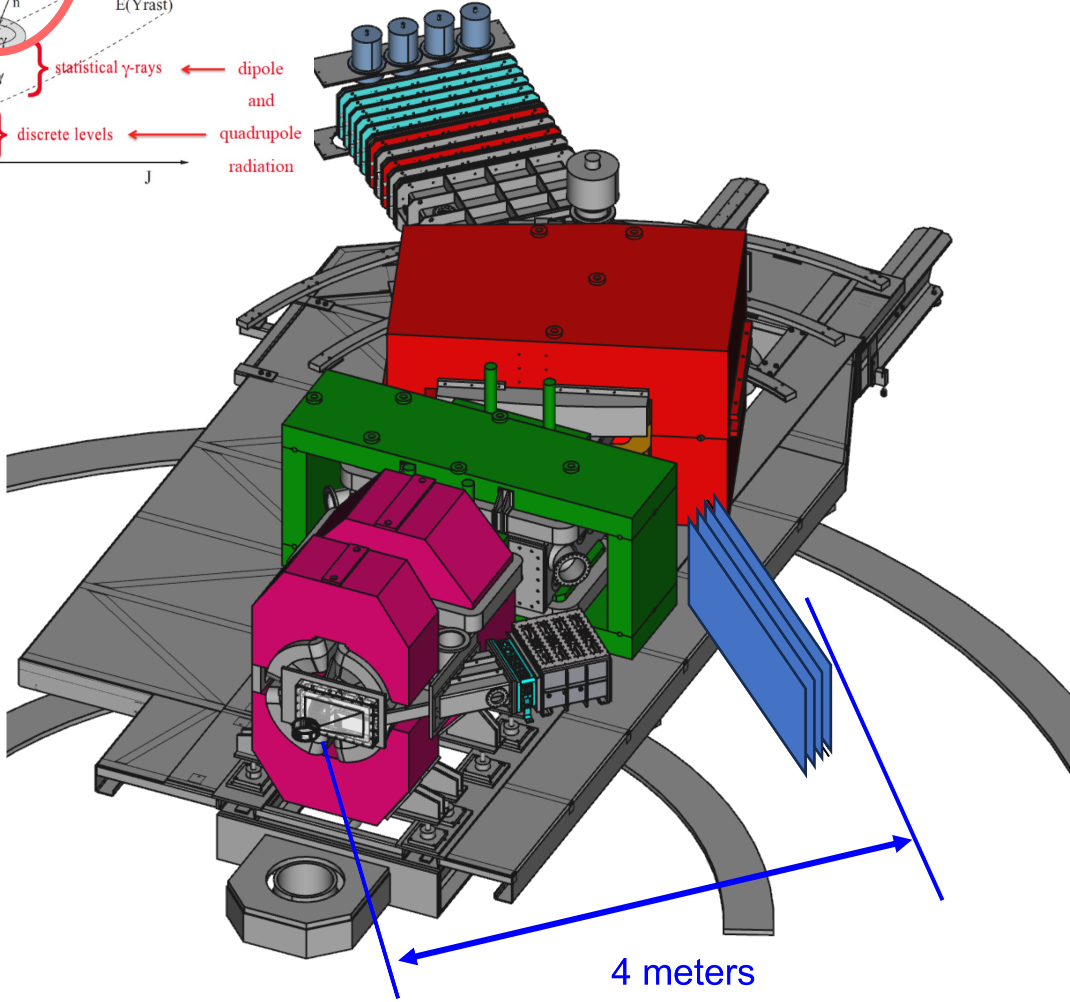
Conclusions

VAMOS is a powerful instrument for heavy ions identification

- Large phase-space acceptance
- High identification resolution



- **NEUTRON WALL @ VAMOS**
  - Neutron multiplicity + **Neutron energy**
  - Disentangle **pre-scission neutrons**



The use of **Inverse-Kinematics combined with the magnetic spectrometers** gives access to **full fission-fragments identification** of exotic fissioning systems

Coulomb Energies favors the access to **Scission-point observables**

The fission@VAMOS program is under **continuous improvements:**

Planning already the next steps:

- PISTA v2
- Neutron Wall
- Extension use of Gas Cell

Fission@VAMOS Collaboration

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Taiki Tanaka (Postdoc
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Cyril Lenain
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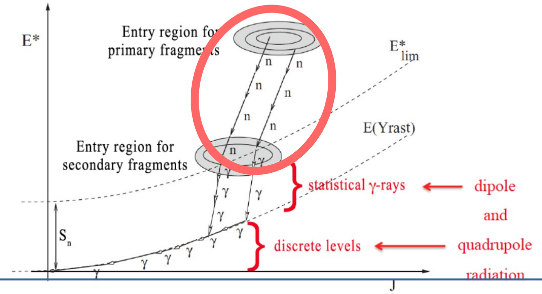
Neeraj Kumar (Postdoc)

USC (Spain)
Manuel Caamano
Beatriz Fernandez
Beatriz Errandonea (PhD)

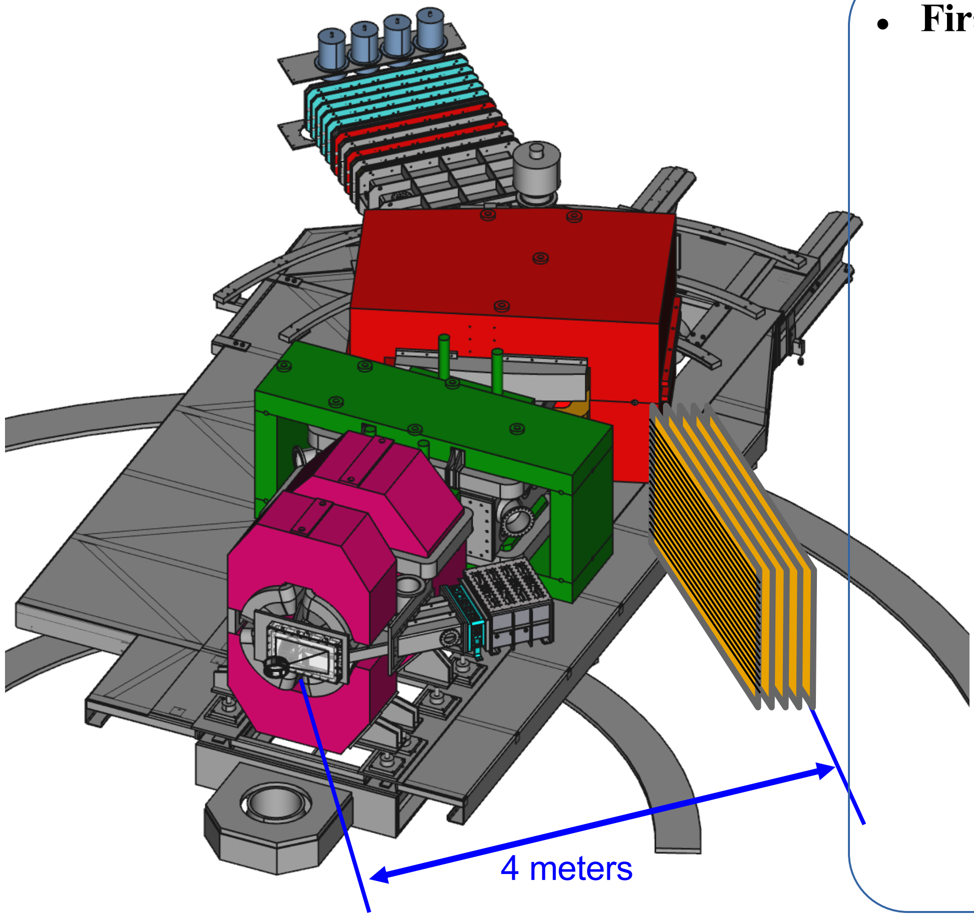
GANIL

- **NEUTRON WALL @ VAMOS**



Requirements :

- High Time resolution (~200 ps) → **Energy resolution ~ 200 keV**
- High Granularity (~2 cm)



- **First Test in 2023 ($^{238}U + ^{12}C$)**