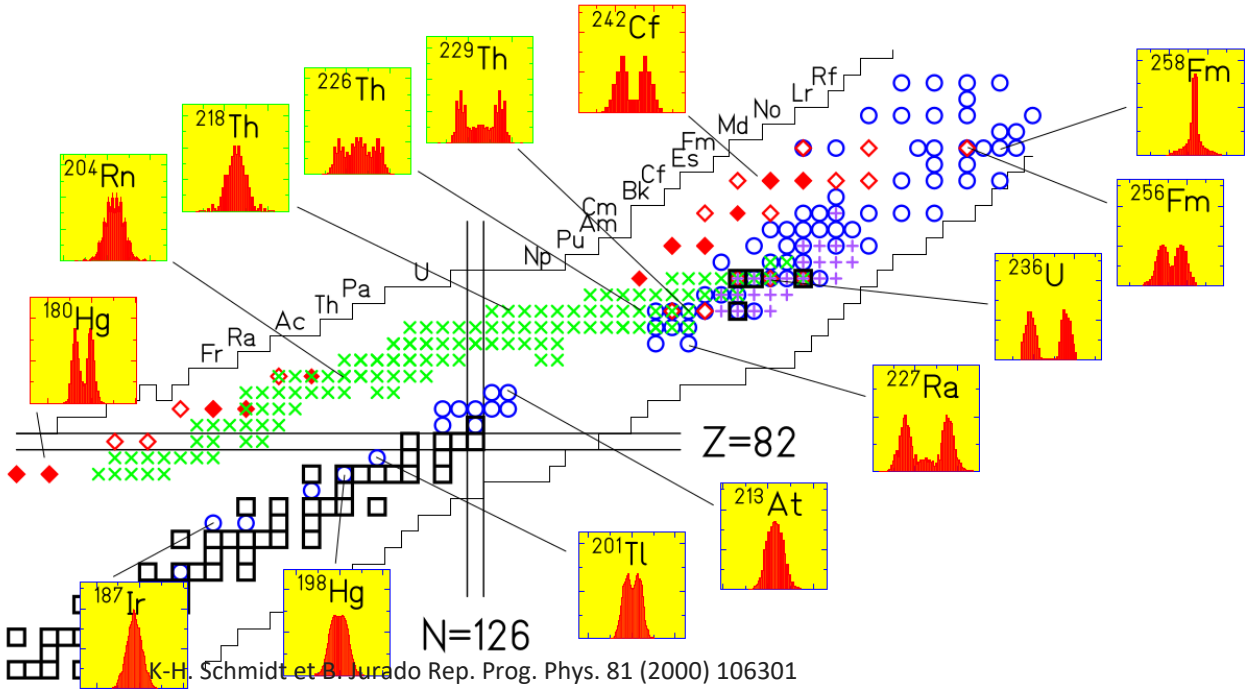
Experimental Fission Campaign at VAMOS++

Diego Ramos

Inverse Kinematics Fission @VAMOS

◆**FISSION@VAMOS**

- Heavy ion Beams (Xe,Th,U, Pb)
- Inverse-Kinematics Surrogate-Induced Fission



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

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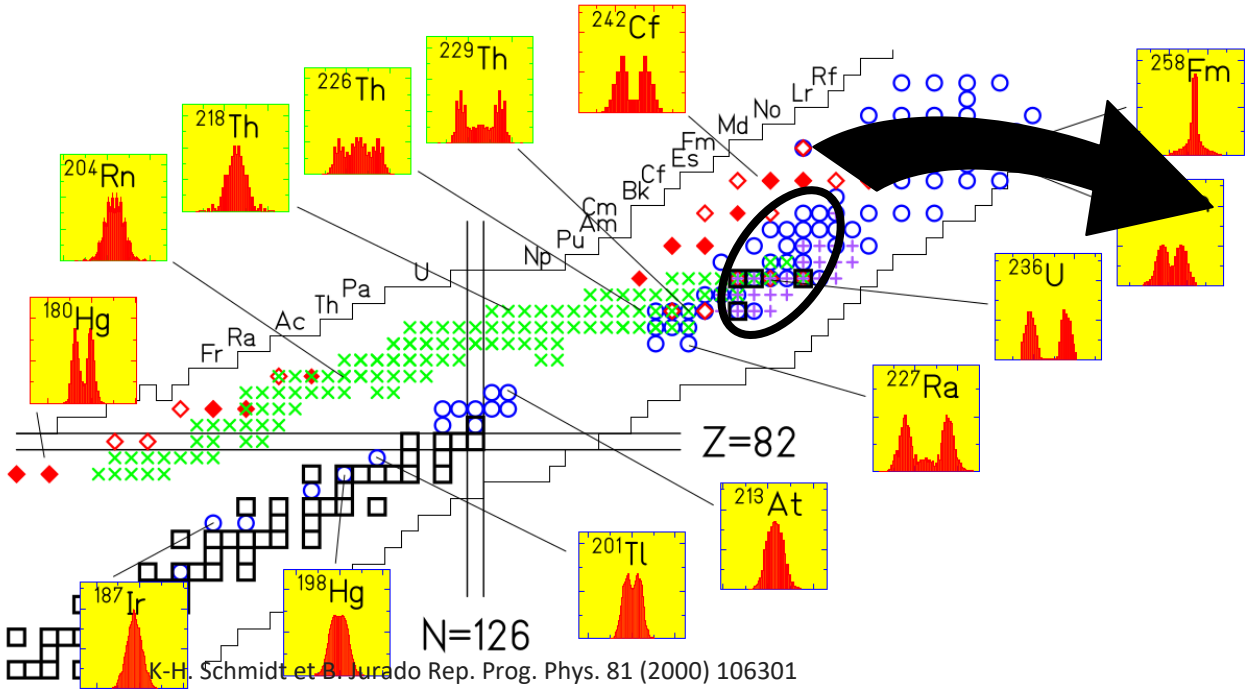

K-H. Schmidt et B. Jurado Rep. Prog. Phys. 81 (2000) 106301

- **MultiNucleon Transfer Reactions**

$^{238}U + {}^{12}C \rightarrow$

$^{236}U + {}^{14}C$
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$^{232}Th + {}^{12}C \rightarrow$

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Inverse Kinematics Fission @VAMOS

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

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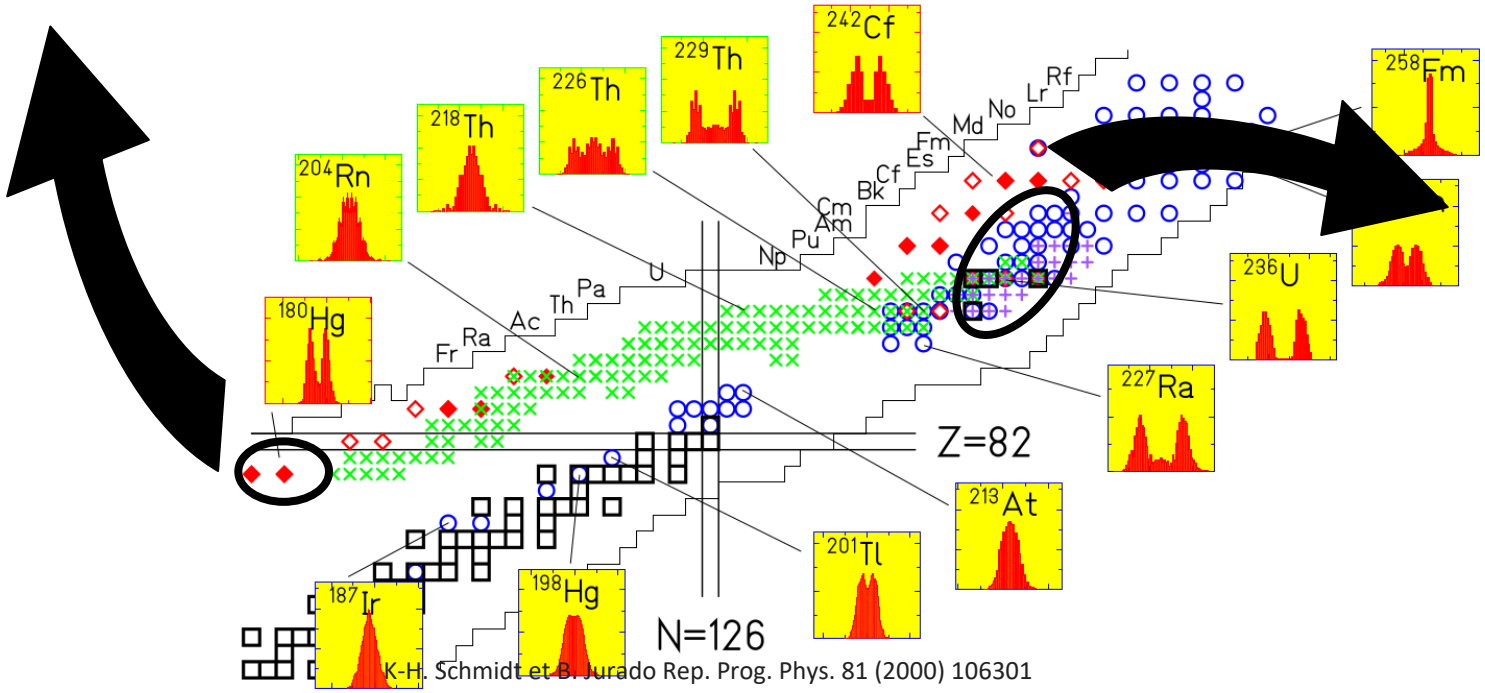

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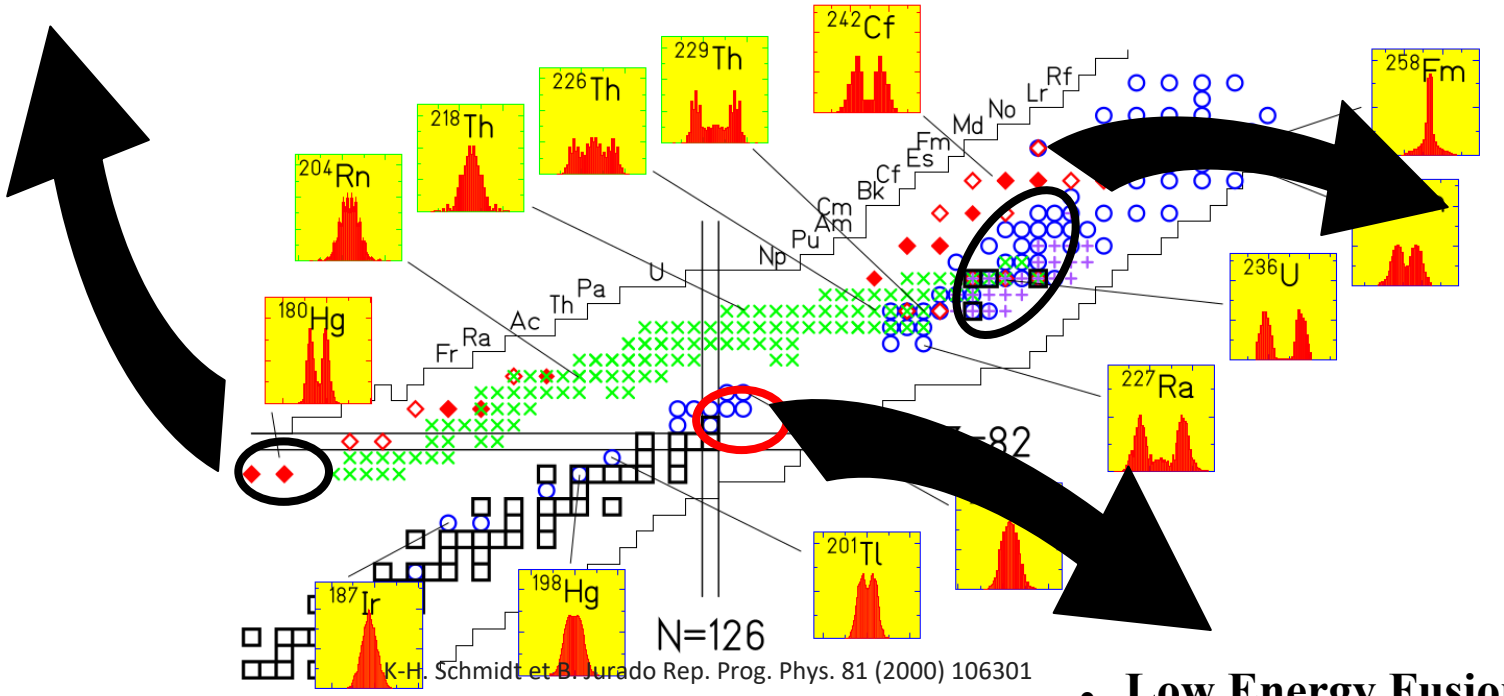

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- **Low Energy Fusion**

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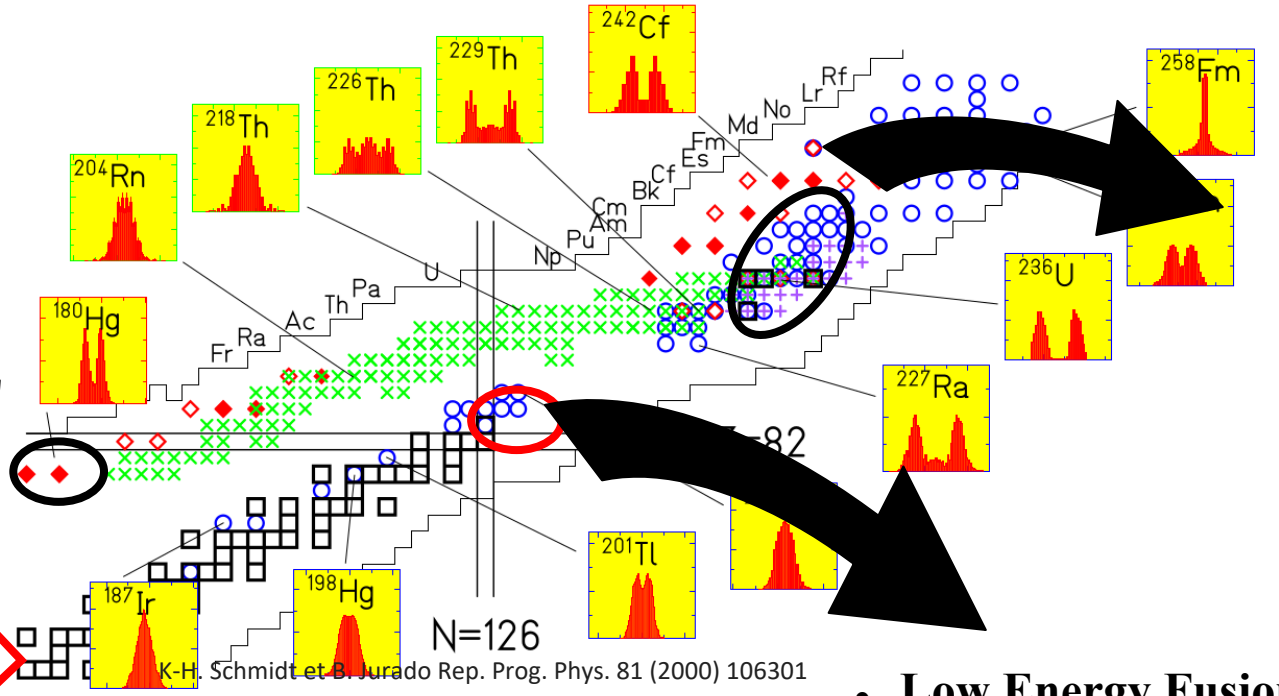

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Complete Isotopic-distribution of fission-fragments Yields

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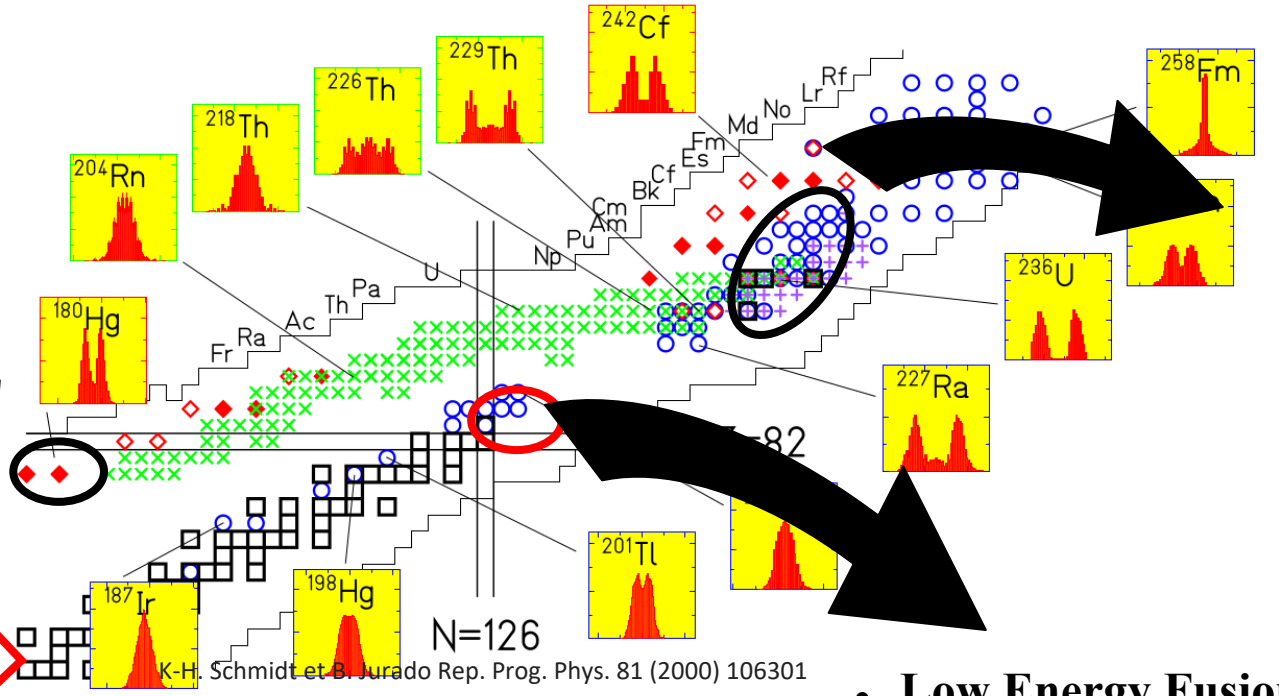

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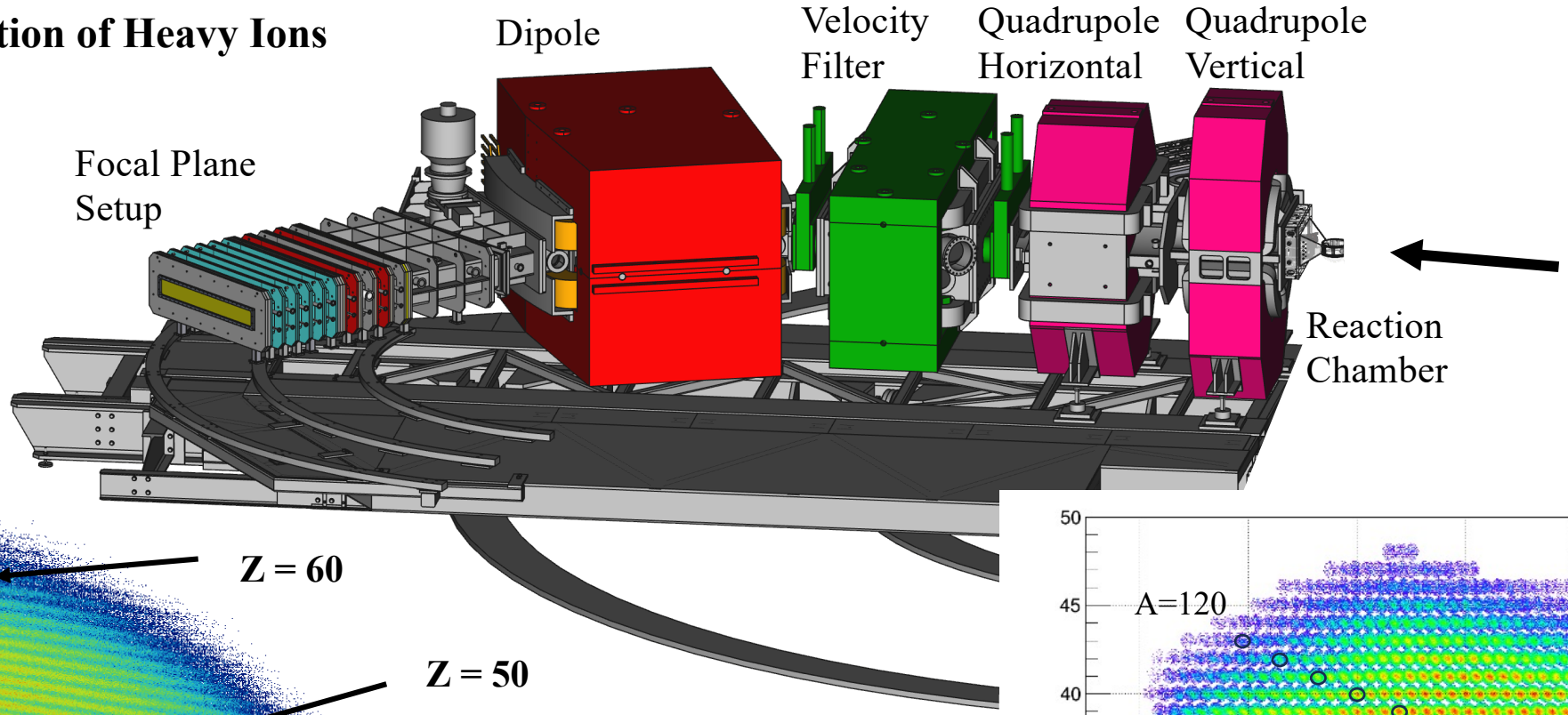
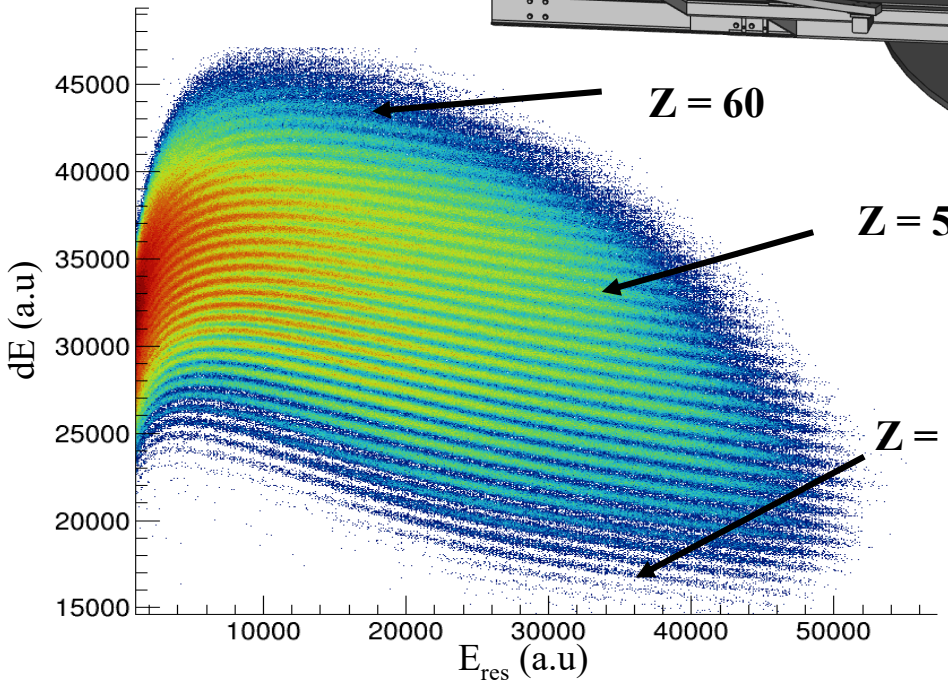
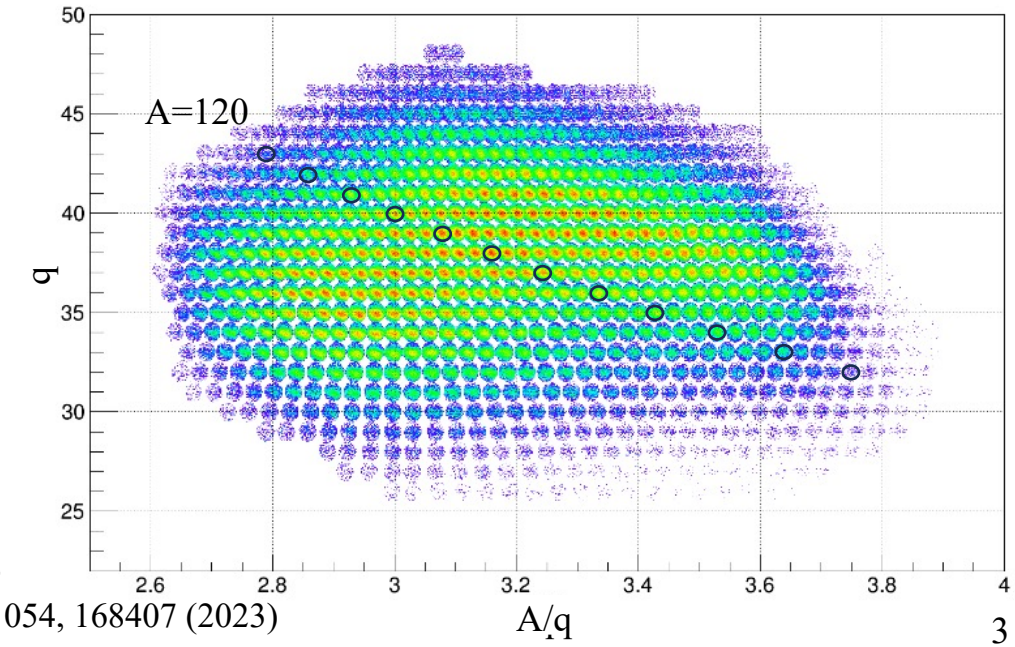
Isotopic Identification of Heavy Ions





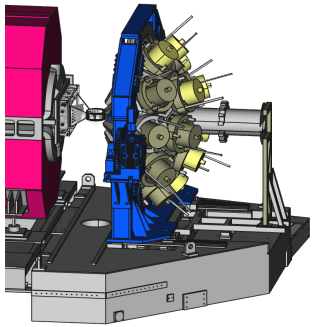


M. Rejmund et al., NIM A 646 (2011) 184
A. Lemasson & M. Rejmund ,NIM A 1054, 168407 (2023)

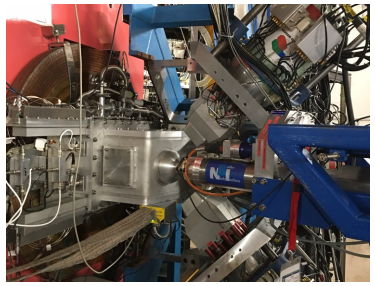
Complementary Setups

Isotopic Identification of Heavy Ions

Fission-Fragments ɣ-decay measurements (HPGe detectors)



AGATA+VAMOS



EXOGAM+VAMOS

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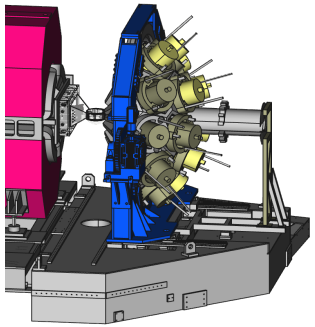

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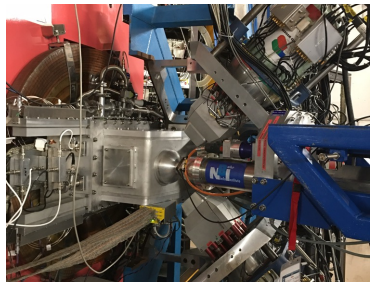
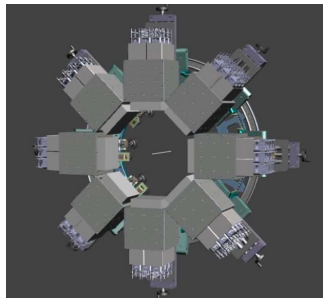


EXOGAM+VAMOS

High-Energy ɣ decay, collectivity measurements (Scintillators)

PARIS+VAMOS: Talk of Michal Ciemala



PARIS+VAMOS

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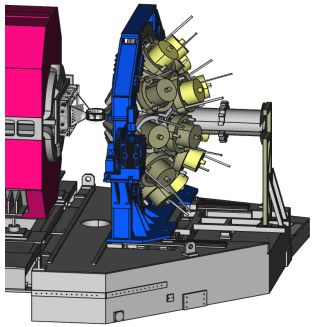

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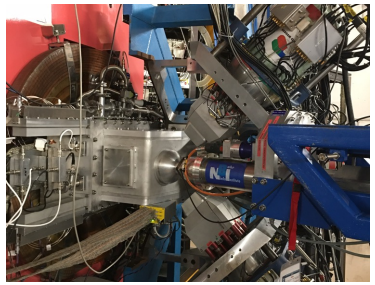

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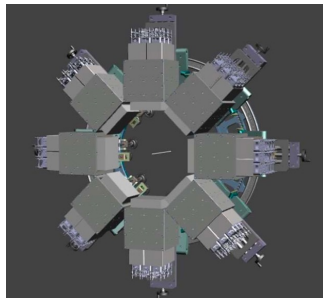
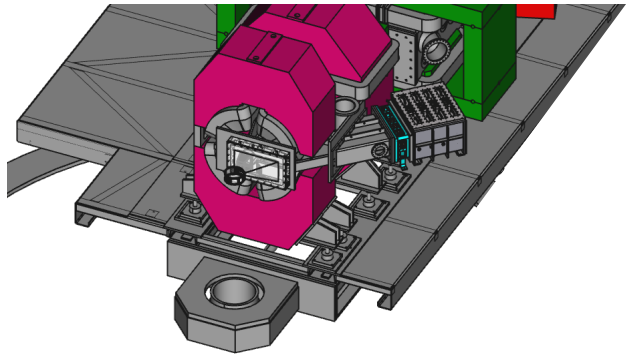
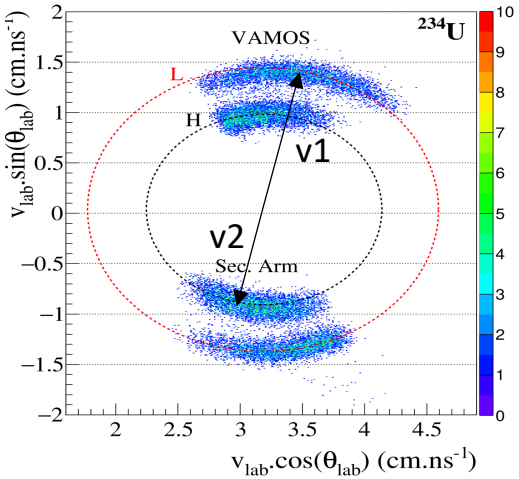


PARIS+VAMOS

SECOND ARM VAMOS



Pre-neutron evaporation fission-fragment masses (Second Arm detection – 2 fragment velocities)



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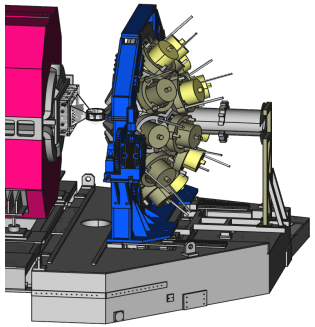

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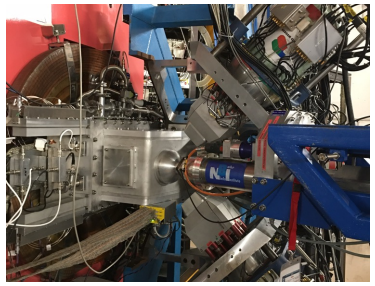

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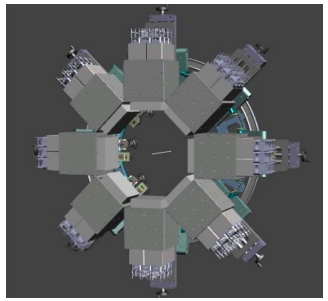

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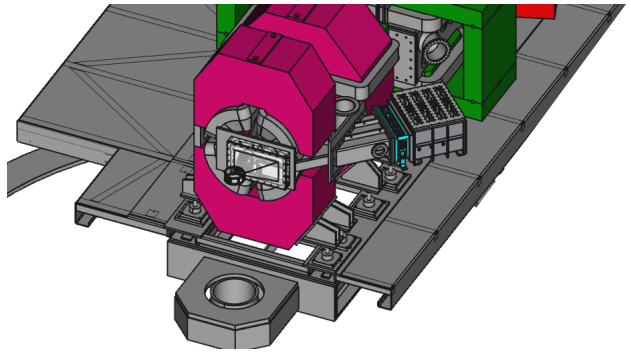

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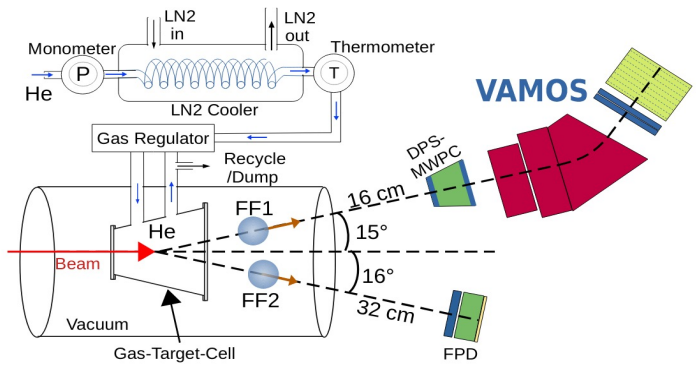
Fusion reactions in Gasseous Targets (GAS CELL target)

NN trajectory reconstruction in Extended Targets
M. Rejmund & A. Lemasson NIM A 1076, 170445 (2025)



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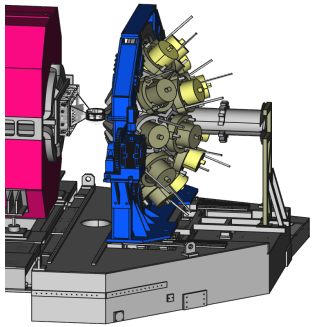

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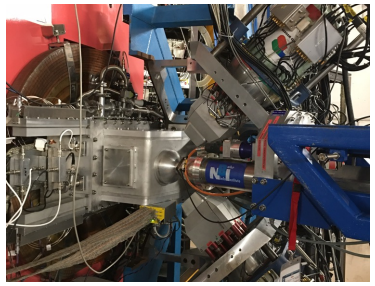

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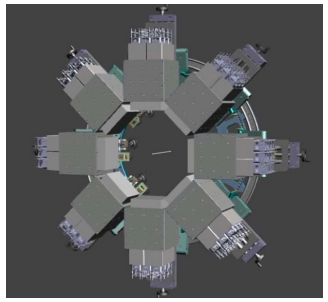

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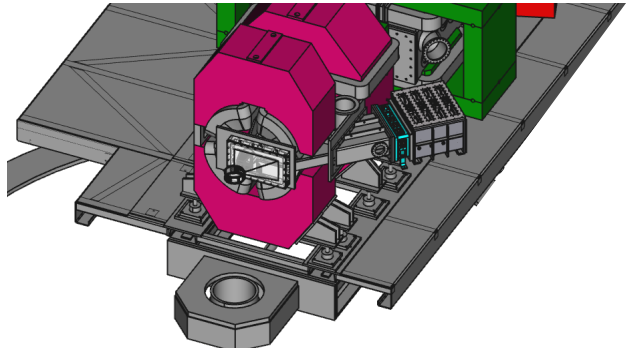

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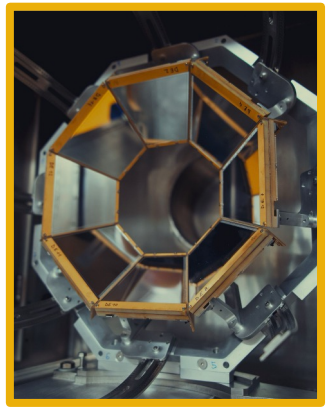
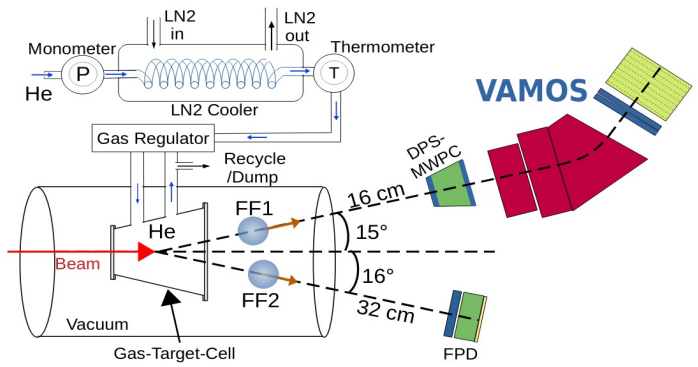


Excitation-Energy measurement in MNT-fission (Target-like detection SPIDER/PISTA)



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Isotopic Identification of Heavy Ions

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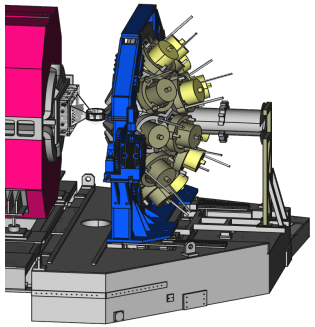

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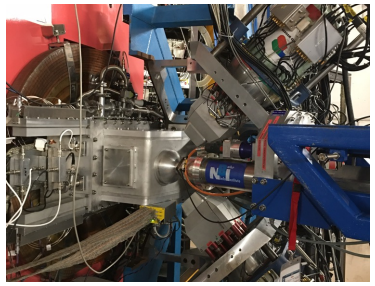

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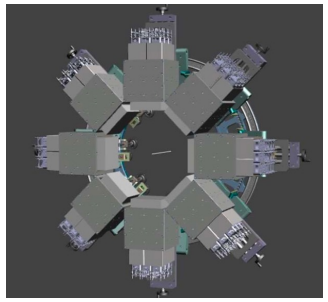

PARIS+VAMOS

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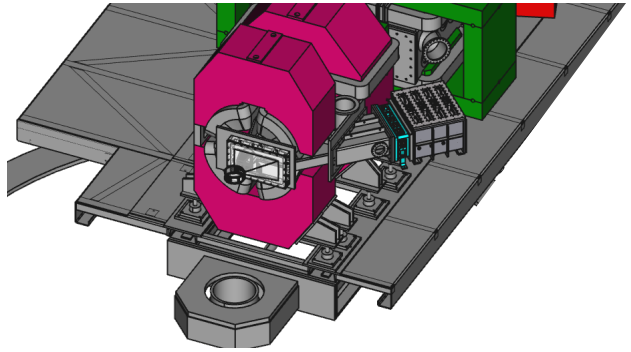

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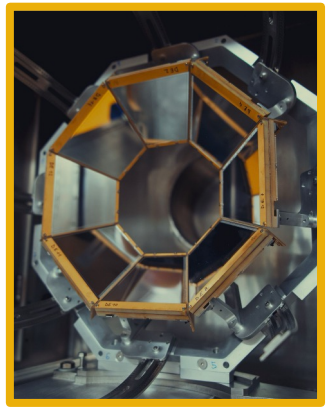
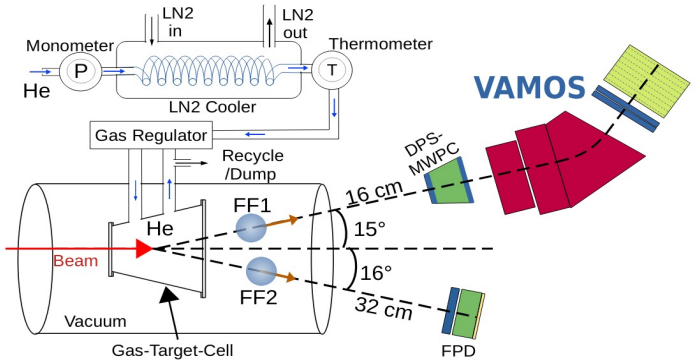




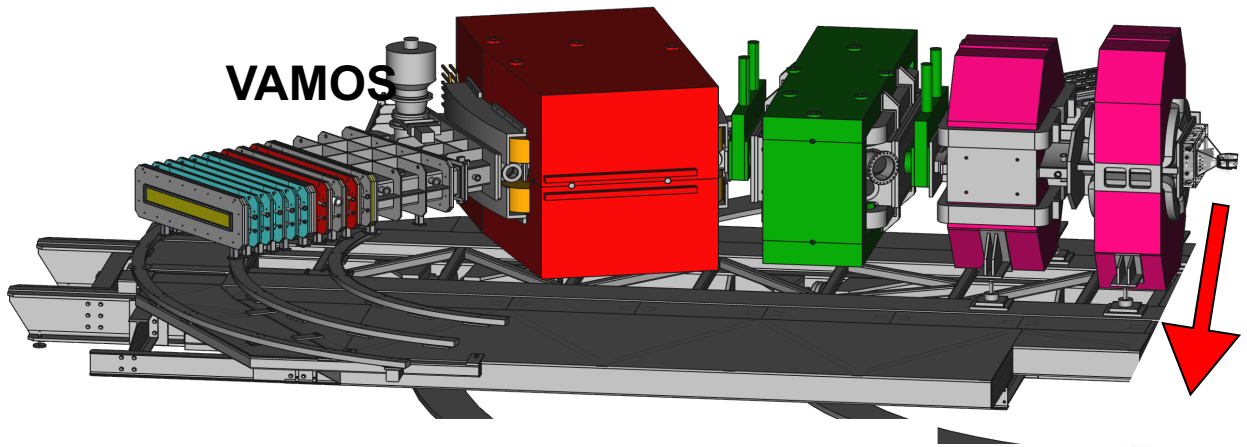
Excitation-Energy measurement in MNT-fission (Target-like detection SPIDER/PISTA)

Multi-nucleon Transfer Reactions

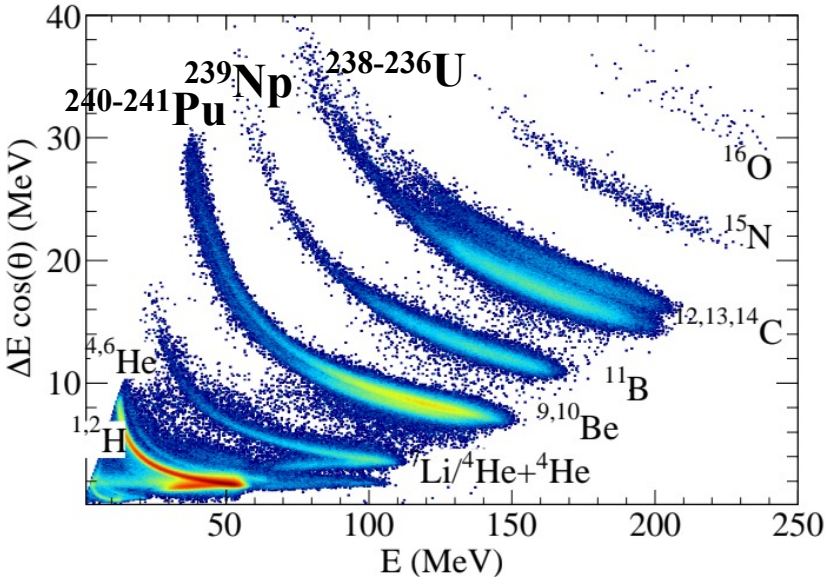
Access to Actinides

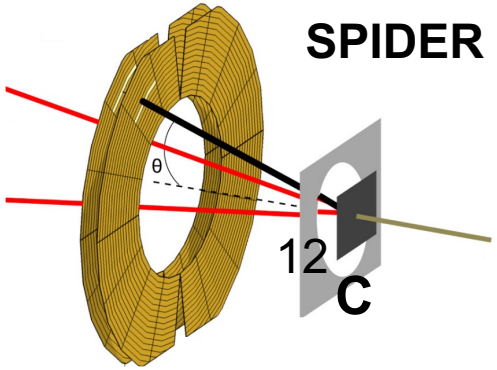
Fissioning System Identification

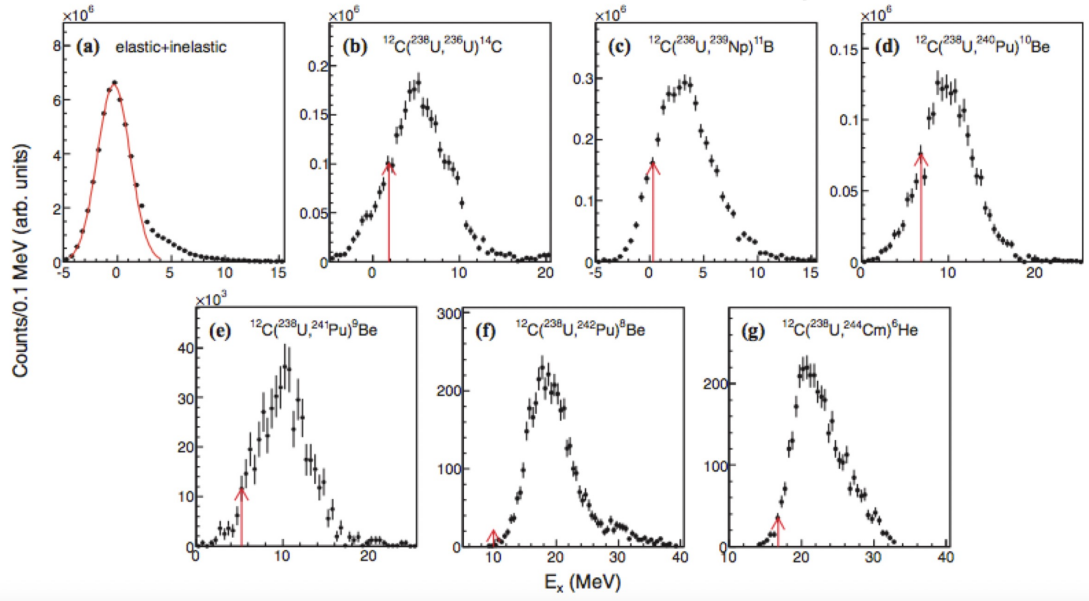
- **^{238}U beam at ~6 MeV/u** (Coulomb energies)



- **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







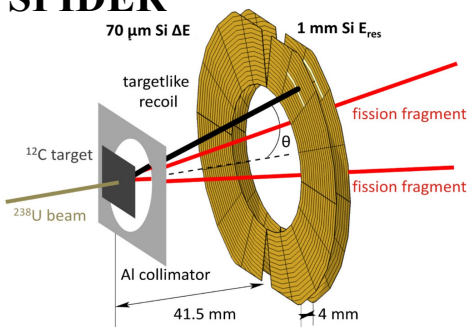
E_x Resolution = 2.7 MeV (FWHM)

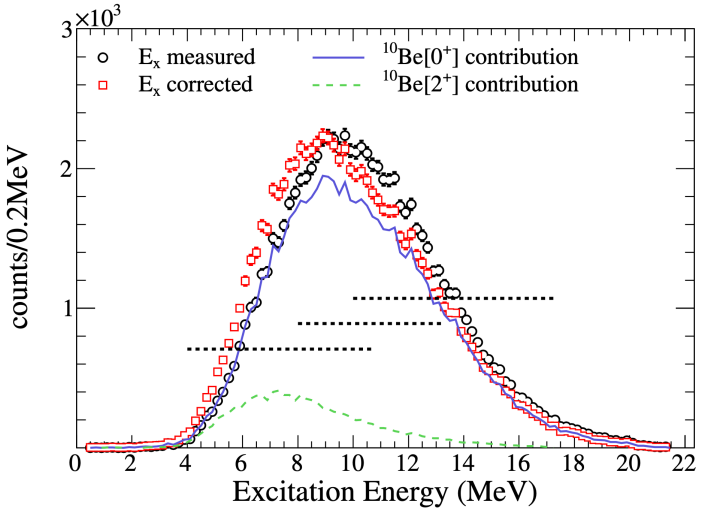
C. Rodríguez-Tajes et al., PRC 89, 024614 (2014)

Isotopic Fission Yieds as a function of E_x

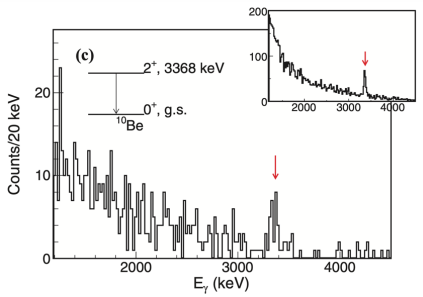
$^{238}U + 2p \rightarrow ^{240}Pu$

SPIDER



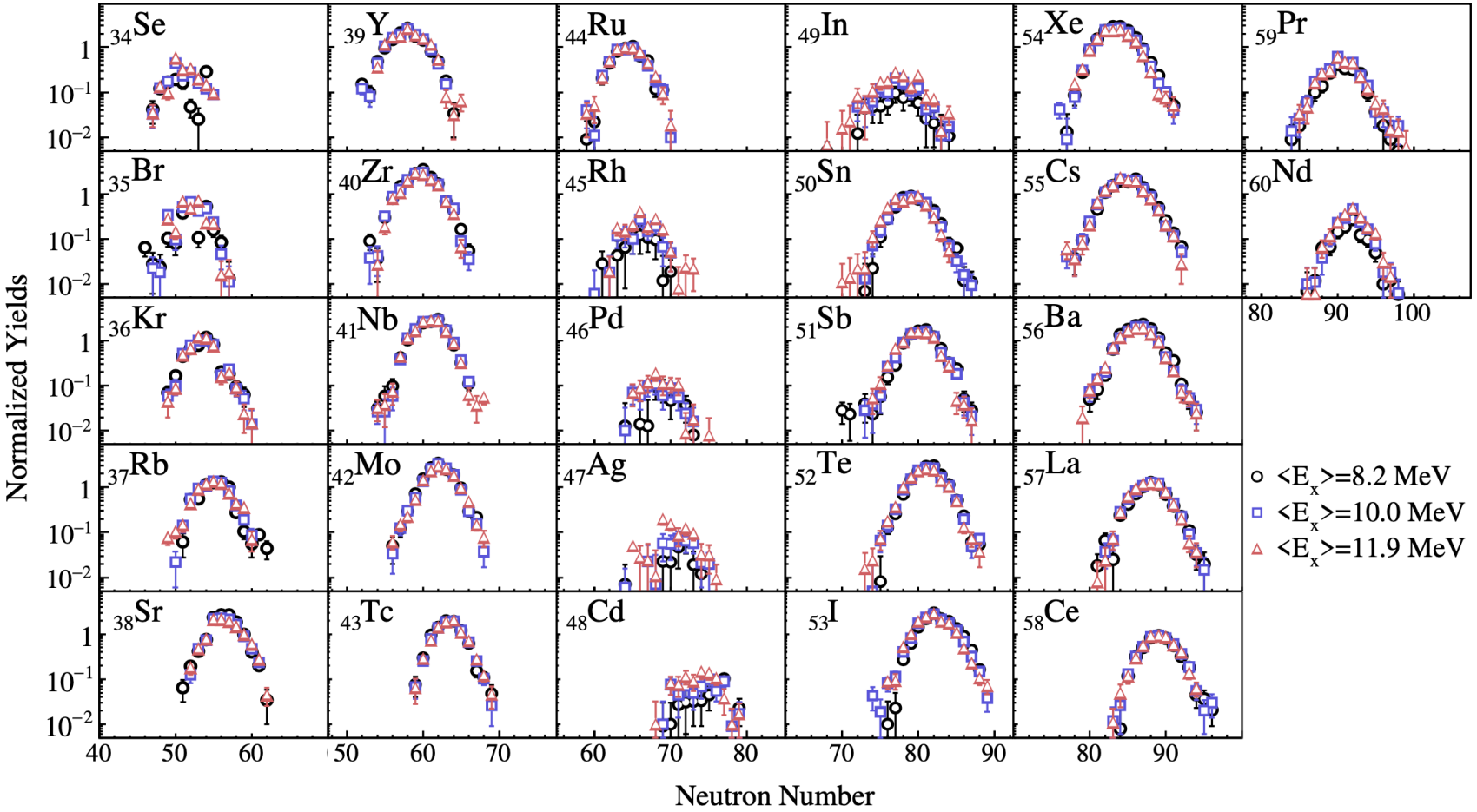


EXOGAM



P(^{10}Be[2$^+$]) = 0.14 ± 0.04

VAMOS

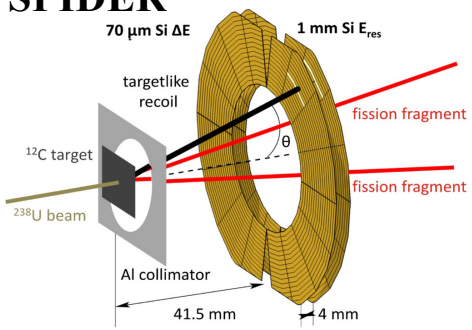


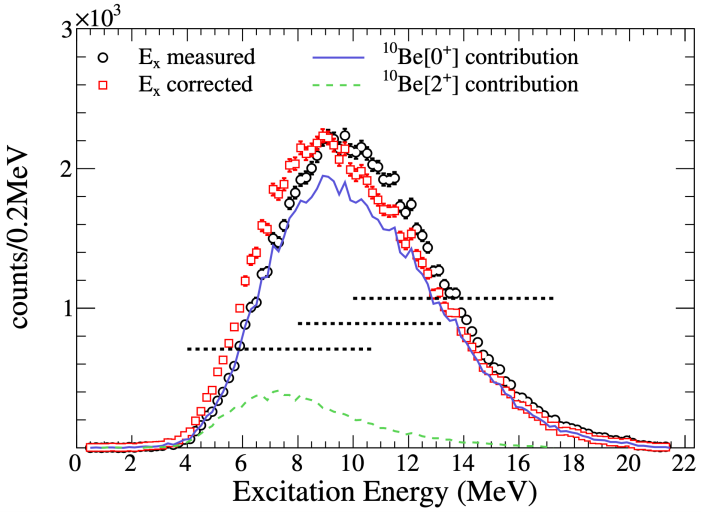
Full distribution of post-neutron evaporation
Isotopic Fission Yields as a function of E_x

Mass yields compared with n-induced

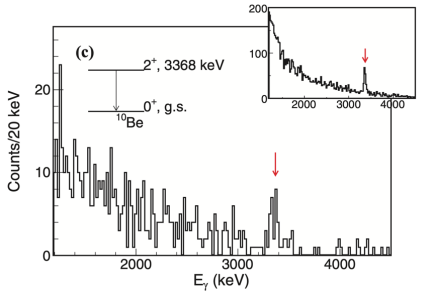
$^{238}U + 2p \rightarrow ^{240}Pu$

SPIDER

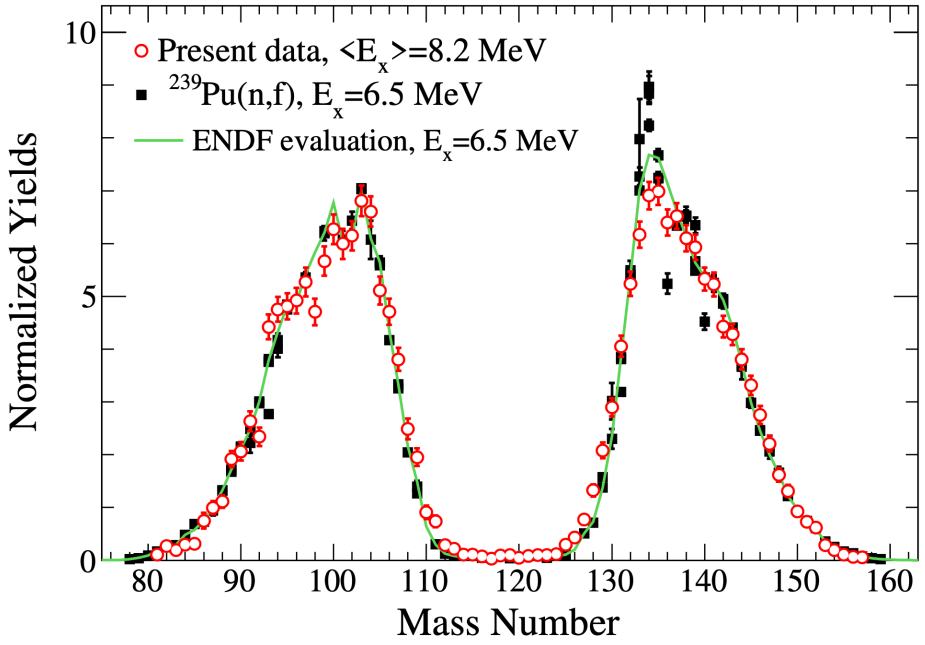




EXOGAM



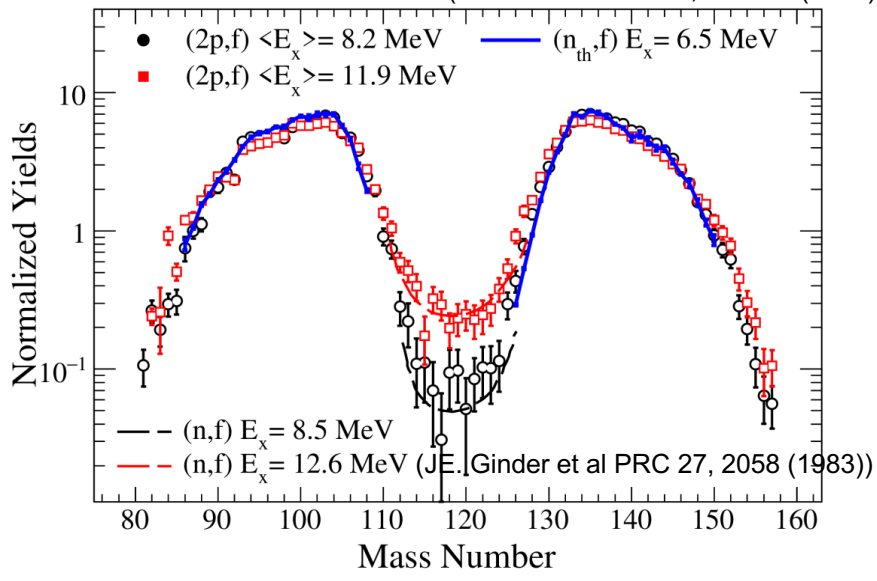
$P(^{10}Be[2^+]) = 0.14 \pm 0.04$



- **Post-neutron evaporation mass yields.**
- Very good agreement with n-induced fission (H. Naik et al. NSE 196, 824 (2022)) and data bases (ENDF)
- Evidence of E_x effect in A ~132

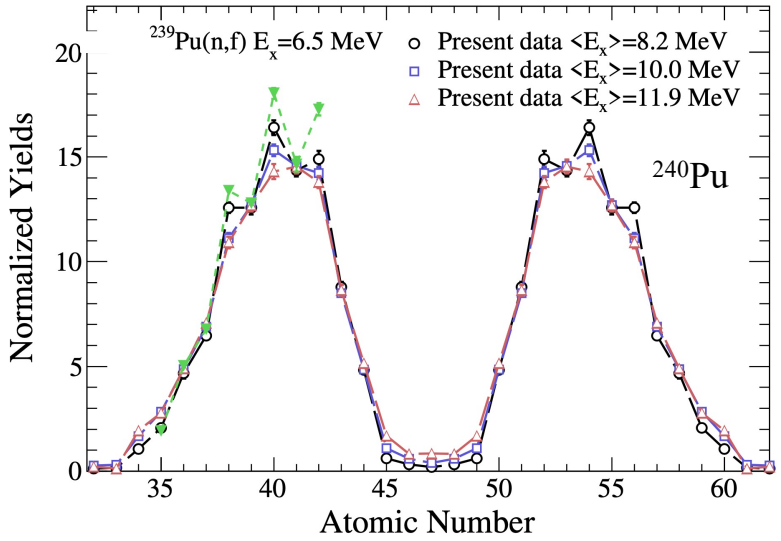
- Same feeding of the symmetric valley with increasing E_x

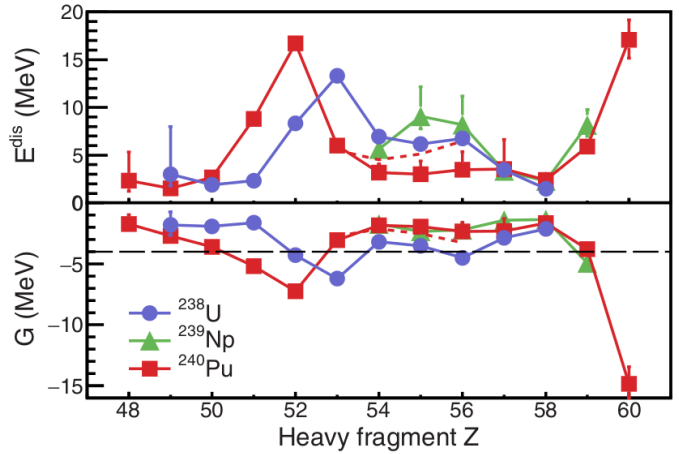
(A.Bail et al. PRC 84, 034605 (2011)



New Observable of Dissipation in Fission

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





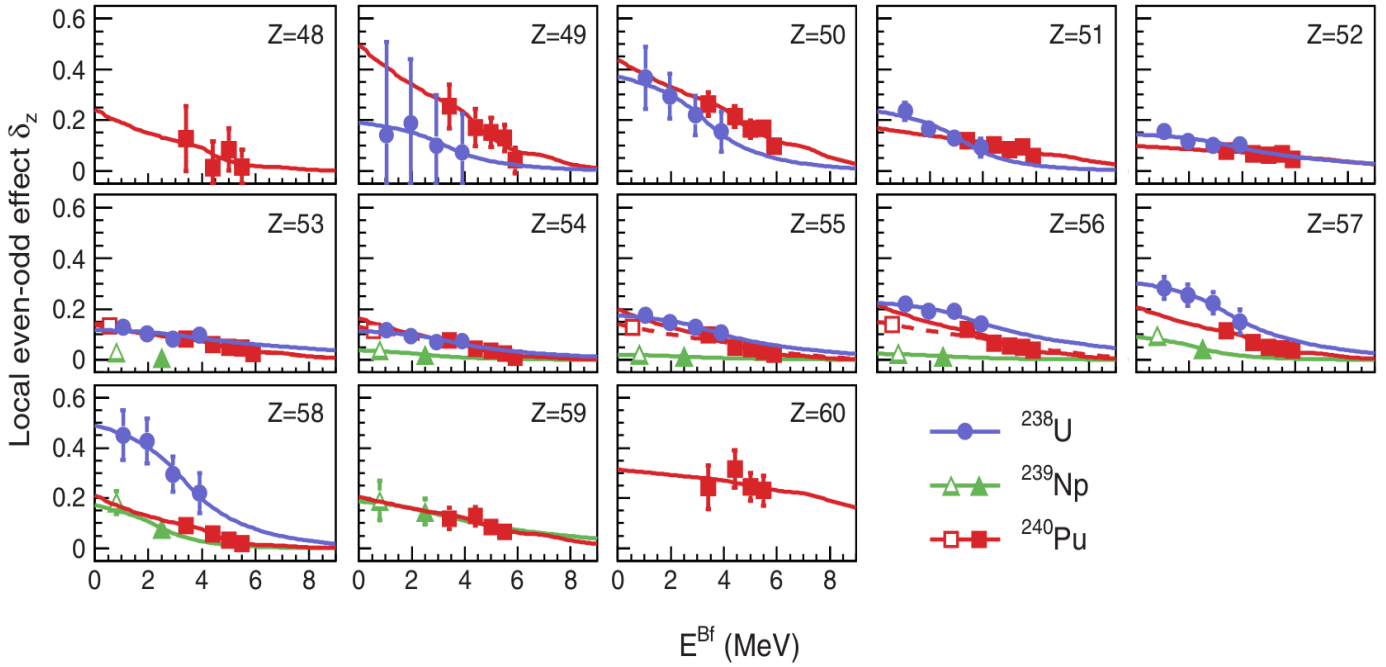
- Proton even-odd effect decreasing for higher inital Excitation energy
- The measurement of δ at different E_x allow to fit the correlation between both and determine E^{dis}

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

$$E^{\mathrm{dis}}(Z) = G(Z)\ln(|\delta_Z|) \quad E^{Bf} \leqslant \Delta.$$

- Intrinsic E_x allows the breaking of proton pairs from Saddle to Scission point

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

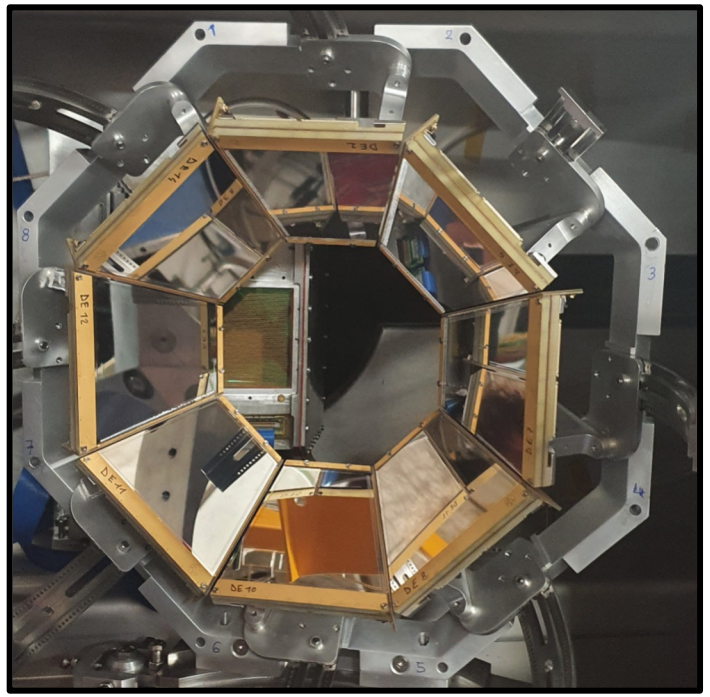


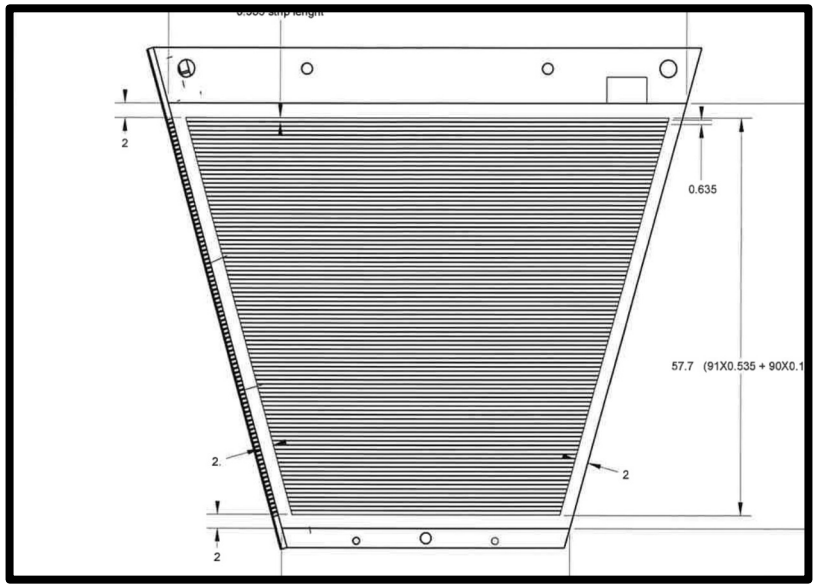
- Higher Dissipation around deformed shell Z=52

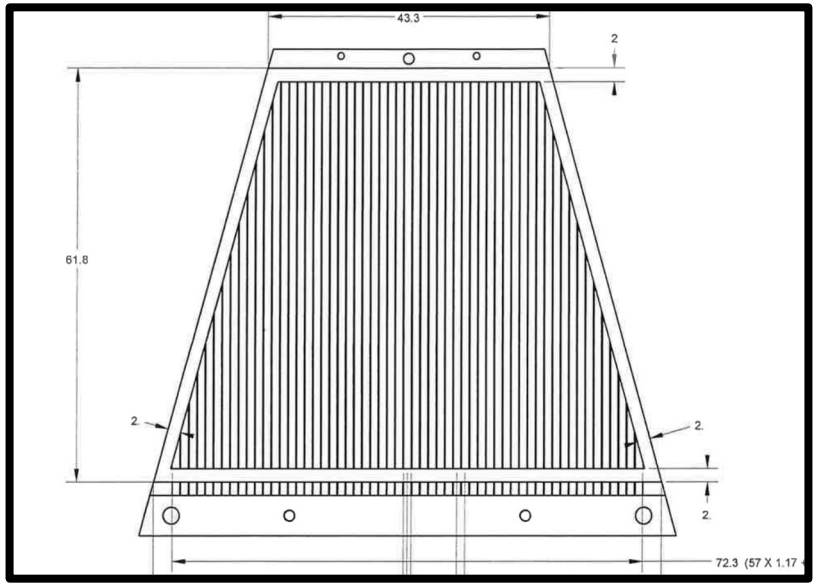
New Detection Generation
PISTA

NEW COLLABORATION: GANIL – CEA-DAM BRUYERES-LE-CHÂTEL

PISTA Detector







DE – E Silicon Telescope

dE :

100 um thick

0.53 mm horizontal strips

E :

1 mm thick

1.17 mm vertical strips

10 cm from the target:

Angular coverage: 30 – 60 deg

Angular precission: < 5 mrad

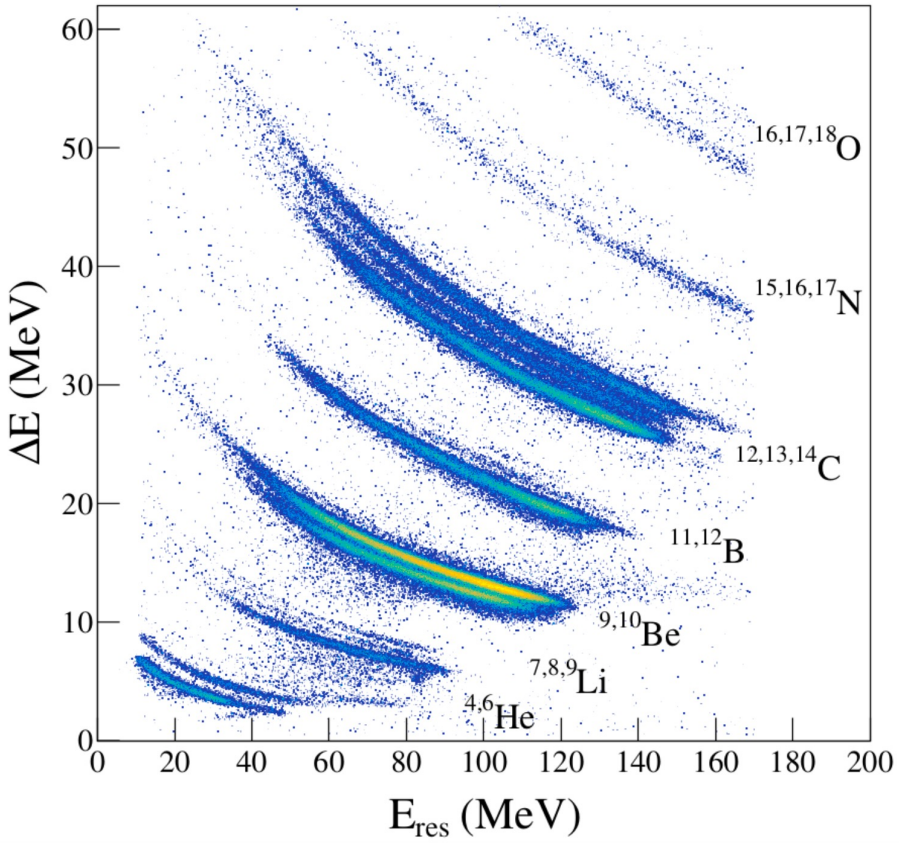
Goals:

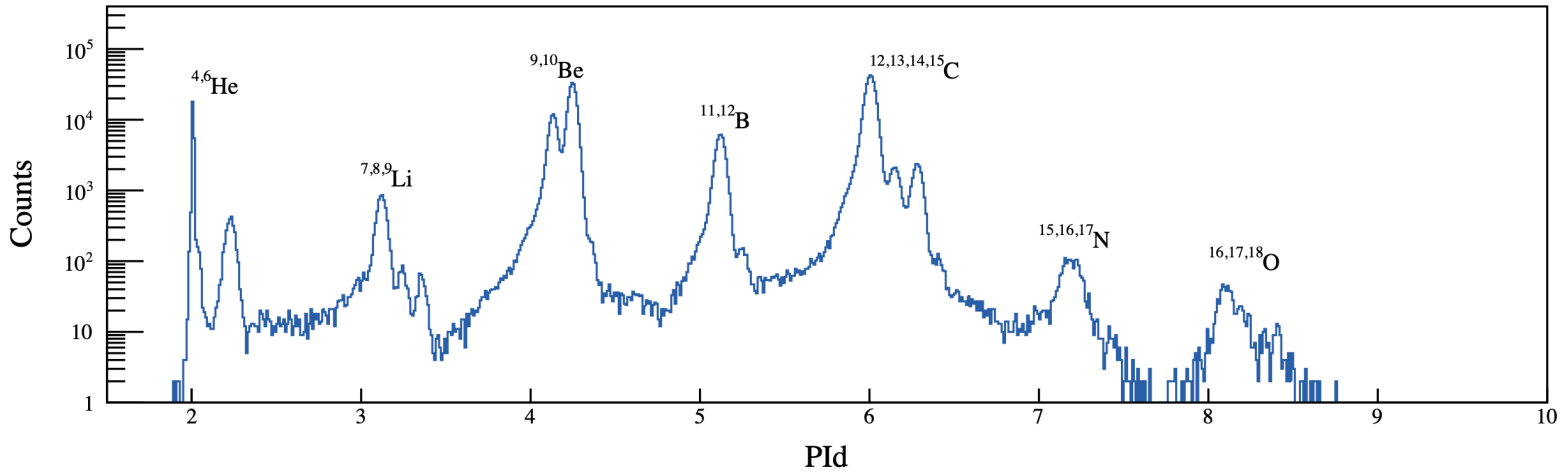
Isotopic identification from He to C

E_x resolution < 1 MeV

^{238}U @ 6MeV/u + ^{12}C

Target-like recoil Identification Matrix





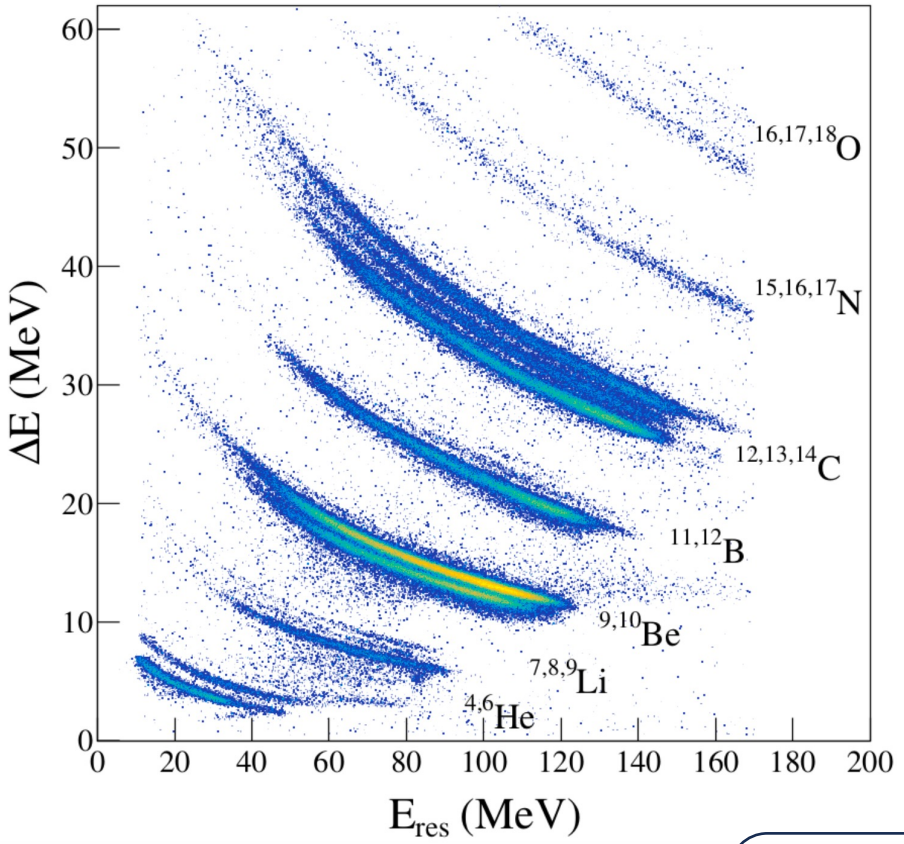
Mass resolution of 1.1% in Carbon region

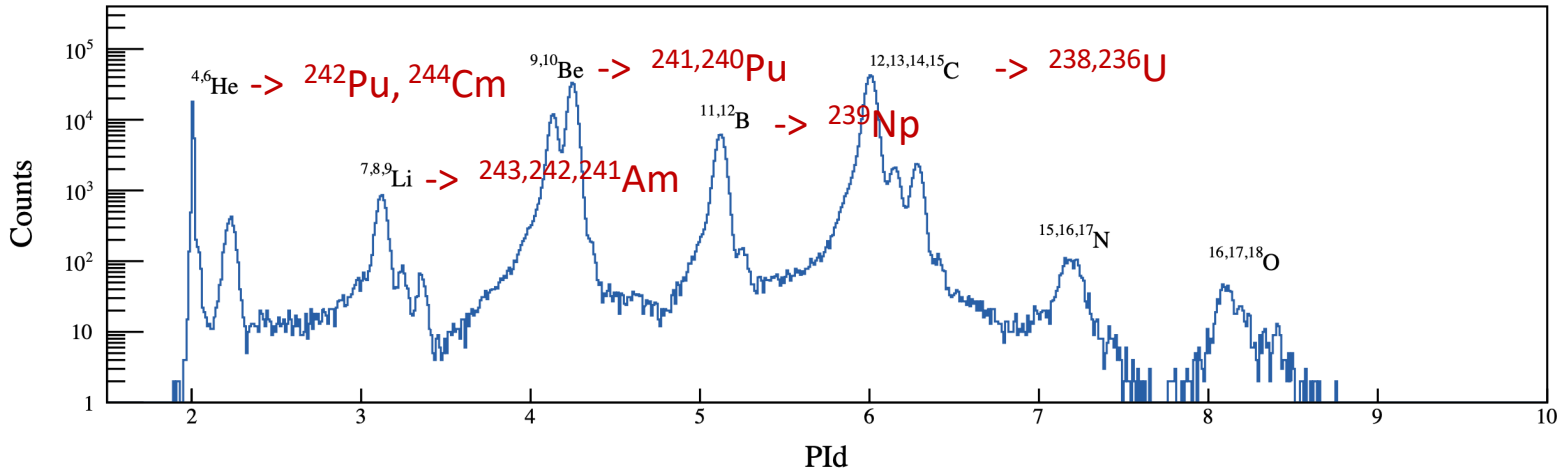
Lucas Begue PhD (GANIL – CEA DAM)

Submitted to NIMA (2026)

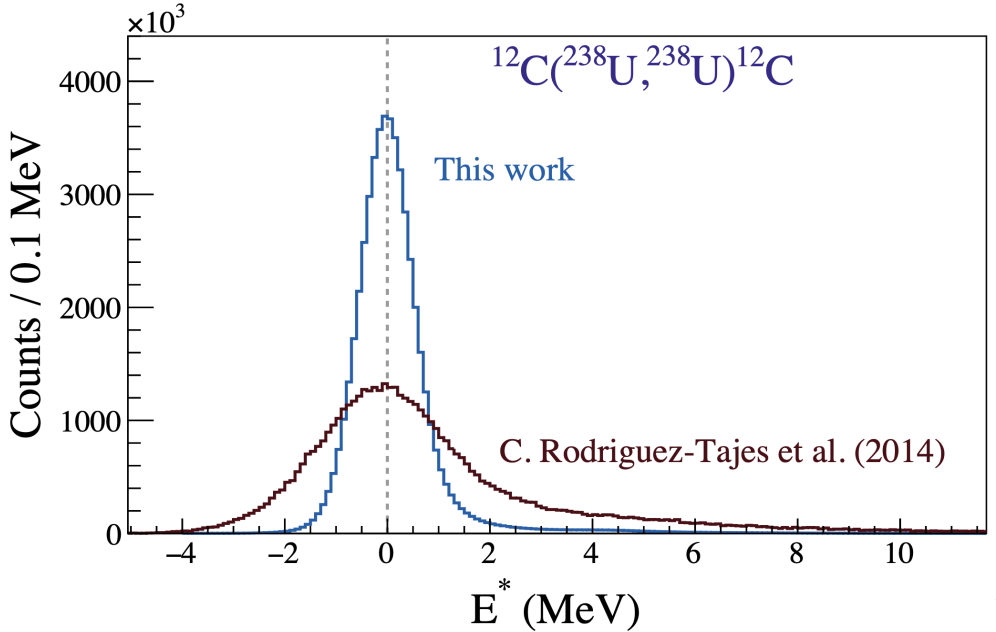
^{238}U @ 6MeV/u + ^{12}C

Target-like recoil Identification Matrix





Mass resolution of 1.1% in Carbon region



Lucas Begue PhD (GANIL – CEA DAM)
Submitted to NIMA (2026)

E_x resolution = 511 keV (elastic)
Expected E_x resolution : 370 keV
(with interaction point at target)

Fission Probability Measurement

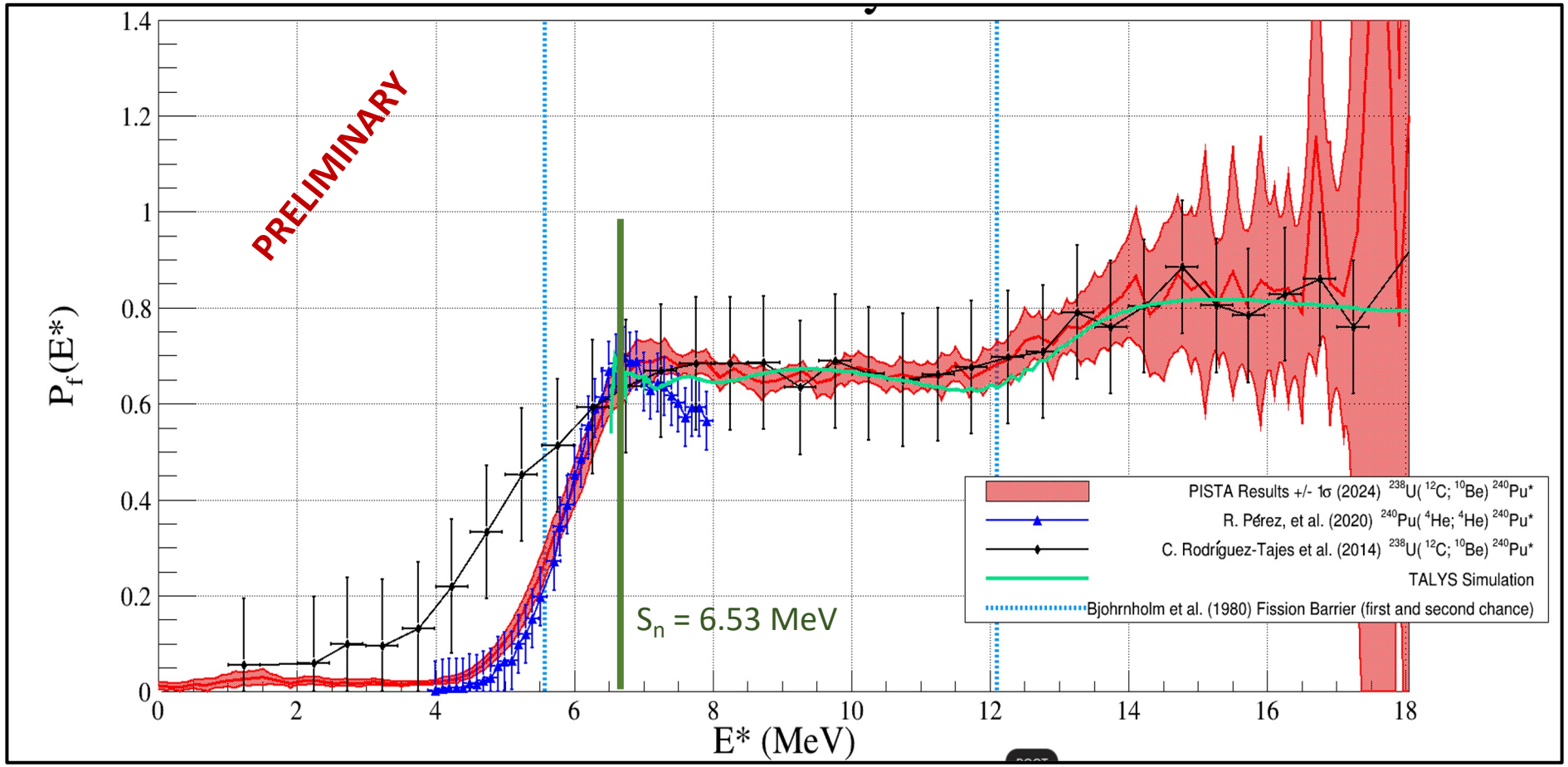
$^{238}U + 2p \rightarrow ^{240}Pu$

PISTA Measurement:

Significant improvent with respect to SPIDER

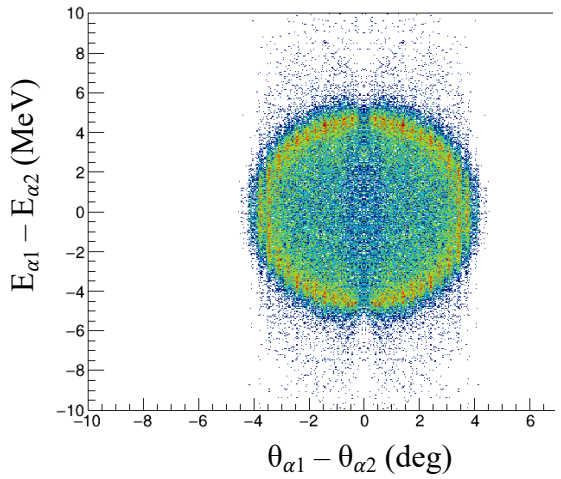
Clear difference with respect Coulomb excitation in $E_x > S_n$

The competition between fission and neutron evaporation seems to be different in both type of reactions



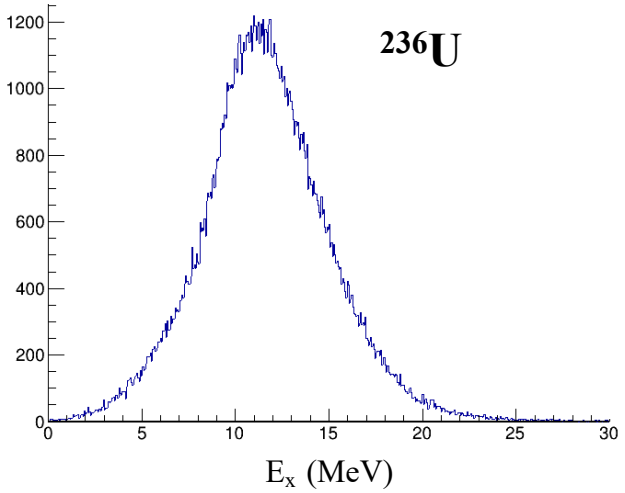
^{236}U from 1α transfer

$^{232}Th + {}^{12}C \rightarrow {}^{236}U + 2\alpha$

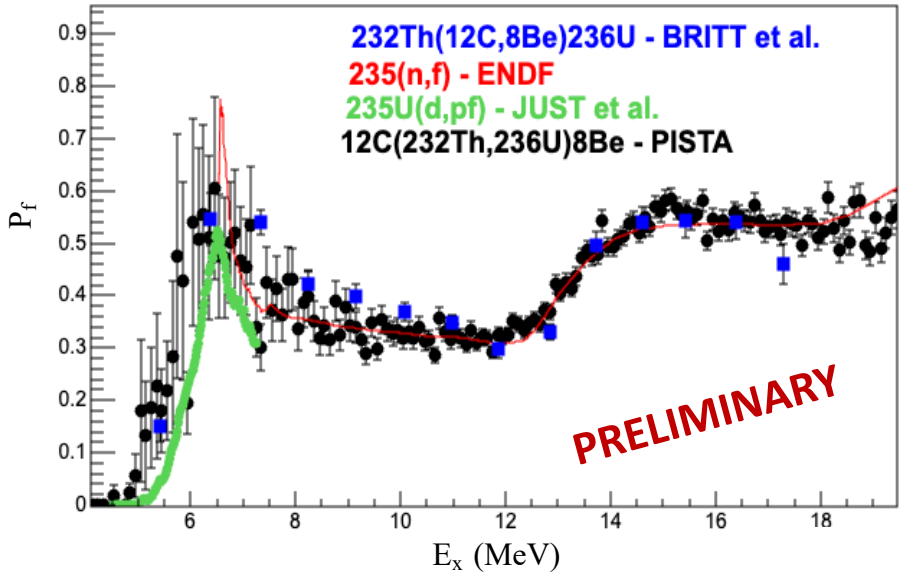


Kinematic Correlation of 2α from ^{8}Be

Excitation energy distribution of ^{236}U without fission condition



Fission probability of ^{236}U from 1α transfer

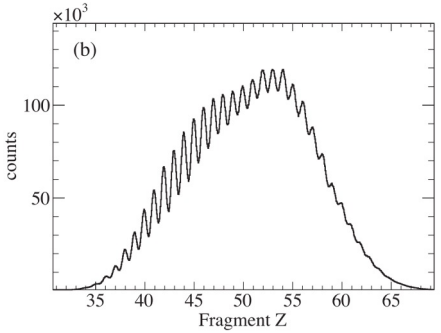


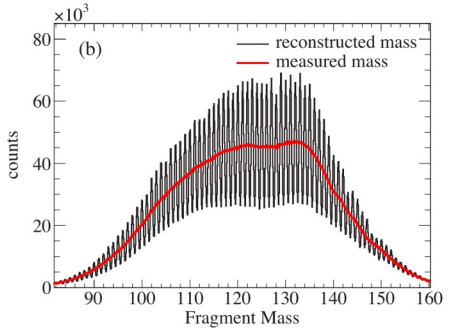
New measurement is foreseen this year:

- **PISTA2 :**
  - **Improved setup for 2α measurement**
  - **Access to low E_x of ^{236}U**

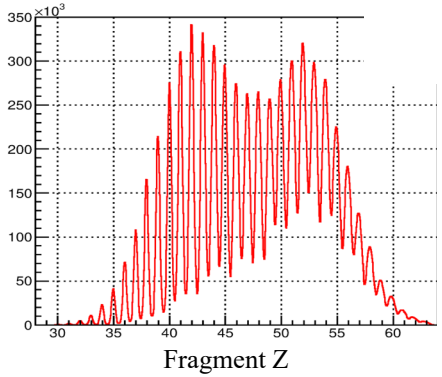
Fission@VAMOS

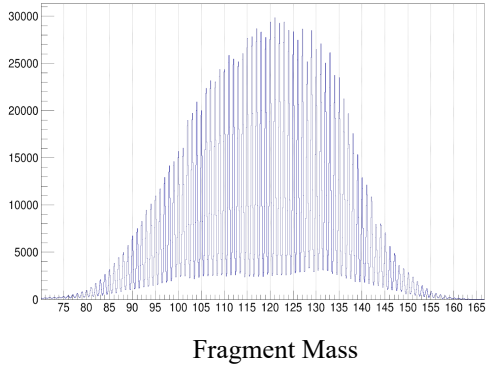
VAMOS



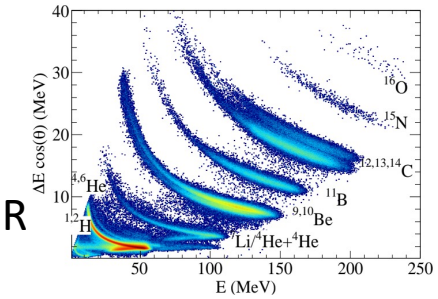


VAMOS++

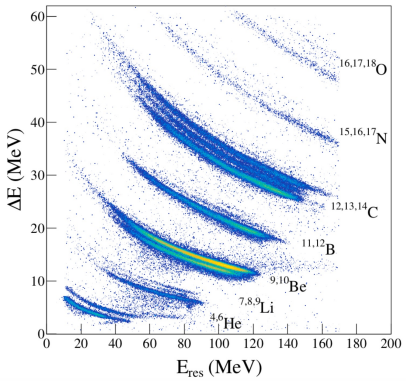




SPIDER



PISTA

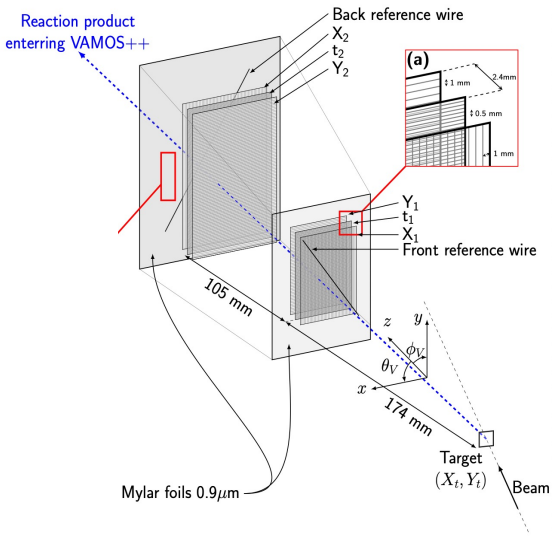


- The fission program at VAMOS/GANIL is a rich, very competitive, and a well stablished program providing experiment fission data for more than 10 years.
- The combination of inverse kinematics at Coulomb energies, a magnetic spectrometer, and complementary setups allows to study fission with a wide set of observables in a common setup.
- New and accurate observables and their correlations are now experimentally available.

Scission Point Reconstruction

$$\langle A_1^* \rangle = A_{FS} \frac{\langle V_2 \gamma_2 \rangle}{\langle V_1 \gamma_1 \rangle + \langle V_2 \gamma_2 \rangle}$$

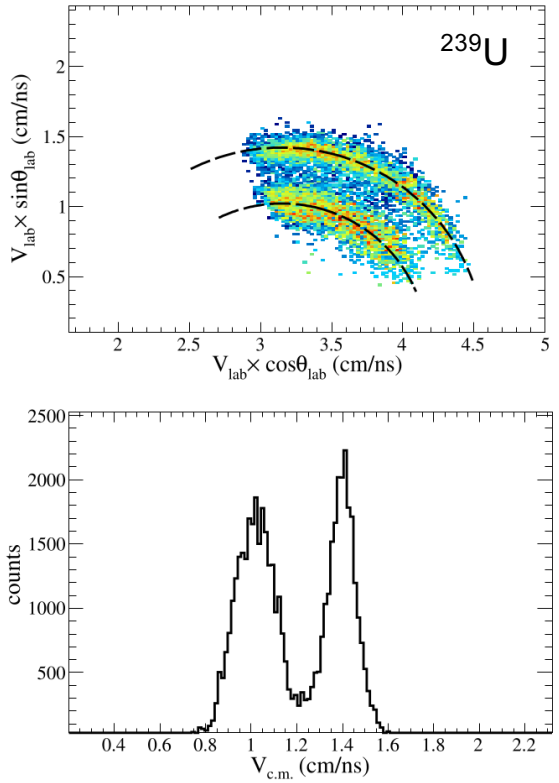
Dual Position-Sensitive MultiWire at Target



M. Vandebrouck et al, NIMA 812, 112 (2016)

D. Ramos et al., Phys. Rev. C 101, 034609 (2020)

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

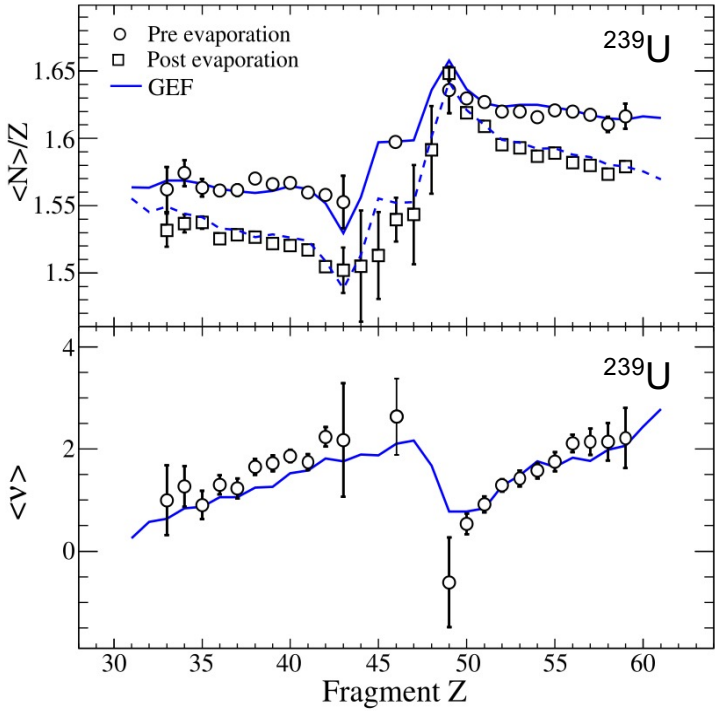


- Momentum conservation allows to determine the mass of fission fragments before neutron evaporation

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

- 2V-method with one fragment detected by fission reaction:
  - Average mass numbers as a function of Z

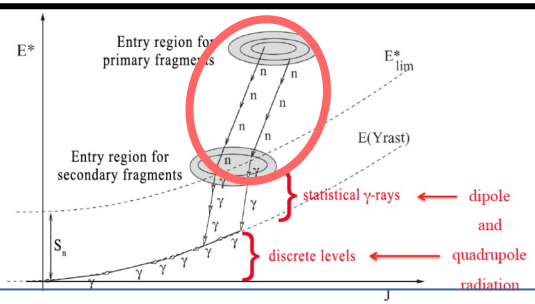
$$\langle A_1^* \rangle (Z_1) + \langle A_2^* \rangle (Z_2) = A^{FIS},\ Z_1 + Z_2 = Z^{FIS}$$

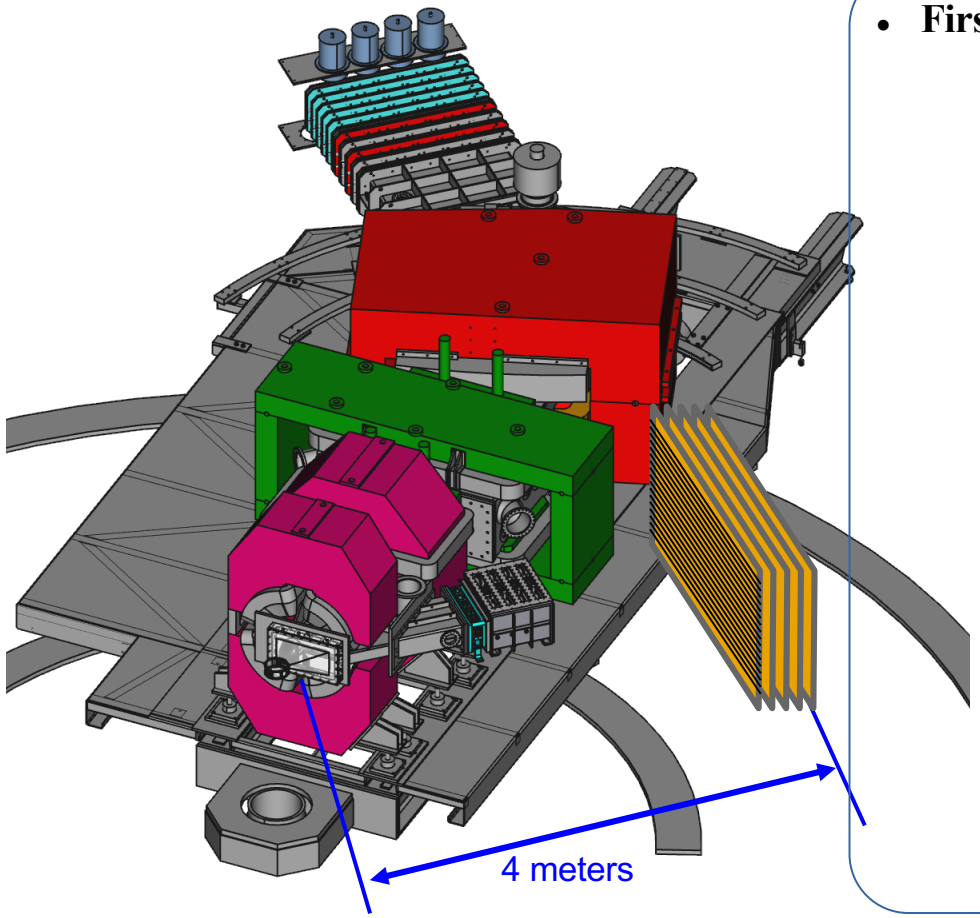


- New fission Observable: Fragments neutron excess
  - Structual effect observed in Z~50, maximum of neutron content.
- Neutron multiplicity show the sawthood shape with a minimum in Z~50

- **NEUTRON WALL @ VAMOS**

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





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