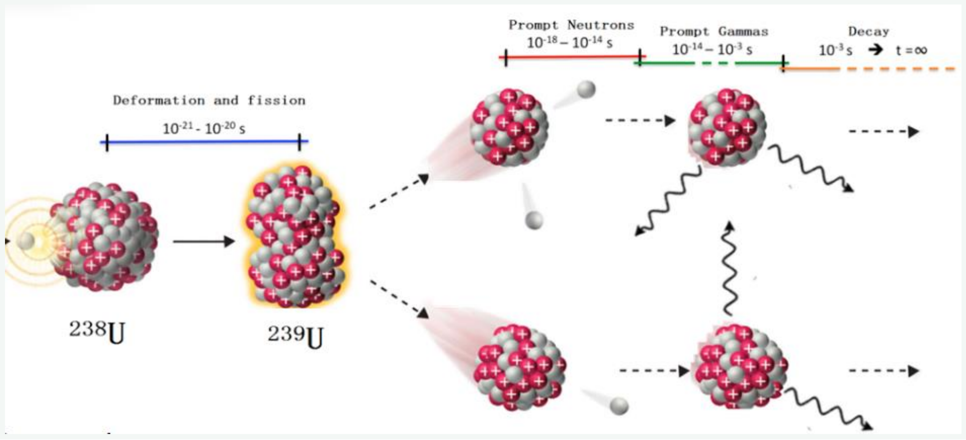
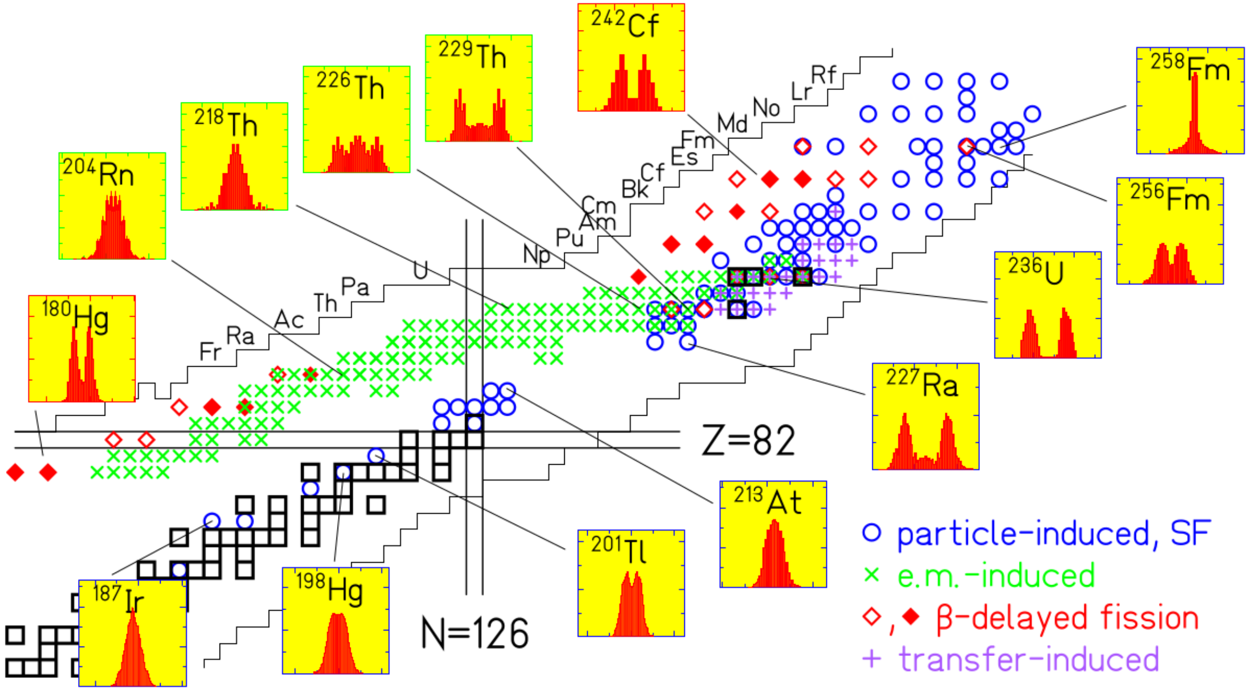
Isotopic Fission Yields of ^{240}Pu around the fission barrier from 2p-transfer reactions

Diego Ramos

Open Questions in Fission





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

- **What does it drive the asymmetric fission ?**

- **Which mechanism does it drive the excitation of fission fragments ?**

- **How the angular momemtum of fission fragments is generated ?**

- **How fast is the fission dynamics ?**

Fission-fragment related **observables** are still needed
- Complete measurements
- More systems to study
- Larger range of energies
- New observables

- **Nuclear Data Needs**

Inverse Kinematics Fission @VAMOS

- **Fusion Reactions**

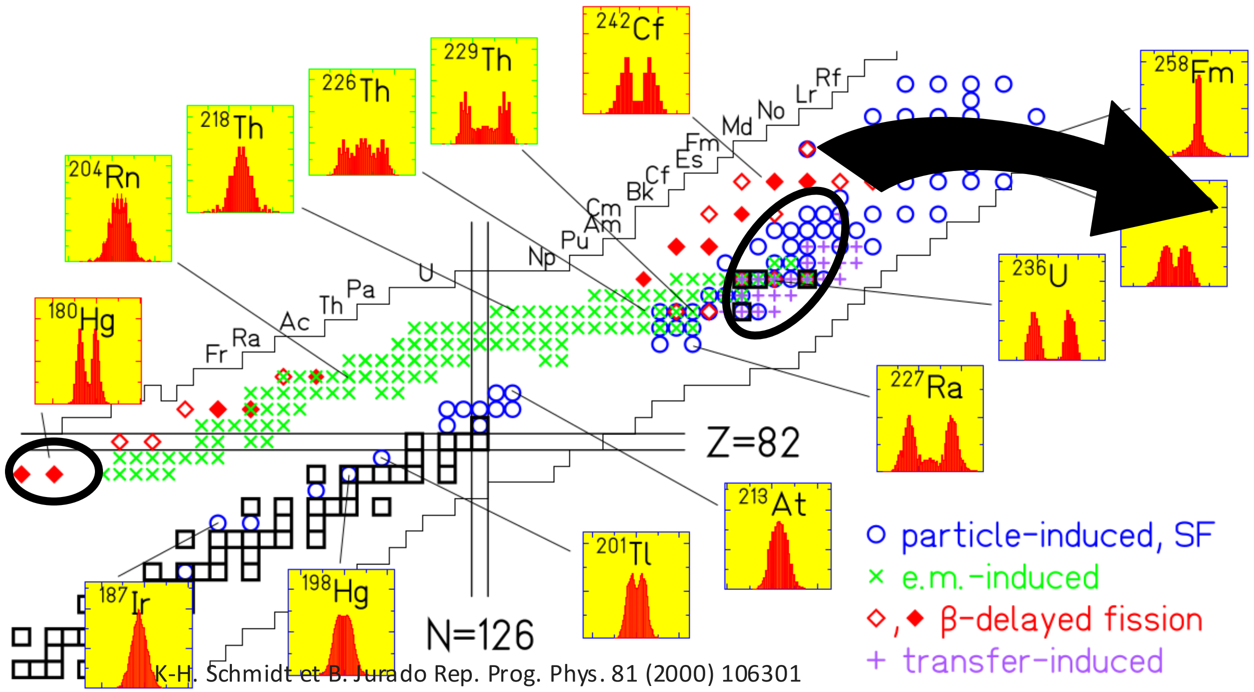
^{124}Xe + ^{54}Fe → ^{178}Hg
^{124}Xe + ^{60}Ni → ^{184}Pb

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

- **MultiNucleon Transfer Reactions**

^{238}U + ^{12}C →
^{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 →
^{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



Complete Isotopic-distribution of fission-fragments Yields

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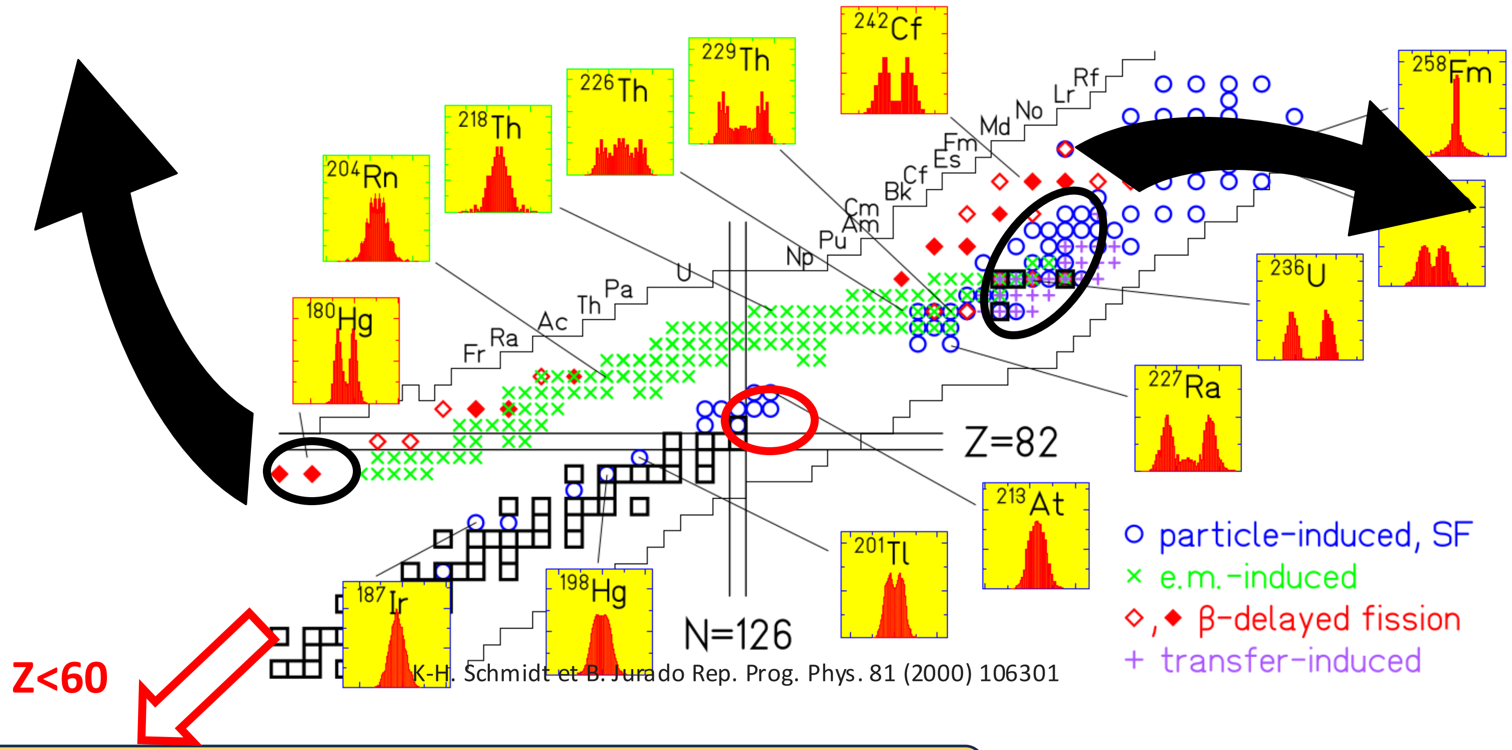
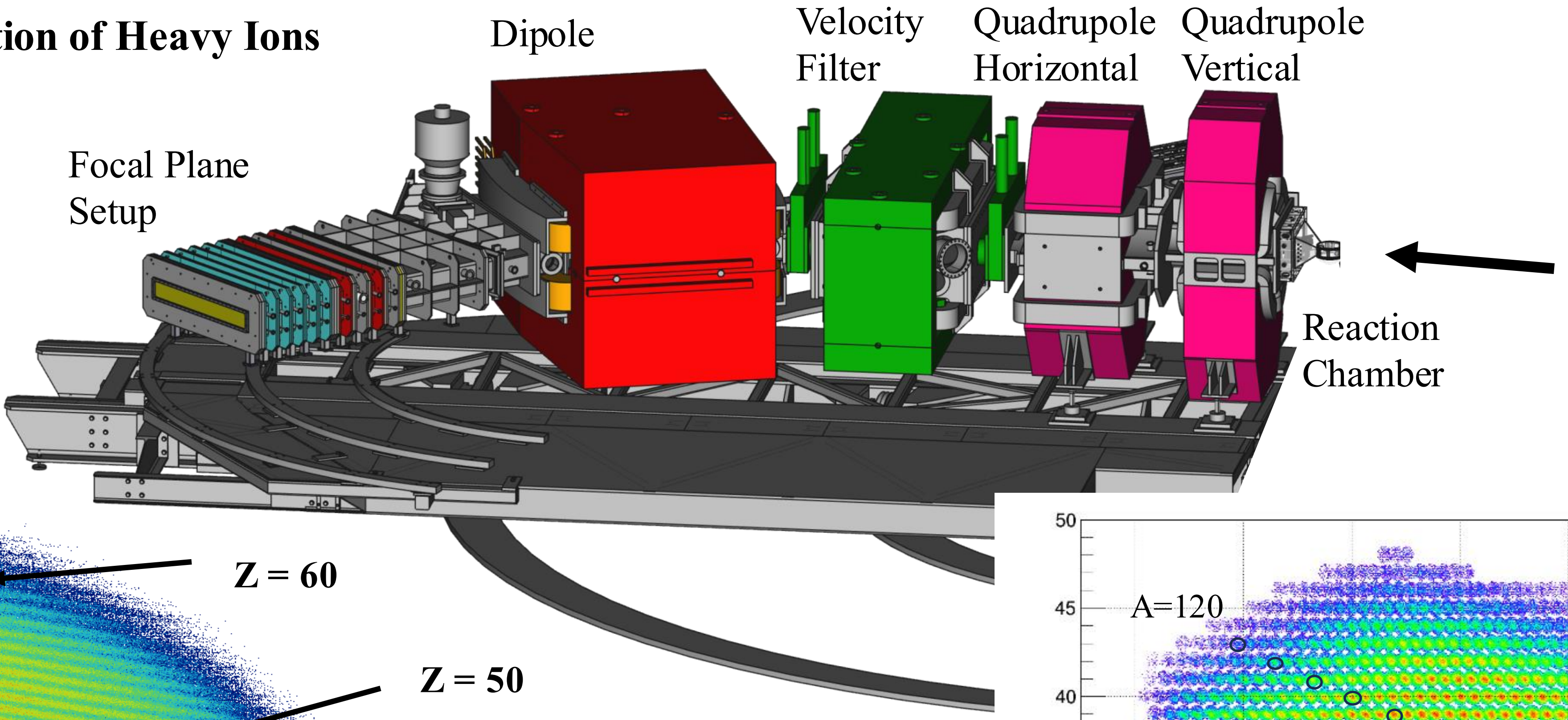
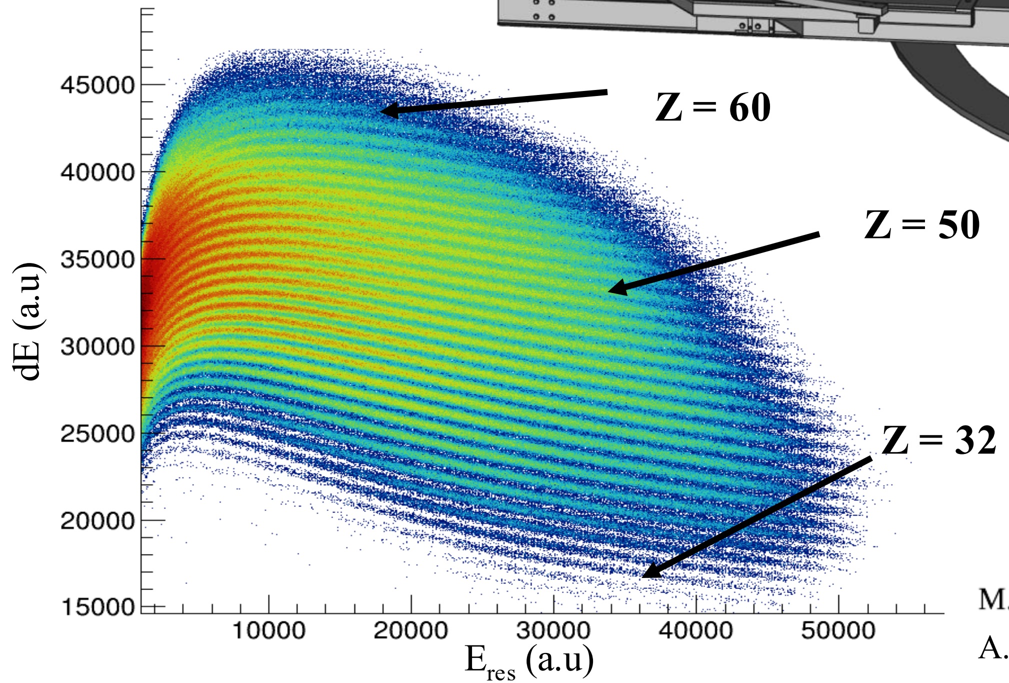
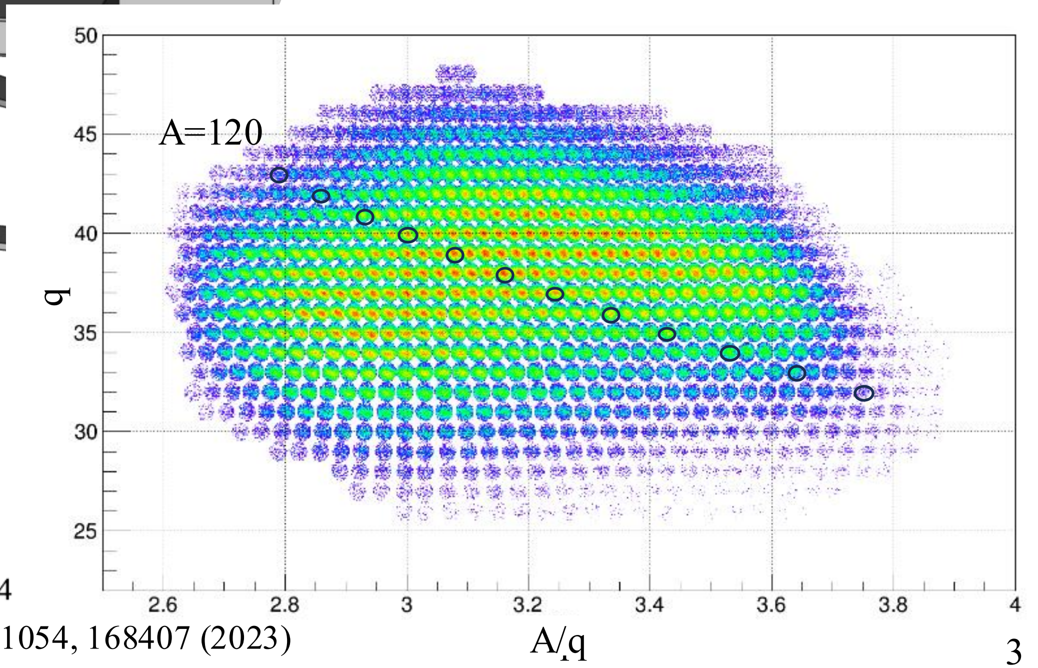


Complete Isotopic-distribution of fission-fragments Yields

Isotopic Identification of Heavy Ions







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

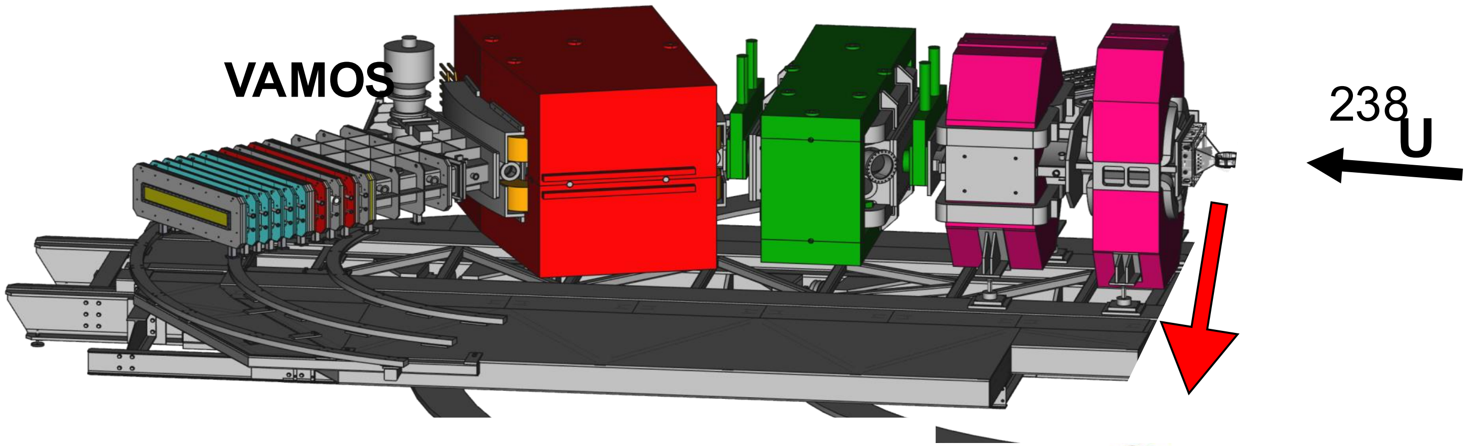
A. Lemasson & M. Rejmund ,NIM A 1054, 168407 (2023)

Multi-nucleon Transfer Reactions

Access to Actinides

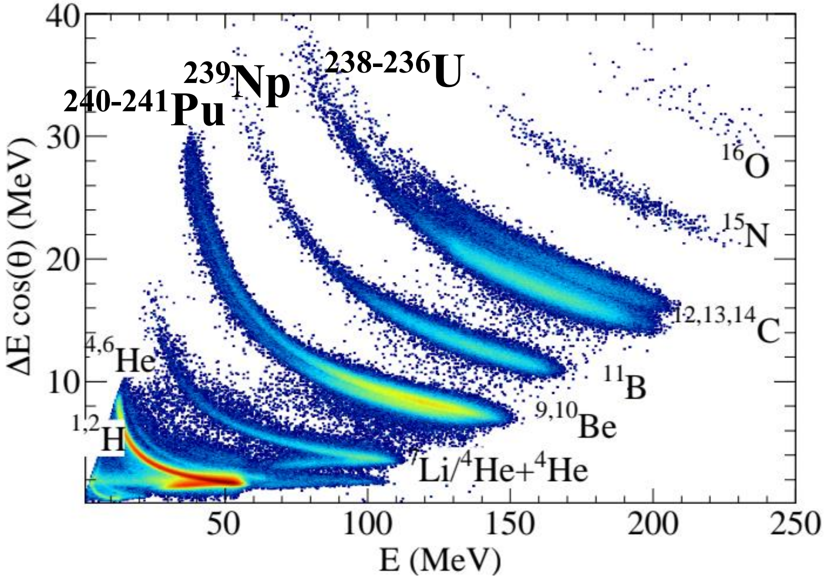
Fissioning System Identification

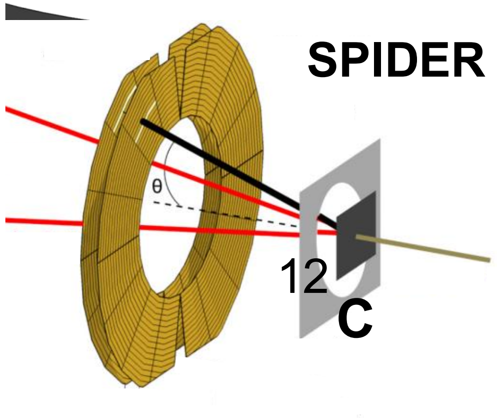
- **^{238}U/ ^{232}Th beam at ~6 MeV/u** (Coulomb energies)

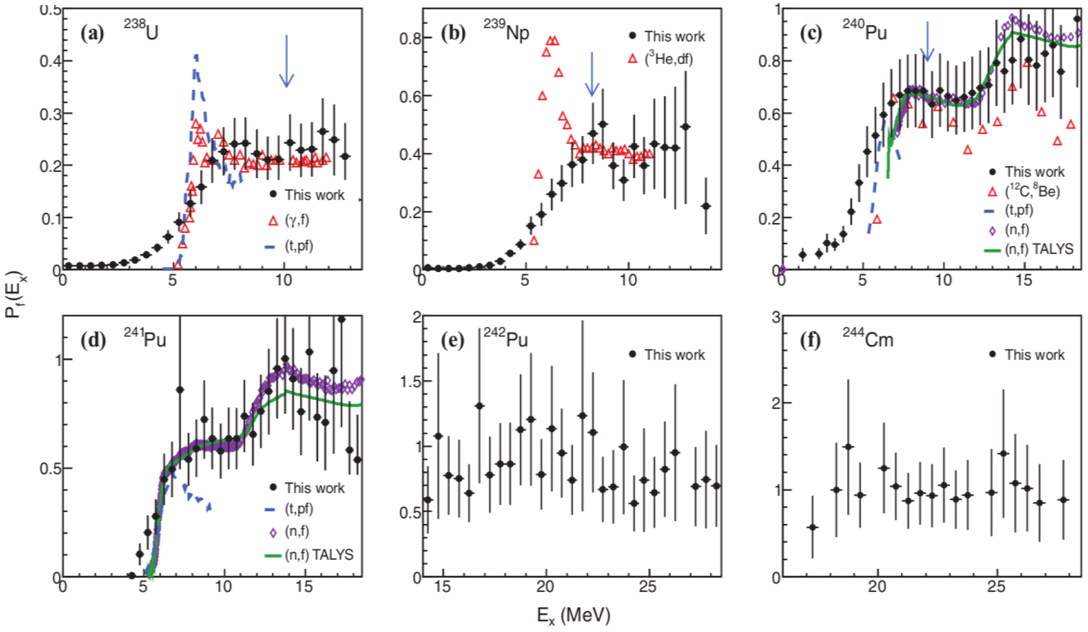


- **STRIP SILICON TELESCOPE**

- 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



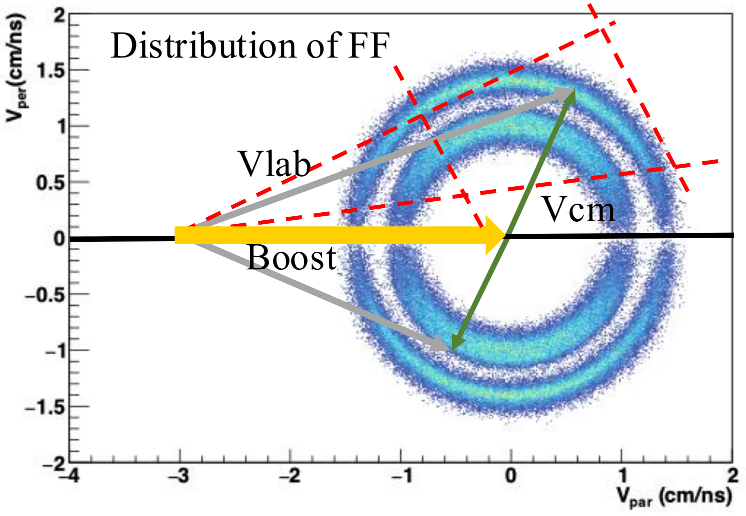


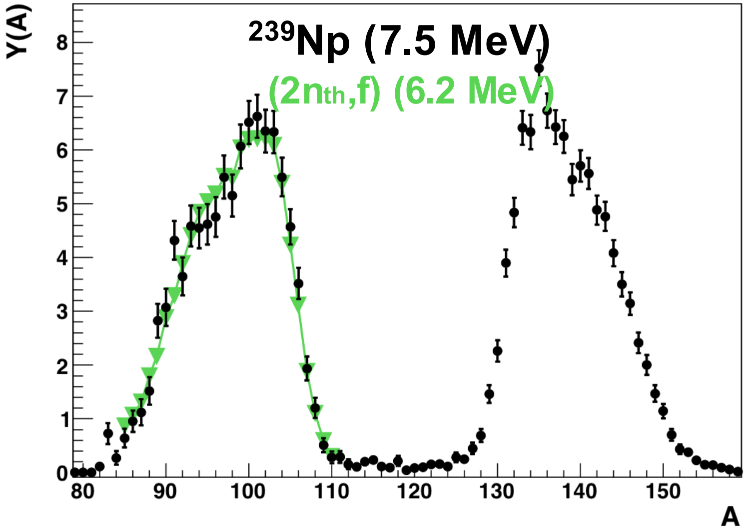


C. Rodríguez-Tajes et al., PRC 89, 024614 (2014)

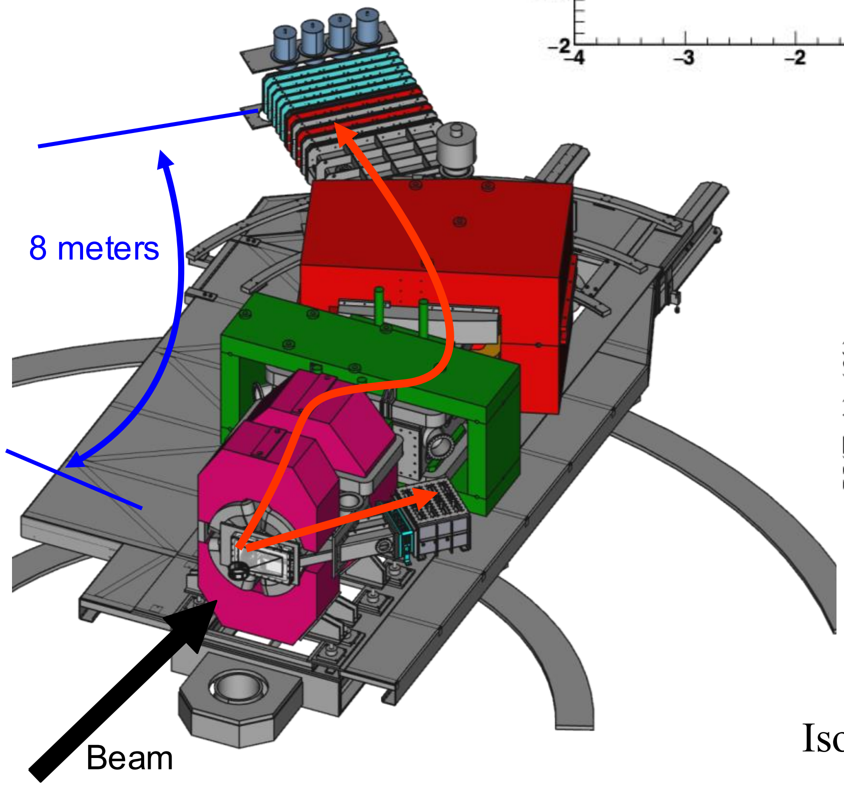
Fission Fragments Detection

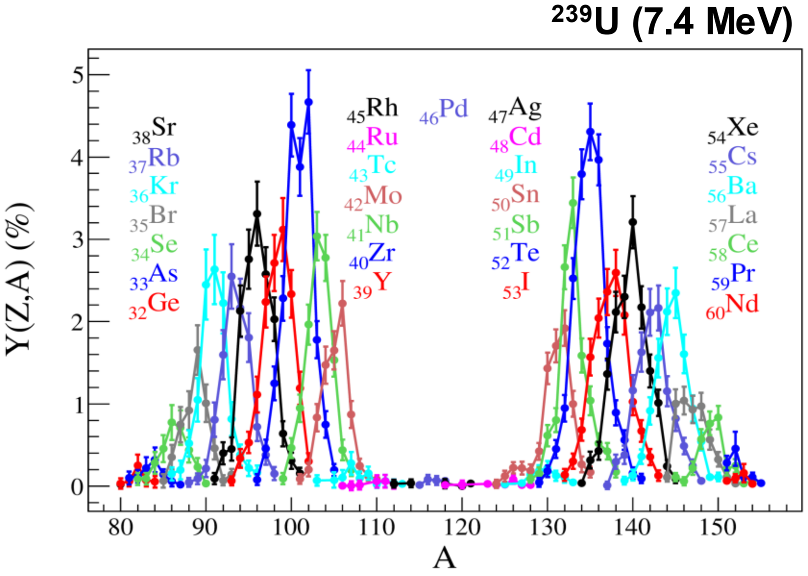
Fission Fragments:
- FF Z : 30 – 70
- FF A : 80 - 160
- FF angle: 0 - 30 deg
- FF Vlab: 1 - 5 cm/ns

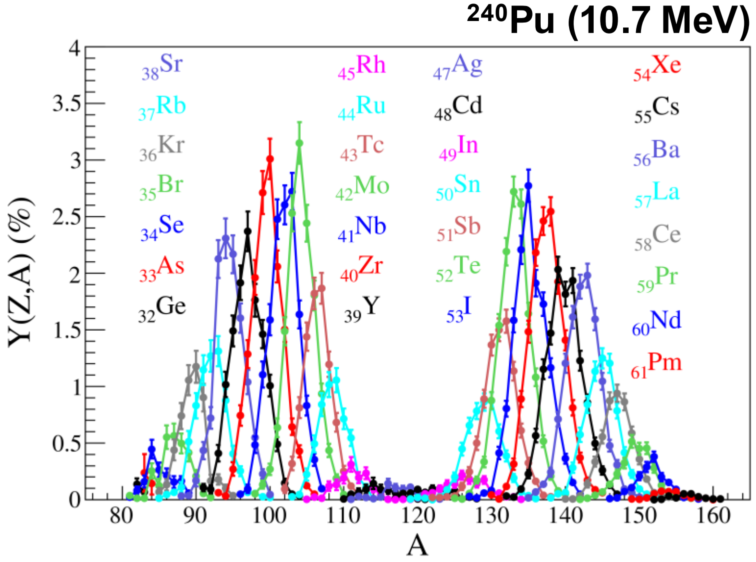




Full distribution of post-neutron evaporation mass yields







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)

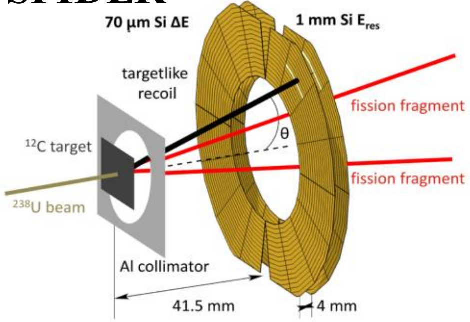
$^{12}C\ (^{238}U,\ ^{240}Pu^{*})\ ^{10}Be$

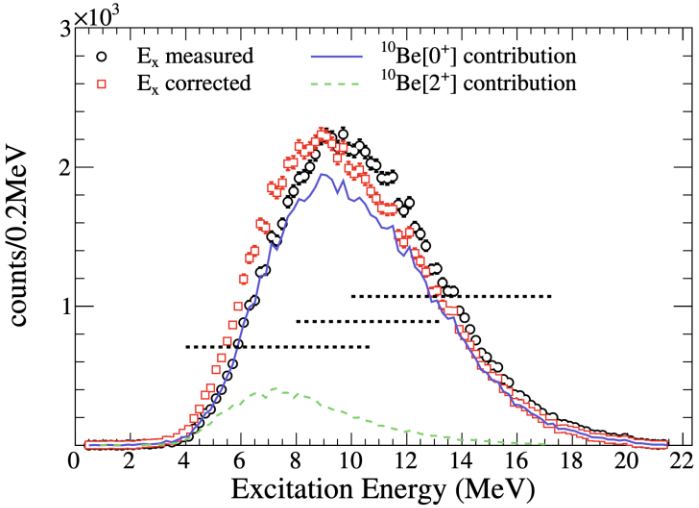
Fission Yields of ^{240}Pu and E_x

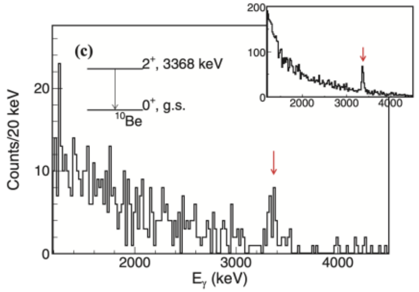
Isotopic Fission Yieds as a function of E_x

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

SPIDER



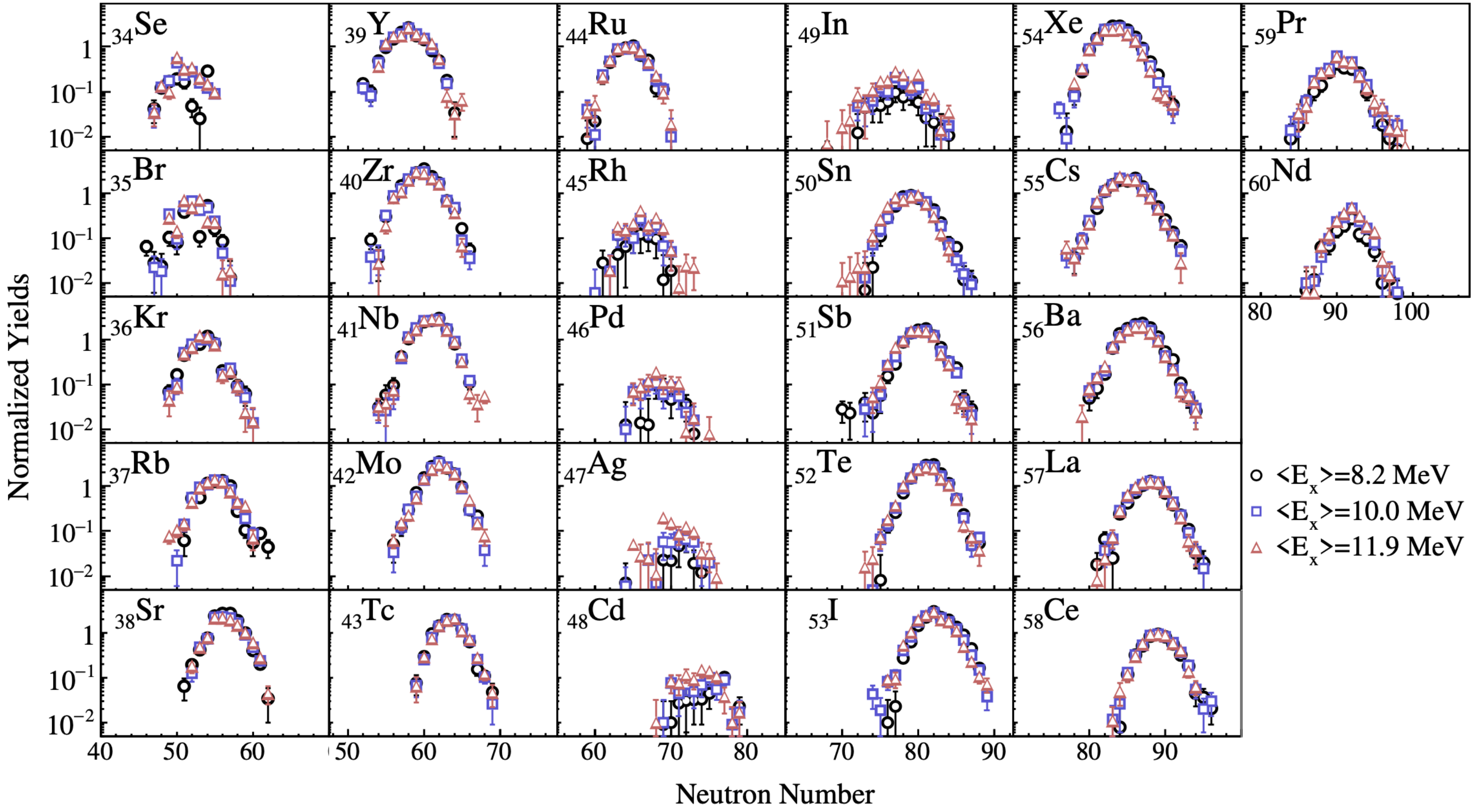




EXOGAM

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

VAMOS



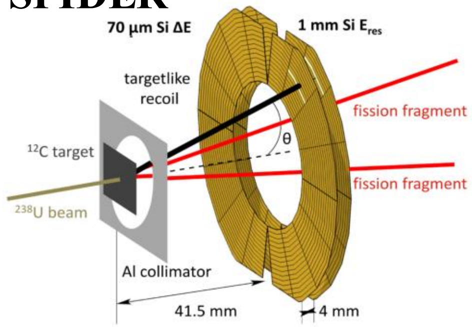
Full distribution of post-neutron evaporation

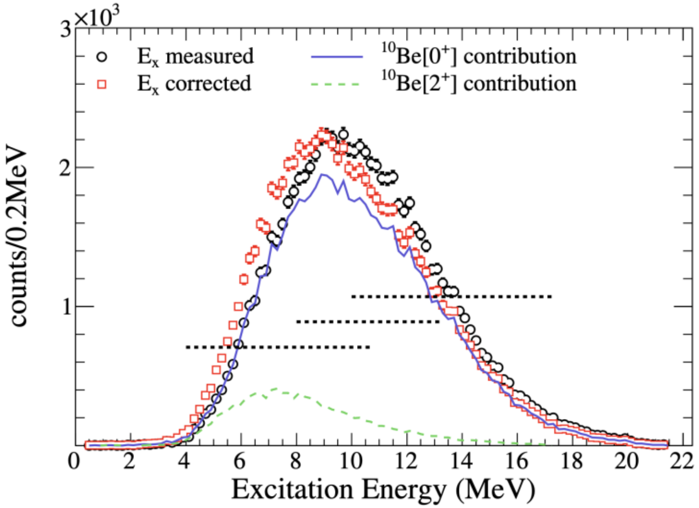
Isotopic Fission Yields as a function of E_x

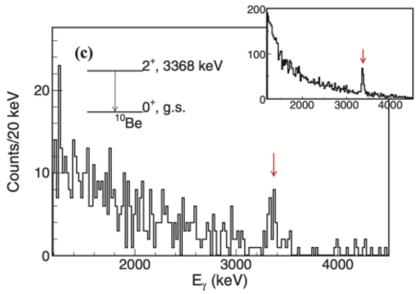
Mass yields compared with n-induced

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

SPIDER







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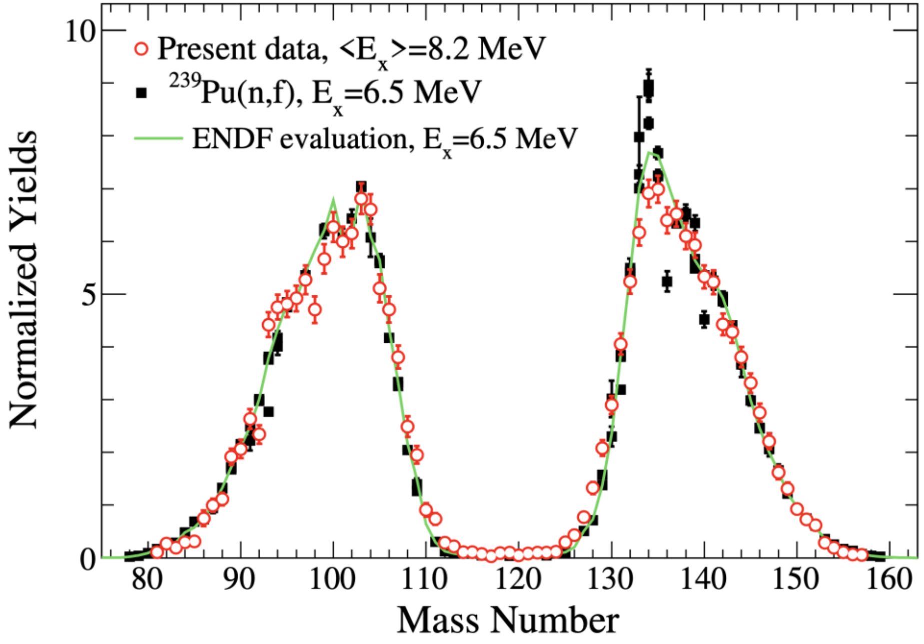
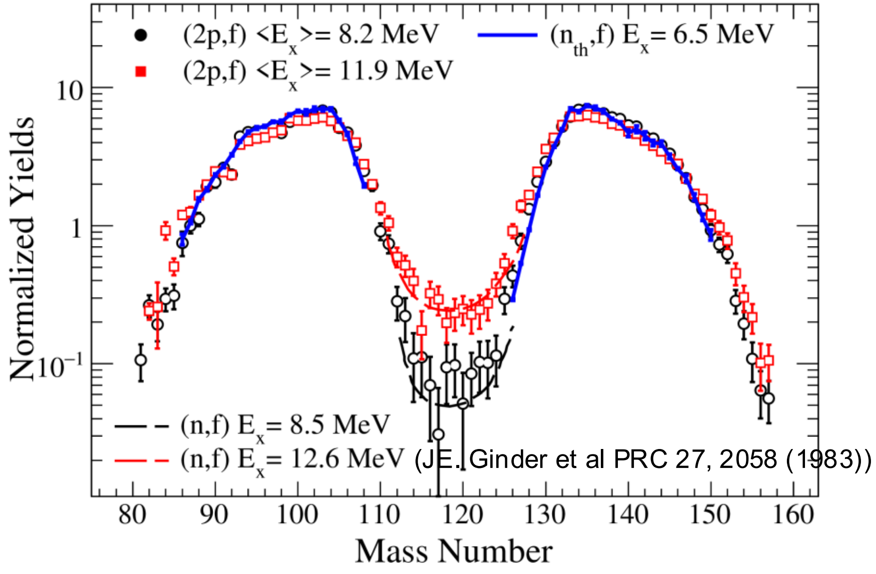


- **Post-neutron evaporation mass yields.**
- Very good agreement with n-induced fission (H. Naik et al. NSE 196, 824 (2022)) and data bases (ENDF)
- Evidence of E_x effect in A ~132

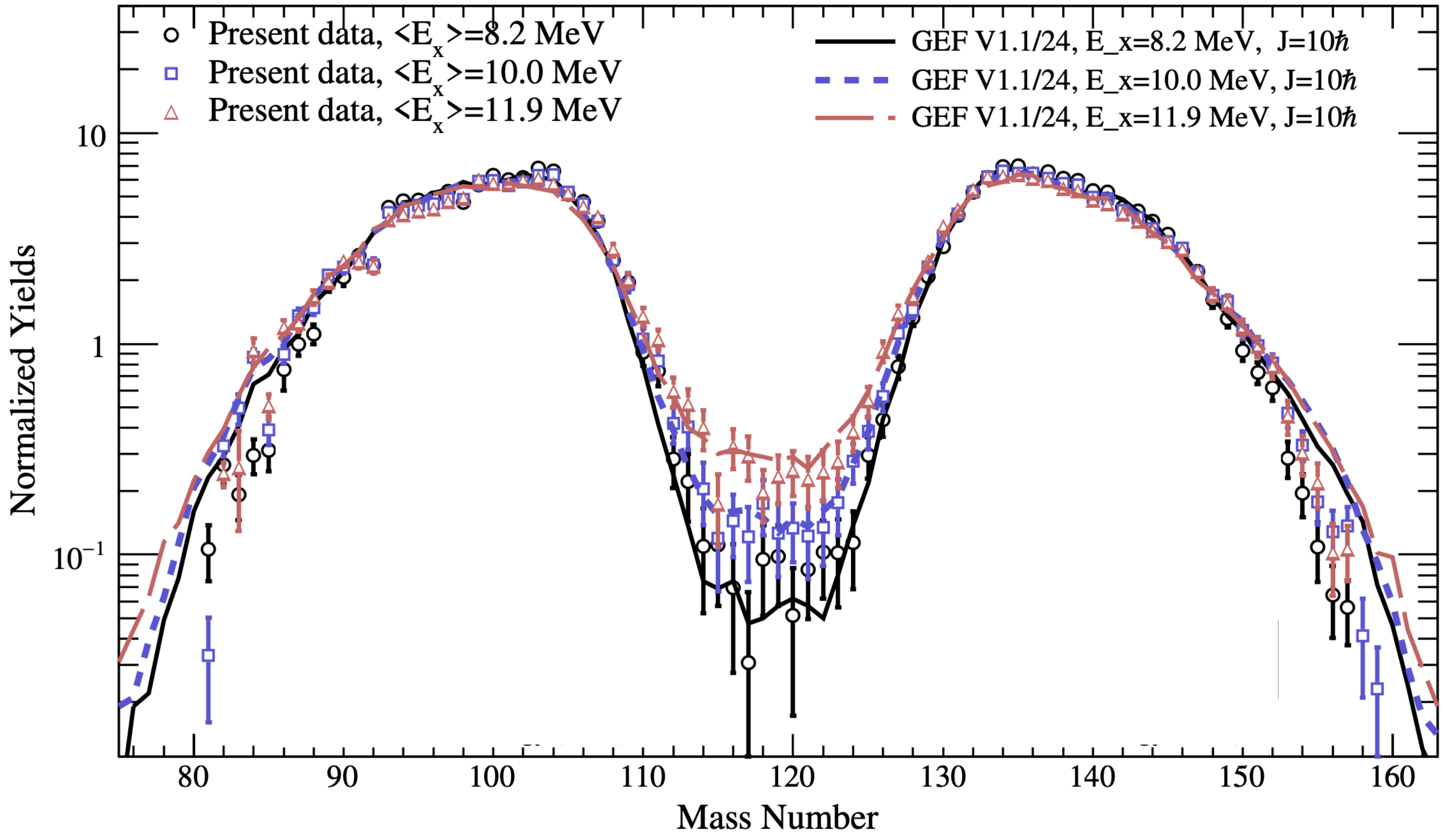
(A.Bail et al. PRC 84, 034605 (2011)



- Same feeding of the symmetric valley with increasing E_x

Mass Yields compared with GEF

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



- Good description of the Damping of Shell effects
- Larger super-asymmetric fission component

Mass Yields compared with GEF

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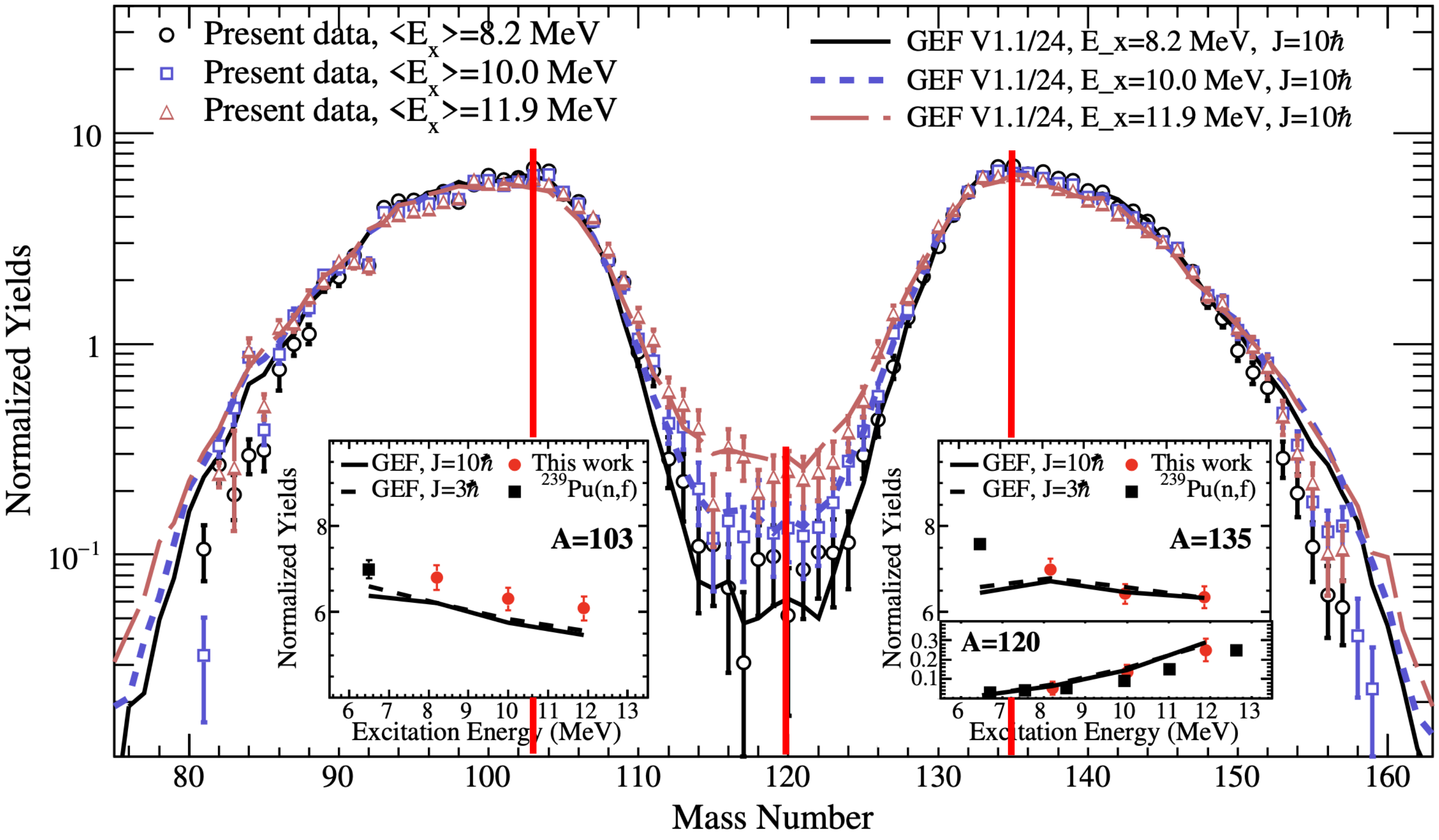


- Good description of the Damping of Shell effects
- Larger super-asymmetric fission component

Inital spin of the system:

n-induced -> J ~ 3ℏ (Talys)

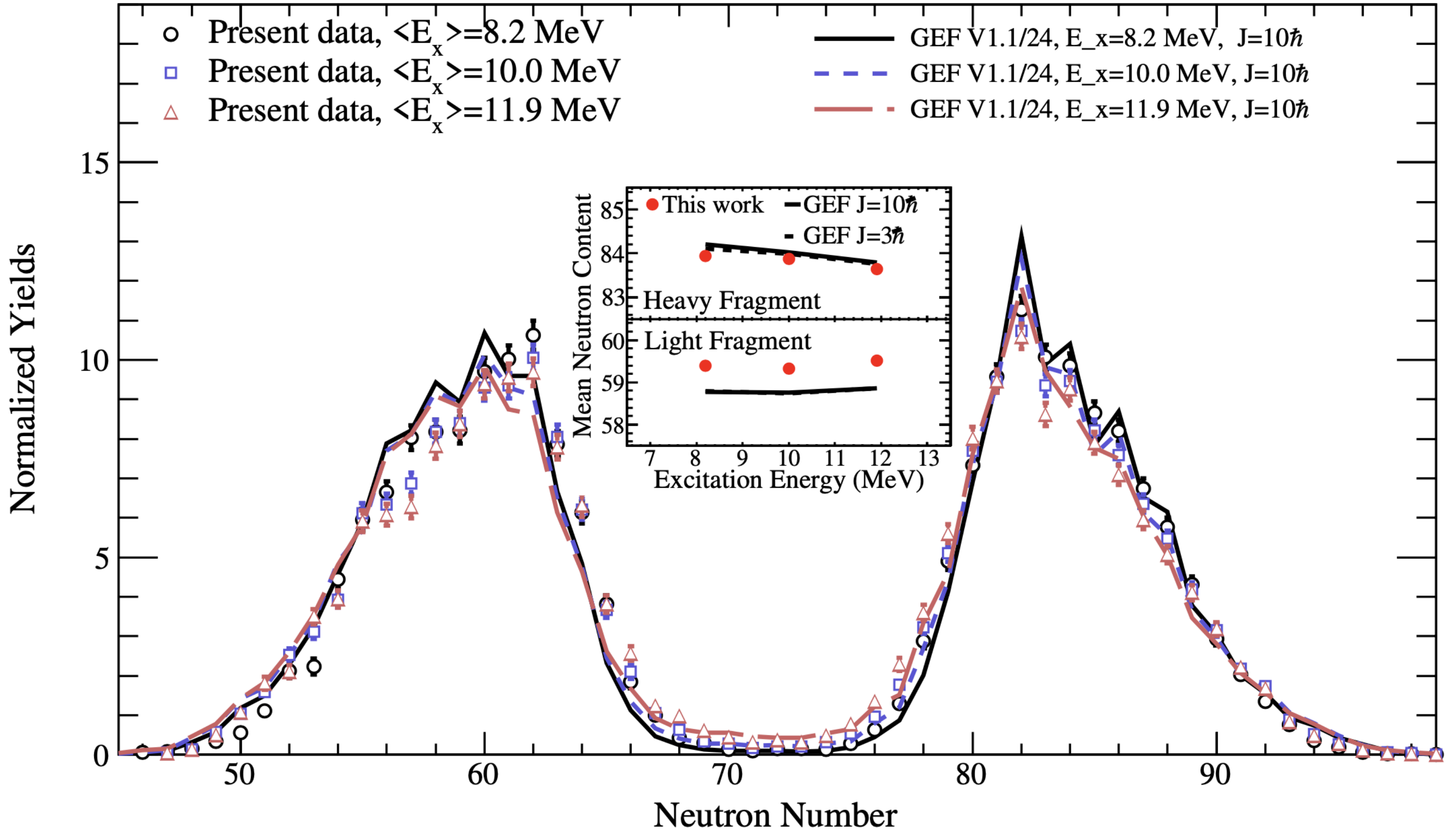
2p-transfer -> J ~ 10ℏ (S. Tanaka et al. PRC 105, L021602 (2022)

- GEF does not predict significant effect of J of the system in mass yields
- The maximum yield in the light fragments is systematically higher than GEF -> Neutron Evaporation

Isotonic Yields compared with GEF

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

- Post-neutron evaporation isotonic fission yields



- Good description of the Damping of Shell effects
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Inital spin of the system:

n-induced -> J ~ 3ℏ (Talys)

2p-transfer -> J ~ 10ℏ (S. Tanaka et al. PRC 105, L021602 (2022))

- GEF does not predict significant effect of J of the system in mass yields

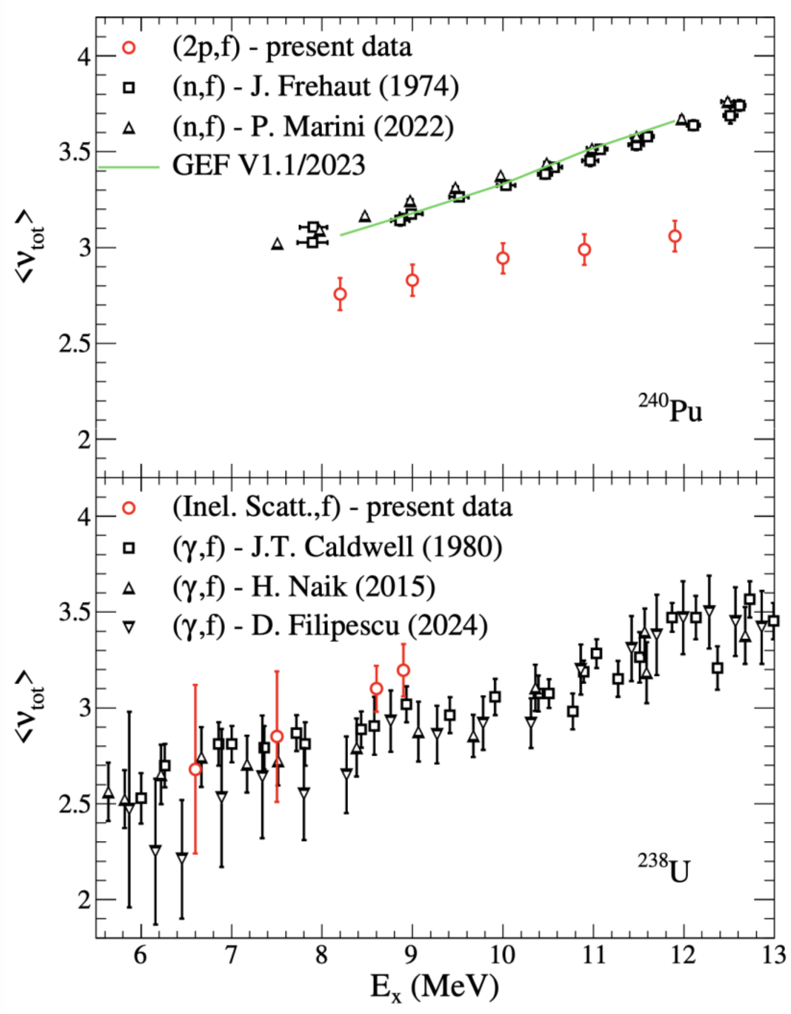
- The maximum yield in the light fragments is systematically higher than GEF -> Neutron Evaporation

- Good agreement in heavy fragments
- Light fragments more neutron-rich than GEF predictions.

Total Neutron Evaporation

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

$$\langle \nu_{tot} \rangle = N_{fis} - \frac{1}{100} \sum_{Z}^{Z_{fis}/2} (\langle N \rangle|_Z + \langle N \rangle|_{Z_{fis}-Z}) \times Y(Z)$$



- Lower neutron evaporation in 2p-transfer reactions than neutron-induced fission
- Same neutron evaporation between Inelastic scattering and ɣ-ray absorption

Total Neutron Evaporation

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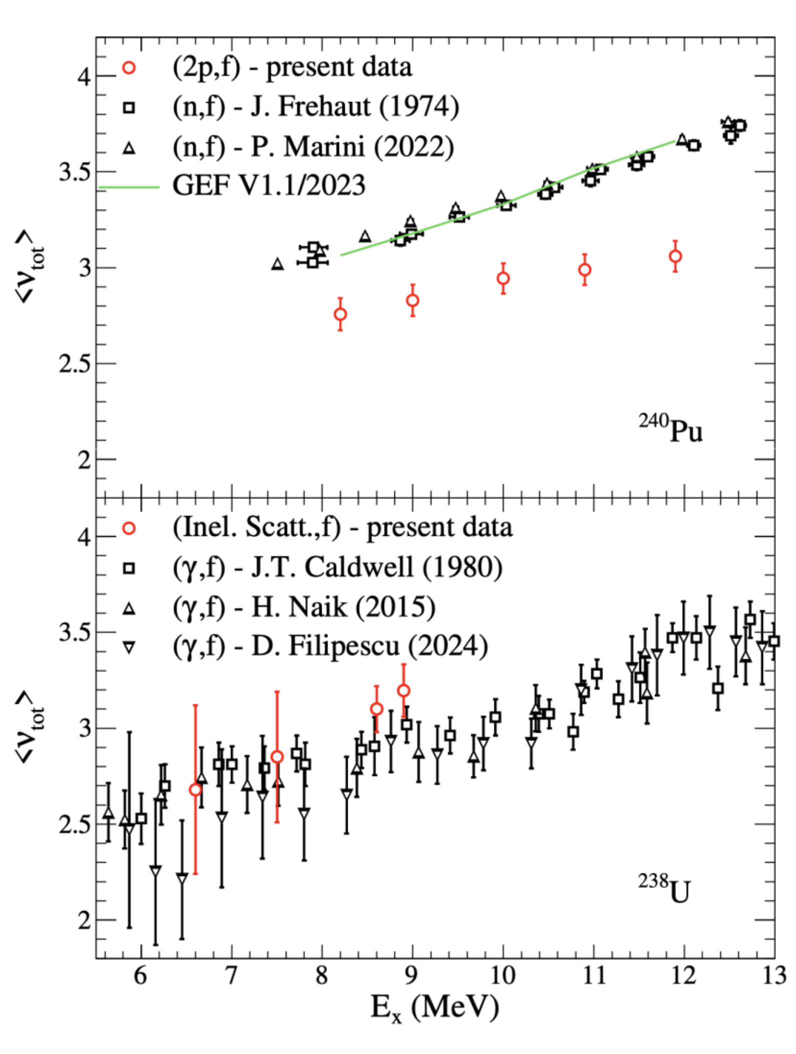
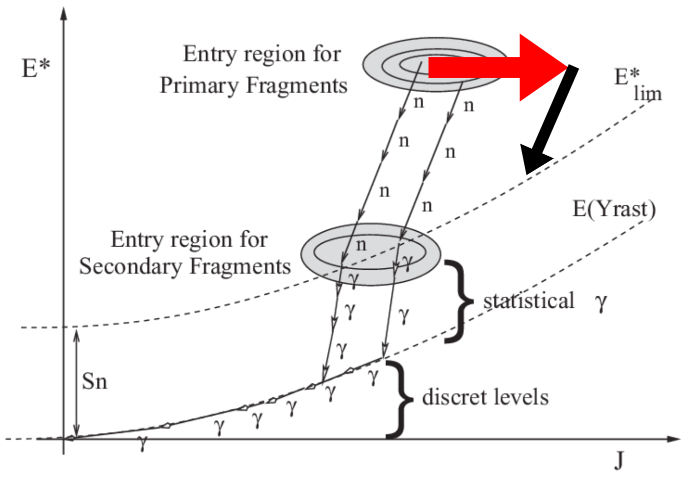


- Lower neutron evaporation in 2p-transfer reactions than neutron-induced fission
- Same neutron evaporation between Inelastic scattering and γ-ray absorption

Inital spin of ^{240}Pu:
n-induced -> J ~ 3$\hbar$ (Talys)
2p-transfer -> J ~ 10$\hbar$ (S. Tanaka et al. PRC 105, L021602 (2022))

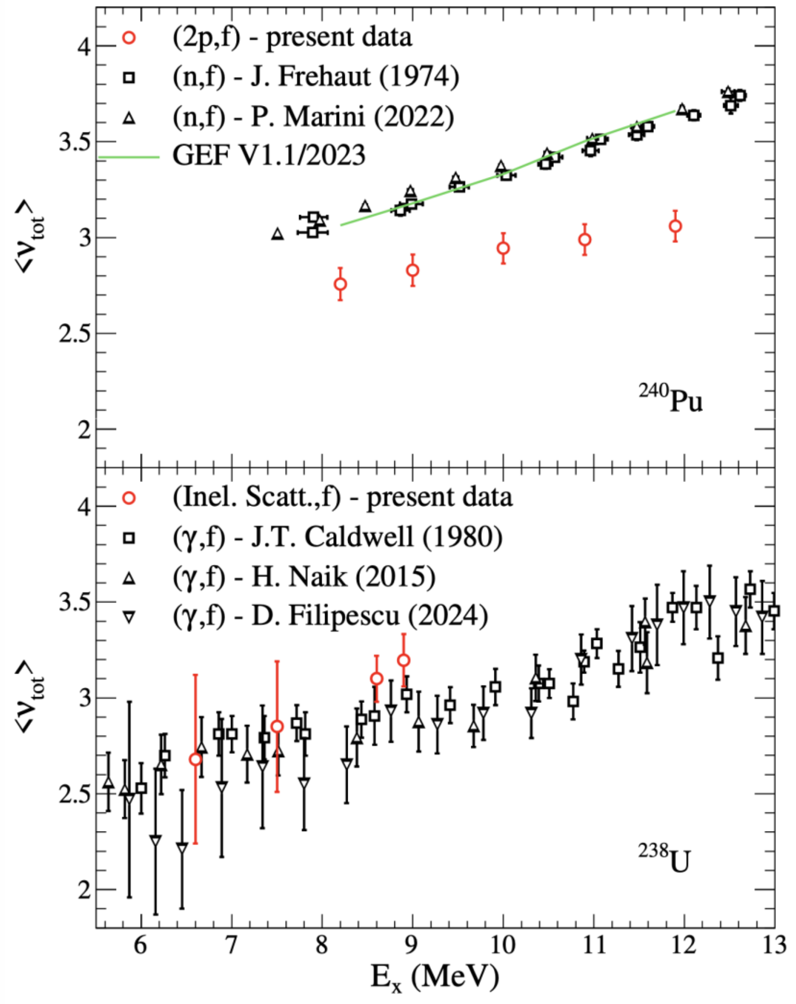
- Part of the initial J goes to the fission fragments (Isomeric ratios: S. Cannarozzo PRC 111, L031601(2025)



Extracted from PRC 82, 054616 (2010)

Total Neutron Evaporation

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

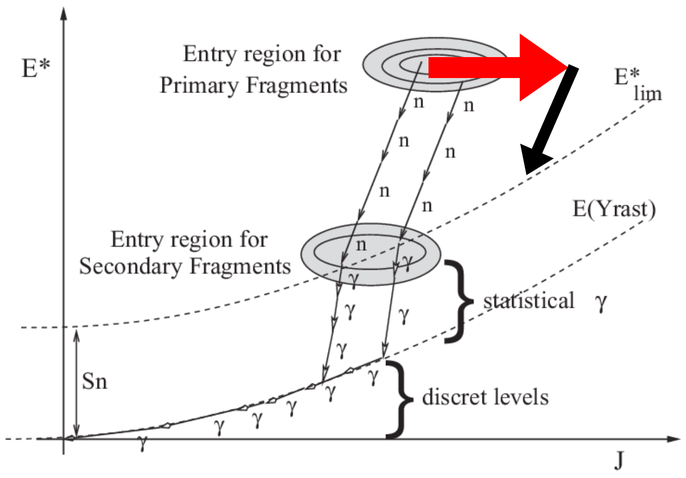


$$\langle \nu_{tot} \rangle = N_{fis} - \frac{1}{100} \sum_{Z}^{Z_{fis}/2} (\langle N \rangle|_Z + \langle N \rangle|_{Z_{fis}-Z}) \times Y(Z)$$

- Lower neutron evaporation in 2p-transfer reactions than neutron-induced fission
- Same neutron evaporation between Inelastic scattering and γ-ray absorption
- Fission fragments neutron evaporation is not enough : Too high J is required
- **Pre-scission neutron evaporation is required. And affected by initial J of the fissioning system**

Inital spin of ^{240}Pu:
n-induced -> J ~ 3$\hbar$ (Talys)
2p-transfer -> J ~ 10$\hbar$ (S. Tanaka et al. PRC 105, L021602 (2022))

- Part of the initial J goes to the fission fragments (Isomeric ratios: S. Cannarozzo PRC 111, L031601(2025))



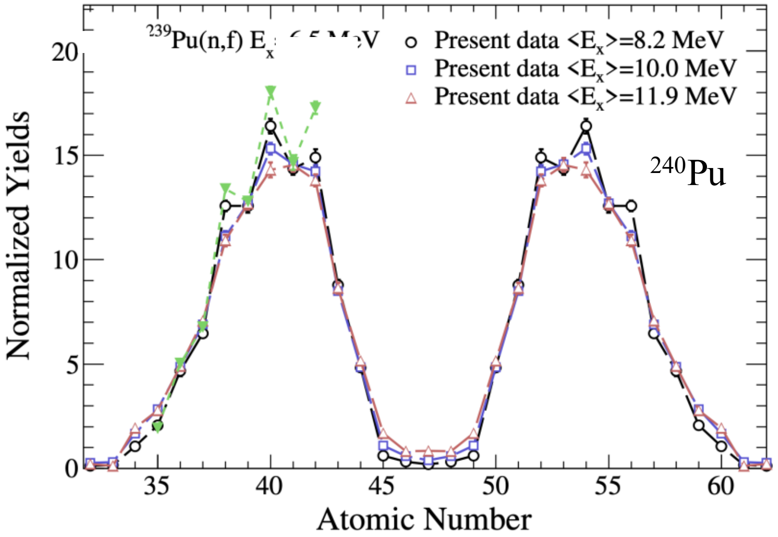
Extracted from PRC 82, 054616 (2010)

New Observable for **Dissipation**
in Fission

GANIL

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

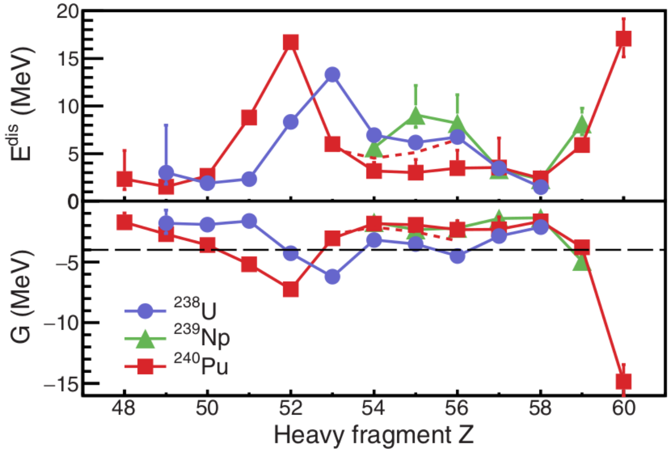
- The measurement of δ at different E$_x$ allow to fit the correlation between both and determine E^{dis}

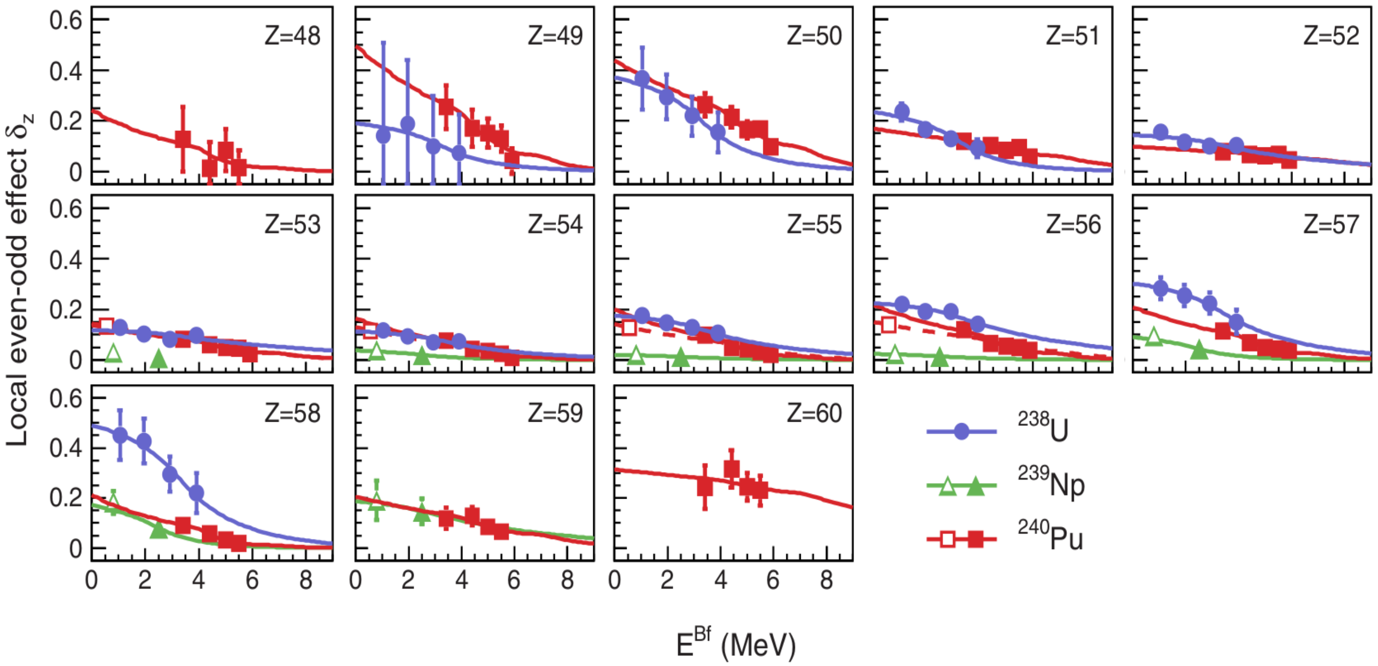
$$E^{\mathrm{dis}}(Z) + [E^{Bf} - \Delta] = G(Z)\ln(|\delta_Z|) \quad E^{Bf} > \Delta,$$

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

- 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

Fission@VAMOS

- The fission program at VAMOS/GANIL is a unique and rich, very competitive, and well stablished program providing experiment fission data for more than 10 years.

- The combination of inverse kinematics at Coulomb energies and a magnetic spectrometer 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.

New measurements:

- «PISTA, a new detection system for transfer-induced fission in inverse kinematics at VAMOS» Lucas Begué-Guillou.
- «Fission dynamics Investigation using VAMOS++ spectrometer and Second Arm » Indu Jangid.
- «Isotopic fission fragments yields in the Thorium region produced in inverse-kinematics with a 232Th beam. » Alex Cobo.
- «Investigation of Shell Effect Damping in Nuclear Fission Using VAMOS and PISTA ». Theodore Efremov.
- « Pre-neutron yields with the VAMOS++ spectrometer and its second arm » Alexis Francheteau.