

APRENDE

Fission yields measurement

Task 2.2.1

SENFY

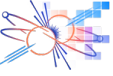
14/04/26

Fanny Farget, GANIL



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Fission in inverse kinematics @ VAMOS

Collaboration

GANIL



DIRECTION DES
Applications
Militaires

UC Lab
Irène Joliot-Curie
Laboratoire de Physique
des 2 Infinis

IPHC
Institut Pluridisciplinaire
Hubert CURIE
STRASBOURG

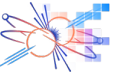
LP2i
Bordeaux

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

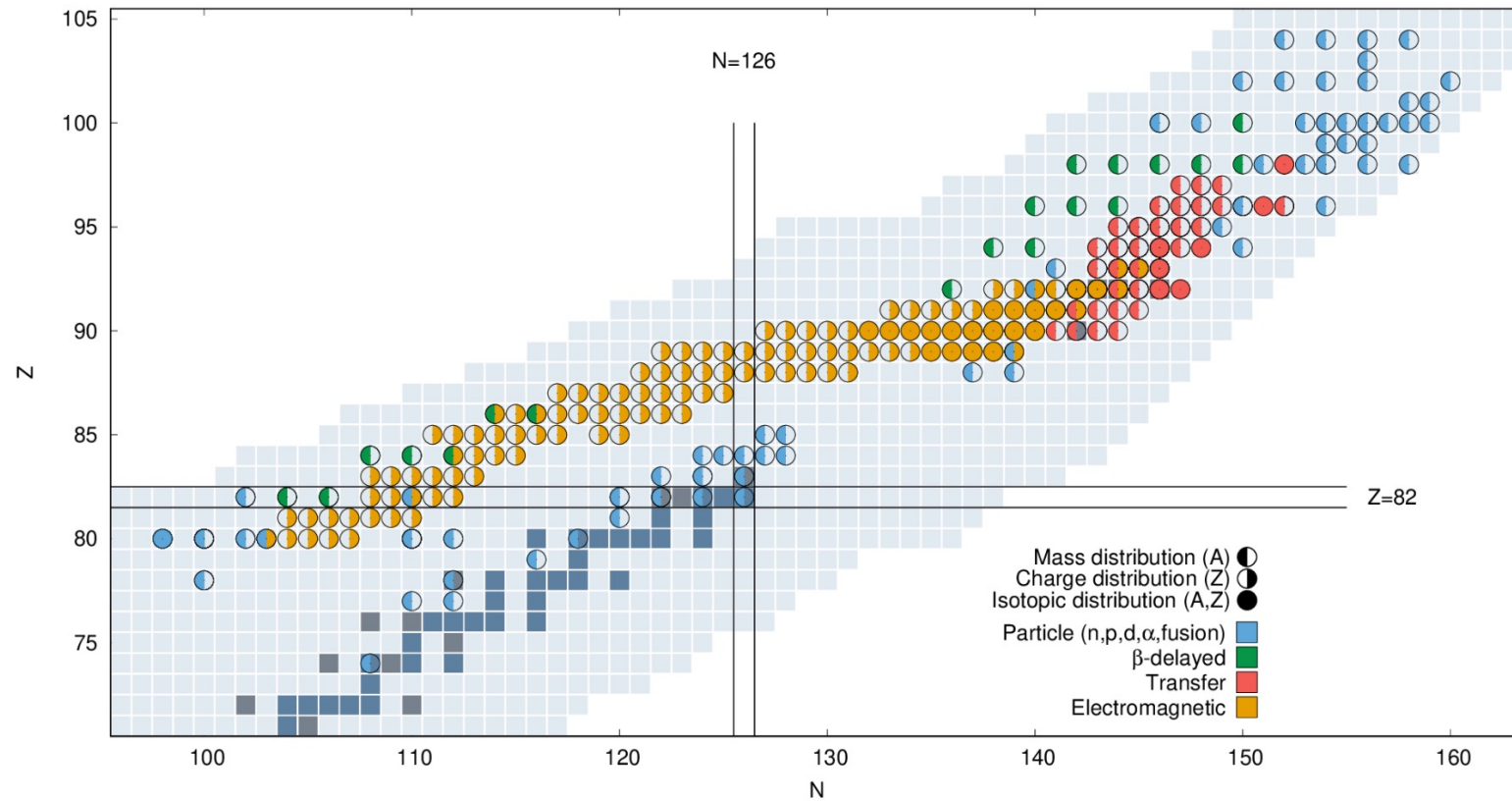


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Fission yields

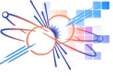


Antoine Lemasson HDR

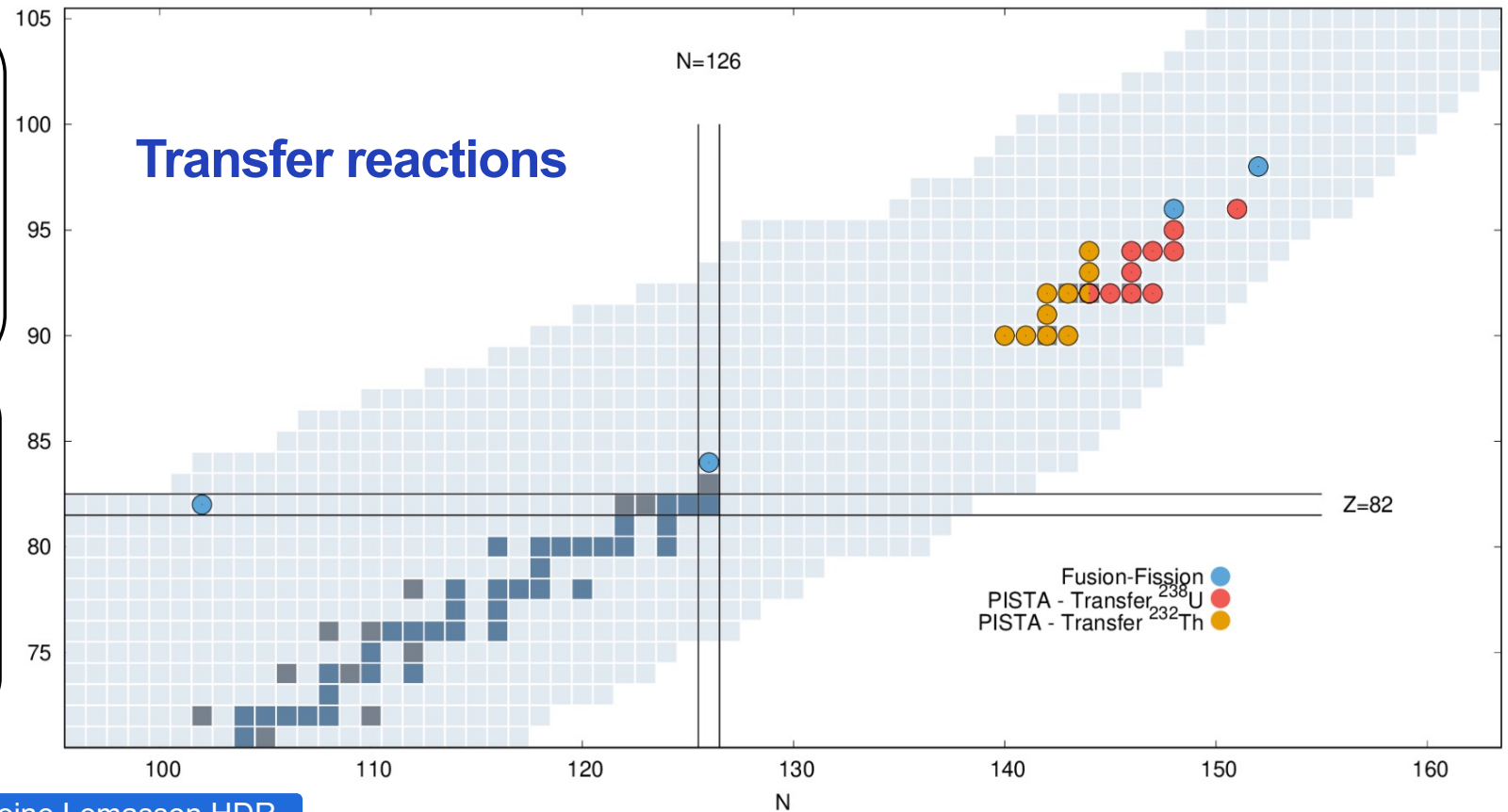
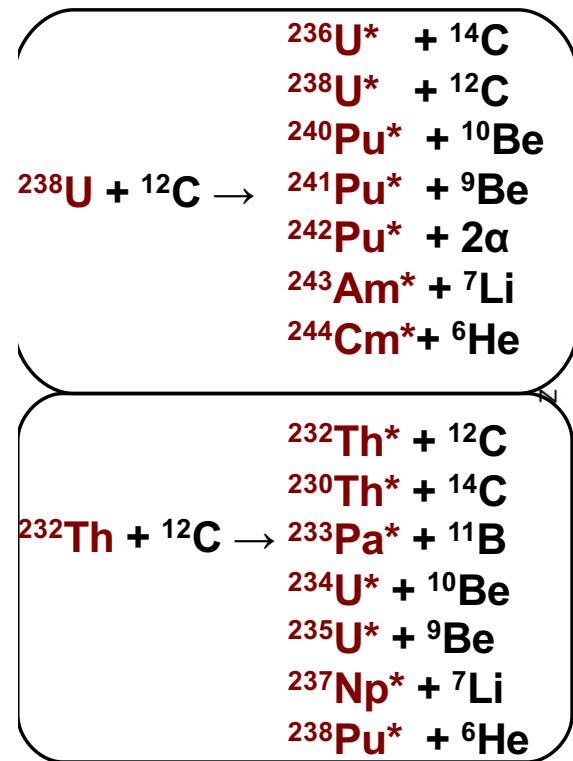


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Fission yields in inverse kinematics @ VAMOS



Antoine Lemasson HDR



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Fission in inverse kinematics @VAMOS

$^{238}\text{U} + ^{12}\text{C}$ @ 6.1 MeV/u
 $^{232}\text{Th} + ^{12}\text{C}$ @ 6.05 MeV/u

EXO GAM

Fissioning nuclei
 produced in Transfer Reactions

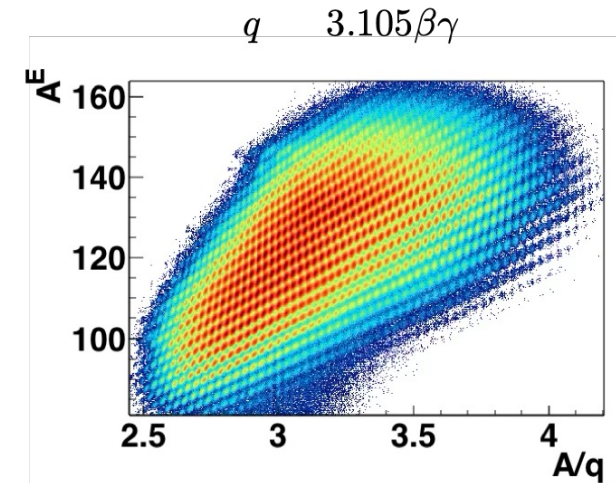
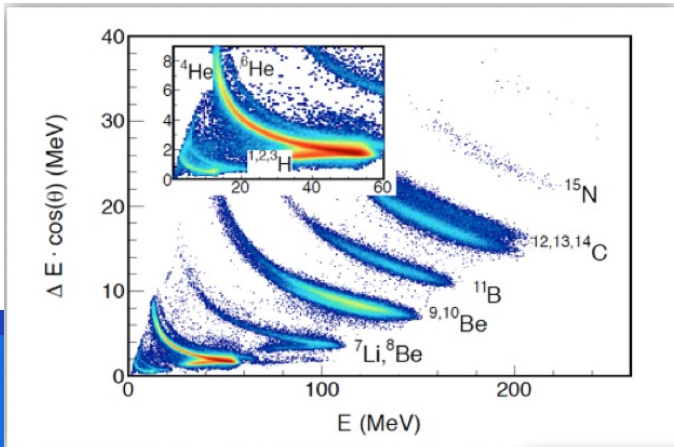
Broad Excitation energy distribution

SPIDER
 ΔE -E, θ

VAMOS

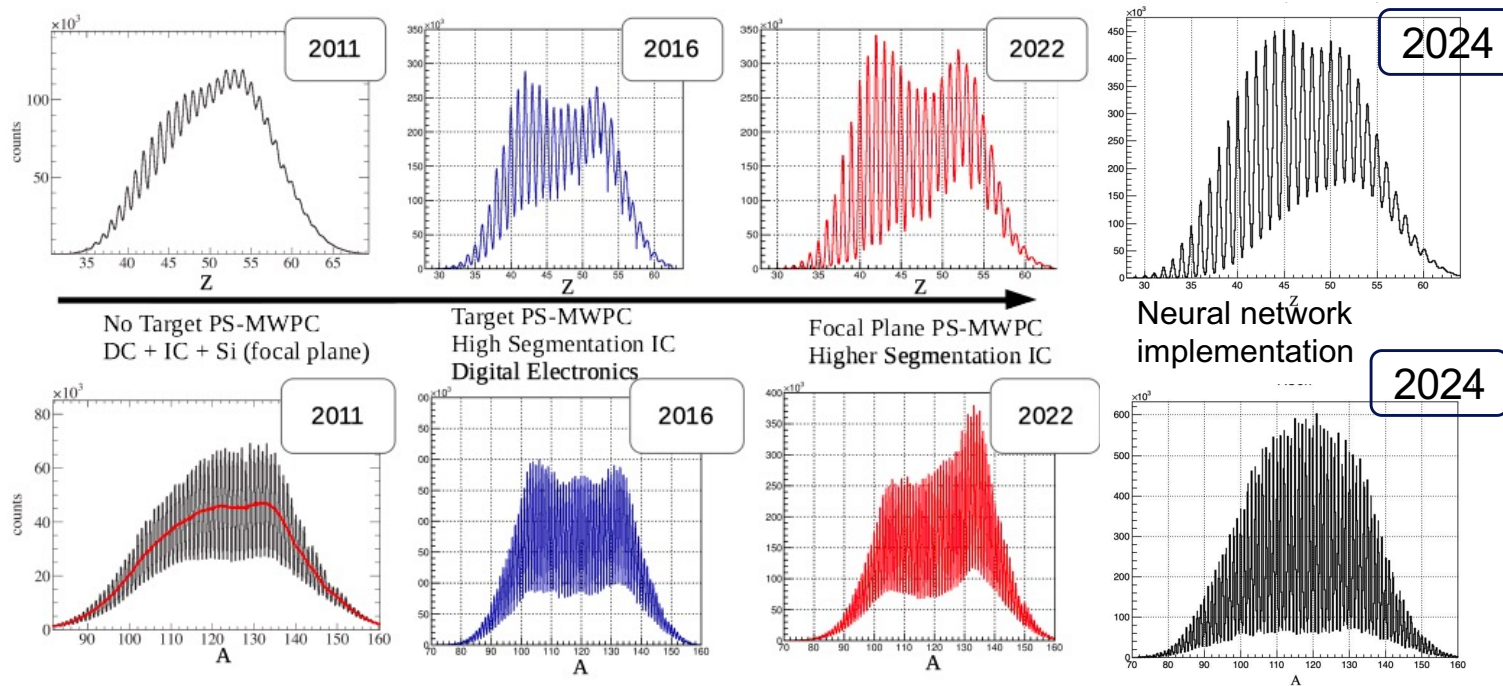
B ρ -ToF- ΔE -E

Complete
 isotopic distribution of
 fission fragments



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Fission in inverse kinematics at VAMOS : A long standing program



Increasing & improving
Acceptance & Resolution
Detection set-up
Trajectory reconstruction
procedure

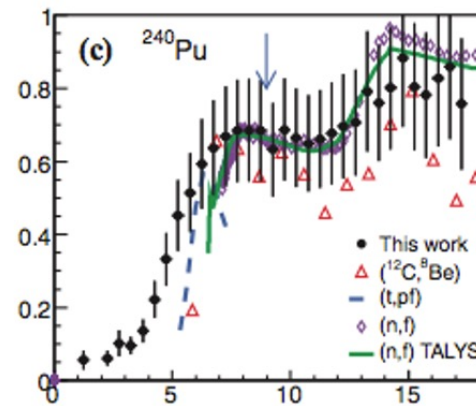
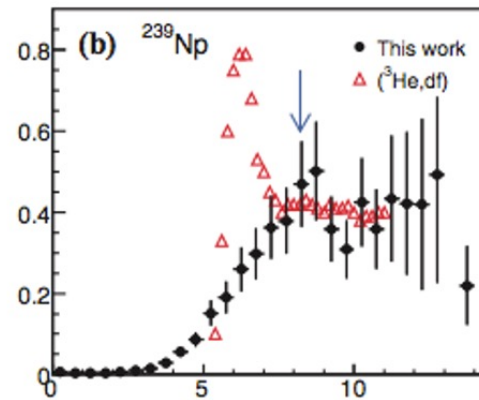
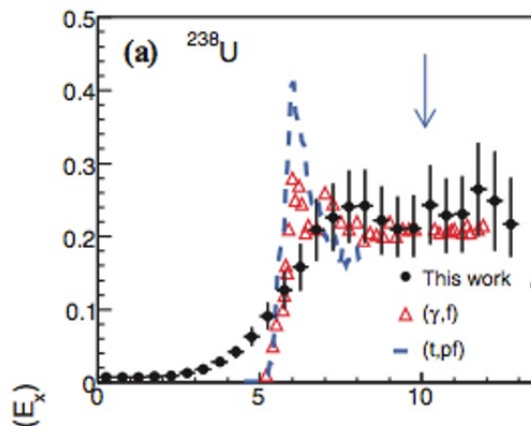
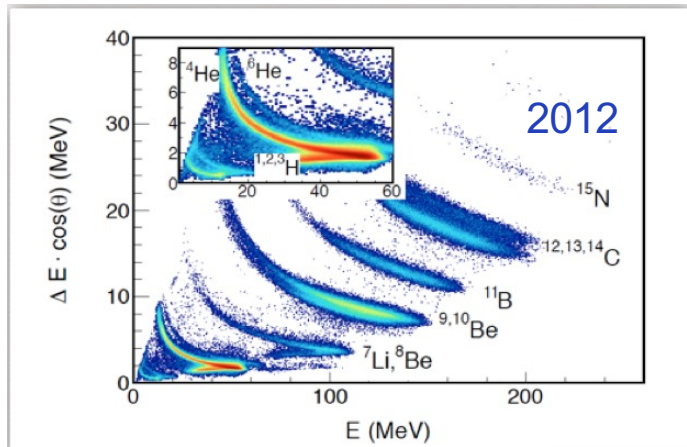
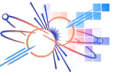
M. Caamaño et al., PRC 88 (2013) 024605
C. Rodriguez-Tajes et al., PRC (2014) 024614
F. Farget et al, EPJA 51, 175 (2015)
M. Caamaño, et al., Phys. Rev. C 92, 034606 (2015).
D. Ramos et al., Phys. Rev. C 99, 024615 (2019).
D. Ramos et al., Phys. Rev. Lett. 123, 092503 (2019).
D. Ramos et al. Phys. Rec. C 101, 034609 (2020).
C. Schmitt et al. Phys. Rev. Lett. 126, 132502 (2021).
A. Jhingan et al. Phys. Rev. C 106, 044607 (2022).
D. Ramos et al., Phys. Rev. C 107, L021601 (2023)
D. Ramos et al. Phys. Rev. C. 113, 054611 (2026).



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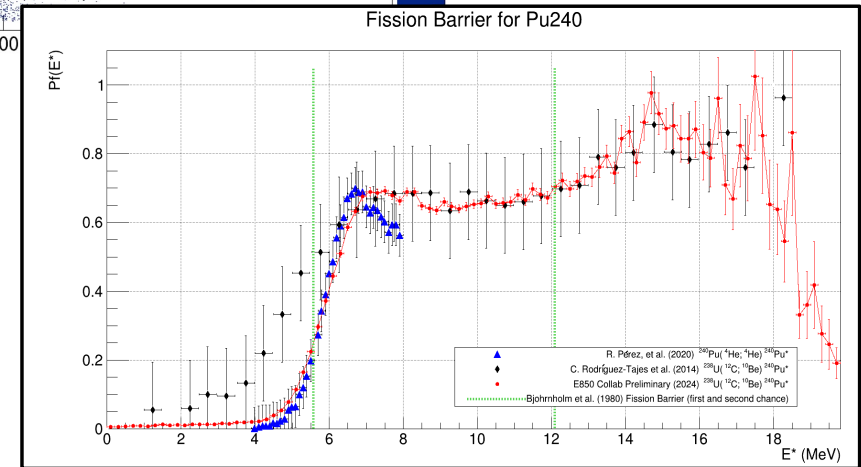
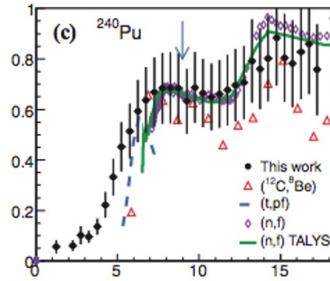
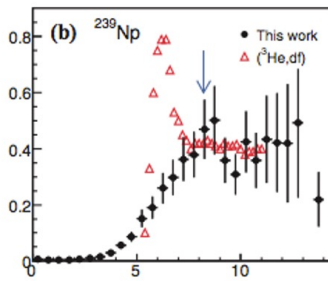
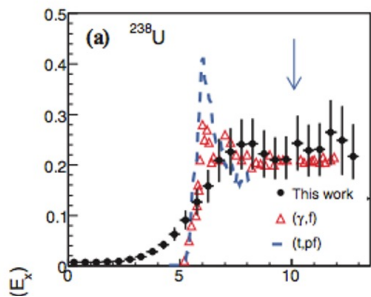
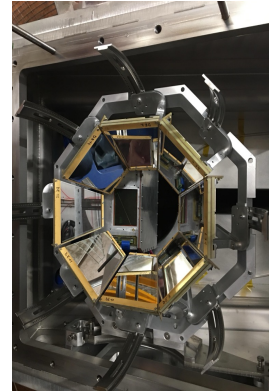
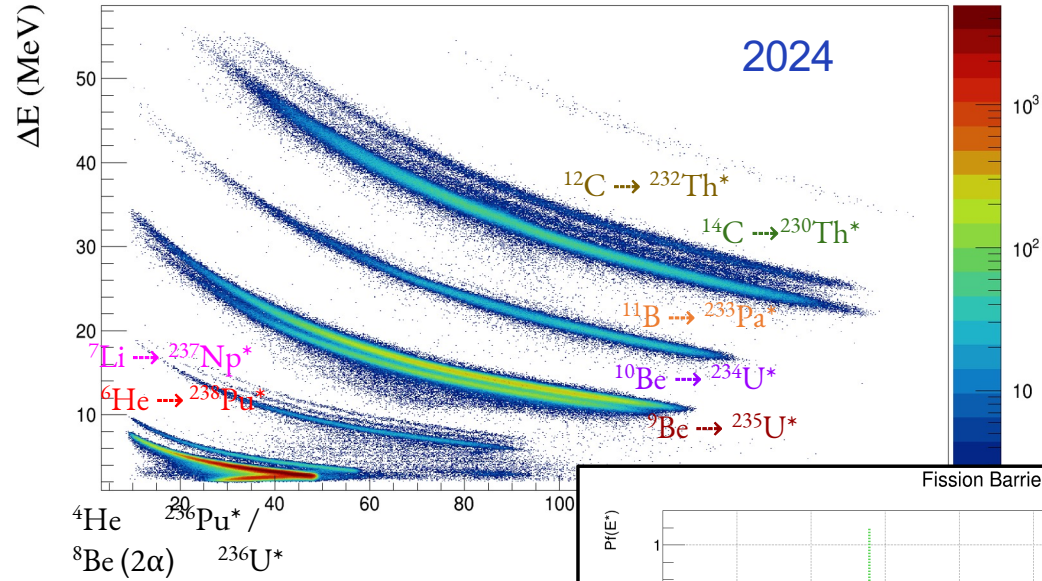
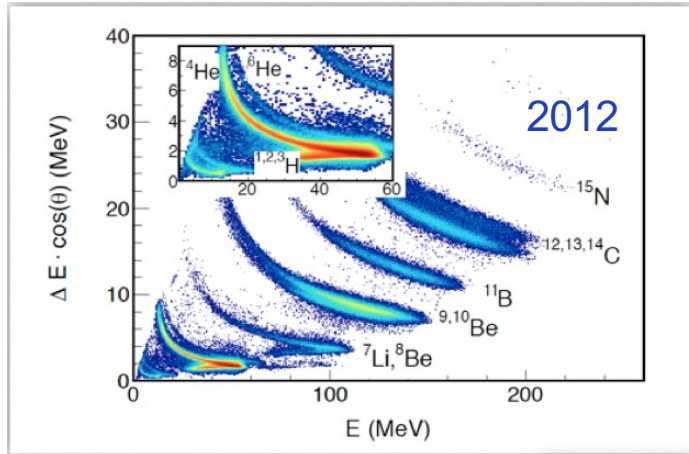
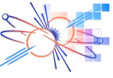
Improvement in the fissioning nucleus definition



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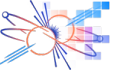
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Improvement in the fissioning nucleus definition



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APRENDE-SENFY

Sensibility study of the fission yields on the evaluation of the decay heat of the used nuclear fuel

- Detailed comparison between the experimental and evaluated isotopic fission-fragment yields, and GEF code estimation
- Collaboration with Lydie Giot @SUBATECH for sensibility calculation (**APRENDE PhD @ SUBATECH**) WP4.
- New data for sensibility study and comparison to GEF code (**APRENDE PhD @ GANIL**)

- Isotopic fission yields of ^{239}Pu in the fast and epithermal energy spectrum :
 - **E849 Th+C, 2024**: $^{232}\text{Th}(^{12}\text{C}, ^4\text{He})^{240}\text{Pu}^*$ 2-alpha transfer. **Alex Cobo**
 - **E516a U+C, 2013**: $^{238}\text{U}(^{12}\text{C}, ^{10}\text{Be})^{240}\text{Pu}^*$ 2-proton transfer. **Phys. Rev. C, 2026, SPIDER**

- Isotopic fission yields of ^{233}U in the fast and epithermal energy spectrum :
 - **E849 Th+C, 2024** $^{232}\text{Th}(^{12}\text{C}, ^{10}\text{Be})^{234}\text{U}^*$ 2-proton transfer. **Paul Parlea + Alex Cobo**

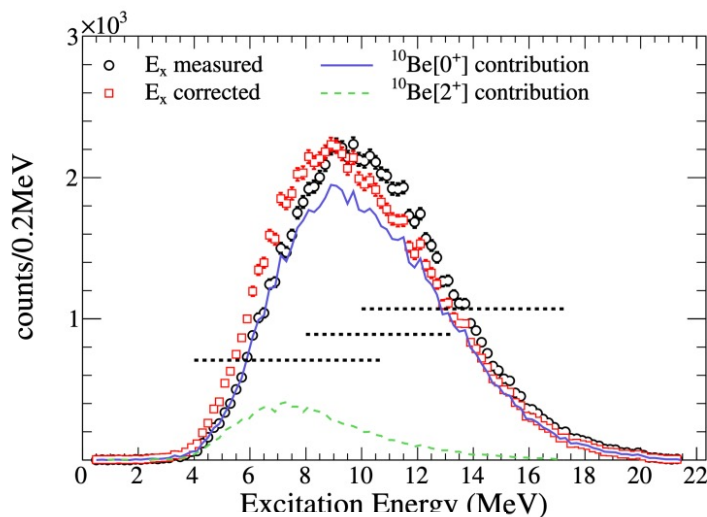
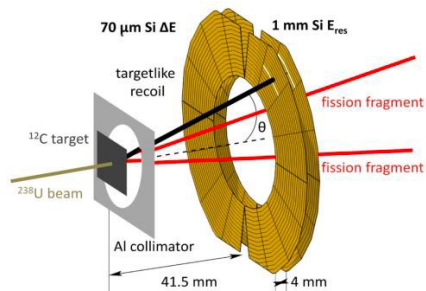
- Isotopic fission yields of ^{243}Cm in the fast and epithermal energy spectrum :
 - **E850 U+ C, 2024** $^{238}\text{U}(^{12}\text{C}, ^6\text{He})^{244}\text{Cm}^*$ 4-proton-2-neutron **Analysis within Collaboration**
 - **E849 Th+ C, 2024** $^{232}\text{Th} + ^{12}\text{C} \rightarrow ^{244}\text{Cm}^*$ Fusion-fission **Alex Cobo**
 - **E516a U+C, 2013** $^{238}\text{U}(^{12}\text{C}, ^6\text{He})^{244}\text{Cm}^*$ 4-proton-2-neutron transfer **D.Ramos Phys. Rev.C 2019**



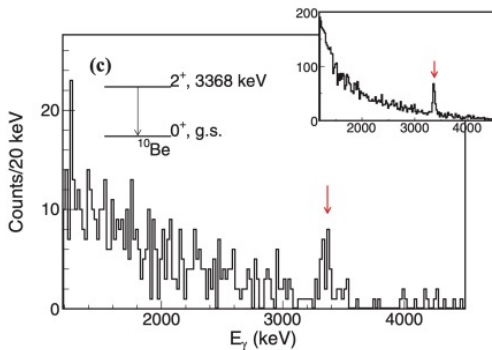
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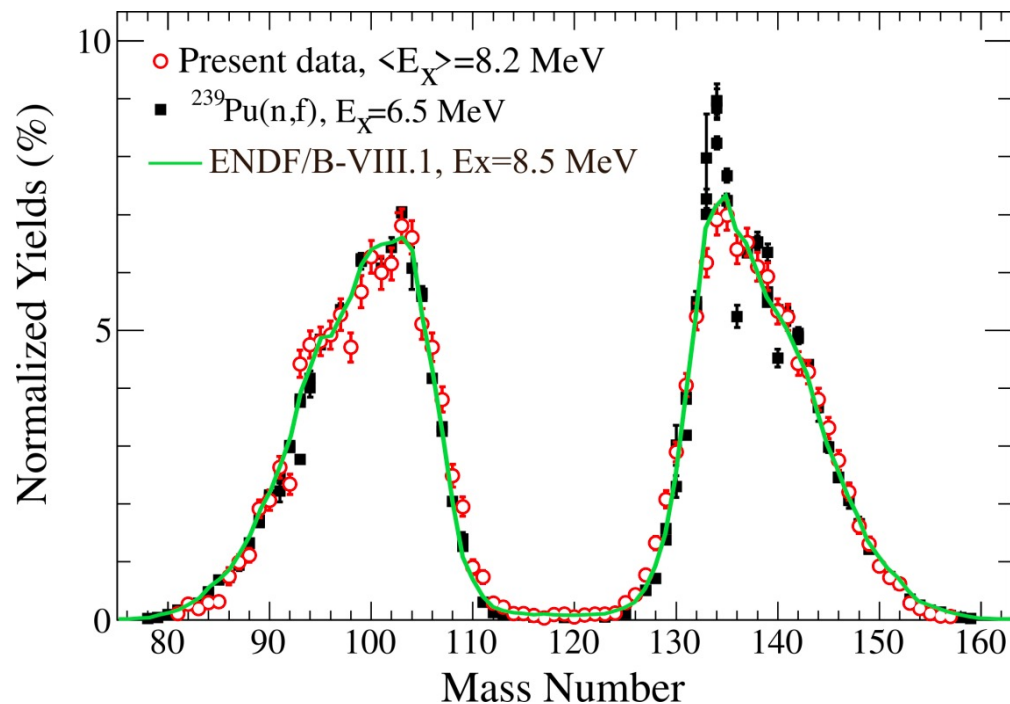
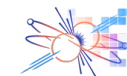
^{240}Pu



$E^* = 8.2 \text{ MeV}$
 $E^* = 10 \text{ MeV}$
 $E^* = 11.9 \text{ MeV}$



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

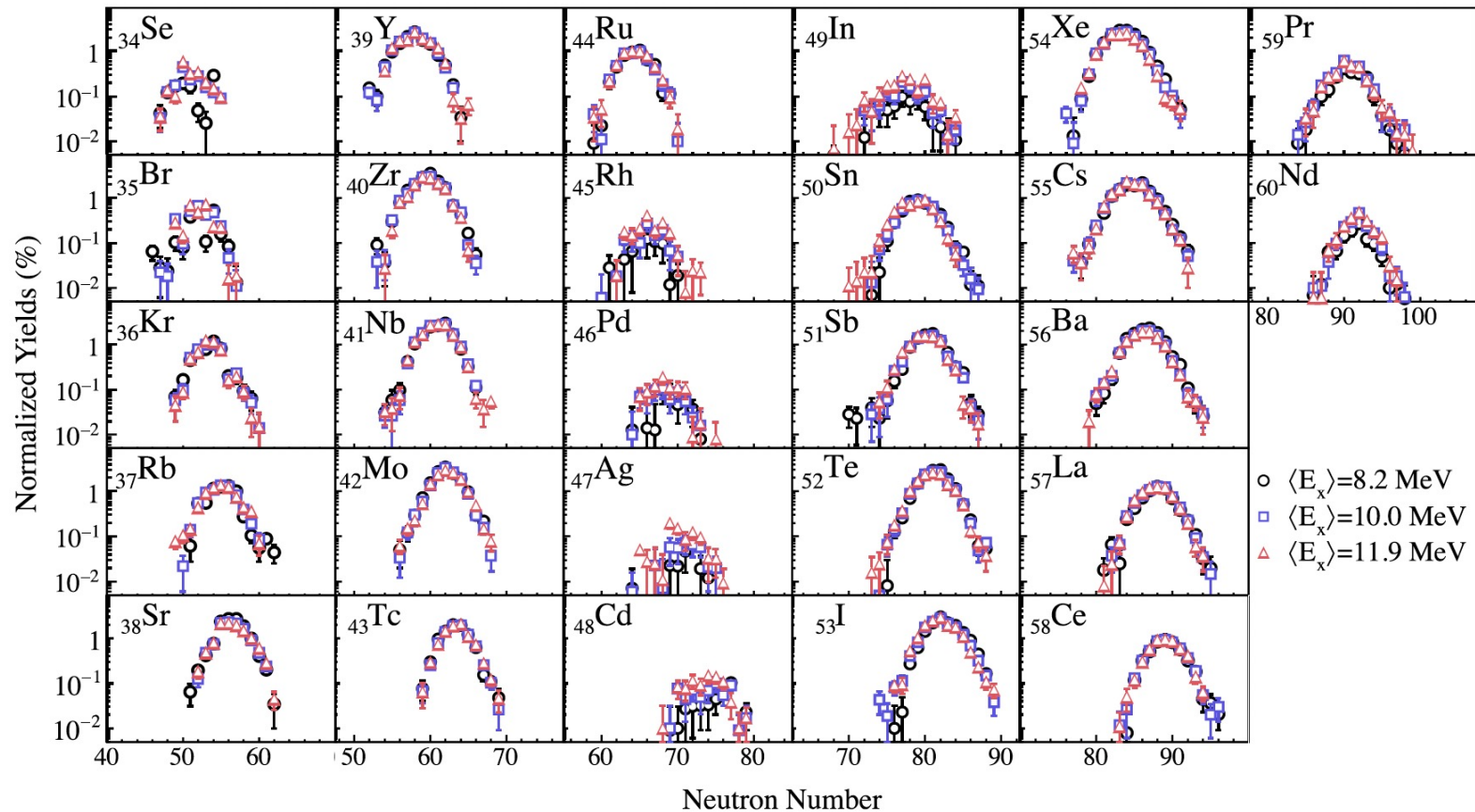
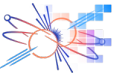


Post-neutron evaporation mass yields.

- Very good agreement with n-induced fission (H. Naik et al. NSE 196, 824 (2022)) and evaluation (ENDF)
- Evidence of E_x effect in $A \sim 132$

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^{240}Pu



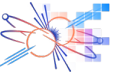
Evolution of
isotopic yields
with E^*



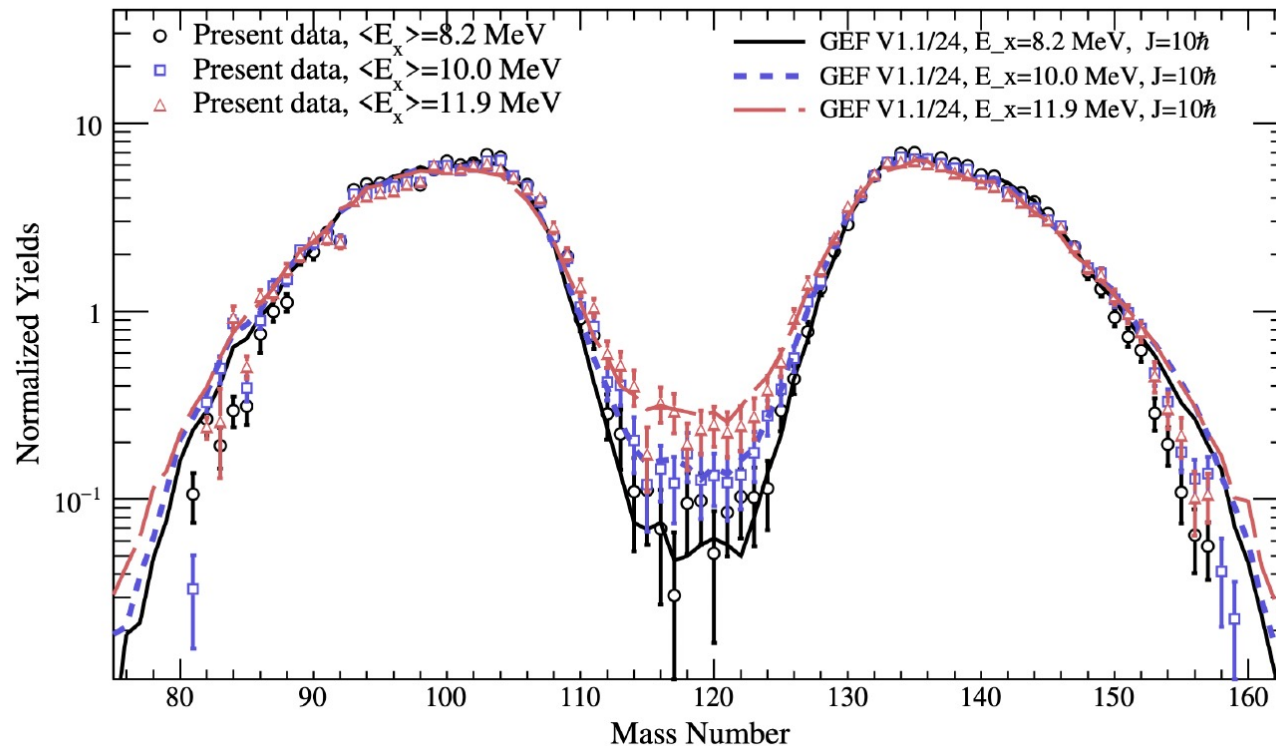
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^{240}Pu



D. Ramos et al. PRC 113, 054611 (2026)



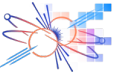
- Good description of the **Damping of Shell effects**
- Larger **super-asymmetric fission component**



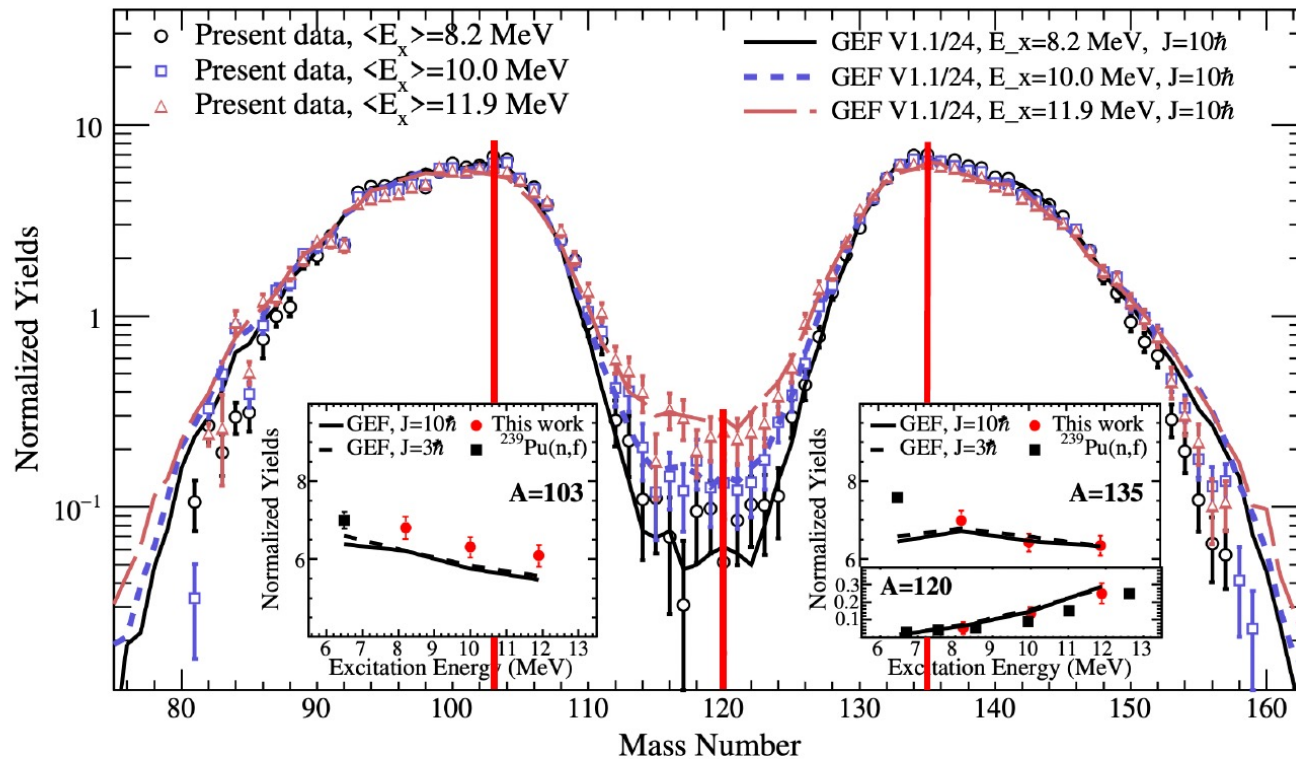
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^{240}Pu



D. Ramos et al. PRC 113, 054611 (2026)



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

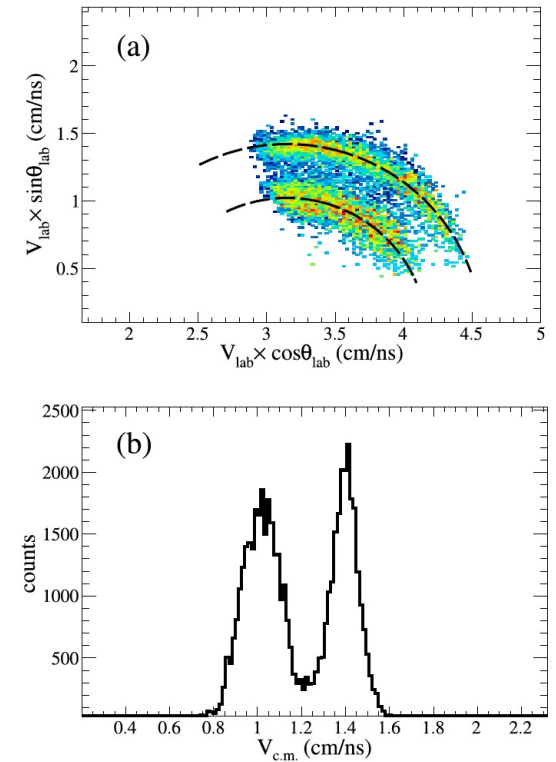
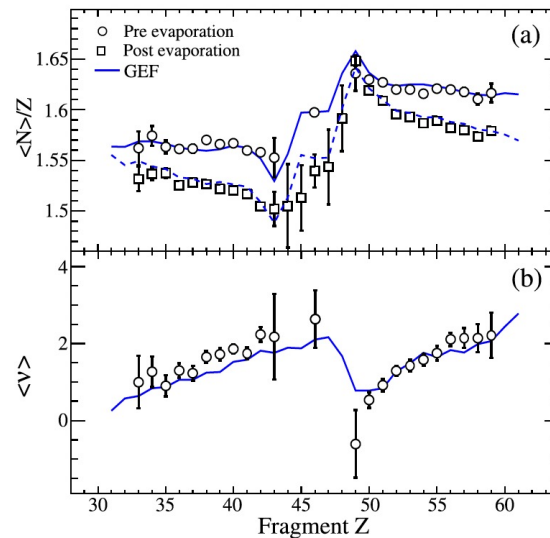
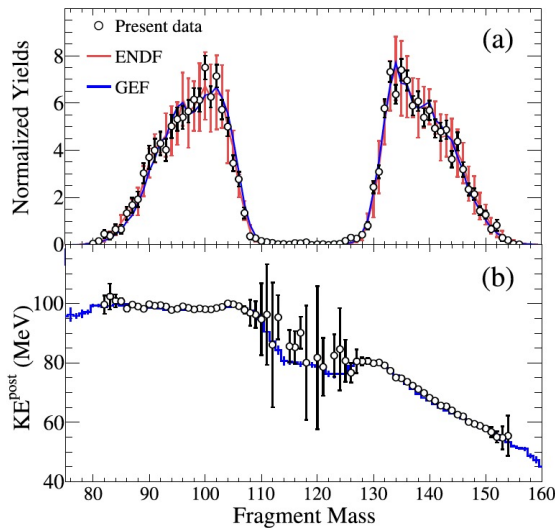


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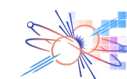
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Data of high quality for improving the codes

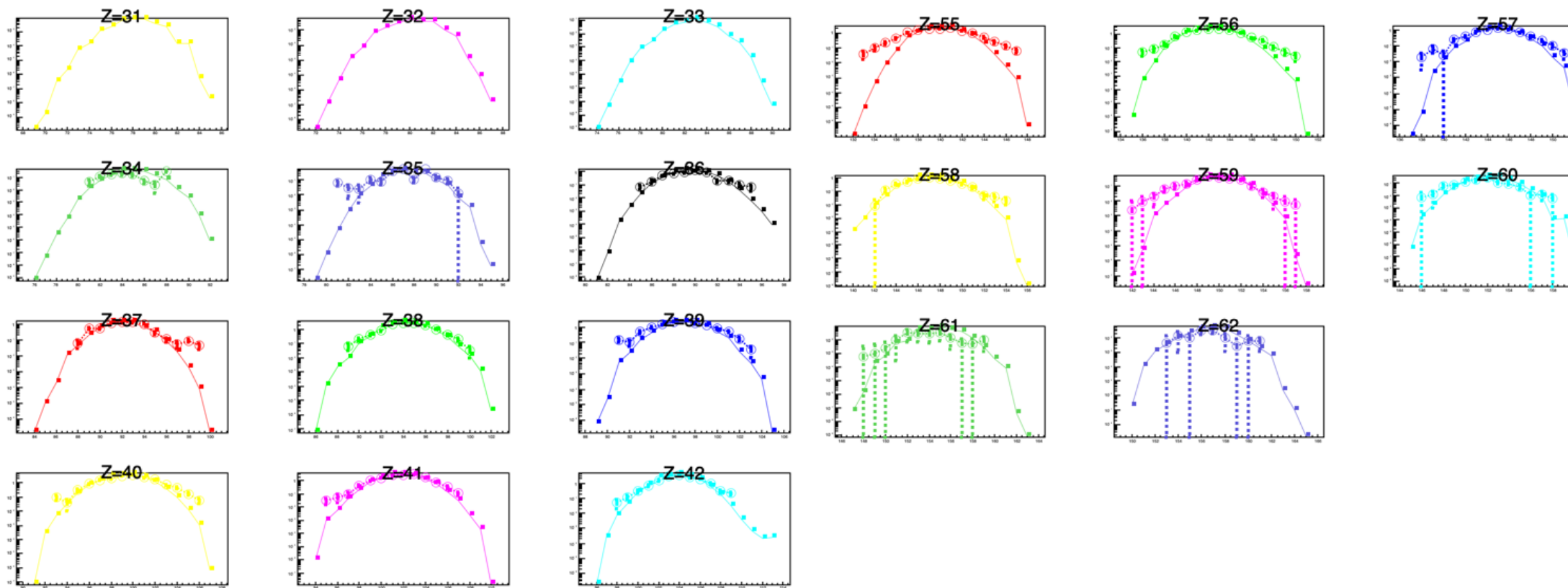
- Isotopic yields
- Even-odd effect
- Velocity of fragment : scission configuration
- Evolution with excitation energy
- Neutron-rich fissioning systems, close to the ones of interest



^{240}Pu



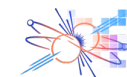
Comparison with JEFF4 - Fast n



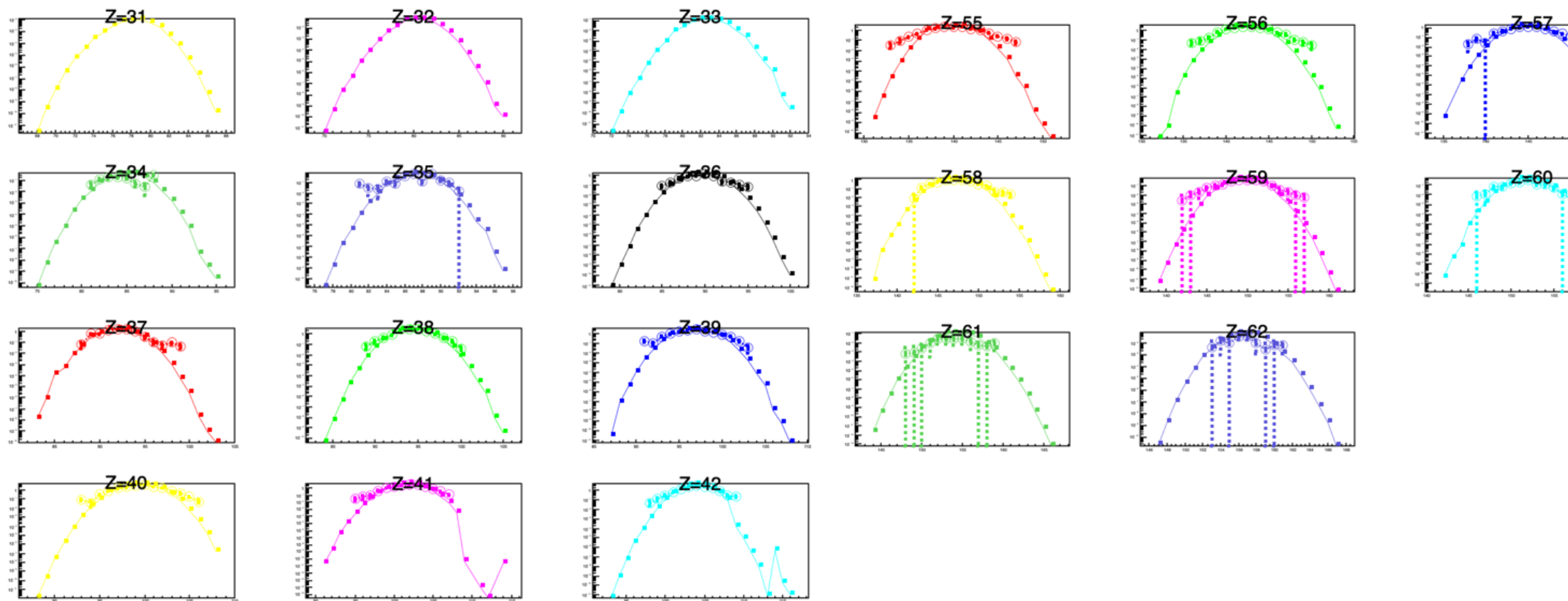
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^{240}Pu



Comparison with JENDL4 - Fast n

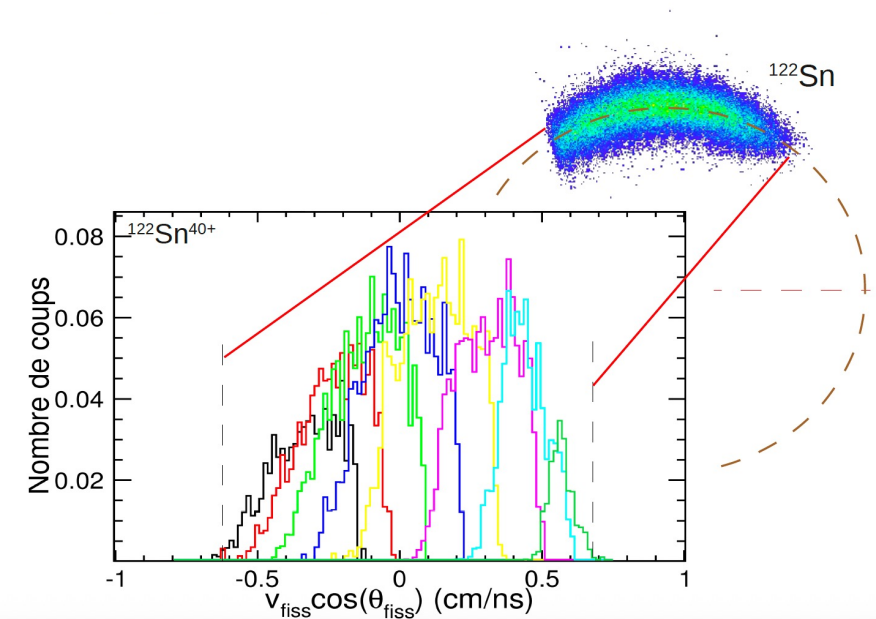


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From the point of view of the evaluator : Some limitations

- Excitation energy of the transfer partner
- Contamination of other fissioning transfer
- Complex reconstruction of the transmission needs high statistics
 - Yields are distributed over
 - Charge states
 - Velocity and angular distribution

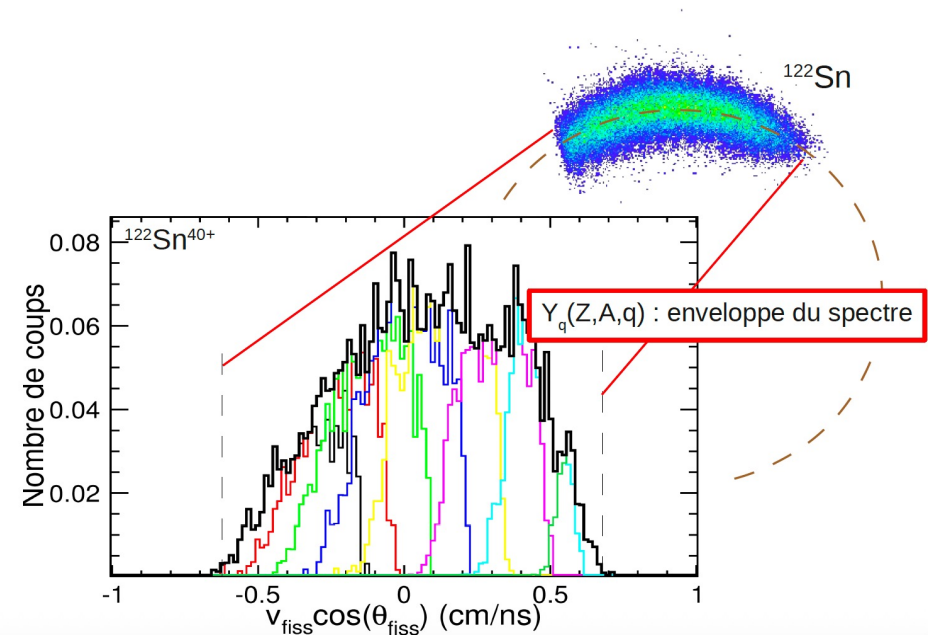


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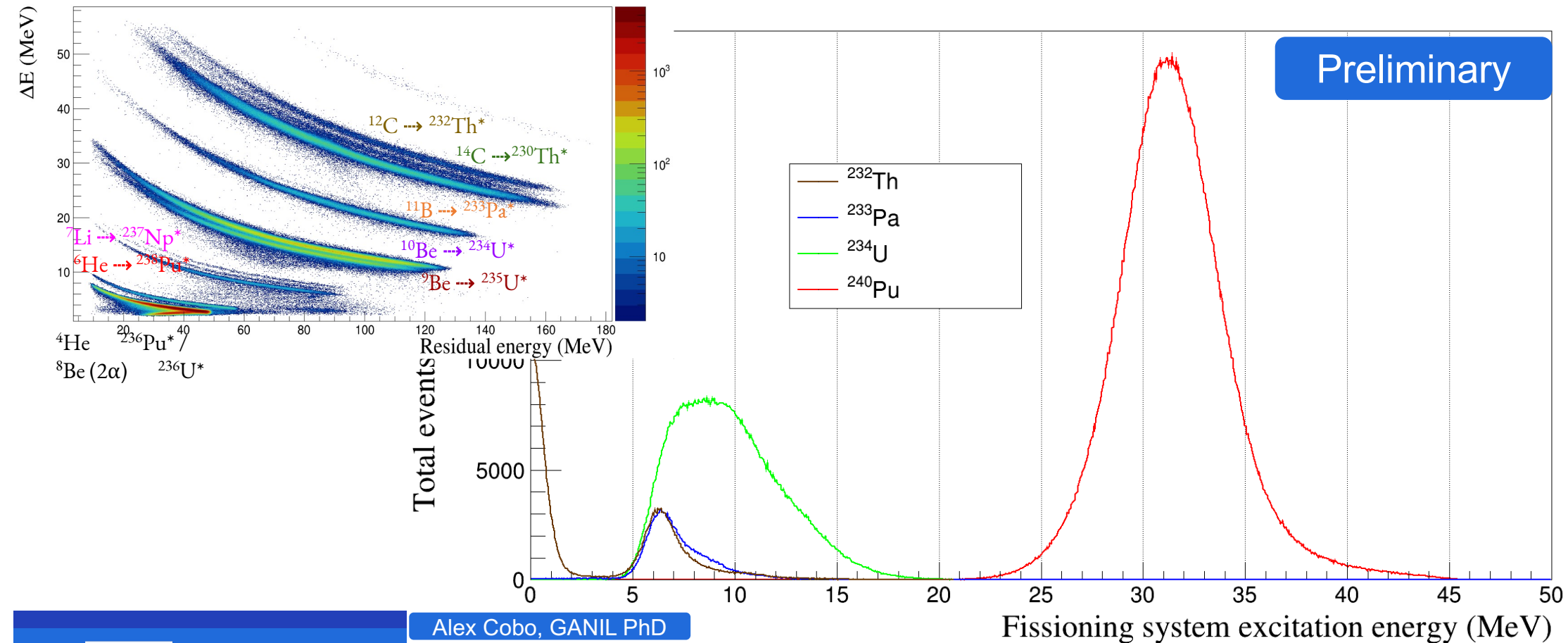


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E849 results : Th+C : Excitation energy of the fissioning system



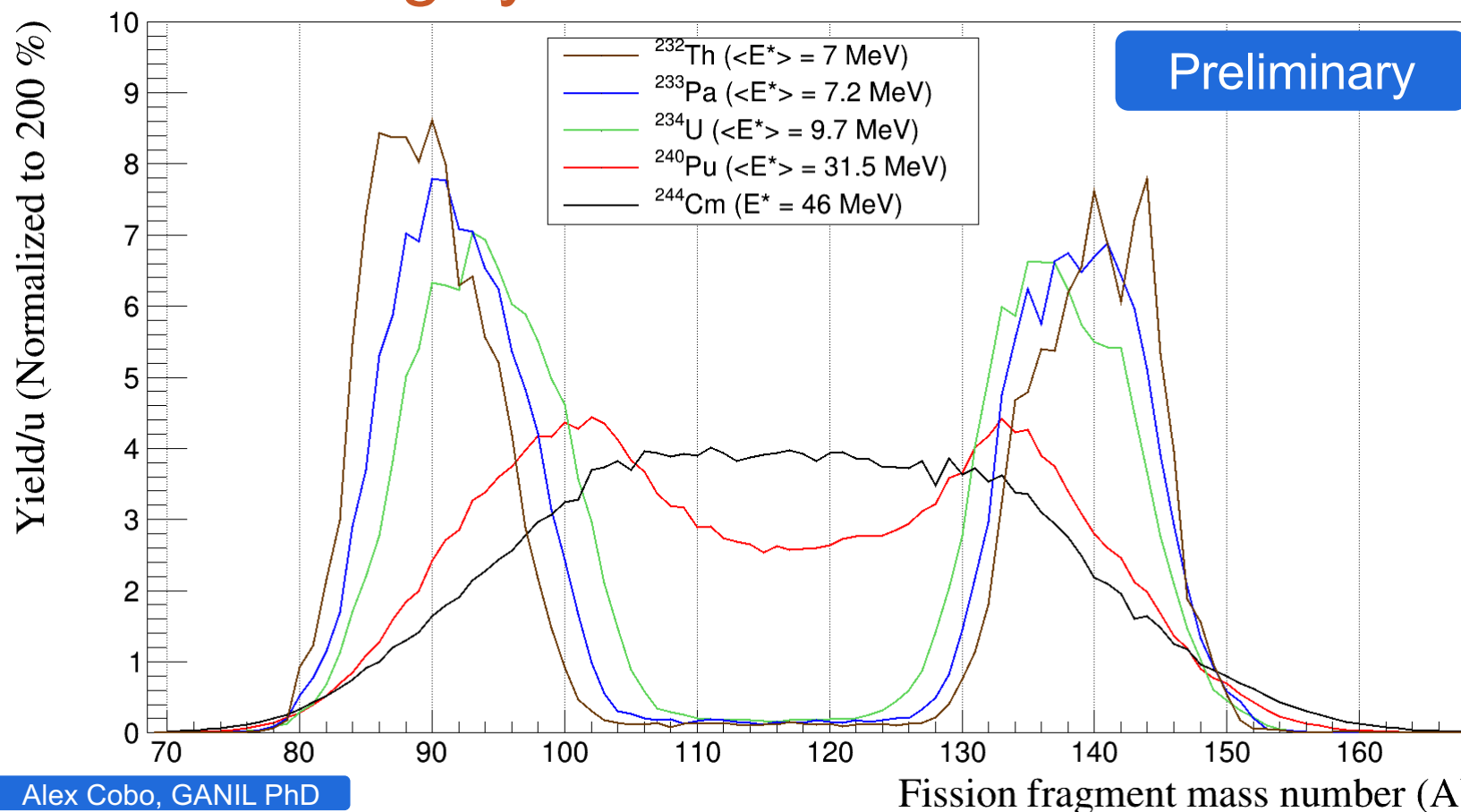
Alex Cobo, GANIL PhD



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E849 results : Th+C : Fission-fragment mass distributions for the different fissioning systems



Alex Cobo, GANIL PhD



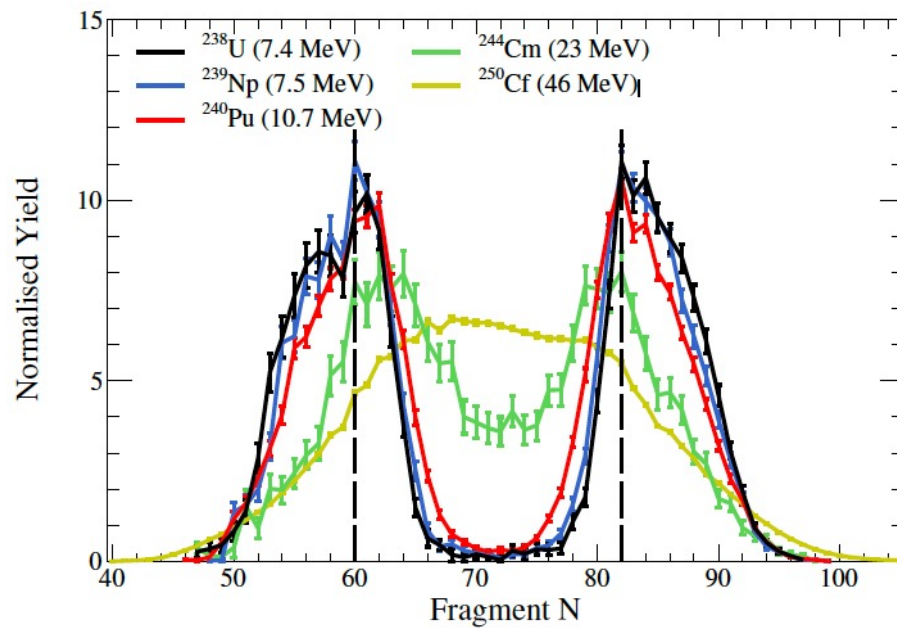
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Cm data:

U+C :

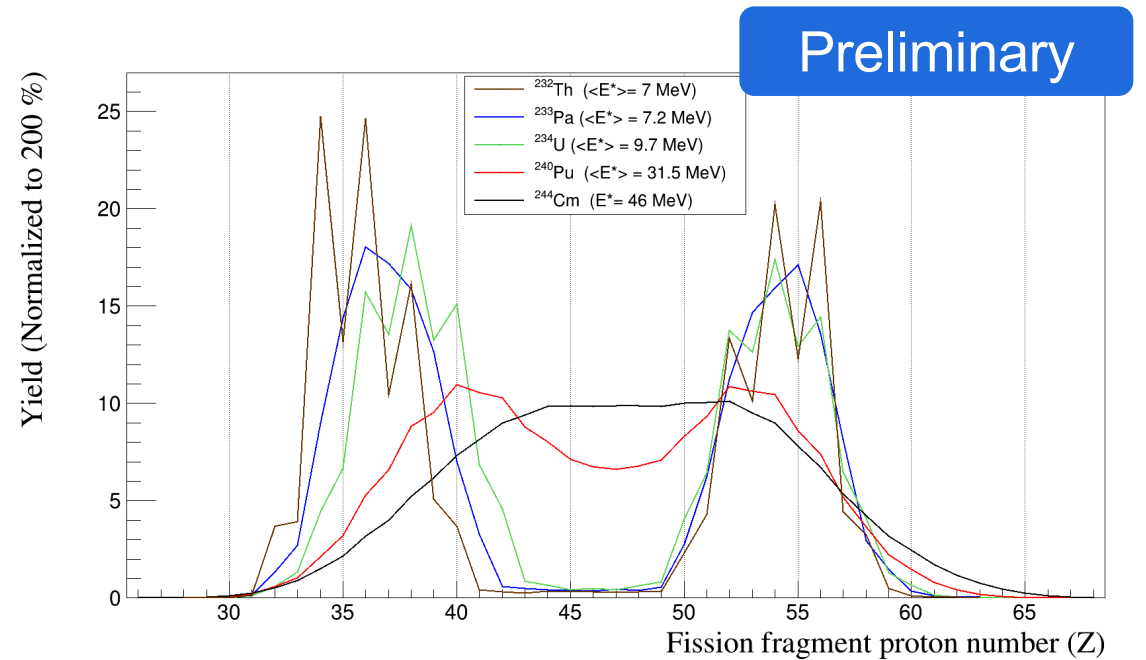
Cm is produced in 4p-2n transfer reaction



D. Ramos et al, PRC2018

Th+C :

Cm is produced in fusion reaction



Alex Cobo, GANIL PhD



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SENFY results



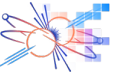
Th+C Experiment successfully performed



Nuclei of interest populated : $^{234}\text{U}^*$, $^{240}\text{Pu}^*$, $^{244}\text{Cm}^*$



Excitation energy range for $^{240}\text{Pu}^*$ and $^{244}\text{Cm}^*$ out of the epithermal and fast neutron induced fission due to the reaction mechanism.

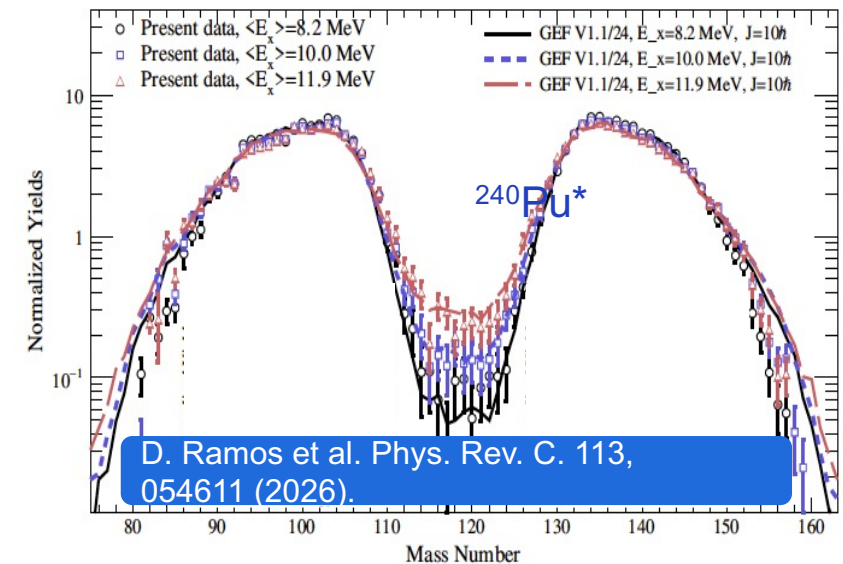
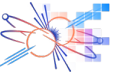


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SENFY results

- 😊 Experiment successfully performed
- 😊 Nuclei of interest populated : $^{234}\text{U}^*$, $^{240}\text{Pu}^*$, $^{244}\text{Cm}^*$
- 🧐 Excitation energy range for $^{240}\text{Pu}^*$ and $^{244}\text{Cm}^*$ out of the epithermal and fast neutron induced fission due to the reaction mechanism.
- 👉 Use previous data from U+C reaction



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SENFY results



Experiment successfully performed



Nuclei of interest populated : $^{234}\text{U}^*$, $^{240}\text{Pu}^*$, $^{244}\text{Cm}^*$



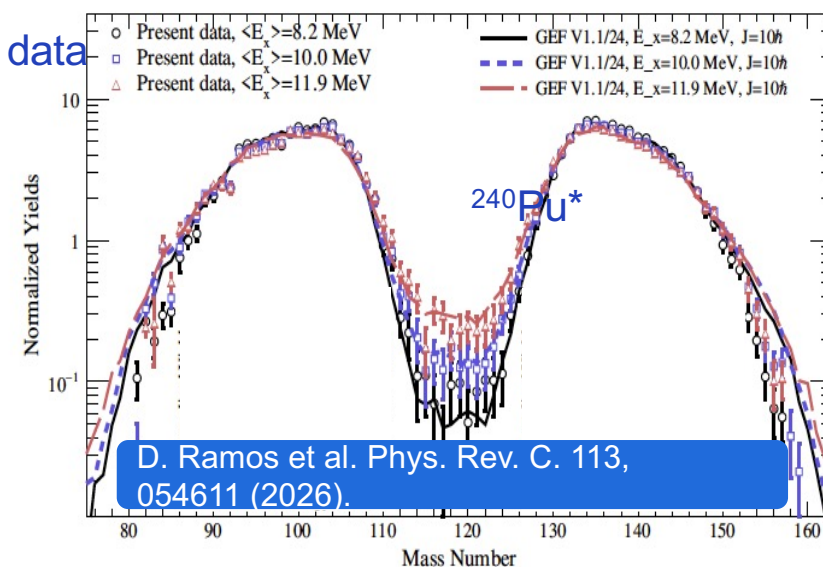
Excitation energy range for $^{240}\text{Pu}^*$ and $^{244}\text{Cm}^*$ out of the epithermal and fast neutron induced fission due to the reaction mechanism.



Use previous data from U+C reaction

Continue the evaluation of the data

And the evaluation of DB



Consider other fissioning system like $^{232}\text{Th}^*$ that can be of interest in fast-spectrum of (n,n') induced fission in the Th-U fuel cycle.



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**Thank you for
your attention**

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Thank you!



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