STUDY OF THE FISSION PROCESS IN ^{263}Bh AND ^{269}Bh ON THE PATH TOWARD THE ISLAND OF STABILITY

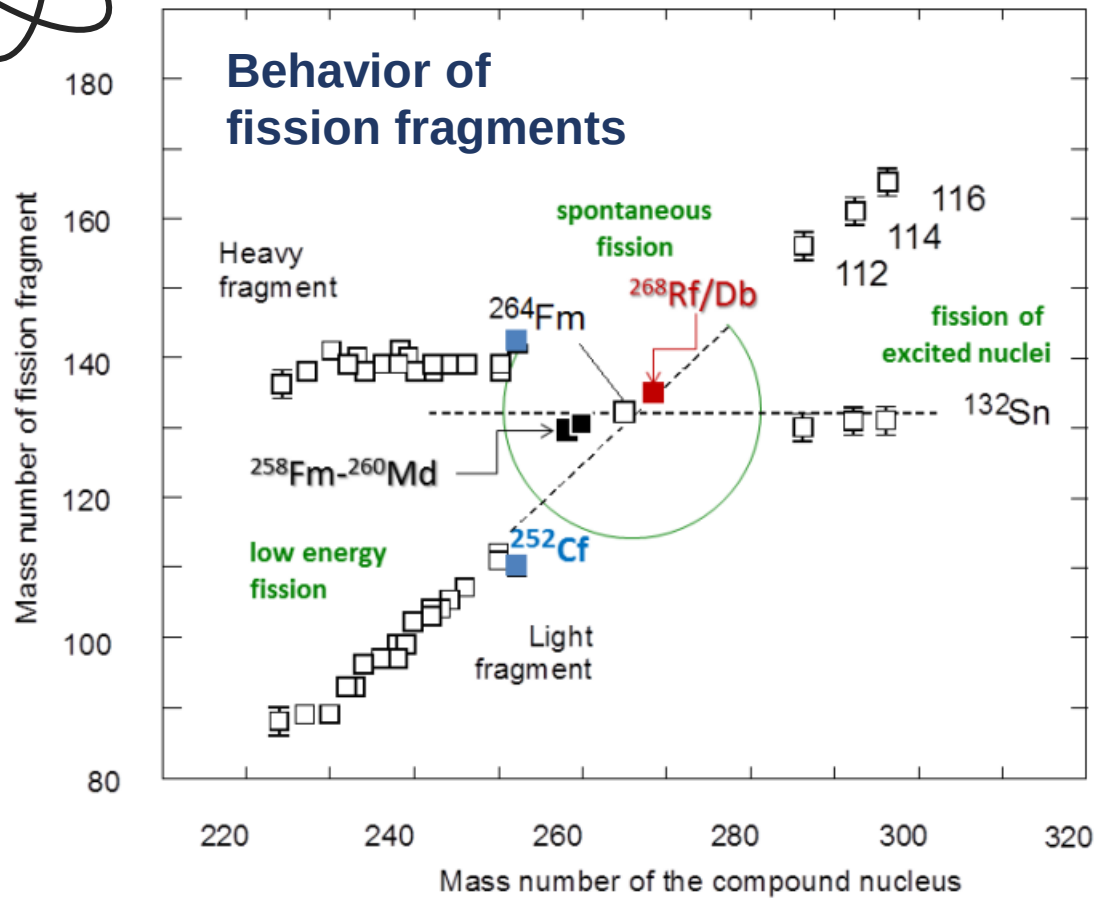
Pia Antonella Setaro

Ministero degli Affari Esteri
e della Cooperazione Internazionale

This work was carried out under the scientific supervision of **Prof. E. Vardaci**

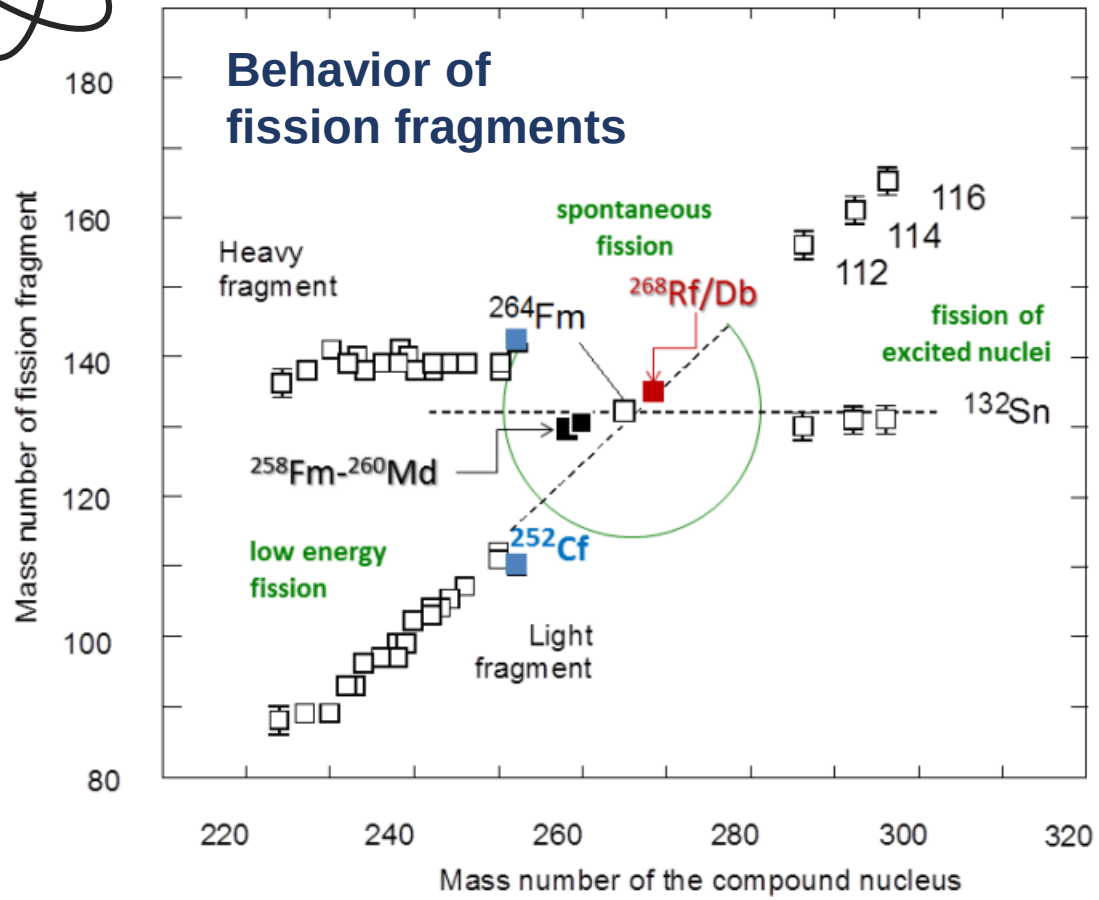
INFN NAPOLI

Fission modes

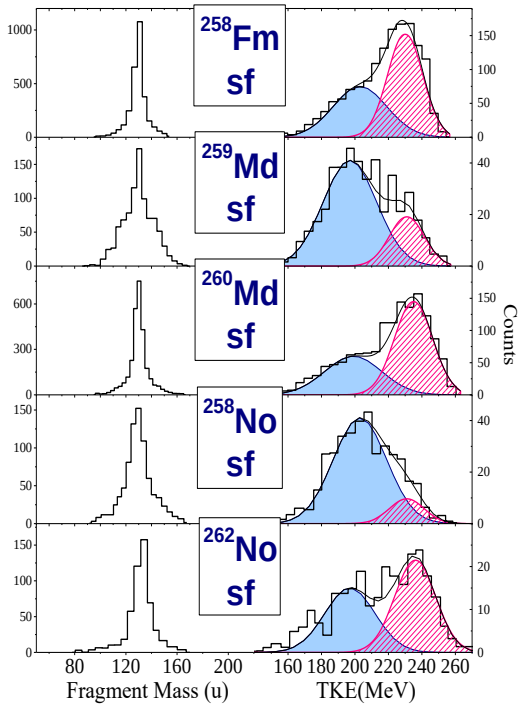


Fission modes

Behavior of fission fragments

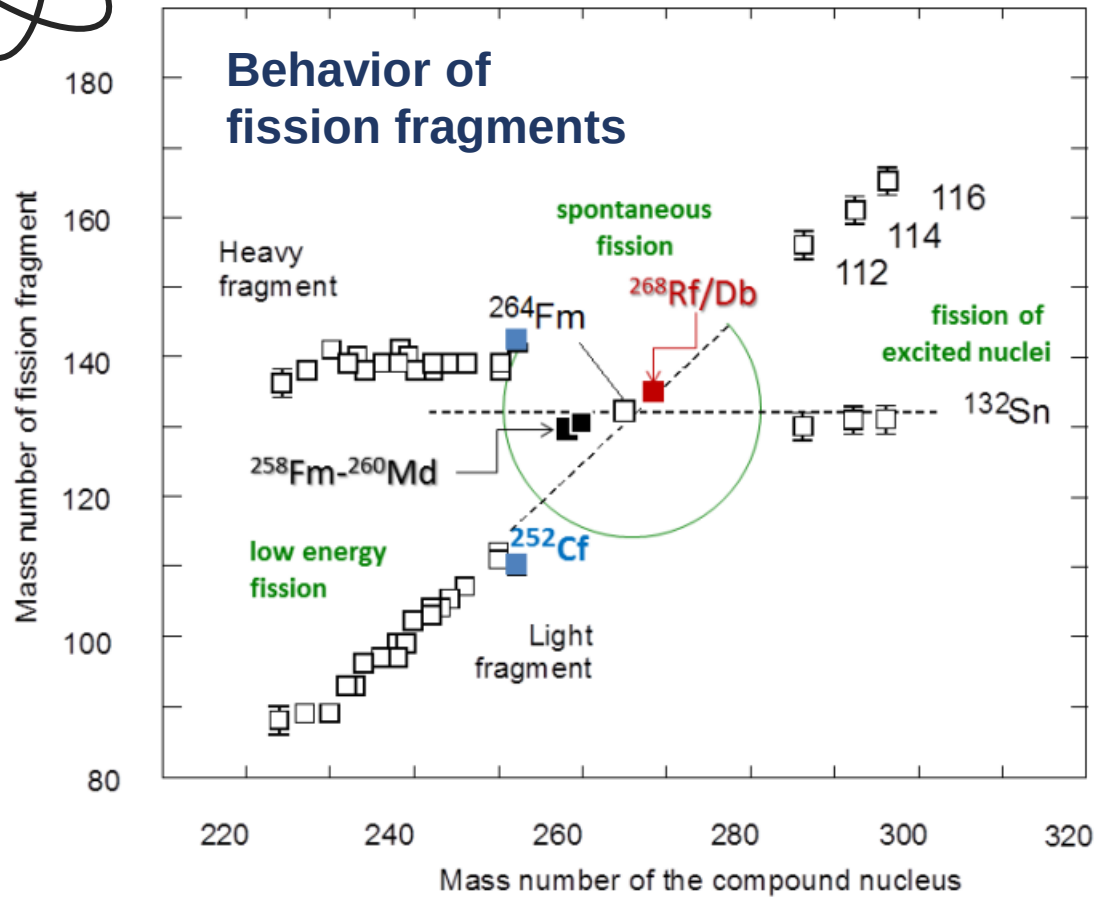


Bimodality fission

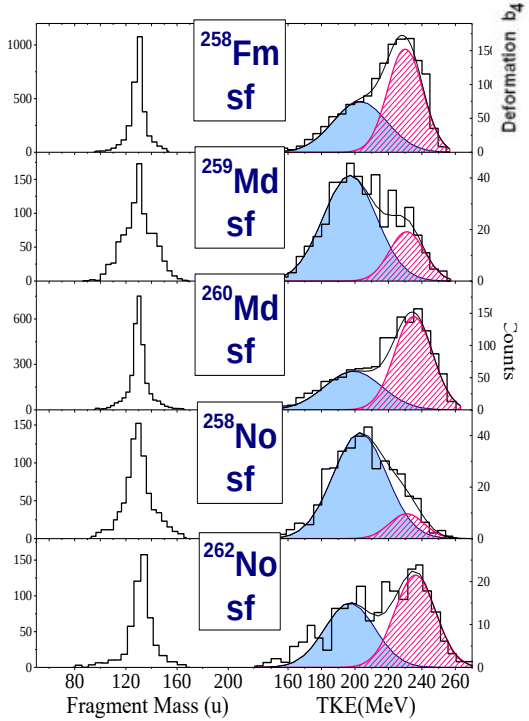


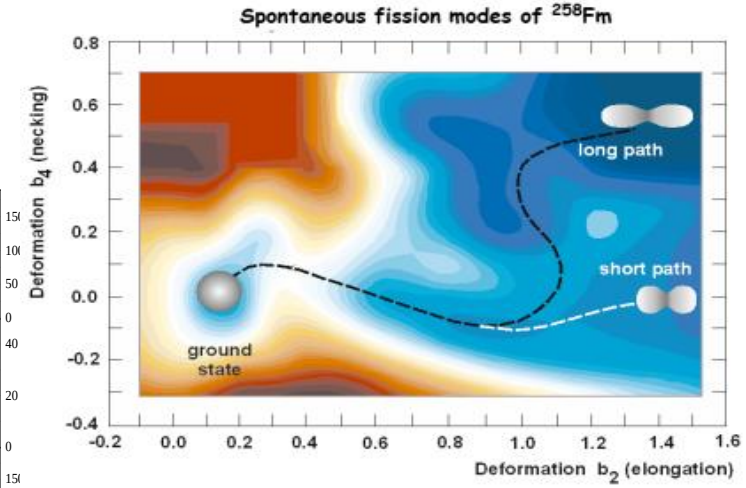
Fission modes

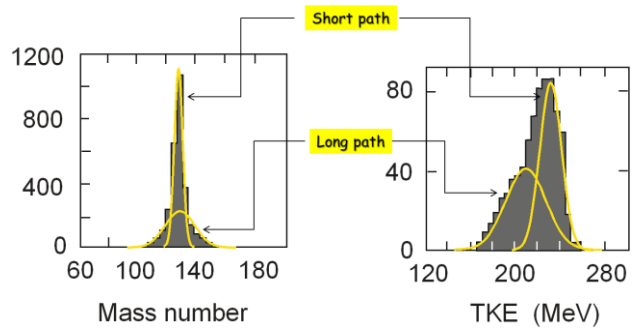
Behavior of fission fragments



Bimodality fission

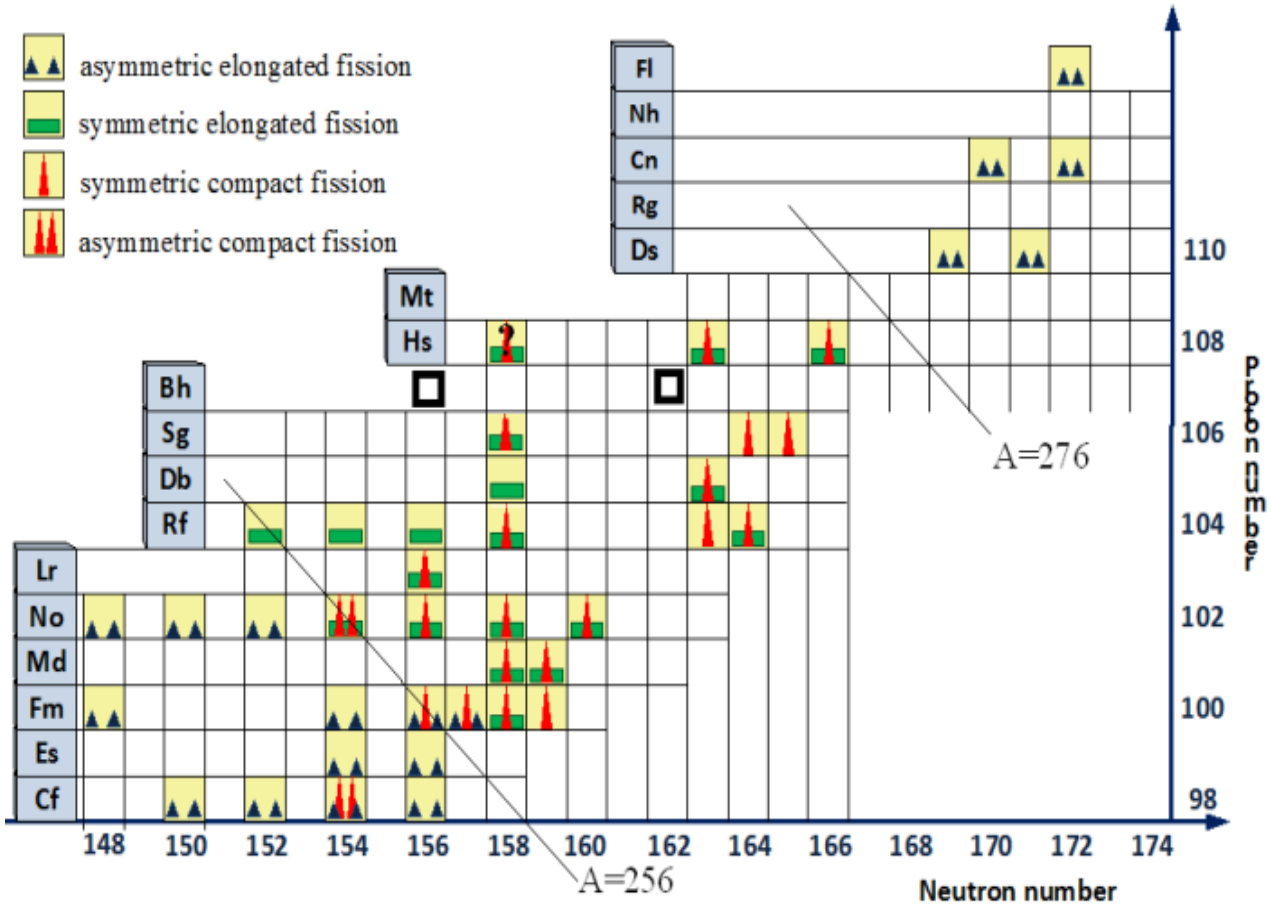






E.K. Hulet *et al.*, Phys. Rev. Lett. **56**, 313 (1986)

Scientific motivation

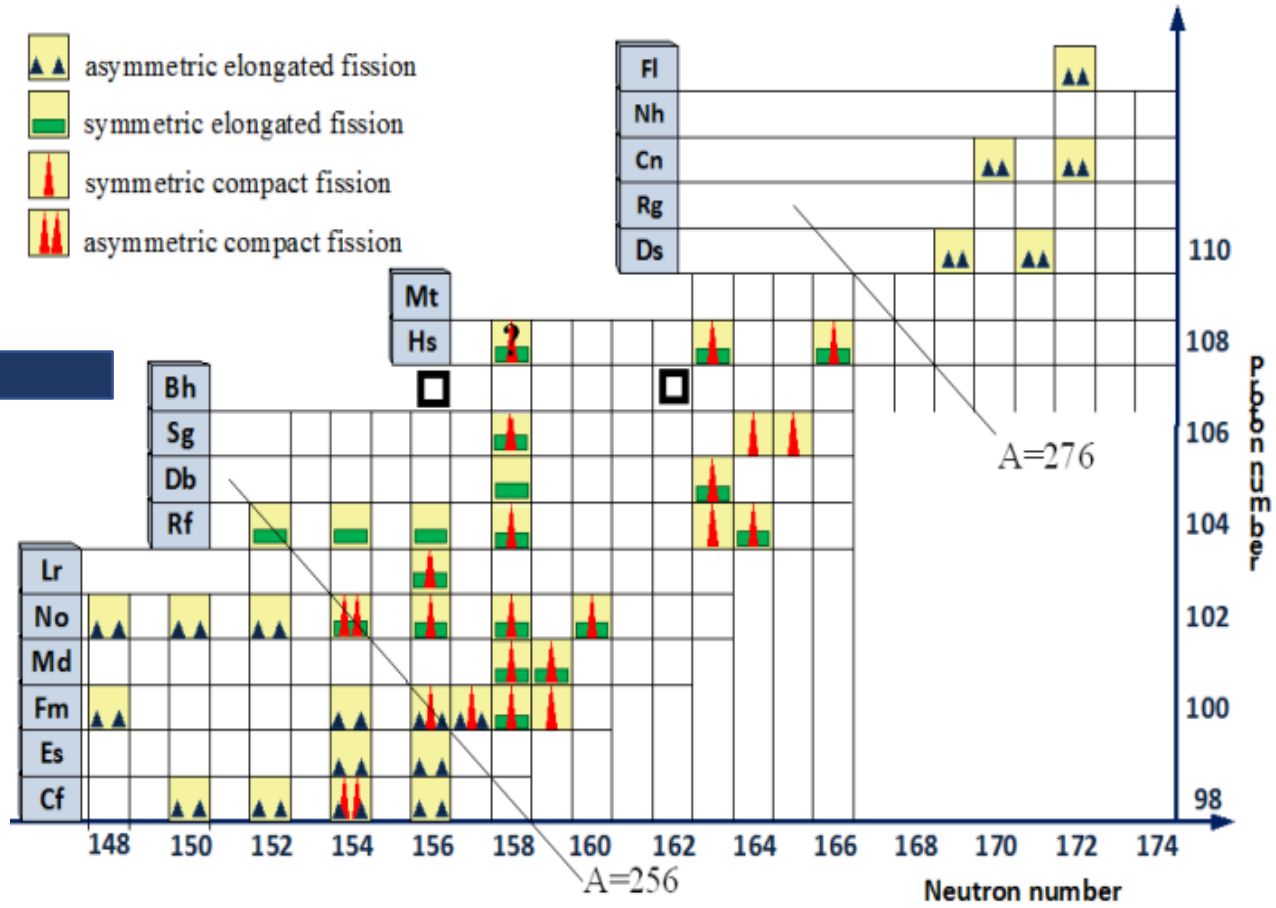


M.G. Itkis, E. Vardaci, I.M. Itkis, G.N. Knyazheva, E.M. Kozulin, Nucl. Phys. **A 944** (2015) 204

Scientific motivation

$^{54}Cr + ^{209}Bi \rightarrow ^{263}Bh$

$^{37}Cl + ^{232}Th \rightarrow ^{269}Bh$

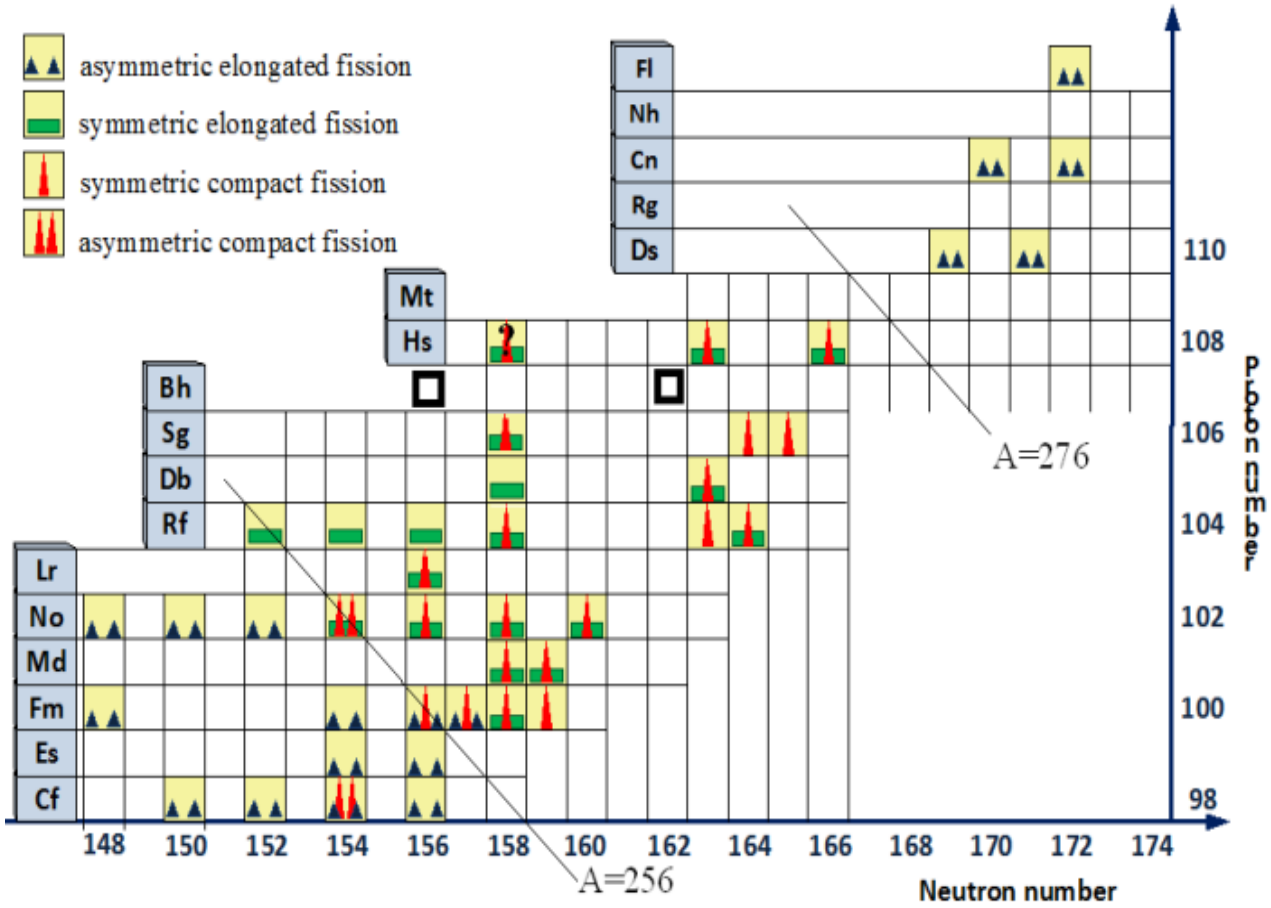


M.G. Itkis, E. Vardaci, I.M. Itkis, G.N. Knyazheva, E.M. Kozulin, Nucl. Phys. **A 944** (2015) 204

Scientific motivation

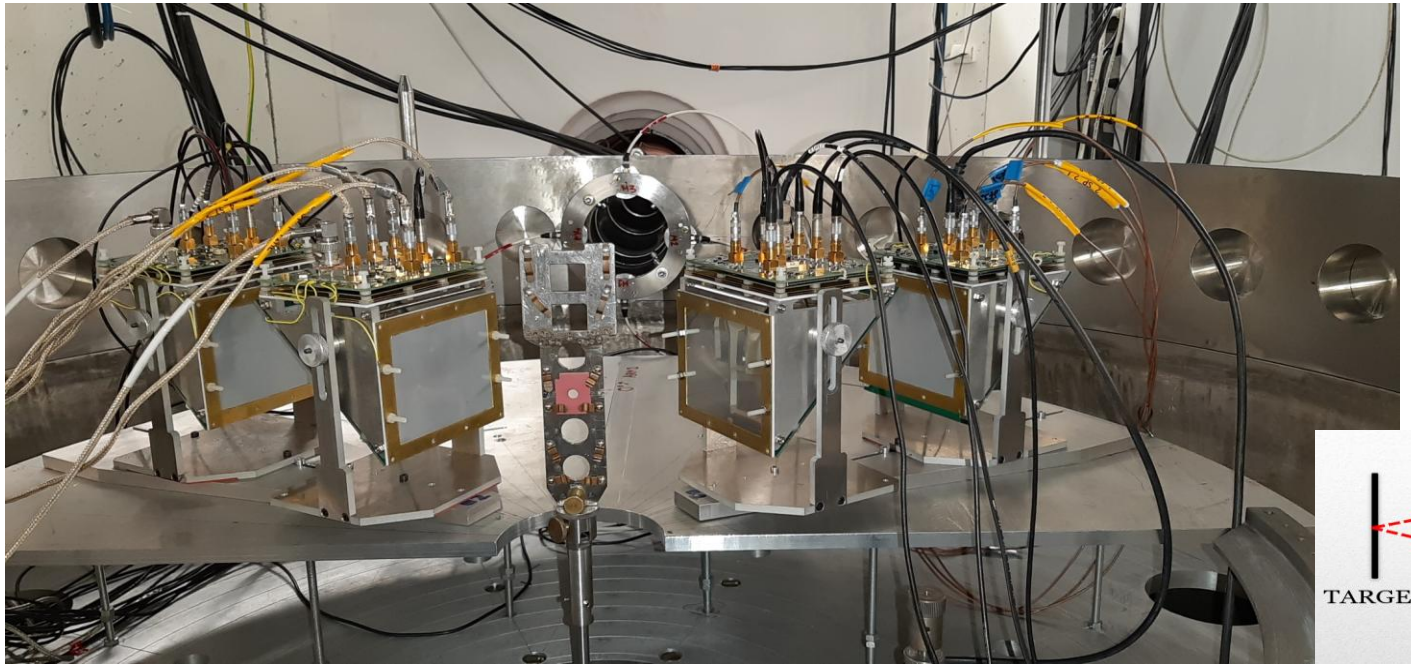
$^{54}Cr + ^{209}Bi \rightarrow ^{263}Bh$ { 15 MeV, 23 MeV, 29 MeV }

$^{37}Cl + ^{232}Th \rightarrow ^{269}Bh$ { 50 MeV, 59 MeV, 76 MeV }

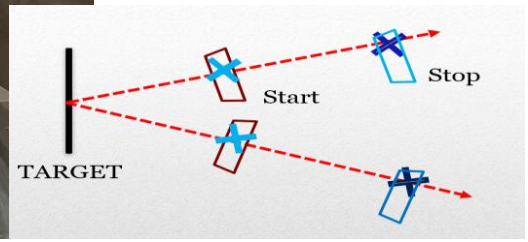


M.G. Itkis, E. Vardaci, I.M. Itkis, G.N. Knyazheva, E.M. Kozulin, Nucl. Phys. **A 944** (2015) 204

The TOF spectrometer: *T*ime *O*f flight sub-nano-second *S*pectrometer for *C*harged radiation *A*pplication (*TOSCA*)



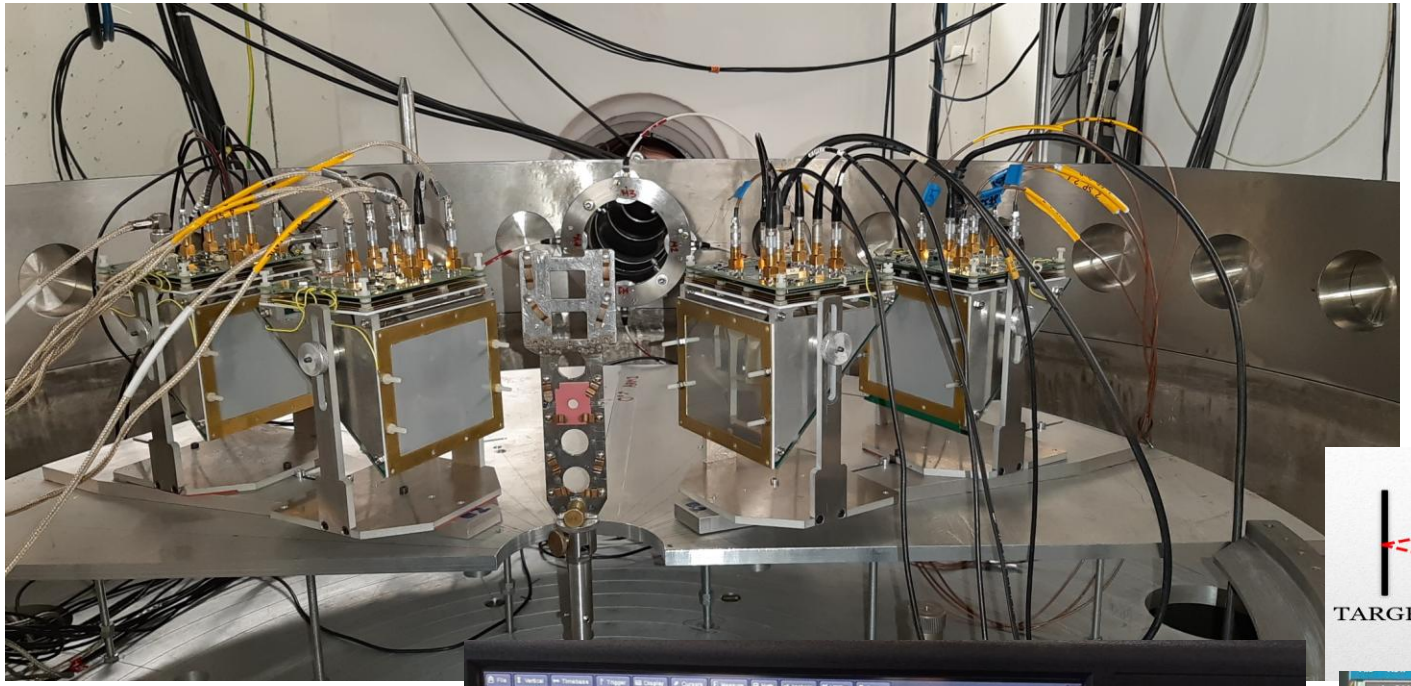
We use the two arms spectrometer to measure the velocity vectors of both fragments (ToF-2V method)



Position resolution	≈1 mm
Time resolution	≈100 ps
ToF base	≈15 cm
Solid angle	100 -200 msr
Angular resolution	0.3°
Mass resolution	2-4 u
Energy resolution	5-10 MeV

E. Vardaci et al., submitted to Nucl. Instr. Methods A

The TOF spectrometer: Time Of flight sub-nano-second Spectrometer for Charged radiation Application (TOSCA)



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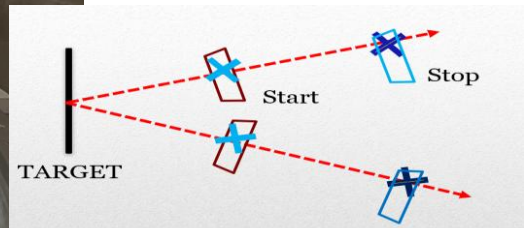

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Solid angle	100 -200 msr
Angular resolution	0.3°
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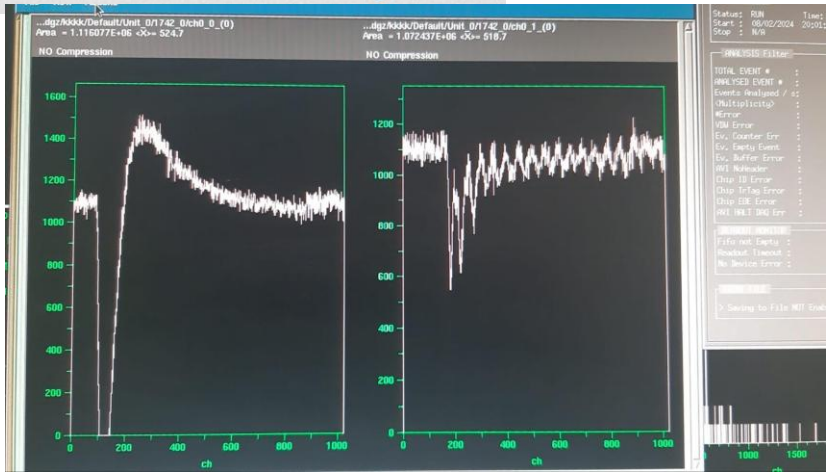
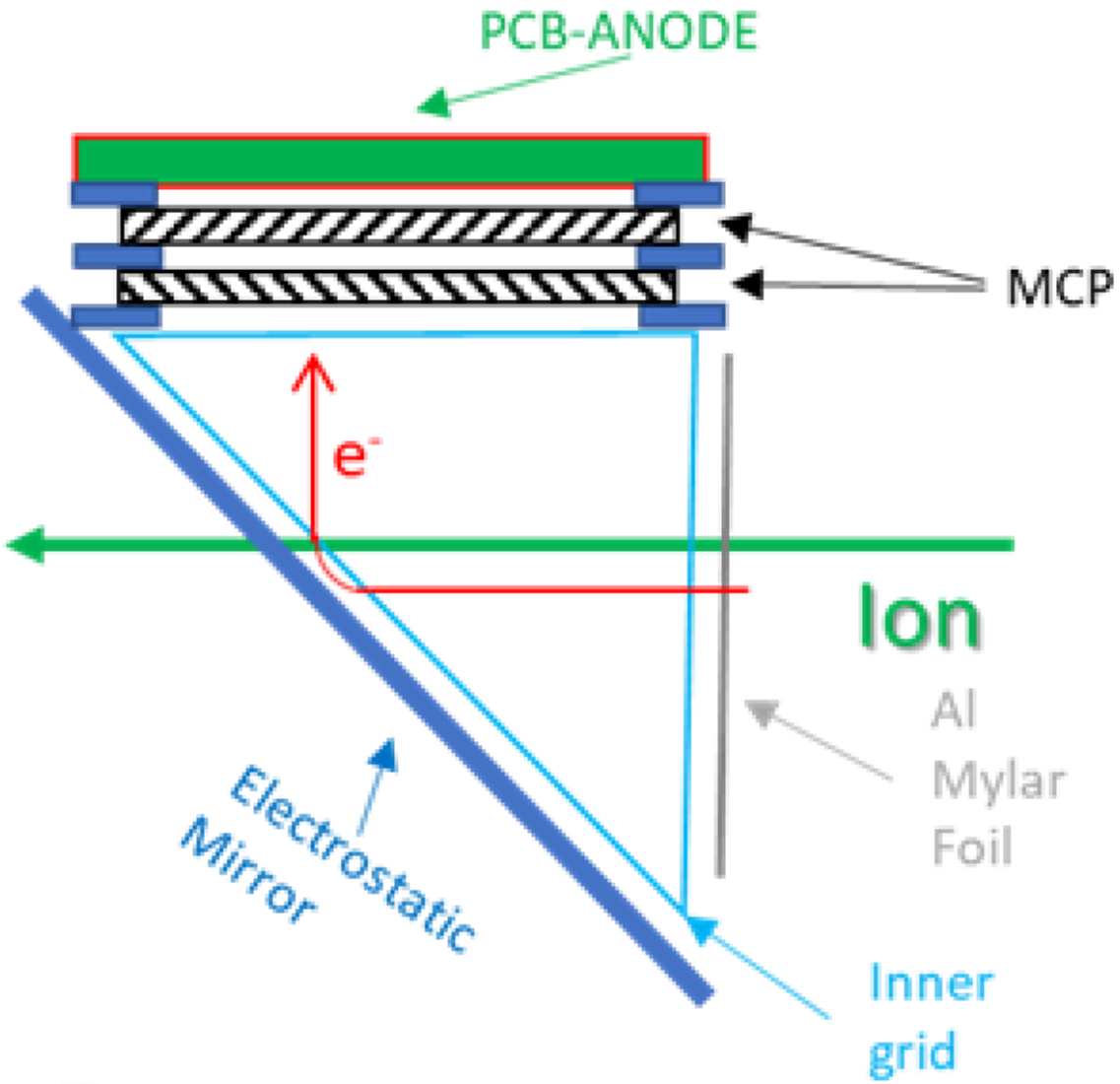
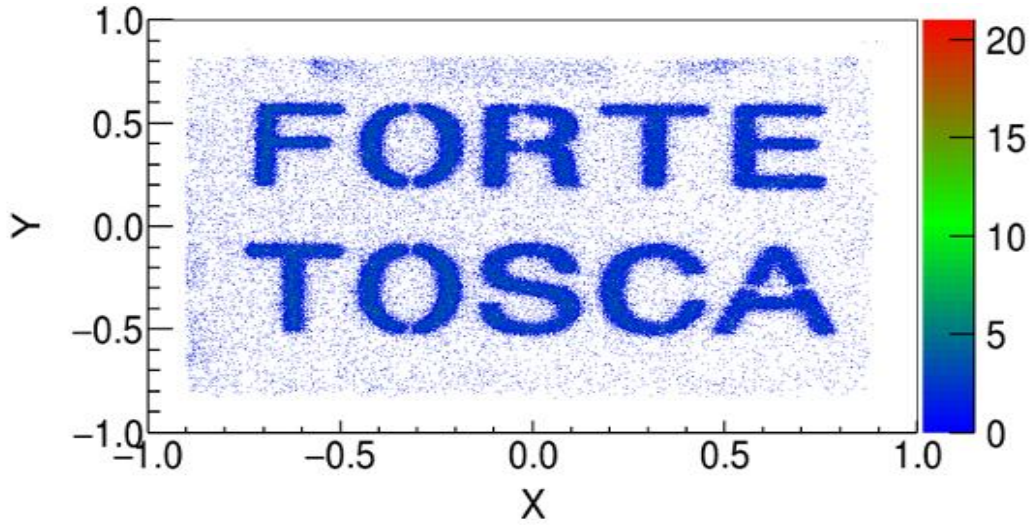
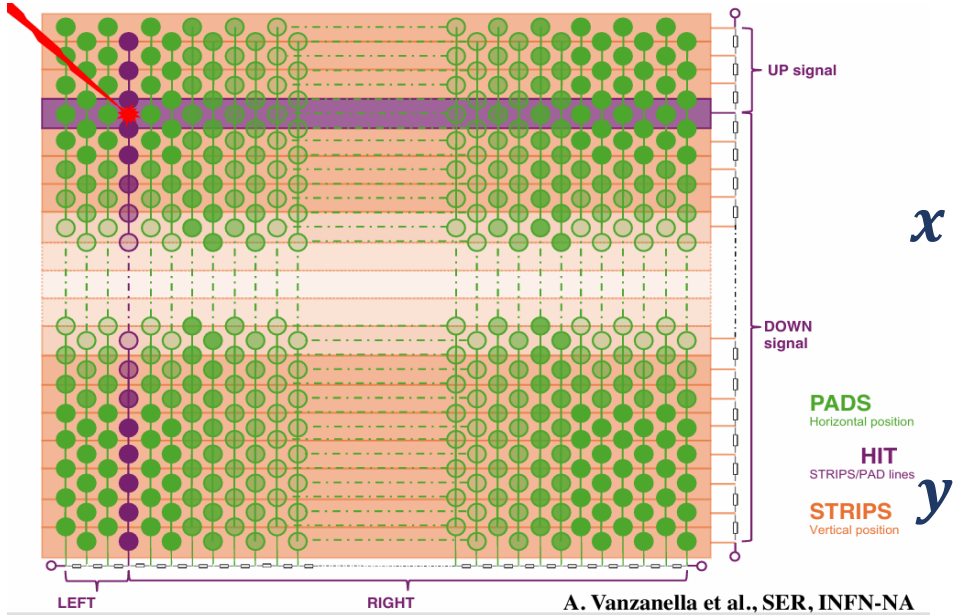
For each arm two time signals are recorded: START and STOP



Working mechanism of TOSCA unit



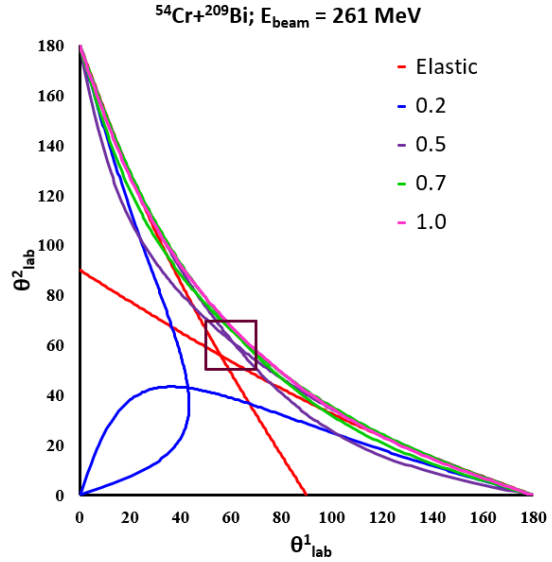


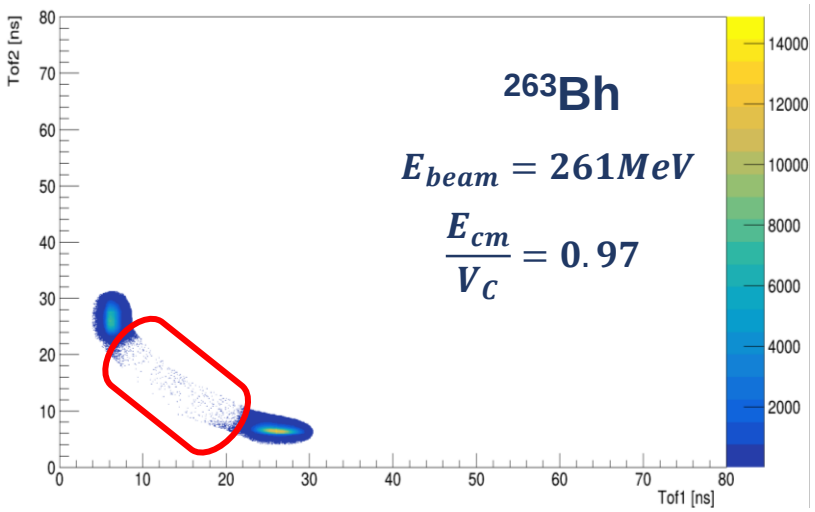


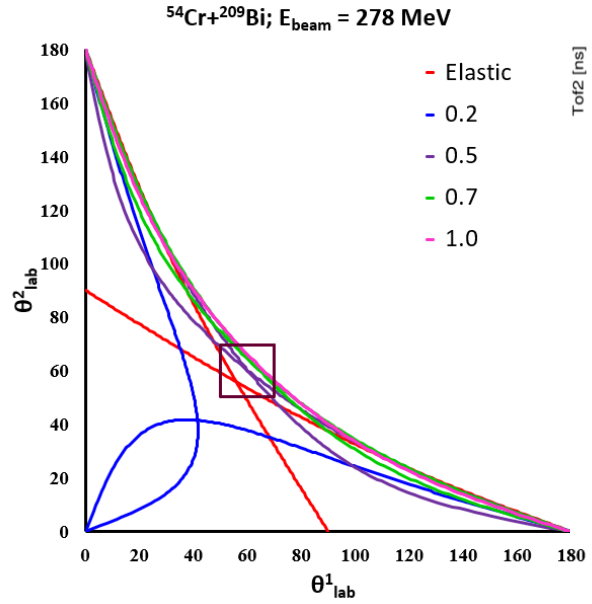
$$x = \frac{Q_R - Q_L}{Q_R + Q_L}$$

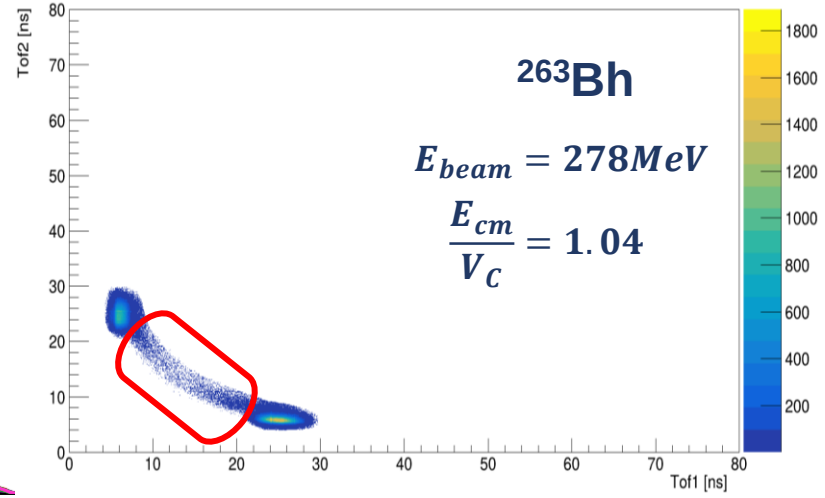
$$y = \frac{Q_T - Q_B}{Q_T + Q_B}$$

$^{54}Cr + ^{209}Bi \rightarrow ^{263}Bh$









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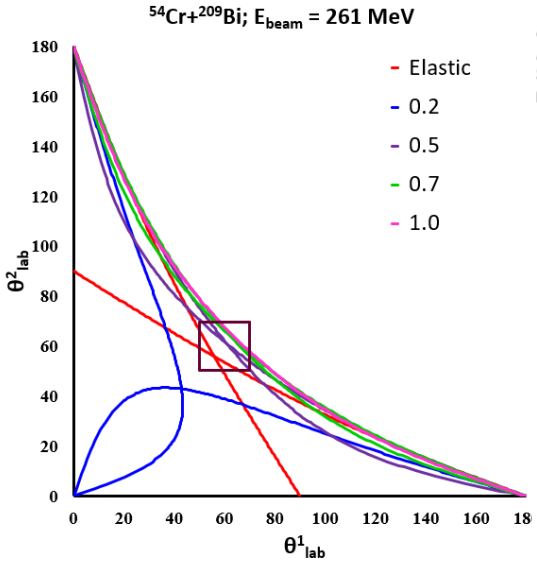
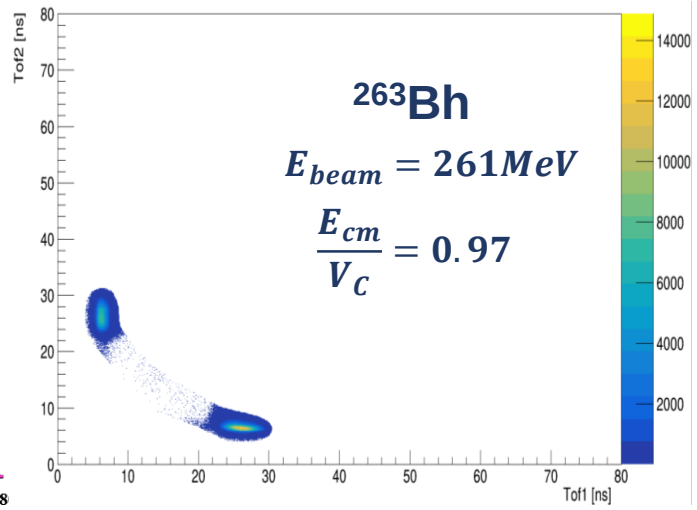
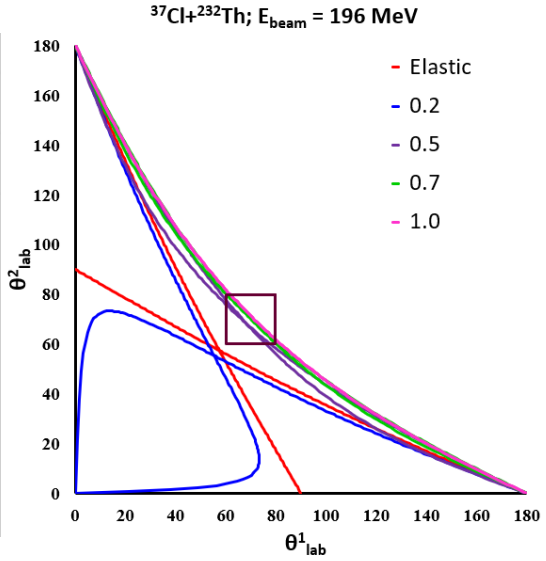
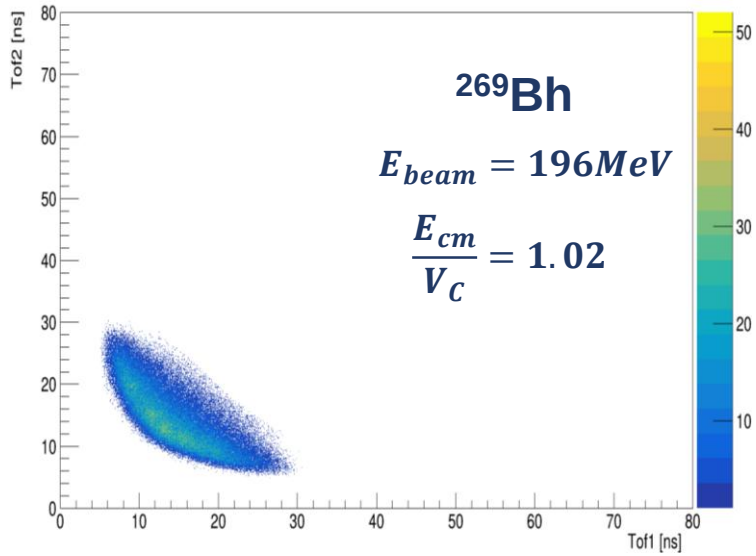
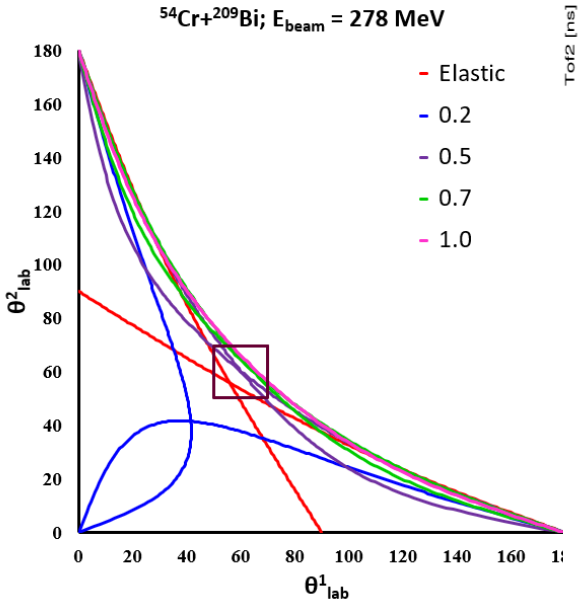
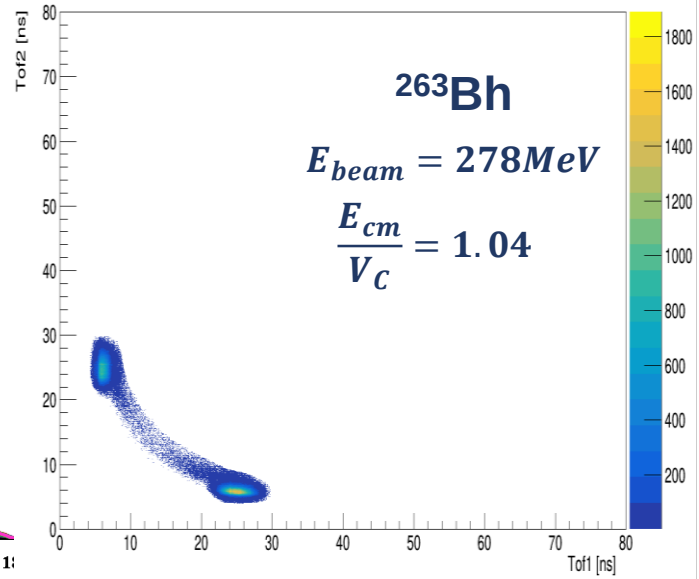


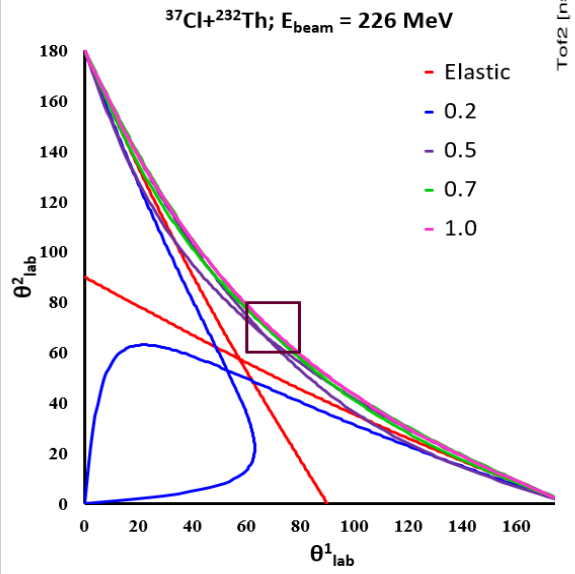


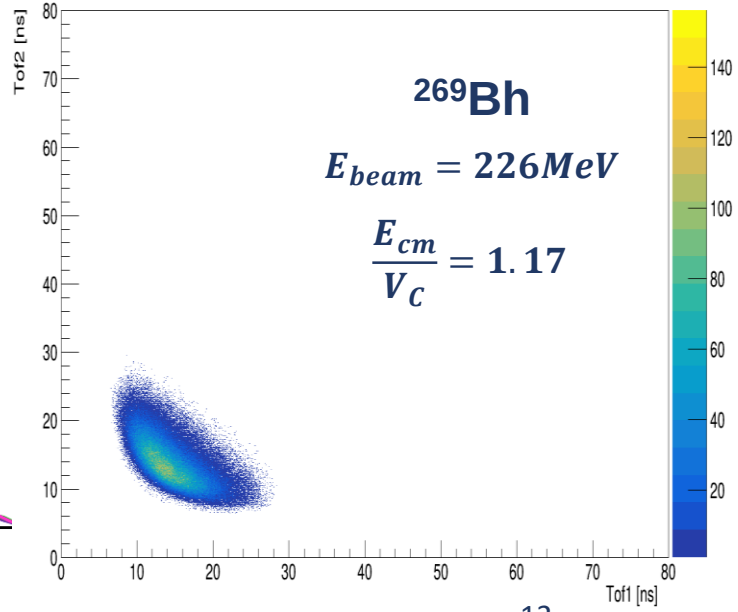




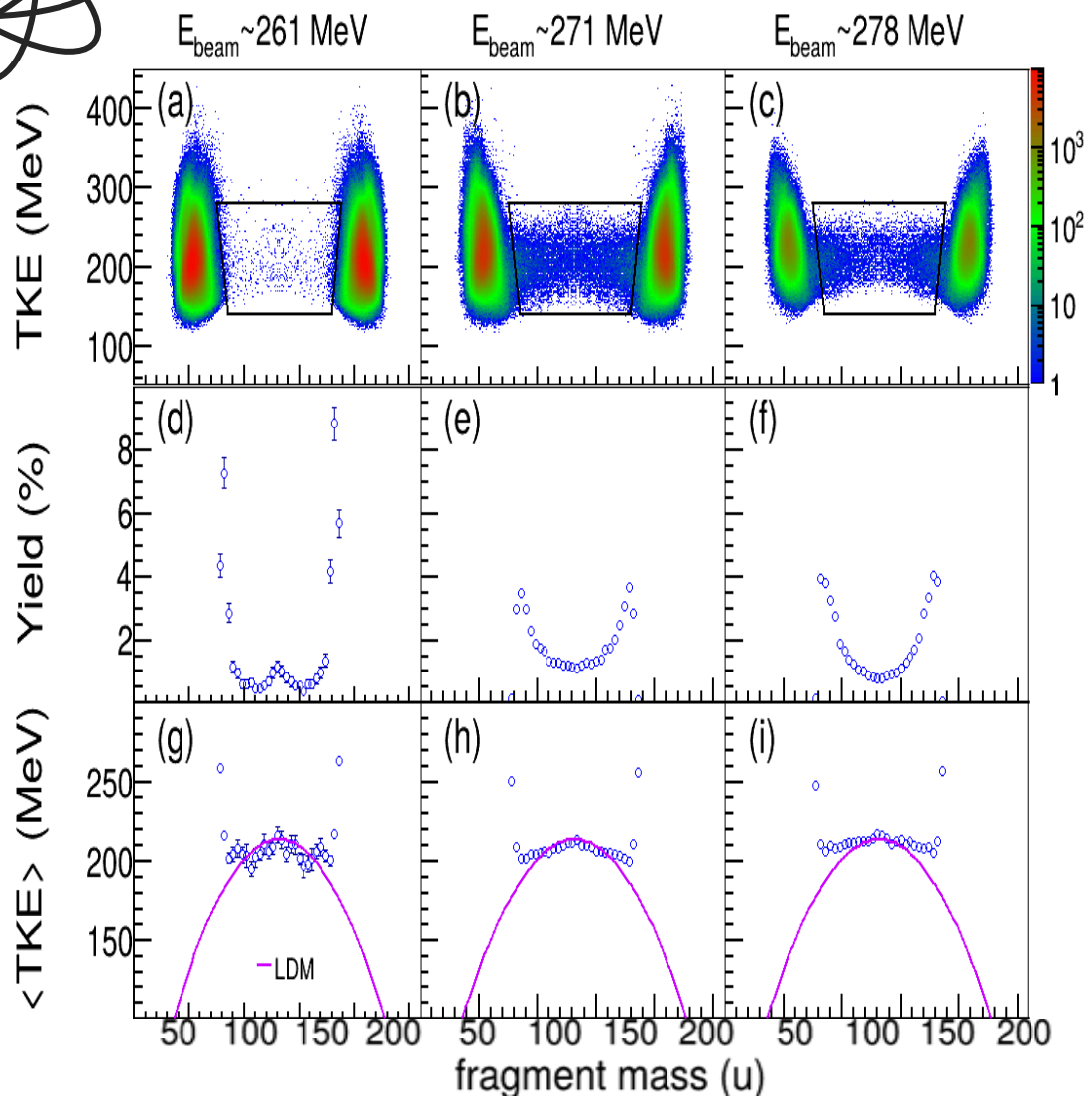




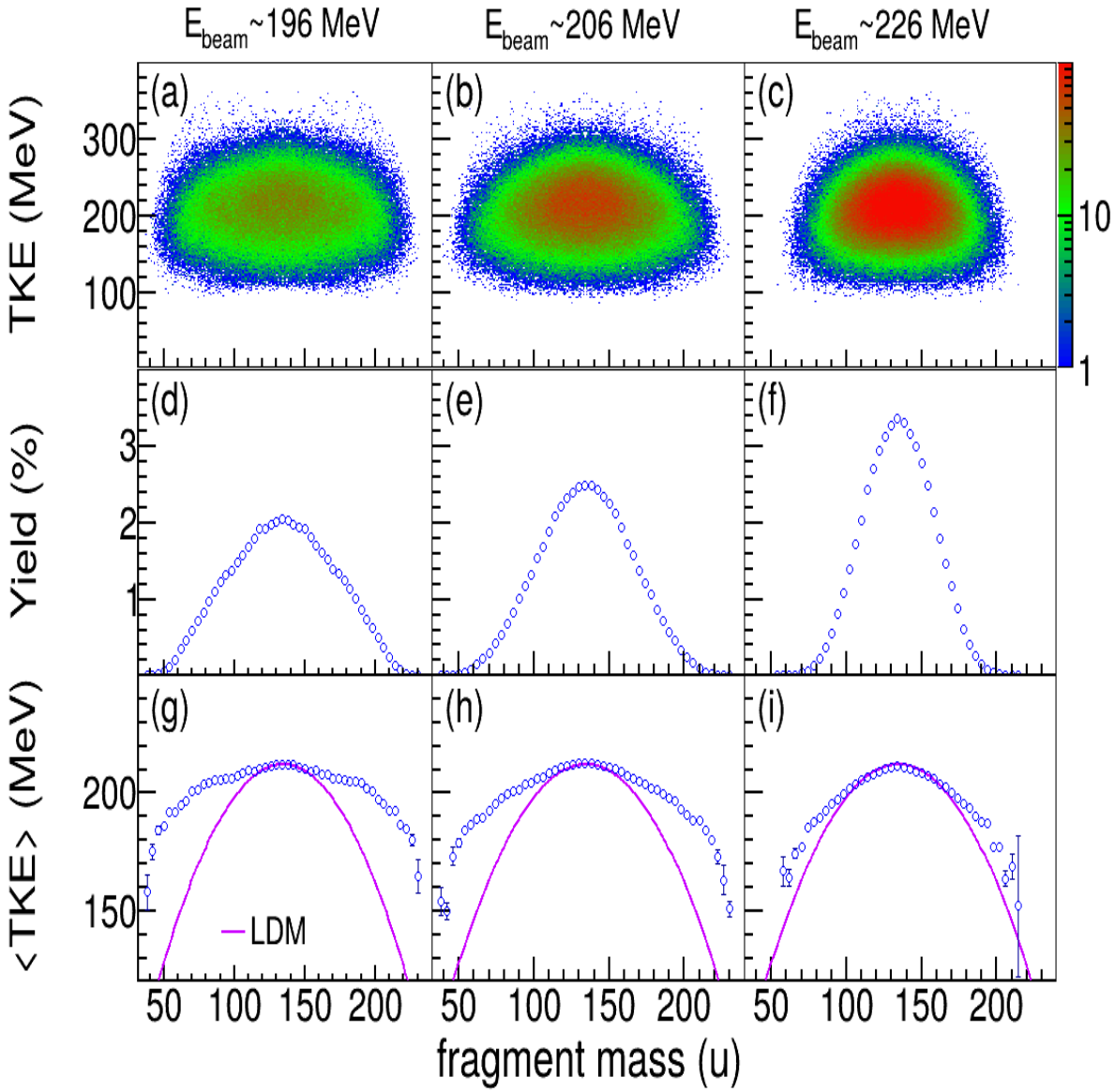




^{263}Bh experimental results



^{269}Bh experimental results



These results are obtained in collaboration with **Dr. T. Banerjee**

How can we constrain the fusion-fission component?

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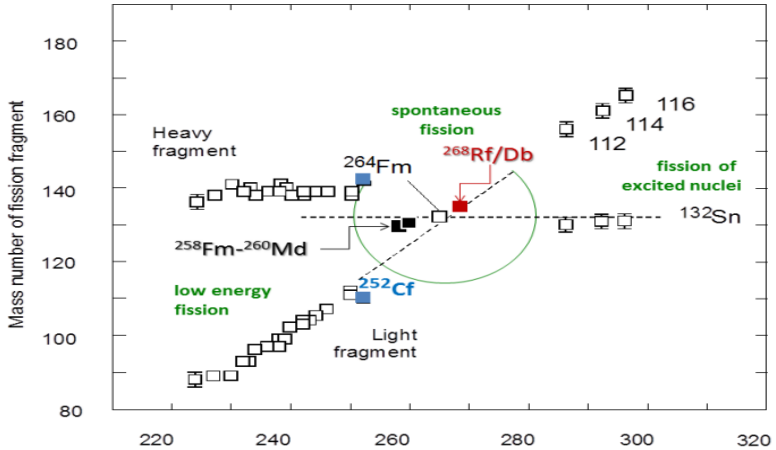
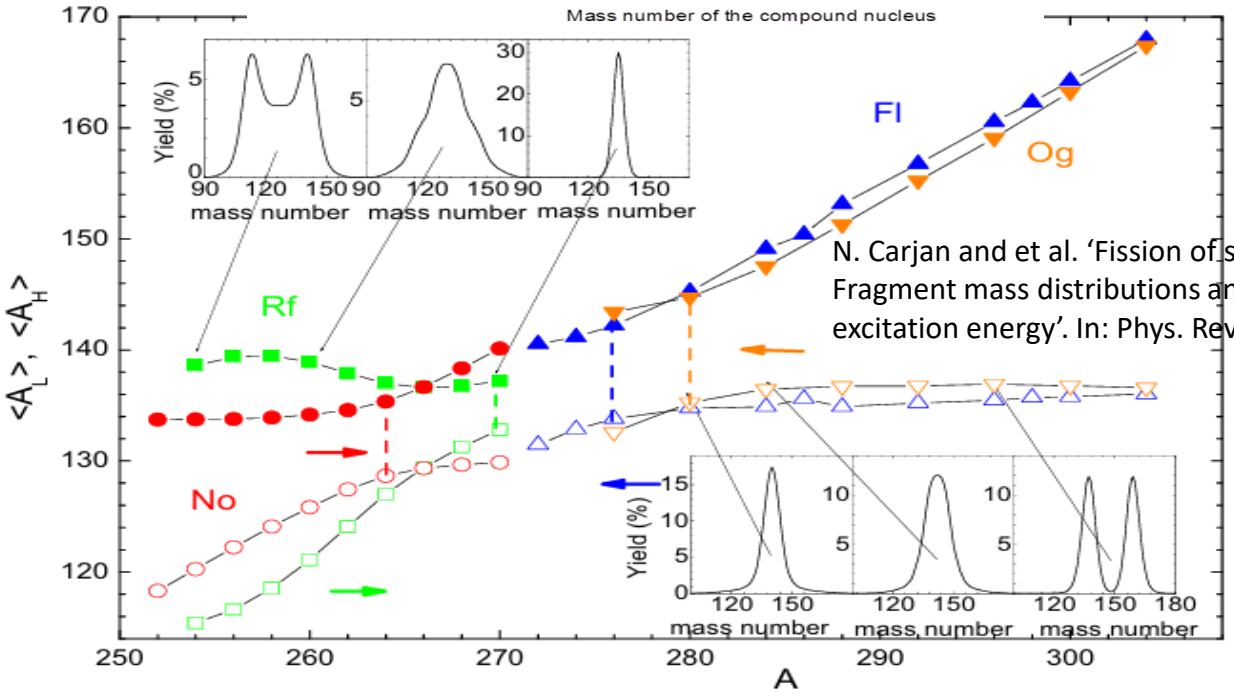
…using a model

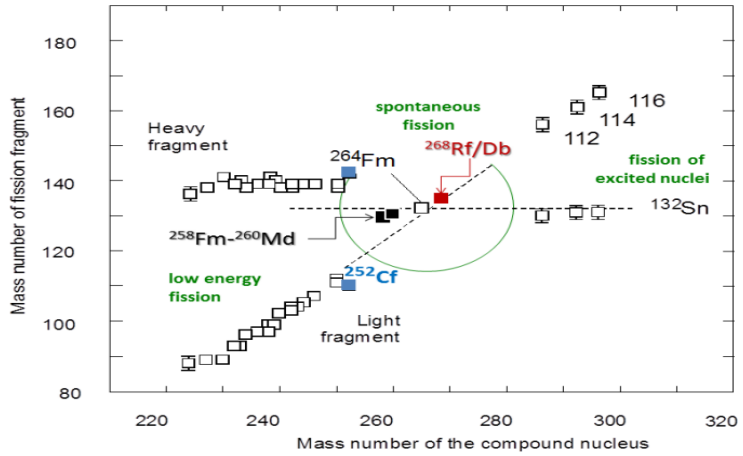
Macro-Micro approach

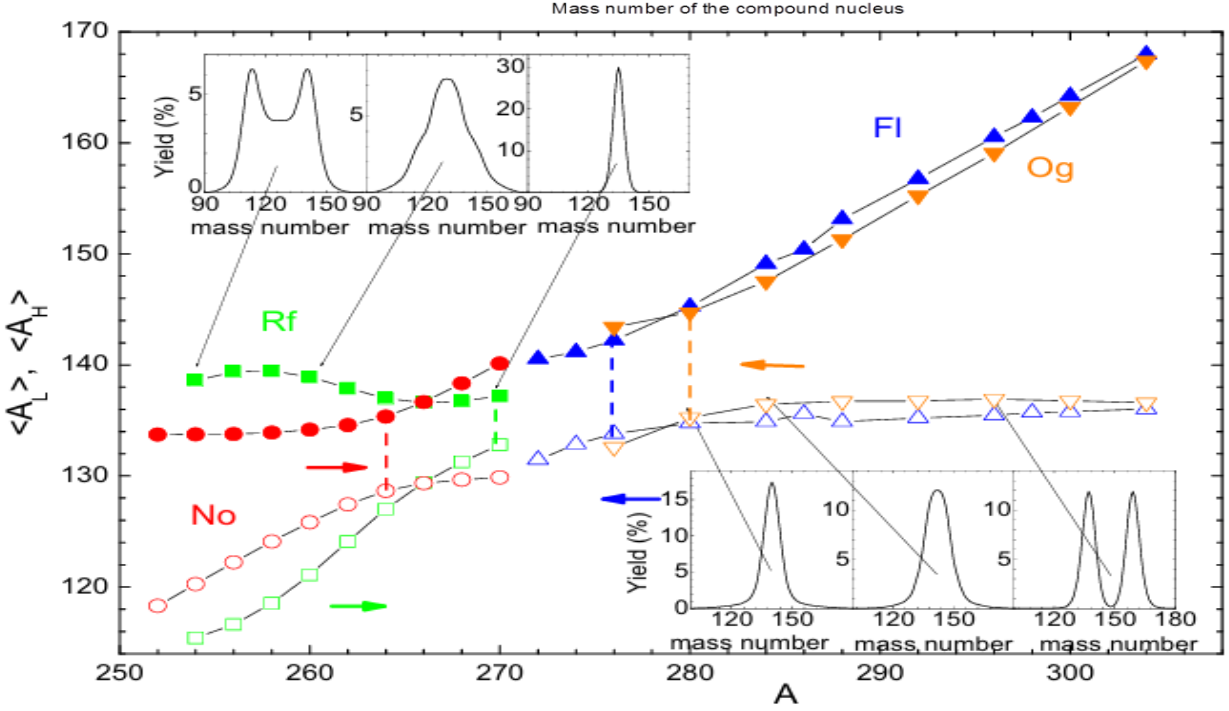




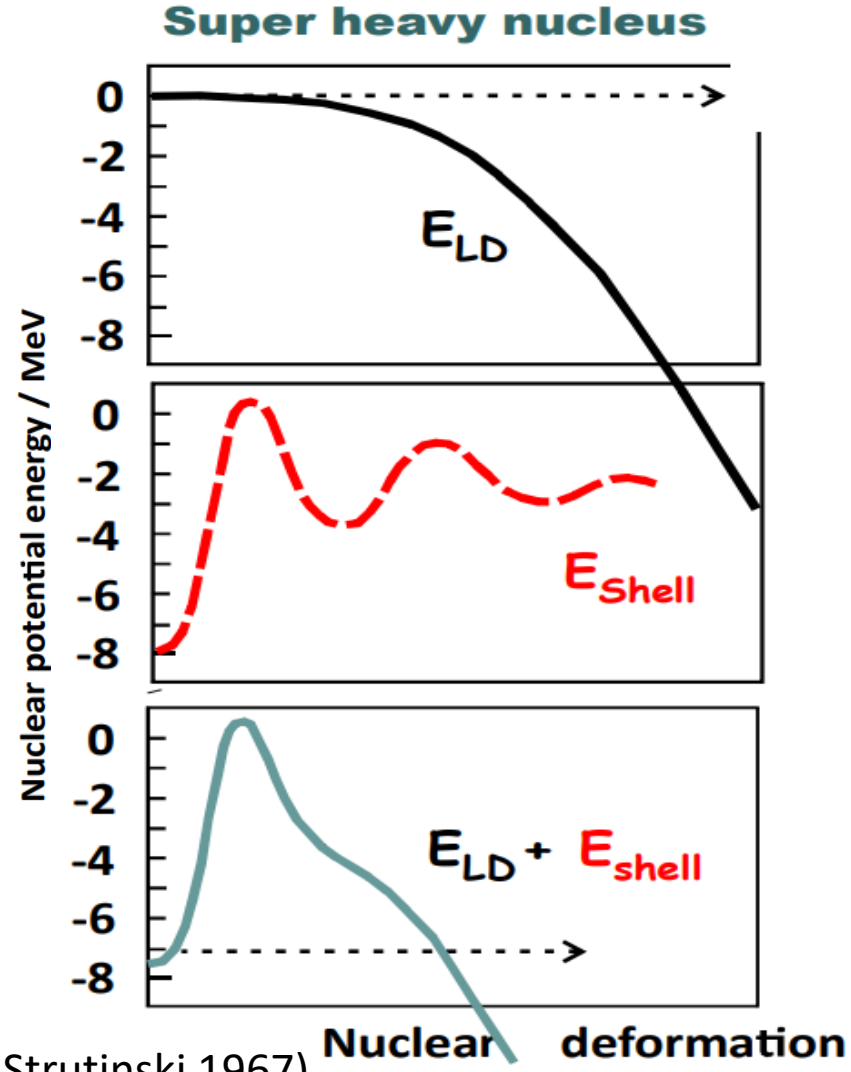
N. Carjan and et al. 'Fission of superheavy nuclei: Fragment mass distributions and their dependence on excitation energy'. In: Phys. Rev. C 99, 064606 (2019)

Macro-Micro approach





$$E_{def}(shape) = E_{def}{}^{LDM}(shape) + \delta E(shape)$$

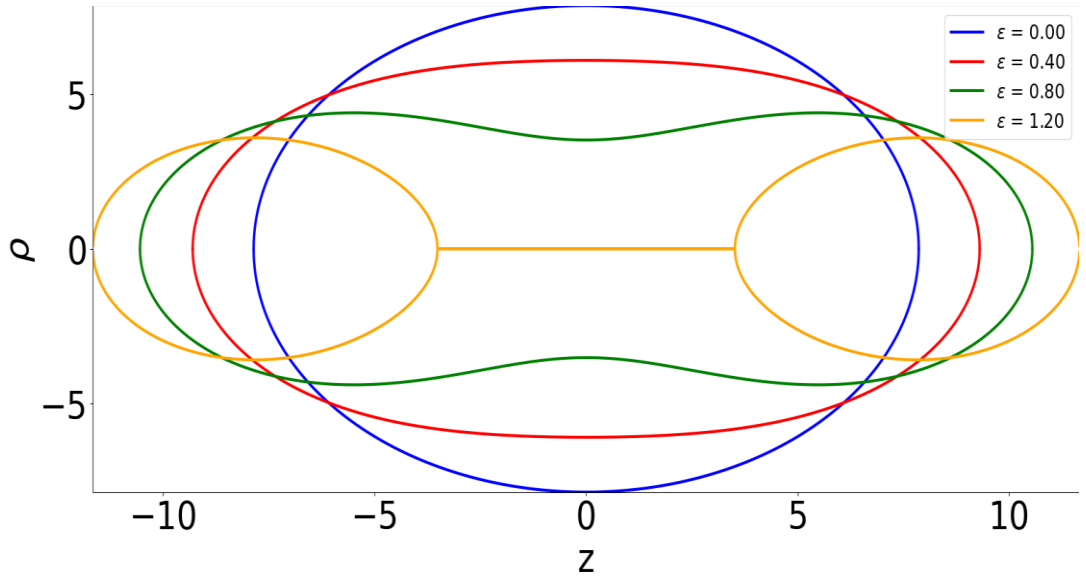


(V.M. Strutinski 1967)

Nuclear shape at scission point

$$R(x) = R_0\left[1 + \sum_n \alpha_n P_n(x)\right]$$

- R_0 is the Cassini oval
- α_n shape's parameters
- P_n Legendre polynomials



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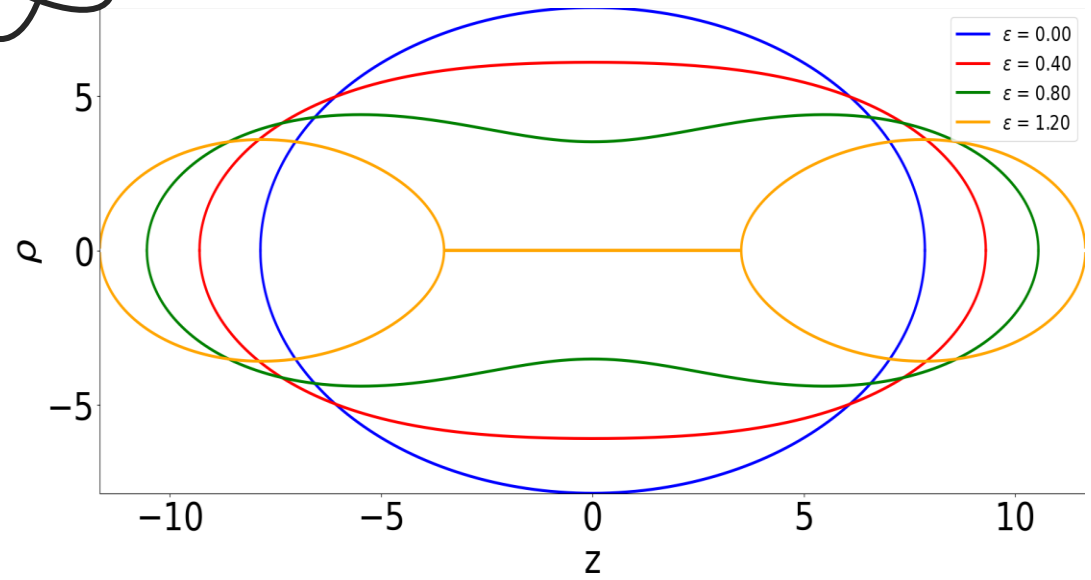

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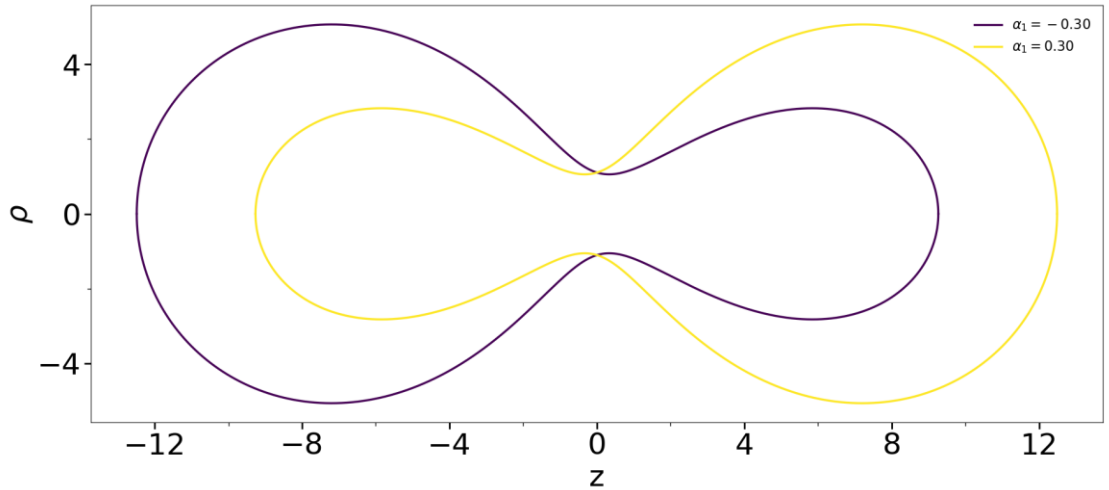
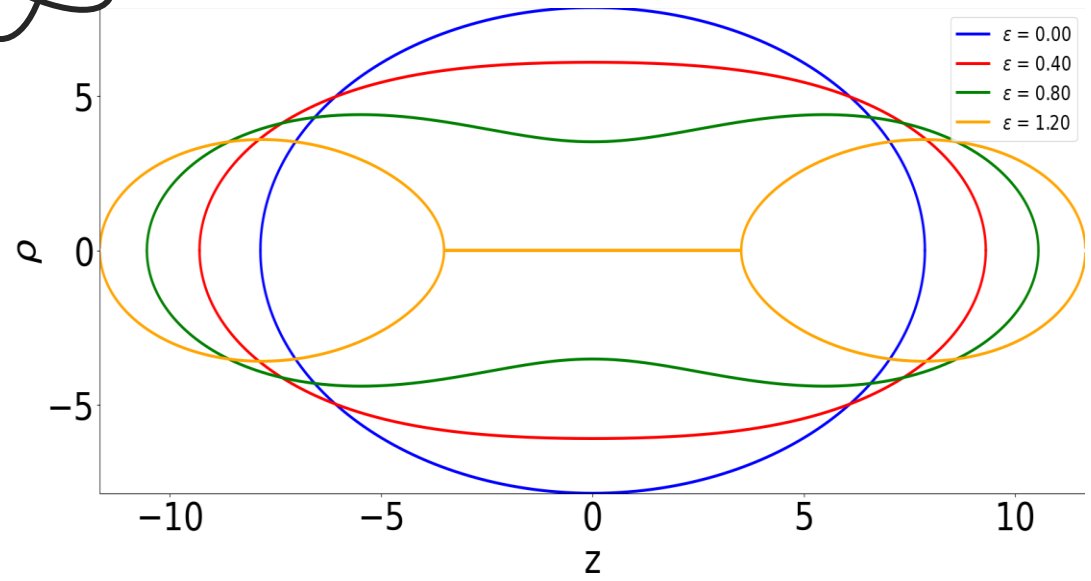


- α_1 means the left-right asymmetry
- α_3 gives different elongation to the fragment
- α_4 acts likes a quadrupole deformation
- α_6 creates small oscillation around deformed shape

Nuclear shape at scission point



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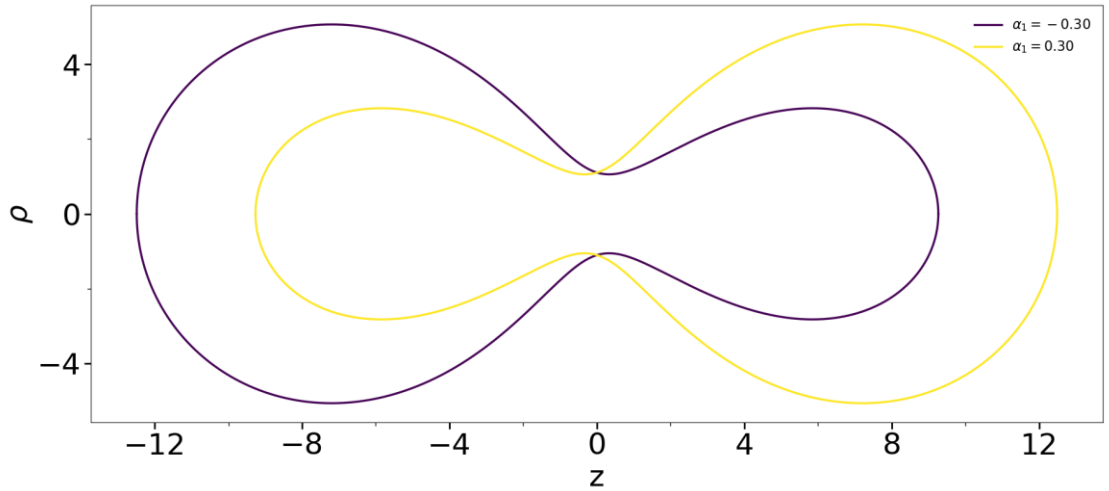
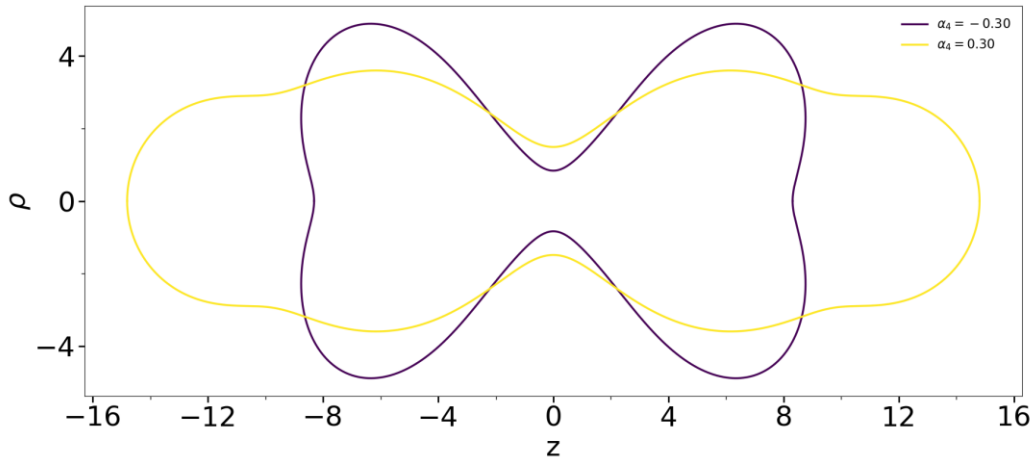
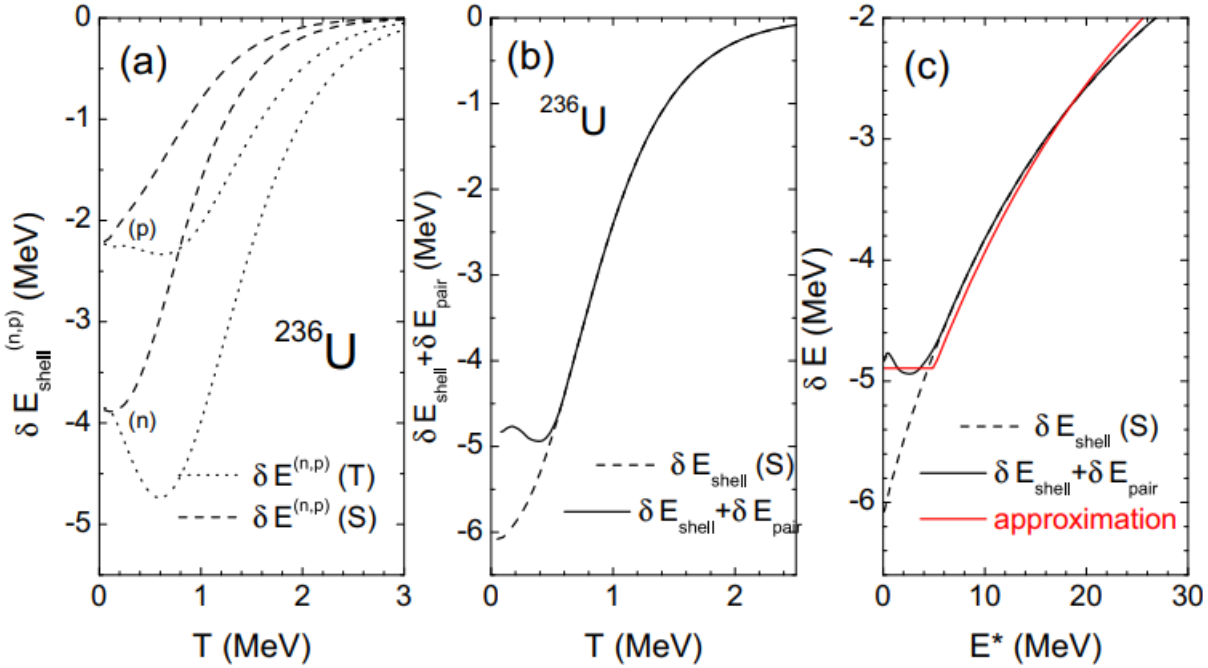




How can we describe the scission process when nuclei have no zero excitation energy and angular momentum?

SAF description in heavy-ions induced reaction



$$\delta E = E - \tilde{E}$$

$$E^* = aT^2$$

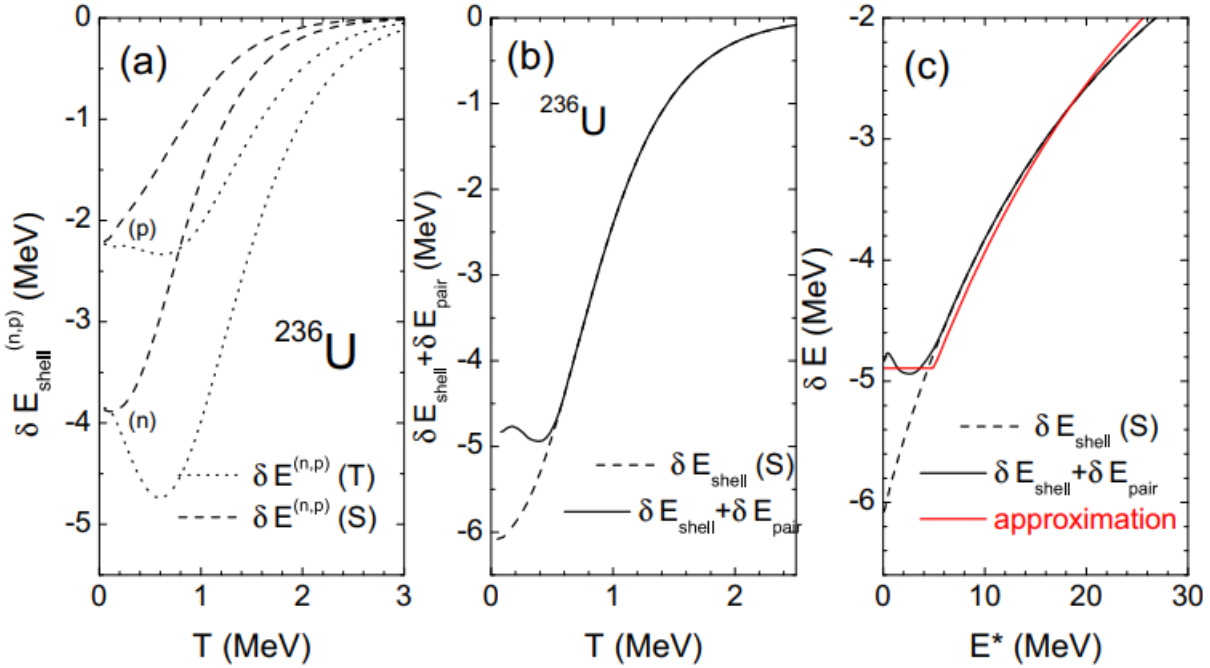
$$\{E^*\} \rightarrow \{T\} \qquad \delta E(T) = E(T) - \tilde{E}(T)$$

$$\delta E(S) = E[T(S)] - \tilde{E}[T(S)]$$

$$\delta E(E^*) = \begin{cases} \delta E(0) & if \ \left|\delta E(0) e^{-E^*/E_d}\right| \geq |\delta E(0)| \\ \delta E(0) e^{-E^*/E_d} & if \ \left|\delta E(0) e^{-E^*/E_d}\right| < |\delta E(0)| \end{cases}$$

N. Carjan and et al. 'Fission of superheavy nuclei: Fragment mass distributions and their dependence on excitation energy'. In: Phys. Rev. C 99, 064606 (2019)

SAF description in heavy-ions induced reaction



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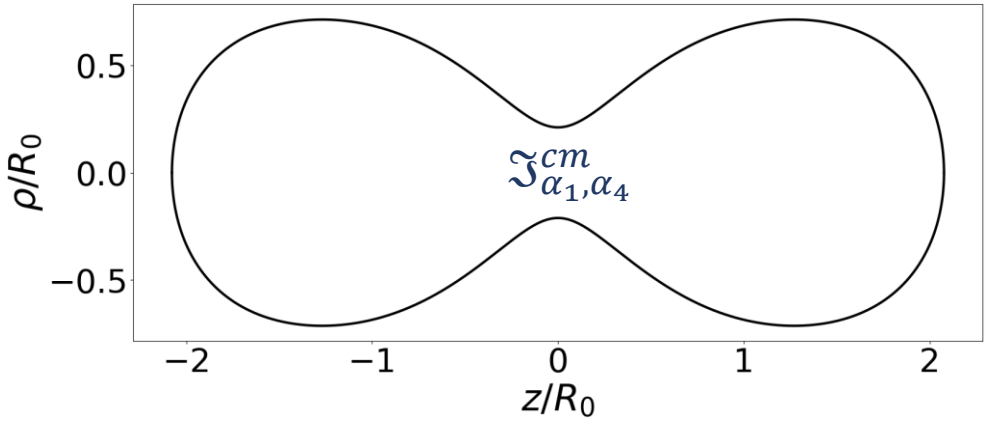
N. Carjan and et al. 'Fission of superheavy nuclei: Fragment mass distributions and their dependence on excitation energy'. In: Phys. Rev. C 99, 064606 (2019)

$$H = T + V(\vec{r}) + V_{s-o} + V_{coul}$$

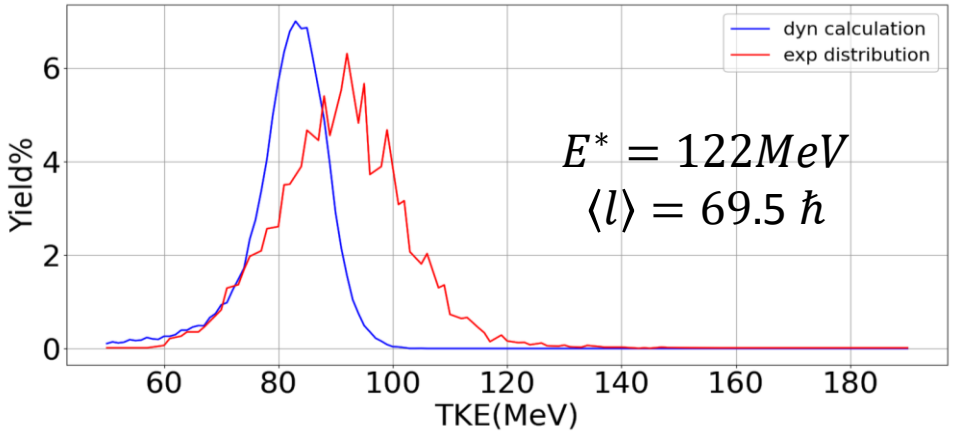
Damgaard, J. et al., A method for solving the independent-particle Schrödinger equation with a deformed average field, Nuclear Physics A135 (1969) 432 444

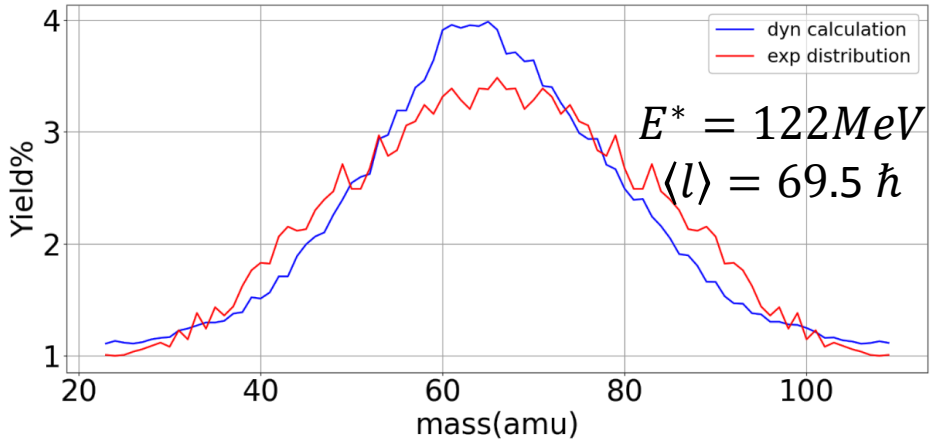
$$E^{rot}_{\alpha_1,\alpha_4} = \frac{\langle l_{FF}\rangle(\langle l_{FF}\rangle + 1)\hbar^2}{2\Im^{cm}_{\alpha_1,\alpha_4}}$$

$$\Im^{cm}_{\alpha_1,\alpha_4} = \Im^{0}_{\alpha_1,\alpha_4} + MD_{\alpha_1,\alpha_4}$$

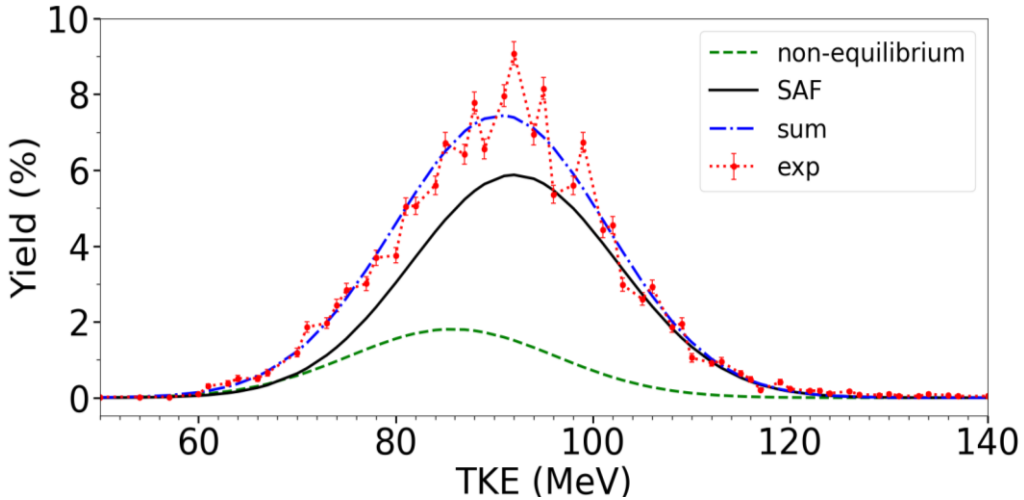


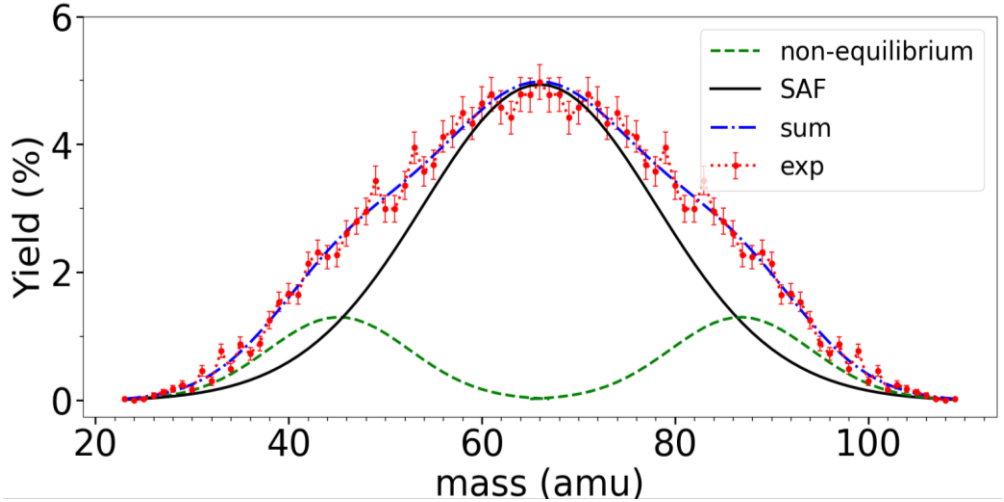
Validation and benchmark of SAF with an Intermediate fissility system: ^{132}Ce





E. Vardaci, P. N. Nadtochy, A. Di Nitto, et al., Phys Rev. C 92, 034610 (2015)





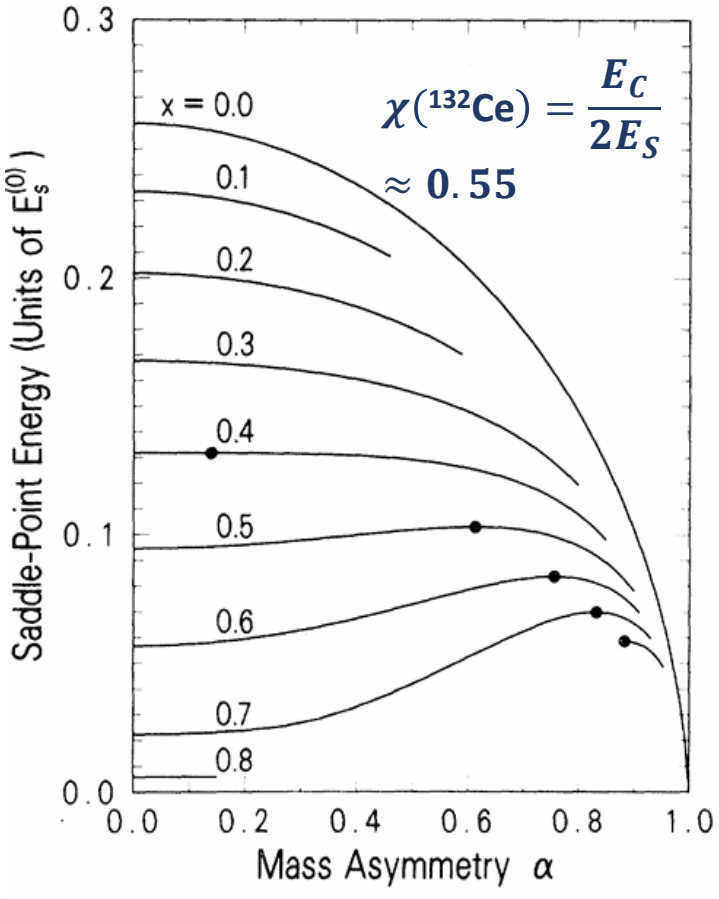
$\langle TKE \rangle_{non-eq.} = 86.46\ MeV$

$\langle m \rangle_{non-eq.} = 45 - 87\ amu$

P. A. Setaro et al., Fission decay of 132Ce with an improved stationary approach, PRC 113, 024613 (2026)

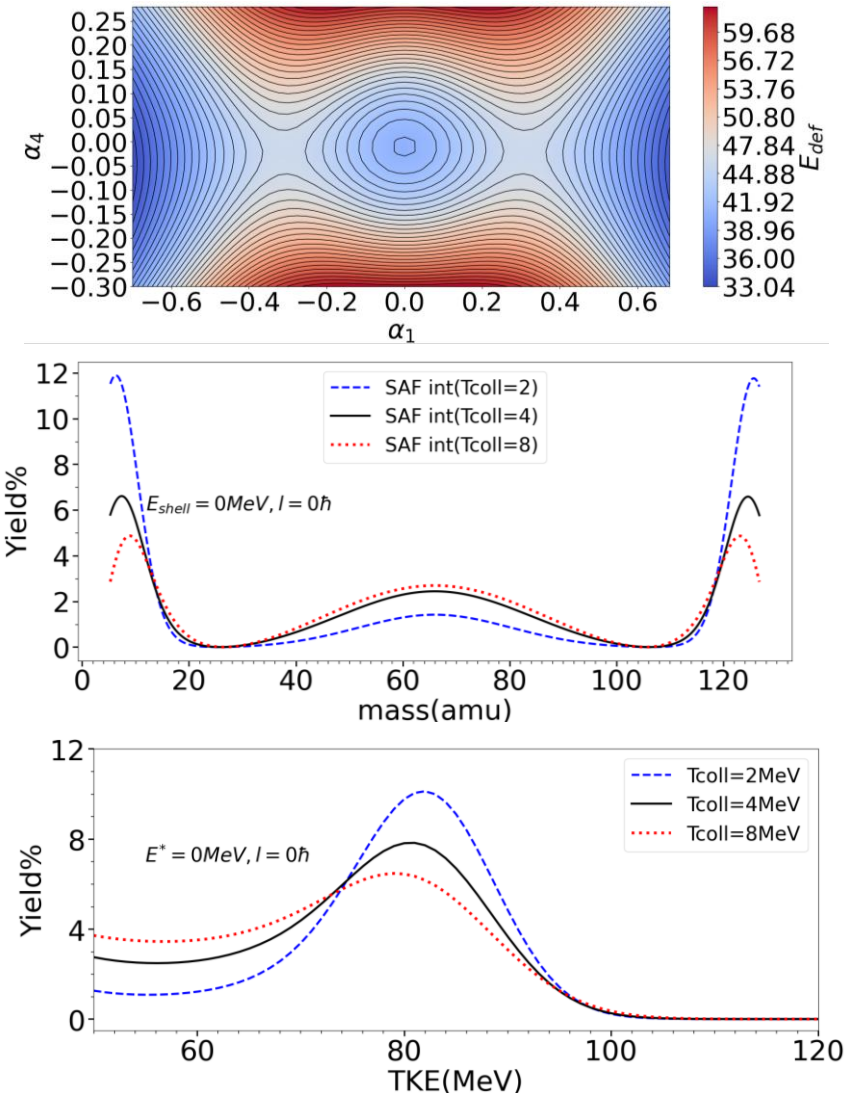
Businaro-Gallone transition

Arnold. J. Sierk. 'Mass-Asymmetric Fission of Light Nuclei'. In: Phys. Rev. Lett. 55, 582 (1985)

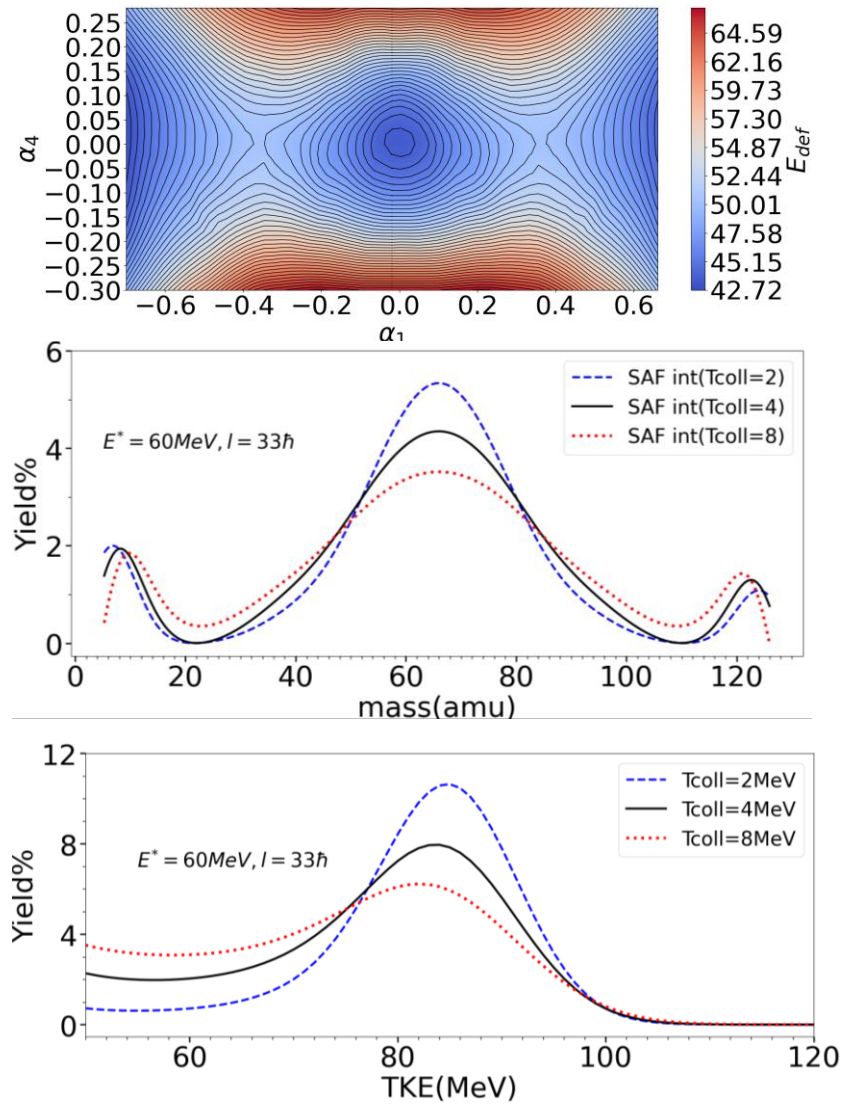


- **Solid points = BG points**

$E^* = 0\ MeV, l = 0\ \hbar$



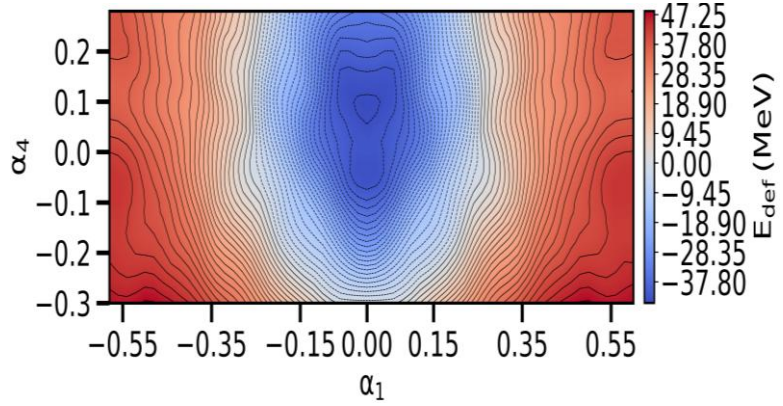
$E^* = 60, MeV, l = 33\ \hbar$

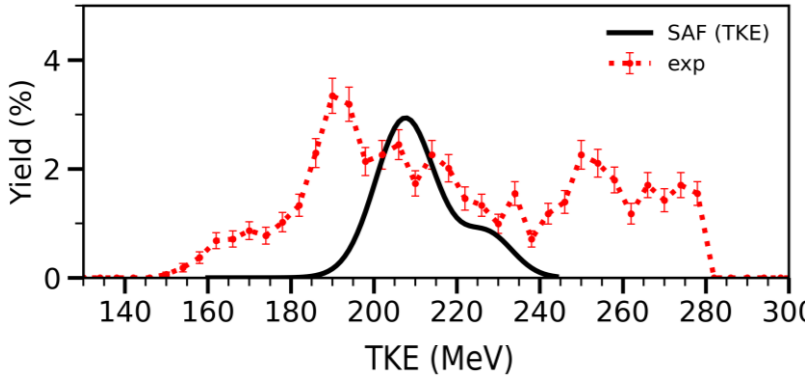


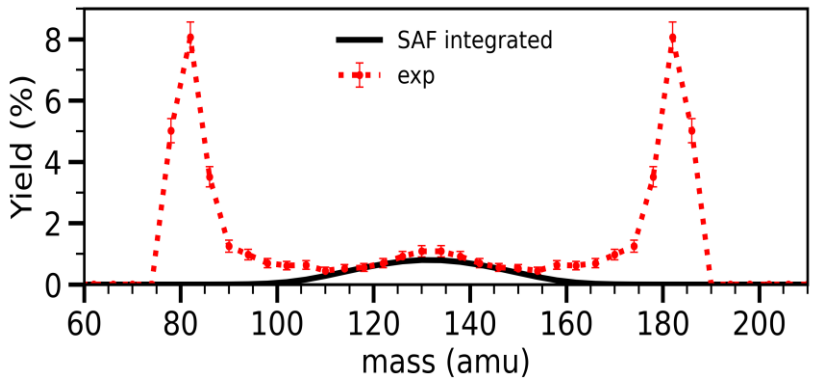
P. A. Setaro et al., Fission decay of 132Ce with an improved stationary approach, PRC 113, 024613 (2026)

Study of ^{263}Bh

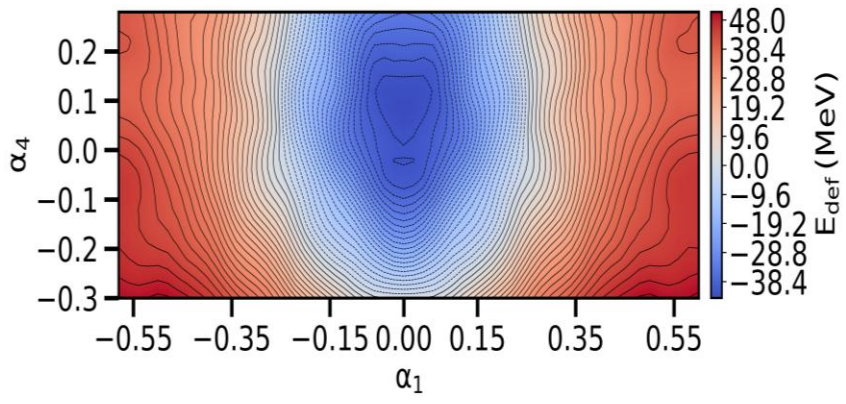
$E^* = 15\ MeV$

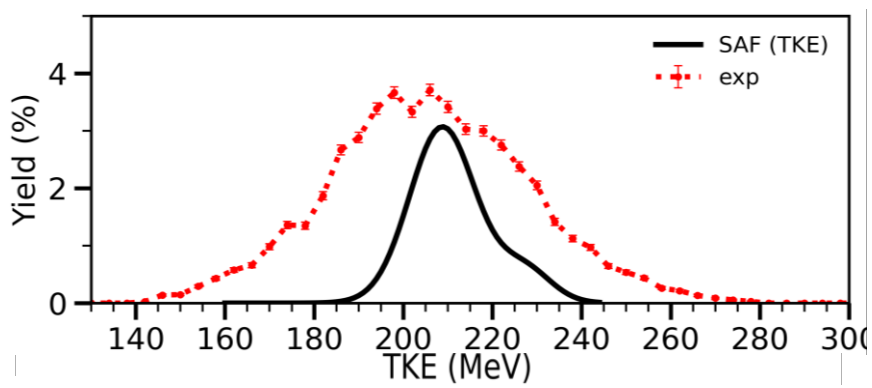


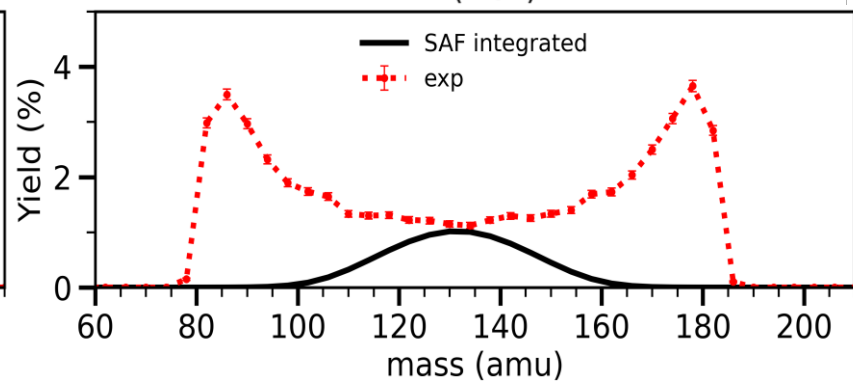




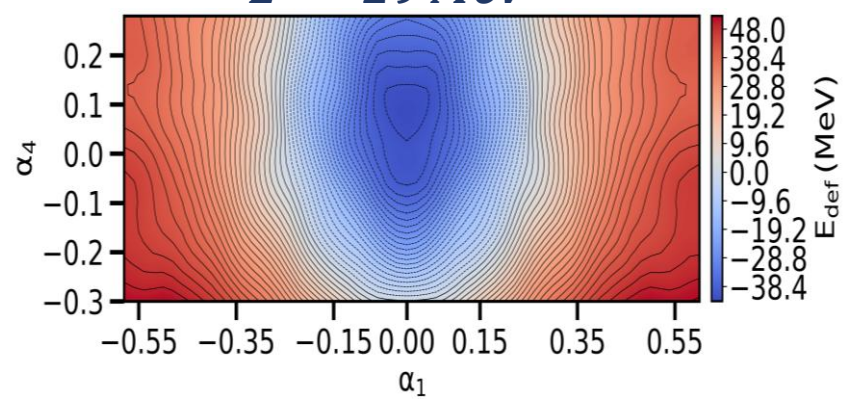
$E^* = 23\ MeV$

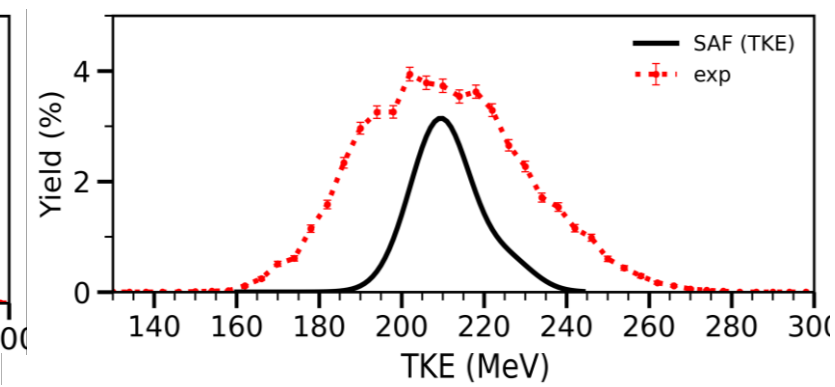


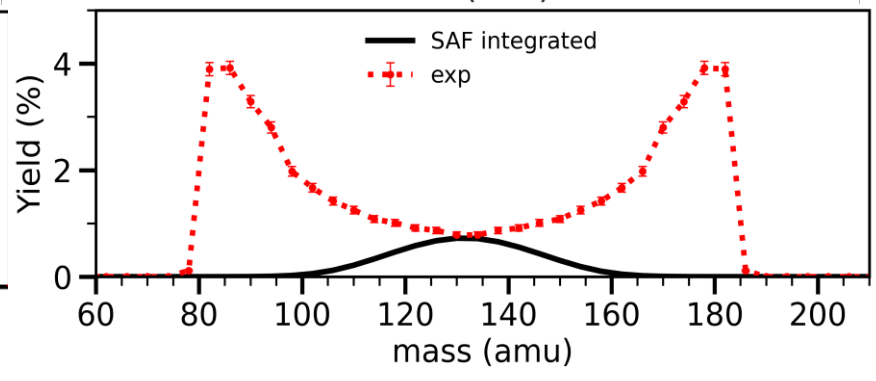




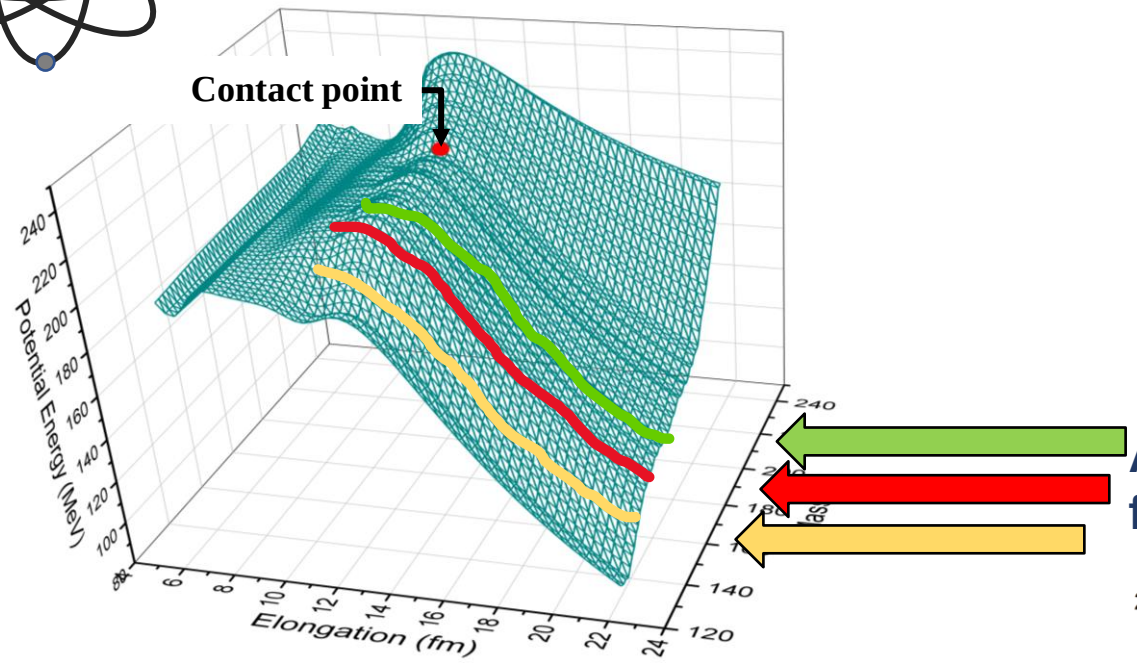
$E^* = 29\ MeV$







Investigation of possible additional contributions for ^{263}Bh



Asymmetric quasi-fission

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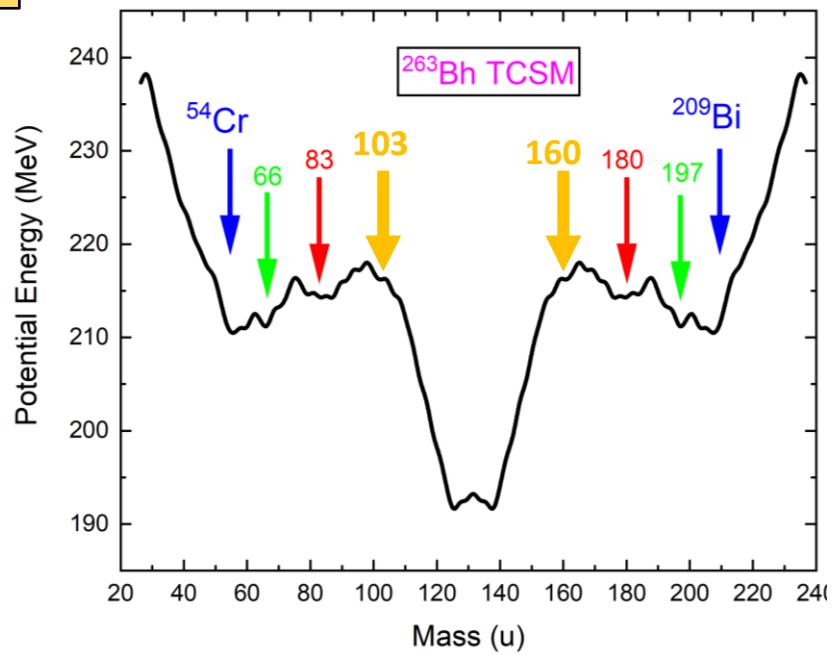
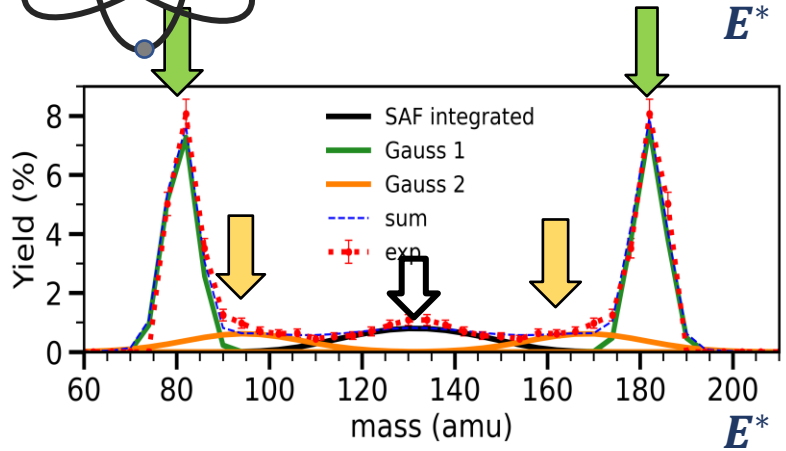
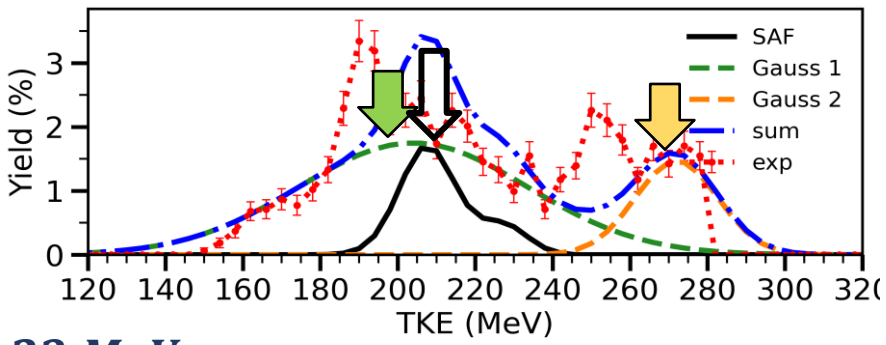


Search for additional no compound minima

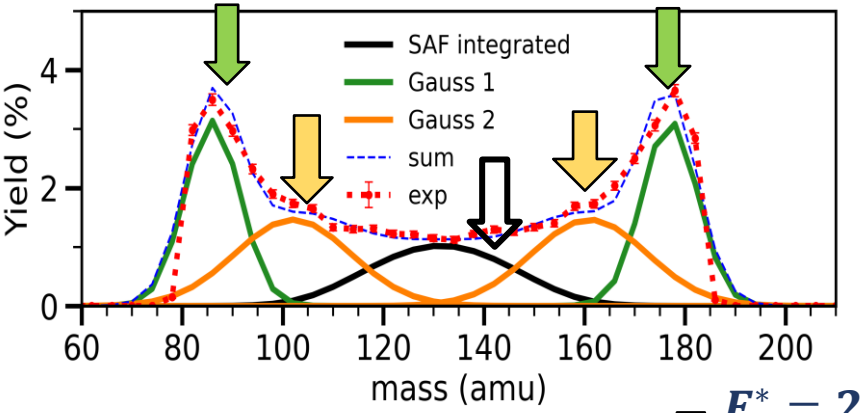
^{263}Bh: results

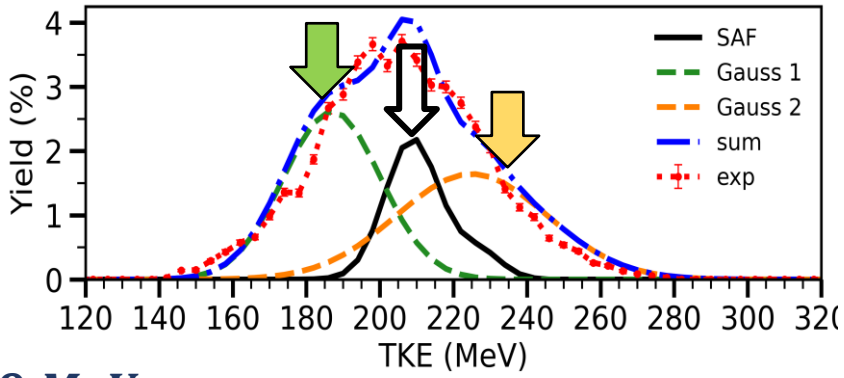
$E^* = 15\ MeV$



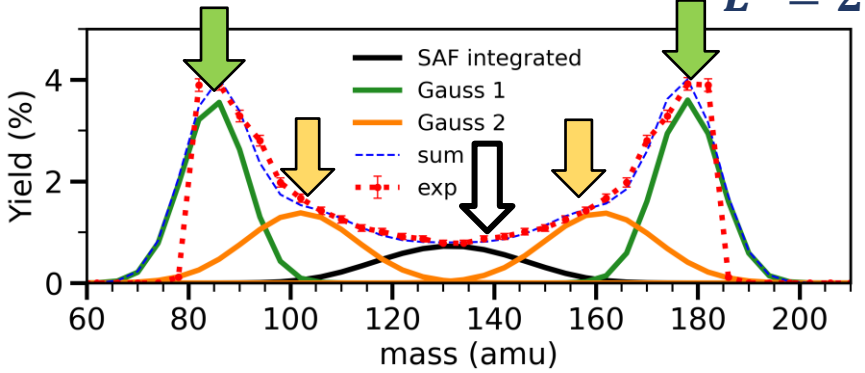


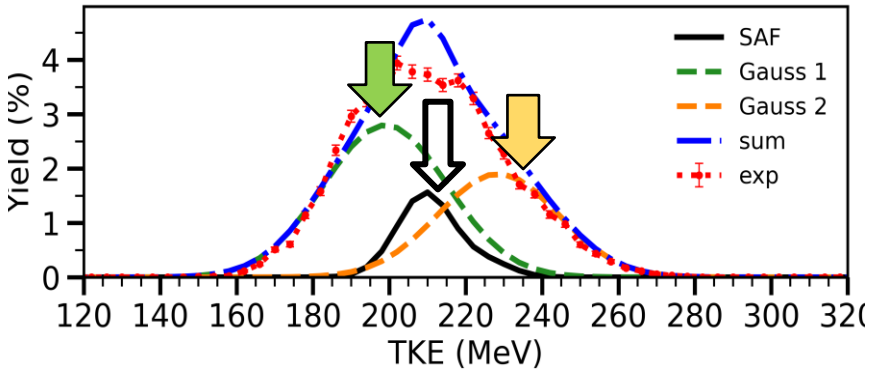
$E^* = 23\ MeV$





$E^* = 29\ MeV$





Asymmetric quasi-fission components

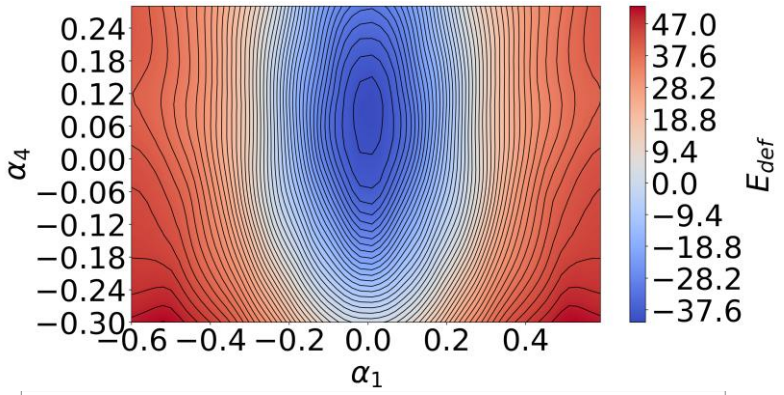
SAF

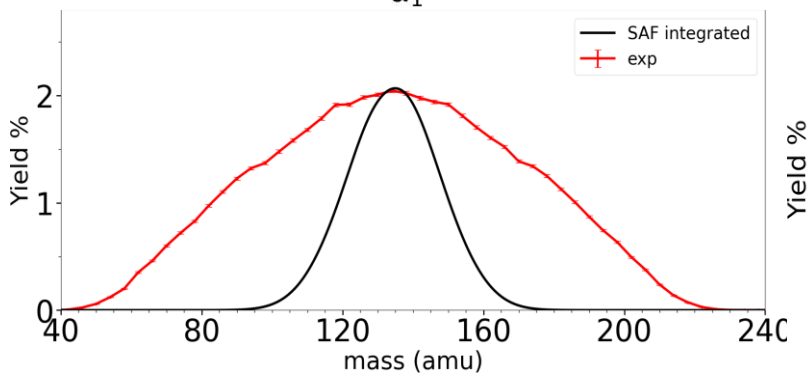
Mass and TKE experimental distributions are not in contrast with the possible coexistence of compact and elongated mode predicted by SAF and the other QF components

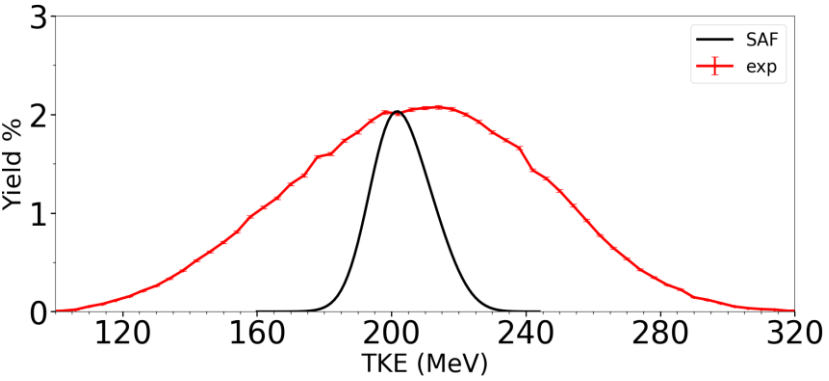
Study of ^{269}Bh

These results were obtained in collaboration with **Prof. N. Carjan**

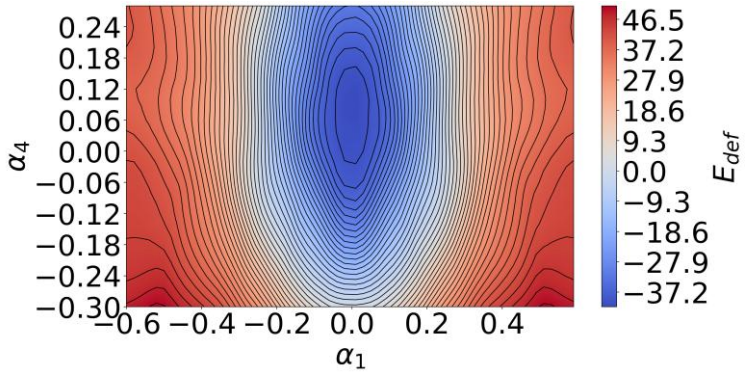
$E^* = 50\ MeV$

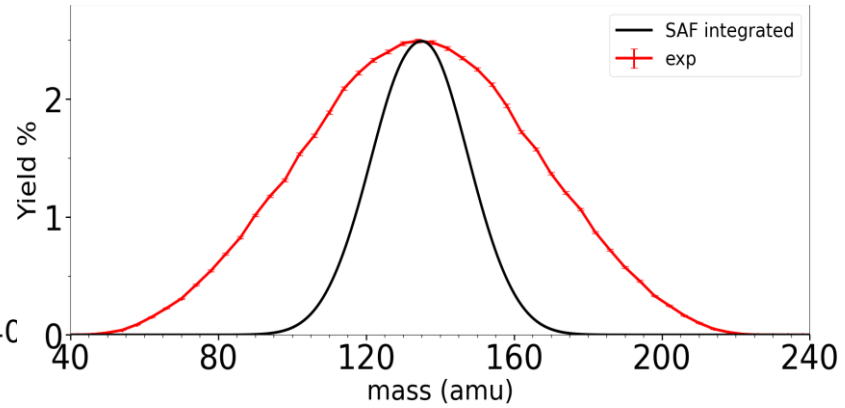


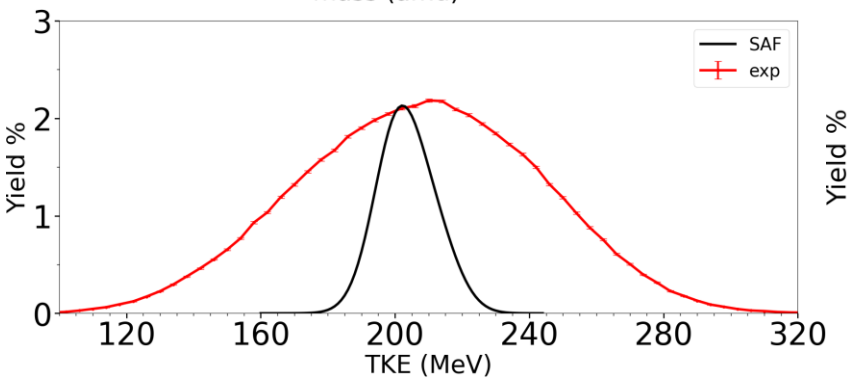




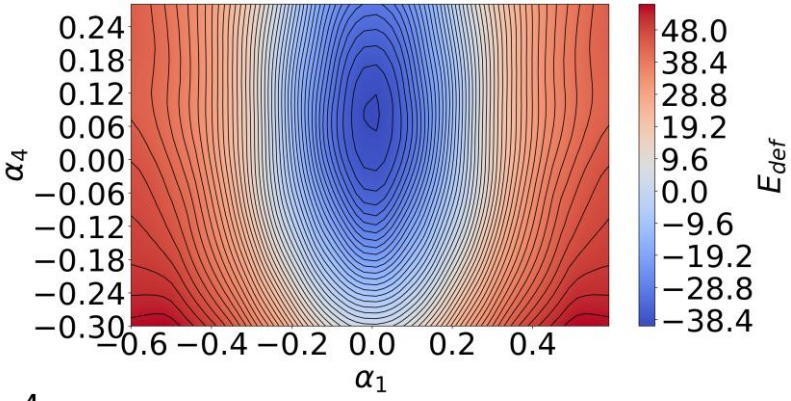
$E^* = 59\ MeV$

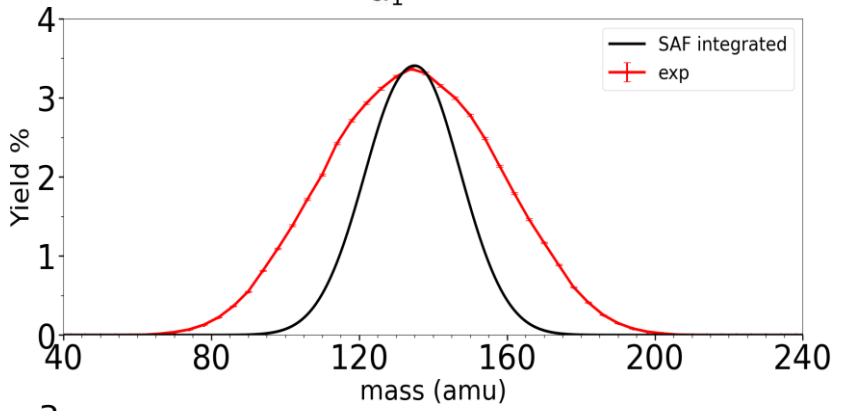


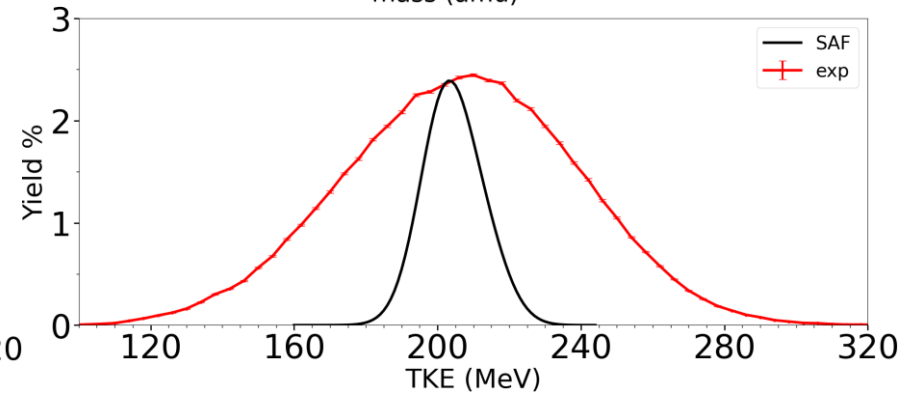




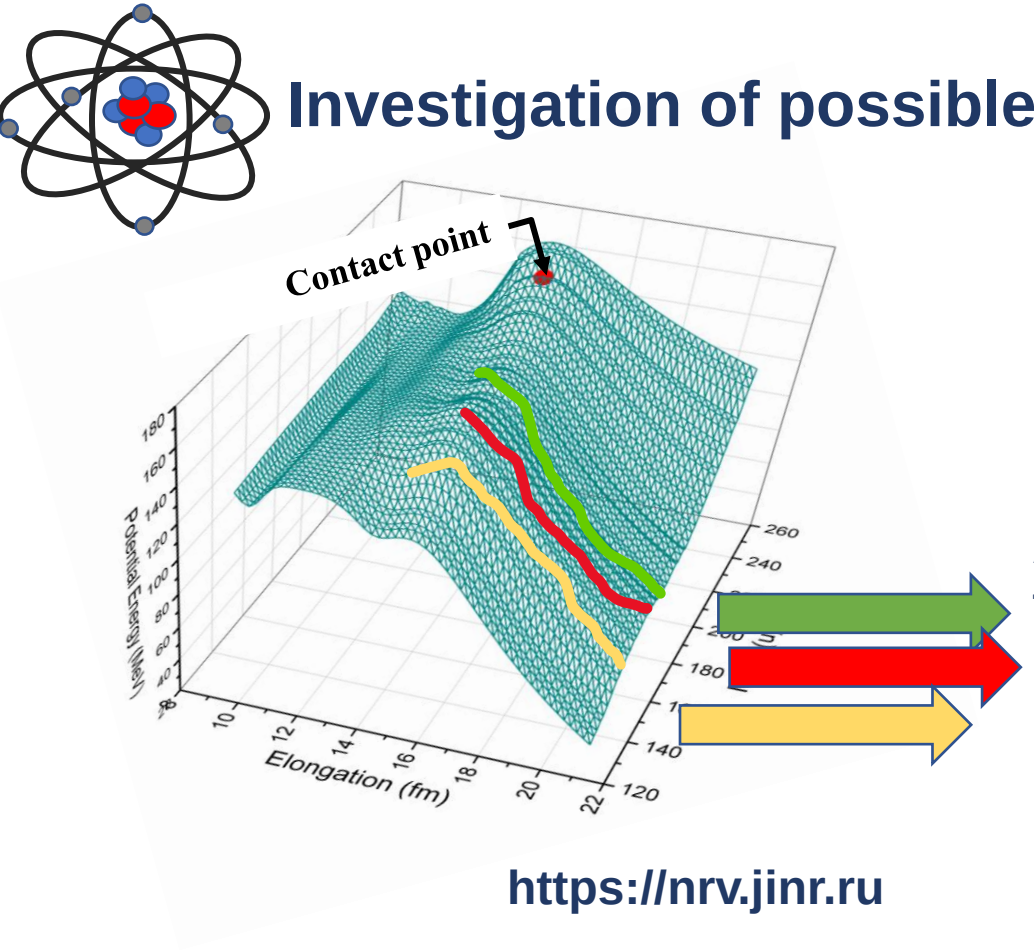
$E^* = 76\ MeV$







Investigation of possible additional contributions for ^{269}Bh



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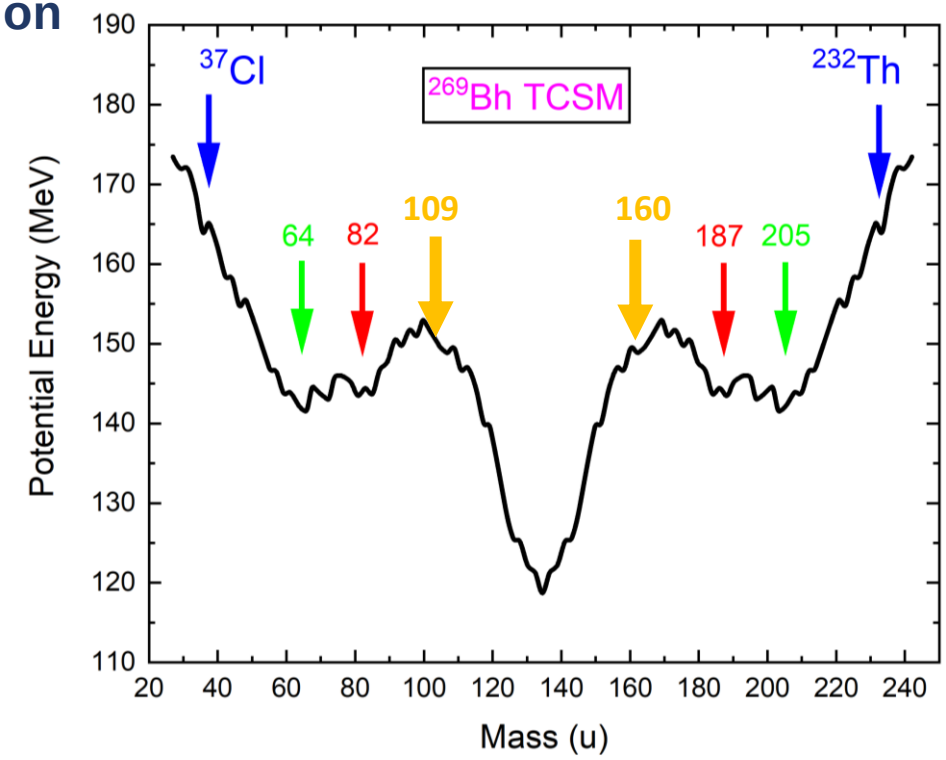
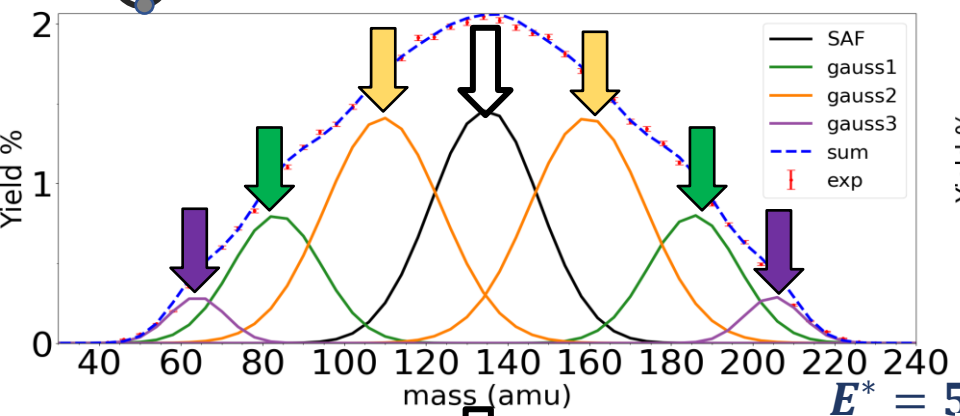
Asymmetric quasi-fission

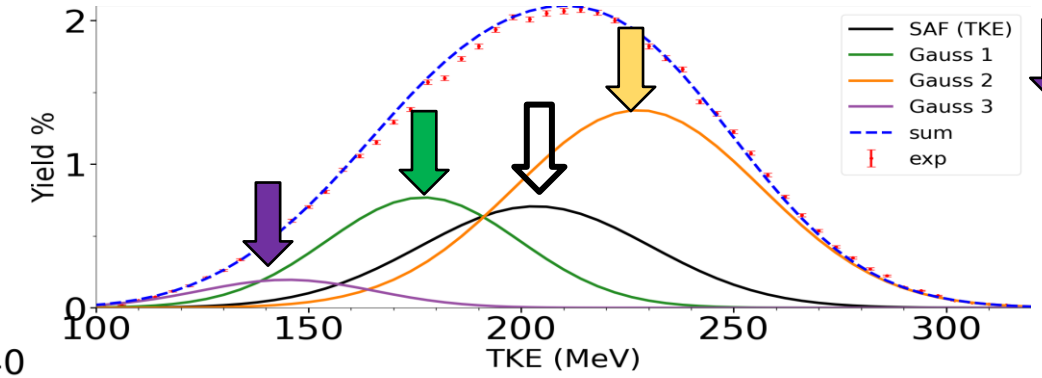


PES cut at 13 fm

^{269}Bh: results

$E^* = 50\ MeV$

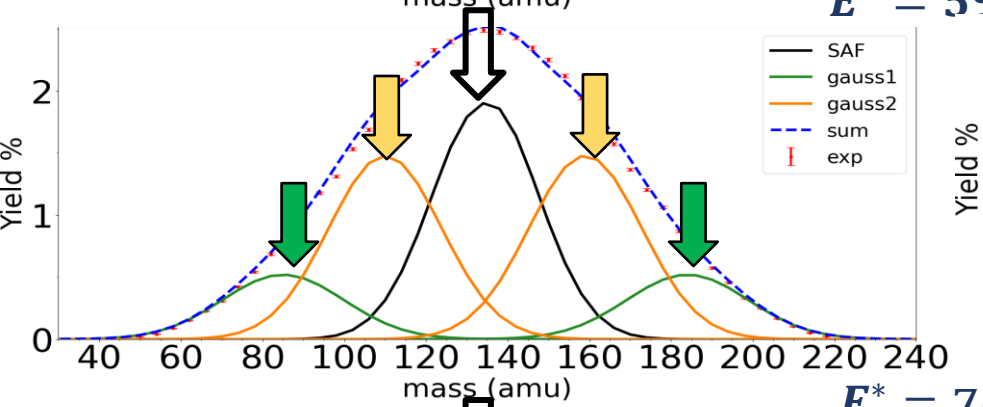


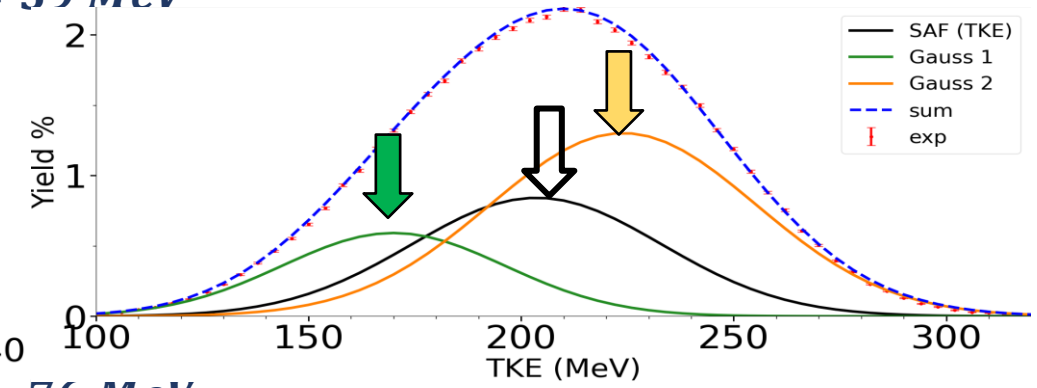


Asymmetric quasi-fission components

SAF

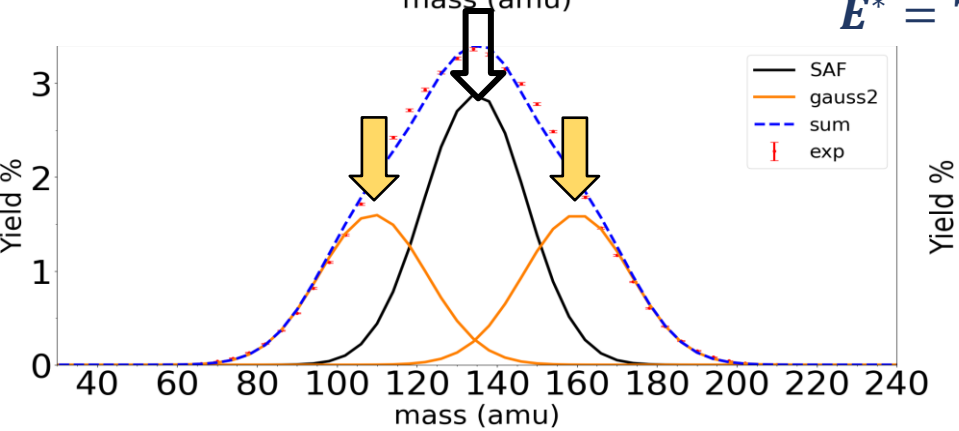
$E^* = 59\ MeV$

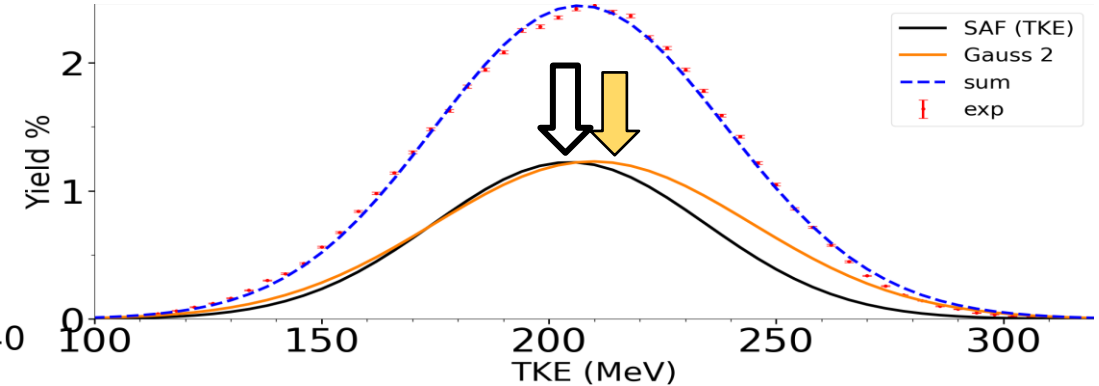




The presence of QF components with different mass asymmetries is compatible with the data

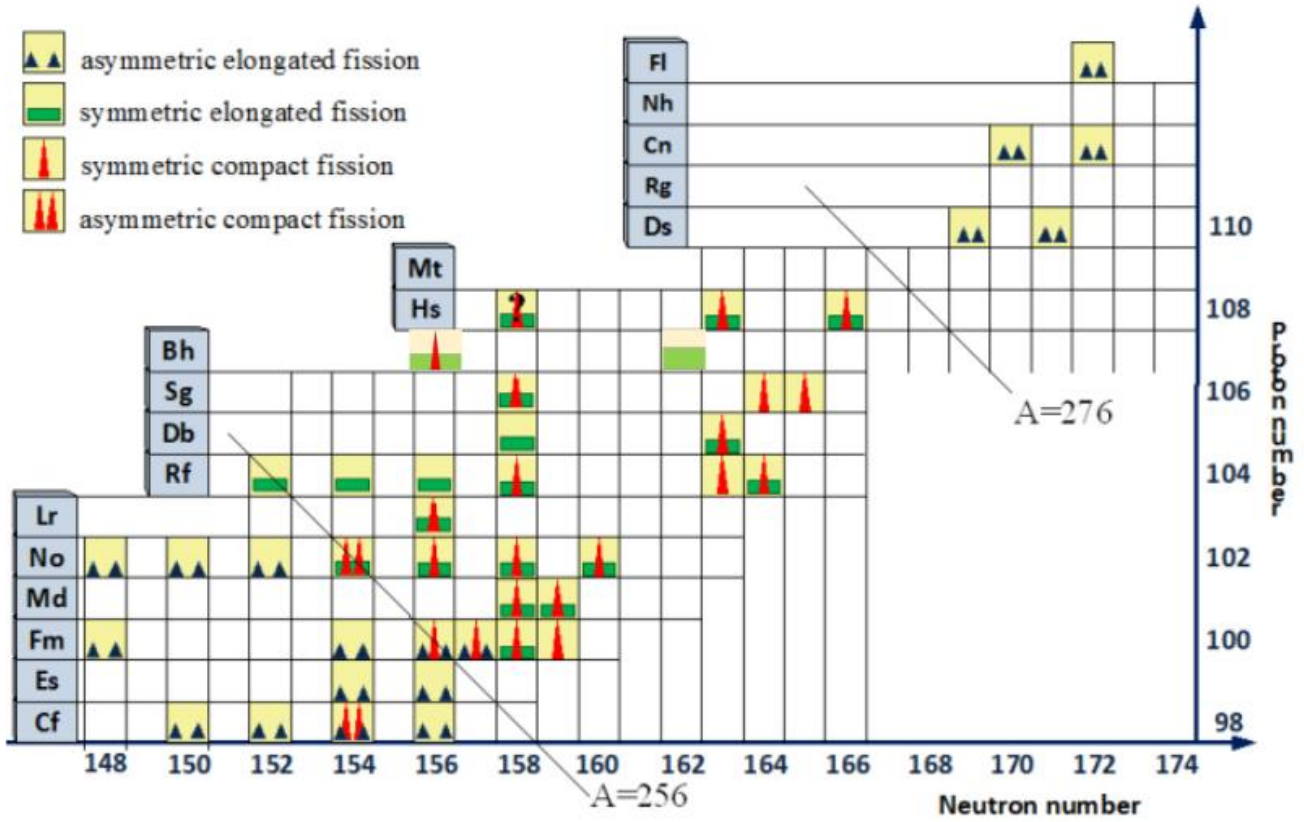
$E^* = 76\ MeV$





Conclusion

- The analysis of Bh isotopes reveals the coexistence of fusion–fission and quasi-fission components, pointing to competing reaction dynamics driven by the interplay between shell effects and energy dissipation.



- **SAF** theoretical description and the systematic analysis of new experimental data enlarge our understanding in the transition region with the main goal to progressively approach the Island of Stability

- **SAF** framework allows a theoretical description for heavy-ions induced reaction, it provides a method to constrain the fusion-fission component in the analysis of experimental data

THANK YOU FOR YOUR ATTENTION

E.Vardaci, A.Di Nitto, G.La Rana, T.Banerjee, G.Alifano, A. Cicchella, S.Di Costanzo, D.Panico and P.A.Setaro

FORTE (CSN3)

Ministero degli Affari Esteri
e della Cooperazione Internazionale

Maeci project

W.Trzaska

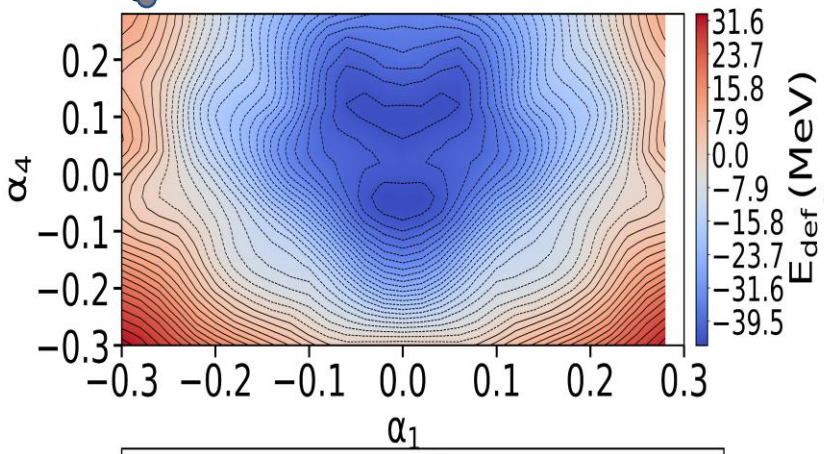
D.Kumar

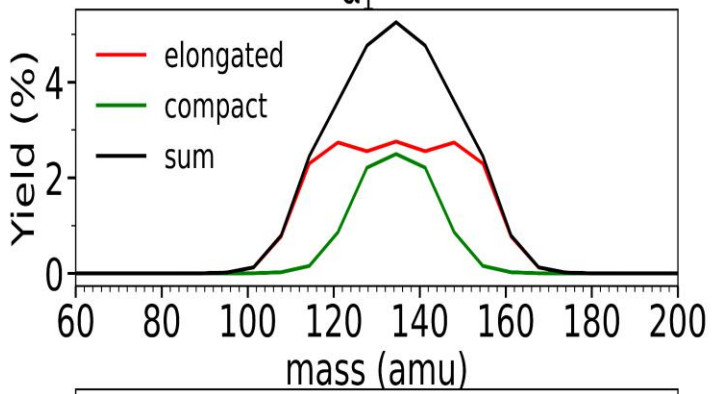
C.Petrone, S.Calinescu

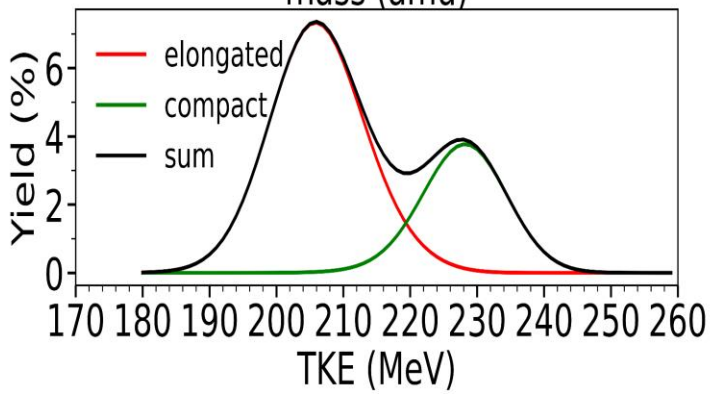
N.Carjan

Spontaneous fission of ^{263}Bh and ^{269}Bh

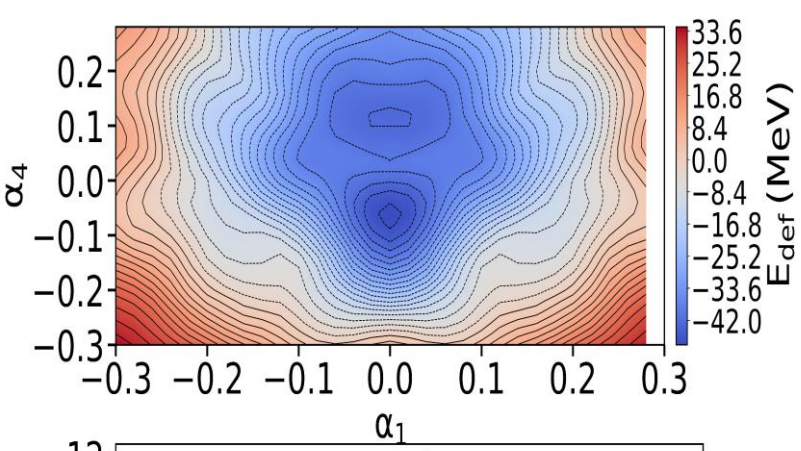
^{263}Bh

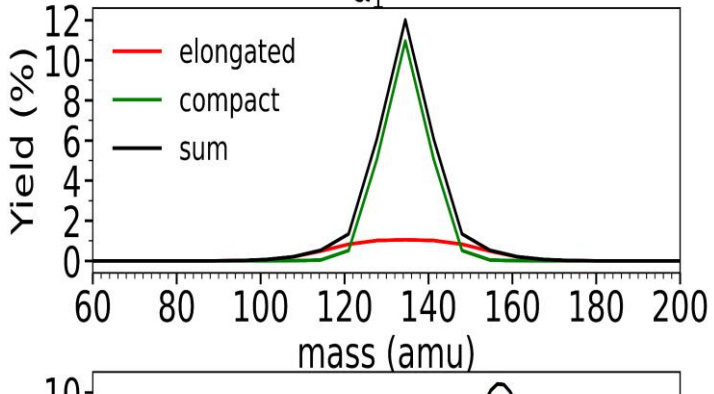


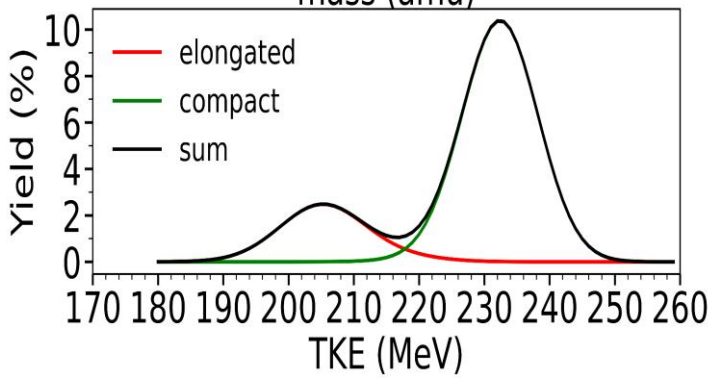




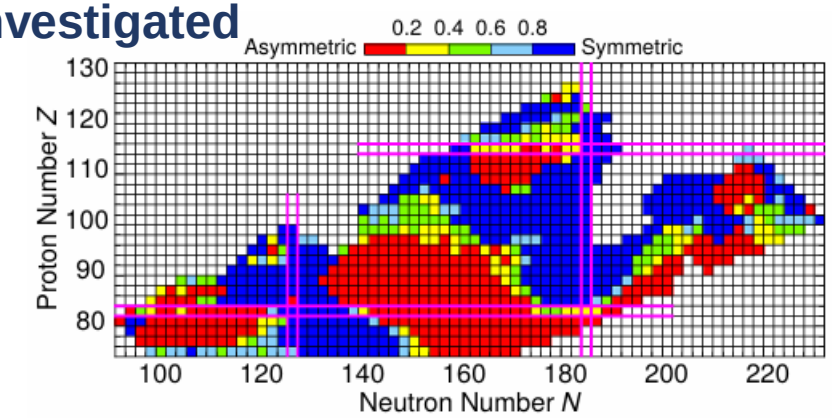
^{269}Bh



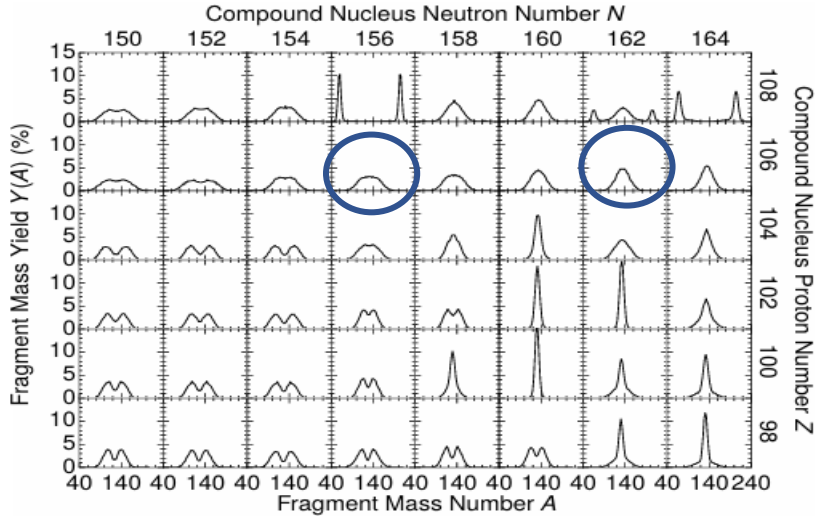




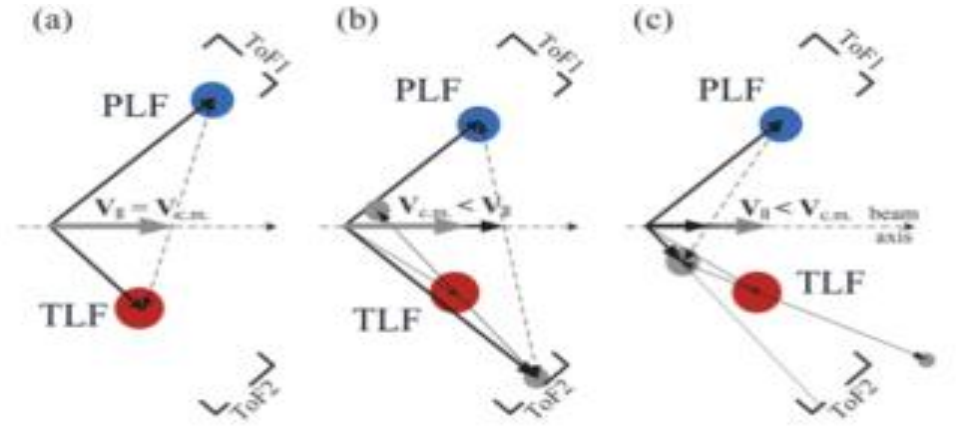
The SAF theoretical distributions are in agree with the near by theoretical system investigated



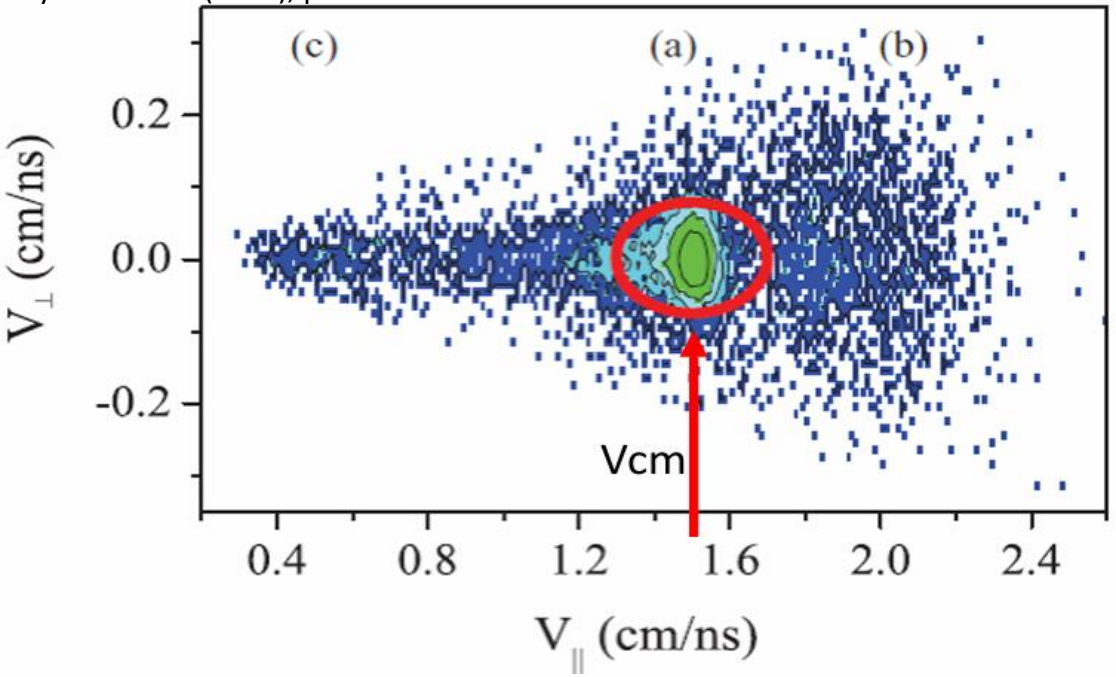
M. Albertsson et al., Calculated fission-fragment mass yields and average total kinetic energies of heavy and superheavy nuclei, Eur. Phys. J. A (2020)

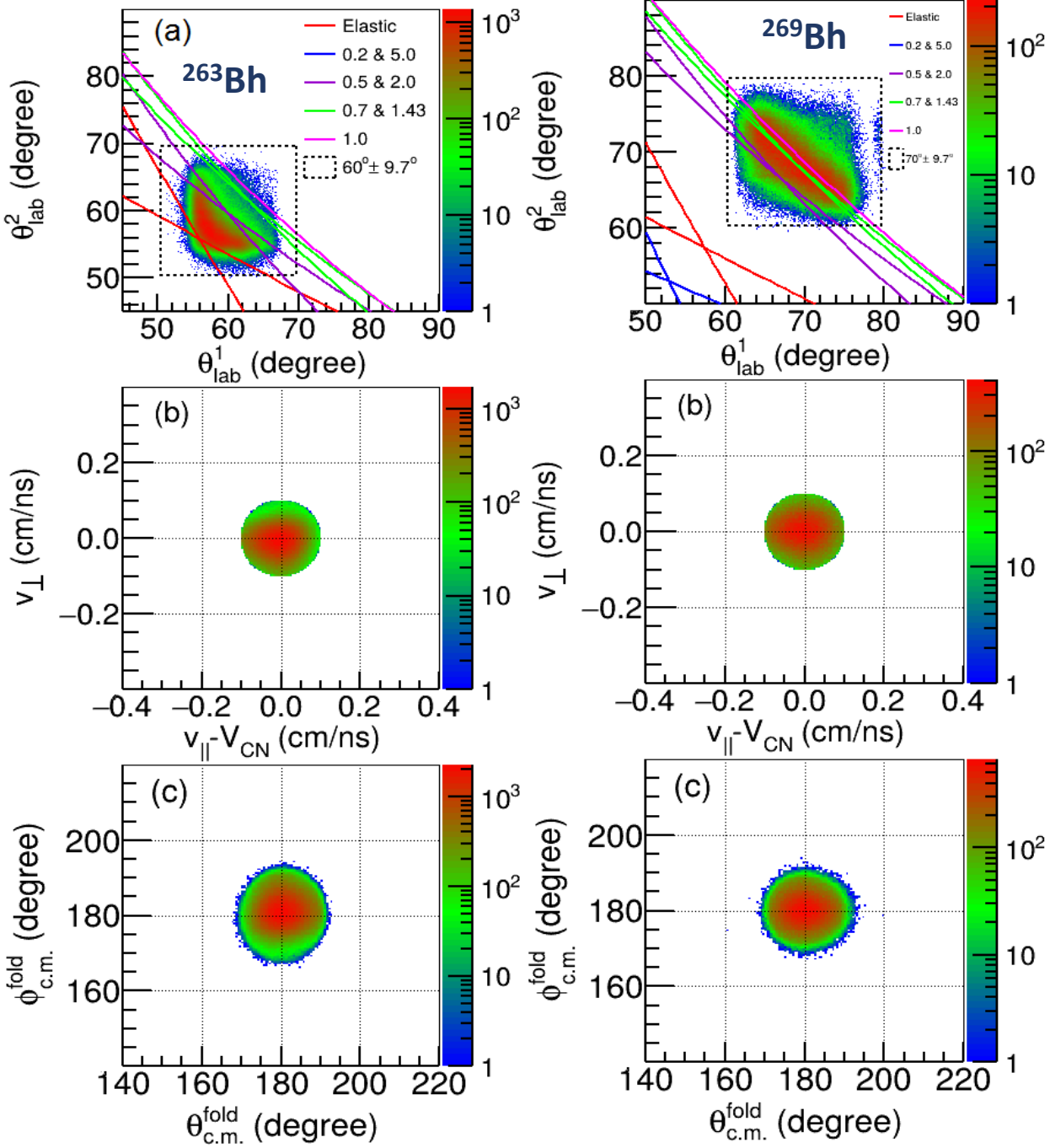


Selection of binary events

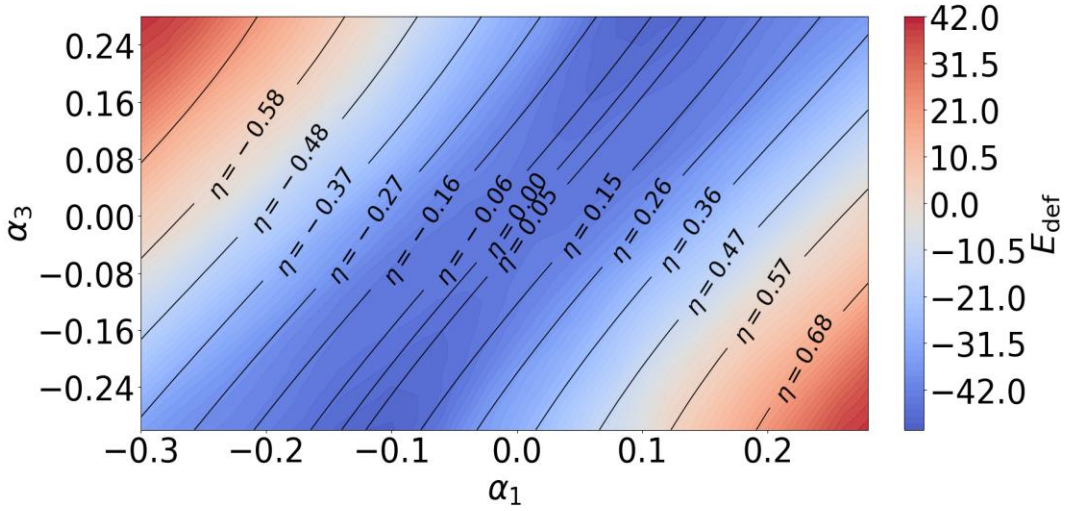


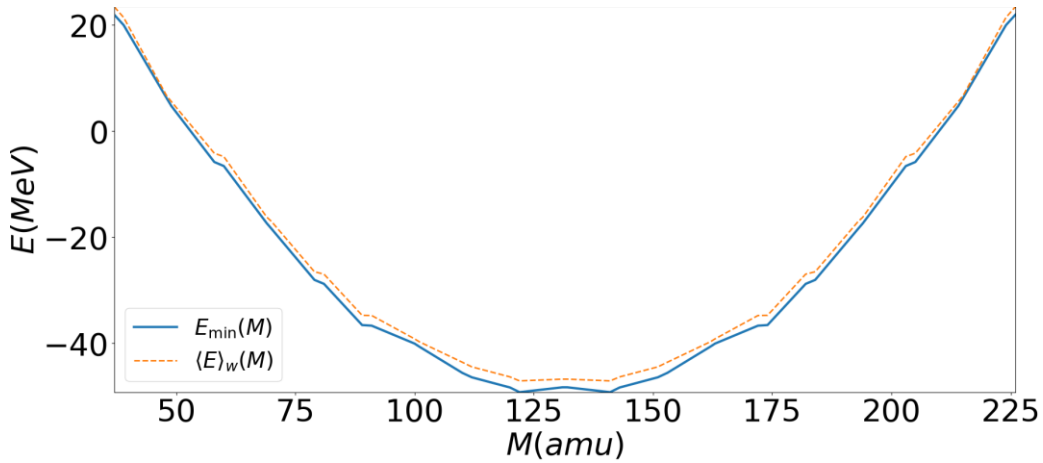
E. M. Kozulin et al. 'Mass distributions of the system 136Xe+208Pb at laboratory energies around the Coulomb barrier: A candidate reaction for the production of neutron-rich nuclei at N = 126'. In: Phys. Rev. C 86 (2012), p. 044611.





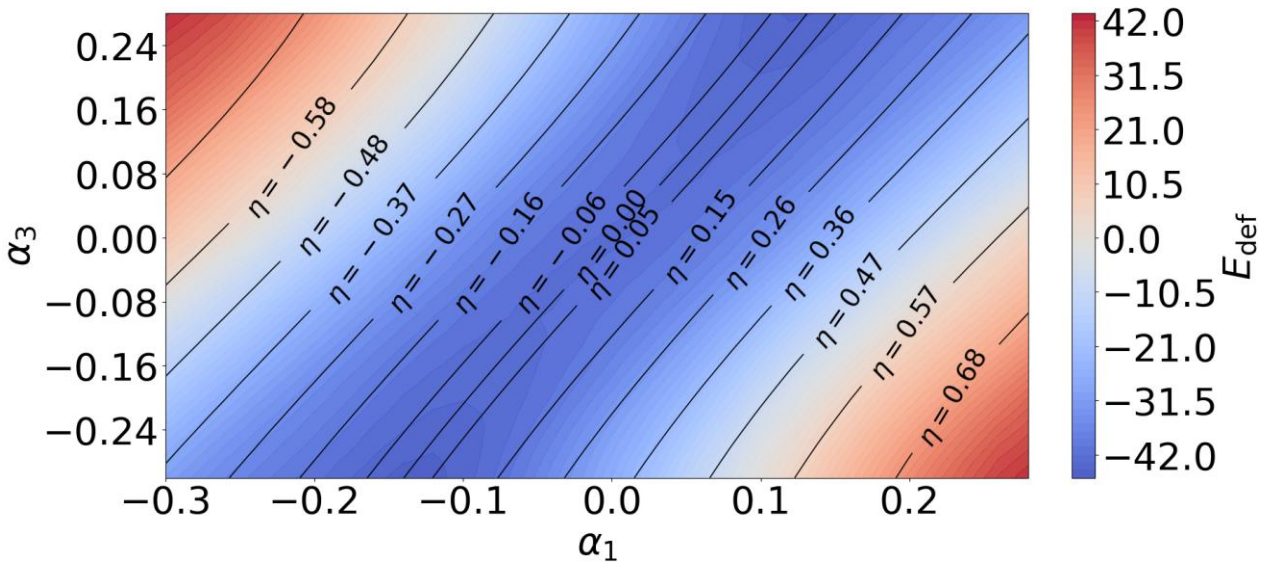
Investigation of possible additional contributions for ^{263}Bh

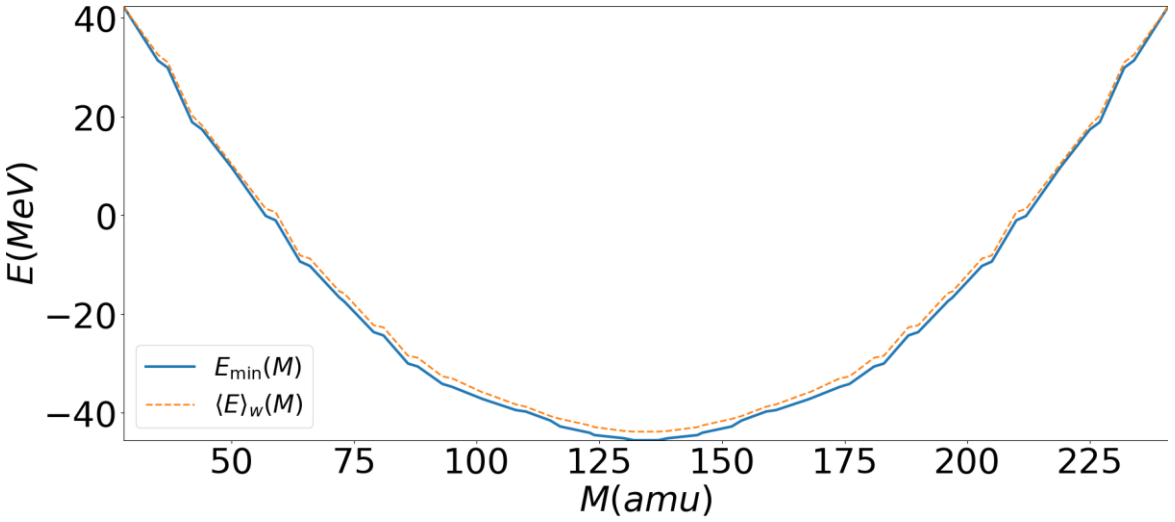




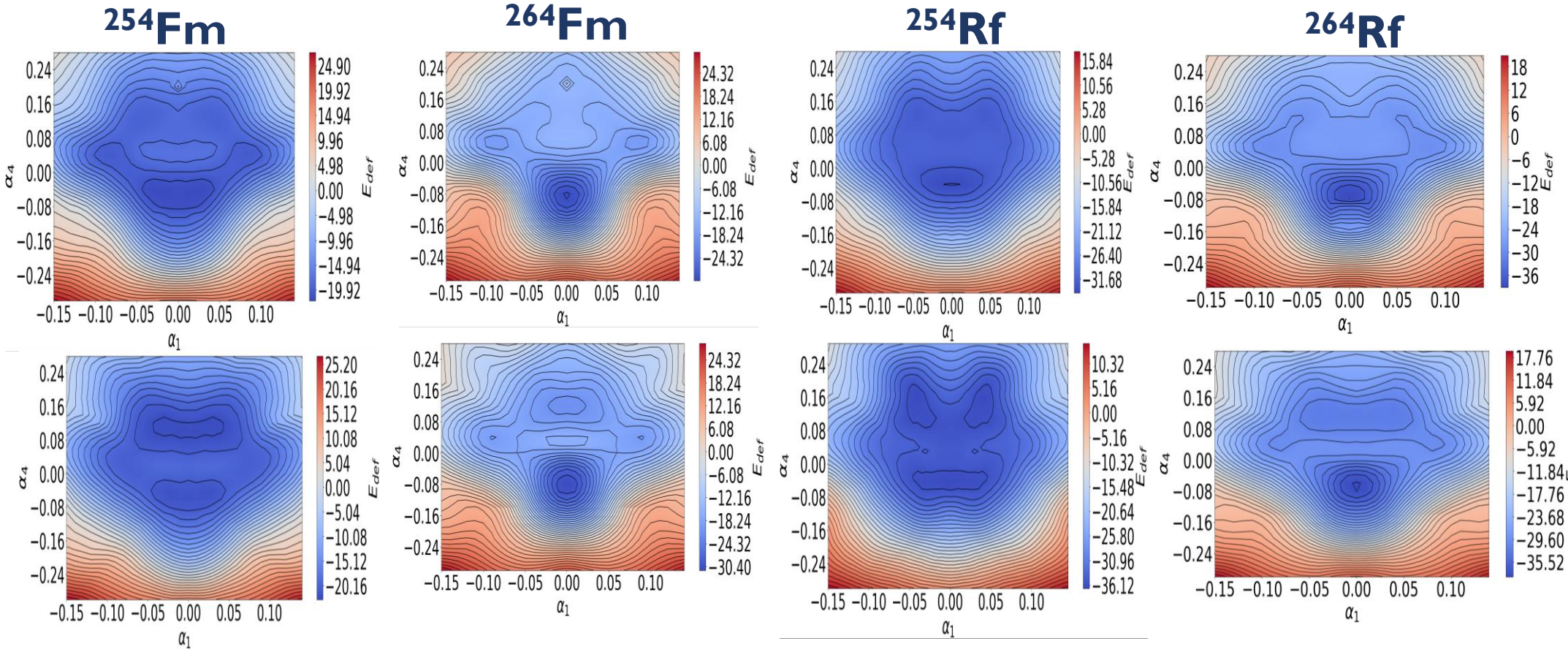
Search for additional FF minima with the inclusion of α_3

Investigation of possible additional contributions for ^{269}Bh





Role of α_6

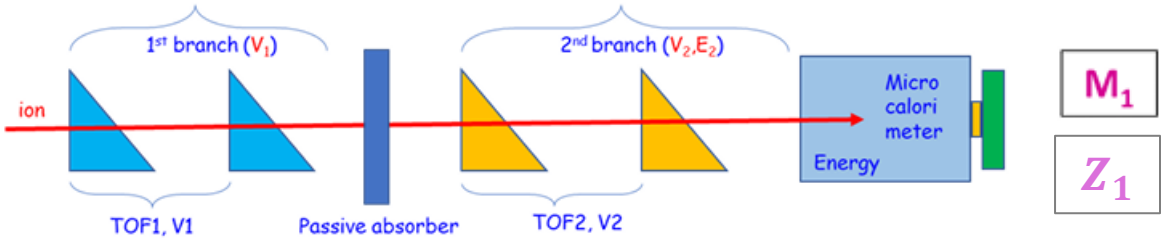


$\alpha_6$highlights the presence of new minima in the PES

The results clearly show a transition from elongated asymmetric fission to compact symmetric one with increasing isotopes mass number

Perspectives

- Measuring velocity vectors, energy and residual energy we can have access a complete characterization (mass and charge) of fragment. **TOF-E-ΔE** method



E. Vardaci et al. In-beam test of a TOF-ΔE-E method for complete identification via mass-(A) and charge-(Z) number of fragments produced in Multi Nucleon Transfer reactions, GSI 2024

- Coupling **TOSCA** with the measure of fragments energy direct reconstruction of the mass with a single arm (**V-E** method).