Fission yield studies in inverse kinematics

SANDA meeting Subtask 2.5.2

CIEMAT July 3-5, 2024

José Benlliure

Universidad de Santiago de Compostela
Spain

Sub-task 2.5.2 objectives

Accurate A, Z fission yields and TKEs from barrier up to some 60 MeV using quasi-free (p,2p) scattering in inverse kinematics as subrogate reaction to investigate the evolution of fission with the excitation energy.

$^{238}U(p,2p) \rightarrow ^{237}Pa \rightarrow FF$, $^{237}Pu(p,2p) \rightarrow ^{236}U \rightarrow FF$, $^{233}Pa(p,2p) \rightarrow ^{232}Th \rightarrow FF$

- Evolution of the fission yields with the excitation energy.
- Shell dumping and level densities evolution with excitation energy.
- Neutrons and gamma rays in coincidence.

- Beam time at GSI:

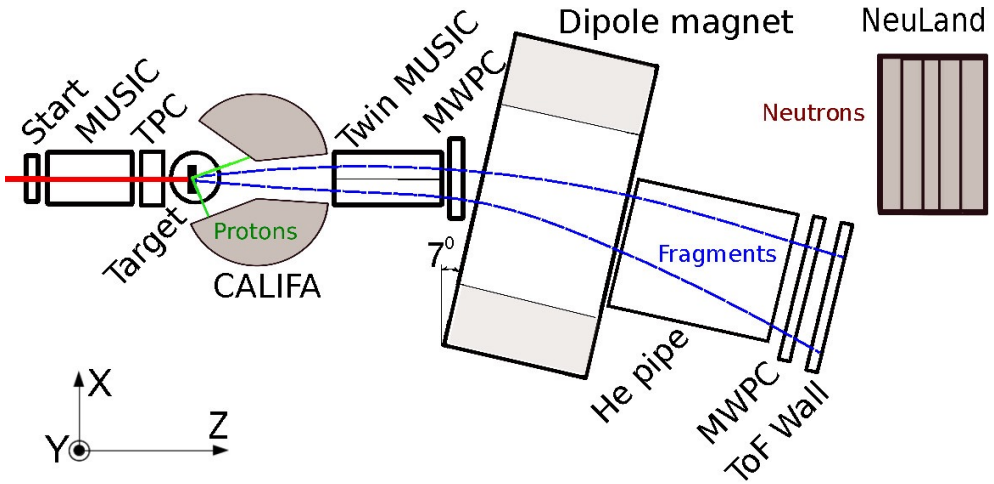
  Setup: SOFIA@R3B

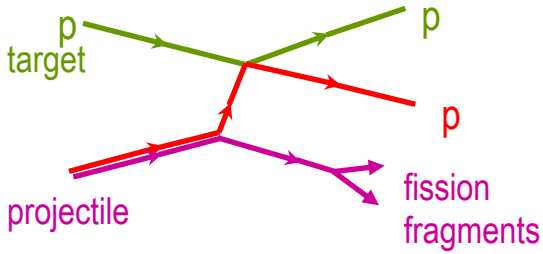
  Beam time granted: 21 shifts main, 15 shifts parasitic

  Running period, March 2021 (Covid period).

(p,2p) induced fission in inverse kinematics @ R3B/FAIR

Coupling CALIFA-tracker + GLAD + NeuLAND + SOFIA

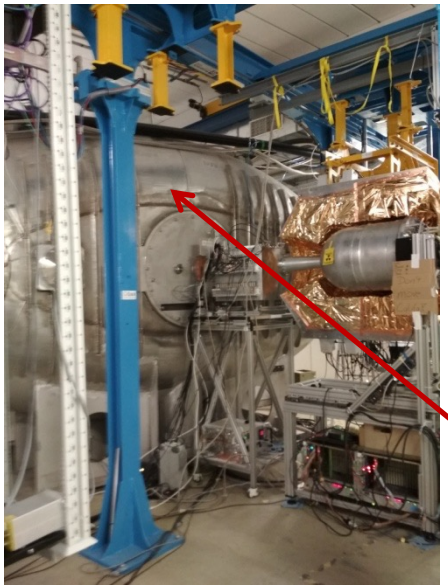


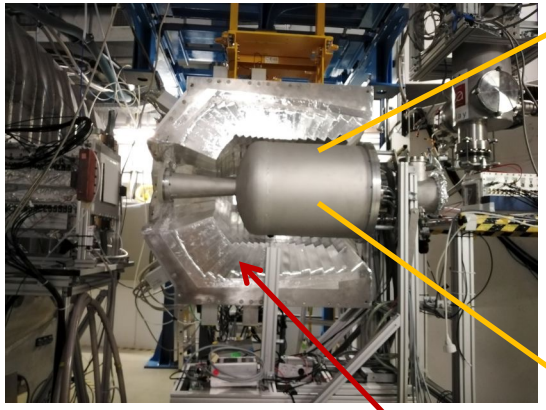


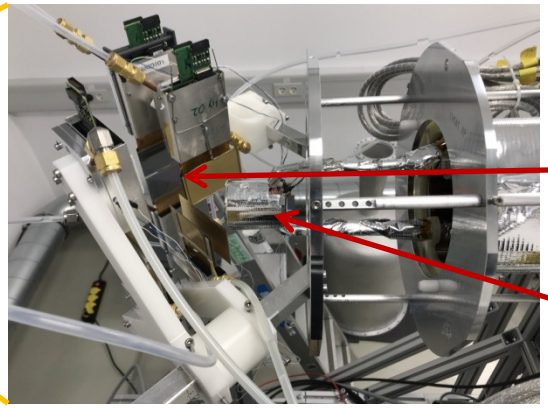
First-ever complete kinematic fission experiment

- ✓ Characterization of the fissioning nucleus (A, Z, E*) → (p,2p) with CALIFA+tracker
- ✓ Characterization of both fission fragments (A, Z, TKE,) → SOFIA
- ✓ Neutrons, gammas and light-charged particles → NeuLAND + CALIFA

Setup as in Feb. 5 2021 ready to run





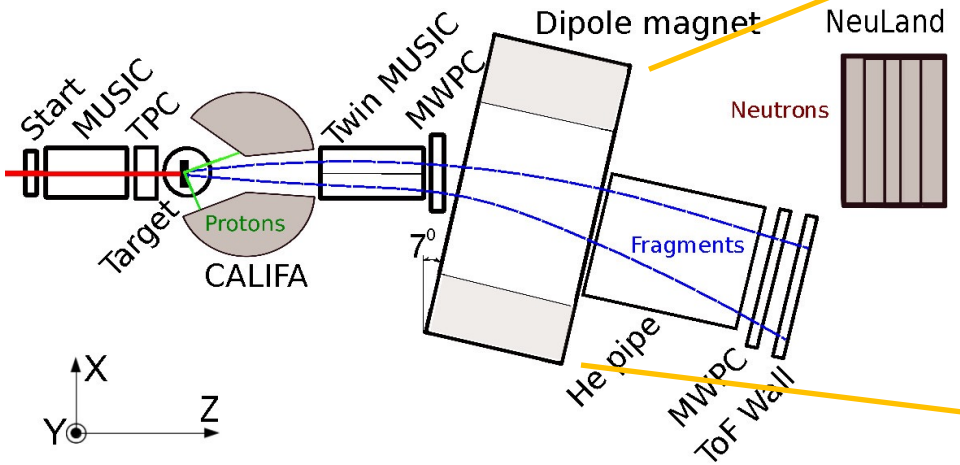


Si tracker

LH_2 target cell

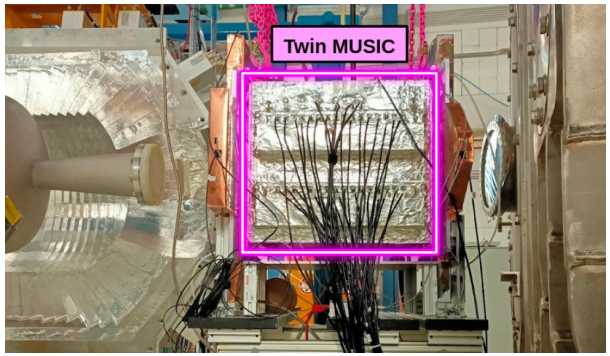
GLAD
Superconducting
Dipole magnet

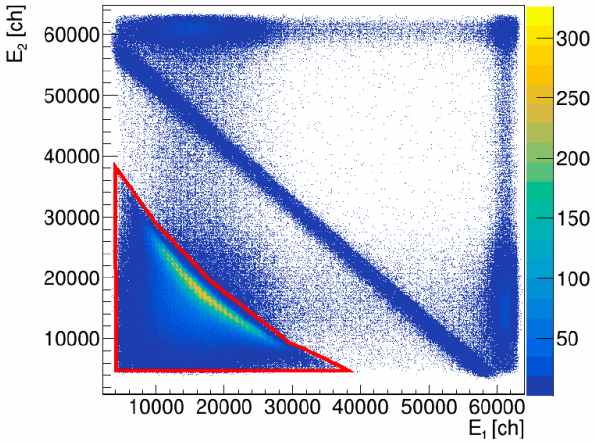
CALIFA
calorimeter

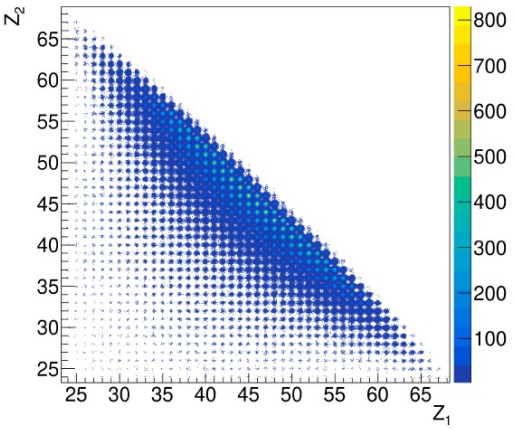


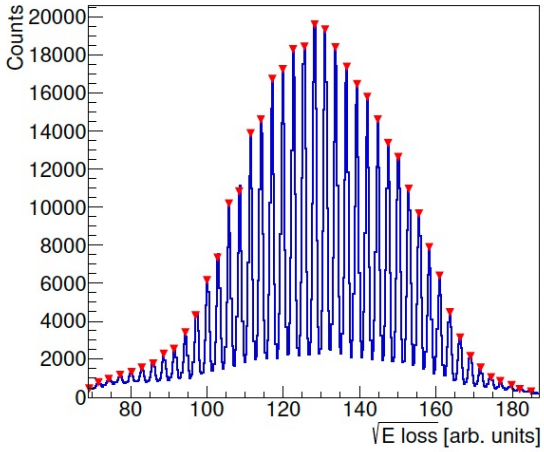
Identification of fission fragments in atomic number

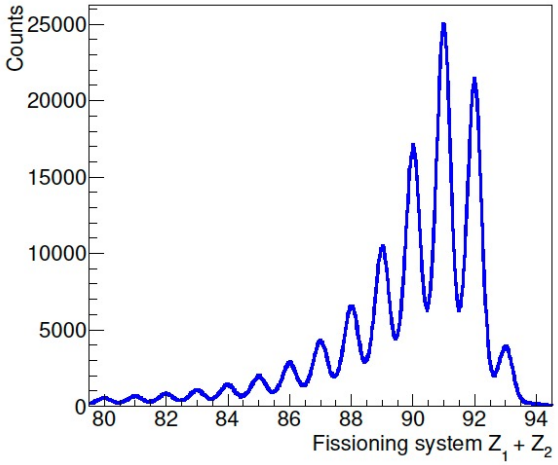
Identification in atomic number from energy loss measurements in the two sections of the Twin-MUSIC









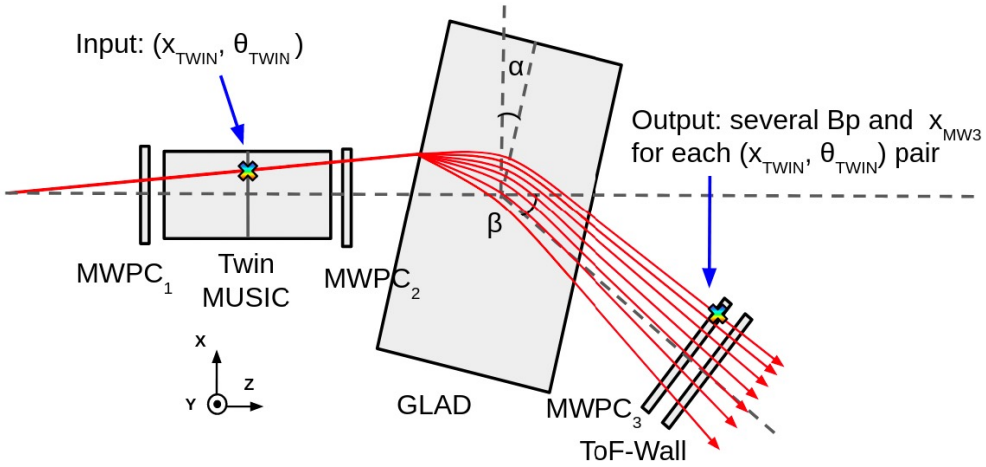


Resolution in atomic number:

$\Delta Z = 0.38$ (FWHM)

Identification of fission fragments in mass number

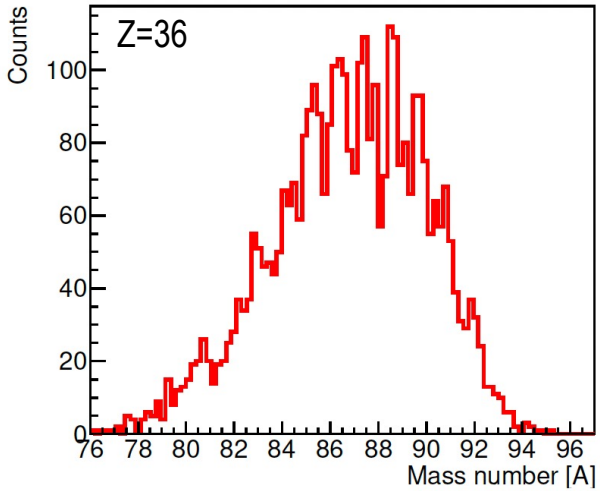
Identification in mass number from Br (tracking) and time-of-flight measurements and the previous Identification in atomic number

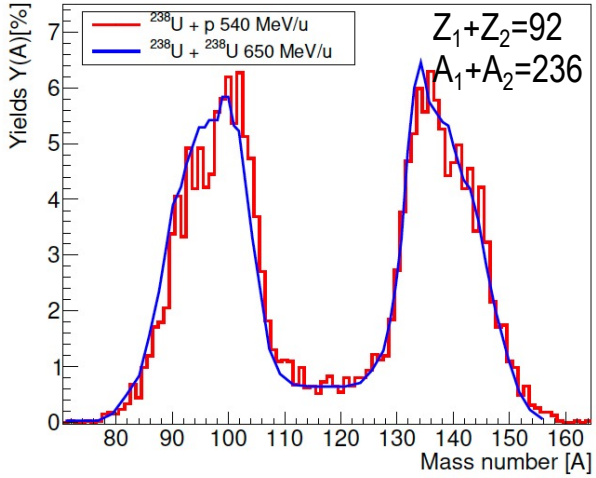


$$B\rho = \frac{A \cdot u}{Z \cdot e} \beta\gamma c$$

Resolution in mass number:

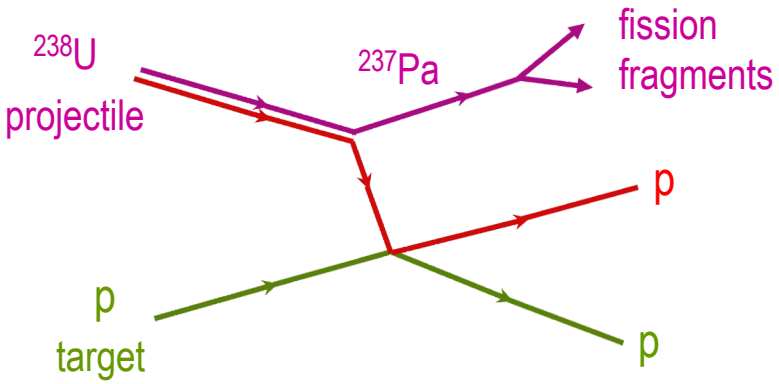
$\Delta A = 0.8$ (FWHM)





Access to the excitation energy of the fissioning nucleus

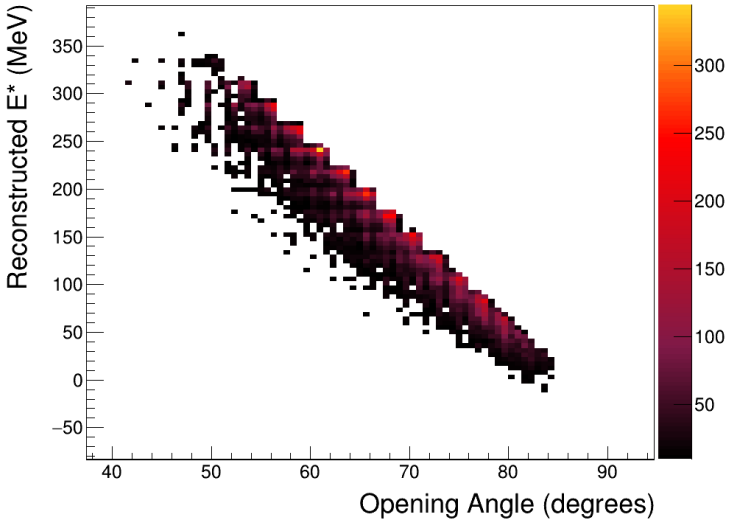
(p,2p) quasi-free scattering to induce fission in inverse kinematics via particle-hole excitations.

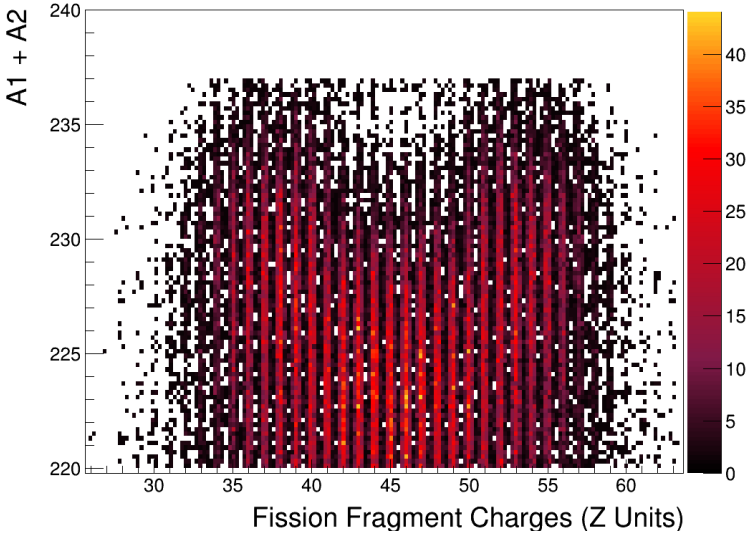


$$\vec{P}_{Beam} + \vec{P}_{Target} = \vec{P}_{Proton1} + \vec{P}_{Proton2} + \vec{P}_{Remanent}$$

$$I_m = \sqrt{(E_{Beam} + m_p c^2 - (E_{p_1} + E_{p_2}))^2 - (p_{p_{1x}} c + p_{p_{2x}} c)^2 - (p_{p_{1y}} c + p_{p_{2y}} c)^2 - (\sqrt{E_{Beam}^2 - m_{Beam}^2 c^4} - (p_{p_{1z}} c + p_{p_{2z}} c))^2}$$

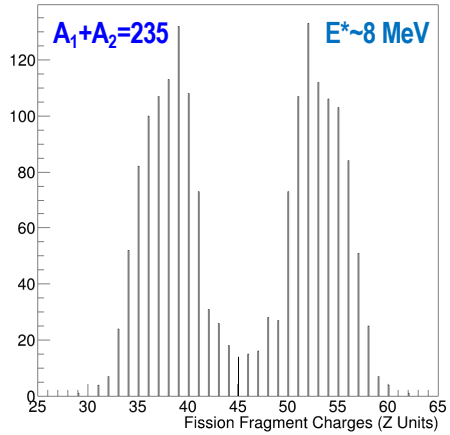
$$E^* = I_m - m_{Remanent} c^2$$

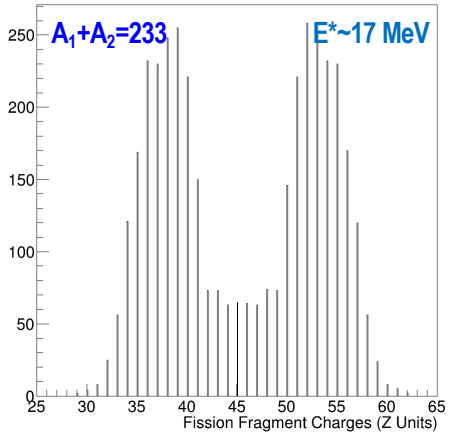


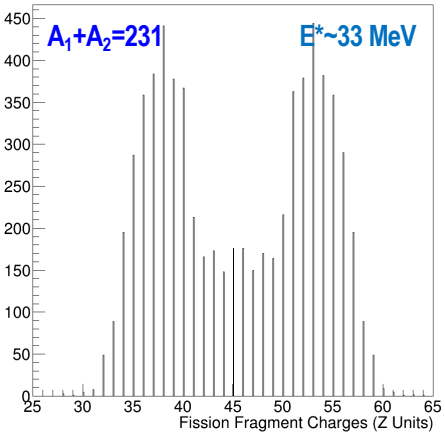


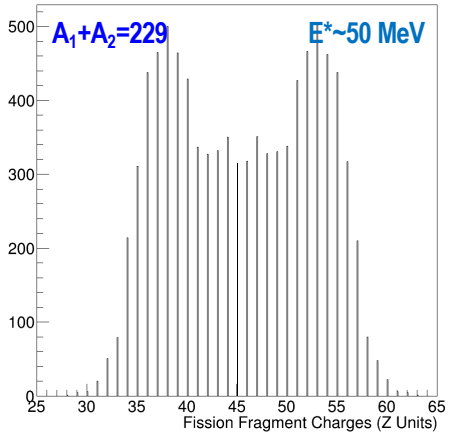
Evolution of the fission yields with the excitation energy

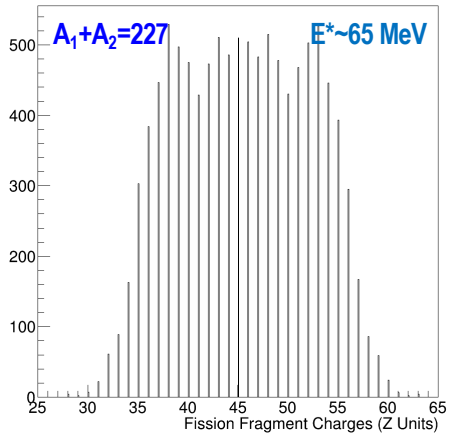
Damping of shell effects with the excitation energy

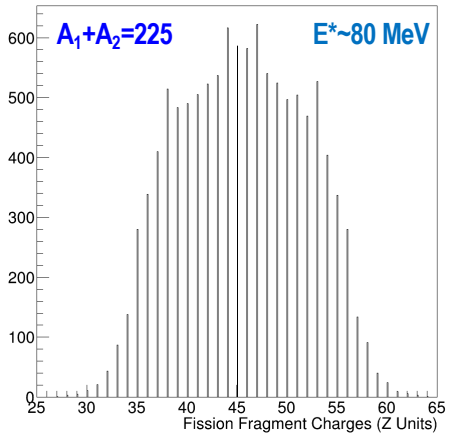


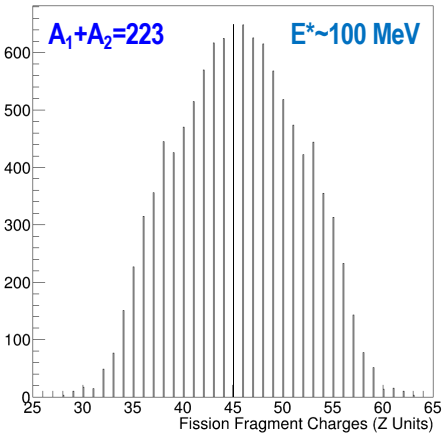


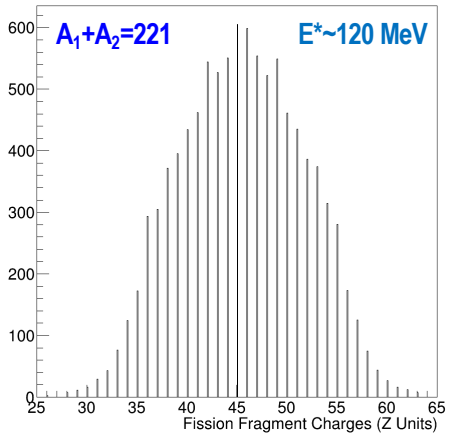






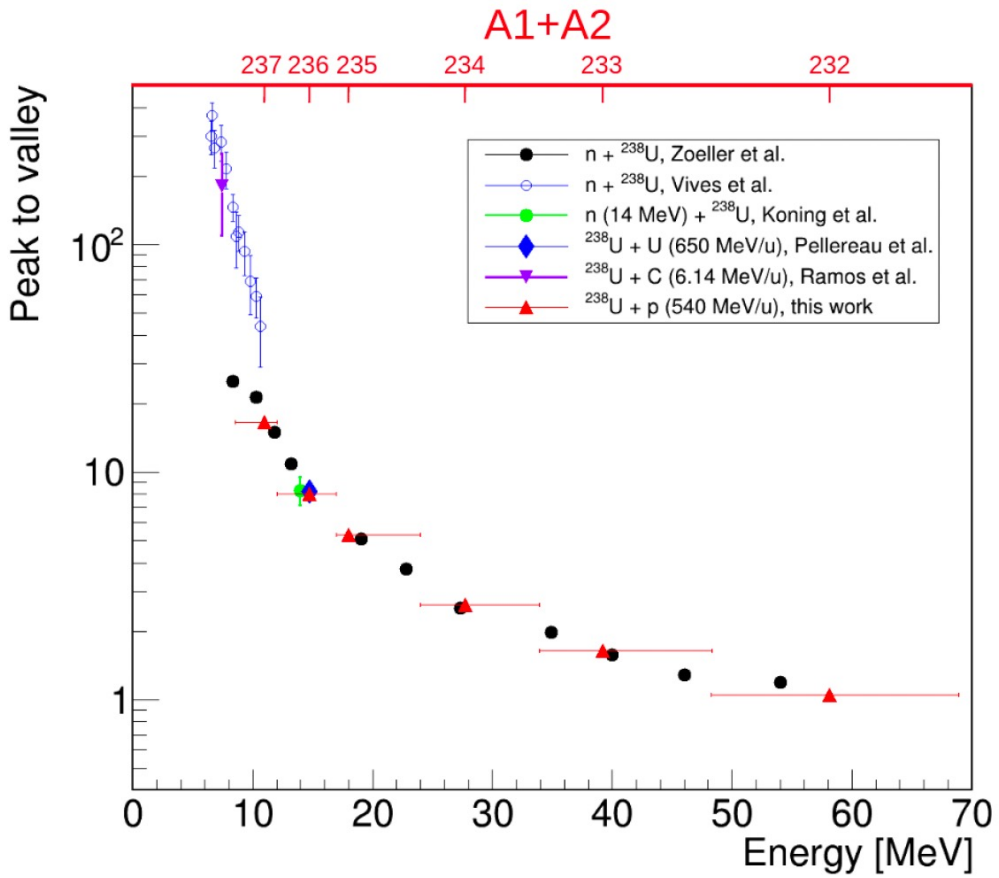






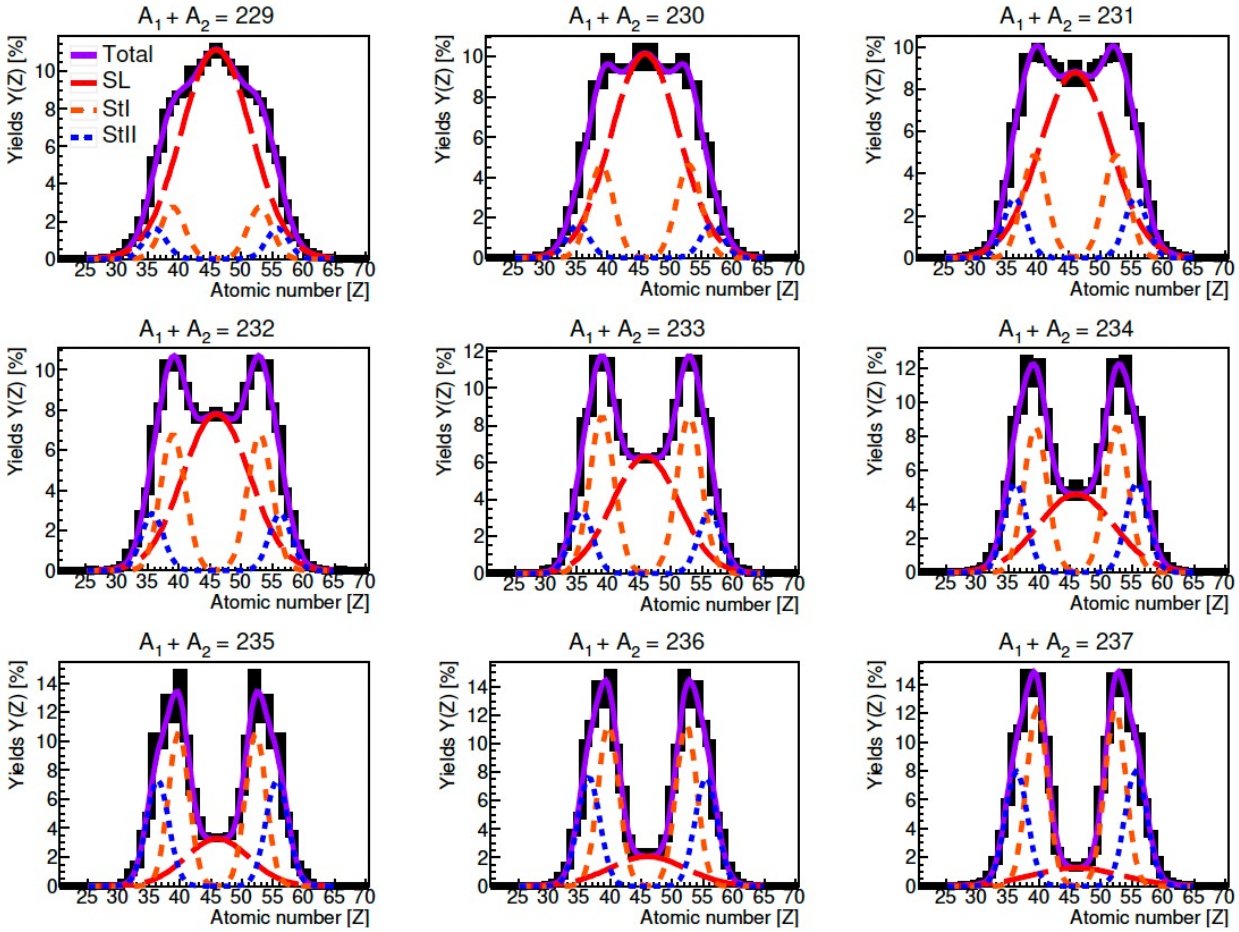
Evolution of the fission yields with the excitation energy

Damping of shell effects with the excitation energy



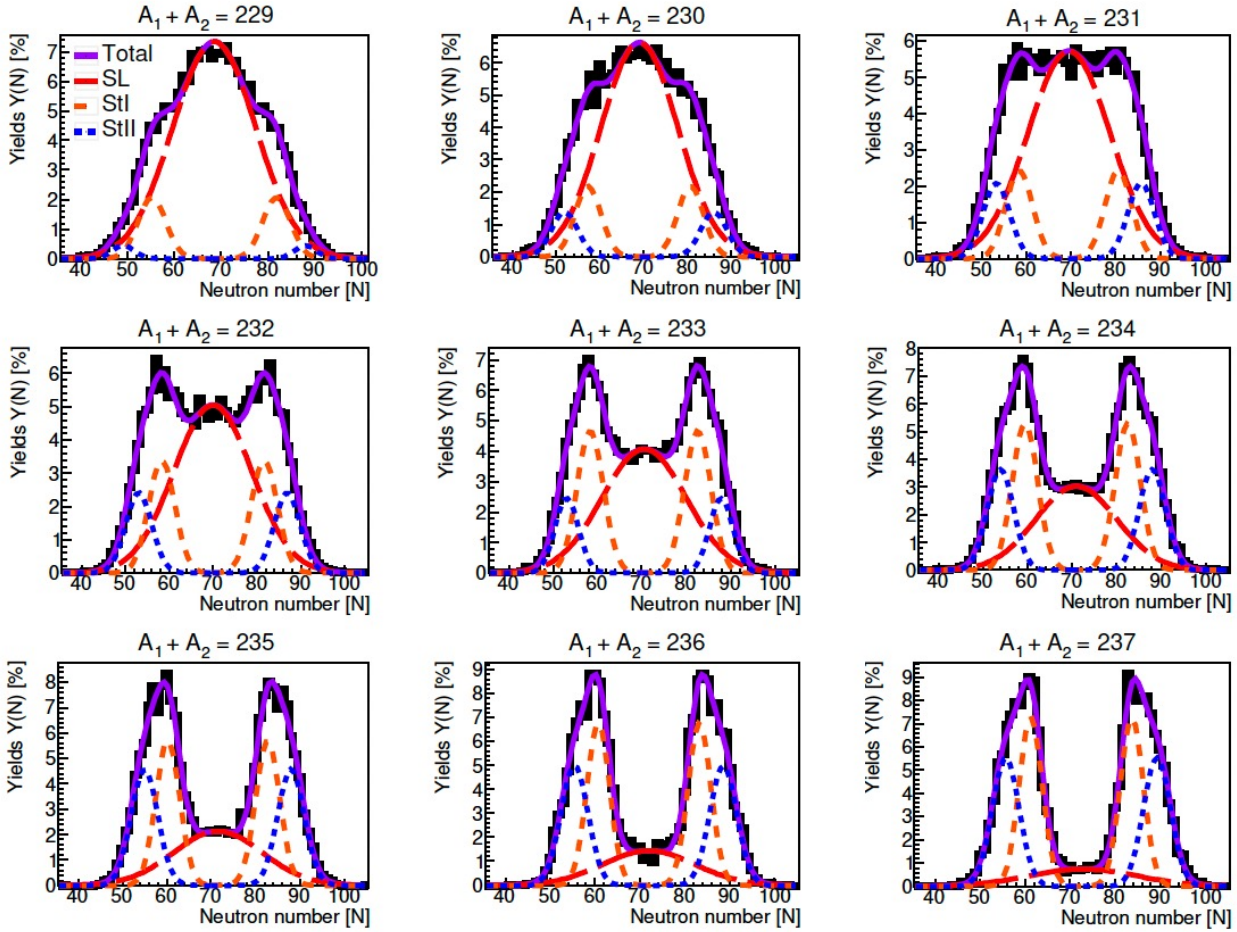
Evolution of the fission yields with the excitation energy

Evolution of fission modes in Z-yields with the excitation energy



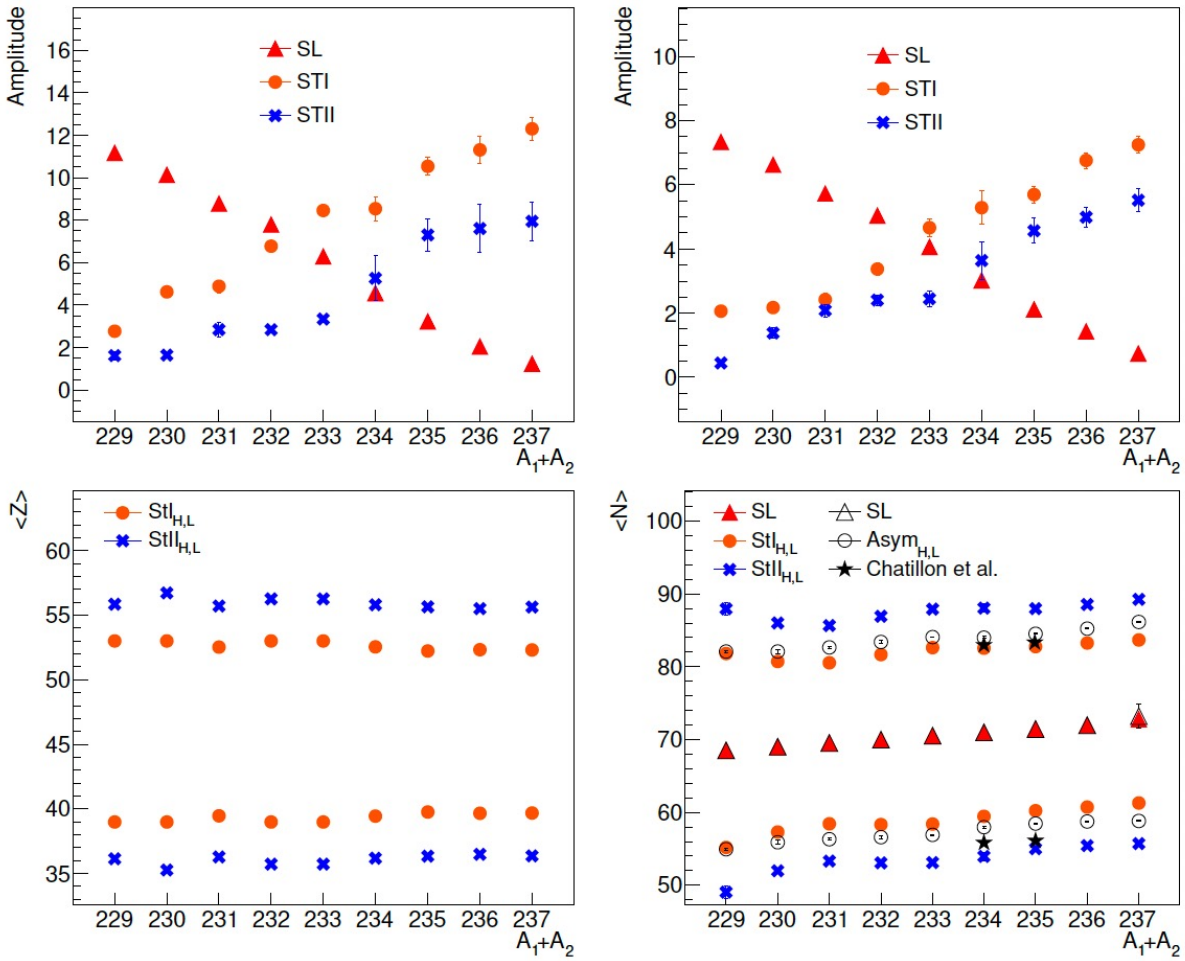
Evolution of the fission yields with the excitation energy

Evolution of fission modes in N-yields with the excitation energy



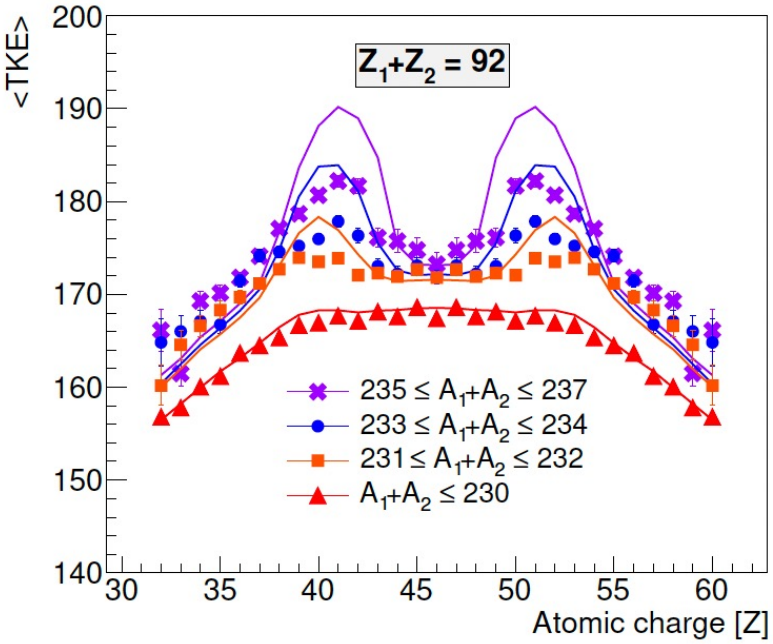
Evolution of the fission yields with the excitation energy

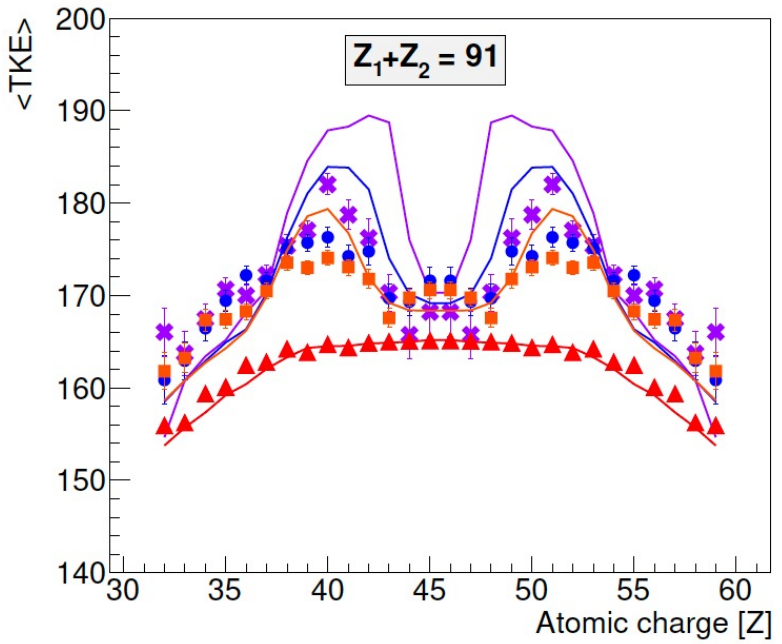
Evolution of fission modes in N- and Z-yields with the excitation energy



Evolution of TKE with the excitation energy

Evolution of total kinetic energies with the excitation energy



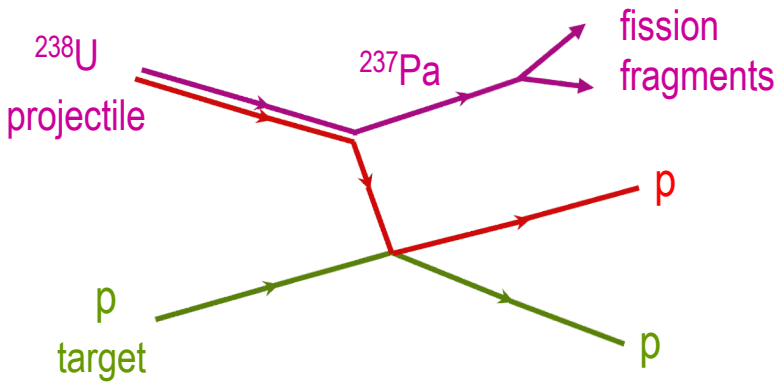


Summary

- ✓ The objectives proposed in subtask 2.5.2 were accomplished and the corresponding deliverable (D 2.14) was submitted on October 15th, 2022.
- ✓ The use of (p,2p) reactions in inverse kinematics to investigate the fission process was validated.
- ✓ The dumpling of shell effects and the evolution of the fission modes with the excitation energy was investigated using N and Z fission yields.
- ✓ The evolution of TKE with the excitation energy was also investigated.
- ✓ Information of neutron and γ-ray multiplicities could also be obtained in future.

QFS-induced fission

(p,2p) quasi-free scattering to induce fission via particle-hole excitations



$$\vec{P}_{Beam} + \vec{P}_{Target} = \vec{P}_{Proton1} + \vec{P}_{Proton2} + \vec{P}_{Remanent}$$

$$I_m = \sqrt{(E_{Beam} + m_p c^2 - (E_{p_1} + E_{p_2}))^2 - (p_{p_{1x}} c + p_{p_{2x}} c)^2 - (p_{p_{1y}} c + p_{p_{2y}} c)^2 - (\sqrt{E_{Beam}^2 - m_{Beam}^2 c^4} - (p_{p_{1z}} c + p_{p_{2z}} c))^2}$$

$$E^* = I_m - m_{Remanent} c^2$$

- ✓ Well defined kinematical conditions
  - Momentum and excitation energy of the recoiling fissioning nucleus
- ✓ Relatively large cross sections
  - 10 – 50 mb
- ✓ CN energy due to particle-hole excitations and nucleon re-scattering
  - up to 80 MeV
- ✓ Possibility to use unstable nuclei
  - inverse kinematics