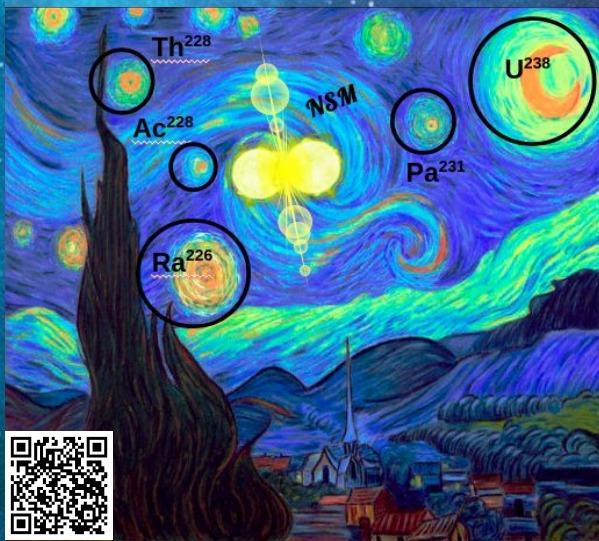


European Nuclear Physics Conference 2022 (EuNPC 2022)

Quasi-free (p,2p) reactions for studying fission and its implications in the nucleosynthesis r-process.

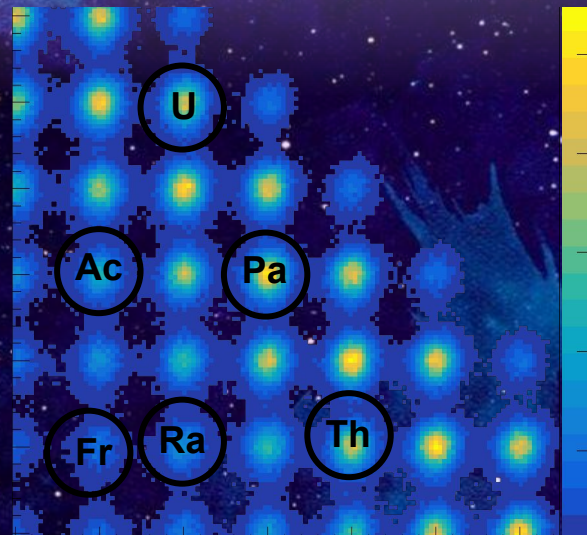
A. Graña González^{a*}, J.L. Rodríguez-Sánchez^a, J. Benlliure^a, A. Chatillon^b, D. Cortina-Gil^a, H. Alvarez-Pol^a, G. García Jiménez^a, P. Morfouace^b, J. Taieb^b, and the R3B collaboration

a) Univ. of Santiago de Compostela, Spain; b) CEA/DAM, France



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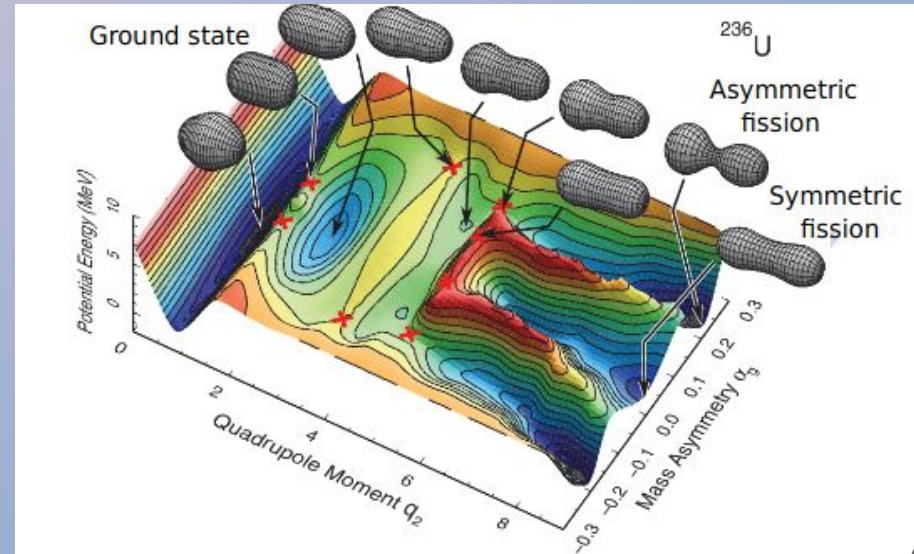
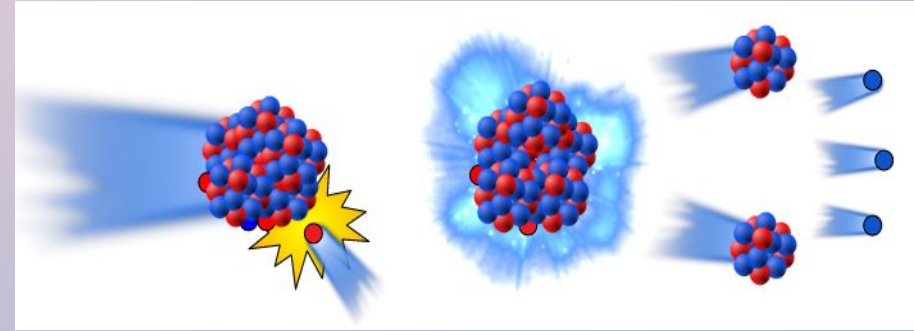


Fission

Fission is the **splitting of a heavy nucleus into lighter nuclei as a consequence of a large-scale collective motion of the nucleons**, plus some other lighter products (n , α , β , γ , etc). Discovered by **Lise Meitner** and **Otto Hahn** in 1938.

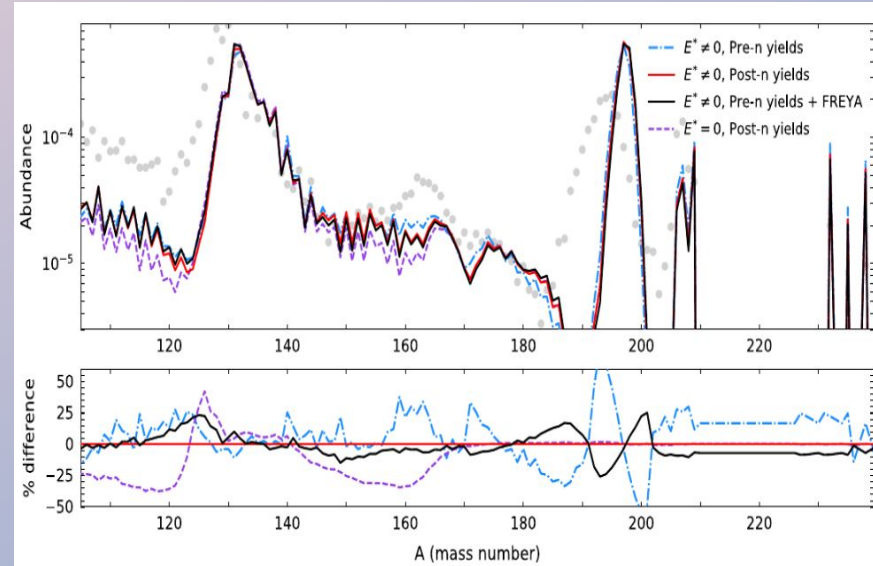
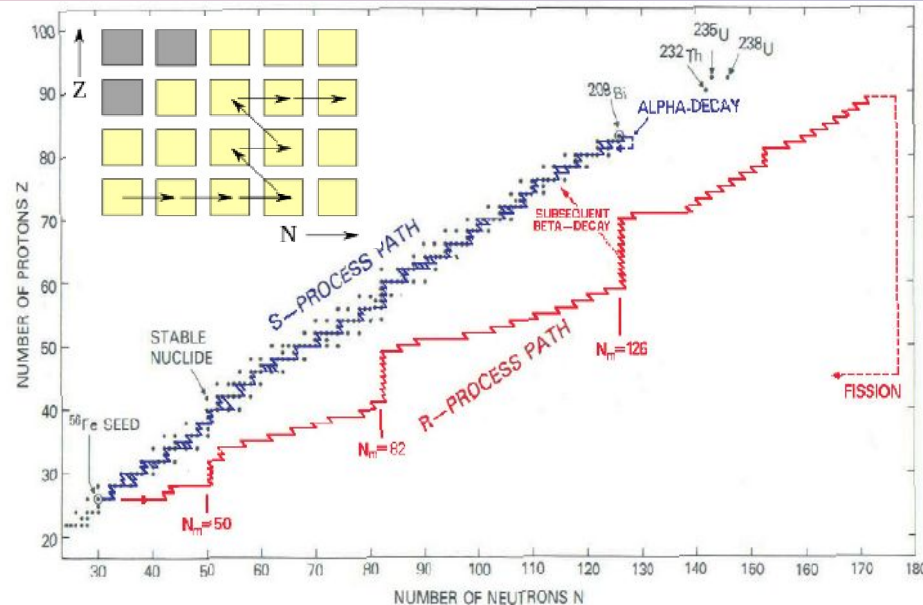
Why fission?

- **Lack of complete understanding of the process due to:**
 - Complex nuclear reaction that involves a big amount of degrees of freedom.
Coupling between intrinsic and collective excitations → Dynamics models
 - **Difficult experimental characterization.**
Isotopic identification of both fission fragments simultaneously reached in inverse kinematics using state-of-the-art R³B detectors.
- Implications in astrophysics → **r process**
- Nuclear reactors, radiotracers in medicine.



Implications in r-process

The r-process was indicated as the main mechanism responsible for the production of the **heaviest elements** in the universe. It consists of consecutive **neutron capture** and **beta decays** in **environments with high neutron flux**, as neutron star mergers or supernovae.

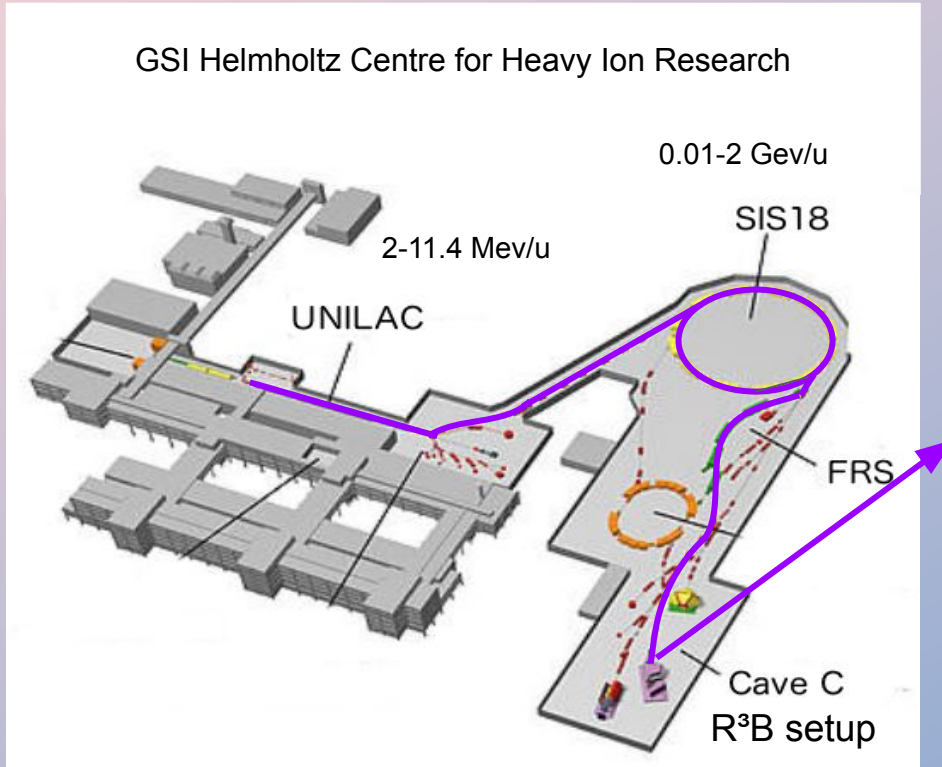


N. Vassh et al., *J. Phys. G: Nucl. Part. Phys.* 46, 065202 (2019)

Fission re-cycling: Fission limits the mass range of the r-process path, having a direct impact on the nuclide abundance. The nucleosynthesis ends when fission takes place, but then the fission products can be used as seed nuclei to start the r-process again.

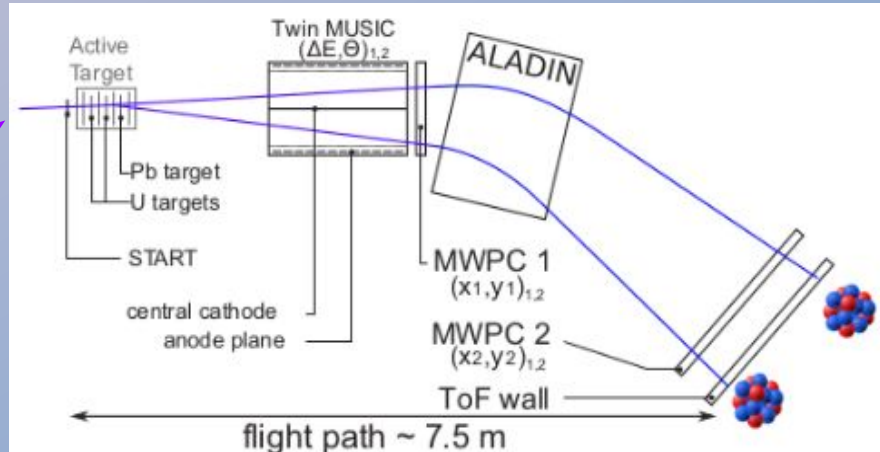
Fission studies within the R³B collaboration at GSI

The **R³B (Reactions with Relativistic Radioactive Beams GSI)** international collaboration conducts its research at the **GSI** center in Germany. The heavy-ion accelerator reaches **1 GeV/u**.



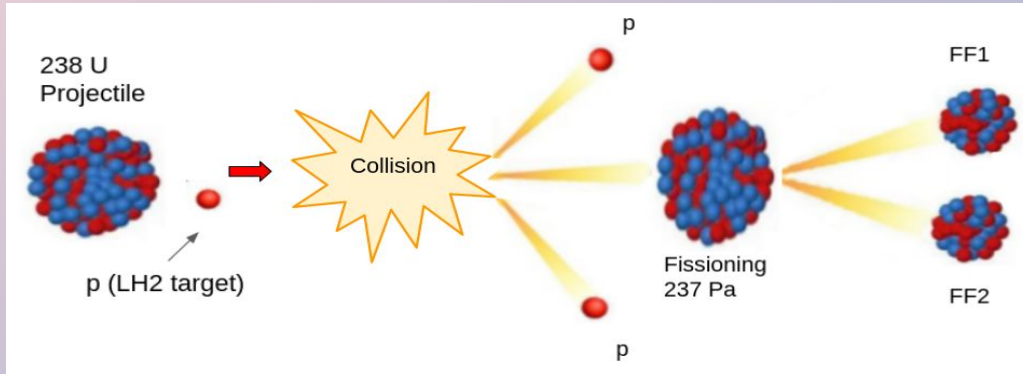
Inverse Kinematics: the heavy nucleus undergoing fission will be the projectile. Advantage: Fission fragments are emitted at high velocities in a narrow cone in the forward direction allowing to identify both simultaneously.

R³B provided in 2012 **the full isotopic identification (A, Z) of both fission fragments simultaneously.**



Phase-0 (p,2p)-fission experiment at GSI (2021)

New approach: obtain the **excitation energy of the fissioning nucleus**. Hence we induce fission via **(p, 2pf) reactions**. The (p, 2p) reaction consists of the direct knockout of a proton from the target and a proton bound to the heavy nucleus with energies between 300 and 700 MeV. In this range of energies, the influence of the other nucleons can be neglected.



Missing energy method: The measurement of the momenta of the outgoing protons allows to reconstruct the excitation energy.

$$\vec{P}_{beam} + \vec{P}_{target} = \vec{P}_p + \vec{P}_p + \vec{P}_{fissioning\ nucleus}$$

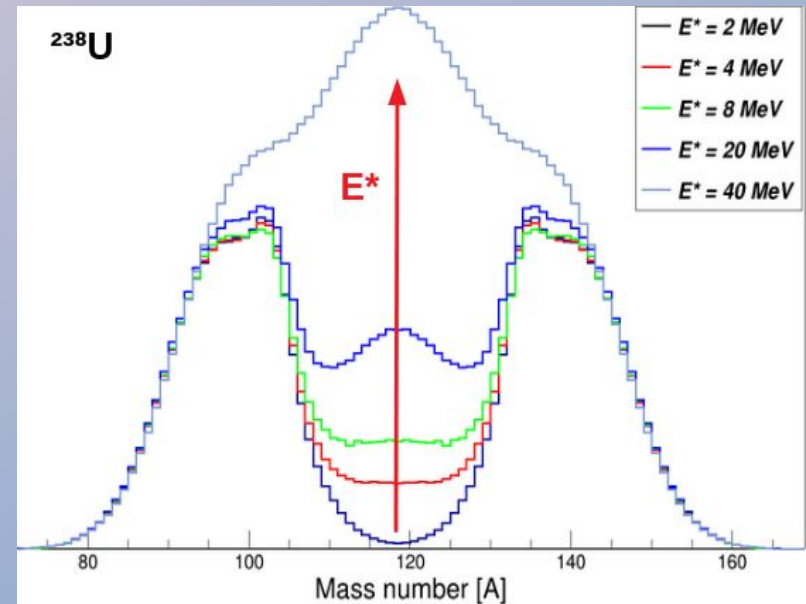
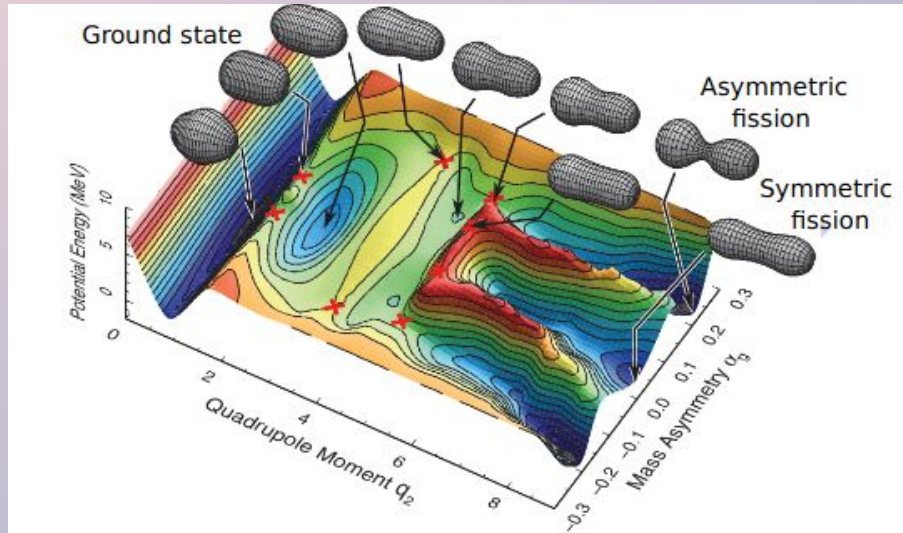
$$\begin{pmatrix} E_A \\ 0 \\ 0 \\ p_{zA}c \end{pmatrix} + \begin{pmatrix} m_p c^2 \\ 0 \\ 0 \\ 0 \end{pmatrix} = \begin{pmatrix} E_{p1} \\ p_{xp1}c \\ p_{yp1}c \\ p_{zp1}c \end{pmatrix} + \begin{pmatrix} E_{p2} \\ p_{xp2}c \\ p_{yp2}c \\ p_{zp2}c \end{pmatrix} + \begin{pmatrix} E_{A-1} \\ p_{xA-1}c \\ p_{yA-1}c \\ p_{zA-1}c \end{pmatrix}$$

$$Q = \frac{\sqrt{(E_A + m_p c^2 - (E_{p1} + E_{p2}))^2 - ((p_{p1x}c + p_{p2x}c)^2 + (p_{p1y}c + p_{p2y}c)^2)}}{+(\sqrt{E_A^2 - m_A^2 c^4 - (p_{p1z}c + p_{p2z}c)^2})}.$$

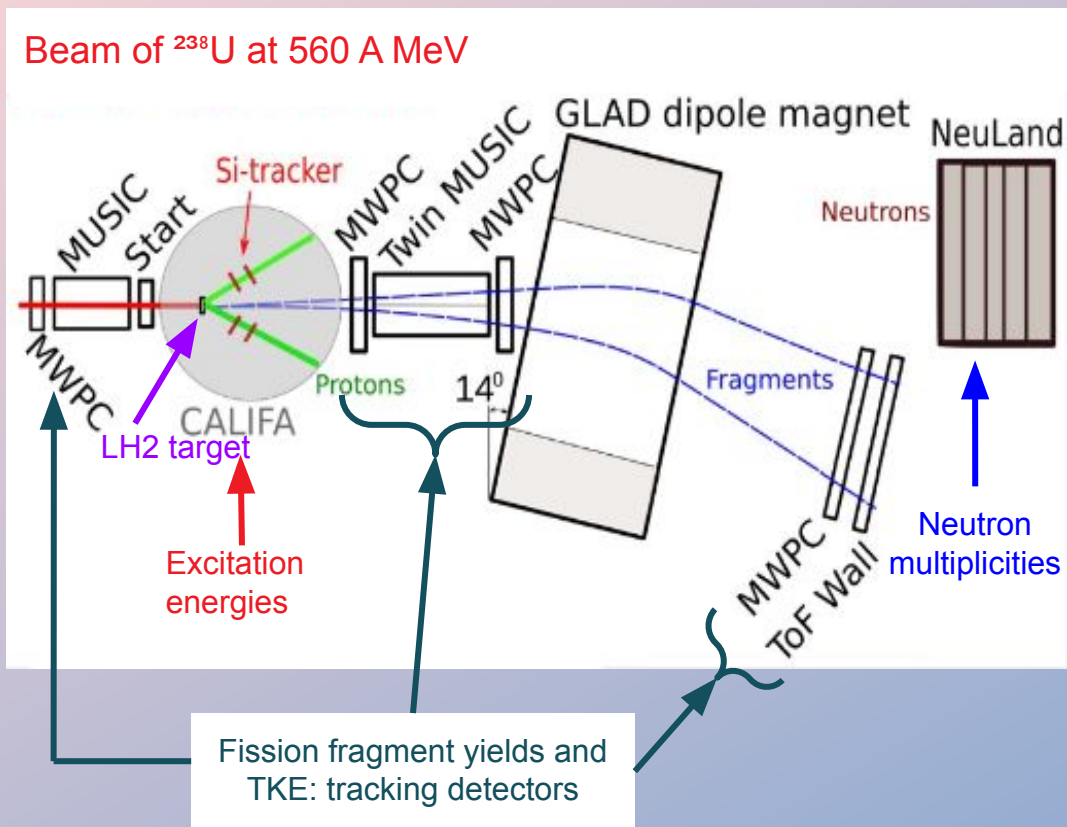
$$E^* = Q - m_{A-1} c^2$$

Phase-0 (p,2p)-fission experiment at GSI (2021)

First (p,2p) - fission experiment to correlate the excitation energy with the fission yields. The excitation energy can populate different regions of the potential energy landscape, leading to different fission paths which will be evidenced in the fission yields distributions. We expect to see a transition from asymmetric to symmetric with the increasing of excitation energy.

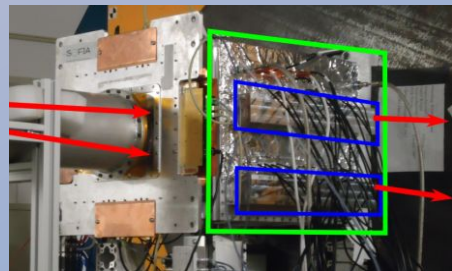


Phase-0 (p,2p)-fission experiment at GSI (2021)



- Fission yields and TKE gained by the fragments:** MWPC's for tracking and TOFWall for TOF measurements. $\Delta Z \sim 0.32$, $\text{ToF} \sim 40\text{ps}$, Position res. $250\mu\text{m}$ (FWHM) $\Delta A \sim 0.3-0.6$ A. Chatillon et al., Phys. Rev. Lett. 102, 202502 (2020)
- Prompt neutron multiplicities:** NeuLand

Twim
Music



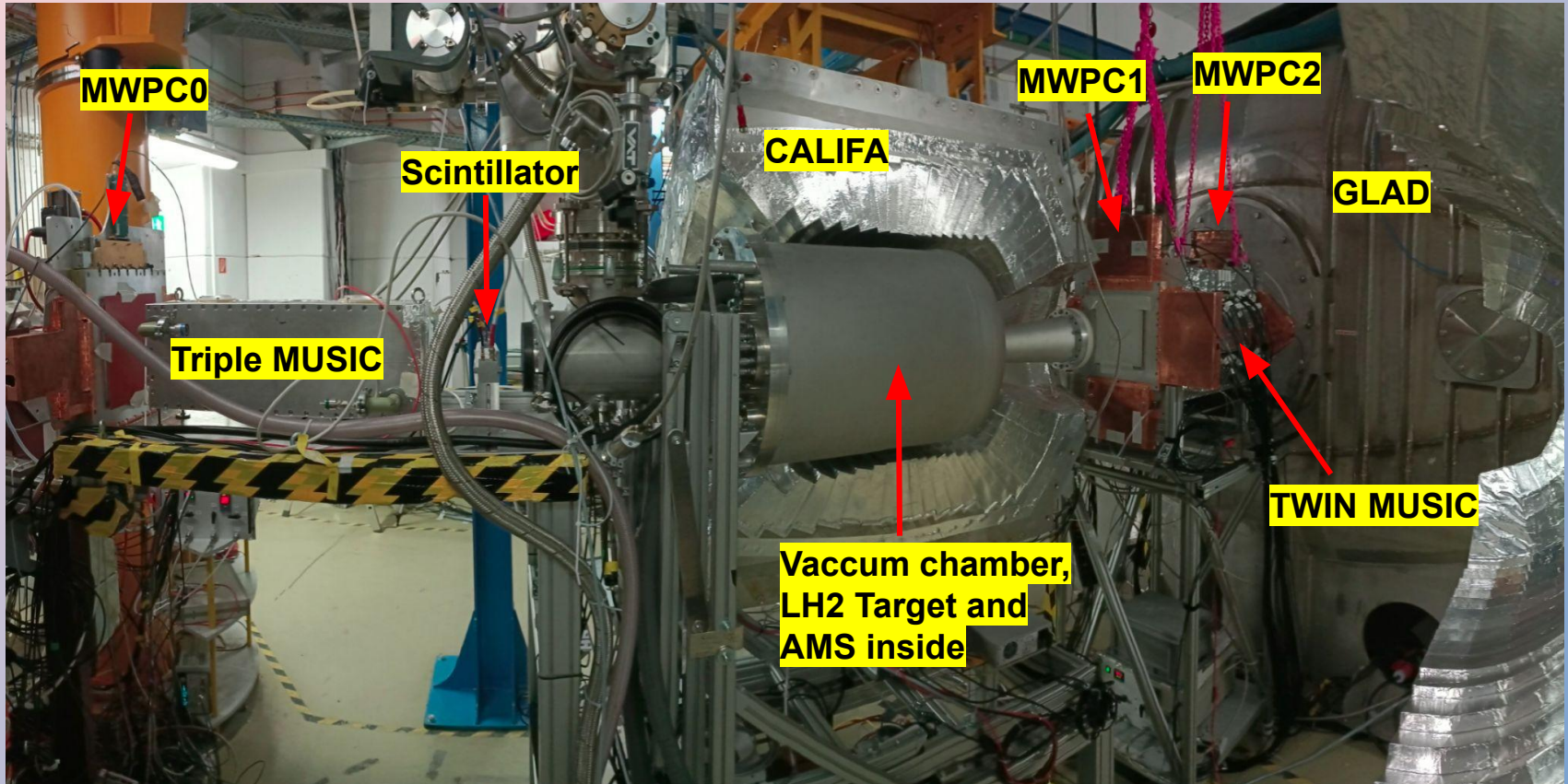
MWPC



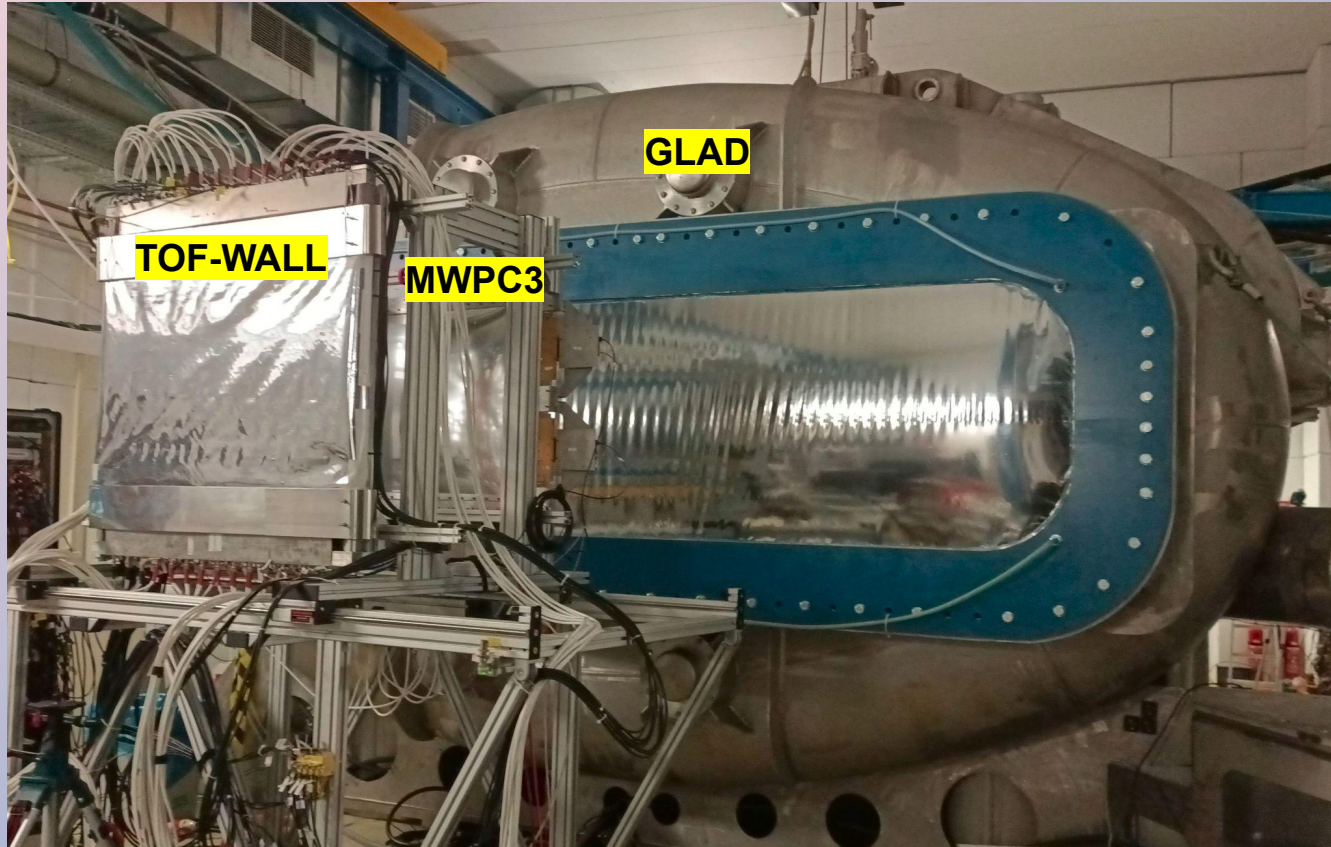
ToF Wall



Phase-0 (p,2p)-fission experiment at GSI (2021)

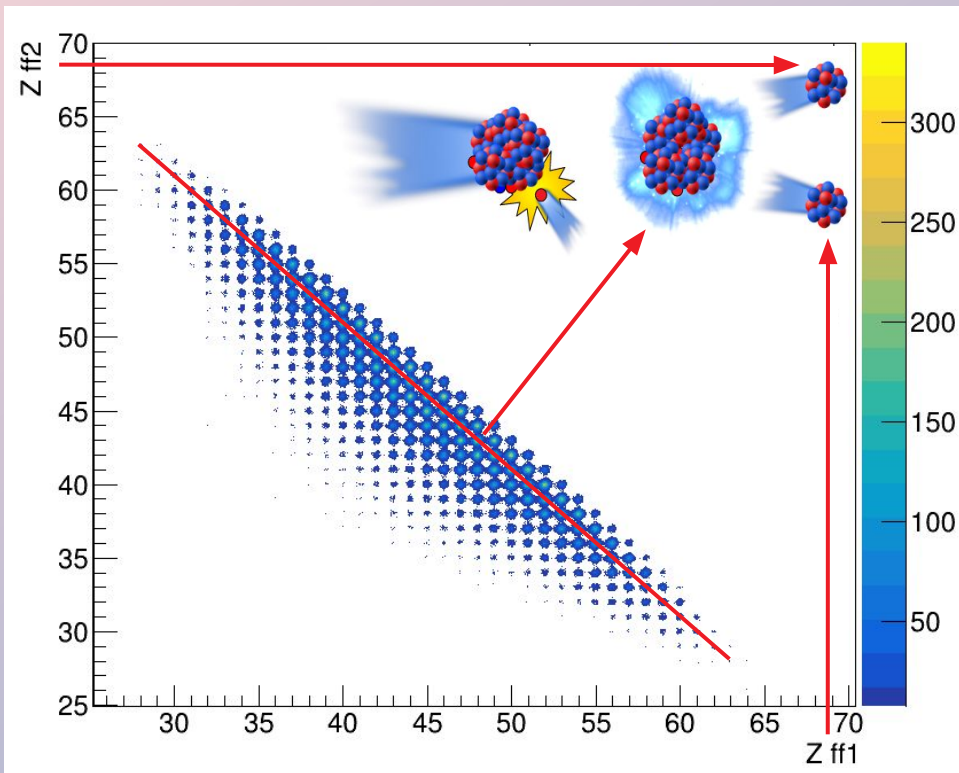


Phase-0 (p,2p)-fission experiment at GSI (2021)

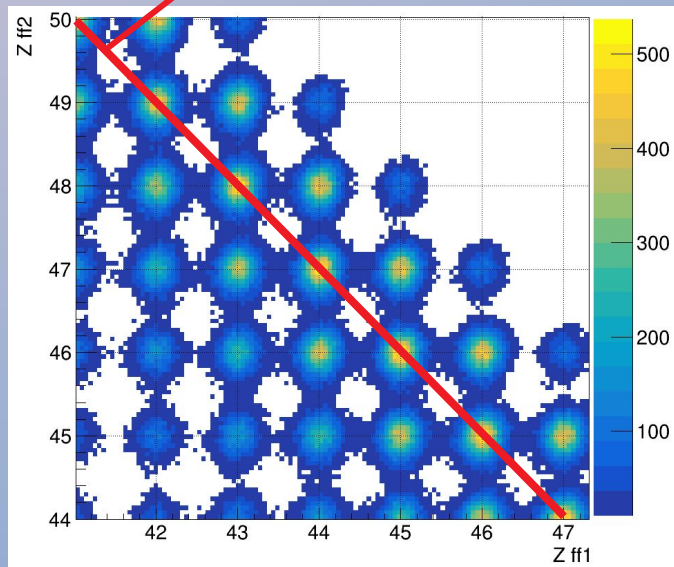
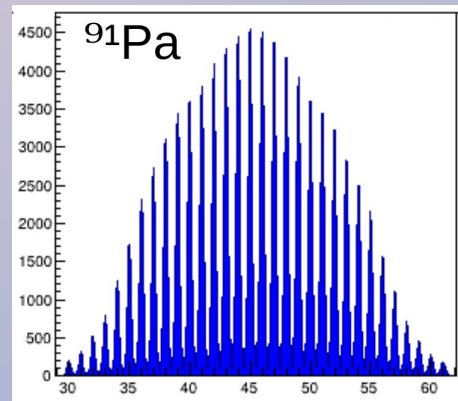


Phase-0 (p,2p)-fission experiment at GSI (2021)

Fission fragment charge identification

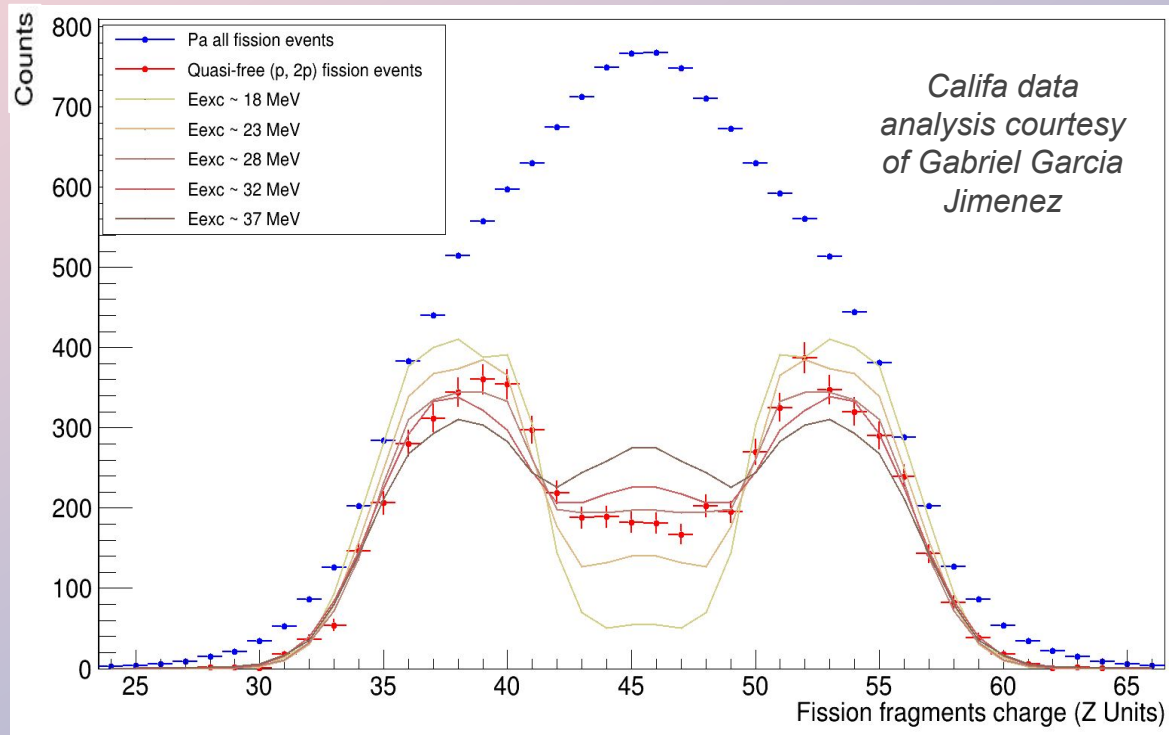


Resolution:
0.38 units
(FWHM)



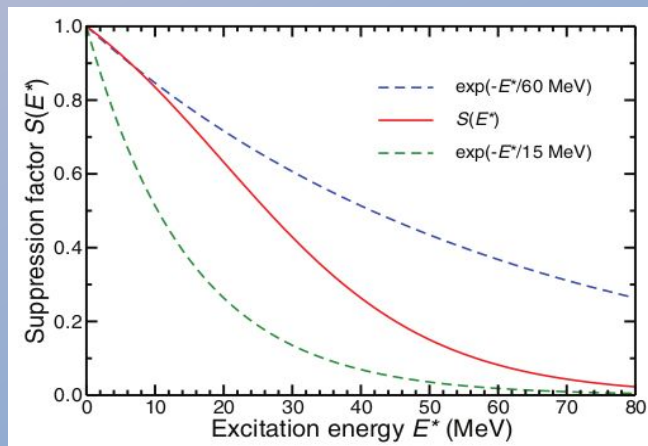
Phase-0 (p,2p)-fission experiment at GSI (2021)

First estimation of the excitation energy of the nucleus. Comparison of data with INCL+ABLA calculations.



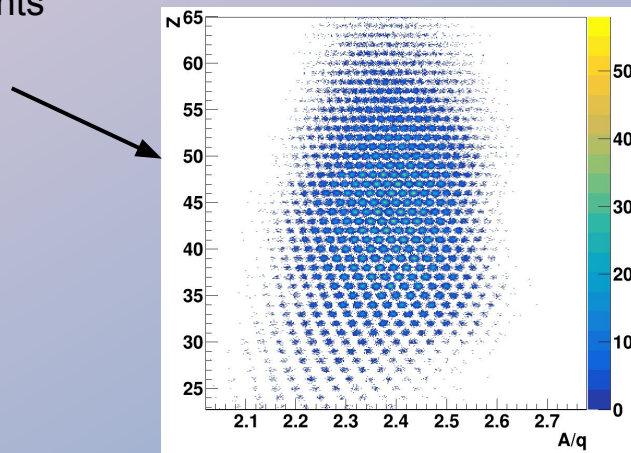
$$E_{\text{Exc}} \approx 25\text{-}30 \text{ MeV}$$

The suppression function tries to quantify the weakening of the shell effects expression with the increasing of the excitation energy.



Conclusions

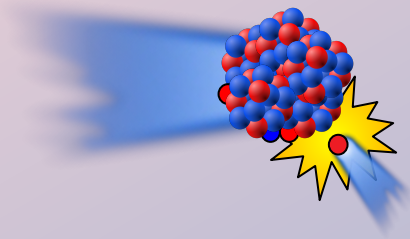
- **First (p,2p)-fission experiment** with ^{238}U to correlate the excitation energy with the fission yields:
- Fission fragments identification with a very good resolution: **0.38 units (FWHM)**
- We checked that the **fission yields** are sensitive to the **excitation energy** of the fissioning system.
- Soon: isotopic identification of fission fragments



- Future (p,2p)-fission experiments at GSI-FAIR neutron-rich heavy nuclei around $N=152$ to constrain theoretical r-process models.
 - Fission barrier heights.
 - Fission yields.

Acknowledgements





The end

