Fairness 2022, 7th Workshop

Quasi-free (p,2p) reactions in inverse kinematics for studying fission and its implication in the nucleosynthesis r-process

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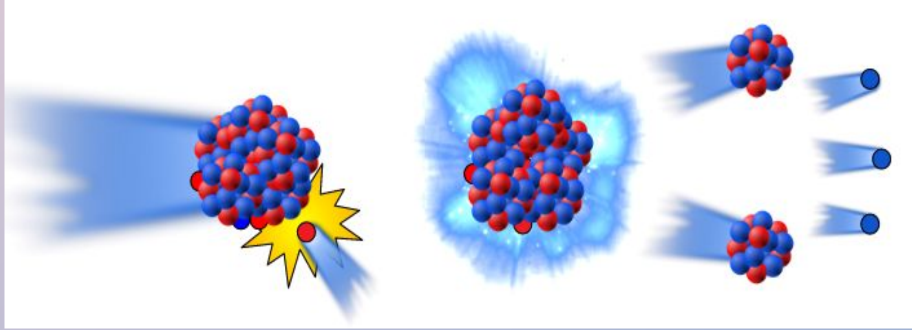
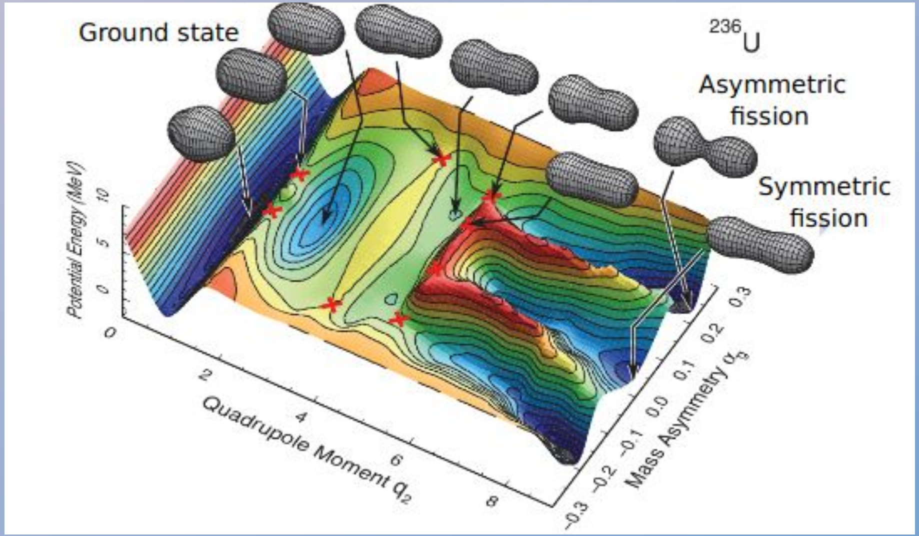
Fission

Fission is the **splitting of a heavy nucleus into lighter nuclei of comparable mass,** plus some products such as neutrons, alpha and beta particles, and high-energy gamma rays. Discovered by **Otto Hahn** and **Lise Meitner** in **1938**.



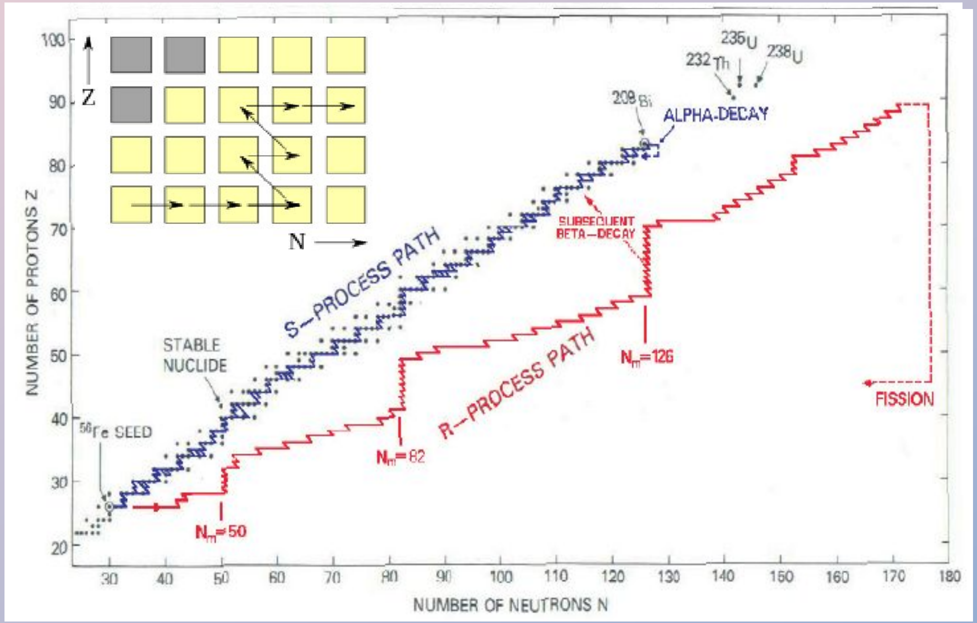
Why fission?

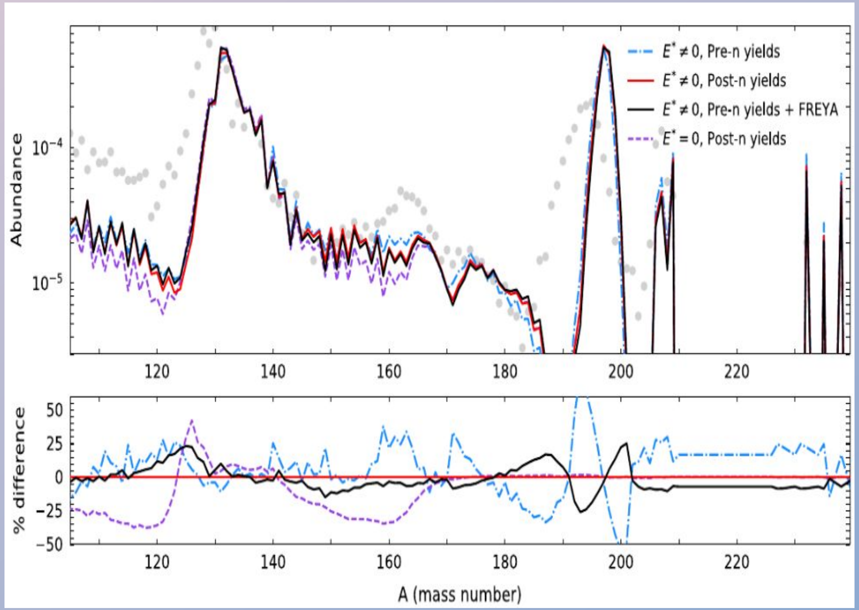
- **Lack of complete understanding of the process:**
  - **Coupling between intrinsic and collective excitations** → Dynamics models
  - **A difficult experimental characterization.** Identification of both fission fragments (A,Z) only reaches in inverse kinematics using state-of-the-art R^3B detectors.
- Nuclear matter dynamics science
- 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.

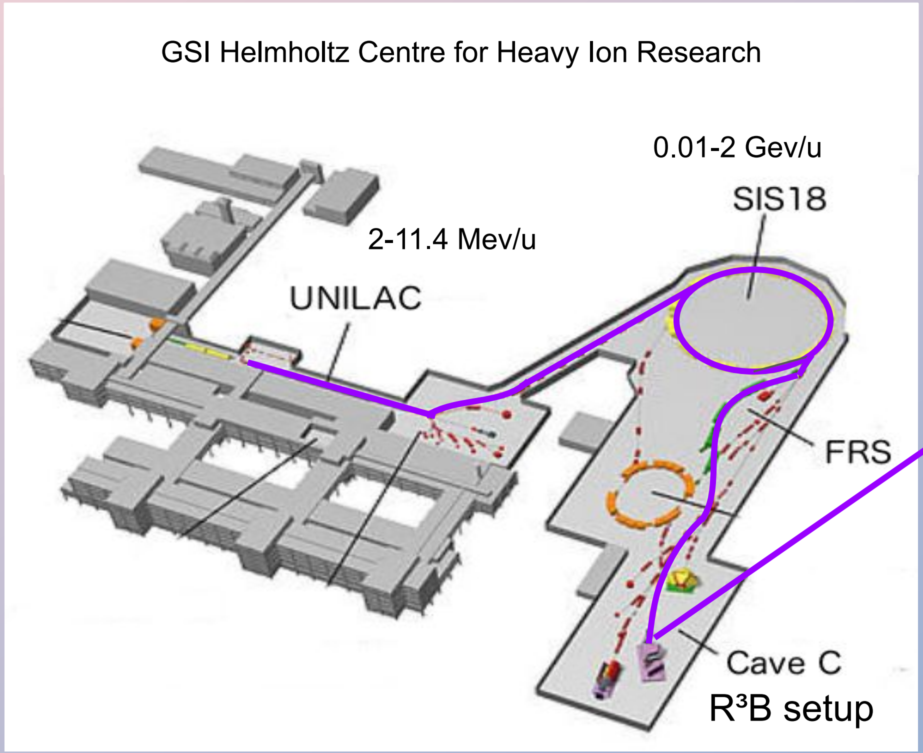




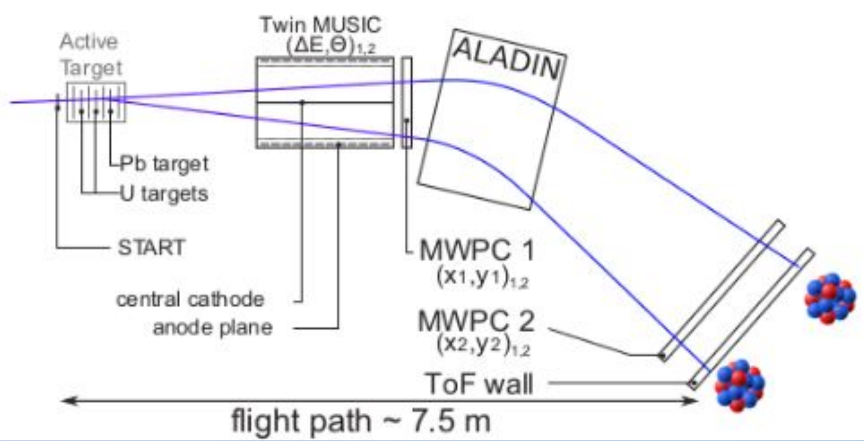
Fission re-cycling: Fission limits the mass range of the r-process path, having a direct impact on the nuclide abundance. The formation goes up to the heaviest nuclei until the fission barrier height drops below the neutron separation energy, which defines the termination of the element synthesis.

State-of-the art experiments within the R³B collaboration

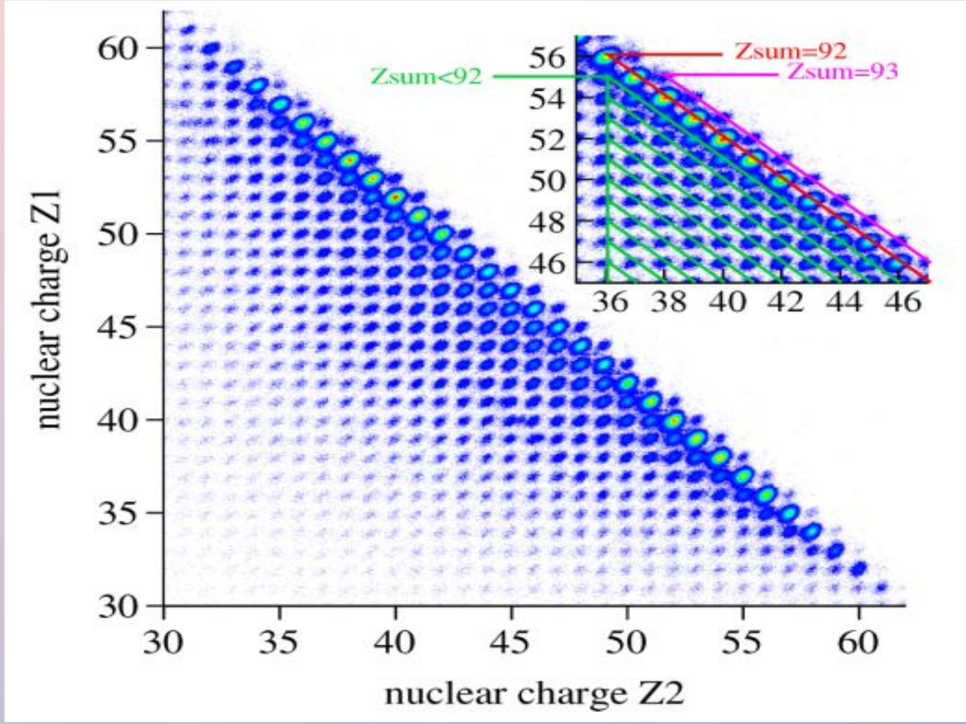
The **R³B (Reactions with Relativistic Radioactive Beams GSI)** international collaboration conducts its research at the **GSI** center in Germany, the only heavy-ion accelerator capable to reach the **1 GeV/u.**

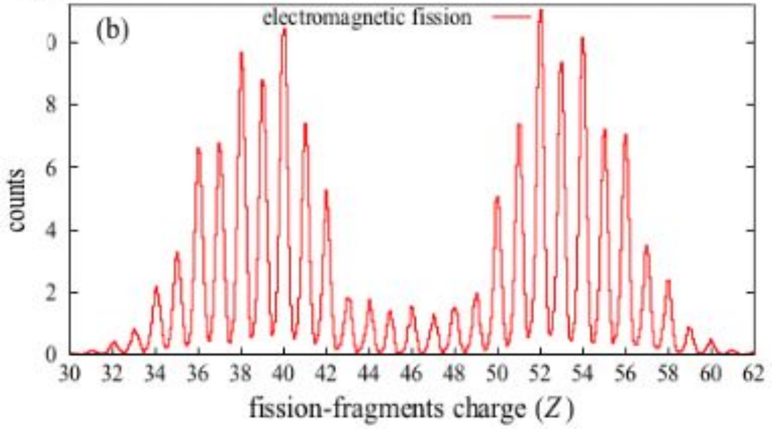


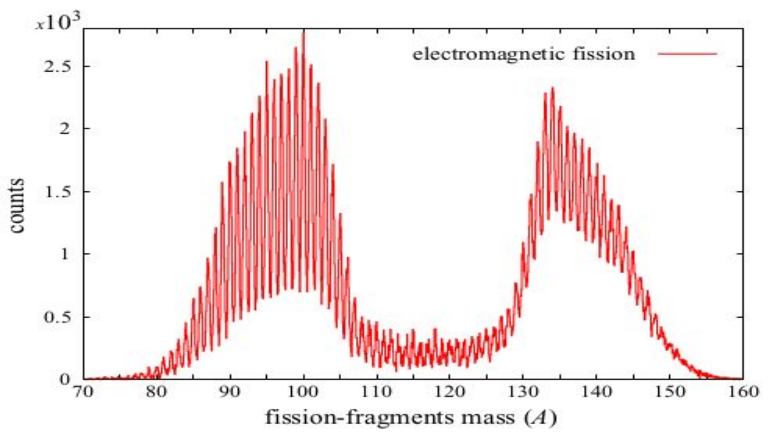
Inverse Kinematics: the heavy nucleus undergoing fission will be the projectile. Fission fragments are emitted at high velocities in a narrow cone in the forward direction allowing to identify both simultaneously. R³B provided in 2012 for the **1st time the complete isotopic identification of both fission fragments in charge and mass.**



State-of-the art experiments within the R3B collaboration





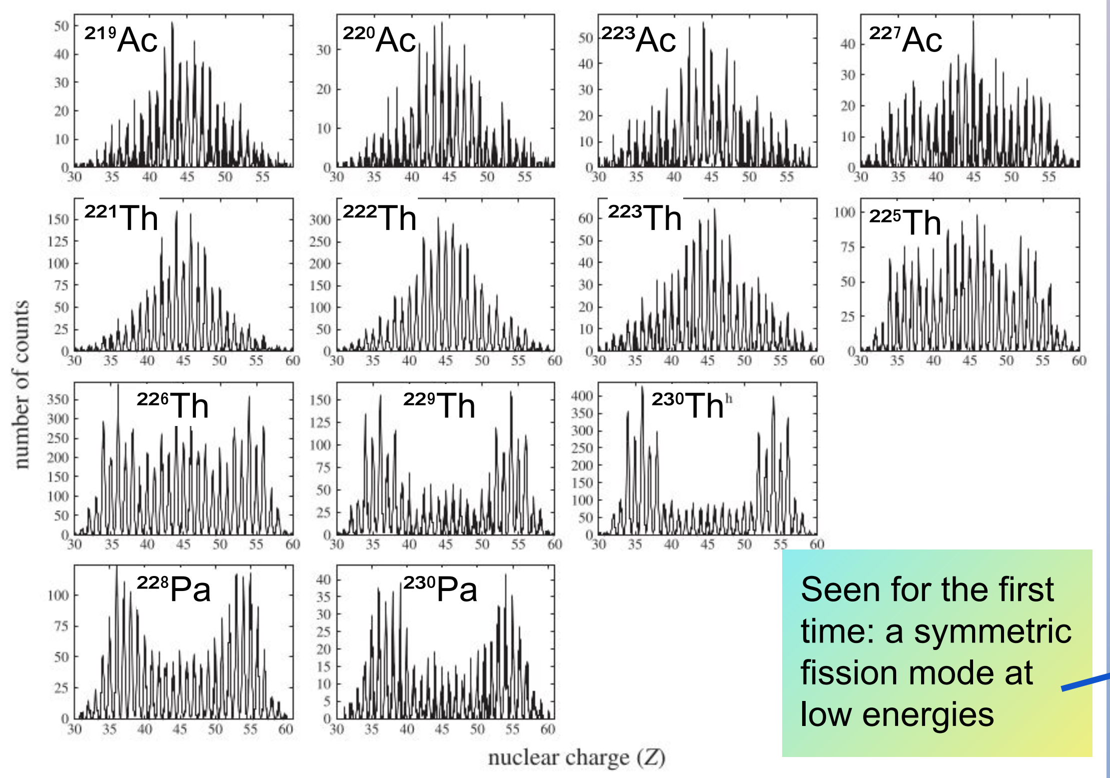


E. Pellereau et al., Physical Review C 95, 054603 (2017)
Julie-Fiona Martin et al., Eur. Phys. J. A (2015) 51: 174
A. Chatillon et al., Phys. Rev. C 99, 054628 (2019)

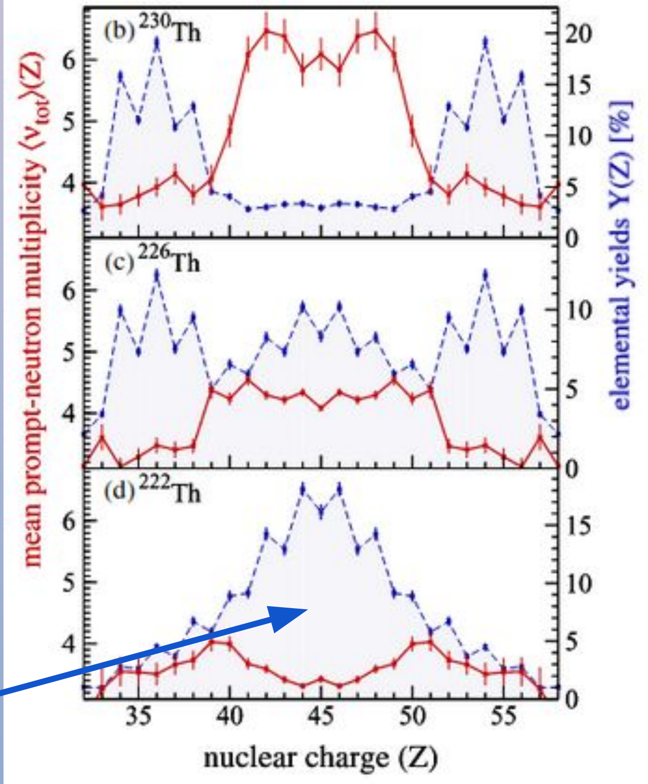
State-of-the art experiments within the R3B collaboration

Nuclear structure: Evidence of a **new fission mode** from fission of Th isotopes.

A. Chatillon et al., Phys. Rev. Lett. 102, 202502 (2020)

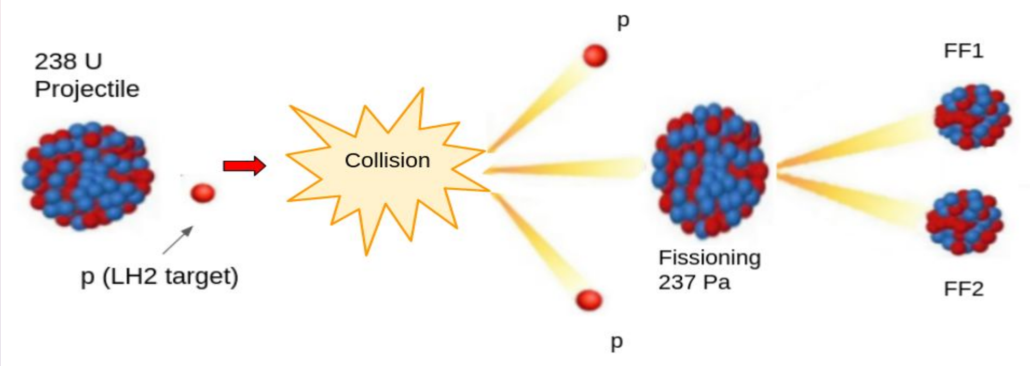


Seen for the first time: a symmetric fission mode at low energies



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 measurement of the momenta of the outgoing protons allows to reconstruct the excitation energy.

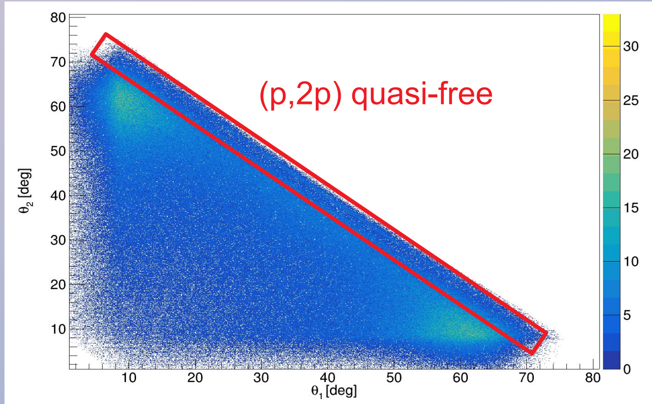


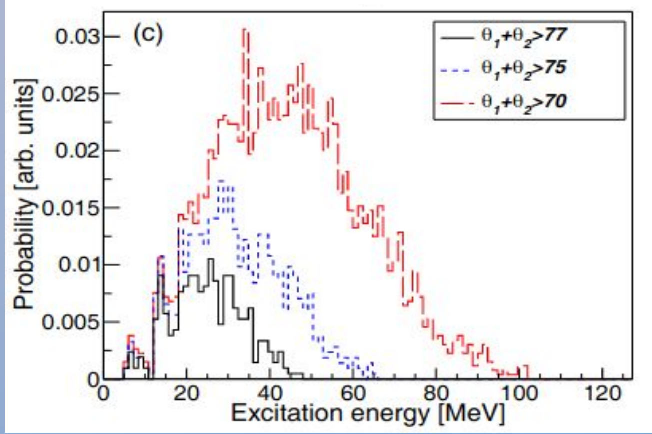
$$\vec{P}_{beam} + \vec{P}_{target} = \vec{P}_p + \vec{P}_p + \vec{P}_{fissioning\, nucleus}$$

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

Missing energy method

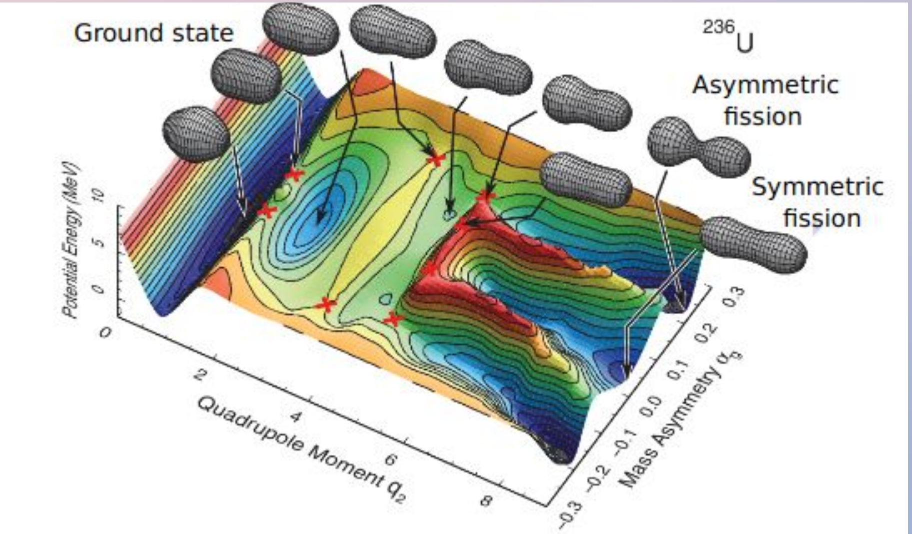
$$E^* = Q - m_{A-1}c^2$$

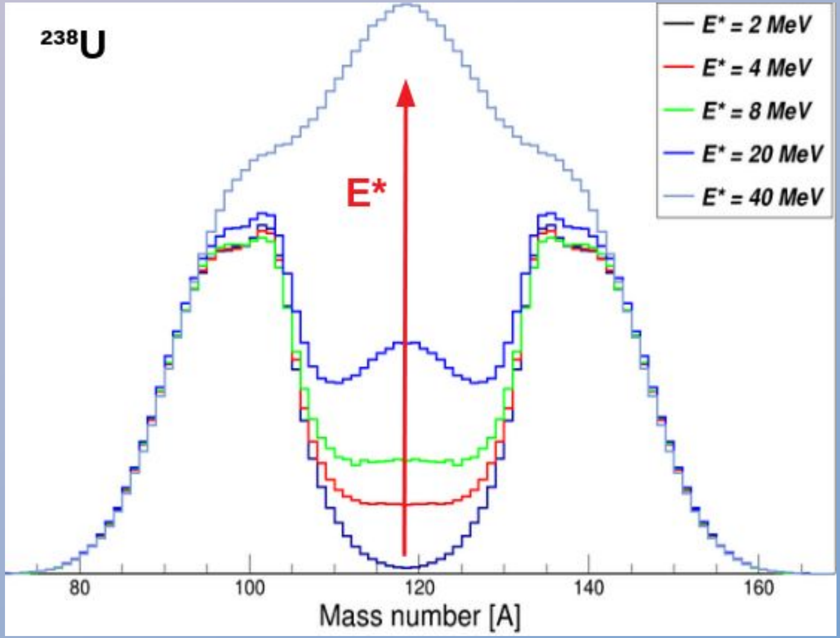




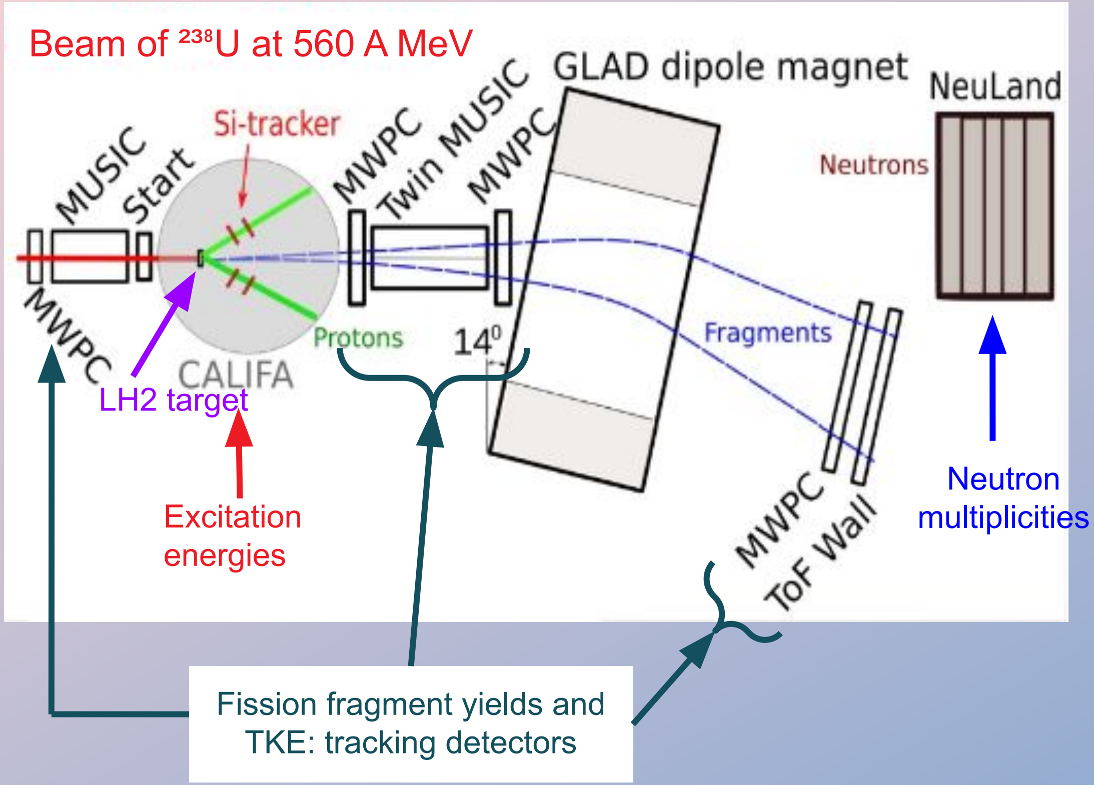
Phase-0 (p,2p)-fission experiment at GSI (2021)

First (p,2p) - fission experiment to correlate the excitation energy with the fission yields. The excitation energy can populate different regions of the potential landscape, leading to different fission paths.



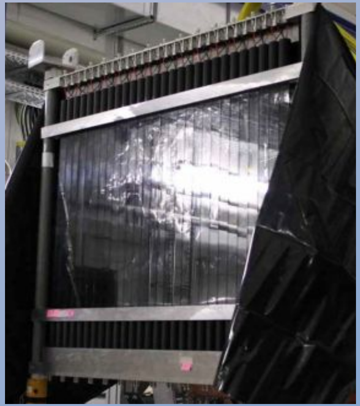


Phase-0 (p,2p)-fission experiment at GSI (2021)

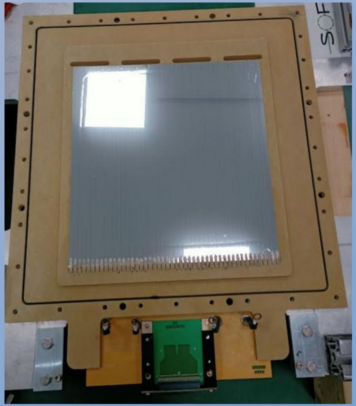


- **Fission yields and TKE gained by the fragments**: MWPC's for tracking and TOFWall for TOF measurements. ΔZ~0.32 , ToF~40ps, Position res. 250μm (FWHM)
- **Prompt neutron multiplicities**: Neuland

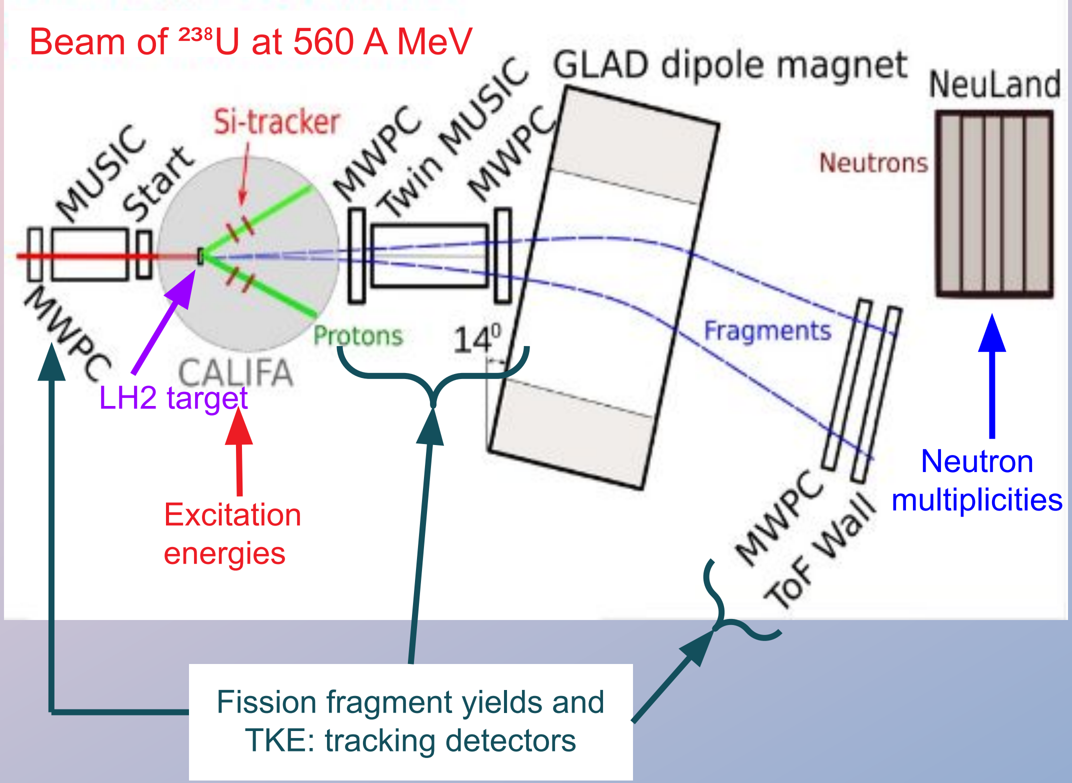
ToF Wall



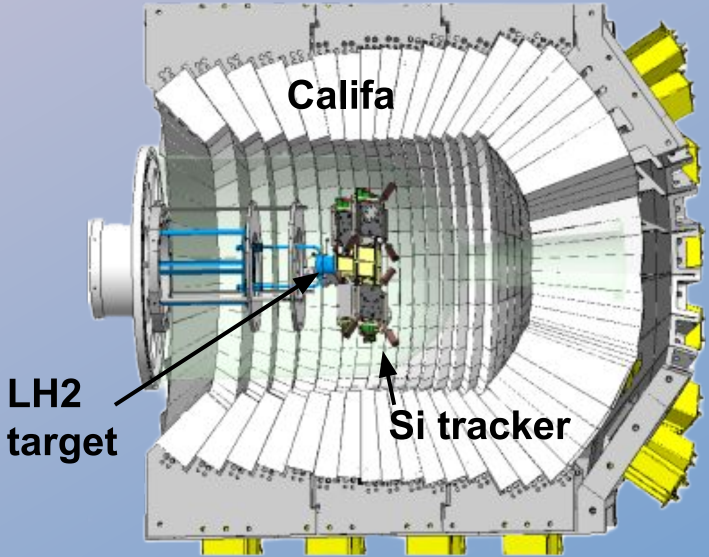
MWPC



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



- **Excitation energy of the fissioning system**: **Califa** and **Silicon tracker** surrounding the **LH2 target**.
  - Energy res. protons(gamma) 1%(5.5% at 1.3 MeV)
  - Position res. 70μm



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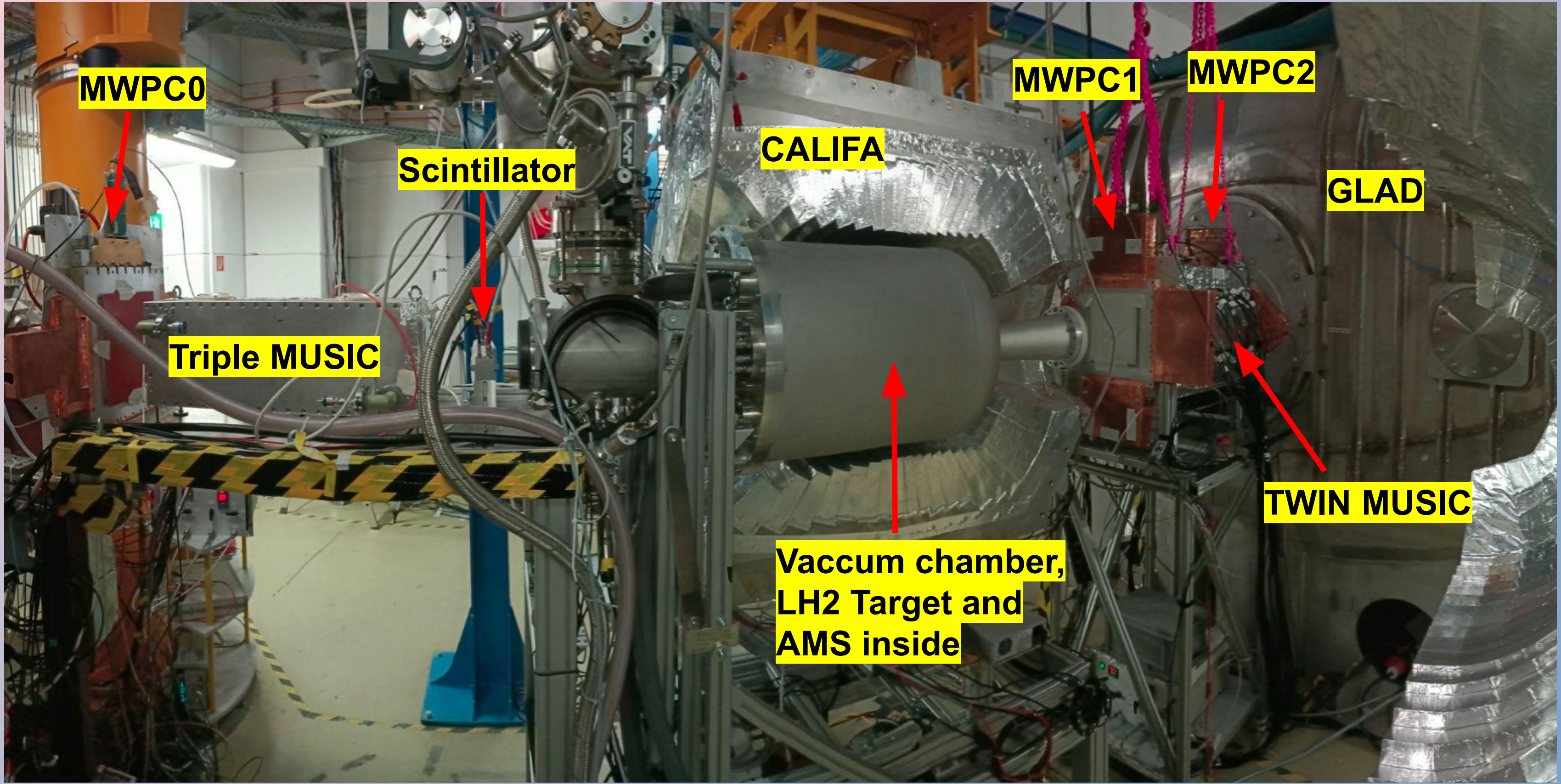

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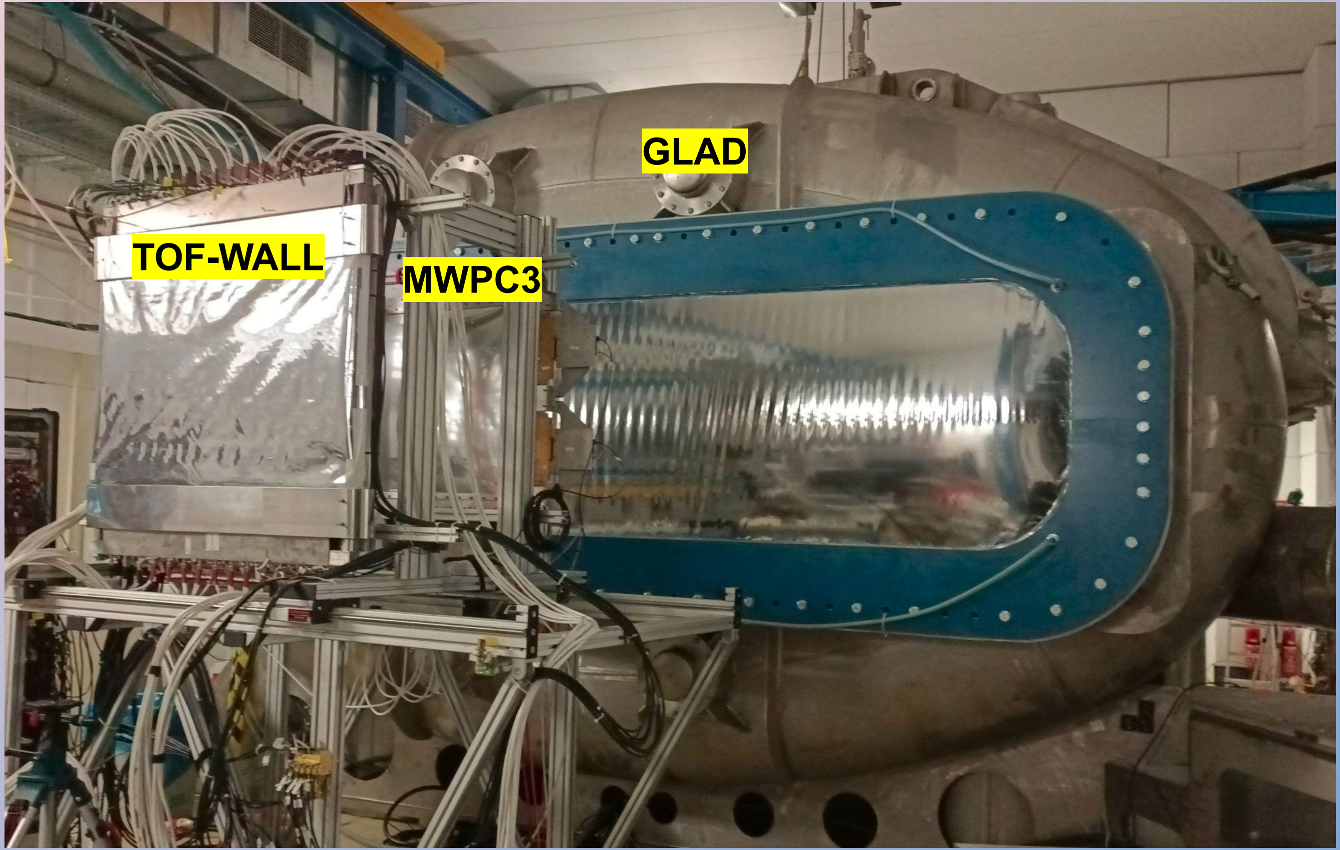
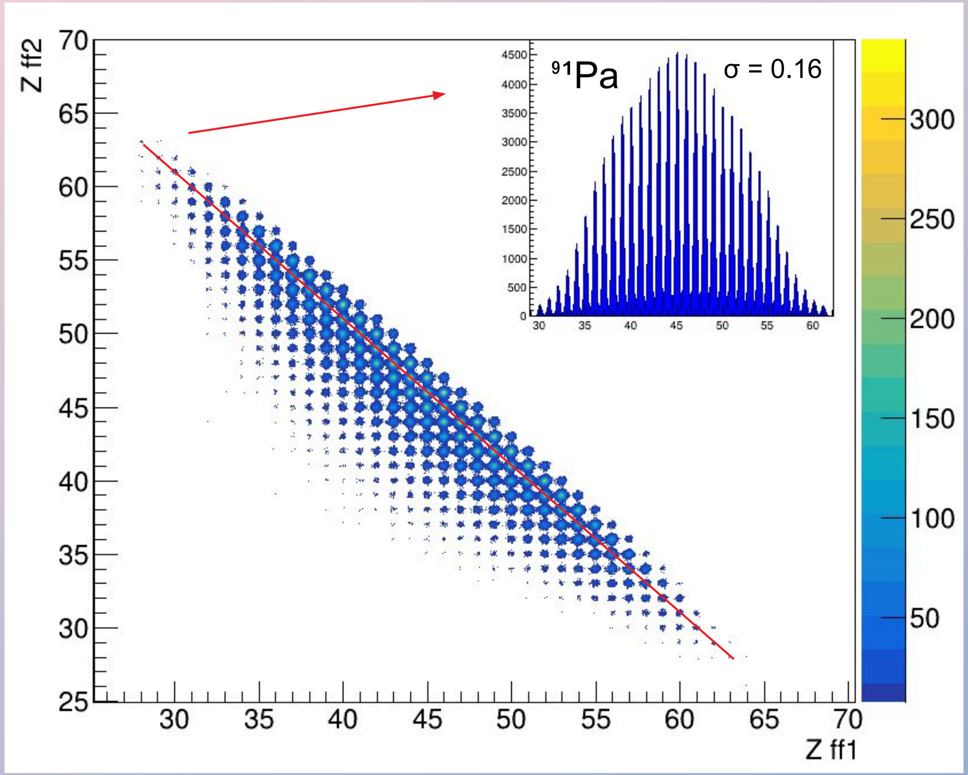
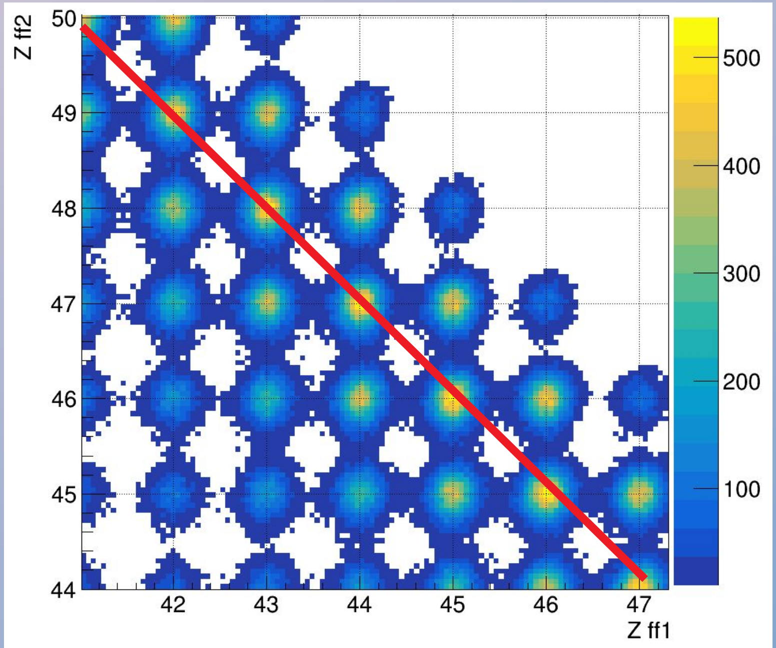


Phase-0 (p,2p)-fission experiment at GSI (2021)

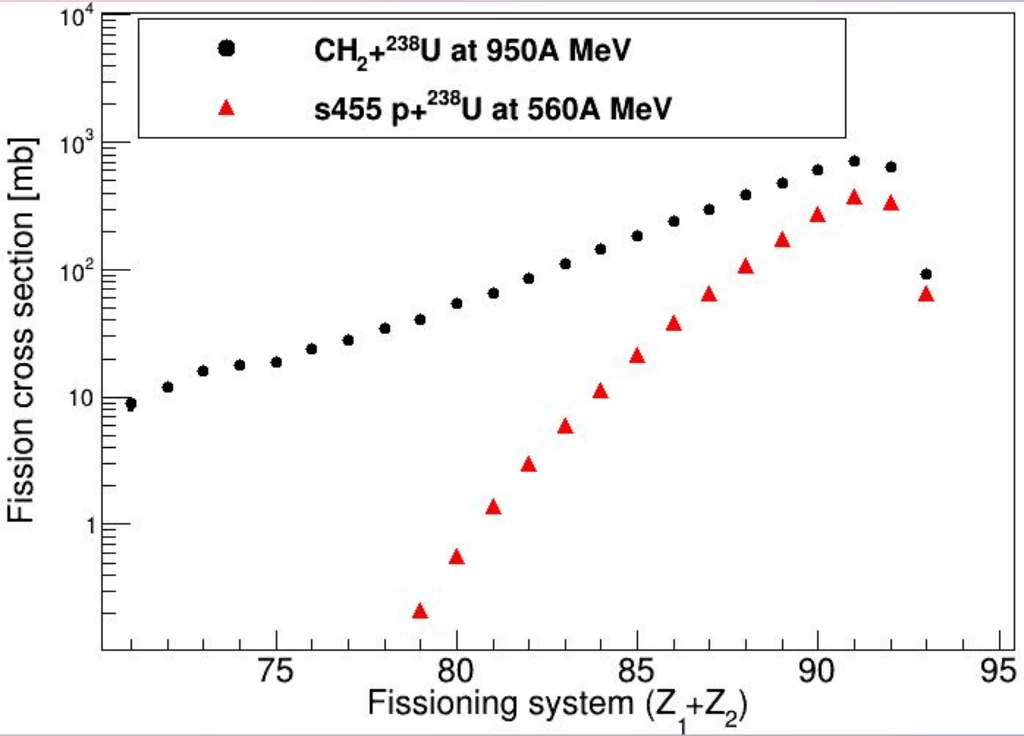
Fission fragment identification





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

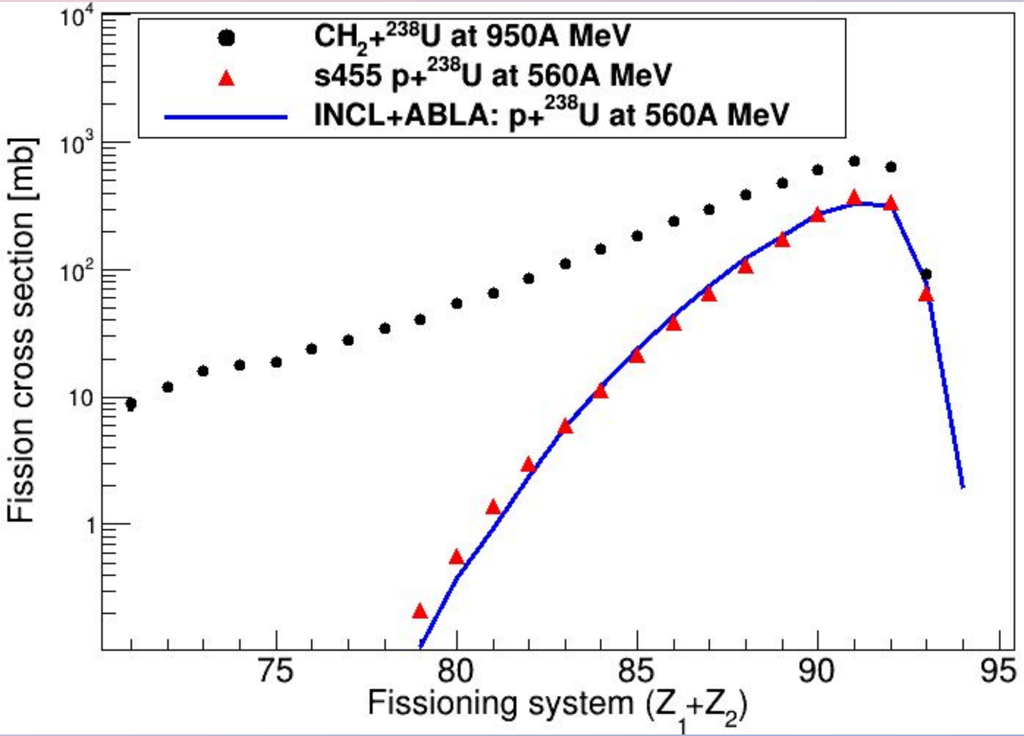
Cross section of each fissioning system obtained multiplying the yields by the fission cross section



As expected, the fission cross sections for the p,2pf reactions (spallation) are lower than the ones from fragmentation reactions. Since less nucleons are removed for the spallation reactions, its fissioning system range is shorter (differentiable peaks between ~79-93).

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

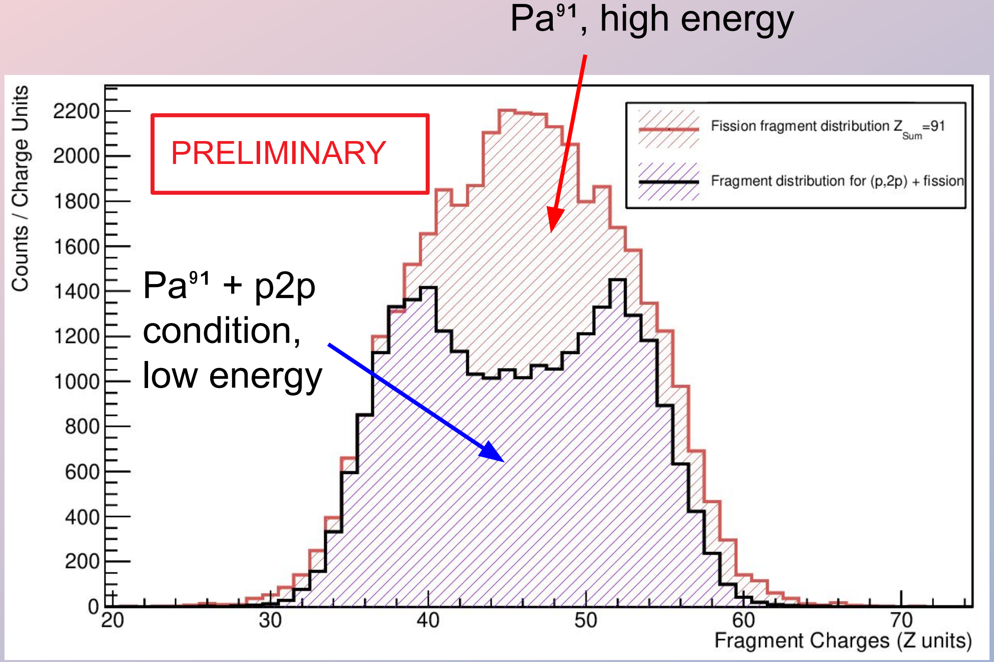
Cross section of each fissioning system obtained multiplying the yields by the fission cross section

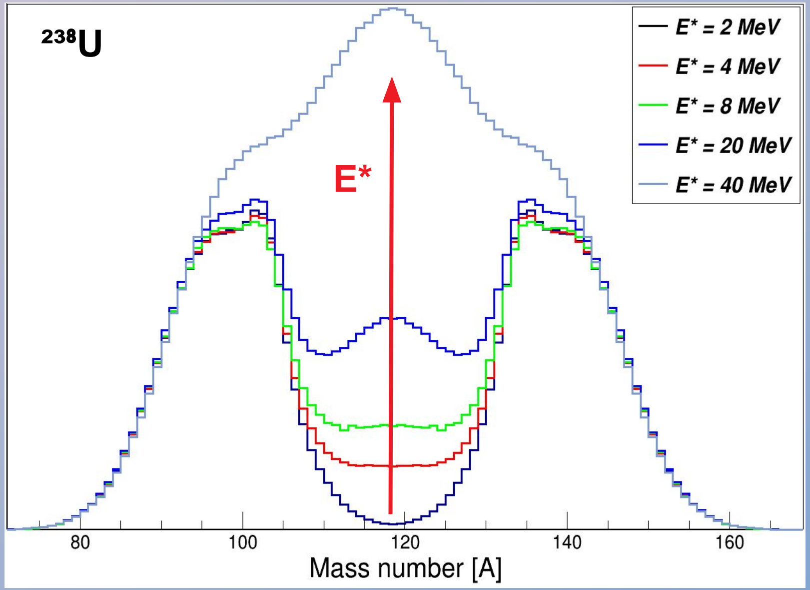


As expected, the fission cross sections for the p,2pf reactions (spallation) are lower than the ones from fragmentation reactions. Since less nucleons are removed for the spallation reactions, its fissioning system range is shorter (differentiable peaks between ~79-93).

Results are compatible with the theoretical calculations from INCL+ABLA.

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





Courtesy of Gabriel Garcia Jimenez

Conclusions

● The state-of-the art fission experiments carried out at GSI are providing valuable data to study the nuclear structure and dynamics of exotic nuclei.

- Discovery of a new fission mode.

● First (p,2p)-fission experiment with ^{238}U to correlate the excitation energy with the fission yields:

- Fission fragments identification.
- Fission cross sections measured.
- Fission fragments charge distribution widths.
- Isotopic identification of fission fragments.
- Fission yields dependence on fissioning system excitation energy.

● 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

USC
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MINISTERIO DE CIENCIA E INNOVACIÓN

AGENCIA ESTATAL DE INVESTIGACIÓN

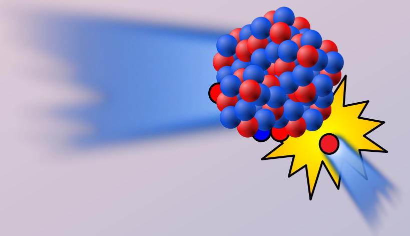
R3B

GENP
Grupo Experimental de Núcleos y Partículas

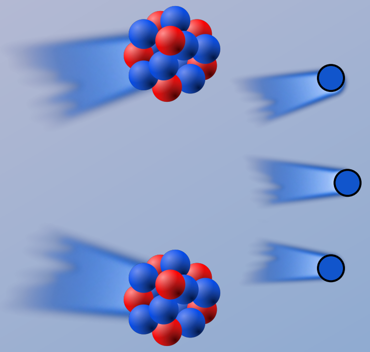
FAIR
GSI

DE LA RECHERCHE À L'INDUSTRIE
cea

TECHNISCHE UNIVERSITÄT DARMSTADT



The end



Backup

Intrinsic and collective degrees of freedom

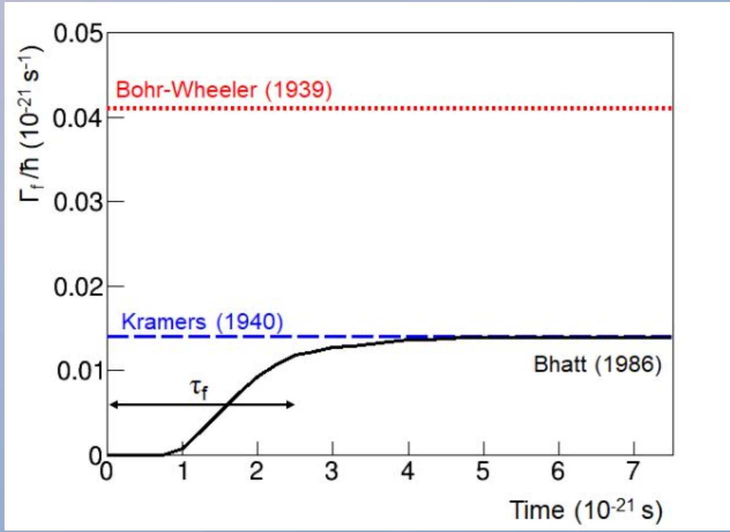
- Intrinsic excitations are based on the states of the individual constituents and form a heat bath.
- Collective modes correspond to the coordinate motion of part or all the nucleons, ie, vibrations, rotations and all kind of deformations.

Coupling: energy exchange between the collective degrees of freedom and the heat bath. Thus, the passage over the saddle point is described as a **diffusion** process where the coupling between intrinsic and collective degrees of freedom is parametrized as a function of a dissipation parameter.
This dissipation parameter introduces a **time delay of the collective motion** of the fissioning system, the so-called **transient time**, owing to the **irreversible energy flow from collective modes to intrinsic excitations**

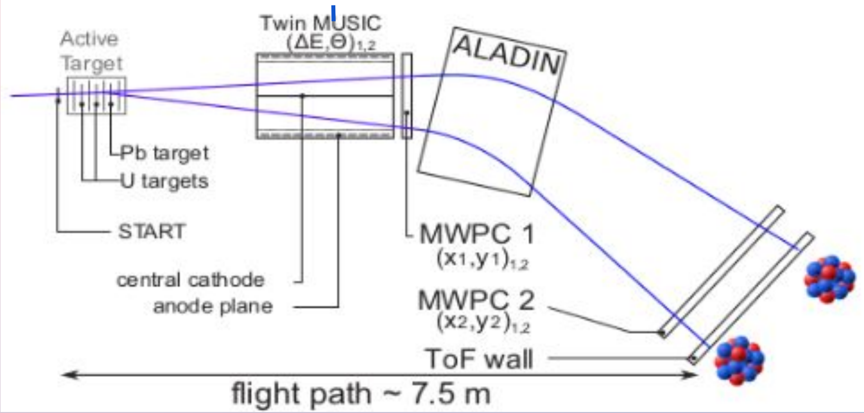
$$\Gamma_{BW} = \frac{1}{2\pi\rho_i(E_i, J_i)} \int d\epsilon \rho_{sad}(E_i - B_f(J_i) - \epsilon)$$

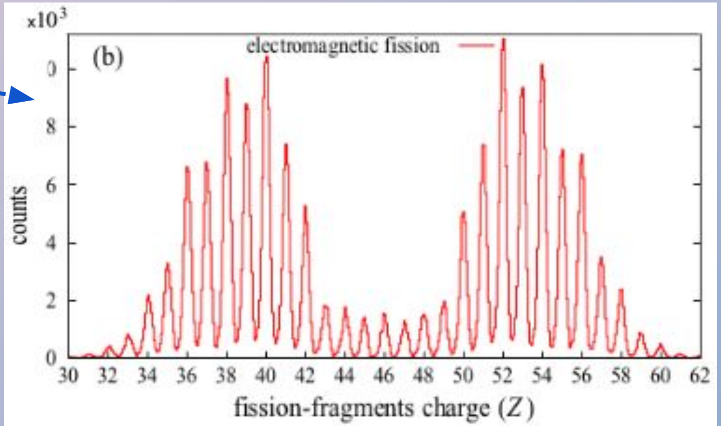
$$\Gamma_f^K = \Gamma_{BW} \cdot K = \Gamma_{BW} \cdot \left(\left[1 + \left(\frac{\beta}{2\omega_0} \right)^2 \right]^{\frac{1}{2}} - \frac{\beta}{2\omega_0} \right)$$

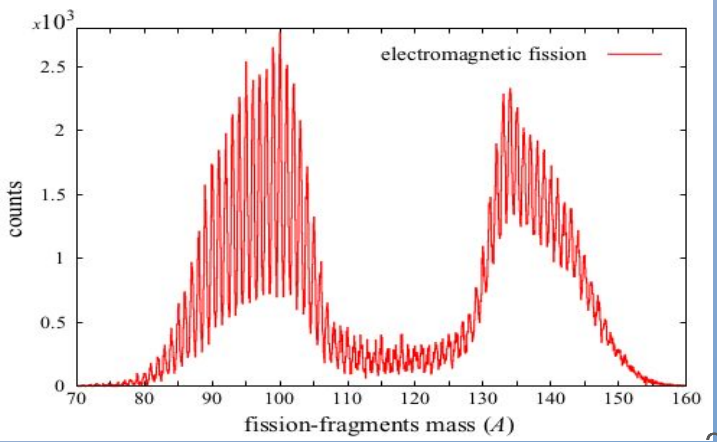
$$\Gamma_f(t) = K \cdot \Gamma_{BW} \cdot \frac{W_n(x = x_b; t, \beta)}{W_n(x = x_b; t \to \infty, \beta)}$$



State-of-the art experiments within the R3B collaboration







Deflection radius
from the tracking

Velocity from the tracking
(mwpc) and tof

Magnetic
field

$$B\rho = \frac{p}{Q} = \frac{A}{q \times e} u\beta\gamma c$$

E. Pellereau et al., Physical Review C 95, 054603 (2017)
Julie-Fiona Martin et al., Eur. Phys. J. A (2015) 51: 174
A. Chatillon et al., Phys. Rev. C 99, 054628 (2019)

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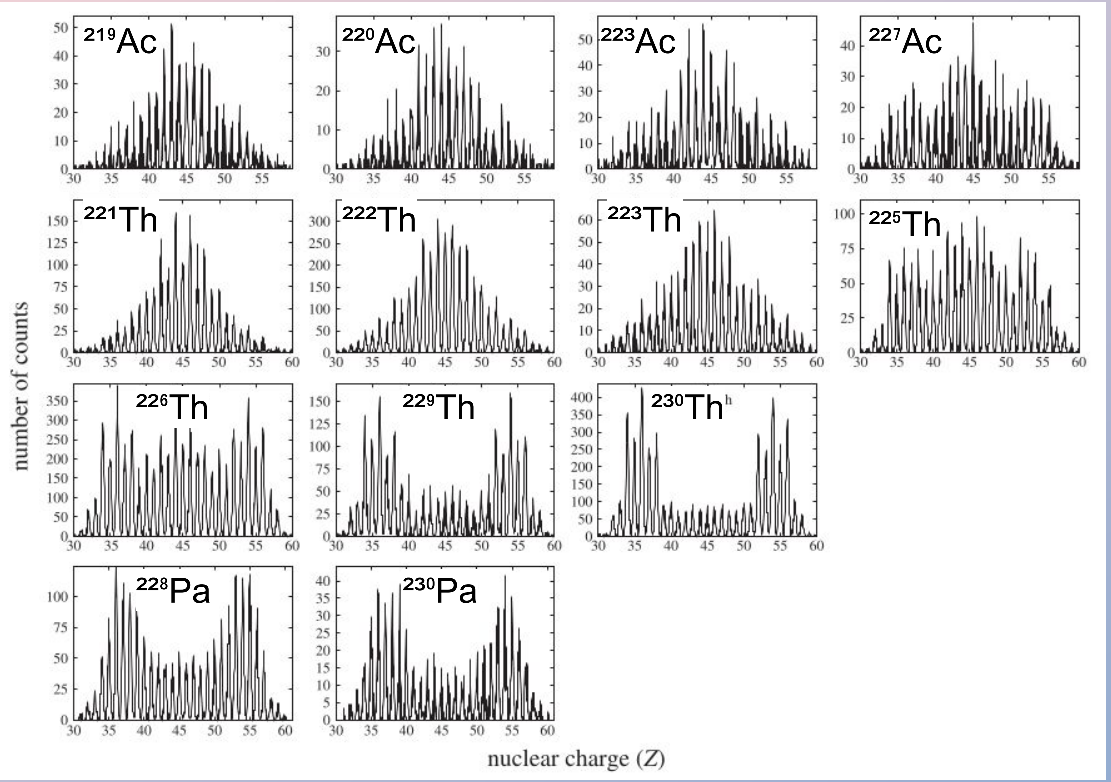
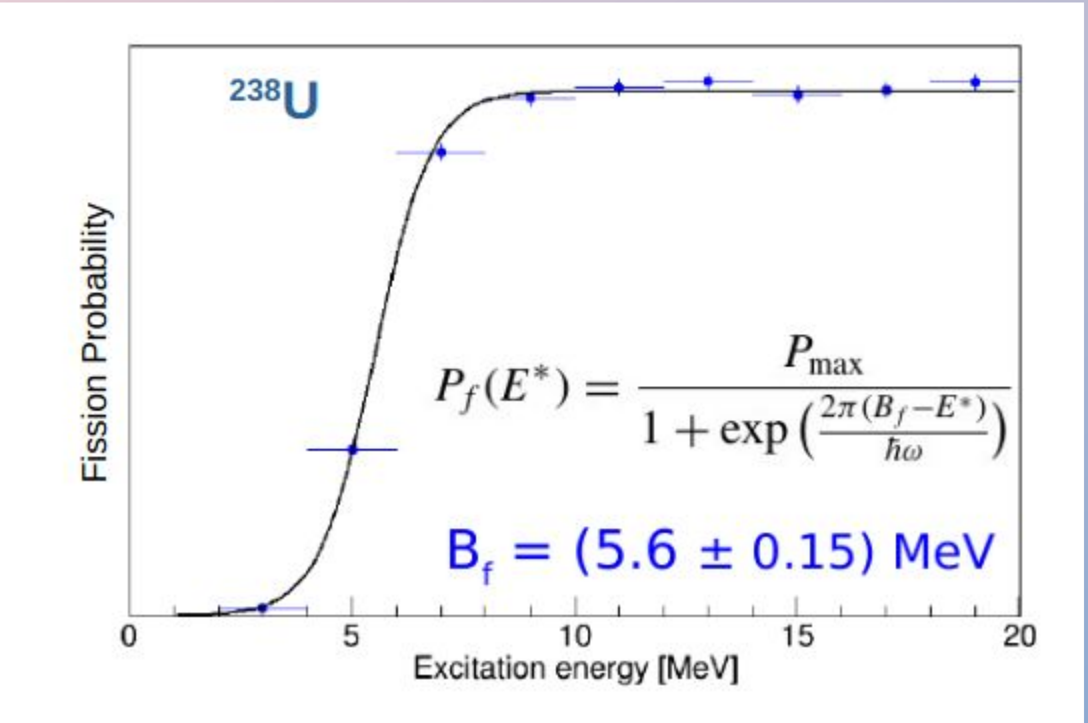
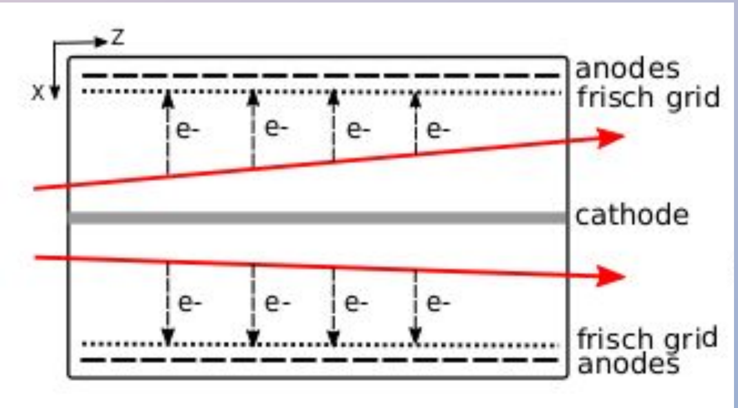


With the increasing of the isospin (N/Z) the coulombian repulsion among proton decreases: the fission barrier for the symmetric component decreases.

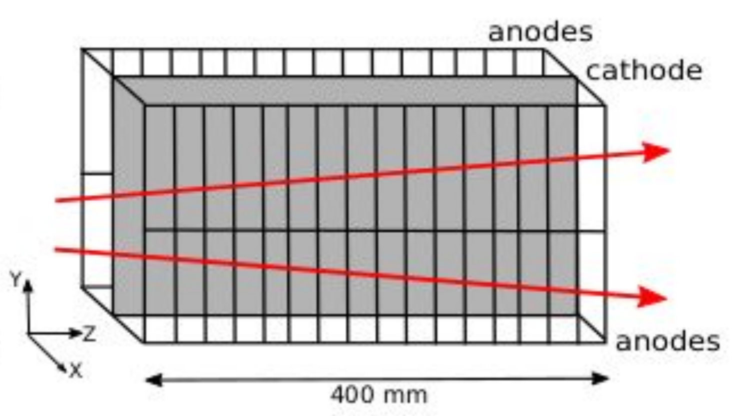
Fission barrier calculation



Twim MUSIC



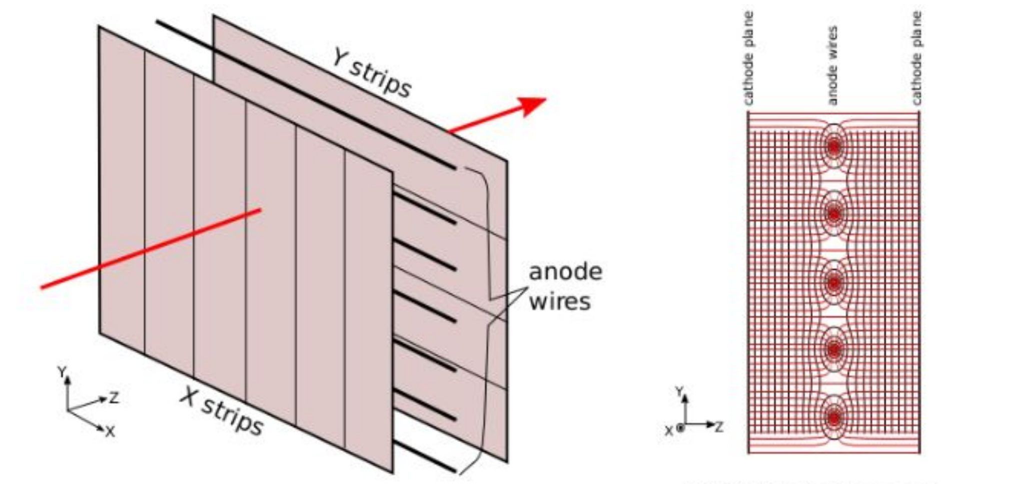
The TWIM MUSIC is composed by two gas-filled chambers. When an ion passes through the chamber, it ionizes the gas into ions and electrons.



The electrons then rapidly move to the plane of the anode, inducing a signal there. The signal is read by different modules and two data are extracted: the energy deposited by the ion in the gas and the drift time of the electrons that reach the anode.
The energy loss of the ion is proportional to the square of its ionic charge.

MWPCs

Wires are set to a high voltage, acting as anodes, while two foils are led to ground potential and serve as cathodes. The chamber is filled with a mixture of gas. When an ion passes through the MWPC, it ionizes the gas. Due to the internal electric field, the electrons drift towards anode wires. Since the electric field near the anode wires has a 1/r dependence, implying a rapid increase in the field towards the anodes, the electrons create an avalanche.



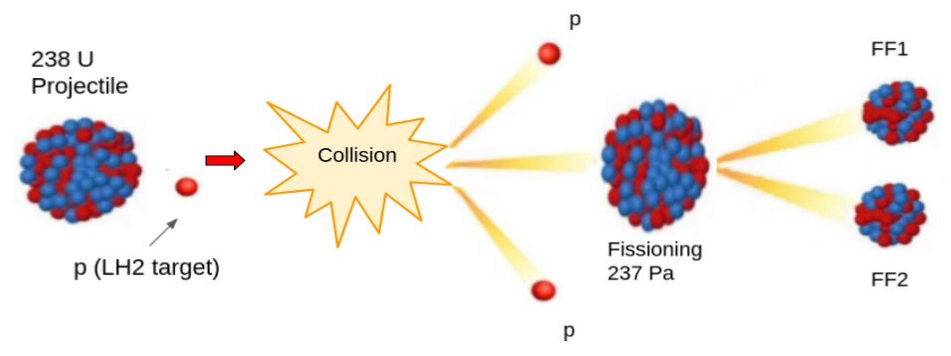
(a) *Sketch of MWPC0*

(b) *Electric field lines and equipotentials in a MWPC*

Finally, all the electrons are rapidly absorbed by the wires and a large quantity of ions are left around, creating a strong electromagnetic influence on both cathodes. The cathode plates are segmented into strips and the influence spreads on strips according to their distances to the location of avalanche. The closer the strip to the avalanche spot, the stronger the signal induced

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,** since the accurate measurement of the momenta of the two outgoing protons allows to reconstruct the excitation energy.



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

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

Invariant mass:

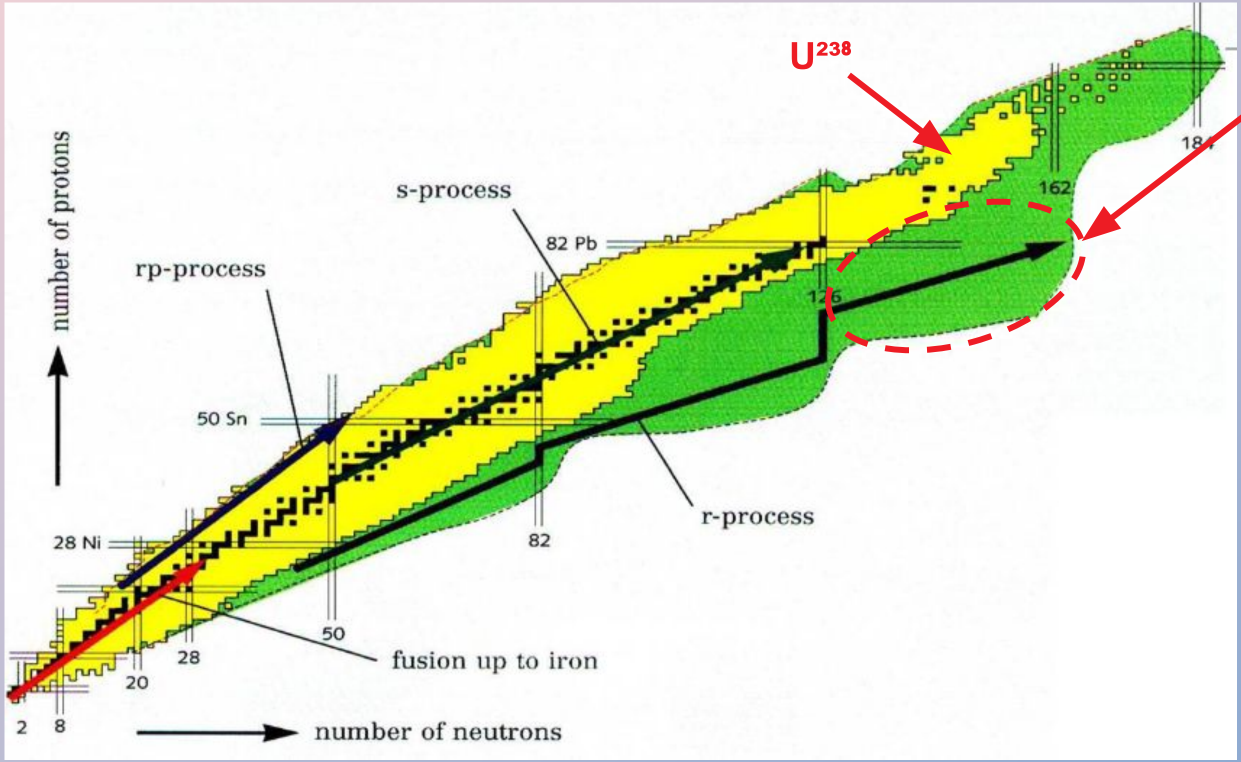
$$Q = \sqrt{(E_A + m_p c^2 - (E_{p1} + E_{p2}))^2 - ((p_{p1x}c + p_{p2x}c)^2 + (p_{p1y}c + p_{p2y}c)^2 + (\sqrt{E_A^2 - m_A^2 c^4} - (p_{p1z}c + p_{p2z}c))^2)}.$$

The missing energy:

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

Future (p,2p)-fission experiment at GSI.

The phase-0 (p,2p)-fission experiment performed in 2021 was the first step towards a series of experiments with exotic neutron-rich nuclei.



The fission barrier heights and fission yields will be measured around N=152 to constrain theoretical r-process models.

Fragmentation reactions:

U^{238}+Be at 1A GeV

H. Alvarez-Pol et al., PRC 82, 041602(R) (2010)

Pb^{208}+Be at 1A GeV

T. Kurtukian-Nieto et al., PRC 89, 024616 (2013)