Fission Studies at GANIL :
Exploiting the inverse-kinematics surrogate and the direct neutron-induced thechniques

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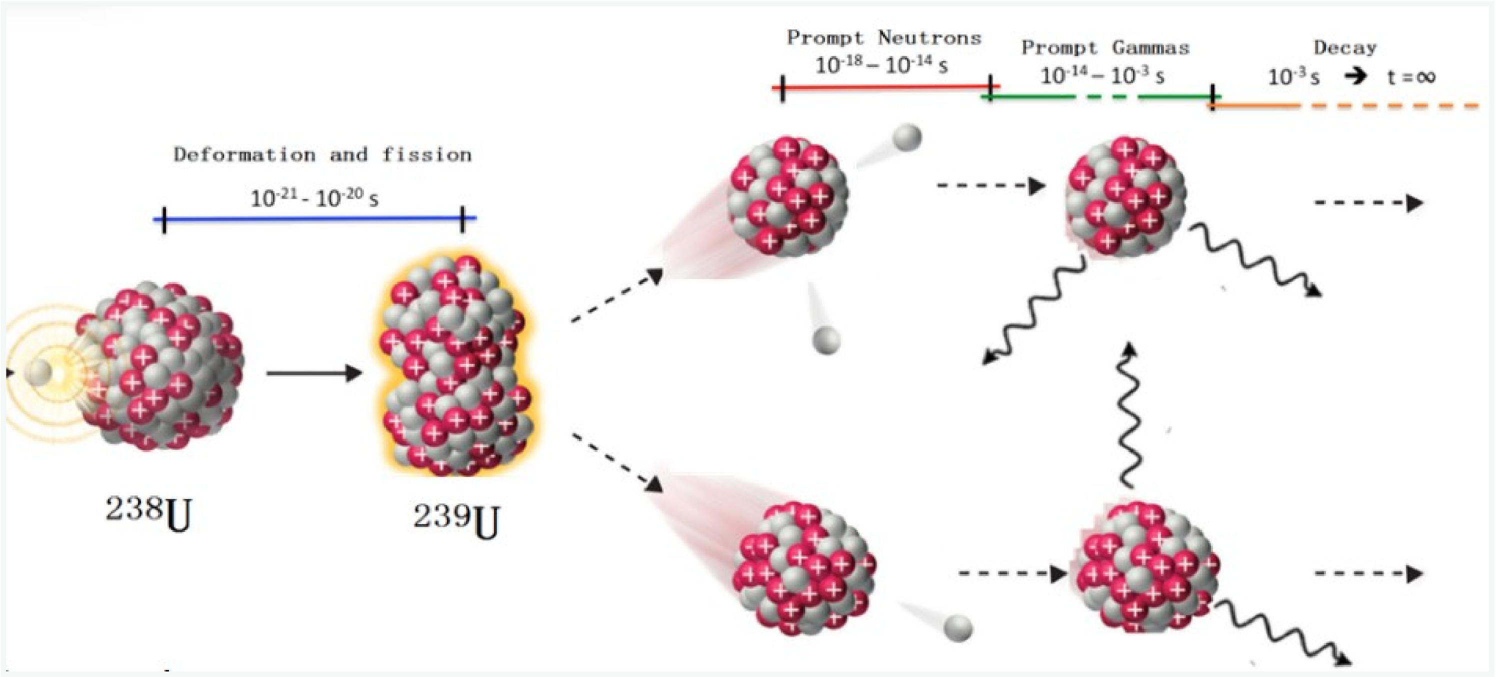
XXII Colloque GANIL

28th September 2021

The Fission Problem

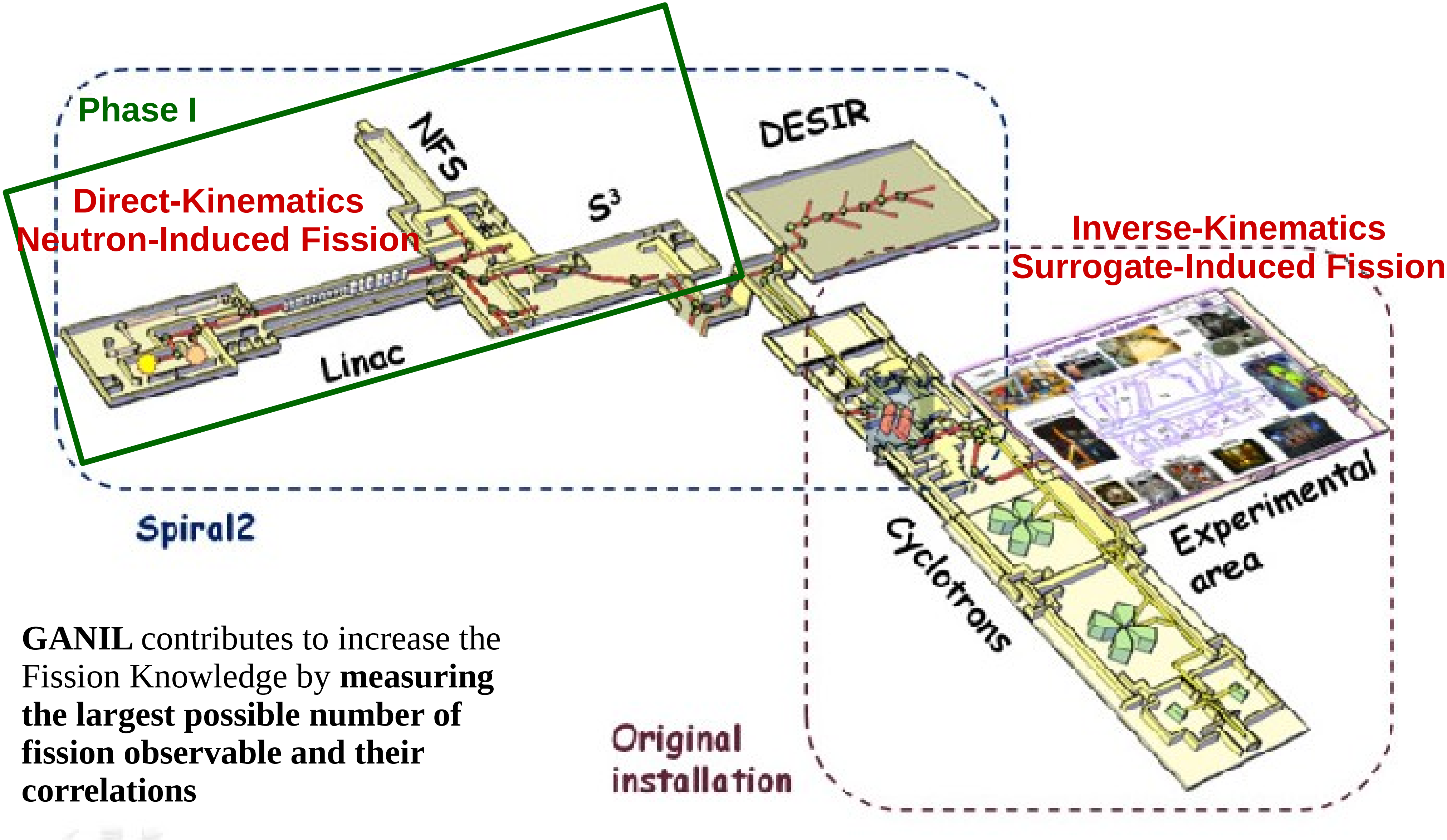


- **Theory:**
  - Interplay between **intrinsic and collective degrees of freedom**
  - **Dynamical evolution** from one system to two individual objects
  - Extreme **deformations**

- **Observation**:
  - **Low-energy heavy nucleus** products
  - **Stochastic process** with large number of nuclei
  - **Particle evaporation and γ-decay** in competition

- **No full microsocopic description of the fission process**
- **No experimental access to the intermediate steps of the fission process**

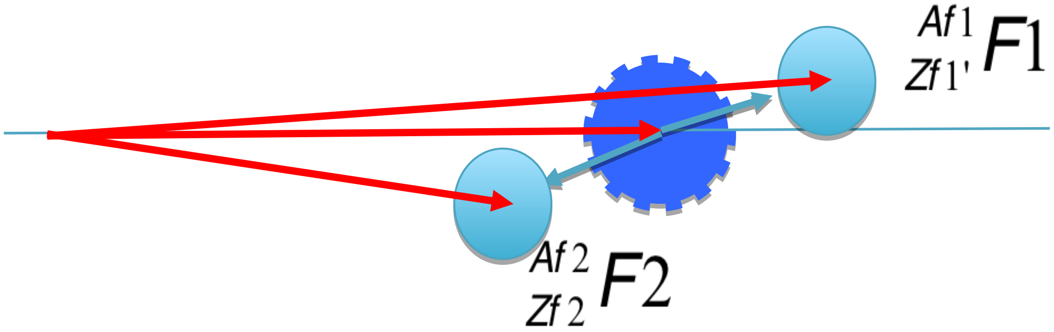
Fission at GANIL



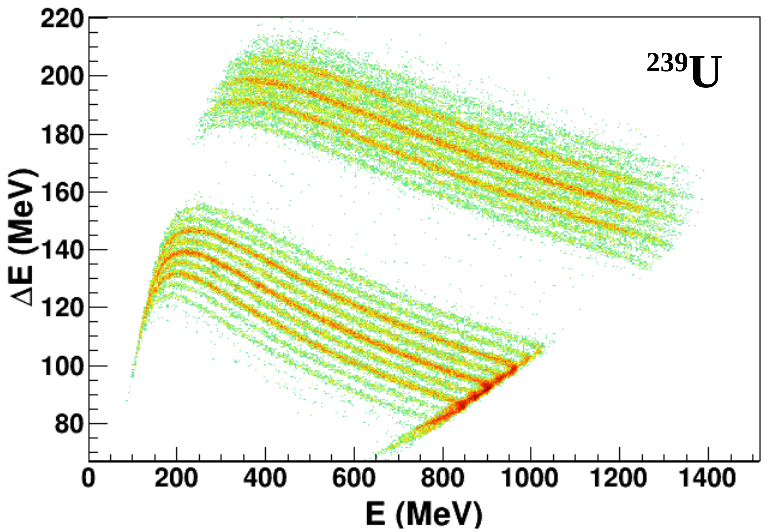
- **GANIL** contributes to increase the Fission Knowledge by **measuring the largest possible number of fission observable and their correlations**

Inverse-Kinematics Fission at GANIL Using the VAMOS++ Spectrometer

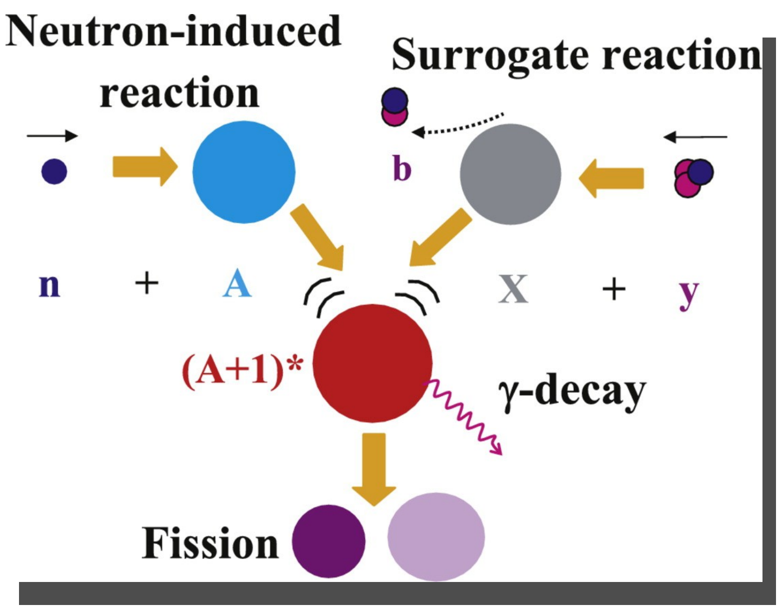
The Inverse Kinematics Technique



- **Heavy ion beam impinging into a light target**
- **Forward fission-fragments emission** with high kinematic boost
- Direct identification of **fission-fragments nuclear charge**



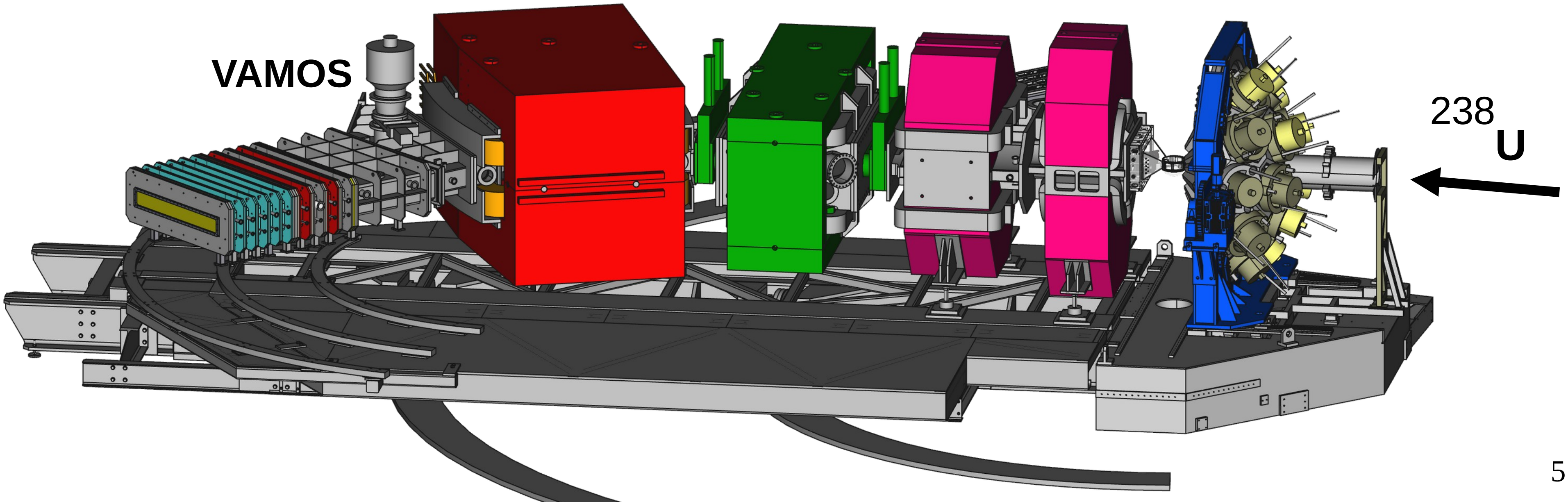
- The inverse-kinematics technique is associated to **Surrogate Reactions**



- Surrogate reactions gives **access to exotic fissioning systems** impossible to produce through n-induced reactions
  - $^{238}U(^{12}C,^{11}B)^{239}Np$
  - $^{238}U(^{12}C,^{6}He)^{244}Cm$

Fission at VAMOS: n-rich actinides region

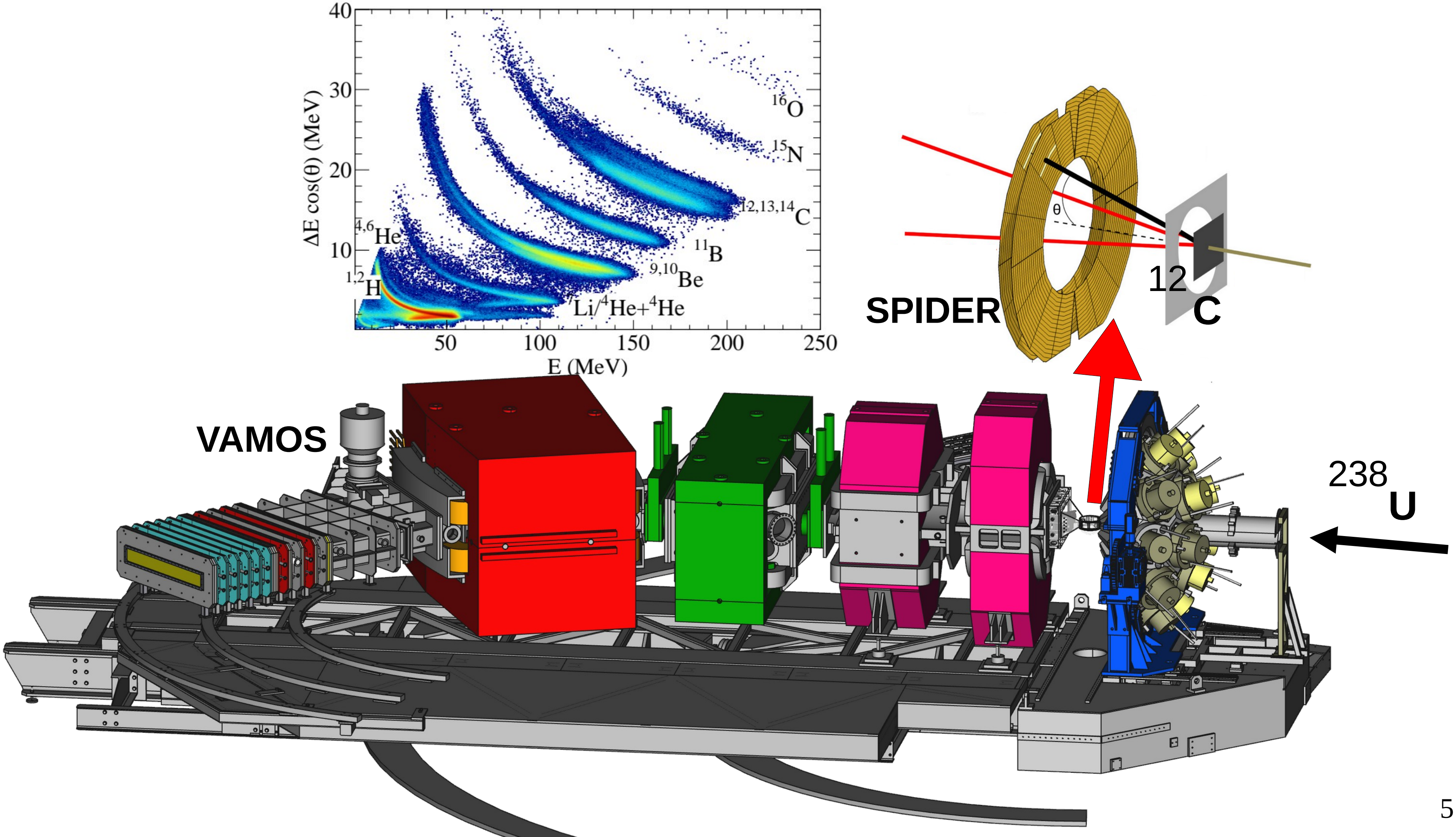
- **^{238}U beam at ~6 MeV/u** (Coulomb energies)
- **C/Be targets**
- **Transfer/Fussion induced fission**



Fission at VAMOS: n-rich actinides region

- ^{238}U **beam at ~6 MeV/u** (Coulomb energies)
- **C/Be targets**
- **Transfer/Fussion induced fission**

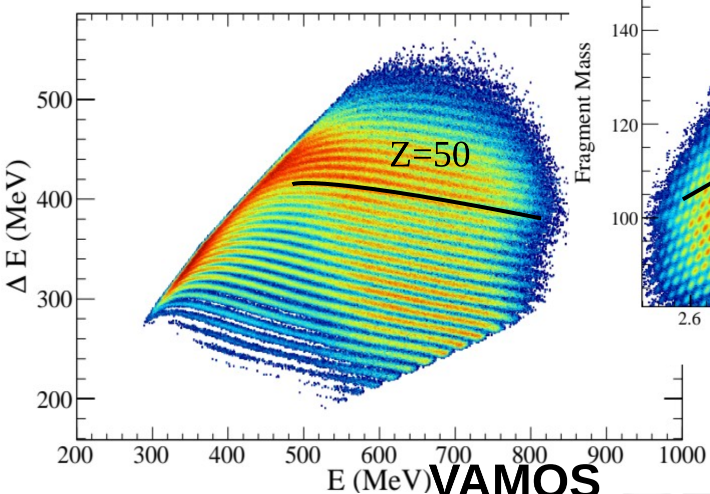
- **SPIDER** :
  Selection of the **incoming channel (A,Z,E_x)**
  - Access to **actinides above Uranium**
  - Control of the fissioning system **excitation energy**

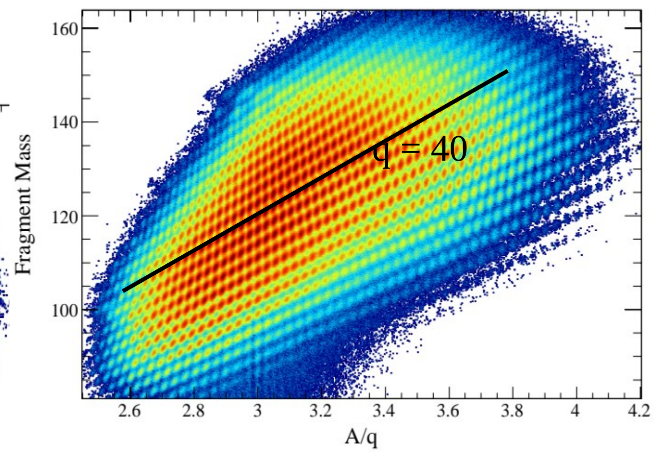


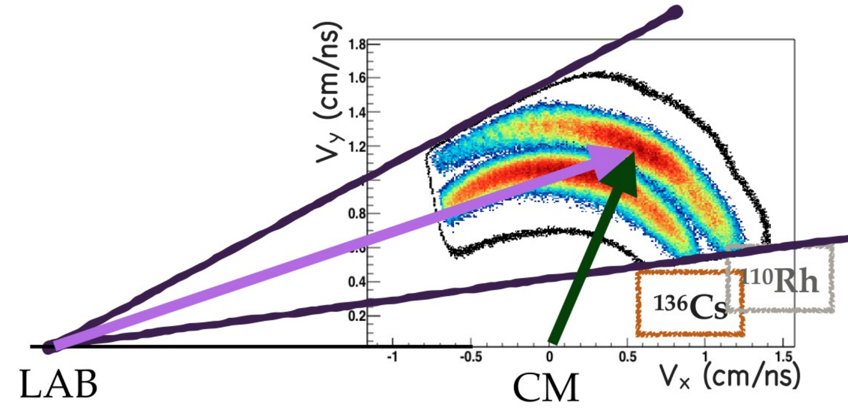
Fission at VAMOS: n-rich actinides region

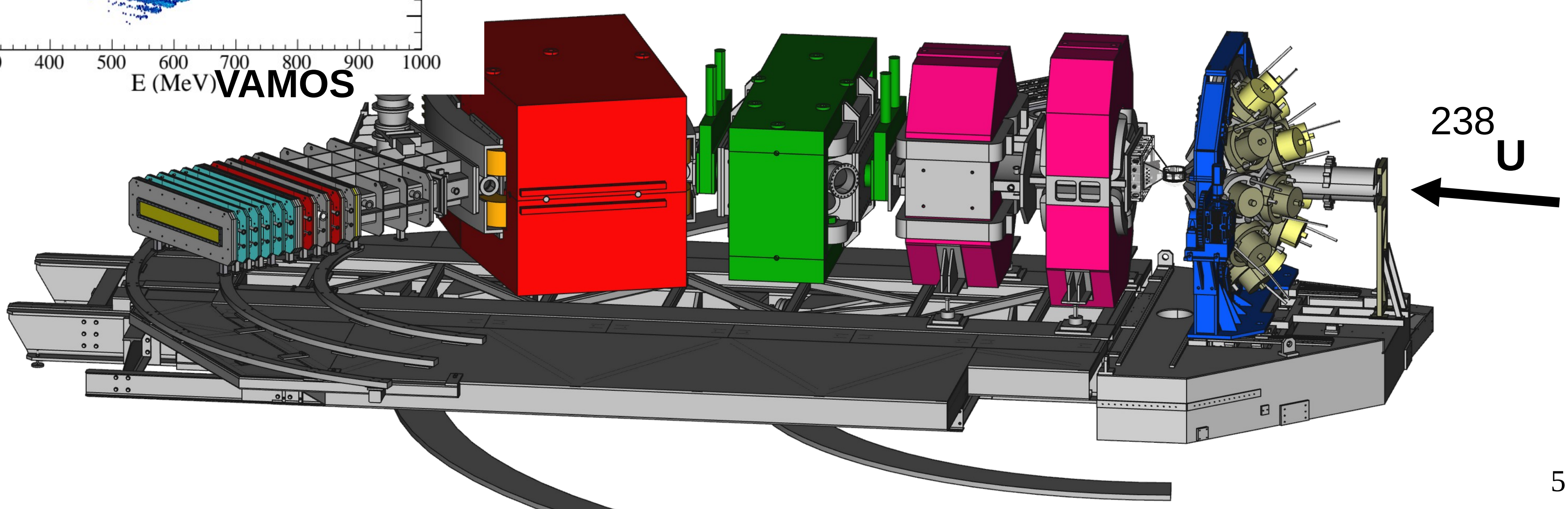
- **^{238}U beam at ~6 MeV/u** (Coulomb energies)
- **C/Be targets**
- **Transfer/Fussion induced fission**

- **VAMOS** :
  - Complete **fission-fragment isotopic identification**
  - Access to the **center of mass kinematics**









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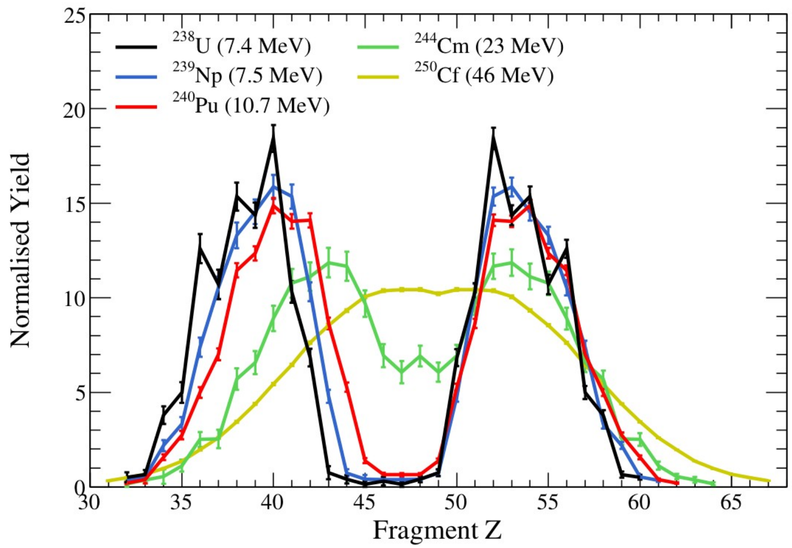
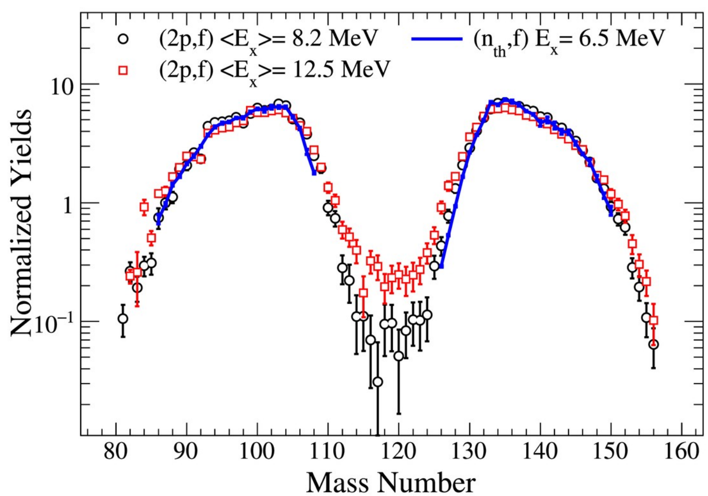
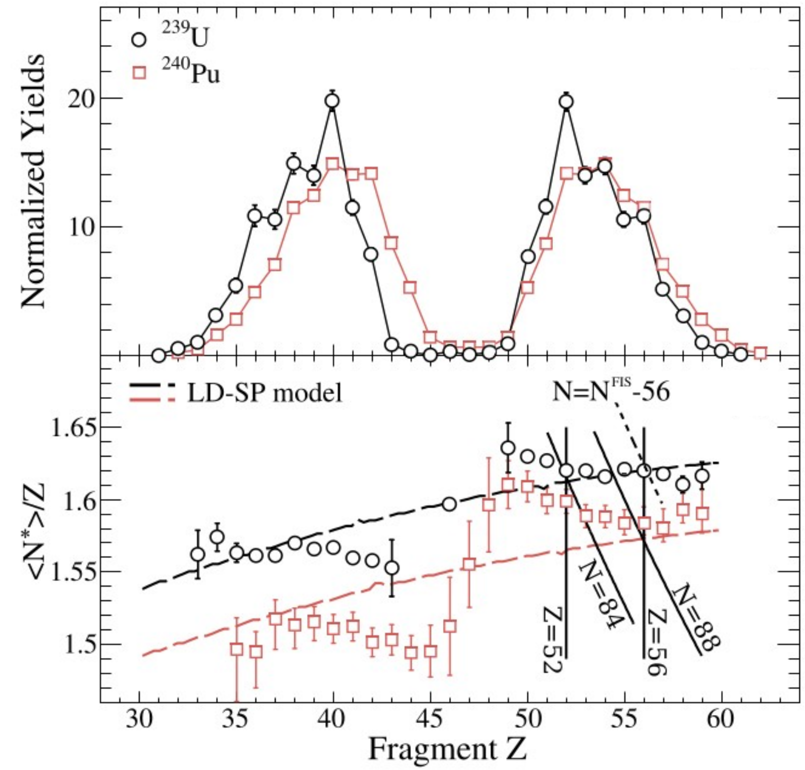


- **Fragments production of exotic systems at different E_x**



M. Caamano et al. Phys. Rev. C. 92, 024605 (2015)
D. Ramos et al. Phys. Rev. C. 97, 054612 (2018)

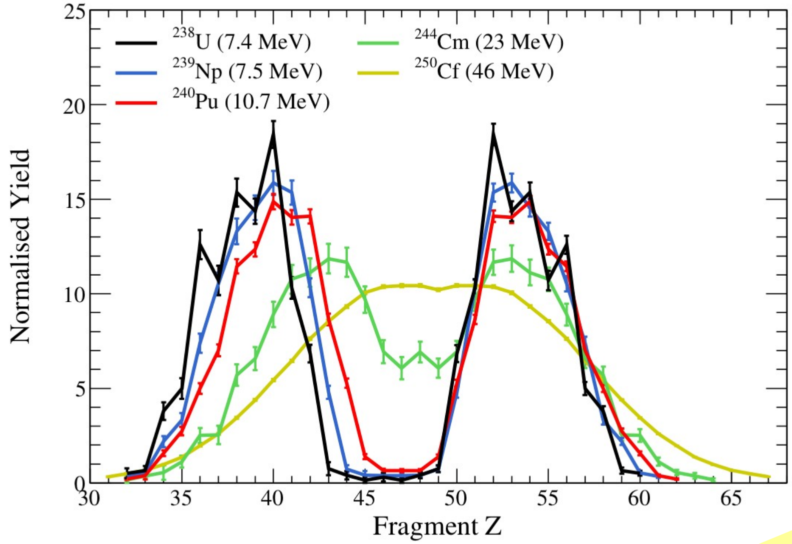
- **First direct measurement of ^{239}U isotopic fission yields.**



- **Neutron excess**: The role of **proton- and neutron- octupole deformed shells** [G. Scamps Nature 564, 382 (2018)] are reflected

D. Ramos et al. Phys. Rev. Lett. 123, 092503 (2019)
D. Ramos et al. Phys. Rev. C. 101, 034609 (2020)

Fission at VAMOS: n-rich actinides region



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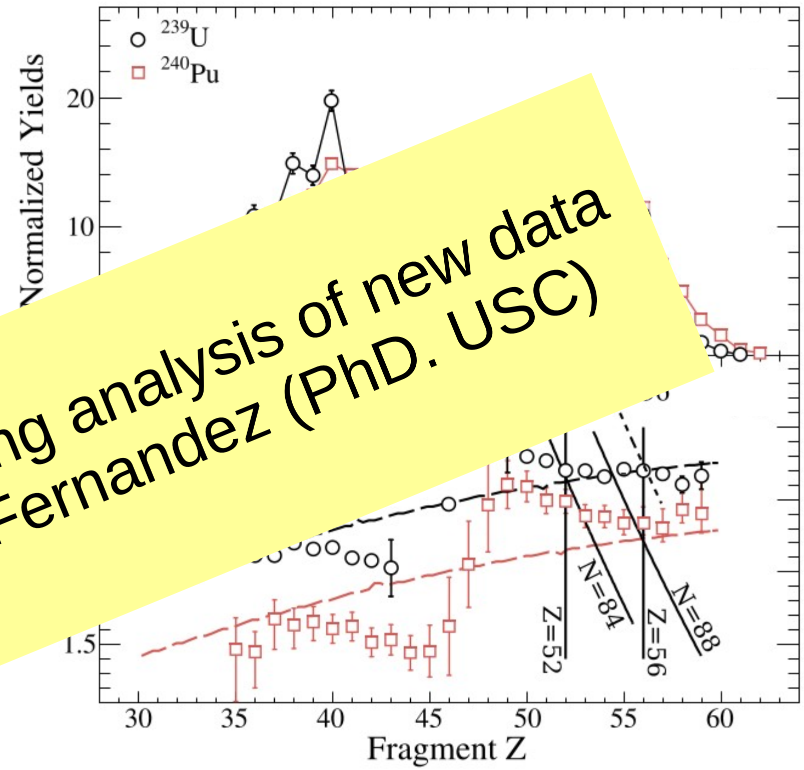

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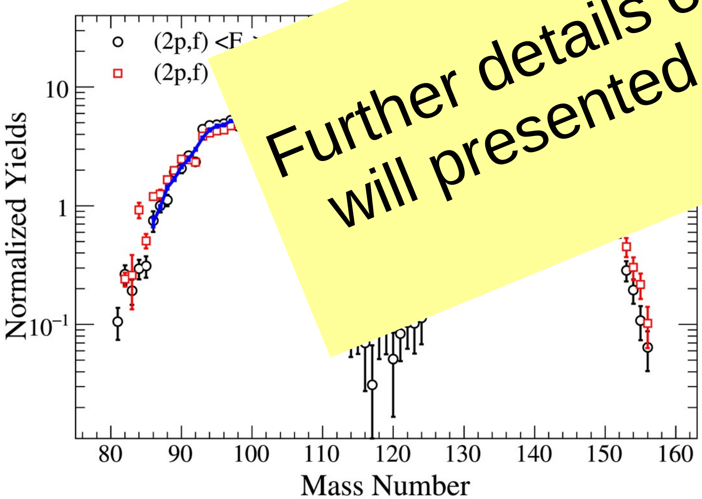

Further details of the ongoing analysis of new data will presented by Daniel Fernandez (PhD. USC)

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M. Caamano et al. Phys. Rev. C. 92, 024605 (2015)
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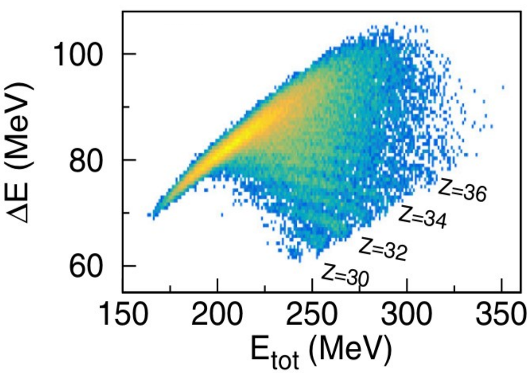
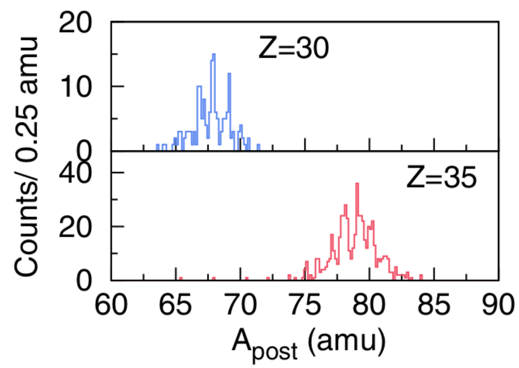
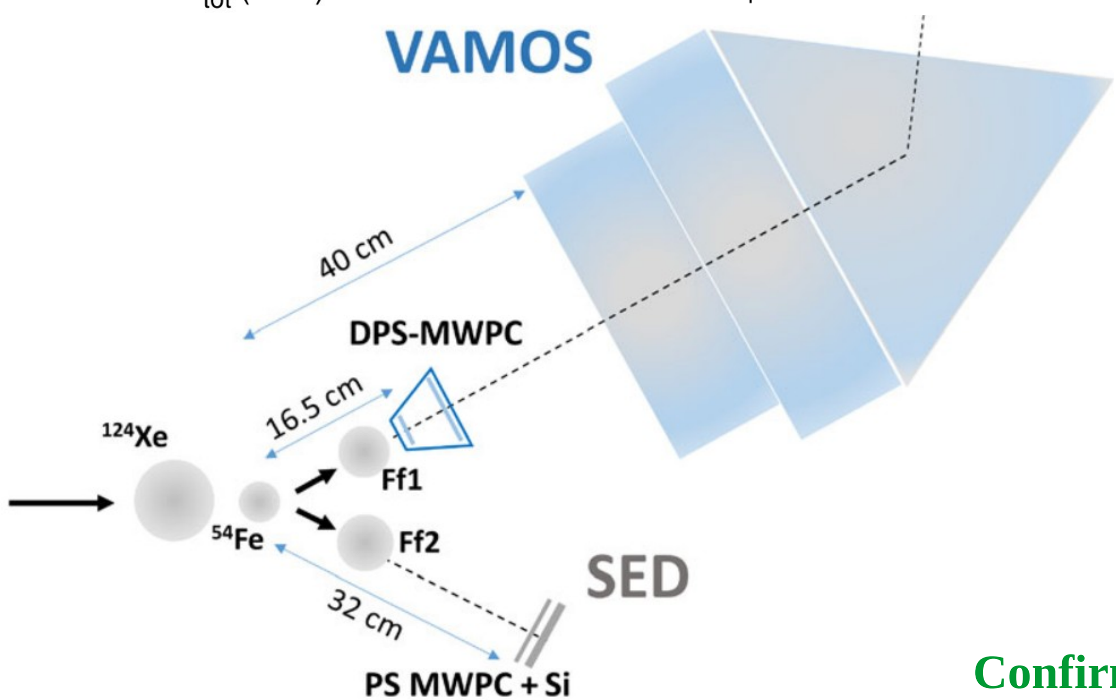
Fission at VAMOS: ^{180}Hg region

- **^{124}Xe (4.3 MeV/u) + ^{54}Fe → ^{178}Hg (E_x=34 MeV)**
- **2 arms at 64° (folding angle)**
- **Complete-Kinematics Measurement**

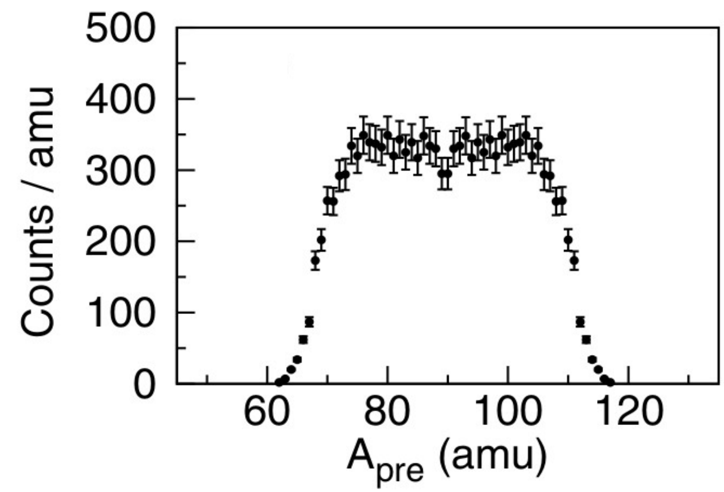






- **VAMOS** :
  - Fission-fragment **Z identification up to Z=38.**
  - **Complete** fission-fragment **mass identification**
  - **Velocity vector** determination
- **2-ARM** :
  - **Complementary fission-fragment velocity vector** measurement
  - **Momentum conservation**: **Pre-neutron** evaporation fission-fragment **masses**

$$\frac{M_1}{M_2} = \frac{\gamma_2 v_2}{\gamma_1 v_1}$$



Confirmed presence of asymetric fission in ^{178}Hg

Fission at VAMOS: ^{180}Hg region

- ^{124}**Xe (4.3 MeV/u) +** ^{54}**Fe →** ^{178}**Hg (E=34 MeV)**
- **2 arms at 64° (folding angle)**
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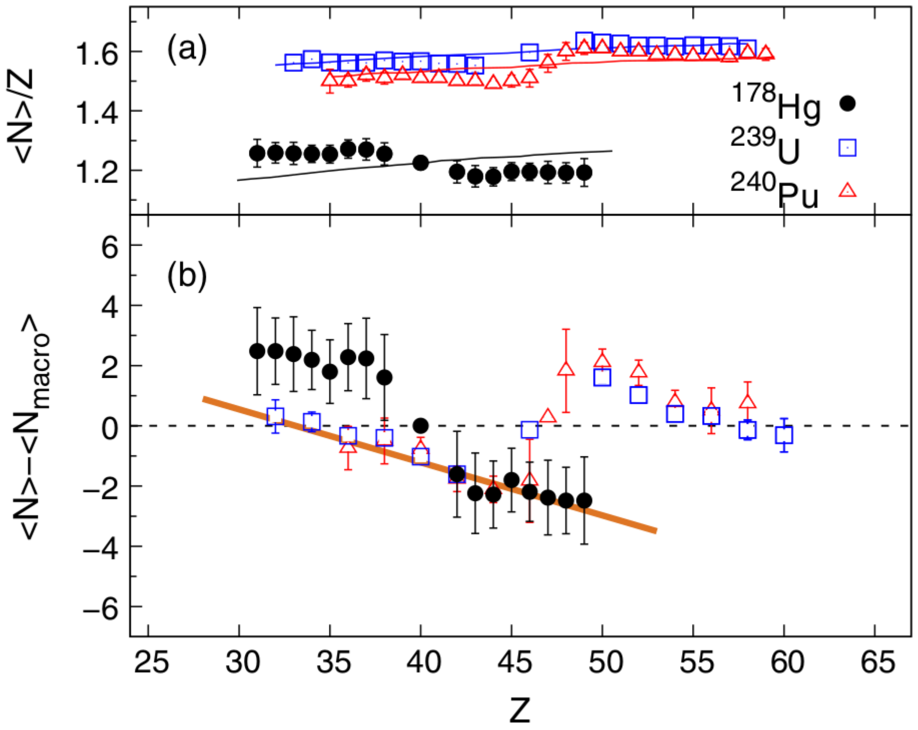
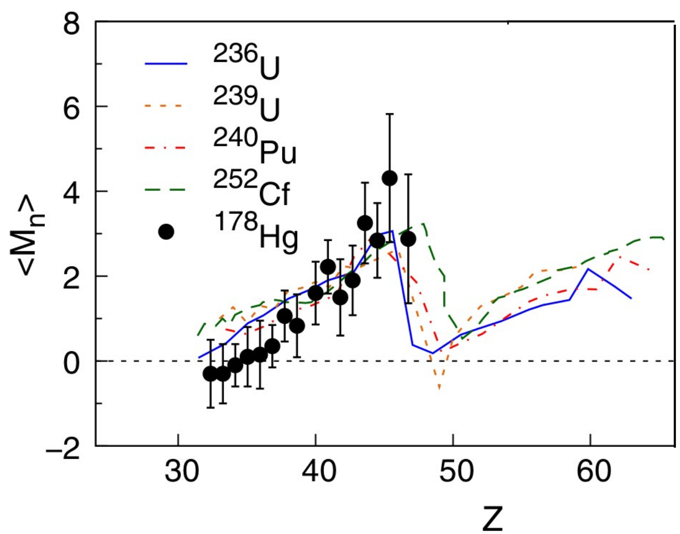


- Fission Fragments **Neutron Excess**:
  - **Opposite behaviour** with respect to actinides
  - **Common driving instrinsic effects from proton in Z[40,46]**

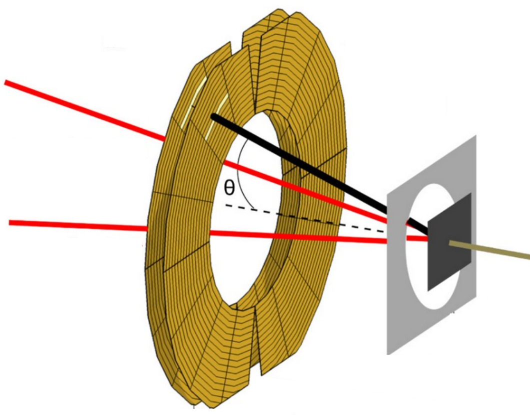
- Fission Fragments **Neutron Multiplicites**:
  - **No effect of additional excitation energy** in the light fragment.
  - **Neutron multiplicity governed by the deformation of the proton subsystem.**

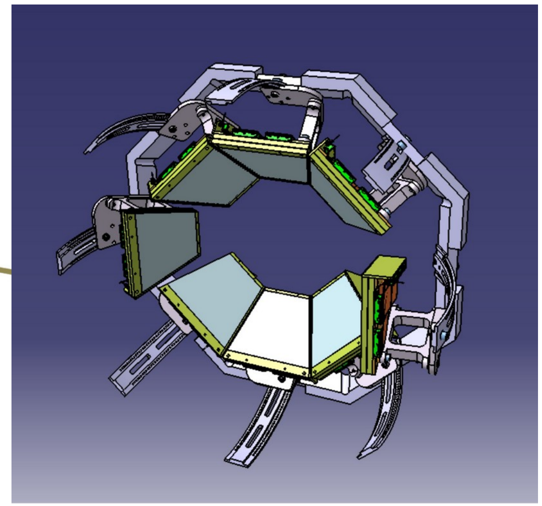


C. Schmitt et al. Phys.Rev.Lett. 126,132502 (2021)

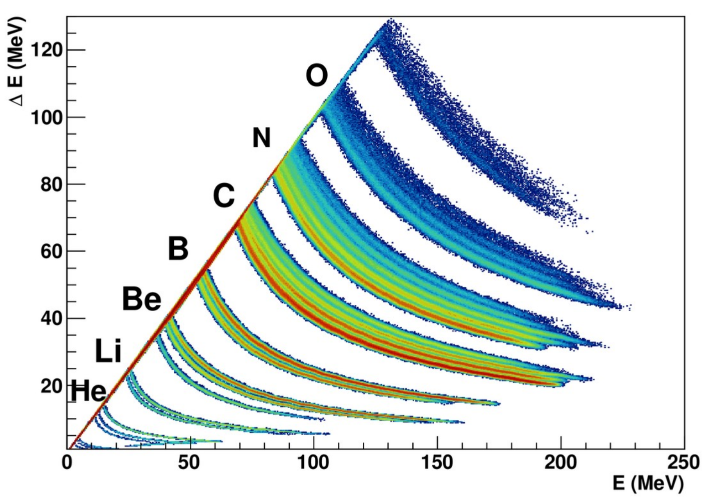
Upgrade of VAMOS

- **<u>Improving the Incoming Channel:</u>**
  <u>From SPIDER to PISTA</u>

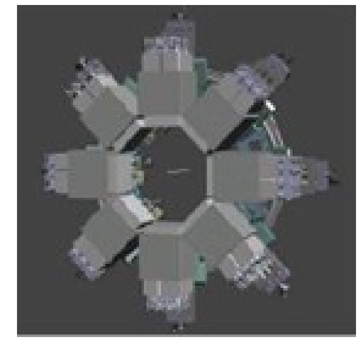




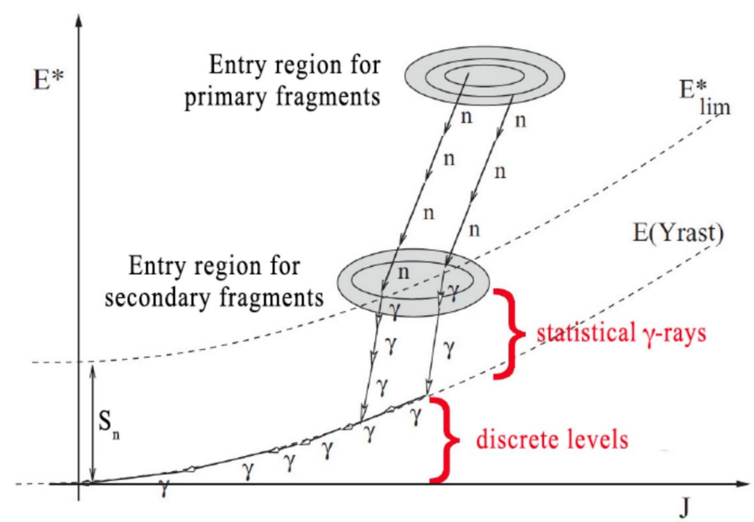
- High particle-identification capabilities
- Higher energy resolution (2.5 MeV → **0.7 MeV**)
- Larger angular coverage



- **<u>Simultaneous Gamma Measurements:</u>**
  <u>PARIS Detector at Target</u>



- Important information in order to reconstruct the entry point of the fission fragment decay (E_x, J)

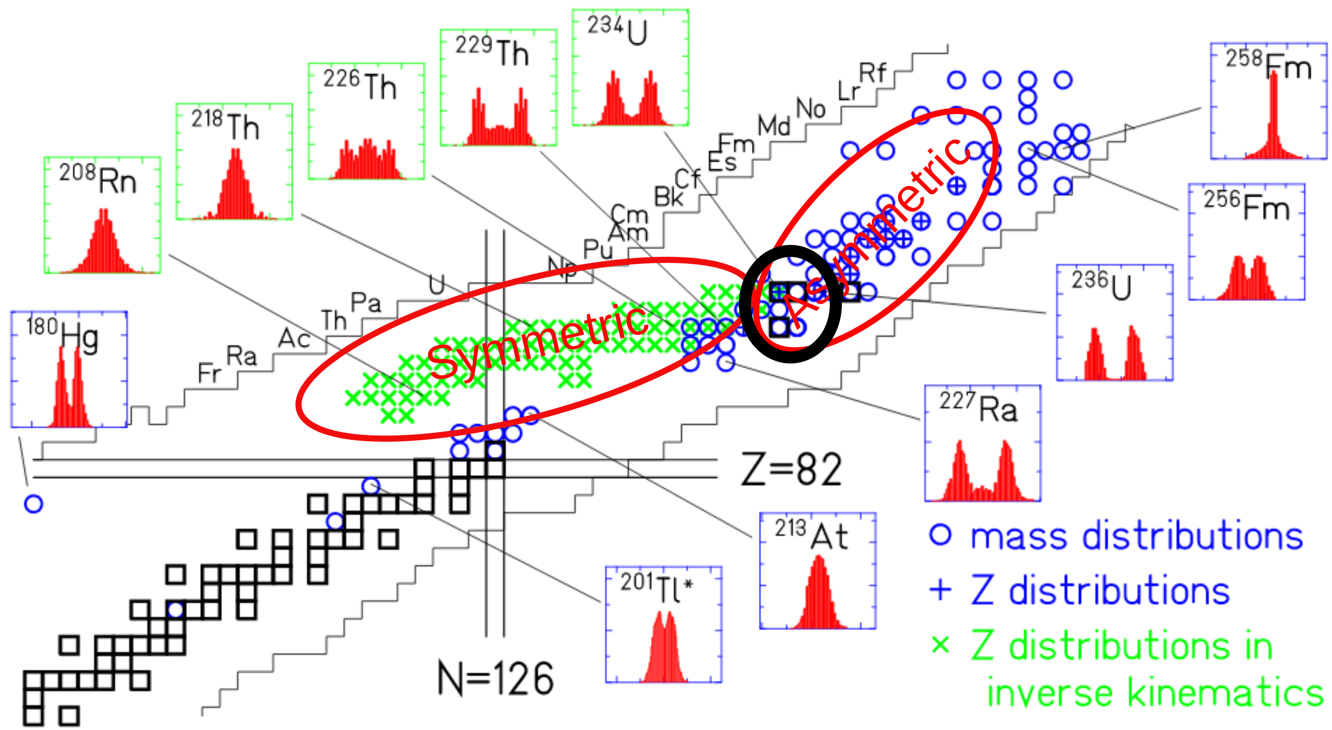


Fission From ^{232}Th beam

Study of the evolution of structural effects in fission

- Access to the vicinity of the **transition region between symmetric to asymmetric fission**
  - Rapid evolution of structural driving effects
  - **New fission mode in Thorium chain**
    (A.Chatillon et al. Phy.Rev.Lett. 124,202502 (2020))

- **Access to a barely explored region**
  - No isotopic or elemental fission Yields
  - No excitation energy measurement around fission barrier



K.H. Schmidt et al. Nucl. Data Sheets 131, 107 (2016)

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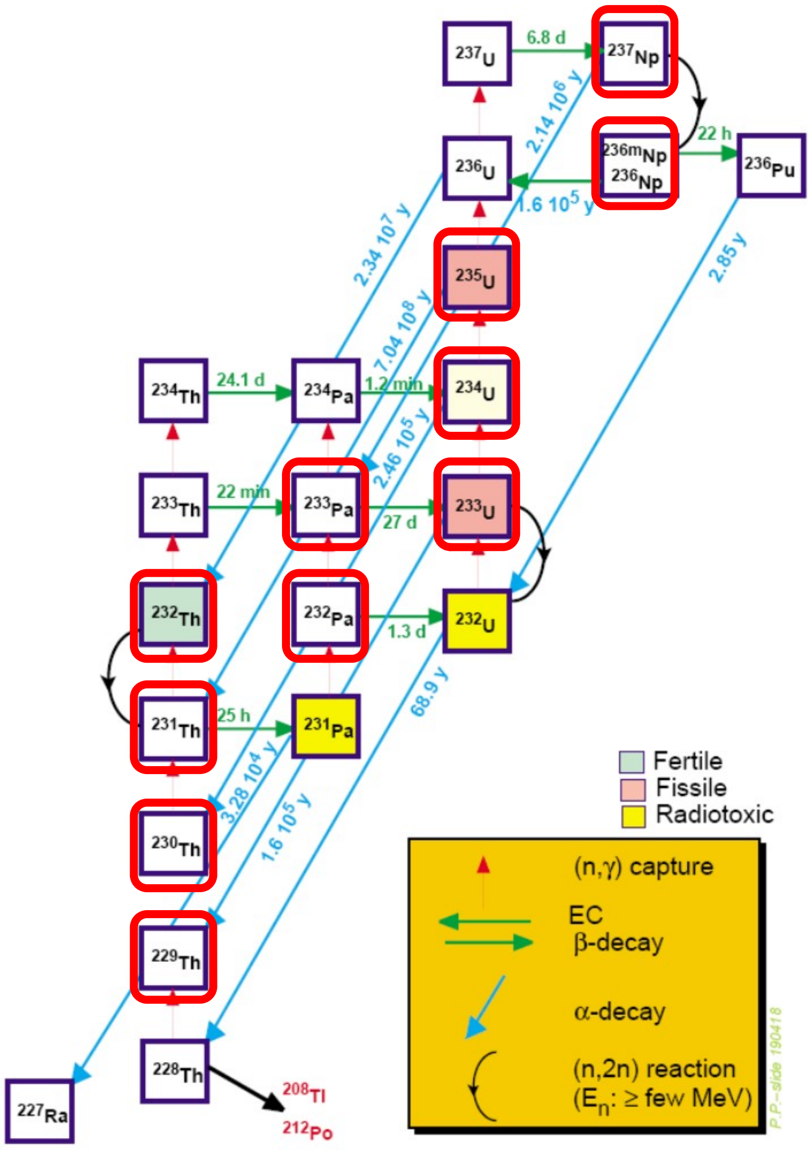


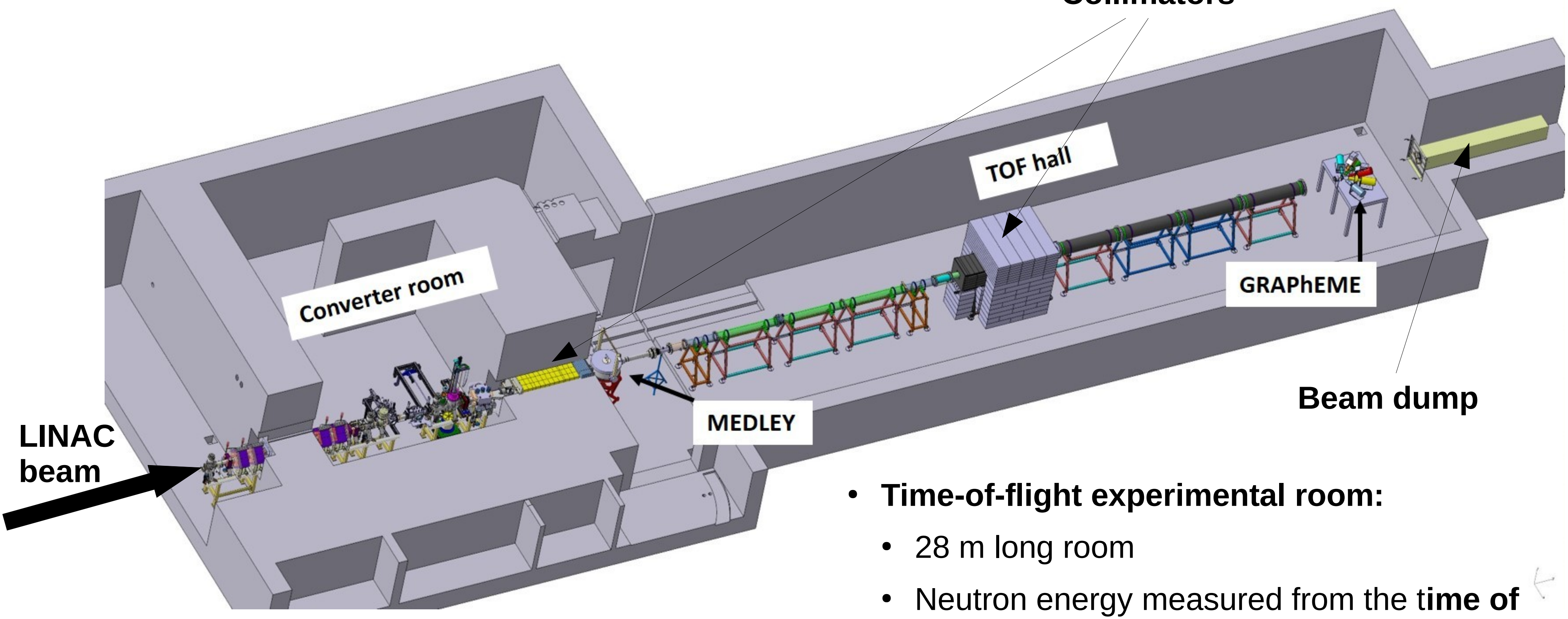
U. Abbondanno et al. CERN/INTC 2001-025

Data for the Th/U cycle

- Energy generation through fast neutron reactions
- Nuclear waste incineration

Neutron-Induced Fission at NFS Using the FALSTAFF Spectrometer

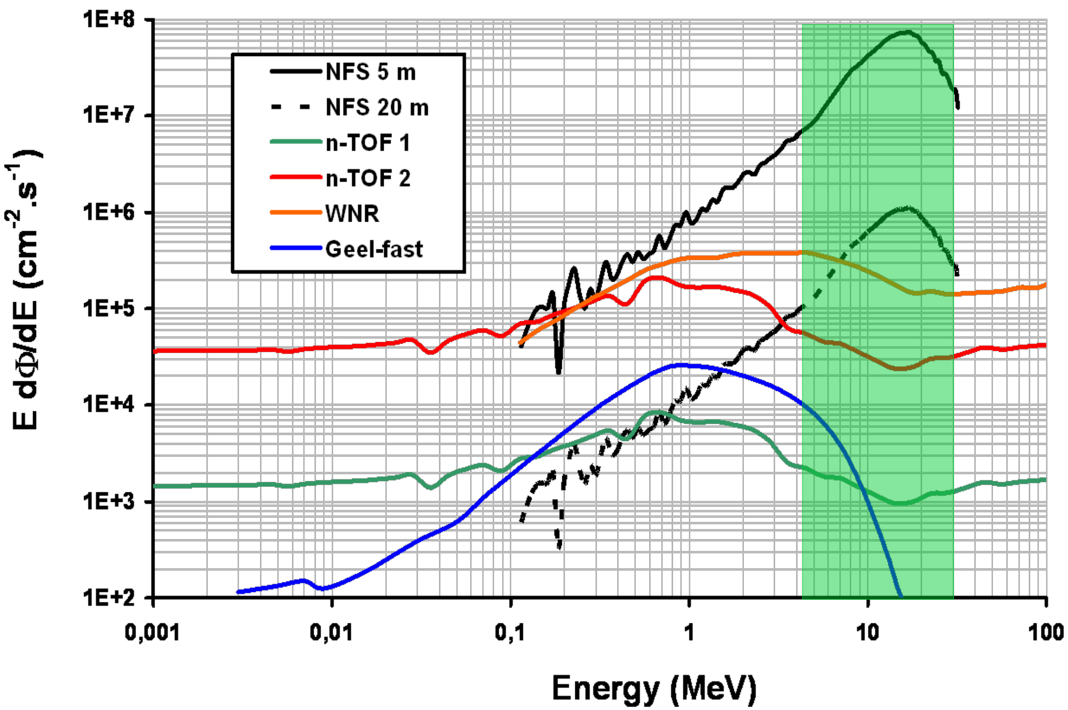
Neutrons For Science Facility



- **Time-of-flight experimental room:**
  - 28 m long room
  - Neutron energy measured from the t**ime of flight technique**
  - **1 us fligh path** → bunch selector 1/100 (5mA → 50uA (3×10^{14} d/s)
  - **secondary collimation** (13 cm → 2 cm beam spot radius)
  - **Water beam dump** → reduced backscatter neutrons
  - **Several setups** placed at the same time

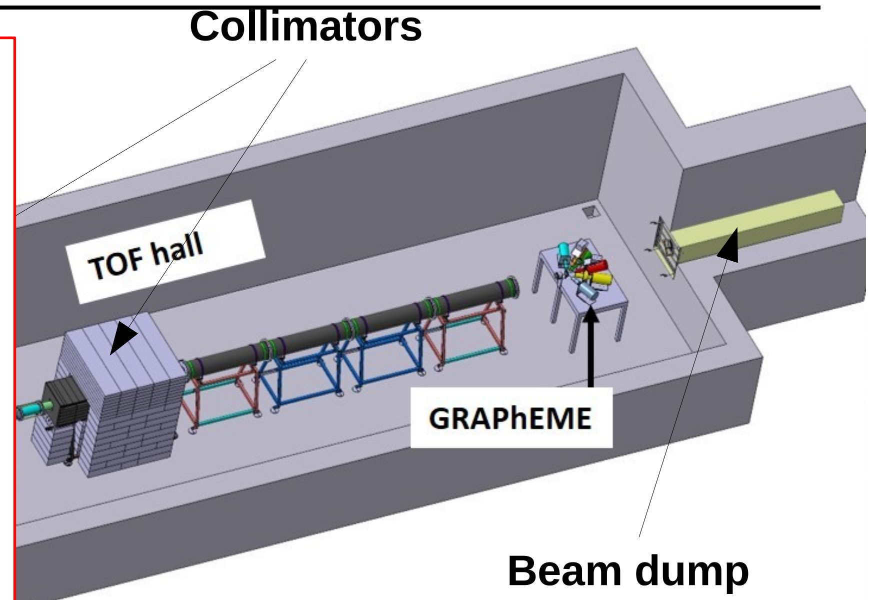
- **Converter/Irradiation room**:
  - Charged particles **irradiation station**
  - Neutrons production:
    - Reactions in **Li or Be converting targets.**
    - **3 m concrete collimator at 0 deg.** with conical inner shape: **1.7 cm radius beam**

Neutrons For Science Facility



- **Neutron from 0.1 MeV to 40 MeV**
- 1 ns acelerator deviation :
  - **good energy resolution**
- High repetition rate :
  - **Reduced gamma-flash**
  - **Low instantaneous flux**

NFS offers a great opportunity to study n-induced fission



ne-of-flight experimental room:

8 m long room

leutron energy measured from the **time of ight technique**

us fligh path → bunch selector 1/100
5mA → 50uA (3x10^{14} d/s)

econdary collimation (13 cm → 2 cm eam spot radius)

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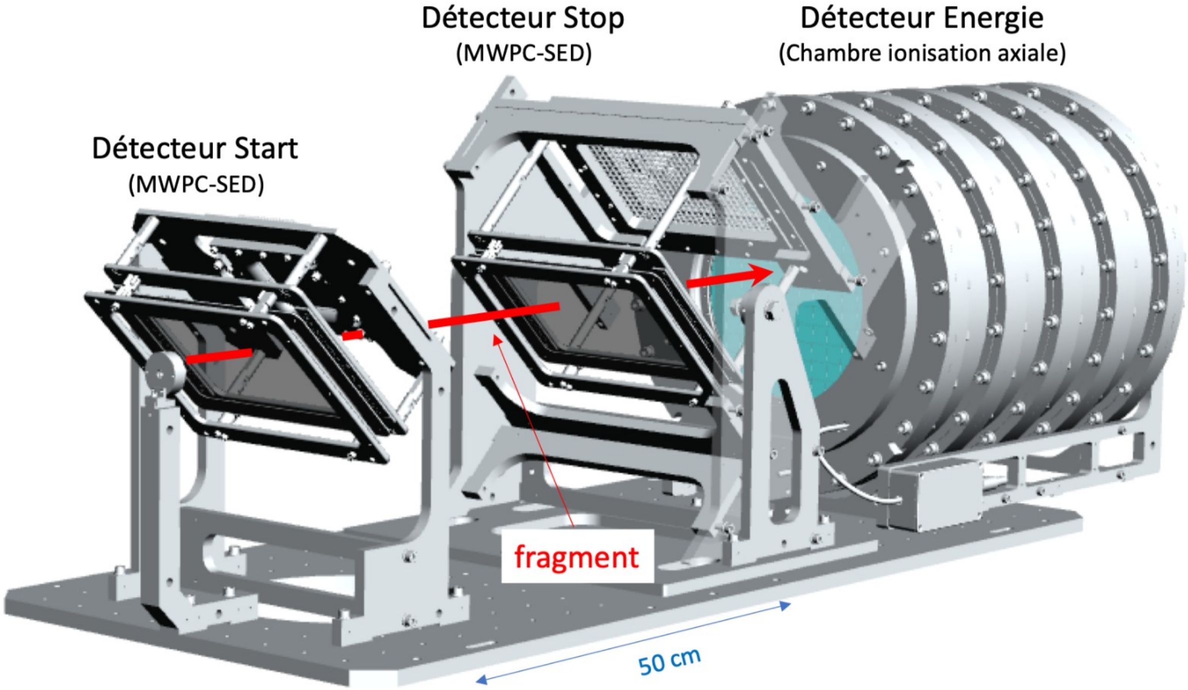
everal setups placed at the same time

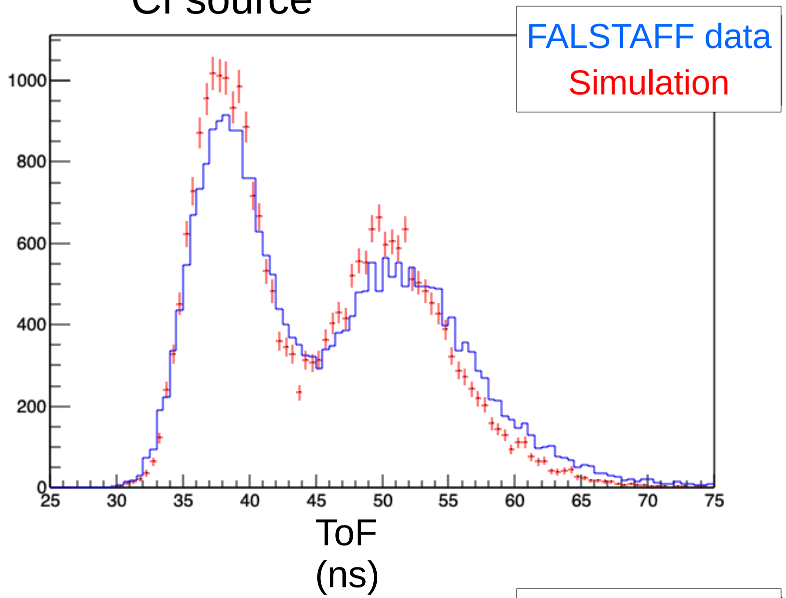
Fission with FALSTAFF at NFS

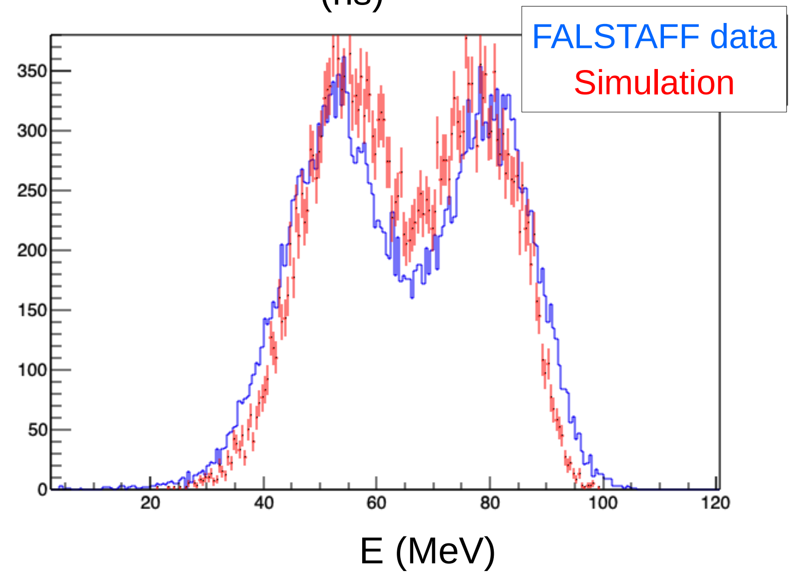


- N-induced fission of thin **actinides targets**:
  - Fission **fragments production** vs **excitation energy**

- **Fission-fragment spectrometer:**
  - 2 position-sensitive **SeD**(position and ToF)
  - **Axial ionization chamber** (Energy profile)
  - Setup designed to be the less disruptive possible

- Data from spotaneous fission of ^{252}Cf source

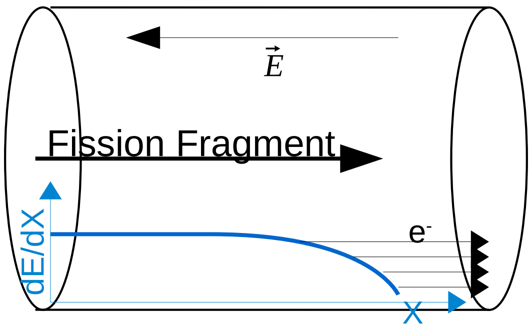




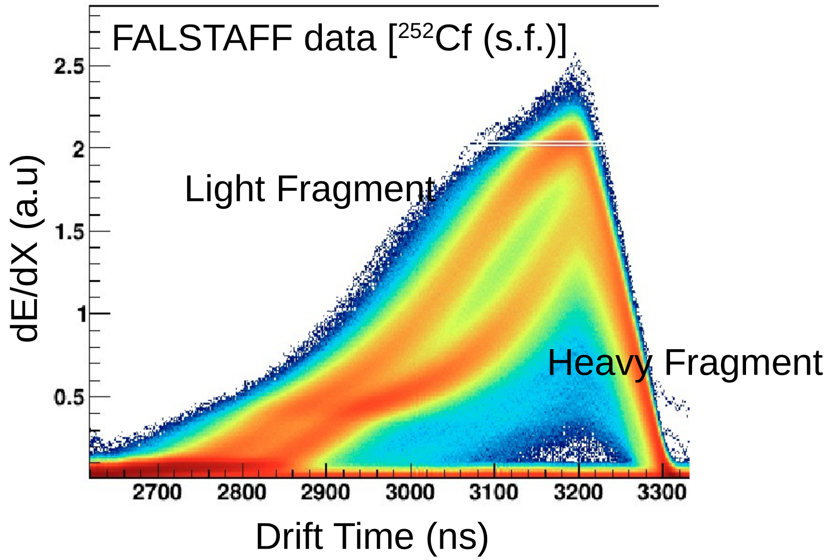
Exploring the FALSTAFF-Z identification capabilities

Axial Ionization Chamber

Electrons **drift to de anode at different times**



- Profile of the FF energy loss as a function of the IC depth



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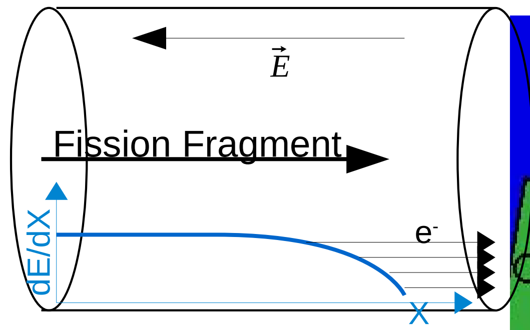

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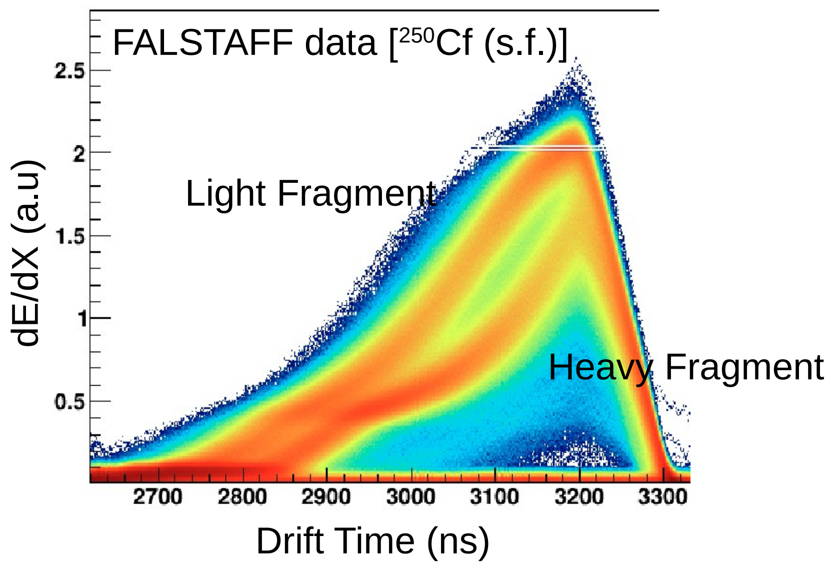
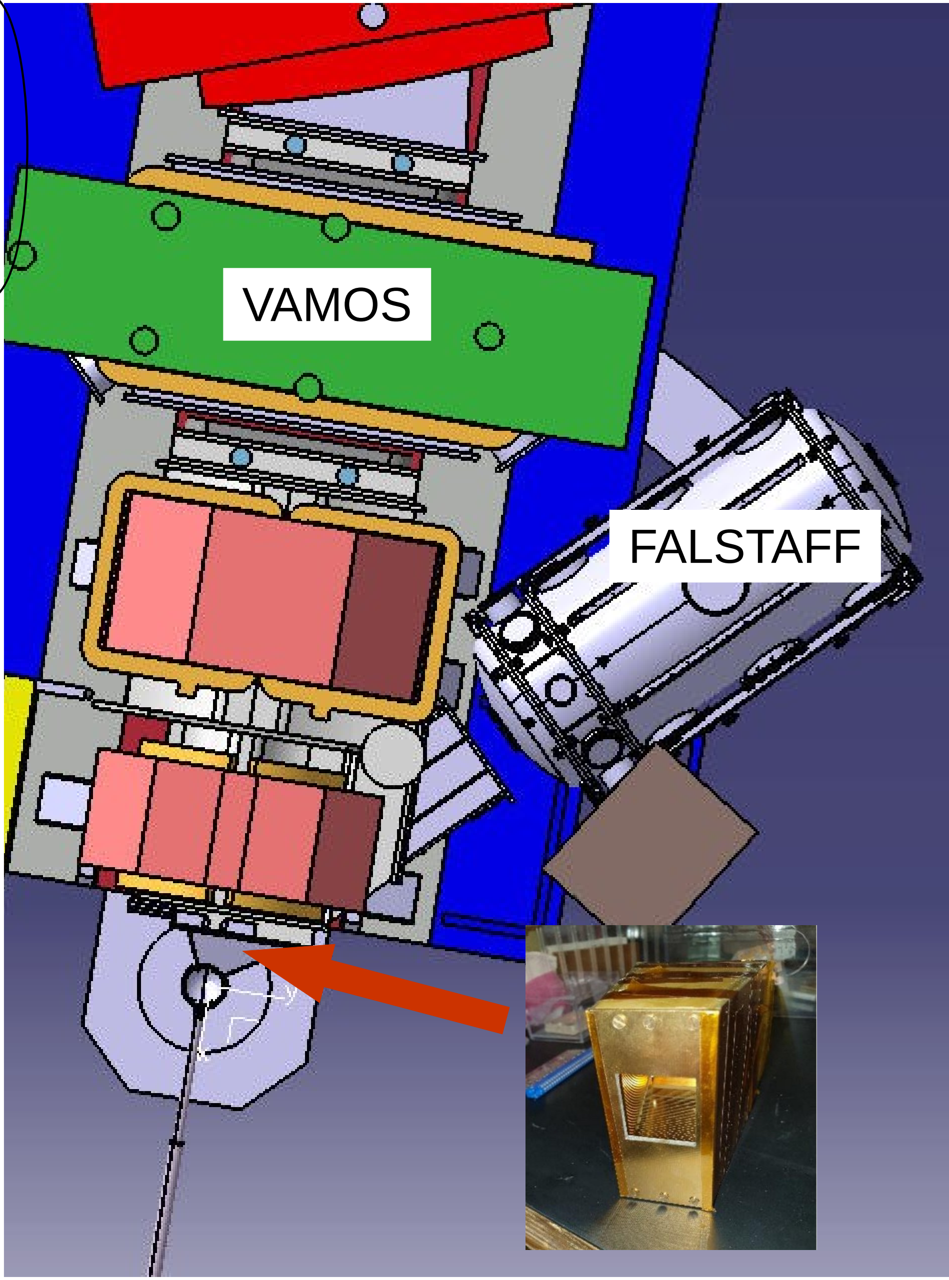
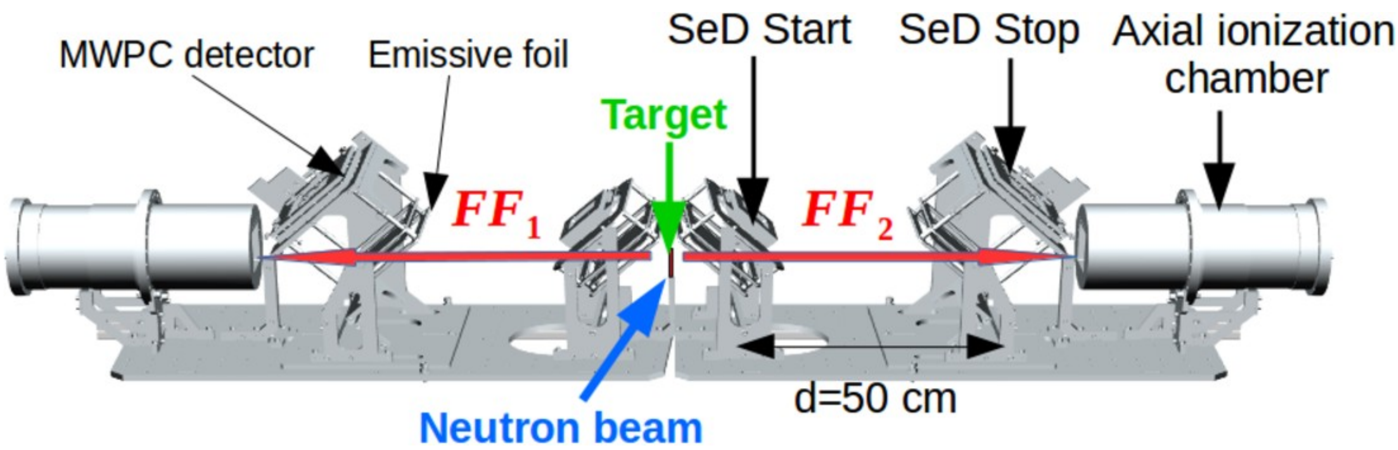


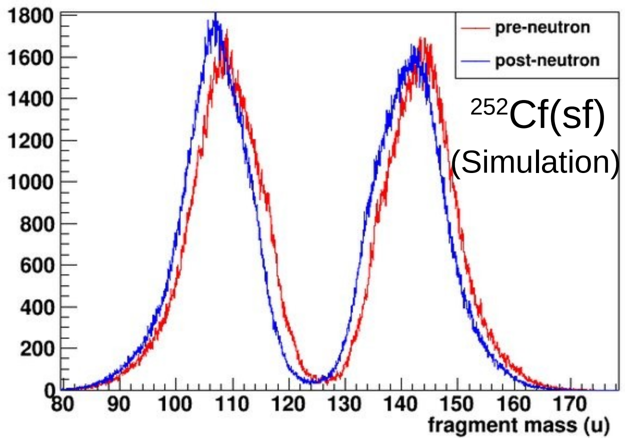


Inverse-kinematics fusion-fission ^{238}U@5.8 MeV/u+^{12}C

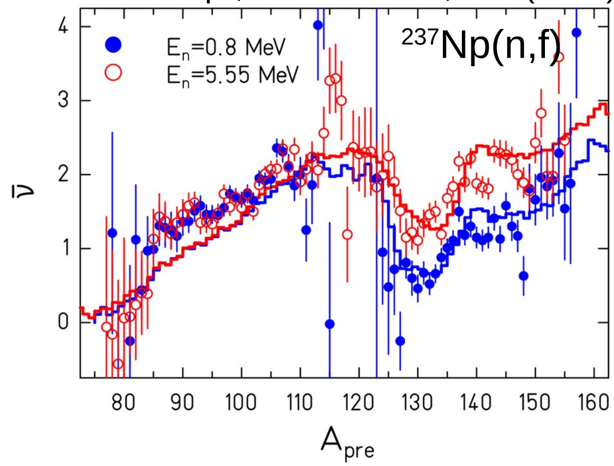
Direct assignment of Z to each dE profile

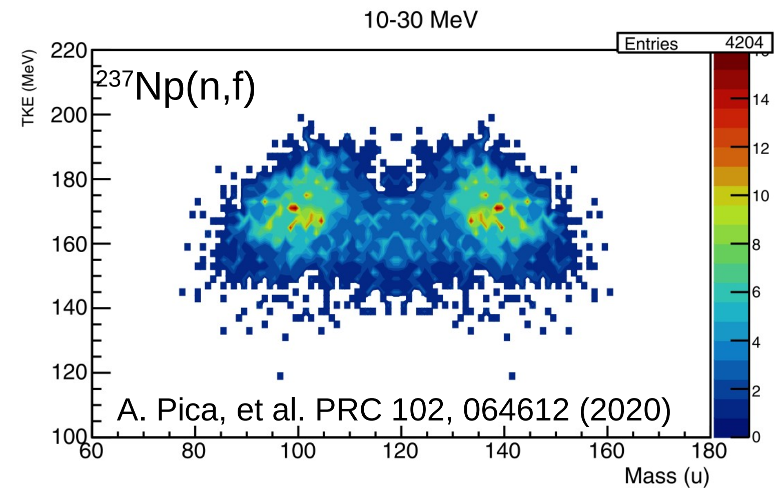
FALSTAFF : 2-arms Setup





A. Naqvi, et al. PRC 34, 218 (1986)

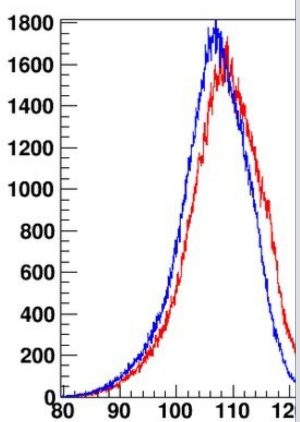




- **Pre- and post-neutron evaporation FF masses**
  - **Neutron evaporation** distribution
    - Information of the **sharing of E_x between FF**
  - Impact of **multichance fission**

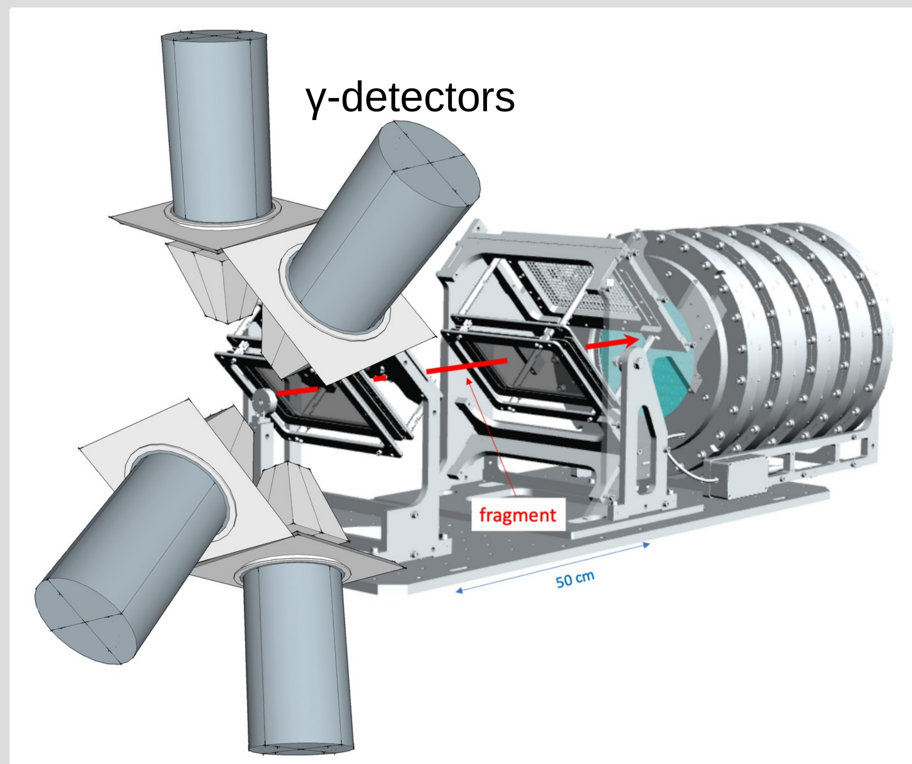
- **Fission Fragment Kinetic Energy**
  - Information of the scission configuration

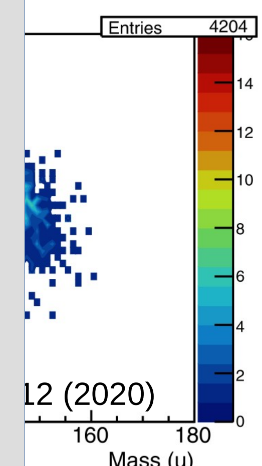
FALSTAFF : 2-arms Setup



FALSTAFF setup + GAMMA detectors

Good opportunity to **explore the excitation of fission fragments** at scission from **controled incomming channel**





- **Pre- and p**
  - **Neutror**
    - Inform
  - Impact of **m**

Energy

on

Summary

The fission process is a wide laboratory for fundamental nuclear studies as well as a useful tool for applications. Nevertheless, the fission process is still far from being fully understood.

GANIL offers a great opportunity to study the fission process from two very different approaches:

- The use of Inverse-Kinematics Surrogate-induced fission combined with the magnetic spectrometer VAMOS++ gives access to full fission-fragments identification of exotic fissioning systems

- The startup of the Neutrons For Science facility will give access to the Direct-Kinematics Neutron-induced fission studies of long-life radioactive actinides. Coupled with the FALSTAFF spectrometer, it offers an unique opportunity to explore the evolution of the scission configuration at fission-barrier energies and above

The fission program at GANIL has been proved to provide the largest number of fission observable correlations. The new NFS facility will contribute to enrich this program with long-term prospectives.

Collaboration

FISSION@VAMOS

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P. Morfouce, J. Taieb, A. Chatillon, B. Mauss

***CEA, DAM,** DIF, Arpajon, France*

M. Caamano, H. Alvarez-Pol, B. Fernandez-Dominguez

***IGFAE,** University of Santiago de Compostela, Spain*

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FALSTAFF@NFS

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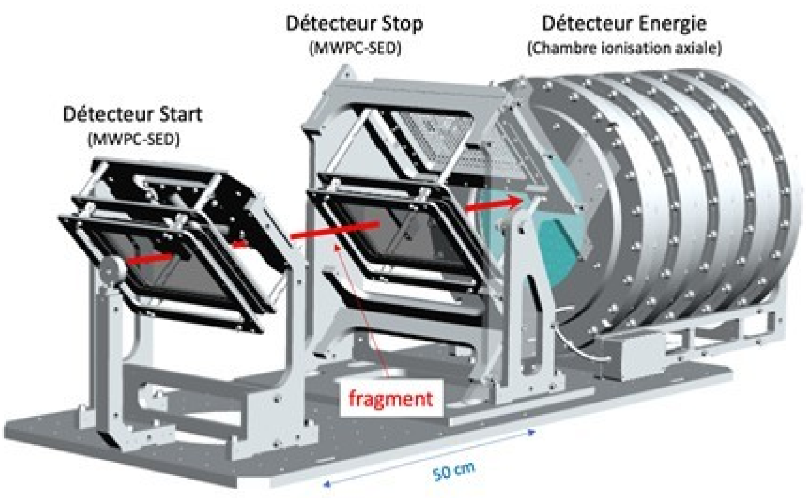
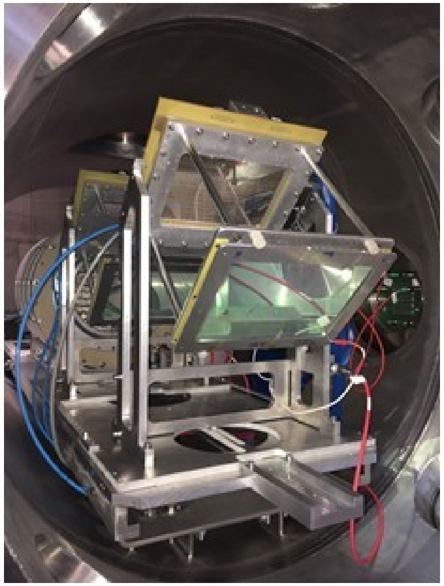
NEWS

27/09/21

FALSTAFF has arrived to GANIL/NFS





Le spectromètre FALSTAFF bénéficiera du flux de neutrons intense disponible au NFS pour étudier le processus de fission dans les actinides. Les fragments de fission seront entièrement identifiés dans la configuration qui est composée de deux détecteurs d'électrons secondaires sensibles à la position pour les mesures ToF et d'une chambre d'ionisation axiale qui mesure l'énergie résiduelle. De plus, la configuration axiale de la chambre d'ionisation permettra d'estimer la charge nucléaire des fragments légers.

The FALSTAFF spectrometer will benefit from the intense neutron flux available at NFS to study de fission process in actinides. Fission fragments will be fully identified in the setup that is compound of two Position-Sensitive Secondary-Electron Detectors for ToF measurements and an Axial Ionization Chamber that measures the residual energy. In addition, the axial configuration of the ionization chamber will allow the estimation of the nuclear charge of light fragments.