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

Diego Ramos
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 microscopic description of the fission process
- No experimental access to the intermediate steps of the fission process
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

- $^{238}\text{U}$ beam at $\sim6$ MeV/u (Coulomb energies)
- C/Be targets
- Transfer/Fussion induced fission
Fission at VAMOS: n-rich actinides region

- $^{238}$U beam at $\sim$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 $\sim$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
Fission at VAMOS: n-rich actinides region

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

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

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

Fission at VAMOS: n-rich actinides region

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

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

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

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

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 asymmetric 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)
- Complete-Kinematics Measurement

- Fission Fragments Neutron Excess:
  - **Opposite behaviour** with respect to actinides
  - **Common driving intrinsic 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.**
Upgrade of VAMOS

- **Improving the Incoming Channel: From SPIDER to PISTA**
  - High particle-identification capabilities
  - Higher energy resolution (2.5 MeV $\rightarrow$ 0.7 MeV)
  - Larger angular coverage

- **Simultaneous Gamma Measurements: PARIS Detector at Target**
  - 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

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

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

Data for the Th/U cycle
- Energy generation through fast neutron reactions
- Nuclear waste incineration

U. Abbondanno et al. CERN/INTC 2001-025
Neutron-Induced Fission at NFS
Using the FALSTAFF Spectrometer
Neutrons For Science Facility

- **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**

- **Time-of-flight experimental room:**
  - **28 m long room**
  - Neutron energy measured from the **time of flight technique**
  - **1 us flight path** → bunch selector 1/100 (5mA → 50μA (3x10^{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
Neutrons For Science Facility

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

NFS offers a great opportunity to study n-induced fission
Fission with FALSTAFF at NFS

- Data from spontaneous fission of $^{252}$Cf source

- 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
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
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

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

**Direct assignment of Z to each dE profile**
FALSTAFF : 2-arms Setup

- 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

- 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

Good opportunity to explore the excitation of fission fragments at scission from controlled incoming channel.
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
A. Lemasson, M. Rejmund, D.Ramos
GANIL, CEA/DRF-CRNS/IN2P3, Caen, France
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
C. Schmitt
IPHC, CNRS/IN2P3-UDS, Strasbourg, France
P. Marini, I. Tsekhmanovich, M. Aiche, L. Mathieu
CENBG, CNRS/IN2P3-Université de Bordeaux, Gradignan, France
L. Audouin
IJCLab, CNRS/IN2P3-Université Paris-Saclay, Orsay, France

FALSTAFF@NFS
D. Doré, E. Berthoumieux, P. Legou, A. Letourneau, T. Materna, L. Thulliez
Irfu, CEA Saclay, France
GANIL, CEA/DRF-CRNS/IN2P3, Caen, France
S. Oberstedt
JRC Geel, Belgium
A. Chebboubi, O. Litaize, O. Serot
DES/IRESNE/DER, CEA Cadarache, France
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 the fission process in actinides. Fission fragments will be fully identified in the setup that consists 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.