Fission studies in Inverse Kinematics: recent results and perspectives

L. Audouin, L. Grente, A. Chatillon, J. Taieb
and the SOFIA collaboration
Fission fragment yields: applied physics

- FF impact the dynamics of nuclear reactors
  - Delayed neutrons
  - Neutronic poisons
  - Increased influence with larger burn-ups
  - Criticality excursions: quick accumulation of FF
- FF are the main source of residual power and radioactivity
  - Shielding for used fuel handling and reprocessing
  - Loss Of Coolant Accident (LOCA)
  - Decay heat

- Fission is the termination of the r-process
  - Nucleosynthesis calculations depend on fission barriers
Fission yields: a unique probe for structure and dynamics

- How do shell effects constrain the yields?
  - Do closed shells act as attractors? N, Z, both?
  - Dampening of shell effects with energy
  - Shell effects at large deformation?
  - Are shell effects sole responsible for asymmetric fission?
- Influence of the pairing: even-odd staggering in the yields
- Splitting of excitation energy among nascent fragments?


Several modelling of the damping of shell effects
Interest of Inverse Kinematics

- Heavy partner (fissioning system) as projectile
- In-flight fission

Identification of the fragments: recoil spectrometer
- Measurement on short-lived nuclei
- High velocity FF: better (up to excellent) Z measurement

Pioneer experiment: K.-H. Schmidt et al. (1996): Z of both FFs
- 2010s: transfer@GANIL (see M. Camaano’s talk), SOFIA@GSI
The SOFIA program

- High-precision measurement (~ % on isotopic yields)
- Simultaneous identification of both fission fragments: A & Z
  - Kinetic energy
  - Deduced total prompt neutron multiplicity
- “West-looking”: products of $^{238}\text{U}$ fragmentation (FRS)
  - Full identification of the fissioning system
- Large-acceptance recoil spectrometer in cave C (GSI)
- Fission trigger: Coulomb interaction
  - Large cross section (~ b)
  - Small $E^*$: excitation of the GDR ($<E^* > \sim 14$ MeV)
    - $^{236}\text{U} (\gamma,f) \sim ^{235}\text{U} (n,f) @ 8.2$ MeV
    - 75% of first chance fission (23% 2nd chance)
  - Significant dispersion of $E^*$: no info event-by-event
High-precision measurements

• High-precision indeed: $\sigma < 1\%$ for light and heavy fragments
• Lighter systems favor larger asymmetry

• Strong even-odd effect on Z
  • Fully decided at scission
  • Dampening due to $E^*$
• Smaller even-odd effect on N
  • Decided by fluctuations of Sn
  • Insensitive to $E^*$
An insight on the shape of fragments at scission

- Spherical prefragment: shorter distance at scission
- ... Hence, larger kinetic energy
Prompt-neutrons: a probe of excitation energy

- $\nu = A_{CN} - A_{FF1} - A_{FF2}$ (measured event-by-event)
- Favored de-excitation channel: directly correlated to $E^*$
- Deformation $\rightarrow$ excitation $\rightarrow$ neutrons
- Even-even split: larger $Q$

$\langle E^* \rangle = 14.1$ MeV
$\langle \nu \rangle = 3.81$ ($^{236}$U)
$\langle \nu \rangle_{th} = 2.45$ ($^{236}$U)
Pre and post neutron emission mass yields

- Subtraction of higher-chance fission
- Yields are correlated: \( Y(A_i) = 236 - \nu(i,j) - Y(A_j) \)

\[
Y(A_1, A_2) = \sum_{\nu_1=0}^{236-A_1-A_2} P^{M_1}(\nu_1) P^{M_2}(\nu_2) X(M_1)
\]

Calculations by L. Grente and J. Taieb
Energy-sorting study through prompt-neutrons yields

SOFIA data: \( \langle \nu \rangle_{\text{LIGHT}} = 1.40 \), \( \langle \nu \rangle_{\text{HEAVY}} = 2.26 \)

Nishio et al.: \( \langle \nu \rangle_{\text{LIGHT}} = 1.42 \), \( \langle \nu \rangle_{\text{HEAVY}} = 1.01 \)

\( \langle E^* \rangle_{1\text{st chance}} = 12.4 \text{ MeV} \)

thermal neutrons

Additional excitation goes *entirely* into the heavy fragment
Energy sorting: an explanation

- K. H. Schmidt and B. Jurado
  - Phys. Rev. C 83 061601(R) (2011)

- The scissioning system behaves as coupled thermostats
- At low energy (superfluid regime) $T \propto A^{-2/3}$
- Energy flows toward the heavy fragment
• Asymmetric fission is understood as a consequence of spherical/deformed shells.
Fission along the nuclear chart

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- Heavier systems tend toward double $^{132}\text{Sn}$-like nuclei (symmetric)
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- For pre-actinides, closed-shell fragments lead to too large asymmetry: symmetry takes precedence.

Courtesy K.H. Schmidt
Transition to symmetry in Th isotopes

- The heavy peak sticks around $Z = 54$
- With lighter systems, such partition gets costly in asymmetry energy
- Coexistence and finally symmetry

- First-ever results on neutrons for light Th isotopes!
- Large reduction of the excitation energy for the symmetric fission
- Colder fissioning system?
Fission along the nuclear chart

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- Heavier systems tend toward double $^{132}$Sn-like nuclei (symmetric).
- For pre-actinides, closed-shell fragments lead to too large asymmetry: symmetry takes precedence.
- Asymmetry appears again for very light, neutron-deficient systems.

A. N. Andreyev et al.
Phys. Rev. Lett. 105, 252502

Courtesy K.H. Schmidt
Fission modes in neutron-deficient pre-actinides

- β-delayed fission at ISOLDE
- Intense theory work!
- Complex potential landscape with no shell effects
- 5D calculations of Möller

- Objective of the next SOFIA measurement (2019)

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Summary and outlook

- New generation of fission experiments
  - High-resolution measurements
  - Exploration of the complete isotopic space of fragments
  - Wide range of fissioning systems
  - Increased number of combined observables
    - SOFIA coupling with NeuLAND: neutron tagging
    - SOFIA coupling with CALIFA: gamma multiplicity
- Measurement of the U-Pu region: $^{242}\text{Pu}$ primary beam
- Exclusive experiments: (e,f) or surrogate reactions at storage ring
- Neutron-rich systems: Super-FRS exotic beams

- Detailed studies of trans-actinides
- Origin of angular momentum from fragments?
- Fission time?
Secondary beam identification

- Standard $B_\rho - \Delta E - \text{ToF}$ method
- High-Z fragments have a large probability to carry electron(s)
Fission fragments identification

\[
\Delta E - B_p - \text{ToF method}
\]

\[
A/Z = B_p / \beta \gamma
\]

- \(B_p\): position from MWPCs
- \(\Theta\): from the Twin-MUSIC
- \(\Delta E\): from the Twin-MUSIC
- \(\text{ToF}\): between START and ToF-wall
Coulomb-induced fission

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- Small $E^*$: excitation of the GDR ($\langle E \rangle \sim 14$ MeV)
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- Significant dispersion of $E^*$: no info event-by-event
- Need to subtract nuclear contribution

![Diagram showing beam, actinide absorption of virtual photons, and GDR excitation between target and Pb.](image)
Rejection of the nuclear contribution

- Selection of events $Z_1 + Z_2 = Z_{\text{beam}}$

- Limiting fragmentation regime:
  - The reaction mechanism does not depend on the target
  - Subtraction of yields obtained on Al target (renormalization)