Modeling fission fragments de-excitation

Valentin Piau

CEA/DES/IRESNE/DER, Cadarache, 13108 Saint-Paul-lez-Durance

present address: Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay
The fission process

- Compound nucleus
- Deformation
- Scission
- FF acceleration
- Prompt neutron & γ-ray emission
- β decay (delayed emission)
The fission process

- Compound nucleus
- Deformation
- Scission
- FF acceleration
- Prompt neutron & $\gamma$-ray emission
- $\beta$ decay (delayed emission)

$t \sim 10^{-18} / 10^{-6}$ s
Prompt de-excitation of the fragment

Fission fragments are left in an excited, unstable state

**Fission fragment**
- Mass (A)
- Charge (Z)
- Excitation energy (E)
- Total angular momentum (J)
- Parity (π)

**Particle emission**
- Remove the excess of excitation energy to reach a more stable state

*Characterize the excitation state of the fission fragment*
Prompt de-excitation of the fragment

Fission fragments are left in an excited, unstable state

**Fission fragment**
- Mass (A)
- Charge (Z)
- Excitation energy (E)
- Total angular momentum (J)
- Parity (π)

**Particle emission**

→ Remove the excess of excitation energy to reach a more stable state

**Neutron emission**

a neutron is expelled from the nucleus:

\[ A \rightarrow A - 1 \]

threshold reaction: \[ E > S_n \]
Prompt de-excitation of the fragment

Fission fragments are left in an excited, unstable state

Fission fragment

- Mass (A)
- Charge (Z)
- Excitation energy (E)
- Total angular momentum (J)
- Parity (π)

Particle emission

- Remove the excess of excitation energy to reach a more stable state

γ-ray (photon) emission

Electromagnetic transition mostly occurs after the neutron emission

Characterize the excitation state of the fission fragment
How is this measured?
Measuring the de-excitation

• Experiments to measure neutrons and/or γ-rays emitted after fission
  o Neutron / gamma-ray multiplicities (number of emitted particles)
  o Neutron / gamma-ray spectra (energy distribution)

  \{ \textit{Fission observables} \}

• Correlations with other parameters, e.g. fragment mass

  Challenges: particles emitted by both fragments, fragments in motion (Doppler effect)

  \begin{center}
  \includegraphics[width=\textwidth]{diagram.png}
  \end{center}

• ‘classical’ systems: $^{252}\text{Cf}$, $^{235,238}\text{U}$, $^{239}\text{Pu}$,…
Measuring the de-excitation

• Experiments to measure neutrons and/or γ-rays emitted after fission
  o Neutron / gamma-ray multiplicities (number of emitted particles)
  o Neutron / gamma-ray spectra (energy distribution)

Fission observables

• Correlations with other parameters, e.g. fragment mass

Challenges: particles emitted by both fragments, fragments in motion (Doppler effect)

• ‘classical’ systems: $^{252}\text{Cf}$, $^{235,238}\text{U}$, $^{239}\text{Pu}$,…

Spontaneous fission
  → CORA @IPHC (Strasbourg)
  → VESPA @EC-JRC (Geel, Belgium)
  → …

Neutron-induced fission
  → LICORNE + nu-ball @ALTO (Orsay)
  → FIPPS @ILL (Grenoble)
  → SCINTIA @GELINA (EC-JRC Geel, Belgium)
  → …
Prompt neutron multiplicity

Number of neutrons emitted in the spontaneous fission of $^{252}$Cf as a function of fission fragment mass

Prompt neutron multiplicity

Number of neutrons emitted in the spontaneous fission of $^{252}$Cf as a function of fission fragment mass


Typical saw-tooth shape

Minimum around A=132

⇒ Shell closure
⇒ « spherical » nuclei
Prompt γ-ray multiplicity

VESPA++ setup @EC-JRC Geel
→ Fission fragments, neutrons & γ-ray detectors

γ-ray multiplicity from VESPA

Prompt γ-ray multiplicity

VESPA++ setup @EC-JRC Geel

→ Fission fragments, neutrons & γ-ray detectors

Also a minimum around A=132

Modeling this complex process
Nuclear models

• Initial state of the fragments
  • energy, total angular momentum, parity
  • experimental & theoretical challenges

Wilson et al., Nature 590, 566 (2021)
Nuclear models

• Initial state of the fragments
  • energy, total angular momentum, parity
  • experimental & theoretical challenges

• Nuclear level scheme
  • represents the excited states of a given nucleus
  • unknown excited states at high energies

\[ E, J, \pi \text{ of the fission fragment} \]

\[ \text{Ground state (E=0)} \]

\[ \text{Experimentaly known levels} \]

\[ \text{A, Z} \]

Nuclear models

• Initial state of the fragments
  • energy, total angular momentum, parity
  • experimental & theoretical challenges

• Nuclear level scheme
  • represents the excited states of a given nucleus
  • unknown excited states at high energies
    \( \Rightarrow \) theoretical excited states \((E,J,\pi)\)

\[
\text{E,J,}\pi \text{ of the fission fragment}
\]

Nuclear models

• Initial state of the fragments
  • energy, total angular momentum, parity
  • experimental & theoretical challenges

• Nuclear level scheme
  • represents the excited states of a given nucleus
  • unknown excited states at high energies
  ➔ theoretical excited states (E,J,\pi)

• Probabilities of emission
  • measured transitions at low energy only
  • different models for different particles (n/\gamma/e⁻)

Monte Carlo code written in C++ and developed by CEA Cadarache.

- Event-by-event simulation of fission
- Sampling of physical variables
- Statistical estimators
  - Fission observables
  - Correlations of observables
  - Non-measurable physical quantities (e.g. angular momentum)

O. Litaize et al., EPJ Web of Conf. 284, 04014 (2023)
FIFRELIN
Fission FRagment Evaporation Leading to an Investigation of Nuclear data

Principle of operation:

- Based on several nuclear models (macroscopic and/or microscopic)
- Fission fragments yields as input (before neutron emission)
- 4 free parameters tuned to reproduce 1 to 2 scalar observables (average number of emitted neutrons)
Impact of nuclear models

• Models of nuclear level density (number of levels in scheme)
  Semi-empirical model (CGCM) vs microscopic+combinatorial model (HFB14)
• Observables: neutron / γ-ray multiplicities as a function of fragment mass
Comparison with experimental data

• Observables: neutron / γ-ray multiplicities as a function of fragment mass

Application to other fissioning systems

Neutron-induced fission of $^{235}$U & $^{239}$Pu

MC1 - Dernières avancées dans la détection et la modélisation de la fission nucléaire
V. Piau
23
Conclusion

• Fission fragments de-excite through the emission of several particles: neutrons, γ-rays and electrons

• Continuous progresses
  • Experimentaly: better detectors, advanced setups
  • Theorically: more & more advanced nuclear models

• FIFRELIN benefits from these progresses
  ➔ simultaneous reproduction of neutron and γ-ray multiplicities after the introduction of a new model

• Applications beyond fission
  ➔ de-excitation of a single nucleus following neutron capture
  ➔ G. Soum poster (this afternoon)