Mesurer la fission: Défis et résultats récents

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The Fission Process

Fragments recover smaller deformation

E* release by prompt neutron emission

E* release by prompt gamma-ray emission

β decay
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A, Z, E*, Jπ

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Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of c. 200 Mev., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole fission process can thus be described in an essentially classical way, without having to consider quantum-mechanical ‘tunnel effects’, which would actually be extremely small, on account of the large masses involved.

Meitner and Frisch, Nature (1939)
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A, Z, E*, Jπ

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85 years of experimental and conceptual challenges

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The importance of fission

Huge amount of energy released per fission event: ~ 200 MeV!
Few eV for combustion of a molecule of coal, gas or oil...

- Nuclear technology => production of
  - electricity (~10% of present electricity production)
  - radio-isotopes for medicine
  - Radioactive Ions Beams
- Nuclear astrophysics, synthesis of elements via the r-process

Fission sets the end point of the r-process and strongly influences the r-process abundances and light curves!
Why Nuclei Fission?

- Competition between nuclear binding (neutrons and protons) and electrostatic repulsion (protons) -> Fission Barrier
- Once separated, the products “slide” of the electrostatic potential
- The energy released is found in their velocities

Fission can be:
- spontaneous:
- induced:
  - By neutrons
  - By photo fission ($\gamma$)
  - By nuclear reactions
A Macroscopic point of view: Fission of a liquid drop of nuclear matter

Caamano et al. (2013)
Aren’t nuclei quantum objects governed by the nuclear Force?

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Following an observation of Curie and Savitch, Hahn and Strassmann found that a group of at least three radioactive bodies, formed from uranium under neutron bombardment, were chemically similar to barium and, therefore, presumably isotopic with radium. Further investigation, however, showed that it was impossible to separate these bodies from barium (although mesothorium, an isotope of radium, was readily separated in the same experiment), so that Hahn and Strassmann were forced to conclude that isotopes of barium (Z = 56) are formed as a consequence of the bombardment of uranium (Z = 92) with neutrons.

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=> Microscopic / Structural effects
The importance of fission for fundamental nuclear physics

Fission is a complete laboratory for studying nuclear dynamics over a broad range of deformation under the influence of shell effects, correlations!

Many key fundamental nuclear properties have to be taken into account!
The richness of fission observables

**Formation:**
- Capture cross sections

**Ground-state to barrier:**
- Fission probability,
  - neutron capture cross sections
  - Fission Barrier (Fission probability)
The richness of fission observables

Formation:
Capture cross sections

• Neutron capture cross sections
• Fission Barrier (Fission probability)
• Fission Fragment Yields (A, (N,Z))
• Kinetic Energies

Ground-state to barrier:
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• Fission Fragment Yields (A, (N,Z))
• Neutron multiplicities
• Gamma-ray Emission
• Cumulative yields

Barrier to well after scission:
Fission fragment yields

Prompt neutrons & gammas

Neutron Cross-Sections for Fission of Uranium and Plutonium
The richness of fission observables

Formation:
Capture cross sections
- L. Mathieu

Ground-state to barrier:
Fission probability,
- L. Audoin (Poster)
- C. Berthelot (Poster)

Barrier to well after scission:
Fission fragment yields
- P. Morfouace
- J-E Ducret (Poster)
- D. Treasa (Poster)

Prompt neutrons & gammas
- V. Piau
- C. Michelagnoli
- G. Soum

- neutron capture cross sections
- Fission Barrier (Fission probability)
- Fission Fragment Yields (A, (N,Z))
- Kinetic Energies
- Neutron multiplicities
- Gamma-ray Emission
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When the system has a lot of energy!

- Q. Fable (Poster)
The richness of fission observables

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Barrier to well after scission:
Fission fragment yields

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New opportunities have revived the field of nuclear fission

• New experimental techniques to measure Fission Fragments yields (compared to spontaneous or n-induced fission)
  • Heavy ion reaction induced fission (fusion, transfer, inelastic excitation)
  • Inverse kinematics with magnetic spectrometers

=> New Opportunities
• Range of fissioning systems (A,Z, Excitation Energy domain)
• Isotopic Identification of fission Fragments ($A_{ff}, Z_{ff}$)
Heavy ions reactions fission studies

Studying « exotic » fissionning systems using heavy ion reactions (changing the content in number of protons and neutrons)

- Fusion (A+B→C)
- Transfert of particules (A + B → C + D)
- Electromagnetic excitation of Radioactive Beams (A+B→A*+B)
- Beta delayed fission
Decades of investigations based on the mass of fission fragments

\[ A = N + Z \]

\( N \) and \( Z \) are the degrees of freedom of nuclei

Related to the challenge of measuring the charge (\( Z \)) of fission fragments
Fission under the inverse kinematics boost

Direct kinematics fission
Light beams + Actinide target → Fission almost at rest
Fission under the inverse kinematics boost

Direct kinematics fission
Light beams + Actinide target $\rightarrow$ Fission almost at rest
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Atomic Charge (Z) identification
Exemple with $\Delta E/E$

- Very low recoil energy of Fission Fragments (1cm/ns)
- Limited identification capabilities
  - Mass 2-4 amu
  - $Z < 40$
- Experimental challenge to overcome

=> Poster FALSTAFF @ NFS / J-E Ducret
Fission under the inverse kinematics boost

**Direct kinematics fission**
Light beams + Actinide target → Fission almost at rest

**Inverse kinematics fission**
Heavy beams + light target → Fission in motion / flight

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- Boosted Fission Fragments (> 3cm/ns)
- Favoured identification capabilities
  - Mass 1/200 (with spectrometer)
  - Complete Z distributions
- Kinematical Focussing
$\Rightarrow$ Improved detection efficiency
Relativistic Fission in inverse kinematics at GSI

K.-H. Schmidt et al.

Fragmentation => cocktail beam of Radioactive Ions of actinides
Electromagnetic excitation (A+B->A^*+B) induced fission
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Fragment Z yield distribution of more than 70 neutron-deficient fissioning systems.
And also kinematical information...
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Fragmentation => cocktail beam of Radioactive Ions of actinides
Electromagnetic excitation (A+B→A*+B) induced fission

1) Stabilization in Z (while observed in A before)
2) Transition and competition between asymmetric and symmetric fission
   => Competing structural effects

Fragment Z yield distribution of more than 70 neutron-deficient fissioning systems. And also kinematical information...
Recent results and perspectives @ SOFIA => Pierre Morfouace

Relativistic Fission in inverse kinematics at GSI

E. Pellereau et al., PRC 95, 054603 (2017)

Accurate access to $Z$ and Mass
Fission in inverse kinematics at VAMOS/GANIL

Inverse Kinematic using beams of $^{238}\text{U}$ around Coulomb Barrier

$\Rightarrow$ Access to « exotic » fissioning systems heavier than $^{238}\text{U}$
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$^{238}\text{U}$

@ 6 AMeV

transfer reaction

$^{12}\text{C}$

target

recoil

SPIDER $\rightarrow$ PISTA:
Recoil
A, Z, E, angle

Surrogate reactions
(transfer induced fission)
$\Rightarrow$ Selection of the fissioning system
$\Rightarrow$ Measurement of the excitation energy

The reconstruction of the binary reaction gives kinematical information and the identification of the fissioning system
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$fission$

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(transfer induced fission)

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The reconstruction of the binary reaction also provides information on the fission barrier
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VAMOS Magnetic Spectrometer

⇒ Direct and Complete isotopic fission fragment yields

⇒ Precise center-of-mass fission fragment velocities isotopically (due to Coulomb barrier energies)
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$^{238}$U @ 6 AMeV

Transfer reaction

$^{12}$C target

Fission

$^{239}$Np (7.5 MeV)

VAMOS Magnetic Spectrometer

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⇒ Precise center-of-mass fission fragment velocities isotopically (due to Coulomb barrier energies)
A set of revisited and new observables
Z and N distributions

The effect of the heavy group lasts until very high excitation energy.

At ~46 MeV the distribution is not yet fully LD.

Even odd effect: pairing of nucleons in fission and damping with the excitation energy.

D. Ramos et al. (2019)
A set of revisited and new observables

Fragments N excess ($\langle N \rangle/Z$)

Reveals fine structural effects otherwise unnoticed

N=82 (~spherical) and N=88 (deformed / Octupolar)
Exploring further the fission landscape

- particle-induced, SF
- e.m.-induced
- β-delayed fission
- transfer-induced

Diagram showing isotopes and nuclear properties.
Exploring further the fission landscape

- particle-induced, SF
- e.m.-induced
- β-delayed fission
- transfer-induced

Actinides N/Z ~ 1.5

Identified shell effects
(Z=52, 56, N=82,88)

Competition between modes
Open questions on the pairing and the damping of shell effects with E*

Z=82

N=126

226Th, 229Th, 242Cf, 256Fm, 236U

180Hg, 201Tl, 227Ra
Exploring further the fission landscape

- Particle-induced, SF
- E.m.-induced
- β-delayed fission
- + transfer-induced

Pre-Actinides N/Z ~ 1.2

Unexpected asymmetric fission in $^{180}\text{Hg}$ (Andreiev et al. PRL (2010))

$\Rightarrow$ New stabilizing effects at $Z \sim 36$ deformed (octupole) configuration

Ongoing programs:
- Fusion Fission GANIL / JAEA
- Electromagnetic probe @ GSI

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Identified shell effects ($Z=52, 56, N=82, 88$)

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$^{256}\text{Fm}$

$^{236}\text{U}$
Exploring further the fission landscape

- particle-induced, SF
- e.m.-induced
- β-delayed fission
- transfer-induced

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Building a coherent picture across the landscape
Fission: A long history and rich perspectives

After 85 years of studies, fission remains a challenging topic.
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- **In the last decade, experimental developments** opened new paths to probe the fission process for a wide range of systems (in terms of content (N/Z) and excitation energy E*)

- **Present and future exclusive measurements (A,Z,E*)** bring new constrains to models to explore the different underlying dynamical and structural mechanisms that drive the fission process **towards a coherent picture** of the fission process across the fission nuclear landscape.
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- **Contributions to nuclear data needs** and evaluation

- Beyond the fission yields (mostly shown today), a large number of observables (Kinetic Energies, neutron multiplicities, prompt gamma-ray spectra) plays a key role in gaining a deeper understanding of the process.

  => V. Piau, C. Michelagnoli

- **Ongoing intense theoretical developments** aiming at a microscopic description of the fission process

  => D. Regnier

Thank you for your attention!