Determination of fission and fragmentation time-scales by Coulomb chronometry

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(INDRA and FAZIA collaborations)
Esym(\(\rho\)) and reaction mechanism
Esym(\(\rho\)) and reaction mechanism

\[ \rho \sim \rho_0 \ T \sim 0 \]

Coulomb barrier

\[ \rho < \rho_0 \ T > 0 \]

Fermi energies

\[ \rho > \rho_0 \ T > 0 \]

Relativistic energies
E_{sym}(\rho) and reaction mechanism

Many approaches

Large deviations

Phenomenology

Microscopic
3-fragment production mode

- Xe + Sn at 8, 12, 15, 18, 20, 25 MeV/A
- Measured with INDRA 4π multidetector
- Most dissipative collisions (Ztot>90)
- Heavy fragment : Z>10
3-fragment production mode

- Xe + Sn at 8, 12, 15, 18, 20, 25 MeV/A
- Measured with INDRA 4π multidetector
- Most dissipative collisions (Z_{tot}>90)
- Heavy fragment : Z>10

- 2-frag dominates at 8 MeV/A
- 3-frag significant above 12 MeV/A
- Continuation of fission or precursor of simultaneous fragmentation?
- Estimation of the involved timescale

From sequential to simultaneous

Velocity Dalitz plots

\[ P_i = (v_{i(jk)}^{\text{exp}} - v_{i(jk)}^{\text{fiss}})^2 + (v_{jk}^{\text{exp}} - v_{jk}^{\text{fiss}})^2 \]

1st splitting 2nd splitting

\[ P_i \ll P_j, P_k : \text{sequential} \]
\[ P_i \sim P_j \sim P_k : \text{simultaneous} \]
From sequential to simultaneous

Velocity Dalitz plots

\[ P_i = (v_{i(jk)}^{exp} - v_{i(jk)}^{fiss})^2 + (v_{jk}^{exp} - v_{jk}^{fiss})^2 \]

1\textsuperscript{st} splitting \quad 2\textsuperscript{nd} splitting

\( P_i \ll P_j, P_k : \) sequential

\( P_i \sim P_j \sim P_k : \) simultaneous

sequential

less sequential

simultaneous ?

12 MeV/A

15 MeV/A

20 MeV/A

25 MeV/A

Beam energy
Splitting sequences

Starting hypothesis: two successive splittings

1. Which fragment has been emitted first?
2. The pair of fragments with relative velocity closest to fission produced during the second step.
Starting hypothesis: two successive splittings
Splitting sequences

\[ t = t_0 + \delta t \]

Starting hypothesis: two successive splittings
Splitting sequences

$t = t_0 + \delta t$

- Starting hypothesis: two successive splittings
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Splitting sequences

Starting hypothesis: two successive splittings
Which fragment has been emitted first?
The pair of fragments with relative velocity closest to fission produced during the second step

\[ t = t_0 + \delta t \]

\[ \sum \text{ASY} \]

\[ \text{EOS} \]

\[ Z_3 \]

\[ v_{(Z_3)} \text{ [cm/ns]} \]

\[ v_{//}(Z_3) \text{ [cm/ns]} \]

\[ Z_3 \text{ velocity diagram} \]
Splitting sequences

$\begin{align*} t &= t_0 + \delta t \\
\end{align*}$

- Starting hypothesis: two successive splittings
- Which fragment has been emitted first?
- The pair of fragments with relative velocity closest to fission produced during the second step

$Z_3$ velocity diagram

- $Z_3$ emitted first
- $Z_2$ emitted first
- $Z_1$ emitted first
Starting hypothesis: two successive splittings
Which fragment has been emitted first?
The pair of fragments with relative velocity closest to fission produced during the second step

- $t = t_0 + \delta t$

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Which fragment has been emitted first?
The pair of fragments with relative velocity closest to fission produced during the second step

\[ t = t_0 + \delta t \]

70-80% efficiency

<table>
<thead>
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<th></th>
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<th>3</th>
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<td>6.0</td>
<td>28.6</td>
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<tr>
<td>2</td>
<td>0.5</td>
<td>26.3</td>
<td>4.9</td>
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<tr>
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<td>28.5</td>
<td>0.3</td>
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Z\(_3\) velocity diagram
- Z\(_3\) emitted first
- Z\(_2\) emitted first
- Z\(_1\) emitted first
Coulomb chronometry

\[ t = t_0 + \delta t \]

\[ t \to \infty \]

\[ v_{12} \]

\[ \langle v_{12} \rangle \text{[cm/ns]} \]

\[ \cos(\theta) \]
Coulomb chronometry

$t = t_0 + \delta t$

$t \to \infty$

$v_{12}$

\[ \langle v_{12} \rangle \text{[cm/ns]} \]

\[ \cos(\theta) \]

- short $\delta t$
- long $\delta t$

\[ t = t_0 + \delta t \]
Coulomb chronometry

\[ t = t_0 + \delta t \]

\[ t \to \infty \]

\[ v_{12} \]

\[ \theta \]

\[ \langle v_{12} \rangle [\text{cm/ns}] \]

\[ \cos(\theta) \]

\[ \bullet \ 25 \text{ MeV/A} \]
\[ \vartriangle \ 20 \text{ MeV/A} \]
\[ \blacktriangle \ 18 \text{ MeV/A} \]
\[ \bullet \ 15 \text{ MeV/A} \]
\[ \blacktriangle \ 12 \text{ MeV/A} \]
\[ \vartriangle \ 8 \text{ MeV/A} \]
Coulomb chronometry

\[ t = t_0 + \delta t \]

\[ t \rightarrow \infty \]

\[ \langle v_{12} \rangle \text{ [cm/ns]} \]

\[ \delta v \text{ [cm/ns]} \]

\[ \cos(\theta) \]

\[ E(\text{beam}) \text{ [MeV/A]} \]

- 25 MeV/A
- 20 MeV/A
- 18 MeV/A
- 15 MeV/A
- 12 MeV/A
- 8 MeV/A
Coulomb chronometry

$t = t_0 + \delta t$

$t \rightarrow \infty$

$v_{12}$ maximum at $\theta \sim 90^\circ$

Amplitude increases with $E$

Distortion parameter $\delta v$

Kinematic correlations

Trajectory calculations

Graphs showing:
- $\langle v_{12} \rangle$ vs $\cos(\theta)$
- $\delta v$ vs $\delta t$ [fm/c]
- $\delta v$ vs $E$(beam) [MeV/A]
Coulomb chronometry

\[ t = t_0 + \delta t \]

\[ t \to \infty \]

\[ \theta \]

\[ v_{12} \]

Kinematic correlations

- \( v_{12} \) maximum at \( \theta \sim 90^\circ \)
- Amplitude increases with \( E \)
- Distortion parameter \( \delta v \)

Chronometer calibration

- 3-body trajectory calculation
- Calibration function \( \delta t = f(\delta v) \)

\[ \langle v_{12} \rangle \text{ [cm/ns]} \]

\[ \delta v \text{ [cm/ns]} \]

\[ \delta t \text{ [fm/c]} \]

\[ E(\text{beam}) \text{ [MeV/A]} \]
Timescale and onset of fragmentation

**Inter-splitting time**

- $\delta t \approx 900 \text{ fm/c at } 8 \text{ MeV/A}$
- $\delta t$ decreases with increasing $E(\text{beam})$
- $\delta t < 100 \text{ fm/c : quasi-simultaneous}$

![Graph showing inter-splitting time vs. $E^*$ and $E(\text{beam})$]
Timescale and onset of fragmentation

Inter-splitting time
- $\delta t \sim 900$ fm/c at 8 MeV/A
- $\delta t$ decreases with increasing $E$(beam)
- $\delta t < 100$ fm/c: quasi-simultaneous

Evolution of the decay mechanism
- 2 successive binary splittings on shorter and shorter timescale
- Onset of multifragmentation above 4 MeV/A excitation energy

D. Gruyer et al., PRC 92, 064606 (2015)
Timescale and onset of fragmentation

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D.Gruyer et al., PRC 92, 064606 (2015)

How to go further?
- Dynamical description of sequential fission process
- No model available on the market
- K. Mazurek and P.N. Nadtochy
Sequential fission model

- 3D potential energy landscape
- Fourth « tilting » coordinate
- Dynamics solving Langevin equations
- Light particle evaporation

K. Mazurek et al., PRC 84, 014610 (2011)
P. N. Nadtochy et al. PRC 89, 014616 (2014)
Sequential fission model

- Compute $E_{FF}$ and $l_{FF}$ of fission fragment
- Both FF injected in the same code
- Sometimes one of them fission again
- At the end 2, 3, or 4 fragments

- 3D potential energy landscape
- Fourth « tilting » coordinate
- Dynamics solving Langevin equations
- Light particle evaporation

K. Mazurek et al., PRC 84, 014610 (2011)
P. N. Nadtochy et al. PRC 89, 014616 (2014)
Fission probabilities and viscosity

![Graph showing probability vs. beam energy](image)

- $P(2\text{-frag})$
- $P(3\text{-frag})$
- $P(4\text{-frag})$

Probability

Beam Energy (in MeV/A)
Fission probabilities and viscosity

Fissión probabilities y viscosidad
Fission probabilities and viscosity

- Sequential fission sensitive to viscosity
- High viscosity (high friction coefficient)
  → long fission time
  → many pre-scission evaporation
  → low temperature and spin to FF
  → low sequential fission probability

- Do not depend on initial CN temperature
- "Chaos-weighted" viscosity works well!
Fission probabilities and viscosity

- Sequential fission sensitive to viscosity
- High viscosity (high friction coefficient) → long fission time
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![Graph showing fission probabilities vs. beam energy](image)

- P(2-frag)
- P(3-frag)
- P(4-frag)

8 MeV/A
12 MeV/A
15 MeV/A

P. N. Nadtochy et al.
PRC 89, 014616 (2014)
Fission probabilities and viscosity

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G. Chaudhuri et al.
PRC 63, 064603 (2001)

P. N. Nadtochy et al.
PRC 89, 014616 (2014)
Fission probabilities and viscosity

- Sequential fission sensitive to viscosity
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  → long fission time
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- Do not depends on initial CN temperature
- « Chaos-weighted » viscosity works well!

Sequential fission probabilities as a function of beam energy:

- 8 MeV/A
- 12 MeV/A
- 15 MeV/A

Chaudhuri et al.
PRC 63, 064603 (2001)

Nadtochy et al.
PRC 89, 014616 (2014)
Primary fragment charge distribution

Xe+Sn @ 8MeV/A
Primary fragment charge distribution

Xe+Sn @ 8MeV/A

Reconstructed experimentally
Primary fragment charge distribution

Xe+Sn @ 8MeV/A

Model calculation

Reconstructed experimentally

3-frag

Preliminary
Primary fragment charge distribution

Xe+Sn @ 8MeV/A

Model calculation

Reconstructed experimentaly

Preliminary
Primary fragment charge distribution

Xe+Sn @ 8MeV/A

Model calculation

Reconstructed experimentaly

3-frag

A_{FF}

l_{FF} (in h)

Z_{FF}/Z_{CN}
How does evolve the decay mechanism from fission to multifragmentation?

Xe + Sn from 8 to 25 MeV/A measured with INDRA
Most dissipative collisions with 3 heavy fragments (Z>10)

2 binary splittings on shorter and shorter timescale
Onset of multifragmentation above 4 MeV/A excitation energy

Dynamical description of sequential fission
Reproduce sequential fission probabilities only with a deformation dependent viscosity
Coulomb chronometry to probe the decay mechanism of hot nuclei


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Coulomb proximity effects

\[ \text{Σ ASY} \]

\[ \text{EOS} \]
Symmetry energy and chronometry

Symmetry energy density-dependence $S(\rho)$

$$j_n - j_p \propto S(\rho) \nabla I + \frac{\delta S(\rho)}{\delta \rho} I \nabla \rho$$

n-p currents

Many approaches Large deviations

Density gradient

Isospin gradient

Coulomb clock

Rotational clock
Indications of in-medium structure

Inelastic scattering
- Itoh, PRL 113(2014)102501 <0.2%
- Rana, PRC 88(2013)021601 ~1%
- Raduta, PLB 705(2011)65 ~17%

Fragmentation
- Structure modification?
- Final-state interaction?

Interaction with the environment

Direct decay

Direct
- L. Quattrocchi, NN2015

Sequential

\[^8\text{Be}+\alpha\rightarrow 3\alpha\]

\[^{12}\text{C}\] 0+

3\(^-\) 9.64
0\(^+\) 7.65
2\(^+\) 4.44

Fusion/evaporation
- C+Mg@25MeV/A CHIMERA
- C+C@95MeV GARFIELD

\[^{12}\text{C}\] Hoyle state

L. Morelli, sub. to JoP.G
Nuclear medium characterisation

$^6\text{Li}^* \rightarrow \alpha + d$

**Thermal model**

- Population of excited states
  \[
  \frac{dn(E)}{dE} \propto e^{-E/T} \sum_i \frac{(2J_i+1)\Gamma_i/2\pi}{(E-E_i)^2 + \Gamma_i^2/4}
  \]

- Relative population of non-overlapping excited states $E_1$ ($N_1$) and $E_2$ ($N_2$) depends on the emission temperature
  \[
  \frac{N_2}{N_1} = \frac{2J_2+1}{2J_1+1} e^{-(E_2-E_1)/T}
  \]

- Higher is $E_1 - E_2$, better is the resolution
- Emission temperature $> T$ (decay chain)
INDRA-FAZIA: physics campaign

O. Lopez, GANIL PAC / J.D. Frankland, GANIL SC

- Direct measurements of radial flow in central collisions
- Full (A,Z)-distributions vs. E* for disassembly of hot nuclei
- Isospin transport in dissipative reactions
- In-medium nuclear structure and environment characterisation
- Effective interaction momentum-dependence
- In-medium n-n cross section
- n/p effective mass
- n/p symmetry potentials
- Symmetry energy density-dependence
- Clustering
- N-body correlations
- Light nuclei particle decay
- Spin assignment
- N-body correlations

Erel ($^{11}$C-p) [keV]