A Monte Carlo Simulation of Prompt Gamma Emission from Fission Fragments

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   - Results & discussion

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4. Conclusion and perspectives
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Gamma heating problematic

Figure 1: Relative neutron and photon heating in the Perle experiment (From Phd student S. Ravaux transport calculation with Tripoli-4.7)

Figure 2: Perle experiment
Prompt fission gamma data in evaluated files

Two spectra used for all the main fissioning isotopes

- \((n+^{239}\text{Pu}, f)\) : based\(^a\) on Verbinski et al. measurement (1973)
- \((n+^{235}\text{U}, f)\) : based\(^b\) on Verbinski et al. measurement (1973)

\(^a\)R. E. Hunter and L. Stewart, LA-4901 (1972)
\(^b\)R. E. Hunter and L. Stewart, LA-4918 (1972)

\[ M_\gamma = 7.78 \ \gamma/f \]

Figure 3: JEFF-3.1.2 fission gamma spectrum for \((n+^{239}\text{Pu}, f)\)
Prompt fission gamma data in evaluated files

Two spectra used for all the main fissioning isotopes

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\[
M_\gamma = 7.17 \, \gamma/f
\]

Figure 3: JEFF-3.1.2 fission gamma spectrum for \((n + ^{235}\text{U}, f)\)
FIFRELIN: A Monte Carlo simulation of fission fragments evaporation

Fissioning nucleus

Figure 4:
Compound nucleus

(T= nuclear temperature)
FIFRELIN: A Monte Carlo simulation of fission fragments evaporation

Figure 4: Compound nucleus

Figure 5: Fully accelerated fragments

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Figure 6: Prompt neutron emission

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FIFRELIN: A Monte Carlo simulation of fission fragments evaporation

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Figure 4: Compound nucleus

Figure 5: Fully accelerated fragments

Figure 6: Prompt neutron emission

Figure 7: Prompt gamma emission

(T = nuclear temperature)
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Model 1

Approximation on neutron/gamma competition

1. Emit neutrons until a limit energy is reached, 
\[ E_{limit} = S_n + E_{rot}(J) \]
2. Decay by gamma and/or conversion electron emissions.

Neutron emission

- Energy sampled in a Weisskopf spectrum:
\[ \chi(\epsilon_n) \propto \sigma_{inv}(\epsilon_n) \epsilon_n e^{-\epsilon_n/T} \]
- Total angular momentum:
\[ J_{A-1} = J_A - 1/2\hbar \]
Model 1

Gamma emission

For one fission fragment

1. Departure from a known excited level \((E_i^*, J_i, \pi_i)\)

2. Decay probabilities calculation:

\[
I_{\gamma}(i \rightarrow j) = \frac{\Gamma_{\gamma}(i \rightarrow j)}{\Gamma_{\gamma,tot}} \quad (1)
\]

\[
\Gamma_{\gamma}(i \rightarrow j) = f_{XL}(\epsilon_{\gamma})\epsilon^{2L+1}\gamma_{fluctuation} \rho(E_f, J_f, \pi_f) \quad (2)
\]

3. Sample one transition

4. Gamma decay until a stable level is reached

Figure 8: Level scheme of the fission fragment
Model 1

Gamma emission

For one fission fragment

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Figure 8: Level scheme of the fission fragment

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Figure 8: Level scheme of the fission fragment

Energy

Continuum bound

Experimental levels

GS

\(E_i J_i \pi_i\)

\(E_\gamma\)

\(dE\)
Model 1: Results for the $^{252}$Cf spontaneous fission

FIFRELIN:
- $\nu = 3.78 \, n/f$
- $M_\gamma = 8.0 \, \gamma/f$
- $E_{\gamma,\text{tot}} = 8.1 \, \text{MeV}$
- $E_{\text{elec}} = 39 \, \text{keV}$
  $(\sigma_{\text{stat}} < 0.1\%)$

Experiments:
- $\nu = 3.76 \pm 0.03 \, n/f$
- $M_\gamma \simeq 8 \pm 0.4 \, \gamma/f$
- $E_{\gamma,\text{tot}} \simeq 7 \pm 0.4 \, \text{MeV}$

Figure 9: Total prompt gamma spectrum
Model 1: Results for the $^{252}$Cf spontaneous fission

![Graph showing prompt gamma spectrum](graph.png)

**Figure 10:** Fifrelin prompt gamma spectrum in the fragment frame (same resolution as Verbinski measurements)

**Verbinski et al. experimental setup**
- Detection threshold: 140 keV
- Thin sample: $\approx 200\,\mu g.cm^{-2}$
  $\Rightarrow$ Doppler effect

Introduction

Model 1: Uncoupled neutron and gamma emission

Model 2: Coupled neutron and gamma emission

Conclusion and perspectives
Model 1: Results for the $^{252}$Cf spontaneous fission

Assumptions:

- $4\pi$ detection of gamma emitted.
- Isotropic emission of gamma rays in the fragment frame.
- No kinetic energy loss in target.
- Lorentzian transformation.

Figure 11: Fifrelin prompt gamma spectrum in the laboratory frame (same resolution as Verbinski measurements)
Model 1: Level density and strength function influence

Level density models:

- CTM: Constant temperature
- CGCM: Composite Gilbert-Cameron
- HFB: Microscopic calculation

Strength function models:

- SLO: Standart Lorentzian
- EGLO: Enhanced Generalized Lorentzian
- HFB: Microscopic calculation
Model 1: Angular momentum of the fragments

\[ P(J) = \frac{(J + 1/2)}{\sigma^2(T)} e^{\frac{(J+1/2)^2}{2\sigma^2(T)}} \]

\[ \bar{J}_H = 6.6\hbar, \quad \bar{J}_L = 5.9\hbar \]

- Before neutron emission:
- During neutron emission:

<table>
<thead>
<tr>
<th>Ref</th>
<th>Wilhelmy(^1,2)(1972)</th>
<th>Skarsvag(^1,2)(1980)</th>
<th>Mukhopadhyay(^1,2)(2012)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J_L )</td>
<td>7\hbar</td>
<td>6\hbar</td>
<td>( \approx 5\hbar )</td>
</tr>
<tr>
<td>( J_H )</td>
<td>8.4\hbar</td>
<td>5.3\hbar</td>
<td>( \approx 12\hbar )</td>
</tr>
</tbody>
</table>

Table 1: Average angular momentum of primary fragments from \( ^{252}\text{Cf} \) SF

1: Only even-even post-neutron fragments are considered.
2: Estimation of the uncertainty: \( \pm 2\hbar \).
Effect of an increase of post-neutron fragment J

Figure 12: Prompt gamma spectrum for the spontaneous fission of $^{252}$Cf

For a good agreement of low energy part of the gamma spectrum post-neutron angular momentum are found to be:

$$J_L \simeq 8\hbar, \quad J_H \simeq 9\hbar$$
From model 1 to model 2 ...

Model 1 results:
- Good agreement of neutron observables with experiments.
- First prediction of a prompt gamma fission spectrum.
- Overestimation of total gamma energy ($E_{\gamma,\text{tot}}$)?
- Prompt gamma spectrum too hard.

Remaining questions:
- Neutron emission before gamma emission?
- Average $\Delta J = 1/2\hbar$ during a neutron emission?
- Initial total angular momentum of the fission fragments?
- Validity of a Weisskopf spectrum at low excitation energy?
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Model 2

Transition probability

\[ p(i \rightarrow j) = \frac{\Gamma(i \rightarrow j)}{\Gamma_{\text{tot}} + \Gamma_{\text{tot}}^{\text{neutron}}} \]  

\( \Rightarrow \) Neutron and gamma emission competition

Neutron width calculation

\[ \Gamma_n(i \rightarrow j) = \frac{T_{l,j}(\epsilon_n)\gamma_{\text{fluctuation}}}{2\pi\rho(E_f, J_f, \pi_f)} \]  

\( T_{l,j}(\epsilon_n) \) are provided by a Talys-1.4 optical model calculation using a Koning-Delaroche spherical potential

Figure 13: Possible decay
Model 2: Preliminary results for the $^{252}$Cf SF

<table>
<thead>
<tr>
<th>Vorobyev (2005)</th>
<th>$&lt;\epsilon_n&gt;$ in FF frame (MeV)</th>
<th>$\nu$</th>
<th>$E^*$ for neutron (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>1.34</td>
<td>3.78</td>
<td>25.7</td>
</tr>
<tr>
<td>Model 2</td>
<td>1.23</td>
<td>4.0</td>
<td>27.4</td>
</tr>
</tbody>
</table>

Table 2: Neutron results

<table>
<thead>
<tr>
<th>Chyzh (2012)</th>
<th>$&lt;\epsilon_\gamma&gt;$ (MeV)</th>
<th>$M_{\gamma}$</th>
<th>$E_{\gamma,tot}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.94</td>
<td>8.16</td>
<td>7.8</td>
</tr>
<tr>
<td>Model 1</td>
<td>1.0</td>
<td>8.0</td>
<td>8.1</td>
</tr>
<tr>
<td>Model 2</td>
<td>0.86</td>
<td>7.5</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Table 3: Gamma results

New observables provided by the model 2

1. $\Delta J_n = 0.1 \ \hbar/n$
2. Average number of gamma emitted before the last prompt neutron: $\simeq 4.10^{-3}\gamma/f$ ($1\gamma$ every 250 fissions)
Model 1 vs Model 2 for the $^{252}$Cf spontaneous fission

Figure 14: Total prompt gamma spectrum
Model 1 vs Model 2 for the $^{252}$Cf spontaneous fission

Figure 14: Total prompt gamma spectrum
Influence of parameters and models

<table>
<thead>
<tr>
<th>Strength function $\gamma$</th>
<th>Level density</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \nu &lt; 1%$</td>
<td>$\Delta \nu \simeq 3%$</td>
</tr>
<tr>
<td>$\Delta \epsilon_\gamma \simeq 12%$</td>
<td>$\Delta \epsilon_\gamma \simeq 6%$</td>
</tr>
<tr>
<td>$\Delta E_{\gamma, tot} \simeq 1%$</td>
<td>$\Delta E_{\gamma, tot} \simeq 4%$</td>
</tr>
<tr>
<td>Shape of the gamma spectrum impacted</td>
<td>Shape of the gamma spectrum impacted</td>
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</tbody>
</table>

Angular momentum of primary FF

High sensitivity of main observables, $+2\hbar$ leads to:

- $\nu$: $-1\%$
- $\epsilon_n$: $-2\%$
- $E_{\gamma, tot}$: $+0.7$ MeV
- $\epsilon_\gamma$: $-7\%$
- $M_{\gamma}$: $+20\%$
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Realized for the moment:

- Implementation of two main cascade models, work on neutron/gamma competition.
- Implementation and comparison of several models of level density and strength function.
- Optimization in speed and memory of the code, parallelization.
- Calculation of several observables of the fission process (post-neutron fragments data, multiplicity for a given fragmentation ...).
Perspectives:

- Impact of the **optical model** used for neutron transmission calculation.
- Investigation on the **energy balance** between neutron and gamma emission.
- Calculation of observables with high sensitivity to angular momentum: anisotropy gamma.
- Measurements at ILL before end of 2012.
- ... 

Other application scope:

- **Neutron capture** calculation: spectrum, multiplicity, branching ratio...
Thank you for your attention!