Investigation of Prompt Fission Neutron and Gamma Spectra with their covariance matrices. Application to $^{239}\text{Pu}+n_{\text{th}}$, $^{238}\text{U}+n_{1.8\text{MeV}}$, $^{235}\text{U}+n_{\text{th}}$

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Geel, Belgium    November 5 - 8, 2013
Activities around PFNS

PFNS and PFGS from Fission Fragment deexcitation

Covariance matrices

Conclusion, Outlook
Activities around PFNS

1. Model for spectra
   Monte Carlo simulation of the fission fragment deexcitation
   (Fifrelin code)
   \(\rightarrow\) Allows to estimate fission observables (spectra, multiplicities,
   correlations, fission yields, …)

2. Model for quantification of covariances
   Production of covariance matrices (Conrad code)
   \(\rightarrow\) Used for cross sections but also any kind of model (in this work:
   Maxwell, Watt, Madland-Nix, Fifrelin PFNS Models)
PFNS and PFGS from Fission Fragment deexcitation

U235 / U238 / Pu239
FIFRELIN: a Monte Carlo code simulating the fission fragment deexcitation

Review of the model:

- Pre-neutron fission fragment mass sampling
- Pre-neutron fission fragment kinetic energy sampling
- Nuclear charge sampling
- Spin and parity sampling
- Excitation energy sharing after full acceleration ($E' = aT^2$)
  - Ignatyuk’s prescription for level density parameter
  - Mass dependent temperature ratio law
- Prompt particle ($n/\gamma$) emission (Weisskopf or Hauser-Feshbach model)
Thermal fission of $^{235}\text{U}$ (Prompt Fission Neutron Spectrum)

\[ ^{235}\text{U} + n_{th} \]
Thermal fission of U235 (Prompt Fission Gamma Spectrum)

\[ {}^{235}\text{U} + n_{th} \]
Weisskopf PFNS softer than Hauser-Feshbach

Influence of the Level Density model at high energies (HFB / CGCM)
Same trend whatever the model parameters
238U + n$_{1.8\text{MeV}}$  (Prompt Fission Gamma Spectrum)

Prompt Fission Gamma Multiplicity (PFGM)

- JEFF-3.1.1
  \[ \overline{M}_\gamma = 8.2 \]

- FIFRELIN-HF
  
  with threshold : 0.1 MeV
  
  time window : 10 ns
  
  \[ \overline{E}_\gamma^{\text{tot}} \approx 9.0 \]
  
  \[ \langle \varepsilon_\gamma \rangle \approx 0.78 \]
Thermal fission of Pu239
(Prompt Fission Neutron Spectrum : ratio to Maxwellian T=1.38 MeV)

\[ ^{239}Pu + n_{th} \]

D. Regnier PhD (October 2013)
Thermal fission of $^{239}$Pu (Prompt Fission Gamma Spectrum)

$^{239}$Pu + $n_{th}$

- Verbinski (1973)
- Calcul

<table>
<thead>
<tr>
<th></th>
<th>$M_\gamma$ [γ/f]</th>
<th>$E_{\gamma,\text{tot}}$ [MeV]</th>
<th>$\varepsilon_\gamma$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Verbinski</td>
<td>7.23</td>
<td>6.81±0.3</td>
<td>0.94</td>
</tr>
<tr>
<td>FIRELIN</td>
<td>7.23</td>
<td>6.83</td>
<td>0.94</td>
</tr>
</tbody>
</table>

D. Regnier PhD (October 2013)
Covariance matrices (U235)
Model parameter adjustment in Conrad code

- **Experimental statistical uncertainty associated to the spectrum at each energy point**

- **Experimental systematic uncertainty due to normalization, detection efficiency, ...**

\[ M_{x}^{\text{marg}} = M_{x}^{\text{stat}} + (G_{x}^{T} \cdot G_{x})^{-1} \cdot G_{x}^{T} \cdot G_{\theta} \cdot M_{\theta} \cdot G_{\theta}^{T} \cdot G_{x} \cdot (G_{x}^{T} \cdot G_{x})^{-1} \]
### Thermal fission of U235

**Correlation matrix for Prompt Fission Neutron Spectrum**

<table>
<thead>
<tr>
<th>Model</th>
<th>parameters</th>
<th>Prior (MeV)</th>
<th>Posterior (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxwell</td>
<td>T</td>
<td>1.32 ± 10%</td>
<td>1.32 ± 0.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>± 2.3%</td>
</tr>
<tr>
<td>Watt</td>
<td>T&lt;sub&gt;W&lt;/sub&gt;</td>
<td>0.90 ± 10%</td>
<td>1.06 ± 1.0%</td>
</tr>
<tr>
<td></td>
<td>E&lt;sub&gt;W&lt;/sub&gt;</td>
<td>0.78 ± 10%</td>
<td>0.38 ± 4.2%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>± 44.7%</td>
</tr>
<tr>
<td>Madland-Nix</td>
<td>T</td>
<td>1.01 ± 10%</td>
<td>0.96 ± 2.3%</td>
</tr>
<tr>
<td></td>
<td>E&lt;sub&gt;S&lt;/sub&gt;</td>
<td>1.07 ± 10%</td>
<td>1.16 ± 4.8%</td>
</tr>
<tr>
<td></td>
<td>E&lt;sub&gt;H&lt;/sub&gt;</td>
<td>0.50 ± 10%</td>
<td>0.25 ± 3.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>± 36.1%</td>
</tr>
</tbody>
</table>

*Systematic uncertainty (normalization) ± 5%*

*Fit based on 5 experiences*

*Statistical uncertainties*

\[ ^{235}U + n_{th} \]

*L. Berge PhD*
MAXWELL MODEL

$^{235}\text{U (n,th),f) PFNS}$

L. Berge PhD

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Thermal fission of U235
(Correlation matrix for Prompt Fission Neutron Spectrum)
Thermal fission of U235
(Correlation matrix for Prompt Fission Neutron Spectrum)

MAXWELL MODEL

$^{235}\text{U} (\eta_{\text{th}}, f) \text{PFNS}$

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Thermal fission of U235

(Correlation matrix for Prompt Fission Neutron Spectrum)

MAXWELL MODEL

$^{235}_{\text{U}} (n,\text{th},f)$ PFNS

Ratio to a Maxwellian ($T=1.42 \text{ MeV}$)

E [eV]

Nefedov, 1983
Nefedov, 1983
Starostov, 1983
Lajtai, 1985

CONRAD after minimization

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L. Berge phD
Thermal fission of U235: Correlation matrix for Prompt Fission Neutron Spectrum

MAXWELL MODEL

$^{235}\text{U} (\eta(\text{th}),\eta) PFNS$

Ratio to a Maxwellian ($T=1.42 \text{ MeV}$)

- Nefedov, 1983
- Nefedov, 1983
- Starostov, 1983
- Lajta, 1985
- Batenkov, 2004
- CONRAD after minimization

E [eV]

L. Berge phD

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Thermal fission of U235

(Correlation matrix for Prompt Fission Neutron Spectrum)

MAXWELL MODEL

$^{235}\text{U} (n,\text{th},f)$ PFNS

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Thermal fission of U235

(Correlation matrix for Prompt Fission Neutron Spectrum)

$^{235}\text{U} (n(H),f)$ PFNS

WATT MODEL

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Thermal fission of U235
(Correlation matrix for Prompt Fission Neutron Spectrum)

WATT MODEL
$^{235}\text{U} (n,\text{th}),\text{t} \text{ PFNS}$

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Thermal fission of U235
(Correlation matrix for Prompt Fission Neutron Spectrum)

WATT MODEL

\(^{235}\text{U} (n,\text{th},f) \text{PFNS}\)

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Thermal fission of U235

(Correlation matrix for Prompt Fission Neutron Spectrum)

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Thermal fission of U235
(Correlation matrix for Prompt Fission Neutron Spectrum)

WATT MODEL

\[^{235}U\text{ }\text{(n,th),T} \text{ PFNS}\]

Ratio to a Maxwellian ($T=1.42 \text{ MeV}$)

- Nefedov, 1983
- Nefedov, 1983
- Starostov, 1983
- Lajtai, 1985
- Batenkov, 2004
- CONRAD after minimization

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WATT MODEL

$^{235}\text{U} \langle n(\text{th}),\text{f} \rangle$ PFNS

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Thermal fission of U235
(Correlation matrix for Prompt Fission Neutron Spectrum)

MADLAND-NIX MODEL

\(^{235}\text{U} (\text{n(th),f}) \text{PFNS}\)

Ratio to a Maxwellian ($T = 1.42 \text{ MeV}$)

+ Nefedov, 1983
+ CONRAD after minimization

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MADLAND-NIX MODEL

\[ {}^{235}\text{U} (\nu(\text{th}),\nu) \text{ PFNS} \]

- Nefedov, 1983
- CONRAD after minimization

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Thermal fission of U235

(Optimal correlation matrix for Prompt Fission Neutron Spectrum)

MADLAND-NIX MODEL

\[^{235}\text{U} (\text{n}(\text{th}),\text{f})\] PFNS

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Thermal fission of U235
(Correlation matrix for Prompt Fission Neutron Spectrum)

MADLAND-NIX MODEL

\(^{235}\text{U} (n(\text{th}),\text{t})\) PFNS

Ratio to a Maxwellian (T=1.42 MeV)

\[ \frac{\text{Ratio}}{\text{Maxwellian (T=1.42 MeV)}} \]

- Nefedov, 1983
- Nefedov, 1983
- Starostov, 1983
- Lajtai, 1985
- CONRAD after minimization

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Thermal fission of U235

(Correlation matrix for Prompt Fission Neutron Spectrum)

MADLAND-NIX MODEL

$^{235}\text{U} (\eta(\text{th}),f) \text{ PFNS}$

Ratio to a Maxwellian ($T=1.42$ MeV)

$E \text{ [eV]}$

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Thermal fission of U235
(Correlation matrix for Prompt Fission Neutron Spectrum)

MADLAND-NIX MODEL

\[ ^{235}\text{U} (n_{th},f) \text{ PFNS} \]

Ratio to a Maxwellian (\(T=1.42\text{ MeV}\))

- Nefedov, 1983
- Starostov, 1983
- Lajtai, 1985
- Batenkov, 2004
- Hambisch, 2010

CONRAD after minimization

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Thermal fission of U235
(Correlation matrix for Prompt Fission Neutron Spectrum)

\[ ^{235}U + n_{th} \]

Without marginalization of the normalization

Maxwell

Watt

Madland-Nix

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Thermal fission of U235

With marginalization of 5% normalization uncertainty

Maxwell

Watt

Madland-Nix

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5% uncertainty on normalization parameter is a more or less realistic value!

\[ \text{-> Depends on the data (past and present),} \]

\[ \text{-> Uncertainty can be higher/lower for a given energy range: need for another experimental parameter: neutron detector efficiency (work in progress).} \]

**Fifrelin model parameter adjustment** from a Conrad/Fifrelin coupled scheme

\[ \text{-> Fifrelin is used as a ‘Nuclear Model’ inside Conrad to adjust some of the 5 free parameters of the code and generate correlation matrices…(from D. Regnier PhD work, in progress …)} \]
Covariance matrices related to prompt fission neutron spectra can be calculated using so-called Maxwell, Watt or Madland-Nix spectra within the CONRAD code and COOL libraries.

Fission observables such as neutron and gamma spectra, multiplicities, fission yields can be calculated through a Hauser-Feshbach model within the FIFRELIN Monte Carlo code and COOL libraries.

Improvement of the fission fragment deexcitation model still in progress within FIFRELIN.

CONRAD / FIFRELIN coupling under investigation for covariance matrix generation
(*) - *Unitary* tests
- *Physics* tests for a given ‘parameter’ related to a given nucleus (average radiation width, branching ratio, …)

(+) *Cadarache Object Oriented Libraries*
Thank you for your attention