Monte Carlo Hauser-Feshbach Calculations of Prompt Neutrons and Gamma Rays

1P.Talou, 2B.Becker, 1T.Kawano, and 2Y.Danon

1Theoretical Division, Los Alamos National Laboratory, NM, USA
2Rensselaer Polytechnic Institute, Troy, NY, USA
Prompt Fission Neutrons and Gamma Rays
Experiments, Theories & Models

- **Experiments**
  - Average spectrum and multiplicity
  - More exclusive data (e.g., F.-J. Hambsch)
  - Prompt $\gamma$ rays: Very limited (and contradictory!) results (new DANCE exp.)

- **Theoretical Understanding**
  - Fragments are produced in deformed and excited states
  - Primary fission fragment yields $Y(A,Z,TKE)$ (cf. talk by J. Randrup)
  - Most neutrons are emitted from fully accelerated fragments
  - Most gamma rays are emitted after the neutrons, but not all ($E_{\gamma}^{\text{tot}} > B_n$)
  - Scission neutrons? (cf. talk N. Carjan) Neutron emission during acceleration?

- **Models & Evaluations**
  - Madland-Nix model (1982), and variations (PbP, $T_\ell \neq T_h$, anisotropy, ...)
  - Watt spectra
  - Prompt fission gamma rays?
Monte Carlo
Weisskopf Evaporation Studies

- Follow the de-excitation cascades using Monte Carlo simulations

→ Exclusive data, correlations, distributions
\[ P(\nu), <\nu>(A,Z,TKE), n-n, \ldots ] vs. Averages [<\nu>, <\chi>] 

- Input:
  - Initial distributions \( Y(A,Z,E_{int}) \) for each fragmentation
  - Nuclear structure data for each fragment

- Important physics questions related to the scission point
  - Energy balance at scission: intrinsic excitation energy, deformation energy, collective modes.
  - Sharing of intrinsic excitation energy between two complementary fragments

**n+^{239}Pu**

Primary Fission Fragment Yields Y(A,Z,KE)

- Reconstructed from partial experimental data on Y(A), P(Z|A), <TKE>(A), etc.

---

**Graphs:**

1. **Fragment Mass (amu)**
   - **Color Scale:**
     - 0
     - 0.01
     - 0.02
     - 0.03
     - 0.04
     - 0.05
   - **Axes:**
     - X: 80 100 120 140 160
     - Y: 40 80 120 160

2. **Fission Fragment Mass (amu)**
   - **Axes:**
     - X: 80 100 120 140 160
     - Y: 0 1 2 3 4 5 6 7 8
   - **Data Points:**
     - Wagemans, 1984
     - Nishio, 1995
     - Surin, 1971
     - Akimov, 1971
     - Least-square fit

---

**References:**

- Wagemans, 1984
- Nishio, 1995
- Surin, 1971
- Akimov, 1971
- Least-square fit
Y(TKE)

Y(Z)

Wagemans, 1984 from full distribution

n_\text{th}^{239}\text{Pu}
Energy Sharing at Scission

- \( (Q_f, \text{TKE}) \rightarrow \text{Total Excitation Energy TXE} \)
- \( \text{TXE} = E_{\text{int}} + E_{\text{def}} + E_{\text{coll}} \)
- Weisskopf Evaporation spectra used for light and heavy fragments with initial *effective* temperatures \( T_l \) and \( T_h \) \( \rightarrow R_T = T_l/T_h \)
- K.-H. Schmidt and B. Jurado proposal for \( E_{\text{int}} \) sorting mechanism
- \( \rightarrow \text{Sorting according to phase space considerations} \)

\[
\langle E_l \rangle = \frac{\int_0^{E_{\text{int}}} E_l \rho_l(E_l) \rho_h(E_{\text{int}} - E_l) dE_l}{\int_0^{E_{\text{int}}} \rho_l(E_l) \rho_h(E_{\text{int}} - E_l) dE_l}
\]
Total Intrinsic Excitation Energy Sorting (KHS & BJ)

- $E_{\text{int}}$ goes to colder fragment
- Nuclear Temperature $T \propto A^{-1/3}$ (without shell effects)
- Importance of shell effects!

![Graph showing fragment excitation energy vs. total excitation energy with data points for 38-Sr-94 and 44-Ru-108, including mass ratios.]
Averaged over Fission Yields $Y(A,Z,TKE)$

Nuclear Temperature

$$\frac{1}{T} \approx \frac{\partial (\ln \rho)}{\partial U}$$

Gilbert-Cameron representation of level density $\rho(U)$

**Caveat**
Results sensitive to exact description of low-energy level densities

Graph showing temperature ratio $T/T_h$ as a function of heavy fragment mass (u) for $^{239}$Pu (n$_{th}$,f) with TXE of 5 MeV and 10 MeV. The graph notes that only 1 Z per A for this figure.
Fit to $<\nu_l>/<\nu_h>(A_h)$

$n_{th}^{+239Pu}$
Average Spectrum & Multiplicity

**Multiplicity**

- **Thermal**
  - $\nu_c = 2.871$
  - $\nu_{\text{B-VII.0}} = 2.8725$
  - $\nu_{\text{std}} = 2.8771 \pm 0.0047$

- **Fast (0.5 MeV)**
  - $\nu_c = 2.932$
  - $\nu_{\text{B-VII.0}} = 2.939$

---

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

- Starostov, 1983
- Knitter, 1975 (0.215 MeV)
- Staples, 1995 (0.5 MeV)
- Bojcov, 1983
- Lajtai, 1985
- ENDF/B-VII.0
- $MC - R_T=1.1$
- $MC - R_T(A)$

**Multiplicities**

- Thermal:
  - $\nu_c = 2.871$
  - $\nu_{\text{B-VII.0}} = 2.8725$
  - $\nu_{\text{std}} = 2.8771 \pm 0.0047$

- Fast (0.5 MeV):
  - $\nu_c = 2.932$
  - $\nu_{\text{B-VII.0}} = 2.939$
Beyond averages

- Average Initial Excitation Energy (MeV)
  - Total Kinetic Energy (MeV)
  - Light fragments
  - Heavy fragments
  - Total

- Average Neutron Kinetic Energy (MeV)
  - Fission Fragment Mass (u)

Tsuchiya, 2000
Monte Carlo, $R_T(A)$
Monte Carlo, $R_T=1.1$
Monte Carlo Hauser-Feshbach

- MCHF code; cf. T.Kawano talk
- Proper treatment of n-\(\gamma\) competition

Gamma rays
(strength function formalism, Kopecky-Uhl)

\[
P(\epsilon_\gamma) dE \propto T_\gamma(\epsilon_\gamma) \rho(Z, A, E - \epsilon_\gamma)
\]

Neutrons
(optical model potential)

\[
P(\epsilon_n) dE \propto T_n(\epsilon_n) \rho(Z, A - 1, E - \epsilon_n - S_n)
\]
**Initial Spin Distribution**

- **Experimental evidence** *(model-dependent!)*
  - [Naik, Dange, Singh, PRC 71, 014304 (2005)]
  - $J_{\text{rms}}$ much greater than ground-state spin, $\sim 6-7\hbar$
  - $J_{\text{rms}}$ increases with $A$
  - Importance of proximity to shell closures

\[
P(J) \propto (2J + 1) \exp \left[ -\frac{(J + 1/2)^2}{B^2} \right]
\]

with $B \sim J_{\text{rms}}$
Preliminary Results – $n_{th} + ^{239}\text{Pu}$

$\langle E_{\gamma}^{\text{tot}}(A) \rangle \rightarrow 12\hbar > J_{\text{rms}} > 6\hbar$

**Graph:**
- **n$_{th}$ + $^{239}\text{Pu}$**
- **Monte Carlo, Hauser-Feshbach**

**Probability vs. Gamma Multiplicity**
- Probability values range from 0 to 0.25
- GammaMultiplicity values range from 0 to 25

**Average Gamma Energy $\langle E_{\gamma}^{\text{cm}} \rangle$ (MeV)**
- Range from 0 to 1.8

**Fission Fragment Mass (amu)**
- Range from 120 to 170

**Constant B = 7\hbar**
$n_{th} + ^{239}\text{Pu}$ Gamma Spectrum

![Gamma Spectrum Graph](graphic)
252Cf (sf) Gamma Rays

Monte Carlo, Hauser-Feshbach
Brunson's Model (Valentine, 1999)
Negative Binomial Model (Valentine, 1999)

Prompt Fission
Gamma Spectrum

P(Nγ)
$N_γ(A)$

- Depends sensitively on $<J>(A)$
- Needs for new experimental data!
Some conclusions

- **Monte Carlo Hauser-Feshbach calculations (MCHF)**
  - Powerful tool to probe in detail the physics of nuclear fission
  - Stringent tests on nuclear level densities

- **New prompt fission gamma-ray measurements needed!**
  - Gamma spectrum, multiplicity
  - + distributions & correlations!

- **Excitation energy sharing at scission**
  - Not yet fully understood
  - Deformation energies? Collective modes?

- **Current MCHF calculations can be improved**
  - Emission during Acceleration of Fragments?
  - Scission neutrons?
  - Anisotropy of emission?