Correlated Prompt Fission Data

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One Fission Event = Vast and Rich Data Set

- Complete fission event, from pre- to post-scission
- Focus on prompt fission data only

Prompt Fission Neutrons & Photons

- Very important quantities for Applications:
  - Neutrons: average spectrum and multiplicity + $P(\nu)$ for neutron multiplicity counting
  - Photons: total $\gamma$-ray energy
- Fundamental Physics
  - Everything! New experiments and new theoretical tools to address those data
Theoretical Approach

- **Hauser-Feshbach formalism** applied to primary fission fragments
- **Monte Carlo implementation → CGMF code**
  - Probability distributions for evaporating neutron or photon sampled at each stage of the decay
    - Optical Model Calculation for neutrons
    - $\gamma$-ray Strength Function for photons
    - Nuclear structure information from RIPL-3 database
  - Correlations & distributions accessible
  - Important physics questions can be addressed
  - Important applications

![Graphs showing mass-energy distribution for cold fission events](image)
Recent experimental efforts

- **Prompt Fission Neutron Spectrum**
  - Chi-Nu (LANL), CEA-BRC, LiCORNE (Orsay), Gatchina
  - IAEA-CRP on PFNS being finalized

- **Prompt Fission $\gamma$ rays**
  - DANCE (LANL, LLNL)
  - IRMM

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Prompt Fission Neutron and Gamma Multiplicities

- $<\nu>$ very sensitive to $<\text{TKE}>$, $<\text{TKE}>(A,Z)$
- $<N_\gamma>$ very sensitive to energy threshold $E_{\text{cut}}$
- Monte Carlo Hauser-Feshbach calculations are very successful in reproducing observed multiplicity average values and distributions!
Total $\gamma$-Ray Energy vs. TKE

$$TXE = Q_f - TKE \simeq n (\epsilon_{cm} + B_n) + E_{\gamma}^{tot}$$

Distinct structures appear due to regularity in neutron binding energies in fission fragments.

- Recent DANCE experiment
- Analysis is ongoing
Results for Specific Fragments

- $\gamma$-ray Spectra
- Specific $\gamma$ transitions $\rightarrow$ study of isomeric ratios, fission yields, $P(\nu)$, etc.
- Hardening of $\gamma$ spectra for near shell-closure nuclei

Experimental Results


PhD thesis work of R. Bilinert
Results for Specific Fragments

- Exclusive neutron spectra
- Very good agreement for most fragments
- Discrepancies near shell closures

n-LF and n-n Angular Correlations

Kinematic boost from FF

n-LF angular distributions for different ($\nu_L, \nu_H$)
Incident Neutron-Induced Fission

- $^{235}\text{U} (n,f)$ and $^{239}\text{Pu} (n,f)$ up to 20 MeV
- Simplified model to calculate pre-neutron fission fragments $Y(A,Z,TKE)$
- Multi-chance fission
- Pre-equilibrium neutrons

![Graph showing neutron energy distribution for $^{239}\text{Pu}$](image)

- $E_{\text{inc}} = 17.5$ MeV
Implementation into MCNP6 Transport Code

- Integration of CGMF Monte Carlo Hauser-Feshbach code into MCNP6 Transport Code (in progress)
- Applications for detector response modeling, list-mode data analysis, non-proliferation, and a better understanding of the fission process
Open Questions

- Many quantities can be calculated accurately, but...
- Calculated average PFNS too soft?
- Input data need improvement
  - Fission fragment yields $Y(A,Z,KE)$ as a function of $E_{inc}$
  - Nuclear structure of fission fragments
- Physics questions not fully settled
  - Excitation energy sorting mechanism(s) at scission
  - Scission neutrons?
  - Angular momentum of the fragments
- Compensating errors?
A powerful simulation tool for many interesting applications and physics questions
Selected Publications