Correlated Prompt Fission Data in Transport Simulations

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The nuclear fission process is complex and rich

Fission Yields, prompt fission neutrons (PFN) and $\gamma$ rays (PFG) are all correlated.
Unanswered questions in evaluated nuclear data

- Multiplicity distribution $P(\nu)$, multiplicity-dependent spectra $\chi(\varepsilon_n)_{\nu}$, neutron data as a function of emitting fragment $\nu(A,Z,KE)$, angular distributions $\Omega_{n-n}$, neutron-gamma ($\nu-\gamma$) correlations.

**Answers needed** for advanced simulation of detectors, correlated signatures, interpretation and design of complex fission experiments, …

*Important new constraints on consistent and predictive capability for fission modeling!*
A New Approach: Event-by-Event Monte Carlo Simulations of the Decay of Fission Fragments

Fragment Yields $Y(A,TKE)$ in Cf-252 (sf)

Prompt emissions of $n$ and $\gamma$ (~$10^{-14}$ sec) + "late" isomeric $\gamma$ emissions up to ~\(\mu\)sec

Follow decay of each excited fission fragment

The **CGMF** code follows the sequential emissions of prompt neutrons and $\gamma$ rays from the excited primary fission fragments, event-by-event. Similar codes (FREYA, FIFRELIN, GEF) are being developed elsewhere.

**Review paper**: Talou, Vogt, Randrup, Rising, Pozzi *et al*, EPJ A 54, 9 (2018) (LANL, LLNL, LBNL, LANL, UM, *et al*)
Complete reconstruction of (post-scission) fission events

- Hauser-Feshbach statistical theory of nuclear reactions
  - Neutron and $\gamma$-ray emission probabilities calculated and sampled at each stage of the decay
  - Weisskopf-Ewing approximation
    - no n-$\gamma$ competition
    - no $(J,\pi)$ conservation

- CGMF/FREYA: Monte Carlo implementations
- Full kinematic reconstruction of fission fragments, neutrons and gammas emitted

Monte Carlo histories of fission events:
Prompt Fission Neutrons & $\gamma$ Rays

- Until recently, models were limited to average observables only
- We can now model prompt neutrons and $\gamma$ rays on an event-by-event basis and infer:
  - Multiplicity Distributions: $P(\nu), P(N_{\gamma})$
  - Angular Distributions: $\Theta_{n-n}, \Theta_{n-FF}$
  - Exclusive data: $\phi(\varepsilon_{\nu}|\nu=3), \phi(\varepsilon_{\gamma}|\gamma-\gamma-\gamma), \ldots$
  - Correlations: $n-n, n-\gamma, \gamma-\gamma, n-\gamma-FF$
  - Time-dependent emissions: $N_{\gamma}(t)$
  - Correlations with emitting fission fragments $(A,Z,KE,J)$
  - ...
Many important physics input needed for neutron-rich fission fragments

- Global optical model calculations
- $\gamma$-ray strength function and importance of the M1 “scissors” mode
- Nuclear structure of neutron-rich nuclei
- Level densities

And intriguing fission physics questions

- Excitation energy sorting at scission? $\rightarrow P(\nu|A,TKE;E_{\text{inc}})$
- Pre-fission neutron emission? “scission neutrons”, pre-scission neutrons, multi-chance fission, pre-equilibrium neutrons
- Relations between fission cross sections, fission fragment angular distributions and prompt fission data? $\rightarrow$ fission paths/channels/barriers
- Experimental $\langle \nu \rangle$ can be reproduced very well, given slight adjustment of $\langle \text{TKE} \rangle$
- $P(\nu)$ requires tuning $Y(\text{TKE})$

A novel approach to estimating $\langle \text{TKE} \rangle$

P. Jaffke, P. Möller, P. Talou, A.J. Sierk, Phys. Rev. C 97, 034608 (2018)
**Multiplicity-dependent $n$ and $\gamma$ spectra**

- Very strong dependence of $\gamma$ spectrum on $N_\gamma$
- Much weaker dependence of neutron spectrum on $\nu$

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![Chart 1: $^{235}$U ($n_{th},f$) and $^{252}$Cf ($sf$)]

- **$^{235}$U ($n_{th},f$)**
  - CGMF
  - PM
  - $N_\gamma=5$
  - $N_\gamma=10$
  - $N_\gamma=15$

- **$^{252}$Cf ($sf$)**
  - Total
  - $\nu = 1$
  - $\nu = 2$
  - $\nu = 3$
  - $\nu = 4$
  - $\nu = 5$

**Never considered in simulations before!**
Angular correlations

- $\Theta_{n-LF}$ neutron vs. Light Fragment axis mostly due to kinematics
- $\Theta_{n-n}$ neutron-neutron aperture, mostly due to fragment $\nu$ ratio

Pringle, 1975
Guseva, 2008
Pozzi, 2014
More exclusive angular correlations

$\Theta_{n-LF}$ function of fragment mass!

$\Theta_{n-n}$ function of $E_n$ threshold
Presence of ns to µs isomers in fission fragments

Prompt Fission Gamma Spectrum

Talou et al., PRC 94, 064613 (2016)
A Host of LANSCE Instruments can be used for correlated measurements

- DANCE – $4\pi$ calorimeter, 160 BaF$_2$ crystals, FP14 Lujan Center
- NEUANCE – 21 stilbene crystals
- Chi-Nu arrays – 45 liquid scintillators (low-energy PFNS) + 26 Li-glass detectors (high-energy PFNS)
Correlated \( (E^\gamma_{\text{tot}}, \text{TKE}) \)

Measurement of \( ^{252}\text{Cf}(\text{sf}) \) at DANCE (\( \gamma \) rays) + NEUANCE (neutrons) + 4 Si detectors to measure correlated n-\( \gamma \)-TKE events – G. Rusev

- NEUANCE (stilbene detectors) inside DANCE 4\( \pi \) \( \gamma \)-ray calorimeter
- 4 Si detectors to measure TKE

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**Leveraging Chi-Nu Arrays**

- Chi-nu arrays were developed to measure PFNS very precisely
- Can also be used to study n-\(\gamma\) correlations

Measured bi-correlation \((\Delta t_1, \Delta t_2)\) histograms of \(^{252}\text{Cf}\) neutrons and photons.

M.J. Marcath, R.C. Haight et al., Phys. Rev. C 97, 044622 (2018).
Gamma-ray Spectroscopy

- Infer fission yields from gamma line intensities
- Several assumptions that require simulations
  - How many $\gamma$ lines are in the energy window considered?
  - How much of the “flux” passes through $2^+ \rightarrow 0^+$ transition
  - Corrections when performing $\gamma - \gamma$ or $\gamma - \gamma - \gamma$ coincidences
Concluding remarks

- New theoretical tool to study the fission process in great detail
- Important questions remain on:
  - The fission process
  - Nuclear structure and reaction data of neutron-rich nuclei
- A fun physics playground with important applications!