The Physics of the CGMF Code

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What is CGMF?

- A **fission event generator** that follows the deexcitation of the fission fragments through emission of **prompt neutrons** and γ **rays**
- A **Monte Carlo** code to study correlations and patterns in fission
- Implementation of the **Hauser-Feshbach statistical theory** of nuclear reaction
- Now included as an option in **MCNP-6.3**
- Note that LANL (Kawano) has developed a deterministic version called **BeOH** to study Independent and Cumulative Fission Yields (includes β decay) – *now used by Lovell et al to evaluate those yields for next release of ENDF/B library.*

How to use CGMF (from the command line)

- [executable] -i [target] -e [energy] -n [number events] -t [time]
- cgmf.x -i 92235 -e 0.5 -n 1e6 -t 50e9

  neutron-induced fission of U-235 at 0.5 MeV with one million events and with a time coincidence window of 50 ns

- Output: history file with one million events:

$$\mathrm{A, Z, KE_{pre}, KE_{post}}, U_i, J_i, \pi_i, \vec{p}_L, \vec{p}_H, \nu_n, \nu_\gamma, \{\vec{p^i}_n\}_{i=1..\nu_n}, \{\vec{p^j}_\gamma\}_{j=1..\nu_\gamma}$$

Fission Fragments

Initial excitation energy, spin & parity

FF momentum vectors

Neutron and gamma multiplicities

Neutron vectors in cm and lab frames

Gamma vectors in cm and lab frames

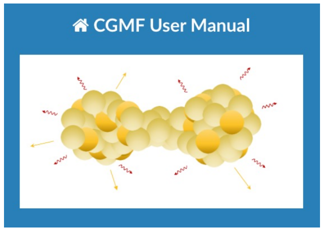
CGMFtk: Python toolkit for CGMF output

Python classes to help in reading and analyzing CGMT Monte Carlo histories

- getNu() → returns array of number of neutrons per fission event
- getKEpre() → returns array of pre-neutron emission fragment kinetic energies
- getULF() → returns array of initial excitation energies in Light Fragments

- Pnu(), Pnug() → returns neutron and gamma multiplicity distributions $P(\nu)$ and $P(N_\gamma)$
- nubarTKE() → returns $<\nu>$(TKE)
- pfns(), pfgs() → returns the Prompt Fission Neutron and Gamma Spectra, $\phi(E_n)$, $\phi(E_\gamma)$

```
from CGMFtk import histories as fh
cgmfHistories = fh.Histories(outputFilename)
cgmfHistories.Pnu()
```



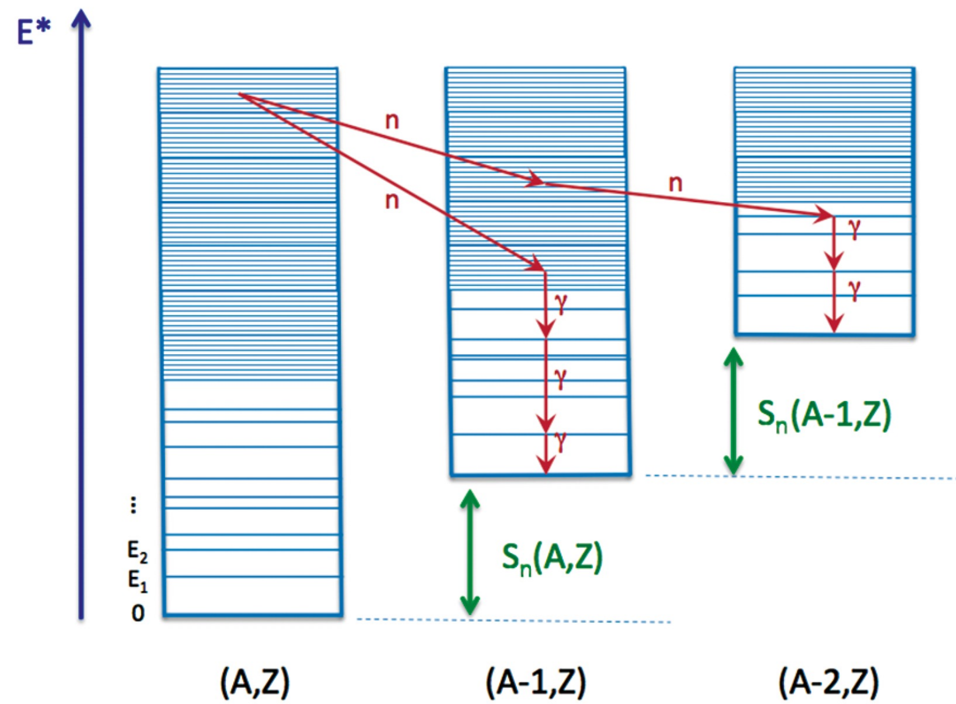
Source & Documentation

- C++
- Open source, BSD-3, LANL copyrights
- Standalone, but also option in MCNP-6.3
- GitHub: https://github.com/lanl/CGMF
- Main reference: Talou, Stetcu, Jaffke, Rising, Lovell, Kawano, Comp. Phys. Commun. **269**, 108087 (2021)
- Documentation: https://cgmf.readthedocs.io/
- Example Jupyter notebooks
- Support: cgmf-help@lanl.gov
- "Correlated prompt fission data in transport simulations," Talou, Vogt, Randrup, Rising, Pozzi et al. EPJ-A **54**, 9 (2018)

Contents

What's inside

- Model for **initial scission fragment yields**
- **Hauser-Feshbach** – At each stage of the decay, the competition between different reaction channels is ruled by probabilities or "decay widths"
- Several physics models and input parameters are used to compute those probabilities
- **Two decay channels only**: neutrons and photons (all charged particles are hindered until much higher excitation energies)



$$P_i = \frac{\Gamma_i}{\sum_i \Gamma_i}$$

Γ_n and Γ_γ

Scission Fragment Yields

$$Y(A,Z,TKE|E_n) = Y(A|E_n) \times Y(TKE|A,E_n) \times Y(Z|A,E_n)$$

- Major input… And yet difficult to assess
  - No direct experiment of pre-neutron emission yields
  - Approximative theoretical predictions
  - Very limited energy-dependent data, which requires $\nu(A,TKE|E_n)$ data…
- Simple three-Gaussian model for Y(A) and Gaussian model for Y(TKE|A) with energy-dependent parameters
- <TKE>, σ_{TKE}, and σ_J fitted to best reproduce $\langle\nu\rangle$, $P(\nu)$, and E_γ^{tot}
- Wahl systematics for $Y(Z|A,E_n)$

Initial Conditions: {U,J,π}

- Total energy balance $\mathrm{TXE} = Q - \mathrm{TKE}$
- Energy sharing between the two nascent fragments
  - RT(A), to reproduce <ν>(A)
  - Max entropy method (assuming equilibrium temperature)

$$\frac{U_L a_H(U_H)}{U_H a_L(U_L)}$$

- Angular momentum conservation $\vec{J}_L + \vec{J}_H + \vec{l} = \vec{J}$
- Spin and parity distribution (in the continuum)

$$\rho(J,\pi) = \frac{1}{2}(2J+1)\exp\left[-\frac{J(J+1)}{2B^2(Z,A,T)}\right]$$

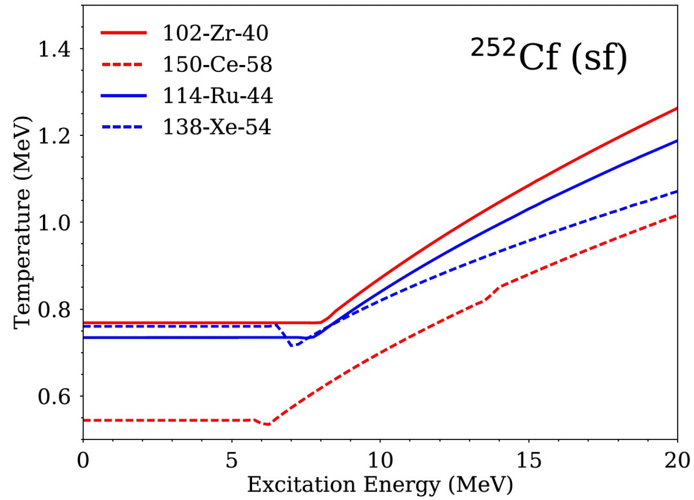
with

$$B^2(Z,A,T) = \alpha\frac{\mathcal{I}_0(Z,A)T}{\hbar^2}$$

Neutron Emission

- Optical model calculations. Transmission coefficients obtained from the S-matrix.
- Global, spherical OMP from Koning-Delaroche, Nucl. Phys. A 713, 231 (2003)
- Continuum level density represented as Gilbert-Cameron (constant-temperature then Fermi gas)
- Discrete states from RIPL3/ENSDF
- At higher incident neutron energies
  - Preequilibrium neutron emission CoH_3)
  - Multi-chance fission probabilities (CoH_3)

$$T_c = 1 - |\langle S_{cc} \rangle|^2$$



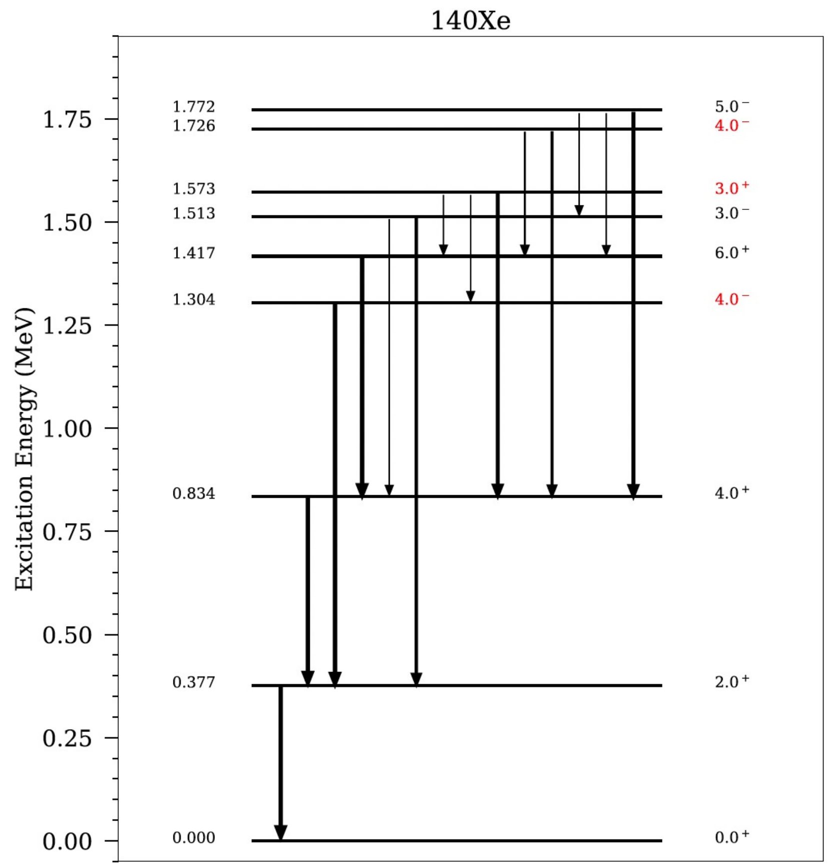
Photon Emission

- Strength function formalism for E1, E2, M1

$$T^{\mathrm{Xl}}(\epsilon_\gamma) = 2\pi f_{\mathrm{Xl}}(\epsilon_\gamma)\epsilon_\gamma^{2l+1}$$

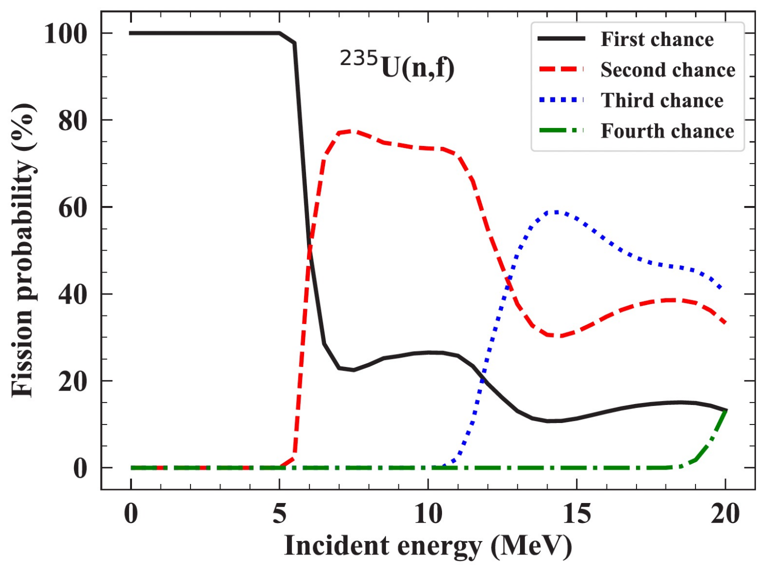
with f_{Xl} following Lorentzian forms

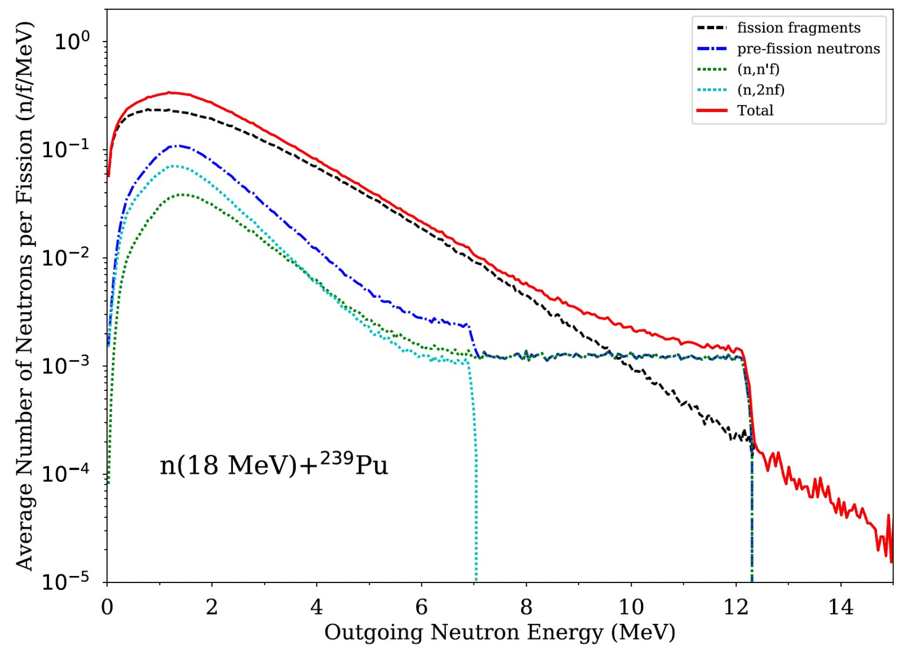
- Low-lying structures (energies, spins, branching ratios) taken from RIPL3 (Reference Input Parameters Library) or ENSDF nuclear structure databases



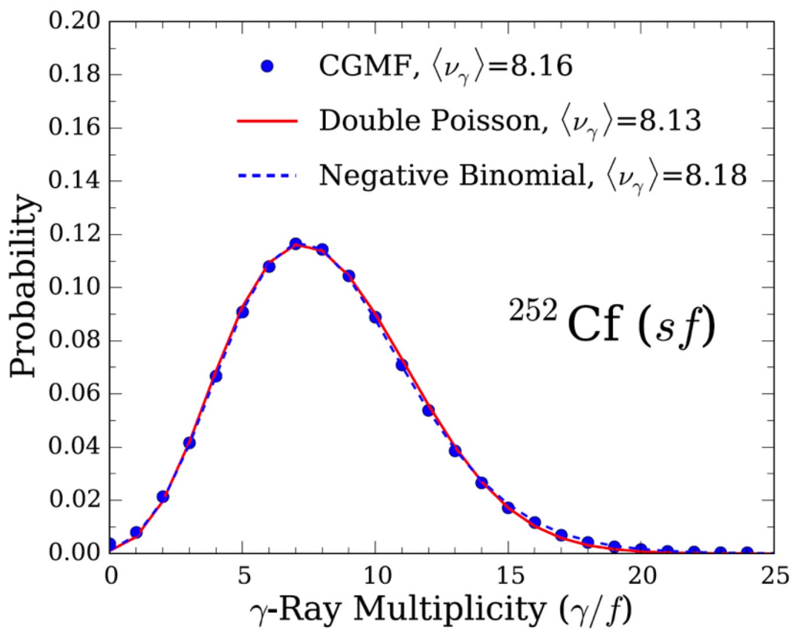
Multi-chance fission

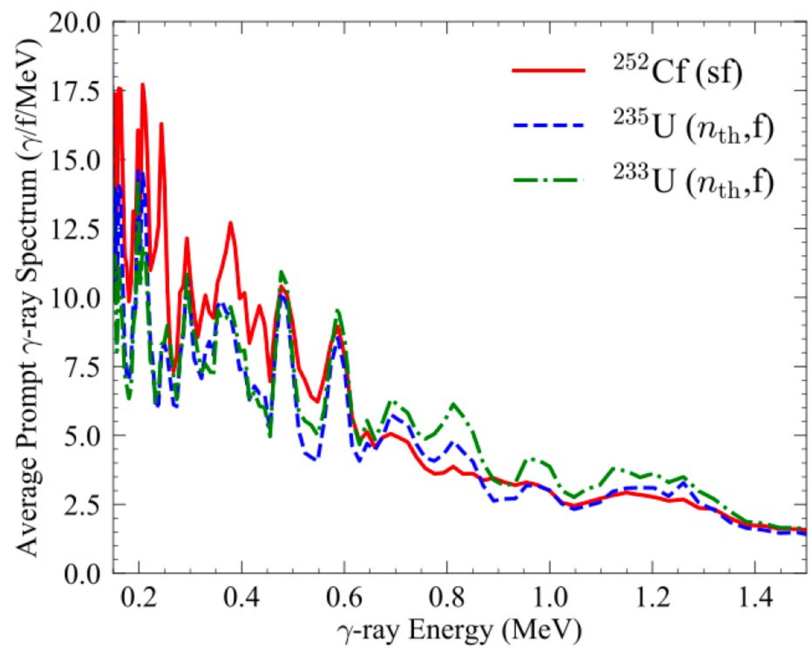
- Fission barrier heights → "multi-messenger" to constrain $P_f(E_n)$
- Consistency among all fission observables
- Lovell et al, PRC 103, 014615 (2021)
- Preequilibrium component (CoH_3)



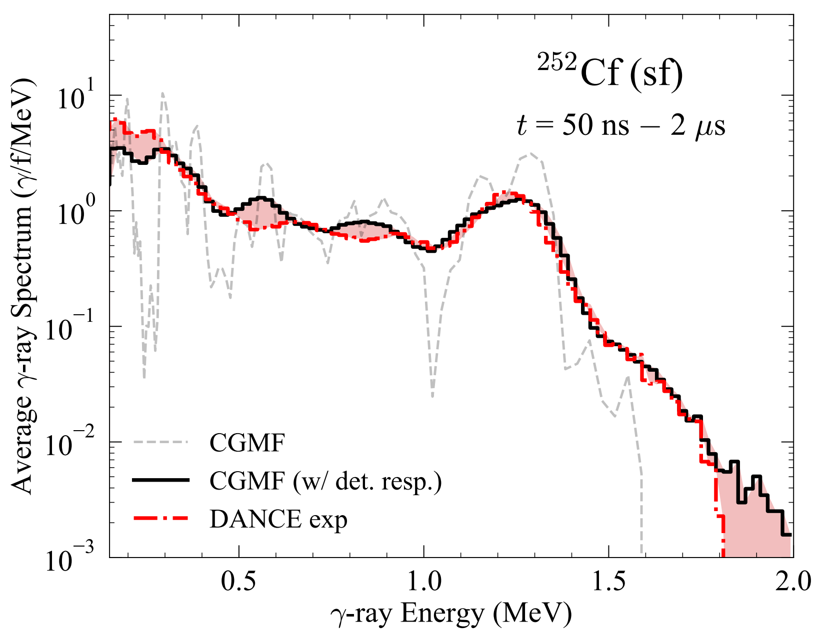


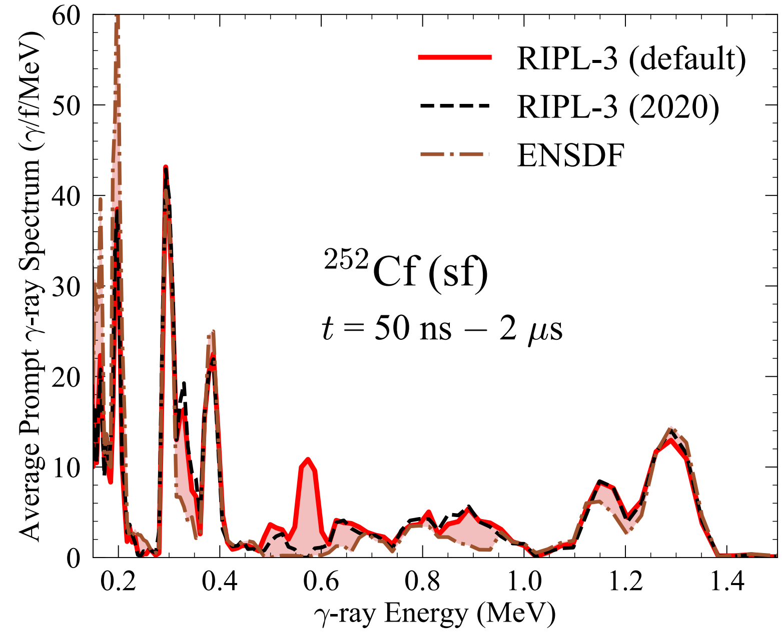
Prompt fission γ rays



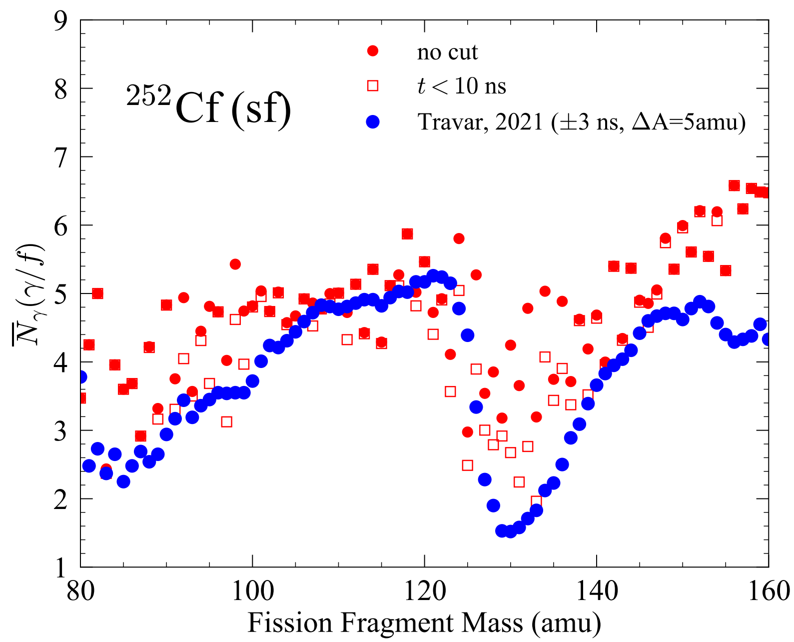


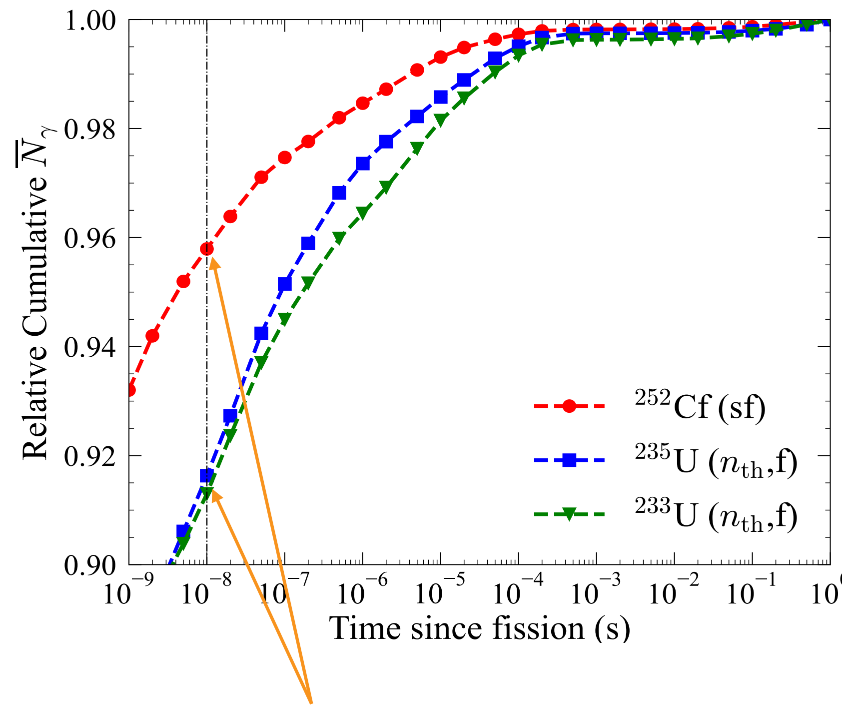
Prompt fission γ rays are not all emitted at once due to the presence of isomers in fission fragments





CGMF can follow the time evolution of γ emission after scission





The presence of these isomers make it difficult to measure <N$_\gamma$>(A) in parts of the mass range (A~130)

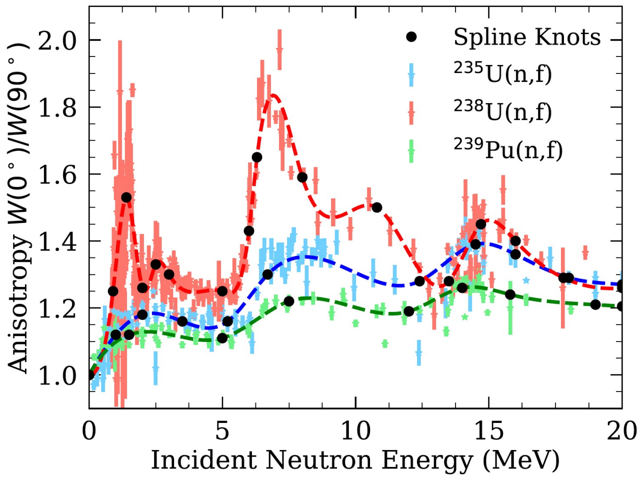
At 10 ns, about 4% (^{252}Cf) to 8% (^{233,235}U) of all γ rays have yet to be emitted

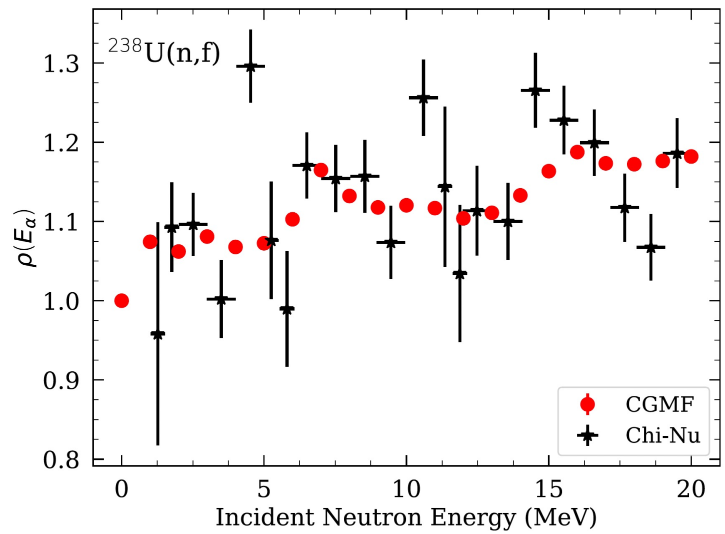
Rusev et al, Phys. Rev. C **111**, 064613 (2025); Talou et al, Phys. Rev. C **112**, 014601 (2025)

Anisotropic emission of prompt fission neutrons

- Fission fragments populated in (J,K,M) transition states
- Pre-equilibrium neutron emission (at higher energies)
- Recoil effects (higher energies)
- Anisotropy of emission in the center-of-mass of the fragments
- Scission neutrons?

Fission fragment anisotropy W(0)/W(90)



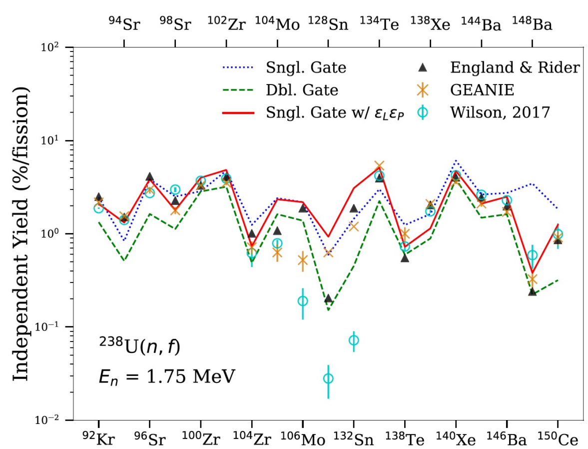


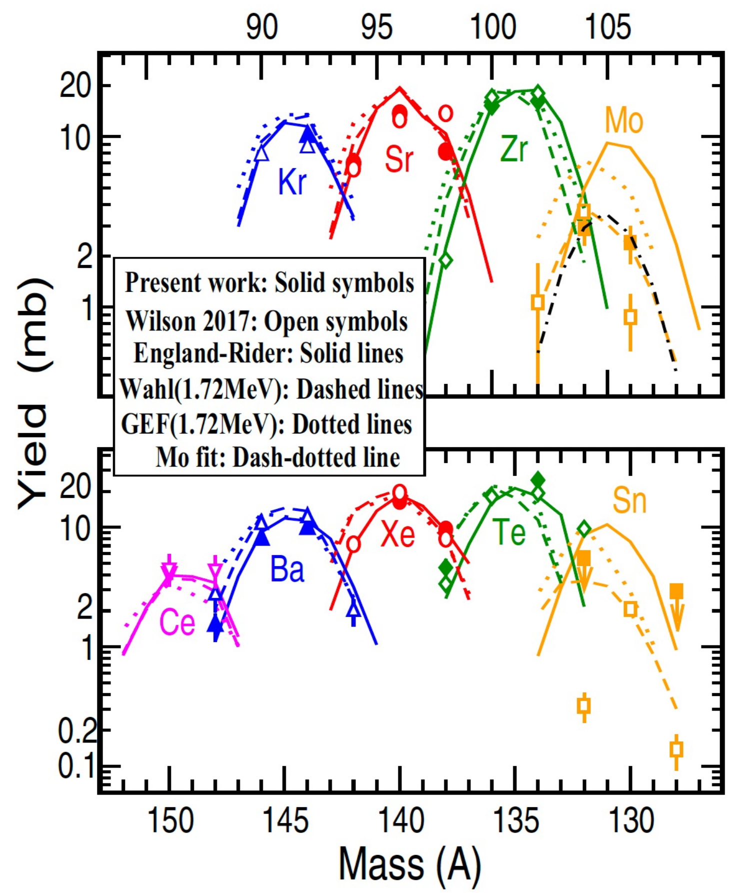
Lovell, Talou, Stetcu, Kelly, Phys. Rev. C **102**, 024631 (2020)

Determining fission fragment yields from γ rays

- γ line intensities are related to FPY, but some assumptions do not always work
- γ–γ–γ correlations to infer FPY
- Wilson et al, Phys. Rev. Lett. **118**, 222501 (2017)
- Fotiades et al, Phys. Rev. C **99**, 024606 (2019)
- D. Ramos et al, Phys. Rev. Lett. **123**, 092503 (2019)

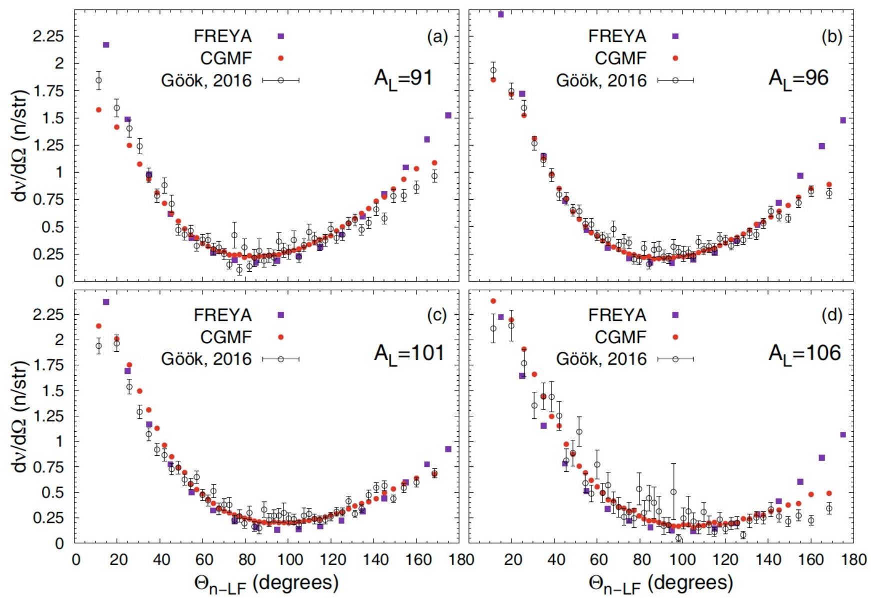
CGMF can be used to provide correction factors for indirect FPY measurements

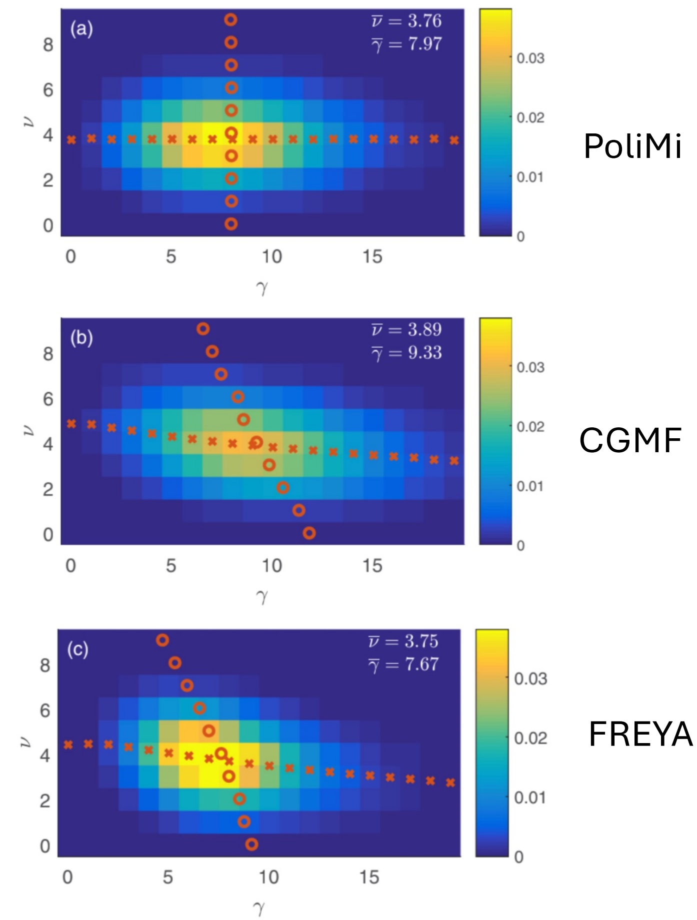




Correlations n-FF, n-n, and n-γ

- Two neutrons emitted preferential with θ_{nn}=0 or θ_{nn}=180 deg is a signature of fission

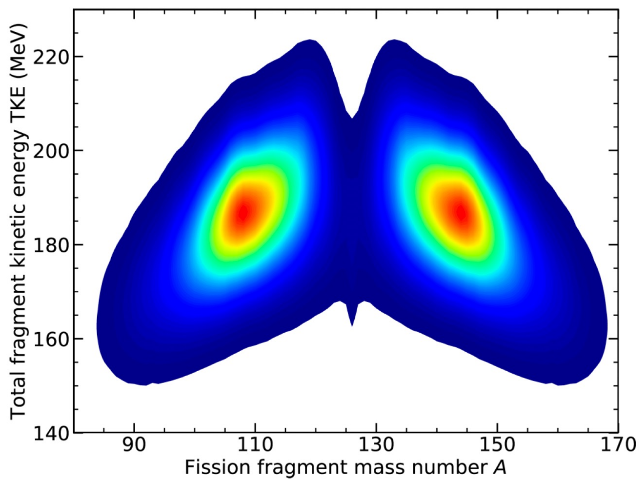


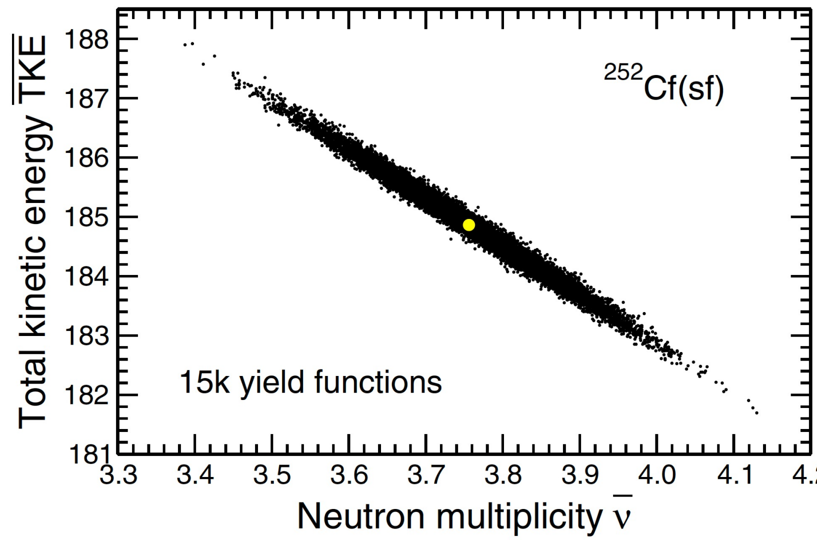


Marcath et al, Phys. Rev. C 97, 044622 (2018)

Constraining <TKE> from <ν>

- Randrup, Talou, Vogt, Phys. Rev. C **99**, 054619 (2019)
  - Evaluated the covariance matrix associated with ^{252}Cf(sf) scission yields Y(A,Z,TKE)
  - Sampled covariance matrix 15,000 times
  - Ran FREYA with 1 million events each time
  - Analyzed correlated results

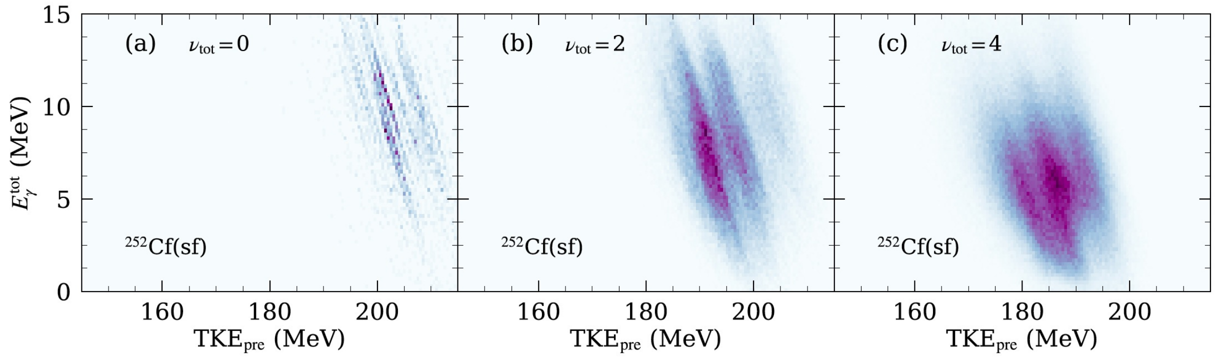




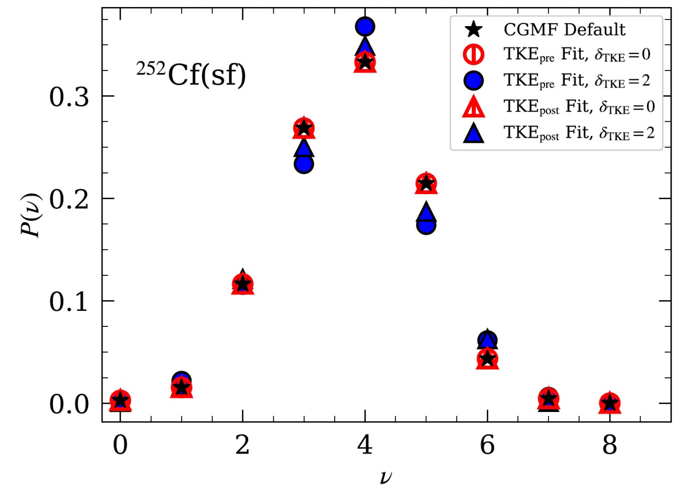
0.4% uncertainty on <ν> implies a standard deviation of 135 keV for <TKE>

Inferring P(ν) from (E_γ^{tot},TKE) measurements

- "Measuring" neutrons with prompt gamma energies and fission fragments
- Lovell et al, Phys. Rev. C **100**, 054610 (2019)



$$f(E_\gamma^{\text{tot}}, \text{TKE}) = \sum_{\nu=0}^{\nu_{\max}} P(\nu) f(E_\gamma^{\text{tot}}, \text{TKE}|\nu)$$



Future

- Working towards CGMF-2.0
  - Coding optimization, emulator
  - Improved physics modeling: γ–γ angular correlations, spin formalism, neutron spectrum
  - Validation
  - Larger suite of fission reactions
  - Extended documentation
- Disentangling experimental effects from theoretical predictions (2E, 2E-2v, neutron emission assumptions, mass, charge and energy resolutions, other systematic biases)
- LANL SPIDER 2E-2v exp (Winkelbauer, Gastis) with γ tagging
- Cold fission (L.Gaudefroy)
- Scission neutrons?
- Consistent evaluation of PFNS and $\langle \nu \rangle$ for U and Pu isotopes up to 20 MeV

One more thing…

At Stardust, we are developing a web App that will allow you to ask questions about evaluated nuclear data libraries in plain English

- What is the (n,2n) cross section of 238U at 14.5 MeV in ENDF/B-VIII.1?
- What is the evaluated uncertainty on the PFNS for 239Pu at 2.5 MeV incident energy?
- Compare the capture cross sections of 197Au between ENDF/B-VIII.1, JENDL-5 and JEFF-4.0

INDRA

INDRA: Intelligent Nuclear Data Retrieval Agent

A **multi-agent AI workflow** that interprets user prompts in plain English, extracts the exact information from **ENDF-formatted libraries**, and returns results in the form of text, numerical values, and plots

→ Working prototype (not public yet), but looking for interested beta testers