Recent Advances in Detailed Modeling of Prompt Fission Neutrons and Photons

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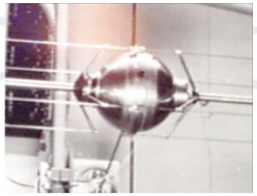
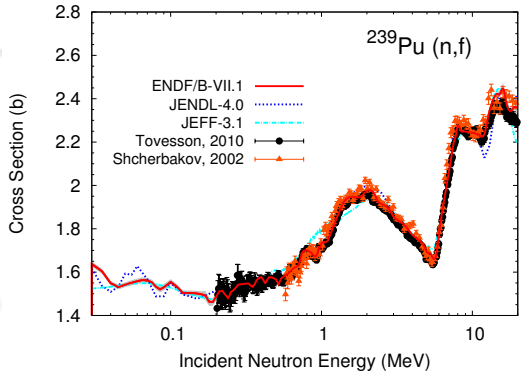
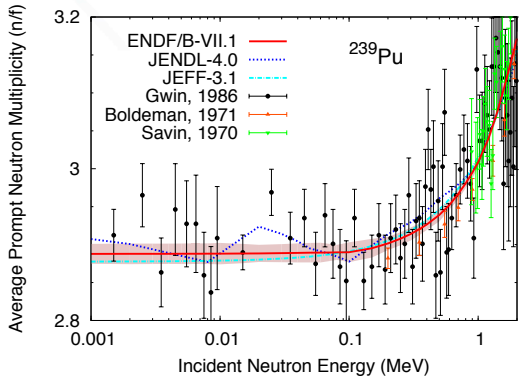
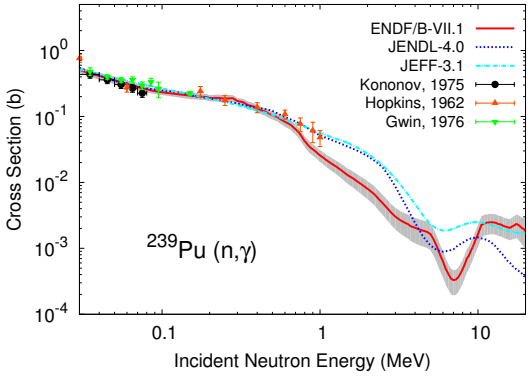
Motivation

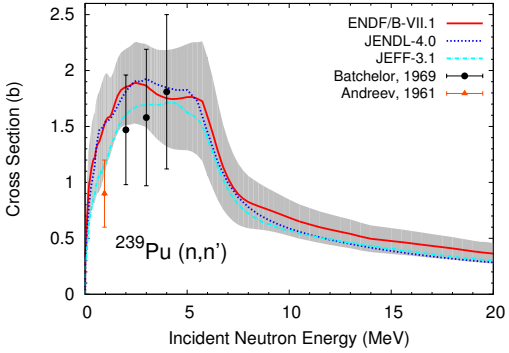


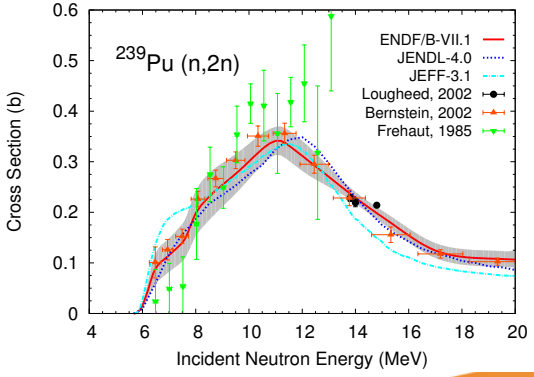
- Very accurate multiplication factors k_{eff} simulated for fast critical assemblies, e.g. Jezebel, Godiva, with different nuclear data libraries [ENDF/B-VII.1, JENDL-4.0, JEFF-3.2]
- **Proof of compensating errors!**
- Need to move beyond average quantities
- Detailed modeling and correlated data will lead to robust and predictive capabilities





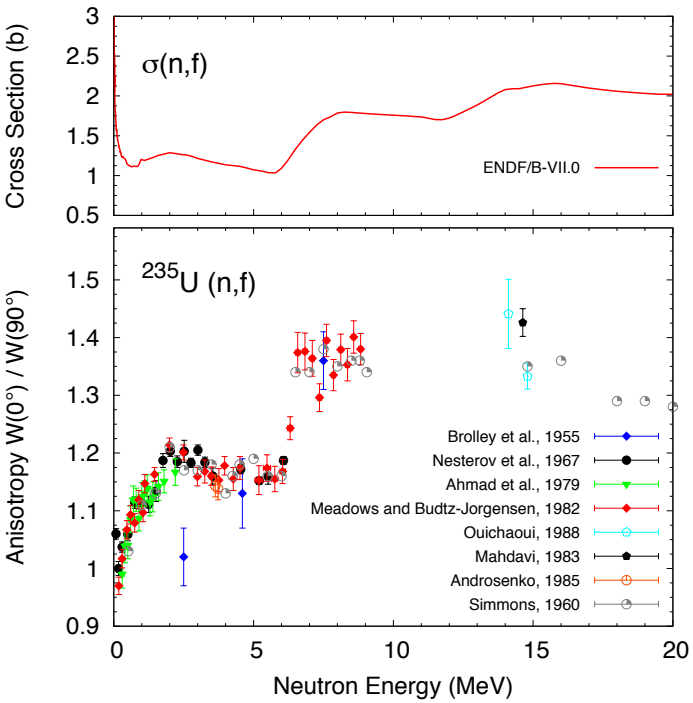


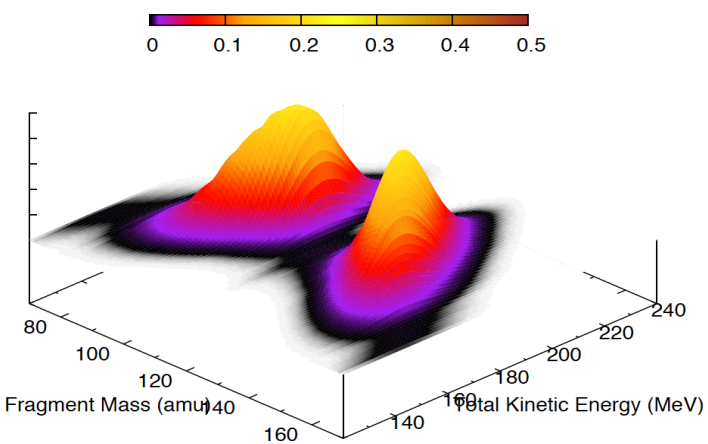




Correlations in Fission Data

- Fission cross sections and fission fragment angular distributions
- Fission cross sections and fission fragment yields
- Prompt fission neutrons and photons





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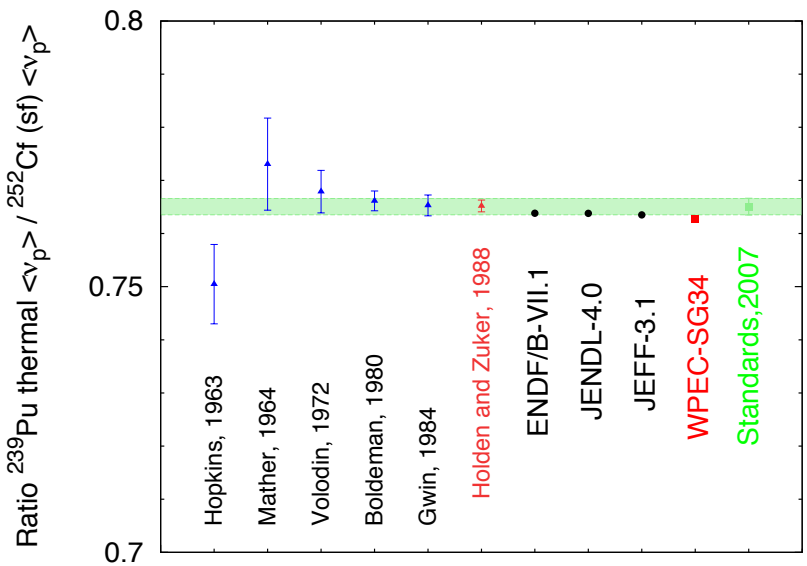
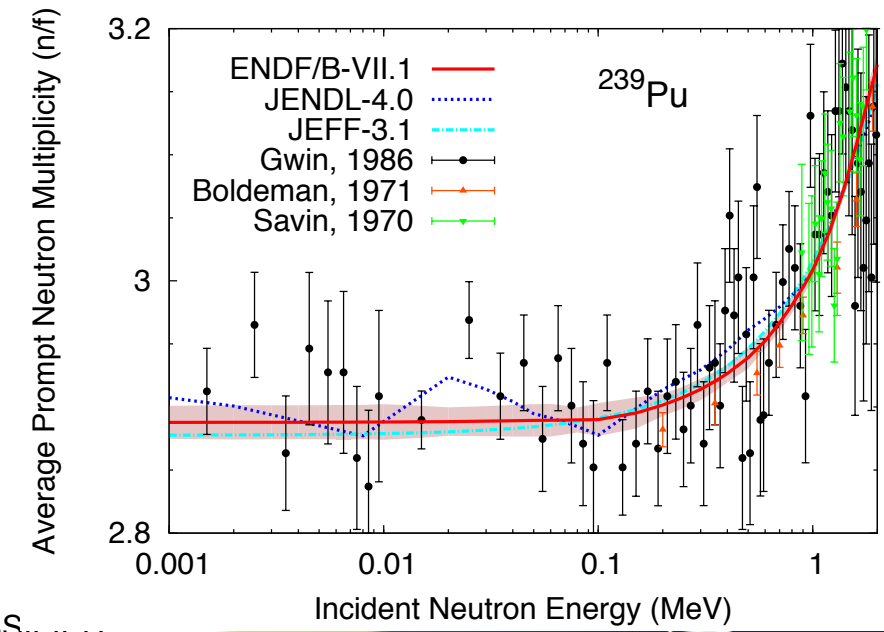
Prompt fission neutron multiplicity

- Prompt neutron multiplicity somewhat adjusted (from least-square analysis of experimental data) in 0.1-1.0 MeV range to fit Jezebel k_{eff}
- Some integral data seem to contradict this adjustment
- Fluctuations in the resolved resonance range





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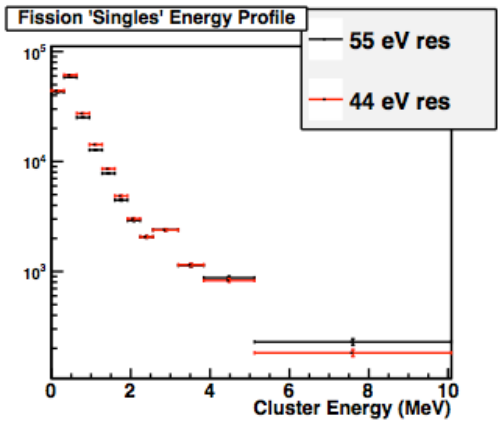
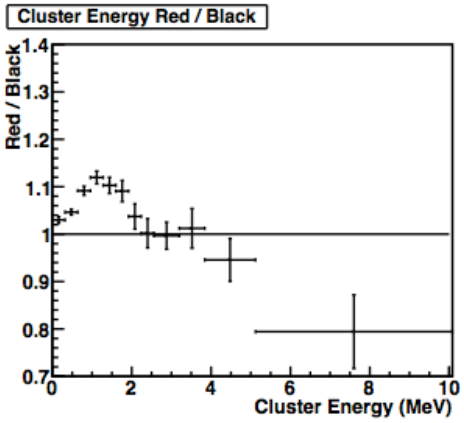
Average neutron multiplicity, ^{239}Pu

Fluctuations in the RRR

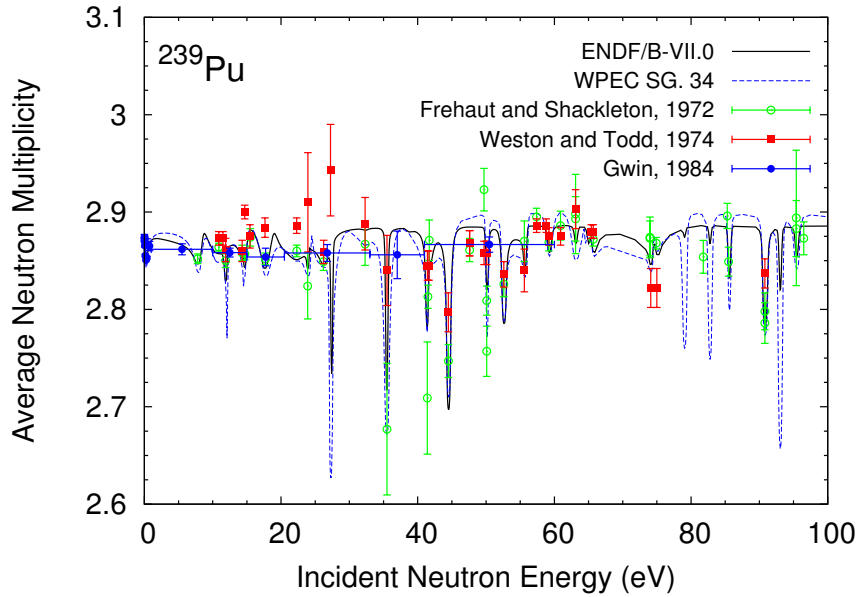
- Physics: (n,γf) or/and Y(A,Z,TKE)?
- Impact on applications?

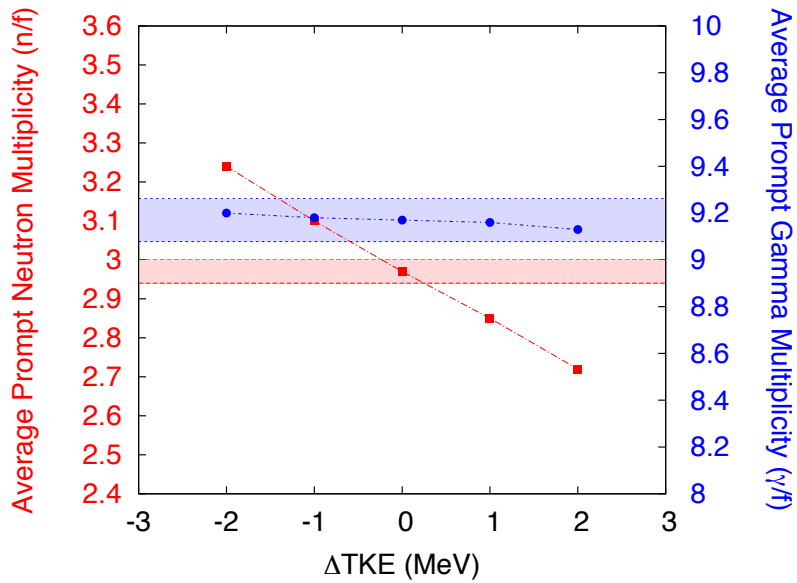




DANCE γ-ray data (Mosby, Couture)

Monte Carlo Hauser-Feshbach calculations with Y(A,Z,TKE+ΔTKE)





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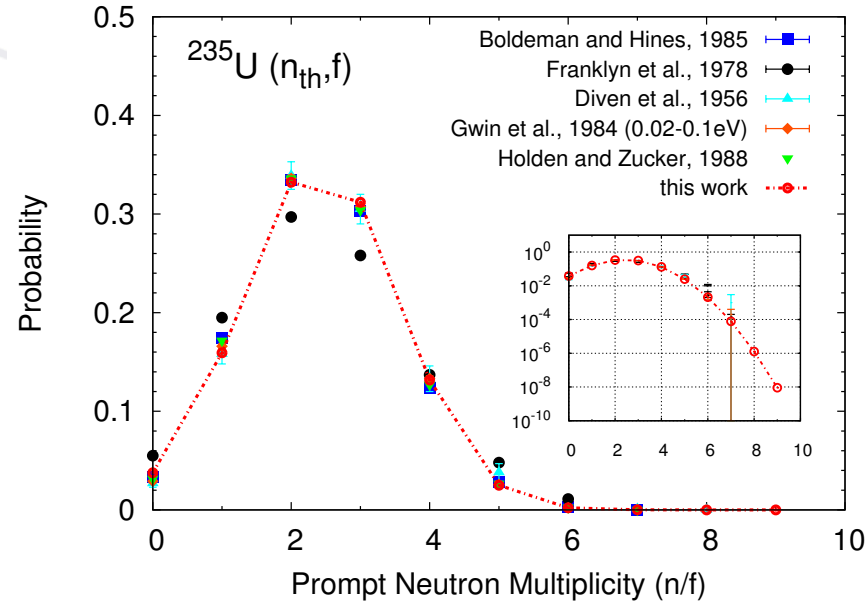
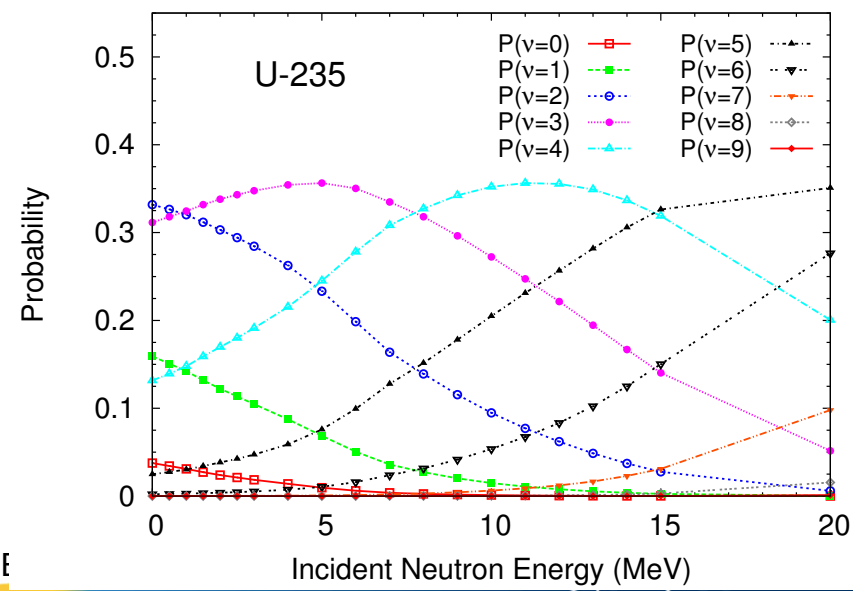
Neutron Multiplicity Distribution P(ν)

- Experiment:
  - very little data, esp. at higher energies
- Modeling:
  - new capabilities with Monte Carlo codes: CGMF, FREYA, FIFRELIN, GEF, …
  - Systematics based on Terrell's formula, and compared to limited data by Frehaut

$$\sum_{n=0}^{\nu} P_n = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{(\nu-\overline{\nu}+1/2+b)/\sigma} exp(-t^2/2)dt$$





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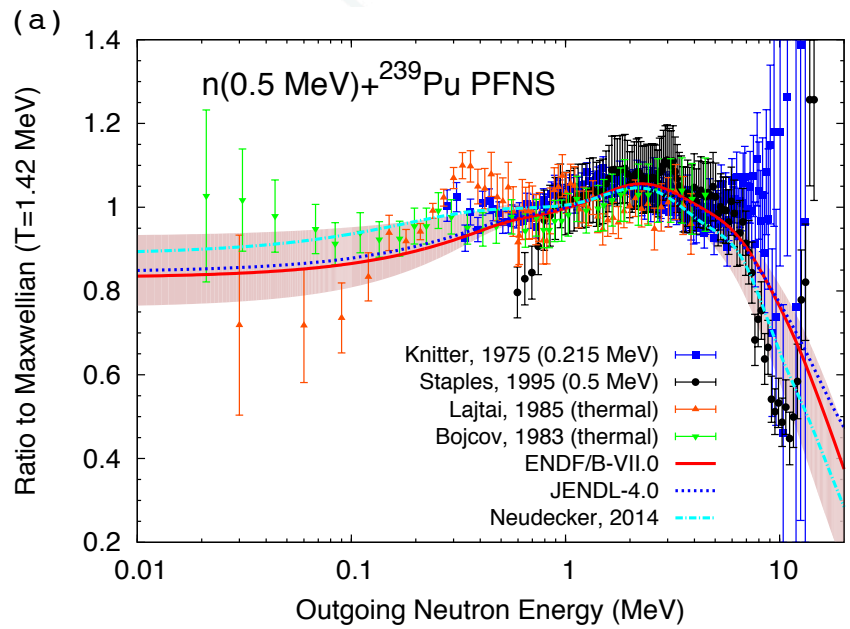
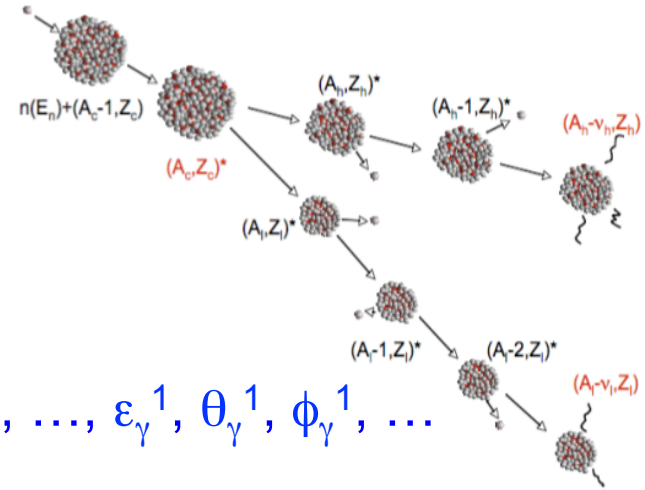
Prompt fission neutron spectrum (PFNS)

- Re-evaluated uncertainties associated with thermal PFNS of Pu-239 (Neudecker et al.)
- NJOY/MCNP simulations (Kahler) + uncertainty propagation
- Jezebel: k_{calc}=0.99878 ± 0.00058 pcm



Neudecker, Talou *et al.*, submitted to NSE

Modeling the fission process event-by-event



- New code CGMF
  - Monte Carlo nuclear reaction code
  - Fission event-by-event
  - Z, A, KE, U_i, J_i, π_i, ε_n^1, θ_n^1, ϕ_n^1, ε_n^2, θ_n^2, ϕ_n^2, …, ε_γ^1, θ_γ^1, ϕ_γ^1, …
  - Access to correlations, distributions
- Collaboration with LLNL and UM (as part of NA22 project) to extend calculations to higher incident energies
- Two (important) outcomes:
  - PFNS evaluation is constrained by other fission data!
  - ν_p is evaluated consistently with PFNS

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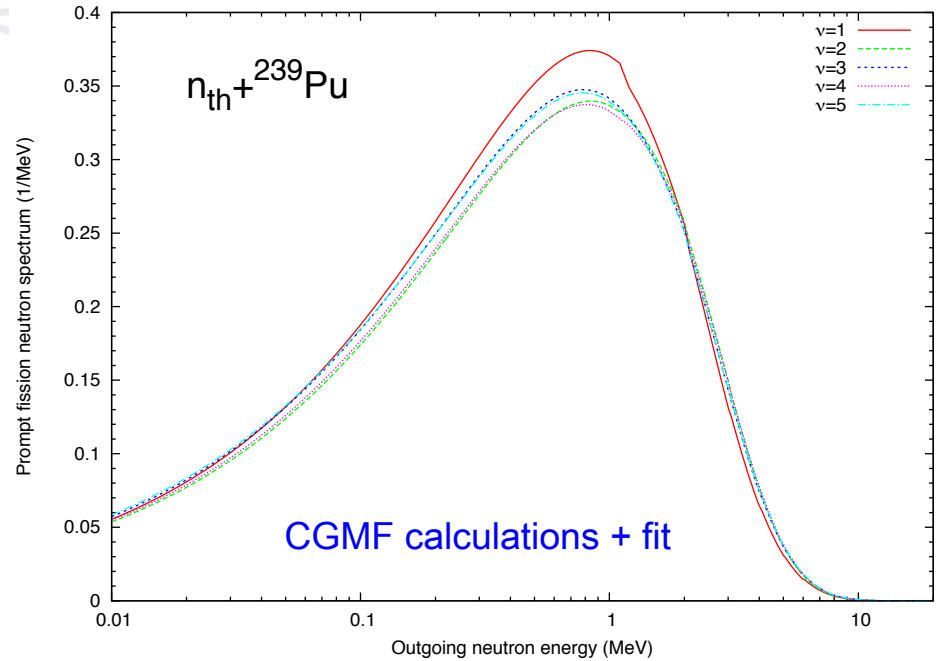
Exclusive spectra



- Different spectra for different values of ν
- Scheme
  - Calculate with CGMF
  - Fit with $x^a \exp(-x/b)$ functions
  - Format in ENDF with P(ν)
- ENDF Format extension proposed to store $P(\nu,E_{inc})$ and $\chi_{i=1,\nu}(E_{inc},E_{out})$
- New ENDF files for ^{239}Pu and ^{235}U

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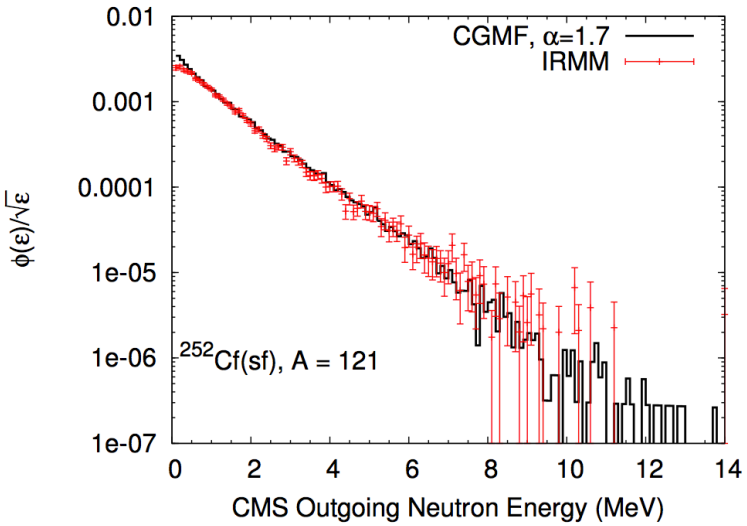
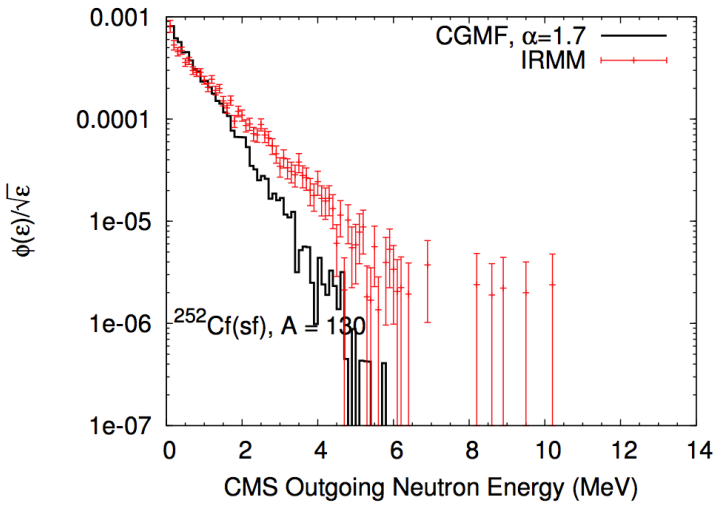
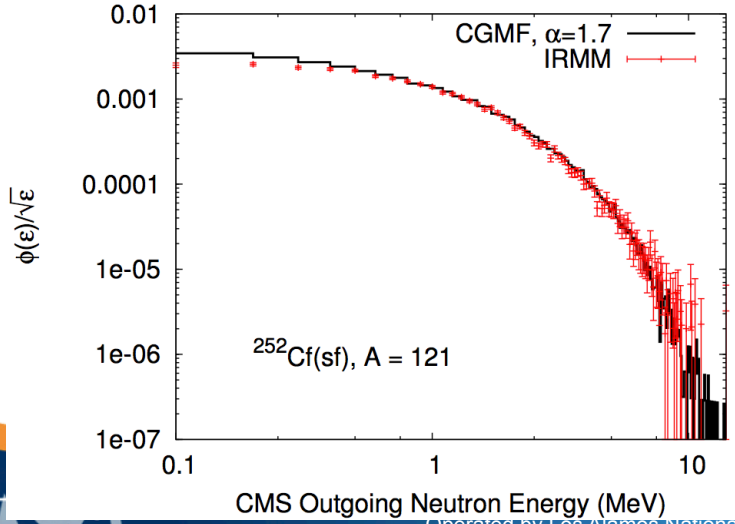
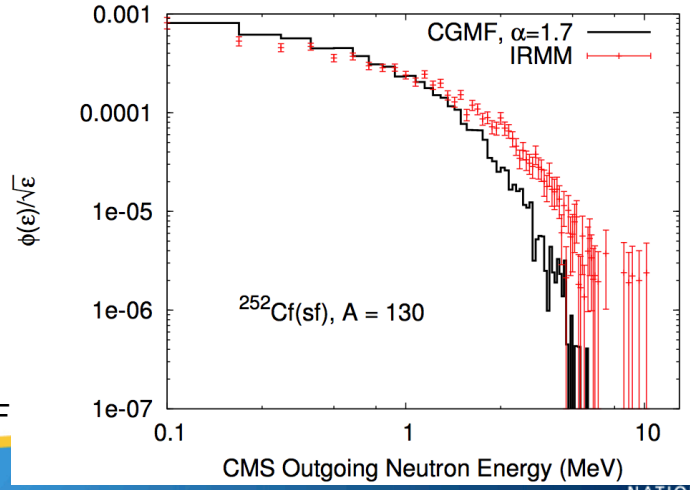
Mass-dependent neutron spectra

- Very good agreement for most fragments
- But discrepancies near shell closure A~132









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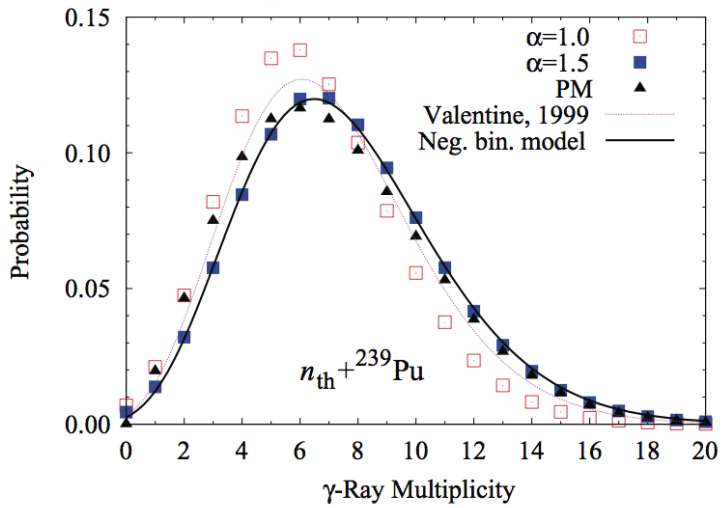
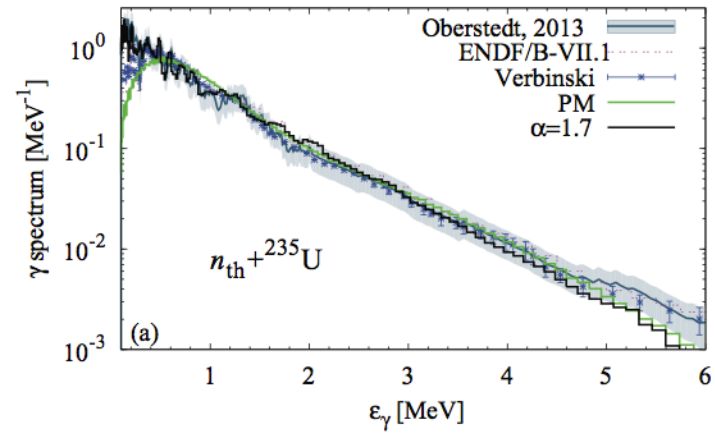
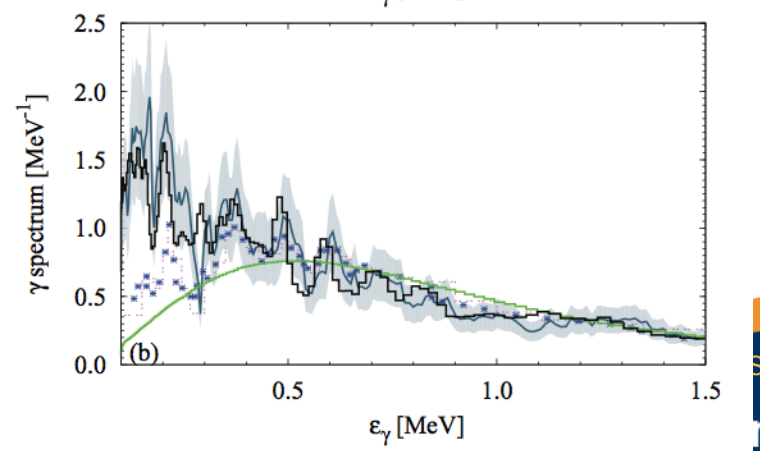
Prompt fission γ rays

- "Properties of prompt fission γ rays," I.Stetcu, P.Talou, T.Kawano, and M.Jandel, Phys. Rev. C 90, 024617 (2014).
- $P(\nu_\gamma)$, γ-ray spectrum







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Exciting prospects

- Extension to higher energies → need $Y(A,Z,TKE)_{|Einc}$ → joint LANL-LLNL work
- Prompt fission γ-ray spectra
- Benchmarking with unique new experiments (differential, integral)
- Address other types of correlations, e.g., neutron-gamma multiplicities
- Integration into transport codes (NA22), e.g., MCNP6

Thanks to: A. C. Kahler, D. Neudecker, M. E. Rising, R. C. Haight, M. C. White