Evaluation of Prompt Fission γ Rays
for Cf-252 (sf), Pu-239 (n,f) and U-235 (n,f)

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Status of Prompt Fission γ-Ray Evaluations

- ENDF sections:
  - MF1, MT458: components of energy released in fission
  - MF15, MT18: prompt fission γ-ray spectrum
- ENDF/B-VII.1:
  - U-235:
    - Taken from B-VI
    - Stewart, Alter, Hunter, ENDF-201 (1976) evaluation based on Verbinski and Sund experimental data (100 nsec after fission)
    - Stewart and Hunter, LA-4918 (1972)
  - Pu-239:
    - Taken from B-V.2
    - Hunter and Stewart, LA-4901 (1972)
    - Verbinski et al. data

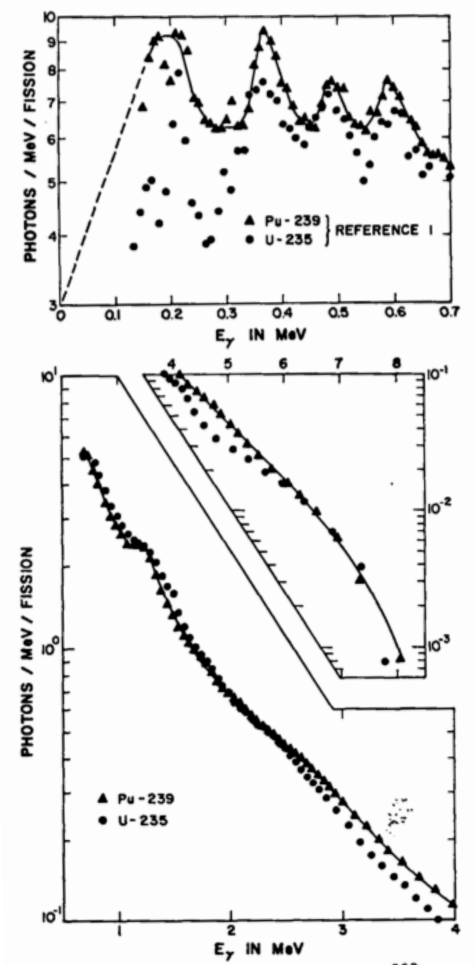


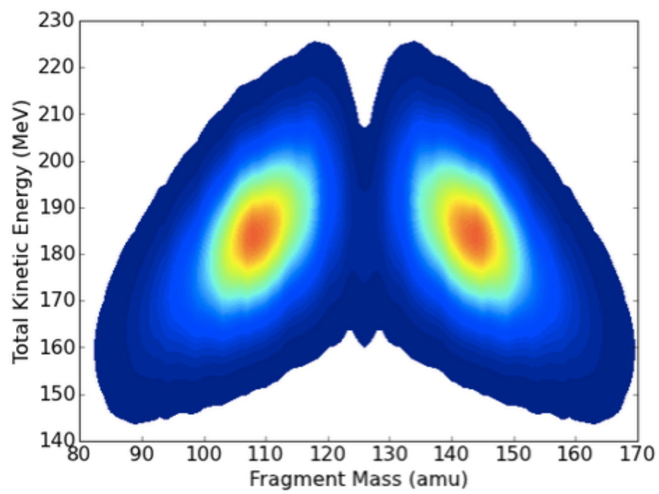
Fig. 2. Photons per MeV per fission for ^{239}Pu and ^{235}U for thermal neutrons as a function of E_γ. The experimental points of Verbinski and Sund[1] are compared with the evaluated data for ^{239}Pu, shown as a smoothed curve.

Verbinski, Phys. Rev. C 7, 1173 (1973)

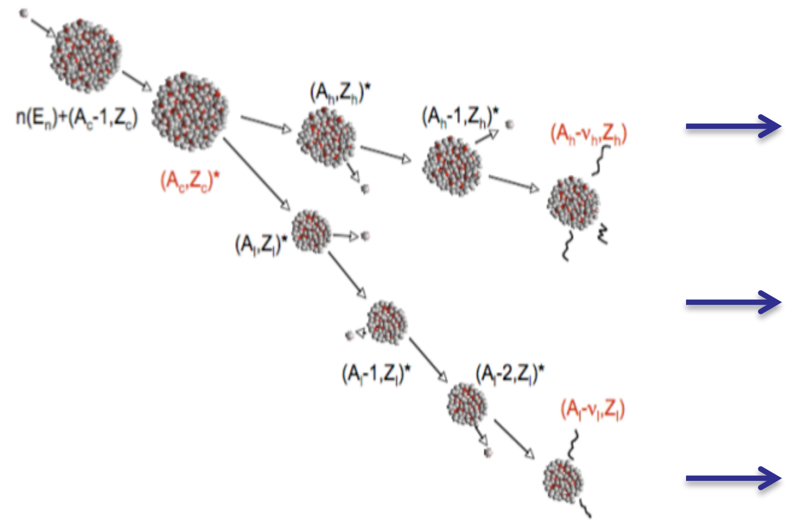
Since then…

- **New experimental data**
  - DANCE, LANL:
    - ^{235}U, ^{239,241}Pu (0.025 eV – 100 keV), ^{252}Cf (sf)
      Wu, Chyzh et al., PRC **90**, 014602 (2014); PRC **87**, 034620 (2013)
  - IRMM, Geel, Belgium:
    - ^{235}U(n_{th},f), ^{241}Pu(n_{th},f), ^{252}Cf (sf)
      Oberstedt, Billnert, Hambsch et al.,, PRC 87, 024601 (2013); PRC 87, 051602(R) (2013), PRC 92, 014618 (2015)
- **New theoretical models and codes**
  - Until B-VII,
    - Models limited to calculation of neutrons
    - Very limited indirect information on average total γ-ray energy
  - New tools being developed at LANL (CGMF), LLNL (FREYA), CEA-Cadarache (FIFRELIN), GSI (GEF)

Modeling Prompt Fission Neutrons and Gamma Rays



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



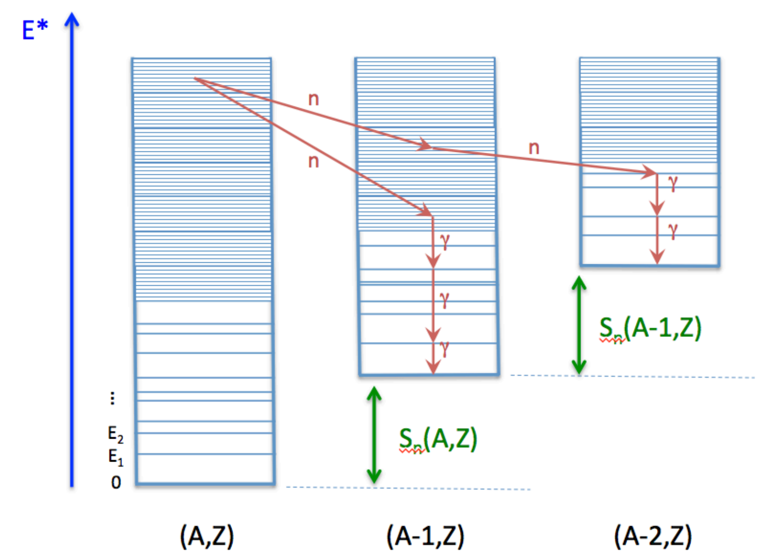
β-decay

Prompt emissions of n and γ
within 10^{-14} sec

Goal: follow the sequential emissions of prompt neutrons and γ rays from the excited primary fission fragments, event-by-event.

Monte Carlo Hauser-Feshbach

- Hauser-Feshbach statistical theory of nuclear reactions
  - Neutron and γ-ray emission probabilities calculated and sampled at each stage of the decay
- **CGMF**: Monte Carlo implementation
- Full kinematic reconstruction of fission fragments, neutrons and gammas emitted

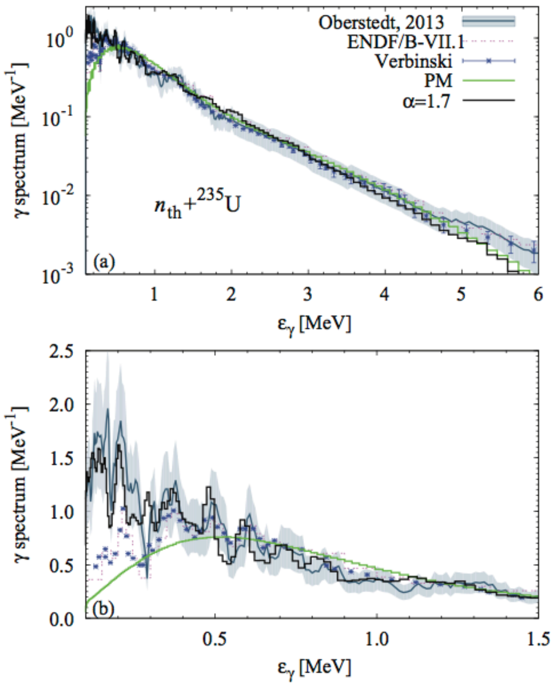


→ Monte Carlo histories of fission events

$$A, Z, KE, U_i, J_i, \pi_i, \nu_n, \nu_\gamma$$
$$\vec{p}_F(\text{pre}), \vec{p}_F(\text{post}) \text{ in LAB frame}$$
$$\{\vec{v}_{n_i}, E_{n_i}\}_{i=1,\nu_n}, \{\vec{v}_{\gamma_j}, E_{\gamma_j}\}_{j=1,\nu_\gamma}$$

Prior CGMF results (2014)

Thermal neutron-induced fission only



- ✧ Very encouraging results, but…
- ✧ Difficulties in describing both neutron and γ data consistently

PHYSICAL REVIEW C **90**, 024617 (2014)

Properties of prompt-fission γ rays

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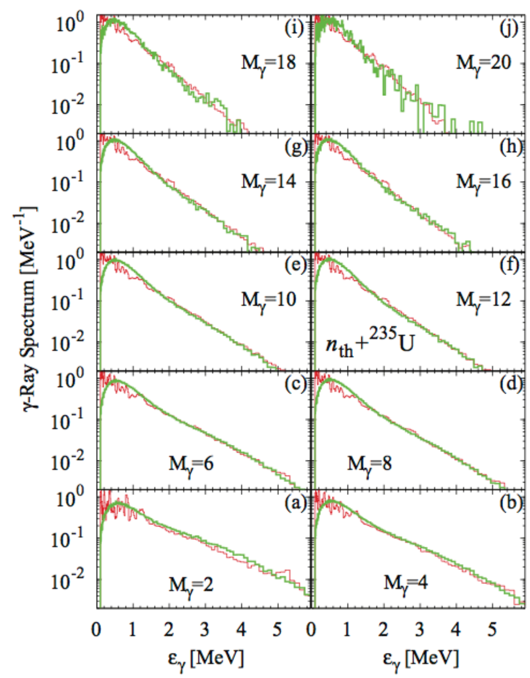
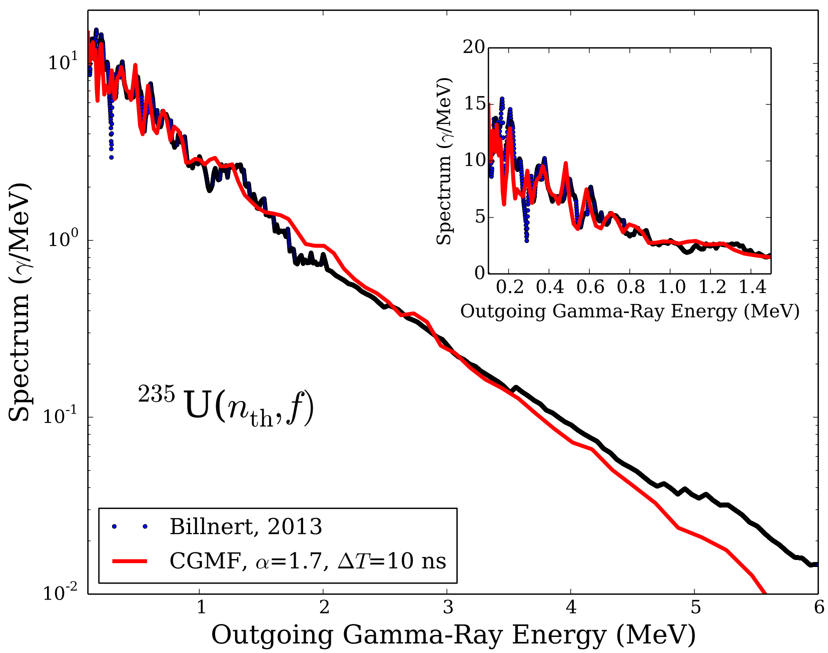
(Received 11 June 2014; published 26 August 2014)

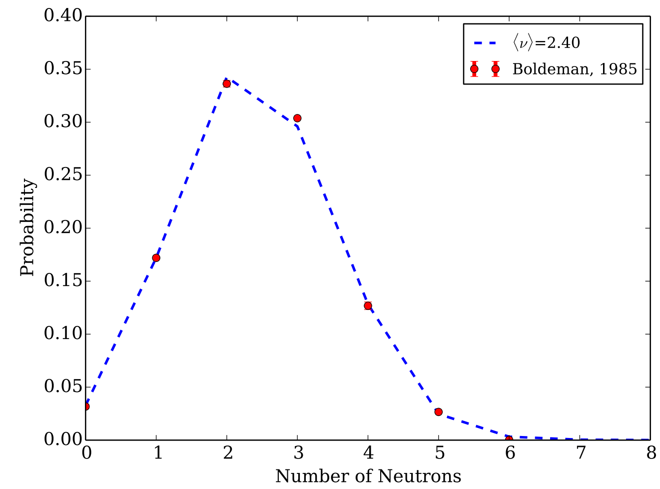
In a Monte Carlo Hauser-Feshbach statistical framework, we describe spectra, average multiplicities, average energy, and multiplicity distributions of the prompt γ rays produced in the thermal neutron-induced fission of ^{235}U and ^{239}Pu, and the spontaneous fission of ^{252}Cf. Comparisons against recent experimental data show reasonable agreement in all cases investigated, after adjustment of the initial spin distribution in the fission fragments. In particular, when we include in the calculation the Doppler broadening we obtain a qualitatively good description of the measured low-energy spectra, where contributions from collective discrete transitions in specific fragments can be identified. At higher energies, both the calculated neutron and γ-ray spectra are softer than experimental data. The impact of selected model parameters on the prompt neutron and γ-ray spectra is analyzed. Finally, we present the prompt γ spectrum and multiplicity distribution for the neutron-induced fission of ^{235}U for 5.5 MeV neutron incident energy, just below the threshold for second-chance fission.

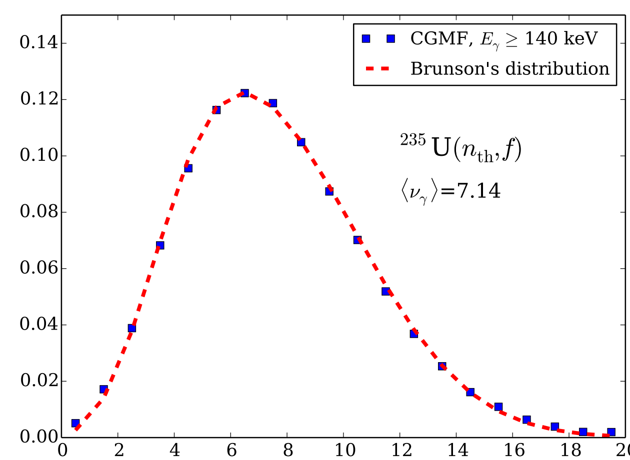


Working toward consistent modeling of prompt fission neutrons and γ rays

- Importance of accurate yields Y(A,Z,TKE)
- Still some parameters to finalize tuning: $R_U(A)$, α

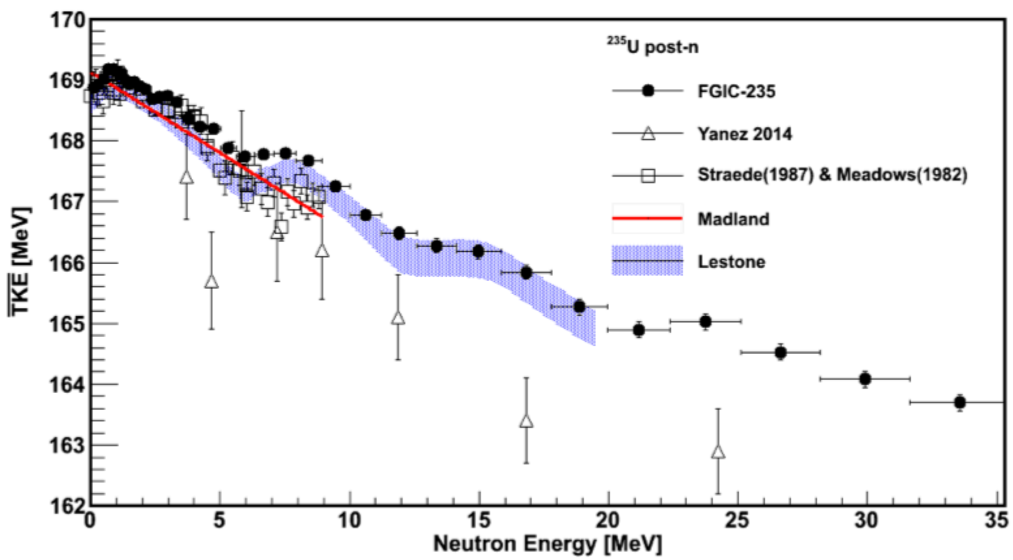


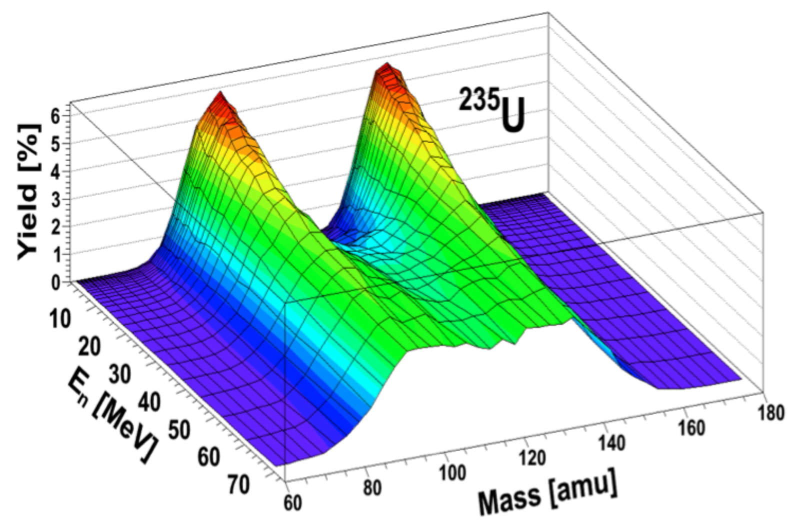




Incident Energy Dependence

- Need accurate fission yields Y(A,Z,TKE) as a function of E_{inc}



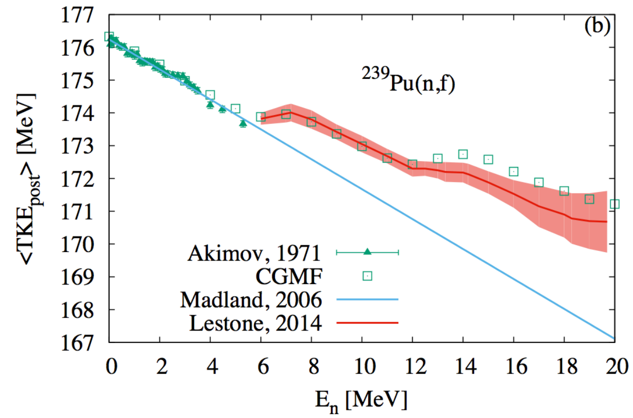


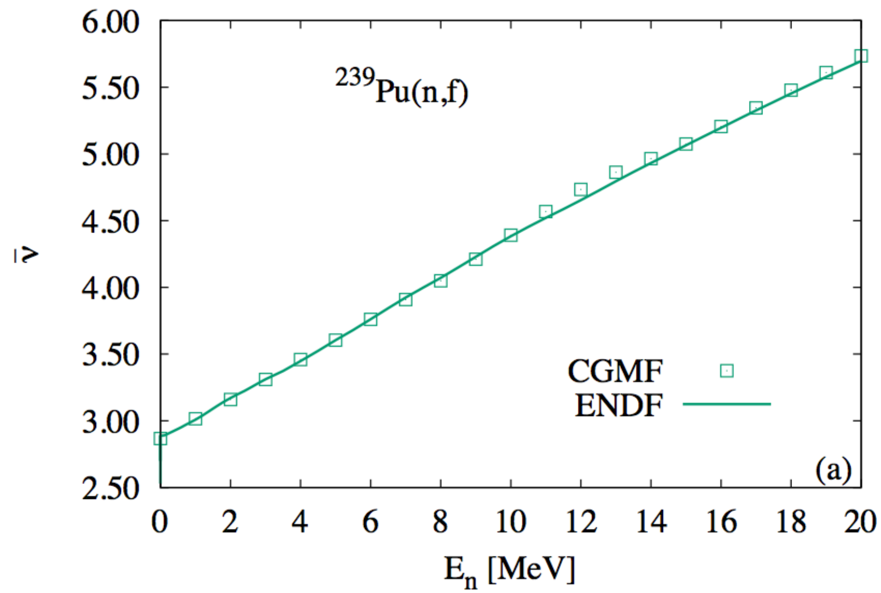
D. Duke, PhD Thesis, LA-UR-15-28829 (2015)

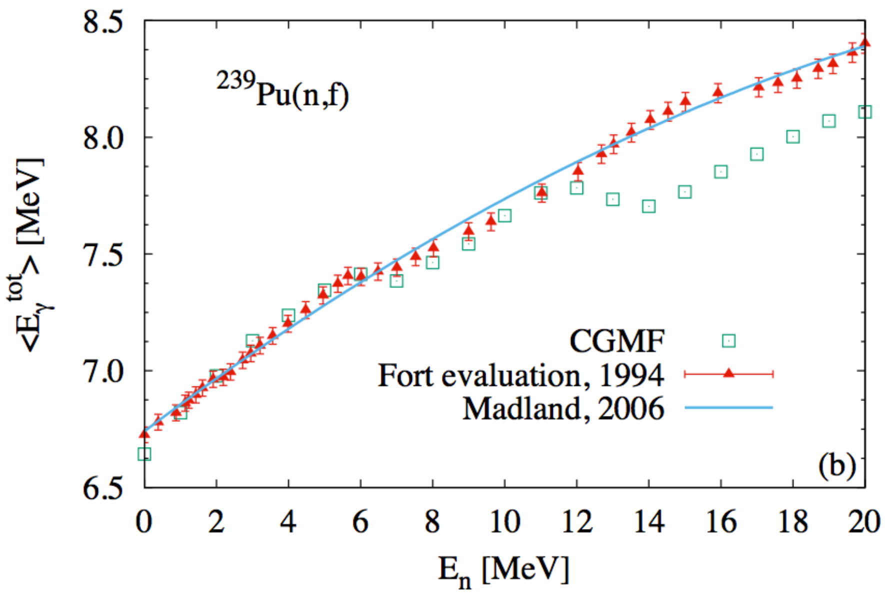
❖ Also, ongoing theoretical work by A.J.Sierk (LANL)

CGMF results at higher incident neutron energies

- Preliminary results for ^{239}Pu (n,f)

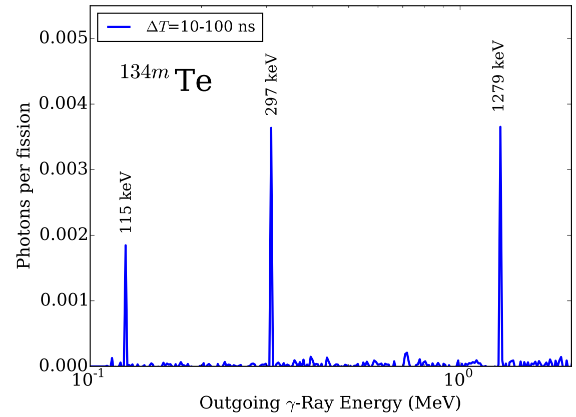


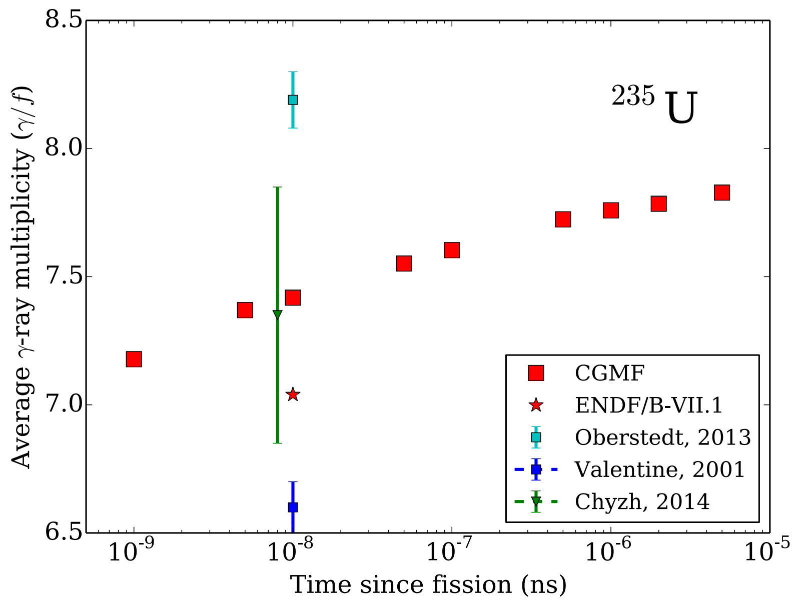


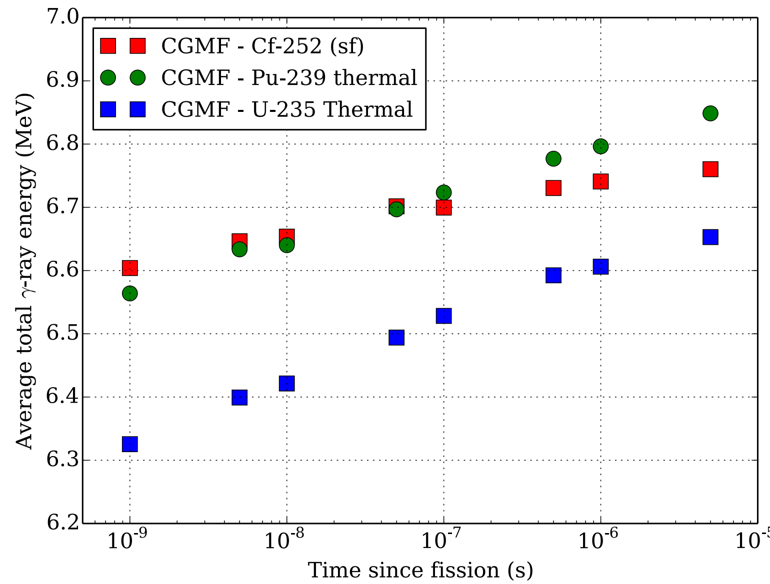


Time-dependence of PFG data

- Isomers in fission fragments lead to different spectra and multiplicities when using different time-coincidence windows







New evaluations (in progress)

- **Plan**
  - Use CGMF-calculated PFGS in MF15, MT18
  - No change to MF1, MT458 (at this point)
  - Use 100 nsec to 1 μsec as time coincidence window
  - Energy threshold? 100 keV in ENDF/B-VII.1
  - UQ + covariances
- **Timeline**
  - Study sensitivity of results to model input parameters (R_T, α, etc.)?
  - New files ready for ^{235}U and ^{239}Pu for next CSEWG in Nov. 2016
  - Some other actinides in FY17

Acknowledgements

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