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Prompt fission neutron and gamma-ray properties in a Monte-Carlo Hauser-Feshbach framework

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Outline

- Motivation
- The Monte-Carlo Hauser-Feshbach method
- Results for prompt particles, discussion select parameters:
  - Initial spin distribution
  - Excitation energy sharing between fragments
  - Sensitivities to other parameters
- Summary and outlook

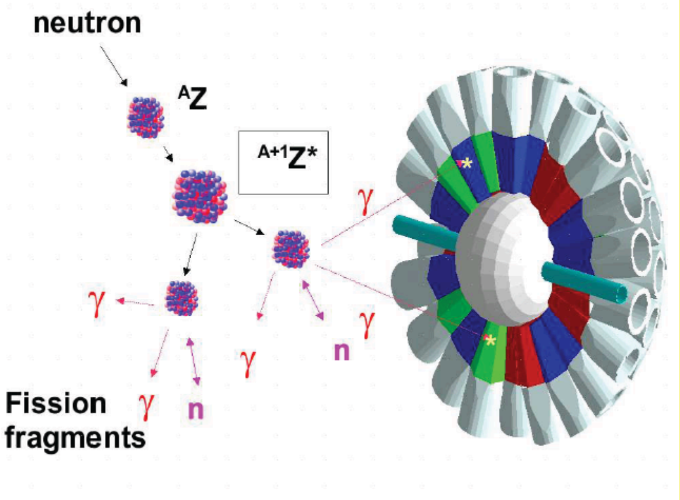
Motivation

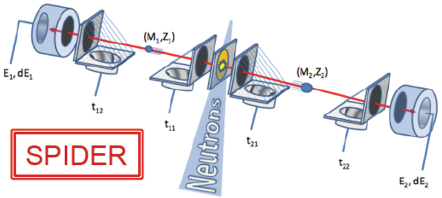
- Basic science:
  - Understand the pre- and post-scission physics
  - Interpret experimental data
  - Provide guidance on detector design

- Applications:
  - Nuclear energy: future reactors (new fuel compositions, new geometries, etc.)
  - Existing fuel cycle (safety, waste management, etc.)
  - Nuclear forensics
  - Astrophysics (reaction networks)

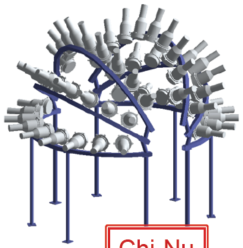
Experiment

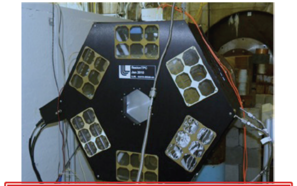
- Specroscopy: GAMMASPHERE (binary/ternary fission) – ANL, BNL
- Calorimetry:
  - DANCE – n-induced fission
  - fusion-fission reactions (Dubna)
  - Crystal ball 162xNaI(TI) 4π array (Darmstadt)
- See talks in FIESTA2014: R.C.Haight, N.Colonna, A.Tsinganis, F.Tovesson, M.Jandel, A.Oberstedt, J. Ullmann etc.



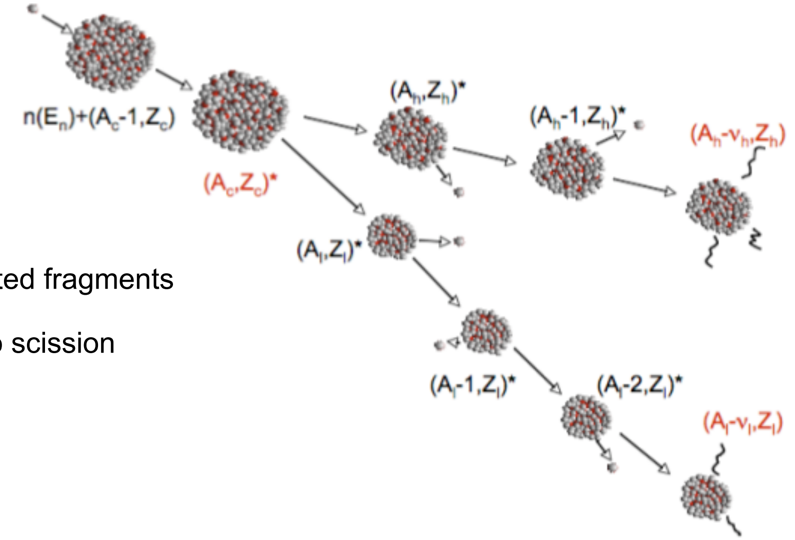


SPIDER


Chi-Nu


Time-Projection Chamber

Fission simulation



- Assumptions:
  - Prompt fission products emitted from the fully accelerated fragments
  - No emission occurs during the evolution from saddle to scission
  - No emission at the neck rupture
  - No time information (stop at the ground/isomeric state)
  - Fission fragments are compound nuclei

- C++ code (MPI implementation) CGMF=CGM+FFD
  - deterministic and Monte-Carlo modes
  - similar to DICEBOX at low energies
  - other similar implementations: FREYA (LLNL), FIFRELIN (CEA), GEF (Schmidt)

Hauser-Feshbach for fission fragments

Treat fission fragments as compound nuclei

Description of:

- average prompt fission neutron spectrum
- average prompt fission neutron multiplicity

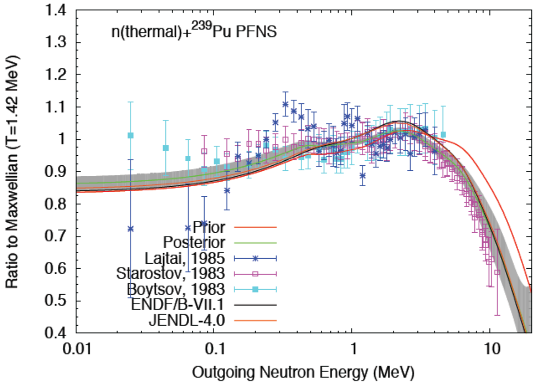
➢ P(ν), ν(A)

➢ prompt gamma observables

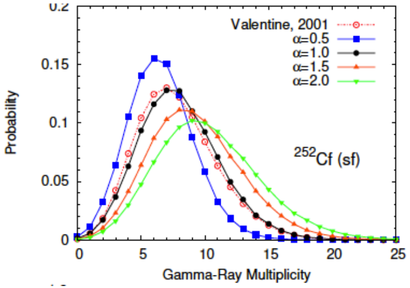
➢ correlations between particles

➢ Same approach applicable to describe beta-delayed neutrons/gammas

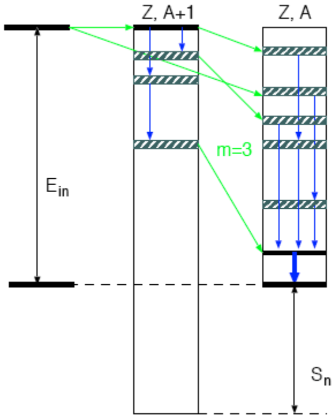
Complication: more parameters, some not well known



Madland-Nix / Los Alamos model

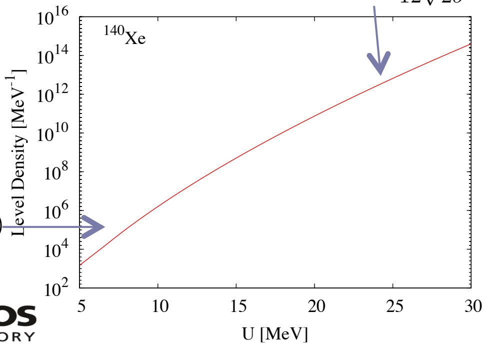


Hauser-Feshbach formalism for n-induced reactions



$$\rho(U) = \frac{1}{12\sqrt{2}\sigma}\frac{\exp(a\sqrt{aU})}{a^{1/4}U^{5/4}}$$

$$\rho(U) = \frac{1}{T}\exp(U/T)$$



- Neutron emission probability:

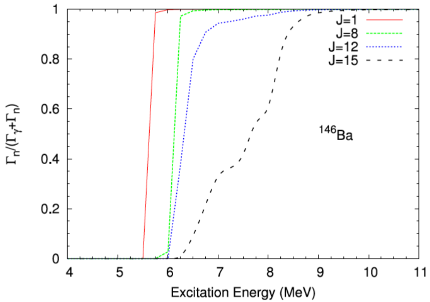
$$P(\epsilon_n)dE \propto T_n(\epsilon_n)\rho(Z, A-1, E-\epsilon_n-S_n)$$

  - ✓ Transmission coefficients computed using an optical model
  - ✓ Density of states

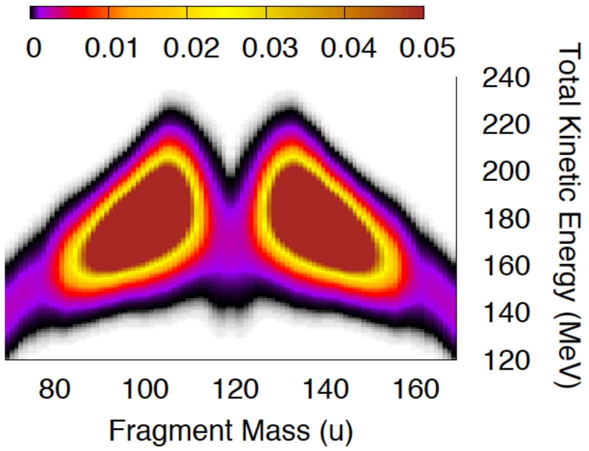
- Gamma emission probability:

$$P(\epsilon_\gamma)dE \propto T_\gamma(\epsilon_\gamma)\rho(Z, A, E-\epsilon_\gamma)$$

  - ✓ Transmission coefficients calculated from the gamma strength function
  - ✓ E1, M1 and E2 transitions only
  - ✓ Density of states
  - ✓ Discrete levels



Input into the fission simulations



- Experimental Information:
  - Primary fission fragment yields
  - Internal excitation energy

$$TXE = Q_f(A_l, Z_l; A_h, Z_h; A_c, Z_c) - TKE$$
$$= M_l + M_h - M_c + E_{inc} + B_n(A_c, Z_c) - TKE$$

  - Ingredients used in HF calculations (gamma strength functions, discrete levels)

- Theory/Model:
  - Charge distribution: from Wahl systematics $Z_p = A_h \frac{Z_c}{A_c} + \Delta Z$
  - Parity distribution: assumed equiprobable
  - Excitation energy sharing: $R_T = \frac{T_l}{T_h}$
  - Initial spin distribution:

$$P(J) \propto (2J+1) \exp\left(-J(J+1)/(2B^2)\right)$$

  - Ingredients used in HF calculations (optical model parameters)

NO DIRECT MEASUREMENTS

- de-excitation feeding patterns of the ground-state bands
- angular anisotropy of prompt fission gamma rays
- isomeric ratios

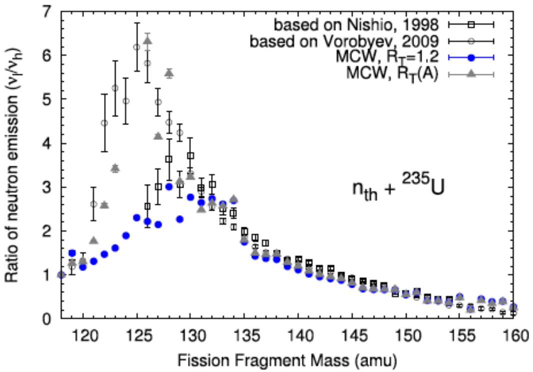
Energy sharing

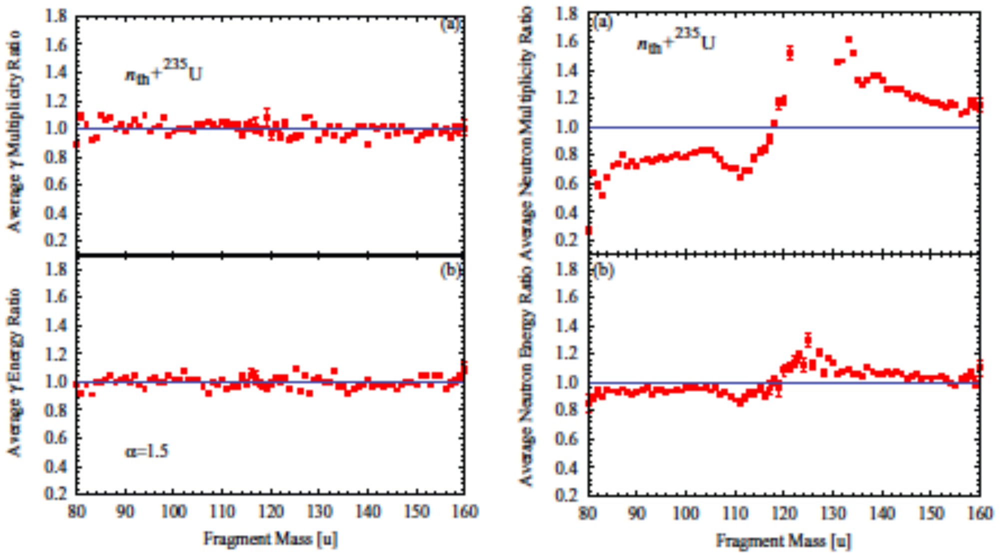
$$R_T = \frac{T_l}{T_h}$$

R_T=1: thermal equilibrium (like in the Los Alamos model)

R_T=constant

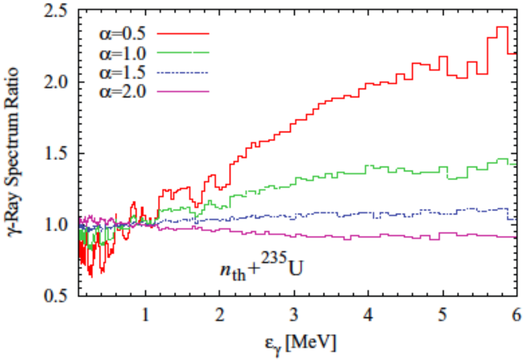
$R_T(A)$





- symmetric fission: R_T=1
- ~130: maximum (closed shell)
- >130 R_T decreases to below one (deformation)

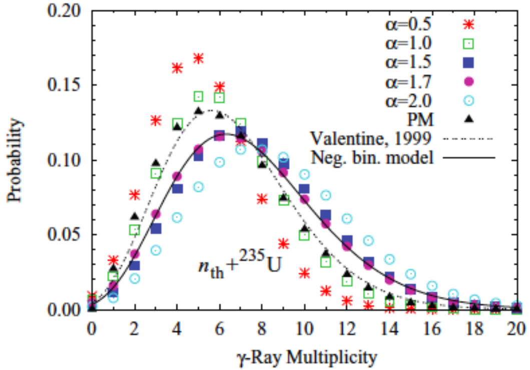
Sensitivity to the initial angular momentum

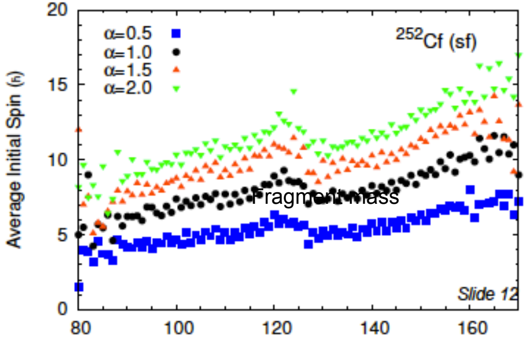


$$P(J) \propto (2J+1)\exp\left(-J(J+1)/(2B^2)\right)$$

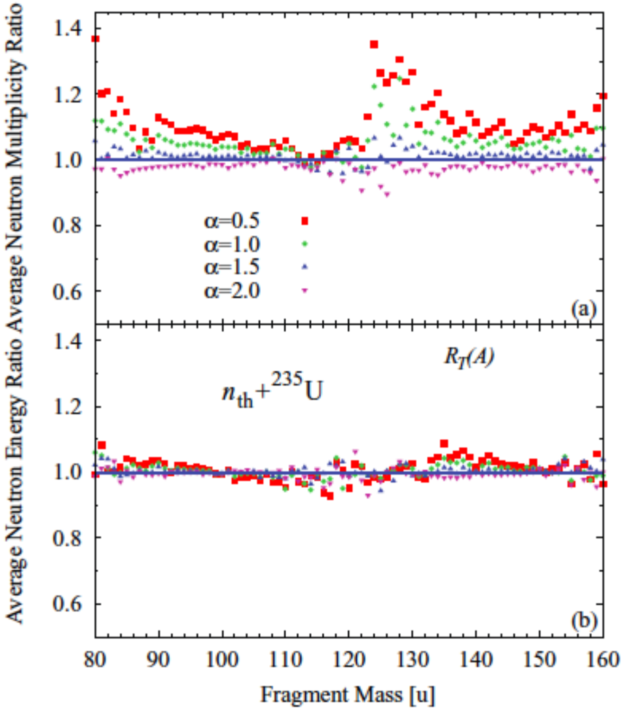
$$B^2 = \frac{\mathcal{I}T}{\hbar^2} \qquad \mathcal{I} = \alpha\,\mathcal{I}^0_{rig}(Z,A,\beta)$$

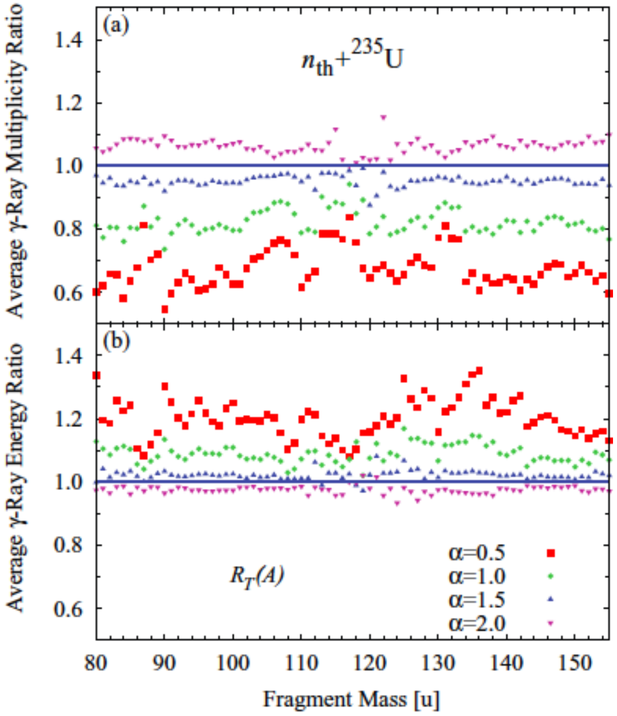
Experimental evidence*: J_{rms}=5-8 for LF and 7-10 for HF



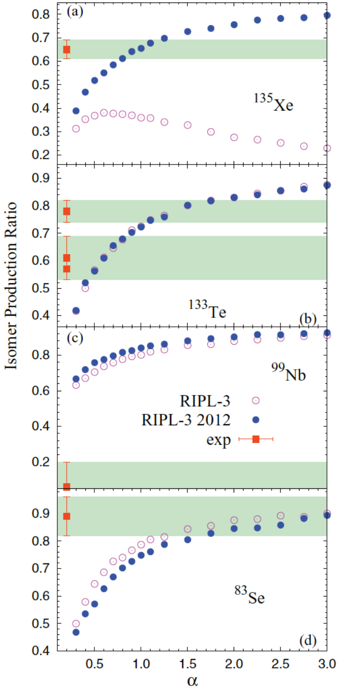


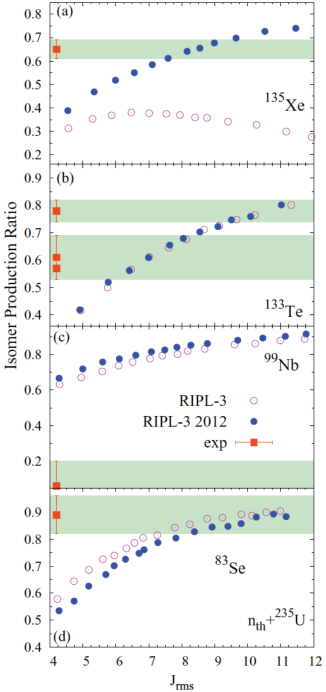
Sensitivity to the initial angular momentum (cont)



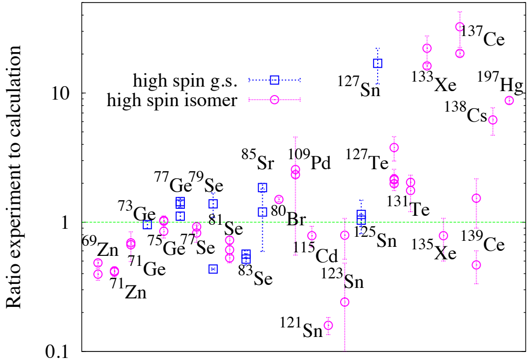


Isomeric ratios and the angular momentum





thermal neutron capture on stable nuclei: better handle on initial spin and excitation energy



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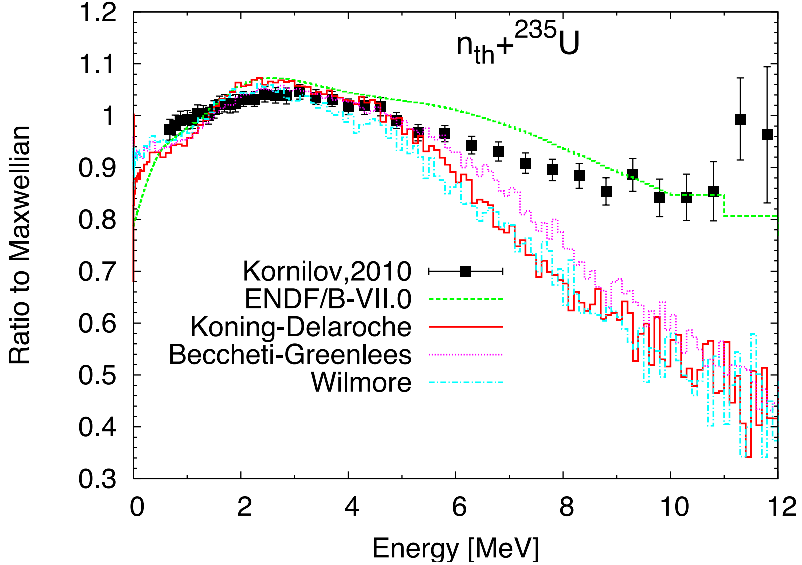
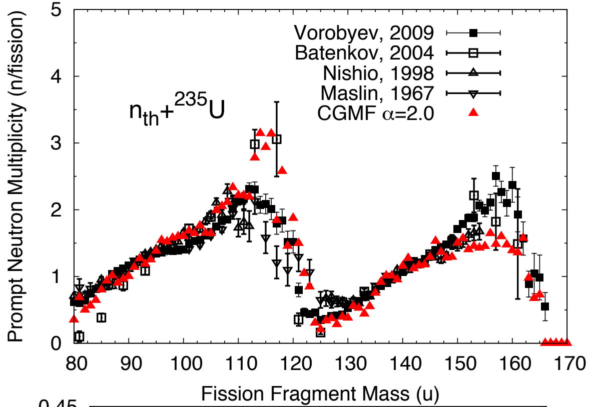
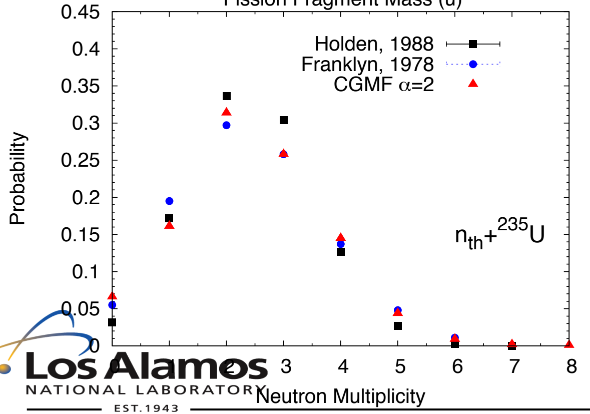
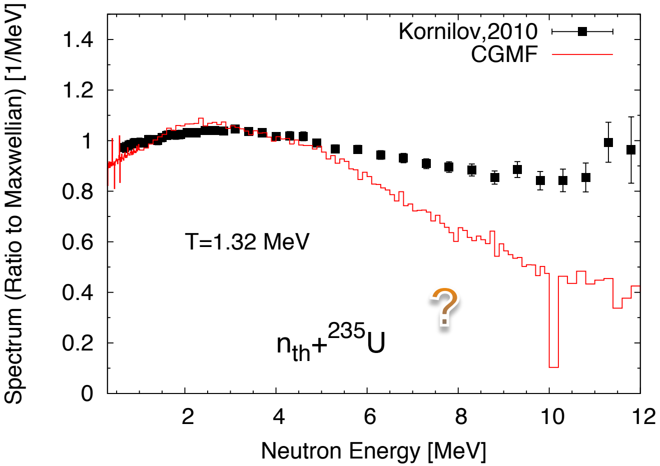
Sensitivity to the optical potential



Selected results for n+^{235}U – neutron observables





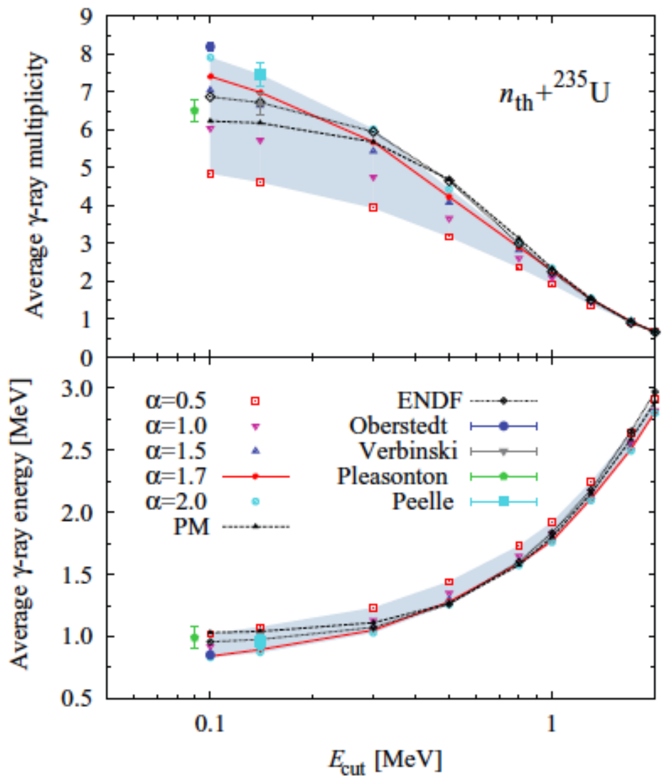


α=2

α	ν
1.0	2.598
1.2	2.557
1.3	2.539
1.4	2.524
1.5	2.507
1.7	1.462
2.0	2.435
3.0	2.326
4.0	2.254

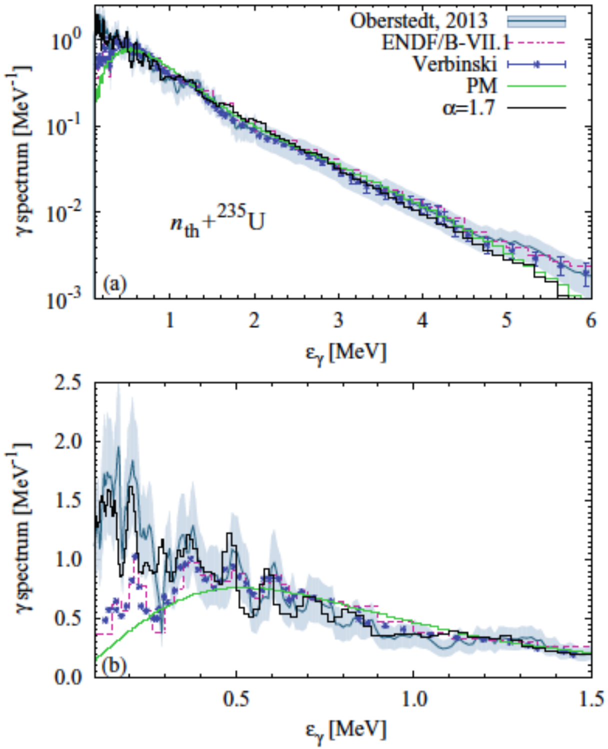
Becker et. al., Phys Rev C **87** (2013) 014617

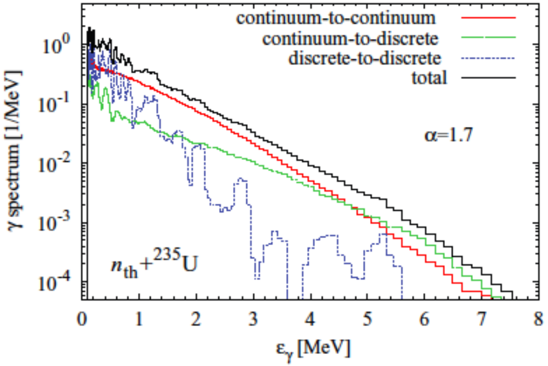
Cutoff γ energy

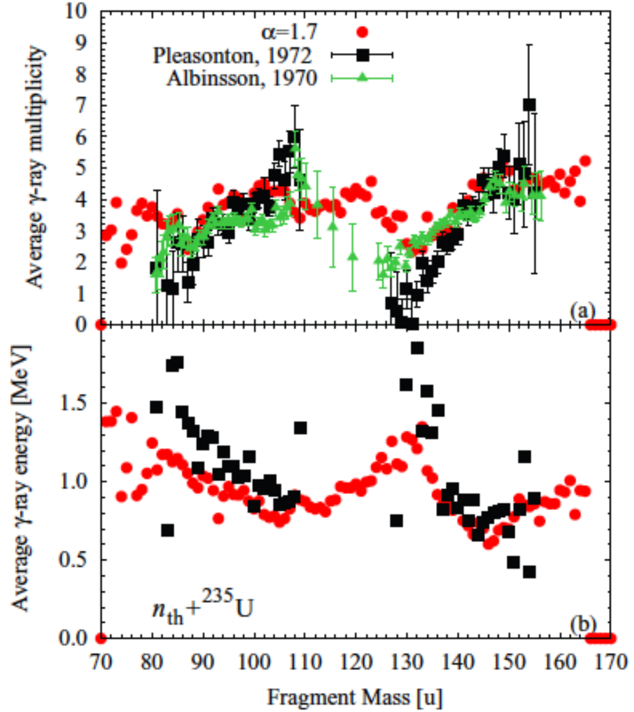


E_{ct} (MeV)	α					PM	Experiment
	0.5	1.0	1.5	1.7	2.0		
^{235}U(n_{th}, f)							
0.1	4.85	6.04	7.04	7.41	7.91	6.23	8.19±0.11 [14]
							6.51 ± 0.31 [11][a]
0.14	4.62	5.73	6.65	6.99	7.46	6.18	7.45 ± 0.32 [10]
							6.69 ± 0.30 [12]
							7.78[b]
0.3	3.94	4.76	5.43	5.68	6.02	5.68	6.11[b]
1.0	1.93	2.10	2.24	2.29	2.35	2.34	2.33[b]
2.0	0.69	0.67	0.66	0.66	0.66	0.67	0.69[b]
^{239}Pu(n_{th}, f)							
0.1	5.57	6.95	7.48	7.87	8.39	7.08	7.38[c]
0.14	5.25	6.52	7.05	7.39	7.88	7.01	7.23 ± 0.30 [12]
0.3	4.40	5.34	5.72	6.38	6.33	6.44	5.95[c]
1.0	2.15	2.36	2.39	2.56	2.51	2.79	2.17[c]
2.0	0.76	0.75	0.74	0.74	0.74	1.06	0.72[c]
^{252}Cf(sf)							
0.1	5.52	6.74	8.04	8.15	8.68	8.02	8.30 ± 0.08 [13]
0.14	5.23	6.34	7.51	7.64	8.12	7.89	7.8 ± 0.3 [12]
							8.01[d]
0.3	4.23	5.02	5.86	5.95	6.29	6.83	6.45[d]
1.0	1.99	2.14	2.31	2.33	2.40	2.22	1.90[d]
2.0	0.73	0.73	0.74	0.74	0.74	0.77	0.67[d]

n_{th}+^{235}U: gamma observables

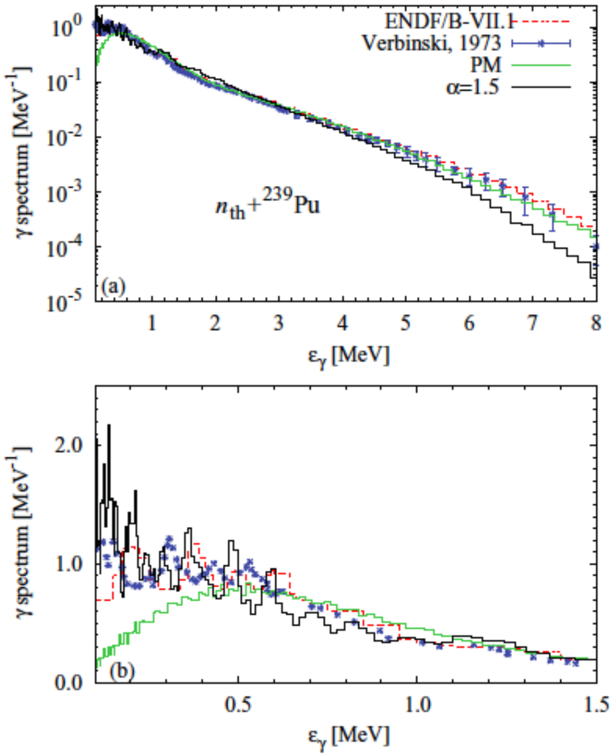


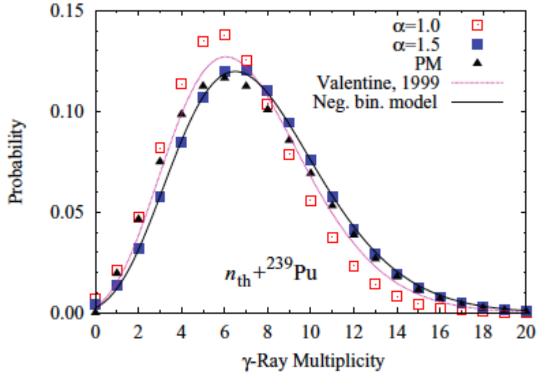




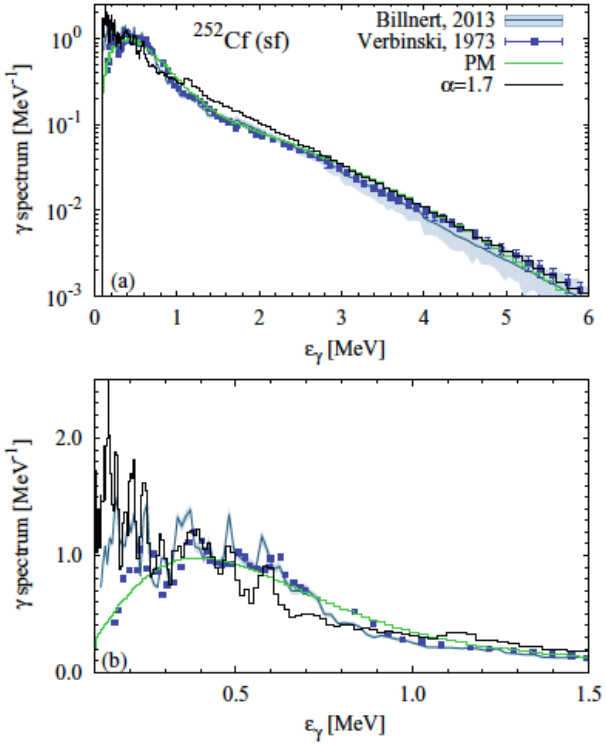
Data from M. Jandel et. al.

n_{th}+^{239}Pu

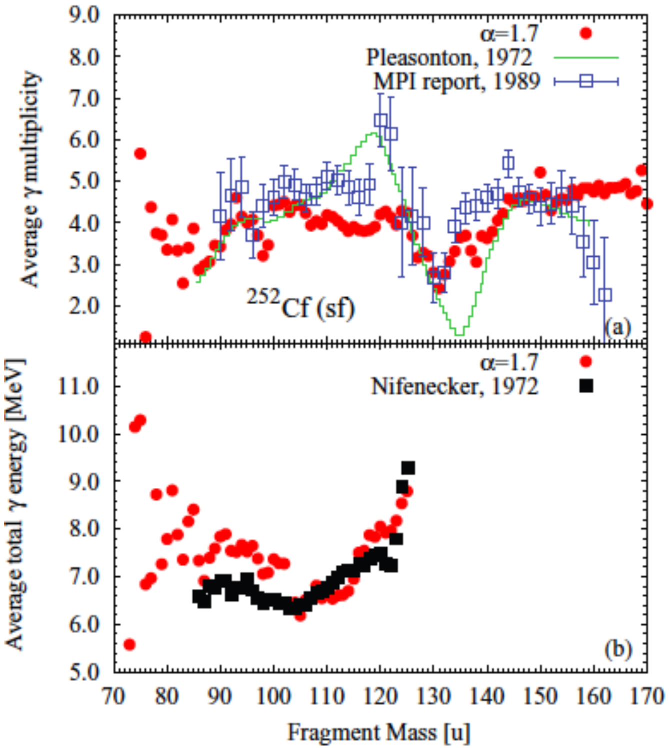

ENDF/B-VII.1
Verbinski, 1973
PM
α=1.5
γ spectrum [MeV-1]
n th+239Pu
(a)
εγ [MeV]
(b)
εγ [MeV]


α=1.0
α=1.5
PM
Valentine, 1999
Neg. bin. model
Probability
n th+239Pu
γ-Ray Multiplicity

^{252}Cf (sf)

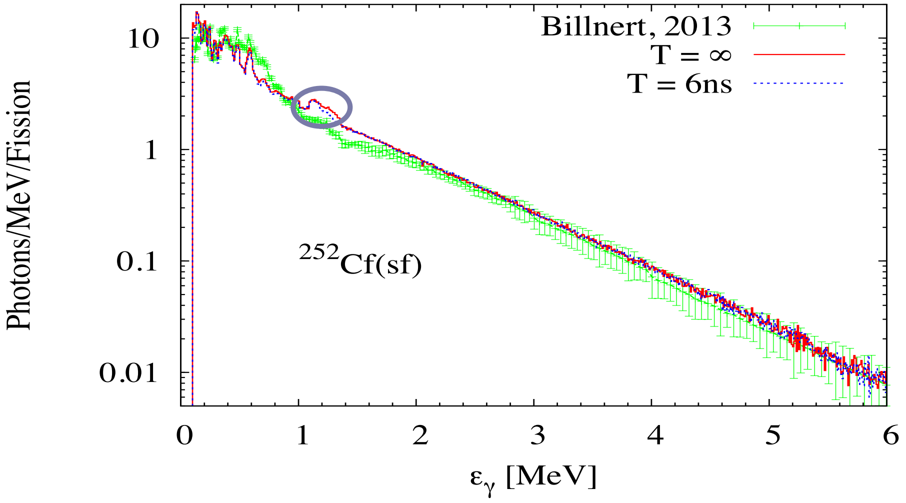


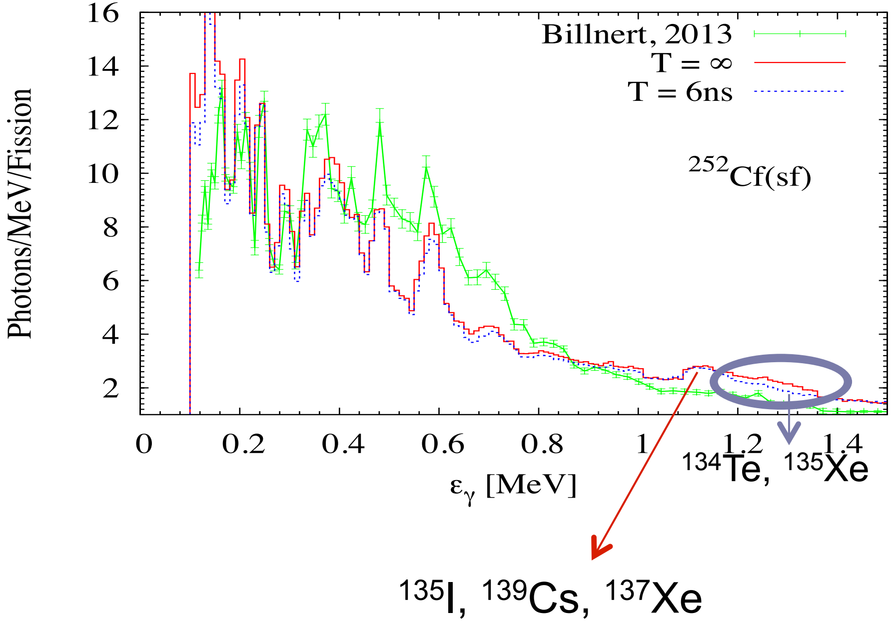
^{252}Cf (sf)
Billnert, 2013
Verbinski, 1973
PM
α=1.7
γ spectrum [MeV^{-1}]
$ε_γ$ [MeV]
(a)
(b)



α=1.7
Pleasonton, 1972
MPI report, 1989
Average γ multiplicity
^{252}Cf (sf)
(a)
α=1.7
Nifenecker, 1972
Average total γ energy [MeV]
(b)
Fragment Mass [u]

Isomeric states in CGMF





Summary and outlook

- De-excitation of fission fragments described within the MCHF formalism
  - Gamma-ray strength
  - OMP for neutron emission
  - Neutron-gamma competition
- MC histories recorded and used to produce average quantities and for post processing
- Good quantitative agreement with experimental data
  - Some discrepancies still exist (neutron/gamma spectra too soft)
- Requires some fine tuning (many parameters)
- Future work: extension other actinides and extend the range of incident enegies