Progress Report on the GEF code*

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JEFF meeting
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OECD Nuclear Energy Agency (NEA), Paris, France

* *The GEF code is available from www.khs-erzhausen.de*

List of topics

- Support of proton-induced fission (New input option)
- Neutron spectrum with variable bin size (User request)
- Gamma spectrum with A conditions (User request)
- Uncertainties, covariances, correlations extended *)
- Emitters and multiplicities of delayed neutrons added (User request)
- Neutron emission between saddle and scission (New effect)
- Empirical masses and consistent level densities in evaporation *)
- Re-adjustment of GEF parameters *)
- Study of energy dependencies *)
- New GEF code (stand-alone and subroutine) *)
- New GEFY tables and GEFY random files *)
- Improved numerical stability for high statistics

*) Topics of the contract

Perturbed-parameter calculations

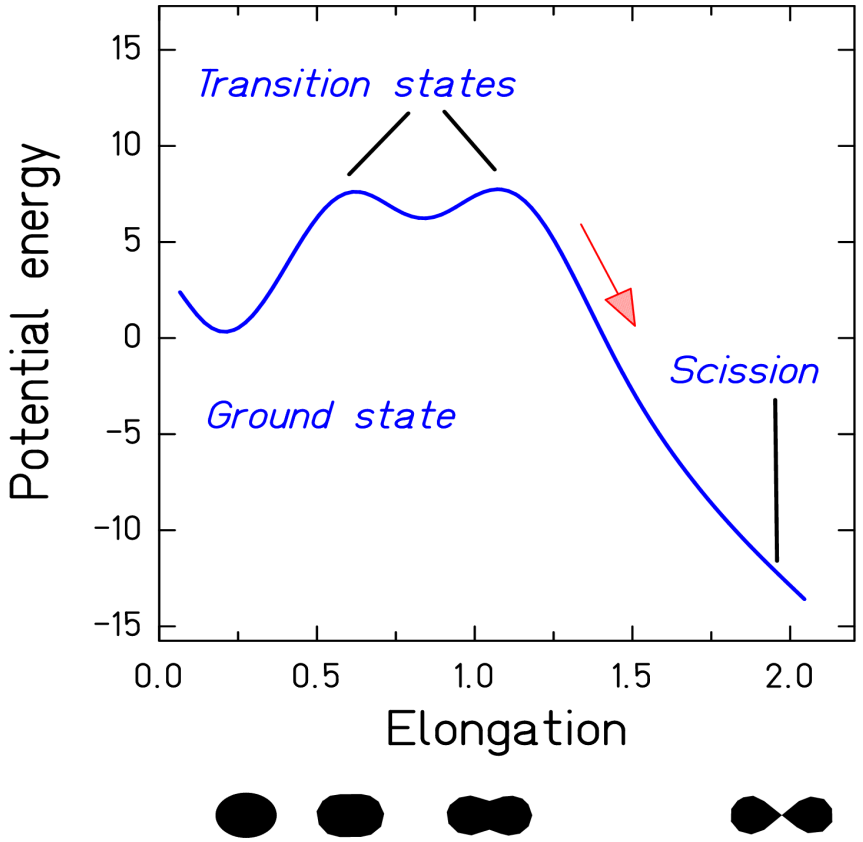
- Uncertainties for
  - Z yields, A yields, nuclide yields (pre- and post)
  - Nuclide yields (cumulative)
  - TKE, TXE
  - <M> and <E> of prompt neutrons
  - <M> and <E> of prompt gammas
  - <M> of delayed neutrons
- Correlations and/or covariances for
  - Z yields, A yields, nuclide yields (pre-and post) for one system and between two systems
- Multivariate distributions for all fission quantities
- Random files of FY in ENDF format

Pre-scission neutrons

Neutrons are emitted between saddle and scission.

Influence of dissipation.

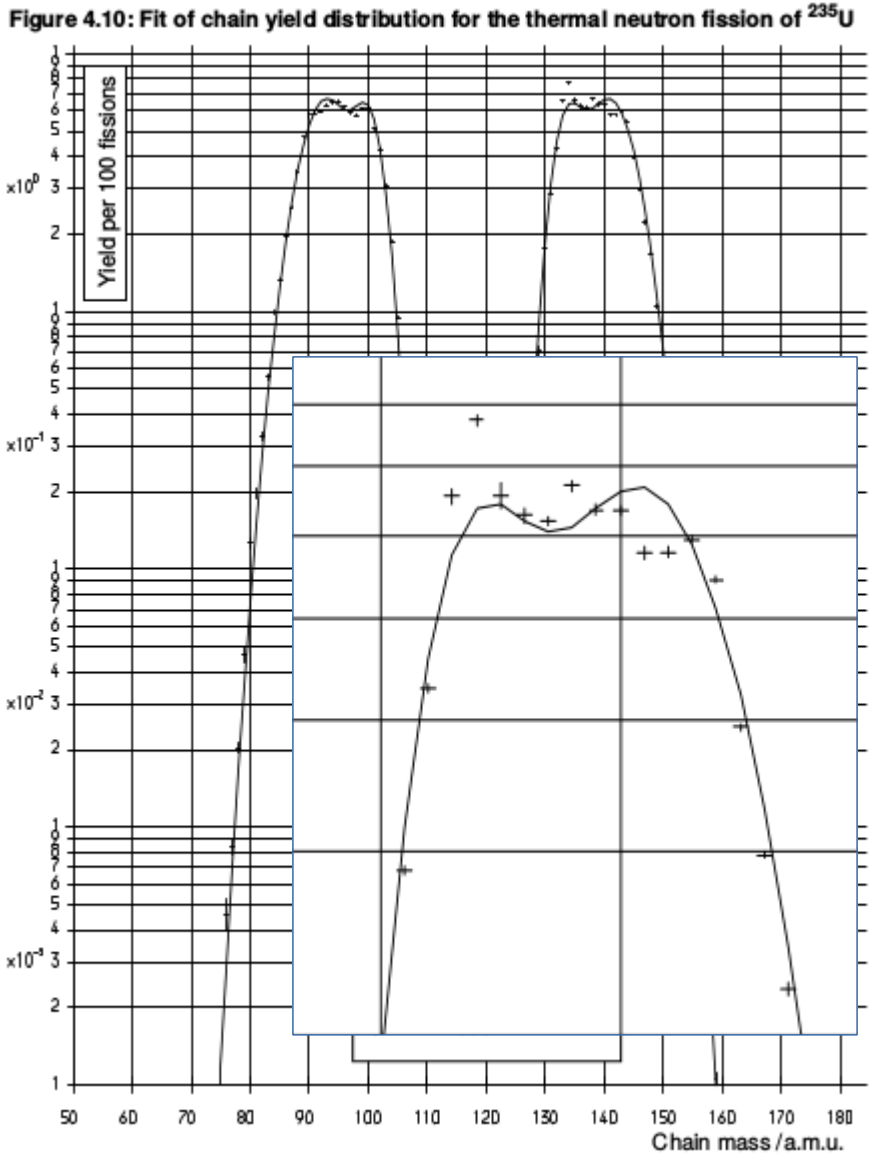
Important effect for E*(scission) > 40 MeV.



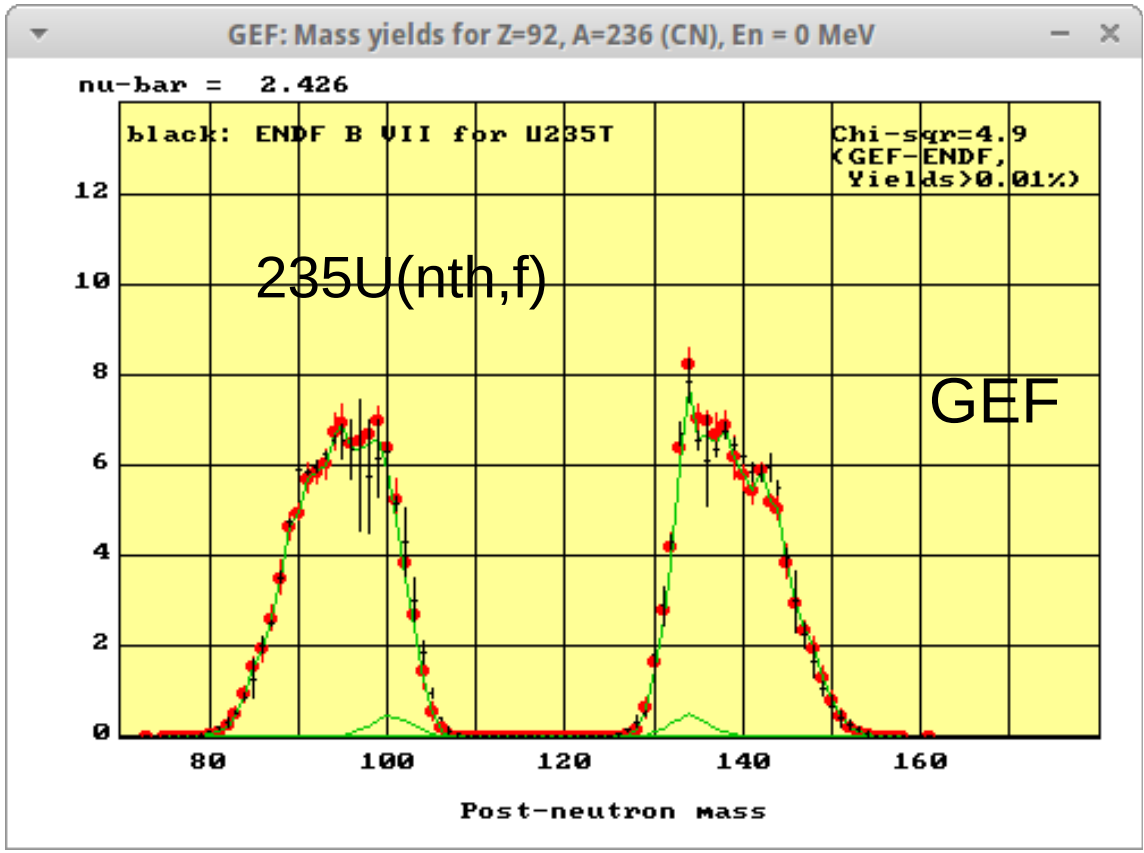
Kinematical properties like pre-fission or scission neutrons!

Less neutrons from fragments.

Structure effects

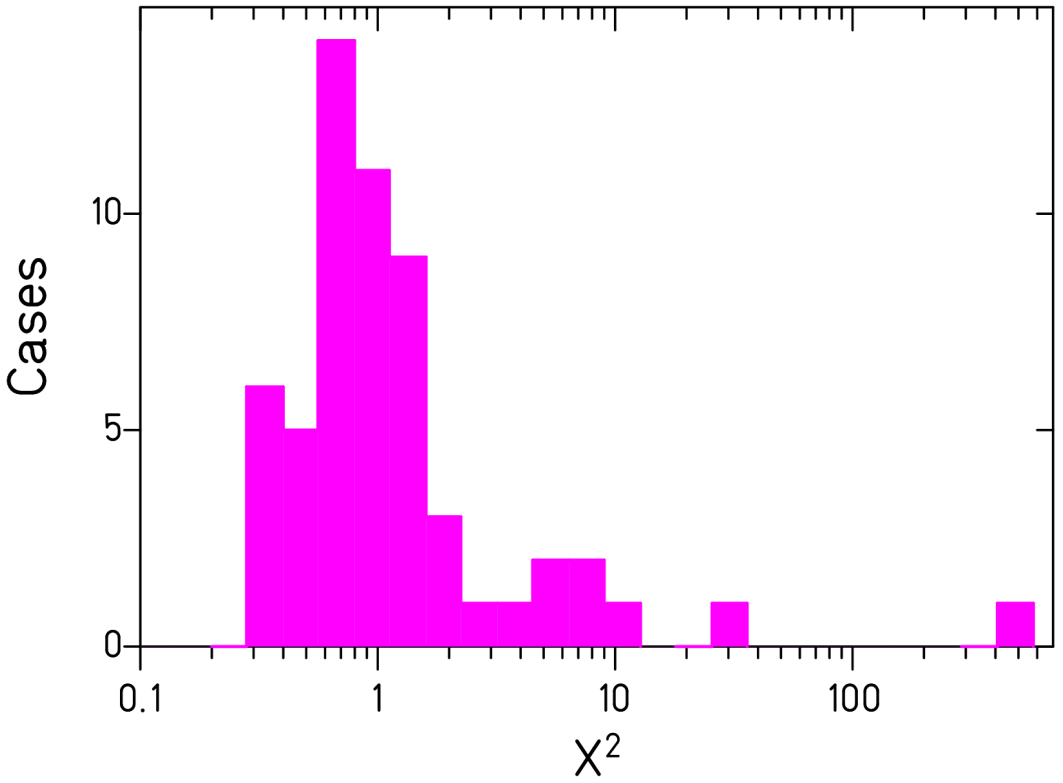


5-Gaussian model (Mills, 1995)



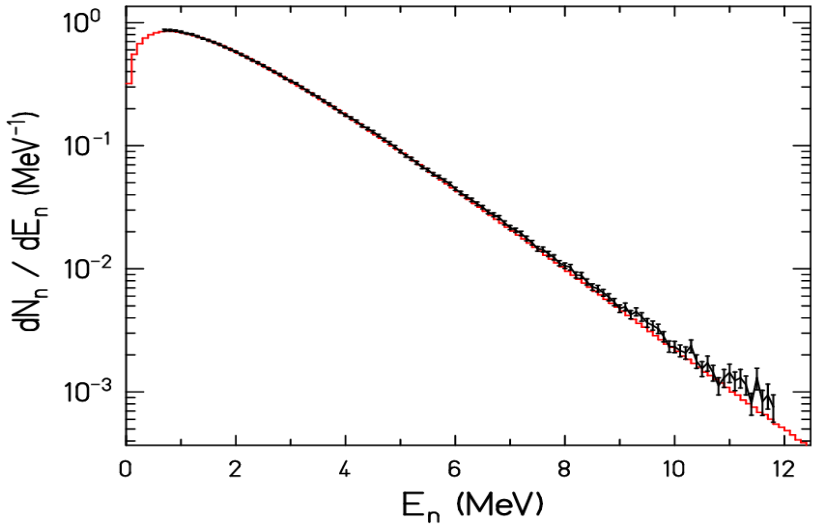
Fine structure in mass distribution is well reproduced by GEF. (New Fit. Strong influence of neutron evaporation. Experimental masses are important!)

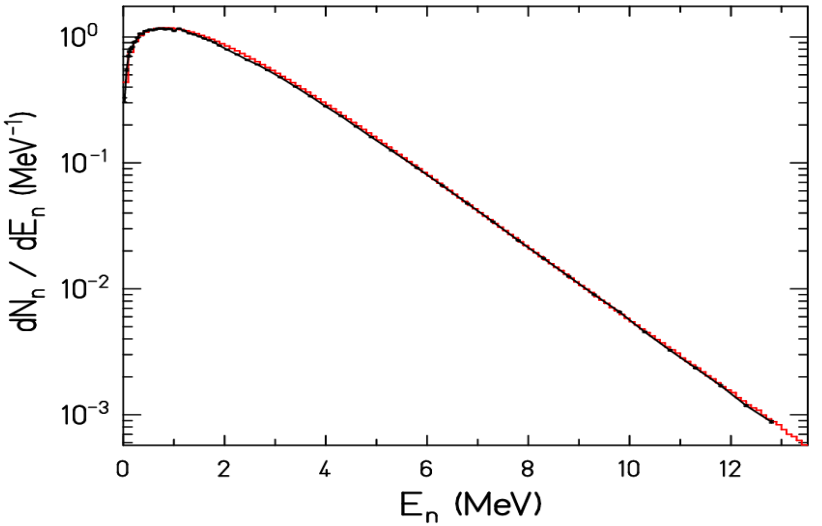
X^2 of mass distributions

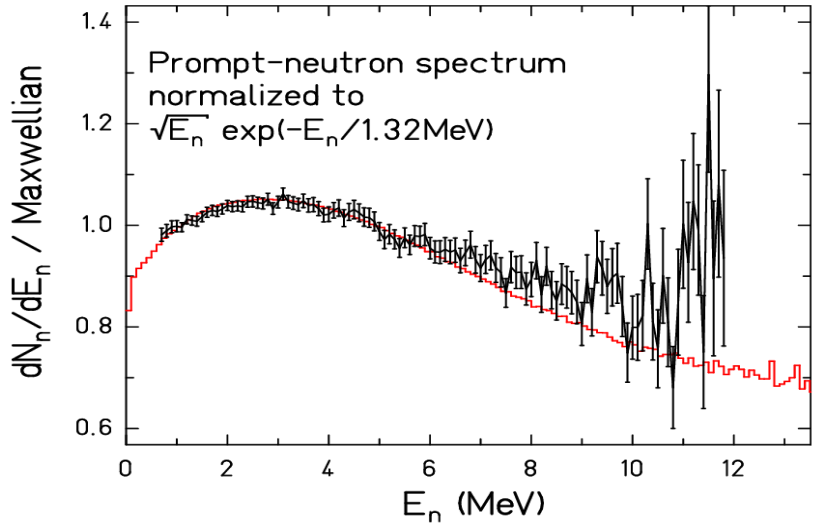


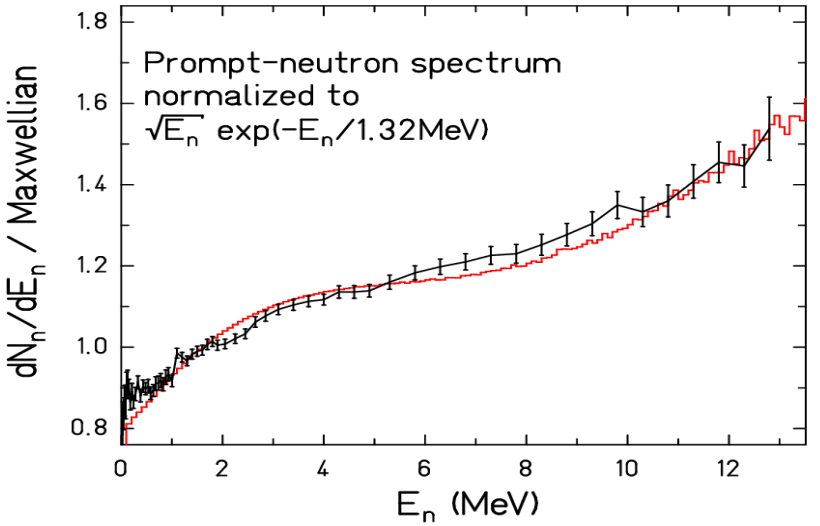
GEF is consistent with most A distributions from ENDF.
Large deviations for 235U(nth,f) due to small exp. errors.

Prompt-neutron spectra



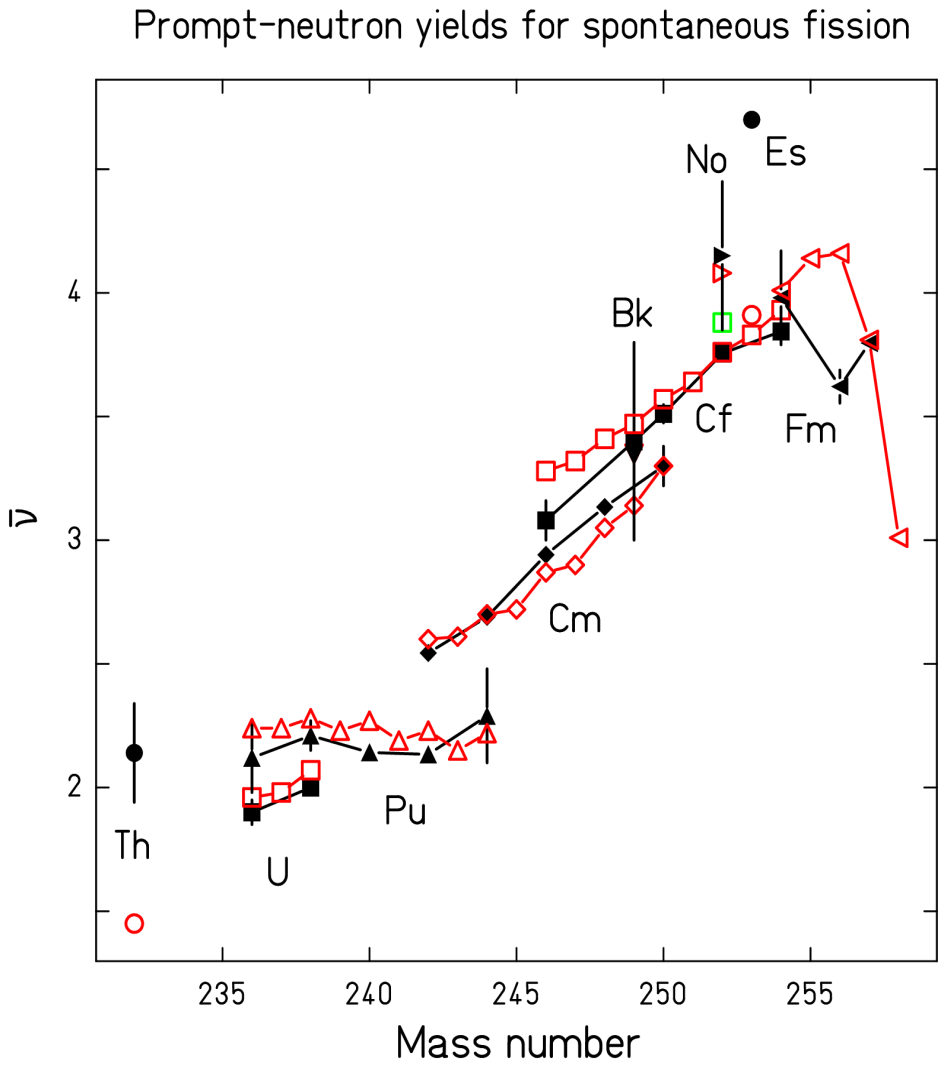


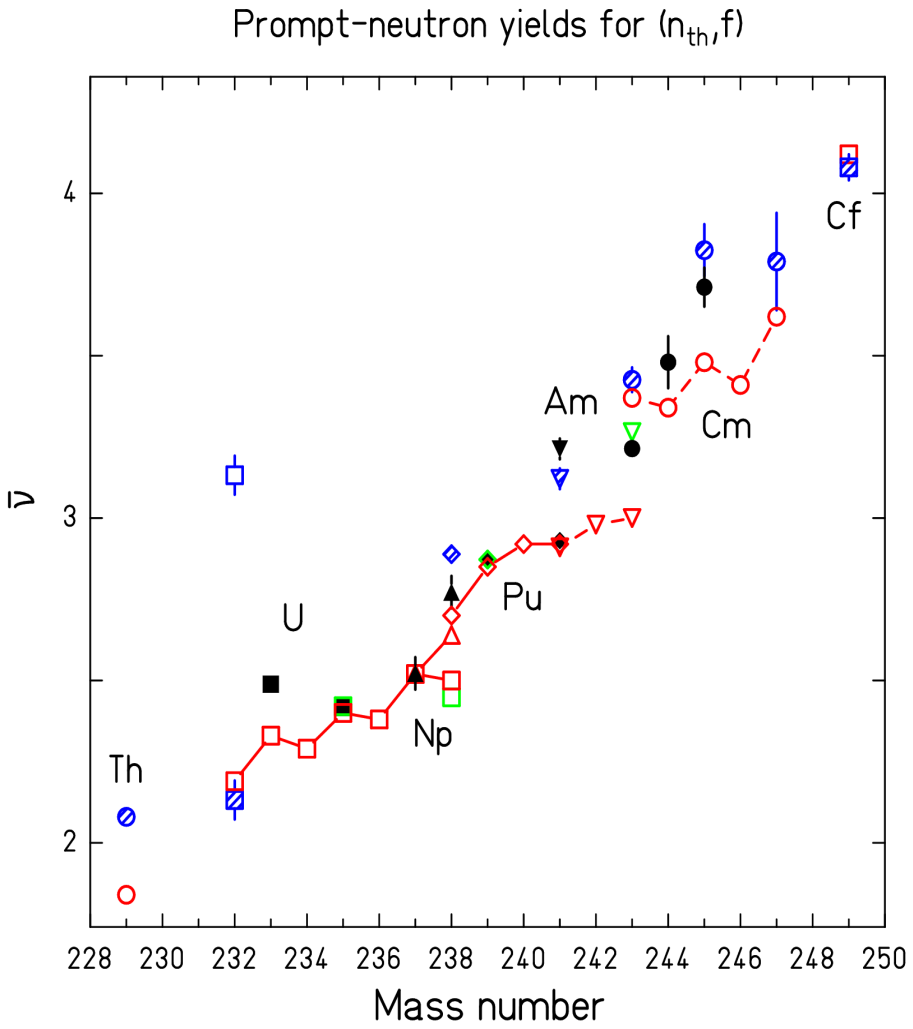




Very good reproduction of PFNS without specific fitting.

Prompt-neutron yields

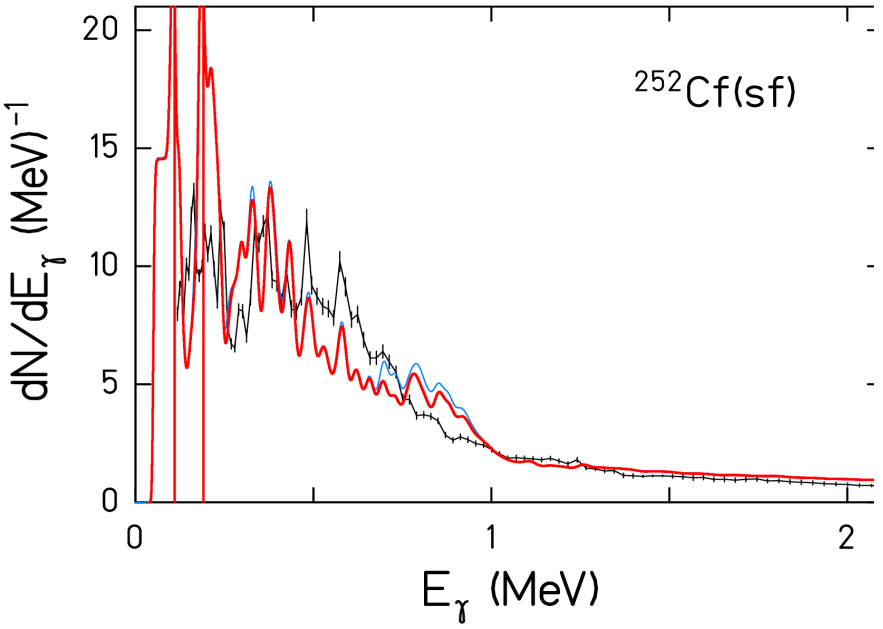




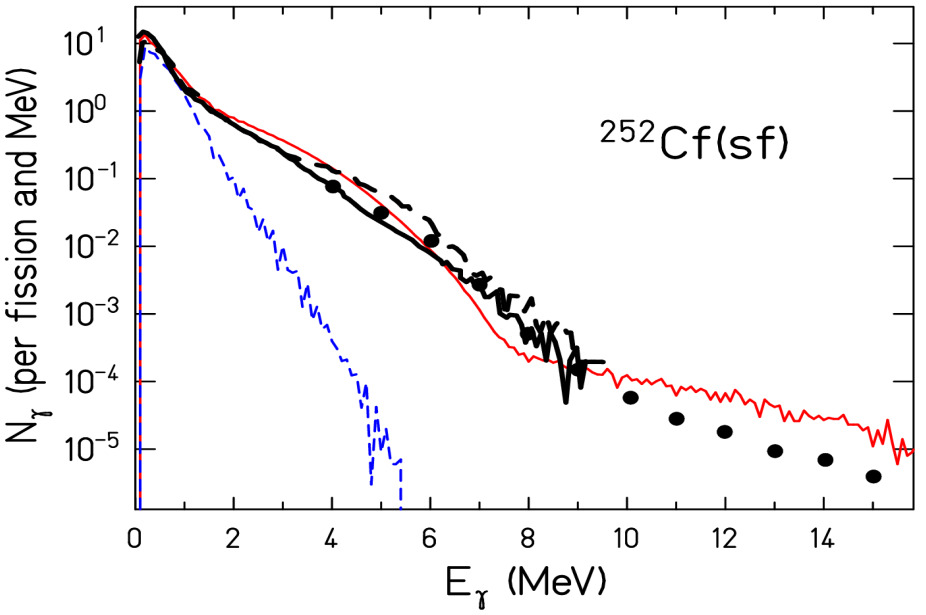
Strong structure effects, inconsistencies in (n,f) data

Prompt-gamma spectrum

Low energies



High energies



Rather good reproduction of the spectrum characteristics

Characteristics of prompt neutrons

		GEF	Exp.	GEF	Exp.	GEF	Exp.
System	En/MeV	<E>/MeV	<E>/MeV	ν_prompt	ν_prompt	ν_delayed	ν_delayed
233U(n,f)	thermal	2.02(1)	2.030(13)	2.36(1)	2.4884(40)	0.77(9) %	0.74(4) %
	5	2.06(1)		3.10(2)		0.79(16) %	
235U(n,f)	thermal	2.00(1)	2.000(10)	2.42(2)	2.4169(36)	1.60(10) %	1.62(8) %
	5	2.06(1)		3.18(2)		1.48(12) %	
238U(n,f)	5	2.01(1)		3.05(2)		3.51(14) %	
237Np(n,f)	thermal	2.02(1)		2.38(6)	2.52(5)	1.47(7) %	1.07(10) %
	5	2.08(1)		3.12(2)		1.05(5) %	
238Np(n,f)	thermal	2.02(1)		2.57(6)	2.77(5)	1.82(15) %	
	5	2.09(1)		3.36(3)		1.40(7) %	
239Pu(n,f)	thermal	2.08(1)	2.073(10)	2.80(4)	2.876(5)	0.68(4) %	0.650(30)%
	5	2.13(1)		3.57(5)		0.61(3) %	
241Pu(n,f)	thermal	2.06(1)		2.88(5)	2.931(6)	1.42(5) %	1.57(15) %
	5	2.12(2)		3.70(4)		1.16(5) %	
241Am(n,f)	thermal	2.87(2)				0.58(6) %	0.44(5) %
252Cf(sf)	------	2.16(2)		3.76(2)	3.759(5)	0.76(12)%	0.86(10)%

GEF uncertainties only from fission. / “exp” from Mills thesis, 1995; WPEG6; Waldo; Capote

Characteristics of prompt gammas

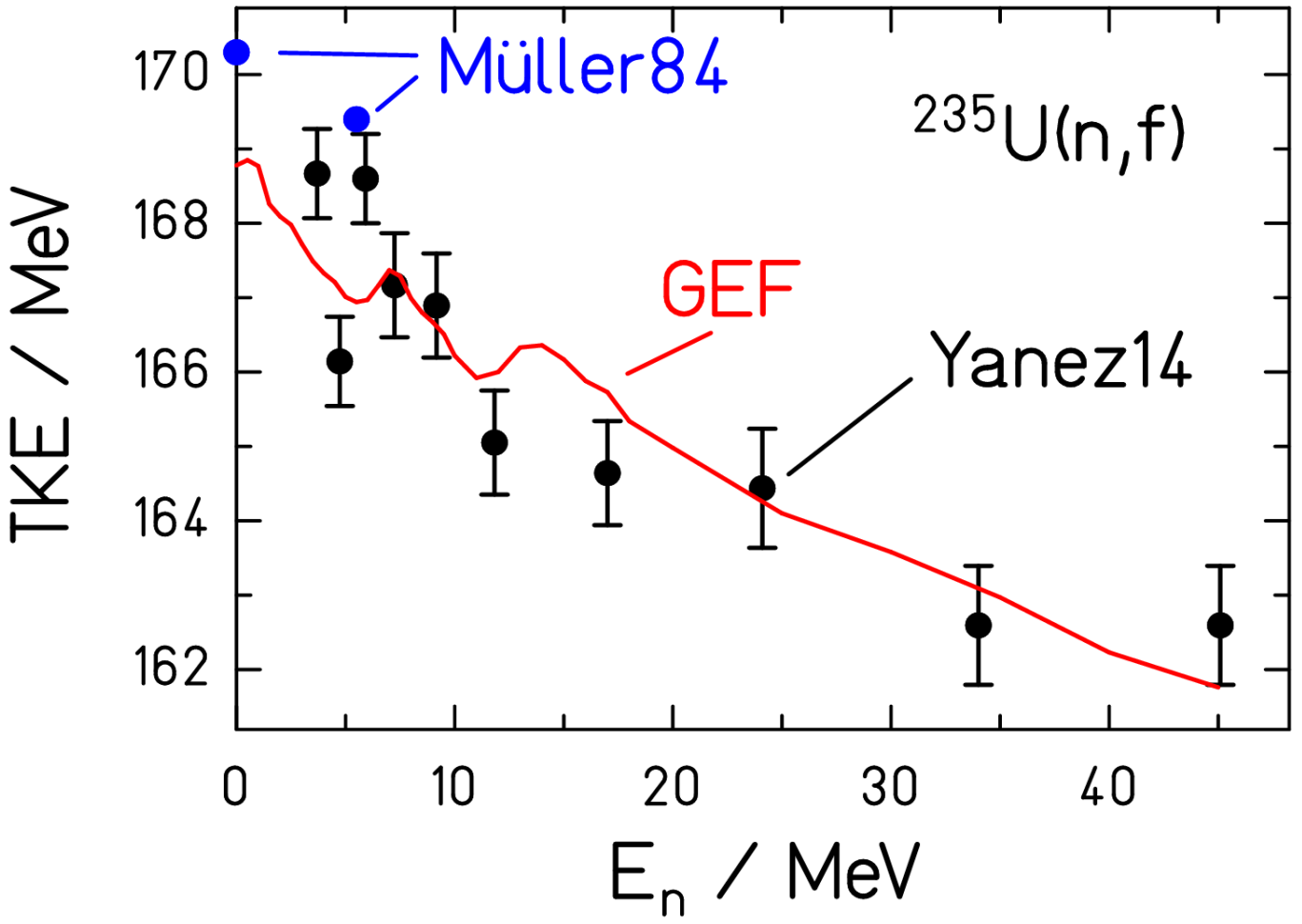
		GEF	Exp.	GEF	Exp.	GEF	Exp.
System	En/MeV	<E>/MeV	<E>/MeV	N_γ	N_γ	E_tot	E_tot
233U(n,f)	thermal	1.00(2)	1.077	6.8(5)	6.76	6.75(40)	7.24
	5	1.00(1)		7.4(4)		7.38(33)	
235U(n,f)	thermal	0.94(1)	1.025	6.9(3)	6.35	6.44(20)	6.48
	5	0.94(1)		7.5(4)		7.03(27)	
238U(n,f)	5	0.87(2)		7.1(4)		6.21(27)	
237Np(n,f)	thermal	0.94(2)		6.8(5)		6.42(33)	
	5	0.94(2)		7.3(6)		6.89(38)	
238Np(n,f)	thermal	0.92(3)		6.8(6)		6.27(35)	
	5	0.92(2)		7.4(5)		6.78(31)	
239Pu(n,f)	thermal	0.94(1)	1.052	6.9(3)	7.1	6.54(18)	7.4
	5	0.94(1)		7.5(4)		7.09(26)	
241Pu(n,f)	thermal	0.90(2)		7.0(4)		6.23(27)	
	5	0.90(2)		7.6(6)		6.81(38)	
252Cf(sf)	------	0.85(2)		7.2(3)		6.14(14)	

GEF uncertainties consider only the fission description. / Exp from Jandel et al., 2013/14

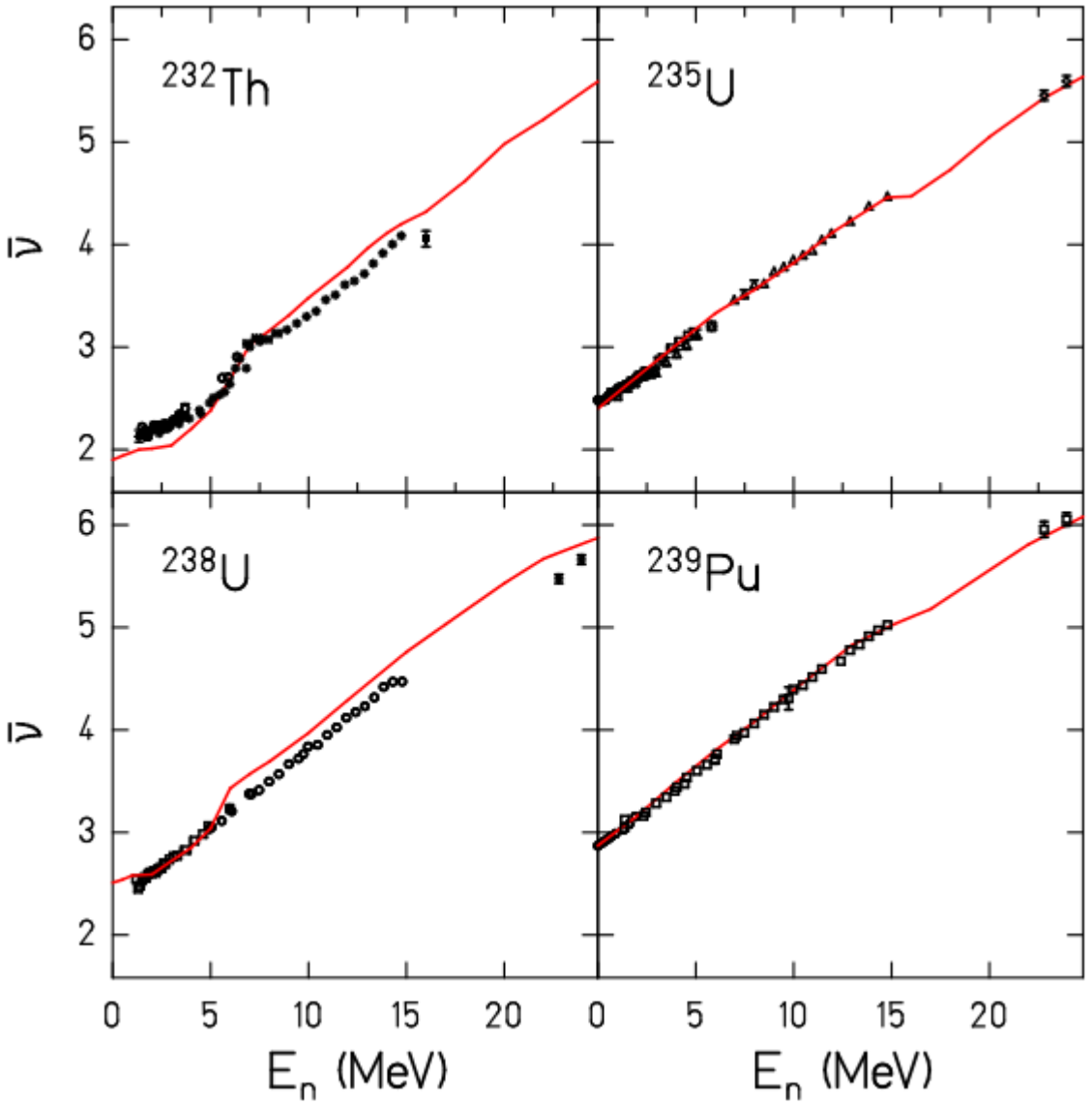
List of delayed neutron emitters

Pn[%]	Z	A	decay
(Pn is the average number of delayed neutrons from the listed decay.)			
6.4e-07	58	154	ground state - beta_n
6.9e-06	54	146	ground state - beta_n
7.44e-06	58	153	ground state - beta_n
7.74e-06	56	149	ground state - beta_n
0.0001425	55	147	ground state - beta_n
2.5e-06	54	145	ground state - beta_n_m
2.5e-06	54	145	ground state - beta_n
0.0002916	57	150	ground state - beta_n
6.84e-05	56	148	ground state - beta_n
0.0004818202	55	146	ground state - beta_n
0.000108	54	144	ground state - beta_n
0.000125	53	142	ground state - beta_n
0.0009448917	57	149	ground state - beta_n
1.97915e-05	56	147	ground state - beta_n
0.005391371	55	145	ground state - beta_n
...			

Energy dependence of TKE



Energy dependence of prompt neutrons

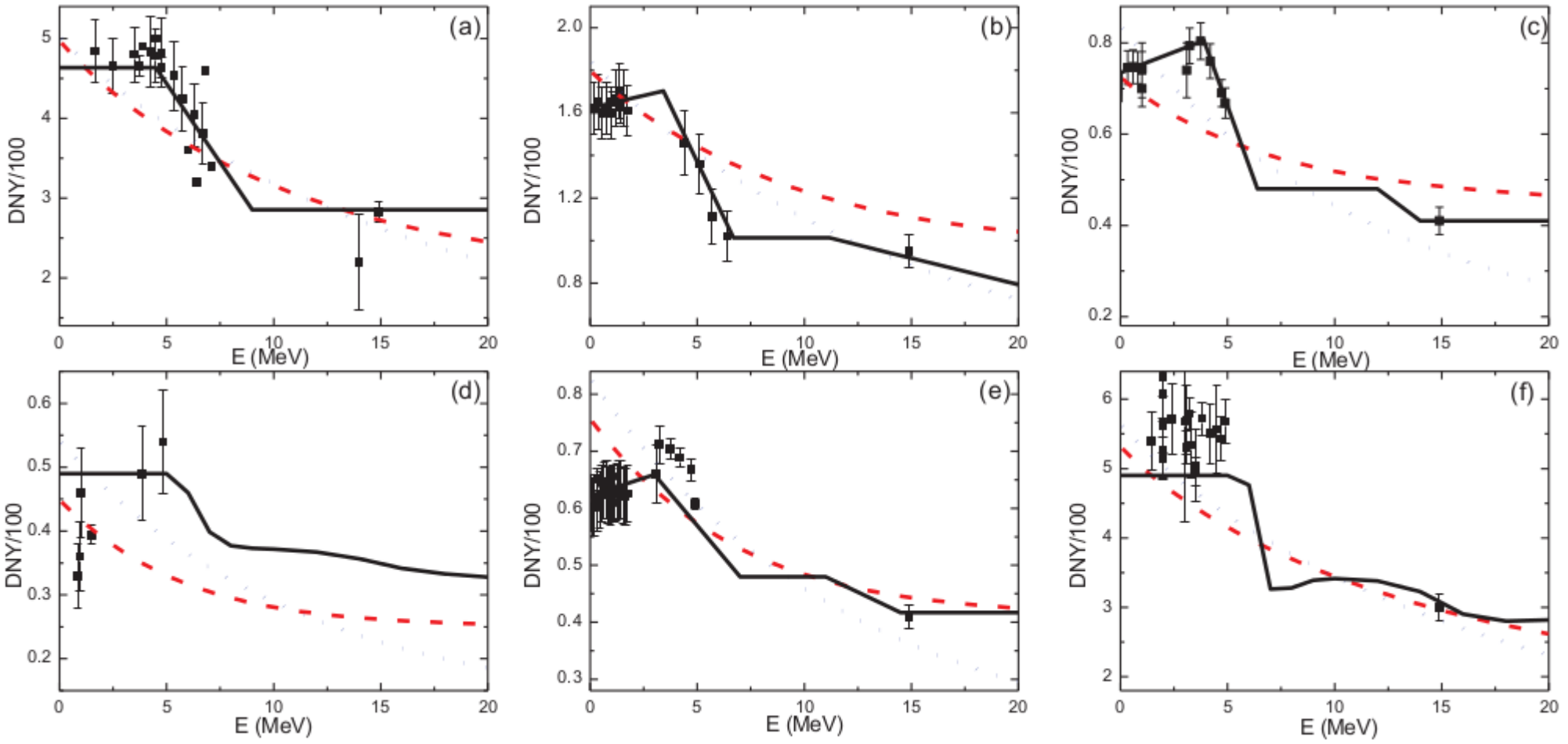


Data / GEF

GEF calculations:
K.-H. Schmidt et al.,
Nucl. Data Sheets
131 (2016) 107

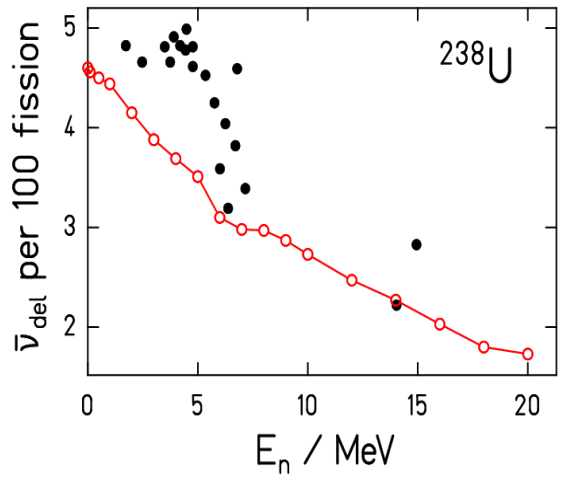
Agreement is rather good.

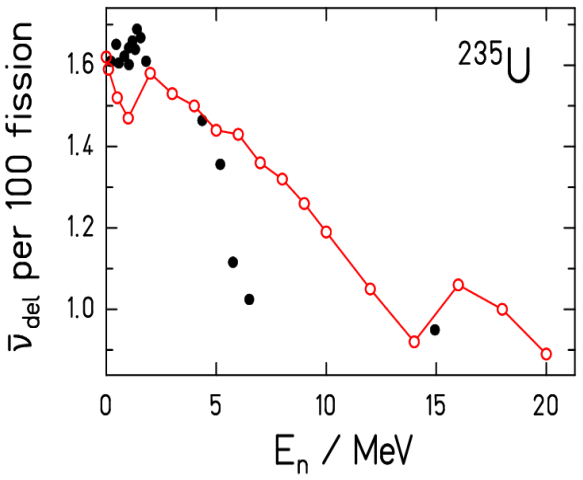
Energy dependence of delayed neutrons

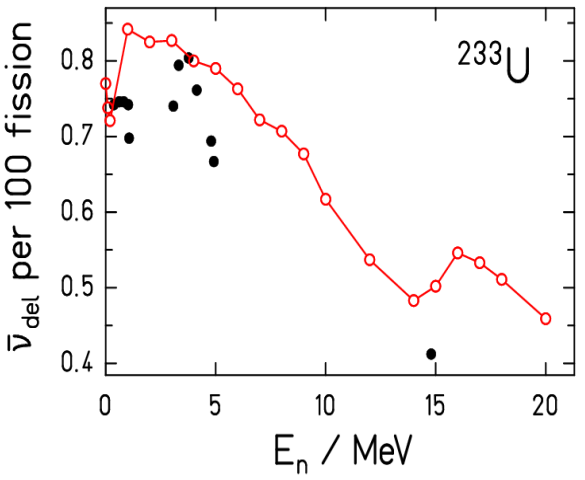


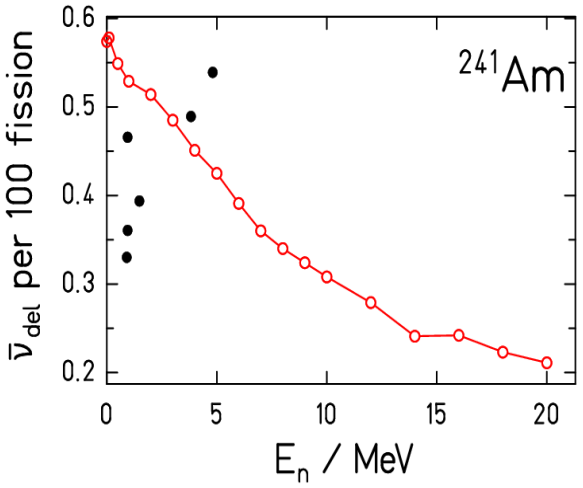
..... Data, ___JENDL 4.0, - - - - Osaka group (emp. model)

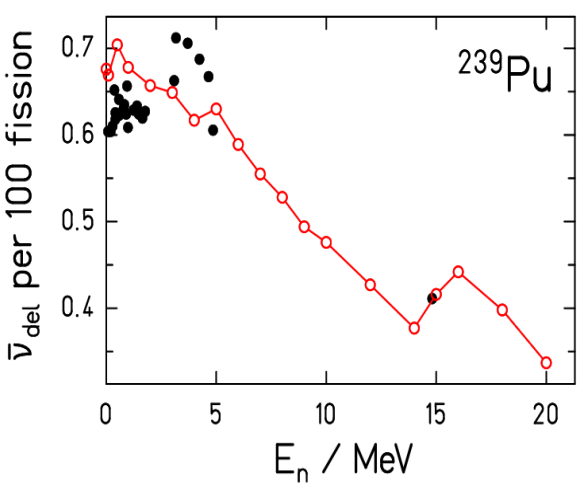
Energy dependence of delayed neutrons

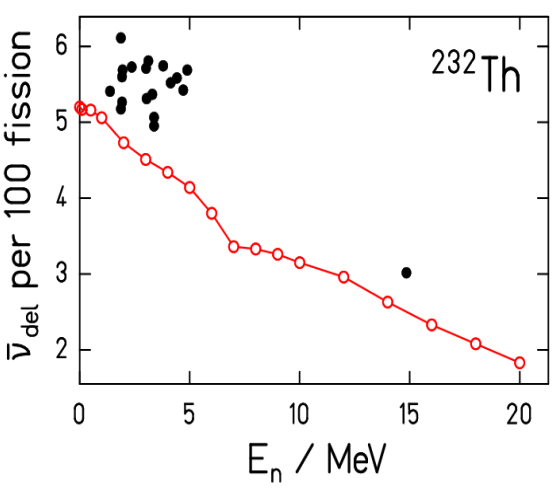








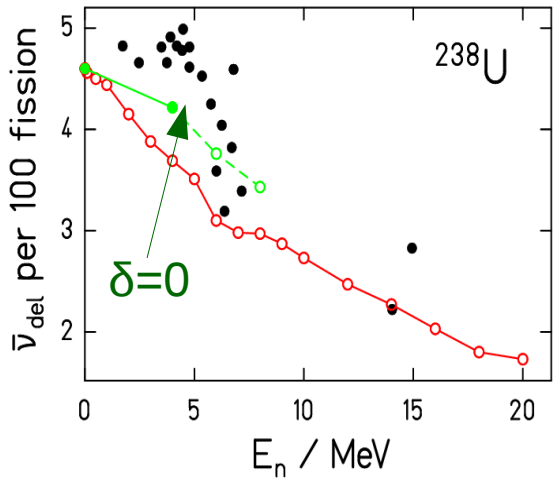


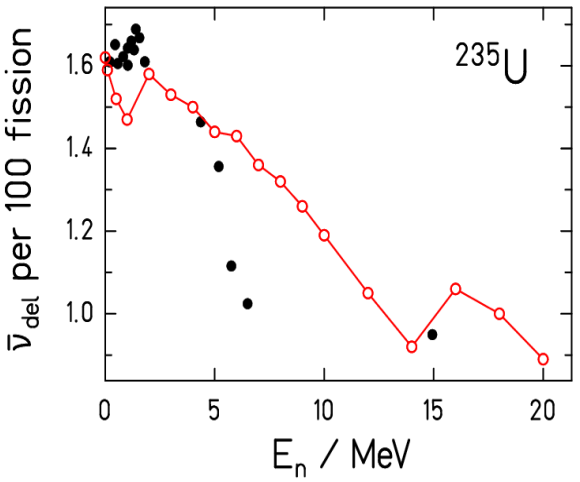


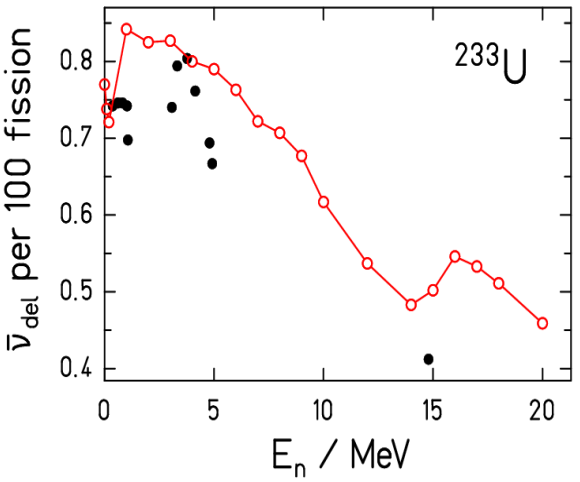
Data / GEF

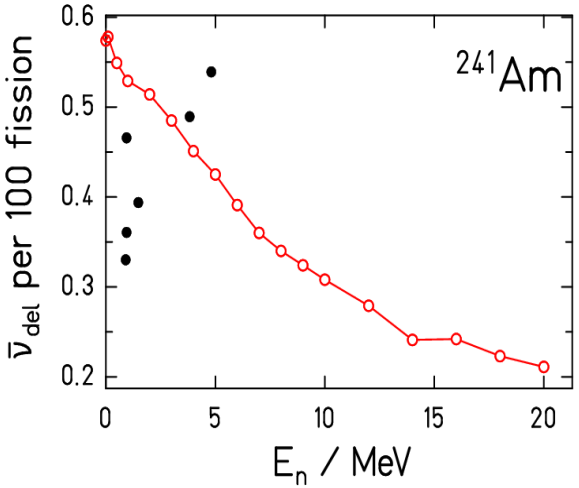
How reliable are the data? Are all structures real?

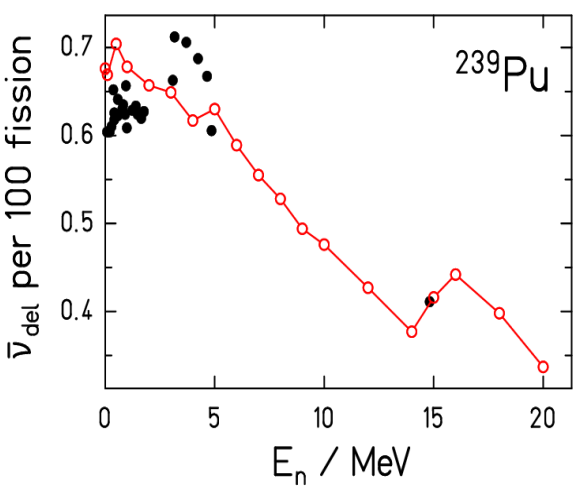
Energy dependence of delayed neutrons

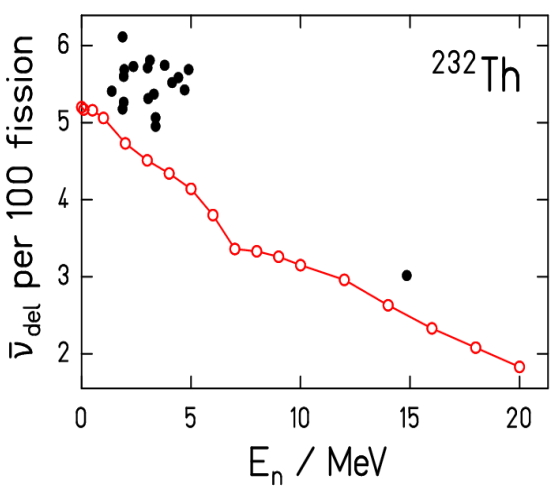












Some influence of even-odd effect in Z, but not enough!

Status

- General fit of GEF to all ENDF FY-data (limited accuracy) cannot be improved much ($X^2 \approx 1$).
  Only 235U(nth,f) mass distributions (from cumulative yields) are much more accurate than the other data.
  But differences between ENDF and JEFF exist (e.g. *A*=129)!
  - Fine structure of 235U(nth,f) well reproduced by GEF.
  - Updated FY of 235U(nth,f) should be exploited together with the precise results of the SOFIA experiment (not yet published) to fine-tune GEF!
- Energy spectra, <E> and multiplicities of PFN and PFG are rather insensitive to GEF parameter values.
- Energy dependences of TKE, nu_bar, delayed neutrons are not to far from experimental data.
  (More accurate data would be helpful.)

Summary

Achievements:

- Extended input option (proton-induced fission).
- Extended output (uncertainties, random files, decay etc.).
- New features (pre-scission neutrons, exp. masses).
- Careful study of 235U(nth,f) (most accurate data).
  - Improved description of fine structure.
  - Open question on the reliability of measured low yields or effects beyond the current GEF description. → Need for accurate data.
- High accuracy for characteristics of prompt neutrons and prompt gammas.

Future work:

- Tests with new JEFF decay data file (e.g. delayed neutrons).
- Comparison with recent data (e.g from SOFIA to be published) → improvements and developments.