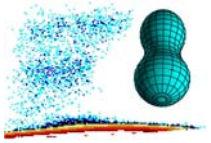


Characteristics of prompt fission γ-ray emission – experimental results and predictions

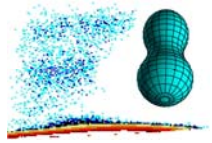
A. Oberstedt

NEMEA-7/CIELO Workshop of the Collaborative International Evaluated Library Organization

IRMM Geel, Belgium

November 5 – 8, 2013

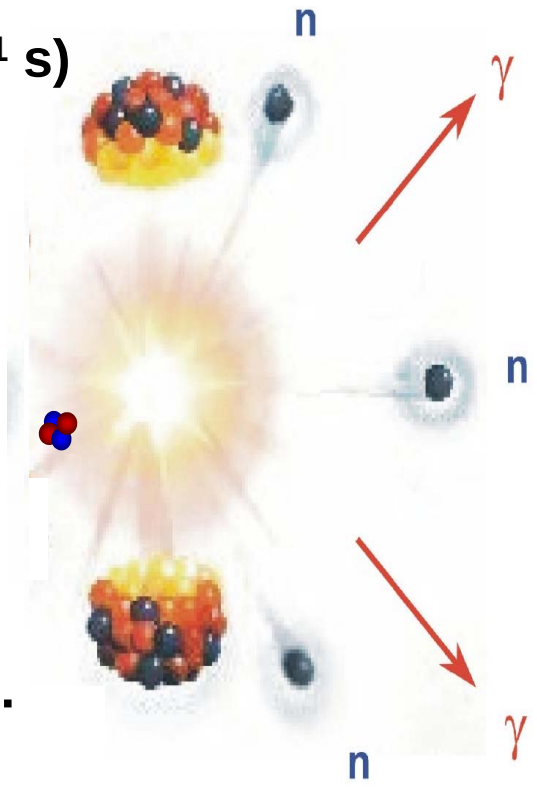
Prompt energy release in fission



prompt neutrons (< 10^{-18} s)

prompt γ-rays (10^{-16} s)

fission fragments (10^{-21} s)

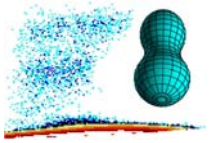


ternary α, t, d, ^{10}Be…

Prompt energy release:

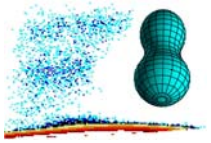
- **kinetic energy of fission fragments**
- **prompt fission neutron emission**
- **prompt fission γ-ray emission**

Outline



- Historical background – the 1970s
- Evaluation of PFGS characteristics
- Renaissance – the 2010s
- New evaluation – systematics
- Fast neutron induced fission
- Predictions for ^{238}U(n, f)
- Conclusions

Historical background
Experiments

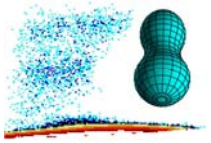


- First comprehensive studies of prompt fission γ-ray spectra (PFGS) in the 1970s on:
  - n_{th} + ^{233}U
  - n_{th} + ^{235}U
  - n_{th} + ^{239}Pu
  - ^{252}Cf (spontaneous)

- Measured PFGS characteristics:
  - $E_{\gamma,tot}$ = average total γ–energy/fission
  - ε_{γ} = average γ–energy/photon
  - $\overline{\nu}_{\gamma}$ = average γ–multiplicity

Historical background

Evaluations



1972: Nifenecker et al. (NPA 189 (1972) 285)

- $E_{\gamma,tot}(\overline{\nu}_n) = 0.75\ \overline{\nu}_n + 2.0$

2001: Valentine (ANE 28 (2001) 191)

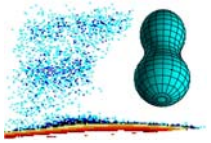
- $E_{\gamma,tot}(\overline{\nu}_n,A,Z) = \varphi(A,Z)\ \overline{\nu}_n + 4.0$ (MeV)
  with
  $\varphi(A,Z) = 2.51(\pm0.01) - 1.13\cdot10^{-5}(\pm7.2\cdot10^{-8})\ Z^2\ A^{1/2}$

- $\varepsilon_\gamma(A,Z) = -1.33(\pm0.05) - 119.6\cdot10^{-5}(\pm2.5)\ Z^{1/3}\ /A$

- $\overline{\nu}_\gamma(\overline{\nu}_n,A,Z) = E_{\gamma,tot}(\overline{\nu}_n,A,Z)\ /\ \varepsilon_\gamma(A,Z)$

Note: A and Z dependencies are purely empirical!

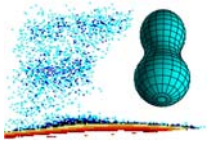
Renaissance
New efforts



- In the 2010s: new measurements and calculations motivated by NEA high priority request lists for
  - n_{th} + ^{235}U and n_{th} + ^{239}Pu
- Investigated reactions:
  - $^{235}U(n_{th}, f)$, $^{239,241}Pu(n_{th}, f)$, $^{252}Cf(sf)$
- Experimental groups:
  - LANL DANCE
  - IRMM/Chalmers/KFKI + others
- Theoretical groups:
  - CEA Cadarache (Serot, Litaize, Regnier)
  - LANL (Talou et al.)
  - K.-H. Schmidt and others

New results - overview

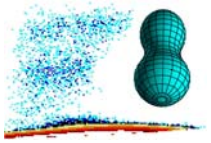
Our work



- Experiments at IRMM and KFKI Budapest:
  - ^{252}Cf(sf) — R. Billnert et al., PRC 87 (2013)
  - ^{235}U(n_{th}, f) — A. Oberstedt et al., PRC 87 (2013)
  - ^{241}Pu(n_{th}, f) — submitted to PRC

- Measured:
  - prompt fission γ-ray spectrum (PFGS)
- Determined:
  - average multiplicity
  - mean energy per photon
  - total photon energy

Comparison of results



General impression for the fissioning systems $^{252}Cf(sf)$, $^{235}U(n_{th}, f)$ and $^{241}Pu(n_{th}, f)$

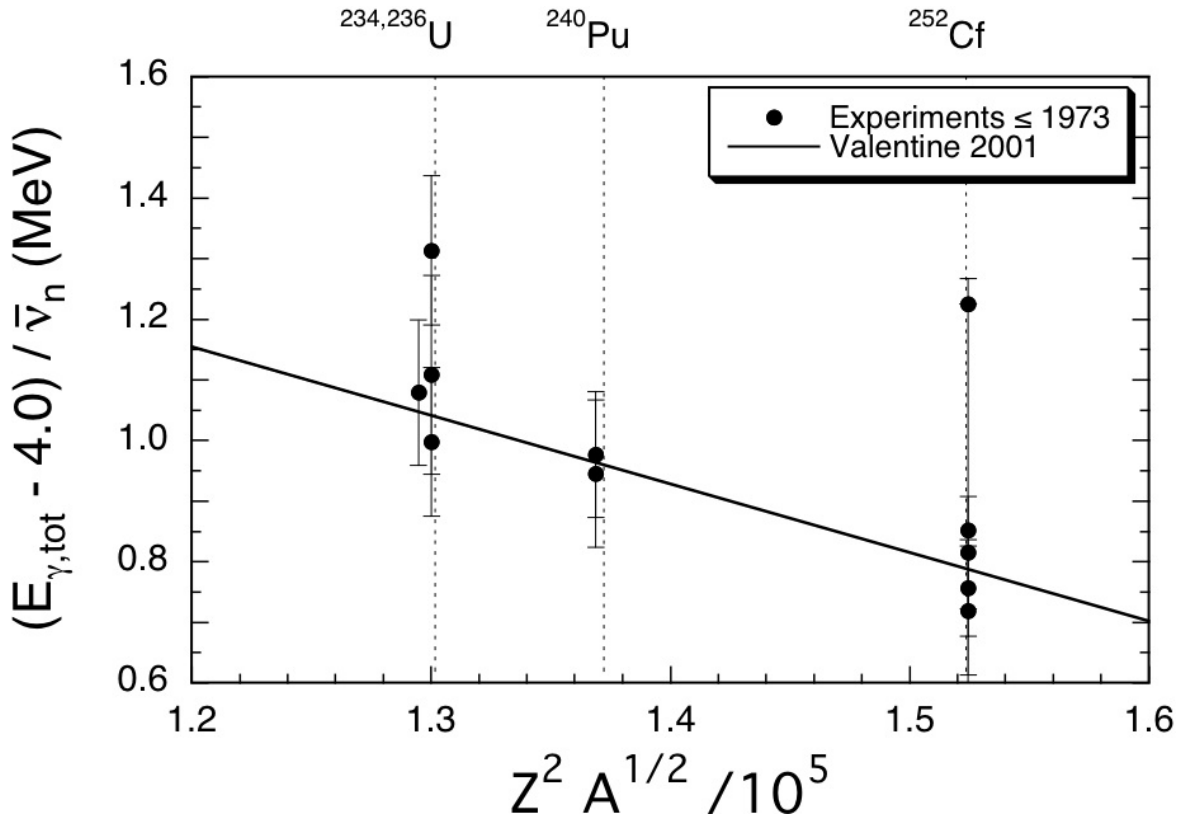
- $E_{\gamma,tot}$ and ε_γ :
  good agreement between our results and those from the early 1970s, while the DANCE values are too high

- ν_γ : our results agree well with the 1970 results, but the DANCE values are too low

- Impact of new results on evaluation according to Valentine?

New evaluation

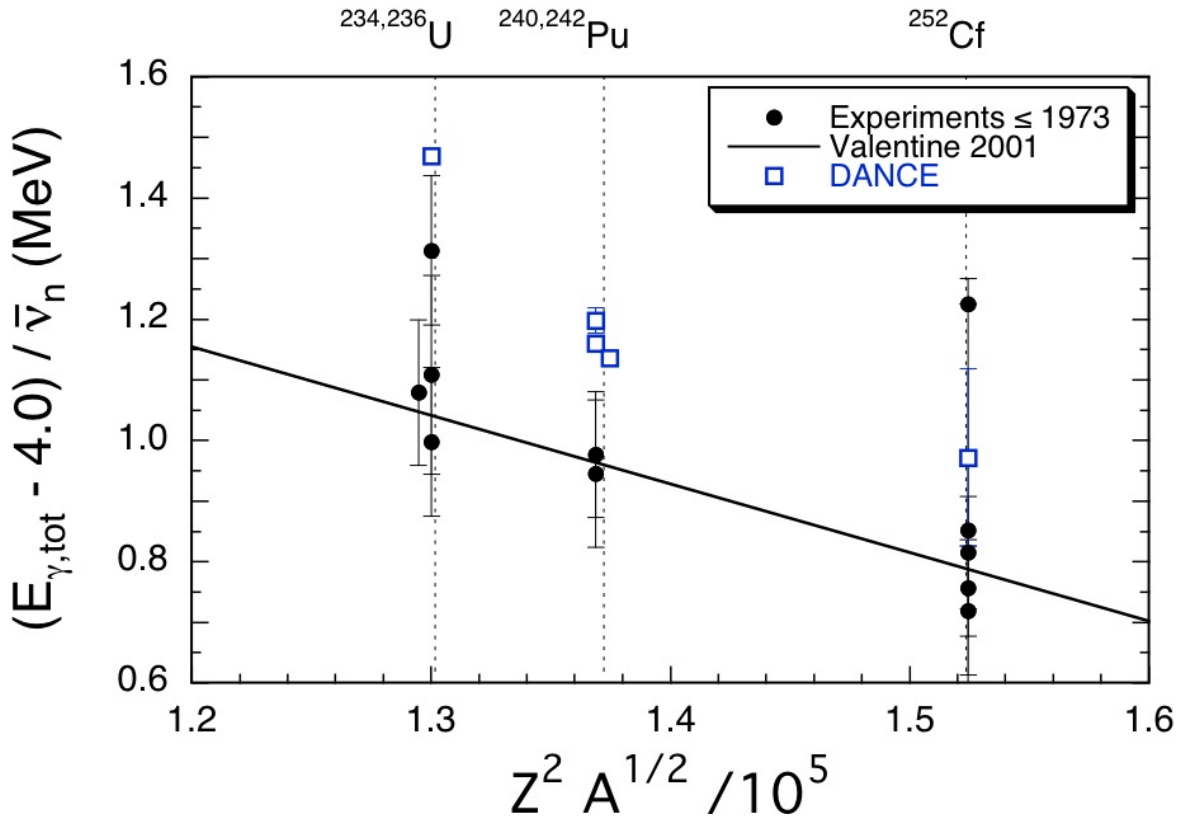
PFGS average total energy per fission



Observe: $\bar{\nu}_n$ taken from experiments.

New evaluation

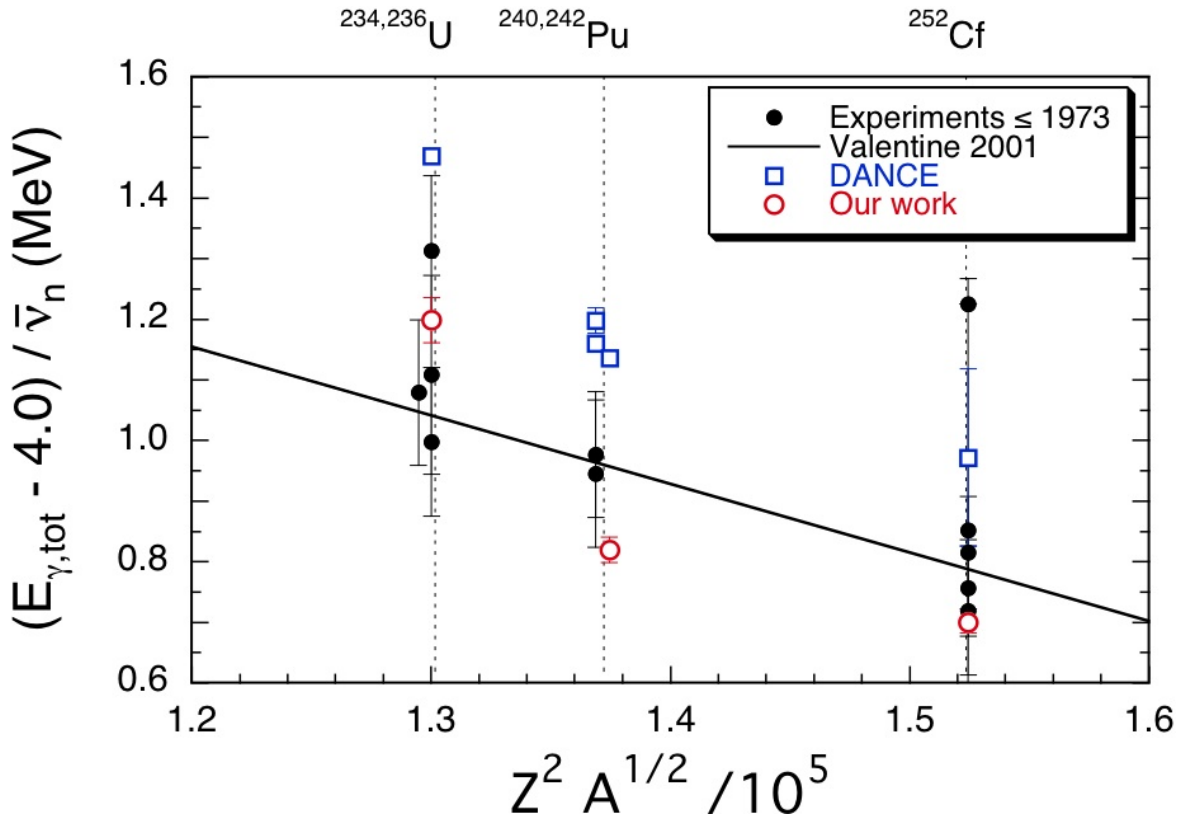
PFGS average total energy per fission



Observe: $\bar{\nu}_n$ taken from experiments.

New evaluation

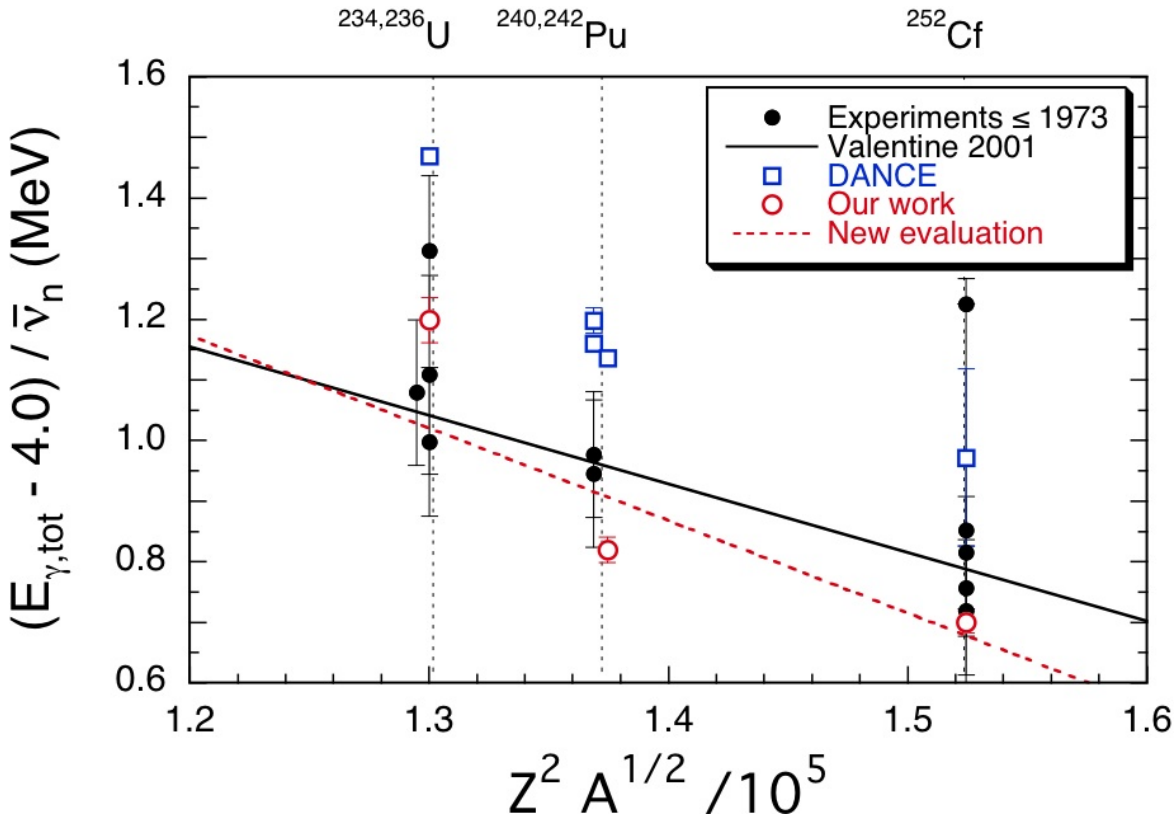
PFGS average total energy per fission



Observe: $\bar{\nu}_n$ taken from experiments.

New evaluation

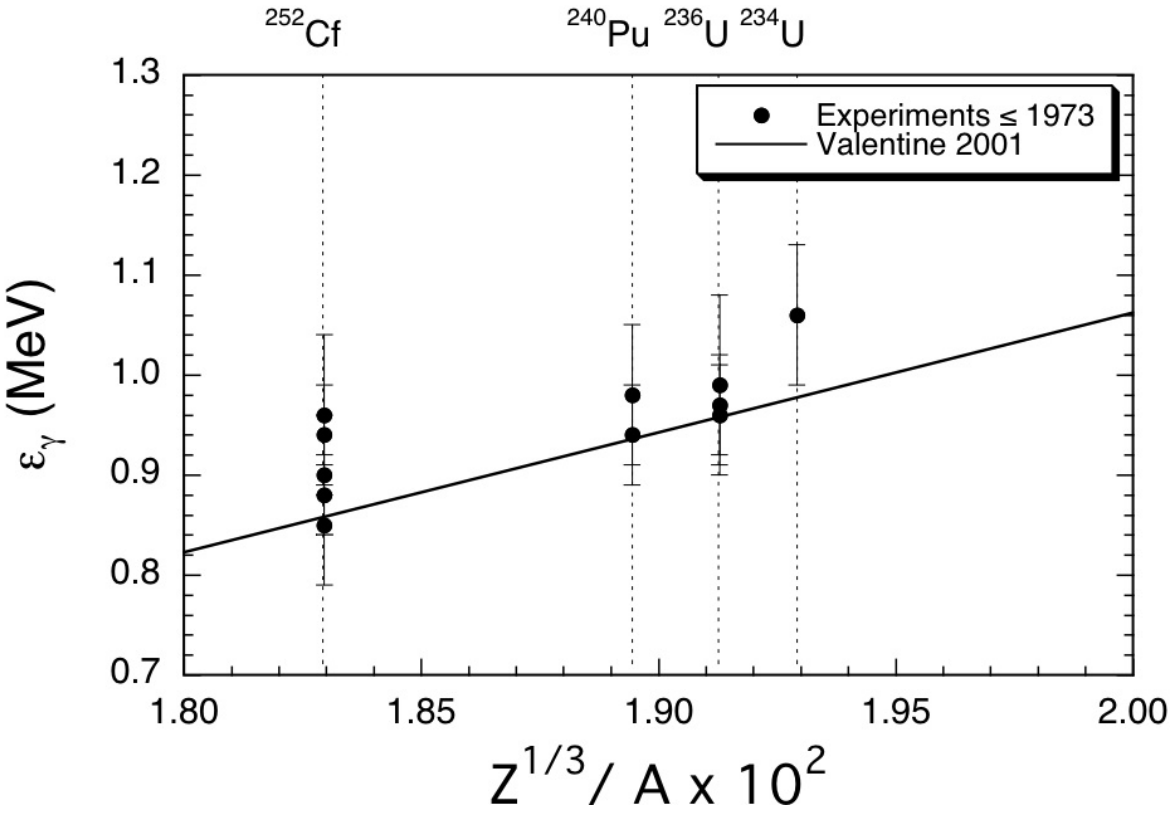
PFGS average total energy per fission



Observe: $\bar{\nu}_n$ taken from experiments.

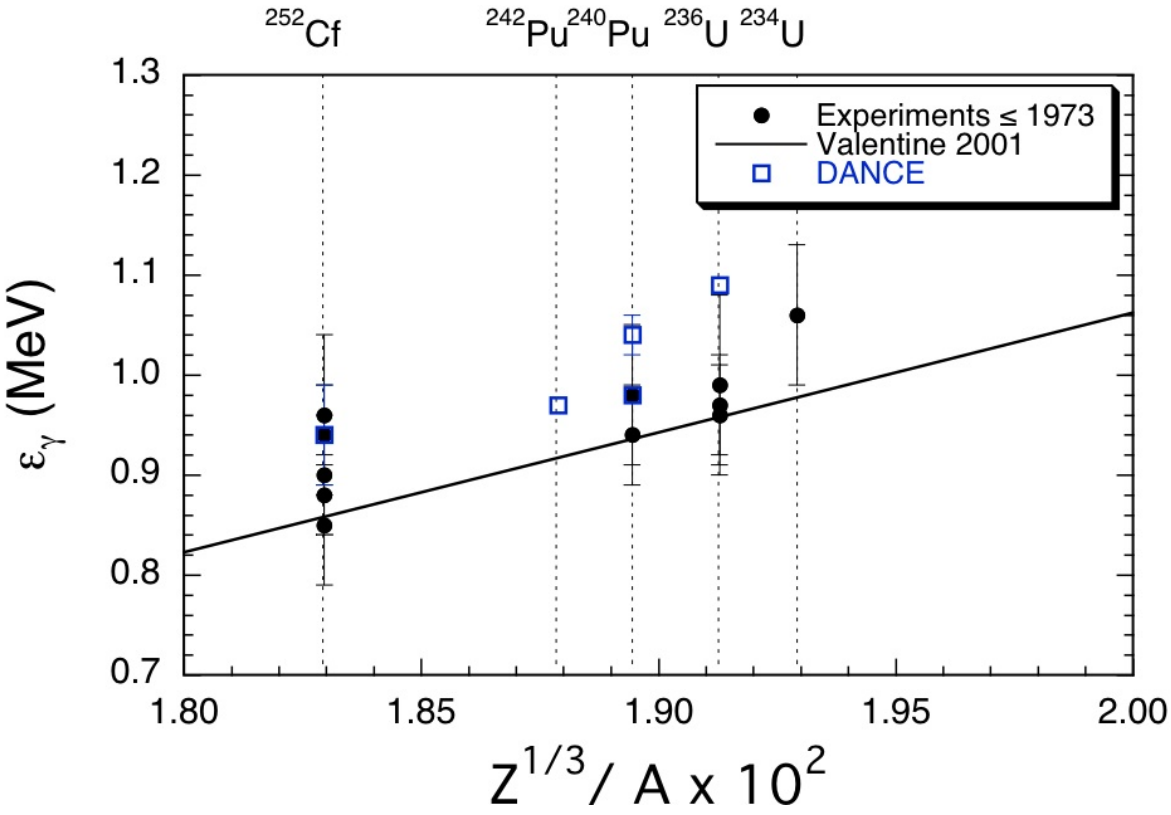
New evaluation

PFGS mean energy per photon



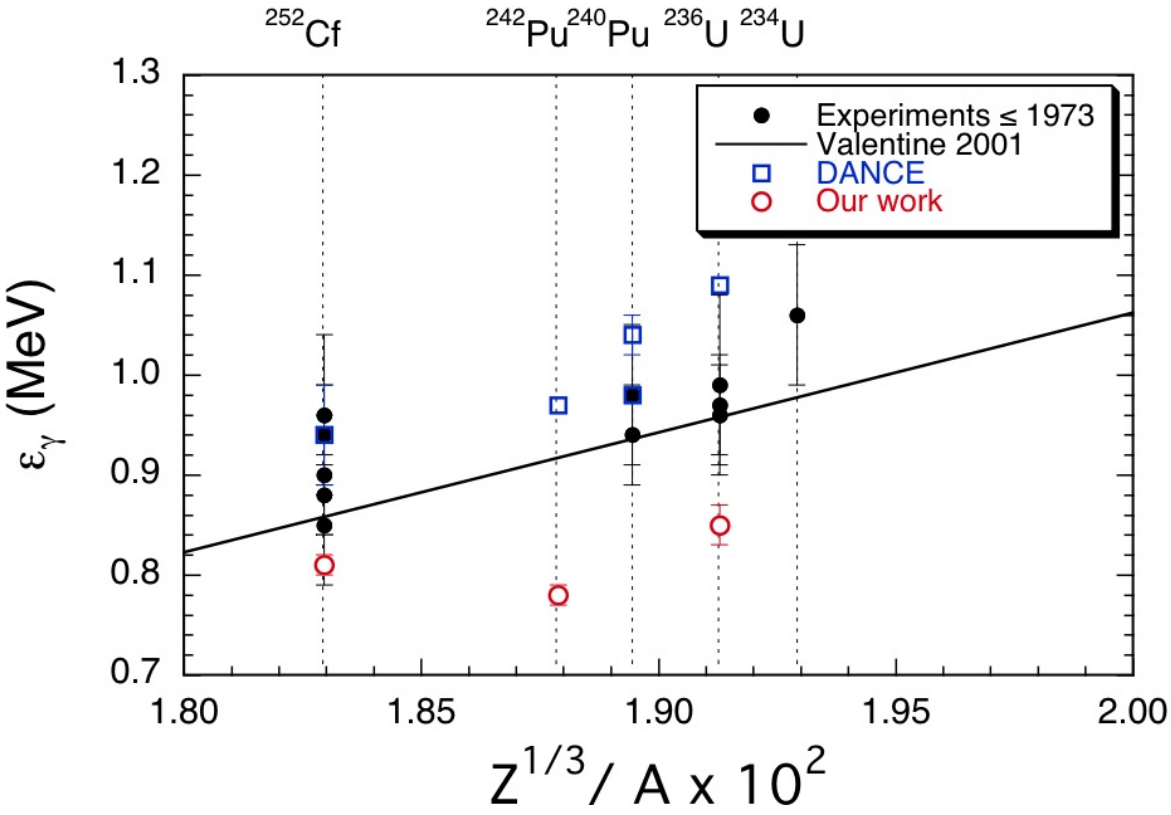
New evaluation

PFGS mean energy per photon



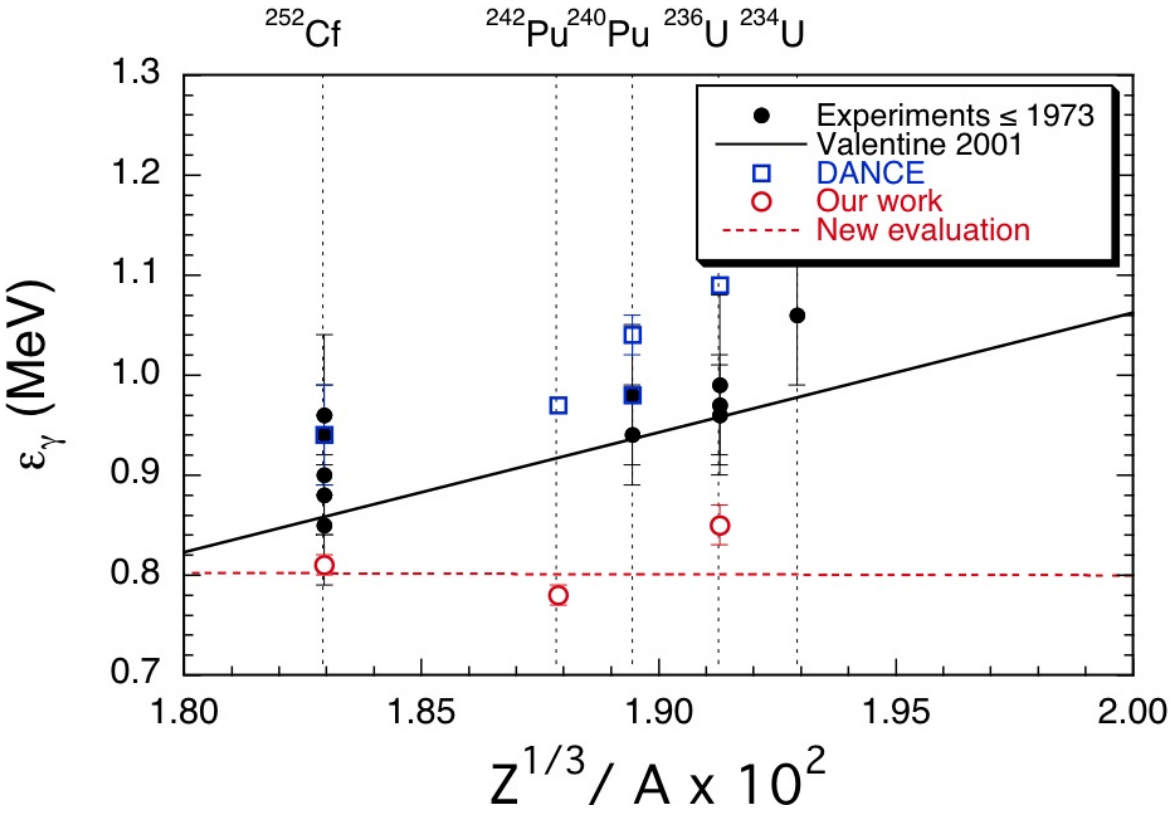
New evaluation

PFGS mean energy per photon

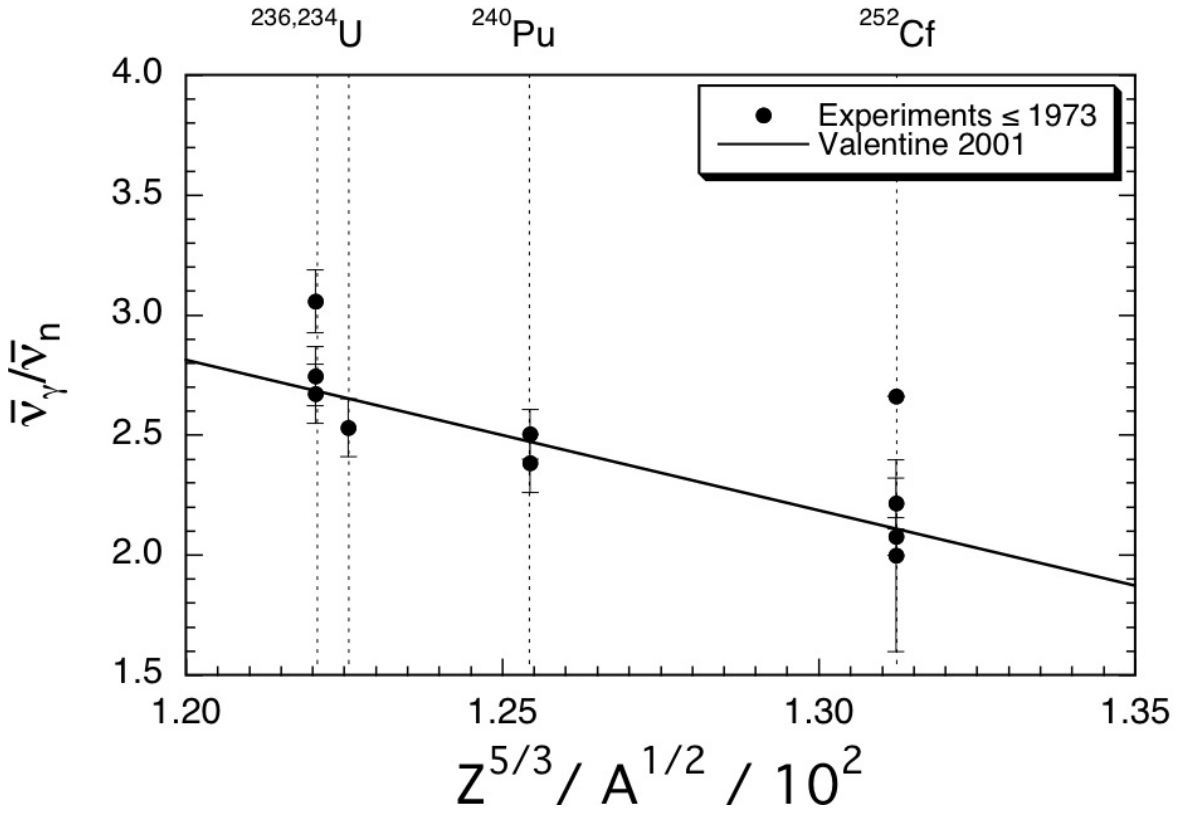


New evaluation

PFGS mean energy per photon



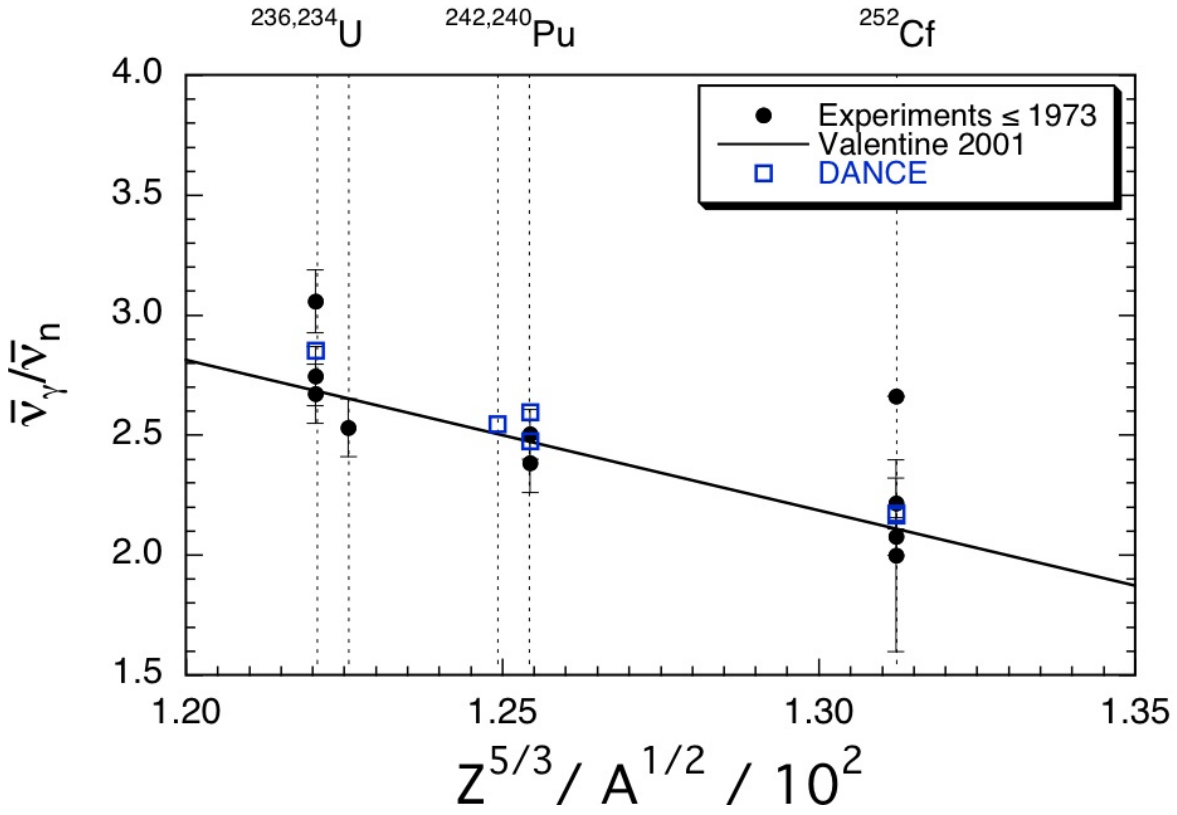
New evaluation
PFGS average multiplicity



Observe: $\bar{\nu}_n$ taken from experiments.

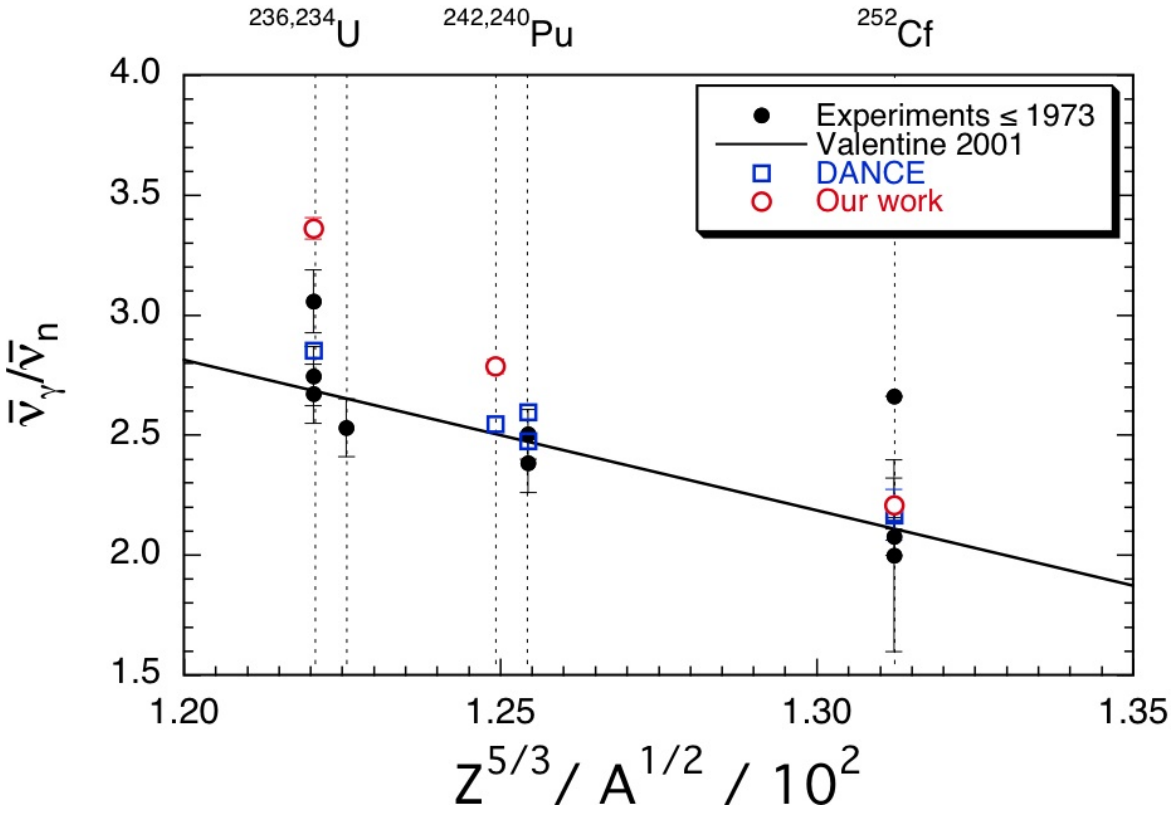
New evaluation

PFGS average multiplicity



Observe: $\bar{\nu}_n$ taken from experiments.

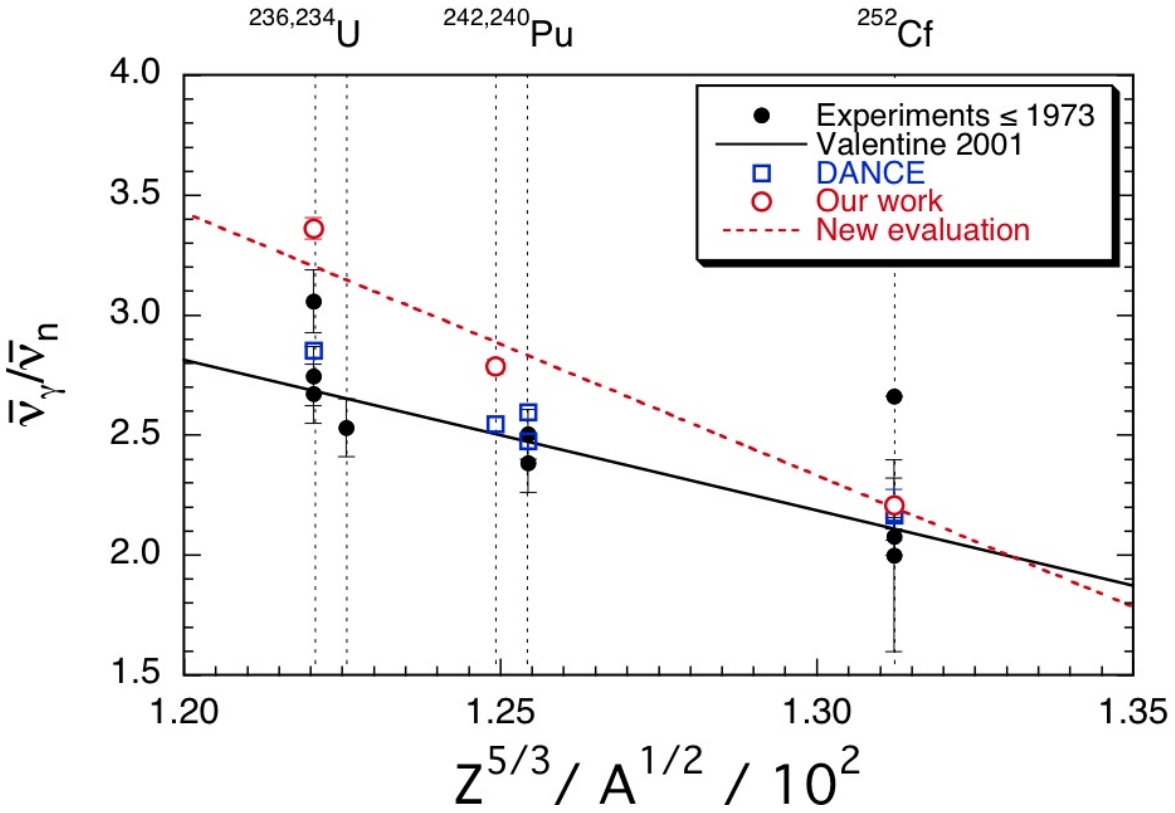
New evaluation
PFGS average multiplicity



Observe: $\bar{\nu}_n$ taken from experiments.

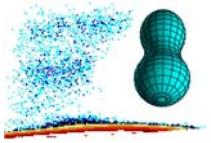
New evaluation

PFGS average multiplicity



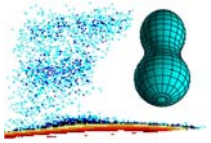
Observe: $\bar{\nu}_n$ taken from experiments.

Summary – so far



- PFGS characteristics as function of A and Z of the compound system
- Agreement between new experimental results and "Valentine's evaluation" is rather good
- Parameters might need an adjustment
- Estimate (interpolations/extrapolation) of PFGS characteristics is possible for nuclei, which are not experimentally accessible
- However: only valid for thermal neutron induced and spontaneous fission?
- Attempt: fast neutron induced fission!
- Example below: ^{238}U(n, f)!

Fast neutron induced fission



Motivation

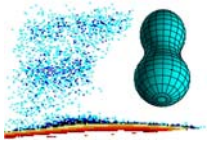
Why n + ^{238}U PFGS?

- Important nuclide for fast reactors
- one of six isotopes in the focus of the CIELO pilot project

- First – preliminary – experimental results from CEA in Bruyères-le-Châtel
  - available at E_n = 1.7 and 15.6 MeV (BGO)
  - in preparation at E_n = 1.7 and 5.2 MeV (BGO)
    (Laborie et al., private communication)

- New experiment performed recently at IPN Orsay
  - LICORNE facility, covering energy range between E_n = 0.7 and 4 MeV
  - First preliminary results obtained

Fast neutron induced fission



Multiple chance fission

Example:

$n + {}^{238}U @ E_n$ → $^{239}U^*$ → fission + neutrons
E_n = 15.6 MeV

$(n' + {}^{237}U @ E_n')$ → $n + {}^{238}U^*$ → fission + neutrons
$E_{n'}$ = 8.25 MeV

$(n'' + {}^{236}U @ E_n'')$ → $n + {}^{237}U^*$ → fission + neutrons
E_n = 2.11 MeV

$(n''' + {}^{235}U @ E_n''')$ → $n + {}^{236}U^*$ → fission + neutrons

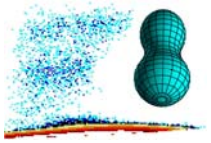
etc.

$$\overline{\nu} = \overline{\nu}_{pre} + \overline{\nu}_{ff} \qquad \text{with}$$

$\overline{\nu}_{pre}$ = pre-fission neutrons

$\overline{\nu}_{ff}$ = prompt neutrons from fission fragments

Fast neutron induced fission



Prerequisites

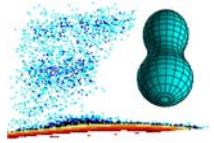
According to Valentine:

- $E_{\gamma,tot}$ depending linearly on $\bar{\nu}_n$, ε_γ independent
- ν_γ approximately proportional to $\bar{\nu}_n$
- Knowledge of $\bar{\nu}_n(E_n)$ important

In case of multiple chance fission:

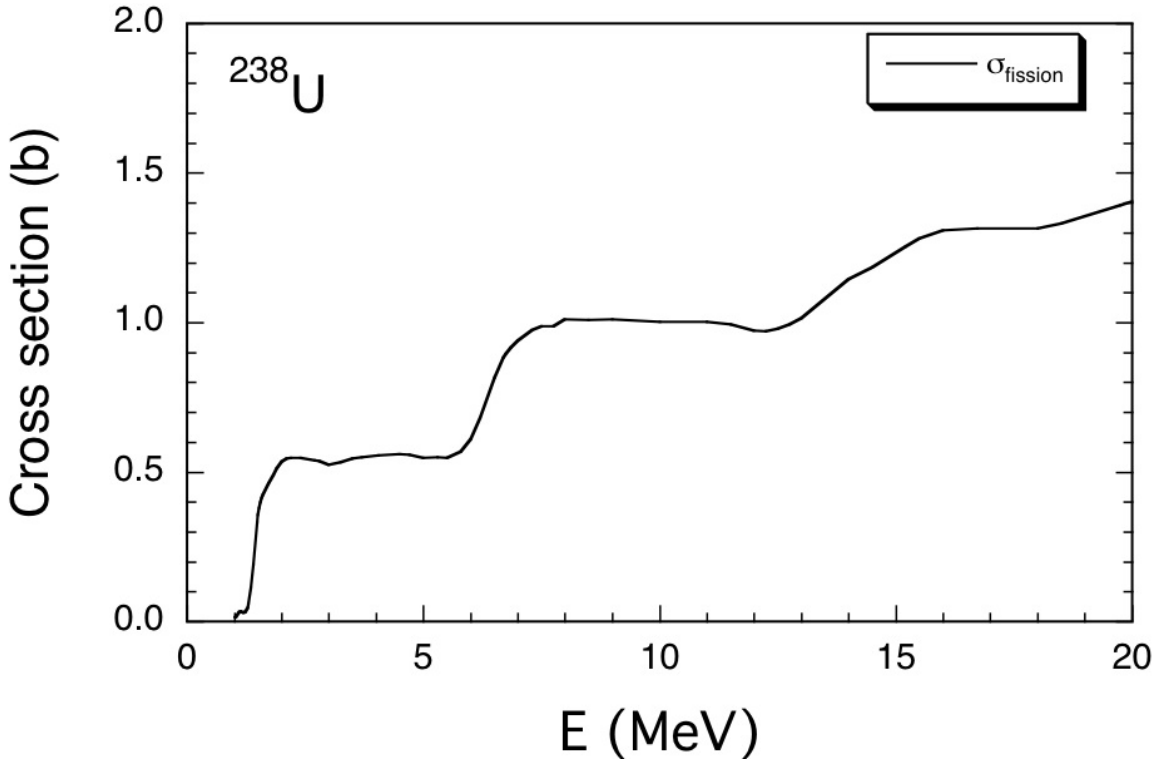
- (n, f) cross section has to be known (ENDF/B-VII.1)
- Contributions from different fission channels have to be taken into account
- $\bar{\nu}_n(E_n)$ for all fissioning systems (ENDF/B-VII.1)

^{238}U(n, f) PFGS characteristics



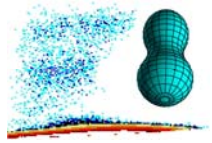
Fission cross section

ENDB/B-VII.1



How to extract contributions from the different fission channels?

^{238}U(n, f) PFGS characteristics



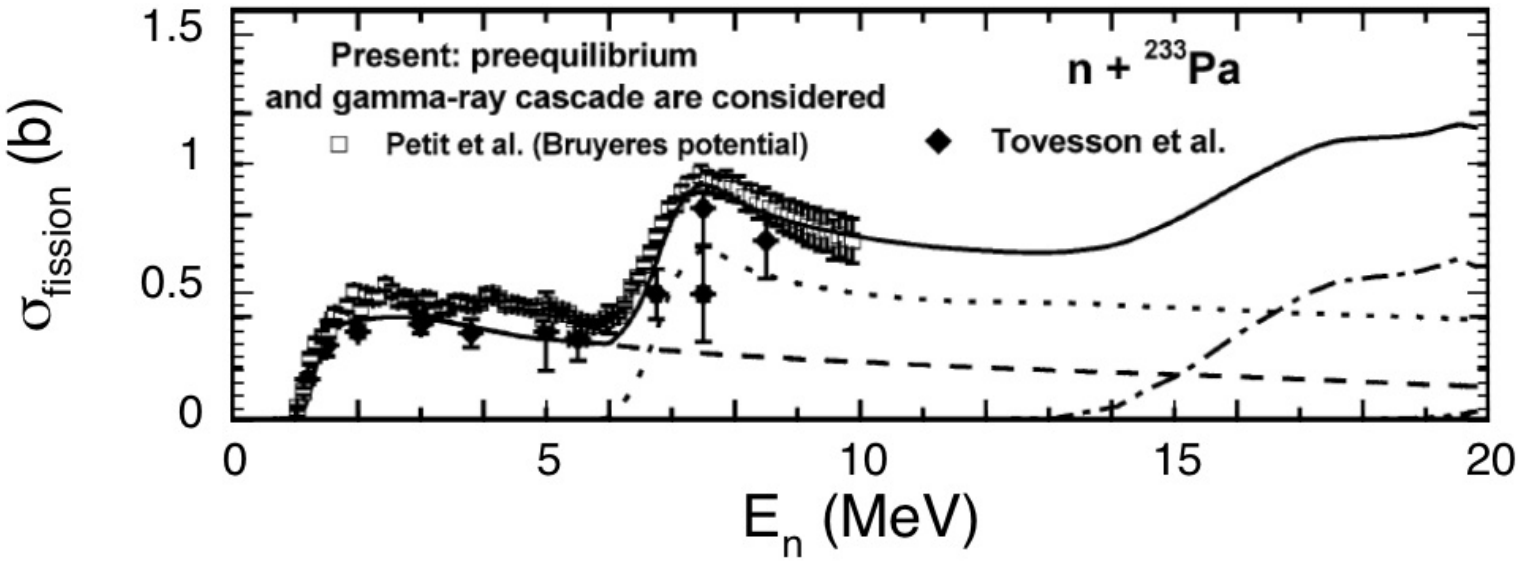
Fission cross section

Answer:

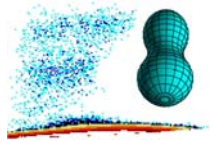
- ask a theoretician to calculate it

Example: n + ^{233}Pa → fission

(picture from: Vladuca et al., NPA 740 (2004) 3)



^{238}U(n, f) PFGS characteristics



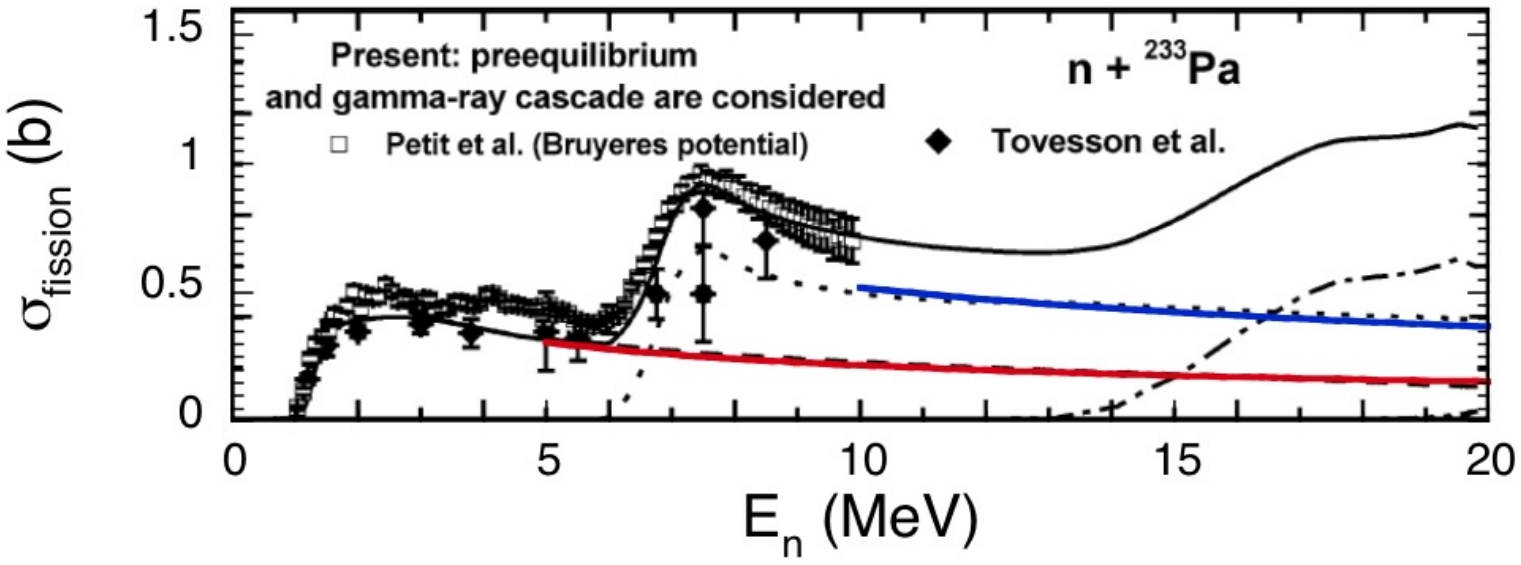
Fission cross section

Answer:

- ask a theoretician to calculate it

Example: n + ^{233}Pa → fission

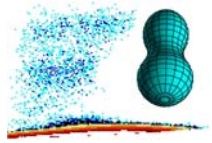
(picture from: Vladuca et al., NPA 740 (2004) 3)



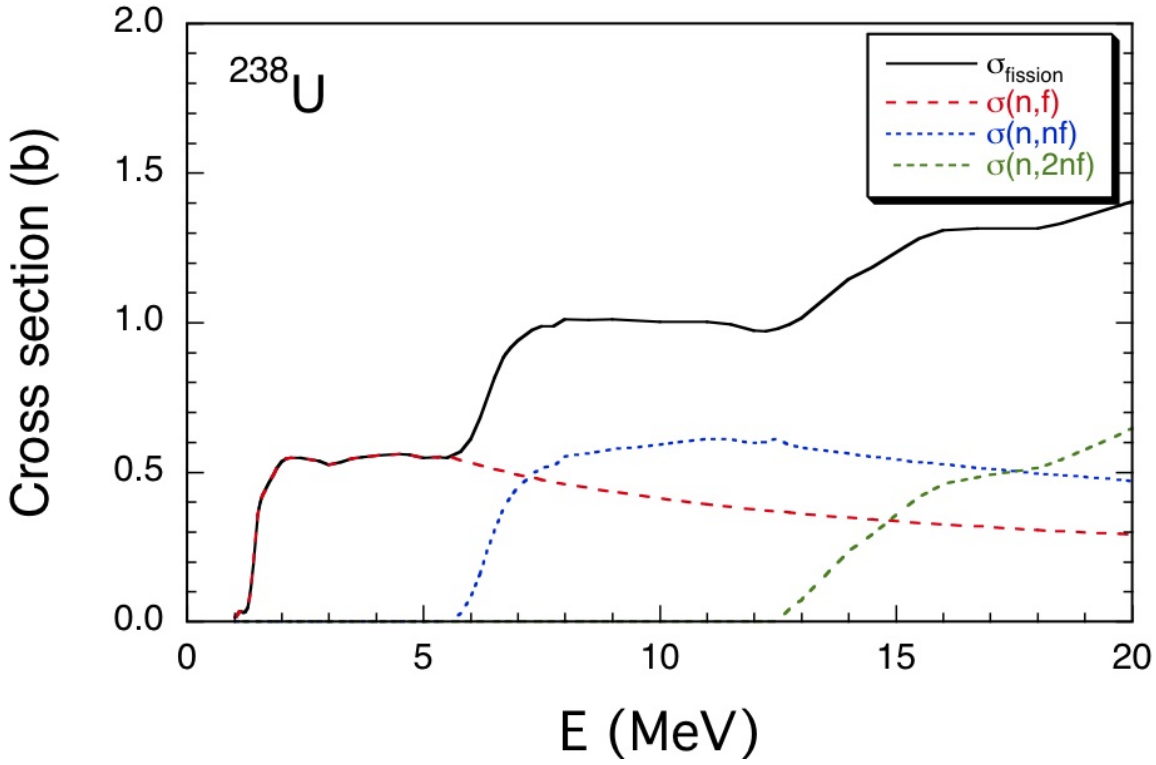
Or:

- or fit the well-known 1/v behaviour!

^{238}U(n, f) PFGS characteristics

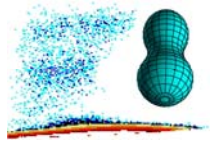


Fission cross section

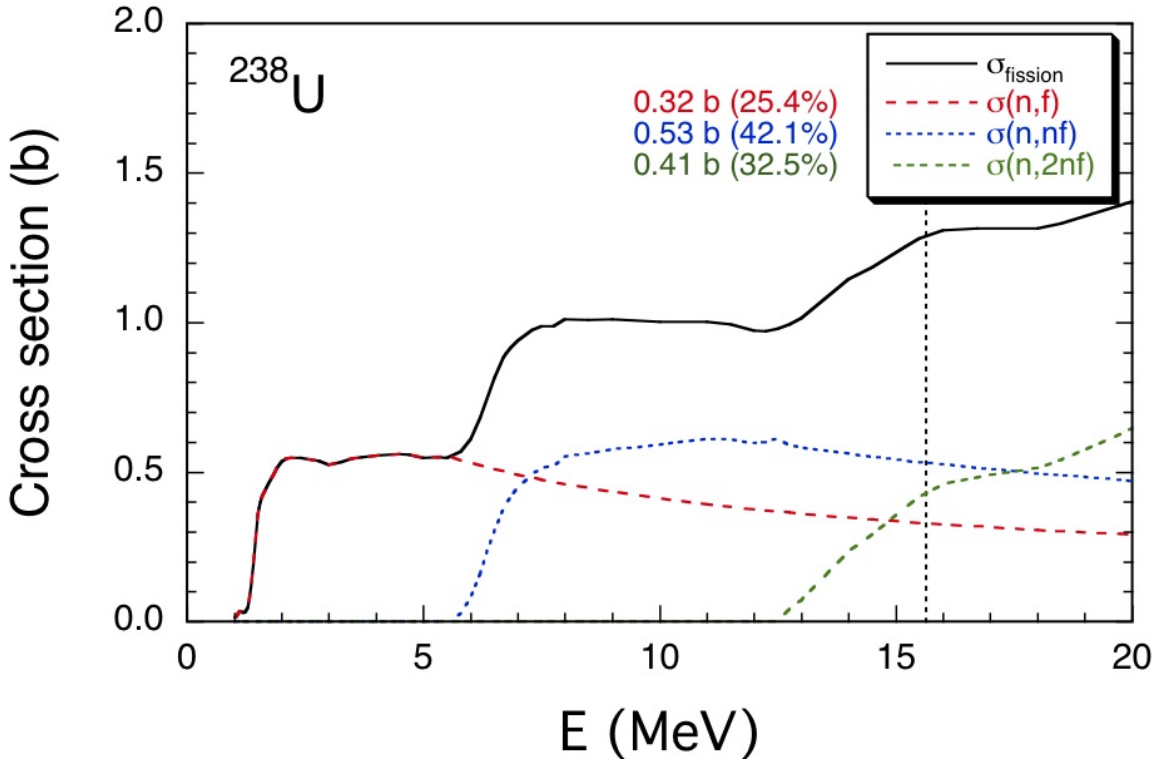


The result makes it possible to estimate the different contributions,

^{238}U(n, f) PFGS characteristics

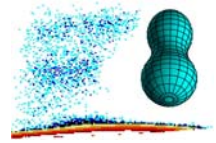


Fission cross section

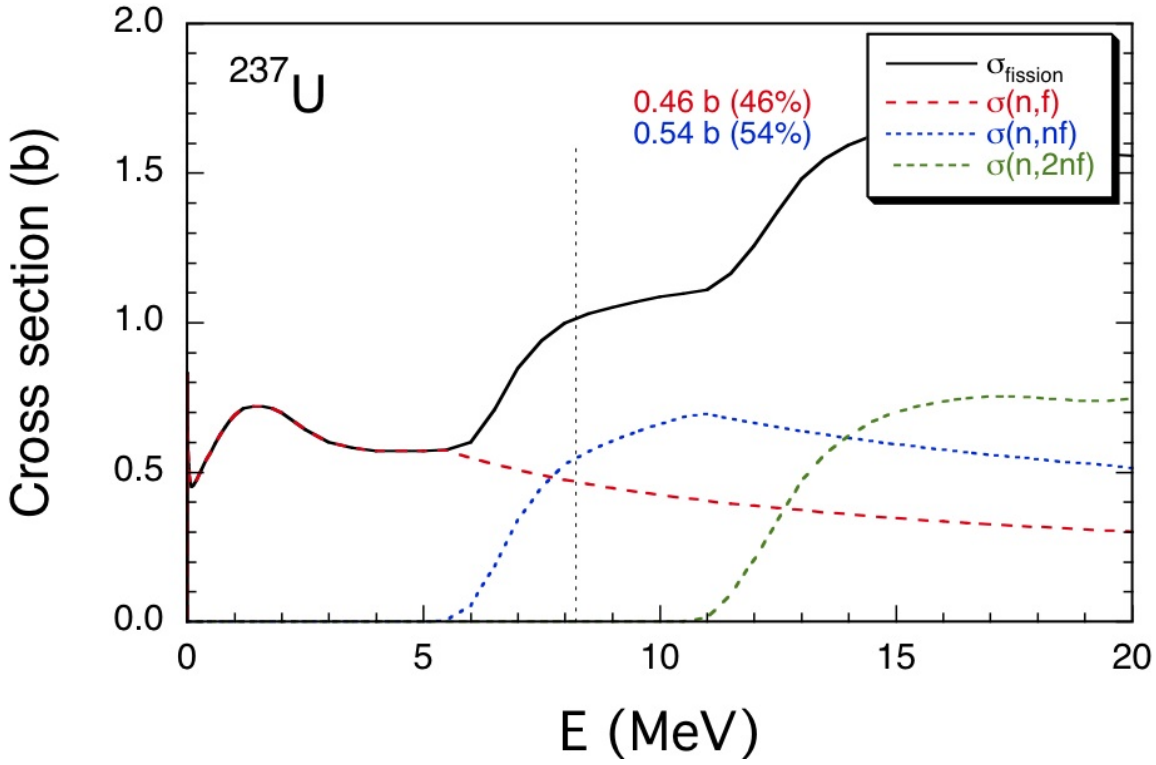


The result makes it possible to estimate the different contributions, e.g. at E_n = 15.6 MeV.

^{238}U(n, f) PFGS characteristics



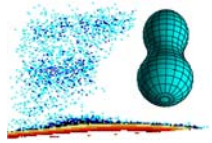
Fission cross section

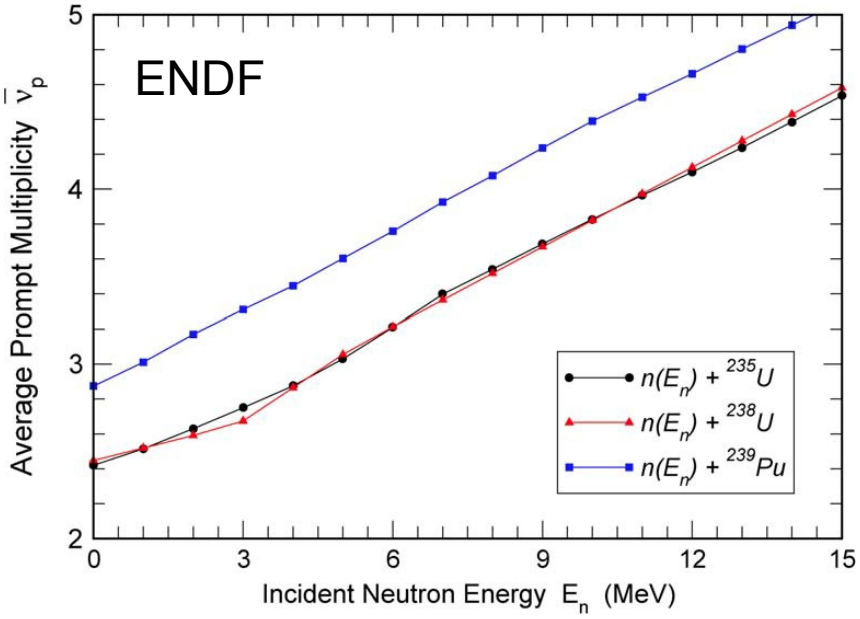


Same procedure for ^{237}U(n, f) …

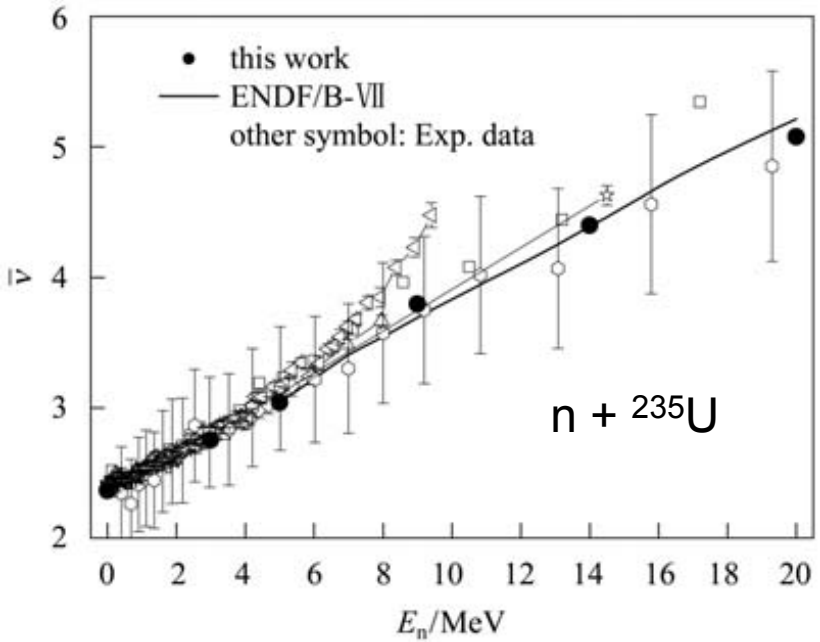
^{238}U(n, f) PFGS characteristics

Prompt fission neutron multiplicity





Madland, NPA 772 (2006) 113

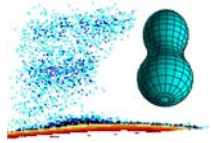


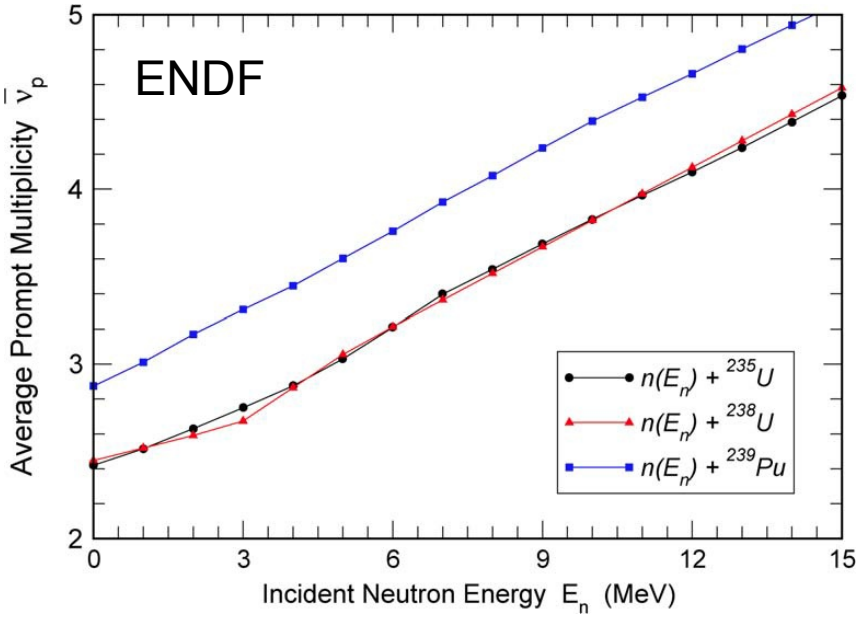
Chen & Liu, CPC 35,4 (2011) 341

Chen & Liu: prompt fission neutrons =
evaporation neutrons (pre-fission) +
prompt neutrons from fission fragments!

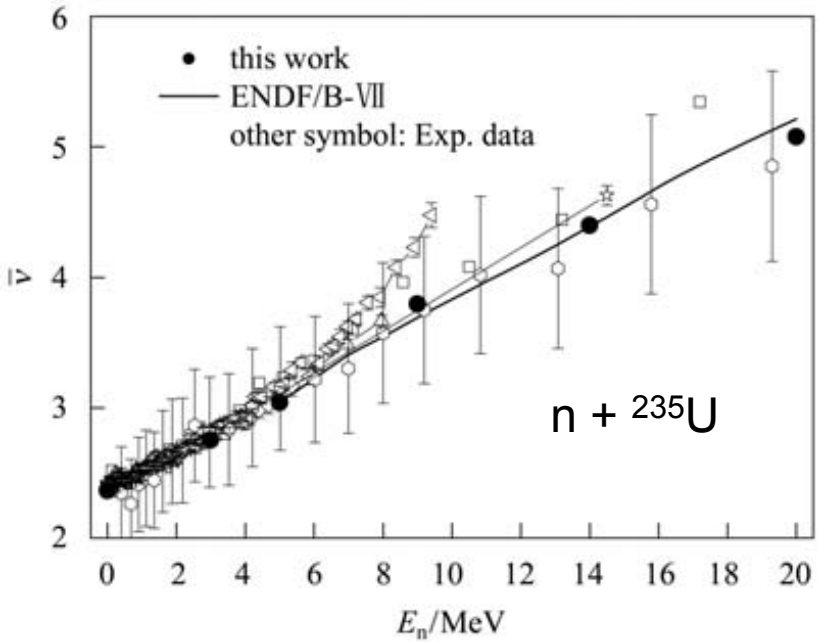
^{238}U(n, f) PFGS characteristics

Prompt fission neutron multiplicity





Madland, NPA 772 (2006) 113

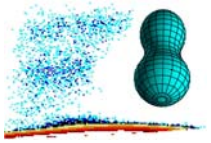


Chen & Liu, CPC 35,4 (2011) 341

Chen & Liu: prompt fission neutrons = evaporation neutrons (pre-fission) + prompt neutrons from fission fragments!

Claim: only the latter may be related to PFGS!

^{238}U(n, f) PFGS characteristics



Prompt fission neutron multiplicity

Energetics:

$$E_x^{A_{CN}} = S_n^{A_{CN}} + E_n; \qquad \langle E_n \rangle = \frac{3}{2}T = \frac{3}{2}\sqrt{\frac{7.524MeV \cdot E_x^{A_{CN}}}{A_{CN}}} \quad *)$$

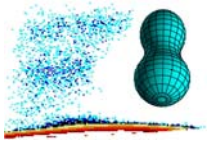
$$E_x^{A_{CN}-1} = S_n^{A_{CN}-1} + E'_n = E_x^{A_{CN}} - S_n^{A_{CN}} - \langle E_n \rangle; \qquad \langle E'_n \rangle = \frac{3}{2}T' = \frac{3}{2}\sqrt{\frac{7.524MeV \cdot E_x^{A_{CN}-1}}{A_{CN}-1}}$$

$$E_x^{A_{CN}-2} = S_n^{A_{CN}-2} + E''_n = E_x^{A_{CN}-1} - S_n^{A_{CN}-1} - \langle E'_n \rangle; \qquad \langle E''_n \rangle = \frac{3}{2}T'' = \frac{3}{2}\sqrt{\frac{7.524MeV \cdot E_x^{A_{CN}-2}}{A_{CN}-2}}$$

etc.

*) According to Chen & Liu: $E_x^{A_{CN}} = \frac{A_{CN}}{7.524MeV}T^2$

^{238}U(n, f) PFGS characteristics



Prompt fission neutron multiplicity – an illustration

According to ENDF/B-VII.1:

$\bar{\nu}$(^{238}U+n at E_n = 15.6 MeV) = 4.584 (interpolated)

$\bar{\nu}$(^{237}U+n at E_n = 8.25 MeV) = 3.760 (interpolated)

$\bar{\nu}$(^{236}U+n at E_n = 2.11 MeV) = 2.639 (interpolated)

Recursively: ^{236}U+n at E_n = 2.11 MeV; 100% (n,f); $\bar{\nu} = \bar{\nu}_{ff}^{237}$ = 2.64

^{237}U+n at E_n = 8.25 MeV; 46% (n,f) + 54% (n,nf);

$$\bar{\nu} = 46\%\ \bar{\nu}_{ff}^{238} + 54\%\ (1+\bar{\nu}_{ff}^{237}) = 3.760$$

$$\bar{\nu}_{ff}^{238} = 3.91$$

^{238}U+n at E_n = 15.6 MeV; 25.4% (n,f) + 42.1% (n,nf) + 32.5% (n,2nf);

$$\bar{\nu} = 25.4\%\ \bar{\nu}_{ff}^{239} + 42.1\%\ (1+\bar{\nu}_{ff}^{238}) + 32.5\%\ (2+\bar{\nu}_{ff}^{237}) = 4.584$$

$$\bar{\nu}_{ff}^{239} = 3.97$$

Hence, with $\bar{\nu}$ = 4.58 follows that

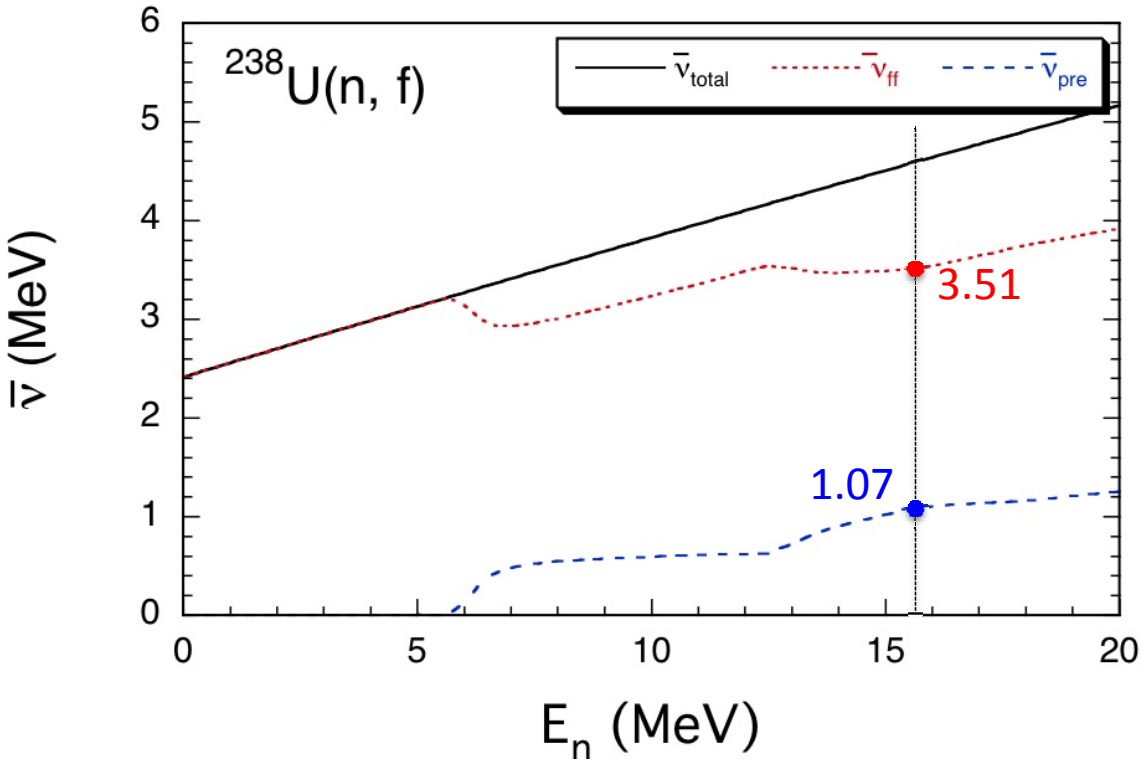
$\bar{\nu}_{pre}$ = 1.07 (from compound system(s)) and

$\bar{\nu}_{ff}$ = 3.51 (from fission fragments)

Note that only the latter multiplicity may be related to prompt fission γ-ray emission!

^{238}U(n, f) PFGS characteristics

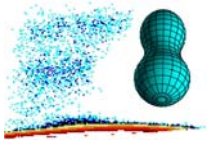
Prompt fission neutron multiplicity



- prompt fission neutrons from ENDF/B-VII.1
- pre-fission neutrons subtracted
- prompt neutrons from fragments for PFGS characteristics

^{238}U(n, f) PFGS characteristics

Calculating energy dependence



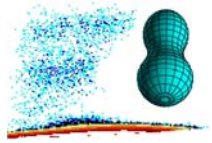
- from PFGS systematics as function of A and Z

$(E_{\gamma,tot} - 4)/\bar{\nu}_n$
ε_γ
$\bar{\nu}_\gamma \quad /\bar{\nu}_n$

} for n + ^{238}U

^{238}U(n, f) PFGS characteristics

Calculating energy dependence



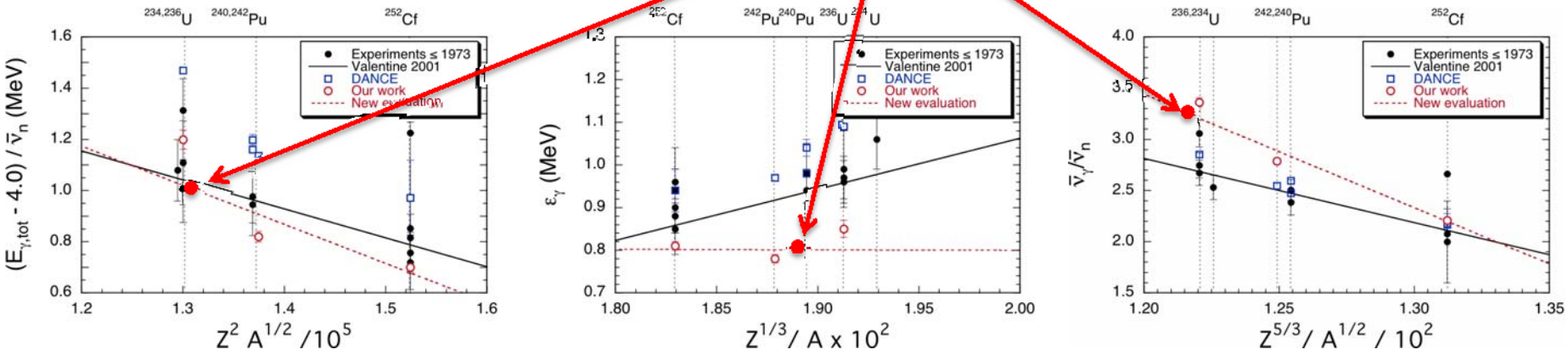
- from PFGS systematics as function of A and Z

$(E_{\gamma,tot} - 4)/\bar{\nu}_n$

ε_γ

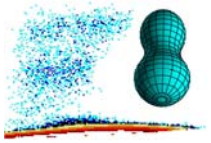
$\bar{\nu}_\gamma \ / \bar{\nu}_n$

} for n + ^{238}U



^{238}U(n, f) PFGS characteristics

Calculating energy dependence



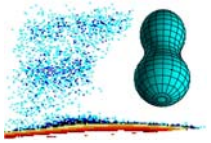
- from PFGS systematics as function of A and Z

  $(E_{\gamma,tot} - 4)/\bar{\nu}_n$
  ε_γ
  $\bar{\nu}_\gamma \quad /\bar{\nu}_n$

  } for n + ^{238}U

- using $\bar{\nu}_n(E_n) = \bar{\nu}_{ff}(E_n)$

^{238}U(n, f) PFGS characteristics



Calculating energy dependence

- from PFGS systematics as function of A and Z

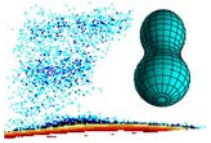
  $(E_{\gamma,tot} - 4)/\bar{\nu}_n$
  ε_γ
  $\bar{\nu}_\gamma \quad /\bar{\nu}_n$

  } for n + ^{238}U

- using $\bar{\nu}_n(E_n) = \bar{\nu}_{ff}(E_n)$
- assuming: only energy dependence = $\bar{\nu}_{ff}(E_n)$

^{238}U(n, f) PFGS characteristics

Calculating energy dependence



- from PFGS systematics as function of A and Z

  $(E_{\gamma,tot} - 4)/\bar{\nu}_n$
  ε_γ
  $\bar{\nu}_\gamma$ $/\bar{\nu}_n$
  } for n + ^{238}U

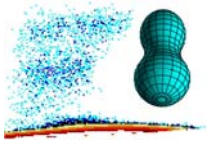
- using $\bar{\nu}_n(E_n) = \nu_{ff}(E_n)$
- assuming: only energy dependence = $\nu_{ff}(E_n)$
- calculating $E_{\gamma,tot}(E_n)$

  $\bar{\nu}_\gamma(E_n)$

  $\varepsilon_\gamma(E_n) = E_{\gamma,tot}(E_n)/\bar{\nu}_\gamma(E_n)$

^{238}U(n, f) PFGS characteristics

Calculating energy dependence



- from PFGS systematics as function of A and Z

  $(E_{\gamma,tot} - 4)/\bar{\nu}_n$
  ε_γ
  $\bar{\nu}_\gamma$ $/\bar{\nu}_n$
  } for n + ^{238}U

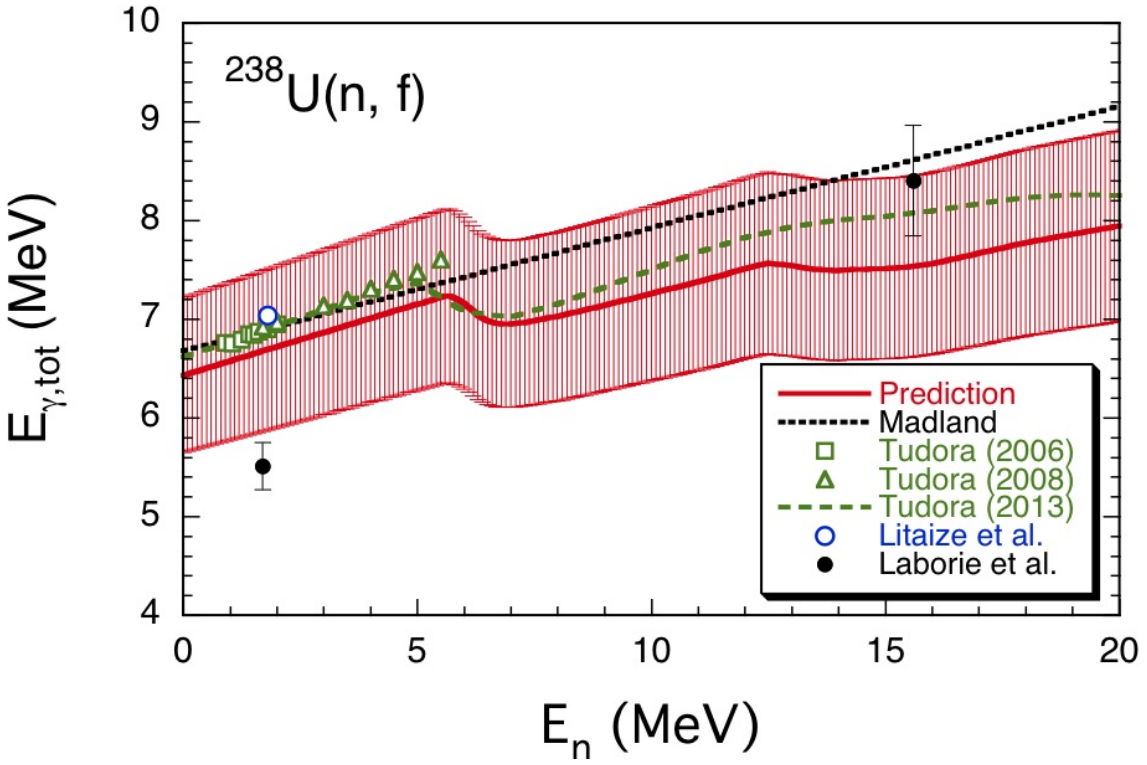
- using $\bar{\nu}_n(E_n) = \nu_{ff}(E_n)$
- assuming: only energy dependence = $\nu_{ff}(E_n)$
- calculating $E_{\gamma,tot}(E_n)$

  $\bar{\nu}_\gamma(E_n)$

  $\varepsilon_\gamma(E_n) = E_{\gamma,tot}(E_n)/\bar{\nu}_\gamma(E_n)$
- comparison with model calculations
- comparison with preliminary experimental results

^{238}U(n, f) PFGS characteristics

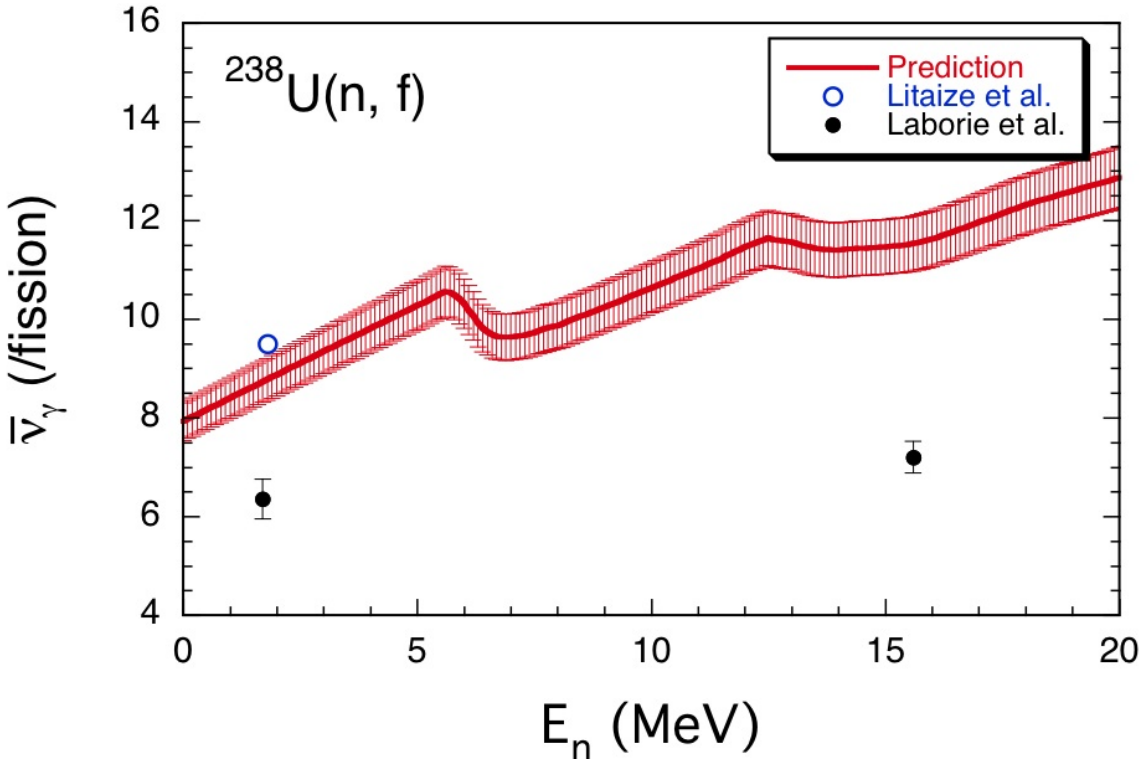
Average total energy per fission



- Litaize et al.: FIFRELIN code (ND 2013, to appear in NDS)
- Tudora: Point-by-Point model

^{238}U(n, f) PFGS characteristics

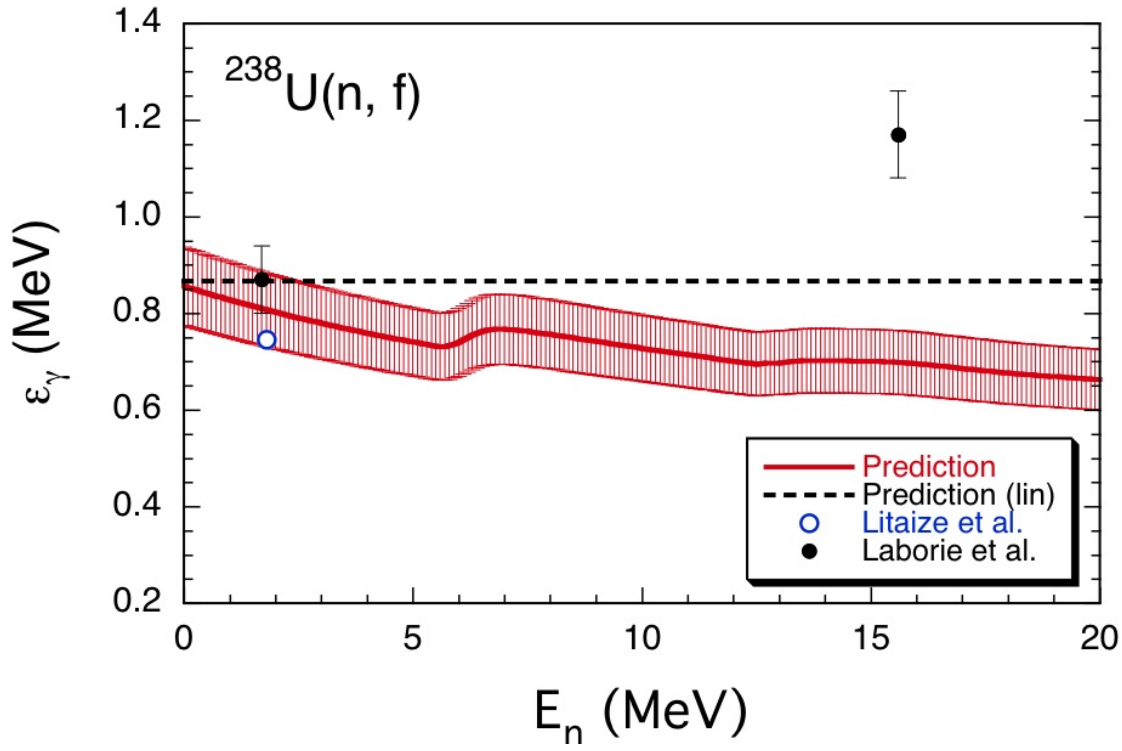
Average γ-ray multiplicity



- Litaize et al.: FIFRELIN code (ND 2013, to appear in NDS)

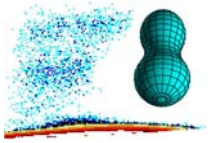
^{238}U(n, f) PFGS characteristics

Mean energy per photon



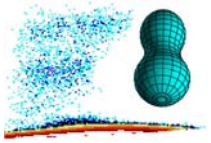
- Litaize et al.: FIFRELIN code (calculated by $E_{\gamma,tot} / \overline{\nu}_{\gamma}$)

Conclusions



- Systematics of PFGS characteristics as function of A and Z of the compound system makes sense for at least thermal neutron induced and spontaneous fission
- Original parameters from Valentine's description might need an adjustment
- Empirical A and Z dependence must be verified
- More experimental data needed
- Predictions for fast neutron induced fission of n + ^{238}U presented
- Good agreement of our predictions with both calculations and preliminary experimental results!

The collaborators



R. Billnert, A. Oberstedt, S. Oberstedt

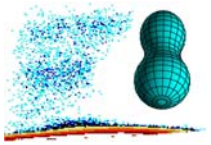
with invaluable support of

T. Belgya, R. Borcea, T. Bryś, C. Chaves, Th. Gamboni, W. Geerts,

A. Göök, C. Guerrero, F.-J. Hambsch, Z. Kis, T. Martinez,

L. Szentmiklosi, K. Takács, M. Vidali and others

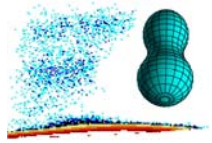
Parts of this work were supported by both the ERINDA programme (agreement number 269499) and the EFNUDAT programme (agreement number 31027) of the European Commission

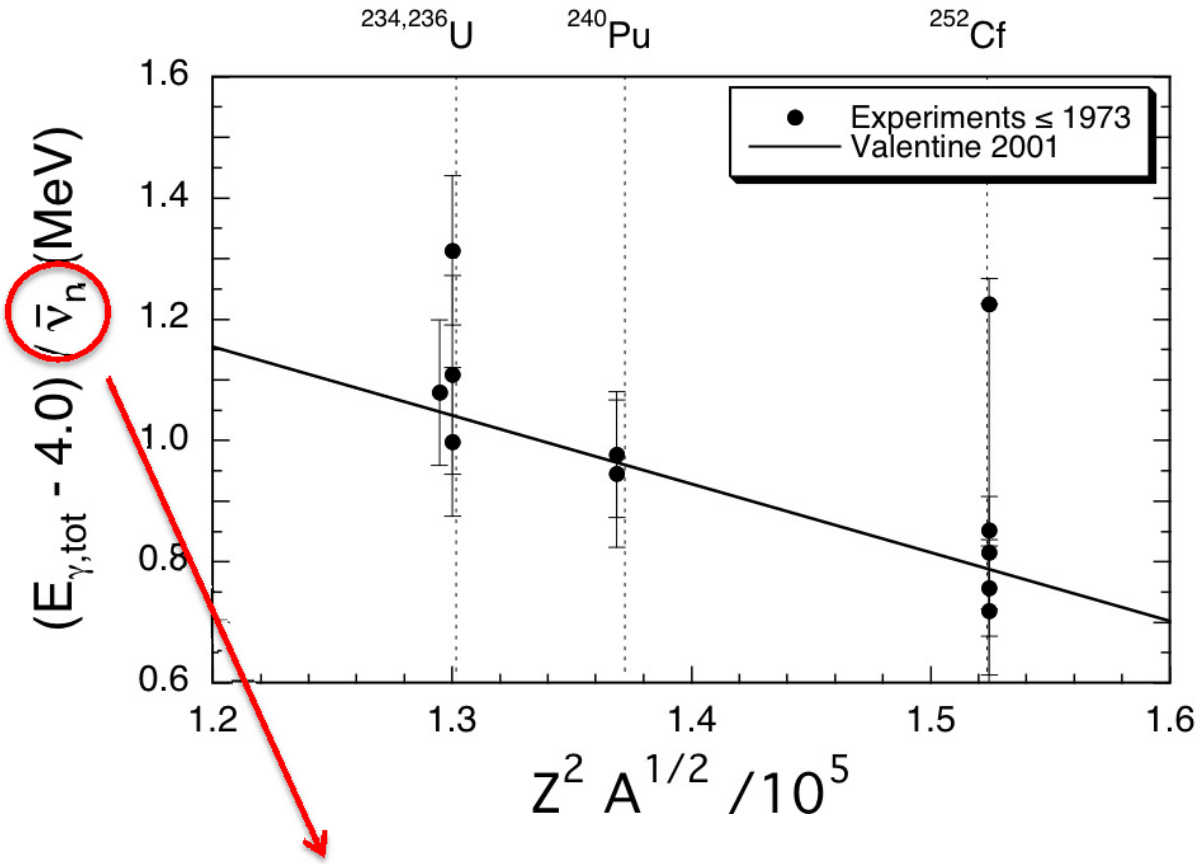


Thank you!

Historical background

Results + evaluation

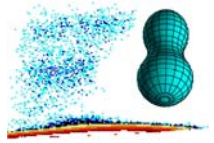


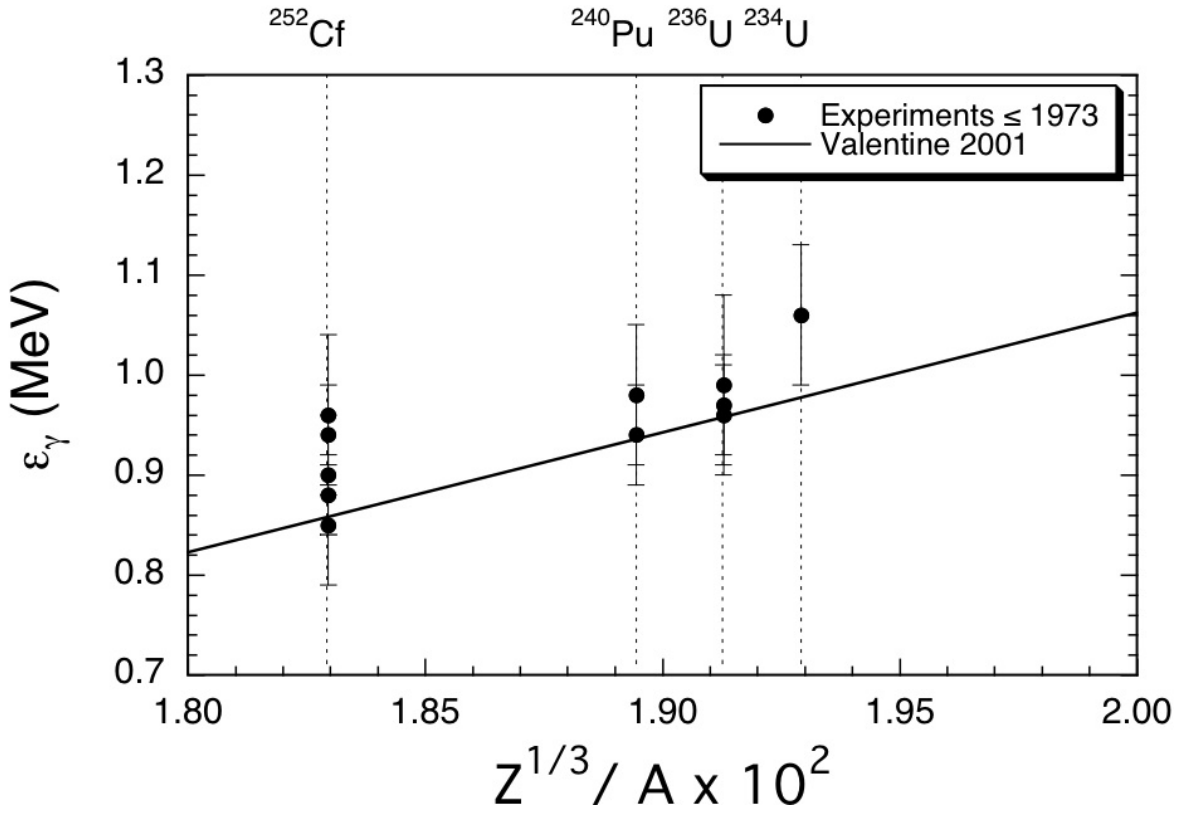


Observe: $\bar{\nu}_n$ taken from experiments.

Historical background

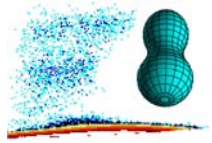
Results + evaluation

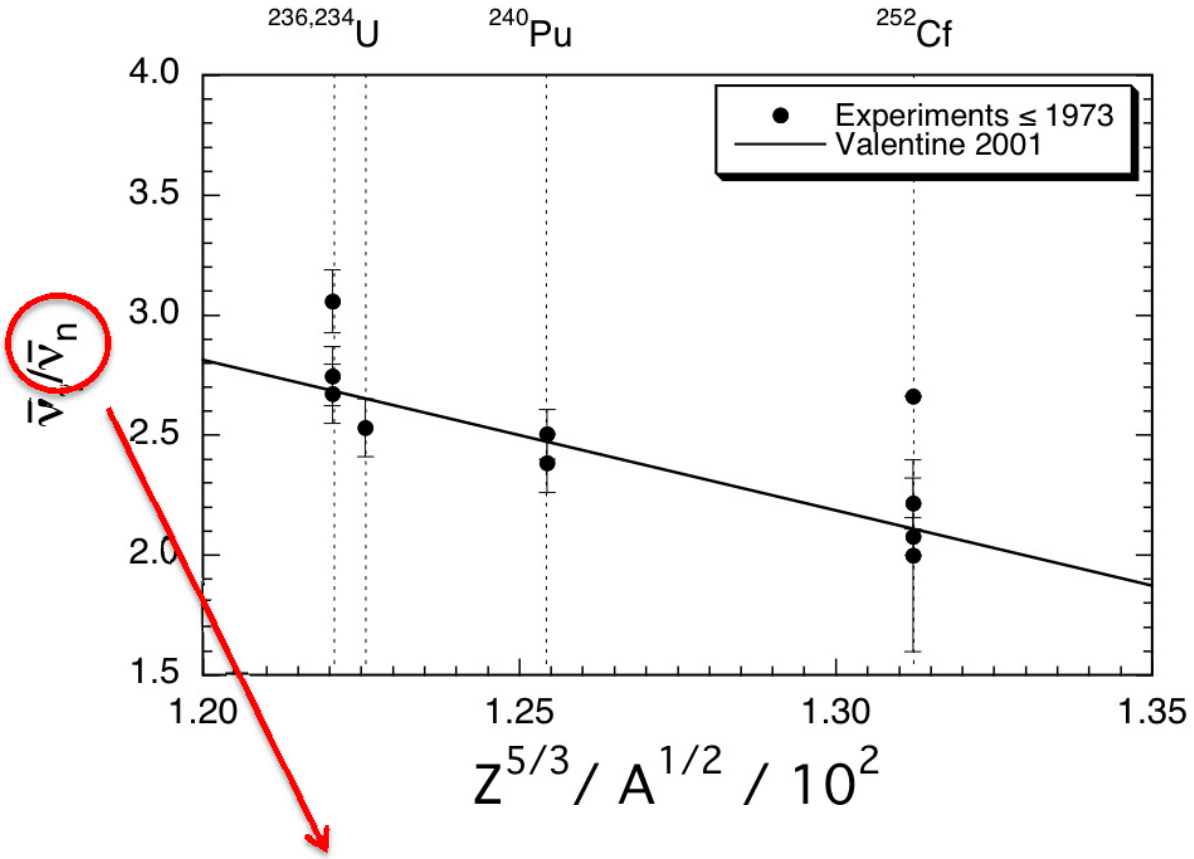




Historical background

Results + evaluation





Observe: $\bar{\nu}_n$ taken from experiments.

New results - overview

^{252}Cf(sf) PFGS characteristics

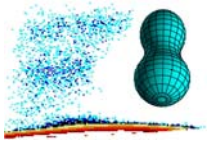
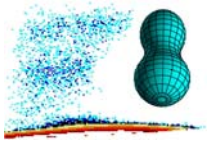


TABLE I. Summary of prompt γ-ray characteristics for the spontaneous fission of ^{252}Cf. Experimental results from this work for the γ-ray multiplicity ν_γ, the average energy ϵ_γ and the total energy $E_{\gamma,tot}$, obtained with three detectors employed in this work, are given and the covered energy range is indicated. Averaged values for the first two detectors are presented as well and compared to previously measured ones from Refs. [3–5] as well as corresponding numbers from the evaluated nuclear data files in ENDF/B-VII.1 [24] and from calculations from Ref. [11–13, 15, 25]. The results denoted by *) are calculated on the basis of the average values (see text for details).

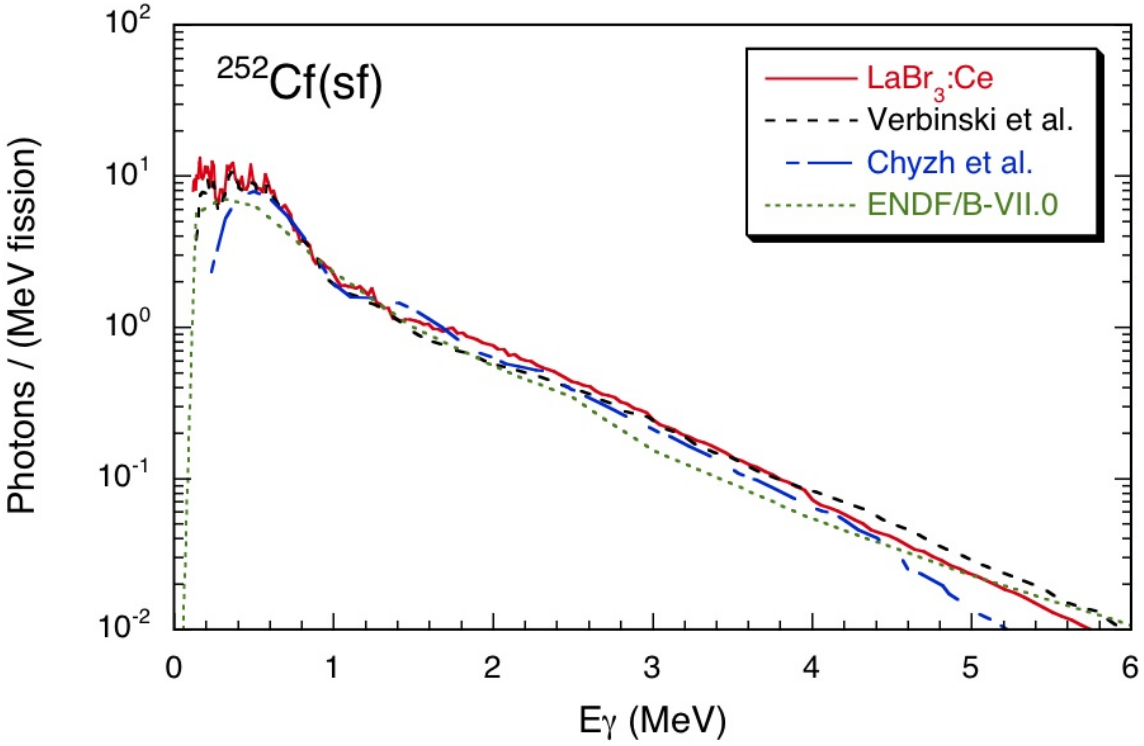
Results	Detector	Diameter × length (in. × in.)	ν_γ (per fission)	ϵ_γ (MeV)	$E_{\gamma,tot}$ (MeV)	Energy range (MeV)	
This work *)	$LaBr_3$:Ce (Q489)	2 × 2	8.28 ± 0.08	0.80 ± 0.01	6.64 ± 0.10	0.1 - 7.2	
This work *)	$CeBr_3$ (315)	1 × 2	8.31 ± 0.10	0.80 ± 0.01	6.61 ± 0.12	0.1 - 6.5	
This work	$LaCl_3$:Ce (SEB 347)	1.5 × 1.5	8.25 ± 0.09	0.81 ± 0.02	6.60 ± 0.22	0.1 - 10.0	*)
This work	Averaged values		8.29 ± 0.06	0.80 ± 0.01	6.63 ± 0.08	> 0.1	
Chyzh *et al.* [3]	DANCE		8.14 ± 0.40	0.94 ± 0.05	7.65 ± 0.55	0.15 - 10.0	
Verbinski *et al.* [4]	NaI	2.3 × 6	7.80 ± 0.30	0.88 ± 0.04	6.84 ± 0.30	0.14 - 10.0	
Pleasonton *et al.* [5]	NaI	5 × 4	8.32 ± 0.40	0.85 ± 0.06	7.06 ± 0.35	> 0.085	
ENDF/B-VII.1 [24]	Evaluation		6.86	0.96	6.58	0.1 - 10.0	
Litaize *et al.* [13]	Calculation				6.77		
Regnier *et al.* [11]	Calculation		8.8	0.70	6.2	0.15 - 10.0	
Regnier [12]	Calculation		8.62	0.72	6.21	0.07 - 10.0	
Talou [25]	Calculation		7.96	0.86	6.85	0.14 - 10.0	
Becker *et al.* [15]	Calculation		9.97	0.85	8.47	0.14 - 10.0	
Chyzh (2013)	Dance		8.16				

*) R. Billnert et al., PRC 87 (2013)

Results
^{252}Cf(sf) PFGS



R. Billnert et al., PRC 87 (2013)



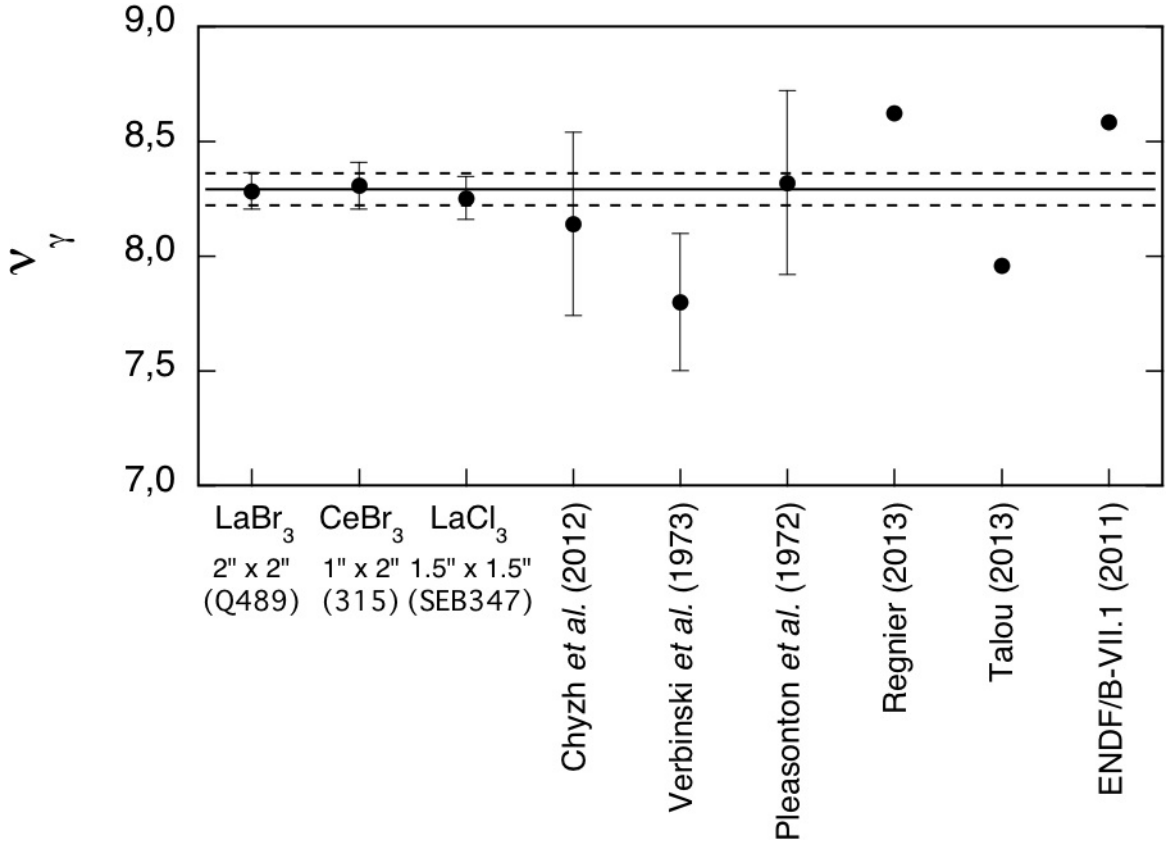
PRC 7 (1973)

PRC 85 (2012)

Below 1 MeV: good agreement with data from Verbinski (1973), but not with those from Chyzh (2012) and ENDF.

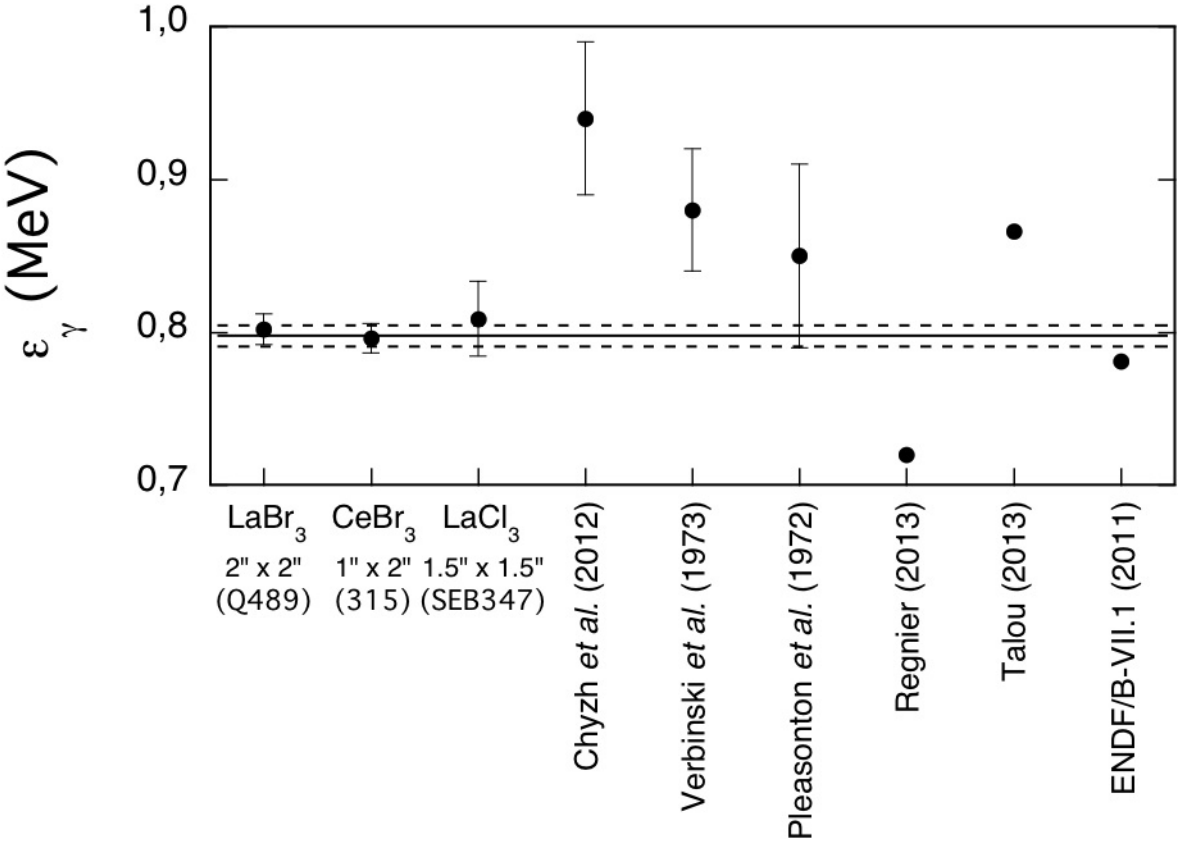
New results - overview

^{252}Cf(sf) PFGS average multiplicity



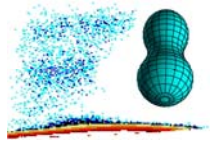
New results - overview

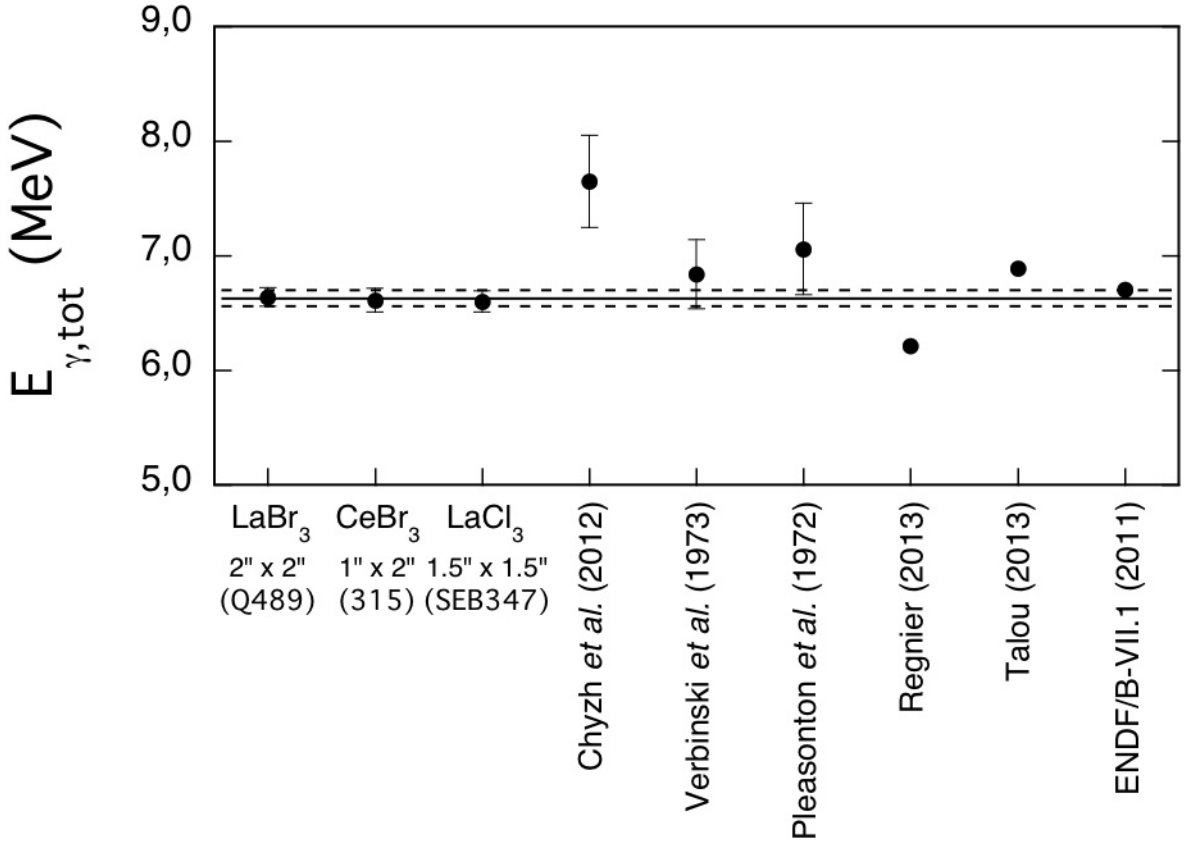
^{252}Cf(sf) PFGS mean energy per photon



New results - overview

^{252}Cf(sf) PFGS total energy per fission





New results - overview

$^{235}U(n_{th}, f)$ PFGS characteristics

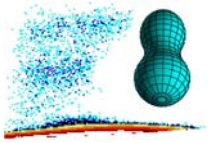


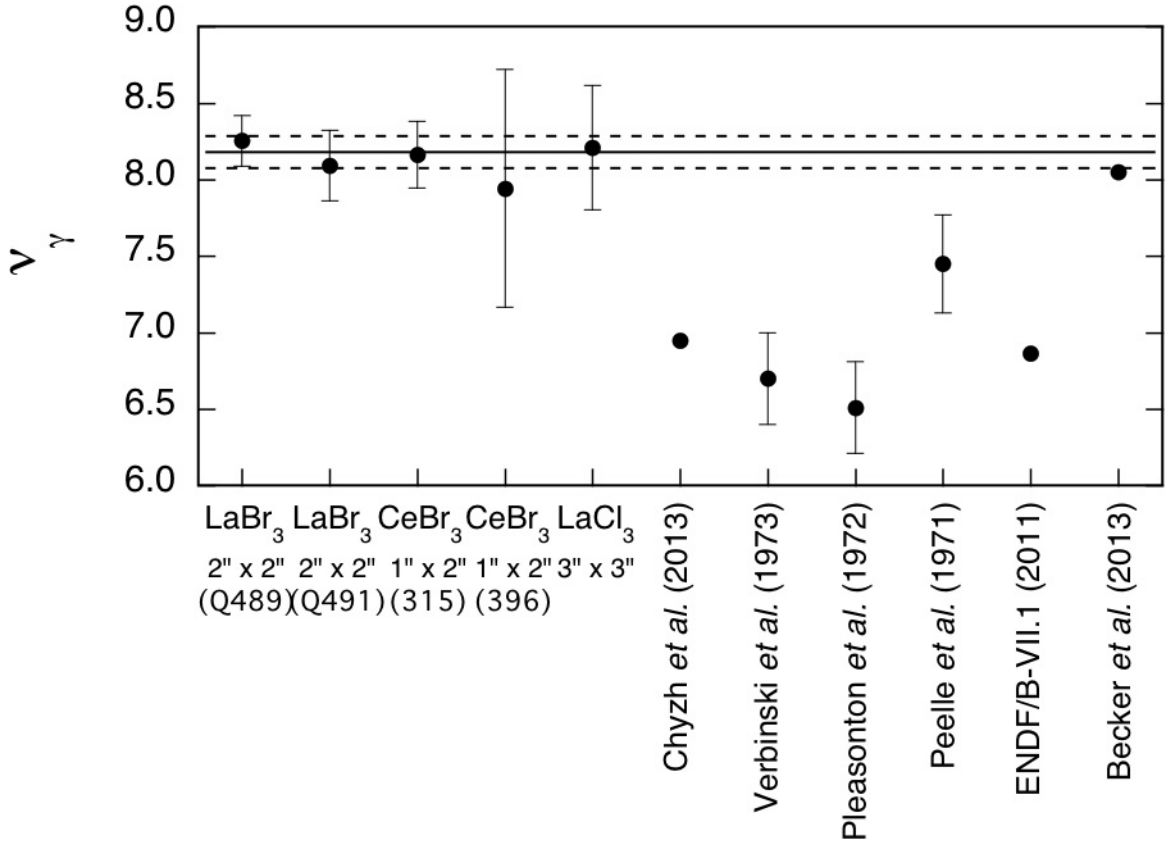
TABLE I. Summary of prompt γ-ray characteristics for the neutron-induced fission of ^{235}U. Experimental results from this work for the γ-ray multiplicity ν_γ, the average energy ϵ_γ and the total energy $E_{\gamma,tot}$, obtained with all five detectors employed in this work, are given and the covered energy range is indicated. Averaged values for the first three detectors are presented as well and compared to previously measured ones from Refs. [4–6] as well as corresponding numbers from the evaluated nuclear data files in ENDF/B-VII.1 [23] and from calculations from Ref. [14]. The results denoted by *) are calculated on the basis of the average values (see text for details).

Results	Detector	Diameter × length (in. × in.)	ν_γ (per fission)	ϵ_γ (MeV)	$E_{\gamma,tot}$ (MeV)	Energy range (MeV)	
This work	$LaBr_3$:Ce (Q489)	2 × 2	8.25 ± 0.17	0.84 ± 0.02	6.94 ± 0.14	0.1 - 6.0	
This work	$LaBr_3$:Ce (Q491)	2 × 2	8.09 ± 0.23	0.84 ± 0.03	6.79 ± 0.18	0.1 - 6.0	
This work	$CeBr_3$ (315)	1 × 2	8.16 ± 0.22	0.86 ± 0.03	7.03 ± 0.19	0.1 - 6.0	
This work	$CeBr_3$ (396)	1 × 2	7.94 ± 0.78	0.86 ± 0.09	6.81 ± 0.99	0.1 - 6.0	*)
This work	$LaCl_3$:Ce	3 × 3	8.21 ± 0.41	0.85 ± 0.05	6.99 ± 0.35	0.1 - 6.0	*)
This work	Averaged values		8.19 ± 0.11	0.85 ± 0.02	6.92 ± 0.09	0.1 - 6.0	
Verbinski *et al.* [4]	NaI	2.3 × 6	6.70 ± 0.30	0.97 ± 0.05	6.51 ± 0.30	0.14 - 10.0	
Pleasonton *et al.* [5]	NaI	5 × 4	6.51 ± 0.30	0.99 ± 0.07	6.43 ± 0.30	0.09 - 10.0	
Peelle *et al.* [6]	NaI	1.75 × 1	7.45 ± 0.35	0.96	7.18 ± 0.26	0.14 - 10.0	
ENDF/B-VII.1 [23]	Evaluation		6.86	0.96	6.58	0.1 - 10.0	
Becker *et al.* [14]	Calculation		8.05	0.88	7.06	0.14 - 10.0	
Chyzh (2013)	Dance		6.95	1.09	7.58		

A. Oberstedt et al., PRC 87 (2013)

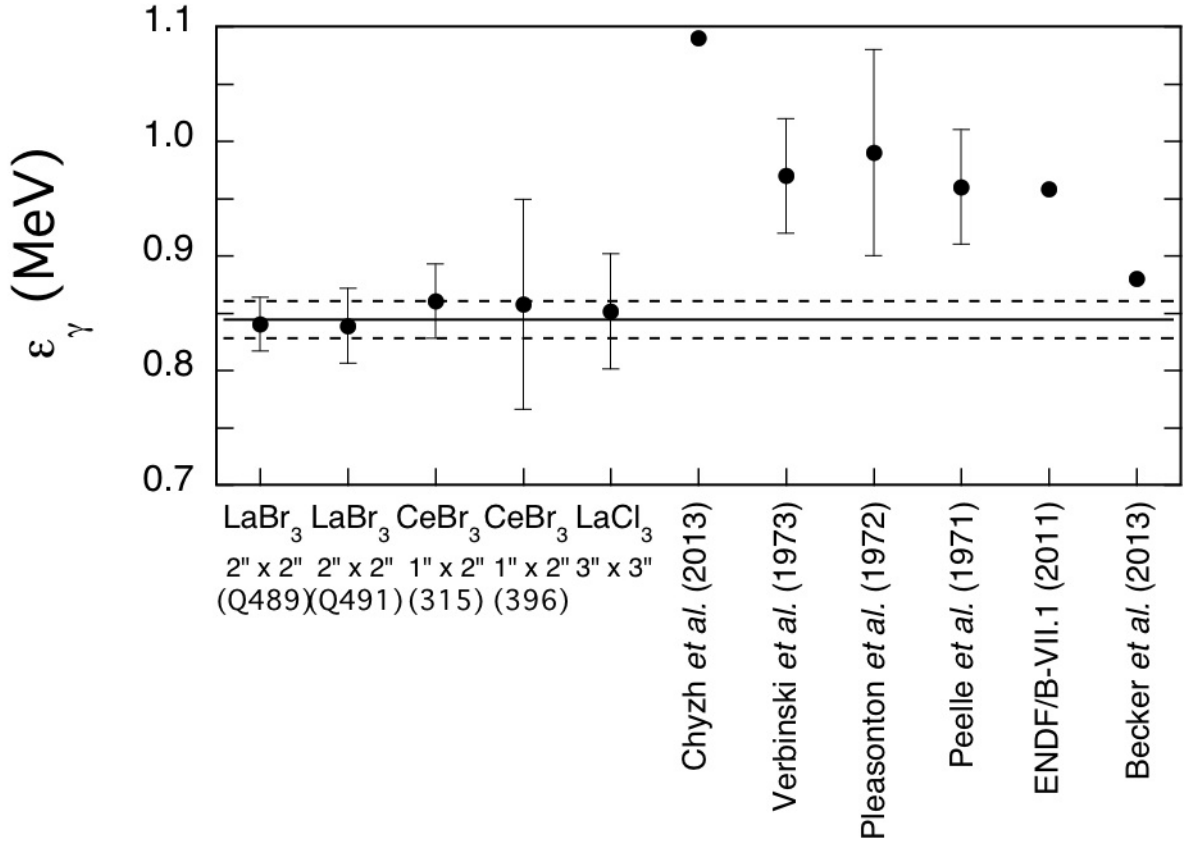
New results - overview

$^{235}U(n_{th}, f)$ PFGS average multiplicity



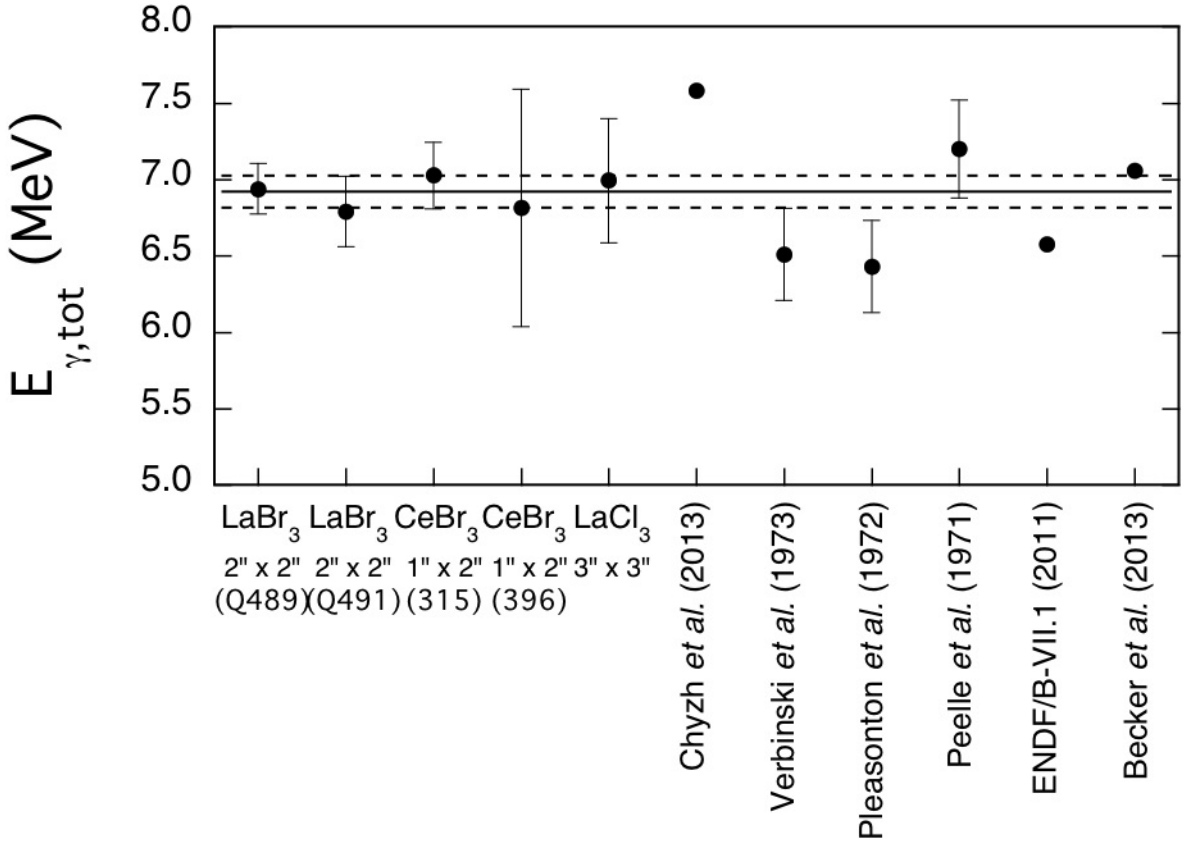
New results - overview

$^{235}U(n_{th}, f)$ PFGS mean energy per photon



New results - overview

$^{235}U(n_{th}, f)$ PFGS total energy per fission



New results - overview

$^{241}Pu(n_{th}, f)$ PFGS characteristics

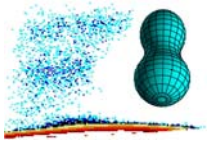


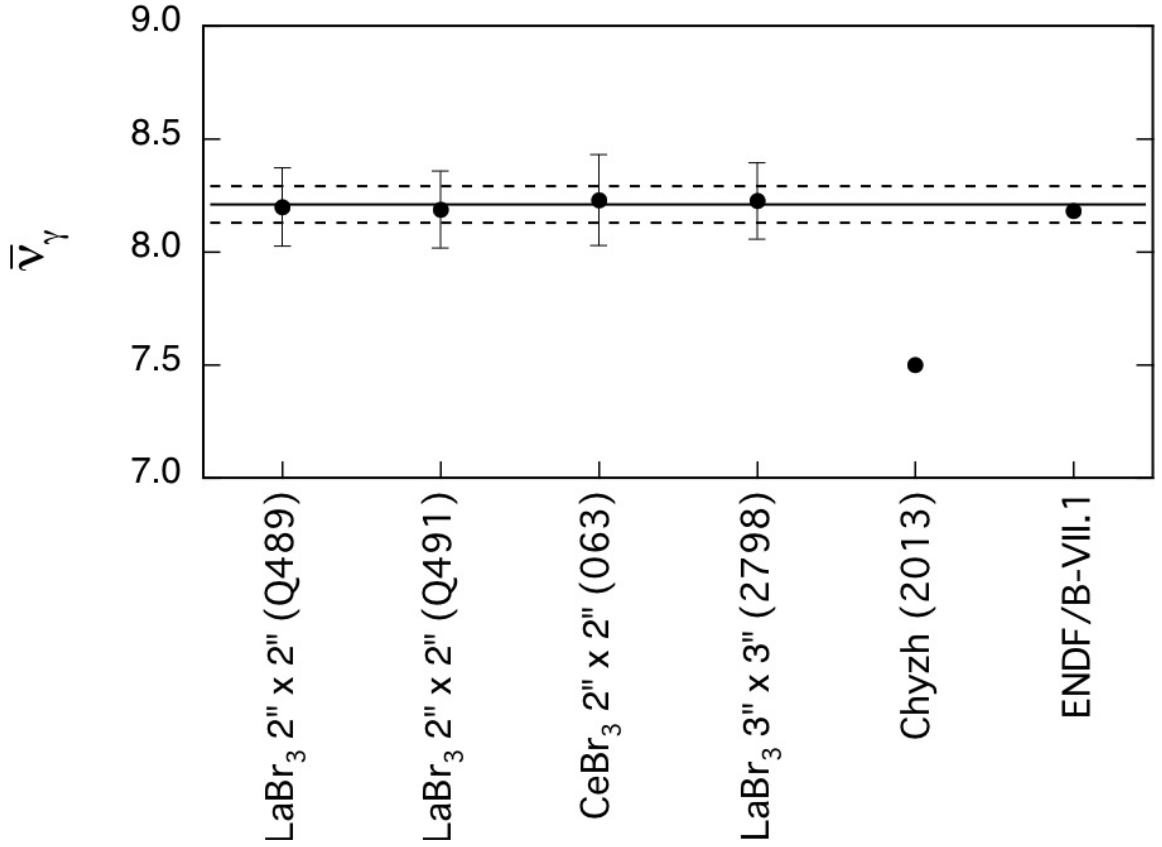
TABLE II. Summary of prompt γ-ray characteristics for the neutron-induced fission of ^{241}Pu. Experimental results from this work for the average γ-ray multiplicity $\overline{\nu}_\gamma$, the average energy ϵ_γ and the total energy $E_{\gamma,tot}$, obtained with all five detectors employed in this work, are given and the covered energy range is indicated. Averaged values for the four detectors are presented as well and compared to the evaluated nuclear data files in ENDF/B-VII.1 [11] and recent data from Chyzh et al.[21]. The uncertainties on their mean values, denoted by *), were estimated from discussed uncertainties in there.

Results	Detector	Diameter × length (cm × cm)	$\overline{\nu}_\gamma$ (per fission)	ϵ_γ (MeV)	$E_{\gamma,tot}$ (MeV)	Energy range (MeV)	
This work	$LaBr_3$:Ce (Q489)	5.08 × 5.08	8.20 ± 0.17	0.78 ± 0.02	6.41 ± 0.12	0.1 - 6.0	
This work	$LaBr_3$:Ce (Q491)	5.08 × 5.08	8.19 ± 0.17	0.78 ± 0.02	6.41 ± 0.12	0.1 - 6.0	
This work	$CeBr_3$ (063)	5.08 × 5.08	8.23 ± 0.20	0.79 ± 0.03	6.48 ± 0.15	0.1 - 6.0	
This work	$LaBr_3$:Ce (2789)	7.62 × 7.62	8.23 ± 0.17	0.78 ± 0.02	6.38 ± 0.11	0.1 - 6.0	
This work	Averaged values		8.21 ± 0.09	0.78 ± 0.01	6.41 ± 0.06	0.1 - 6.0	
ENDF/B-VII.1 [11]	Evaluation		8.18	0.76	6.19	0.1 - 10.0	
Chyzh *et al.* [21]	DANCE (BaF_2)		7.5 ± 0.3	0.92 ± 0.06	6.90 ± 0.53	0.15 - 9.5	*)

manuscript, to be published

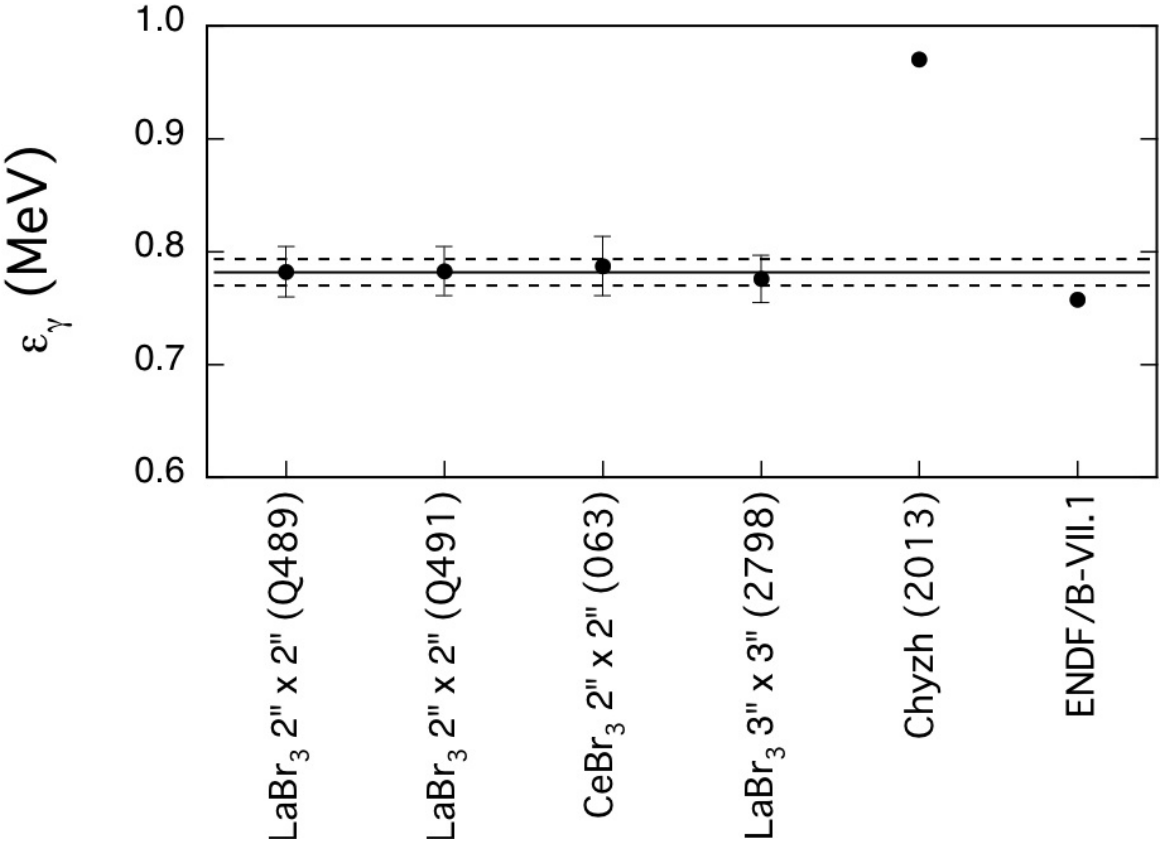
New results - overview

$^{241}Pu(n_{th}, f)$ PFGS average multiplicity



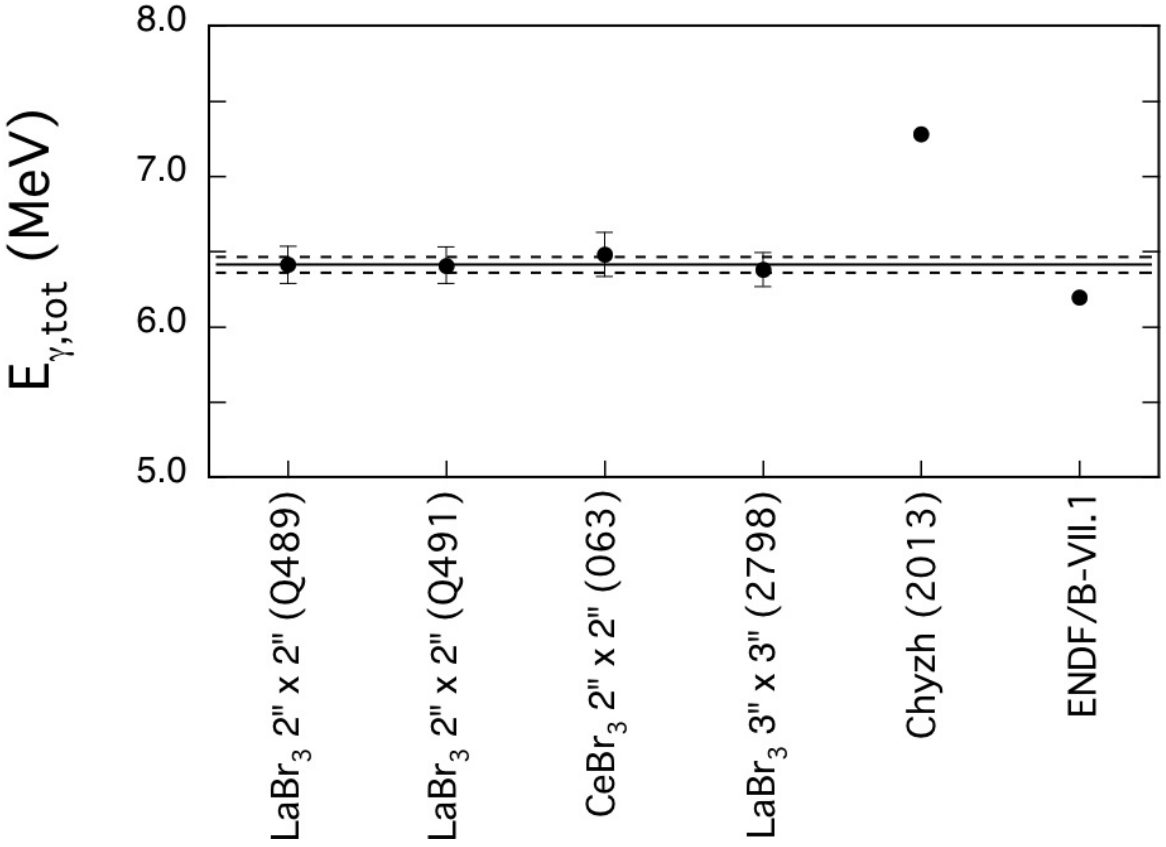
New results - overview

$^{241}Pu(n_{th}, f)$ PFGS mean energy per photon



New results - overview

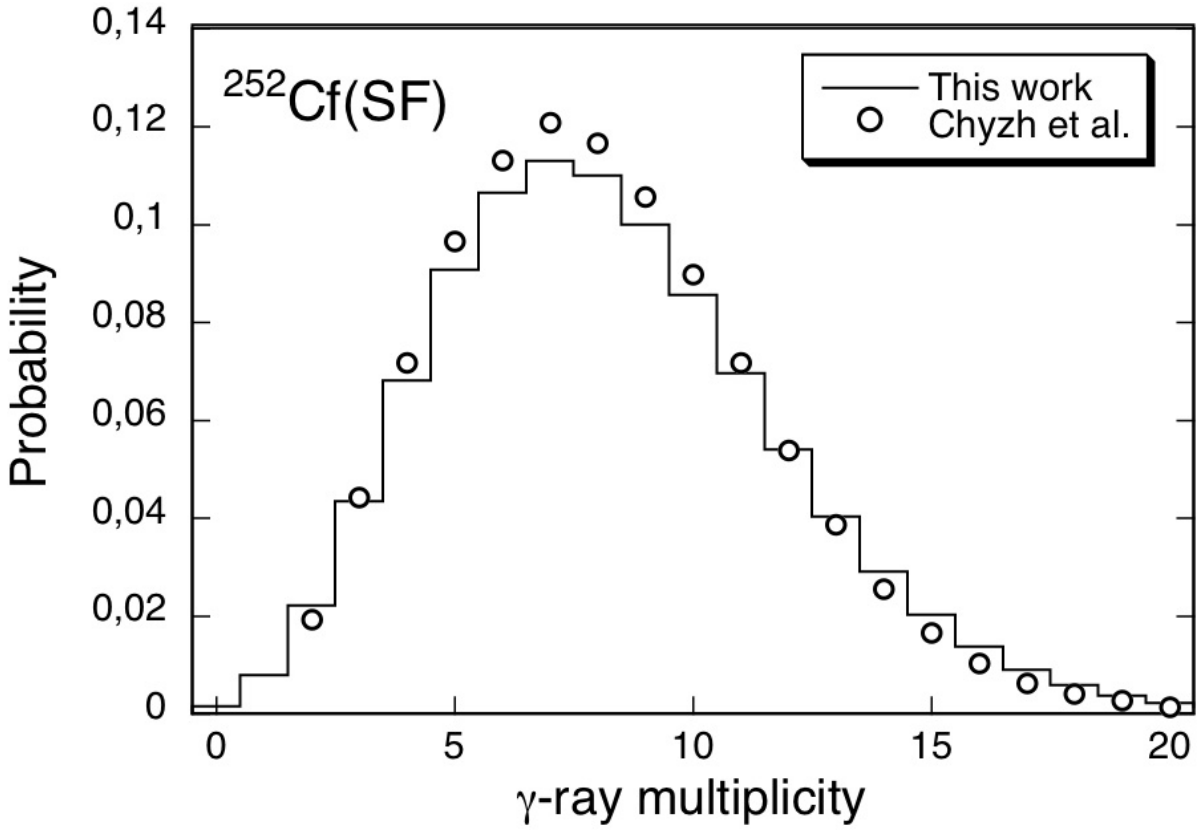
$^{241}Pu(n_{th}, f)$ PFGS total energy per fission



New results

^{252}Cf(sf) PFGS multiplicity distribution

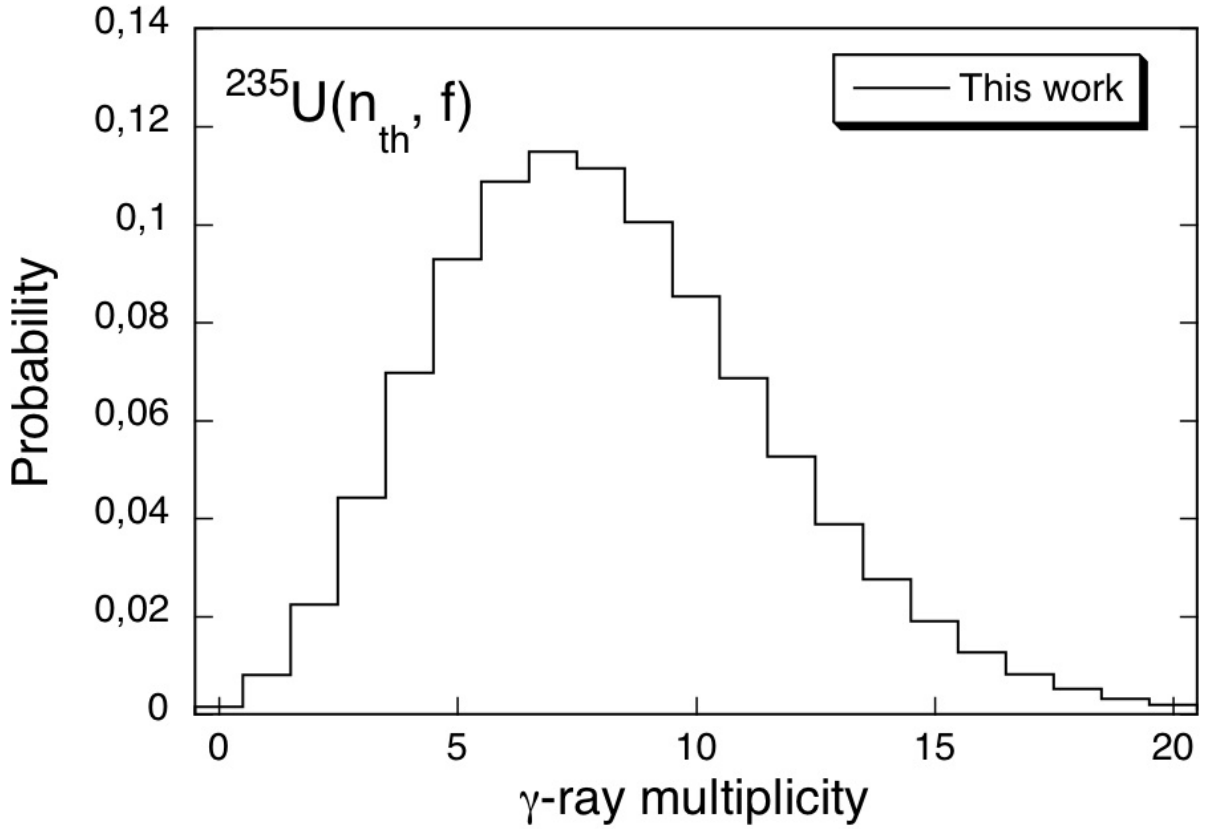
Model: negative binomial distribution (Valentine)



New results

$^{235}U(n_{th}, f)$ PFGS multiplicity distribution

Model: negative binomial distribution (Valentine)



Results

$^{241}Pu(n_{th}, f)$ PFGS multiplicity distribution

Model: negative binomial distribution (Valentine)