Budapest Neutron Centre
Centre for Energy Research

n-induced fission prompt gamma-ray measurements, simulation of neutron capture gamma-ray spectra

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BNC
Budapest Neutron Centre

Hands-on school on nuclear data from Research Reactors, Budapest, Hungary, 25-29 Sept 2023
Supported by the H2020-ARIEL project

BME NTI

Accelerator and Research reactor Infrastructures for
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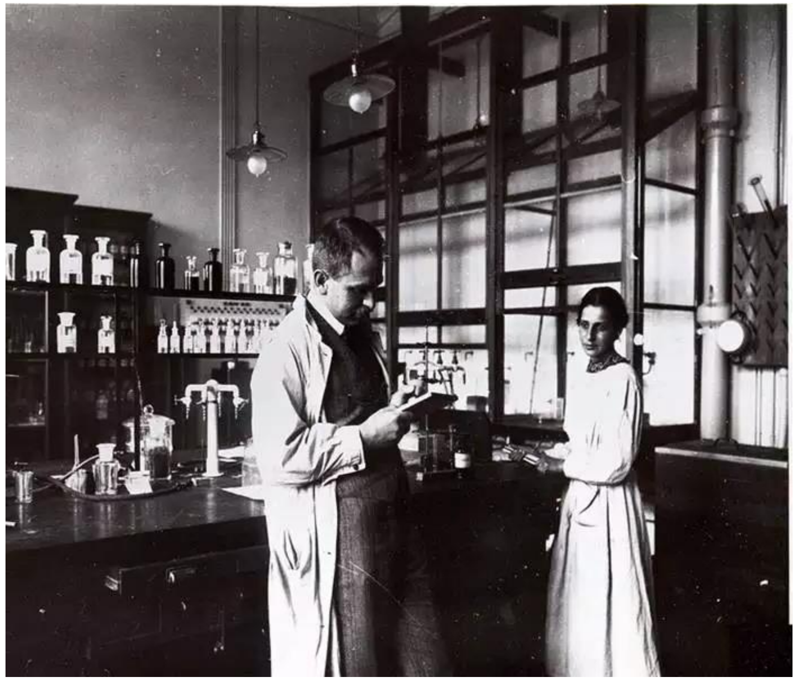
First part

Cold neutron induced fission

Fission of atomic nucleus

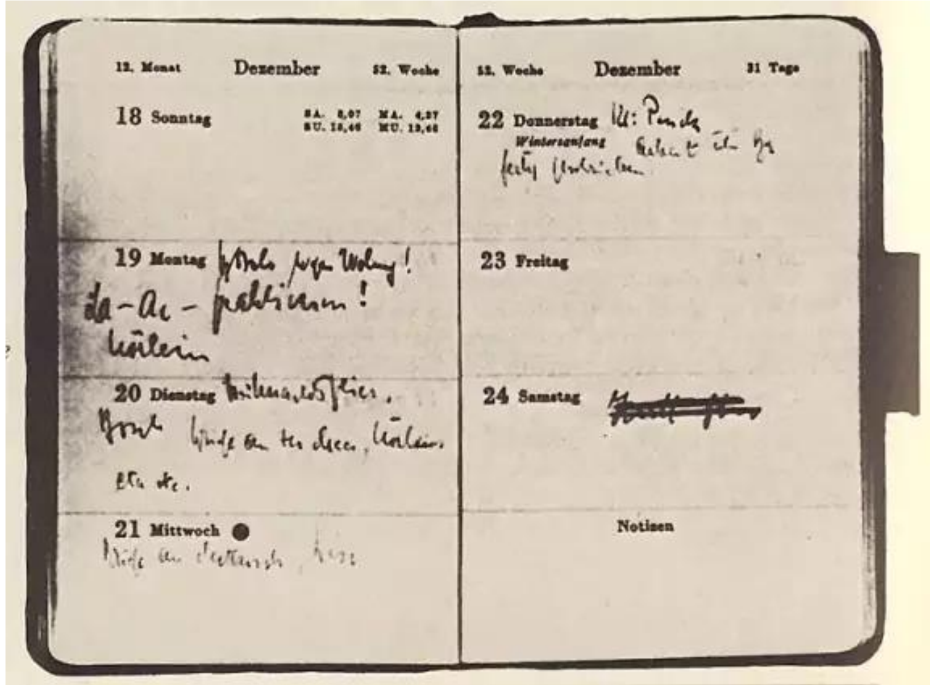
Nuclear fission was discovered at the Kaiser Wilhelm Institute for Chemistry on **19 December 1938**. While bombarding uranium with neutrons, Otto Hahn and his colleague Fritz Straßmann discovered that fission products such as barium were also created in the process.

In January 1939, Lise Meitner and her nephew Otto Frisch provided an explanation, based on the droplet model of the nucleus.



Lise Meitner and Otto Hahn in the Berlin laboratory in 1913. Source: MPG Berlin-Dahlem archive

Information: from Max Plank Institute for Chemistry https://www.mpic.de/3549655/die-entdeckung-der-kernspaltung



12. Monat Dezember 52. Woche

18 Sonntag

19 Montag Bosch wegen Wohnung! La-Ac-Fraktionen! Hörlein

20 Dienstag

21 Mittwoch ●

52. Woche Dezember 31 Tage

22 Donnerstag
Winteranfang

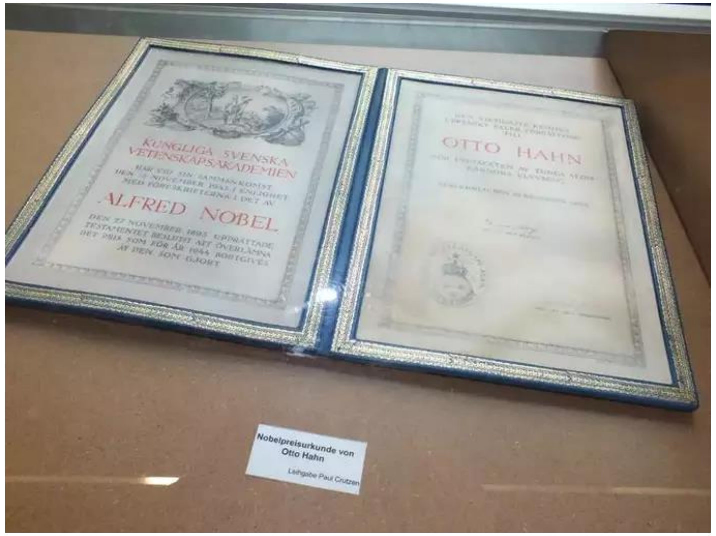
23 Freitag

24 Samstag

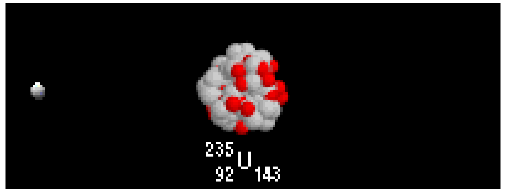
Notizen

Bosch wegen Wohnung! La-Ac-Fraktionen! Hörlein	Bosch for an apartment! La-Ac Fractions! Hörlein

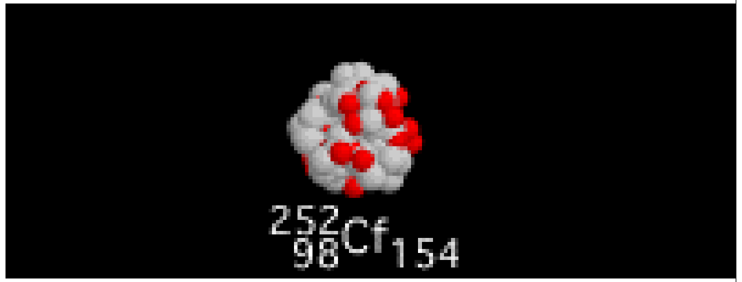
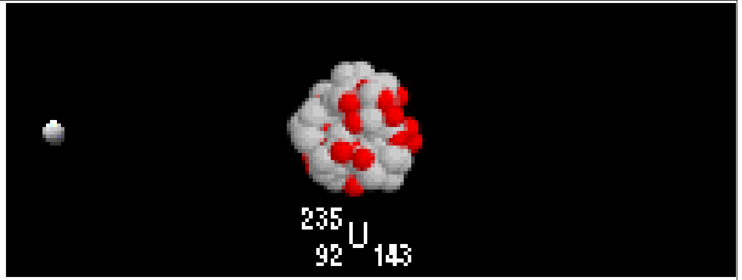
Hahn was probably referring to **Carl Bosch**, then **president** of the KWS, and **Heinrich Hörlein**, then **treasurer** of the Institute.



Nobel Prize certificate from Otto Hahn. Photo Susanne Benner



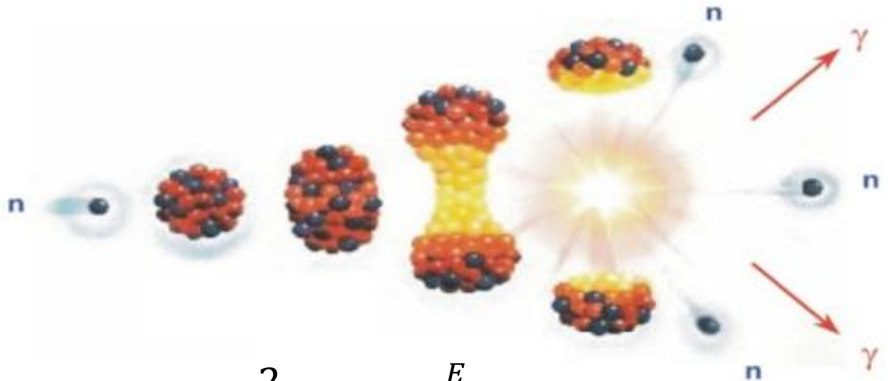
Fission process

Spontaneous	
Induced	

Spontaneous fission can occur above mass number 232. Spontaneous fission is created by the ever-increasing Coulomb interaction through the tunnelling effect.

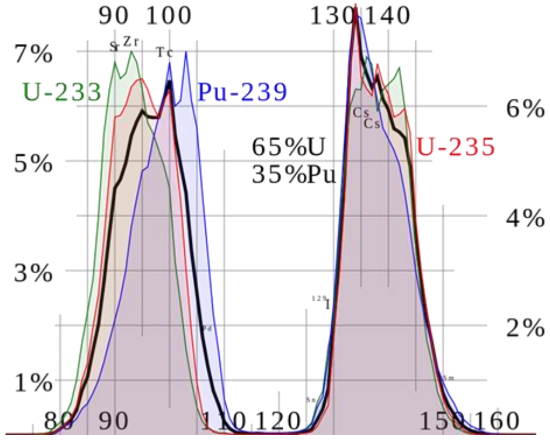
Fission induced by neutron capture (e.g., ^{235}U(n,f) reaction in nuclear reactors). In the case of symmetrical splitting, approx. 200 MeV of energy is released. 0.1% of the mass of the core is converted into energy and an average of 2.4 neutrons are produced. **Chain reaction is possible in reactors!**

Nucleus	Half-life	Spontaneous fission/decay	Neutron/ fission	Neutron/gram/sec
235U	7.04x10^{8} y	2.0x10^{-9}	1.86	3.0x10^{-4}
238U	4.47x10^{9} y	5.4x10^{-7}	2.07	0.0136
239Pu	2.41x10^{4} y	4.4x10^{-12}	2.16	0.022
250Cm	6900 y	0.61	3.31	1.6x10^{10}
252Cf	2.638 y	3.09x10^{-2}	3.73	2.3x10^{12}



$$P(E)=\frac{2}{\sqrt{\pi T_M^3}}\sqrt{E}\,e^{-\frac{E}{T_M}}\mathrm{P(E)}=\ \text{or}\ \ \mathrm{P(E)}=0.4865\cdot\sinh(\sqrt{2E})e^{-E}$$

Fission prompt-neutron energy distribution
(Maxwell) or (Watt)
J. Terrell, PRC 113 (1959) 527-541



Fission products mass-distribution

FP6 EFNUDAT project – fission exp.@BNC

Measurement of the ^{235}U prompt fission-neutron spectrum (PFNS)

Motivation: the shape of the PFNS vs. model shape

Preparation of enriched ^{235}U sample for the time of flight (TOF) experiment on the BNC's PGAA facility in Dec. 2008.

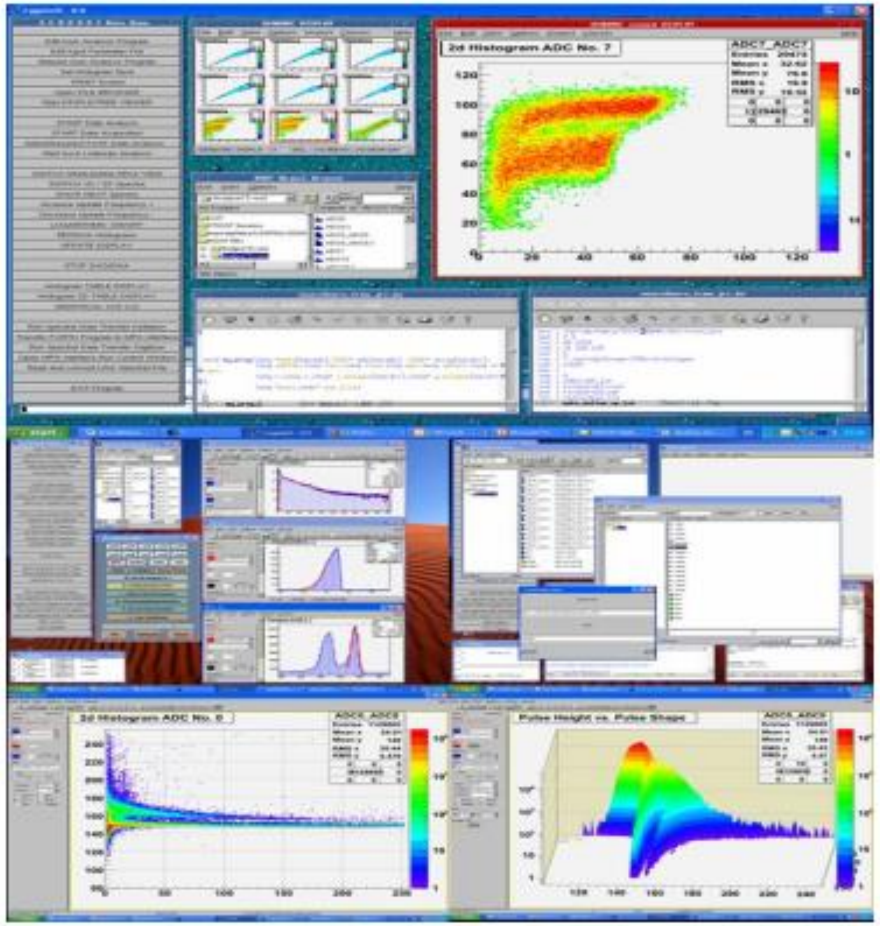
The 3 shielded neutron detectors (LS301 (NE213 equivalent)) placed @ 3 m from the source

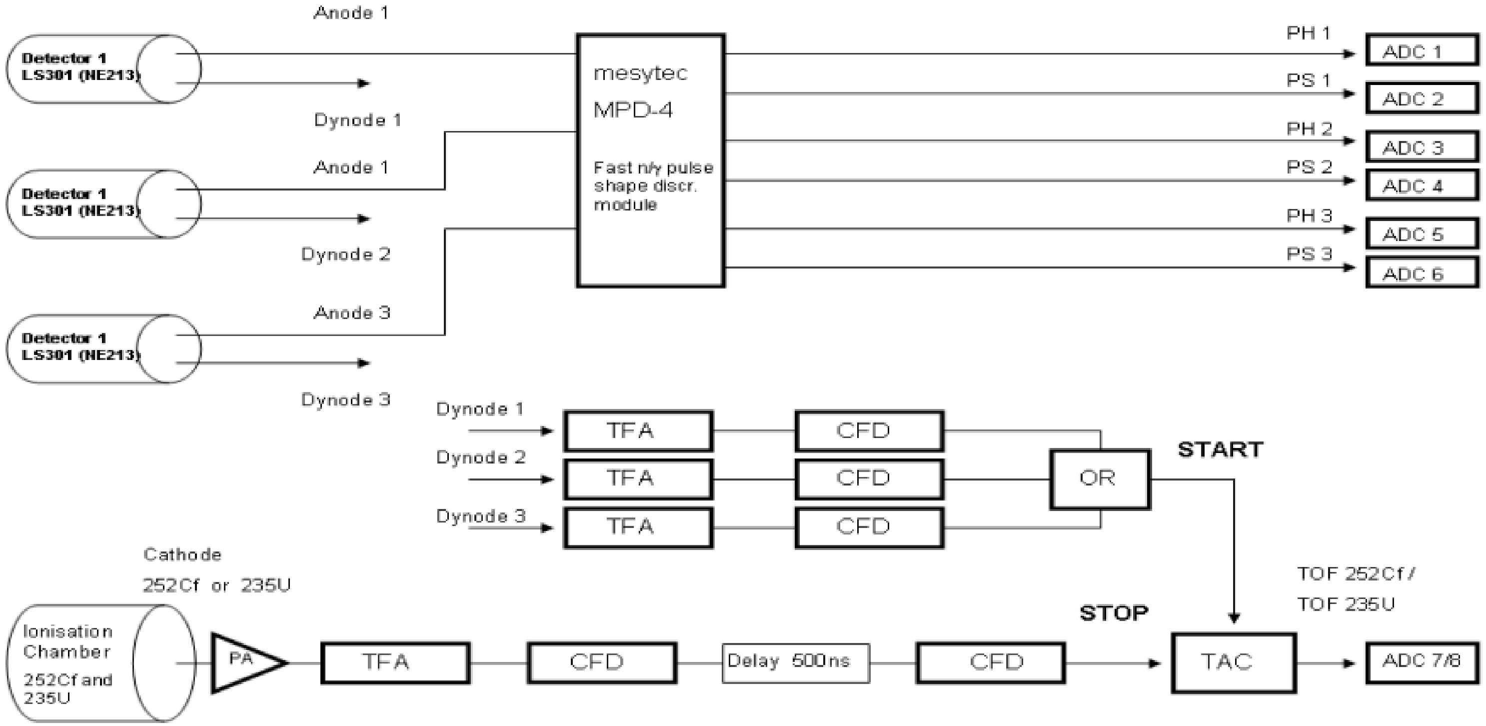
^{235}UF$_4$ ~97.7% enrichment in ^{235}U, ∅=30 mm!

1 Nicolay Kornilov, 2 Zoltán Kis, 3 Franz-Josef Hambsch, 4 Tamás Belgya,
5 Stephan Oberstedt, 6 Imrich Fabry, 7 Lászó Szentmiklósi

Users (1,3,5,6) from JRC IRMM with 2.5-ton instrumentation

Measurement





- Pulse height & pulse shape measured simultaneously for n and γ discrimination
- On-line n/γ discrimination
- Optimised for liquid scintillators
- **STAR** by neutron detectors (rarer signal)
- **STOP** for TOF: by fission chamber
- Acquisition program: **GENDARC** developed; C++-based ROOT (CERN-software)

Kornilov, N., Hambsch, F.-J., Fabry, I., Oberstedt, S., Belgya, T., Kis, Z., Szentmiklosi, L., & Simakov, S. (2010). The ^{235}U(n, f) prompt fission neutron spectrum at 100 K input neutron energy. Nuclear Science and Engineering, 165(1).

Main results

R(E)=C/E is the ratio of the Maxwellian (C) prompt fission neutron spectrum (PFNS) over the measured (E) PFNS

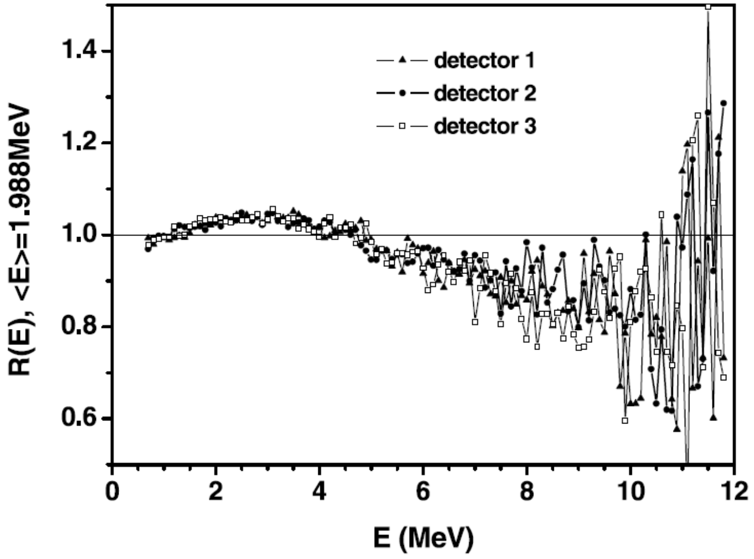
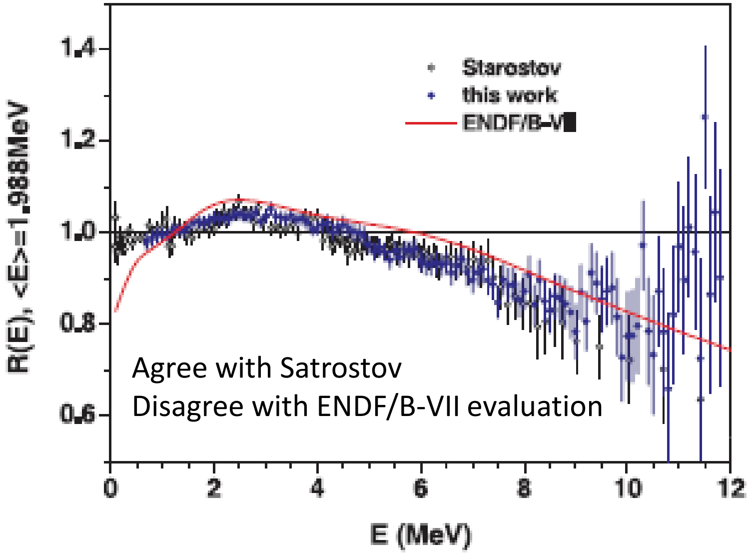


Fig. 6. The PFNS measured by three detectors as a ratio to Maxwellian with average energy $\langle E\rangle = 1.988$ MeV.



Agree with Satrostov

Disagree with ENDF/B-VII evaluation

Fig. 7. Comparison between our results averaged over all detectors and Ref. 18. The data are shown as a ratio to Maxwellian spectra.

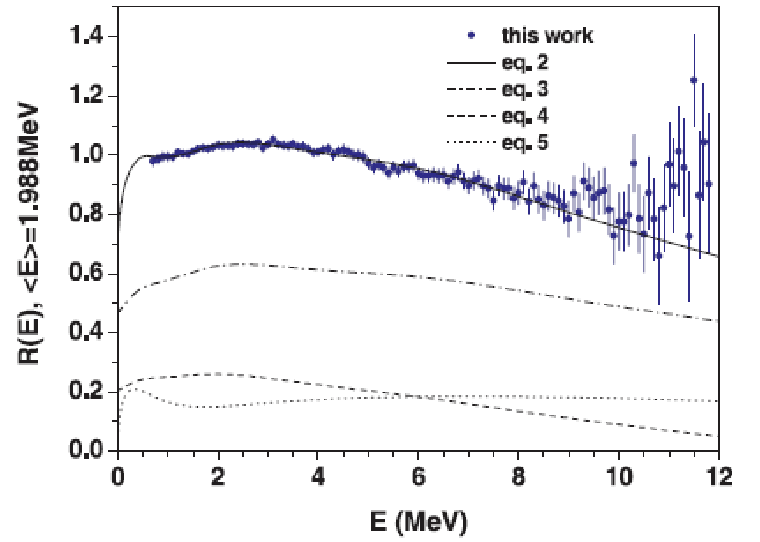


Fig. 14. Experimental spectrum and different components of the three-source model according to Eqs. (1) through (4).

Average Parameters of the PFNS for the Reaction $^{235}U(n_{th}, f)$

Detector Number	Angle (deg)	$\langle E\rangle$ (MeV)	ν-Prompt
1	72	1.987	2.491
2	102	1.990	2.548
3	132	1.987	2.378

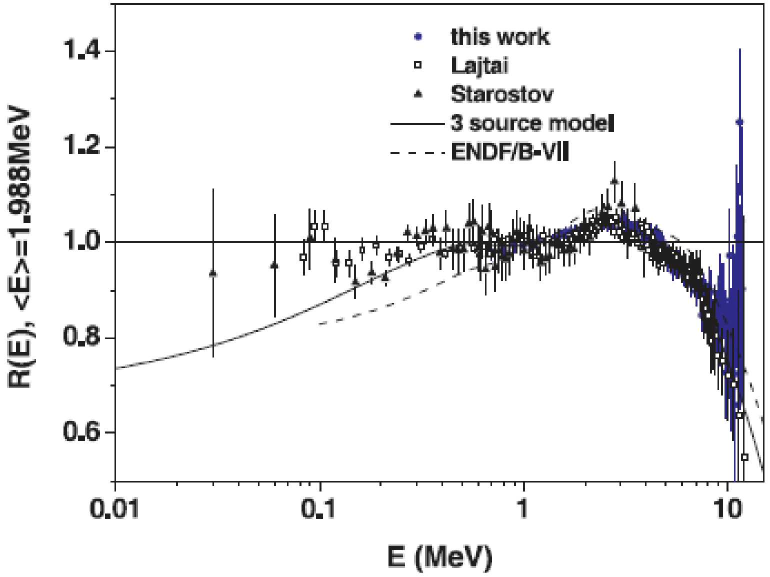


Fig. 15. Experimental spectra, ENDF/B-VII data, and the result of the three-source model calculation in logarithmic scale.

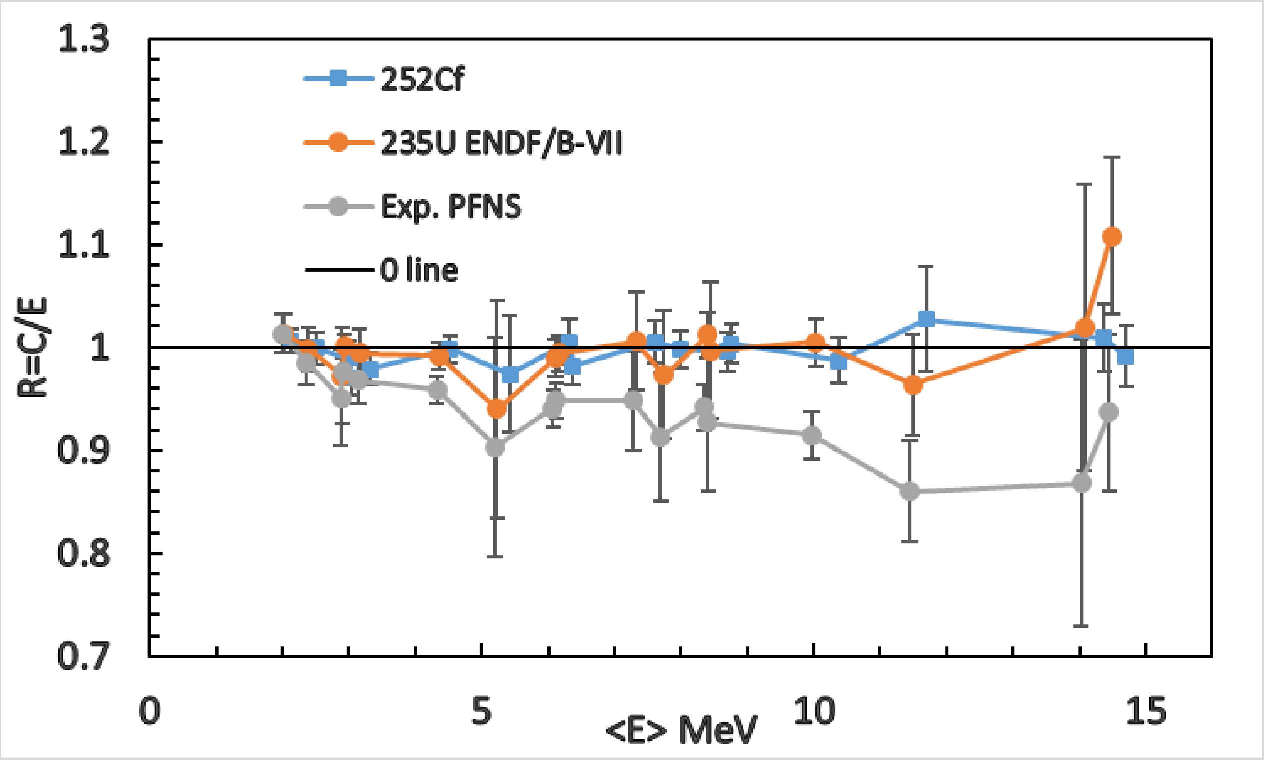
The 3-source model:

1. Neutrons from fragments after fission of nucleus mass# A+1
2. Neutrons from accelerated fragments from fission of nucleus mass# A
3. Scission neutrons (SCN) are ejected just before or under scission

Without SCN the Los Alamos model does not describe the measured PFNS

$\langle E_{cal}\rangle = 1.986$ MeV. The residual chi-square is $\chi^2 = 0.64$.

Integral experiments



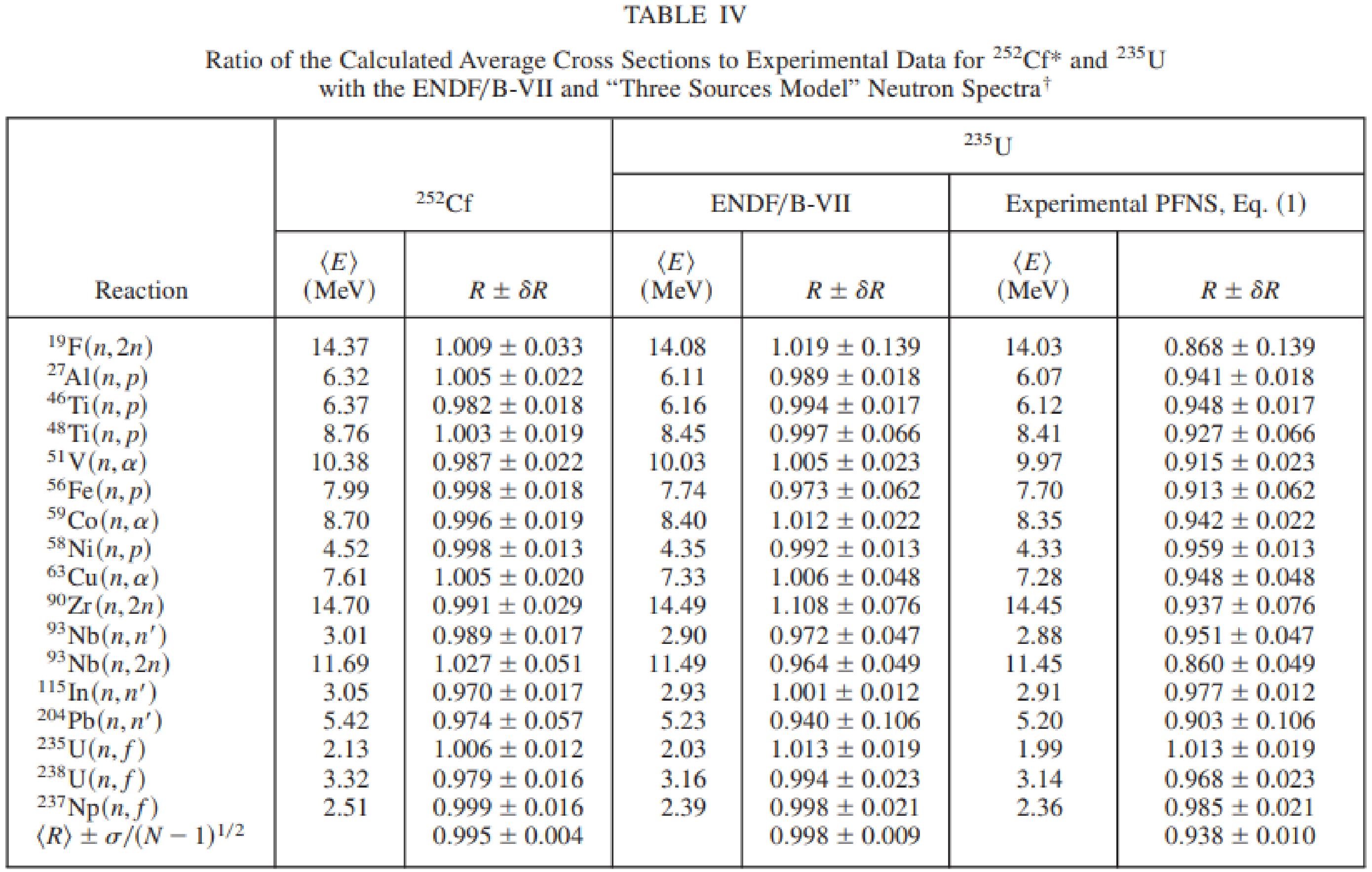


TABLE IV

Ratio of the Calculated Average Cross Sections to Experimental Data for ^{252}Cf* and ^{235}U with the ENDF/B-VII and "Three Sources Model" Neutron Spectra†

Reaction	^{252}Cf		^{235}U			
			ENDF/B-VII		Experimental PFNS, Eq. (1)	
	$\langle E \rangle$ (MeV)	$R \pm \delta R$	$\langle E \rangle$ (MeV)	$R \pm \delta R$	$\langle E \rangle$ (MeV)	$R \pm \delta R$
^{19}F$(n,2n)$	14.37	1.009 ± 0.033	14.08	1.019 ± 0.139	14.03	0.868 ± 0.139
^{27}Al(n,p)	6.32	1.005 ± 0.022	6.11	0.989 ± 0.018	6.07	0.941 ± 0.018
^{46}Ti(n,p)	6.37	0.982 ± 0.018	6.16	0.994 ± 0.017	6.12	0.948 ± 0.017
^{48}Ti(n,p)	8.76	1.003 ± 0.019	8.45	0.997 ± 0.066	8.41	0.927 ± 0.066
^{51}V(n,α)	10.38	0.987 ± 0.022	10.03	1.005 ± 0.023	9.97	0.915 ± 0.023
^{56}Fe(n,p)	7.99	0.998 ± 0.018	7.74	0.973 ± 0.062	7.70	0.913 ± 0.062
^{59}Co(n,α)	8.70	0.996 ± 0.019	8.40	1.012 ± 0.022	8.35	0.942 ± 0.022
^{58}Ni(n,p)	4.52	0.998 ± 0.013	4.35	0.992 ± 0.013	4.33	0.959 ± 0.013
^{63}Cu(n,α)	7.61	1.005 ± 0.020	7.33	1.006 ± 0.048	7.28	0.948 ± 0.048
^{90}Zr$(n,2n)$	14.70	0.991 ± 0.029	14.49	1.108 ± 0.076	14.45	0.937 ± 0.076
^{93}Nb(n,n')	3.01	0.989 ± 0.017	2.90	0.972 ± 0.047	2.88	0.951 ± 0.047
^{93}Nb$(n,2n)$	11.69	1.027 ± 0.051	11.49	0.964 ± 0.049	11.45	0.860 ± 0.049
^{115}In(n,n')	3.05	0.970 ± 0.017	2.93	1.001 ± 0.012	2.91	0.977 ± 0.012
^{204}Pb(n,n')	5.42	0.974 ± 0.057	5.23	0.940 ± 0.106	5.20	0.903 ± 0.106
^{235}U(n,f)	2.13	1.006 ± 0.012	2.03	1.013 ± 0.019	1.99	1.013 ± 0.019
^{238}U(n,f)	3.32	0.979 ± 0.016	3.16	0.994 ± 0.023	3.14	0.968 ± 0.023
^{237}Np(n,f)	2.51	0.999 ± 0.016	2.39	0.998 ± 0.021	2.36	0.985 ± 0.021
$\langle R \rangle \pm \sigma/(N-1)^{1/2}$		0.995 ± 0.004		0.998 ± 0.009		0.938 ± 0.010

Conclusion:

The calculated integral average Xsection does not agree with the experimental one.

What is the physical reason for the formation of a more energetic spectrum in the integral experiments in comparison with microscopic data? And what is happening inside nuclear reactors?

Experimetal average Xsection is measured in 235U fission neutron field and listed in the "Summary Report of the Final Technical Meeting on International Reactor Dosimetry File: IRDF-2002, INDC(NDS)-448 (2003)" https://www-nds.iaea.org/publications/indc/indc-nds-0448.pdf

Centre for Energy Research

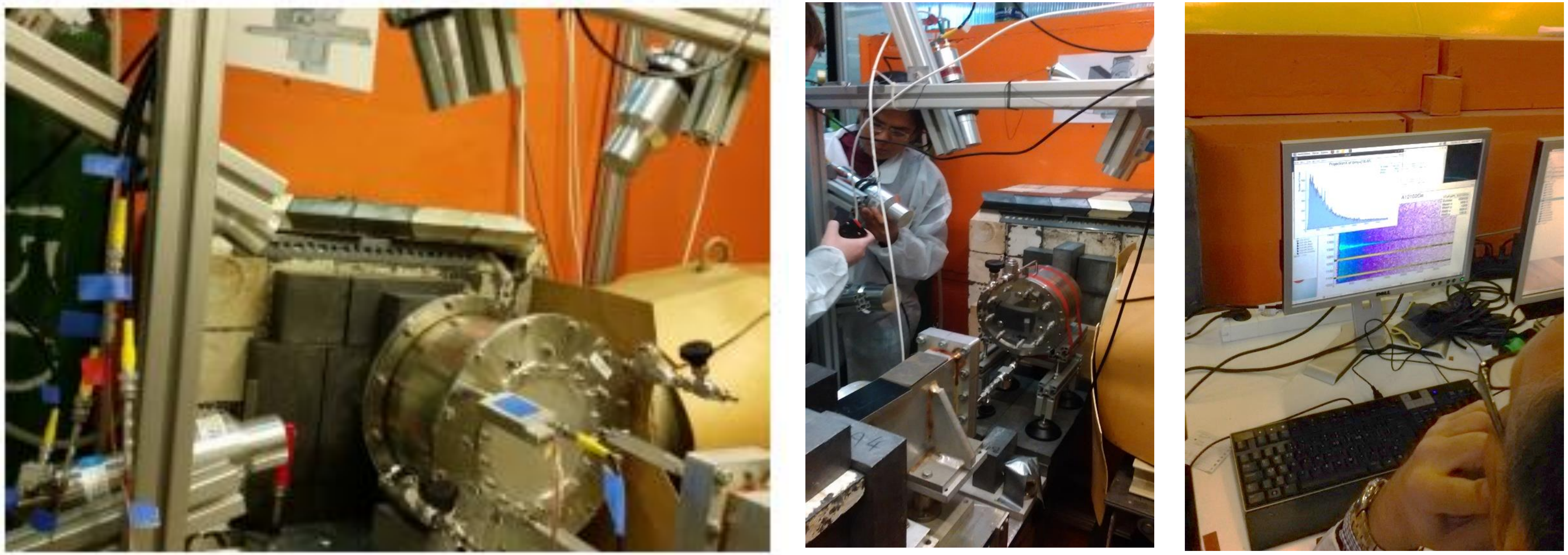
Prompt-fission γ-ray spectra

Budapest Neutron Centre

Motivation

New values especially for γ-ray multiplicity and mean photon energy release per fission in the thermal neutron-induced fission of ^{235}U and ^{239}Pu are requested for GEN IV reactor calculations.

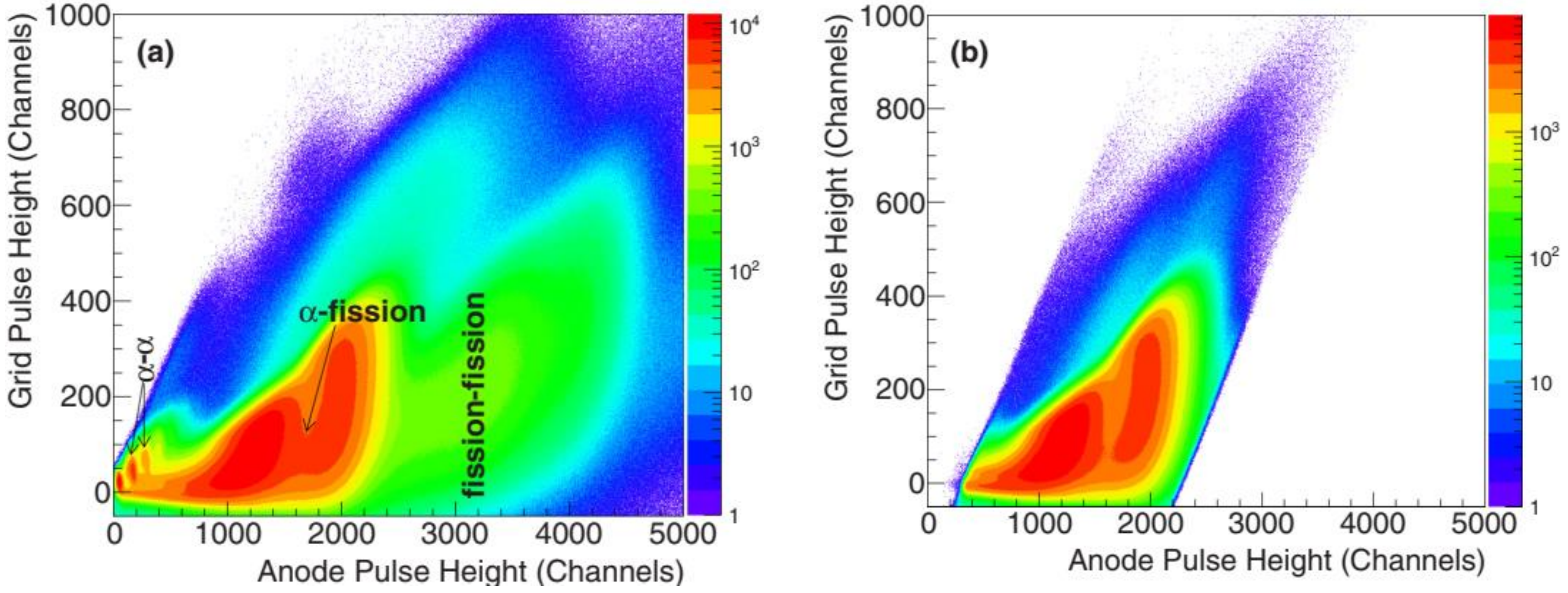
- Prompt-fission γ-rays are the most important source of non-local heating in reactors
- Prompt-fission γ-ray spectra were measured for 3 fissile isotopes of $^{235}\mathrm{U}(n_{cold},f\gamma)$, $^{239}\mathrm{Pu}(n_{cold},f\gamma)$ and $^{241}\mathrm{Pu}(n_{cold},f\gamma)$
- NEA Nuclear Data High Priority Request List: https://www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=421
  Reason: Recent benchmark exercises on nuclear reactors have revealed an underestimation of prompt γ heating by 10% to 28% for ^{235}U and ^{239}Pu
- PhD work of Angelica Gatera from JRC IRMM, Geel was to measure and evaluate PFGS of $^{239}\mathrm{Pu}(n_{cold},f\gamma)$



- Target: 430 μg 99.97% ^{239}Pu
- Frisch-grid ionization Chamber (~ 1 MBq α activity)
- 4 LaBr3:Ce g-ray detectors
- 14-bit wave-form digitizers with a sampling rate of 400 MS/s
- Trigger was on the γ-ray signals, all the signal traces were digitized and saved
- On average 2000 coincidences/s were acquired
- TOF were registered for the g-rays to identify prompt signals

These works were supported by the FP6 EFENUDAT, FP7 ERINDA and CHANDA projects, under Agreement numbers of 31027, 269499 and 605203 respectively. A.Gatera et al. PHYSICAL REVIEW C 95, 064609 (2017) Prompt-fission γ-ray spectral characteristics from 239Pu(n_{th}, f).

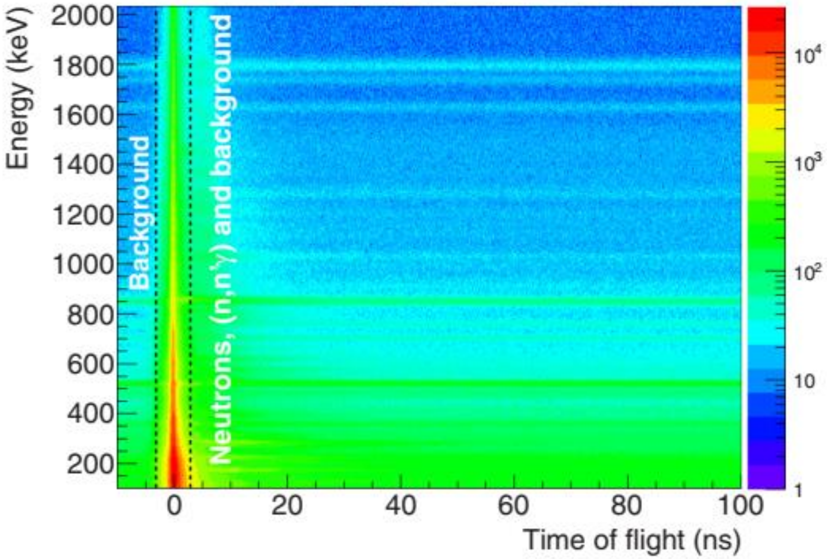
Signal processing



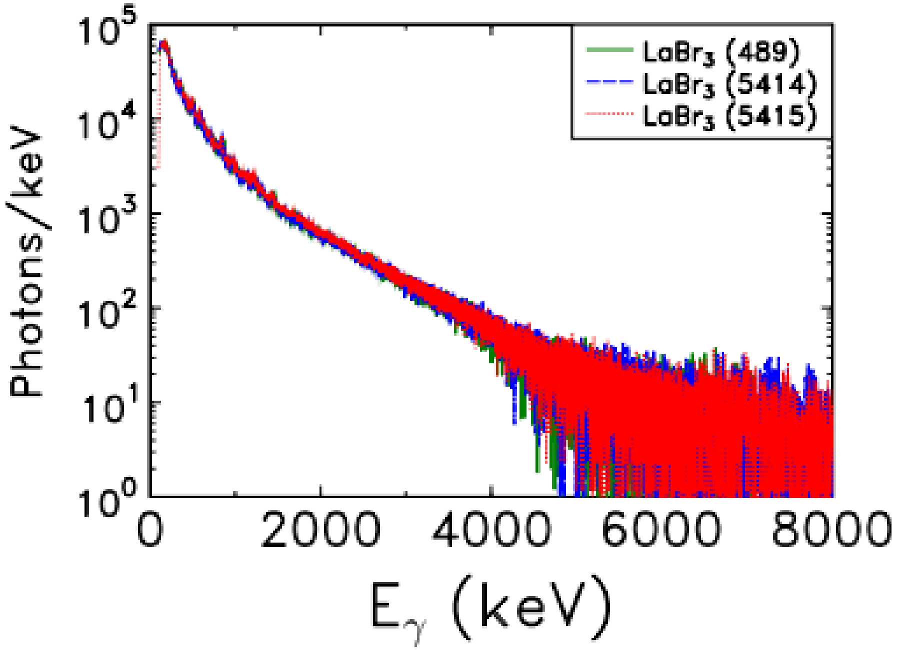
Before

After

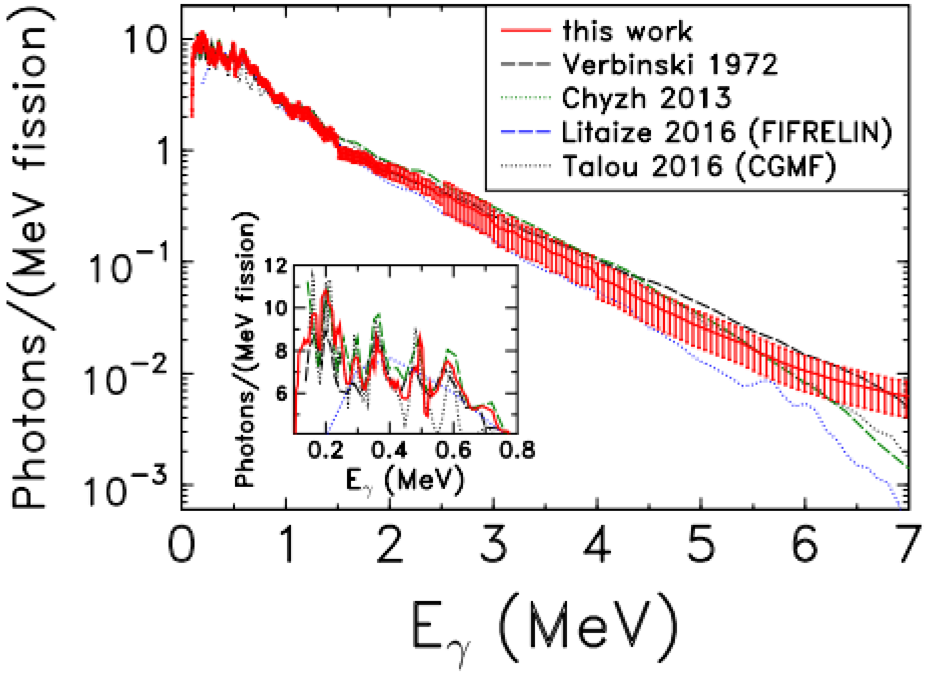
Pileup filtering of α-f, α-α and f-f pileups



Identification of prompt γ-rays
From event time diagram (TOF)



Raw γ-ray spectra of La-Br detectors



Unfolded γ-ray spectra compared to measurements and modelling
The agreement is quite good compared to the uncertainty

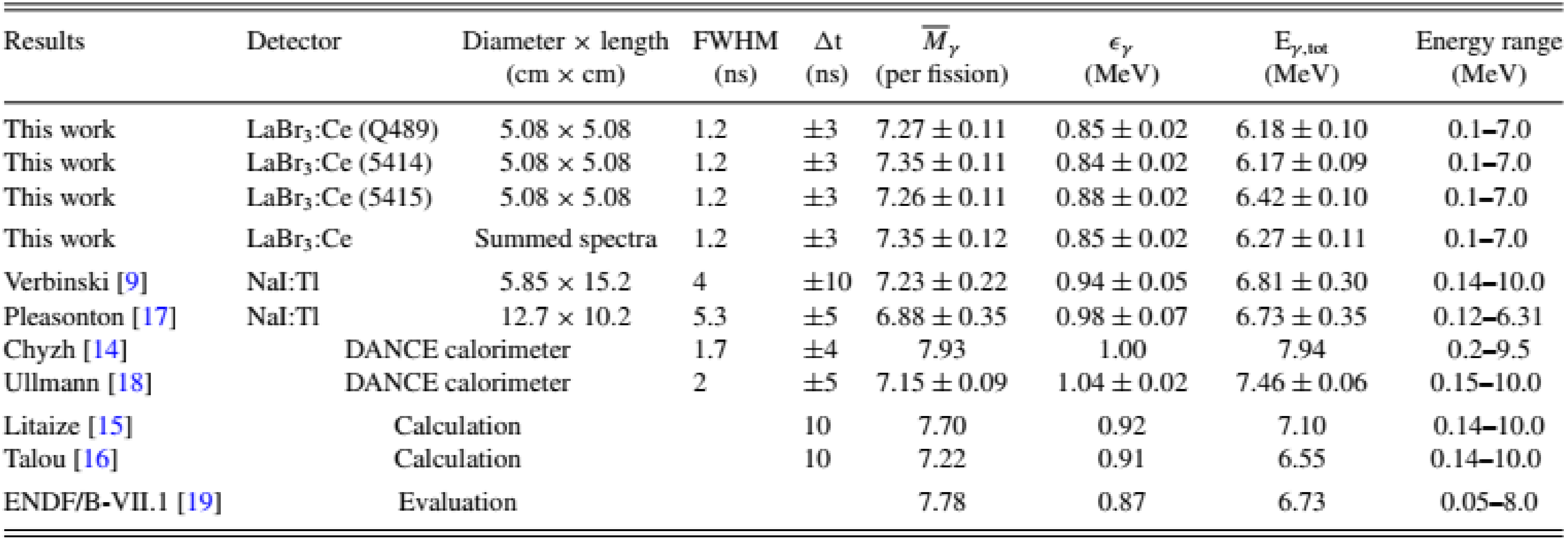
Results & conclusion

Characteristic parameters for prompt-fission γ-ray emission, like the average number of photons per fission, $\overline{M}_\gamma$, the average total energy per fission, $E_{\gamma,tot}$, and the mean photon energy, ε_γ , were obtained according to

$$\overline{M}_\gamma = \int N_\gamma(E_\gamma)dE_\gamma,$$

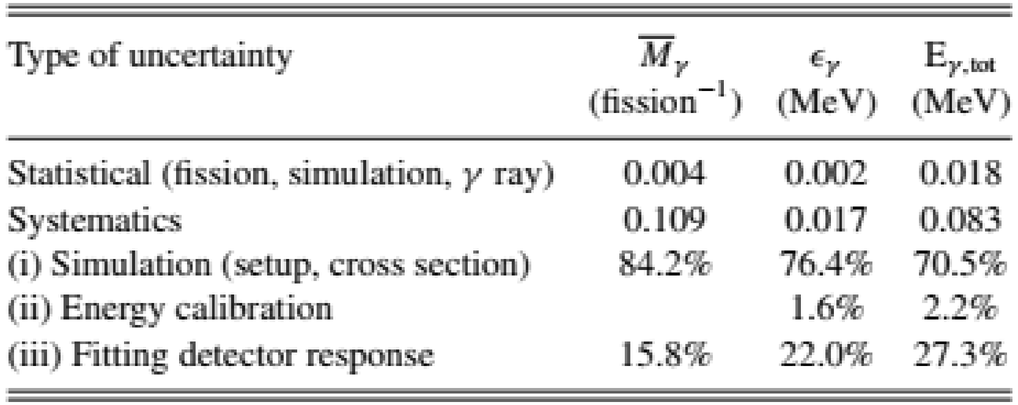
$$E_{\gamma,\mathrm{tot}} = \int E_\gamma \times N_\gamma(E_\gamma)dE_\gamma,$$

$$\epsilon_\gamma = E_{\gamma,\mathrm{tot}}/\overline{M}_\gamma,$$



Results	Detector	Diameter × length (cm × cm)	FWHM (ns)	Δt (ns)	$\overline{M}_\gamma$ (per fission)	ϵ_γ (MeV)	$E_{\gamma,\mathrm{tot}}$ (MeV)	Energy range (MeV)
This work	LaBr$_3$:Ce (Q489)	5.08 × 5.08	1.2	±3	7.27 ± 0.11	0.85 ± 0.02	6.18 ± 0.10	0.1–7.0
This work	LaBr$_3$:Ce (5414)	5.08 × 5.08	1.2	±3	7.35 ± 0.11	0.84 ± 0.02	6.17 ± 0.09	0.1–7.0
This work	LaBr$_3$:Ce (5415)	5.08 × 5.08	1.2	±3	7.26 ± 0.11	0.88 ± 0.02	6.42 ± 0.10	0.1–7.0
This work	LaBr$_3$:Ce	Summed spectra	1.2	±3	7.35 ± 0.12	0.85 ± 0.02	6.27 ± 0.11	0.1–7.0
Verbinski [9]	NaI:Tl	5.85 × 15.2	4	±10	7.23 ± 0.22	0.94 ± 0.05	6.81 ± 0.30	0.14–10.0
Pleasonton [17]	NaI:Tl	12.7 × 10.2	5.3	±5	6.88 ± 0.35	0.98 ± 0.07	6.73 ± 0.35	0.12–6.31
Chyzh [14]	DANCE calorimeter		1.7	±4	7.93	1.00	7.94	0.2–9.5
Ullmann [18]	DANCE calorimeter		2	±5	7.15 ± 0.09	1.04 ± 0.02	7.46 ± 0.06	0.15–10.0
Litaize [15]	Calculation			10	7.70	0.92	7.10	0.14–10.0
Talou [16]	Calculation			10	7.22	0.91	6.55	0.14–10.0
ENDF/B-VII.1 [19]	Evaluation				7.78	0.87	6.73	0.05–8.0

- New PFGS characteristics for ^{239}Pu(*n,f*) were measured with high statistical accuracy.
- Our results are in good agreement, within uncertainties, with other published results.
- We have found quite small deviations from the evaluated nuclear data in ENDF/B-VII.1, too small to explain the observed shortcomings with respect to benchmark calculations, thus **we can exclude that thermal-neutron-induced fission causes to the underestimation of γ heating**.



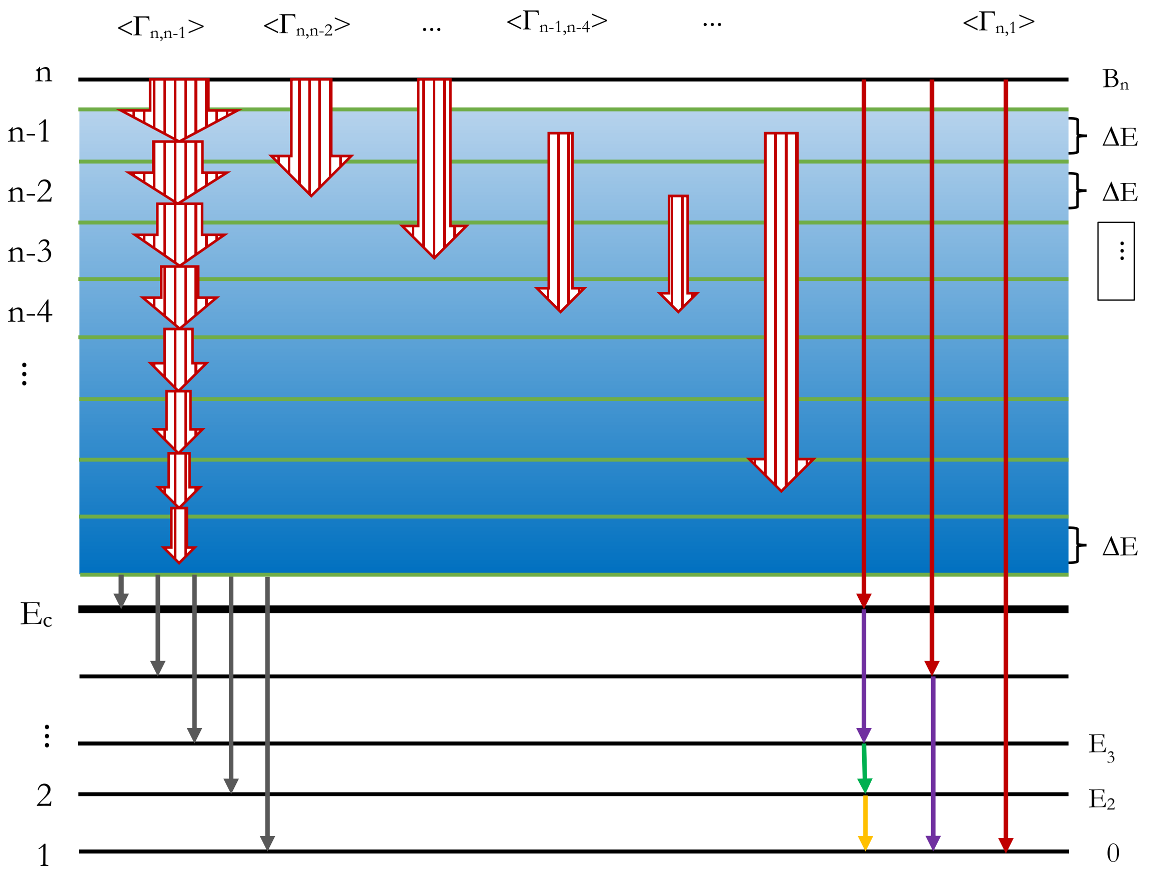
Type of uncertainty	$\overline{M}_\gamma$ (fission^{-1})	ϵ_γ (MeV)	$E_{\gamma,\mathrm{tot}}$ (MeV)
Statistical (fission, simulation, γ ray)	0.004	0.002	0.018
Systematics	0.109	0.017	0.083
(i) Simulation (setup, cross section)	84.2%	76.4%	70.5%
(ii) Energy calibration		1.6%	2.2%
(iii) Fitting detector response	15.8%	22.0%	27.3%

Second part

Simulation of neutron capture gamma-ray spectra

Introduction to simulating γ-ray spectra

- Importance of Photon Strength Functions (PSF) in theoretical modelling of nuclear reactions is clear, since γ-decay is frequently a competing outgoing channel in the reaction.
- The (n,γ) reactions play a major role in the nuclear reactor operation, production of medical isotopes and in the synthesis of elements.
- There are two kinds of modelling of γ-decays following capture between levels of the excited nucleus
  - DICEBOX like Monte Carlo model where discrete nuclear levels are created randomly from a level density model, then γ-decay cascades are generated by the Porter-Thomas distributions around the PSF values between the generated discrete levels, keeping the spin-parity selection rules. Finally an average is made by creating many nuclear level-scheme realisations.
  - Bin type model where the levels within an energy bin are considered to decay the same way determined by the average g-width calculated from the PSF and spin-parity selection rules
- Both models are using the low-laying decay scheme up to the so called critical energies E_c



${}^{A}\mathbf{X}(\mathbf{n},\gamma)^{A+1}\mathbf{X}$

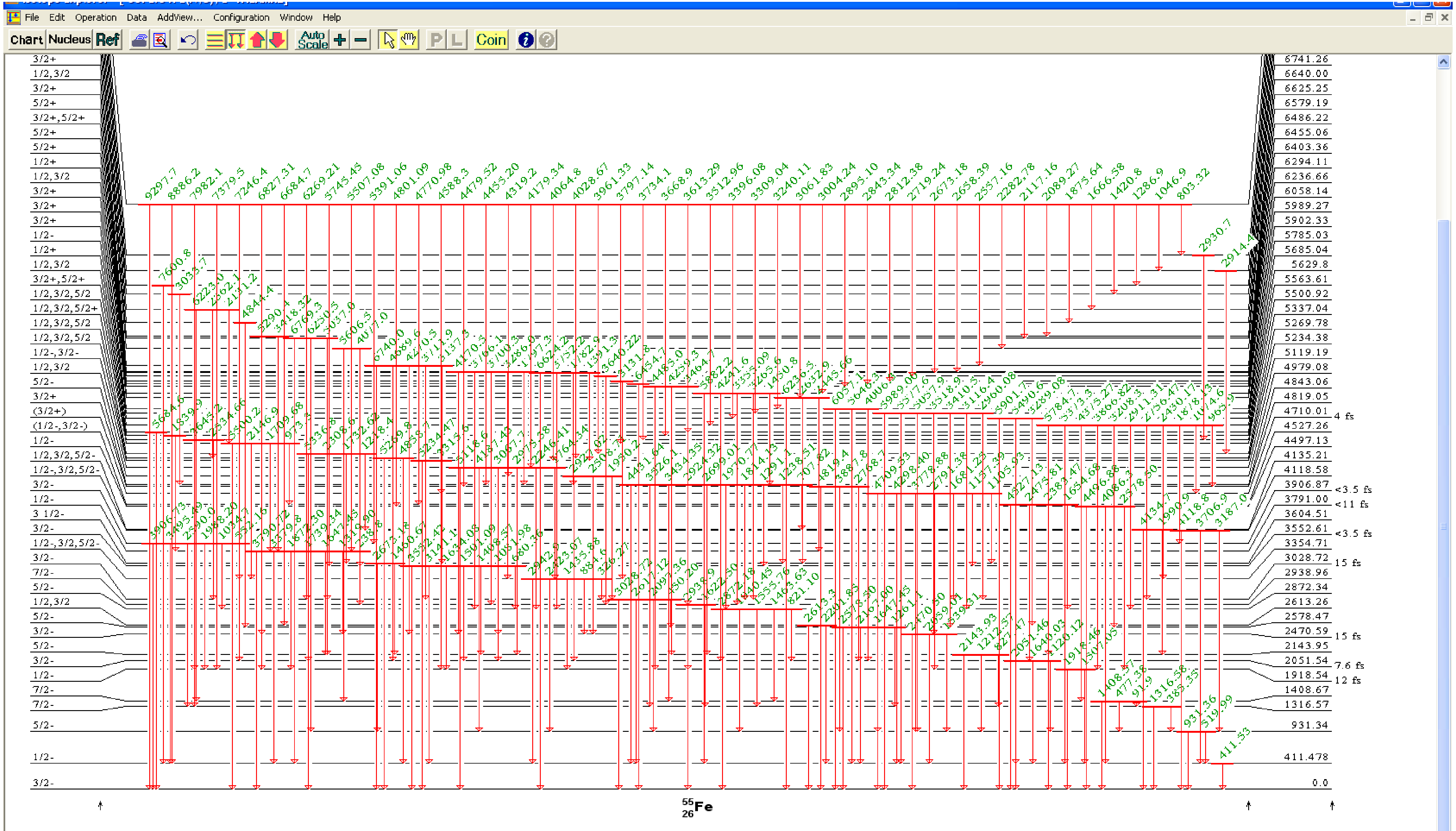
Axel-Brink hypothesis is that the average level width $\langle\Gamma_\gamma\rangle$ can be described with the product of PSF and the average level distance

$$E_i = E_f - E_\gamma \,;\, \Gamma = \hbar/\tau \ \ wehre\ \tau\ is\ lifetime\ of\ states$$

PSF: $\overleftarrow{f}_{XL,f}(E_\gamma) = \dfrac{\langle\Gamma_{\gamma,f}\rangle}{E_\gamma^{(2L+1)} D_{l,i}}$ for decay   Partial level width: $\langle\Gamma_{\gamma,f}\rangle = E_\gamma^{(2L+1)}\overleftarrow{f}_{XL,f}(E_\gamma) D_{l,i}$ where *D* is the average level distance

For simple n–capture decay scheme

Like ^{55}Fe from ^{54}Fe(n,γ)^{55}Fe reaction



From partial γ-ray prod. Xs to total capture Xs

Method	Equation	Notes
1	$\sigma_{th} = \dfrac{\sigma_\gamma}{\theta P_\gamma}$	P_γ must be known, for example from beta decay if the captured nucleus is unstable.
2	$\sigma_{th} = \sum_{f=1}^{n-1} \sigma_{\gamma\, C \to f} (1 + \alpha_f + PCC_f)$	The sum of all primary transitions from the capture state can be used for nuclei with a relatively simple decay scheme. Conversion α and pair conversion PCC coefficients must be known for methods 2-5.
3	$\sigma_{th} = \sum_{i=2}^{n} \sigma_{\gamma\, i \to g.s.} (1 + \alpha_i + PCC_i)$	The sum of all ground state transitions can be used for nuclei with a relatively simple decay scheme.
4	$Q = \min\left(\sum_{\substack{1 \le f \le n-1 \\ 1 \le s \le n-1}} (T_f - \sigma_{th}) w_{f,s} (T_s - \sigma_{th}) \right)$	Well balanced and relatively simple decay scheme. See Ref. for definition of *T* and *w*.
5	$\sigma_{th} = \sum_i E_i \sigma_{\gamma i} (1 + \alpha_i + PCC_i) / B_n$	The energy weighted sum can be used for any nuclei with unfolded gamma-spectrum, B_n is the binding energy.

For nuclei with simple decay scheme

For any nuclei

T is the so call crossing intensity sum in Eq. (4), which must be constant

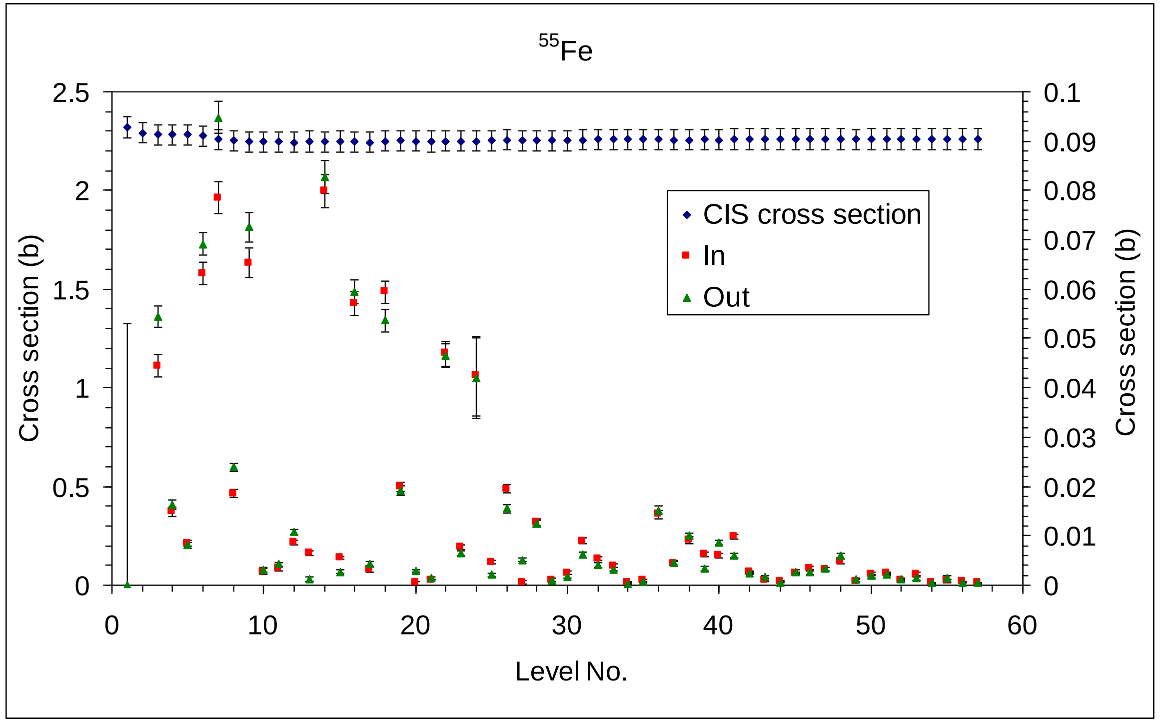
Belgya, T., Improved accuracy of gamma-ray intensities from basic principles for the calibration reaction $^{14}N(n,\gamma)^{15}N$. Physical Review C, 74, 024603-1-8(2006)

Example ^{54}Fe(n,γ)^{55}Fe

Evaluation of Mughabghab

Isotope	abundance %	thermal Xsection (b)	Uncertainty
Fe-00		2.56±0.03	1%
Fe-54	5.845	2.25±0.18	8%
Fe-56	91.754	2.59±0.14	5%
Fe-57	2.119	2.48±0.3	12%
Fe-58	0.282	1.28±0.05	4%

Xsection uncertainty of this basic structural material is surprising



Sum of primaries	2.26(5) b
Sum of g.s.	2.32(5) b
Energy weighted	2.26(4) b
Mughabghab	2.25(18) b

- New measurement on highly enriched isotopes (^{54,56,57}Fe) were done in the EFNUDAT project (F. Gunsing) in Budapest on the BNC PGAA facility
- The thin metallic sample were received from CERN to check the purity
- However from these experiments the thermal neutron cross section can also be obtained
- Evaluation of the data is in collaboration with Richard B, Firestone (LBNL)

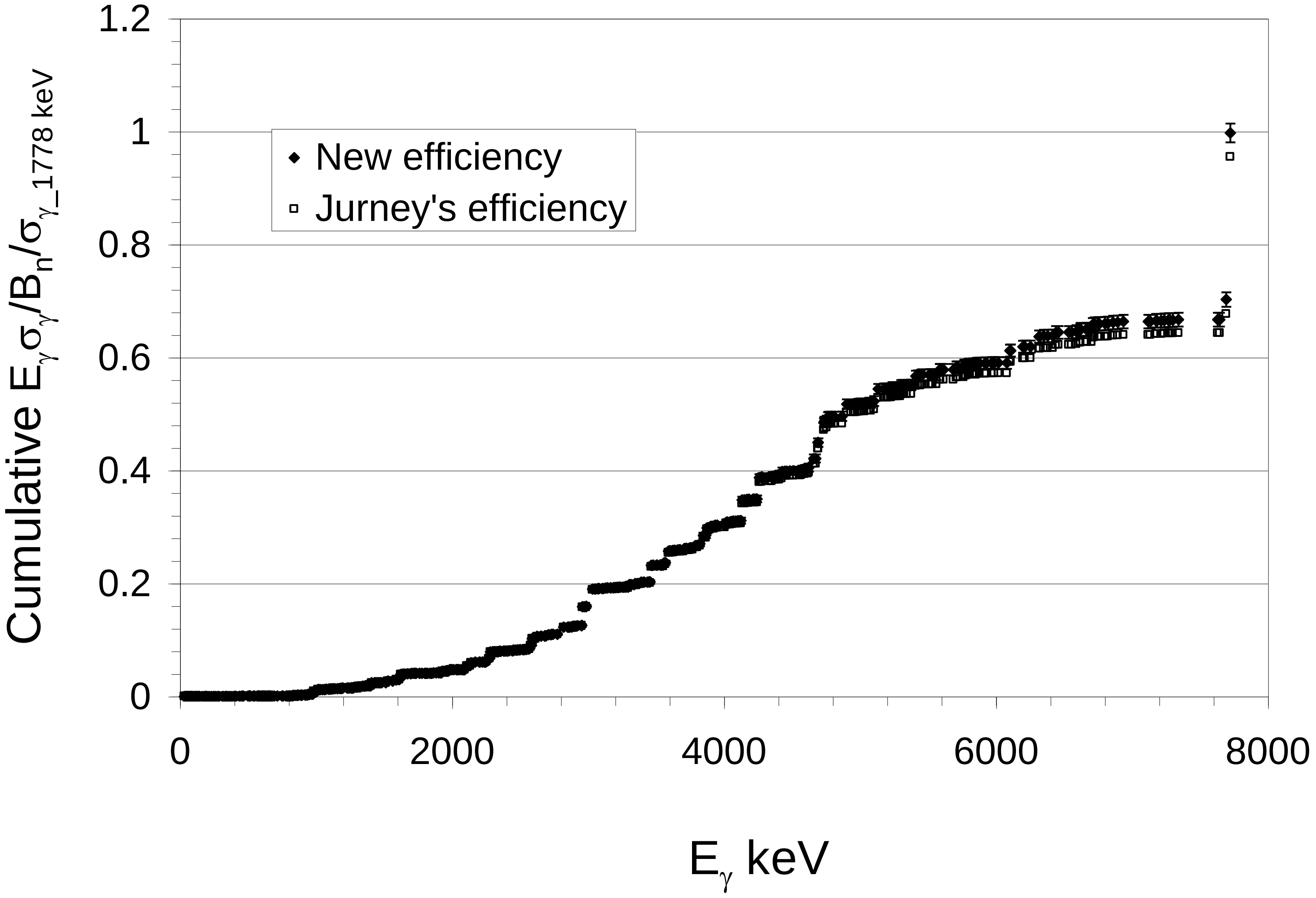
-The new Xsection agrees with Mughabghab’s eval.

-The bigger value for g.s. sum may indicates week invisible transitions and/or some small inconsistency of the low vs. high energy detection efficiency

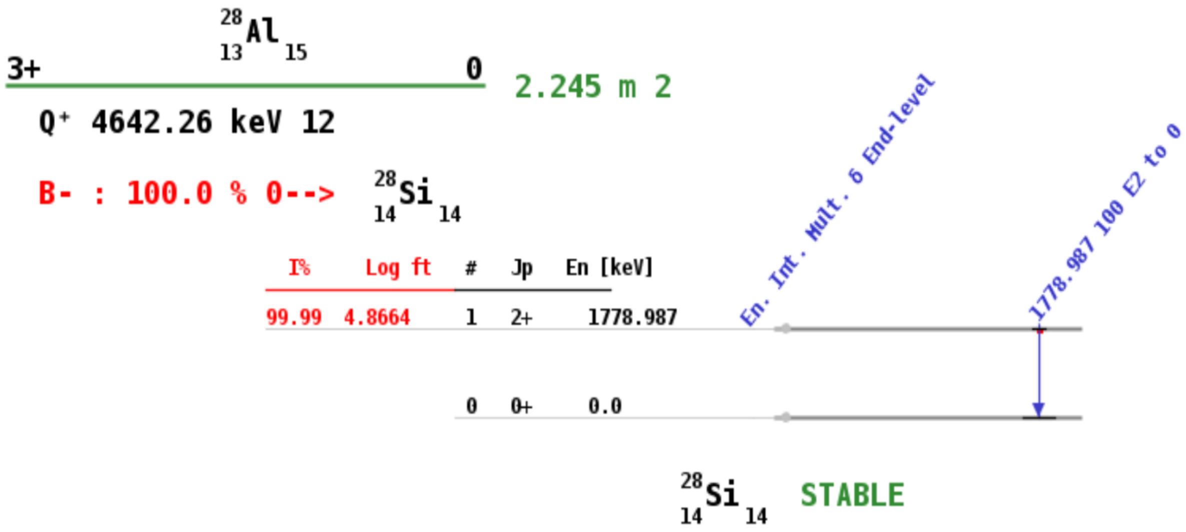
-Uncertainty decreased to 2%

Using Eq. (5) for ^{27}Al(n,γ)^{28}Al(β^-)^{28}Si

Cumulative energy weighted intensity (σ_γ) sum for ^{27}Al(n,γ) fitted peaks, method 5



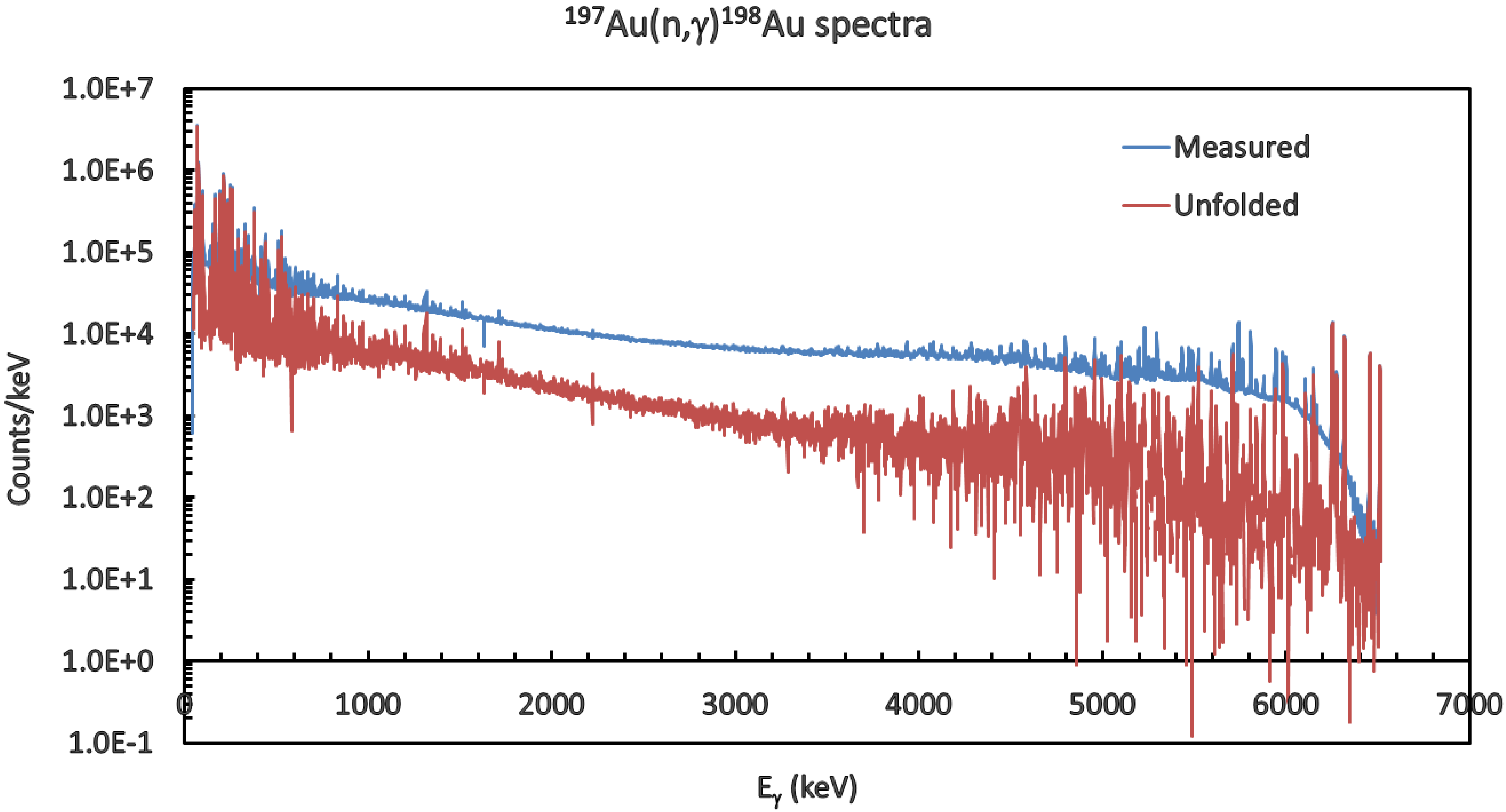
Al checks the New intensities of the high energy nitrogen calibration standard



From LiveChart of nuclei
https://www.iaea.org/resources/databases/livechart-of-nuclides-advanced-version

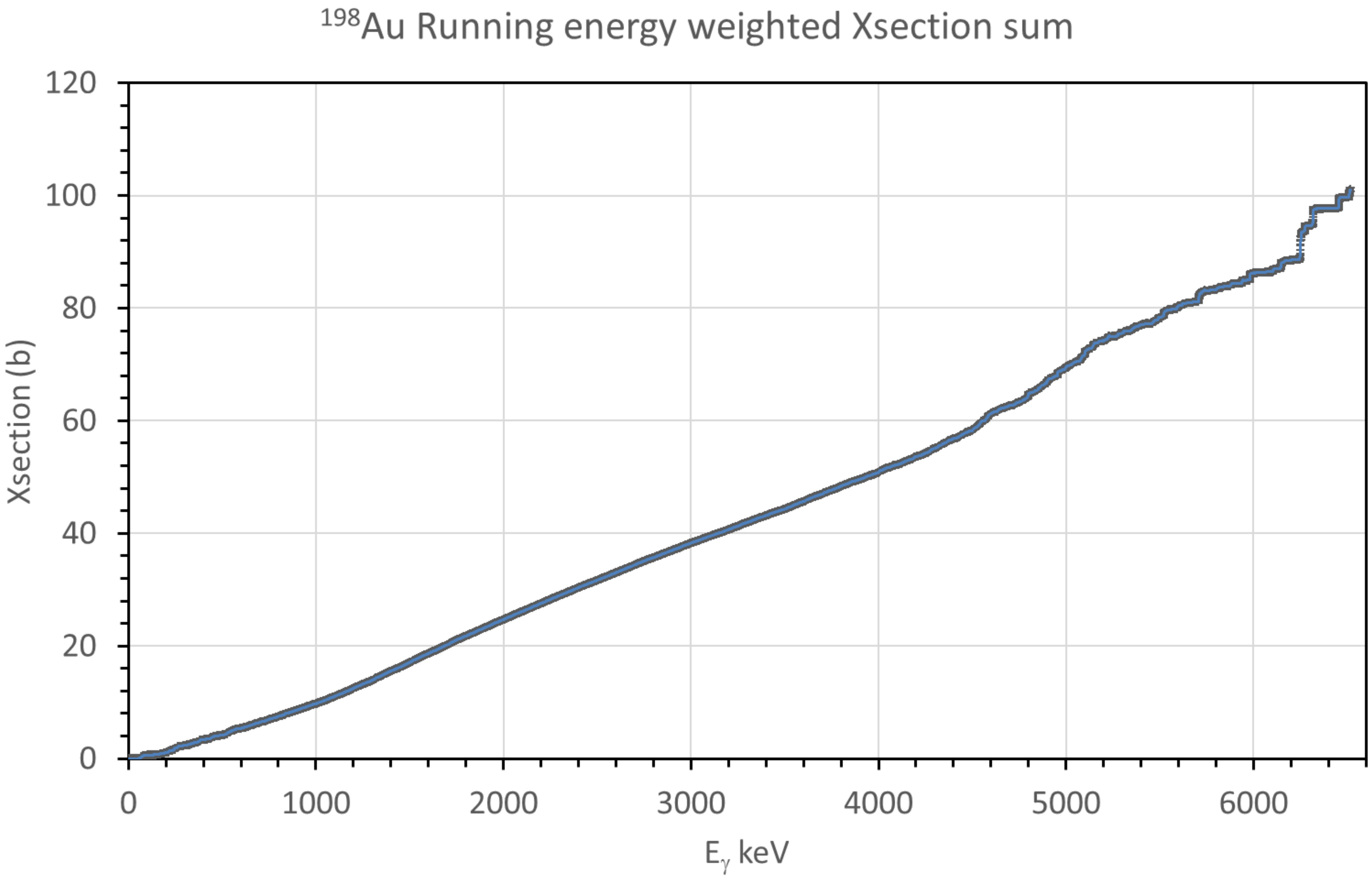
Belgya, T. (2008). New gamma-ray intensities for the ^{14}N(n,γ)^{15}N high energy standard and its influence on PGAA and on nuclear quantities. *Journal of Radioanalytical and Nuclear Chemistry*, *276*(3). https://doi.org/10.1007/s10967-008-0607-9

More complicated spectrum



Belgya, T., & Szentmiklósi, L. (2021). Monte-Carlo calculated detector response functions to unfold radiative neutron capture spectra. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *991*(December 2020), 165018. https://doi.org/10.1016/j.nima.2021.165018

Response function corrected spectra $^{197}Au(n,\gamma)^{198}Au$



$\sigma_{\gamma,tot} =$ 101.05 (37) b

Adding low energy, conversion electron contribution

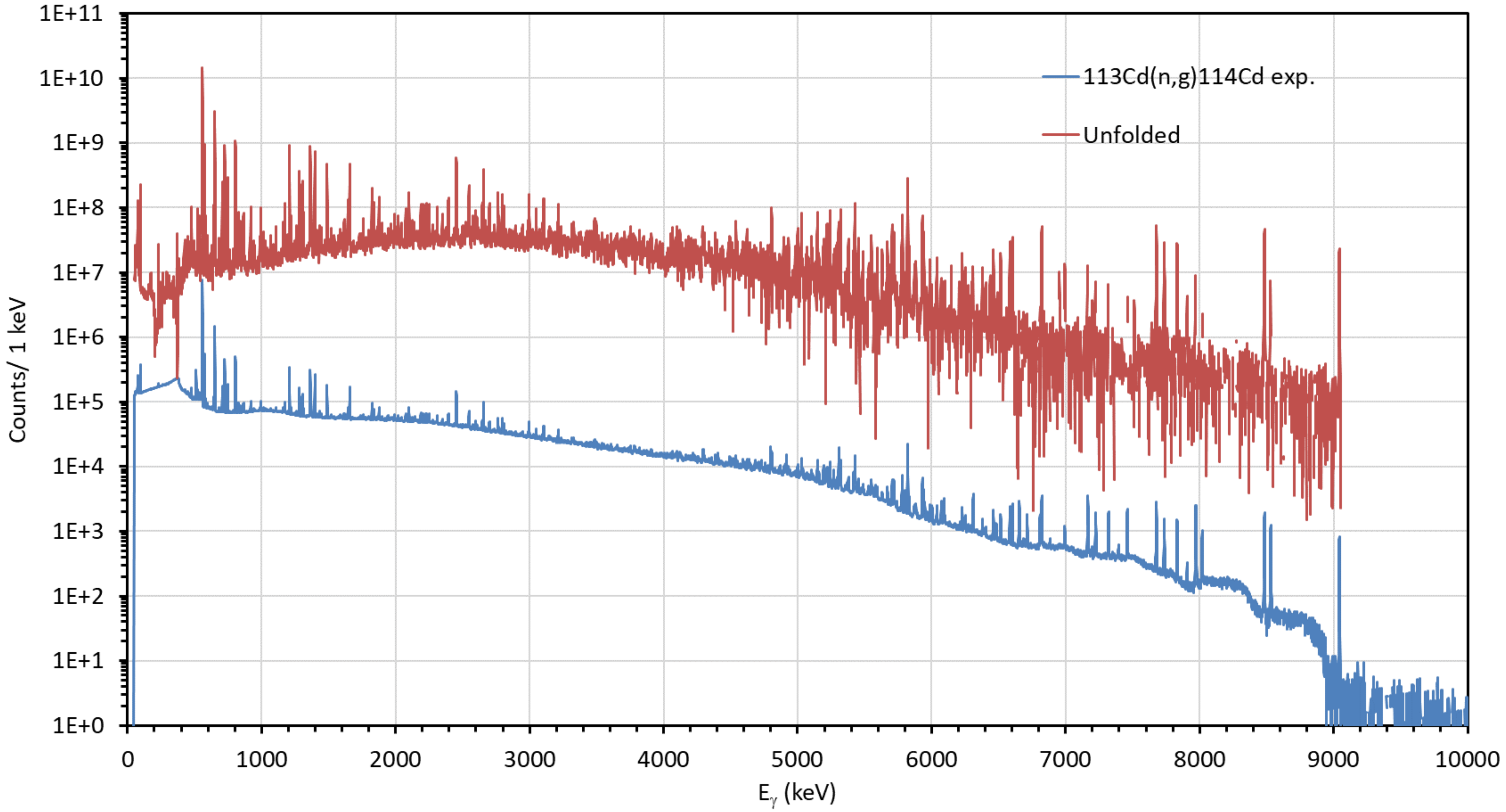
$\sigma_{tot} =$ 101.55 (50) b

$\sigma_{lit} =$ 98.65 (9) b

Method 5 is used to calculate the total Xsection: $\sigma_{\gamma,i} = \sum_{m=1}^{i} \frac{E_m \sigma_{\gamma,m}}{B_n}$; B_n is the neutron binding energy

Modelling example

Using home made Bin Type Simulation (BITS) program for modelling (n,γ) spectrum of ^{113}Cd(n,γ)^{114}Cd reaction



Experimental and unfolded and full-energy detector efficiency corrected or detector response corrected spectrum obtained in ^{113}Cd(n,γ)^{114}Cd reaction experiments on the BNC PGAA facility

Modelling the **Response function corrected spectra** $^{113}Cd(n,\gamma)^{114}Cd$

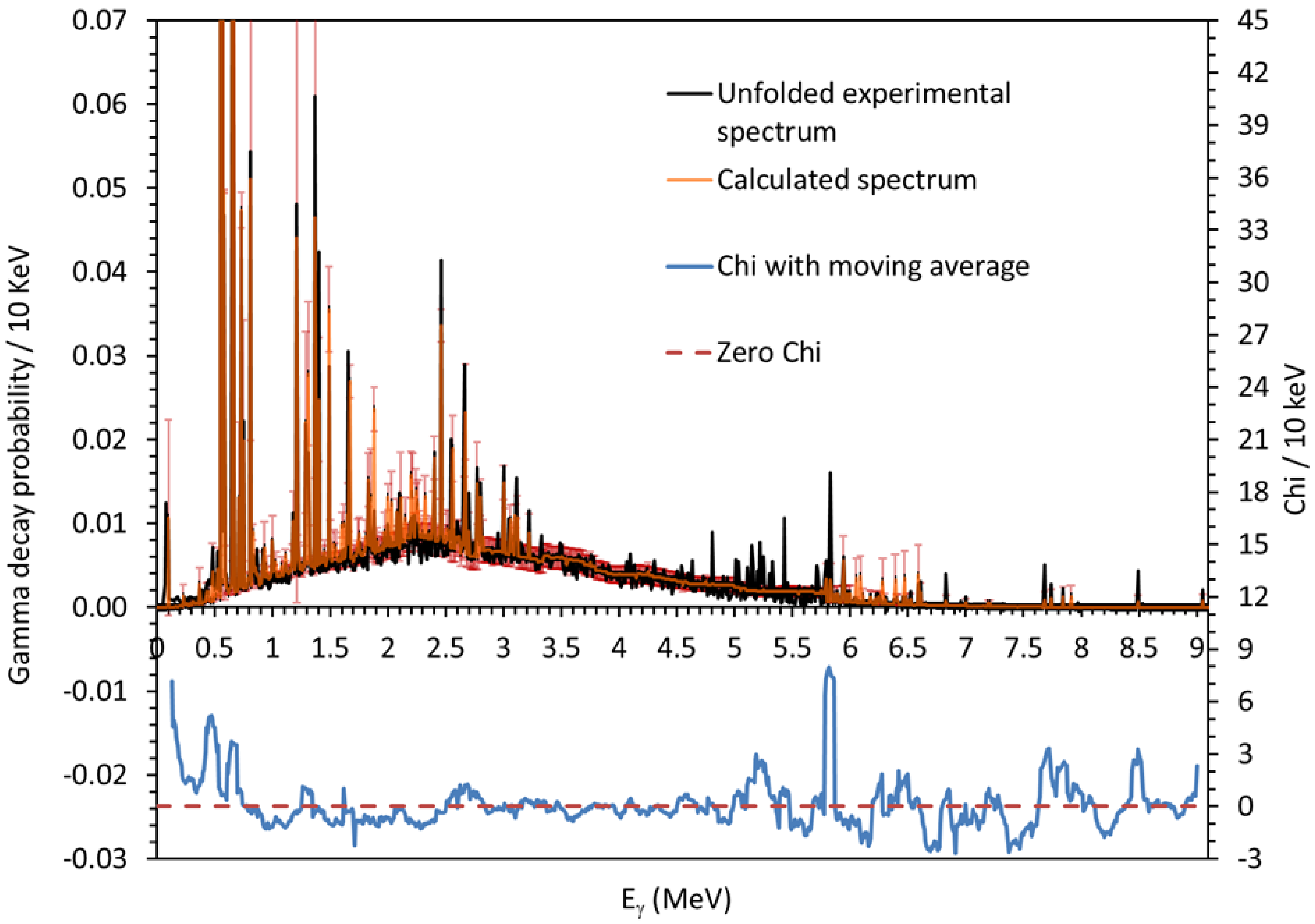


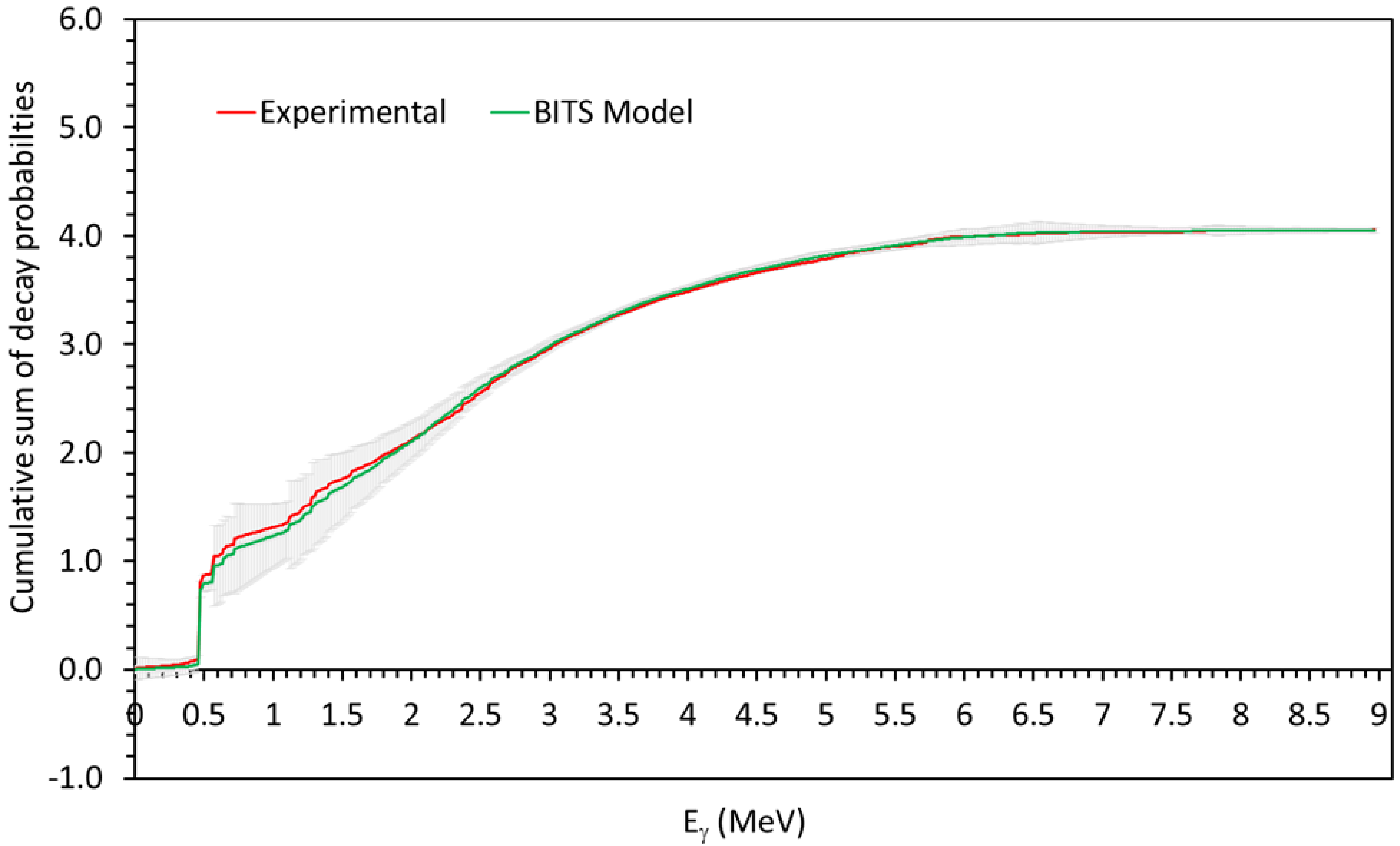
Table 1. Decrease of Chi-square as the smoothing averaging width is growing.

Width×(10 KeV)	1	3	5	7	9
Freedom (*f*)	898	896	894	892	890
χ^2	12.5	4.8	3.2	2.5	2.1

BITS model was used to simulate the response corrected radiative neutron capture spectrum of ^{113}Cd. The program uses the D1M+QRPA calculation of Goriely et al. provided level density and PSFs for E1 and M1 transitions and the RIPL-3 E2 PSF.

E1&M1 https://www-nds.iaea.org/PSFdatabase/Datafiles/d1m.zip
Level densities are from RIPL-3 RIPL-3: Reference Input Parameter Library (iaea.org) HFB Data Files (total 486.6MB) HFB README File (3.1kB)
HFB corrections File (30kB) HFB corrections README File (2kB)

^{113}Cd(n,γ)^{114}Cd experimental & BITS model multiplicity



Non 1/v nucleus

Energy weighted Xsection sum: 21466 (324) b

Multiplicity:

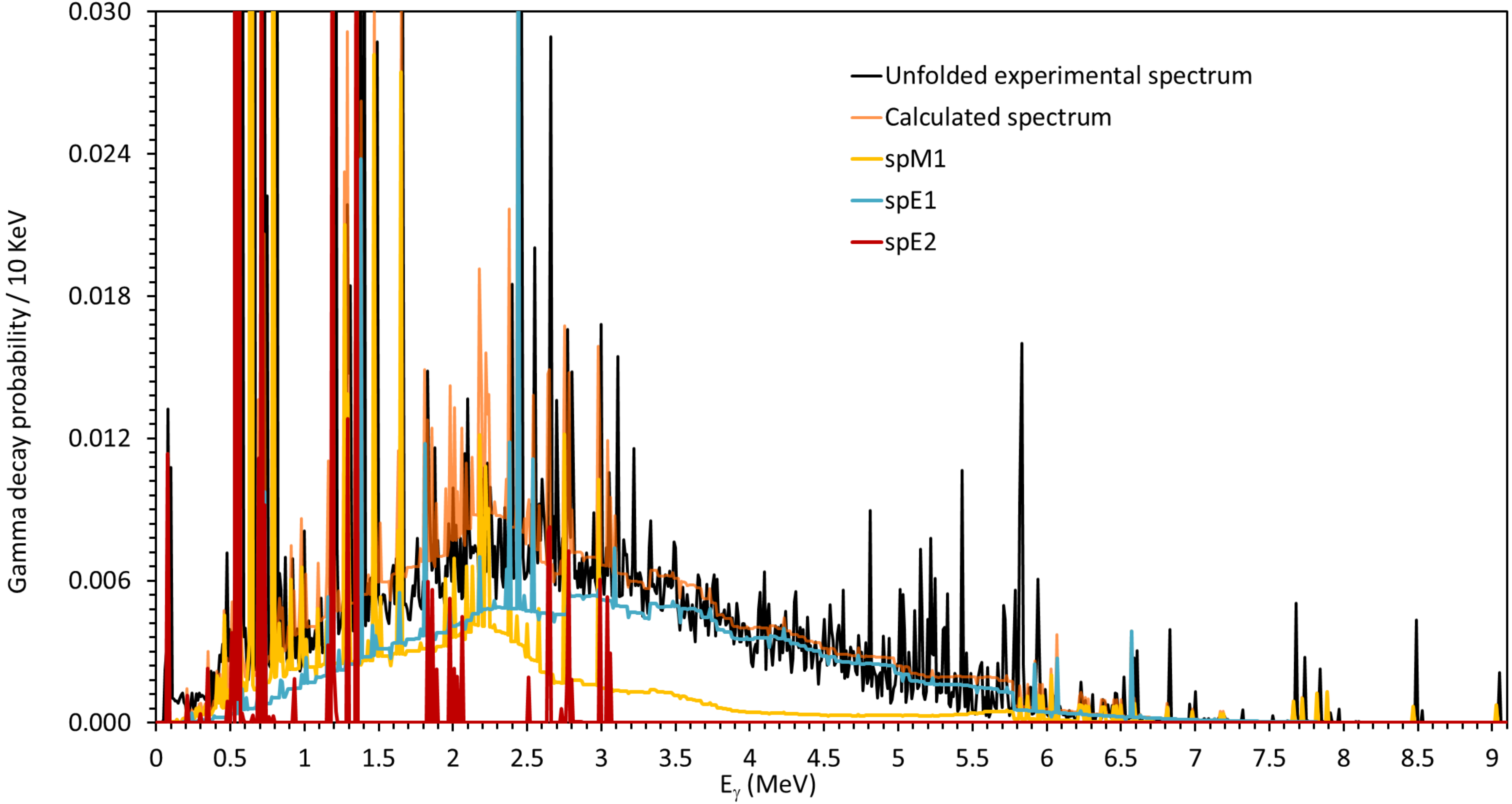
$$M_{\gamma-exp} = 4.056(4)$$

$$M_{\gamma-calc} = 4.05(7)$$

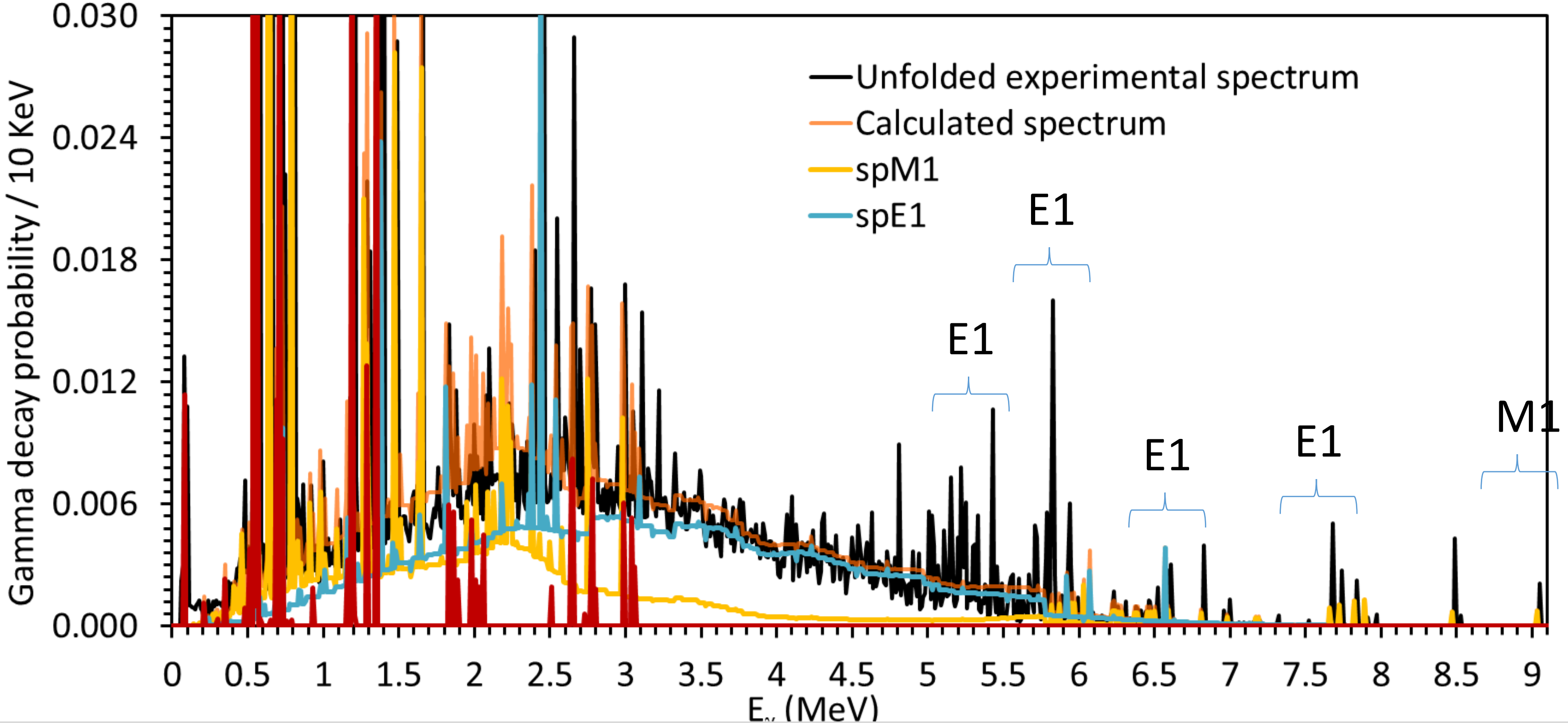
Mughabgab’s Xs
20600 (400) b

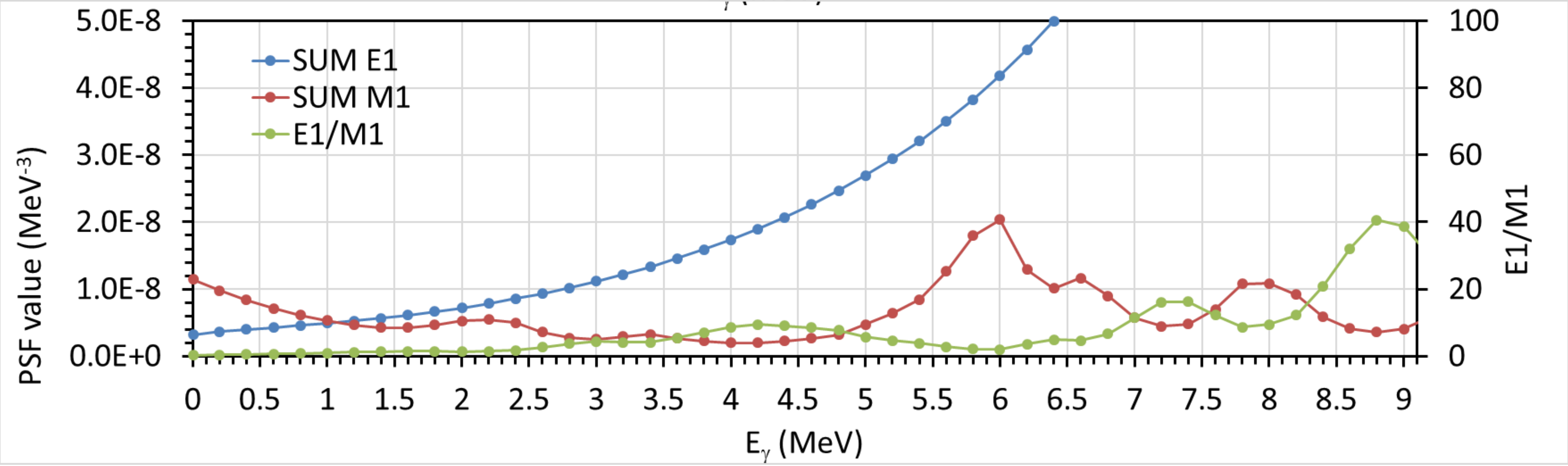
Contributions of multipolarities

Contributions of M1, E1 and E2 types of γ-transition to the γ-decay spectrum



Matchup γ-strength functions with exp. decay spectrum





Thank you for your attention!

BNC
Budapest Neutron Centre

Gamma rates for ideal samples

Gamma rate $A_{X\gamma} = P_{X\gamma} \int_V d\underline{r}^3 \varepsilon(E_\gamma,\underline{r}) n_X(\underline{r}) g(E_\gamma,\underline{r}) \int_0^\infty d\nu \int_\Omega d\Omega \cdot \sigma_X(\nu) \Phi(\nu,\underline{\Omega},\underline{r},t)$

1./The cross section of the sample materials are of 1/*v* behavior. This means that the cross section can be expressed with the thermal (th) values

$$\sigma(\nu) = \sigma(\nu_{th}) \frac{\nu_{th}}{\nu}$$

2./ The number density of atoms does not depend on the position in the sample (homogeneous sample). Thus $n_X(\underline{r}) = n_X / V$ so the constant can be moved out from the integral.

3./ The flux does not change in time (this is almost always true for reactors, if unexpected events do not happen).

4./ Gamma absorption of the target is negligible i.e. g=1.

5./ The variation of the detection efficiency is small throughout the target volume

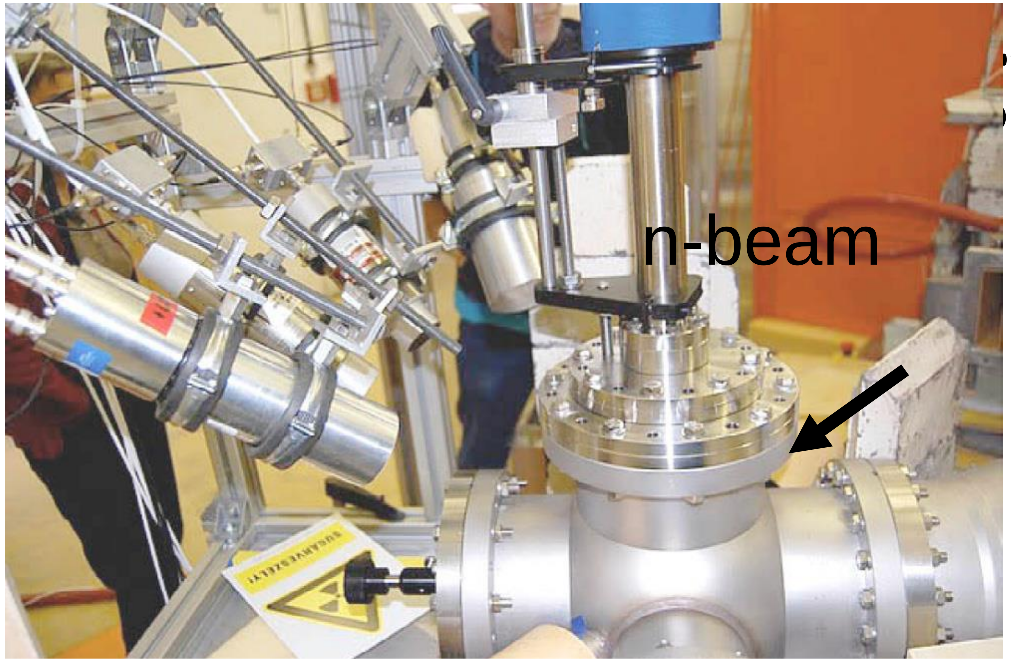
$$A_{X\gamma} = P_{X\gamma} \varepsilon(E_\gamma) n_X \sigma_X(\nu_{th}) \nu_{th} \frac{1}{V} \int_V d\underline{r}^3 \int_\Omega d\Omega \int_0^\infty d\nu N(\nu,\underline{\Omega},\underline{r})$$

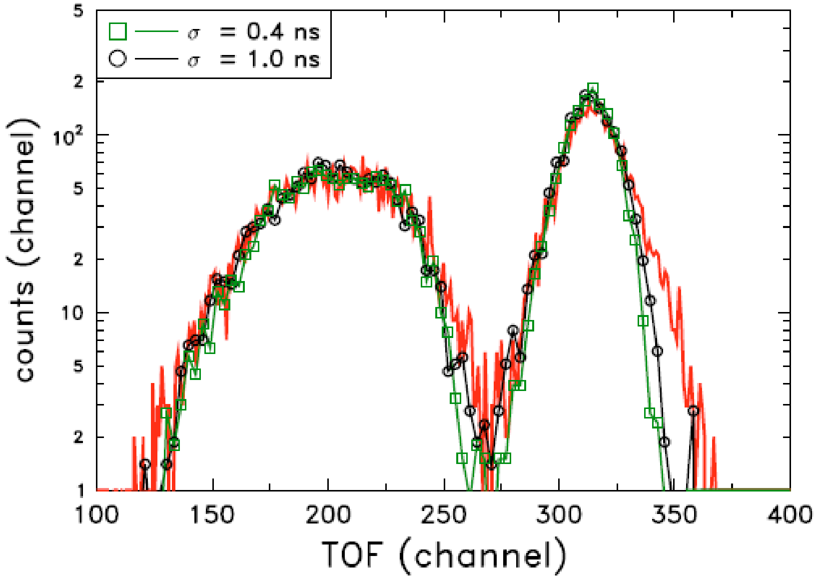
using $\sigma_{X\gamma} = P_{X\gamma} \sigma_X(\nu_{th})$ and $\phi_{th} = \frac{\nu_{th} N}{V}$ ➞ $\boxed{A_{X\gamma} = \varepsilon(E_{X\gamma}) n_X \sigma_{X\gamma} \phi_{th}}$

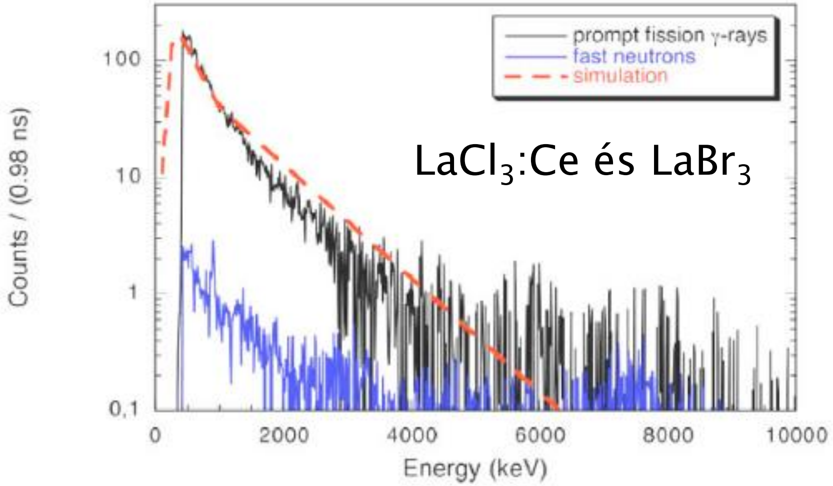
Budapest Neutron Centre

Fission spectroscopy

(EU FP6 EFNUDAT







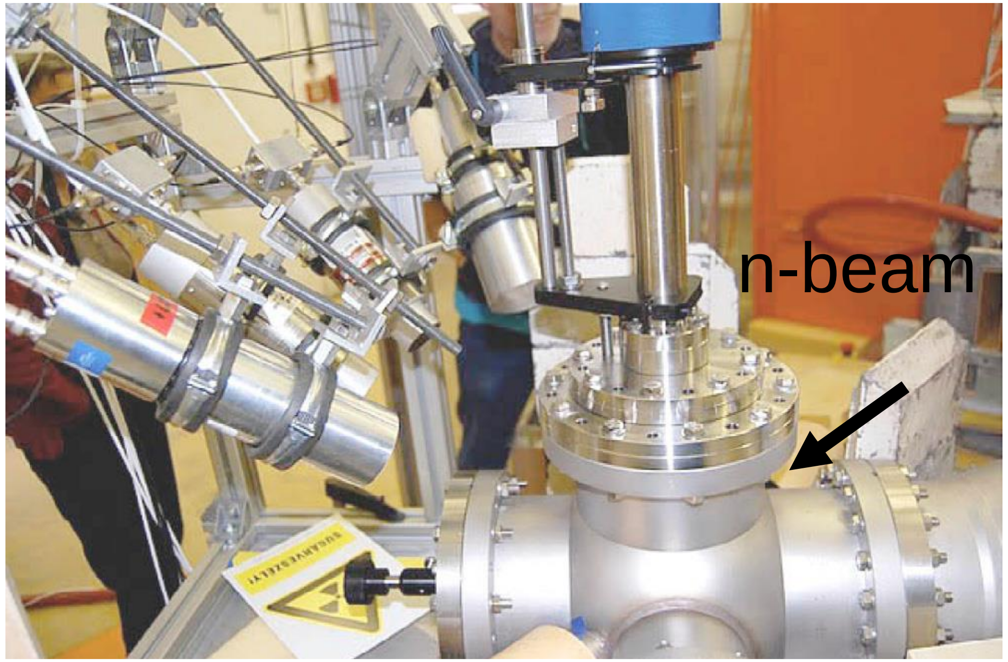
Measurement with VERDI (IRMM) at the PGAA-NIPS facility

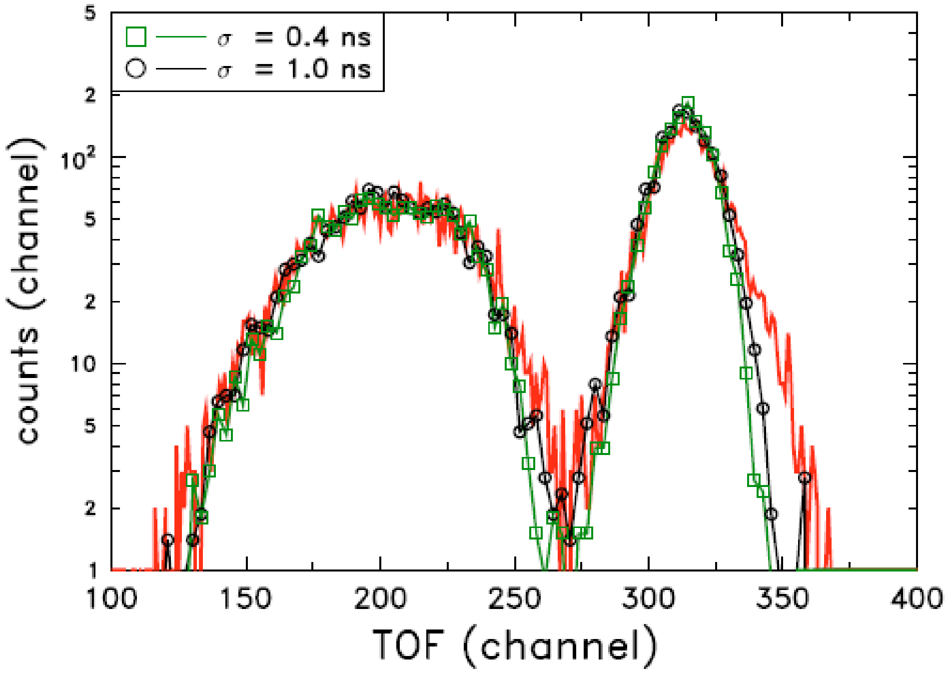
The ν, E distribution of fission products and the correlation of prompt fission γ-ray were measured

Oberstedt, S., T. Belgya, R. Billnert, R. Borcea, D. Cano-Ott, A. Göök, F.J. Hambsch, J. Karlsson, Z. Kis, T. Martnez, A. Oberstedt, L. Szentmiklósi, and K. Takács, *Correlation measurements of fission-fragment properties* in: **EPJ Web of Conferences 8**, Paris, France (2010) 03005

Fission process spectroscopy

(EU FP6 EFNUDAT)





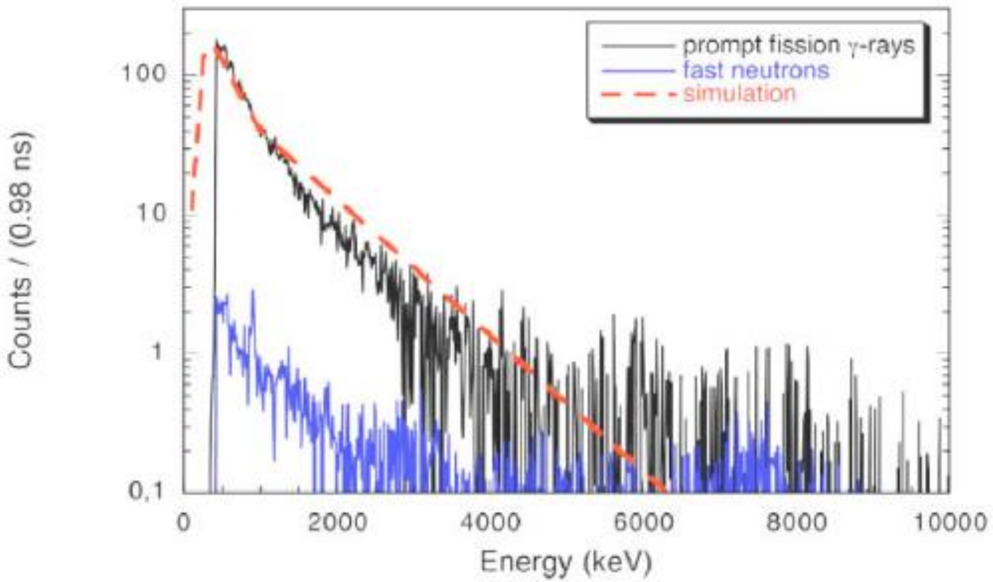
VERDI (IRMM) test measurement at the Budapest RR

To measure v, E of fission fragments

$LaCl_3$:Ce nad $LaBr_3$ detectors

To measure prompt fission gammas

S. Oberstedt et al. EPJ Web of Conferences **8**, 03005 (2010)



Prompt-fission γ-ray spectra Referenc

High-precision prompt-γ-ray spectral data from the reaction 241Pu(nth, f)
S. Oberstedt,1,* R. Billnert,1,2 T. Belgya,3 T. Bry´s,1 W. Geerts,1 C. Guerrero,4,5 F.-J. Hambsch,1 Z. Kis,3
A. Moens,1 A. Oberstedt,2,6 G. Sibbens,1 L. Szentmiklosi,3 D. Vanleeuw,1 and M. Vidali1 1European
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3Centre ofEnergy, Institute for Energy Security and Environmental Safety (EKBI), HAS, H-1525 Budapest
POB 49, Hungary 4CERN Physics Department, CH-1211 Gen`eve 23, Switzerland
5Universidad de Sevilla, Facultad de Fisica, 41012 Sevilla, Spain 6OSSOLUTIONS Consulting, S-70353
Or¨ ebro, Sweden (Received 3 February 2014; published 26 August 2014) In

Prompt fission g-rays from the reactions 252Cf(SF) and
235U(nth,f)–newdata EPJ Web of Conferences 62, 02003
(2013)

Prompt-fission γ -ray spectral characteristics from 239Pu(nth, f)
A. Gatera,1,2 T. Belgya,3 W. Geerts,1 A. Göök,1 F.-J. Hambsch,1 M. Lebois,4 B. Maróti,3 A. Moens,1
A. Oberstedt,5 S. Oberstedt,1,* F. Postelt,6 L. Qi,4 L. Szentmiklósi,3 G. Sibbens,1 D. Vanleeuw,1 M.
Vidali,1 and F. Zeiser7