EUROPEAN UNION

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"Investing in Sustainable Development"

Systematic measurements of prompt fission γ-rays and what they tell us about fission fragment de-excitation

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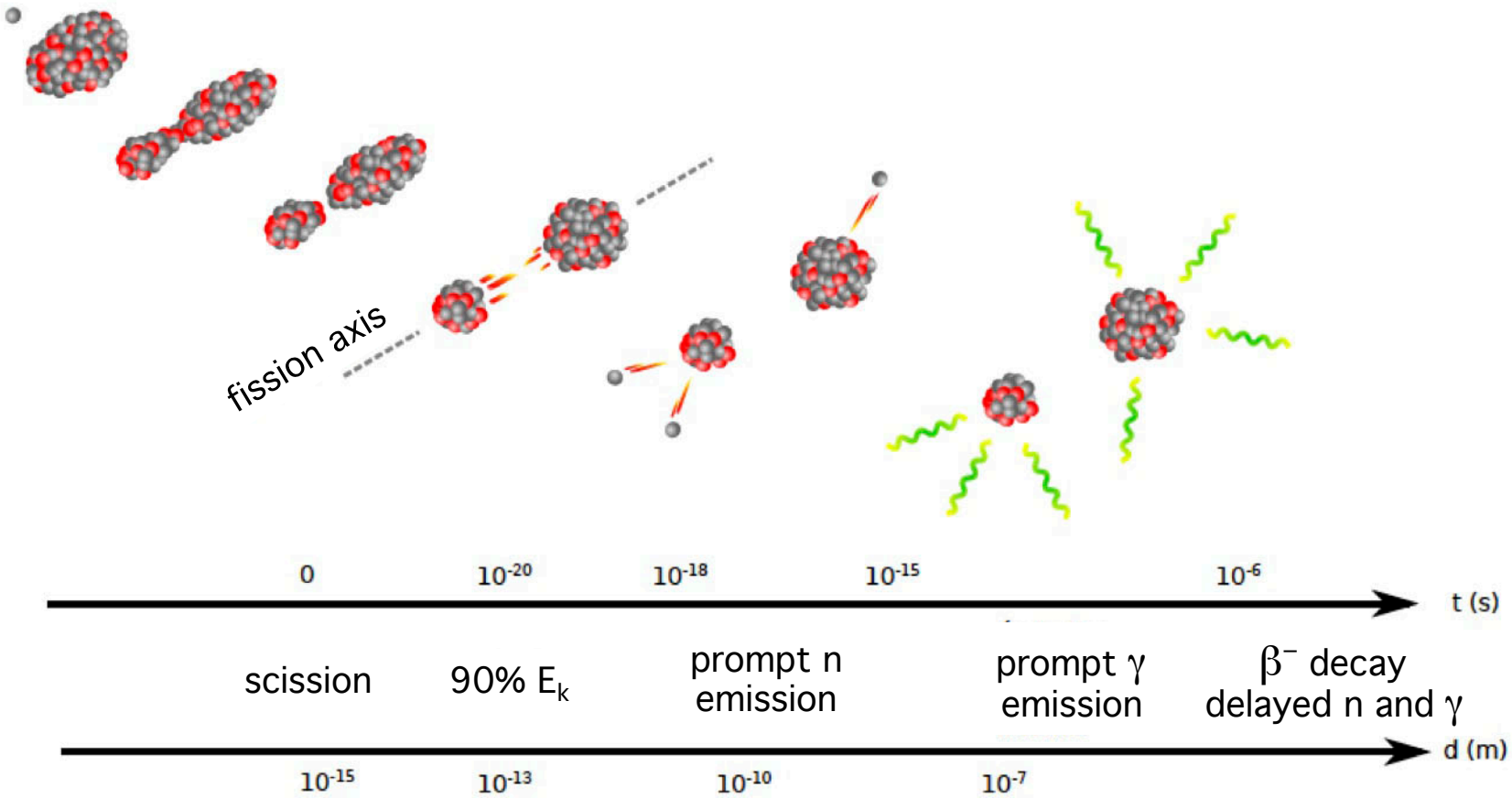
WONDER-2018, Aix-en-Provence (France), October 8 – 12, 2018

The fission process



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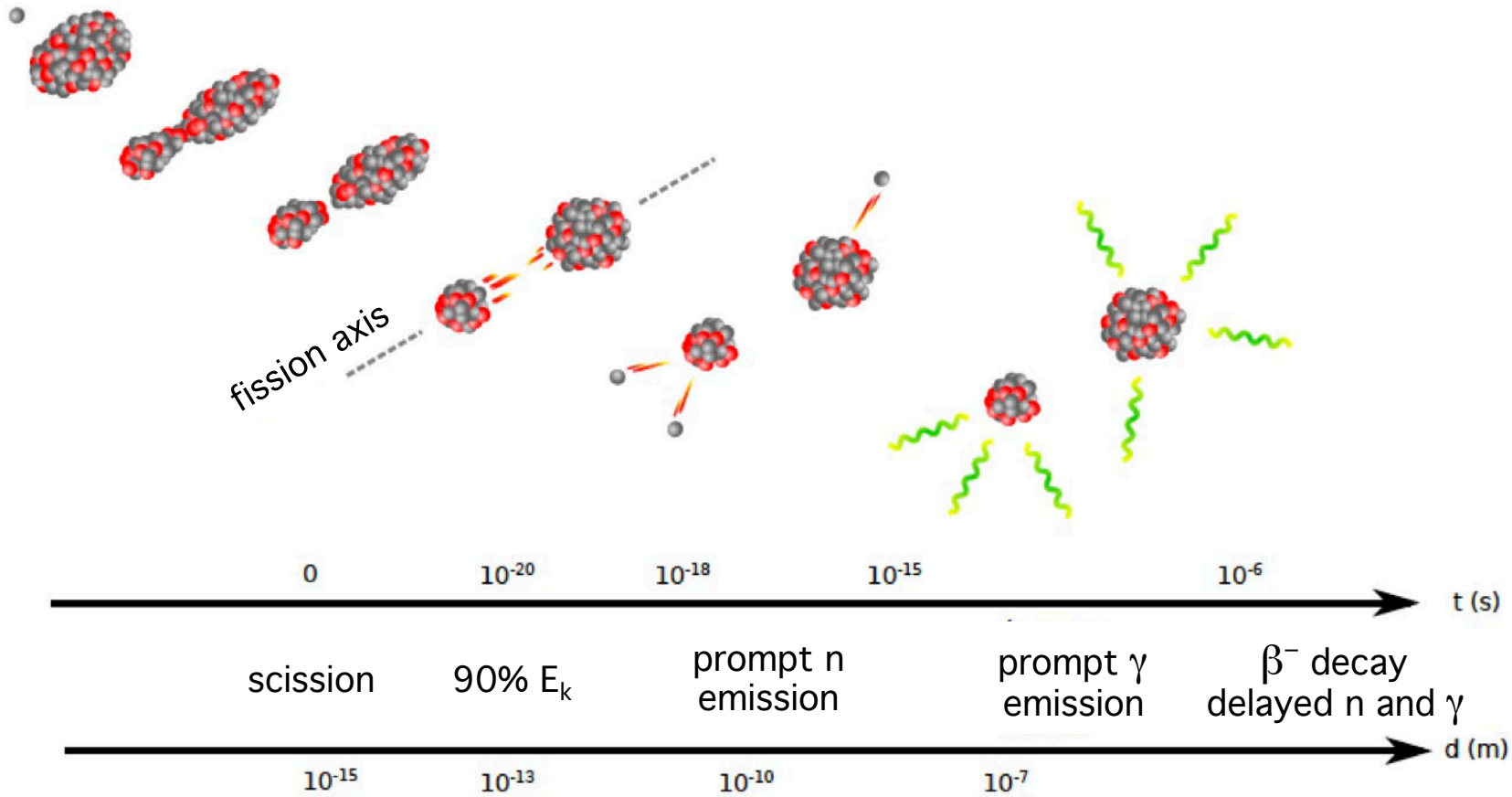
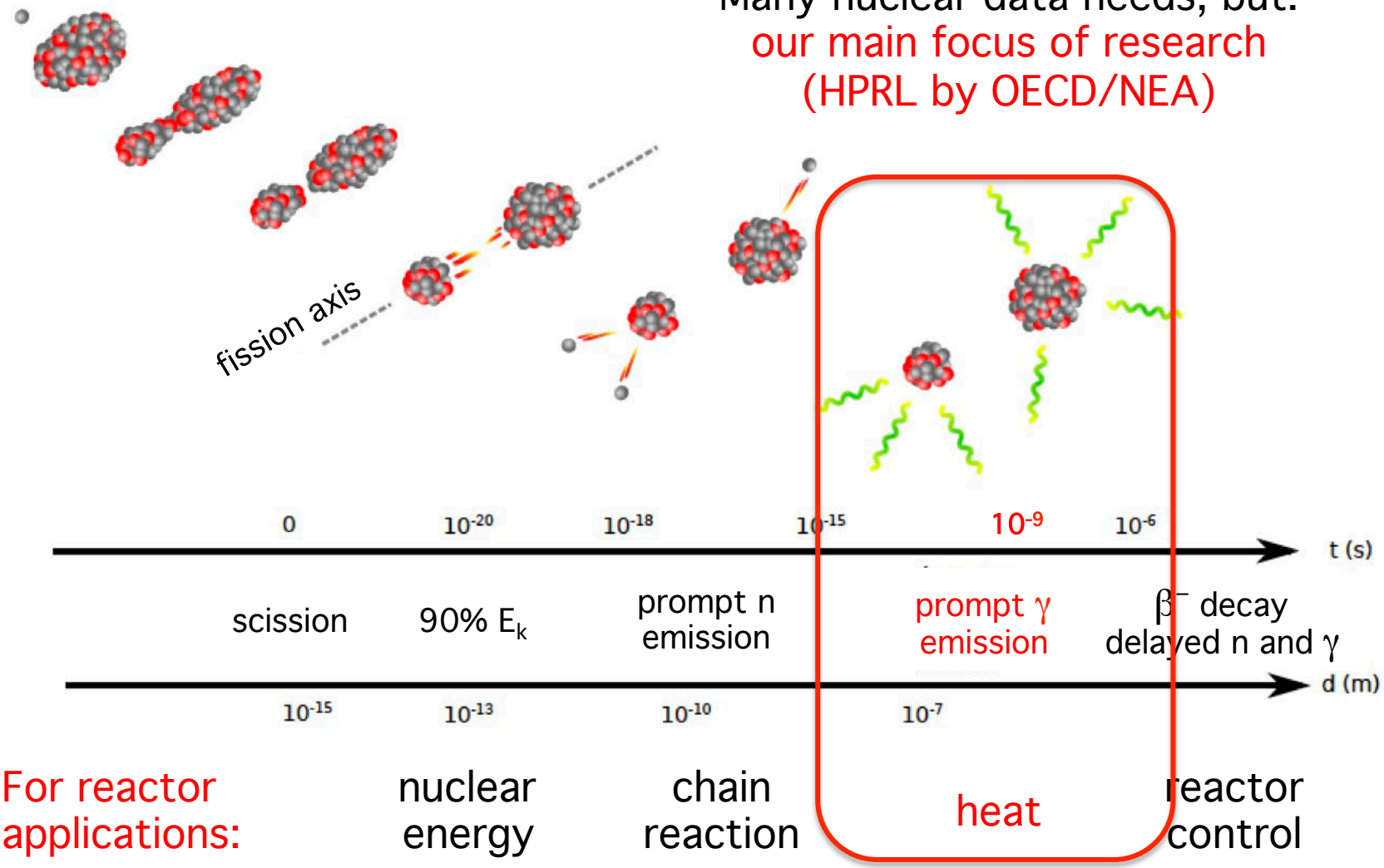


For reactor applications:	nuclear energy	chain reaction	heat	reactor control

The fission process

Many nuclear data needs, but:
our main focus of research
(HPRL by OECD/NEA)



Outline

- Introduction
- Experimental setup
- Data treatment
- Results: PFGS
  - characteristics
  - dependence of compound system
  - impact of excitation energy
  - angular distribution & multipolarities
- Summary
- Outlook

Introduction

- For the past years: precise measurement of prompt fission γ-ray spectra (PFGS)

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- Determination of characteristics:
  - $< M_\gamma >$, $< \varepsilon_\gamma >$, and $<E_{\gamma,tot}>$

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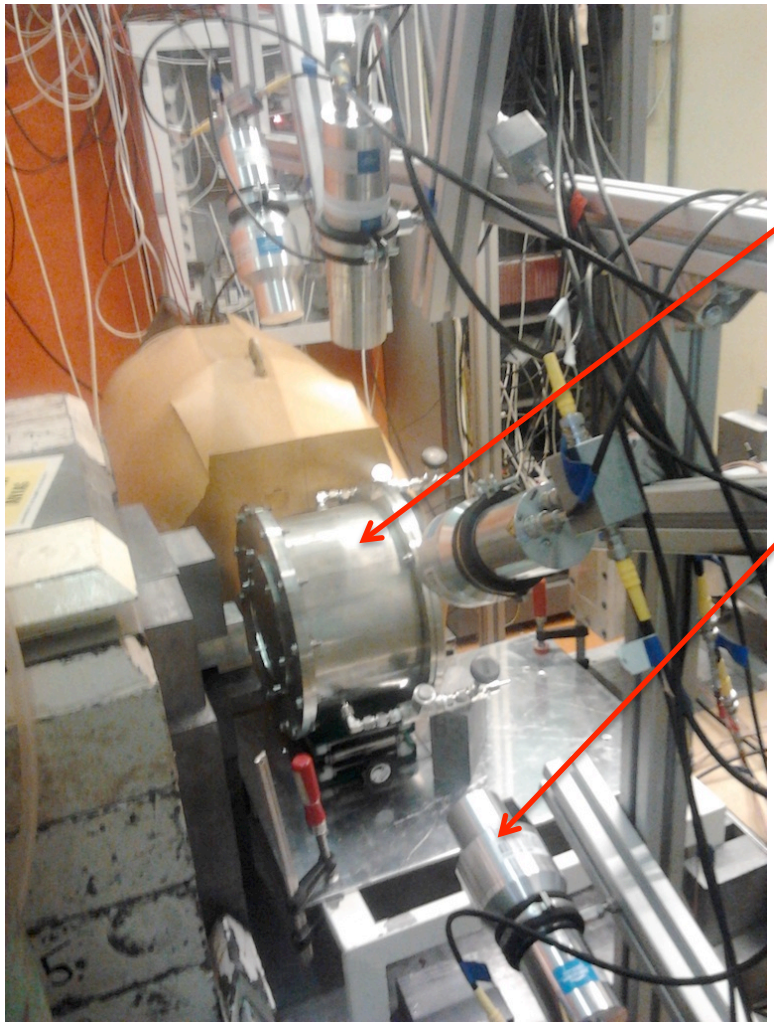
- Study of the dependence of A and Z
- Study of energy dependence
- Details about the de-excitation process of fission fragments

Experimental setup

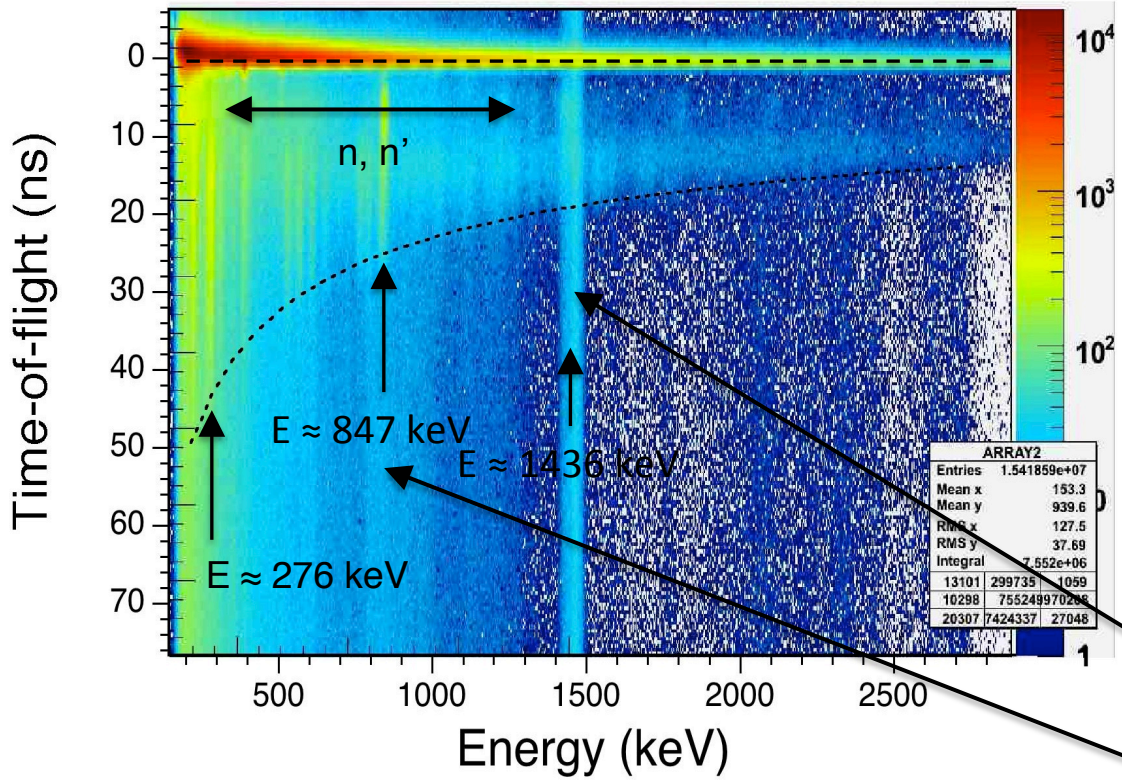
Fission fragment – γ-ray coincidences



- (Frisch-grid) ionization chamber
  (fission trigger)
- $LaBr_3$:Ce and $CeBr_3$ scintillation detectors (plus BaF_2 and/or NaI:Tl/$LaBr_3$:Ce phoswich detectors
  (gamma rays)
- Coincidences
- Time-of-flight measurement
  (n/γ discrimination)

Experimental setup

n/γ discrimination by time-of-flight



Prompt fission γ-rays

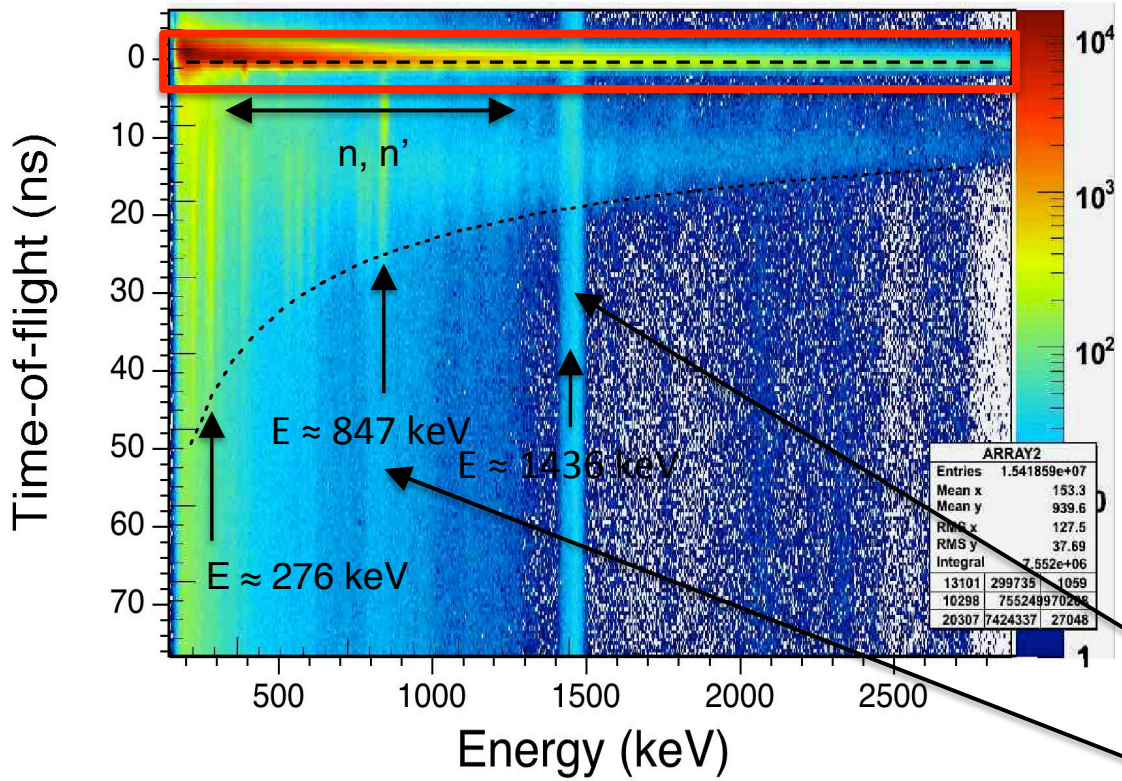
γ-decay after inelastic neutron scattering

Intrinsic and external background

Due to good resolving power + excellent timing resolution of $LaBr_3$:Ce detectors

Experimental setup

n/γ discrimination by time-of-flight



Prompt fission γ-rays

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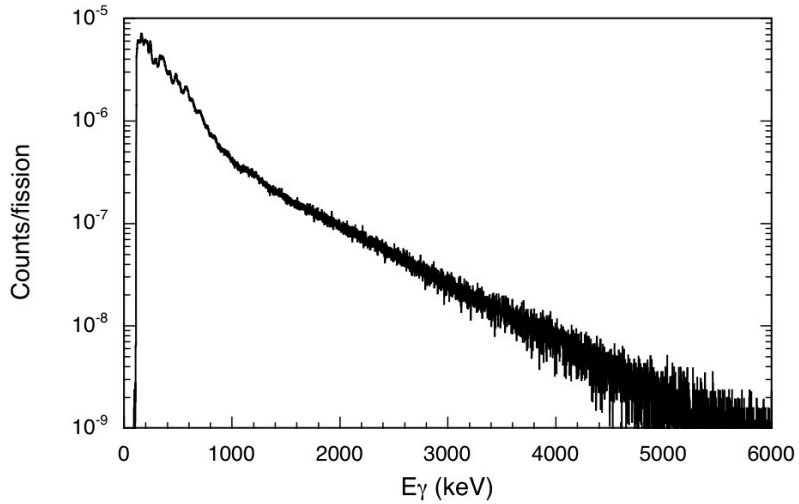
Data treatment

Unfolding the detector response

measured spectrum

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ \\ y_n \end{pmatrix}$$

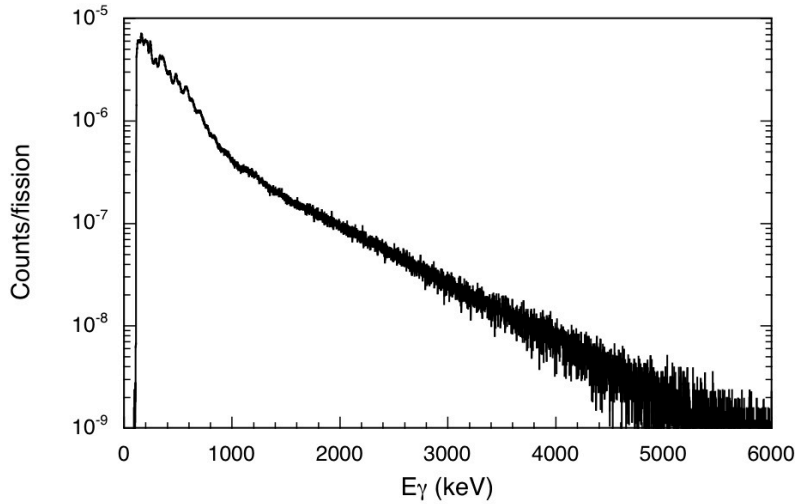


Data treatment

Unfolding the detector response

measured spectrum — response matrix — emission spectrum

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ \\ y_n \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & & & \\ \vdots & & & \vdots \\ \\ r_{n1} & & \cdots & r_{nn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ \\ x_n \end{pmatrix}$$



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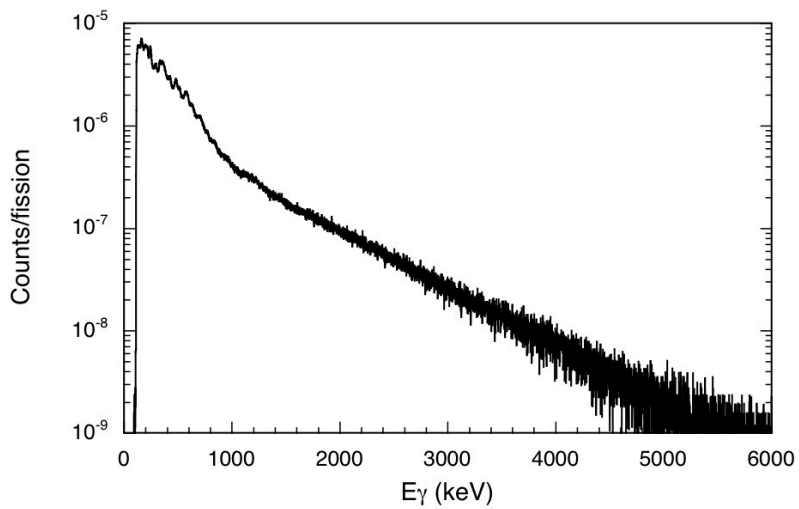

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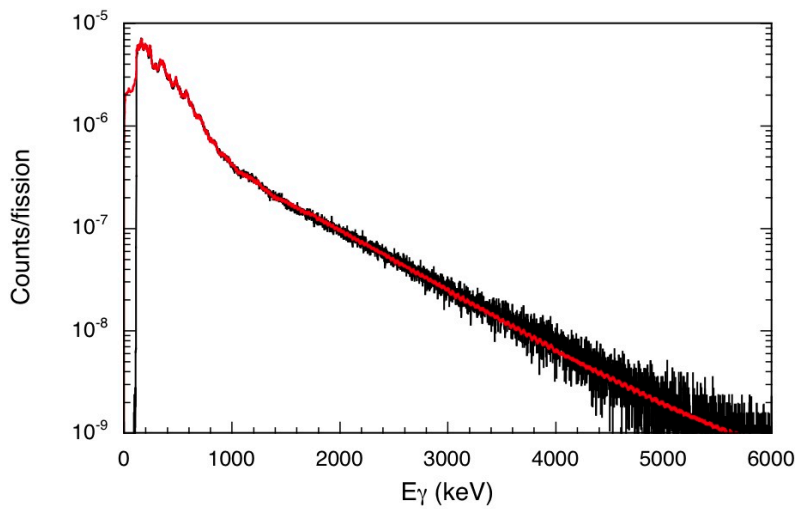

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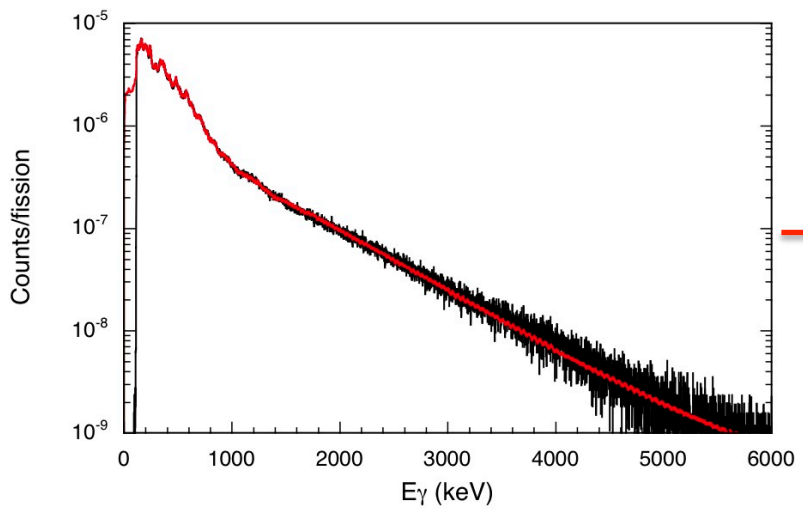

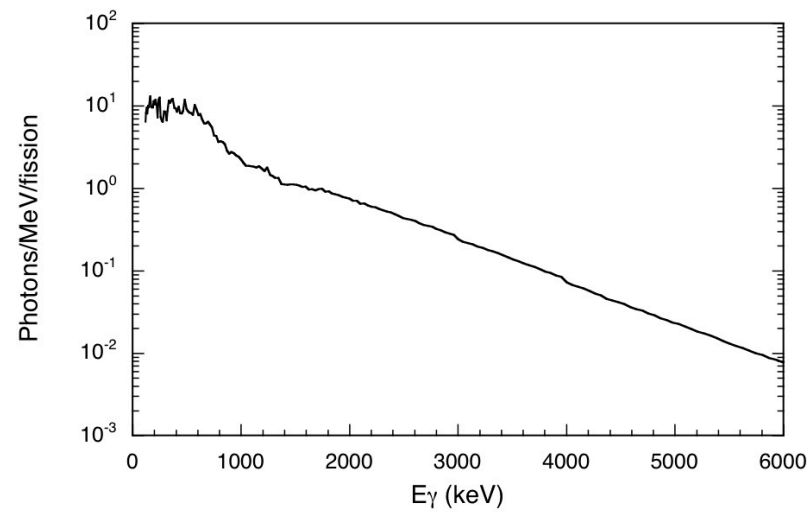

Results: PFGS

Overview: studied systems so far

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Previous work: ☐ (sf)

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Recent experiments: (sf)

Results: PFGS

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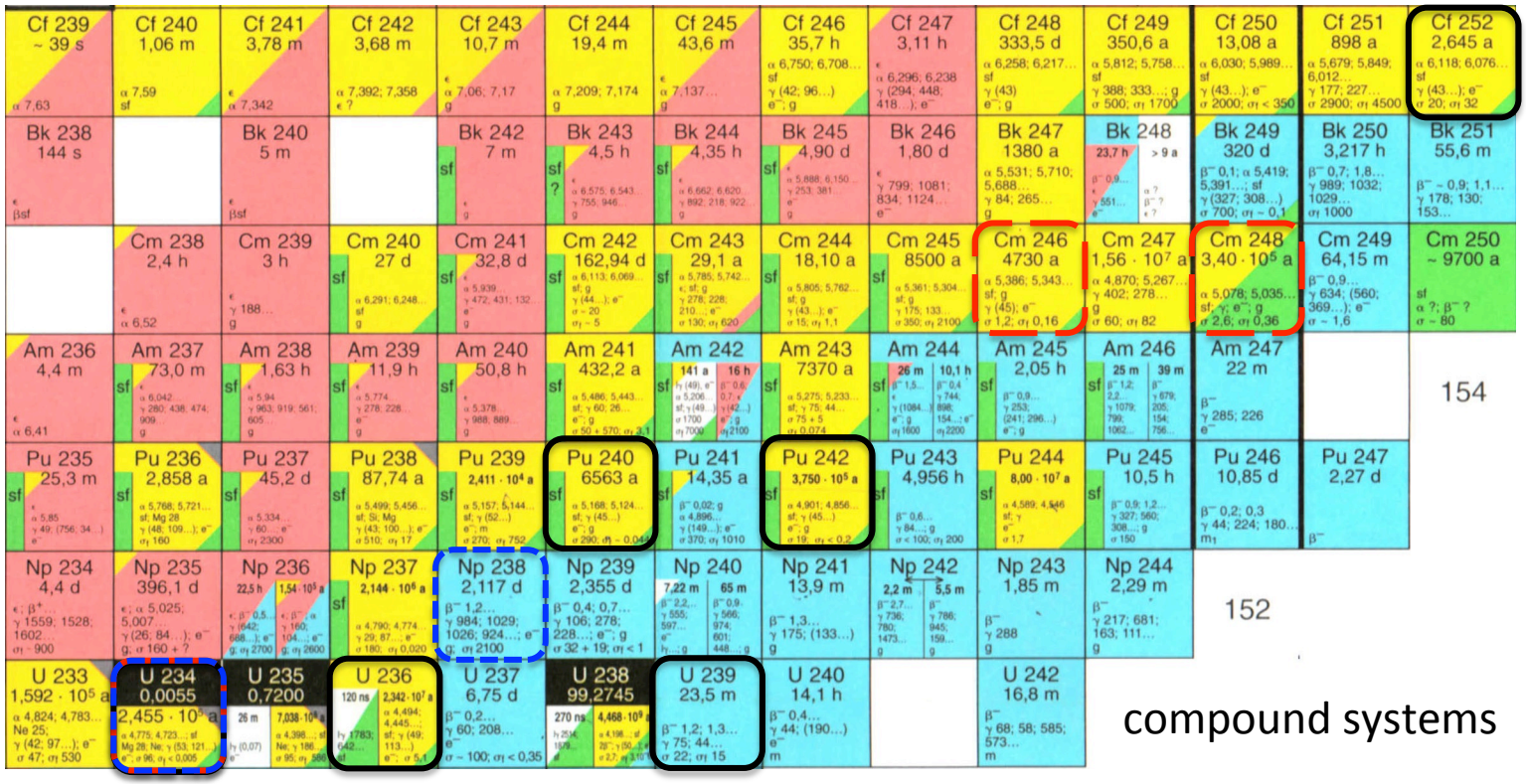


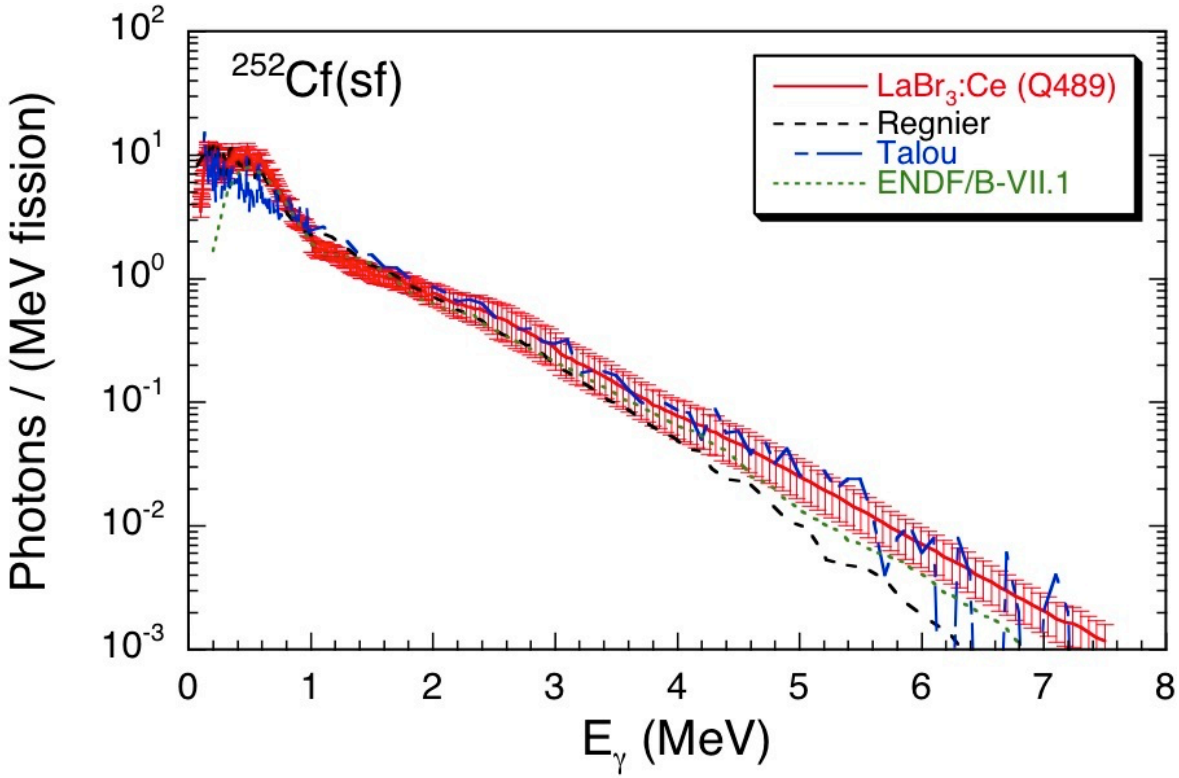
Previous work: (sf), (n_{th}, f), (n, f), (d, pf)

Recent experiments: (n_{th}, f)

Approved proposals: (n, f)

Results: PFGS

High precision γ-ray measurements



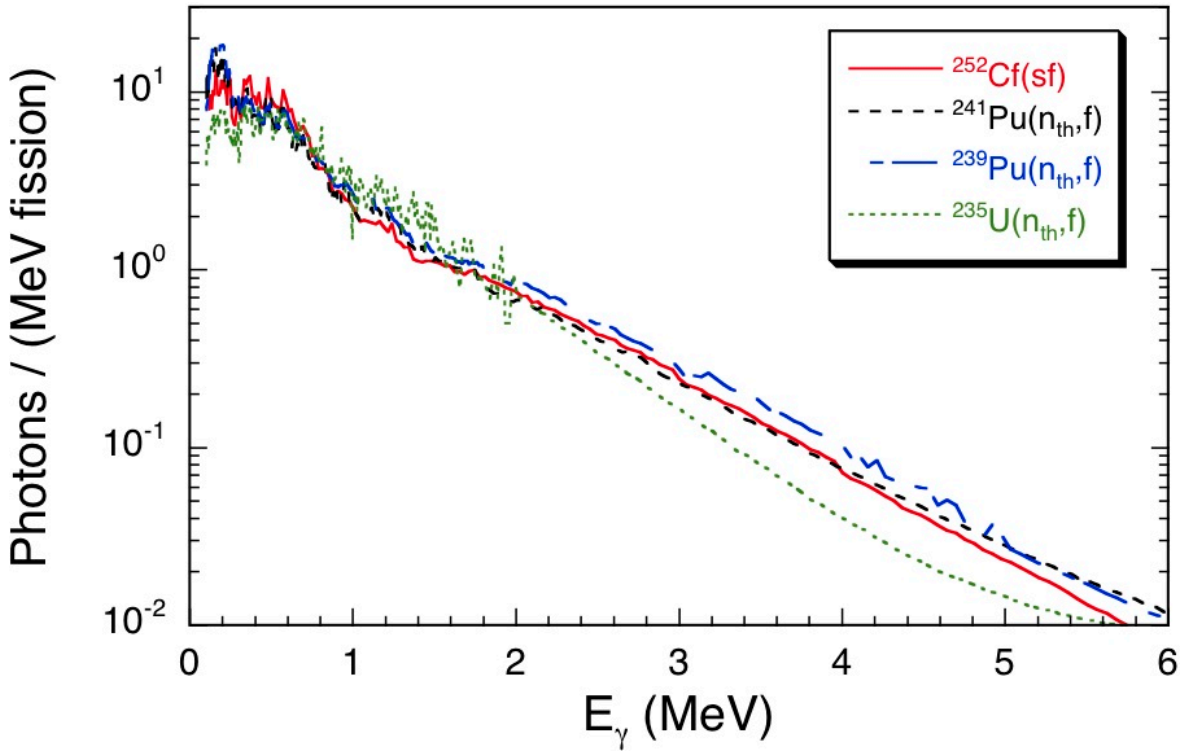
Excellent agreement between our experimental results and those from advanced model calculations *)

*) full Hauser-Feshbach Monte Carlo simulations by

- D. Regnier et al. (code: FIFRELIN, CEA Cadarache)
- P. Talou et al. (code: CGMF, LANL)

Results: PFGS

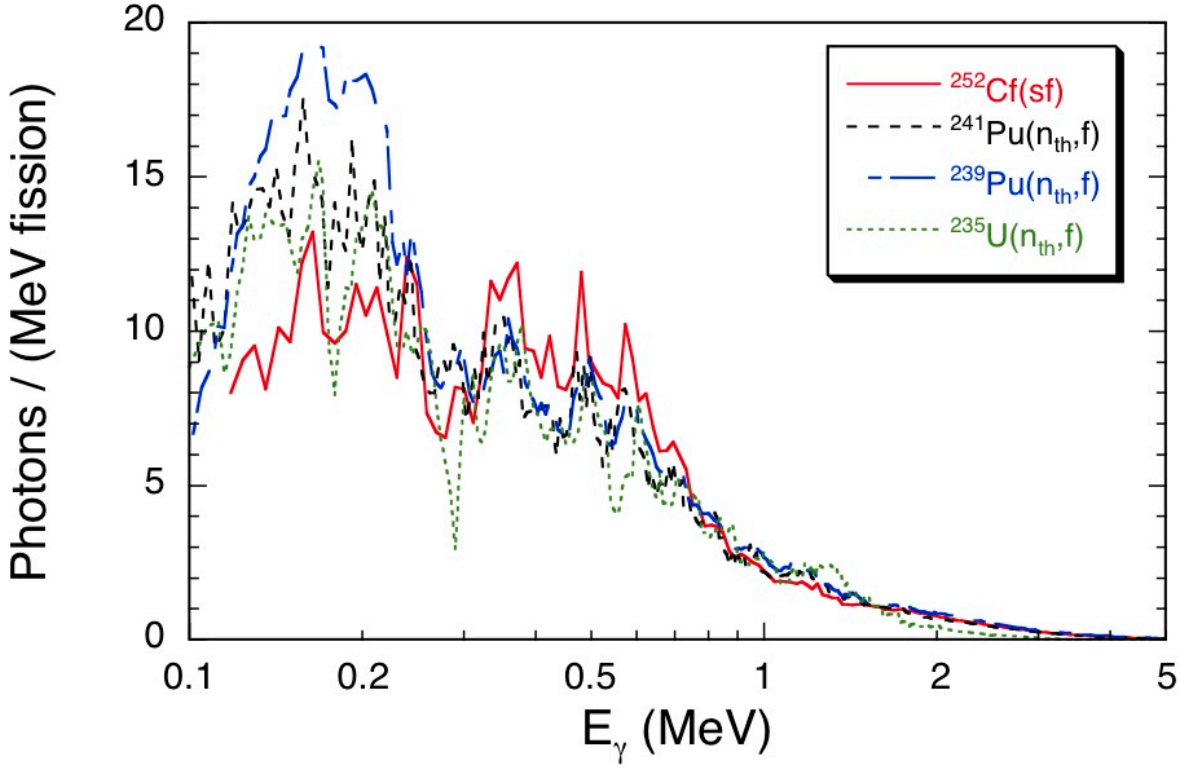
High precision γ-ray measurements



Examples for different compound systems

Results: PFGS

High precision γ-ray measurements



Examples for different compound systems

Similar low energy peak structures !

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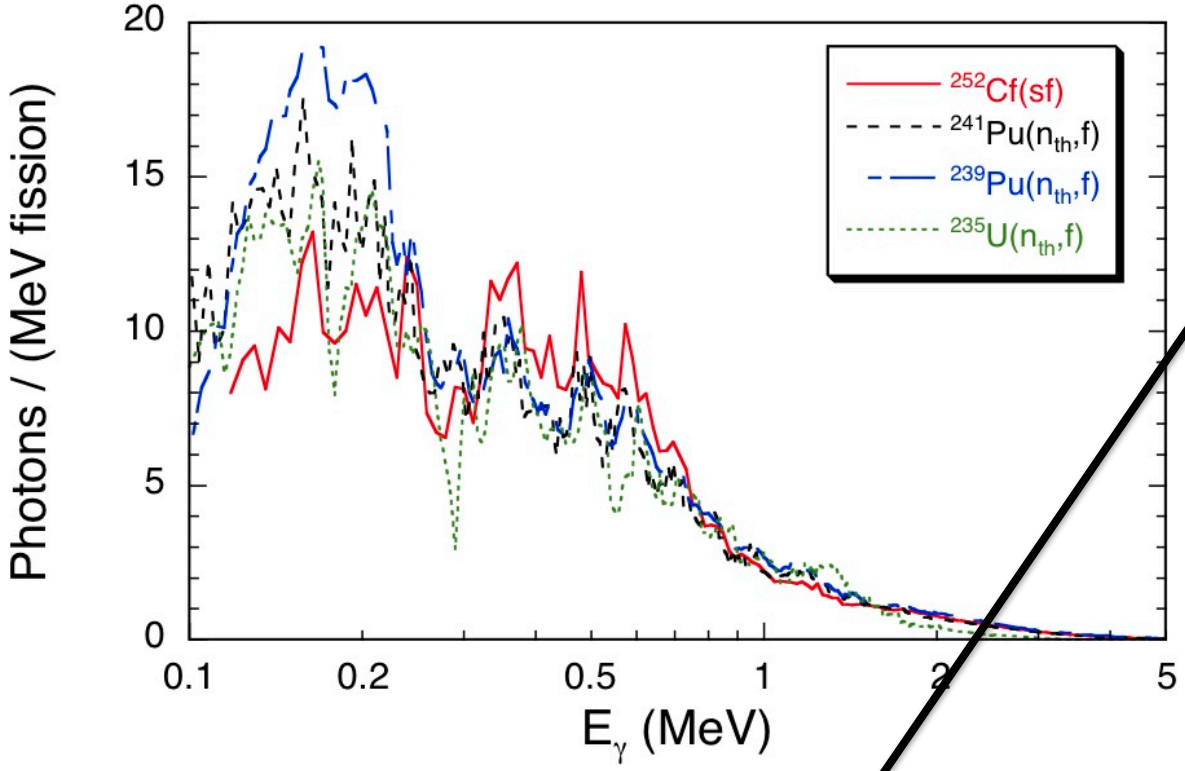
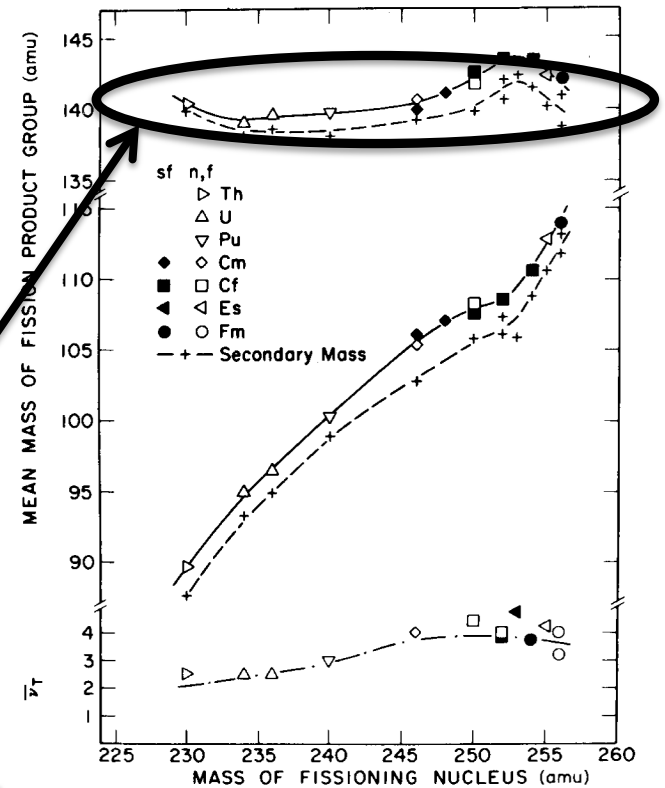




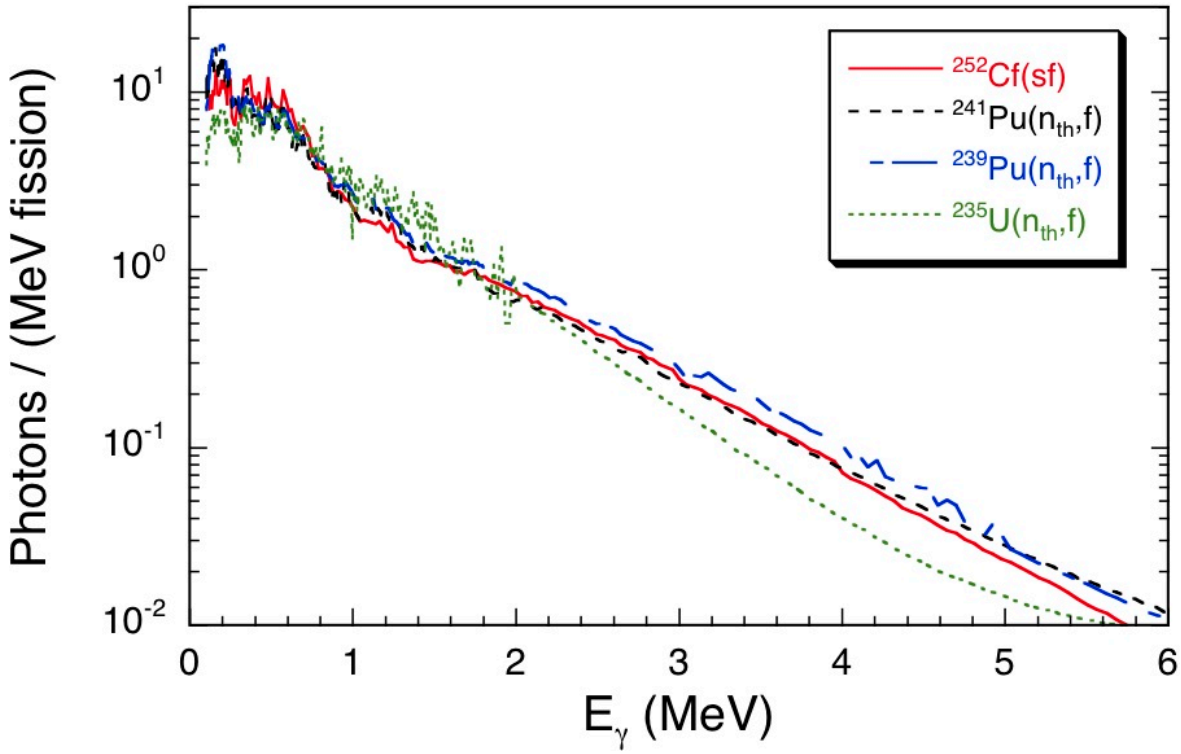
(J. Wagemans)

Similar low energy peak structures !

Due to de-excitation of the (same) heavy fragments ?

Results: PFGS

High precision γ-ray measurements



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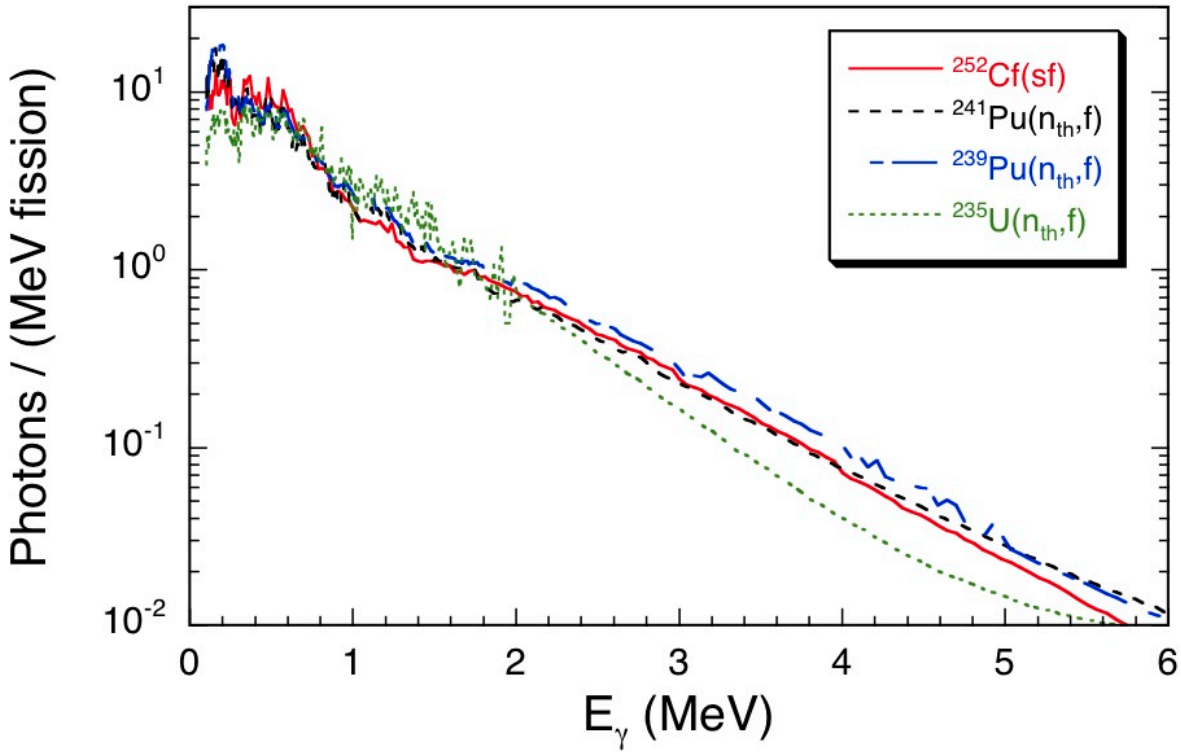

Examples for different compound systems

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

PFGS characteristics:

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

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

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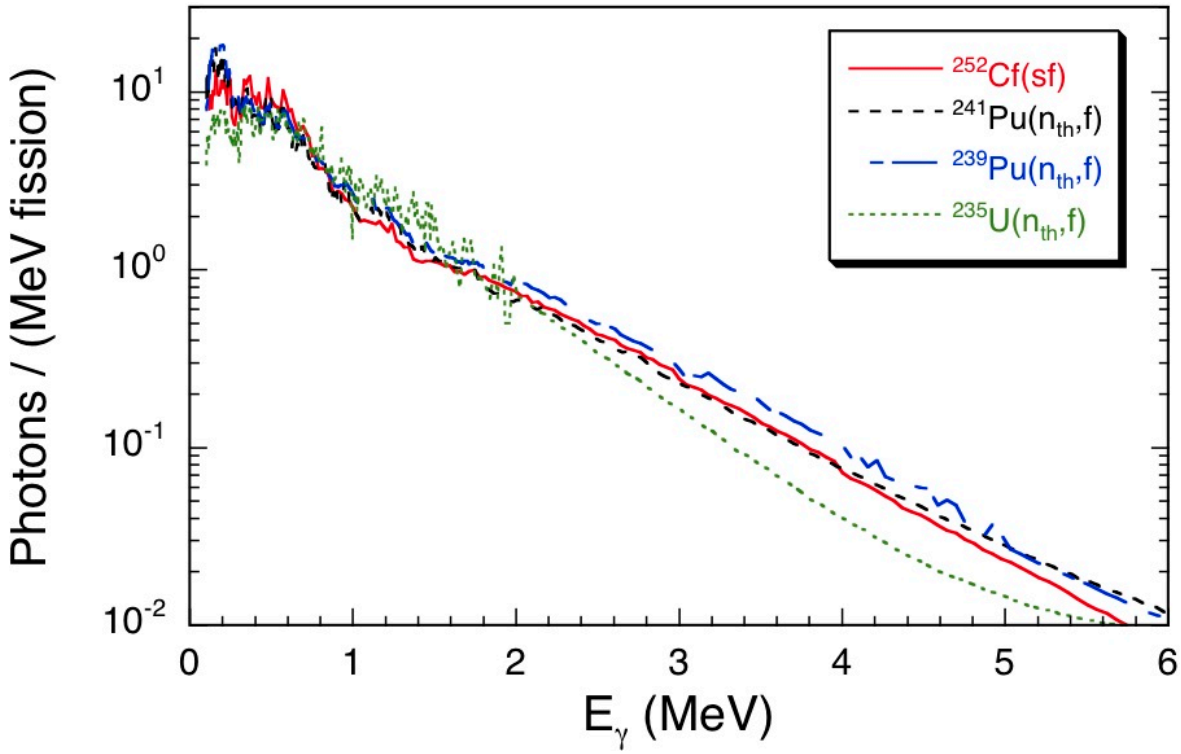

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PFGS characteristics:

↳ Systematics !

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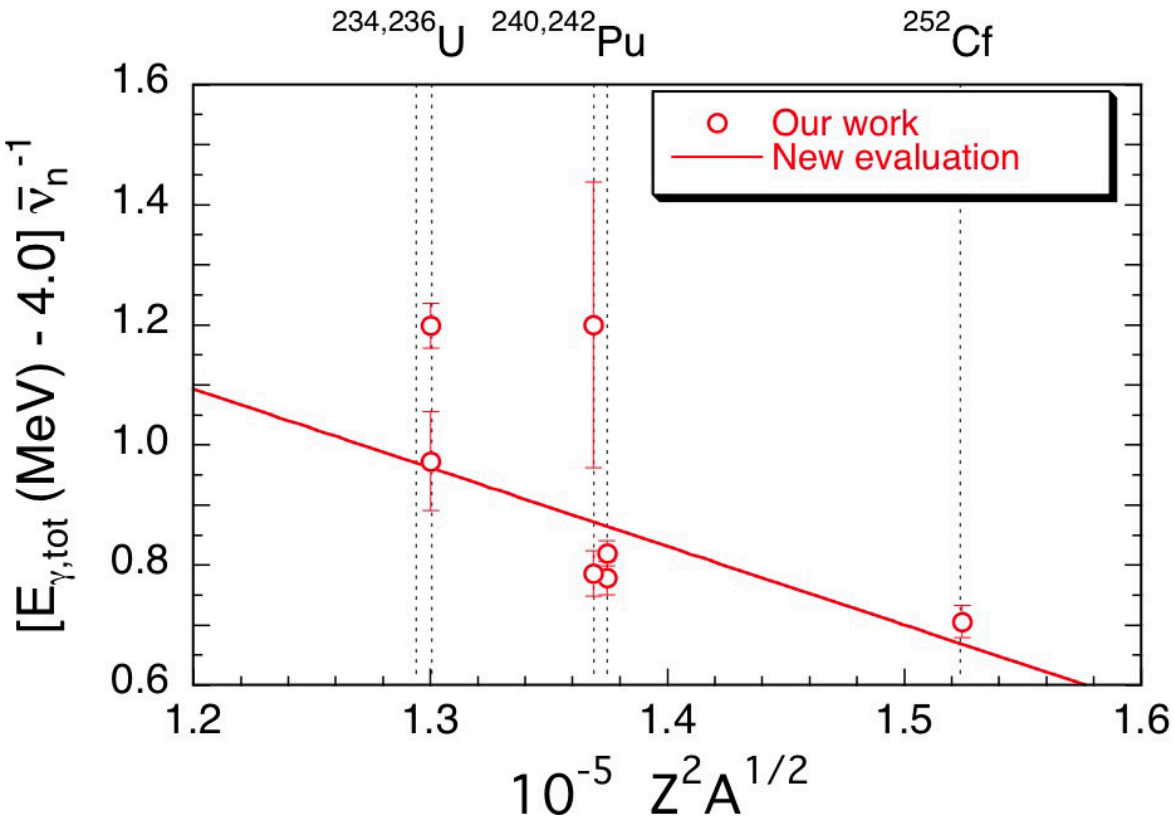
Results: A and Z dependence

Systematics of PFGS average total energy per fission



(n_{th},f) and (sf) only!

According to Nifenecker (1972) and Valentine (2001), revised 2017: A. Oberstedt et al., PRC 96, 034612

Results: A and Z dependence

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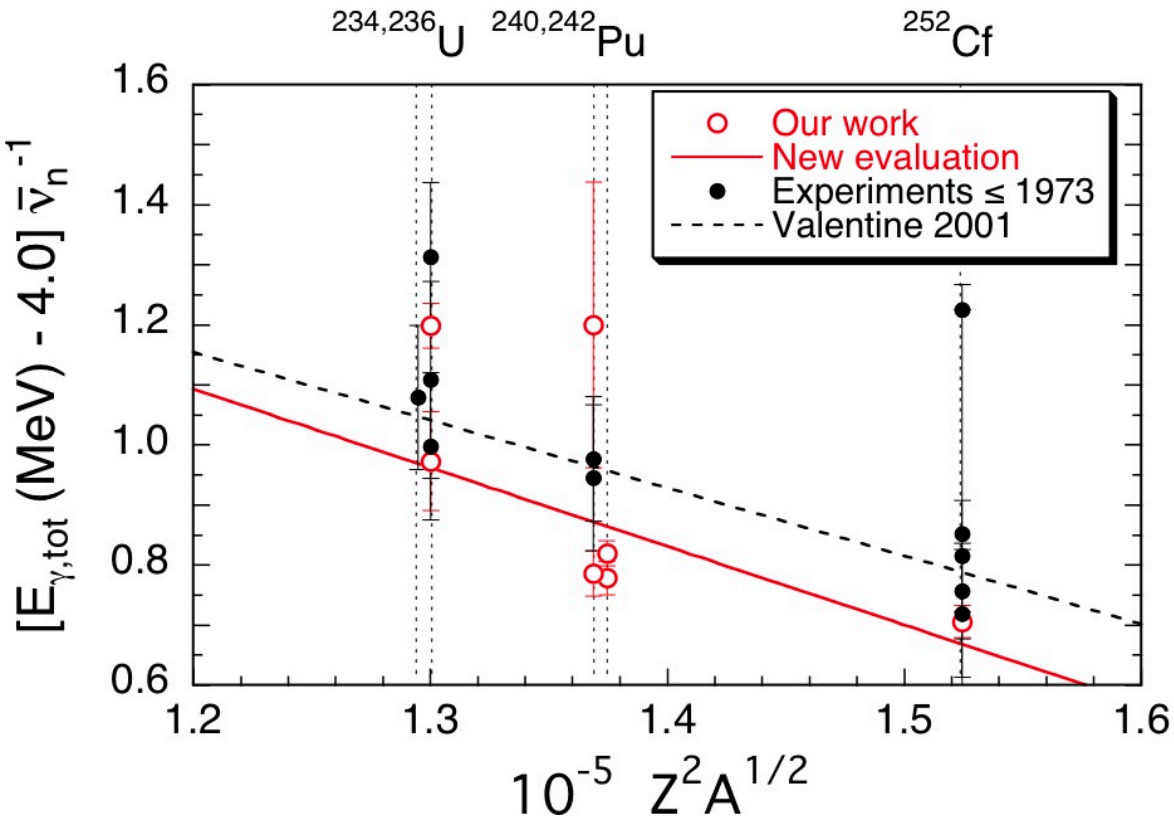

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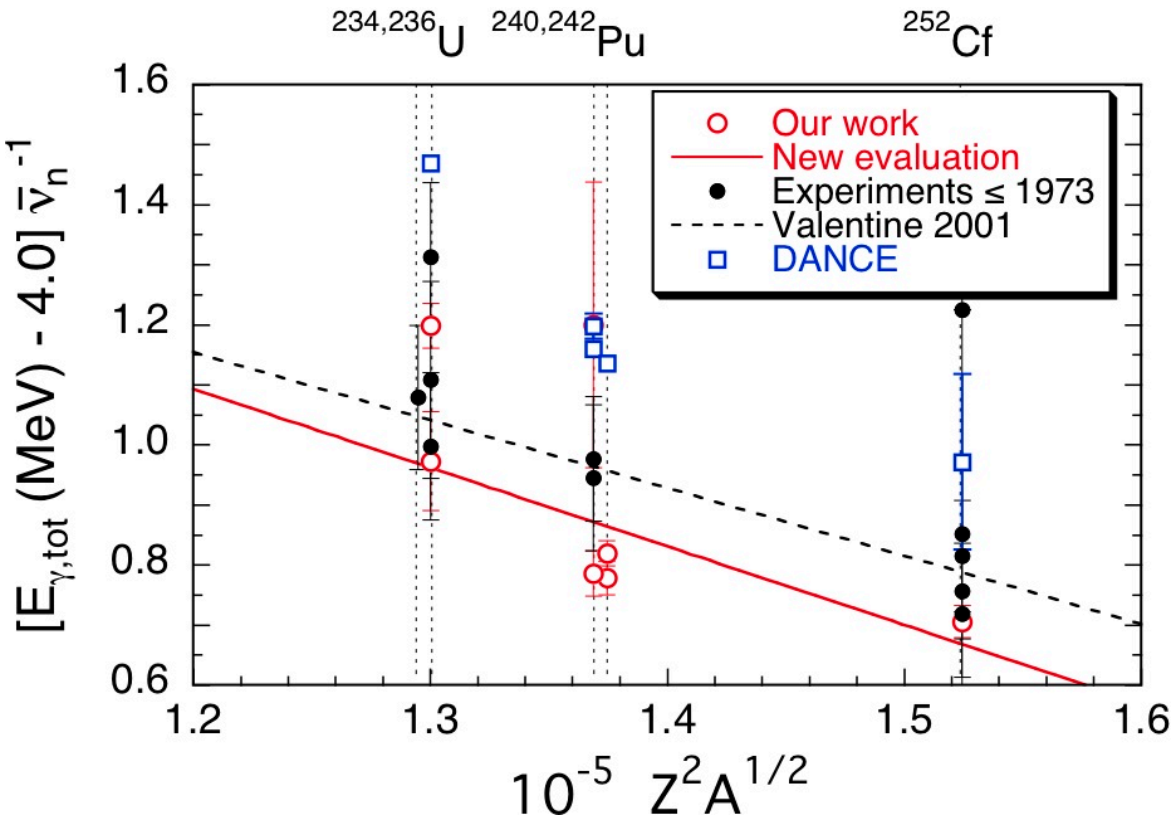

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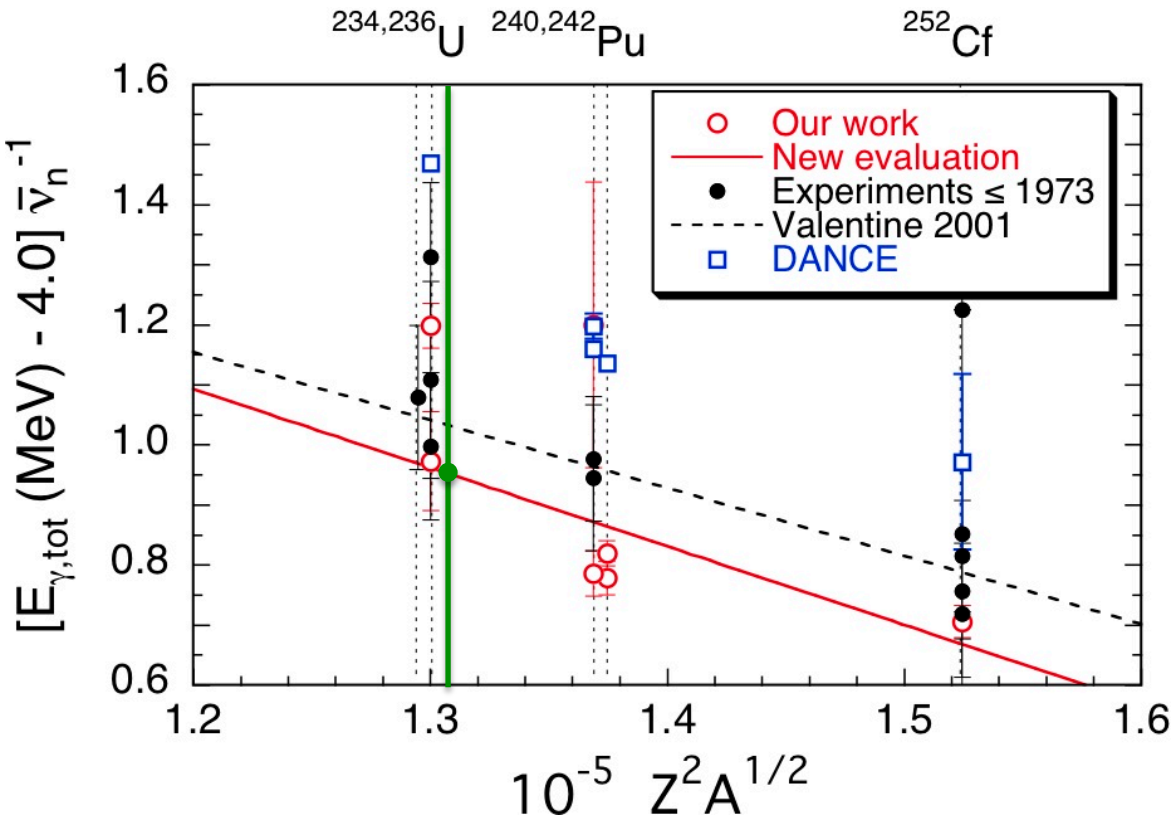


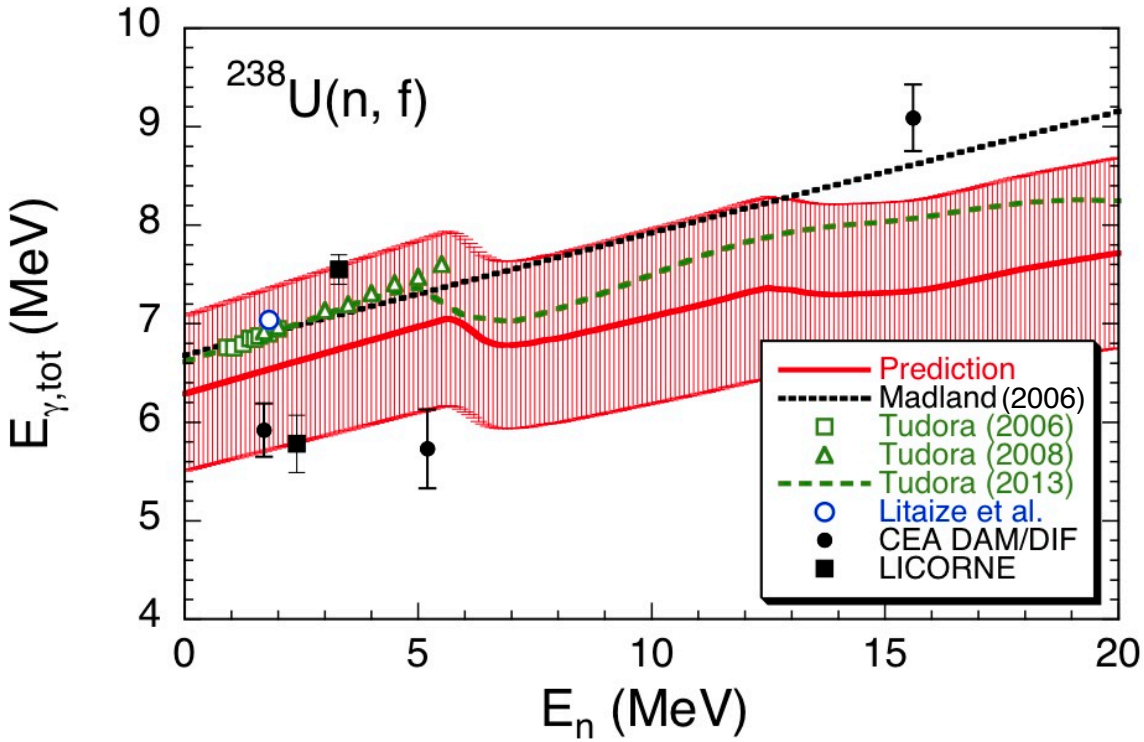
(n_{th},f) and (sf) only!

Allows interpolation to unmeasured fissioning systems, here $^{238}U(n_{th},f)$: A. Oberstedt et al., PRC 96, 034612

Results: energy dependence

Average total energy per fission

From thermal to fast neutron-induced fission



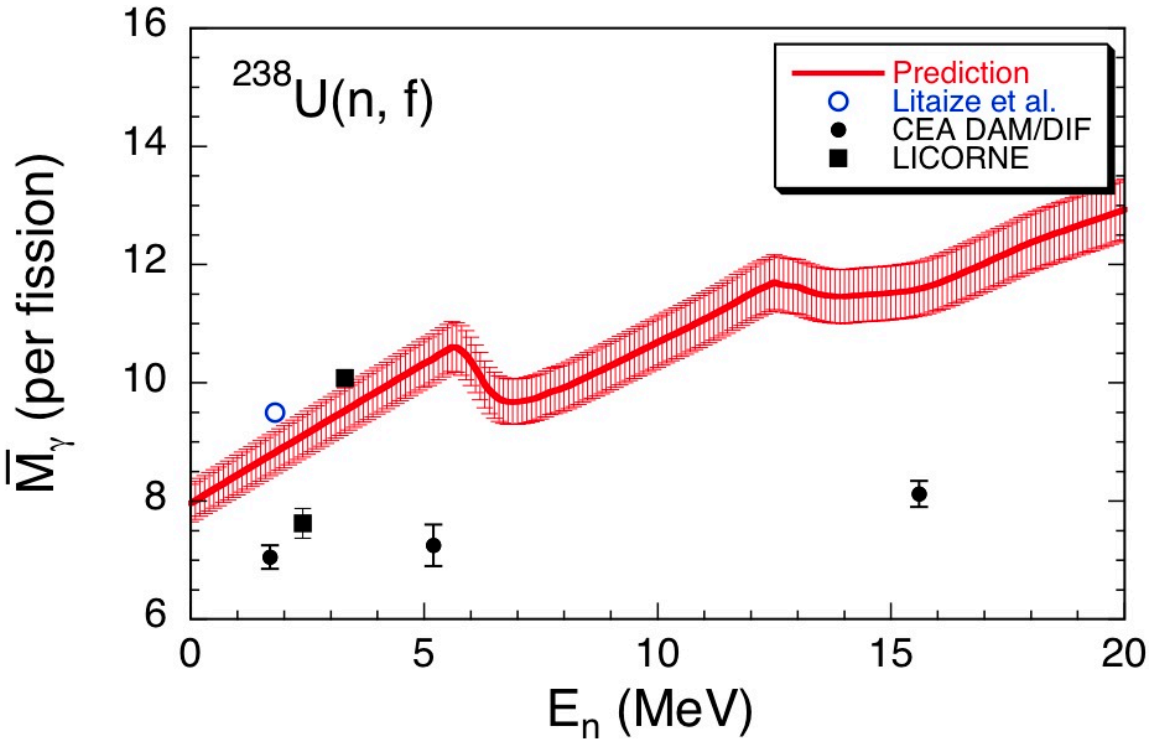
A. Oberstedt et al., PRC 96, 034612 (2017)

- Tudora: Point-by-Point model
- Litaize et al.: FIFRELIN code, Nucl. Data Sheets 118, 216 (2014)
- CEA DAM/DIF & LICORNE: preliminary experimental results

Results: energy dependence

Average γ-ray multiplicity

From thermal to fast neutron-induced fission



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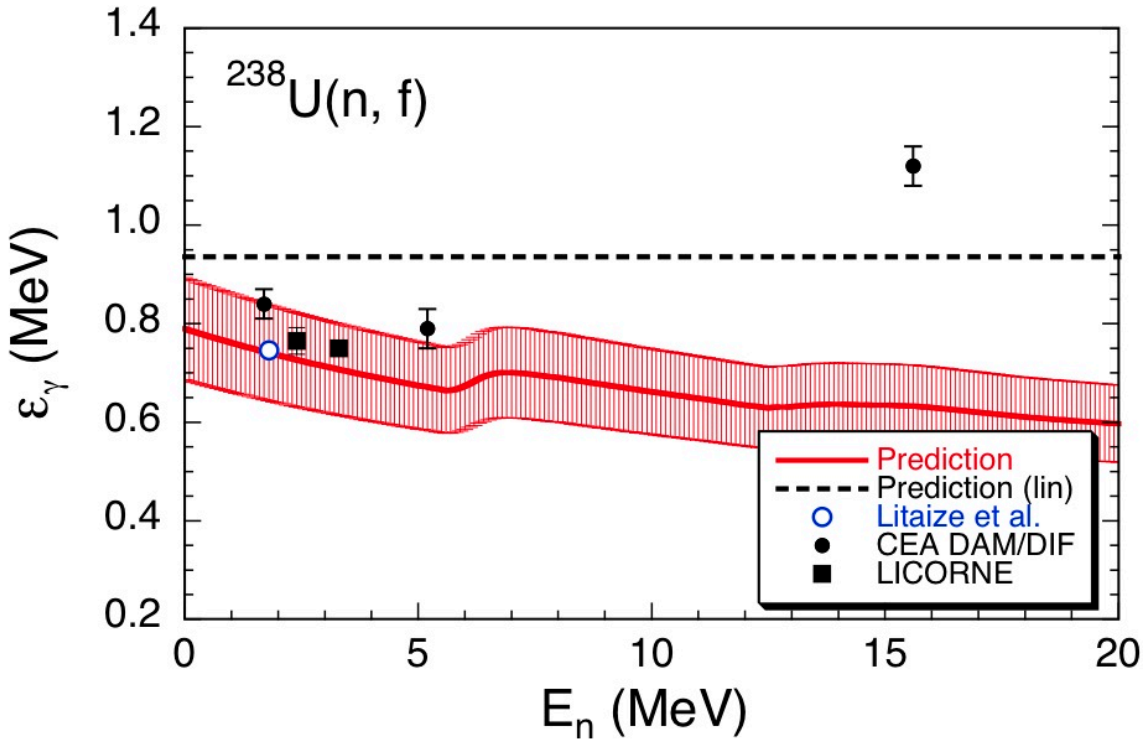
Results: energy dependence

Mean energy per photon

From thermal to fast neutron-induced fission



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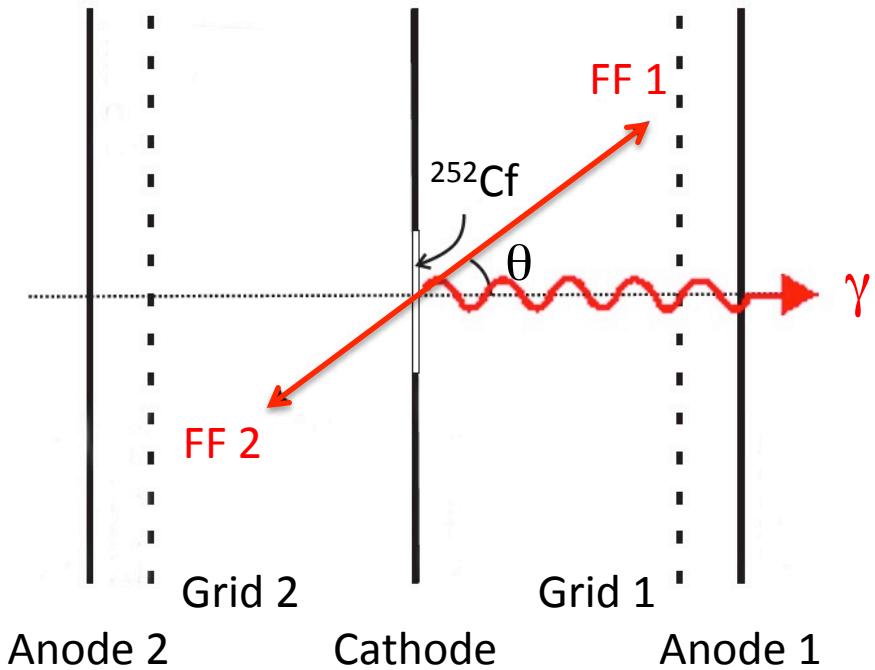
Experimental setup

Frisch grid ionization chamber + $LaBr_3$ detector

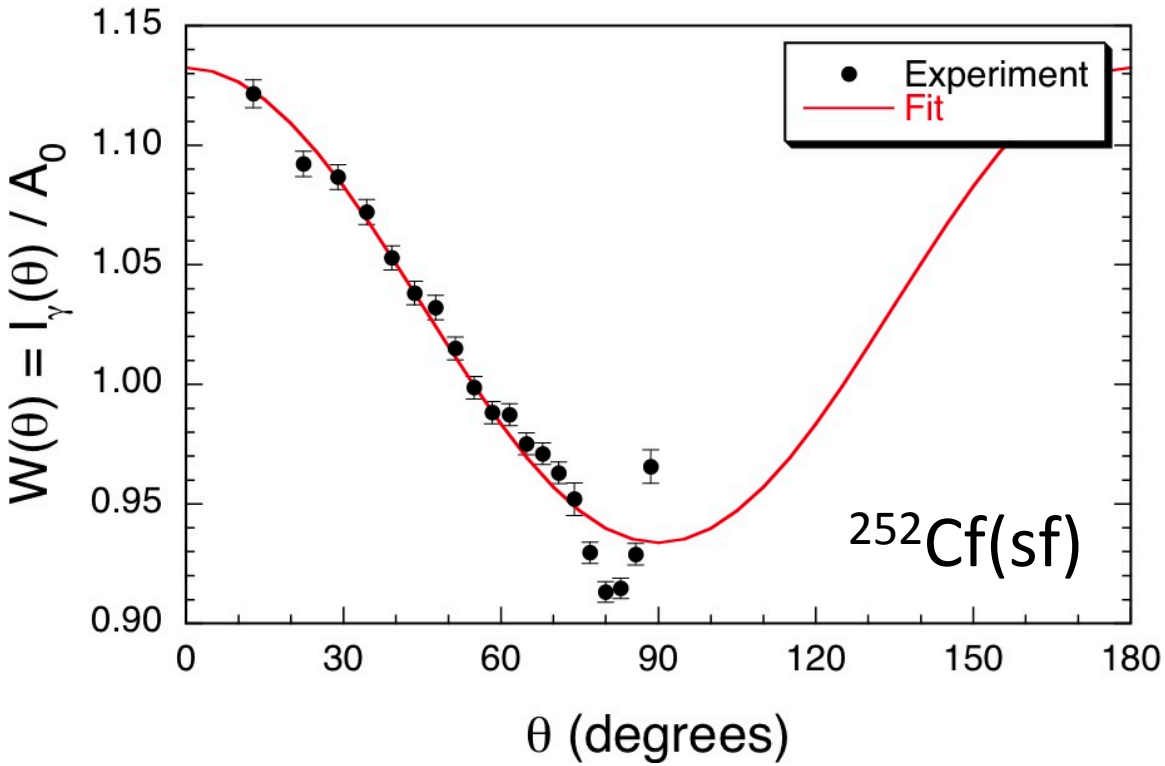


3 in. × 3 in.

Correlations between fission fragments and γ-rays

Results: angular distribution

Prompt fission γ-ray multipolarities

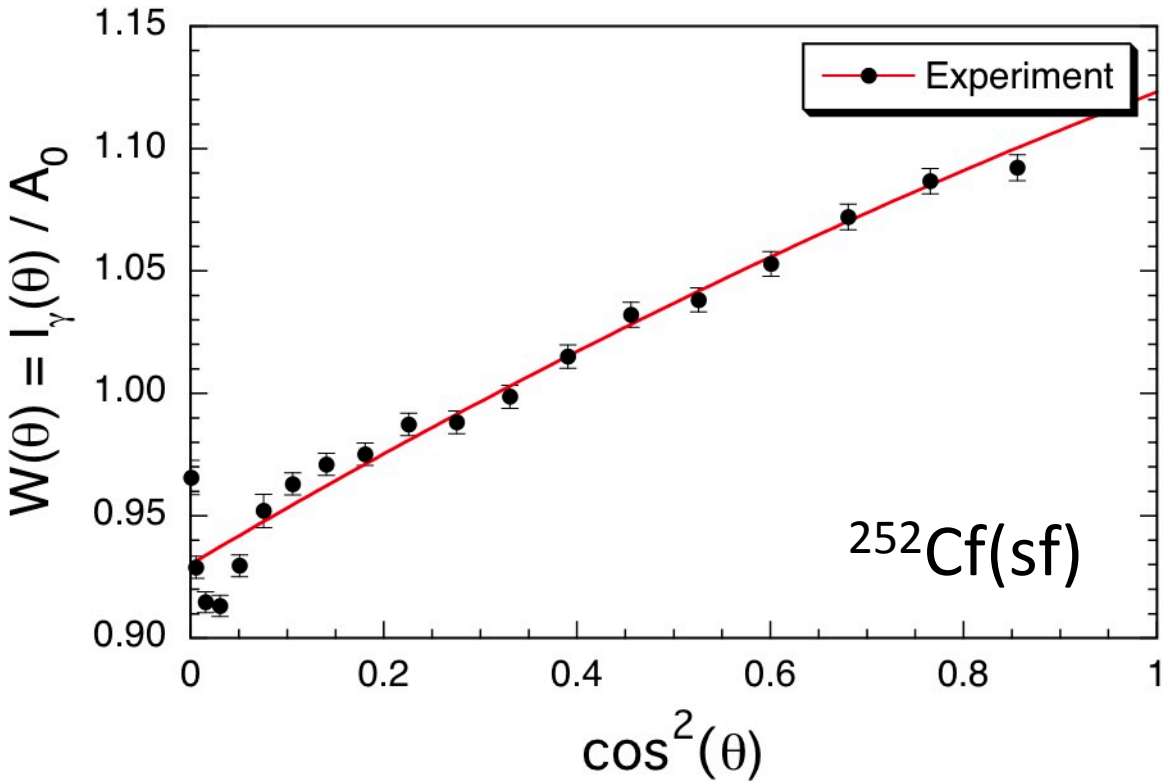


Statistical uncertainties only!

Fit: $W(\theta) = A_0 [1 + \{A_2/A_0\}P_2(\cos\theta) + \{A_4/A_0\}P_4(\cos\theta)]$

Results: angular distribution

Prompt fission γ-ray multipolarities

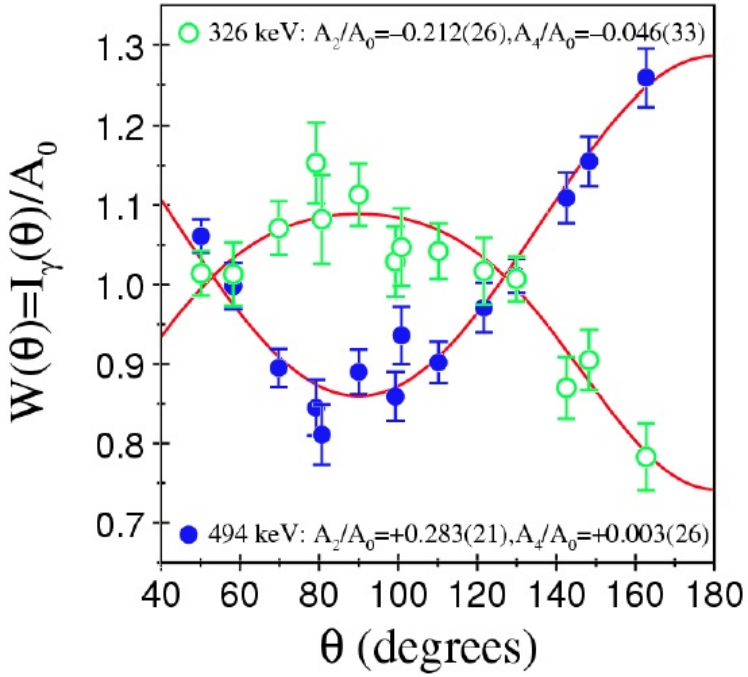


Statistical uncertainties only!

Fit result: $\{A_2/A_0\} = 0.13 \pm 0.03$

Results: angular distribution
Theory

Angular Distributions in ^{109}Te

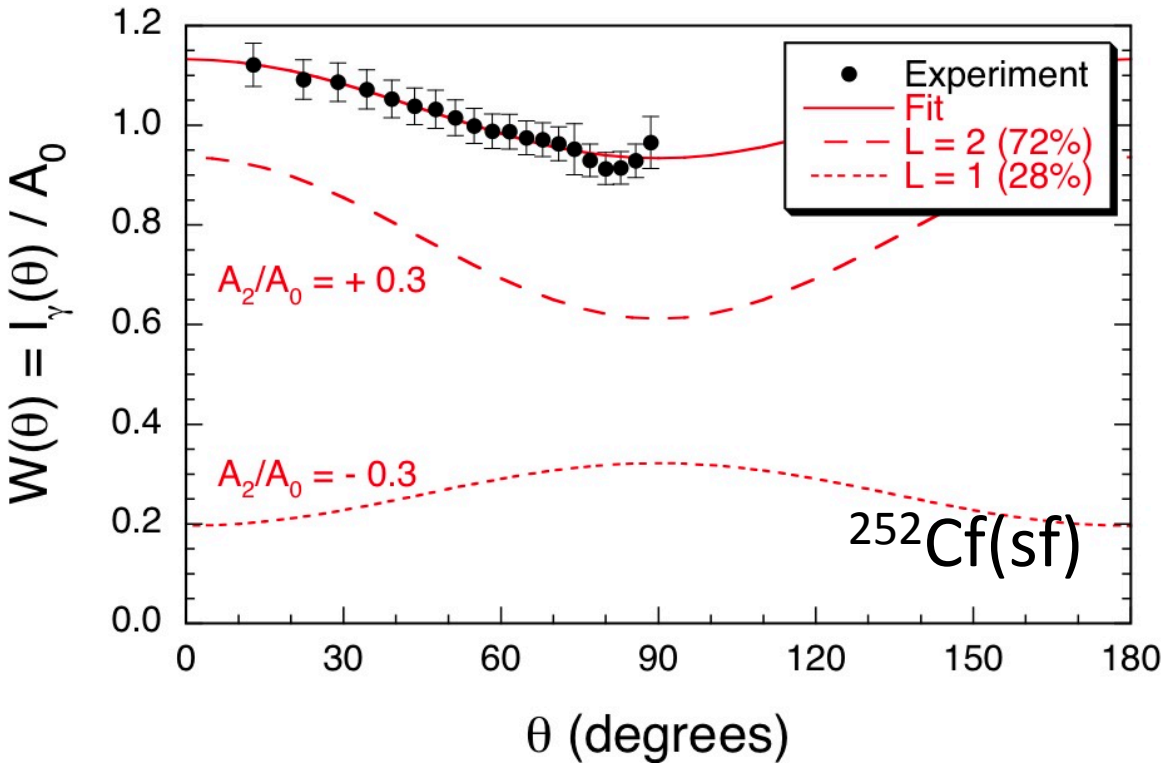


- Typically A_4/A_0 is close to zero
- And A_2/A_0 ~ +0.3 for a pure quadrupole (ΔI = 2) transition
- Or A_2/A_0 ~ -0.3 for a pure dipole (ΔI = 1) transition

30/08/2013 Postgraduate Summer School, Bristol : E.S. Paul 13

Results: angular distribution

Prompt fission γ-ray multipolarities



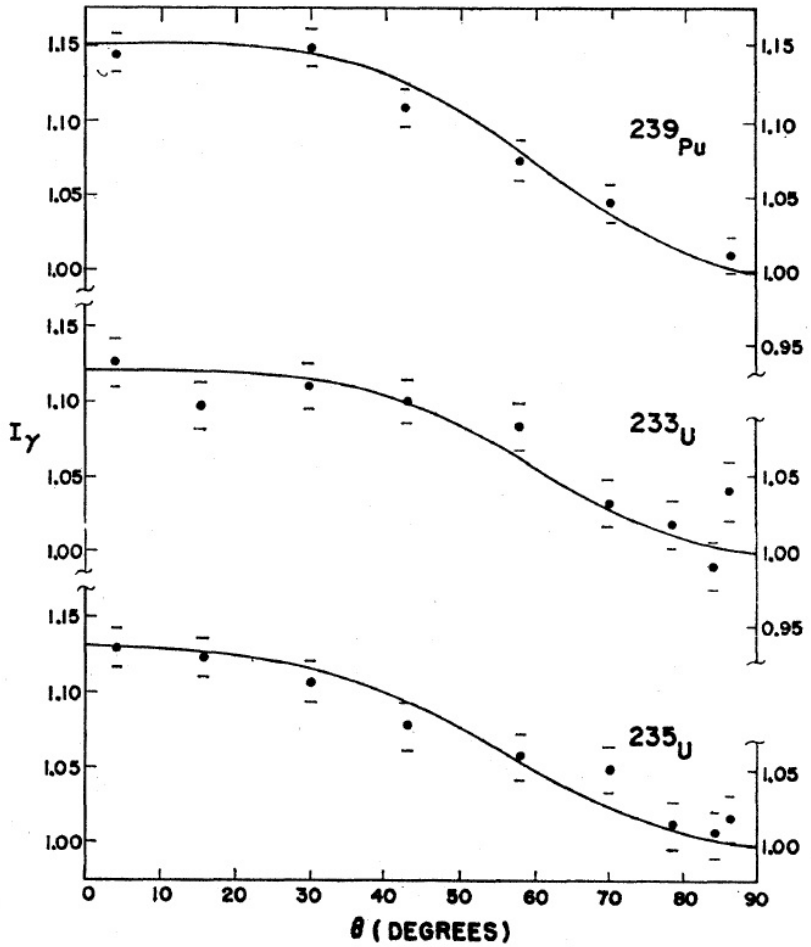
Statistical + systematic uncertainties!

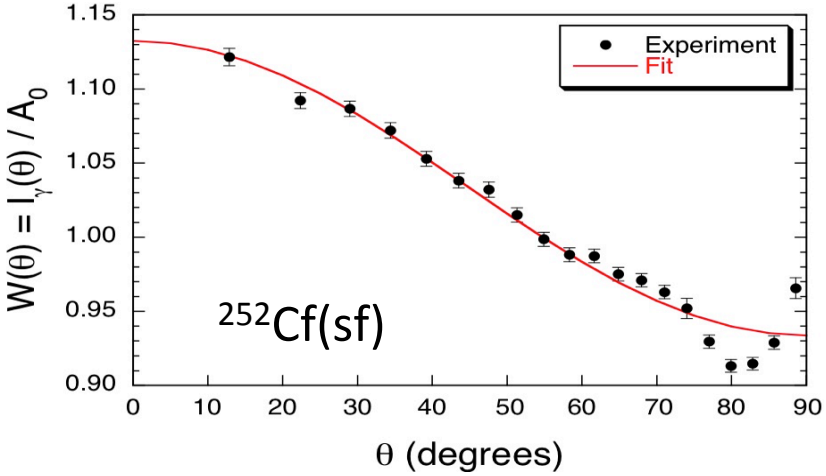
Theory: $\{A_2/A_0\} = +\ 0.3$ for quadrupole radiation

$\{A_2/A_0\} = -\ 0.3$ for dipole radiation

Results: angular distribution

Comparison with previous measurements *)



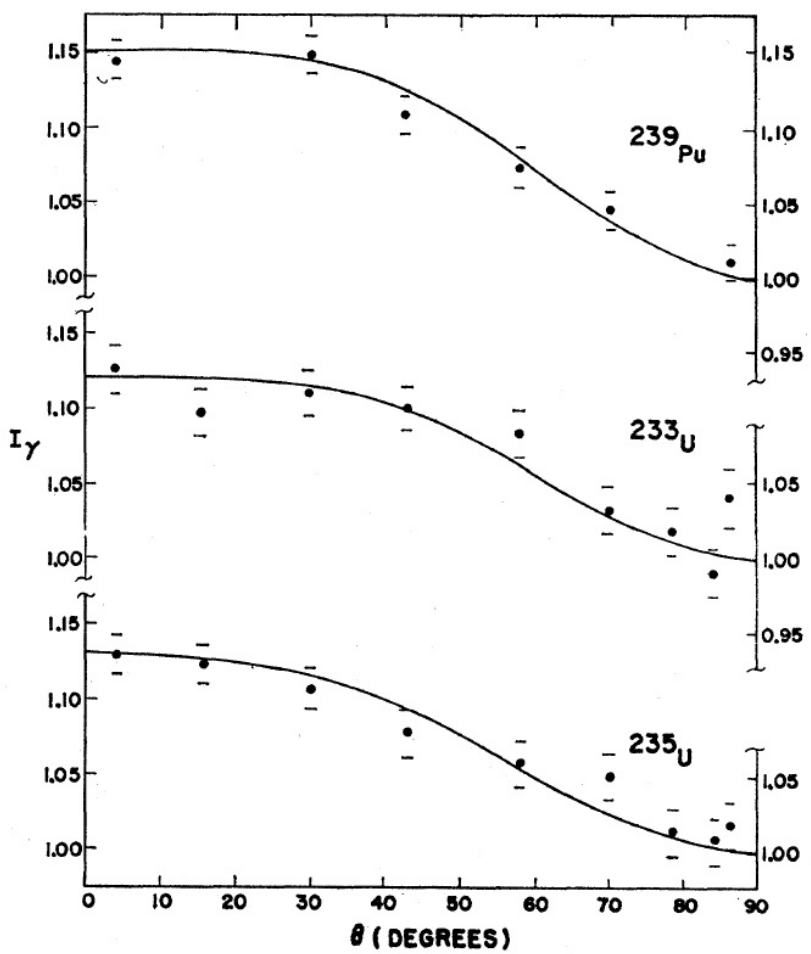


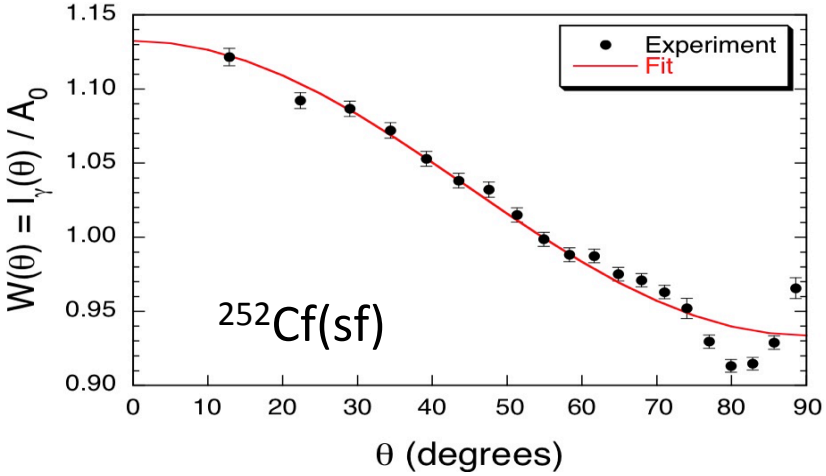
E_γ = 0.1 – 7.2 MeV

*) Hoffman, Phys. Rev. 133 (1964)

Results: angular distribution

Comparison with previous measurements *)





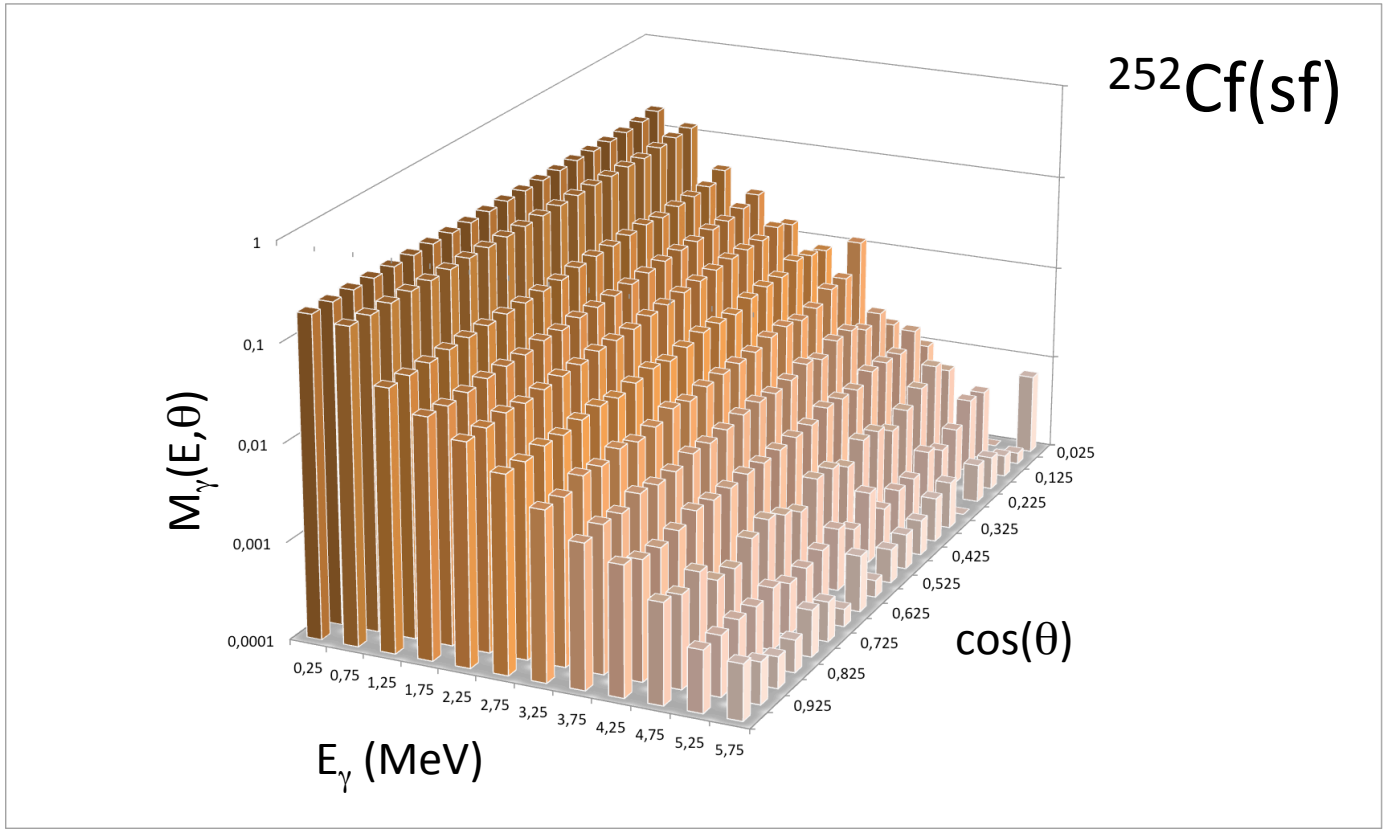
E_γ = 0.1 – 7.2 MeV

Good agreement in dominating E2 character !

*) Hoffman, Phys. Rev. 133 (1964)

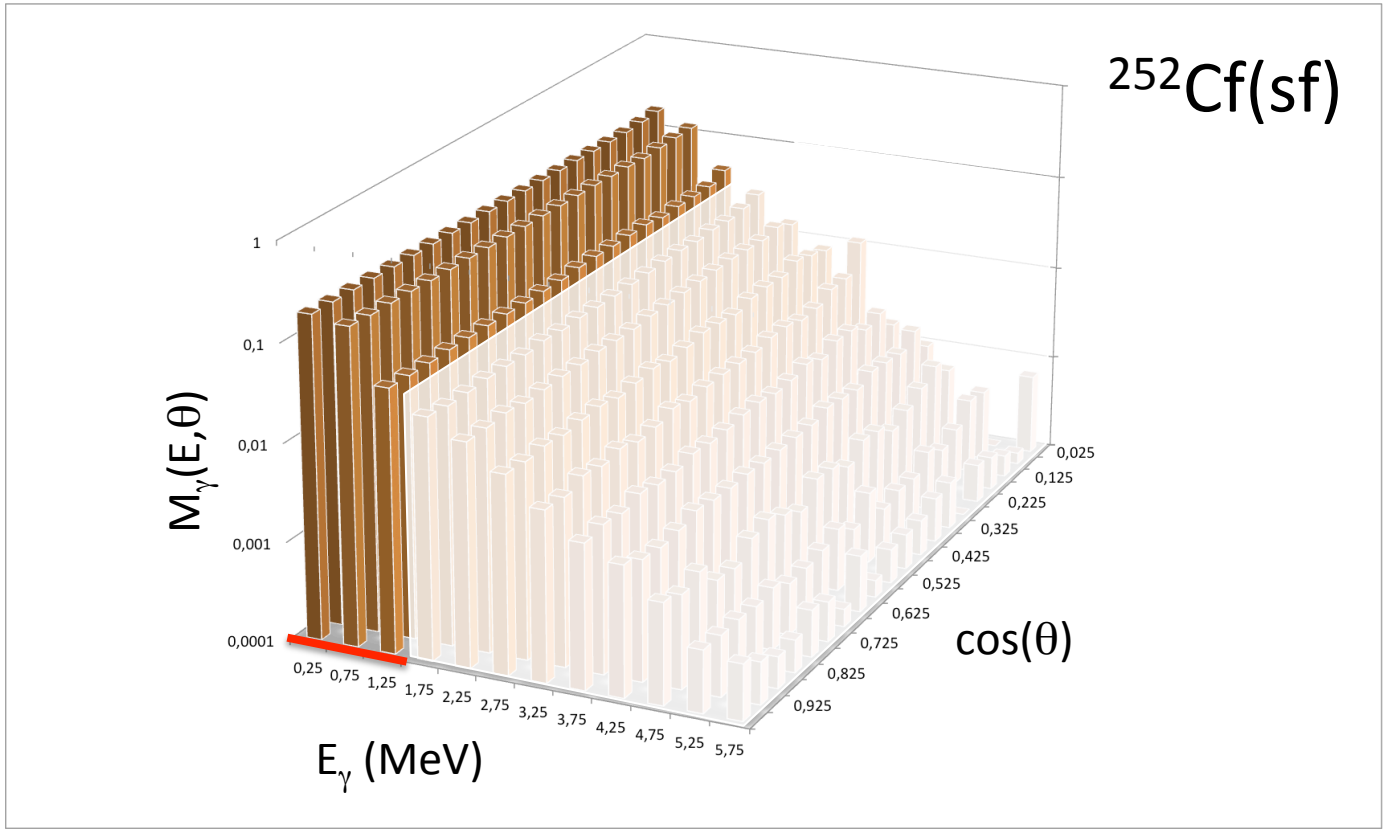
Results: PFGS

Angular distributions for 500 keV energy bins



Results: PFGS

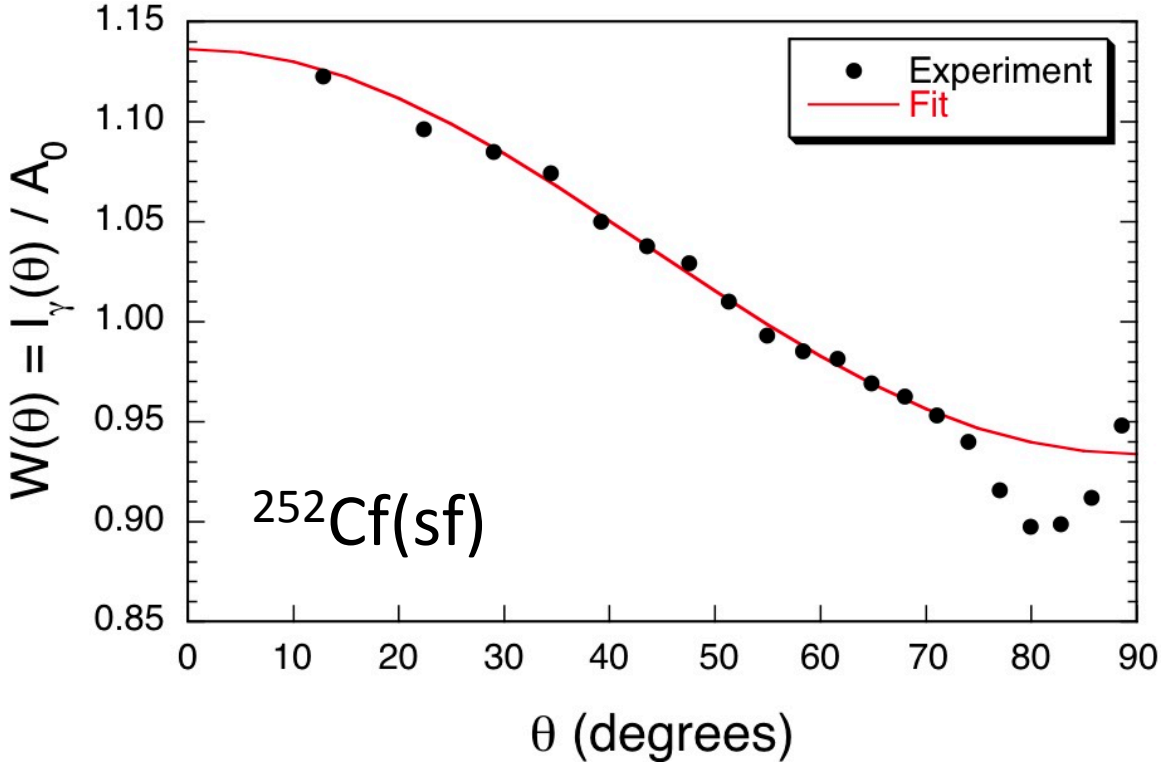
Angular distributions for 500 keV energy bins



→ consider energy range E_γ = 0.1 – 1.5 MeV

Results: angular distribution

Comparison with previous measurements



For E_γ = 0.1 – 1.5 MeV :

Results: angular distribution

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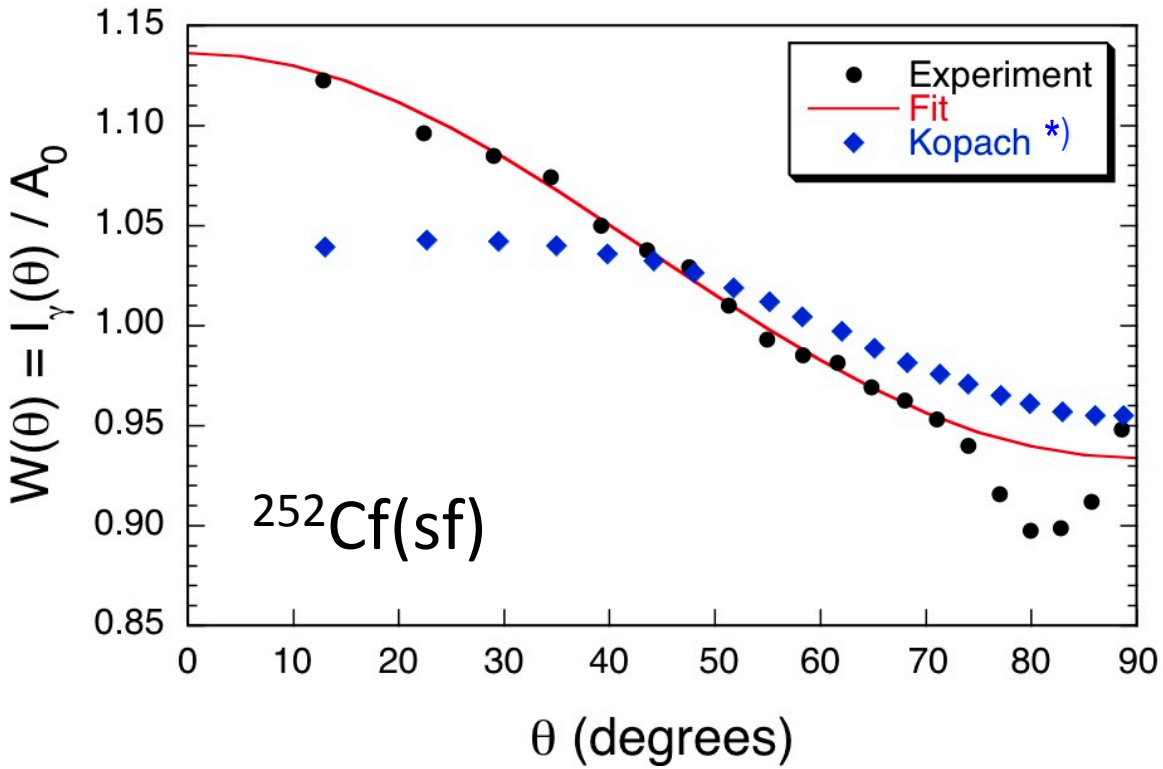
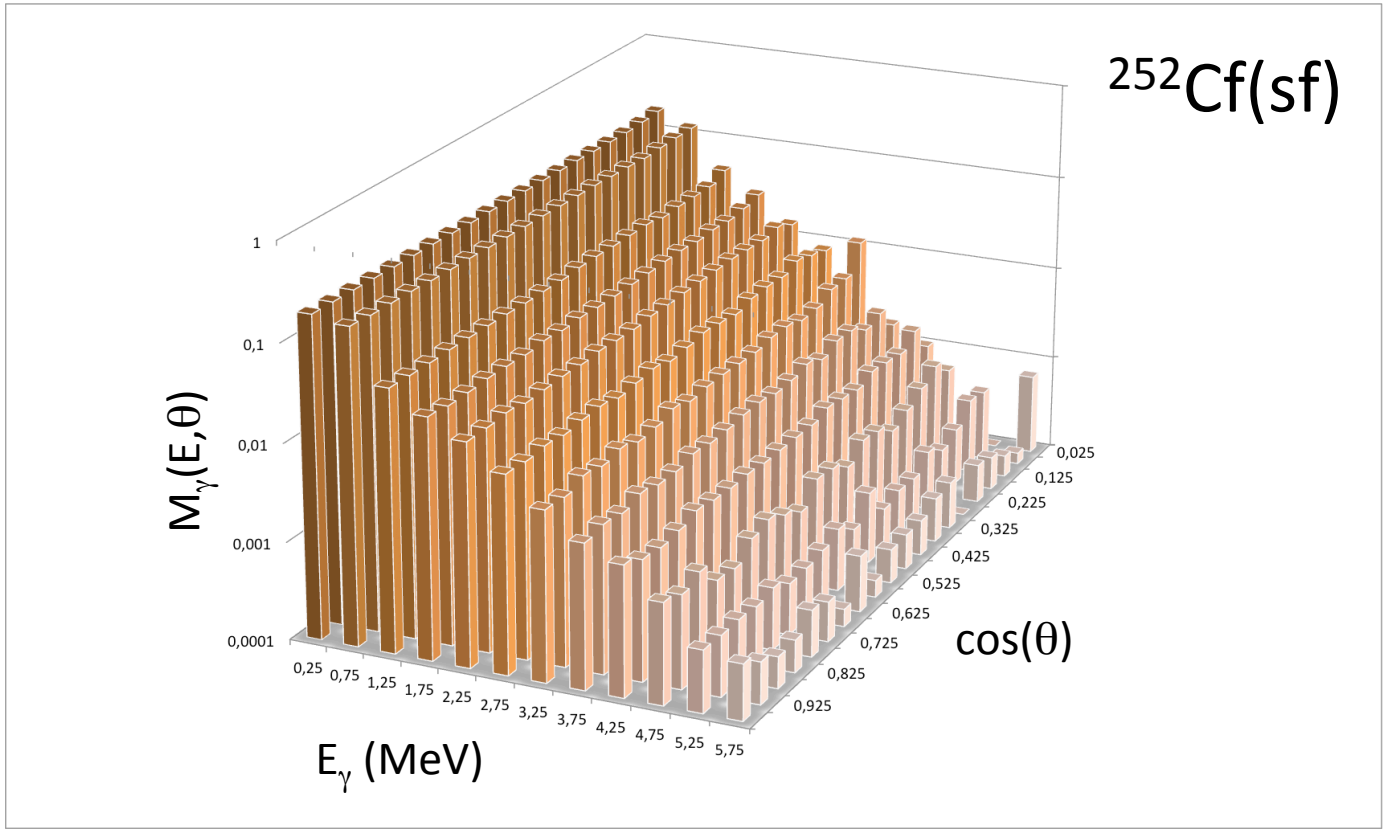


For E_γ = 0.1 – 1.5 MeV : → differences !

*) Kopach et al., Phys. Rev. Lett. 82 (1999)

Results: PFGS

Angular distributions for 500 keV energy bins

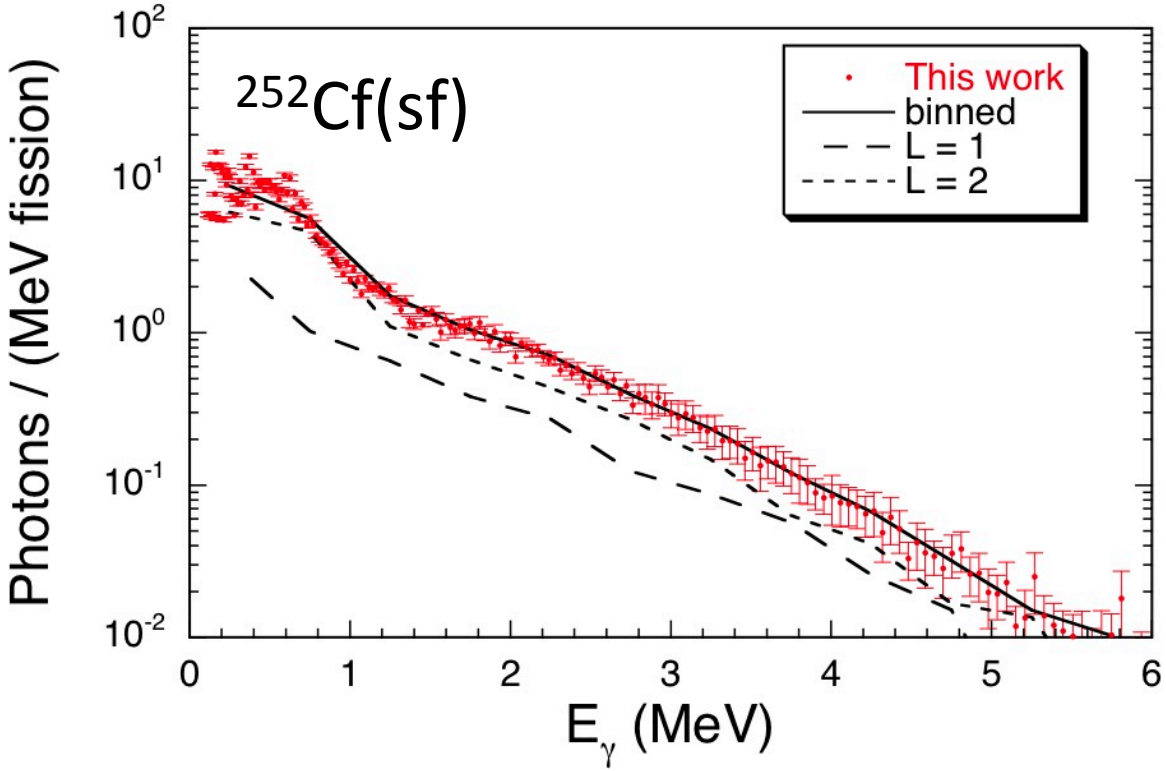


→ again: fit of Legendre polynomials

→ decomposition of multipolarities L = 1 and 2

Results: PFGS

Decomposition of multipolarities

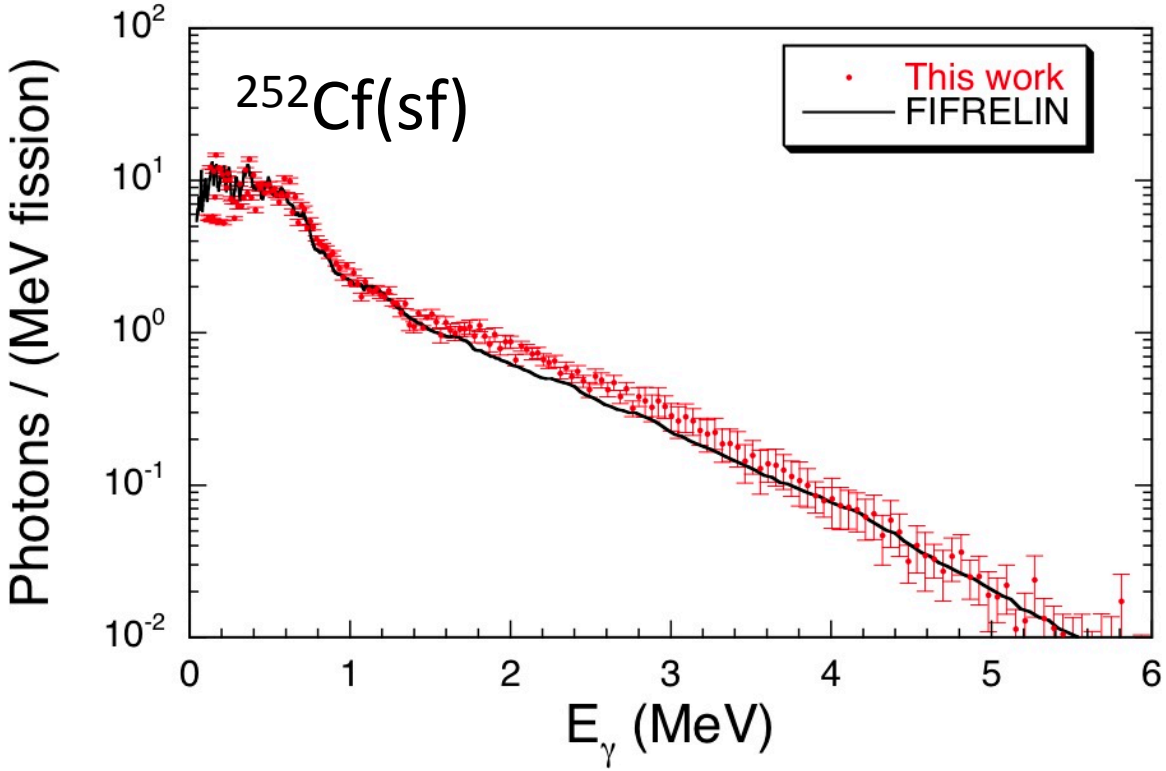


→ multipolarity-dependent spectra

→ multipolarity-dependent PFGS characteristics

Results: PFGS

Comparison with FIFRELIN calculations *)



*) A. Chebboubi, priv. comm.

Good agreement between integral spectra!

Results: PFGS

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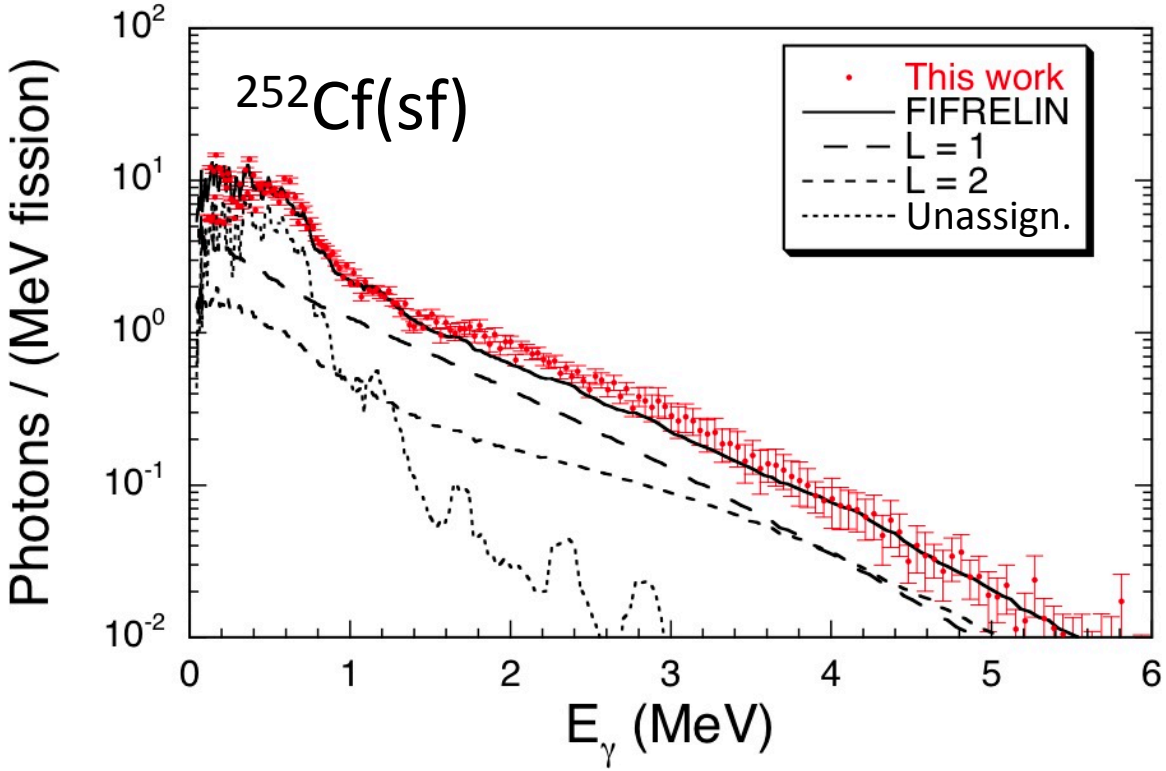

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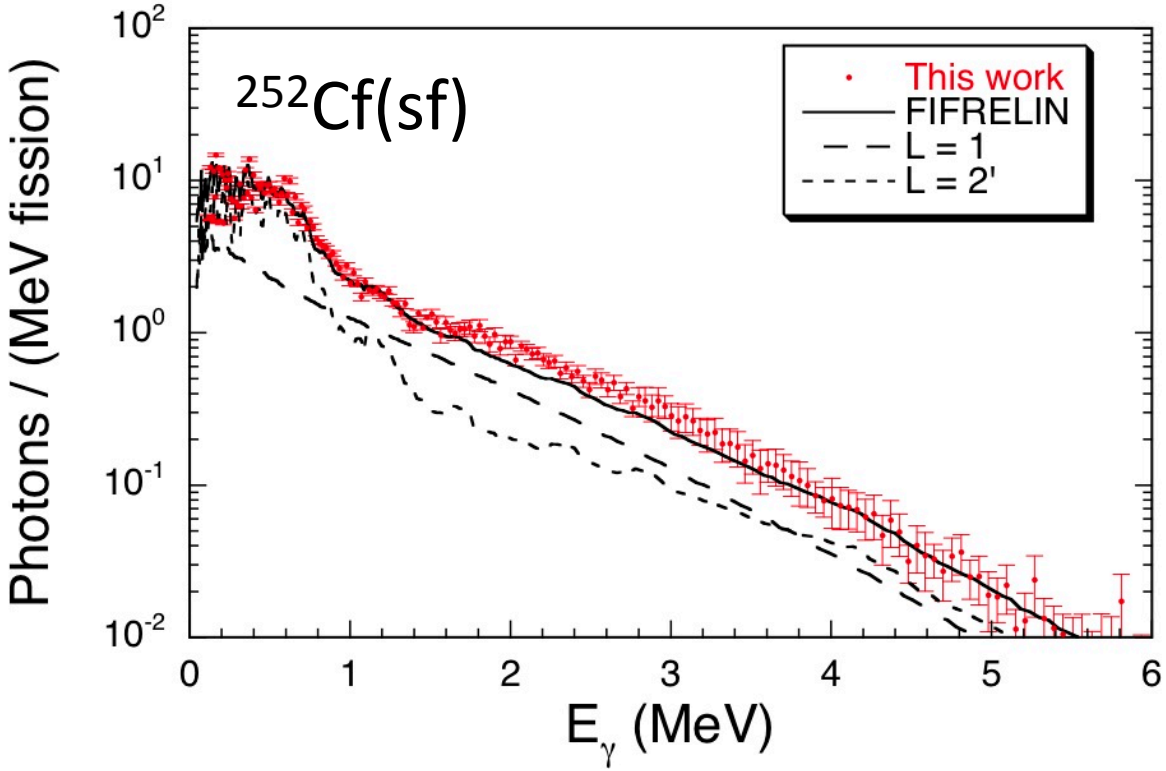
Good agreement between integral spectra!

But FIFRELIN also provides multipolarity-dependent PFGS.

Results: PFGS

Comparison with FIFRELIN calculations *)



*) A. Chebboubi, priv. comm.

From our observations: unassigned transitions → L = 2, L = 2 + unassigned → L = 2'.

Results: angular distribution

Comparison with FIFRELIN calculations *)

^{252}Cf(sf)	Experiment (this work)		Calculations (FIFRELIN)	
$\bar{M}_\gamma$	8.28 ± 0.51		8.28	(adjusted)
$\bar{M}_\gamma$ (L = 1)	2.40	(29 %)	3.20	(39 %)
$\bar{M}_\gamma$ (L = 2')	5.88	(71 %)	5.08	(61 %)
$\bar{M}_\gamma$ (unassign.)	---		---	
$\bar{\varepsilon}_\gamma$	0.81 ± 0.10	(MeV)	0.76	(MeV)
$\bar{\varepsilon}_\gamma$ (L = 1)	0.88	(MeV)	0.94	(MeV)
$\bar{\varepsilon}_\gamma$ (L = 2')	0.79	(MeV)	0.65	(MeV)
$\bar{\varepsilon}_\gamma$ (unassign.)	---		---	
$\bar{E}_\gamma$	6.75 ± 0.76	(MeV)	6.30	(MeV)
$\bar{E}_\gamma$ (L = 1)	2.11	(MeV)	3.00	(MeV)
$\bar{E}_\gamma$ (L = 2')	4.64	(MeV)	3.30	(MeV)
$\bar{E}_\gamma$ (unassign.)	---		---	

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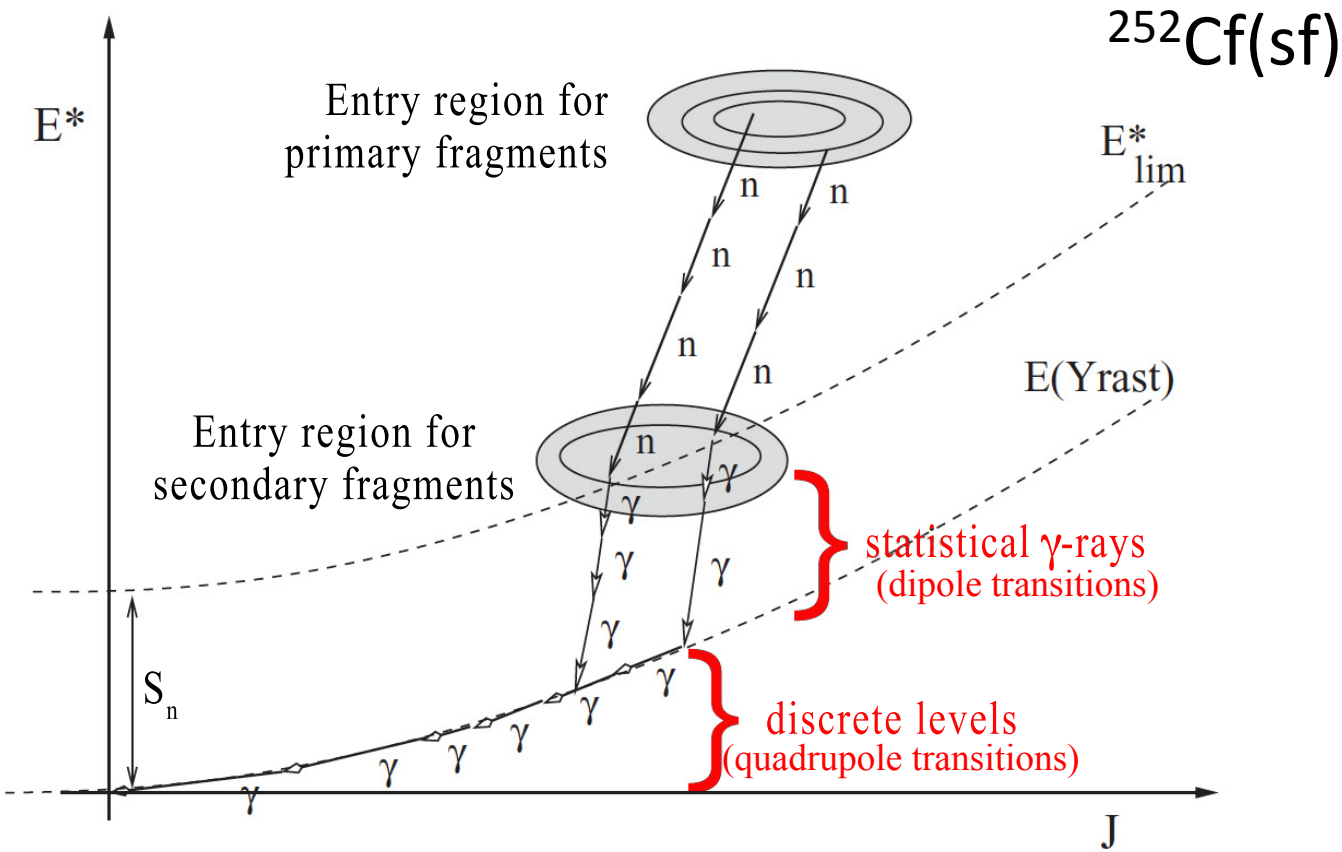
Summary I

- High precision PFGS measurements → reference for model calculations – e.g.: ^{252}Cf(sf)

Summary I

Sequential emission of neutrons and γ-rays



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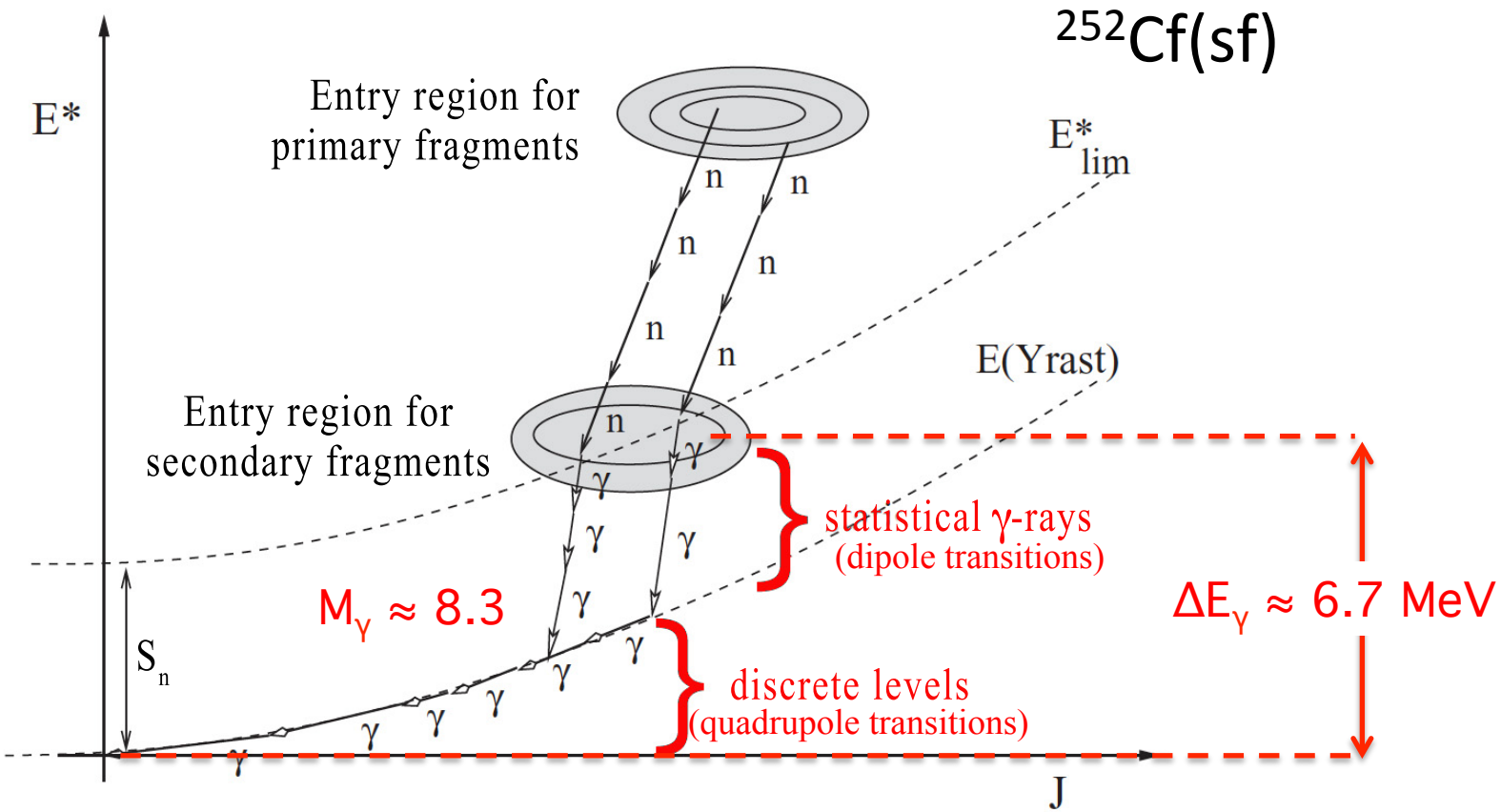

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- High precision PFGS measurements → reference for model calculations – e.g.: ^{252}Cf(sf)
- Revised systematics for spontaneous and thermal neutron-induced fission
- Predictions of PFGS characteristics for fast neutron-induced fission -> rather good agreement
- Measured γ-ray angular distribution from ^{252}Cf(sf) → dominant E2 character, in good agreement with previous observations + FIFRELIN calculations
- Preliminary results : $\langle M_{\gamma,L=1} \rangle \approx 2.4$ and $\langle M_{\gamma,L=2} \rangle \approx 5.9$, as well as $\langle E_{\gamma,tot(L=1)} \rangle \approx 2.1$ MeV and $\langle E_{\gamma,tot(L=2)} \rangle \approx 4.6$ MeV

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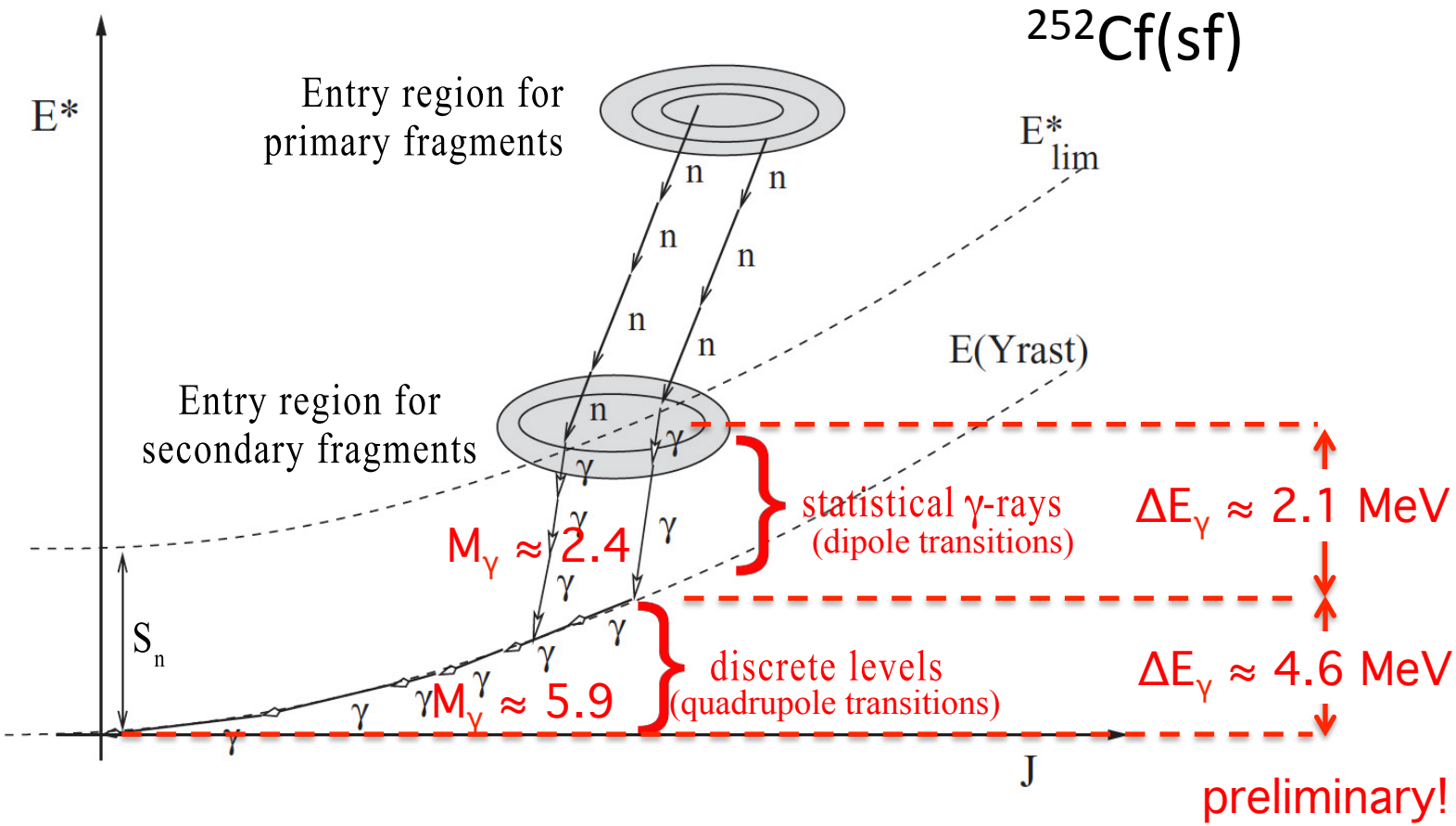

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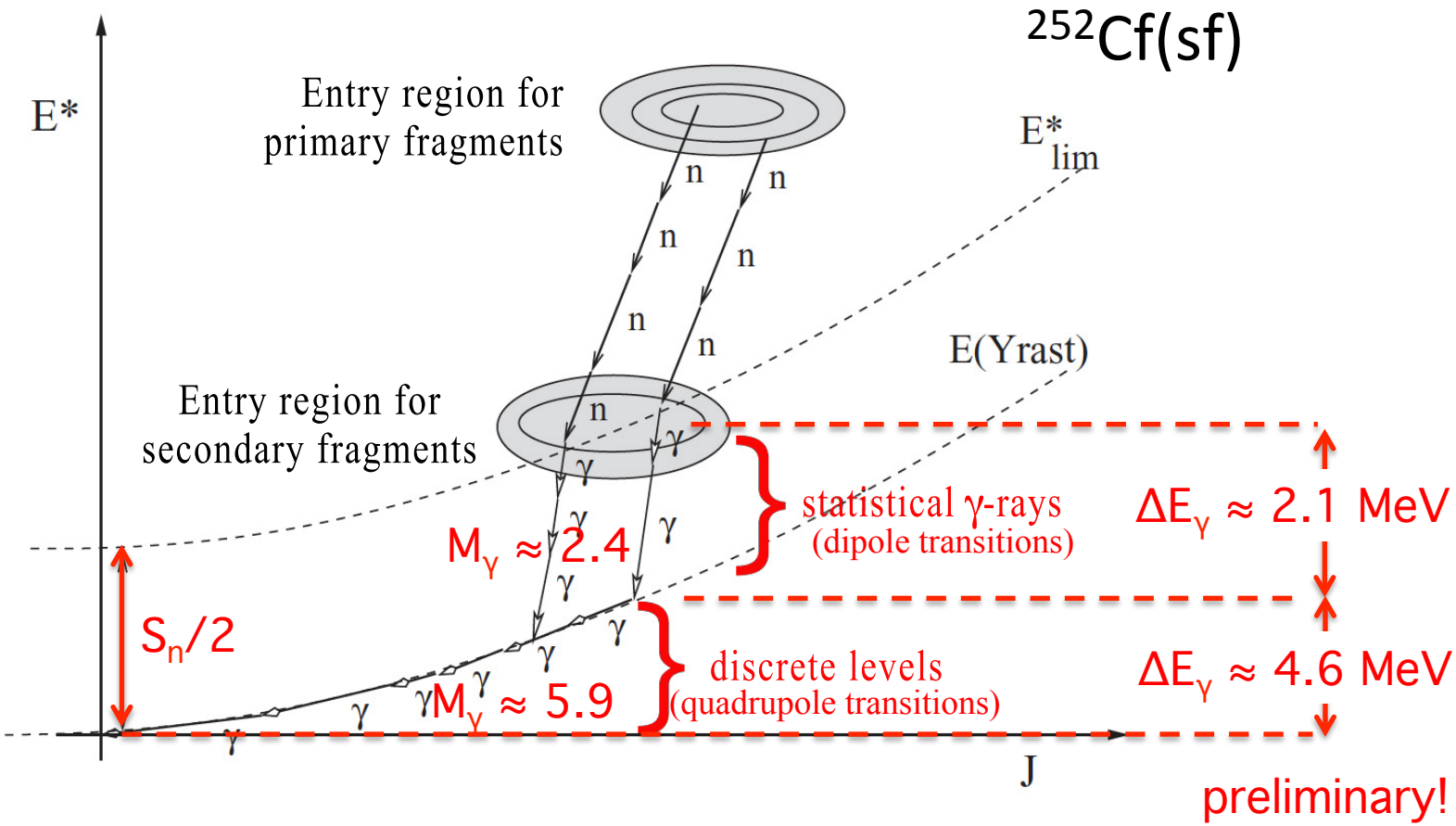

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- Average spin of fission fragments : $\Delta J \approx 14\ \hbar$

Summary I

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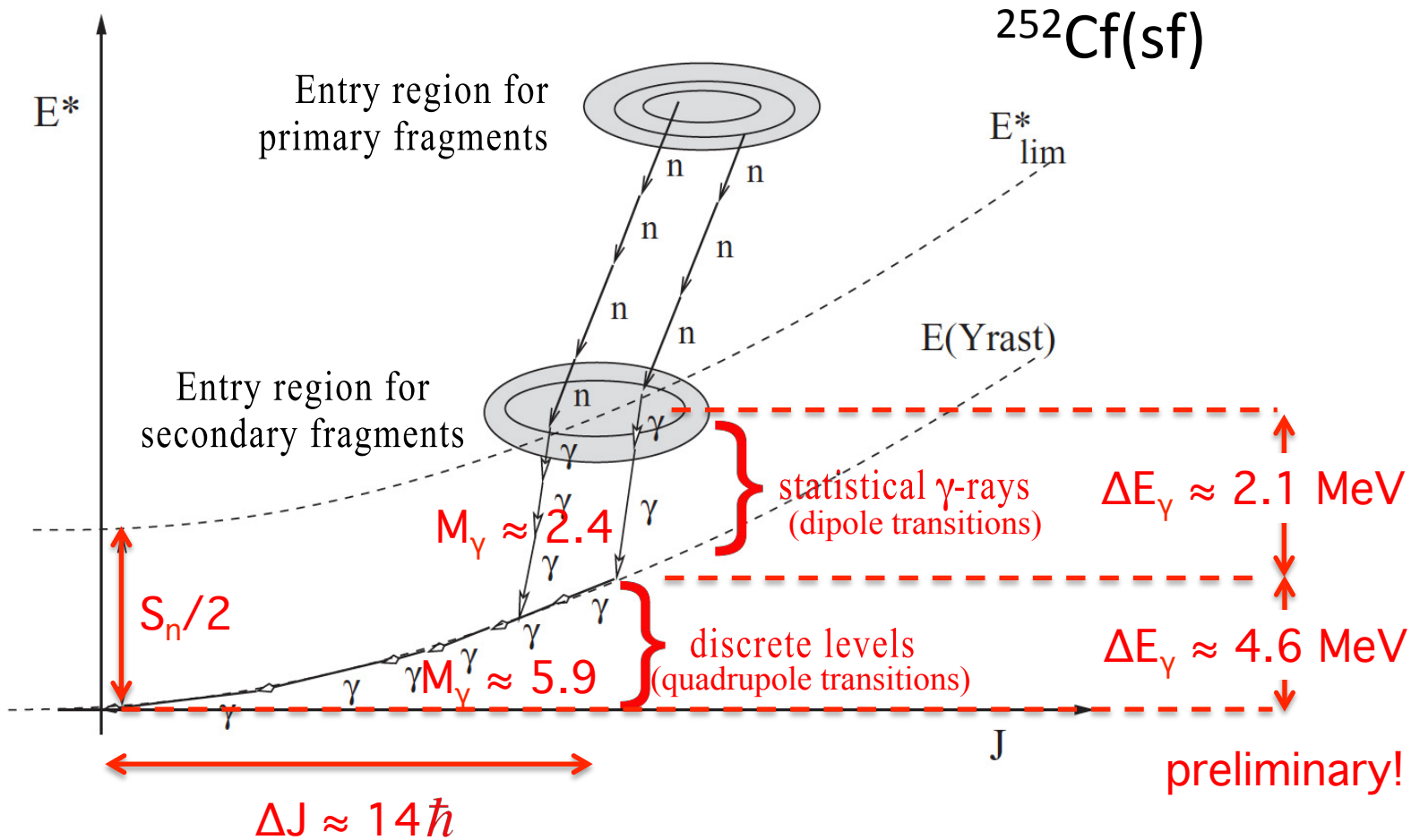

Summary II

But:

- Discrepancies compared to Kopach et al., PRL 88 (1999)
- From angular distribution :

  $\langle S_n \rangle = 2 \times \langle E_{\gamma,tot(L=1)} \rangle \approx 4.2$ MeV, while weighted with fission fragment distribution : $\langle S_n \rangle \approx 5.9$ MeV !

  (fission fragment distributions from GEF, $S_n(Z,A)$ according to Vogt et al., PLB 517 (2001))
- High energy quadrupole γ rays (of several MeV) observed, whose origin cannot be explained with rotational states

- To be continued ...

Outlook I

- New results from recent measurements
- New experiments are approved and scheduled
- Study of PFGS characteristics depending on fission fragment mass
- Study of entrance channel effects
  - (n,f) vs. (d,pf)
  - (p,p'f) vs. (γ,f)
  - etc.

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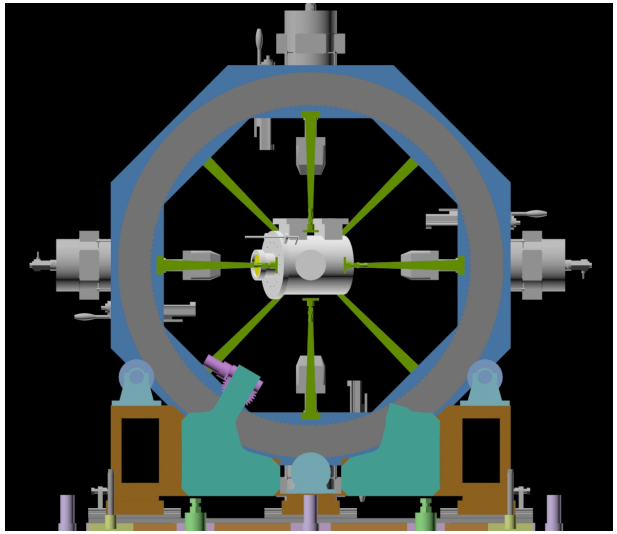
- And last but not least:

  → Photo-fission at ELI-NP !

Outlook II

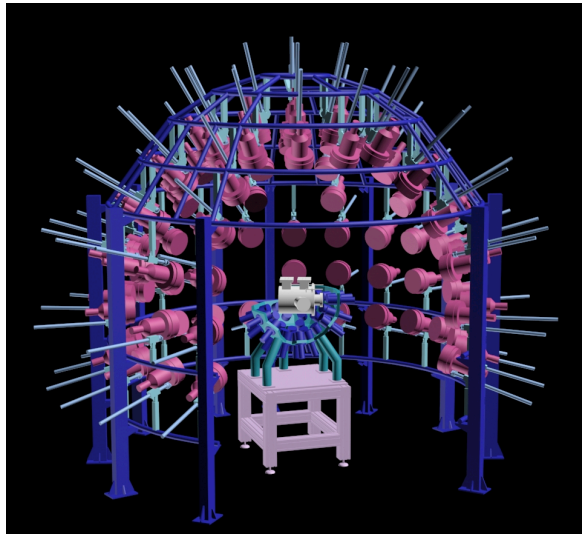
ELI-NP and further photo-fission physics goals

ELIADE



8 CLOVER Ge detectors + 4 large-volume $LaBr_3$ detectors (3” x 3”)

ELIGANT



17 $LaBr_3$ + 17 $CeBr_3$ detectors (3” x 3”) and 33 liquid + 29 ^6Li glass scintillation detectors

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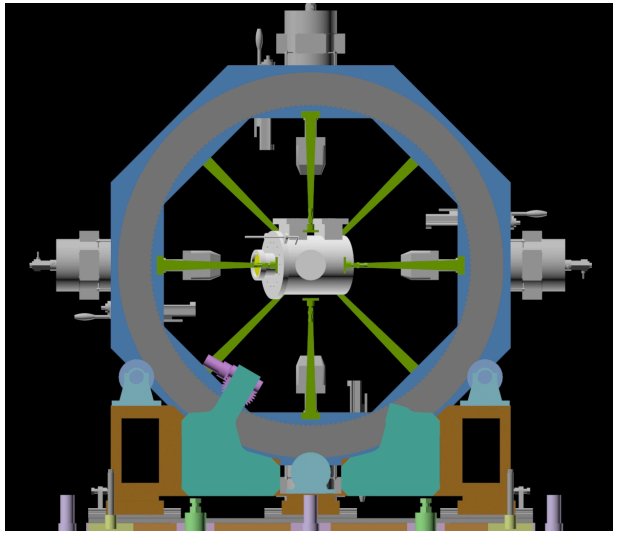
New position-sensitive twin FGIC (TU Darmstadt)

+

ELIADE



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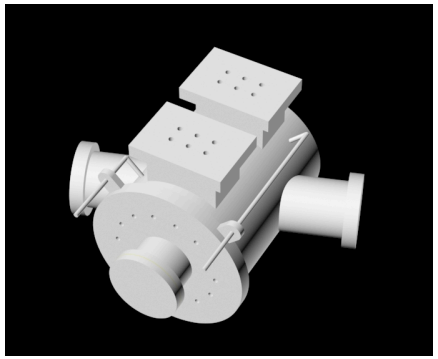
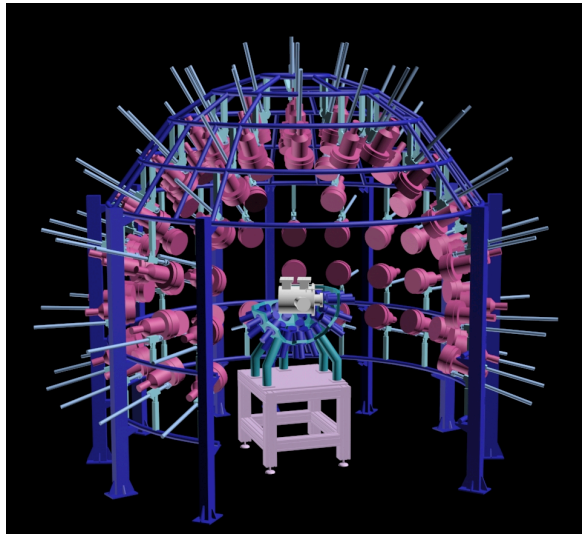


(courtesy M. Peck)

+

ELIGANT



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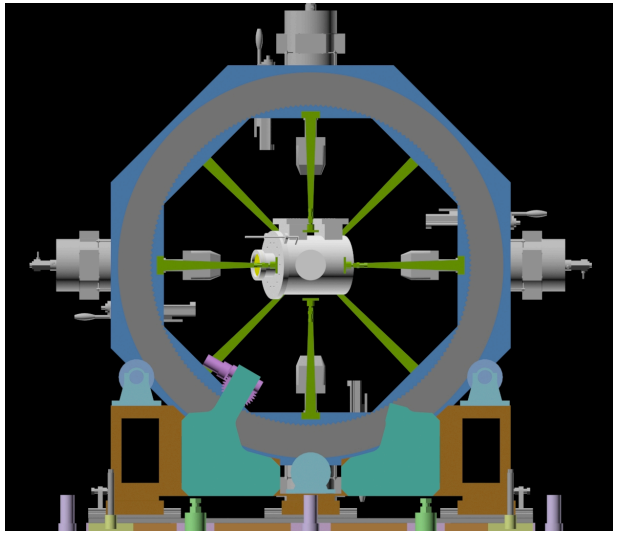

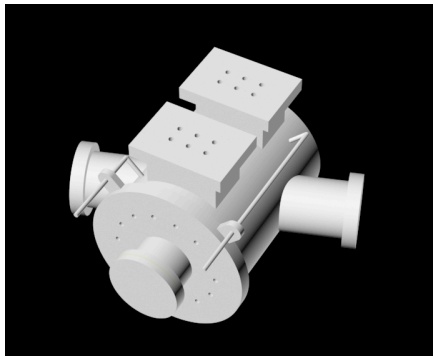

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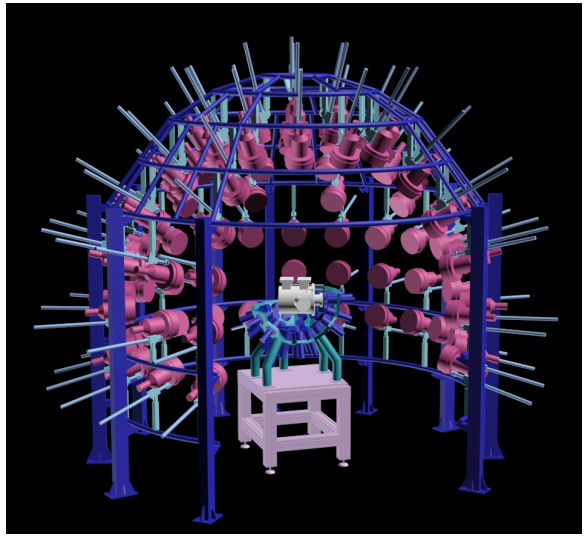

- Study of the fission fragment de-excitation process
  - measurement of fission fragments, γ rays and neutrons
  - correlations !

The collaborators

T. Belgya, R. Billnert, R. Borcea, T. Brys, A. Chatillon, D. Choudhury, A. Cita, S. Courtin, J. Enders, M. Fallot, G. Fruet, A. Gatera, W. Geerts, G. Georgiev, A. Göök, C. Guerrero, P. Halipré, F.-J. Hambsch, D.G. Jenkins, Z. Kis, B. Laurent, M. Lebois, L. Le Meur, A. Maj, P. Marini, B. Maróti, T. Martinez, I. Matea, A. Moens, L. Morris, V. Nanal, P. Napiorkowski, D. Nichita, M. Peck, A. Porta, F. Postelt, A. Oberstedt, S. Oberstedt, L. Qi, L. Szentmiklosi, K. Takàcs, S.J. Rose, G. Sibbens, S. Siem, C. Schmitt, O. Serot, M. Stanoiu, D. Vanleeuw, M. Vidali, B. Wasilewska, J.N. Wilson, A.-A. Zakari, F. Zeiser ...

PhD students

Thank you!