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Fission-fragment de-excitation: Prompt neutron and γ-ray emission

S. Oberstedt

Joint ICTP-IAEA School, Trieste, Oct. 19 – 30, 2015

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- PFNS - Measurement techniques
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The fission process

prompt neutrons (10^{-18} s)

prompt γ-rays (10^{-16} s)

fission fragments (10^{-21} s)

ternary α, t, d, ^{10}Be…

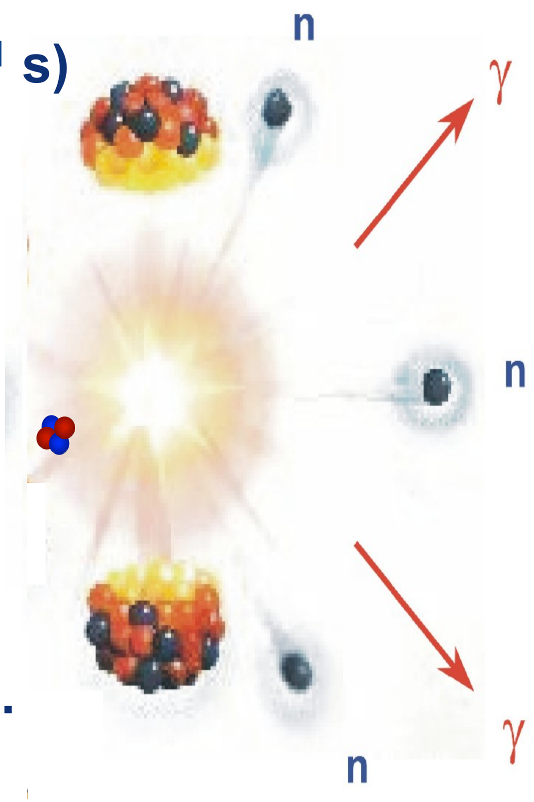
kinetic energy prompt γ-rays	heat
prompt neutrons (delayed neutrons)	chain reaction
ternary α, t, d	gas production in the fuel (waste)
fission fragments	decay heat, toxicity (waste)

The fission process

prompt neutrons (10^{-18} s)

prompt γ-rays (10^{-16} s)

fission fragments (10^{-21} s)



ternary α, t, d, ^{10}Be…

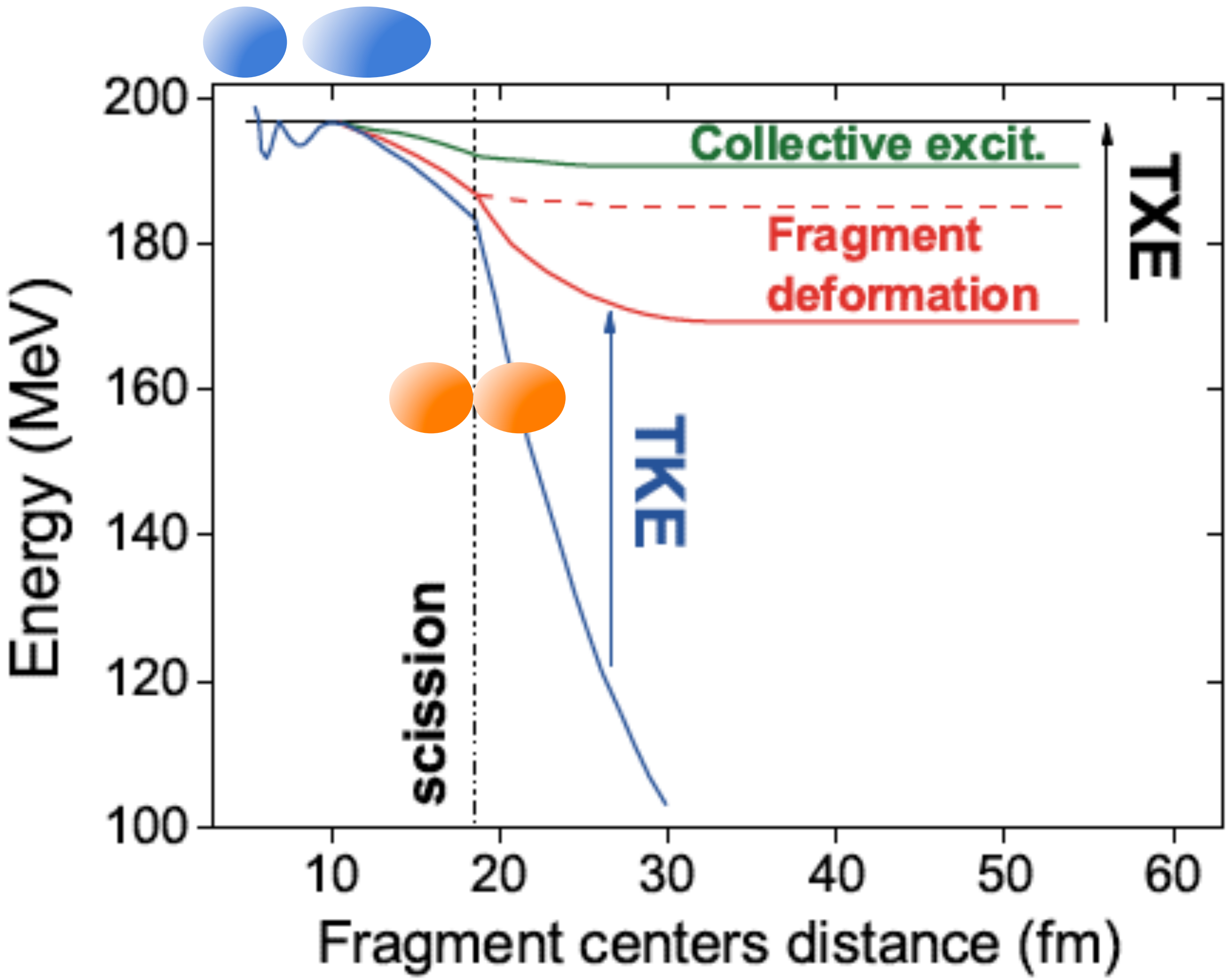
kinetic energy
prompt γ-rays
} heat

prompt neutrons
(delayed neutrons)
} chain reaction

ternary α, t, d — gas production in the fuel (waste)

fission fragments — decay heat, toxicity (waste)

The fission process



The fission process

- **During acceleration the deformed fragments reorganize to get close to their ground state state**

- **After acceleration the fragments reach their final kinetic energy → total kinetic energy (TKE)**

- **150 < TKE and TKE > 200**
- **E.g. <TKE>(^{252}Cf) = 183.5 MeV**

- **About 40 MeV goes into excitation energy of each fragment ranges between 0 < E_x < 40 MeV**

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Fission fragment de-excitation

De-excitation		E (MeV)	σ (MeV)
Prompt component	Total kinetic energy $<E_{tot}>_n$ $<E_{tot}>_\gamma$	169.12 4.79 6.97	0.49 0.07 0.50
Delayed component	$<E_{tot}>_{n,delayed}$ $<E_{tot}>_{\gamma,delayed}$ β-decay $<E_{tot}>_{anti-neutrinos}$	7.4×10^{-3} 6.33 6.50 8.75	0.001 0.050 0.050 0.070
Total		202.47	0.13

$^{235}U(n_{th},f)$: JEFF 3.1.2

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Fission fragment de-excitation

$$TXE = Q - TKE$$

$$E^{*} = a\,T^{2}$$

$$TXE = a_{sc} T_{sc}^{2} + E_{def} + E_{coll}$$ @ scission

$$TXE = a_{L} T_{L}^{2} + a_{H} T_{H}^{2} + E_{L}^{rot} + E_{H}^{rot}$$ fully accel.

$$TXE - (E_{L}^{rot} + E_{H}^{rot}) = E_{L}^{*} + E_{H}^{*}$$

$$E^{rot} = \frac{\hbar^{2} J(J+1)}{2\Im}$$

$$a = \tilde{a}\,(1 + \delta W\,(1 - e^{-\gamma U^{*}})/U^{*})$$

FIFRELIN, O. Serot, O. Litaize, D. Regnier

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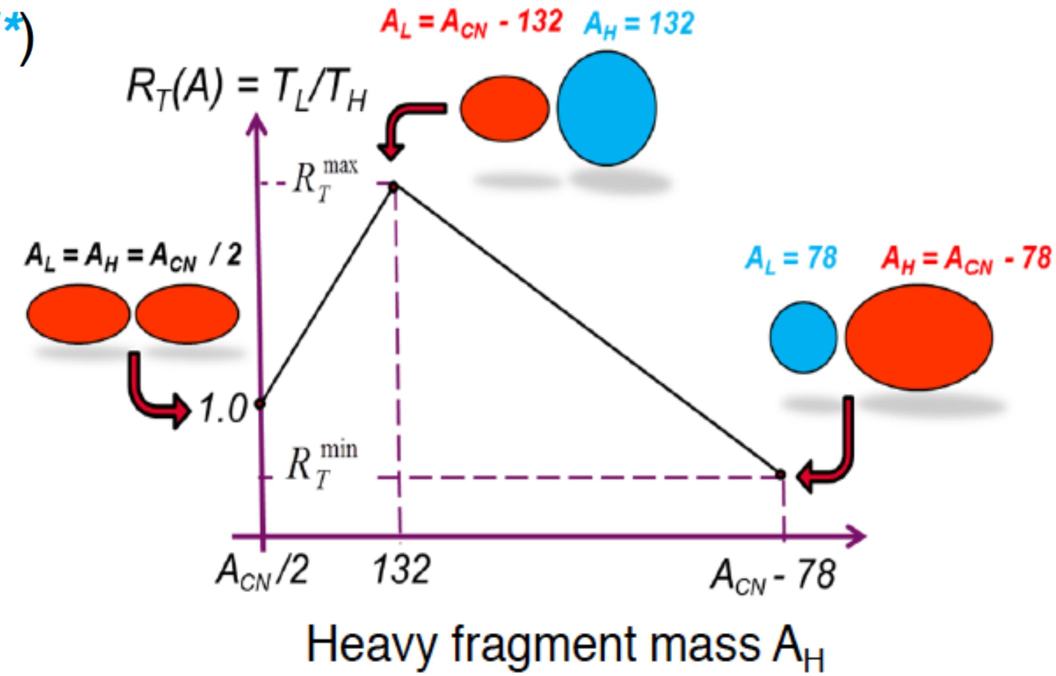
Fission fragment de-excitation

1. Mass (*A*)
2. Kinetic Energy (*KE*)
3. Nuclear Charge (*Z*)
4. Spin, Parity (J^{π})
5. Excitation Energy (E^*)

Required input to describe prompt neutron and γ emission



FIFRELIN, O. Serot, O. Litaize, D. Regnier

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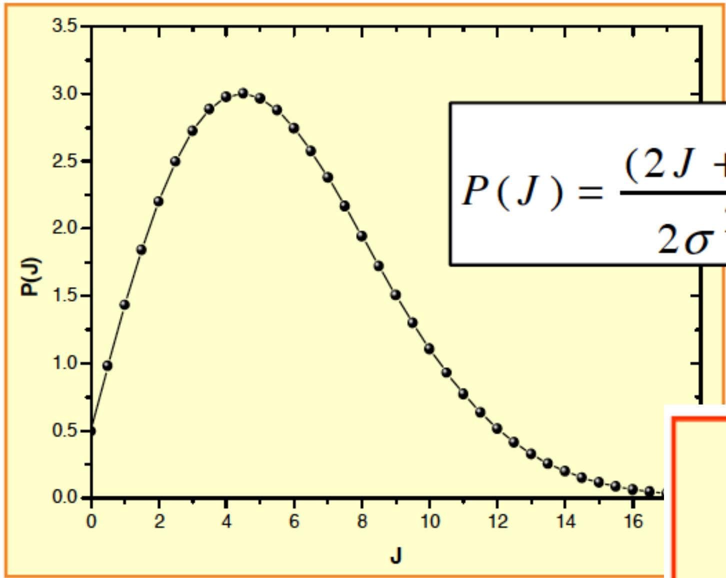
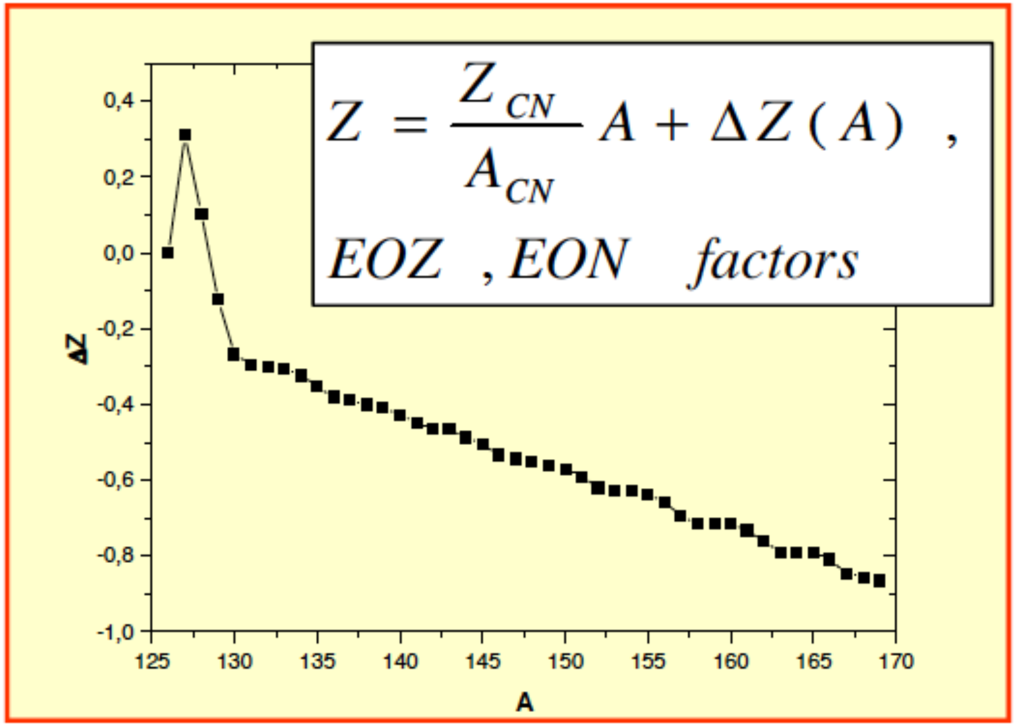
Fission fragment de-excitation



$$P(J) = \frac{(2J+1)}{2\sigma^2} e^{-\frac{(J+1/2)^2}{2\sigma^2}}$$

from stable nuclei!!!



$$Z = \frac{Z_{CN}}{A_{CN}} A + \Delta Z(A) \ ,$$

EOZ , EON *factors*

LOHENGRIN measurements

FIFRELIN, O. Serot, O. Litaize, D. Regnier

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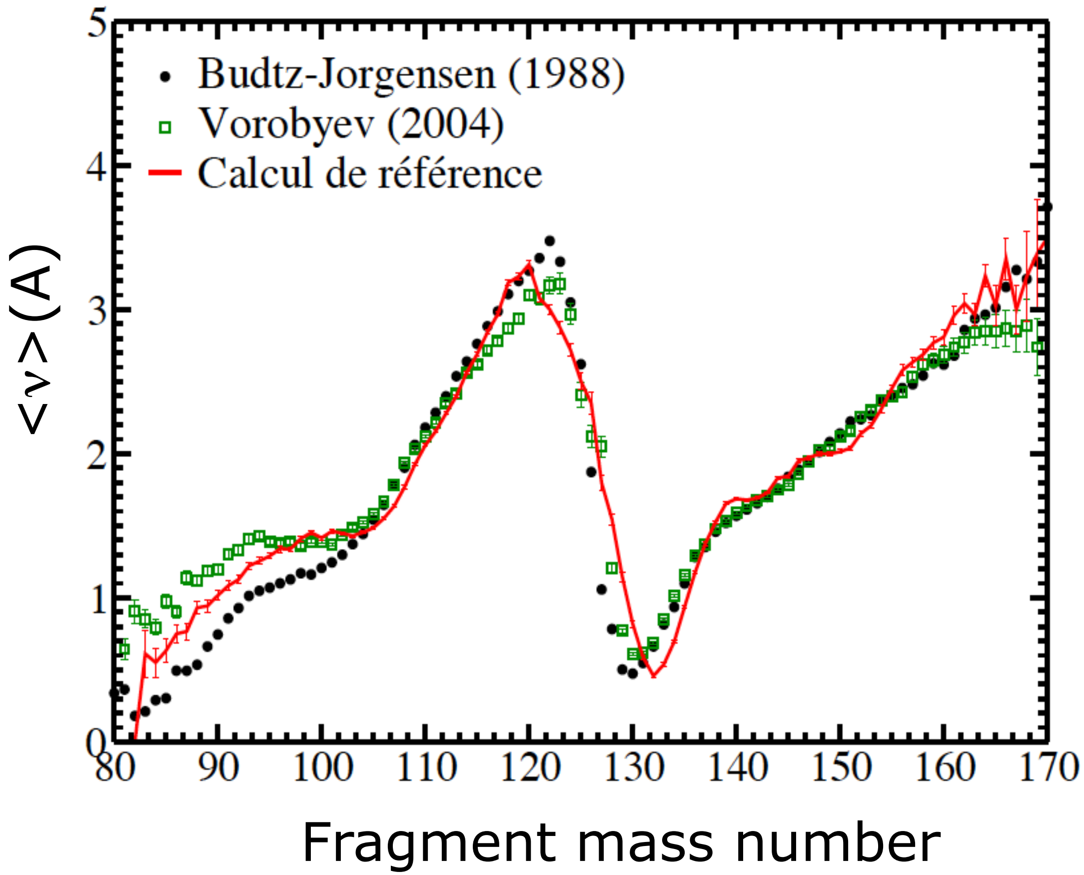
Fission fragment de-excitation

- Excitation energy of the fragments is dissipated through particle emission, here essentially neutrons and γ-rays

- In average 2 – 4 neutrons are released
- The exact value depends on the isotope and the excitation energy of the compound nucleus

Fission fragment de-excitation



See also: A. Göök et al., Phys. Rev. C90, 064611 (2014)

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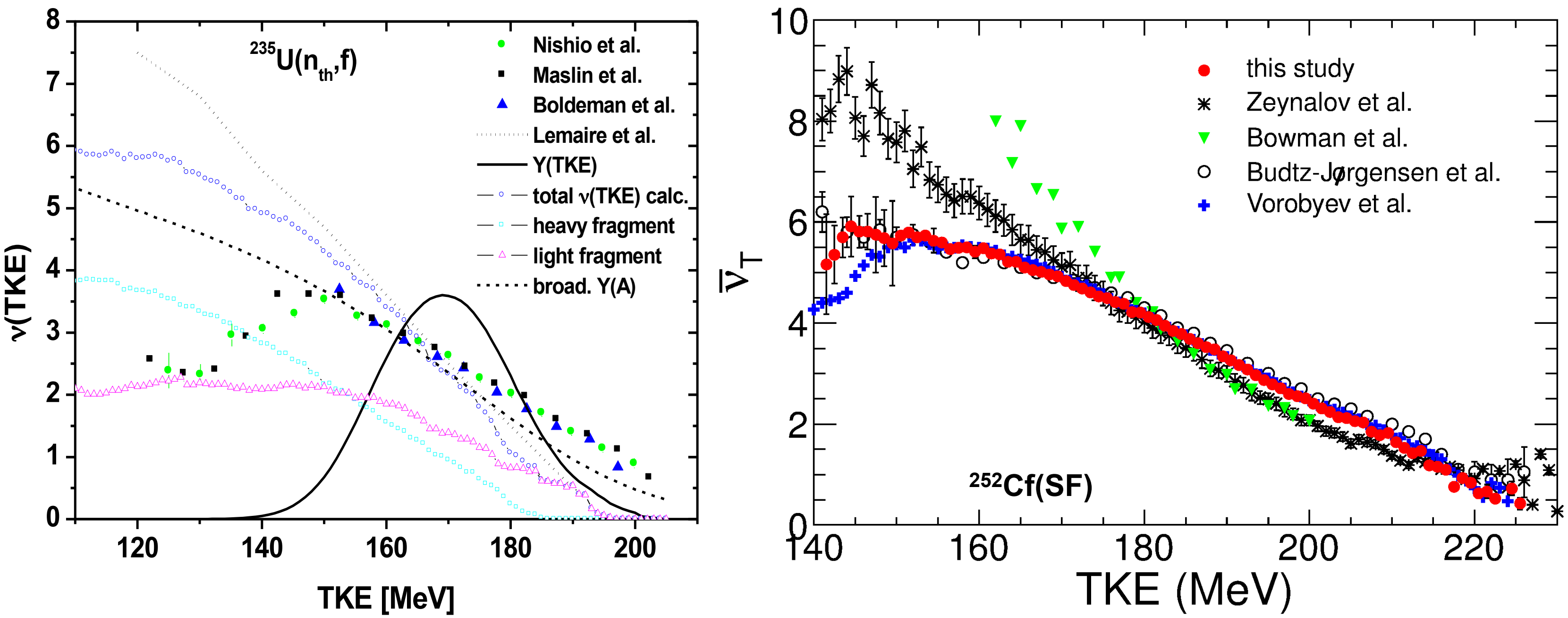
Fission fragment de-excitation



A. Göök et al., Phys. Rev. C90, 064611 (2014)

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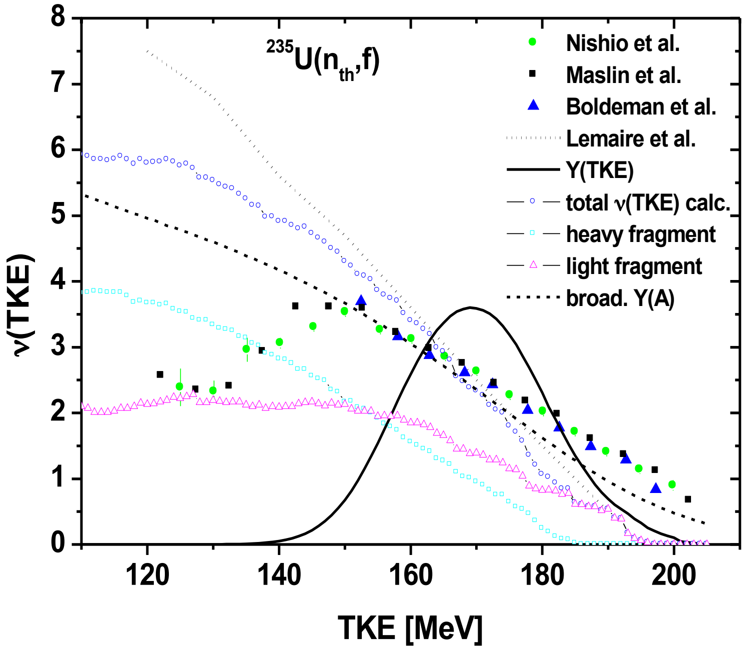

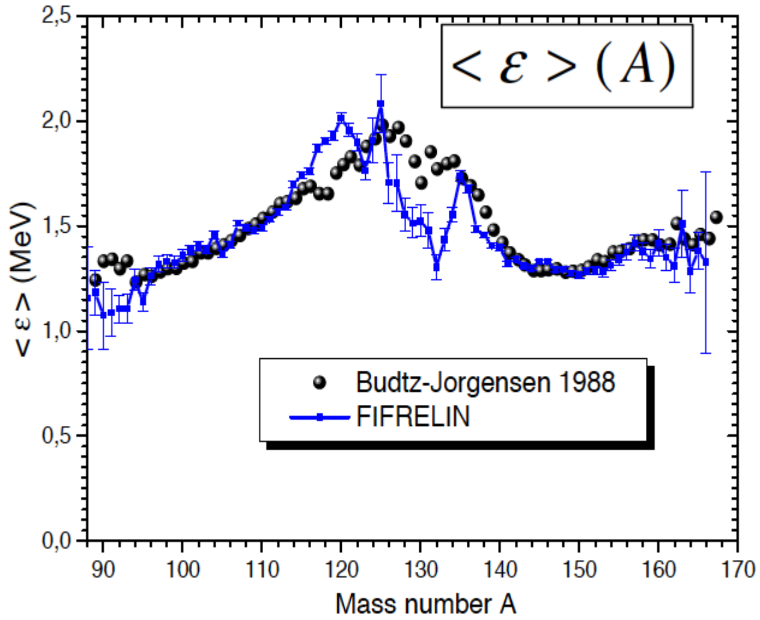

Fission fragment de-excitation

- **Excitation energy of the fragments is dissipated through particle emission, here essentially neutrons and γ-rays**

- **In average 2 – 4 neutrons are released**
- **The exact value depends on the isotope and the excitation energy of the compound nucleus**

- **The average energy of a neutron in the LS is around 2 MeV**

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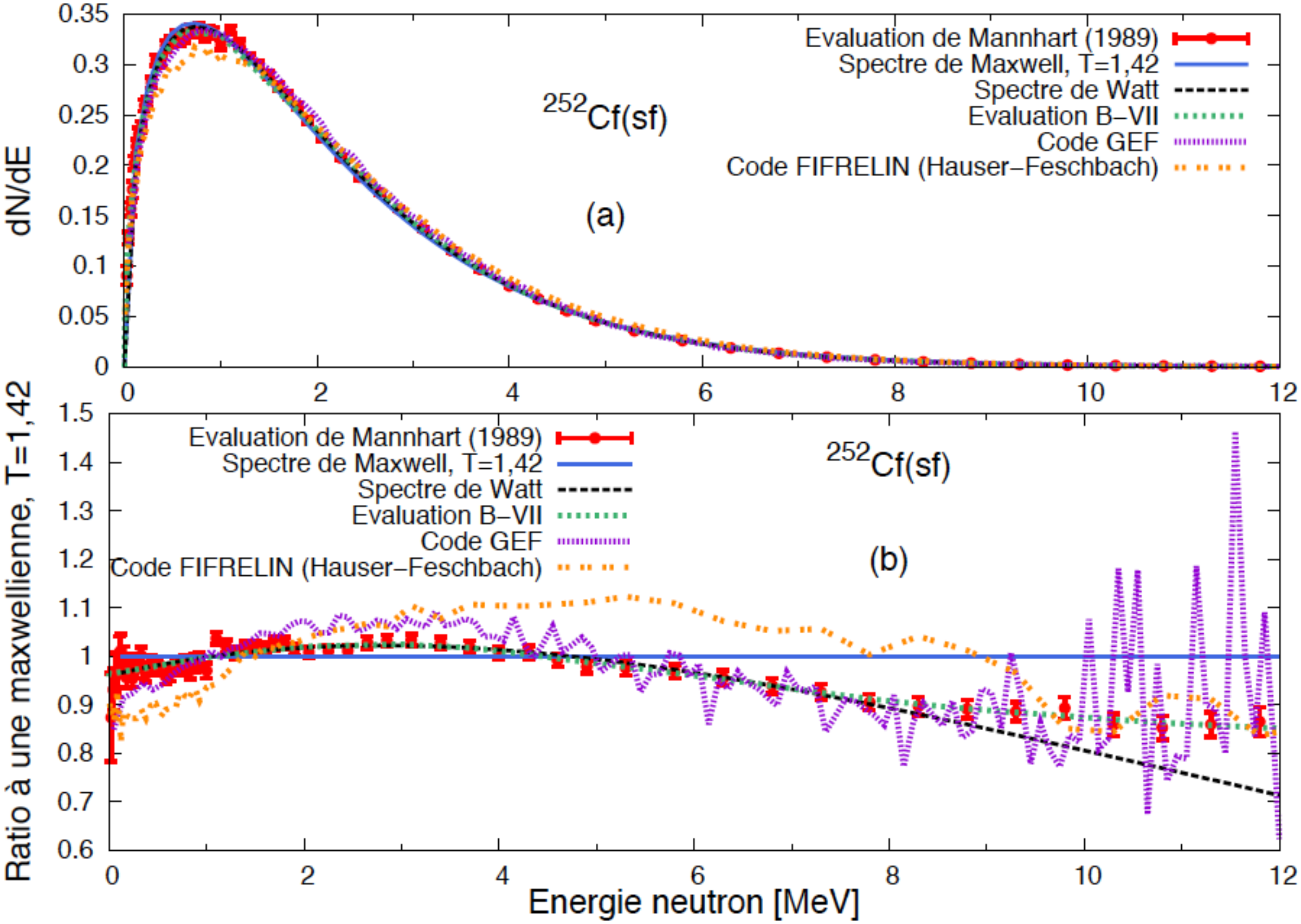
Fission fragment de-excitation



PhD thesis, A. Sardet, Université Paris Sud (2015)

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Fission fragment de-excitation

- **Parameterization of prompt neutron spectra:**

$$P_{Maxwell}(E) = \frac{2}{\sqrt{\pi}} T^{-3/2} \sqrt{E} e^{-\frac{E}{T}}$$

$$< E_{Maxwell} >= \frac{3}{2} T$$

^{252}Cf(SF): T = 1.42 MeV

<E> = 2.13 MeV

E_p = 0.71 MeV

$$P_{Watt}(E) = \frac{2T_e^{-\frac{3}{2}}}{\sqrt{\pi A}} e^{\frac{-AT_e}{4}} e^{-\frac{E}{T_e}} sh(\sqrt{AE})$$

$$< E_{Watt} >= \frac{3}{2} T_e + E_f$$

$$\mathrm{A} = \frac{4E_f}{T_e^2}$$

E_f (A_L) ≈ 1 MeV

E_f (A_H) ≈ 0.5 MeV

E_f : energy/nucleon

T_e : temperature after neutron emission

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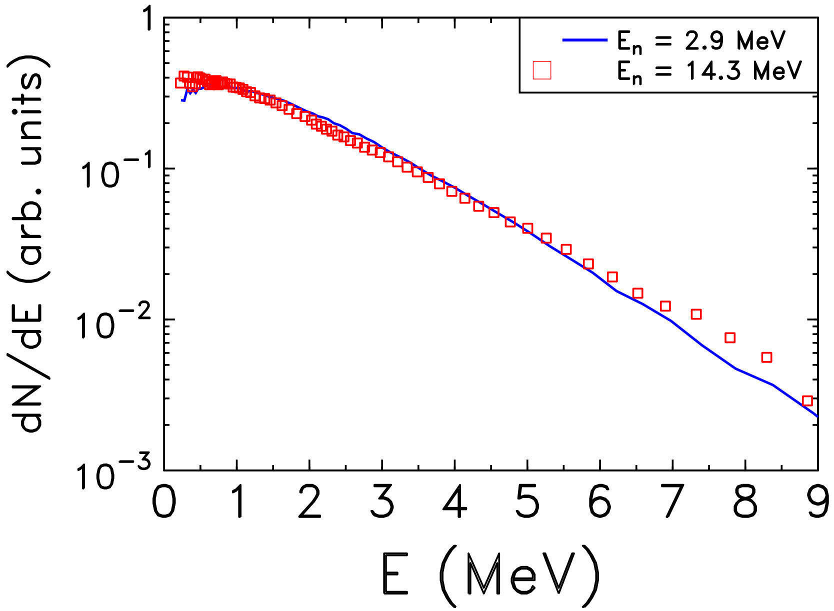
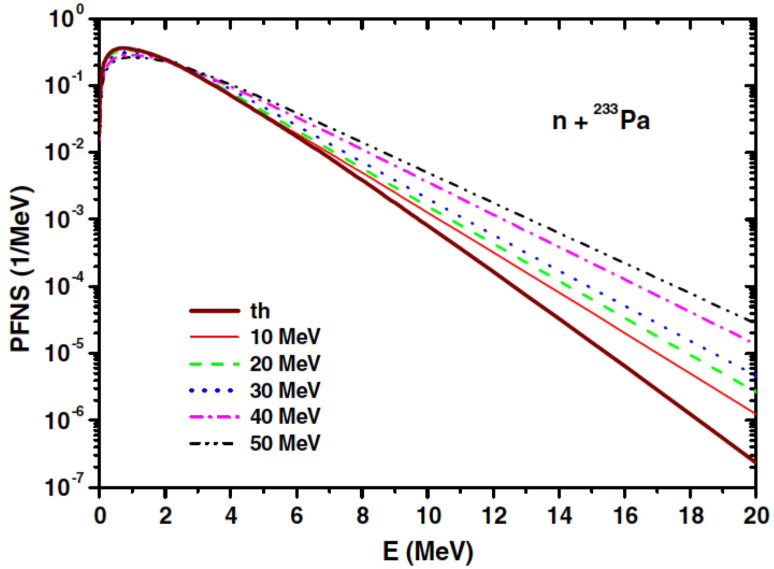
Fission fragment de-excitation

➢ Energy dependence of PFN emission



Boikov et al., EXFOR: 41110



A. Tudora et al. et al., ANE 35 (2008) 1131

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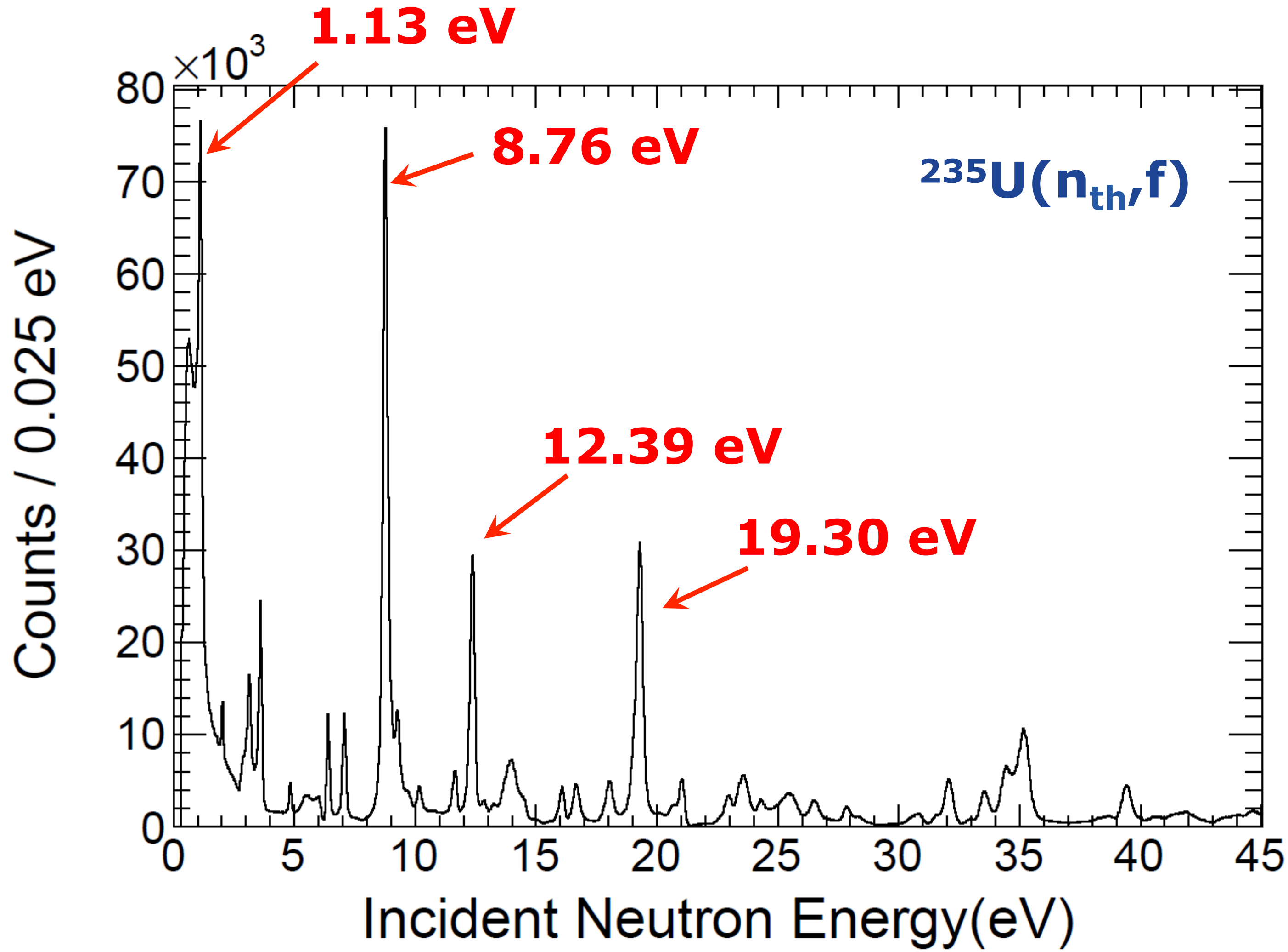
Fission fragment de-excitation

- Energy dependence of PFN emission



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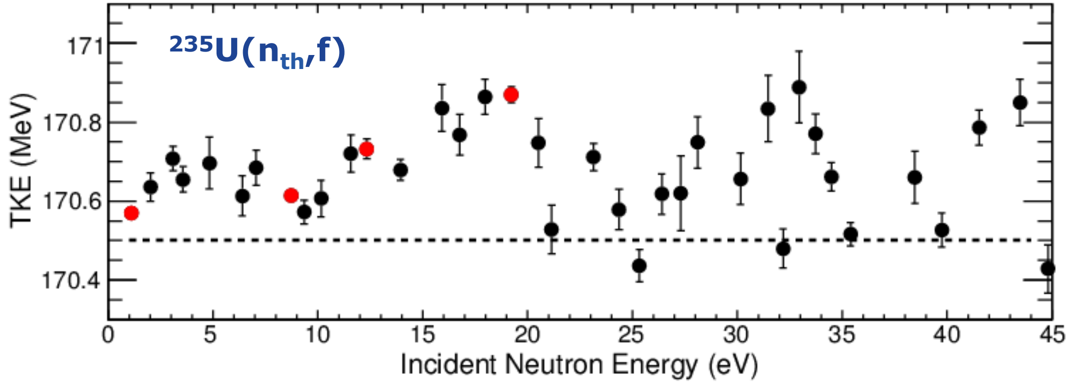
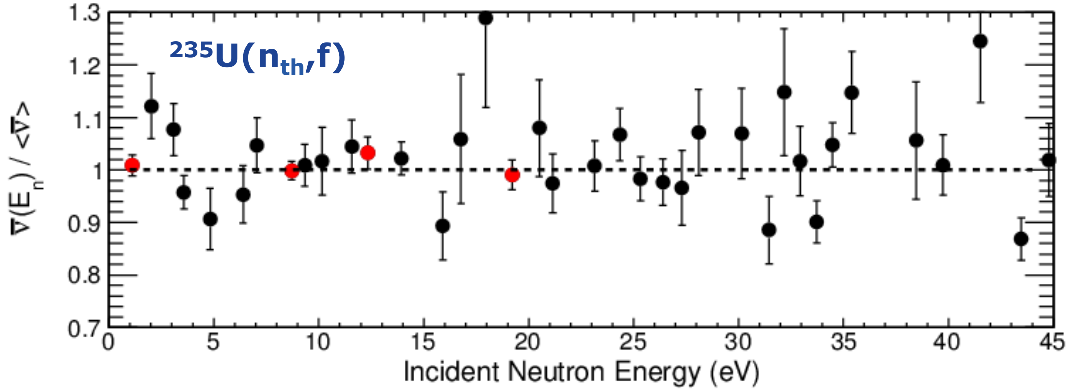
Fission fragment de-excitation

➢ **Energy dependence of PFN emission**



Cd overlap filter



10m flight path

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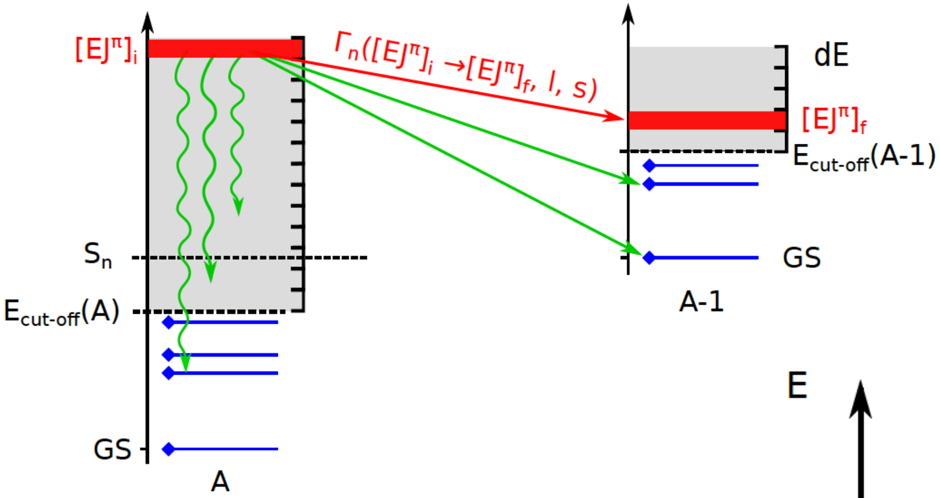
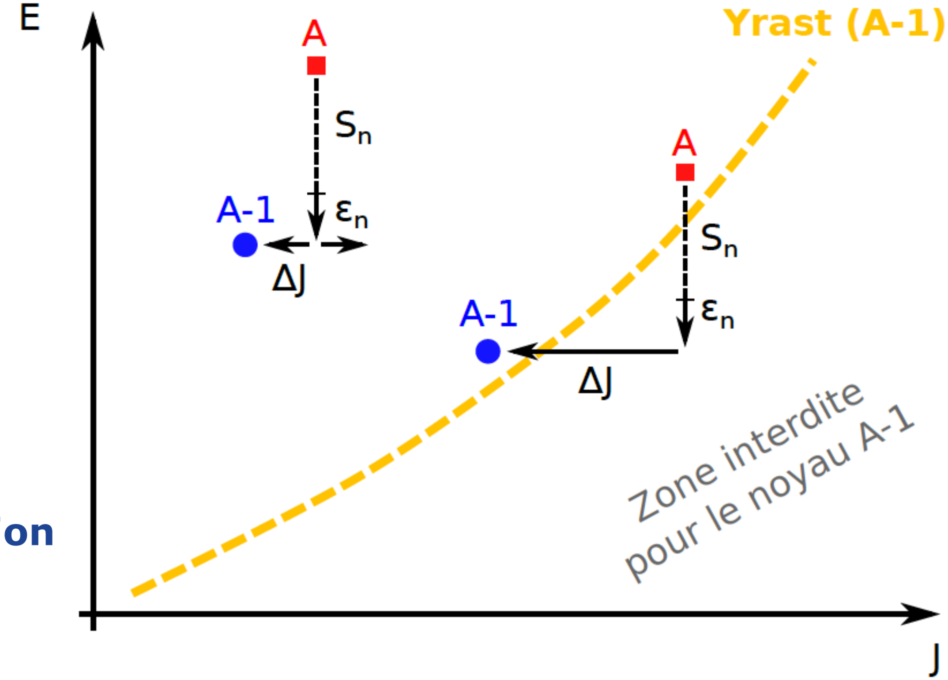
Fission fragment de-excitation



$$H\phi = E\phi \qquad \pi\phi = \pm\phi$$

$$J^2\phi = J(J+1)\hbar^2\phi \qquad J_z\phi = M\hbar\phi$$

$$\phi = |E, J, M, \pm >$$



Nuclear levels are quantized

No level in A-1 after neutron emission

➢ **γ-emission instead**

D. Regnier, PhD-thesis (2013)

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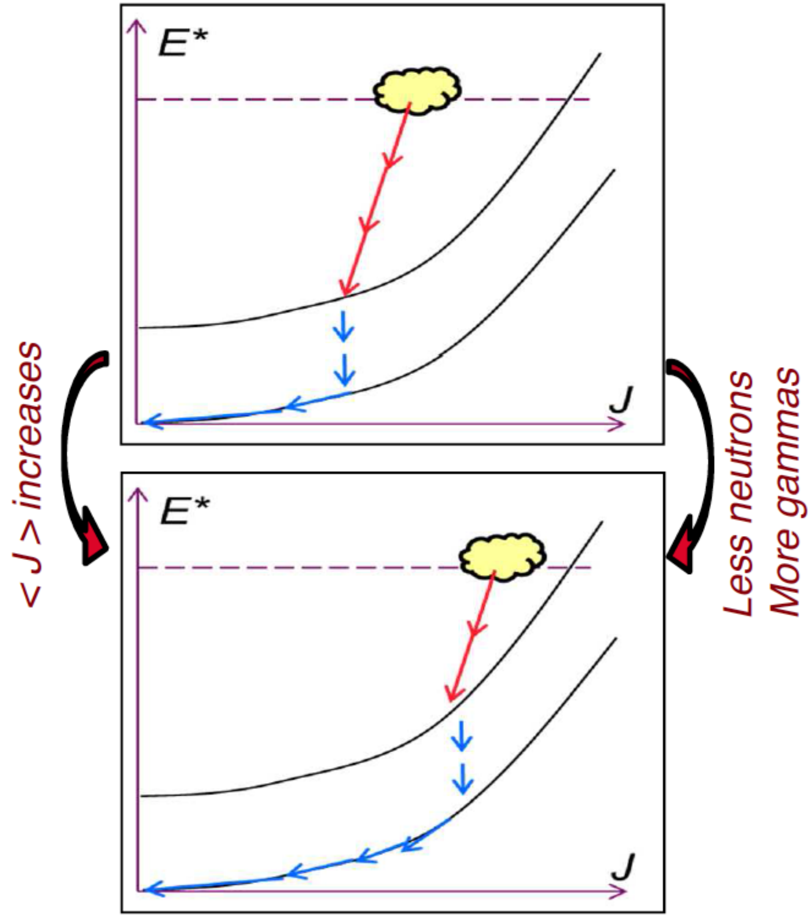
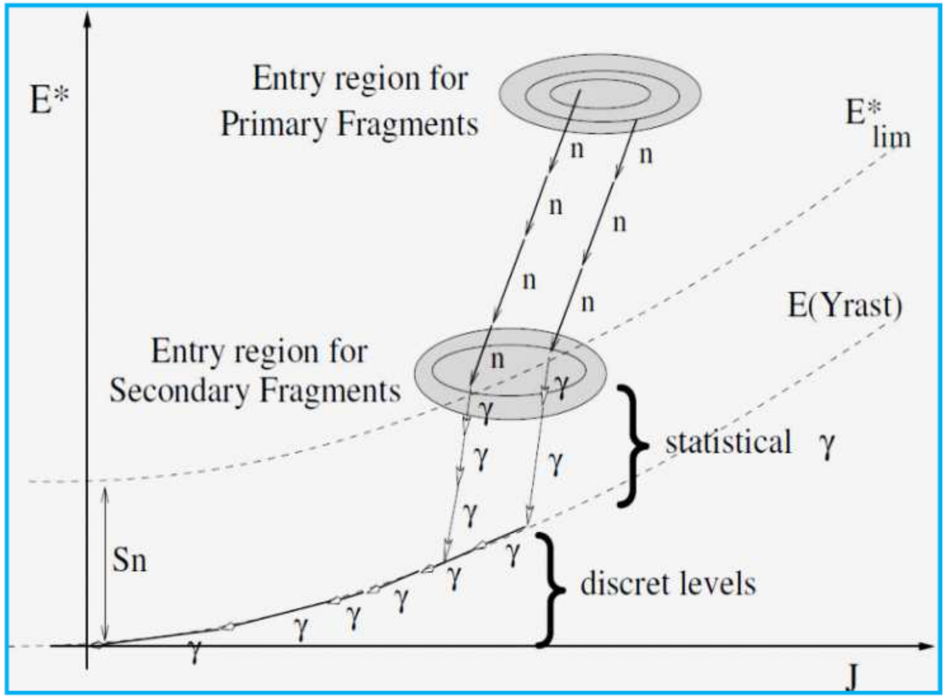
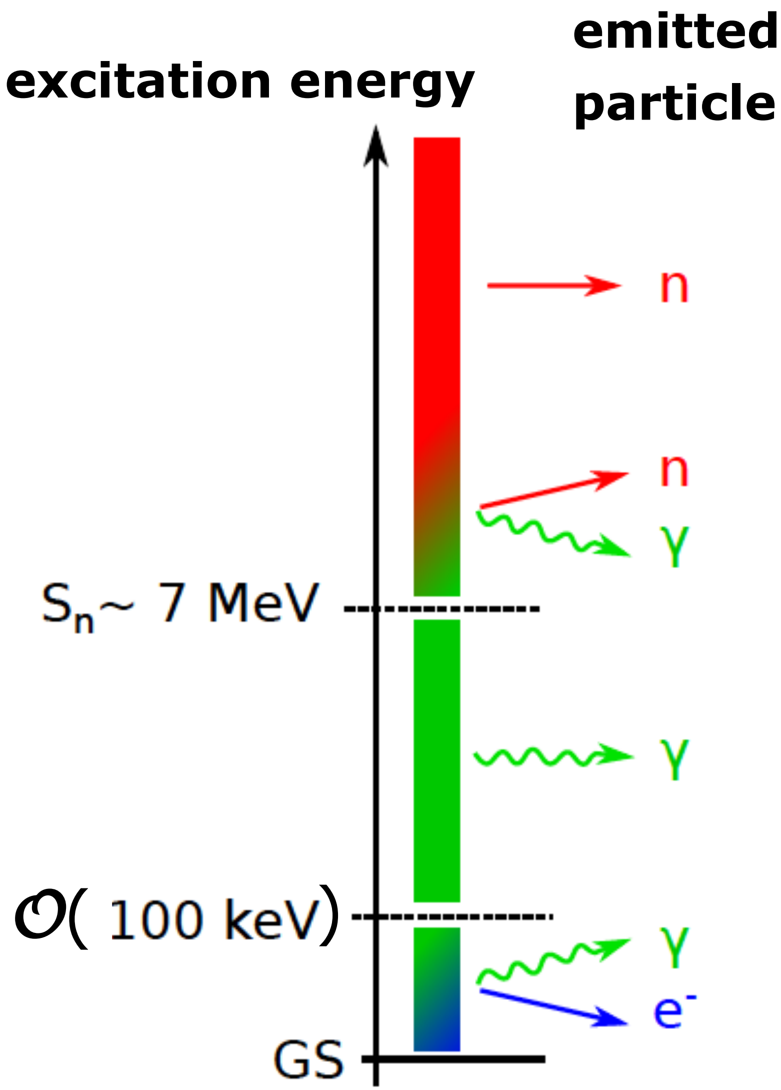
Fission fragment de-excitation





O. Litaize et al., GAMMA-2 Workshop, Sremski Karlovci, RS

Fission fragment de-excitation



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Fission fragment de-excitation

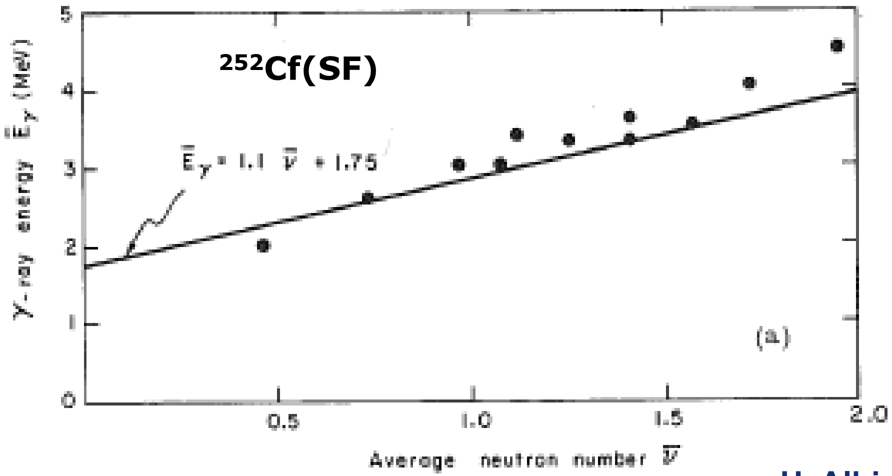
- Excitation energy of the fragments is dissipated through particle emission, here essentially neutrons and γ-rays

- In average 2 – 4 neutrons are released
- The exact value depends on the isotope and the excitation energy of the compound nucleus

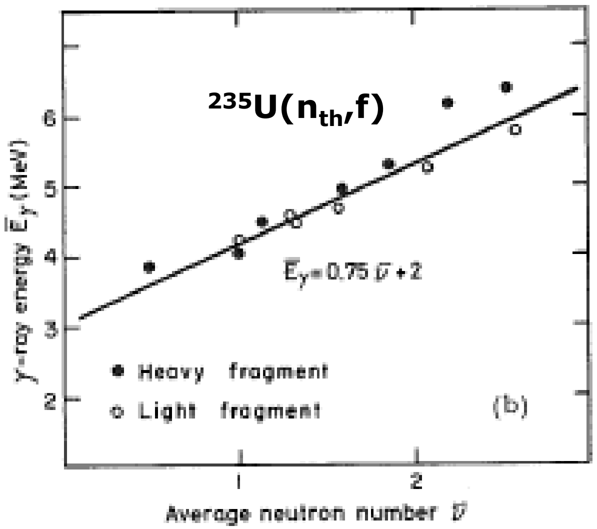
- The average energy of a neutron in the LS is around 2 MeV

- In average 6 – 10 γ-rays are emitted too, with a mean total energy release of about 7 – 9 MeV

Fission fragment de-excitation

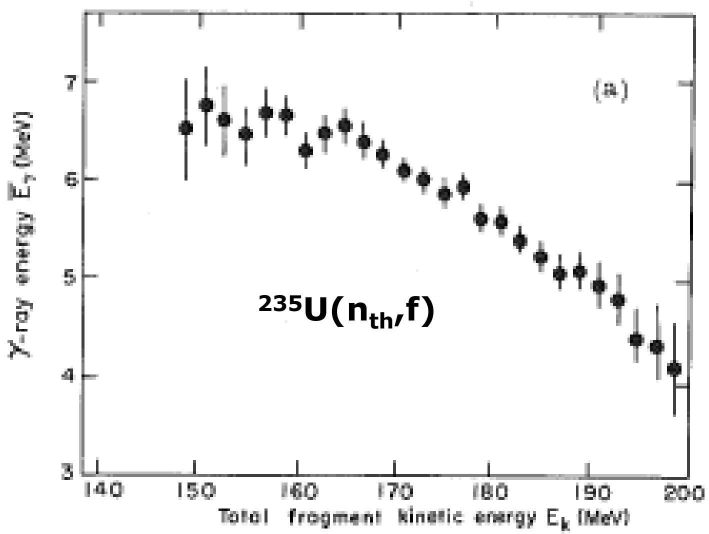


H. Albinsson, Int. Rep. AE-417 (1971)



W. John et al.,
Phys. Lett. 30B (1969)

Fission fragment de-excitation



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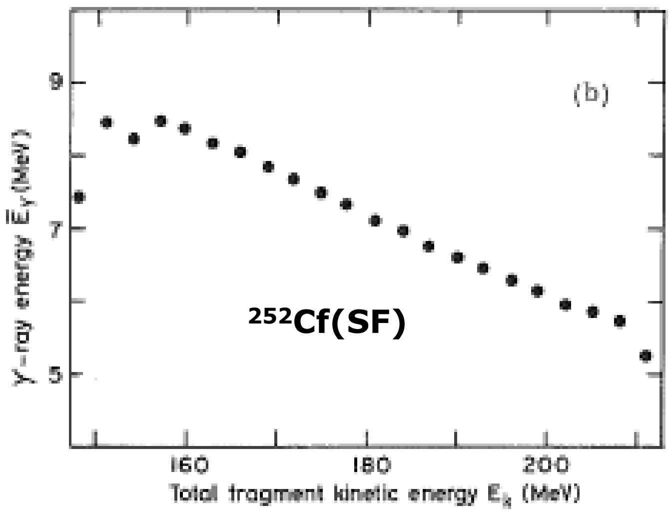

H. Nifenecker et al.,
Nucl. Phys. A189 (1972) 285

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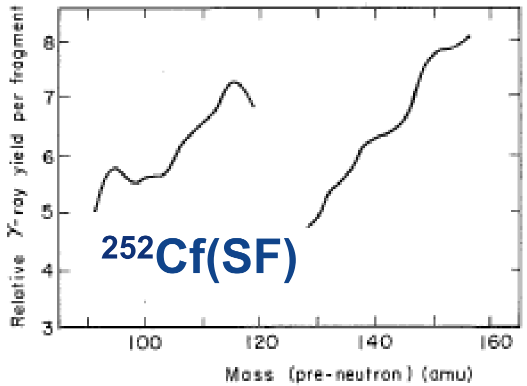
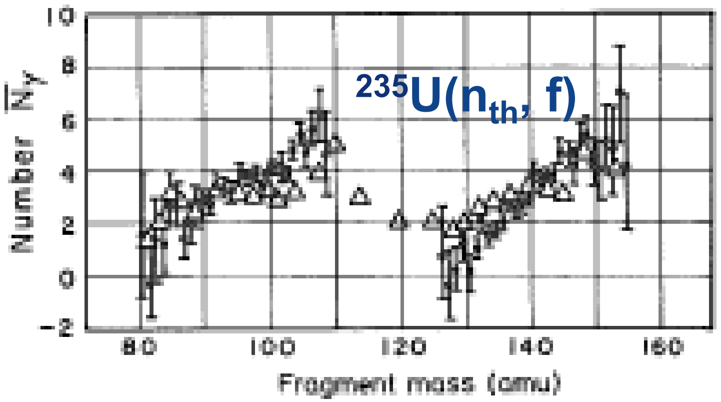
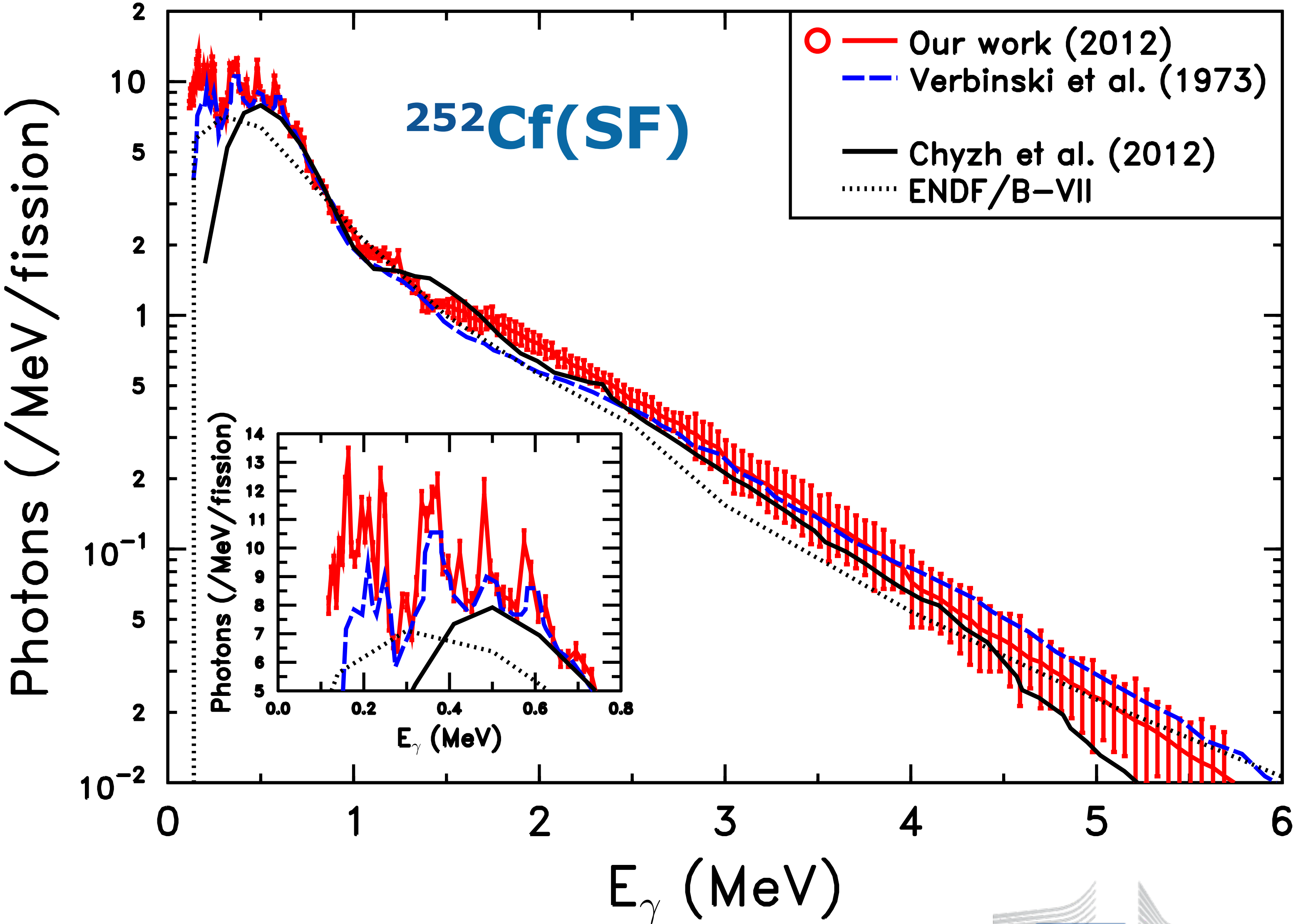
Fission fragment de-excitation





- ^{252}Cf(SF), thermal neutrons on ^{235}U, ^{239}Pu
- Nifenecker: review article (IAEA-SM-174/207, 1973)

Fission fragment de-excitation



PhD thesis work of R. Billnert
R. Billnert et al., Phys. Rev. C 87, 051602 (2013)

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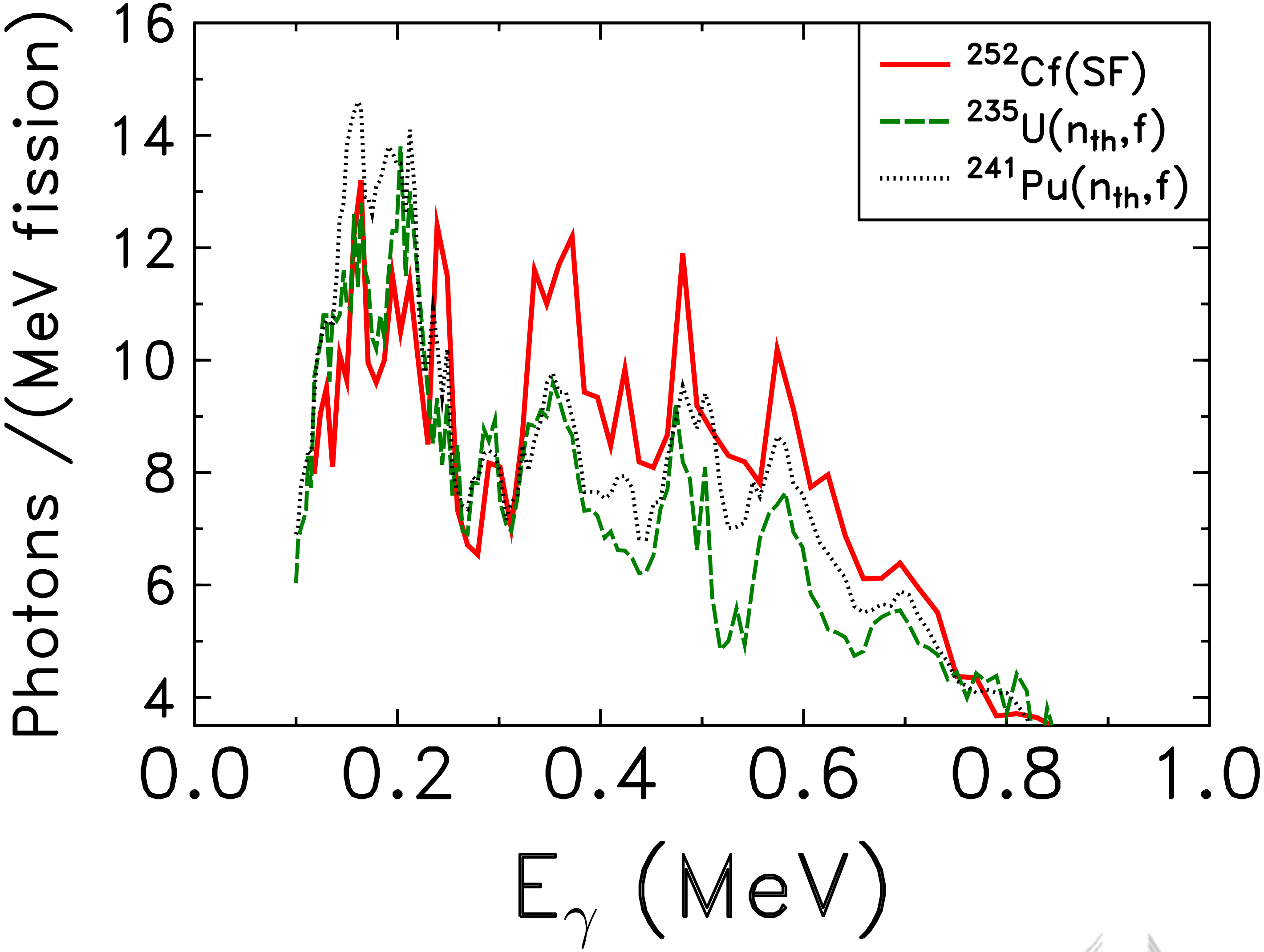
Fission fragment de-excitation



PhD thesis work of R. Billnert

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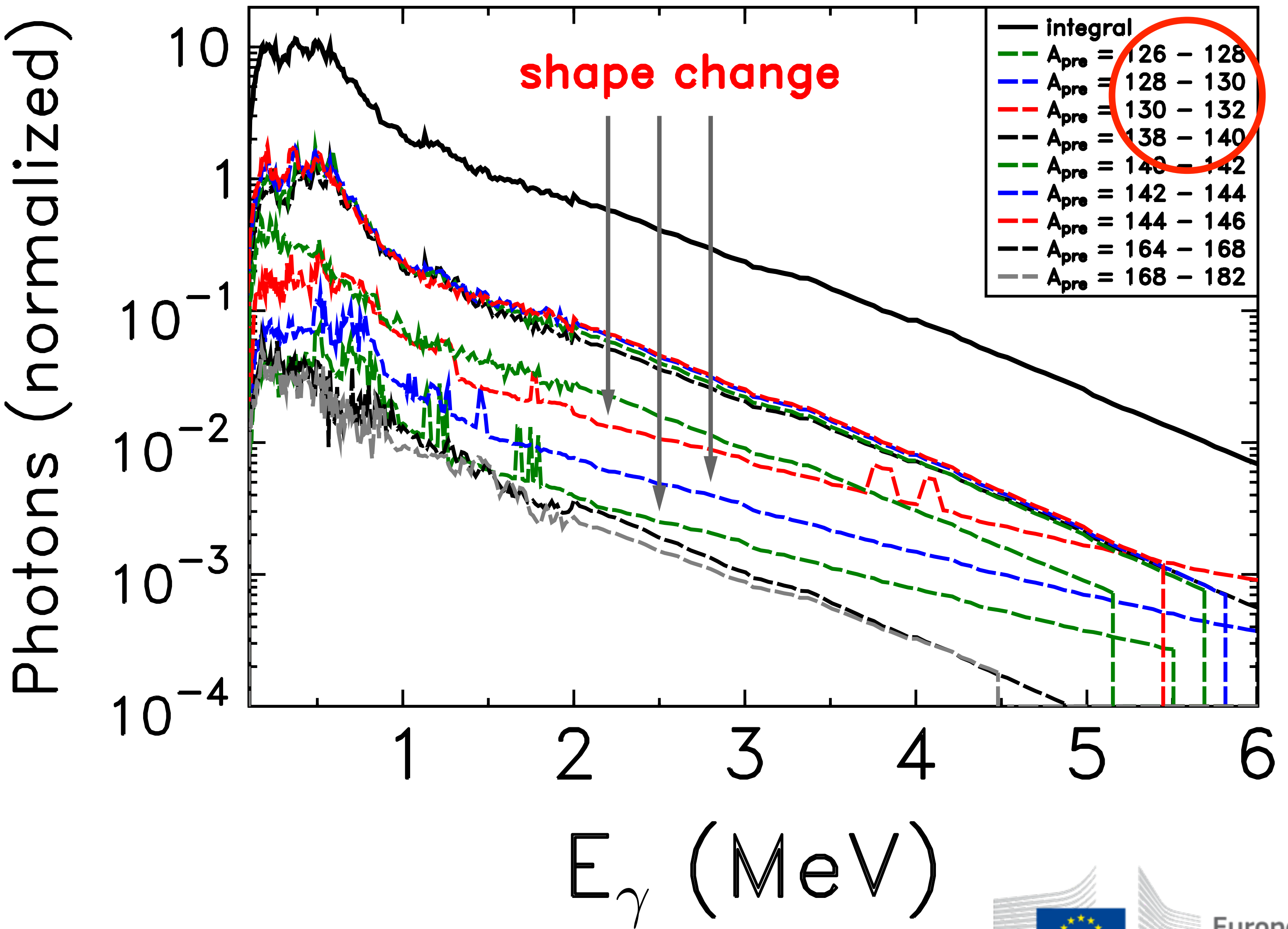
Fission fragment de-excitation



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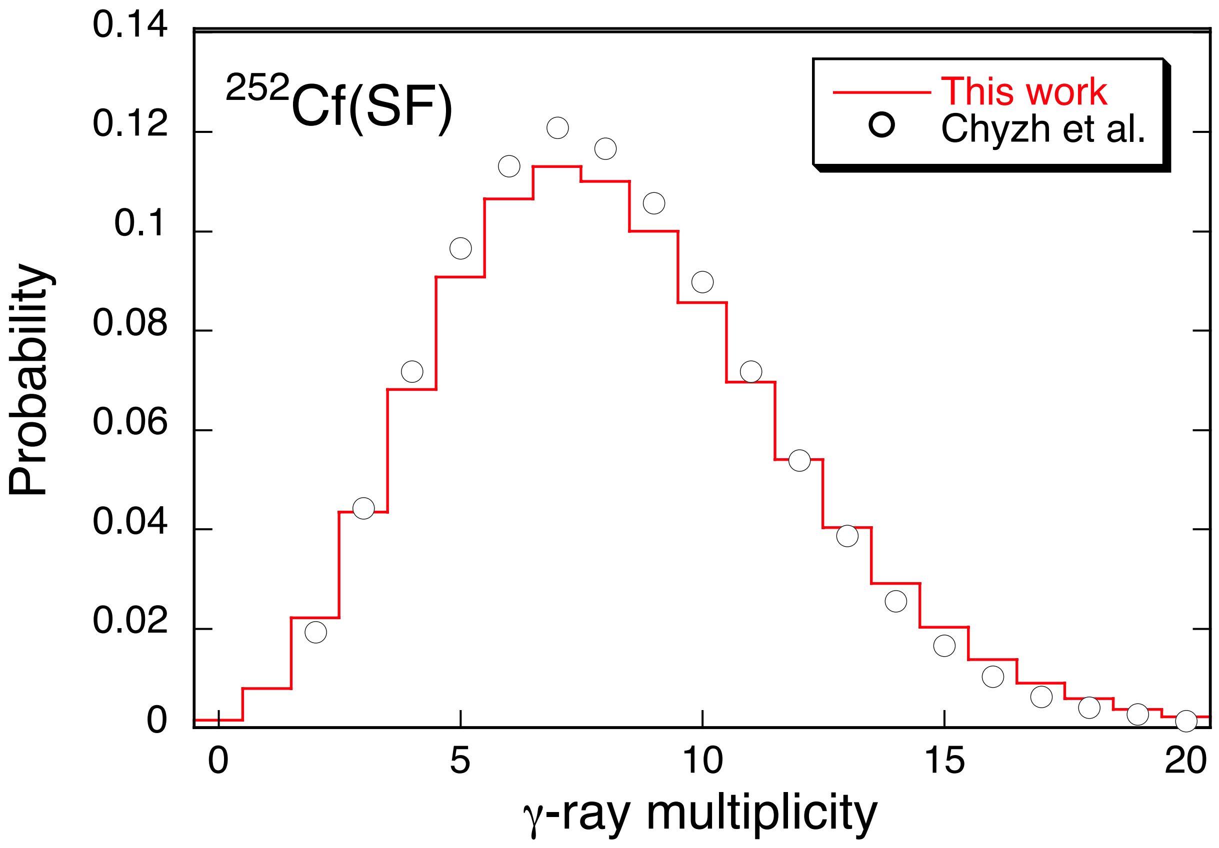
Fission fragment de-excitation



A. Oberstedt et al., Phys. Rev. C92, 014618 (2015)

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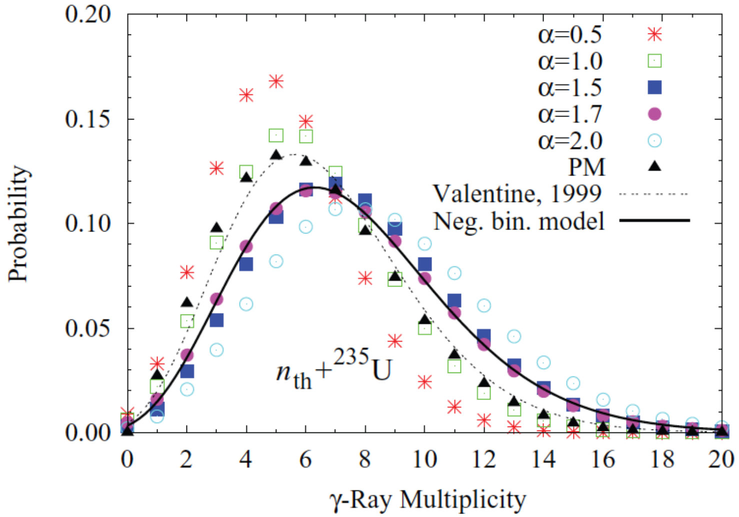
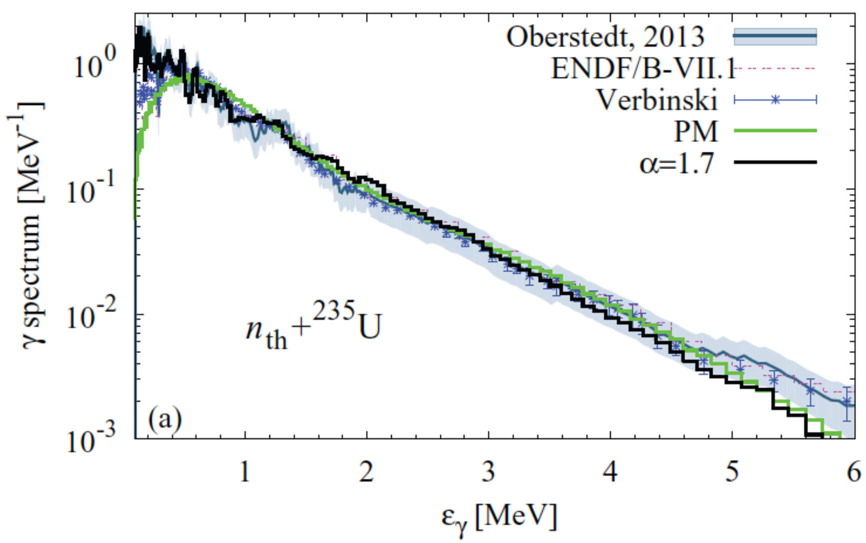
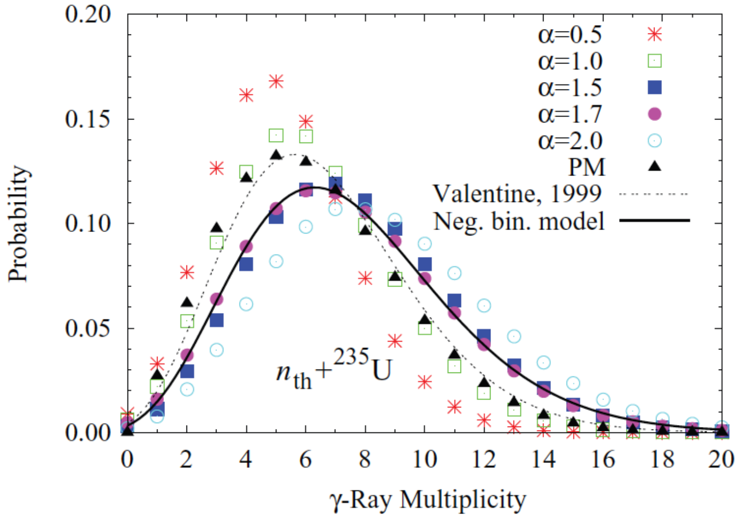
Fission fragment de-excitation

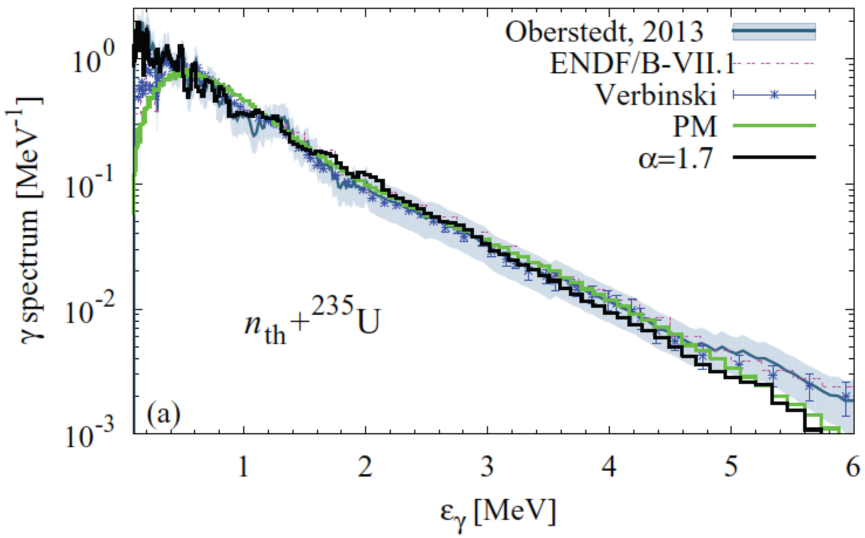




I. Stetcu et al., Phys. Rev. C90, 024617 (2014)

Fission fragment de-excitation





$$P(J) = \frac{(2J+1)}{2\sigma^2} \exp\left(-\frac{(J+1/2)^2}{2\sigma^2} \right)$$

We need more information about σ !!!

I. Stetcu et al., Phys. Rev. C90, 024617 (2014)

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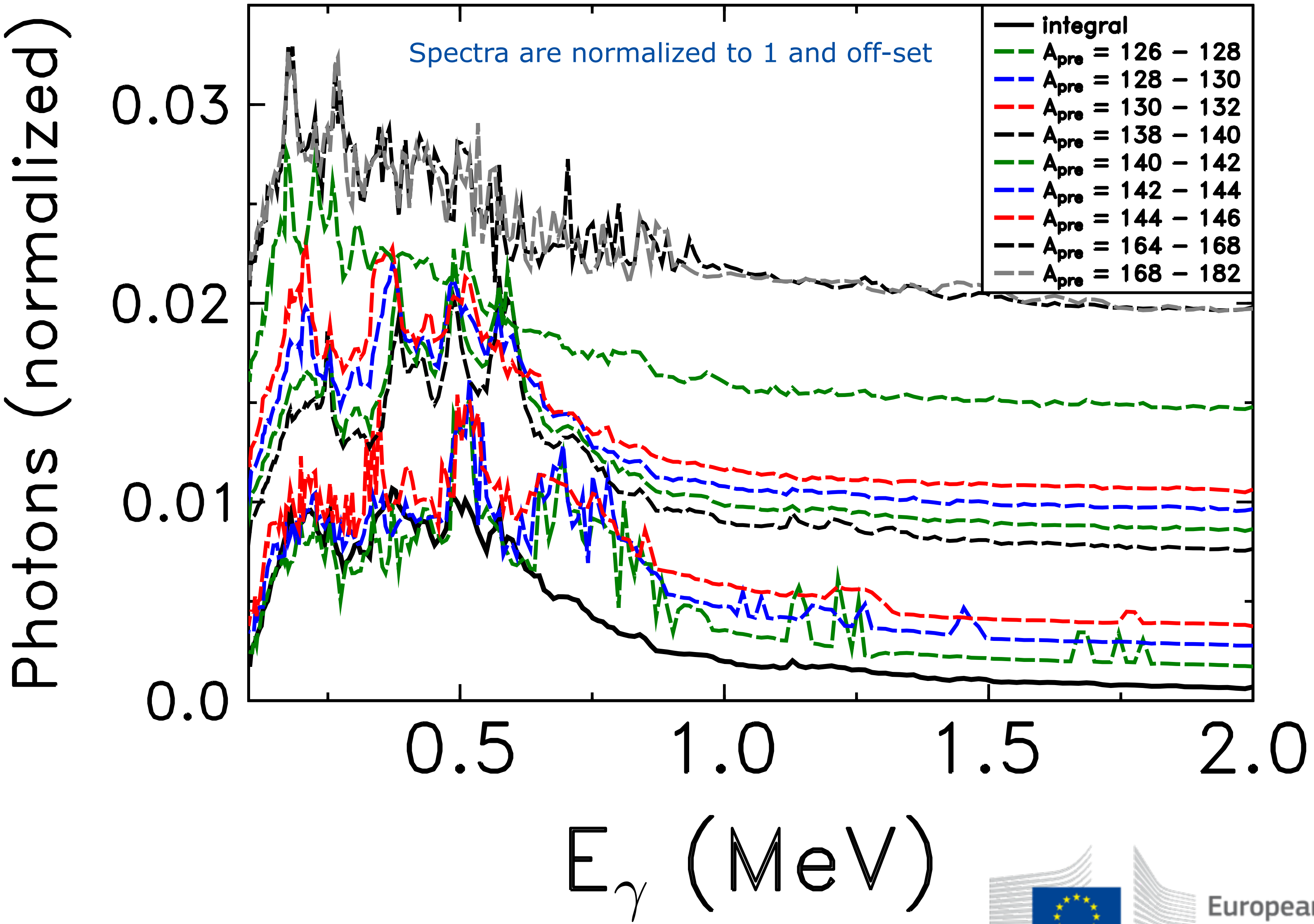
Fission fragment de-excitation



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Fission fragment de-excitation

- **Observable quantities:**
  - **Spectral characteristics (neutrons and γ-rays)**
    - **Average multiplicity** (/fission)
    - **Average total energy** (/fission)
    - **Average photon energy** (/fission)
  - **Correlations with fission fragment characteristics**
    - **ν(A*, TKE), $\langle E_{tot} \rangle$(A*, TKE),**
  - **Correlation of prompt γ-ray data with PFN**

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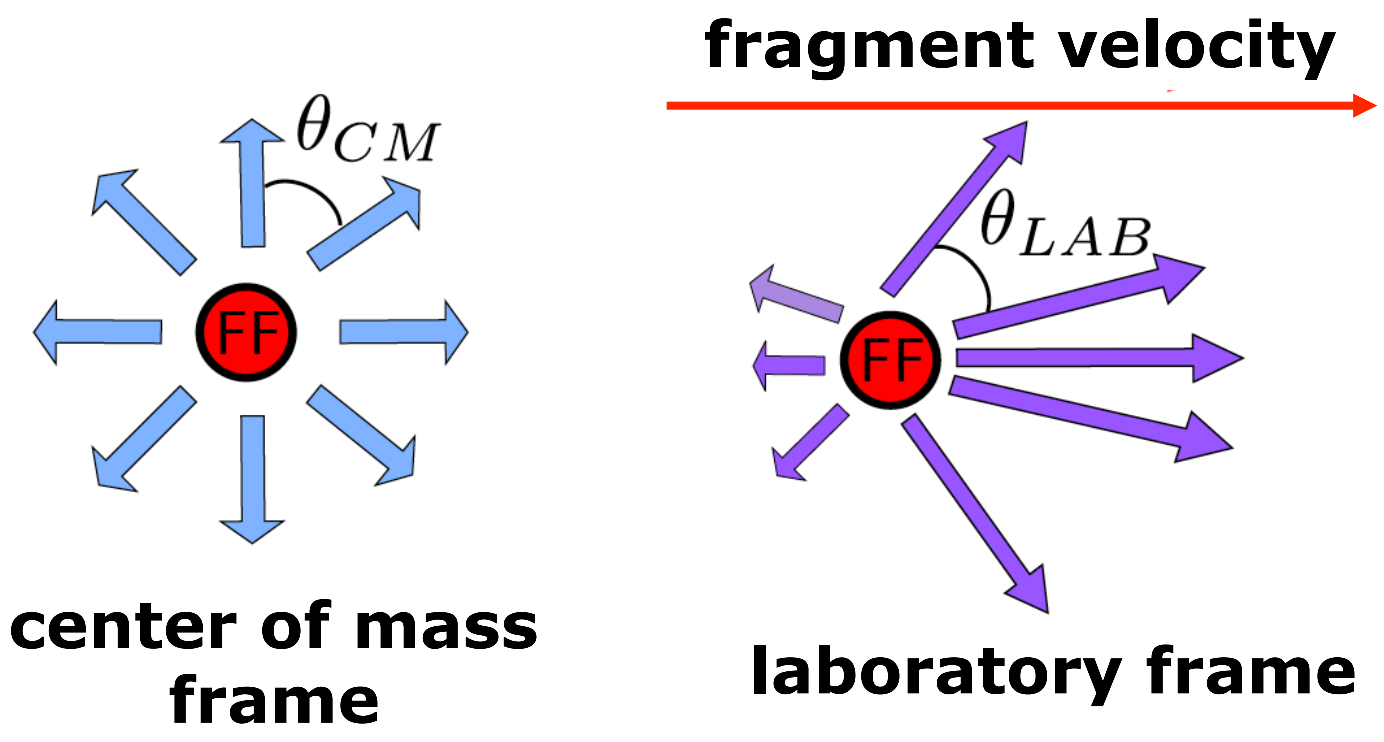
How to measure neutrons and γ-rays

- **Prompt neutron measurements**
- **Prompt γ-ray measurements**

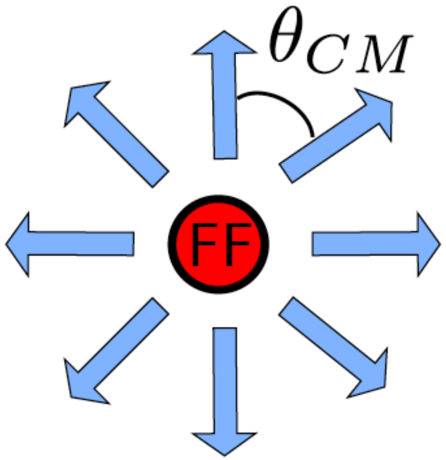
How to measure neutrons and γ-rays

➢ **Prompt neutron measurements**



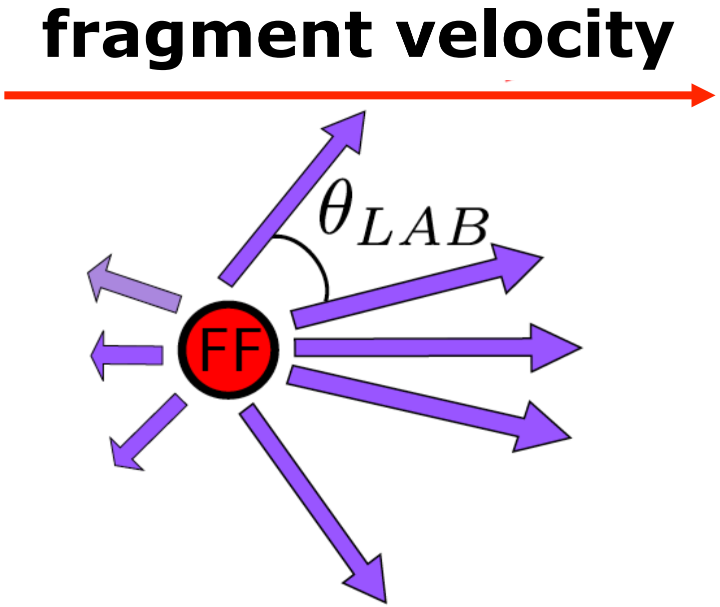
How to measure neutrons and γ-rays

- **Prompt neutron measurements**



center of mass frame

To extract physics



laboratory frame

What you measure, relevant for application

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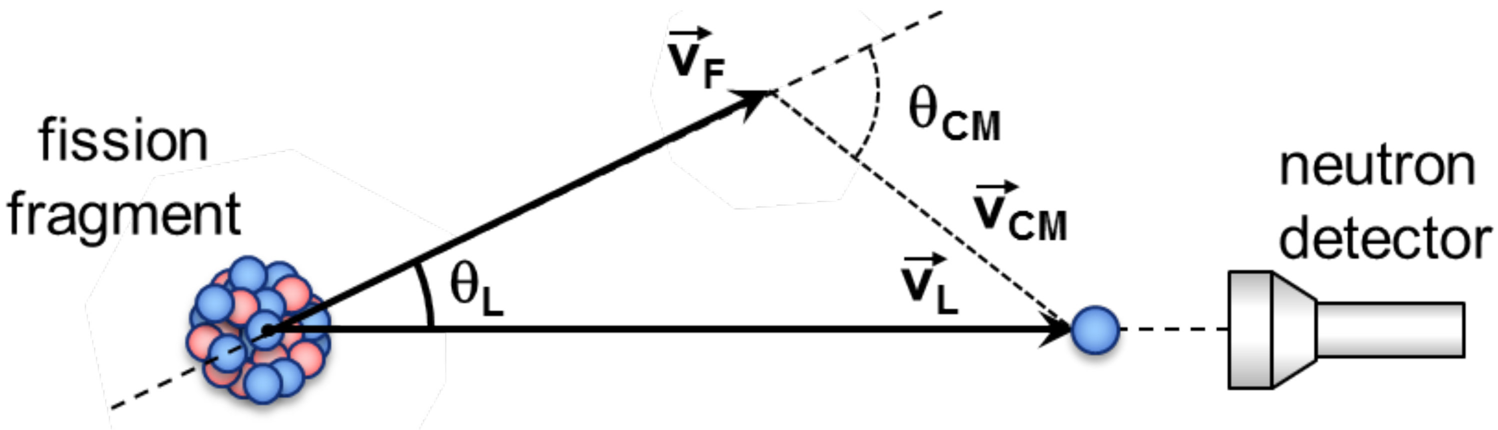
How to measure neutrons

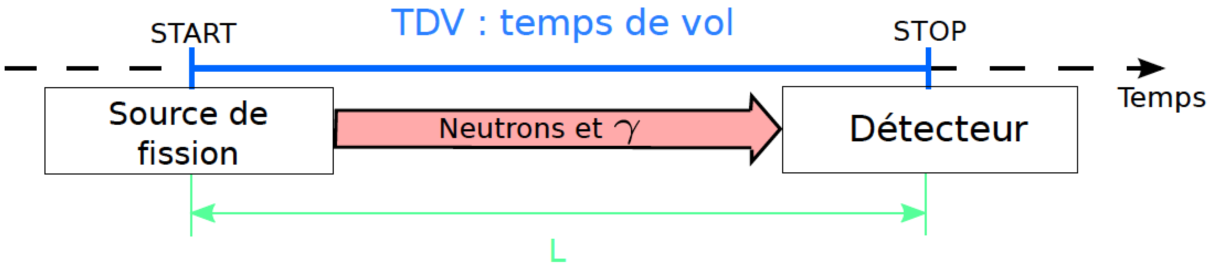
- **Emission of neutrons from fully accelerated fragments**
  - **Obtain basic kinematic information in laboratory-frame**
  - **Reconstruct emission process in fission fragment rest-frame**



- **Unbiased selection of events: $\cos\theta_{CM} \geq 0$**

How to measure neutrons

➢ Prompt neutron measurements



$$E_n = (\gamma - 1) m_n c^2 = \left(\frac{1}{\sqrt{1 - \frac{L^2}{\Delta t^2} \frac{1}{c^2}}} - 1 \right) m_n c^2$$

- m_n = 939.56533 MeV/c^2
- c = 0.299792458 m/ns
- Δt : time of flight (TOF)

$$\left(\frac{\sigma_E}{E} \right)^2 = 2 \left[\left(\frac{\sigma_L}{L} \right)^2 + \left(\frac{\sigma_{\Delta t}}{\Delta t} \right)^2 \right]$$

PhD thesis, A. Sardet, Université Paris Sud (2015)

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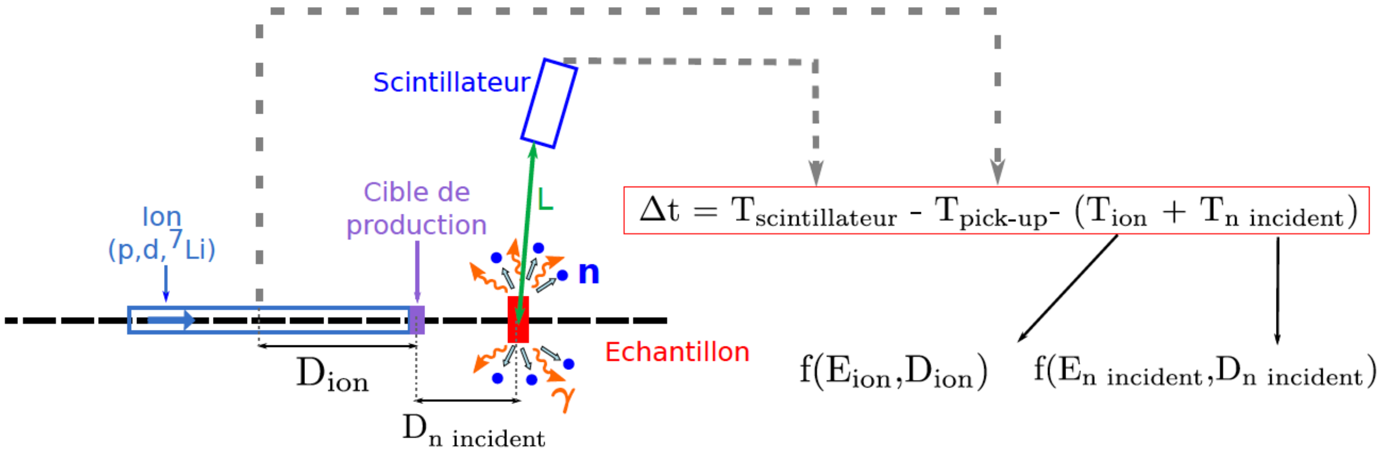
How to measure neutrons

- **Measurement with passive sample**



- **Use of massive targets (several g)**
- **Pulsed neutron beam (usually low beam currents; 1 – 2 μA)**
- **In general leads to a sufficiently high event rate**

- **Resolution depends on beam pulse**
- **Minimum neutron energy depend on incident neutron energy**
- **Multiple scattering in the sample**

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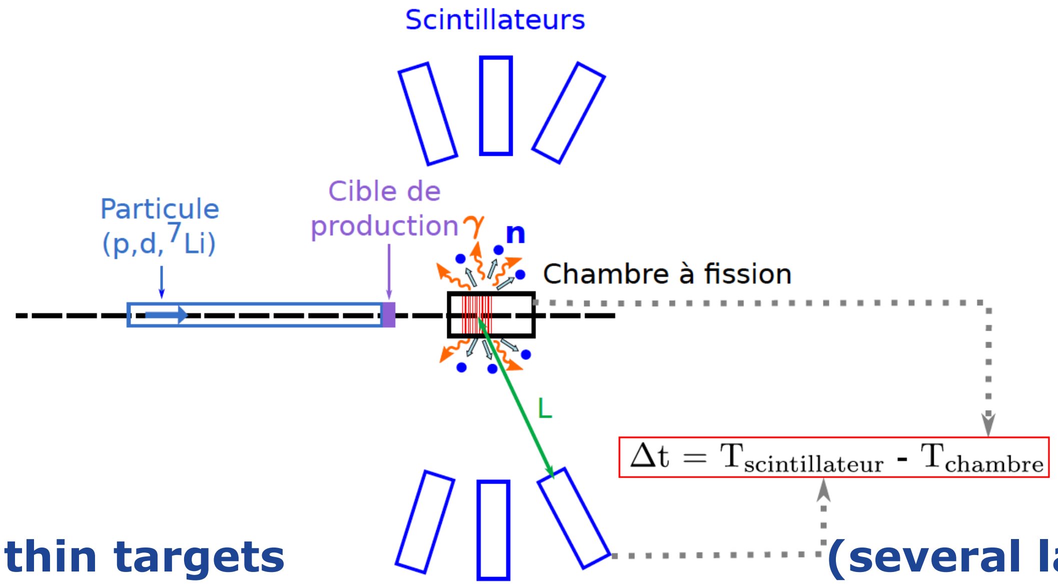
How to measure neutrons

- **Measurement with an active sample**



- **Use of thin targets (several layers)**
- **Continuous neutron beam (high beam currents; > 20 μA)**
- **Allows to measure neutrons below the beam energy**
- **Allows measuring at different energies at the same time with a pulsed particle beam**

- **Multiple scattering in the detector to be taken care of**

PhD thesis, A. Sardet, Université Paris Sud (2015)

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How to measure neutrons

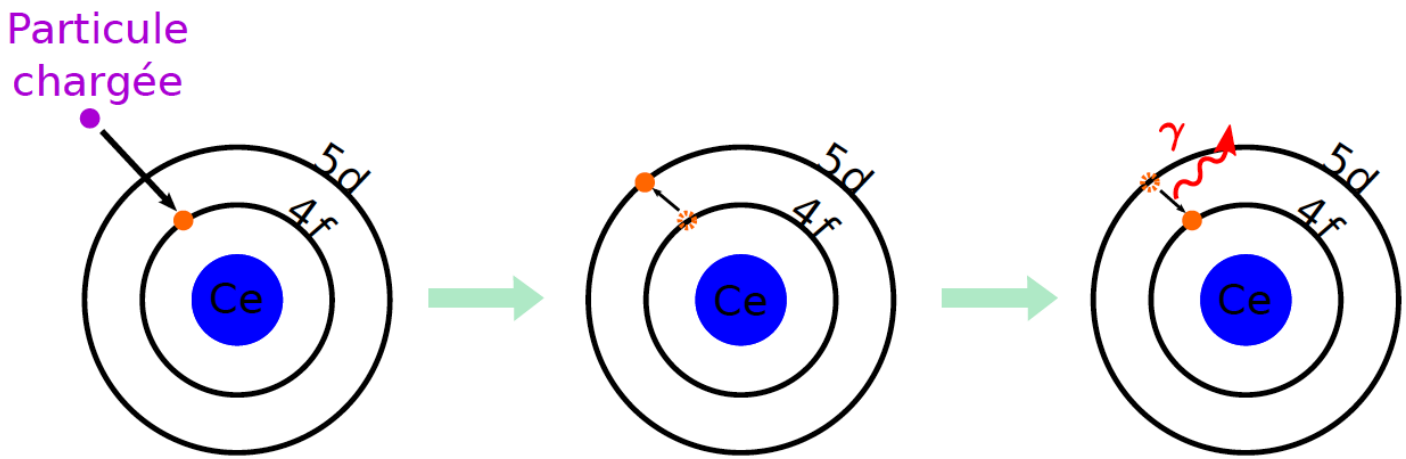
- Suitable detectors

  - Any detector containing boron (BF_3)

  - Lithium-glass detectors
  - Liquid scintillator detectors

How to measure neutrons

- **Lithium-glass detectors:**
  - **Containing lithium**
  - **Enriched in ^{6}Li: $^{6}Li(n,t)\alpha$**
  - **Doped with cerium**



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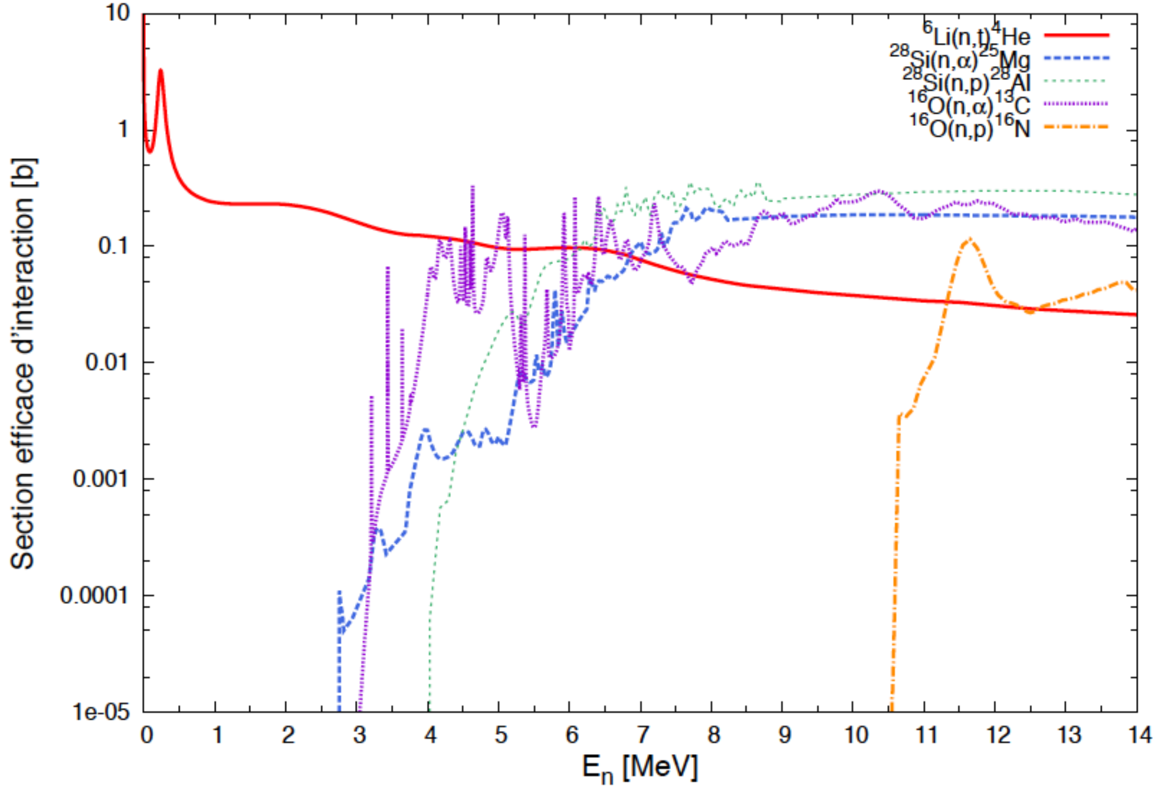
How to measure neutrons

➢ **Lithium-glass detectors:**



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How to measure neutrons

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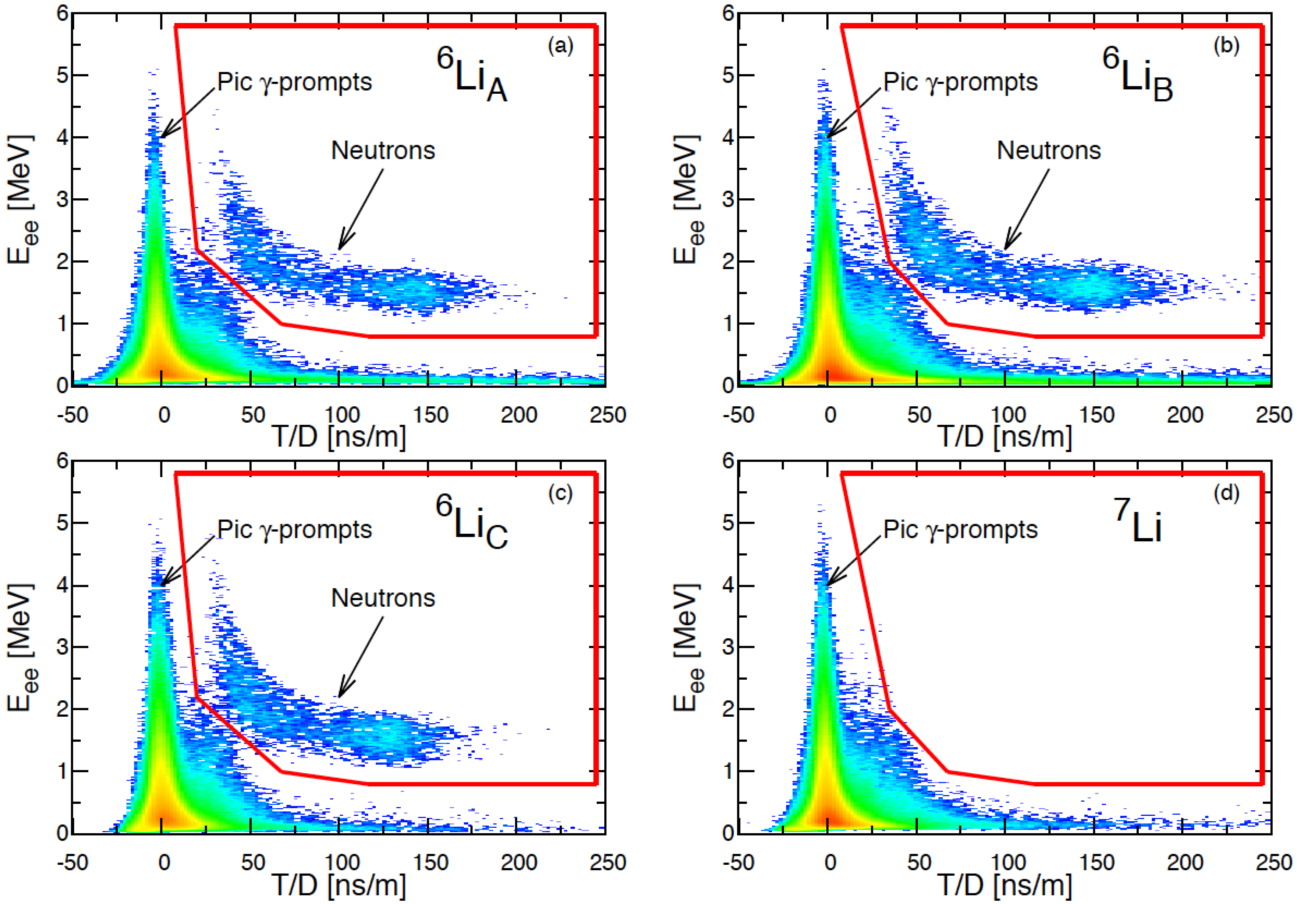

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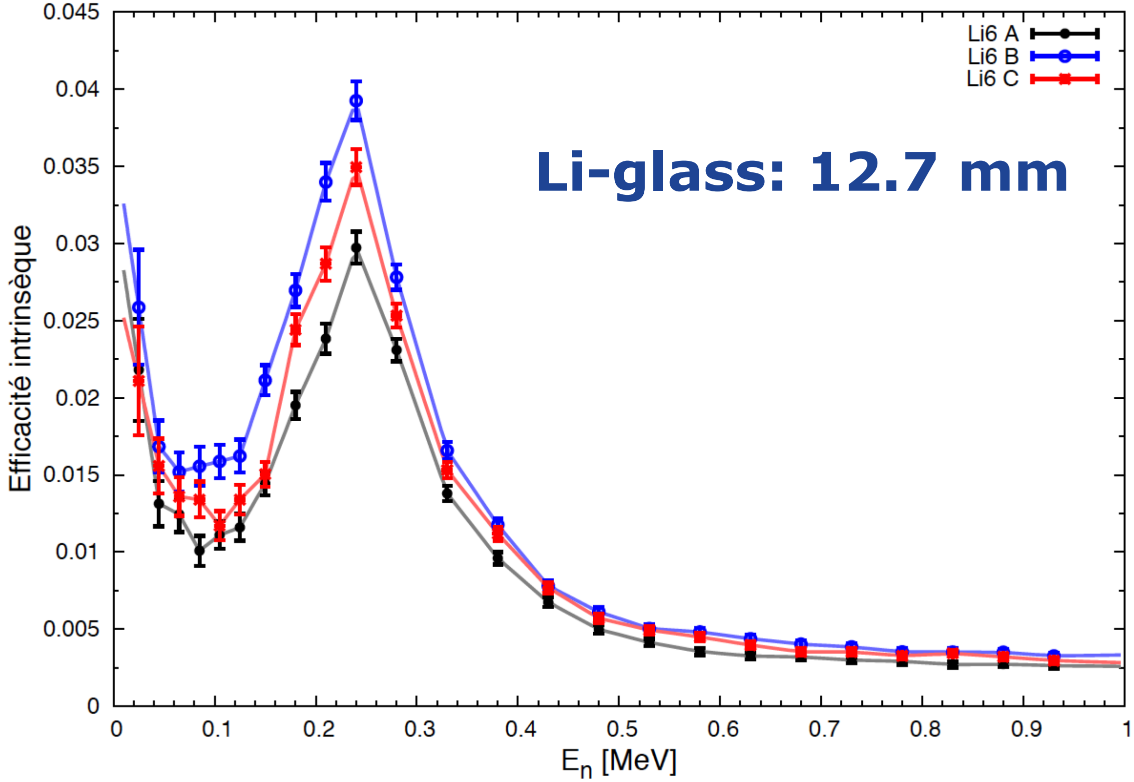
How to measure neutrons

- **Lithium-glass detectors:**



PhD thesis, A. Sardet, Université Paris Sud (2015)

European Commission

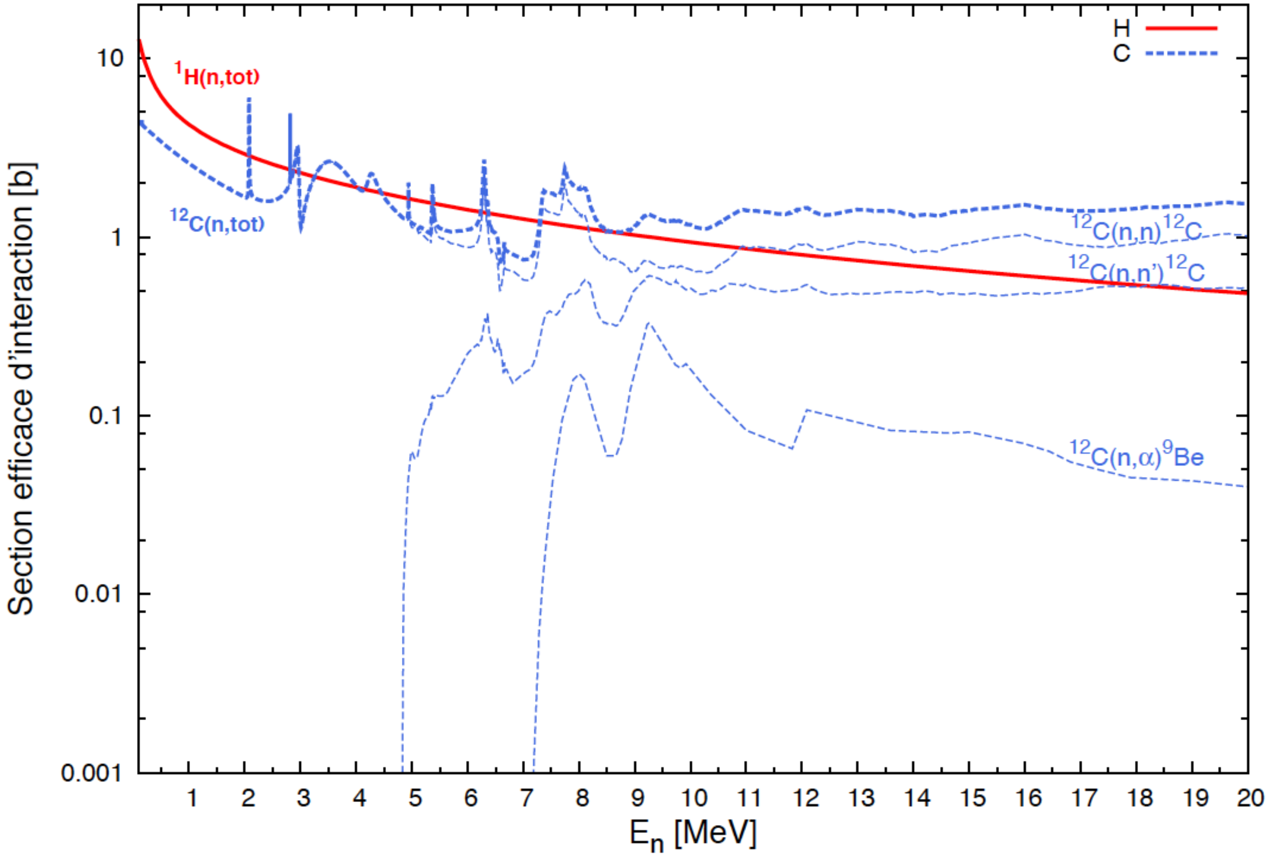
How to measure neutrons

- Lithium-glass detectors:
  - Relatively low detection efficiency
  - Bad timing resolution prevents from using longer crystals
  - One would have to use many detectors

PhD thesis, A. Sardet, Université Paris Sud (2015)

How to measure neutrons

➢ **Detectors based on liquid scintillator(s):**



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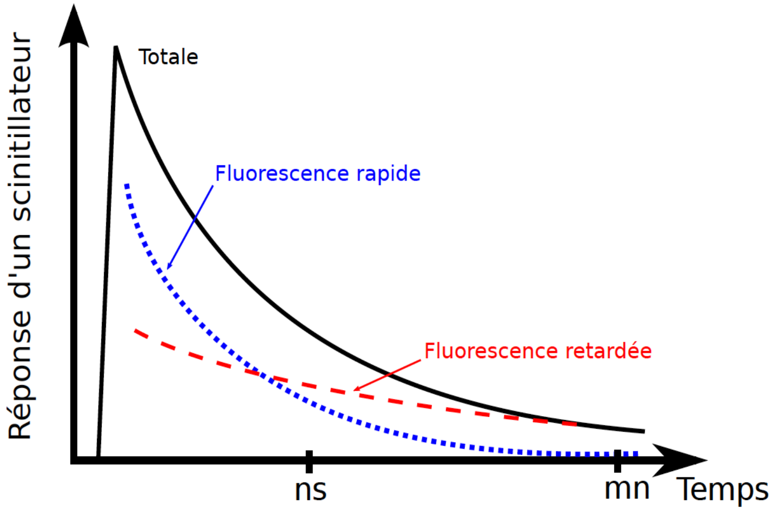
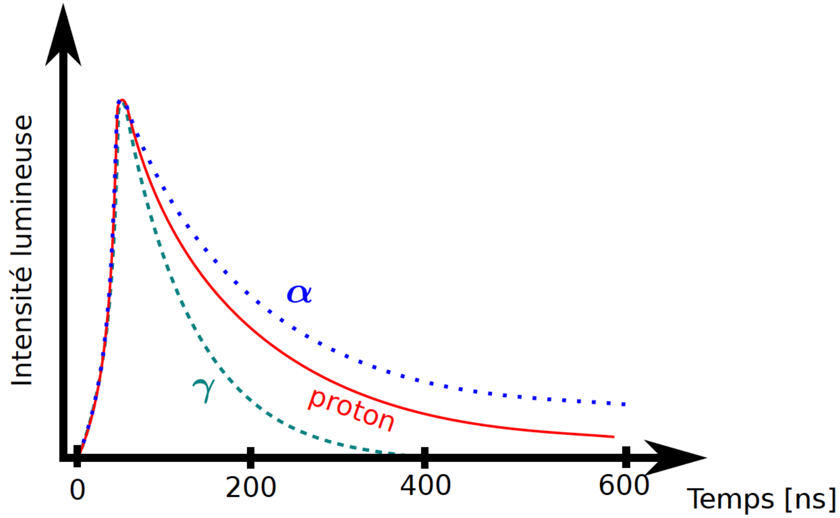
How to measure neutrons

- **Detectors based on liquid scintillator(s):**
  - **Allow pulse shape discrimination**
  - **Electrons and recoil protons excite different fluorescent levels**
  - **Detector signal shows different fall times**





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How to measure neutrons

- Detectors based on liquid scintillator(s):
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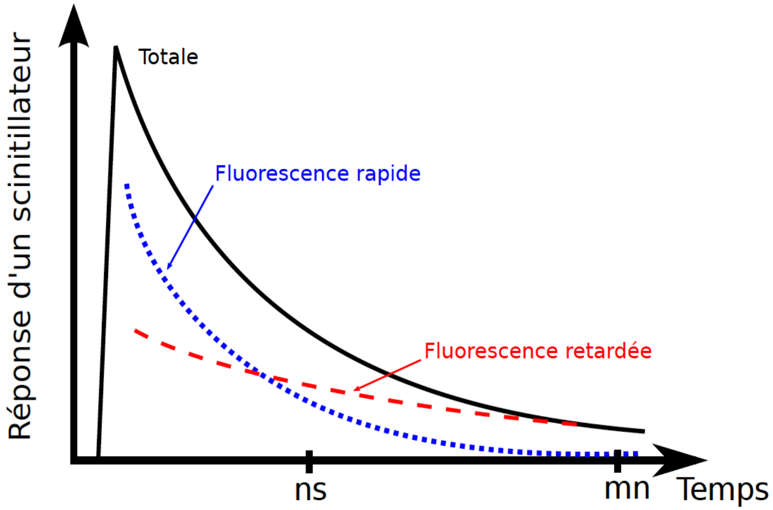

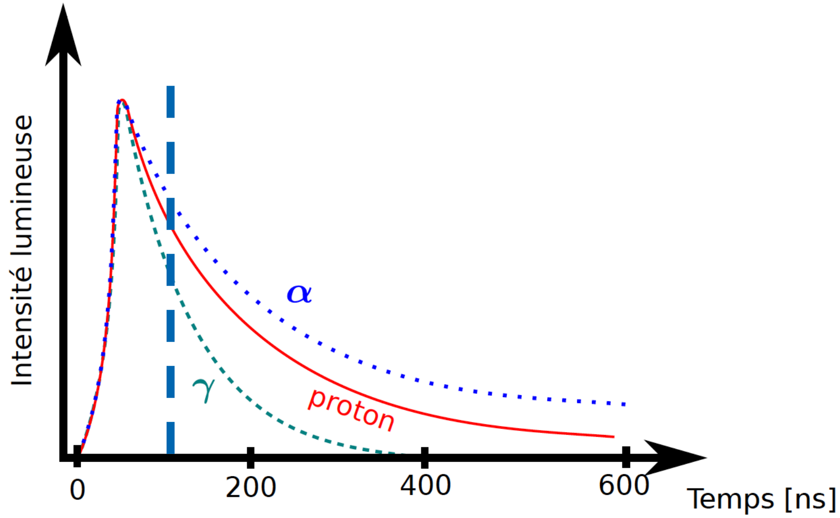

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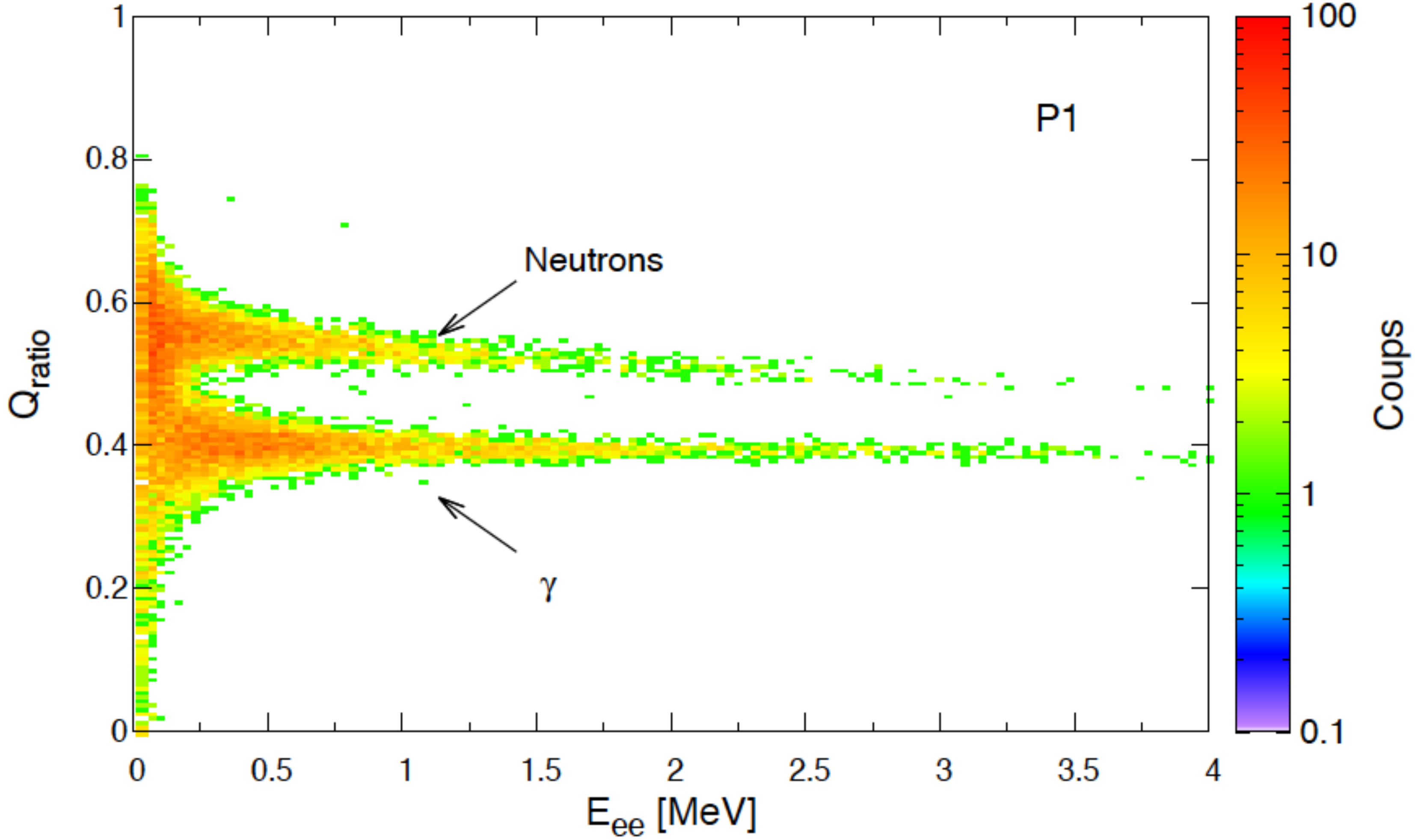
How to measure neutrons



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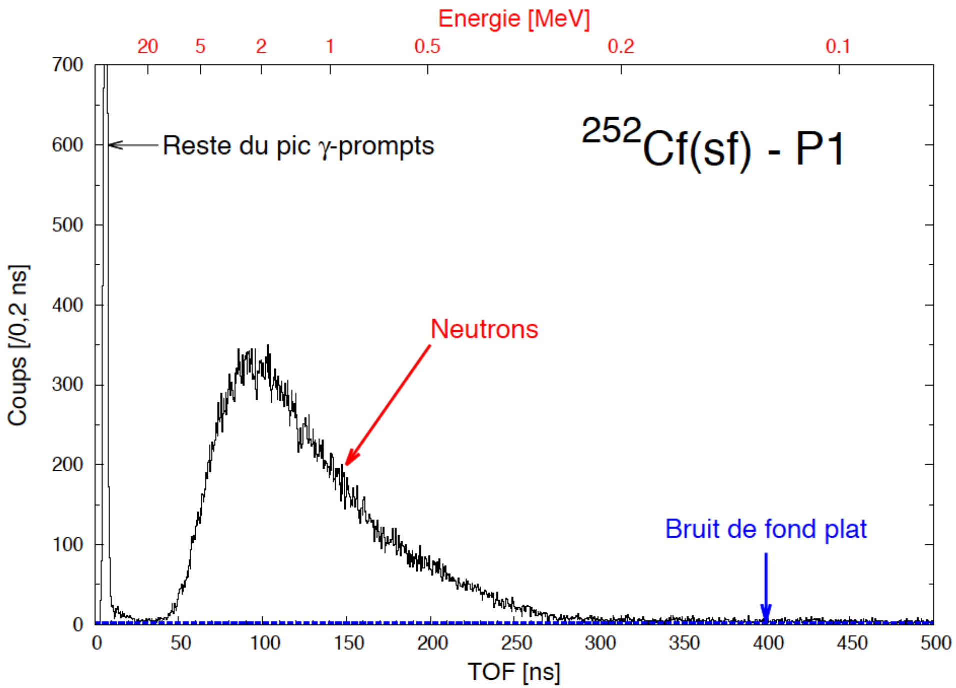
How to measure neutrons

- **Detectors based on liquid scintillator(s):**
  - **Very fast detectors: $\sigma_t < 1$ ns**
  - **Neutron – γ separation by means of TOF**



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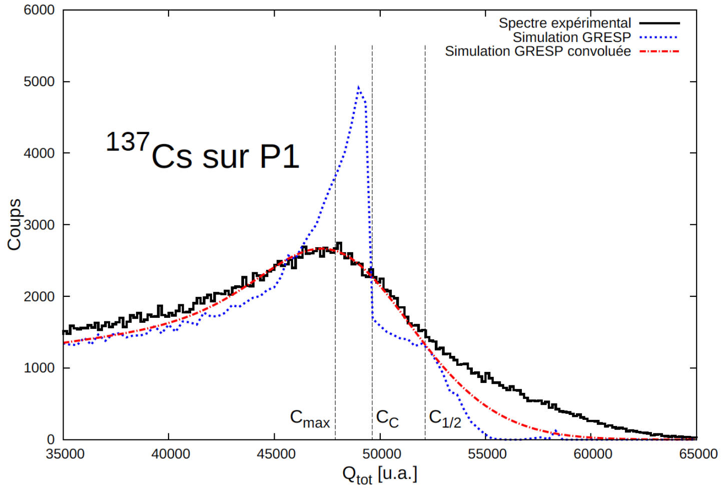
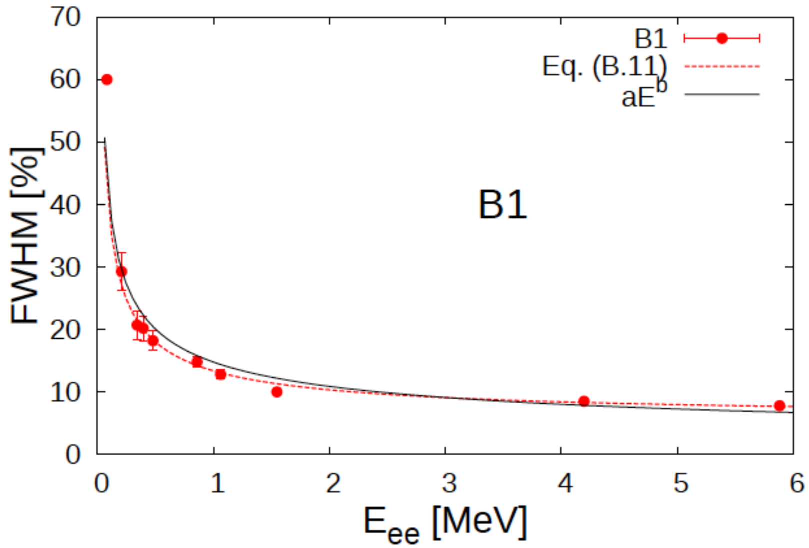
How to measure neutrons

➢ **Response of LS detectors to neutrons and γ-rays:**



$$\frac{\Delta E}{E} = 1.5\frac{C_{1/2} - C_{max}}{C_{1/2}}$$

$$\frac{\Delta E}{E} = \sqrt{\alpha^2 + \frac{\beta^2}{E} + \left(\frac{\gamma}{E}\right)^2}$$



A. Sardet, et al., NIM A792 (2015) 74

PhD thesis, A. Sardet, Université Paris Sud (2015)

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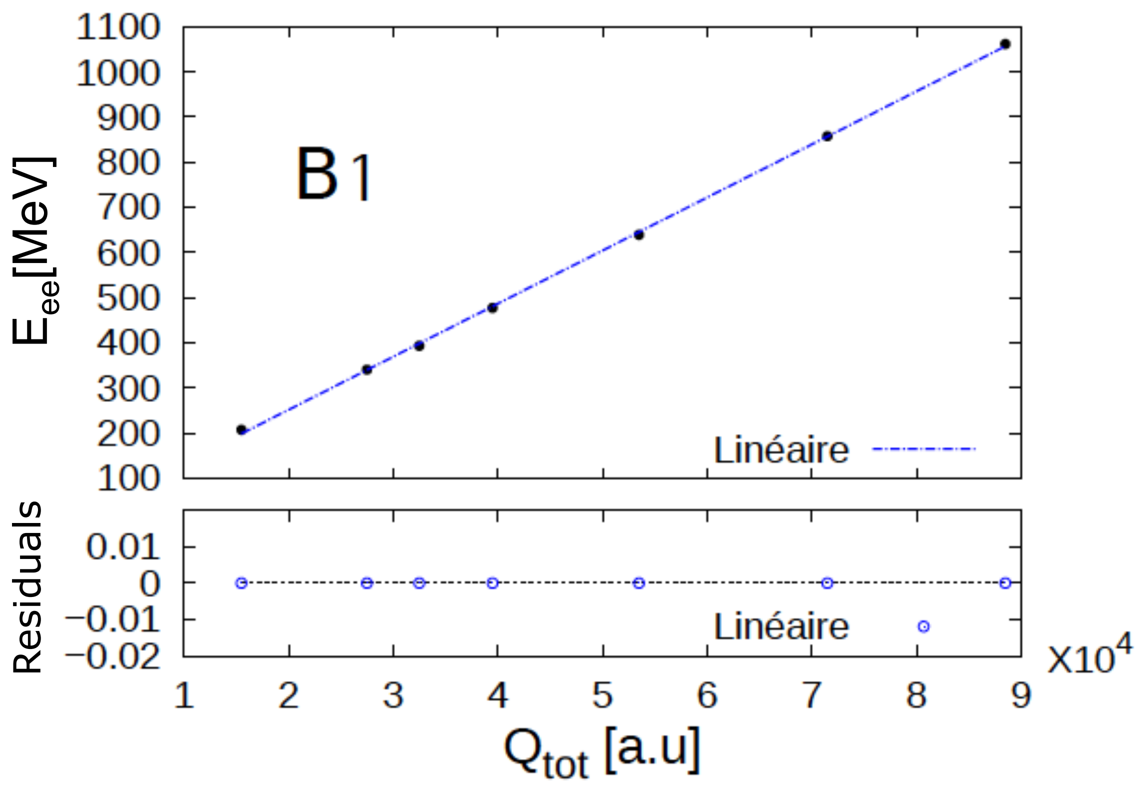
How to measure neutrons

- **Response of LS detectors to neutrons and γ-rays:**



PhD thesis, A. Sardet, Université Paris Sud (2015)

How to measure neutrons

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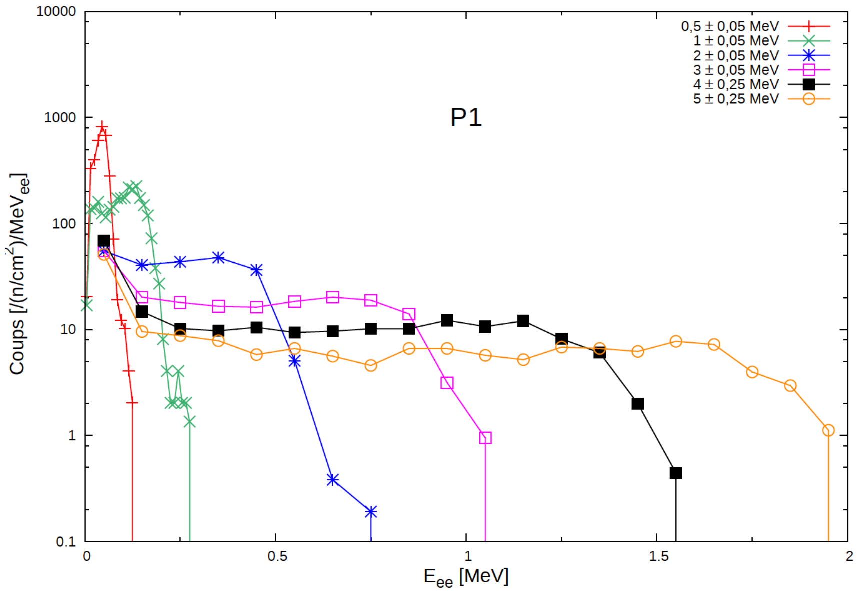
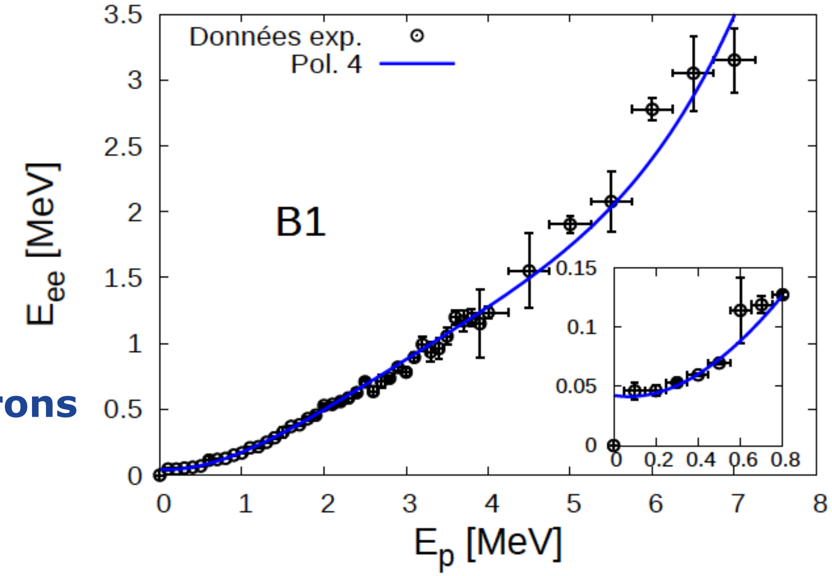




- **Response for mono-energetic neutrons**

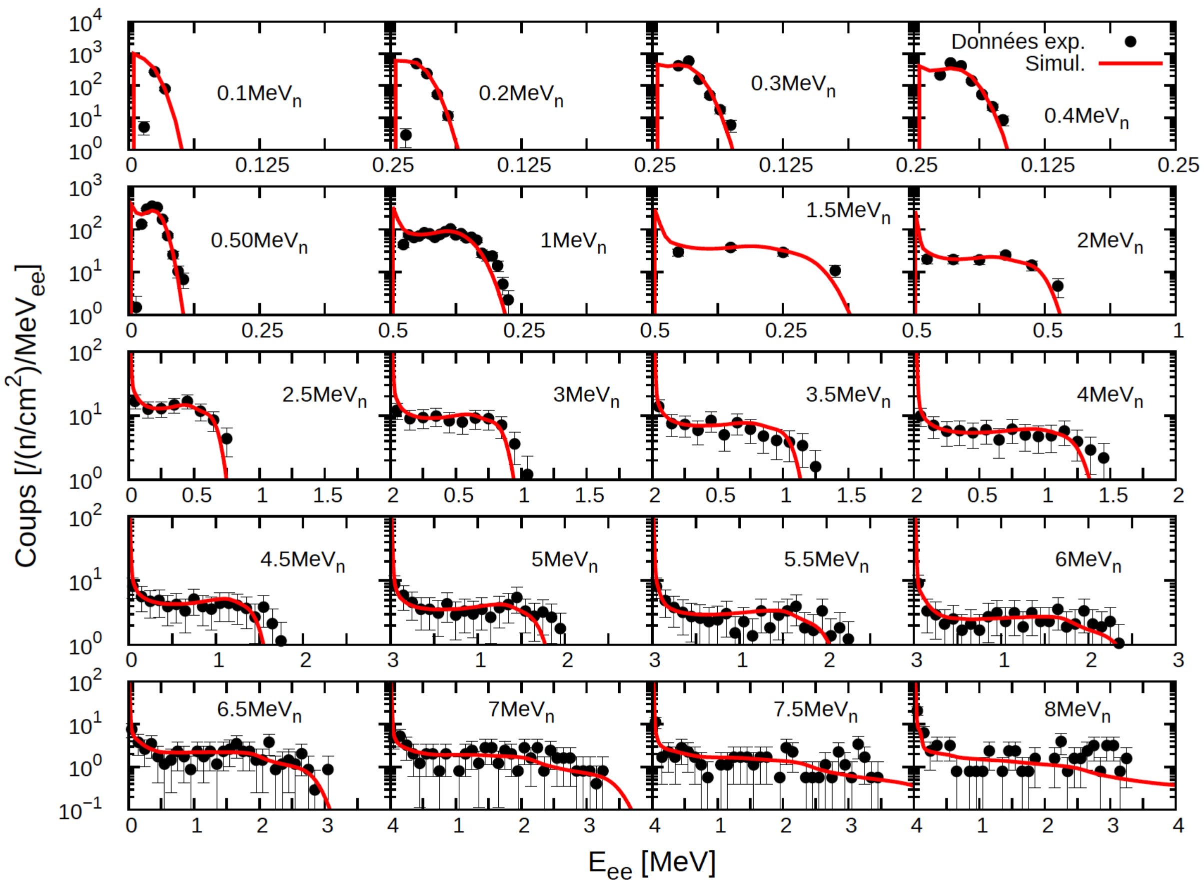
- **Selection from the TOF information**
- **Calibrated neutron beam**

A. Sardet, et al., NIM A792 (2015) 74

PhD thesis, A. Sardet, Université Paris Sud (2015)

How to measure neutrons

- **Response of LS detectors to neutrons and γ-rays:**



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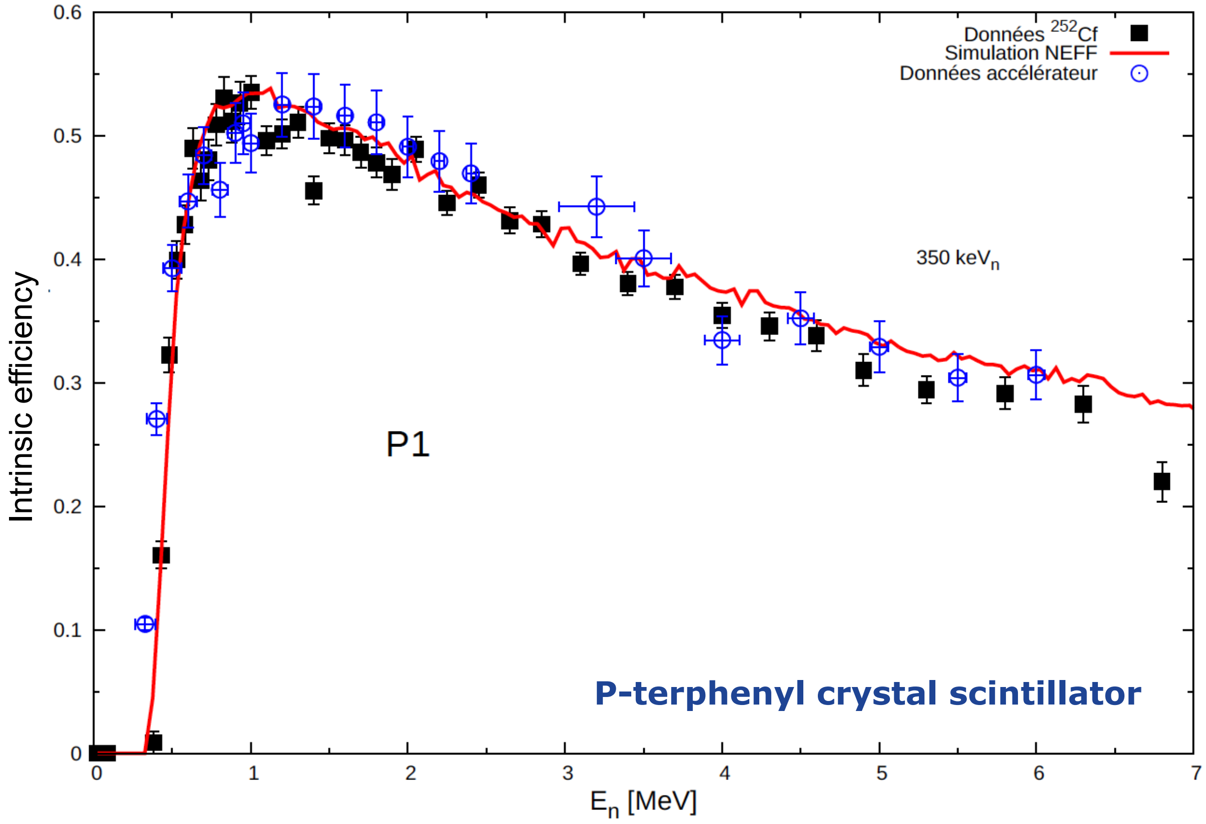
How to measure neutrons

- **Response of LS detectors to neutrons and γ-rays:**



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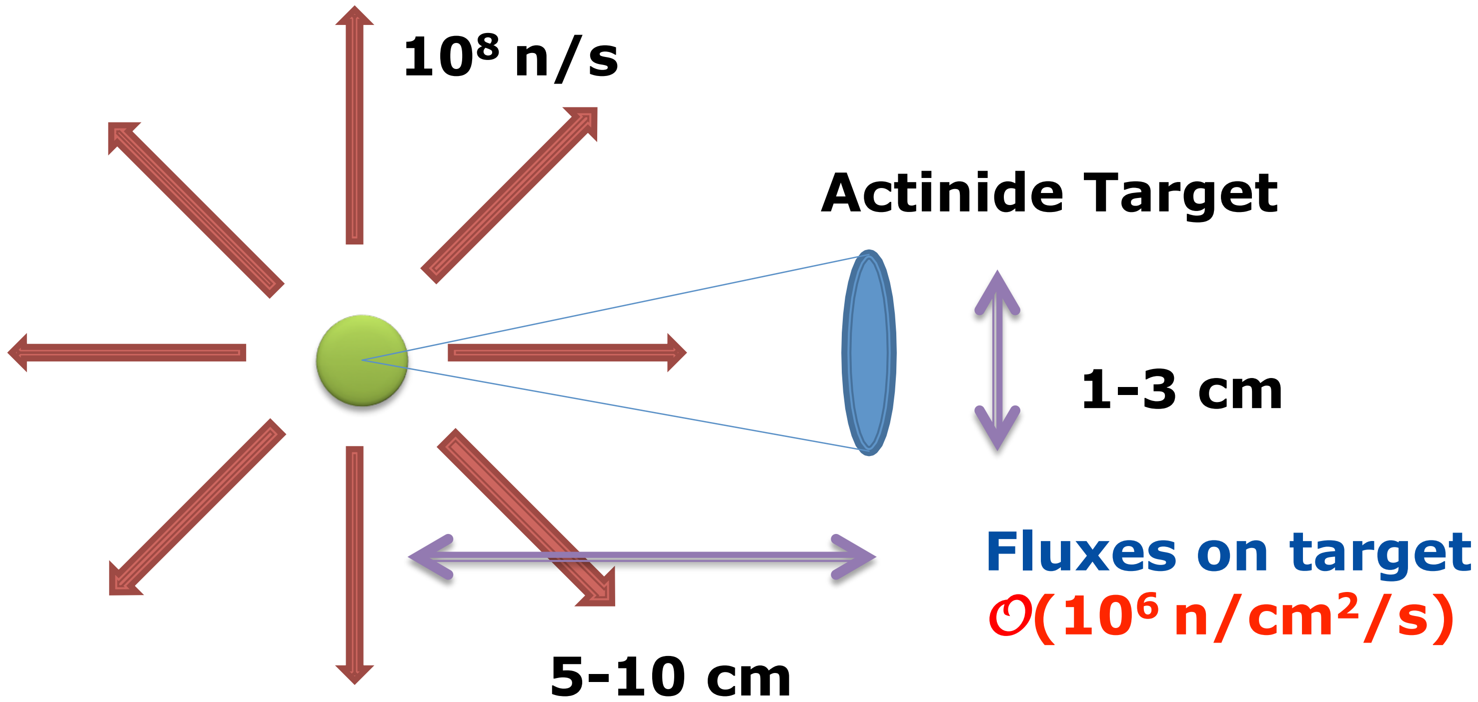
How to measure neutrons

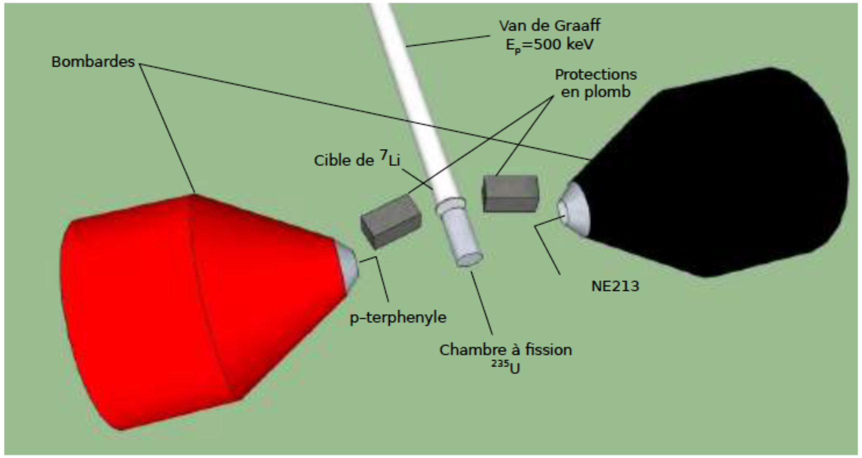
- The measurement environment (direct reaction):

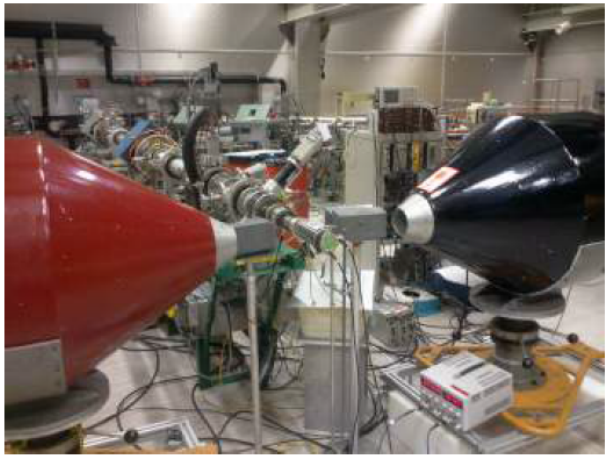


- Typically 99% of neutrons **wasted!**
- Wasted neutrons contribute to the room background
- Placement of n-detectors impossible w/o heavy shielding

How to measure neutrons

- The measurement environment (direct reaction):





- Limited number of detectors
- Contributions from neutron scattering
- Simulation by means of MCNP or Geant4

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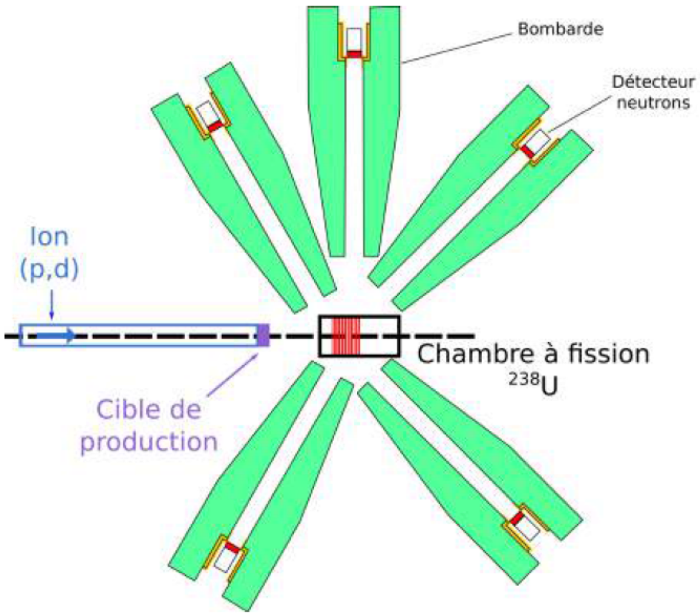
How to measure neutrons

- The measurement environment (direct reaction):

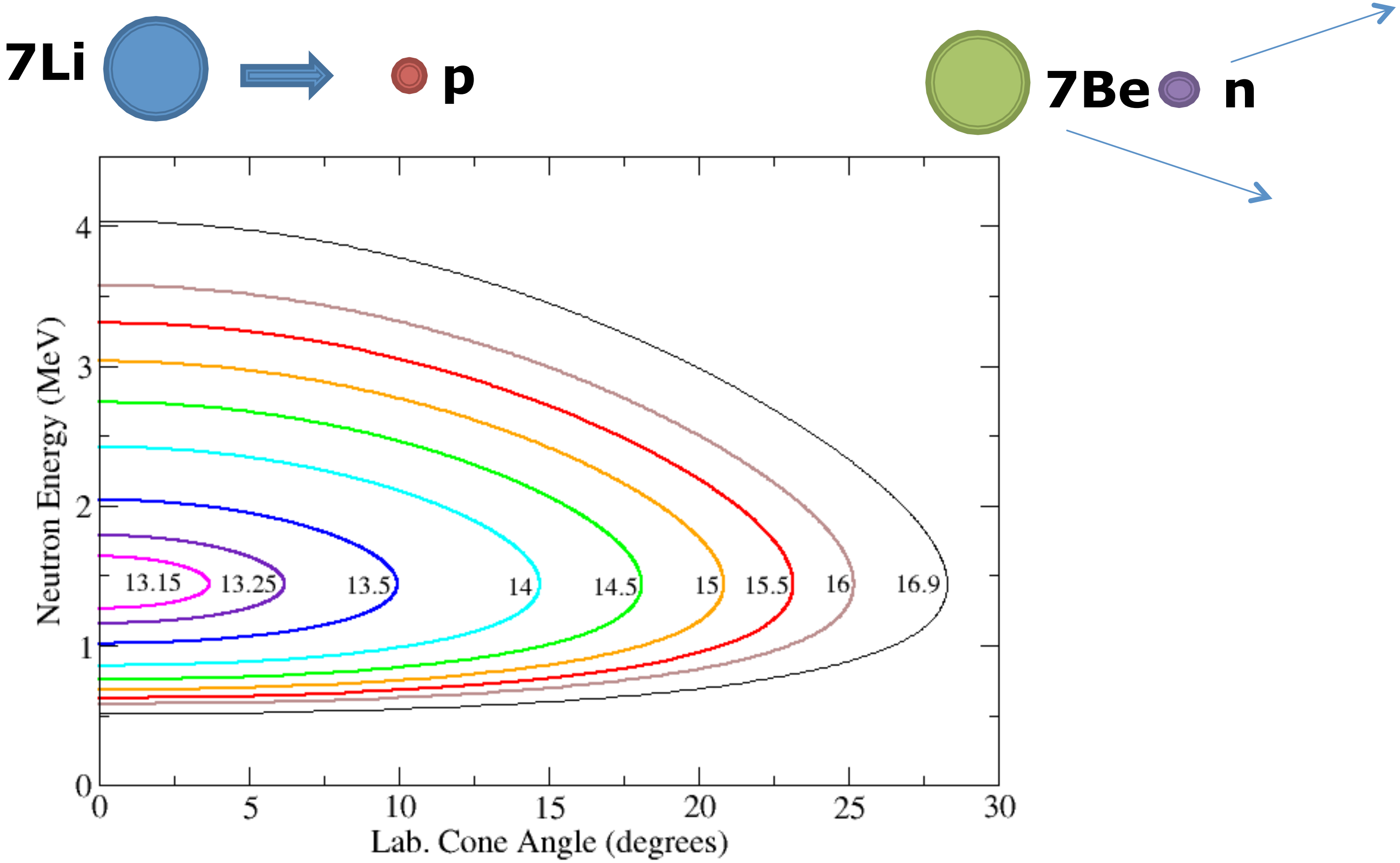


- Limited number of detectors
- Contributions from neutron scattering…

PhD thesis, A. Sardet, Université Paris Sud (2015)

How to measure neutrons

➢ **Neutron beam from inverse kinematics reactions:**



M. Lebois, J.N. Wilson, A. Oberstedt, SO et al., NIMA735 (2014)

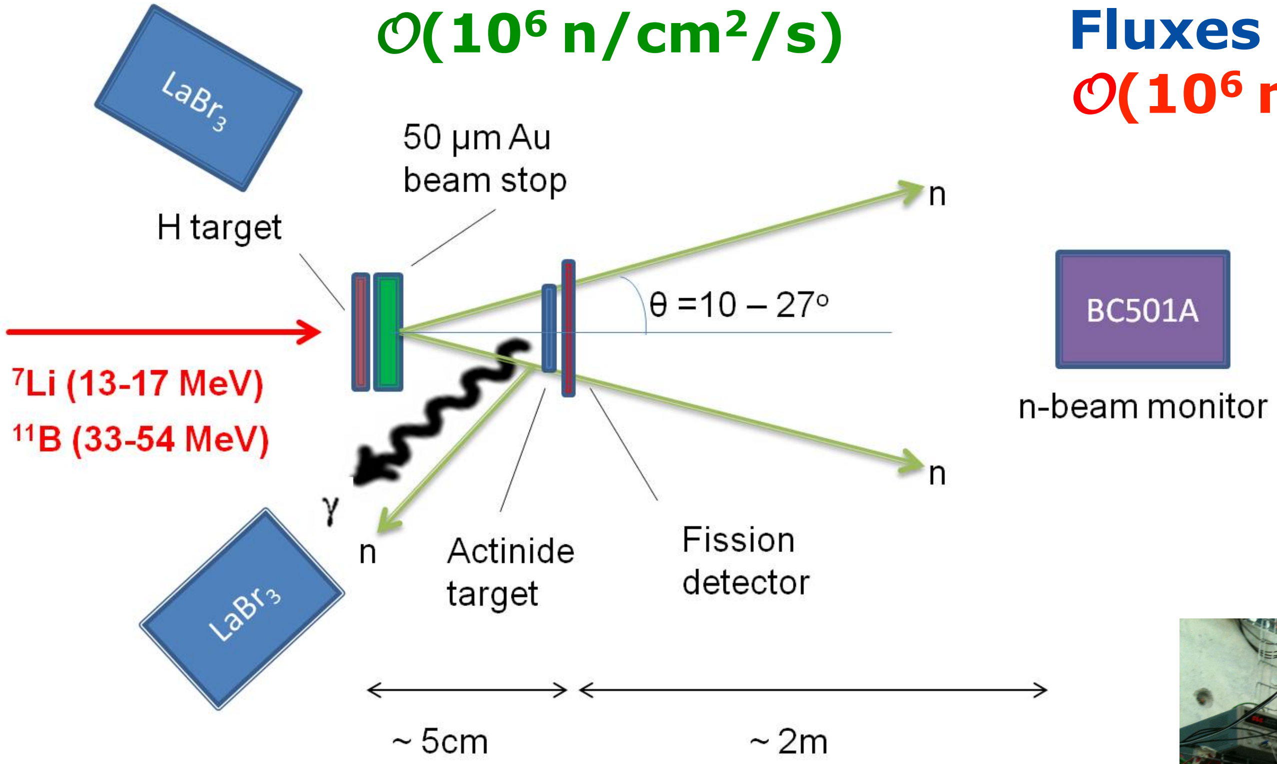
European Commission

How to measure neutrons

➢ **Neutron beam from inverse kinematics reactions:**

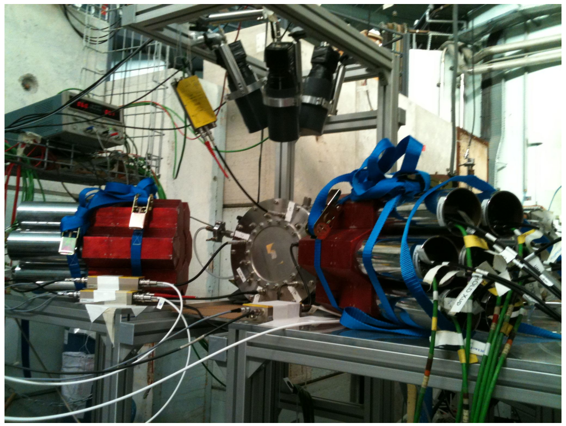
Fluxes from source
$\mathcal{O}(10^6\ n/cm^2/s)$

Fluxes on target
$\mathcal{O}(10^6\ n/cm^2/s)$!



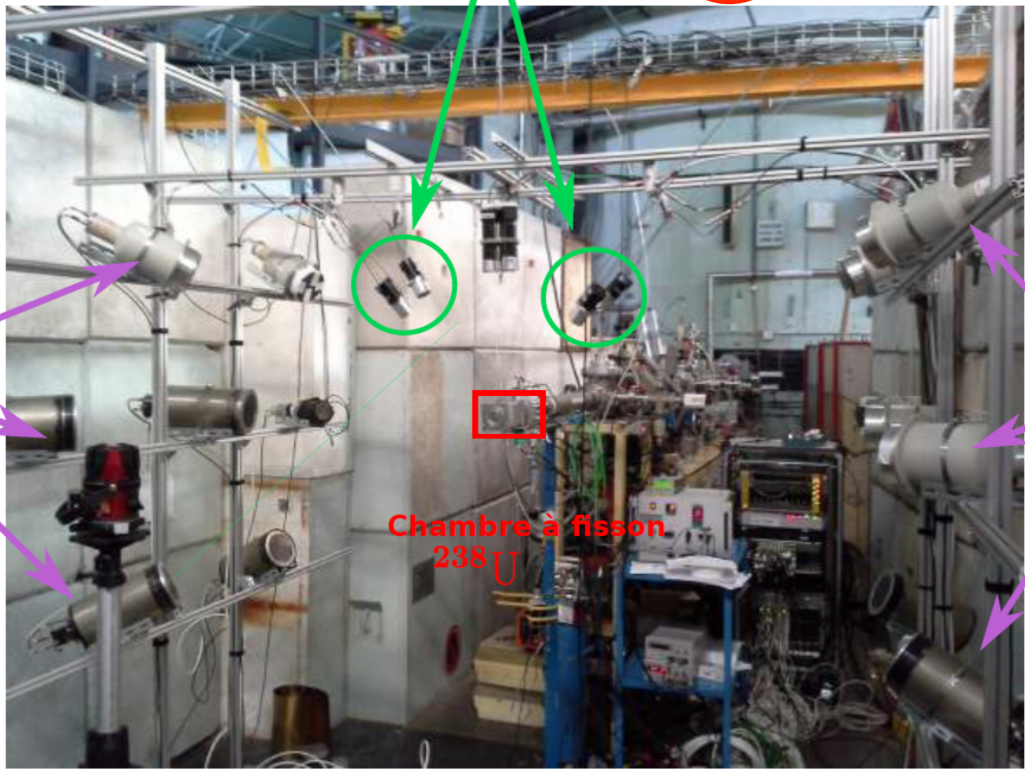
LICORNE

M. Lebois, J.N. Wilson, A. Oberstedt, SO et al., NIMA735 (2014)



How to measure neutrons

➢ **Neutron beam from inverse kinematics reactions:**

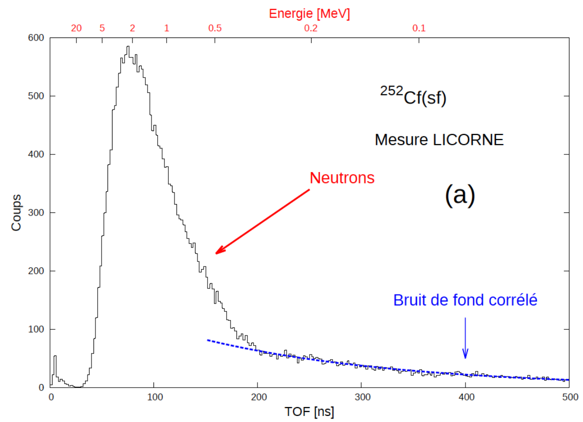


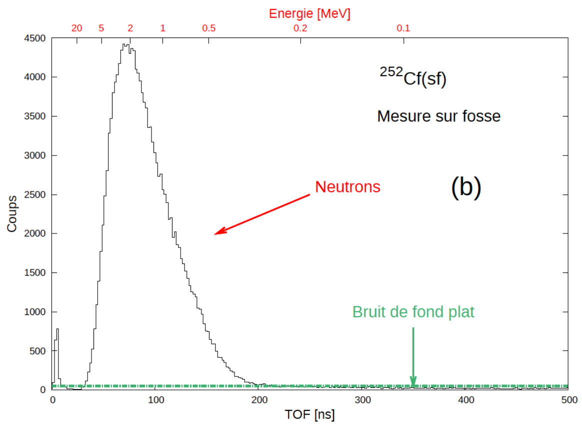
PhD thesis, A. Sardet, Université Paris Sud (2015)

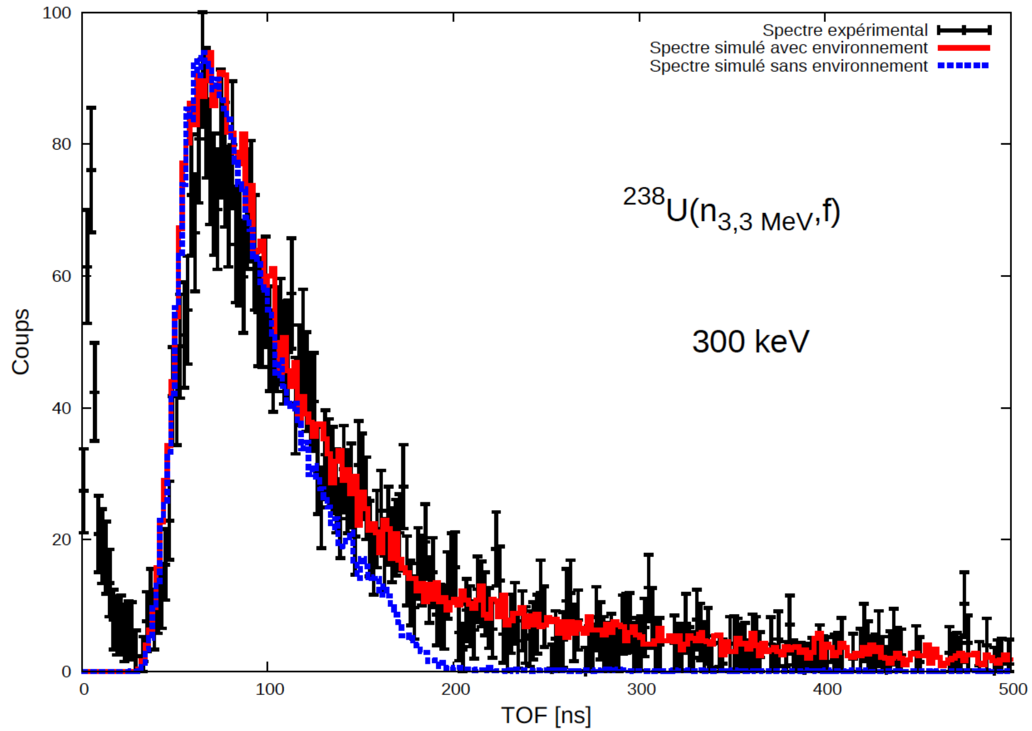
European Commission

How to measure neutrons

- ➢ **Neutron beam from inverse kinematics reactions:**
  - ➢ **Nothing is perfect (yet ☺)**

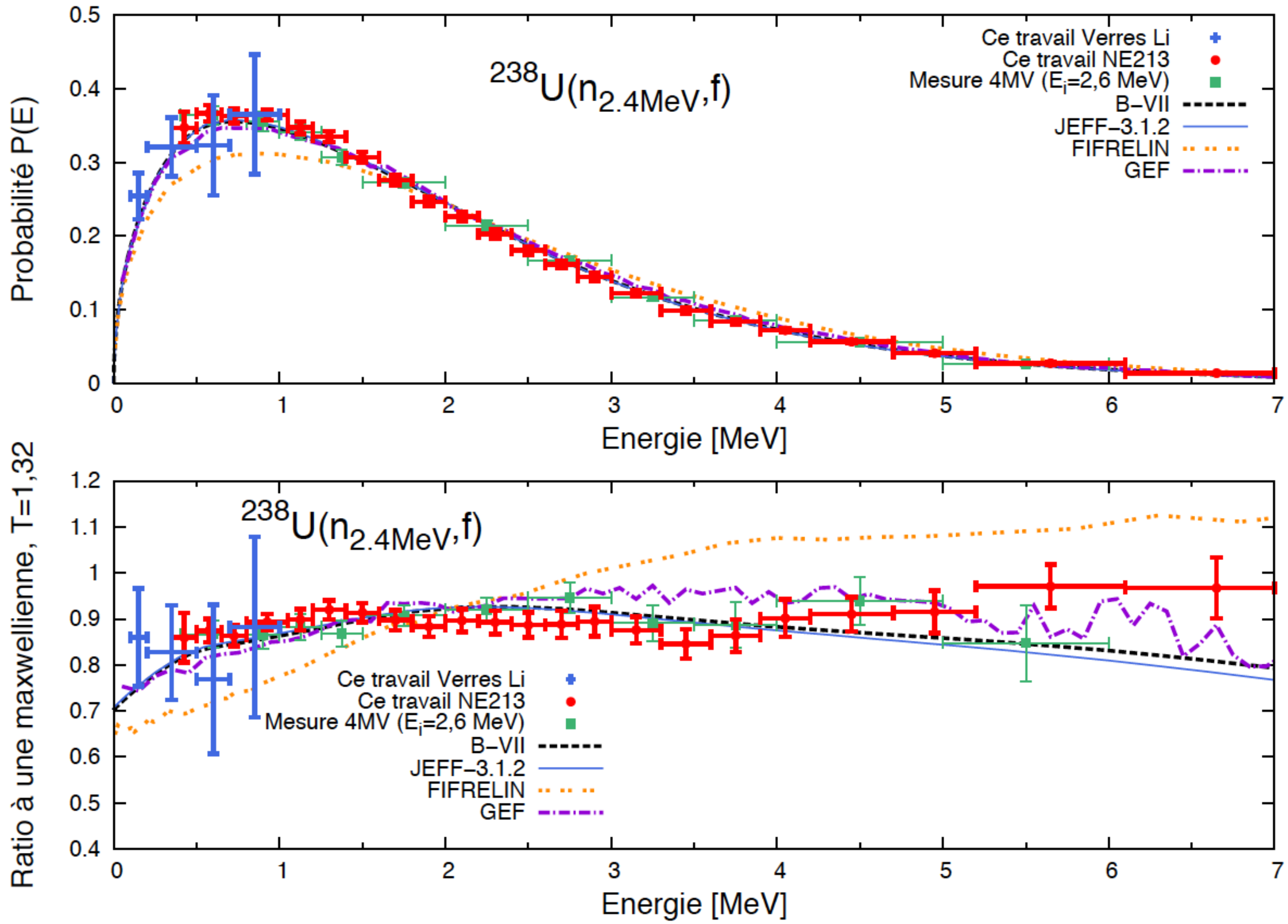






How to measure neutrons

- And finally: a prompt fission neutron spectrum



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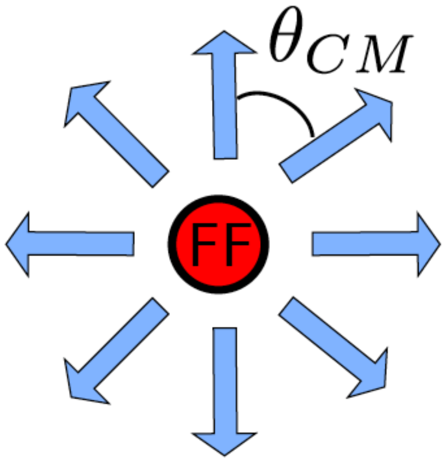
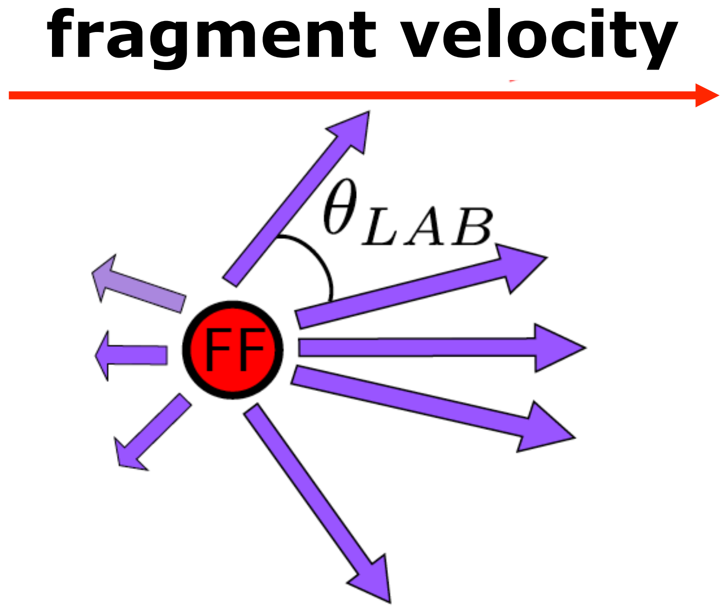
How to measure neutrons

- And for extracting physics, remember this:





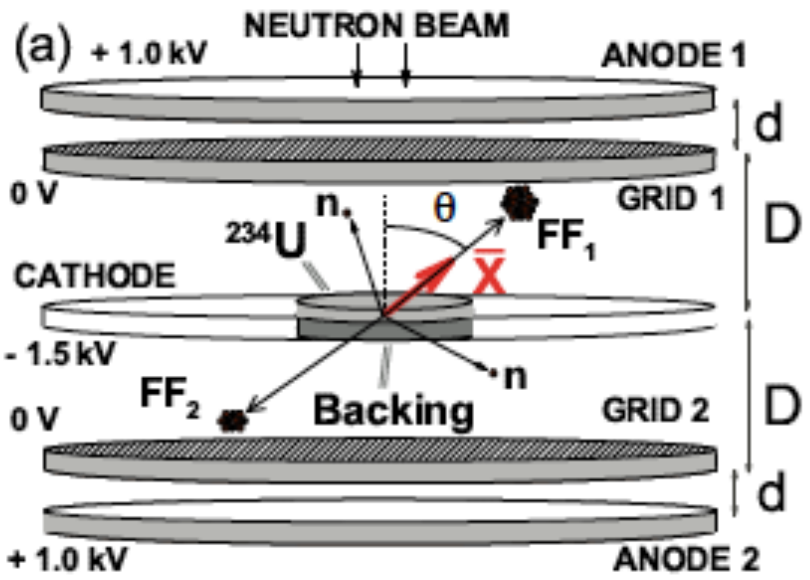
center of mass frame

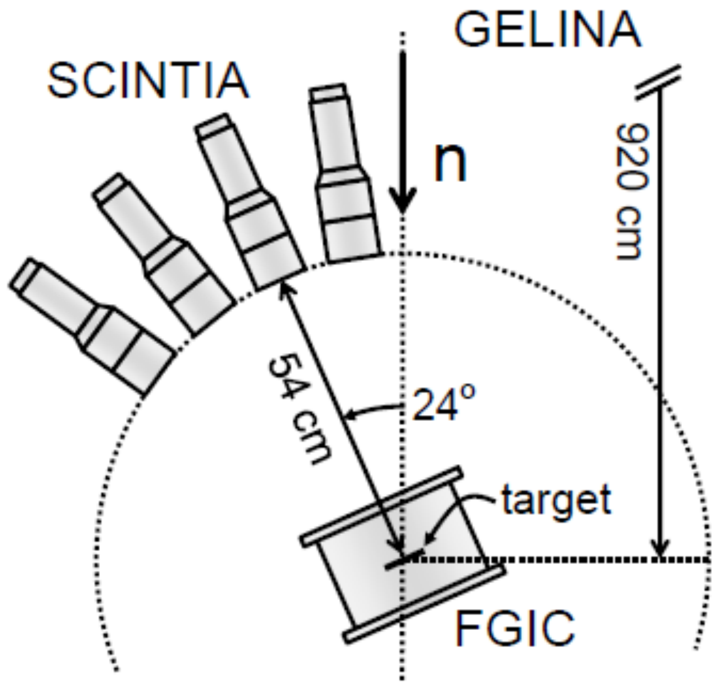
laboratory frame

Transformation from the LS to CMS

How to measure neutrons

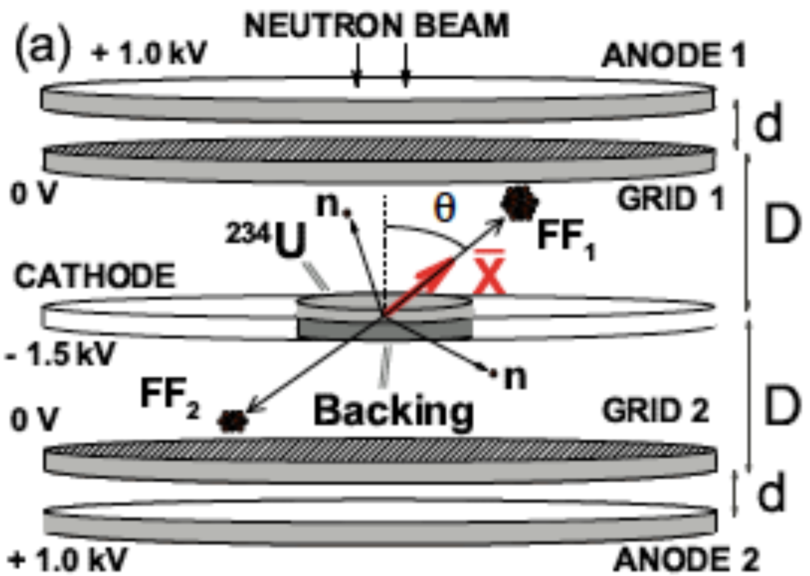
- The angle between the fission axis and the neutron vector is needed:

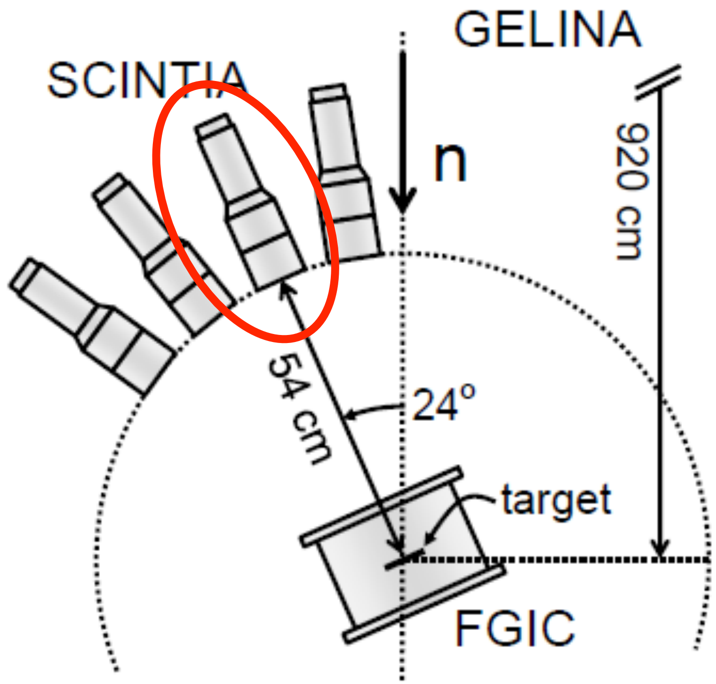




How to measure neutrons

- The angle between the fission axis and the neutron vector is needed:

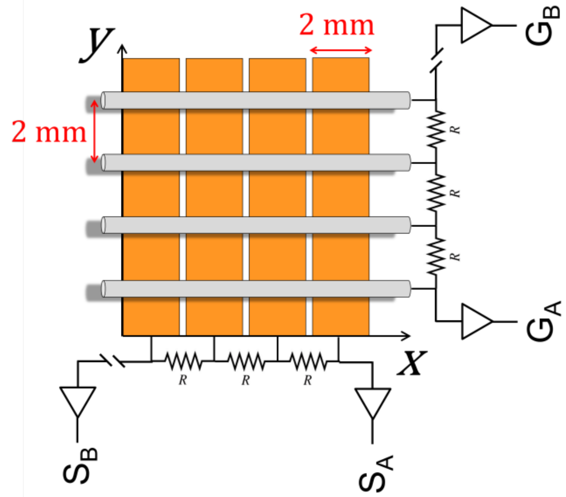




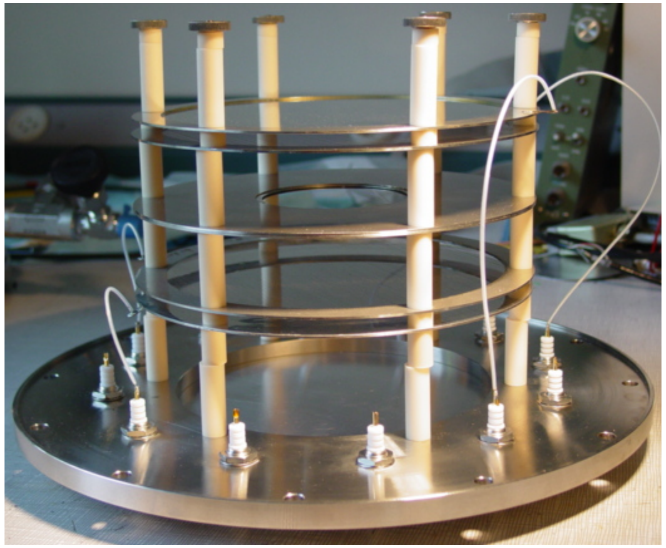
How to measure neutrons

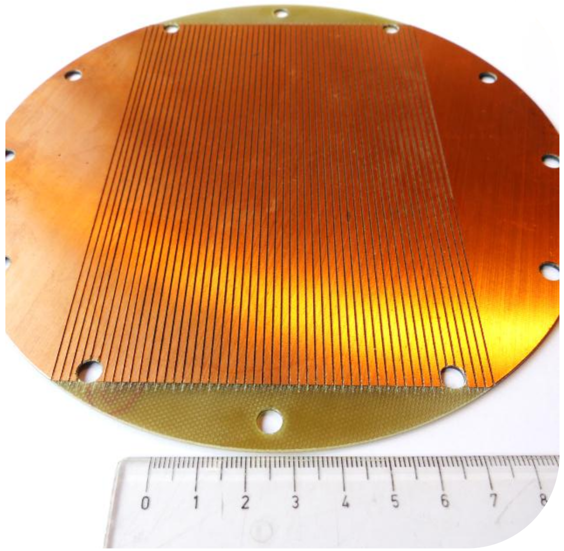
➢ **Position Sensitivity is required**

- ✓ Electron collector in ionization chamber replaced by position sensitive electrode
- ✓ Charge-division readout



✓ **Orientation of fission-axis in 3D-space**



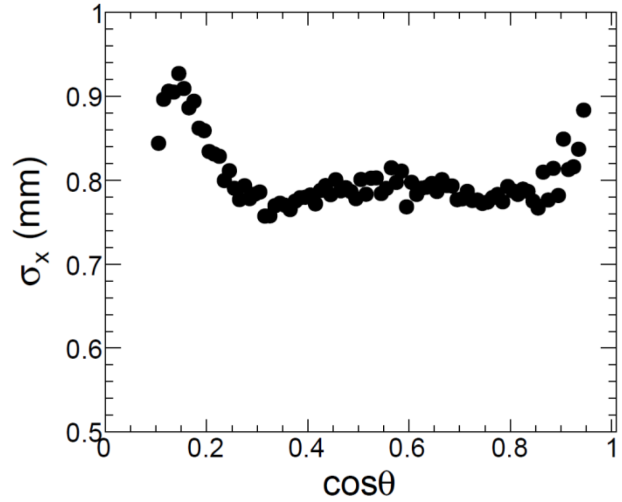


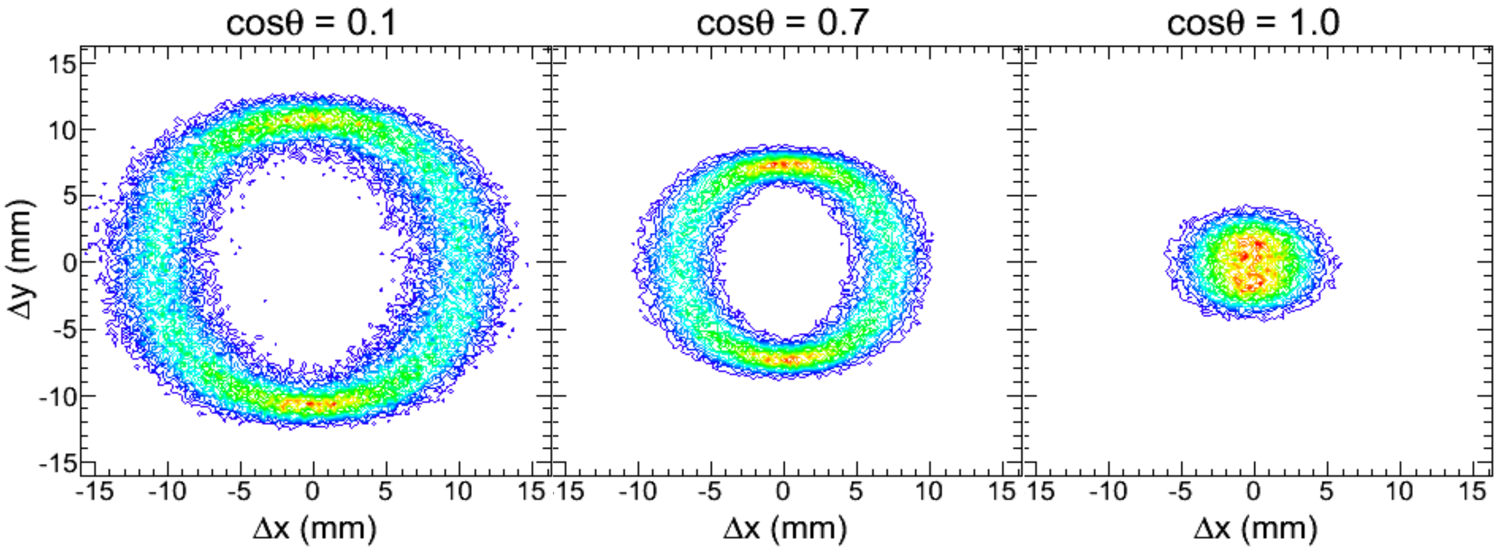
A. Göök

European Commission

How to measure neutrons

- **Demonstration of position sensitivity**
  - (x,y)-coordinate on anode plane for selections in polar angle
- **Analysis of the width of circles**
  - ✓ Resolution ≈ 1.8 mm (FWHM)





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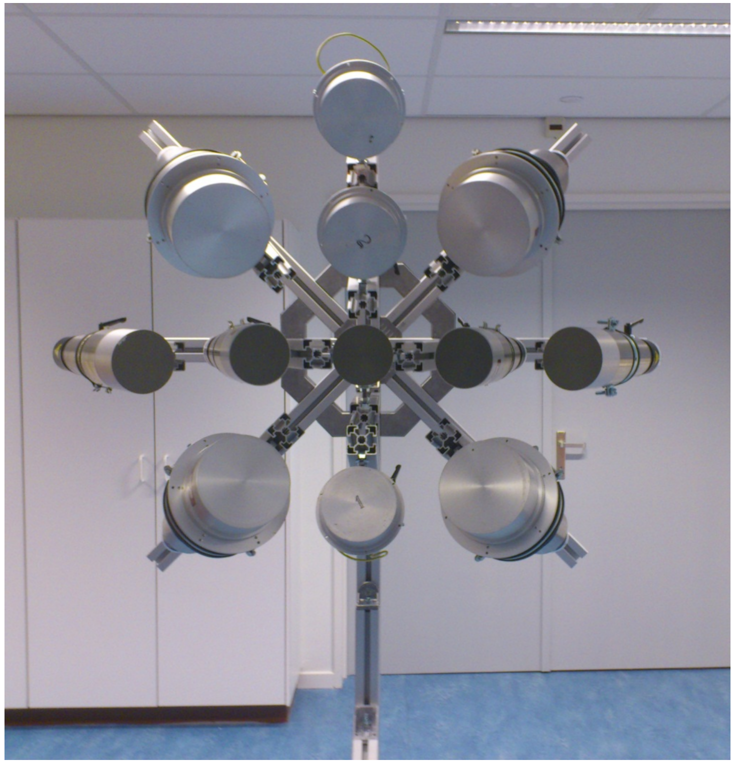
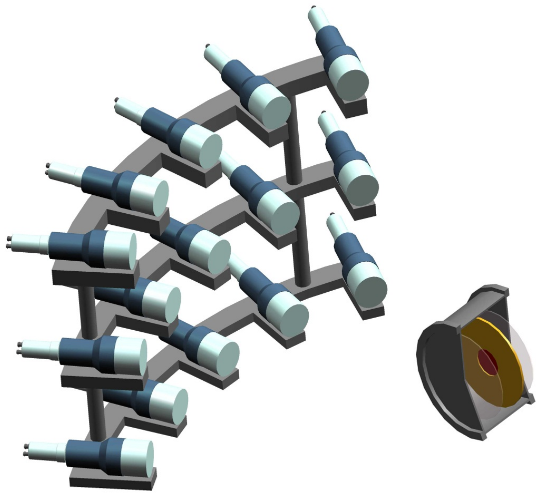
How to measure neutrons



➤ **SCINTIA array (2015)**

- ✓ **Array of 15 neutron detectors**
  - ✓ 10 SCIONIX LS301 (Φ=13 cm, h=7 cm)
  - ✓ 5 P-Therphenyl (Φ=8.5 cm, h=6.8 cm)

- ✓ **Double Frisch-grid (θ, ϕ) - sensitive IC**



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How to measure neutrons and γ-rays

- **Prompt γ-ray measurements**
- **Separation of γ-rays from prompt neutrons**
  - Time-of-flight method
  - Excellent timing resolution of the combined γ-ray and fission detector
  - Determines the geometrical efficiency of your instrument
- **Best possible energy resolution**

European Commission

How to measure neutrons and γ-rays

- **Prompt γ-ray measurements**

- **Fission detectors: FGIC, Si-detectors, single-crystal diamond detectors (σ_t < 100 ps)**

- **Choice of suitable γ-ray detectors:**

  - **High purity germanium detectors**
  - ✓ **Excellent energy resolution, bad timing resolution**
  - **Fragments moving → Doppler broadened γ-peak**
  - **Very neutron sensitive**

European Commission

How to measure neutrons and γ-rays

- **Prompt γ-ray measurements**

- **Choice of suitable γ-ray detectors:**
  - ~~High purity germanium detectors~~
  - ✓ ~~Excellent energy resolution, bad timing resolution~~
  - ~~Fragments moving → Doppler broadened γ-peak~~
  - ~~Very neutron sensitive~~

  - Scintillation detectors
  - Limited energy resolution, worse peak-to-total
  - ✓ In general much better timing resolution
  - ✓ Higher efficiency, larger sizes available

How to measure neutrons and γ-rays

➢ Scintillation detectors:

In the 1970s sodium iodine (NaI) was used

- ✓ **Timing resolution of the order of 5 – 7 ns**
- ✓ **Energy resolution 7% @ 662 keV**
- ✓ **TOF distance 1m or larger**
- \- **Limited geometrical efficiency**

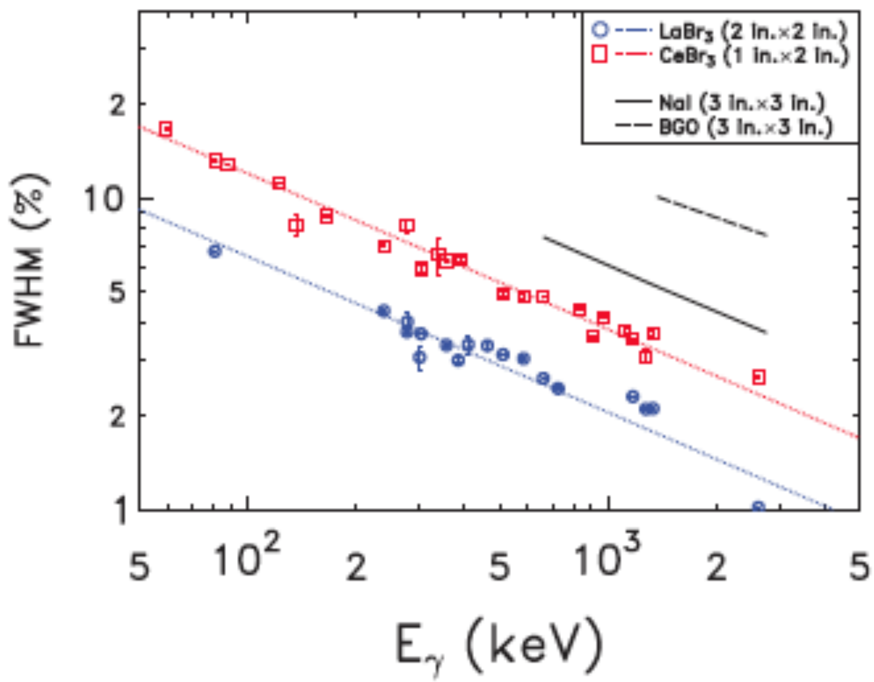
Nowadays we have to cope with limited resources in terms beam time, staff…

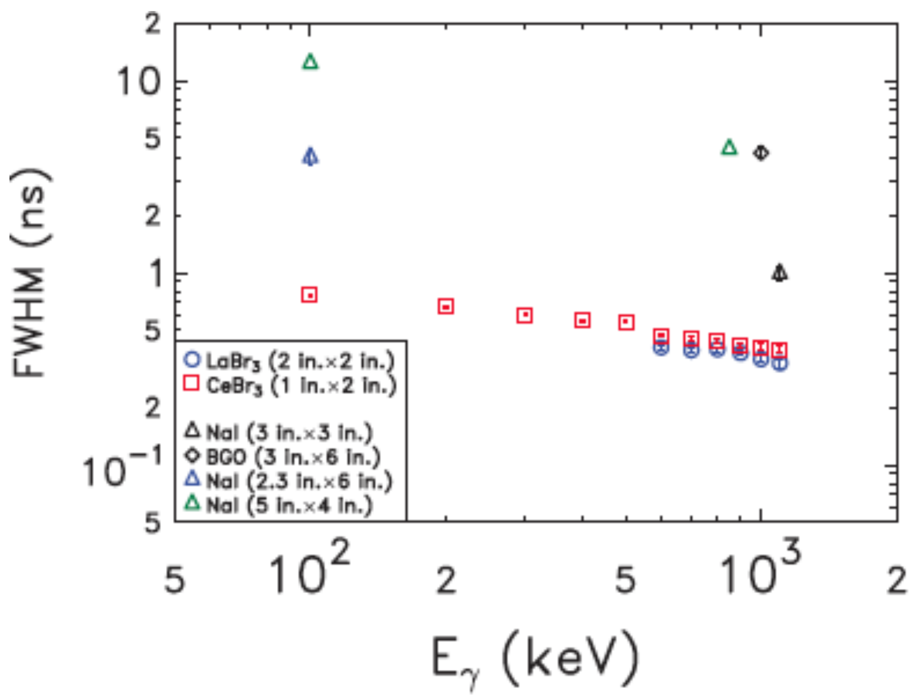
Need of a more compact, efficient set-up!

How to measure prompt fission γ-rays

➢ Lanthanide halide detectors:

- Cerium-doped lanthanum chloride ($LaCl_3$:Ce)
- Cerium-doped lanthanum chloride ($LaBr_3$:Ce)
- Cerium bromide ($CeBr_3$)





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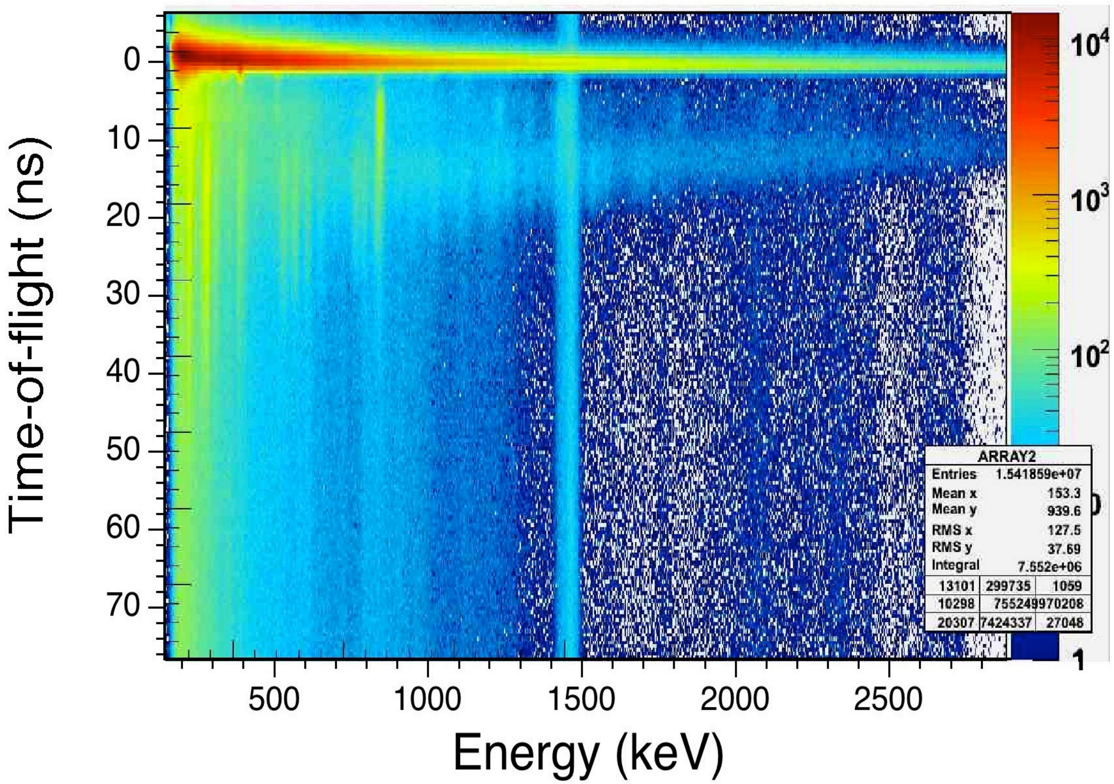
How to measure prompt fission γ-rays



Photons in coincidence with fission fragments

A. Oberstedt, R. Billnert, SO et al., NIM A708 (2013) 7

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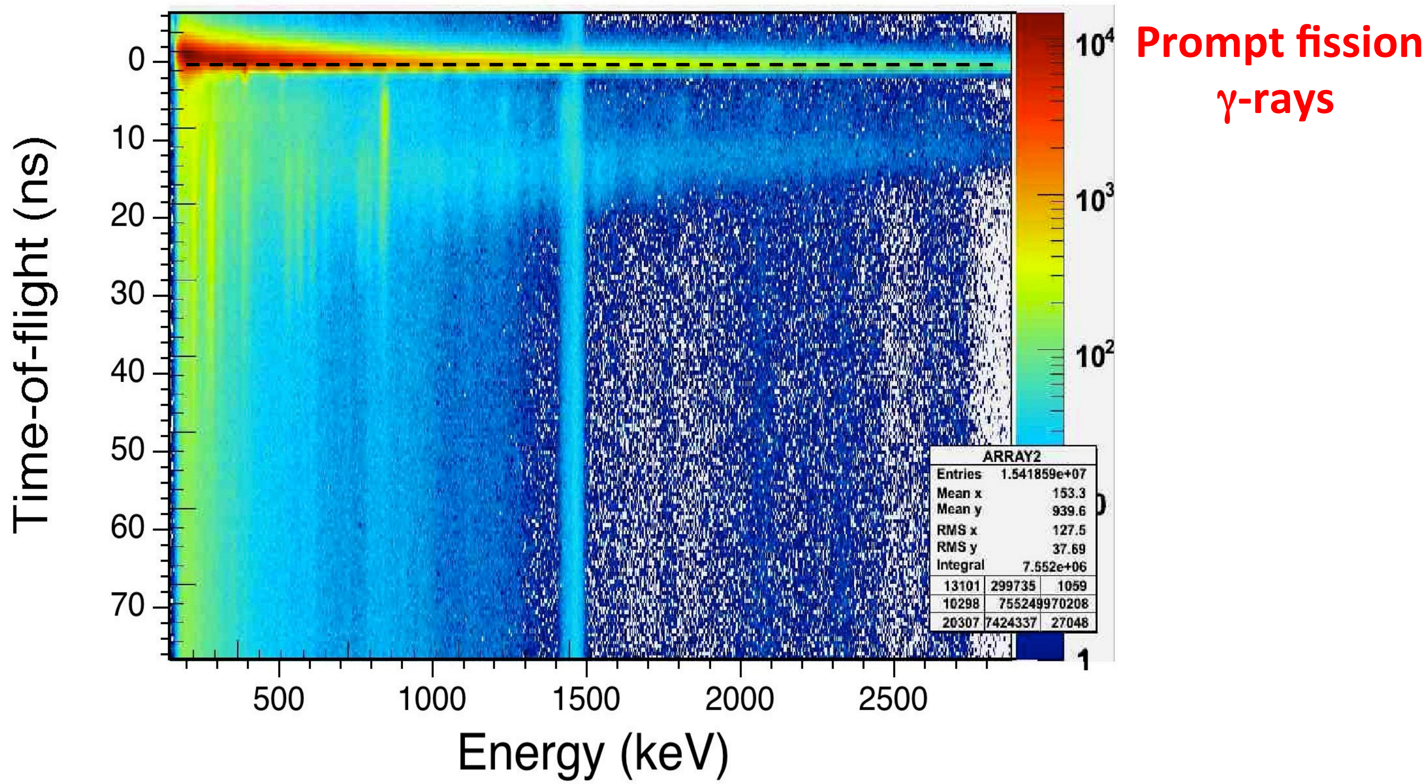
How to measure prompt fission γ-rays



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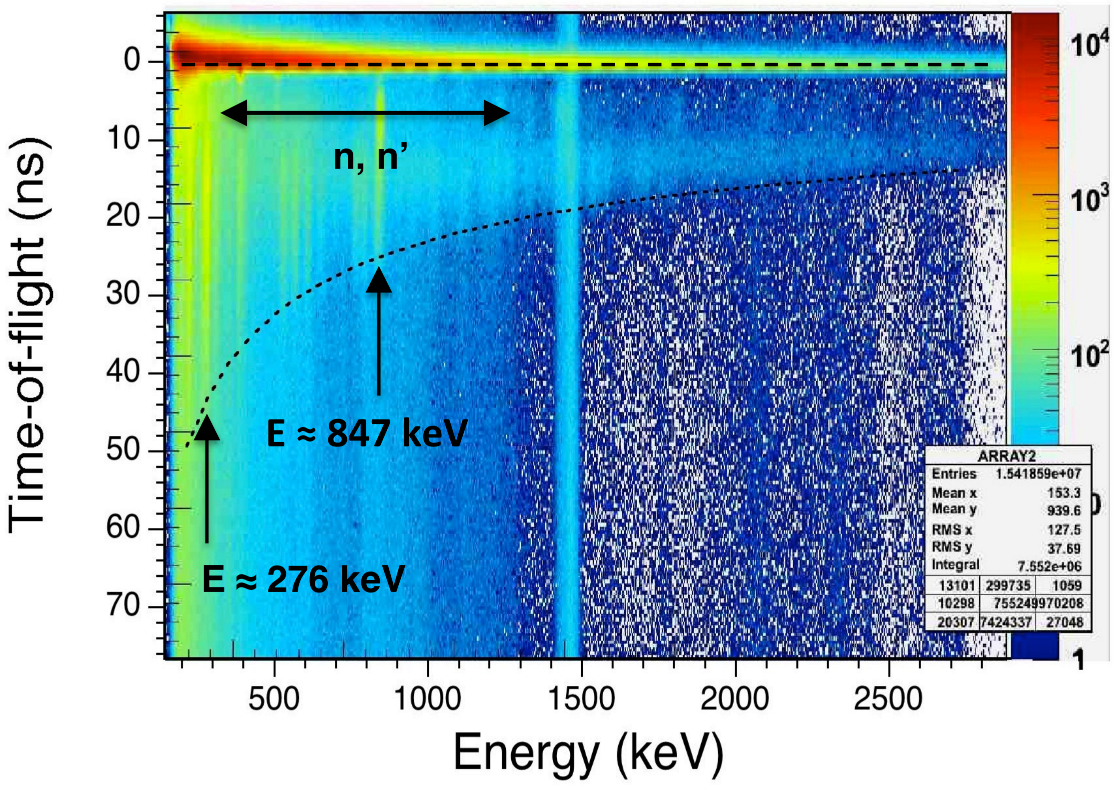
European Commission

How to measure prompt fission γ-rays



Prompt fission γ-rays

γ-decay after inelastic neutron scattering

Photons in coincidence with fission fragments

A. Oberstedt, R. Billnert, SO et al., NIM A708 (2013) 7

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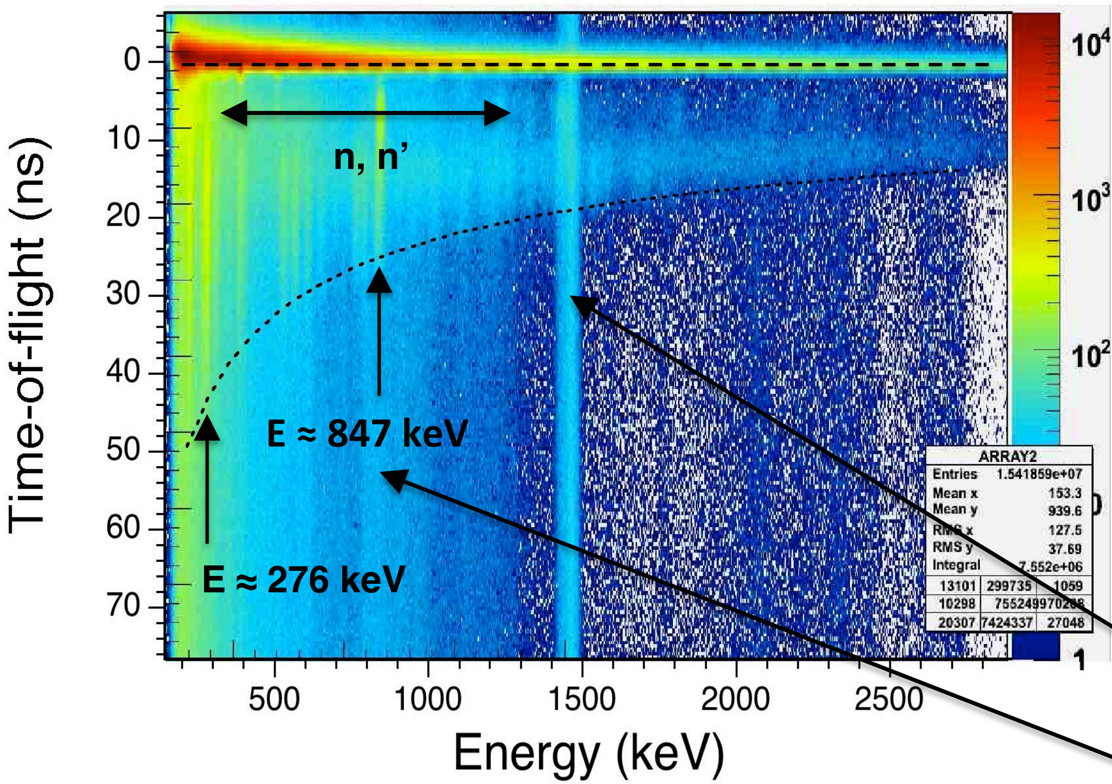
How to measure prompt fission γ-rays



Prompt fission γ-rays

γ-decay after inelastic neutron scattering

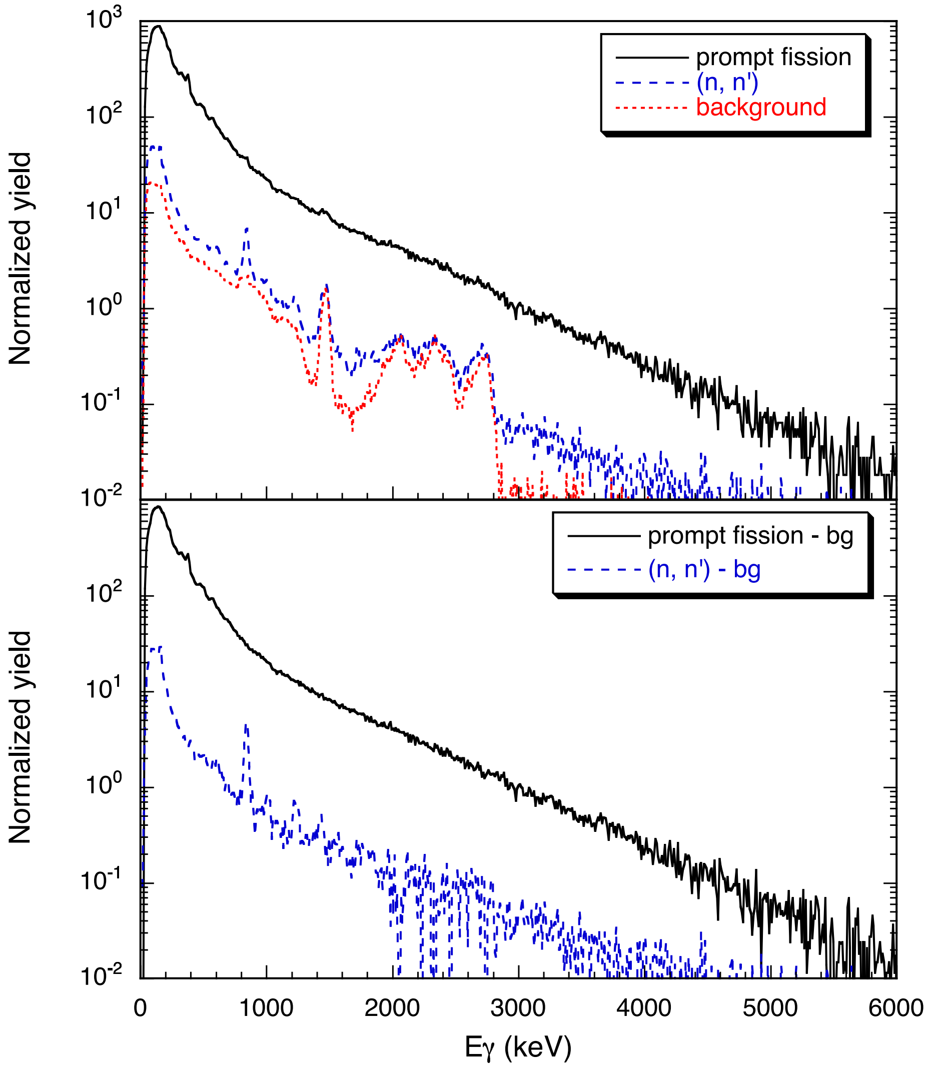
Intrinsic and external background

Photons in coincidence with fission fragments

A. Oberstedt, R. Billnert, SO et al., NIM A708 (2013) 7

European Commission

How to measure prompt fission γ-rays



$^{252}Cf(SF)$

$LaCl_3:Ce(5\%)$

A. Oberstedt et al., Nucl. Inst. Meth. A668 (2011)14-20

A. Oberstedt, SO et al., NIM A668 (2012) 14

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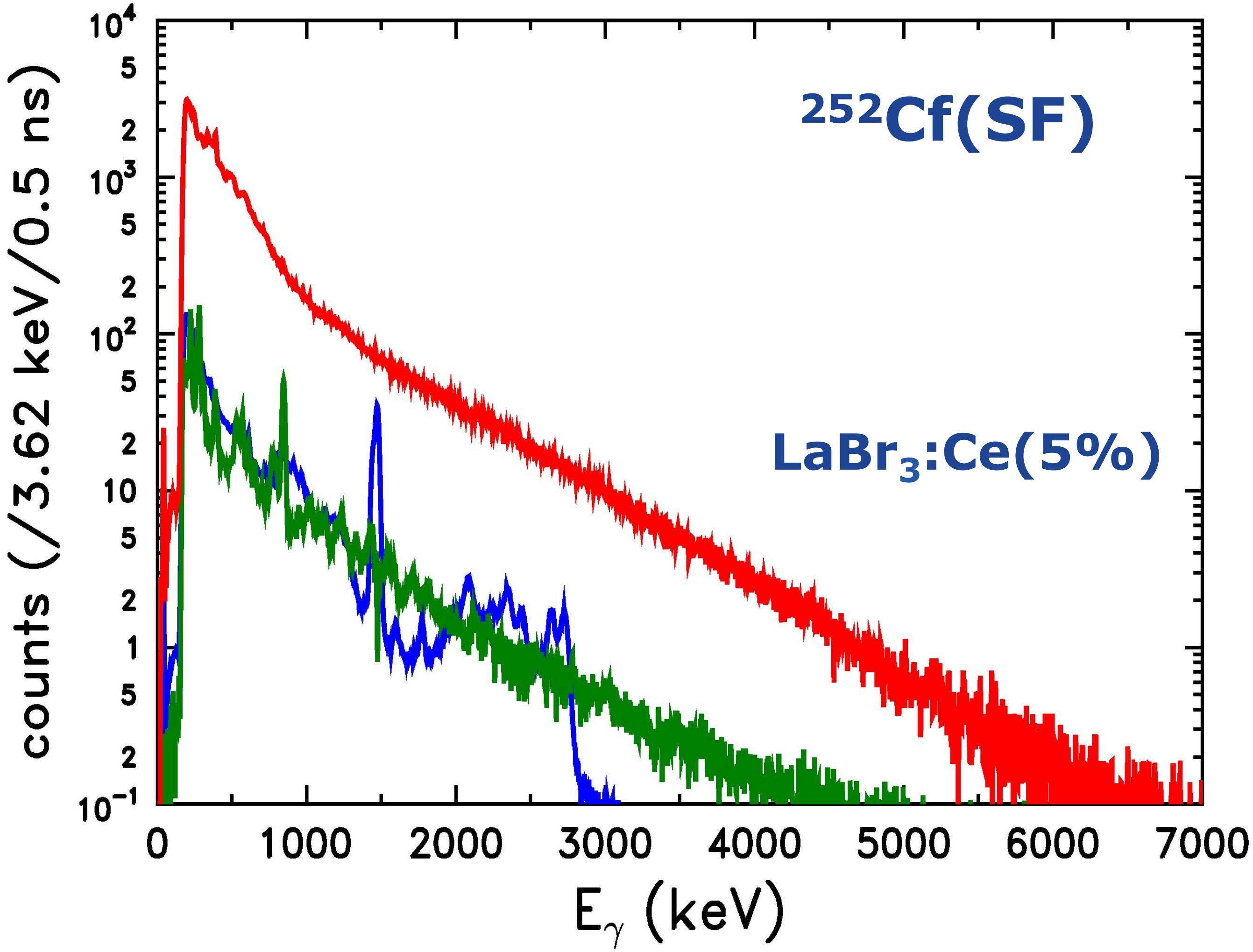
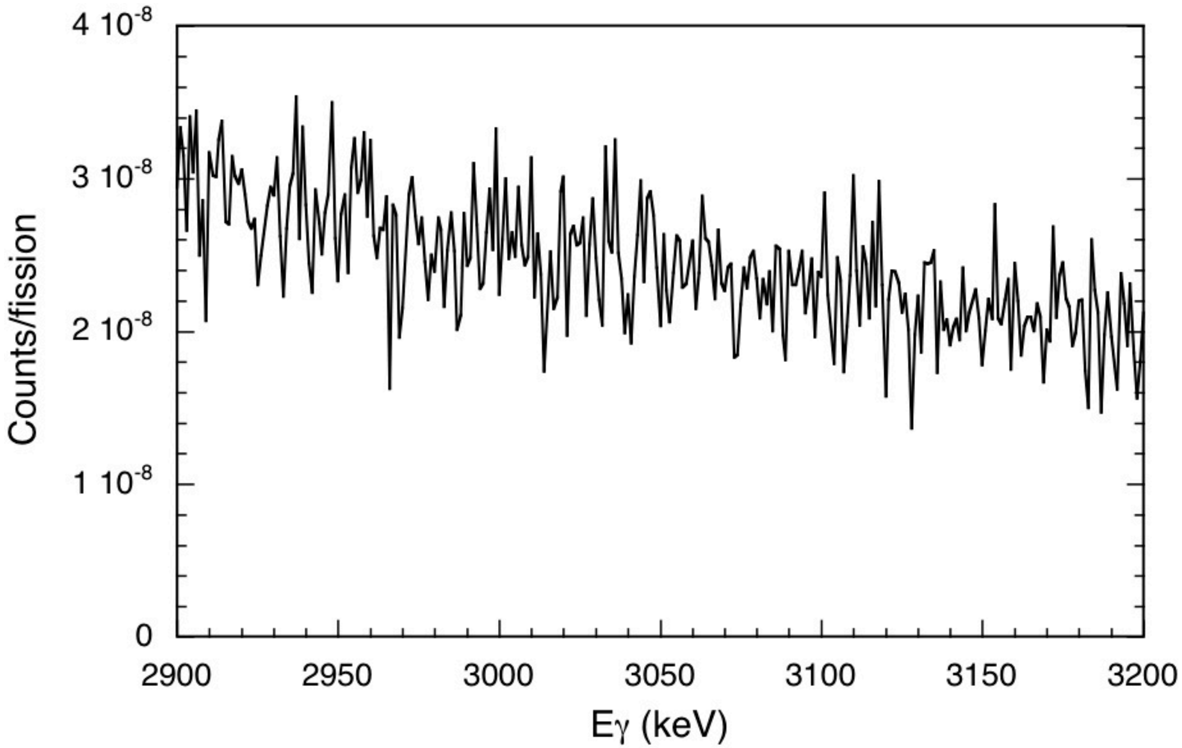
How to measure prompt fission γ-rays



European Commission

How to measure prompt fission γ-rays

➢ **Unfolding the detector response**



Measured ^{252}Cf(SF) prompt fission γ-ray energy spectrum

→ e.g. zooming into region around 3 MeV

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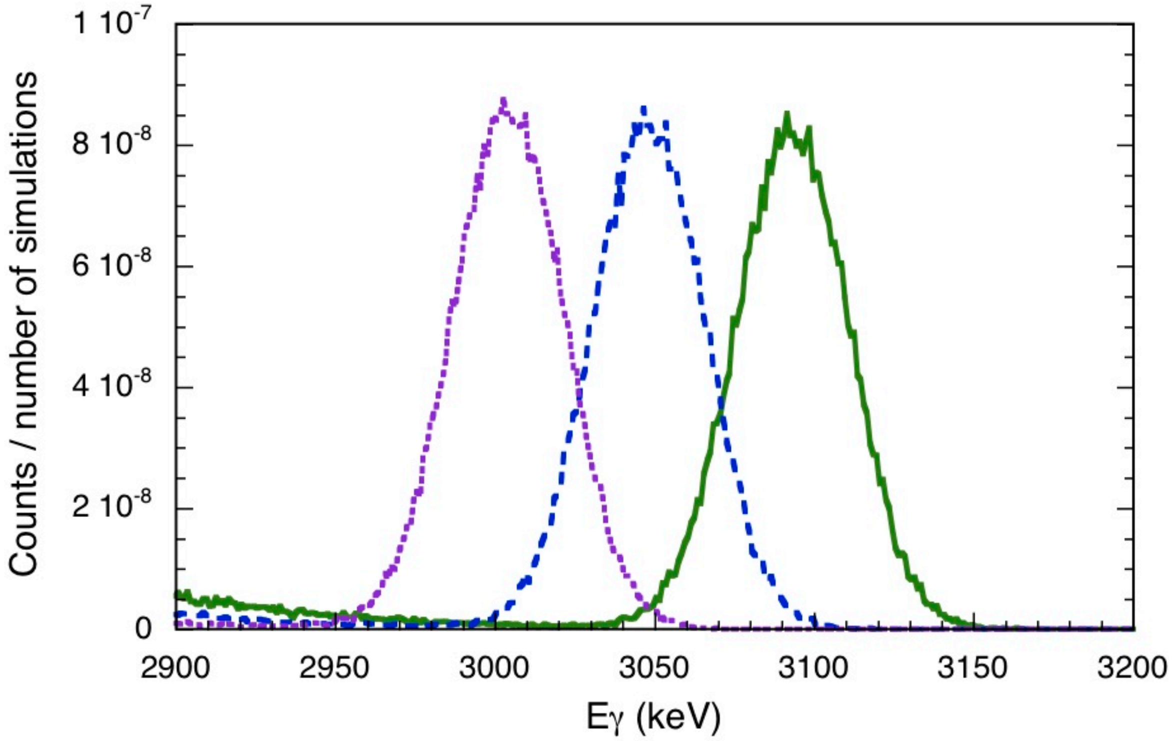
How to measure prompt fission γ-rays

➢ Unfolding the detector response



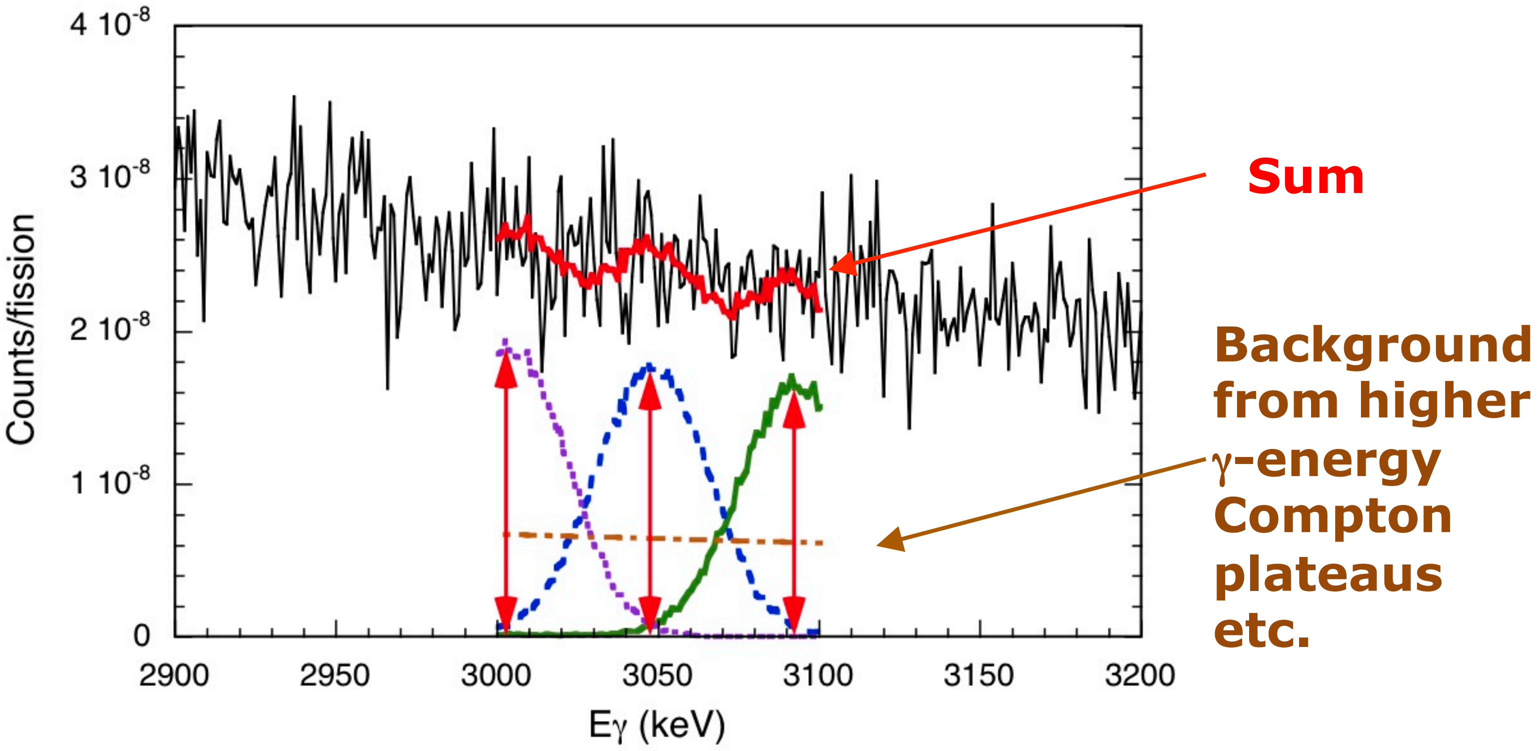
Simulating response function for mono-energetic γ-rays,

distance: FWHM from energy resolution measurements

European Commission

How to measure prompt fission γ-rays

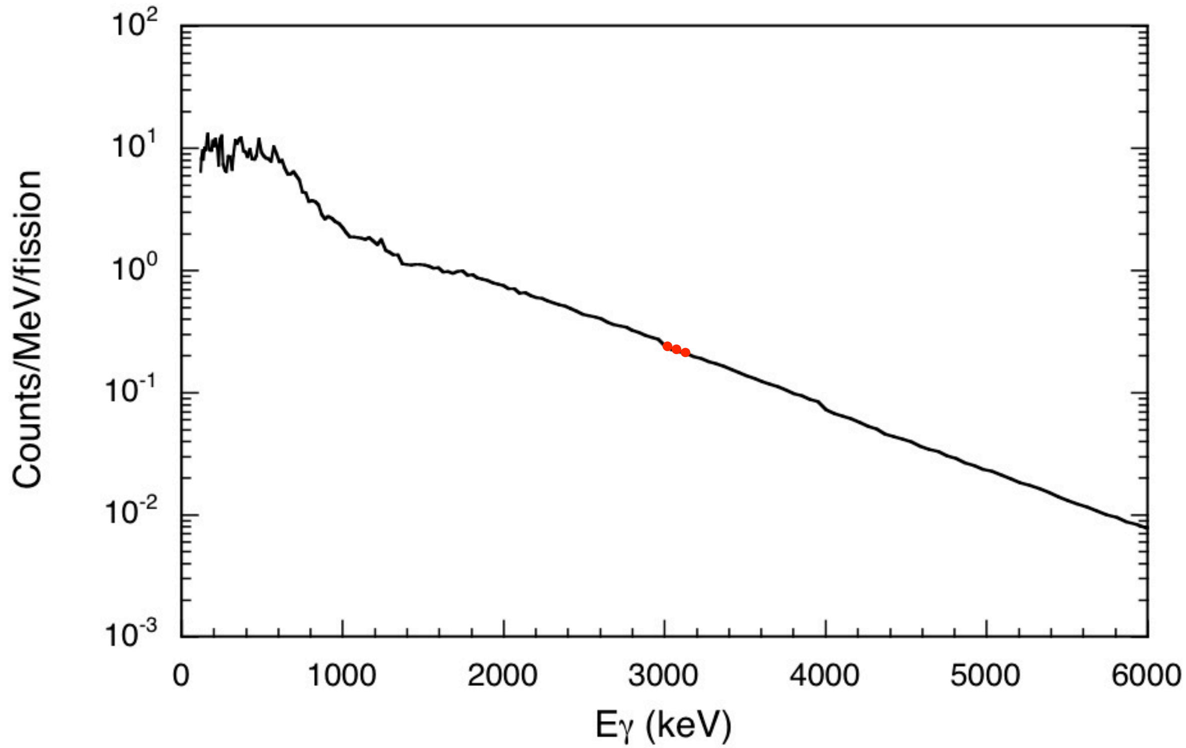
➢ **Unfolding the detector response**



Adjusting simulated spectra to measured γ-ray spectrum and determining the scaling factors

How to measure prompt fission γ-rays

➢ Unfolding the detector response

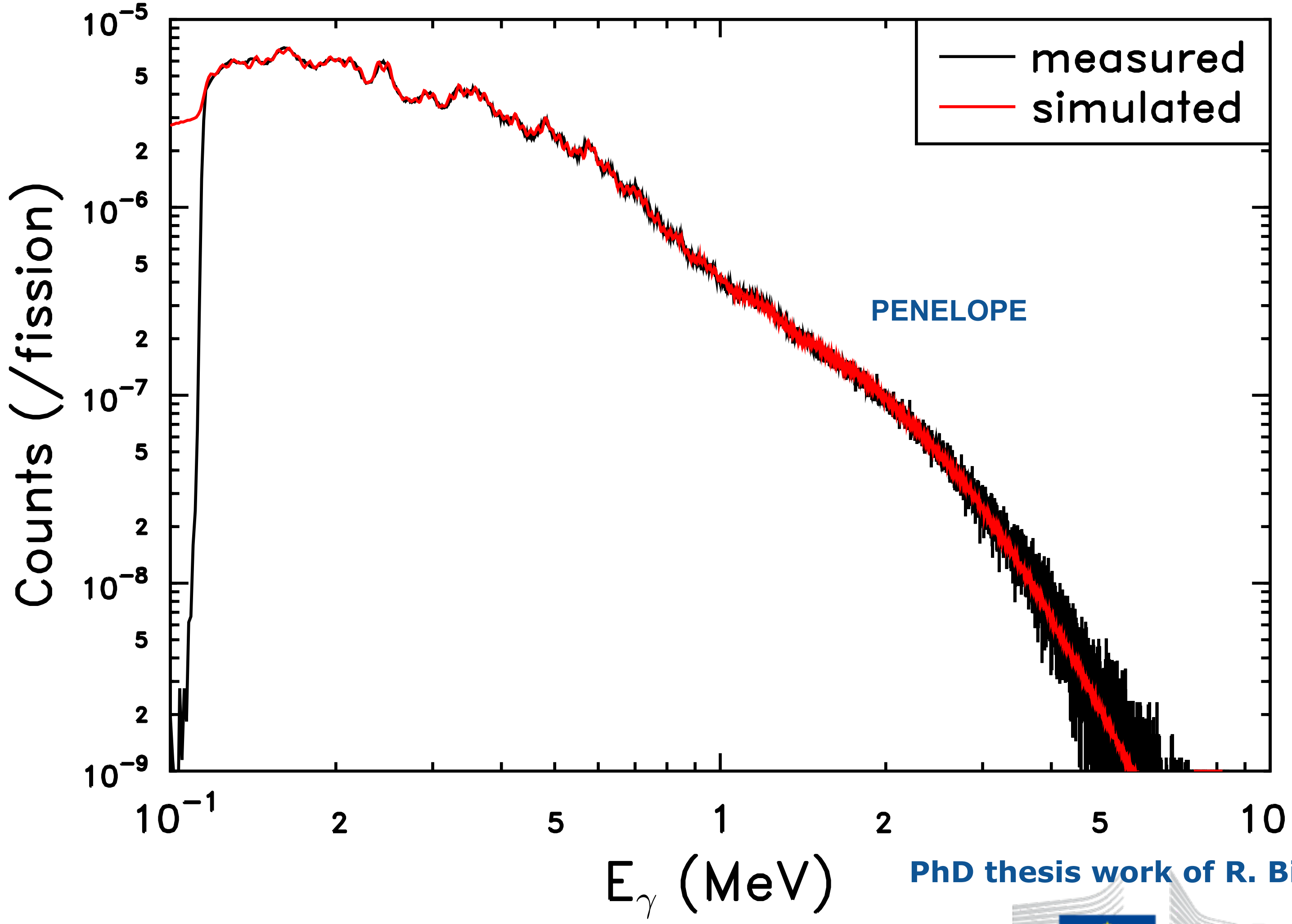


Properly normalized scaling factors

→ emission spectrum!

How to measure prompt fission γ-rays

➢ Unfolding the detector response

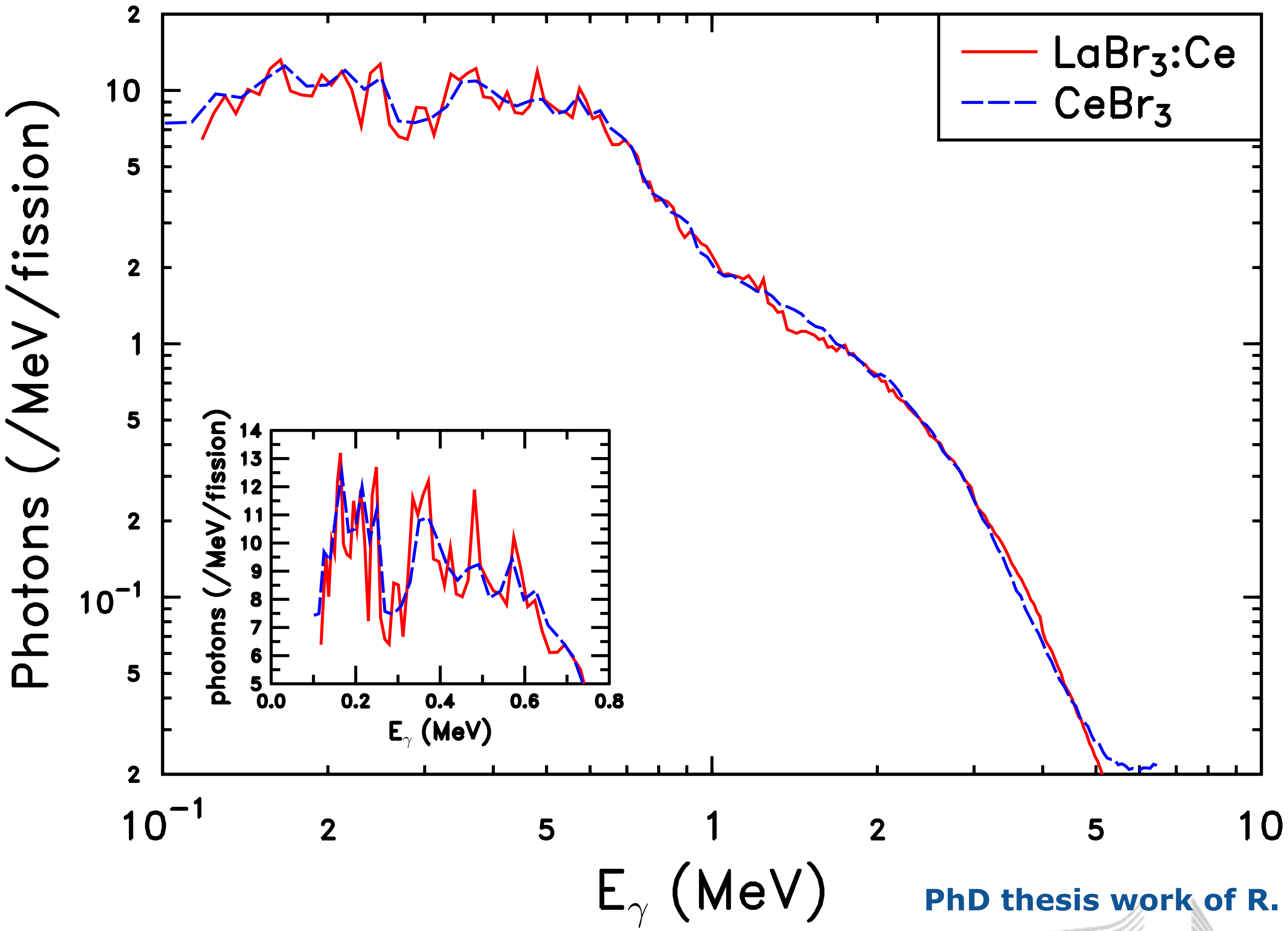


PhD thesis work of R. Billnert

R. Billnert, A. Oberstedt, SO et al., Phys. Rev. C87, 024601 (2013)

How to measure prompt fission γ-rays

- Et voilà, the emission spectrum



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R. Billnert, A. Oberstedt, SO et al., Phys. Rev. C87, 024601 (2013)

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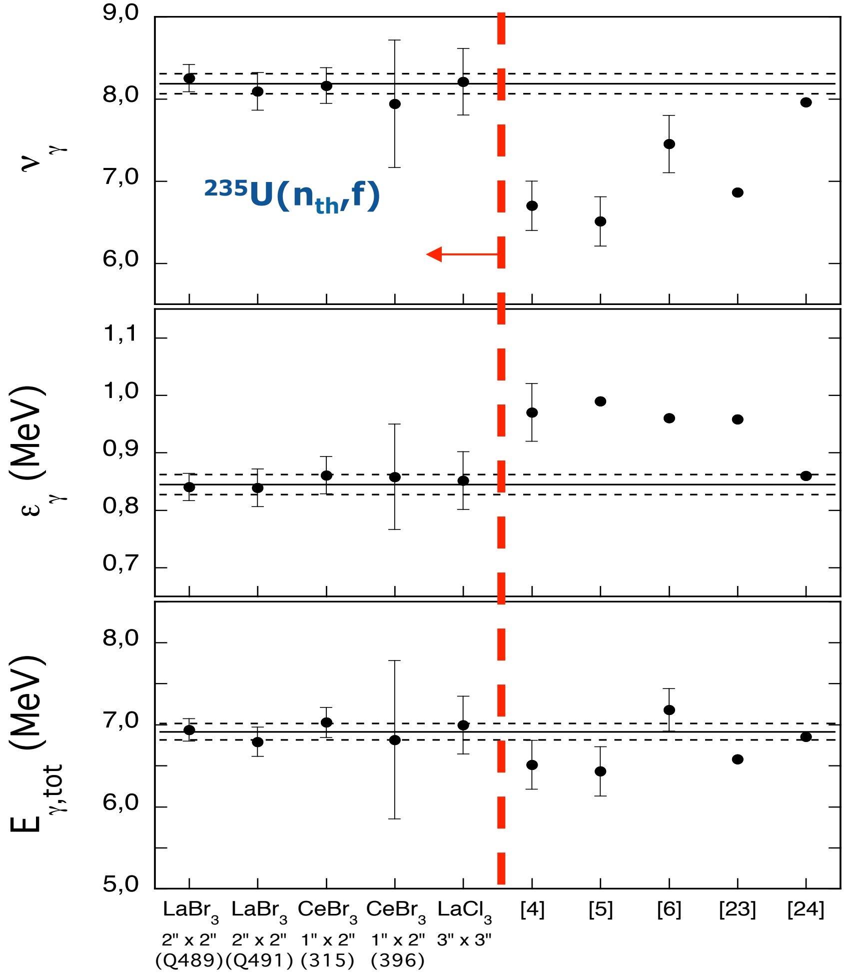

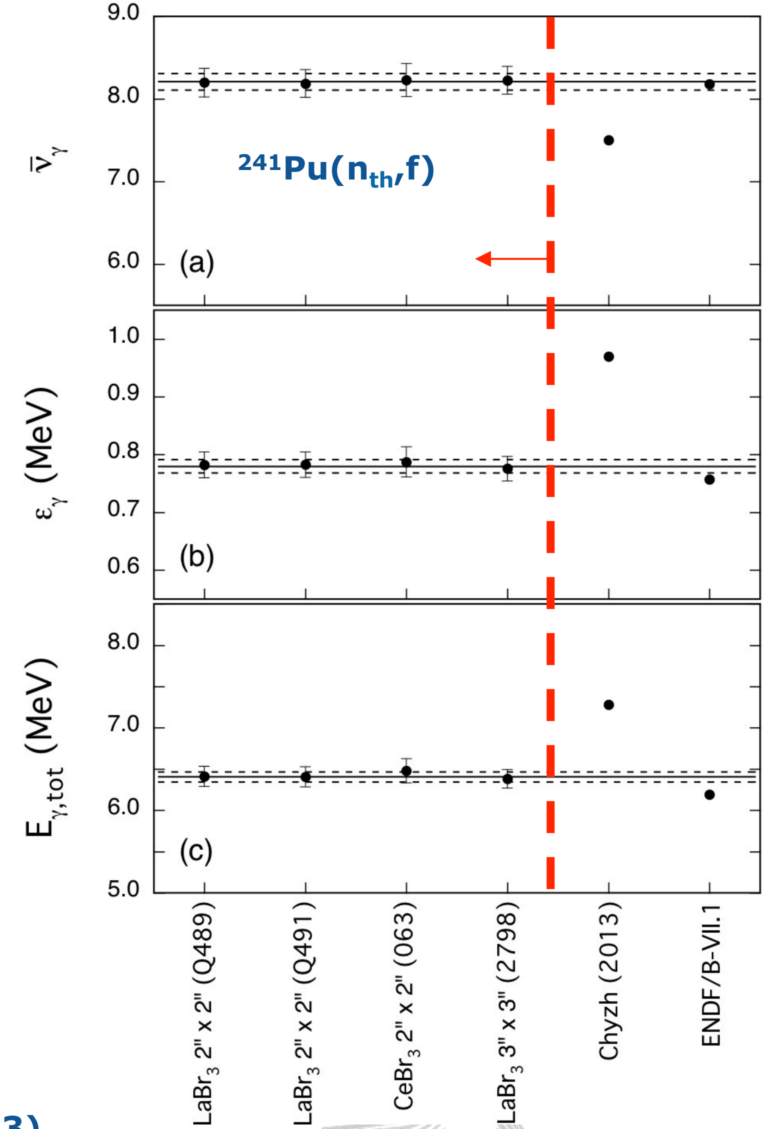

PhD thesis work of R. Billnert
A. Oberstedt et al., Phys. Rev. C 87, 051602 (2013)
S. Oberstedt et al., Phys. Rev. C 90, 024618 (2014)

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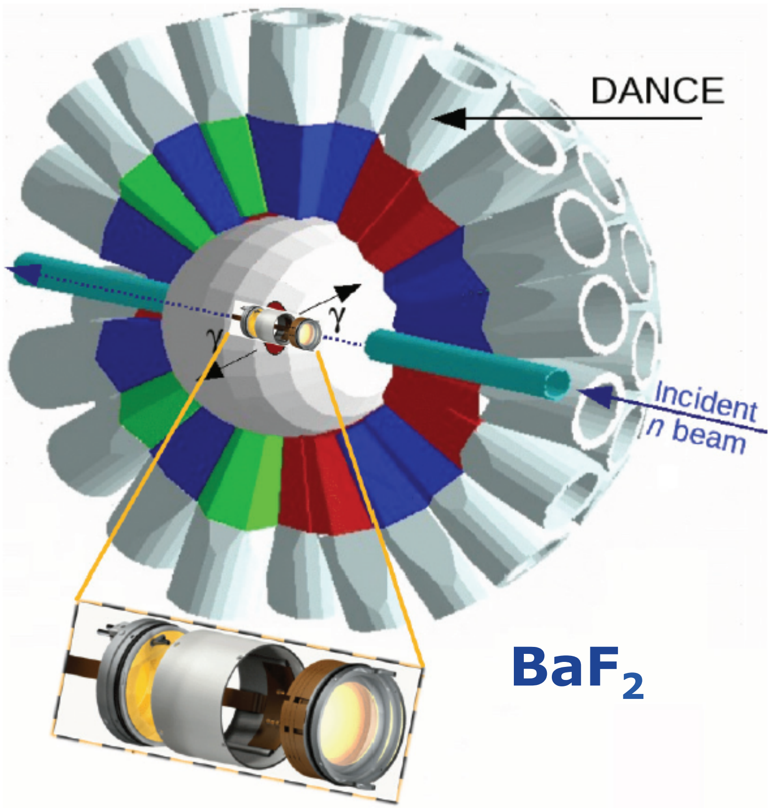
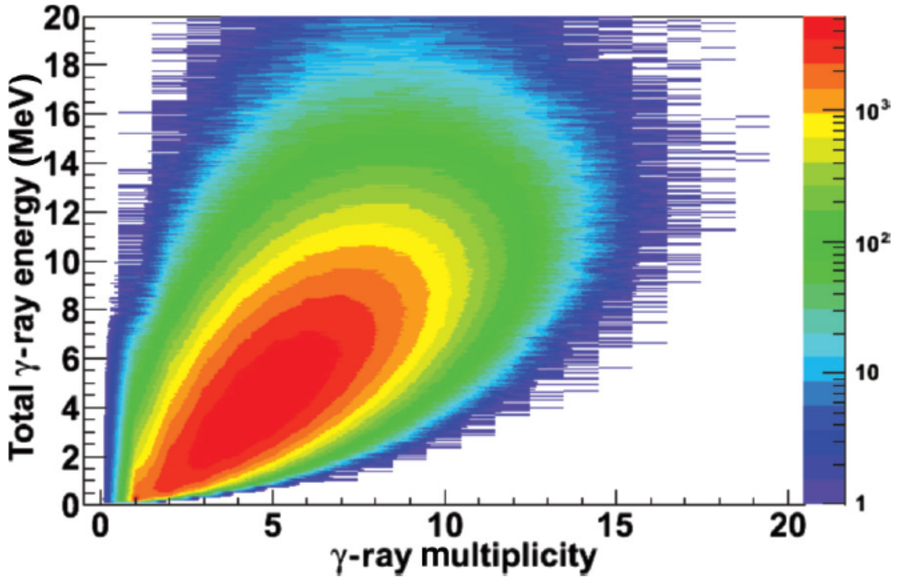
- **Other observables, as $Y(E_{tot})$, $Y(M_\gamma)$:**
  - **Calorimeter (LS tank, 4π array detector array)**





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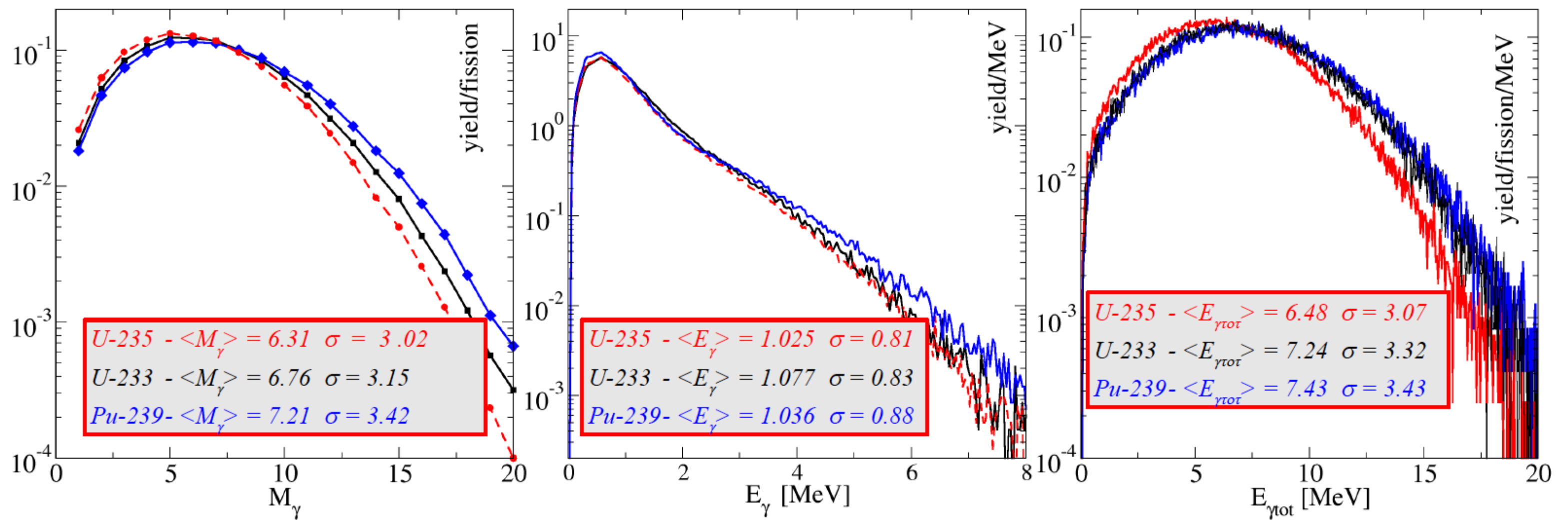
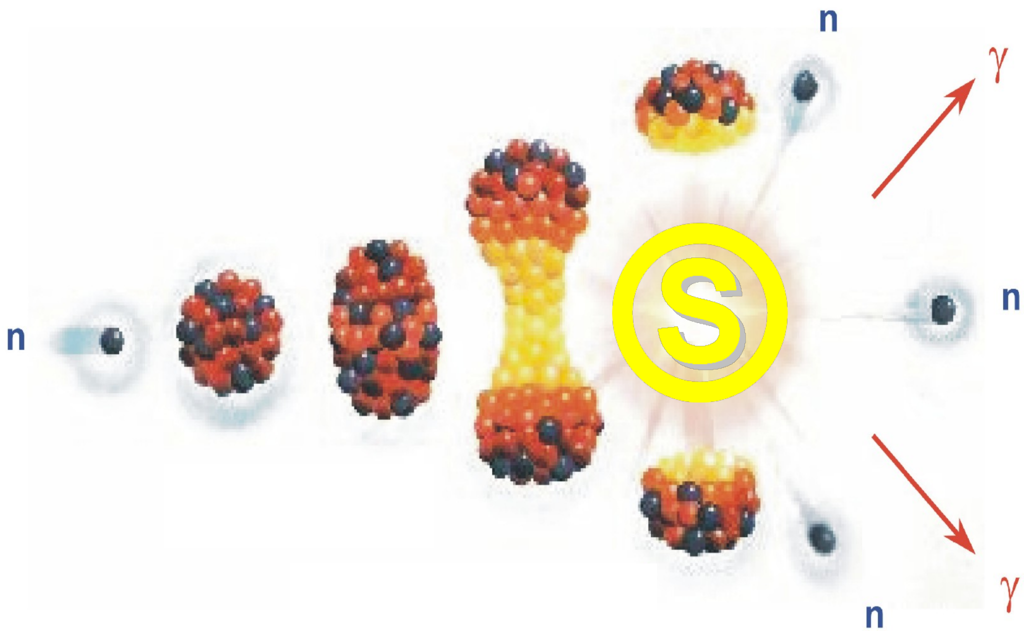


Thank you very much for Your attention



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Literature

Experimental data, measurement techniques

- "The Nuclear Fission Process", C. Wageman (ed.), CRC Press (1991), ISBN 0-8493-5434-X
- H.J. Krappe, K. Pomorski, Lecture Notes in Physics 838, Springer (2012), ISBN 978-3-642-23514-6
- "Fission Neutrons", N. Kornilov, Springer (2015), ISBN 978-3-319-07132-9
- "Practigal Gamma-ray spectroscopy", 2nd edition, G. Gilmore, Wiley (2008), ISBN 978-0-470-86196-7
- H. Nifenecker, C. Signarbieux, R. Babinet, J. Poitou, Phys. and Chem. of Fission 1973, Vol. II, Proc. of a Symp., Rochester, New York, 13 - 17 August 1973, IAEA, Vienna, STI/PUB/347 (1974) 117
- R. Capote et al, Nucl. Dt. Sheets (2016) in press
- C. Budtz-Jorgensen and H.-H. Knitter, Nucl. Phys. A490, 307 (1988)
- F.-J. Hambsch, H. H. Knitter, C. Budtz-Jørgensen, and J. P. Theobald, Nucl. Phys. A491, 56 (1989)
- F.-J. Hambsch, I. Ruskov, and L. Dematte, in Proc. Scientific Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gamma Rays (Theory-1), EUR 24802 (Sinaia, Romania, 2011) 41
- N.V. Kornilov, I. Fabry, S. Oberstedt, F.-J. Hambsch, NIM A599 (2009) 226
- N. V. Kornilov et al., Nucl. Sci. Eng. 165, 117 (2010)
- R. E. Howe, T. W. Phillips, and C. D. Bowman, Phys. Rev. C13, 195 (1976)
- A. Al-Adili, F.-J. Hambsch, S. Pomp, and S. Oberstedt, Phys. Rev. C86, 054601 (2012)
- V. Dushin et al., Nucl. Instrum. Methods Phys. Res., Sect. A516, 539 (2004)
- R. Walsh and J. Boldeman, Nucl. Phys. A276, 189 (1977)
- V. Zakharova and D. Ryazanov, Sov. J. Nucl. Phys. 30, 19 (1979)
- C. Signarbieux, J. Poitou, M. Ribarg, and J. Matuszek, Phys. Lett. B39, 503 (1972)

Literature

Experimental data, measurement techniques

- J. Frehaut, D. Shackleton, Phys. and Chem. of Fission 1973, Vol. II, Proc. of a Symp., Rochester, New York, 13-17 August 1973, IAEA, Vienna, STI/PUB/347 (1974) 201
- J. Frehaut, INDC(NDS)-220 (1989) 99
- Pleasonton, F., Ferguson, R.L., Schmitt, H.W., Physics Review C6 (3), 1023 (1972)
- Pleasonton, F., Physics Review A213 (2), 413 (1973)
- V. V.Verbinski, H. Weber, and R. E. Sund, Phys. Rev. C7 (1973) 1173
- H. van der Ploeg, C.R. Laurens, J.C.S. Bacelar, T. van der Berg, V.E. Iacob, J.R. Jongman, and A. van der Woude, Phys. Rev. Lett. 68 (1992) 3145; 69 (1992) 1148(E)
- H. van der Ploeg, J.C.S. Bacelar, A. Buda, C.R. Laurens and A. van der Woude, Phys. Rev. C 52 (1995) 1915
- T.E. Valentine, Ann. Nucl. Energy 28 (2001) 191
- R. Billnert, F.-J. Hambsch, A. Oberstedt, and S. Oberstedt, Phys. Rev. C 87, 024601 (2013).
- A. Oberstedt, T. Belgya, R. Billnert, R. Borcea, T. Brys, W. Geerts, A. G o ok, F.-J. Hambsch, Z. Kis, T. Martinez, S. Oberstedt, L. Szentmiklosi, K. Takacs, and M. Vidali, Phys. Rev. C 87, 051602(R), 2013.
- S. Oberstedt, R. Billnert, T. Belgya, T. Brys, W. Geerts, C. Guerrero, F.-J. Hambsch, Z. Kis, A. Moens, A. Oberstedt, G. Sibbens, L. Szentmiklosi, D. Vanleeuw, and M. Vidali, Phys. Rev C 90, 024618 (2014)
- M. Heil, R. Reifarth, M.M. Fowler, R.C. Haight, F. Käppeler, R.S. Rundberg, E.H. Seabury, J.L. Ullmann, J.B. Wilhelmy, K. Wisshak, Nucl. Instr. and Meth. A 459 (2001) 229
- A. Sardet, C. Varignon, B. Laurent, T. Granier, A. Oberstedt, NIM A792 (2015) 74

Literature

Theory and Modelling:

- W. Mannhart, in Proceedings of an Advisory Group Meeting on Properties of Neutron Sources Organized by the International Atomic Energy Agency and Held in Leningrad, USSR, 9–13 June 1986 (IAEA, Vienna, 1987) 158
- B. Becker, P. Talou, T. Kawano, Y. Danon, and I. Stetcu, Phys. Rev. C 87, 014617 (2013).
- P. Talou, I. Stetcu, T. Kawano, Phys. Proc. 59 (2014) 83.
- P. Talou, T. Kaweno, I. Stetcu, R. Vogt, J. Randrup, Nucl. Dt. Sheets 118 (2014) 227.
- I. Stetcu, P. Talou, T. Kawano, and M. Jandel, Phys. Rev. C 90, 024617 (2014).
- R. Vogt, J. Randrup, Phys. Proc. 47 (2013) 3.
- R. Vogt, J. Randrup, Nucl. Dt. Sheets 118 (2014) 220.
- J.M. Verbeke, J. Randrup, R. Vogt, Comp. Phys. Comm. (2015) 191 (2015) 178.
- D. Regnier, O. Litaize, O. Serot, Phys. Proc. 59 (2012) 59.
- D. Regnier, Phys. Proc. 47 (2013) 47.
- O. Litaize, D. Regnier, O. Serot, Phys. Proc. 59 (2014) 89.
- O. Serot, O. Litaize, D. Regnier, Phys. Proc. 59 (2014) 132.
- A. Tudora, F.-J. Hambsch, S. Oberstedt, C. Manailescu, Phys. Proc. 31 (2012) 43.
- A. Tudora, F.-J. Hambsch, S. Oberstedt, G. Giubega, I. Visan, Phys. Proc. 59 (2014) 95.
- K.-H. Schmidt, OECD/NEA, JEF/DOC 1398 (2012).
- K.-H. Schmidt and B. Jurado, OECD/NEA, JEF/DOC 1423 (2012).
- K.-H. Schmidt, B. Jurado, Ch. Amouroux, JEFF-Report Data Bank, Nuclear-Energy Agency, OECD (2015).