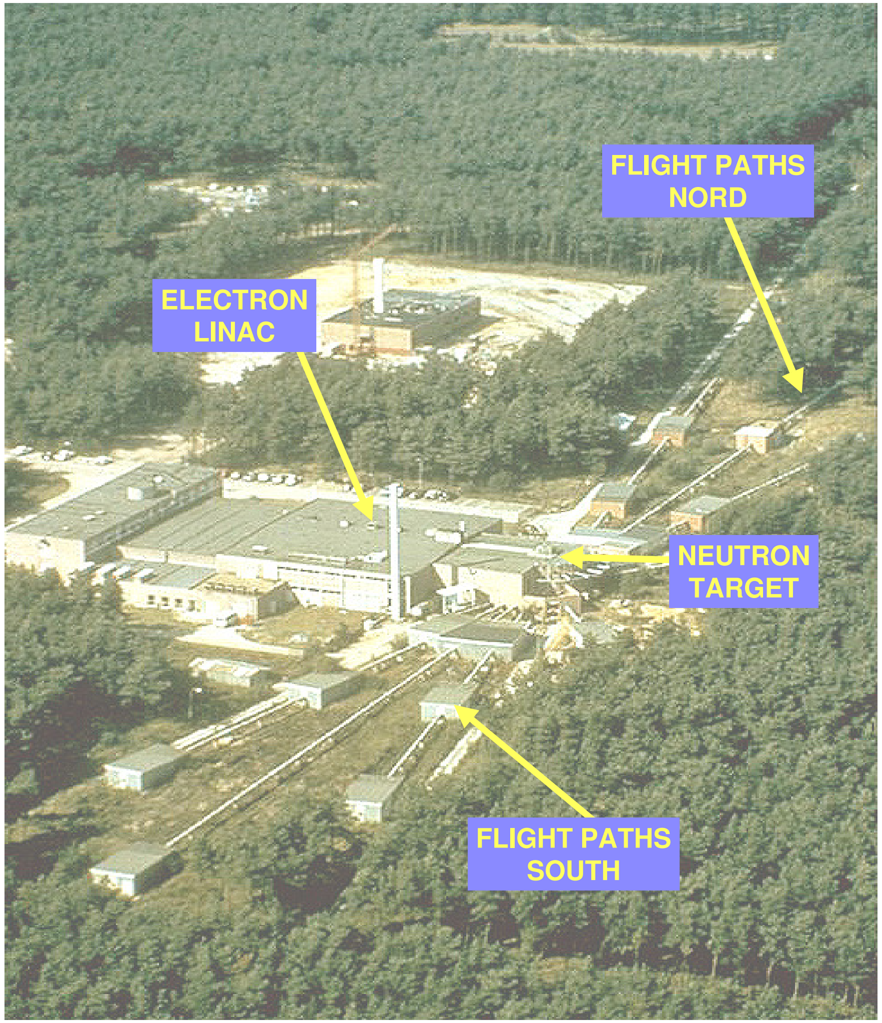
Capture cross section measurements for ^{197}Au at GELINA from 5 – 80 keV

C. Lampoudis, S. Kopecky, C. Massimi,

M. Moxon and P. Schillebeeckx

Joint Research Centre (JRC)
IRMM - Institute for Reference Materials and Measurements
Geel - Belgium
http://irmm.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

GELINA



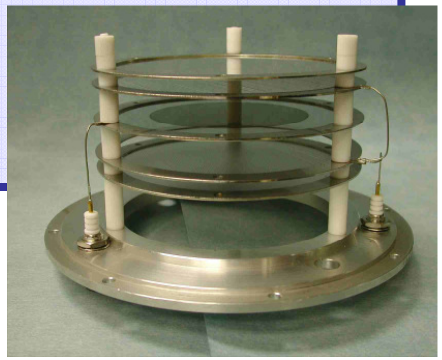
- **Time-of-flight facility**
- **Pulsed white neutron source**
  (1 meV < E_n < 20 MeV)
- **Multi-user facility with 10 flight paths (10 m - 400 m)**
- **The measurement stations have special equipment to perform:**
  - Total cross section measurements
  - Partial cross section measurements

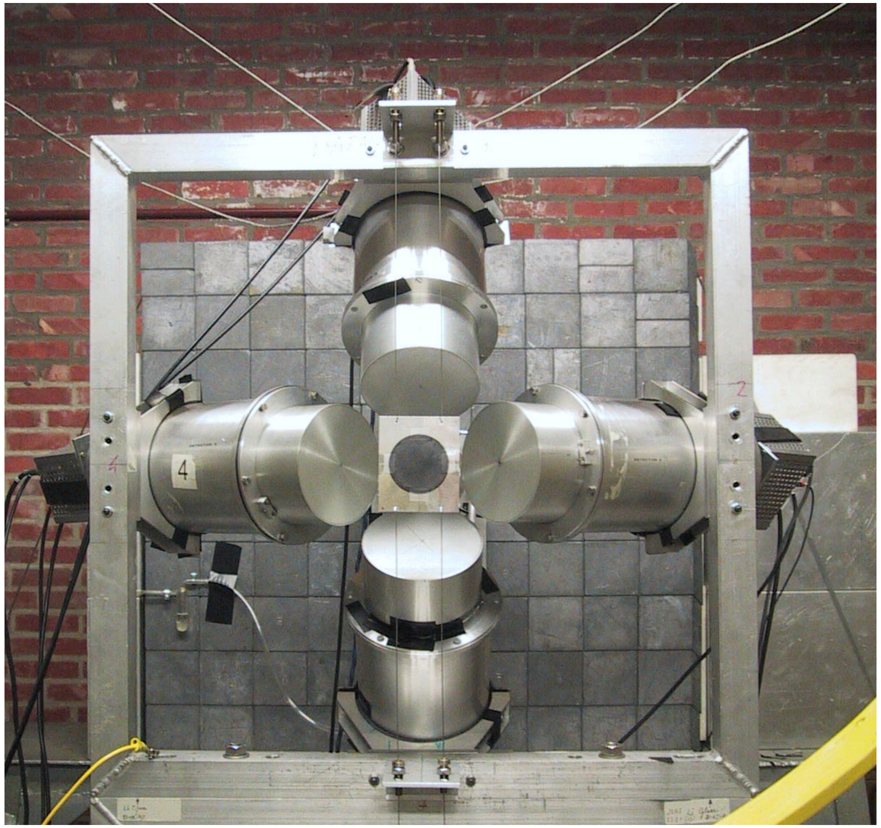
Pulse Width	**: 1ns**		
Frequency	**: 50 Hz**	**–**	**800 Hz**
Average Current	**: 4.7 μA**	**–**	**75 μA**
Neutron intensity	**: 1.6 10^{12} n/s**	**–**	**2.5 10^{13} n/s**

Capture cross section measurements

Total energy detection

- **Flux measurements (IC)**
  - $^{10}B(n,\alpha)$
- **C_6D_6 liquid scintillators**
  - 125°
  - PHWT





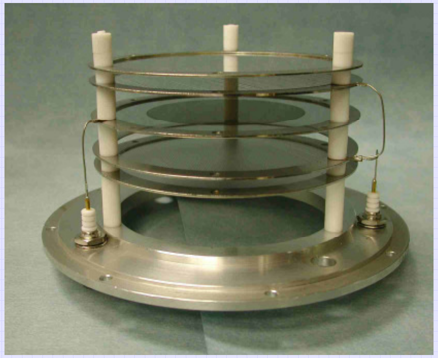
$$Y_{exp} = N_Y \frac{\sigma_\varphi}{\varepsilon_c} \frac{C'_w - B'_w}{C'_\varphi - B'_\varphi}$$

WF : from MC simulations

$$C'_n(T_n) = \int C'_c(T_n, E_d)\, WF(E_d)\, dE_d$$

$$\varepsilon_c = S_n + E_n$$

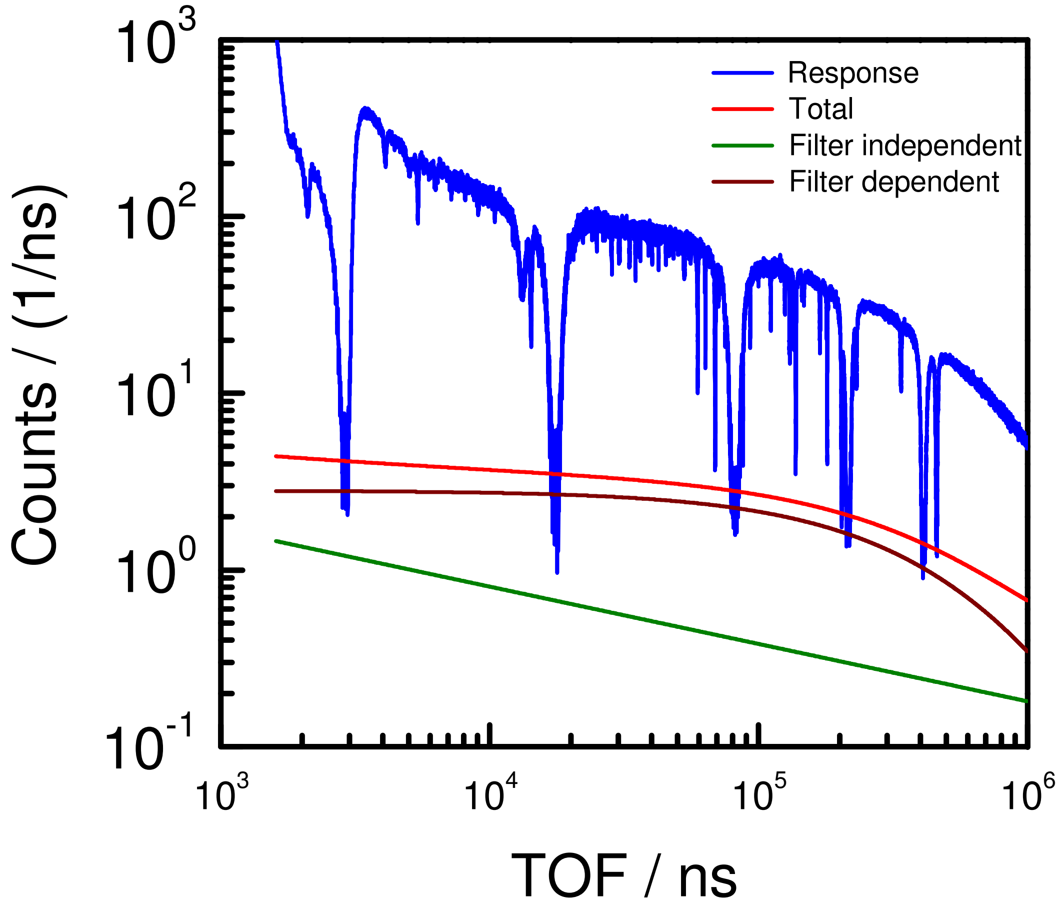
Capture measurements on ^{197}Au



- **Flux**
  - ^{10}B(n,α) to exclude impact of kinematic effects
    ⇒ Back-to-back layer : ≈ equal thickness (6 % difference)
  - Background :
    ⇒ Black resonance filters (fixed filters: S and Na)
- **Capture**
  - WF for each target-detector combination by MC-simulations
    ⇒ Validated by experiment
    ⇒ Correction for gamma-ray attenuation in target
  - Background : dedicated measurements and fixed filters (S and Na)
  - Normalization (internal)
    ⇒ Saturated resonance: 4.9 eV resonance of ^{197}Au
    ⇒ Verification by :
    Rh (1.26 eV) , Ag (5.1 eV) , Fe (1150 eV)

Flux : background

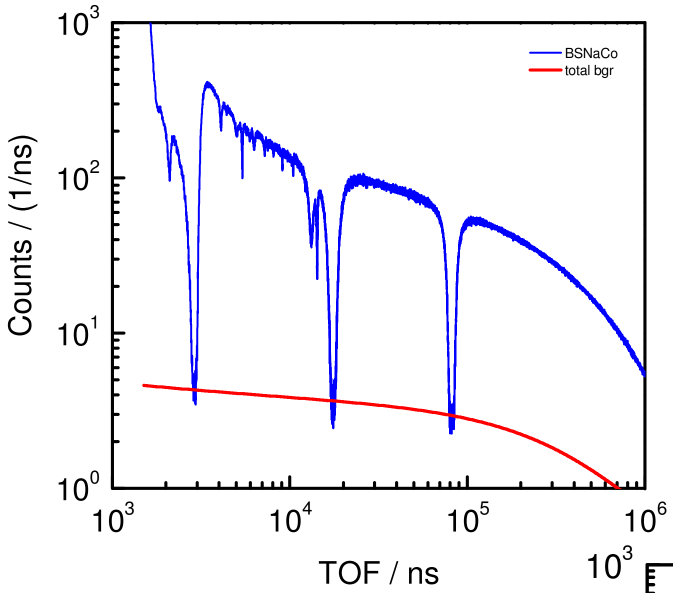
$$B_{\varphi}(t) = a_0 + a_1(t + t_0)^{c_1} + a_2 e^{-c_2 t}$$



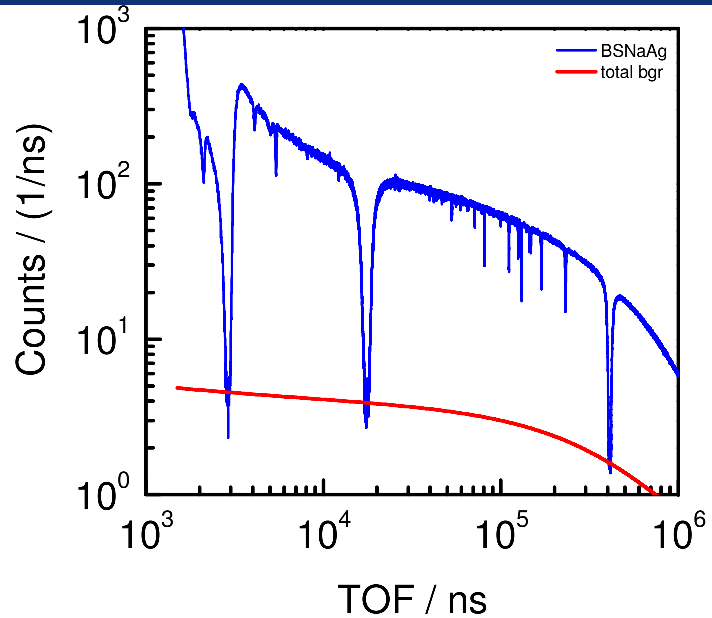
c_1 and c_2 filter independent

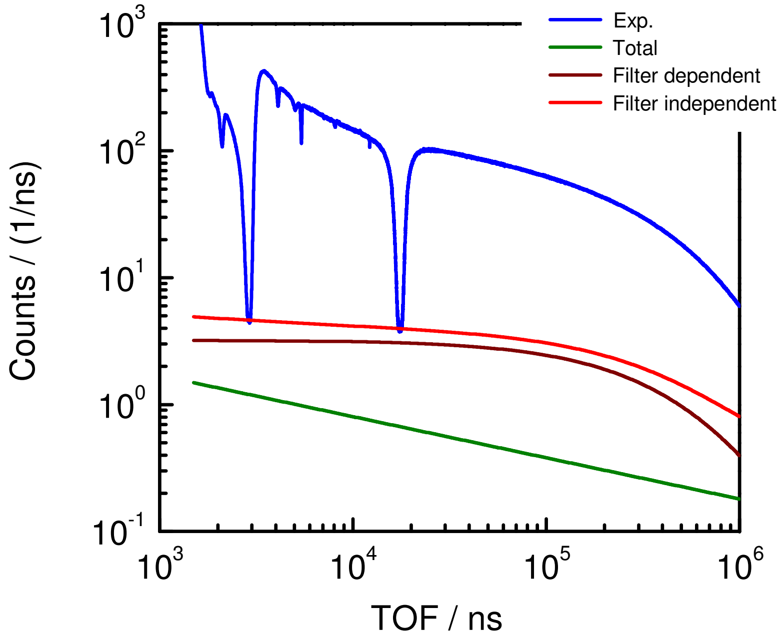
a_0 : filter independent (neglegible)
a_1 : filter independent
a_2 : filter dependent

Flux : background



$C'_{\varphi} - B'_{\varphi}$





Use of fixed background filters

$\Rightarrow \delta B'_{\varphi} / B'_{\varphi} \leq 3\%$

with

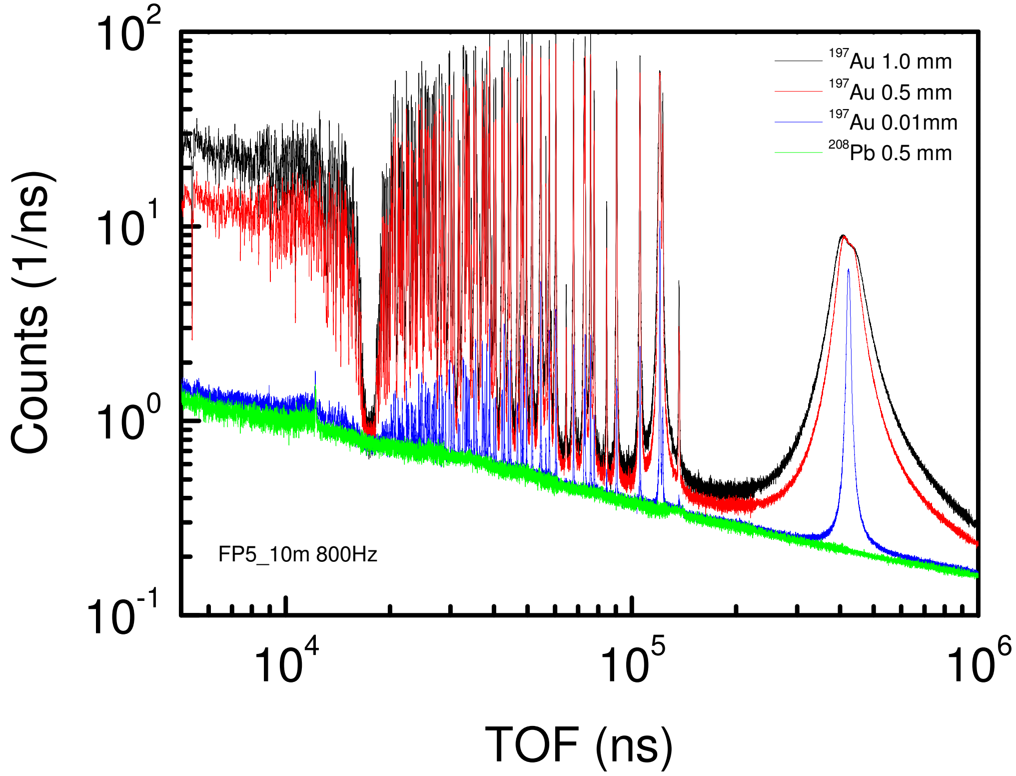
$B'_{\varphi} / C'_{\varphi} \leq 7\%$ at 5 eV

$\leq 4\%$ in URR

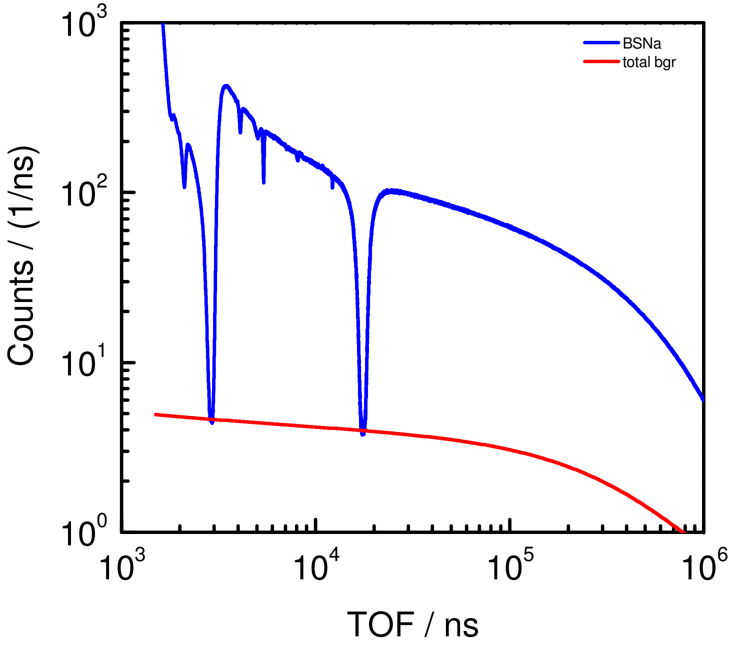
Capture : background

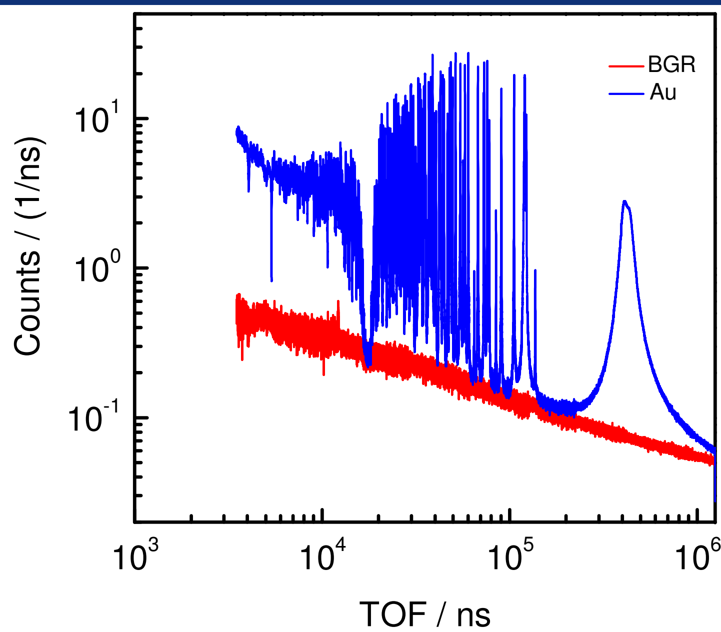
$$B_c(t) = b_0 + B_1(t) + B_2(t)$$

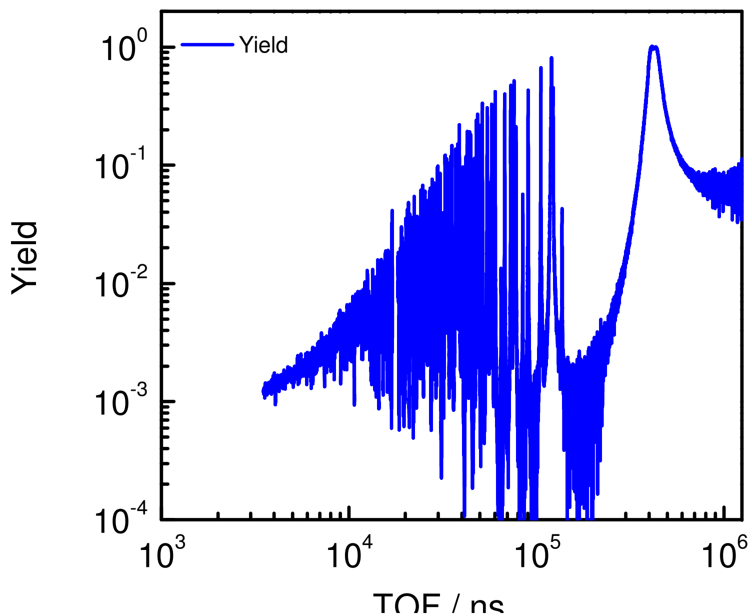
b_0 : ambient (or activity)
B_1 : sample independent without sample
B_2 : sample dependent n and γ-scattering



Use of fixed background filters
$\Rightarrow \delta B_c / B_c \leq 5\ \%$
with
$B_c / C_c \leq 2.5\ \%$ at 5 eV
$\leq 10\%$ in URR (0.5 mm)


BSNa
total bgr
Counts / (1/ns)
TOF / ns
10^3
10^2
10^1
10^0
10^4
10^5
10^6


BGR
Au
Counts / (1/ns)
TOF / ns
10^1
10^0
10^-1
10^3
10^4
10^5
10^6


Yield
Yield
TOF / ns
10^0
10^-1
10^-2
10^-3
10^-4
10^3
10^4
10^5
10^6

Normalization of capture data

- **Capture response** : $C'_w - B'_w$
- **Flux measurements (IC)** : $C'_\varphi - B'_\varphi$
  - $^{10}B(n,\alpha)$ < 150 keV
  - $^{235}U(n,f)$ > 150 keV

$$Y_{exp} = \frac{C'_w - B'_w}{C'_\varphi - B'_\varphi} \frac{\varepsilon_\varphi}{\varepsilon_r} \frac{\Omega_\varphi}{\Omega_r} \frac{A_\varphi}{A_r} \sigma_\varphi$$

$$Y_{exp} = N \frac{C'_w - B'_w}{C'_\varphi - B'_\varphi} \sigma_\varphi$$

Normalization constant N

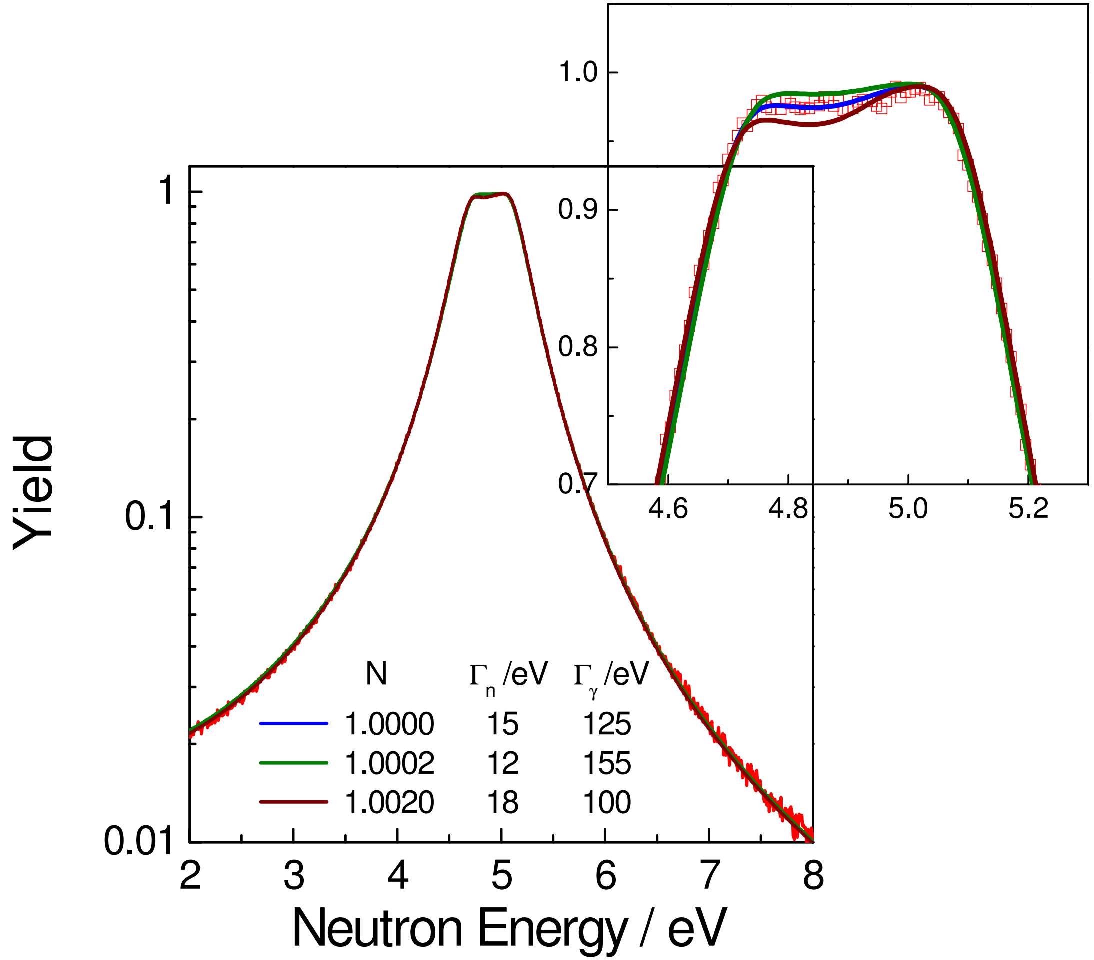
- **Saturated resonance**
  - ^{197}Au : 4.9 eV
  - ^{109}Ag : 5.2 eV
  - ....
- **Resonance with : $\Gamma_n << \Gamma_\gamma$**
  - Γ_n from transmisson
  - ^{56}Fe : 1.15 keV

Internal normalization:

⇒ Reduction of systematic effects

Borella et al., NIM A, 577 (2007) 626

Normalization: saturated resonance



$n\sigma_{tot} >> 1$ and $\sigma_\gamma \approx \sigma_{tot}$

$$Y_\gamma \cong \frac{\sigma_\gamma}{\sigma_{tot}}\left(1-e^{-n\sigma_{tot}}\right)+\ldots$$

$$Y_\gamma \cong 1$$

$$\Rightarrow N \cong \frac{C'_\varphi - B'_\varphi}{C'_w - B'_w}\,\frac{1}{\sigma_\varphi}$$

N is independent of :

- **target thickness of reference sample**
- **nuclear data**

σ_φ : only the relative energy dependence is required

$\Rightarrow {}^{10}B(n,\alpha) \sim 1/v$

$$\frac{u_{Y_{exp}}}{Y_{exp}} \leq 2\,\%$$

Correction for γ-ray attenuation in sample

Distribution of γ-rays

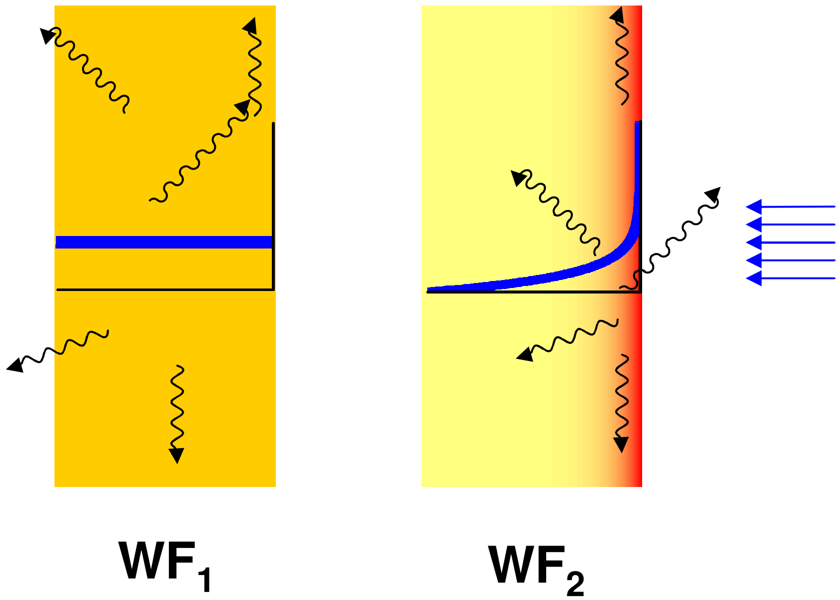
- **Weak resonance : homogeneous distr.**
- **Strong resonance : exponential**

(Affects also the observed shape)

Procedure:

(1) Apply WF_1 on experimental data

(2) Correction factor on calculated yield



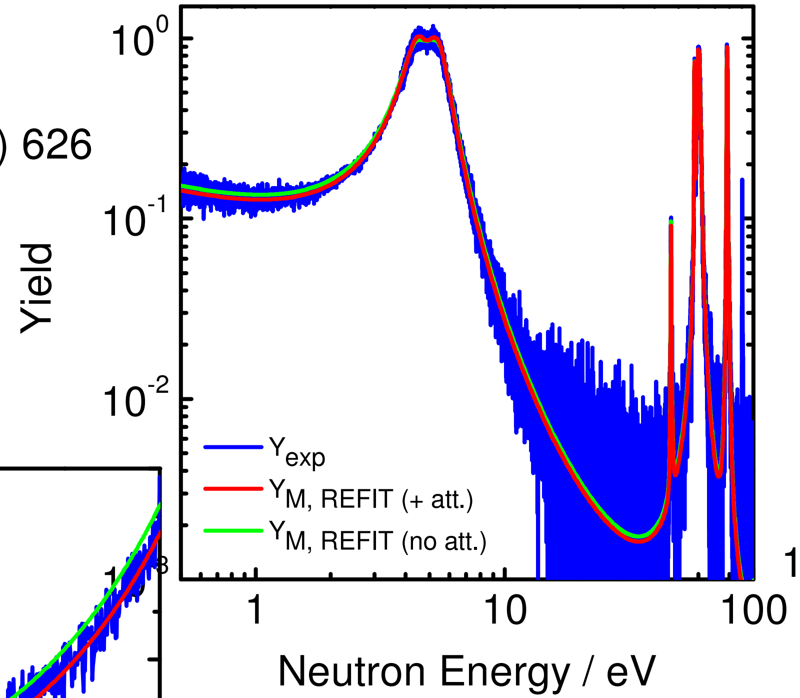
$$K_c(n\sigma_t) = \frac{< WF_1 >}{< WF_2 >}$$

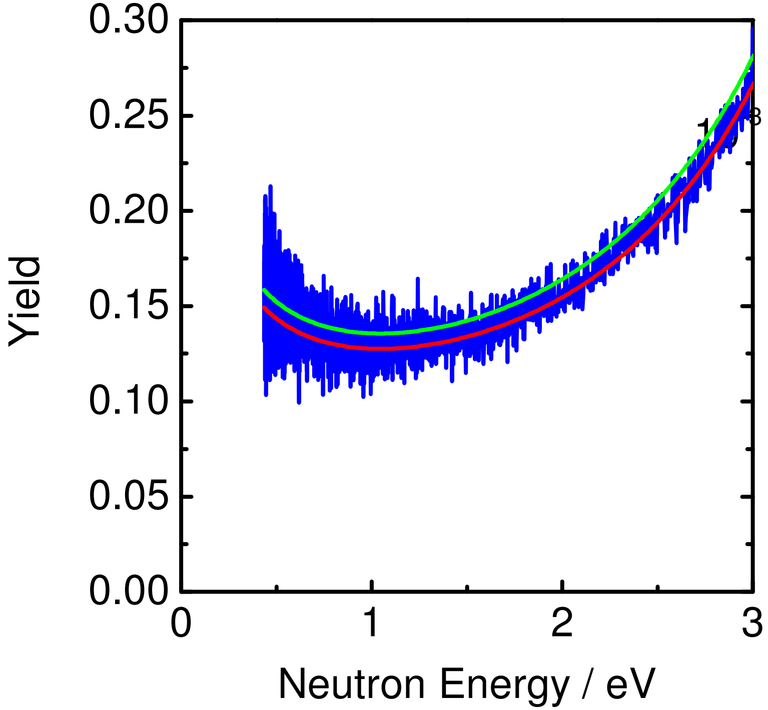
$$Y_{exp} = N \int R(\, T_n - f(E_n)\,)\,(K_c \varepsilon_c Y_c + \varepsilon_n\, Y_n)\, dE_n$$

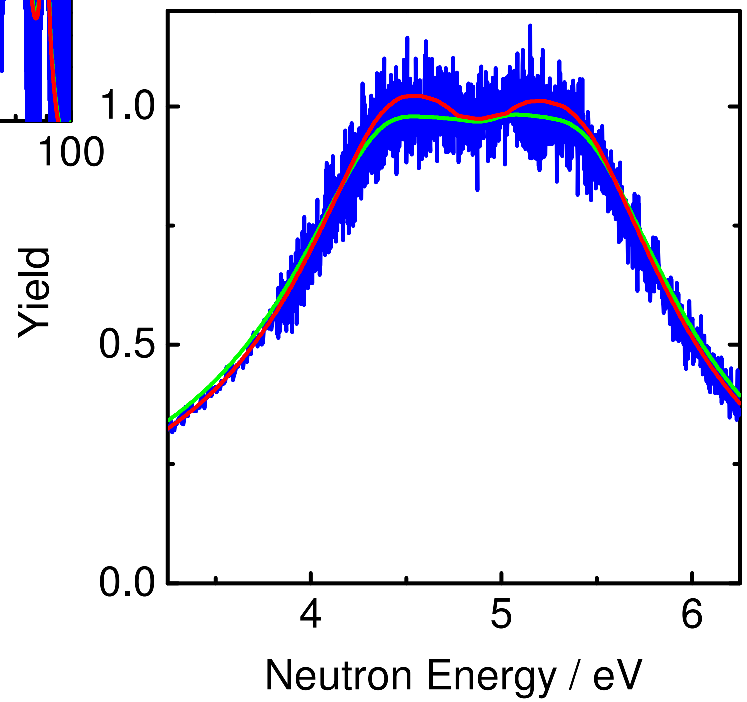
Correction for γ-attenuation in sample

Implemented in REFIT
EFNUDAT : IRMM – Moxon
Borella et al., NIMA 577 (2007) 626

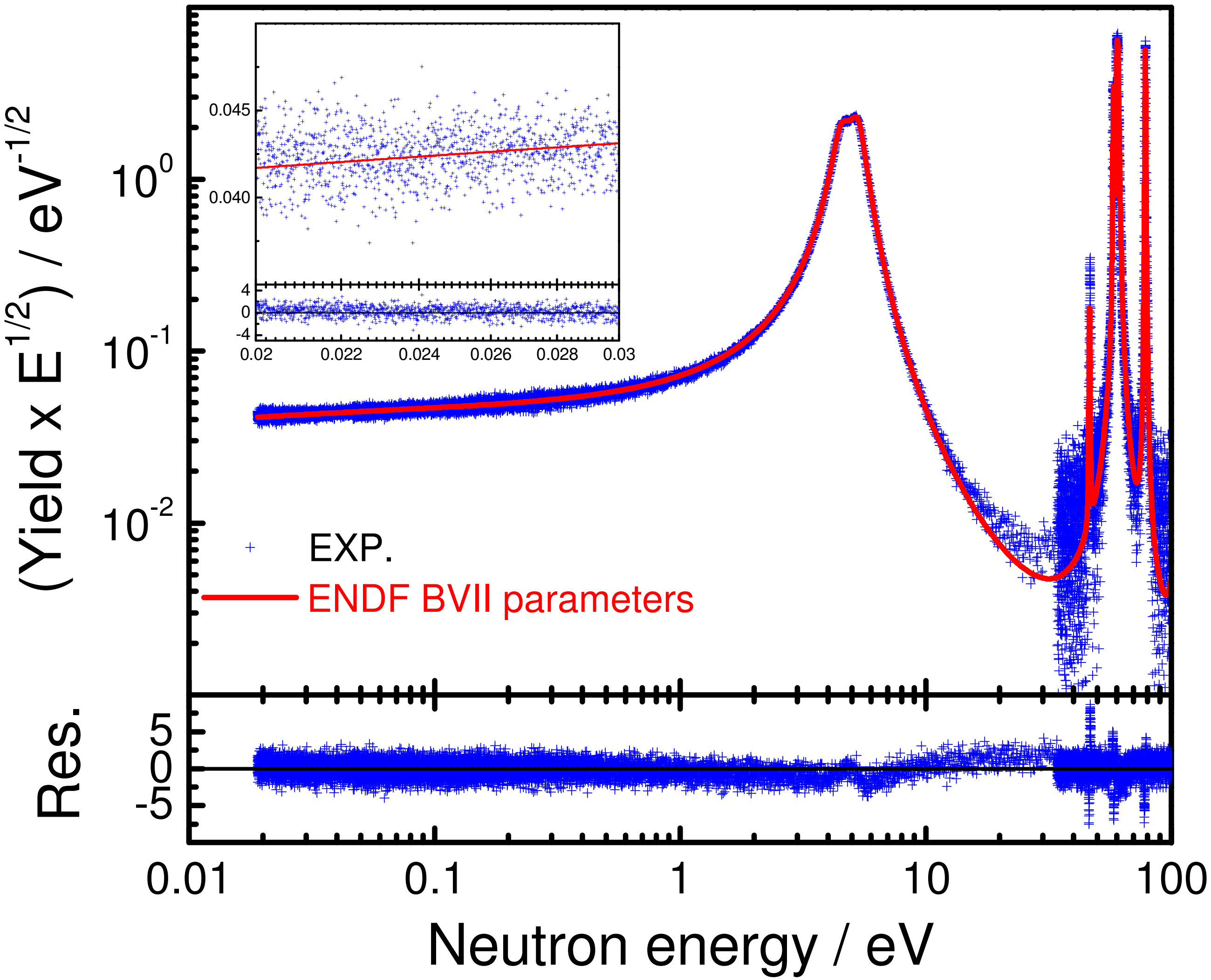
^{197}Au + n
4.9 eV



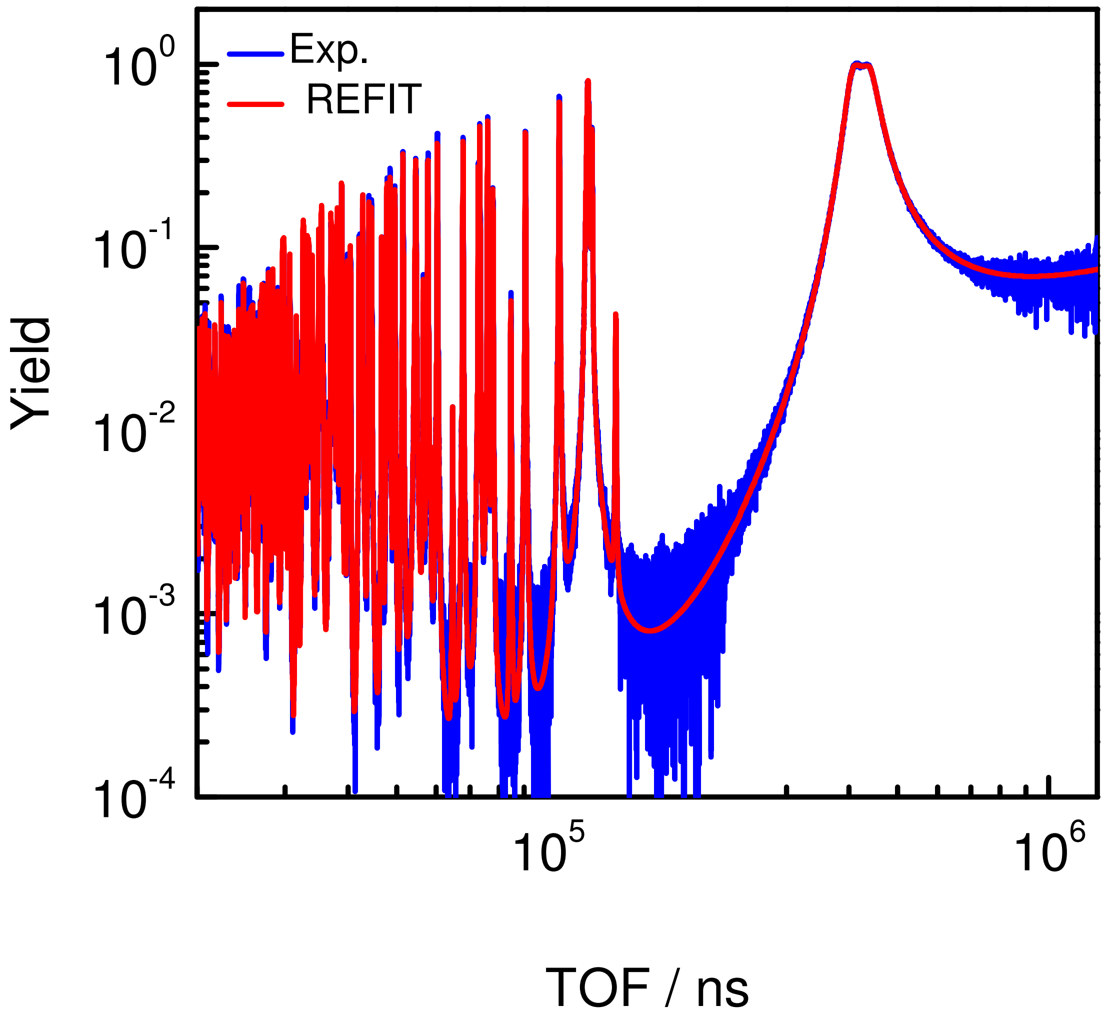




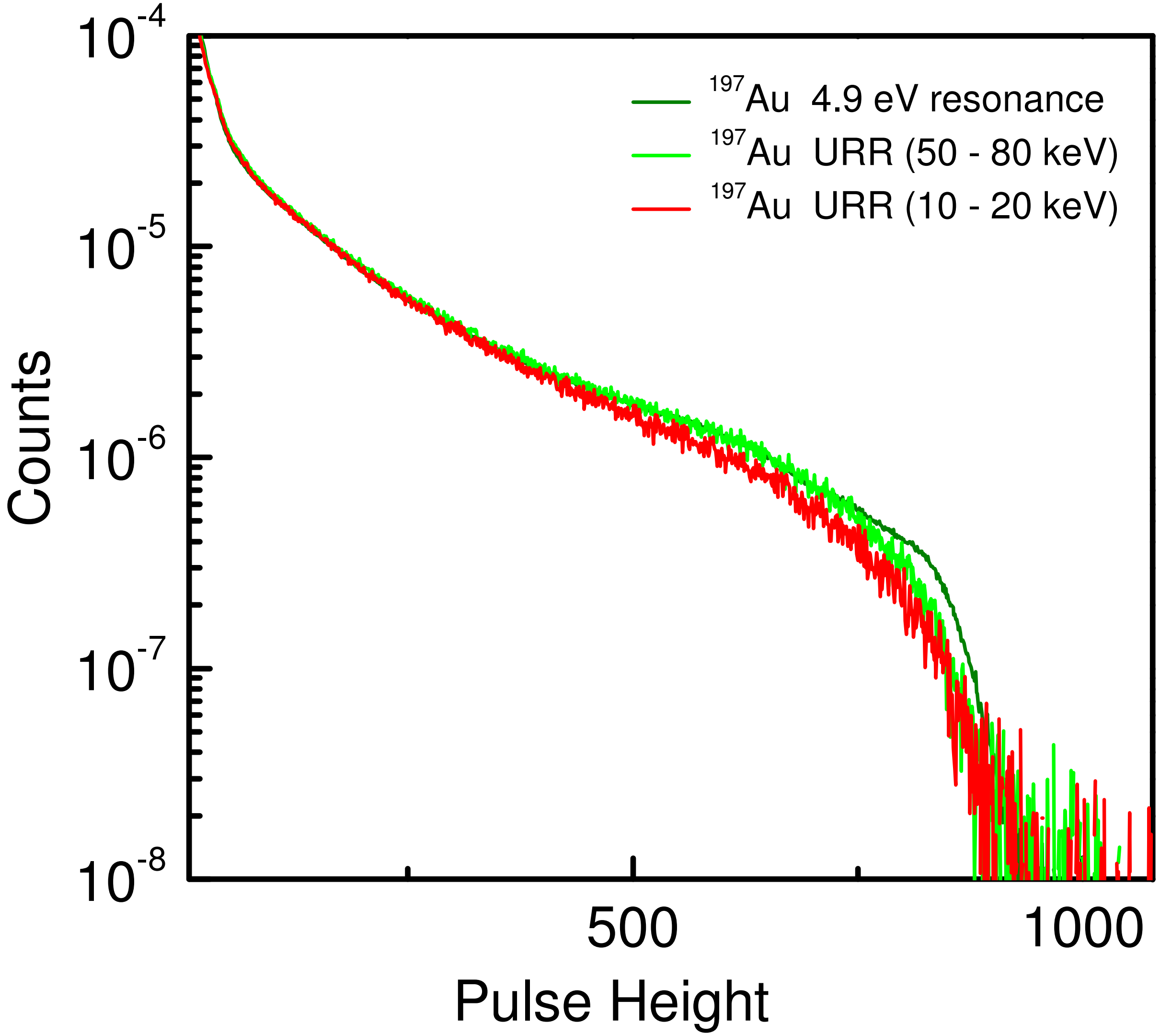
^{197}Au: $\sigma(n_{th}, \gamma)$ = (98.7± 0.1) b
from capture measurements (99.0 ± 1.0) b



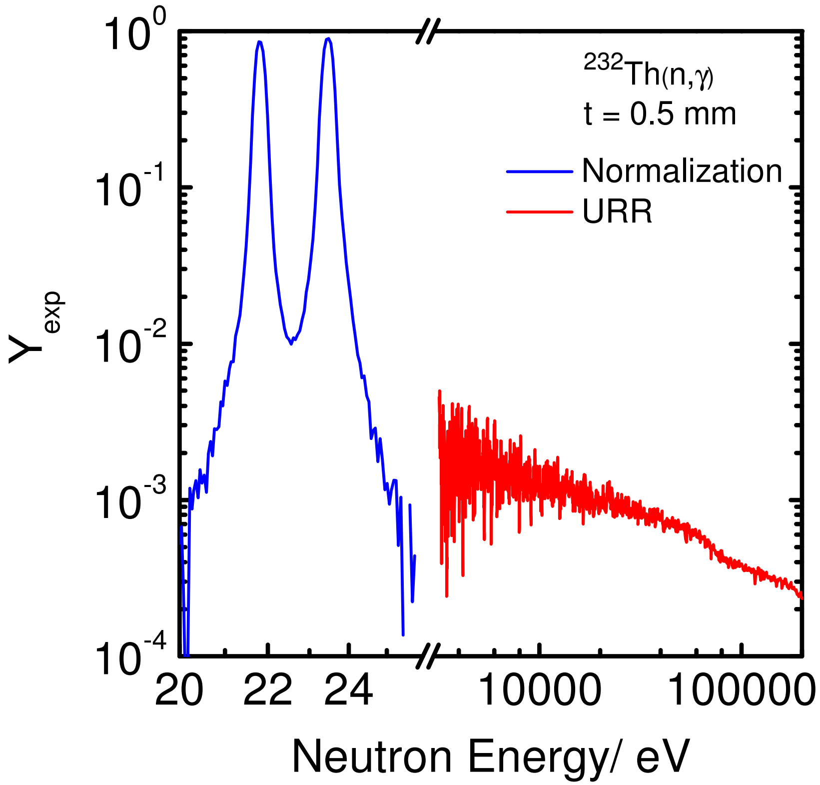
Yield compared with expected yield

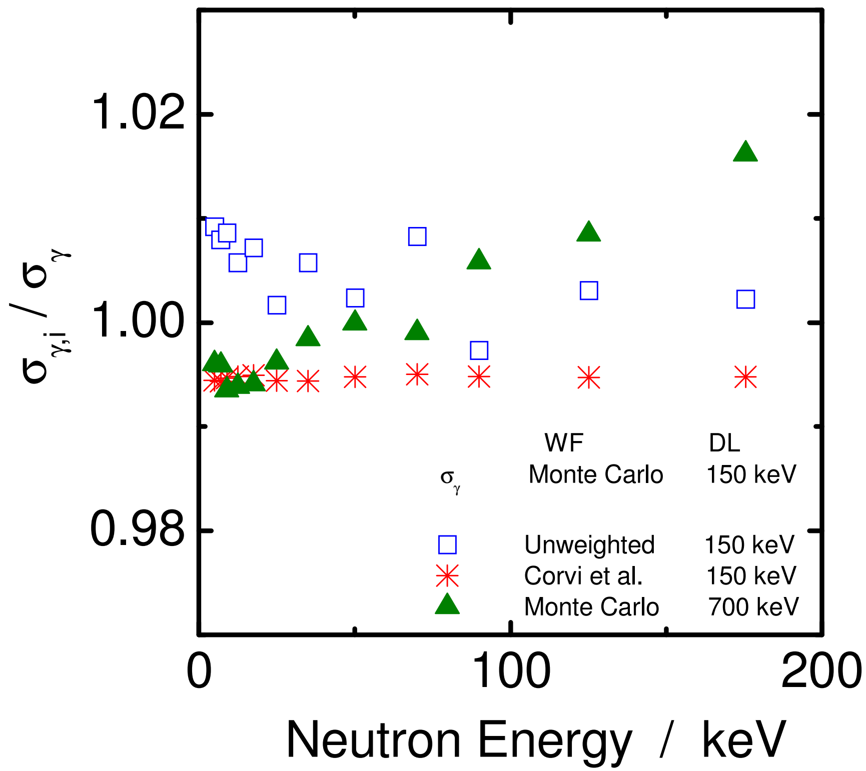


Impact of γ-ray spectrum



Internal normalization : $^{232}Th(n,\gamma)$ in URR





Ref.	E_r = 21.8 eV		E_r = 23.5 eV		N / 0.339
	Γ_n / meV	Γ_γ / meV	Γ_n / meV	Γ_γ / meV	
Olsen et al.	2.08	25.3	3.82	26.9	1.000
Kobyashi et al.	2.09	25.2	3.88	26.1	1.000
Chrien et al.	2.10	24.0	3.70	26.0	0.994

Borella et al., Nucl. Sci. Eng. 152 (2006) 1-14

Overall uncertainty : 1.7 %
normalization : 1.5 %
uncorrelated : 0.2 %
+ dead time, self-shielding

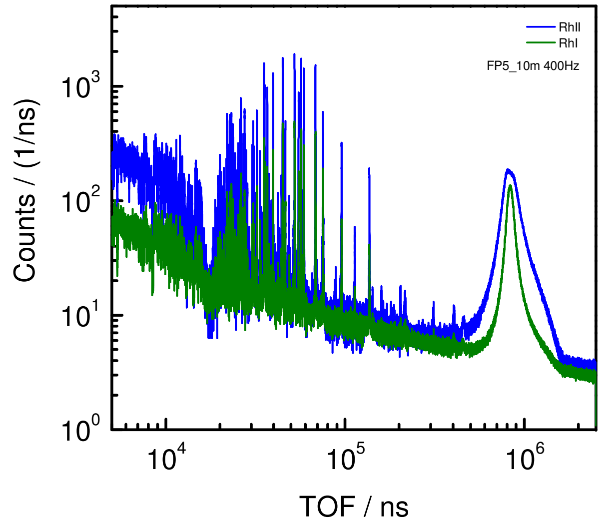
Verification of WF, γ-ray attenuation and normalization

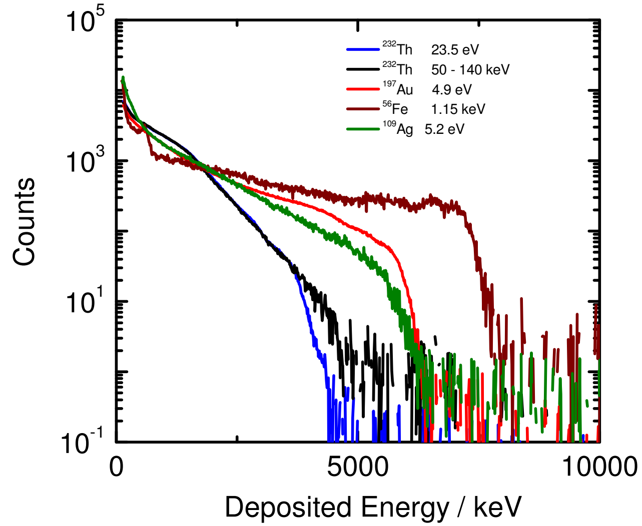
γ-ray attenuation

- ^{197}Au(n,γ) 1.0, 0.5 and 0.01 mm thick sample

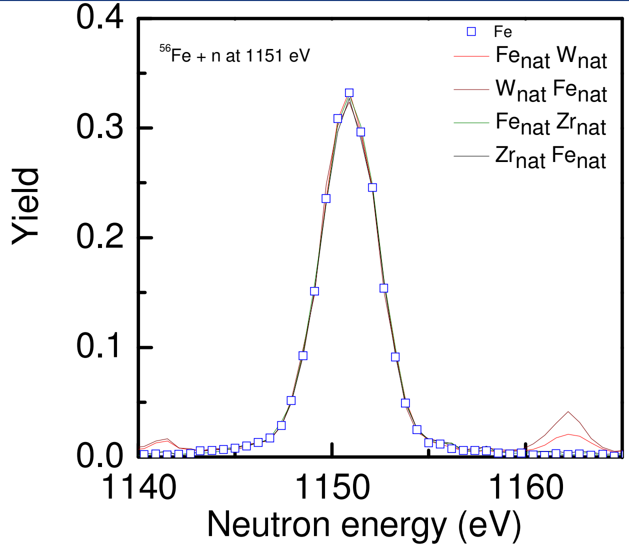
Normalization + WF

- ^{103}Rh(n,γ) at 1.2 eV saturated
- ^{109}Ag(n,γ) at 5.1 eV saturated
- ^{56}Fe(n,γ) at 1550 eV $\Gamma_n << \Gamma_\gamma$



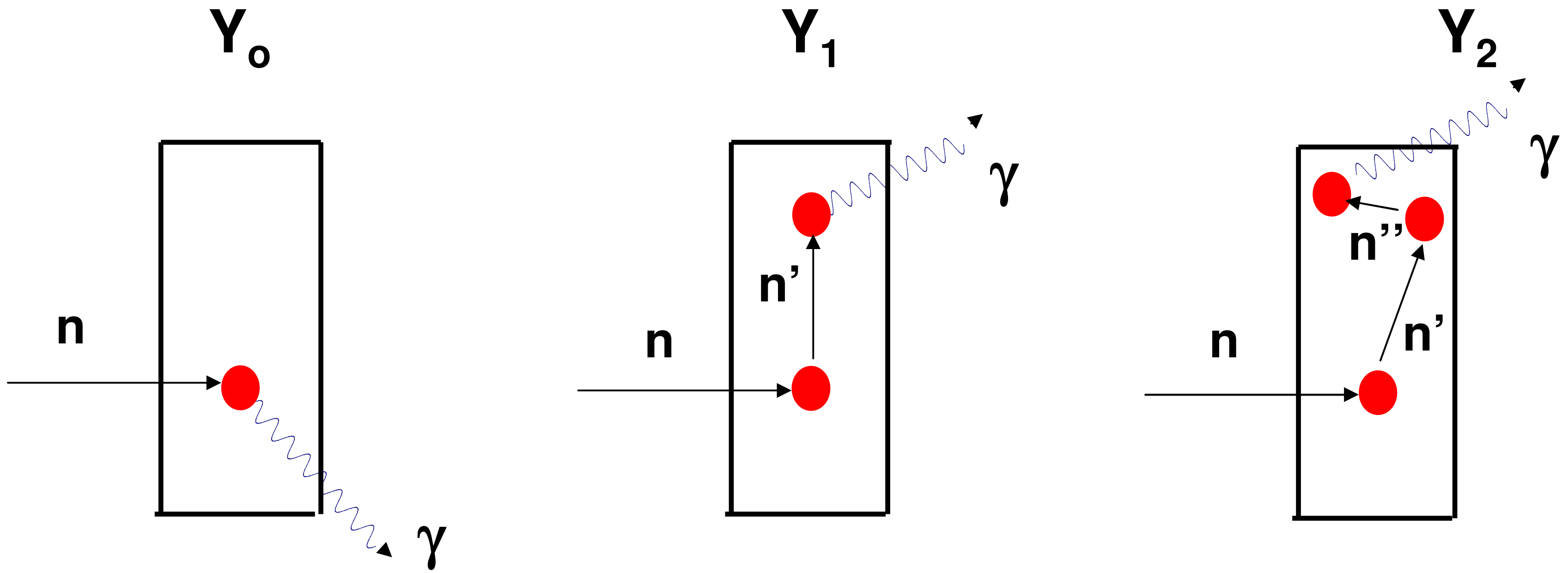


Example: normalization based on ^{56}Fe experimental validation of WF



Sample	Length / m	Normalization	
	REFIT MCNP resolution	REFIT MCNP resolution	SAMMY Analytical resolution
^{nat}Fe	58.5660 ± 0.0004	28.16 ± 0.25	27.80 ± 0.25
^{nat}Fe / ^{nat}W	58.5670 ± 0.0004	27.88 ± 0.25	28.50 ± 0.25
^{nat}Fe / ^{nat}Zr	58.5671 ± 0.0004	27.68 ± 0.25	28.10 ± 0.25
^{nat}W / ^{nat}Fe	58.5678 ± 0.0004	27.41 ± 0.25	28.30 ± 0.25
^{nat}Zr / ^{nat}Fe	58.5674 ± 0.0004	27.19 ± 0.25	27.70 ± 0.25
Average	58.5671	27.67	28.08
Stdev	0.0007	0.38	0.34
Stdev (%)	0.0011	1.4	1.2

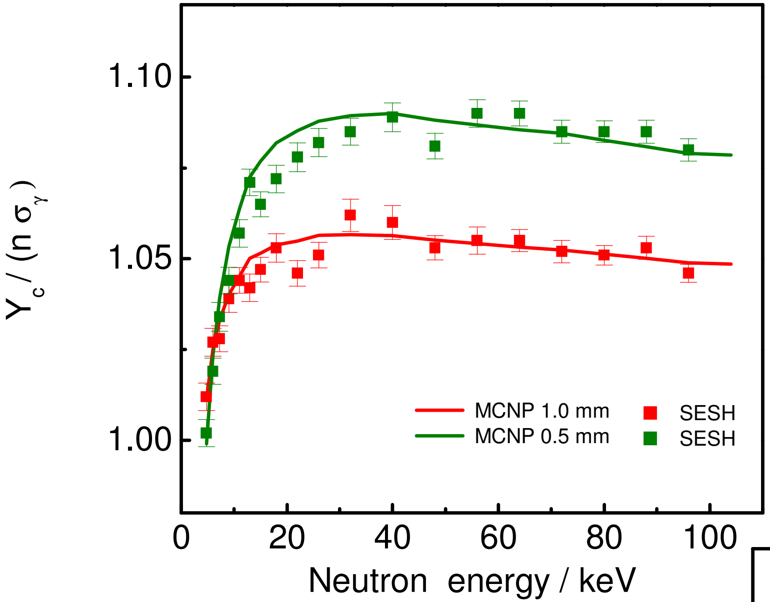
Capture experiments: relatively thick samples self-shielding and scattering+capture

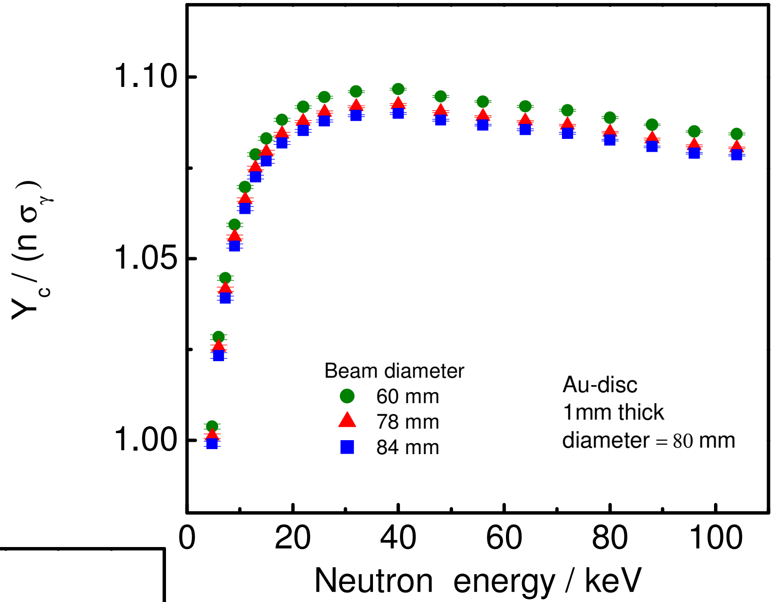


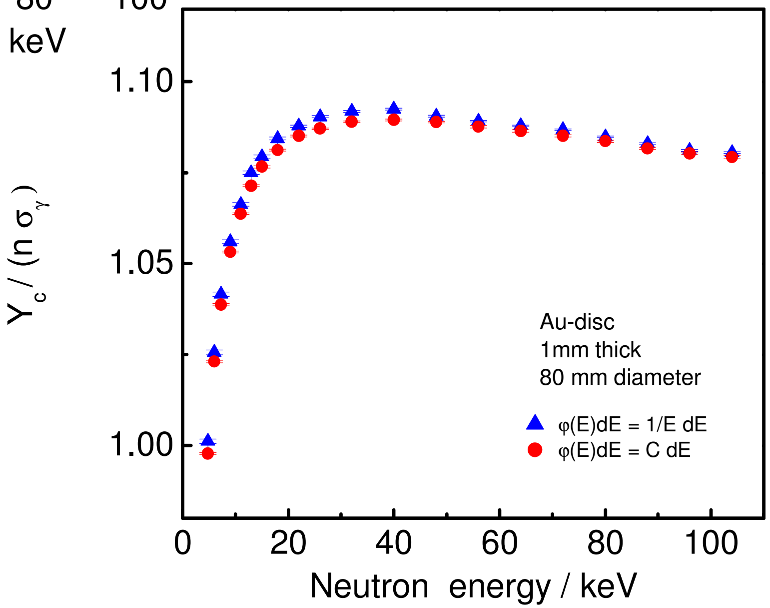
$$Y_o = \frac{\sigma_\gamma}{\sigma_{tot}}(1 - e^{-n\,\sigma_{tot}})$$

$$< Y_{exp} > = F \; < n\sigma_\gamma >$$

Correction for self-shielding and scattering+capture

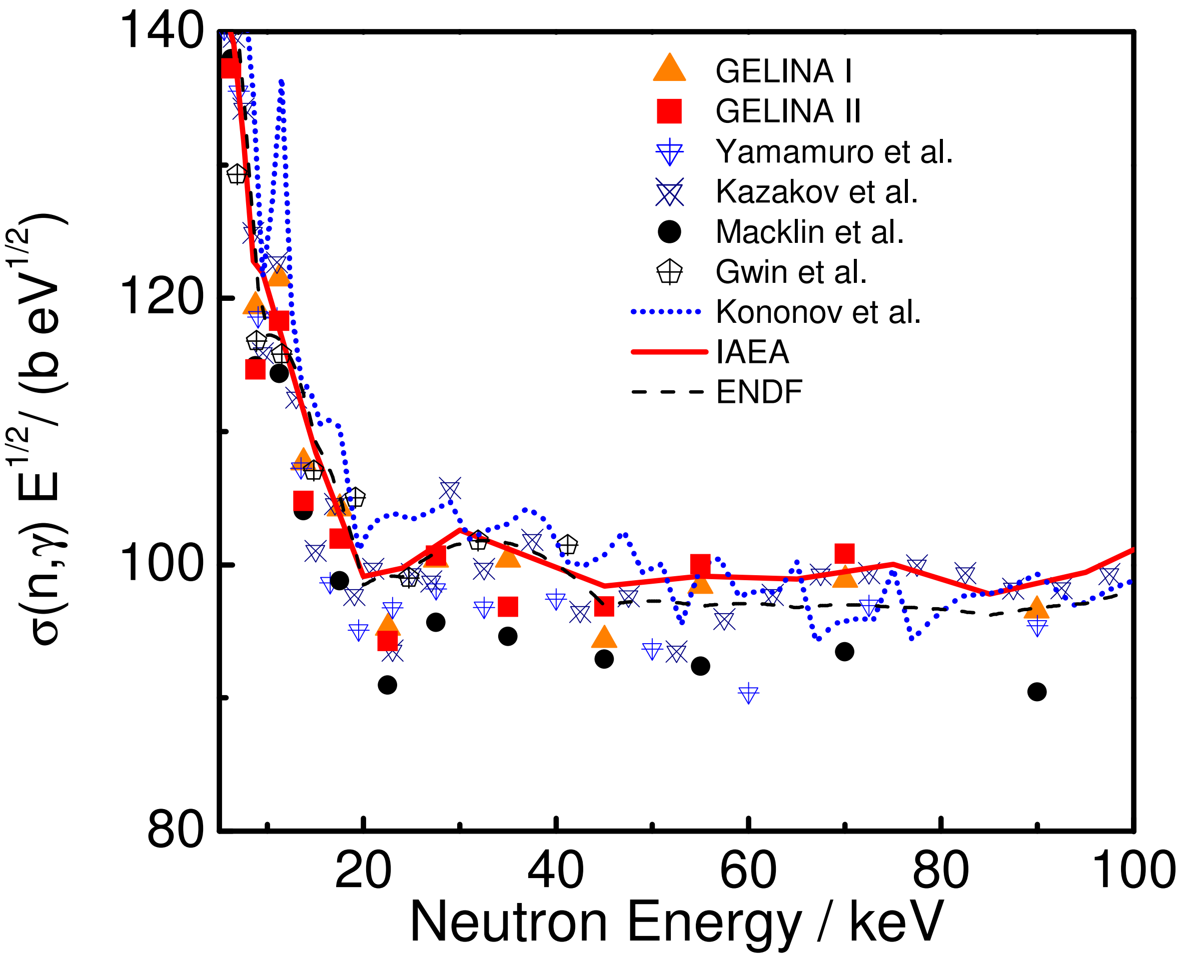






JRC
EUROPEAN COMMISSION

Results (without WF for GELINA II)

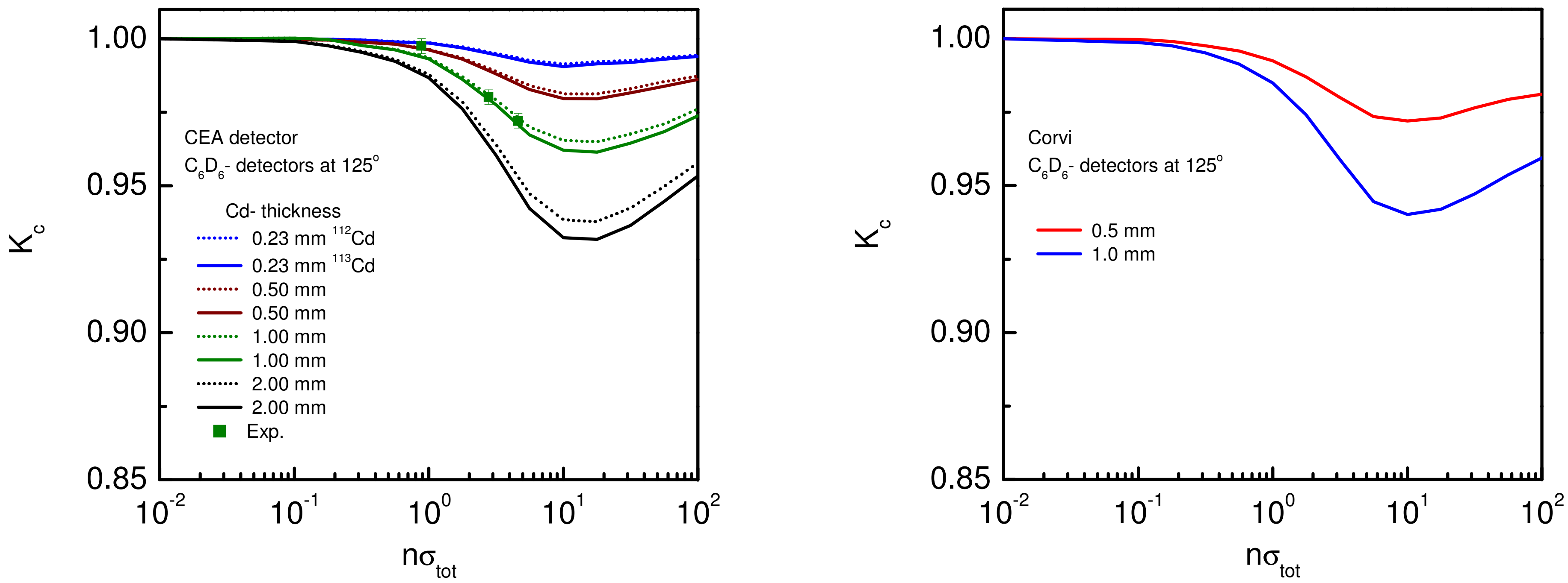


Conclusions

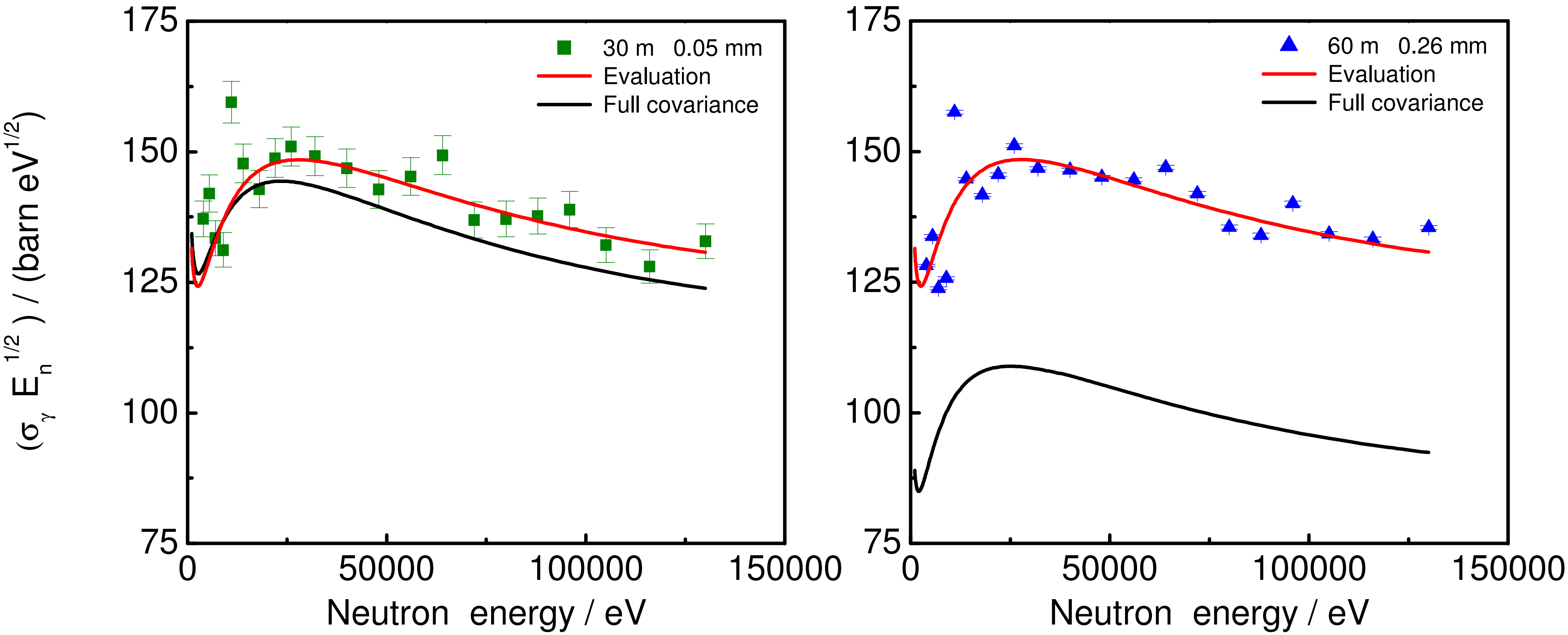
New measurements at GELINA

- Fixed background filters (Na and S)
  - advantage : reduction of bias effects (error)
  - disadvantage: useful energy region limited to 5 keV – 80 keV
- Internal normalization based on saturated resonance with $\Gamma_n << \Gamma_\gamma$
  - verification of normalization by Rh, Ag, Fe
  - experimental verification of WF and γ-ray correction
- Only reference to the shape of $^{10}B(n, \alpha_0 + \alpha_1)$ cross section
- Verification of self-shielding and scattering correction

New data confirm the results of Borella et al. (similar conditions)


1.00
0.95
0.90
0.85
K_c
CEA detector
C_6D_6- detectors at 125°
Cd- thickness
0.23 mm ^112Cd
0.23 mm ^113Cd
0.50 mm
0.50 mm
1.00 mm
1.00 mm
2.00 mm
2.00 mm
Exp.
10^-2
10^-1
10^0
10^1
10^2
nσ_tot
Corvi
C_6D_6- detectors at 125°
0.5 mm
1.0 mm

Peelle's Pertinent Puzzle: e.g. ^{103}Rh(n,γ) in URR



$$(N, \vec{Y}) = f(N, S_\ell, T_\ell) = (N, \frac{\vec{Z}_{HF}}{N})$$

$$\chi^2(N, \overline{Z}) = ((N_{exp}, \vec{Y}_{exp}) - f(N, S_\ell, T_\ell))^T \; V^{-1}_{(N,Y)} \; ((N_{exp}, \vec{Y}_{exp}) - f(N, S_\ell, T_\ell))$$

^{232}Th(n,γ) in URR
Uncertainty propagation AGS

Correlated: uncertainty dead time, background (capture)

E_{min}	E_{max}	σ_γ	$\delta\sigma_\gamma$	$\delta\sigma_{\gamma,u}$	ρ												
keV	keV	mb	(%)	(%)													
4	6	1107.9	0.49	0.17	1.00	0.60	0.57	0.58	0.55	0.53	0.62	0.58	0.56	0.61	0.58	0.54	0.51
6	8	934.2	0.44	0.19		1.00	0.55	0.56	0.53	0.51	0.60	0.57	0.55	0.60	0.56	0.53	0.49
8	10	845.1	0.43	0.21			1.00	0.54	0.51	0.49	0.58	0.55	0.52	0.57	0.54	0.51	0.47
10	15	749.1	0.38	0.15				1.00	0.52	0.50	0.59	0.56	0.54	0.59	0.55	0.52	0.49
15	20	638.7	0.39	0.18					1.00	0.48	0.57	0.54	0.52	0.56	0.53	0.50	0.47
20	30	571.3	0.36	0.14						1.00	0.55	0.52	0.50	0.54	0.51	0.48	0.45
30	40	490.3	0.32	0.18							1.00	0.61	0.59	0.64	0.61	0.57	0.54
40	50	429.6	0.31	0.19								1.00	0.56	0.61	0.58	0.54	0.51
50	60	382.9	0.33	0.22									1.00	0.59	0.56	0.52	0.49
60	80	311.4	0.30	0.18										1.00	0.61	0.57	0.54
80	100	242.5	0.33	0.22											1.00	0.54	0.51
100	120	217.8	0.33	0.23												1.00	0.48
120	140	201.6	0.33	0.24													1.00

Borella et al. NSE 152 (2006) 1-14

^{232}Th(n,γ) in URR
Uncertainty propagation AGS

Correlated: uncertainty dead time, background, + normalization (1.5%)

E_{min} keV	E_{max} keV	σ_γ mb	$\delta\sigma_\gamma$ (%)	$\delta\sigma_{\gamma,u}$ (%)	ρ												
4	6	1107.9	1.70	0.17	1.00	0.85	0.85	0.86	0.86	0.87	0.88	0.88	0.88	0.89	0.89	0.88	0.88
6	8	934.2	1.64	0.19		1.00	0.88	0.89	0.89	0.89	0.91	0.91	0.91	0.92	0.92	0.91	0.91
8	10	845.1	1.63	0.21			1.00	0.89	0.89	0.90	0.91	0.91	0.91	0.92	0.92	0.91	0.91
10	15	749.1	1.61	0.15				1.00	0.90	0.91	0.93	0.92	0.93	0.93	0.93	0.93	0.92
15	20	638.7	1.61	0.18					1.00	0.91	0.92	0.92	0.93	0.93	0.93	0.93	0.92
20	30	571.3	1.59	0.14						1.00	0.93	0.93	0.93	0.94	0.93	0.93	0.93
30	40	490.3	1.56	0.18							1.00	0.95	0.95	0.96	0.95	0.95	0.95
40	50	429.6	1.56	0.19								1.00	0.95	0.96	0.95	0.95	0.95
50	60	382.9	1.55	0.22									1.00	0.96	0.96	0.95	0.95
60	80	311.4	1.55	0.18										1.00	0.96	0.96	0.96
80	100	242.5	1.56	0.22											1.00	0.96	0.95
100	120	217.8	1.55	0.23												1.00	0.95
120	140	201.6	1.55	0.24													1.00

Borella et al. NSE 152 (2006) 1-14

AGS : Analysis of Geel Spectra

- **Transforms count rate spectra into observables (T, Y_{exp}, Y_{SI})**
- **Full uncertainty propagation starting from counting statistics**

$$V_Z = U_Z + S_{\vec{a}} S_{\vec{a}}^T$$

dim. (n x n) dim. n dim. (n x k)

- **Reduction of space for data storage**
- **Documents all uncertainty components involved in data reduction**
  - **Study the impact of uncertainty components on RP and cross sections**
  - **Provides full experimental details to EXFOR compilers**
- **Recommended by International Network of Nuclear Reaction Data Centres**
- **WPEC sub-group 36**

  "Reporting and usage of experimental data for evaluation in the RRR "

Uncertainty propagation in AGS

Conditions :

(1) Data reduction starts from spectra subject only to uncorrelated uncertainties

(2) Additional computations using parameters with well defined covariance matrix

(3) Channel – channel operations (+, - , x , ÷) and log, exp, …

$$Z = F(\vec{a}, Y) \quad \text{e.g.} \quad Z(t) = Y(t) - (a_1 + a_2 t^{a_3})$$

Covariance matrix V_a well defined

⇒ symmetric and positive definite

⇒ Cholesky transformation

$$V_{\vec{a}} = L_{\vec{a}} \, L_{\vec{a}}^{T}$$

L_a : lower triangular matrix

V_Y only diagonal terms :

⇒ $D_Y = V_Y$ $\quad v_{Y,i\neq j} = 0$

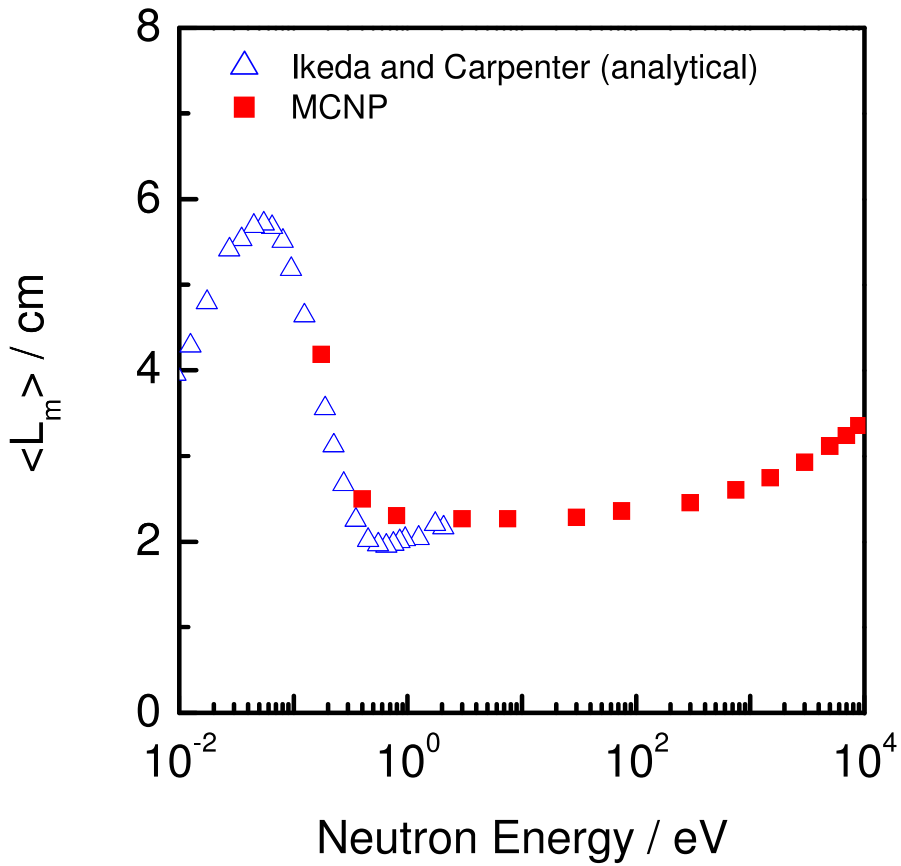
$$V_Z = U_Z + S_{\vec{a}} \, S_{\vec{a}}^{T}$$

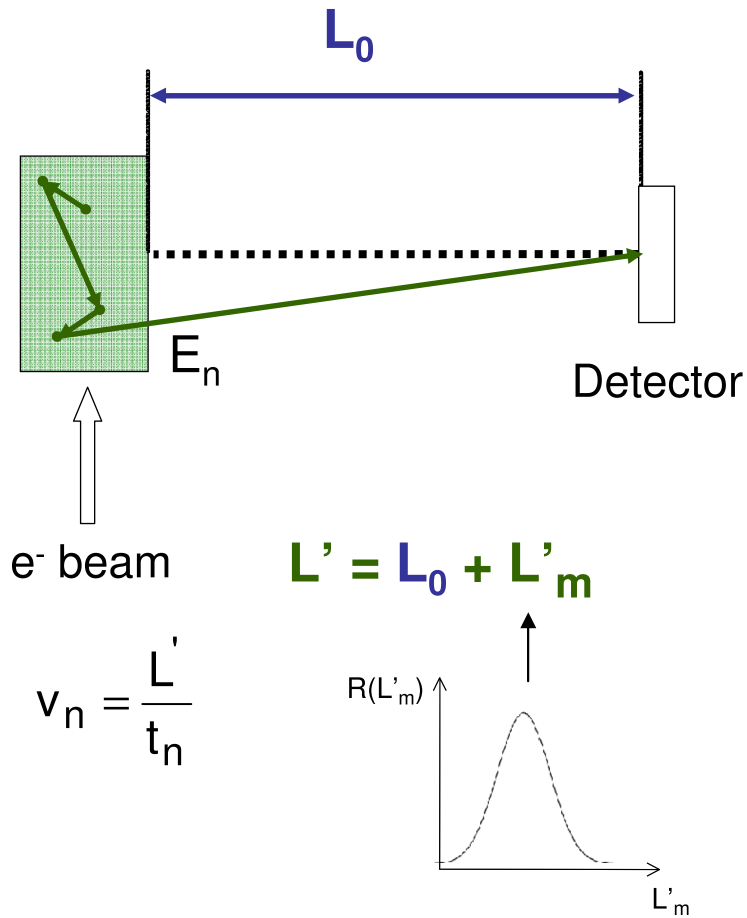
diagonal : n values

dimension: n x k

EUROPEAN COMMISSION JRC

Time-of-flight <-----> Energy





Analytical expressions in REFIT include storage term of Ikeda & Carpenter

Normalization at saturated resonance

E_r = 5.2 eV ^{109}Ag + n

Sample	Ag g/cm^2	Pb g/cm^2	∅ mm	N	N / <N>
Ag	0.088		60	4.746 ± 0.074	0.995 ± 0.016
Ag	0.191		60	4.804 ± 0.074	1.007 ± 0.016
^{nat}PbAg	0.104	1.099	60	4.772 ± 0.074	1.001 ± 0.016
^{206}PbAg	0.088	1.213	60	4.755 ± 0.074	0.997 ± 0.016
Mean				4.769	
Std				0.026	
Std (%)				0.539	

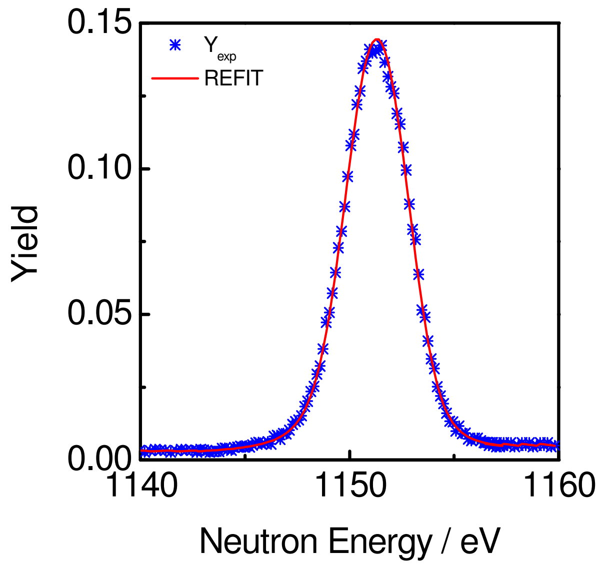
E_r = 4.9 eV ^{197}Au + n

Sample	Au g/cm^2	∅ mm	N	N / <N>
Au1	0.095	80	3.199 ± 0.049	1.002 ± 0.015
Au2	0.217	80	3.196 ± 0.049	1.001 ± 0.015
Au3	1.965	80	3.184 ± 0.048	0.997 ± 0.014
Mean			3.193	
Std			0.008	
Std (%)			0.239	

$^{56}Fe(n,\gamma)$: Γ_n for E_r = 1.15 keV

Sample	Fe g/cm^2	X	∅ mm	Γ_n / meV	
Fe1	0.105		60	62.6	± 1.3
Fe2	0.394		60	62.5	± 1.1
Fe3	0.905		60	60.2	± 1.0
Fe^{206}Pb *	0.394	1.213	60	63.1	± 1.1
FePb*	0.422	1.103	60	62.6	± 1.1
FePb*	0.422	2.725	60	62.6	± 1.1
Fe4	0.202		80	61.2	± 1.1
Fe5	0.795		80	60.3	± 1.1
Fe6	0.998		80	61.2	± 1.1
FeAu	1.708	0.118	80	61.3	± 1.1
Fe_2O_3	1.404	0.603	80	59.1	± 1.0
Mean				61.5	
Std				1.3	
Std (%)				2.1	

* Sandwich



Γ_γ = 574 meV

ORELA

Transmission

Perey et al. : Γ_n = 61.7 ±0.9 meV

Capture (thin + thick sample)

Macklin : Γ_n = 61.8 ± 1.9 meV

⇒ **Uncertainties of 2% can be reached**