Capture cross section measurements for ^{197}Au at GELINA

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Cross section measurements

Transmission

$$T = e^{-n\,\sigma_{tot}}$$

$$T_{exp} = \frac{C_{in}}{C_{out}}$$

- Incoming flux cancels
- Detection efficiency cancels

+ direct relation: $T \Leftrightarrow \sigma_{tot}$
  good geometry
  homogeneous sample

Reaction

$$Y_r \cong (1 - e^{-n\sigma_{tot}})\,\frac{\sigma_r}{\sigma_{tot}} + \ldots$$

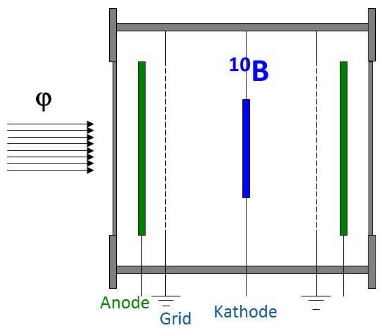
$$Y_{r,exp} = \frac{C_r}{\varepsilon_r\,\Omega\,P_r\,A_r\,\varphi}$$

- φ Neutron flux
- ε_r Detection efficiency
- Ω_r solid angle (target-detector)
- P_r Escape probability
- A_r Effective area

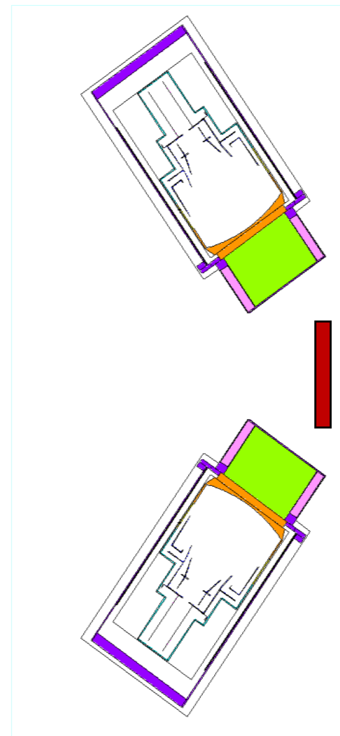
+ complex relation : $Y \Leftrightarrow \sigma_r$
  $Y_r = f\,(\sigma_r\,,\,\sigma_{tot}\ \&\ \sigma_n)$
  only for $n\sigma_{tot} << 1$: $Y_r \cong n\,\sigma_r$

σ(n,γ) measurements at GELINA

Flux measurement

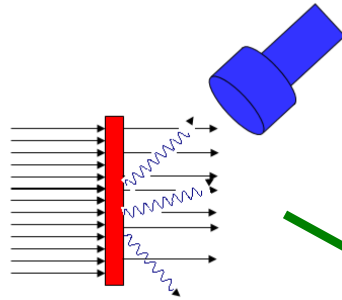


Capture detection system



$\sigma(n,\gamma)$ measurements

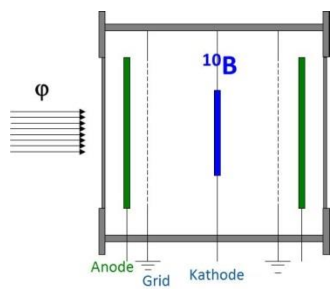
$$C_\gamma = \varepsilon_\gamma \, \Omega_\gamma \, P_\gamma \, Y_\gamma \, A_\gamma \, \varphi$$



- φ Neutron flux
- ε_γ Detection efficiency
- Ω_γ solid angle (target-detector)
- P_γ Escape probability
- A_γ Effective area

$$Y_{\gamma,exp} = \frac{\varepsilon_\varphi}{\varepsilon_\gamma} \frac{\Omega_\varphi}{\Omega_\gamma} \frac{P_\varphi}{P_\gamma} \frac{A_\varphi}{A_\gamma} \frac{C_\gamma}{C_\varphi} Y_\varphi$$

$$C_\varphi = \varepsilon_\varphi \, \Omega_\varphi \, P_\varphi \, Y_\varphi \, A_\varphi \, \varphi$$



$\Rightarrow$ $Y_{\gamma,exp}$ is the ratio of results of 2 measurements

$\Rightarrow$ Y_φ is required,
i.e. standard reaction with known cross section

$\sigma(n,\gamma)$ measurements

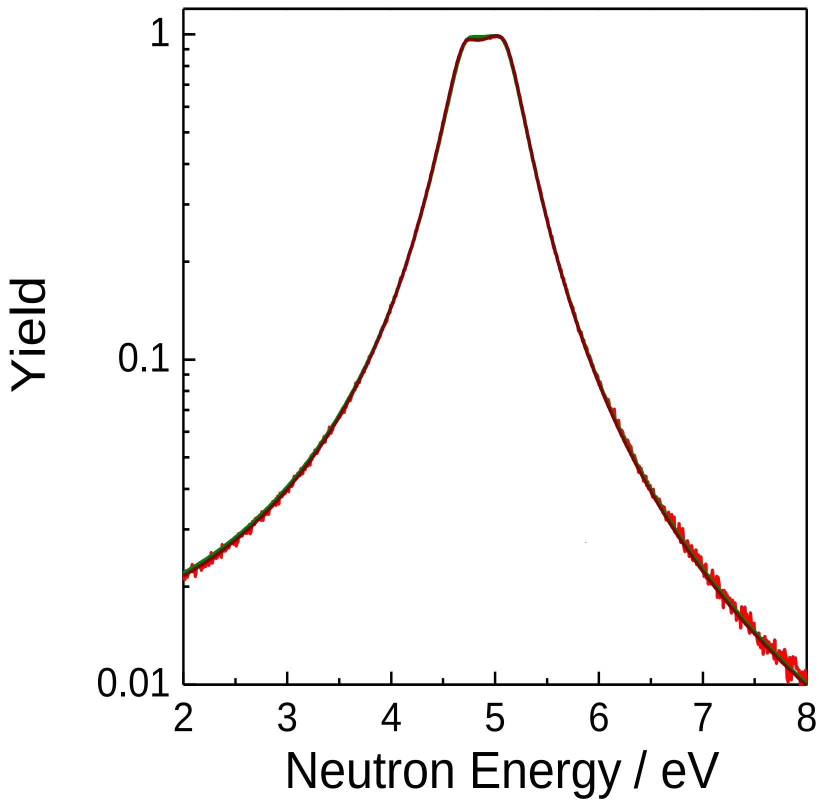
- Absolute measurements
  - All parameters (P, A Ω, ε) have to be determined
  - Y_φ has to be determined absolutely
    (absolute cross sections needed)

$$Y_{\gamma,exp} = \frac{\varepsilon_\varphi}{\varepsilon_\gamma}\frac{\Omega_\varphi}{\Omega_\gamma}\frac{P_\varphi}{P_\gamma}\frac{A_\varphi}{A_\gamma}\frac{C_\gamma}{C_\varphi}Y_\varphi$$

- Normalisation
  - N accounts for all energy independent parameters &
    absolute value of neutron flux
  - Y_φ only energy dependence is needed
    (shape of cross sections needed)
  - N : determined at energy where Y_γ is known

$$Y_{\gamma,exp} = N\frac{C_\gamma}{C_\varphi}Y'_\varphi$$

Normalization at saturated resonance



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

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

$$Y_\gamma \cong 1$$

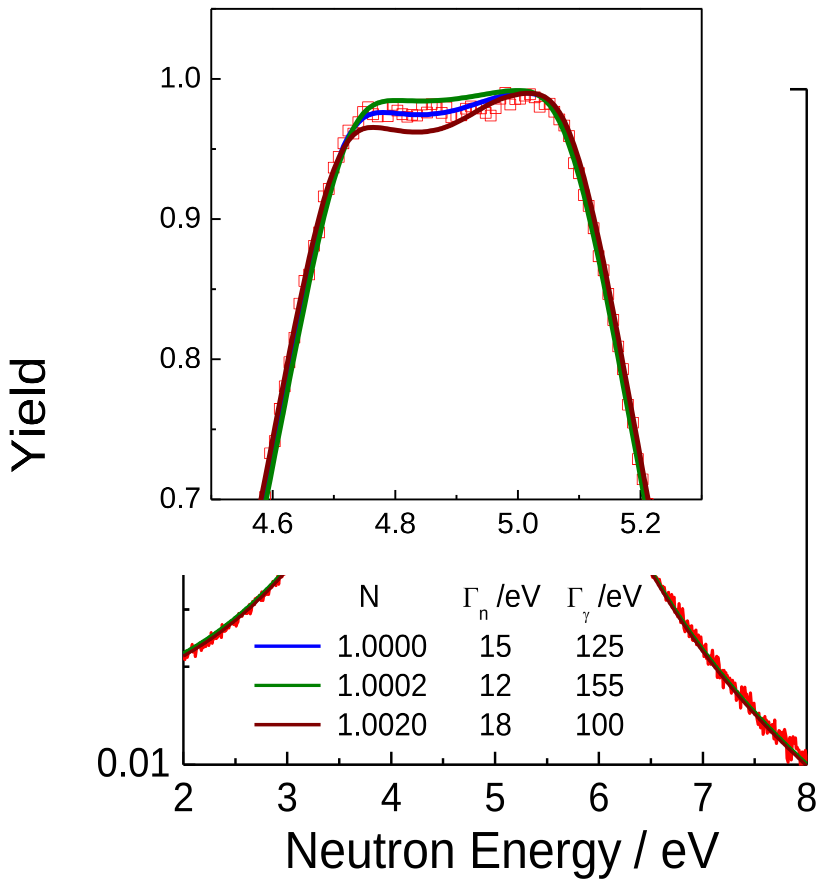
$$\Rightarrow N \cong \frac{C_\varphi}{C_\gamma}\frac{1}{Y'_\varphi}$$

σ_φ : only the relative energy dependence is required

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

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

Normalization at saturated resonance



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

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

$$Y_\gamma \cong 1$$

$$\Rightarrow N \cong \frac{C_\varphi}{C_\gamma}\frac{1}{Y'_\varphi}$$

N is independent of :

- sample thickness
- nuclear data

σ_φ : only the relative energy dependence is required

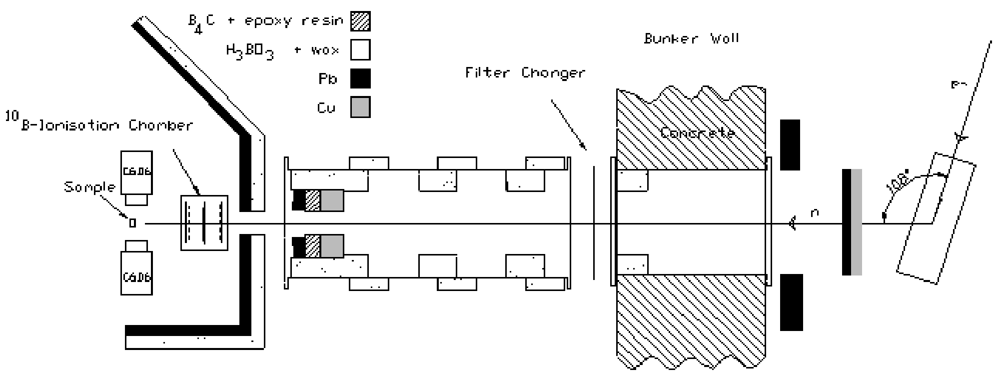
$\Rightarrow {}^{10}B(n,\alpha) \sim 1/v$

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

$\sigma(n,\gamma)$ measurements for ^{197}Au at GELINA

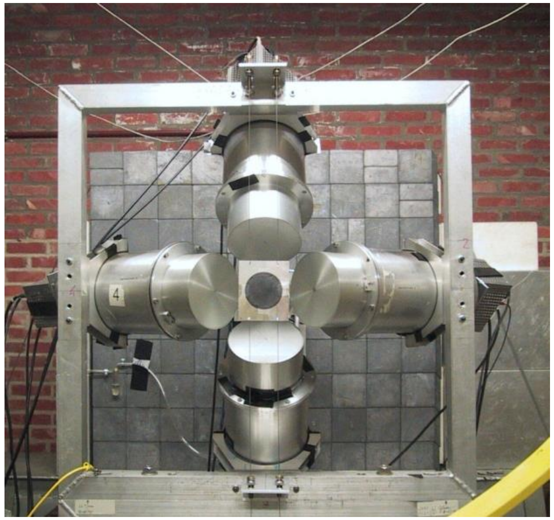
- Neutron source
  - moderated neutron beam
  - 18° with normal of moderator face viewing FP4
- Filters :
  - ^{10}B (0.005 at/b) overlap filter
  - S and Na fixed black resonance filter
- Sample
  - Au-metal disc (80 mm diameter)
  - 3.026 (0.001) 10^{-3} at/b & 5.596 (0.001) 10^{-3} at/b

- Neutron flux detector
  - Frisch-gridded ionisation chamber
  - $^{10}B(n,\alpha)$ reaction
  - 2 back-to-back layers of ^{10}B (84 mm diameter)
  - 2 x 2.4 10^{-6} at/b
  - at 12.121 m from centre of neutron source
- Capture
  - C_6D_6-liquid NE230-scintitllator
  - 10 cm diameter
  - 7.5 cm length
  - at 12.938 m from centre of neutron source



- Measurement principles
  - Total energy detection principle + Pulse Height Weighting Technqiue
  - WF: Monte Carlo calculations
  - Internal normalisation: 4. 9 eV resonance

$\sigma(n,\gamma)$ measurements for ^{197}Au at GELINA



Total energy detection

- **C_6D_6 liquid scintillators**
  - 125°
  - Total energy detection principle + pulse height weighting technique
  - Weighting function: MC-simulations

$$C_w(T_n) = \int C_c(T_n, E_d)\, WF(E_d)\, dE_d$$

$$\varepsilon \propto E_\gamma \quad \Rightarrow \quad \varepsilon_c \propto S_n + E_n \frac{A}{1+A}$$

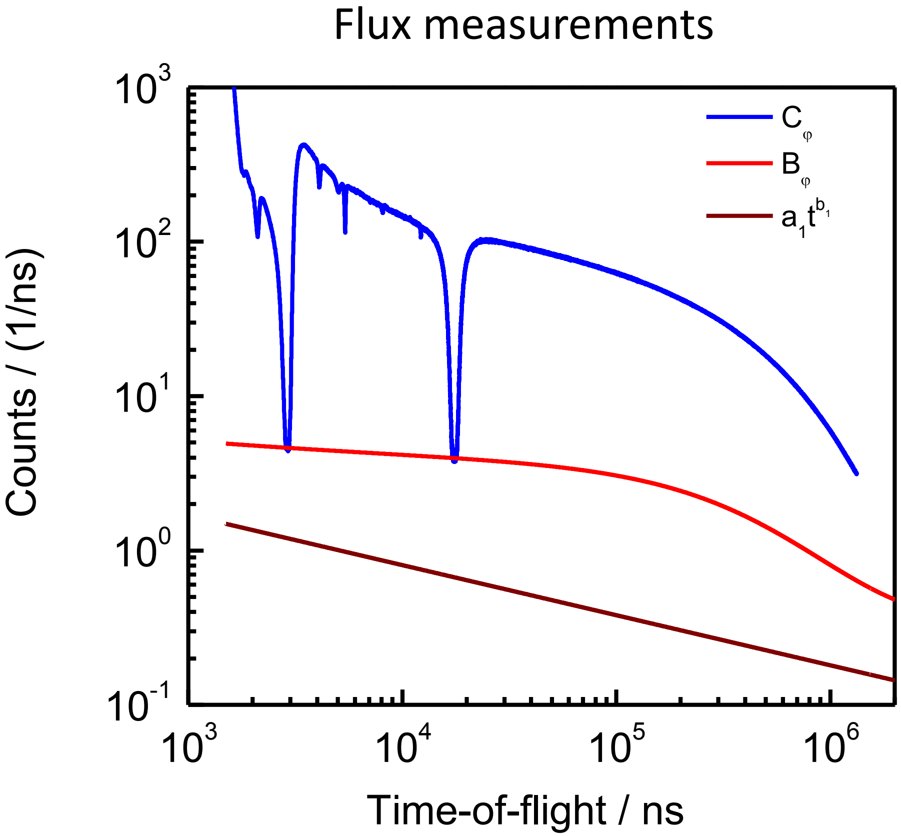
- **Flux measurements (IC)**
  - $^{10}B(n,\alpha)$

TOF - spectra

Background determination
⇒ black resonance technique

$B_{\varphi}(t) = a_0 + B_n(t) + B_{ov}(t)$

- a_o time independent ($< 10^{-1}$)
- $B_n(t)$ scattered neutrons
  $a_1 t^{b_1}$

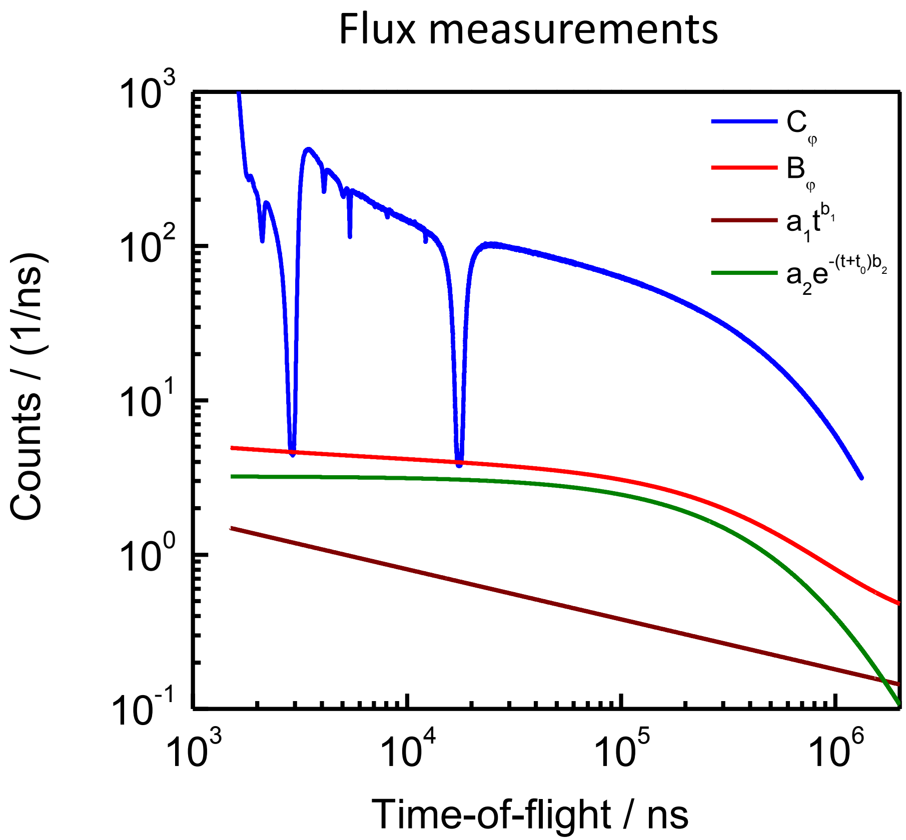


TOF - spectra

Background determination
⇒ black resonance technique

$B_\varphi(t) = a_0 + B_n(t) + B_{ov}(t)$

- a_o time independent ($< 10^{-1}$)
- $B_n(t)$ scattered neutrons $a_1\, t^{b_1}$
- $B_{ov}(t)$ overlap neutrons $a_2\, e^{-b_2(t+t_o)}$



$$B_\varphi = a_0 + a_1\, t^{b_1} + a_2\, e^{-b_2(t+t_o)}$$

TOF - spectra

Background determination
⇒ black resonance technique

$B_\varphi(t) = a_0 + B_n(t) + B_{ov}(t)$

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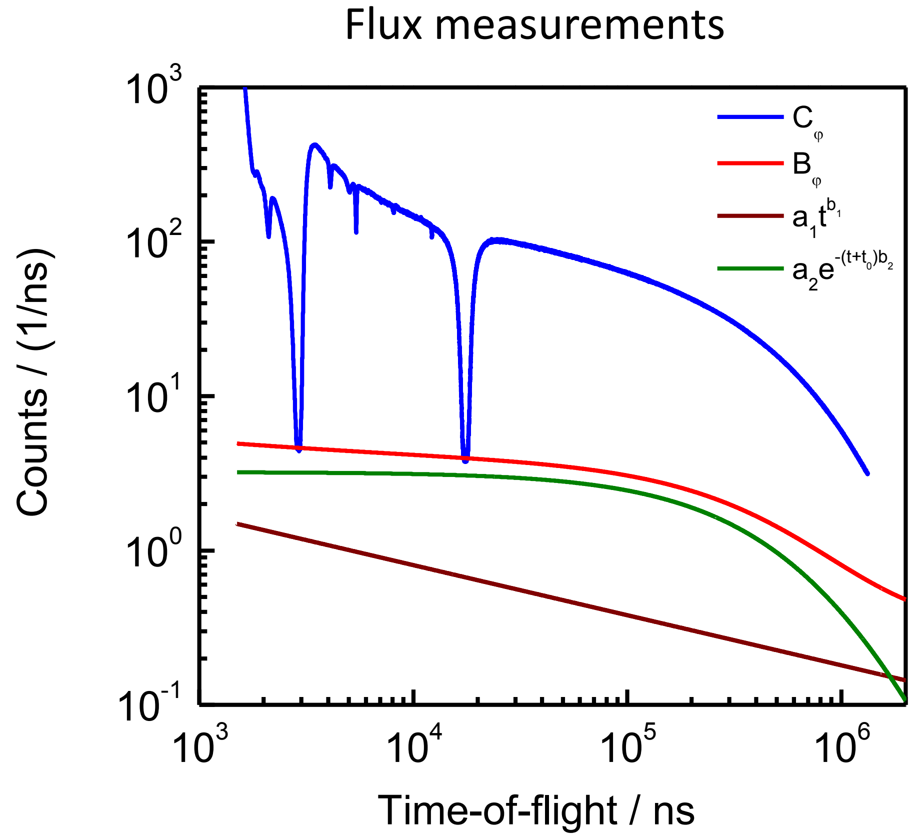


Background influenced by sample
⇒ use of fixed background filters to adjust a_1 and a_2

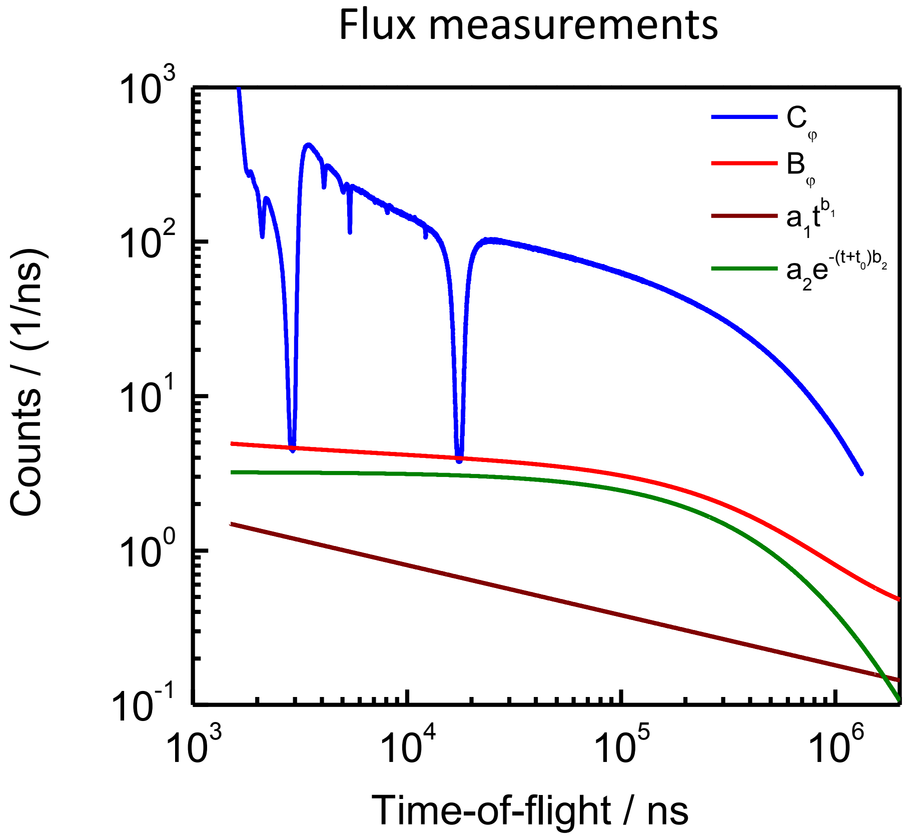
$$B_\varphi = a_0 + a_1\, t^{b_1} + a_2\, e^{-b_2(t+t_o)}$$

TOF - spectra

Background determination
$\Rightarrow$ black resonance technique

$B_{\varphi}(t) = a_0 + B_n(t) + B_{ov}(t)$

- a_o time independent ($< 10^{-1}$)
- $B_n(t)$ scattered neutrons $a_1\, t^{b_1}$
- $B_{ov}(t)$ overlap neutrons $a_2\, e^{-b_2(t+t_o)}$



$$\frac{u_{B_{\varphi}}}{B_{\varphi}} \leq 3\% \quad \Rightarrow \quad \frac{u_{(C_{\varphi}-B_{\varphi})}}{C_{\varphi}-B_{\varphi}} \leq 0.3\%$$

Use of fixed BGR filters

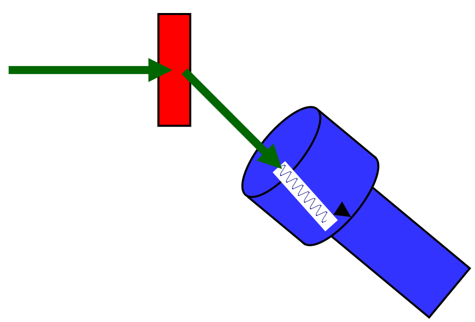
$$B_{\varphi} = a_0 + a_1\, t^{b_1} + a_2\, e^{-b_2(t+t_o)}$$

TOF - spectra

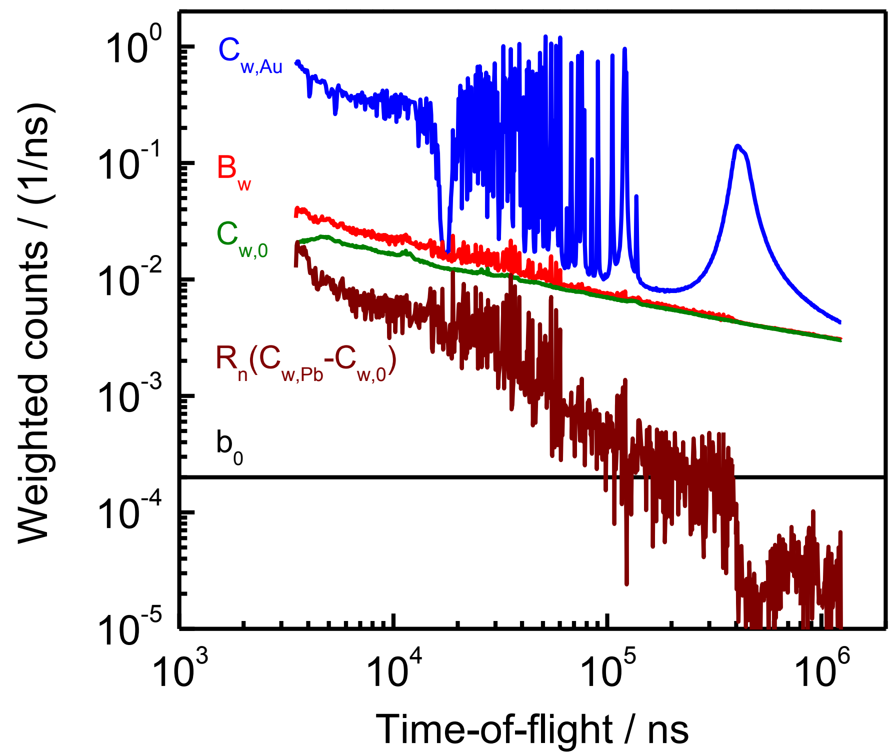
Background determination
⇒ additional measurements

$B_w(t) = c_0 + \quad C_{w,0}(t) + \quad R_n(C_{w,Pb} - C_{w,0})(t)$

- c_0 time independent background
- $C_{w,0}(t)$ neutrons scattered in environment
  + measurement without sample
- $C_{w,ns}(t)$ neutron sensitivity of detection system
  + measurements with ^{208}Pb metal disc



Capture measurements



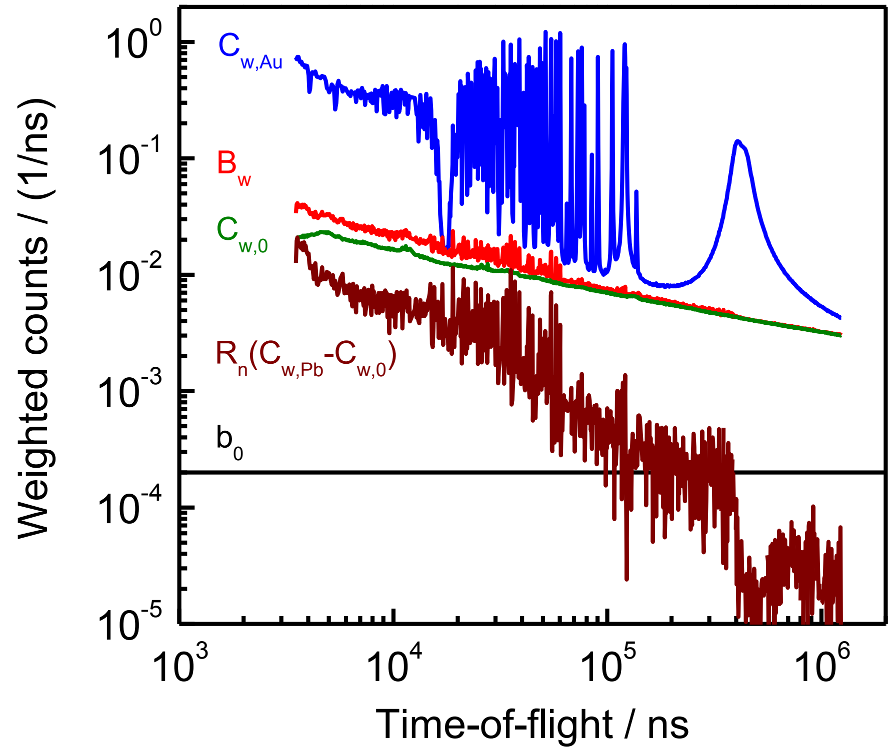
TOF - spectra

Background determination
⇒ additional measurements

$B_w(t) = c_0 + \; C_{w,0}(t) + \; R_n(C_{w,Pb} - C_{w,0})(t)$

- c_0 time independent background
- $C_{w,0}(t)$ neutrons scattered in environment
  + measurement without sample
- $C_{w,ns}(t)$ neutron sensitivity of detection system
  + measurement with ^{208}Pb sample
  $R_n(C_{w,Pb} - C_{w,0})$
  R_n is the ratio neutron yield $Y_{n,Au}/ Y_{n,Pb}$

Capture measurements



TOF - spectra

Background determination
⇒ additional measurements

$B_w(t) = c_0 + k_1 C_{w,0}(t) + k_2 R_n(C_{w,Pb} - C_{w,0})(t)$

Uncertainties of systematic effects

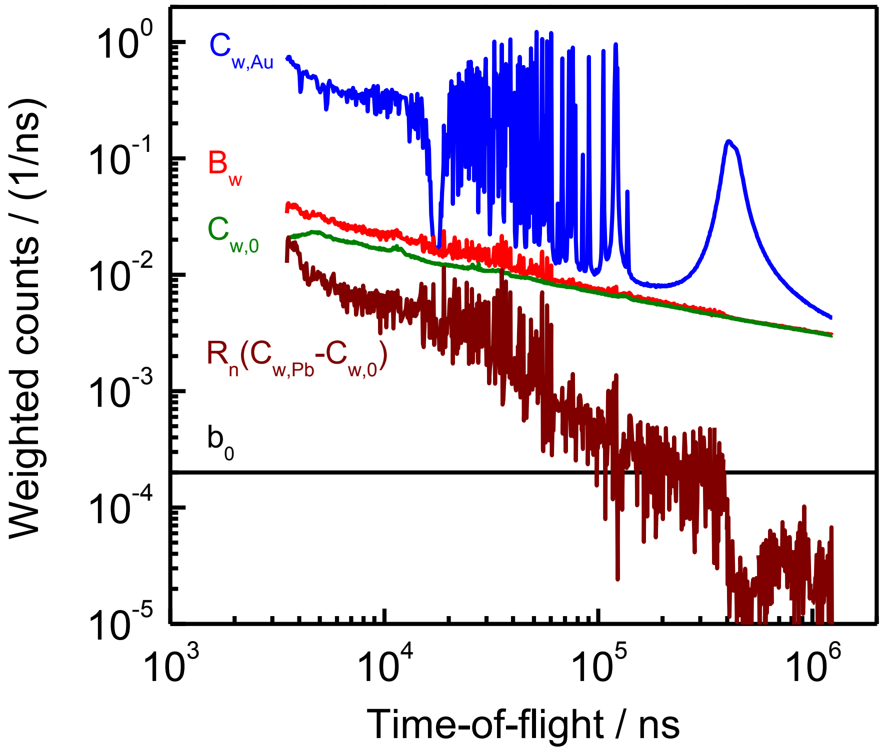
- $C_{w,0}(t)$ $k_1 = 1.00 \pm 0.03$

Use of fixed BGR filters

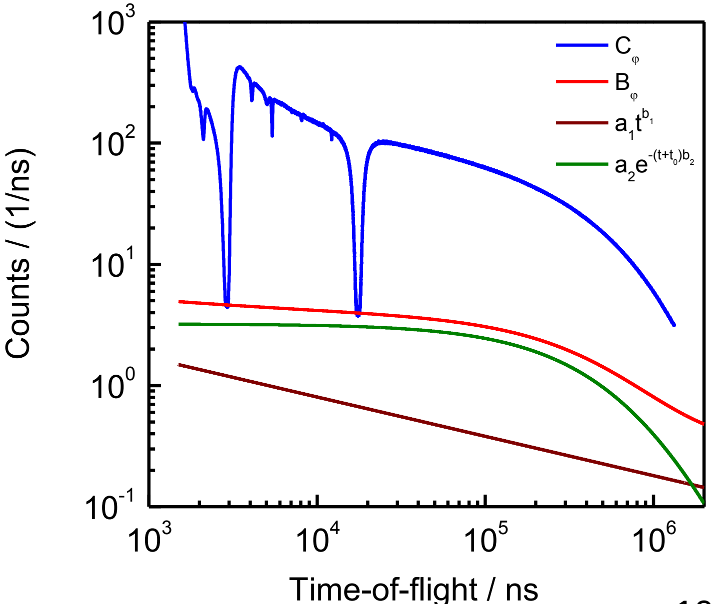
- $C_{w,ns}(t)$ $k_2 = 1.00 \pm 0.05$

⇒ (u_{k_1}, u_{k_2}) correlated uncertainty components

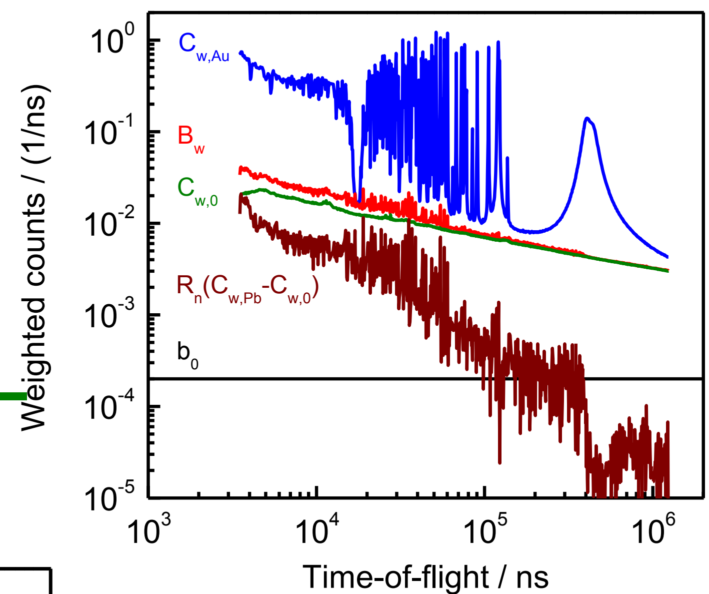
Capture measurements

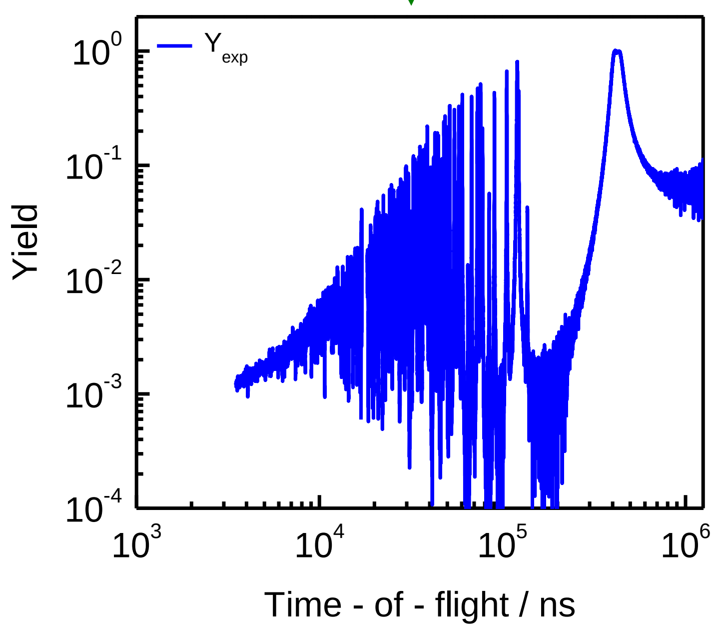


Capture yield



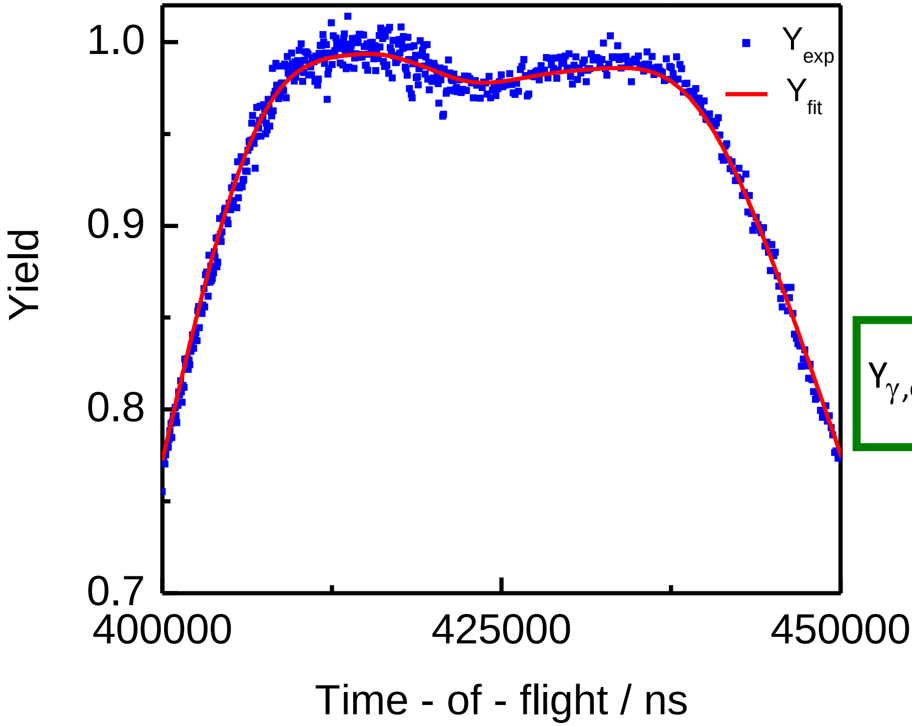
$$Y_{\gamma,exp} = N_C \frac{C_w - B_w}{C_\varphi - B_\varphi} Y_\varphi$$



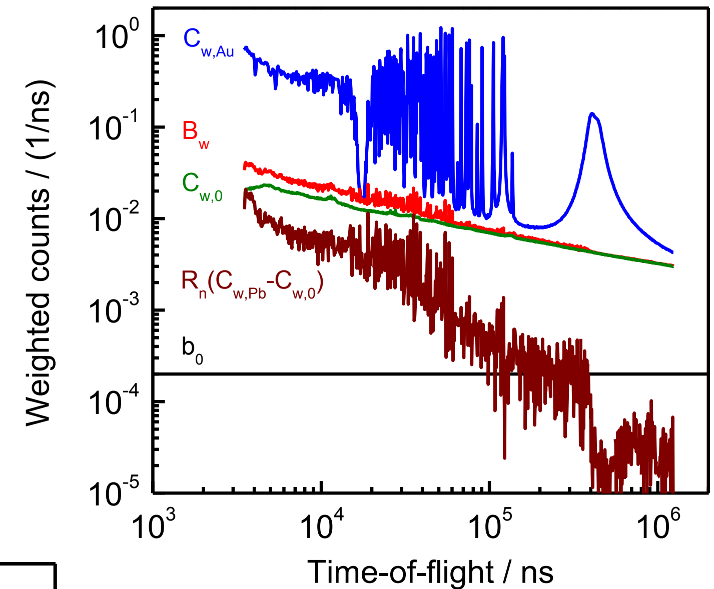


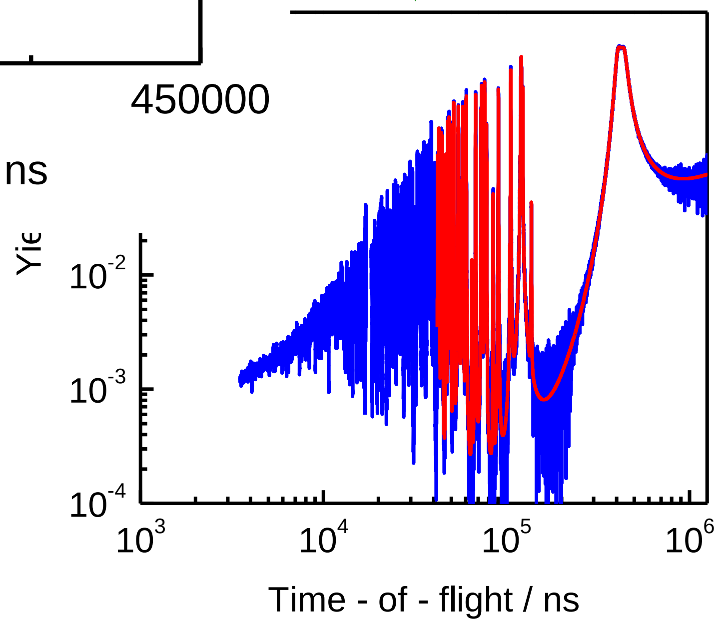
Use of fixed BGR filters :
reduces impact of systematic effects due to background

Normalization at saturated resonances (internal)



$$Y_{\gamma,exp} = N_C \frac{C_w - B_w}{C_\varphi - B_\varphi} Y_\varphi$$

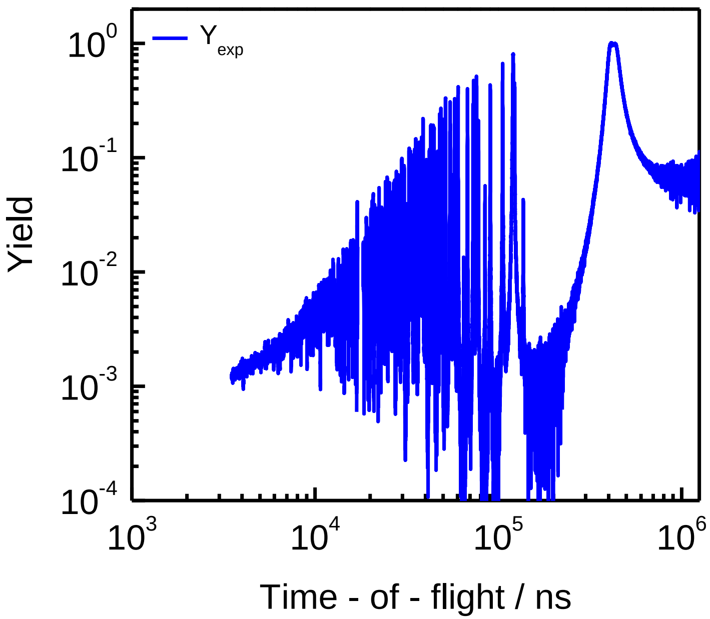


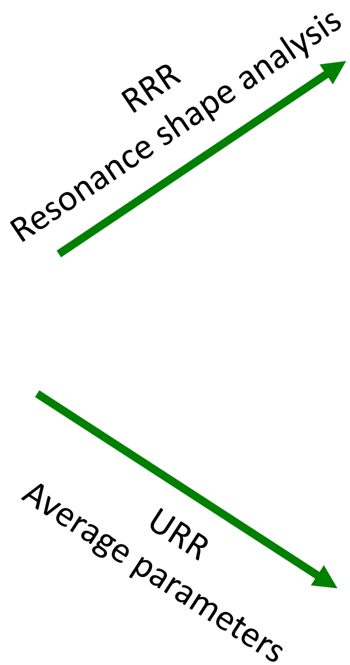


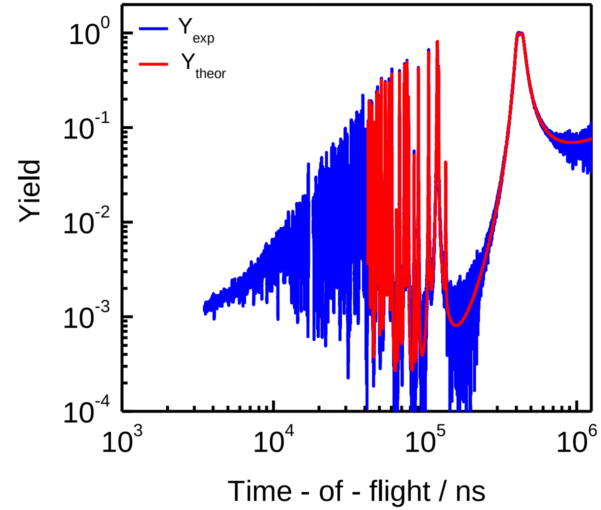
Saturated resonance at 4.9 eV
with $\Gamma_n << \Gamma_\gamma$
$\Rightarrow$ no reference cross section
except for shape of $^{10}B(n,\alpha)$

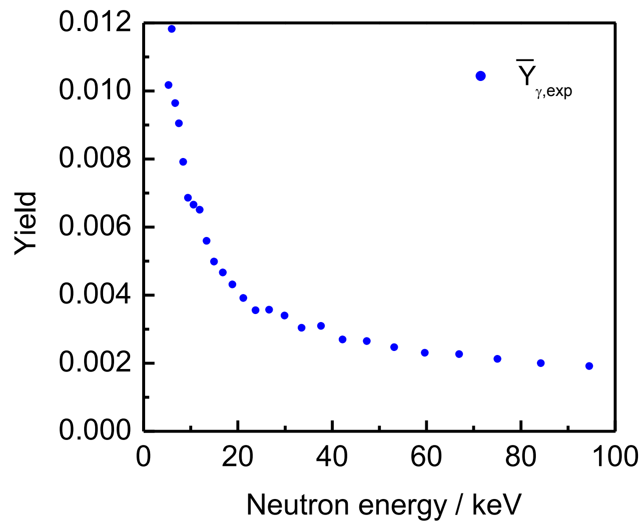
$$\frac{u_{N_C}}{N_C} \approx 1\%$$

Data analysis



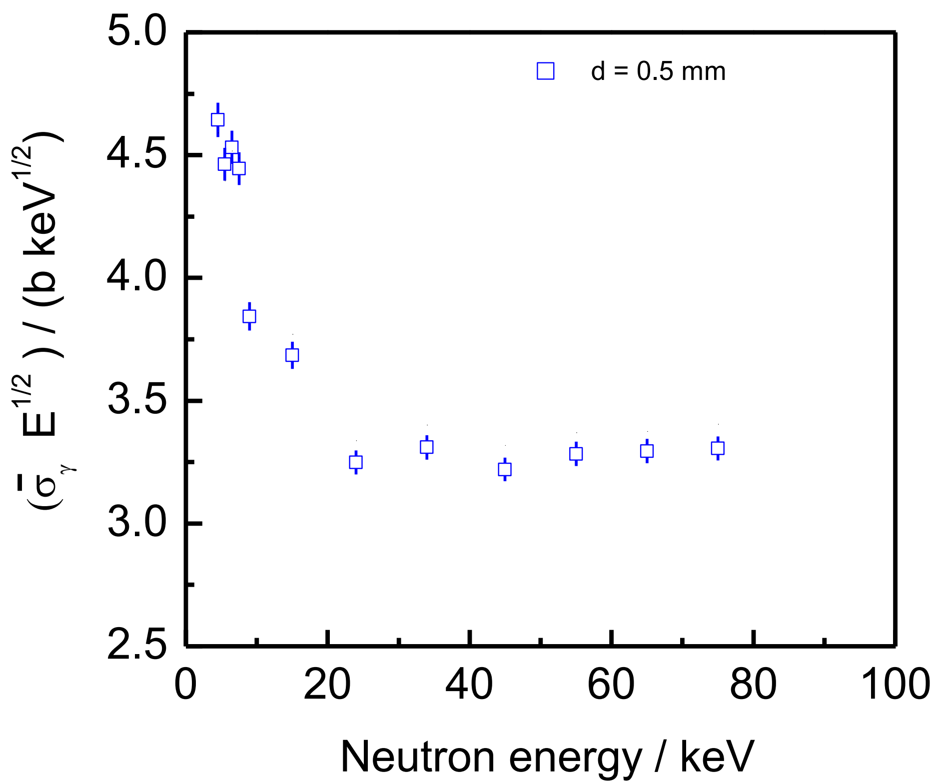


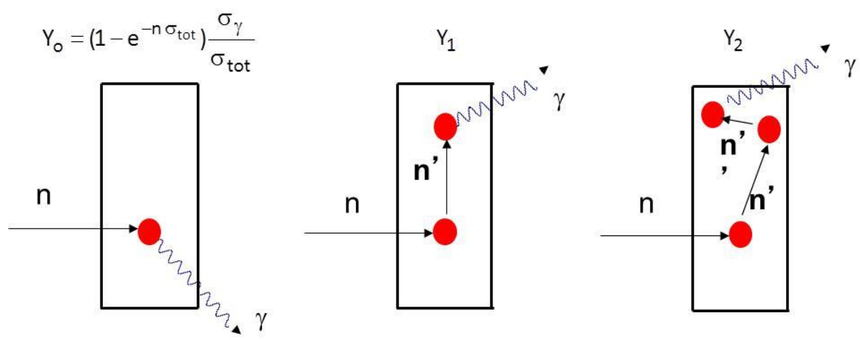




From average $\overline{Y}_{exp}$ to average $\overline{\sigma}_{\gamma}$

$$\overline{\sigma}_{\gamma} = \frac{\overline{Y}_{\gamma,exp}}{n}$$



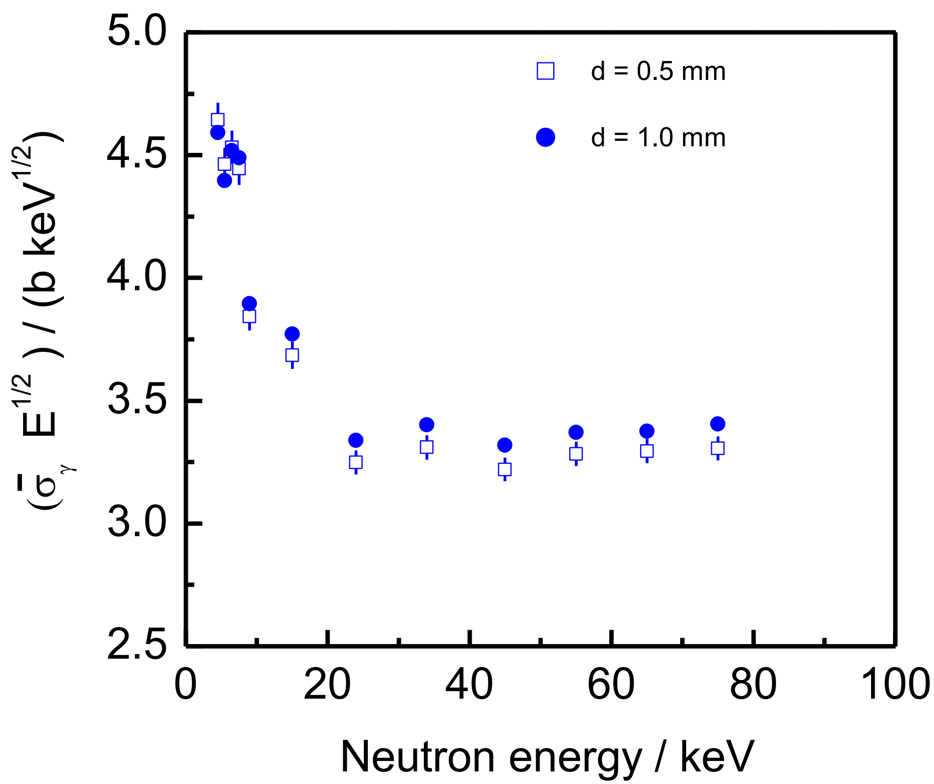


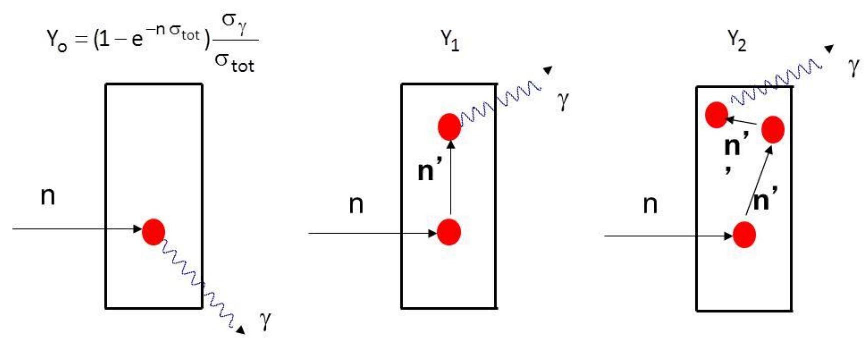
$$\overline{Y}_{\gamma,exp} = \overline{Y}_0 + \overline{Y}_1 + \overline{Y}_2 + \ldots$$

$$\overline{Y}_{\gamma,exp} \neq n\,\overline{\sigma}_{\gamma}$$

From average $\overline{Y}_{exp}$ to average $\overline{\sigma}_\gamma$

$$\overline{\sigma}_\gamma = \frac{\overline{Y}_{\gamma,exp}}{n}$$



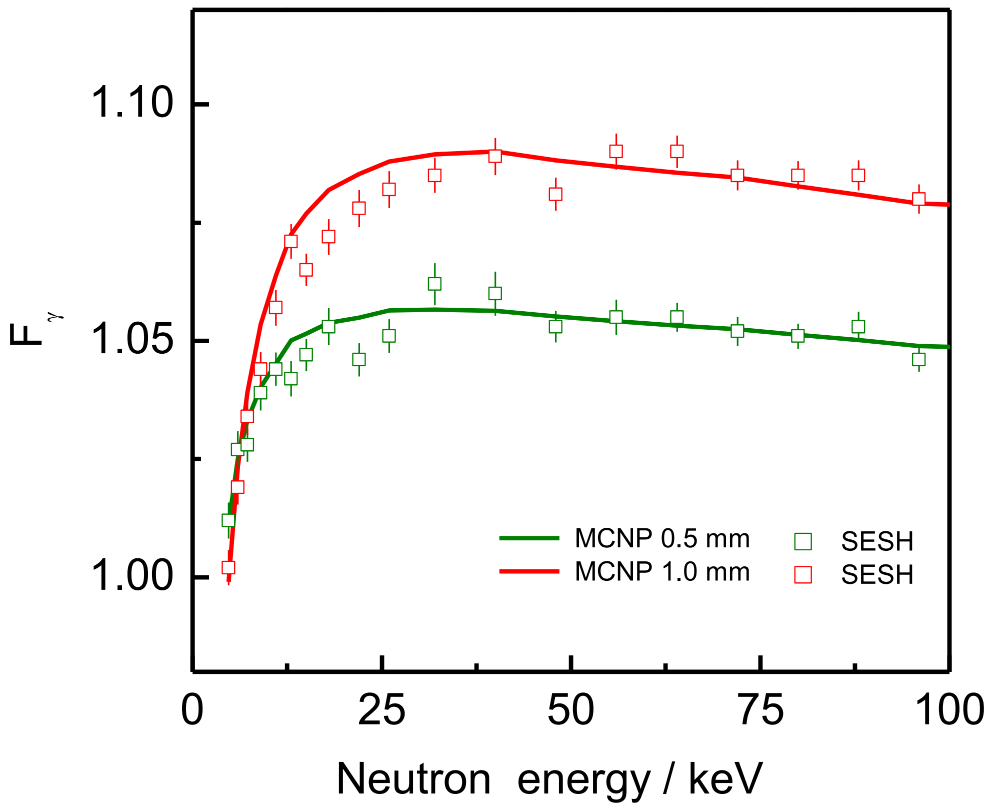


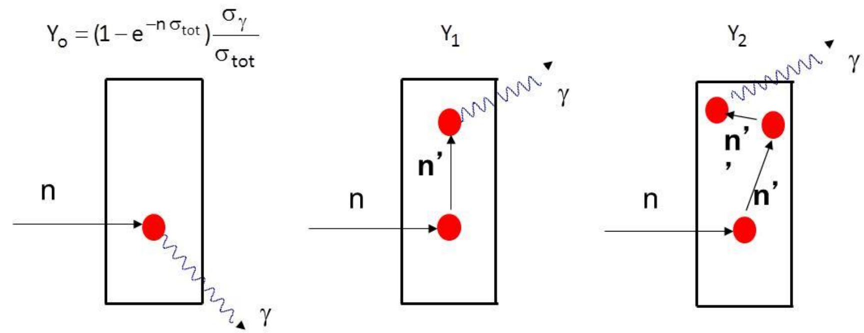
$$\overline{Y}_{\gamma,exp} = \overline{Y}_0 + \overline{Y}_1 + \overline{Y}_2 + \ldots$$

$$\overline{Y}_{\gamma,exp} \neq n\,\overline{\sigma}_\gamma$$

$$\overline{Y}_{\gamma,exp}(n) \cong n\,\overline{\sigma}_\gamma$$ only for thin samples

From average $\overline{Y}_{exp}$ to average $\overline{\sigma}_\gamma$





$$\overline{Y}_{\gamma,exp} = \overline{Y}_0 + \overline{Y}_1 + \overline{Y}_2 + \ldots$$

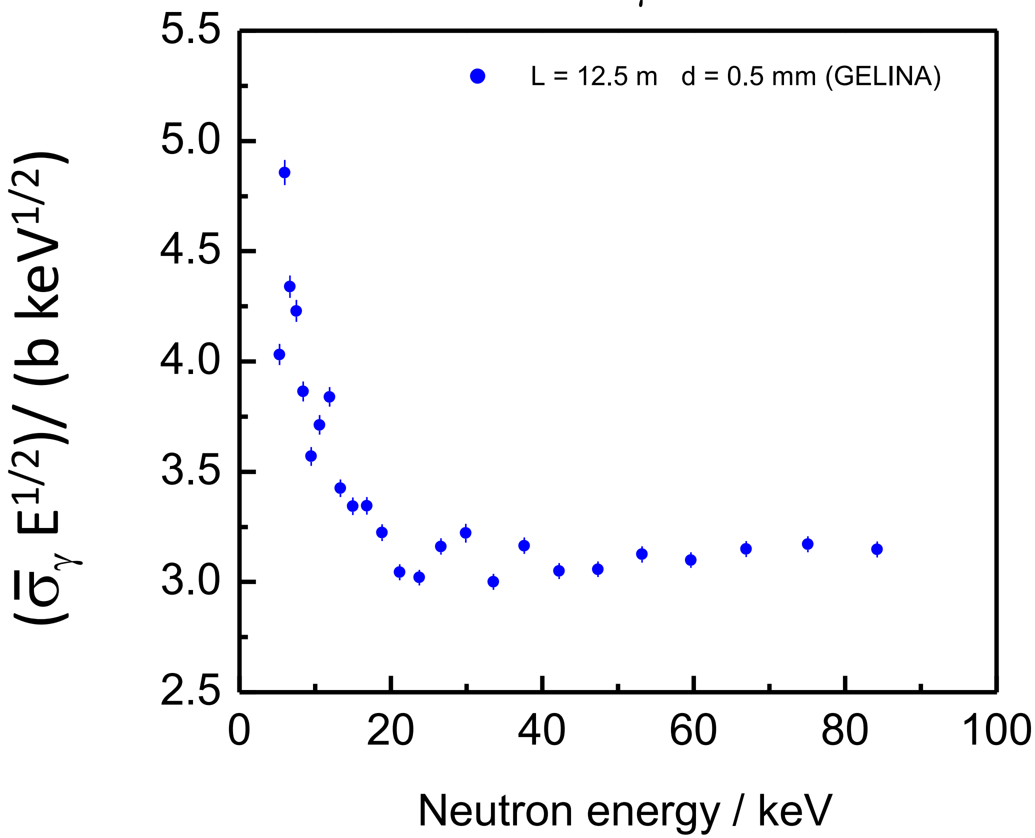
$$\overline{Y}_{\gamma,exp} \neq n\,\overline{\sigma}_\gamma$$

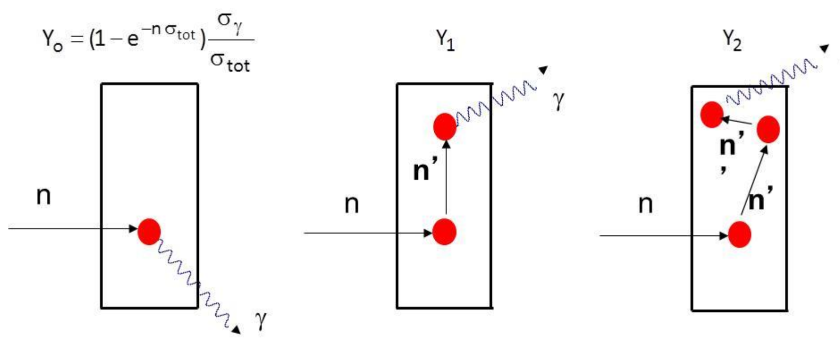
$$\overline{Y}_{\gamma,exp}(n) = F_\gamma\, n\,\overline{\sigma}_\gamma$$

$$F_\gamma = \frac{\overline{Y}_\gamma(n)/n}{\overline{Y}_\gamma(n_{thin})/n_{thin}}$$

From average $\bar{Y}_{exp}$ to average $\bar{\sigma}_\gamma$

$$\bar{\sigma}_\gamma = \frac{\bar{Y}_{\gamma,exp}}{F_\gamma\, n}$$





$$\bar{Y}_{\gamma,exp} = \bar{Y}_0 + \bar{Y}_1 + \bar{Y}_2 + \ldots$$

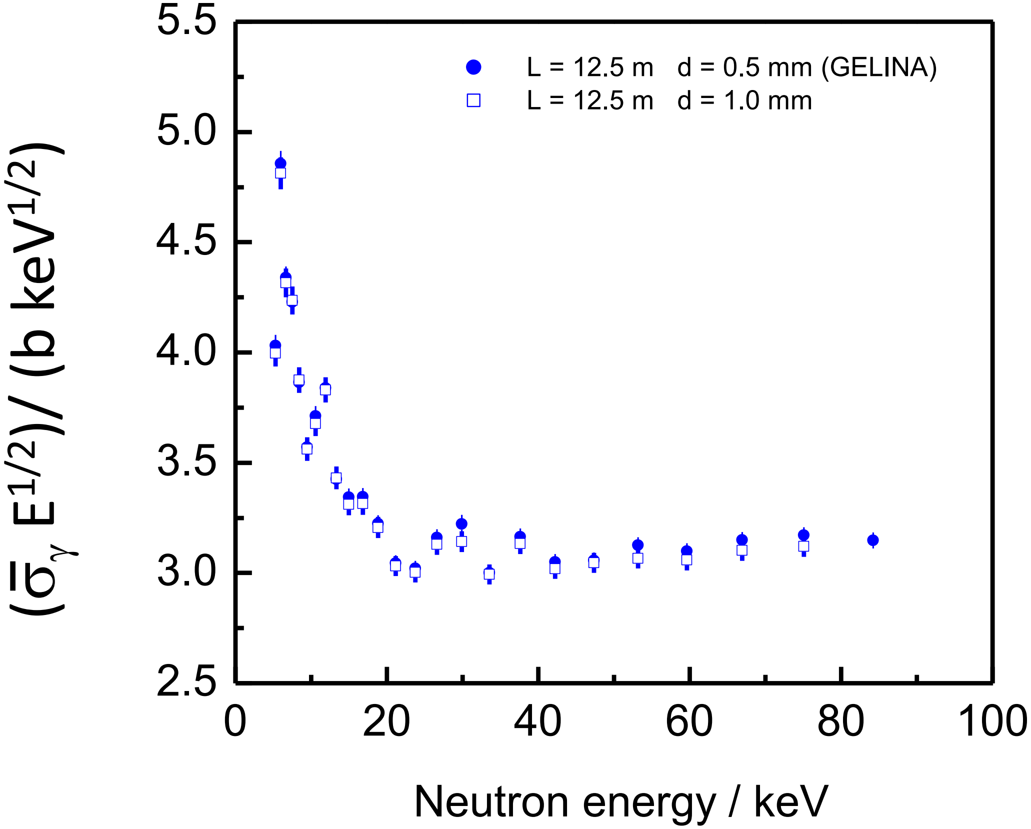
$$\bar{Y}_{\gamma,exp} \neq n\,\bar{\sigma}_\gamma$$

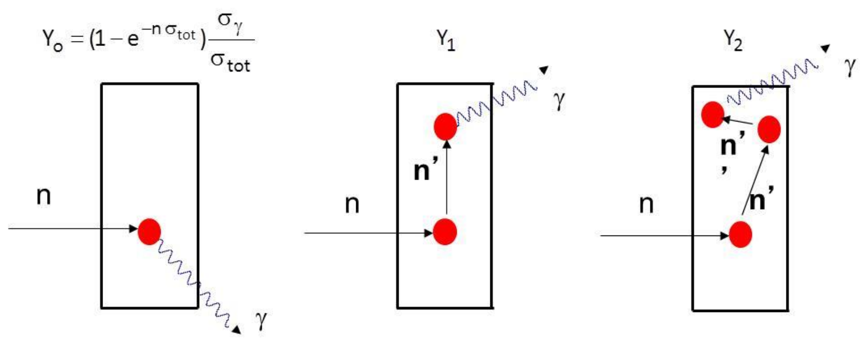
$$\bar{Y}_{\gamma,exp}(n) = F_\gamma\, n\,\bar{\sigma}_\gamma$$

$$F_\gamma = \frac{\bar{Y}_\gamma(n)/n}{\bar{Y}_\gamma(n_{thin})/n_{thin}}$$

From average $\overline{Y}_{exp}$ to average $\overline{\sigma}_\gamma$

$$\overline{\sigma}_\gamma = \frac{\overline{Y}_{\gamma,exp}}{F_\gamma\, n}$$





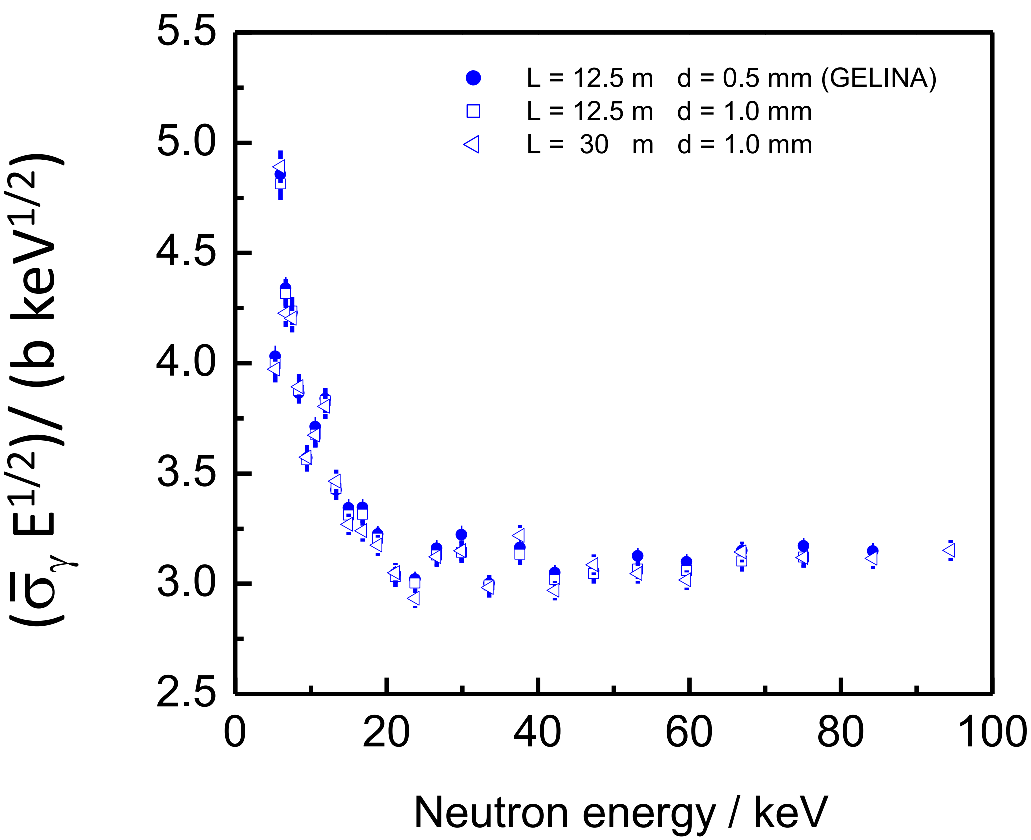
$$\overline{Y}_{\gamma,exp} = \overline{Y}_0 + \overline{Y}_1 + \overline{Y}_2 + \ldots$$

$$\overline{Y}_{\gamma,exp} \neq n\,\overline{\sigma}_\gamma$$

$$\overline{Y}_{\gamma,exp}(n) = F_\gamma\, n\,\overline{\sigma}_\gamma$$

$$F_\gamma = \frac{\overline{Y}_\gamma(n)/n}{\overline{Y}_\gamma(n_{thin})\,/\,n_{thin}}$$

Average $\bar{\sigma}_\gamma$ from measurements at GELINA



$$Y_{\gamma,exp} = N_C \frac{C_w - B_w}{C_\varphi - B_\varphi} Y_\varphi$$

$$B_w(t) = c_0 + k_1 C_{w,0}(t) + k_2\ R_n(C_{w,Pb} - C_{w,0})(t)$$

$$\frac{u_{N_C}}{N_C} \approx 1\% \qquad \frac{u_{k_1}}{k_1} \approx 3\% \qquad \frac{u_{k_2}}{k_2} \approx 5\%$$

$$\bar{\sigma}_\gamma = \frac{\bar{Y}_{\gamma,exp}}{F_\gamma\ n} \qquad \frac{u_{\bar{\sigma}_\gamma}}{\bar{\sigma}_\gamma} \approx 1.2\%$$

Reporting $\overline{\sigma}_\gamma$

Table 4. Average capture cross section ($\overline{\sigma}_\gamma$) and total uncertainty derived from the data obtained in this work. The information to derive the full covariance matrix based on the AGS concept (eq. (7)) is given: the diagonal elements of the uncorrelated components, $u_u = \sqrt{U_u}$ are in column 6, whereas columns 7–10 represent the matrix $S_{\eta=\{b_0,k_1,k_2,N_c\}}$. A high precision is given to ensure that the resulting covariance matrix can be inverted. The correction factor F_c for self-shielding multiple interaction is given in column 3.

E_l/eV	E_h/eV	F_c	$\overline{\sigma}_\gamma$/b	$u_{\overline{\sigma}_\gamma}$/b	AGS				
					u_u/b	S_{b_0}/b	S_{k_1}/b	S_{k_2}/b	S_{N_C}/b
3500	4000	0.9893	2.8696	0.0354	0.0084	−0.001731	−0.012957	−0.004330	0.031566
4000	4500	1.0022	2.2833	0.0284	0.0070	−0.001352	−0.010596	−0.003448	0.025116
4500	5000	1.0113	2.0888	0.0251	0.0058	−0.000981	−0.007942	−0.002375	0.022977
5000	5500	1.0180	1.5480	0.0190	0.0047	−0.000803	−0.006683	−0.001828	0.017028
5500	6000	1.0232	2.1886	0.0259	0.0057	−0.000734	−0.006767	−0.003384	0.024075
6000	6500	1.0273	1.7350	0.0207	0.0051	−0.000649	−0.006058	−0.001689	0.019085
6500	7000	1.0306	1.7219	0.0204	0.0049	−0.000567	−0.005428	−0.001737	0.018941
7000	8000	1.0345	1.5664	0.0184	0.0036	−0.000554	−0.005162	−0.001519	0.017230
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9000	10000	1.0414	1.1502	0.0137	0.0032	−0.000437	−0.004116	−0.001166	0.012652
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$(C_w, C_{w,0}, C_{w,Pb}, C_\varphi)$

↓

$$Y_{\gamma,exp} = N_C \frac{C_w - B_w}{C_\varphi - B_\varphi} Y_\varphi$$

↓

$\overline{Y}_{exp}$

↓

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Reporting $\overline{\sigma}_\gamma$ + covariance data (AGS-formalism)

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					u_u/b	S_{b_0}/b	S_{k_1}/b	S_{k_2}/b	S_{N_C}/b
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4000	4500	1.0022	2.2833	0.0284	0.0070	−0.001352	−0.010596	−0.003448	0.025116
4500	5000	1.0113	2.0888	0.0251	0.0058	−0.000981	−0.007942	−0.002375	0.022977
5000	5500	1.0180	1.5480	0.0190	0.0047	−0.000803	−0.006683	−0.001828	0.017028
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Reporting $\bar{\sigma}_\gamma$ + covariance data (AGS-formalism)

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Reporting $\overline{\sigma}_\gamma$ + covariance data (AGS-formalism)

Table 4. Average capture cross section ($\overline{\sigma}_\gamma$) and total uncertainty derived from the data obtained in this work. The information to derive the full covariance matrix based on the AGS concept (eq. (7)) is given: the diagonal elements of the uncorrelated components, $u_u = \sqrt{U_u}$ are in column 6, whereas columns 7–10 represent the matrix $S_{\eta=\{b_0,k_1,k_2,N_c\}}$. A high precision is given to ensure that the resulting covariance matrix can be inverted. The correction factor F_c for self-shielding multiple interaction is given in column 3.

E_l/eV	E_h/eV	F_c	$\overline{\sigma}_\gamma$/b	$u_{\overline{\sigma}_\gamma}$/b	AGS				
					u_u/b	S_{b_0}/b	S_{k_1}/b	S_{k_2}/b	S_{N_C}/b
3500	4000	0.9893	2.8696	0.0354	0.0084	−0.001731	−0.012957	−0.004330	0.031566
4000	4500	1.0022	2.2833	0.0284	0.0070	−0.001352	−0.010596	−0.003448	0.025116
4500	5000	1.0113	2.0888	0.0251	0.0058	−0.000981	−0.007942	−0.002375	0.022977
5000	5500	1.0180	1.5480	0.0190	0.0047	−0.000803	−0.006683	−0.001828	0.017028
5500	6000	1.0232	2.1886	0.0259	0.0057	−0.000734	−0.006767	−0.003384	0.024075
6000	6500	1.0273	1.7350	0.0207	0.0051	−0.000649	−0.006058	−0.001689	0.019085
6500	7000	1.0306	1.7219	0.0204	0.0049	−0.000567	−0.005428	−0.001737	0.018941
7000	8000	1.0345	1.5664	0.0184	0.0036	−0.000554	−0.005162	−0.001519	0.017230
8000	9000	1.0385	1.3120	0.0156	0.0034	−0.000494	−0.004555	−0.001419	0.014432
9000	10000	1.0414	1.1502	0.0137	0.0032	−0.000437	−0.004116	−0.001166	0.012652
10000	12000	1.0446	1.1625	0.0135	0.0023	−0.000374	−0.003588	−0.001109	0.012788
12000	14000	1.0475	0.9572	0.0113	0.0022	−0.000324	−0.003234	−0.000963	0.010529
14000	16000	1.0495	0.8569	0.0102	0.0022	−0.000283	−0.002963	−0.000830	0.009426
16000	18000	1.0509	0.8215	0.0097	0.0022	−0.000250	−0.002674	−0.000756	0.009037
18000	20000	1.0519	0.7329	0.0087	0.0021	−0.000225	−0.002411	−0.000705	0.008062
20000	24000	1.0529	0.6418	0.0076	0.0015	−0.000195	−0.002145	−0.000650	0.007060
24000	28000	1.0538	0.6165	0.0072	0.0015	−0.000168	−0.001929	−0.000703	0.006781
28000	32000	1.0542	0.5842	0.0076	0.0026	−0.000242	−0.002914	−0.000896	0.006426
32000	36000	1.0544	0.5160	0.0062	0.0016	−0.000144	−0.001835	−0.000669	0.005676
36000	40000	1.0544	0.5168	0.0061	0.0015	−0.000122	−0.001581	−0.000575	0.005685
40000	44000	1.0543	0.4709	0.0056	0.0014	−0.000103	−0.001343	−0.000487	0.005180
44000	52000	1.0539	0.4403	0.0051	0.0010	−0.000089	−0.001119	−0.000440	0.004843
52000	60000	1.0533	0.4192	0.0049	0.0011	−0.000088	−0.001074	−0.000610	0.004612
60000	68000	1.0526	0.3894	0.0045	0.0009	−0.000062	−0.000739	−0.000523	0.004284
68000	76000	1.0517	0.3771	0.0043	0.0009	−0.000054	−0.000632	−0.000500	0.004148
76000	84000	1.0508	0.3429	0.0039	0.0009	−0.000054	−0.000619	−0.000335	0.003772

$(C_w, C_{w,0}, C_{w,Pb}, C_\varphi)$

$$B_w(t) = b_0 + k_1 C_{w,0}(t) + k_2 R_n(C_{w,Pb} - C_{w,0})(t)$$

$$Y_{\gamma,exp} = N_C \frac{C_w - B_w}{C_\varphi - B_\varphi} Y_\varphi$$

$$\overline{Y}_{exp}$$

$$\overline{\sigma}_\gamma = \frac{\overline{Y}_{\gamma,exp}}{F_\gamma\, n}$$

+ covariance data

u_u and $S_{(b_0,k_1,k_2,N_C)}$

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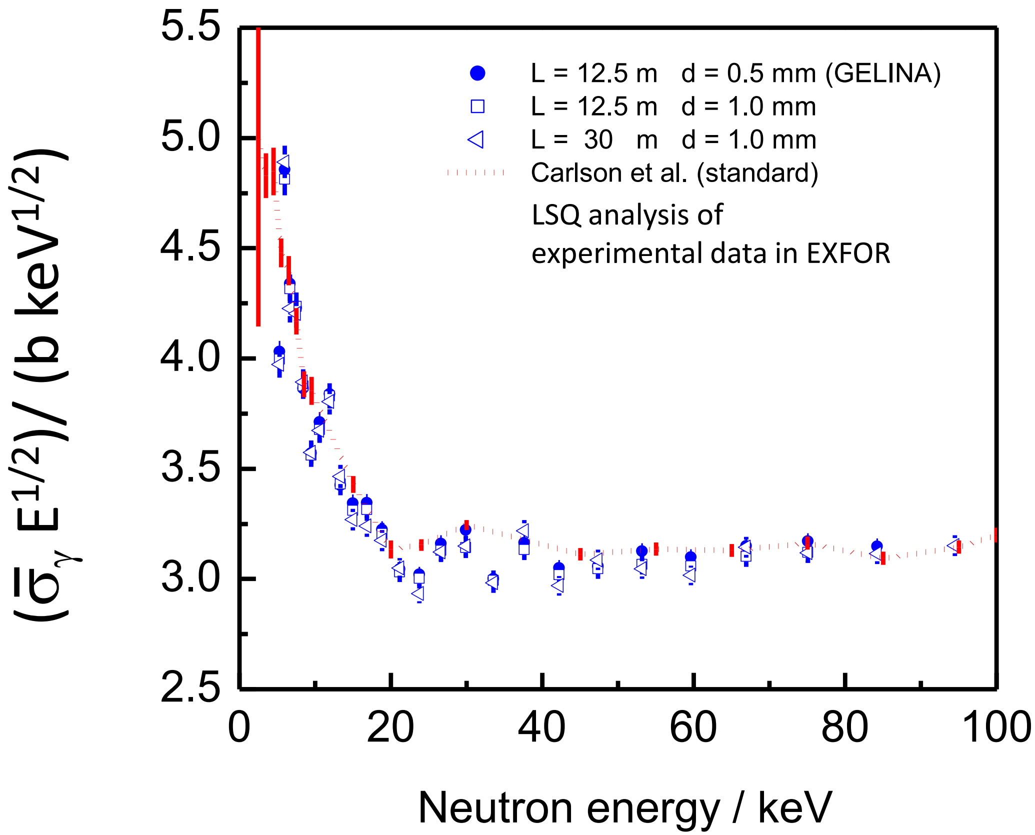
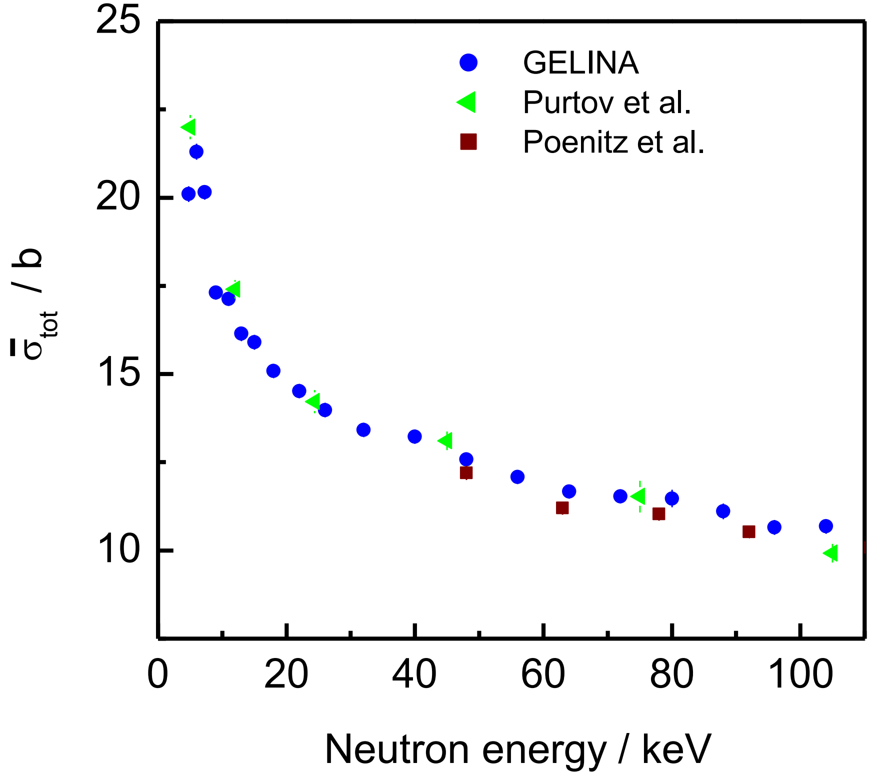
Comparison with data in the literature

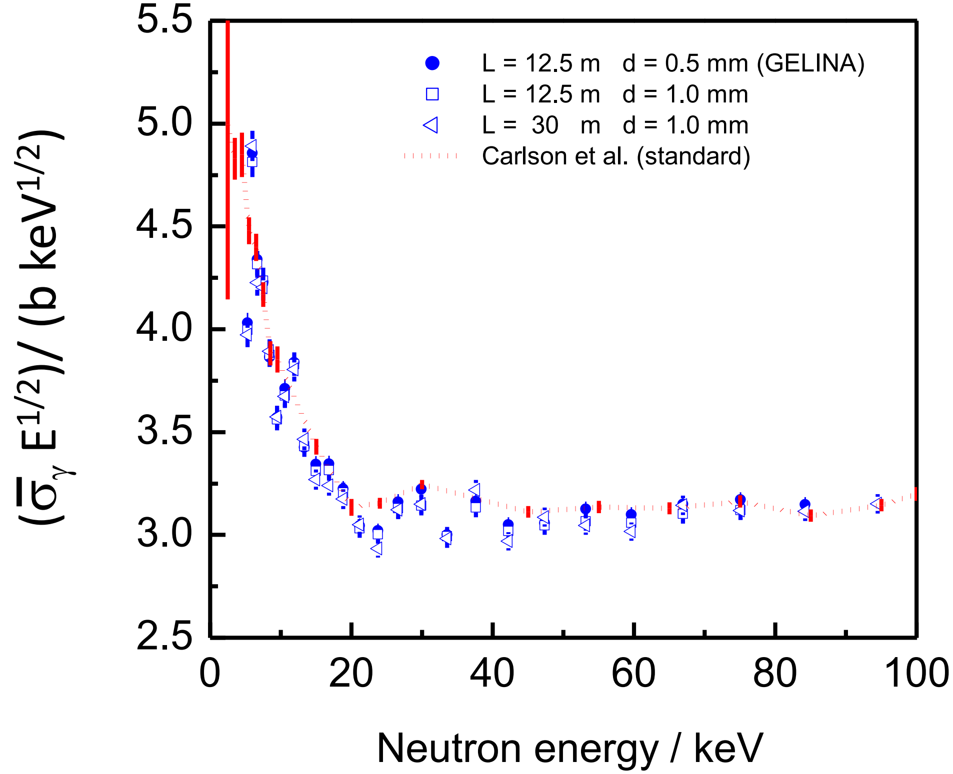


$$\frac{u_{\bar{\sigma}_\gamma}}{\bar{\sigma}_\gamma} \approx 1.2\%$$

Evaluation for ^{197}Au + n in URR



$$\frac{u_{\bar{\sigma}_{tot}}}{\bar{\sigma}_{tot}} \approx 1\% - 2\%$$



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Evaluation for $^{197}Au + n$ in URR