The European Commission's science and knowledge service

Joint Research Centre

Neutron time-of-flight measurements and transmission measurements

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Workshop on the Evaluation of Nuclear Reaction Data for Applications
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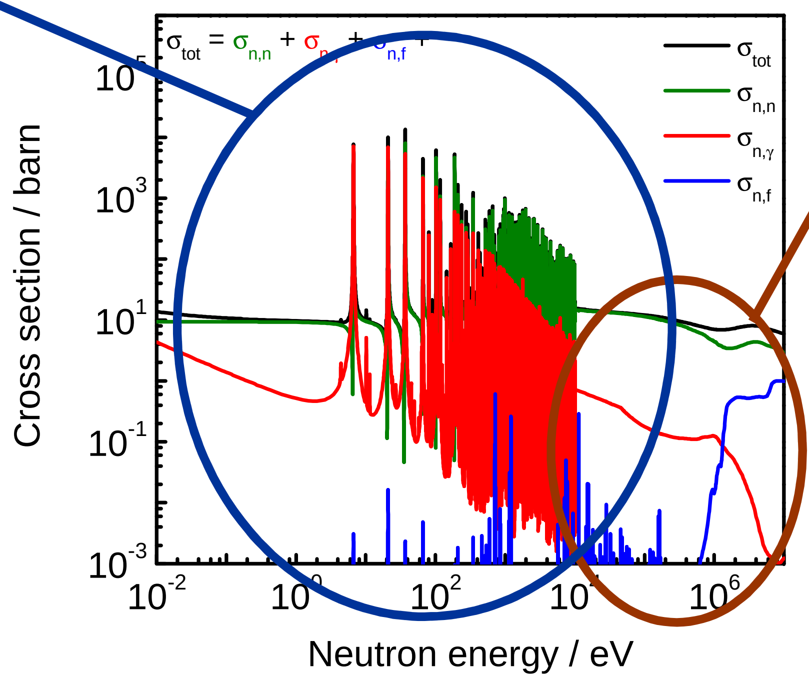
ICTP, Trieste, Italy

European Commission

Neutron induced reaction cross sections

GELINA

^{238}U+n



Van de Graaff

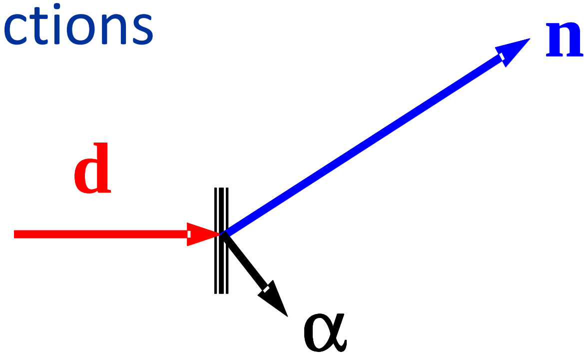
White neutron source
+
Time-of-flight (TOF)

Mono-energetic neutrons
(cp,n) reactions

Mono-energetic neutron beams by (cp,n) reactions

quasi mono-energetic neutrons produced via nuclear reactions

e.g. T(d,n)^{4}He

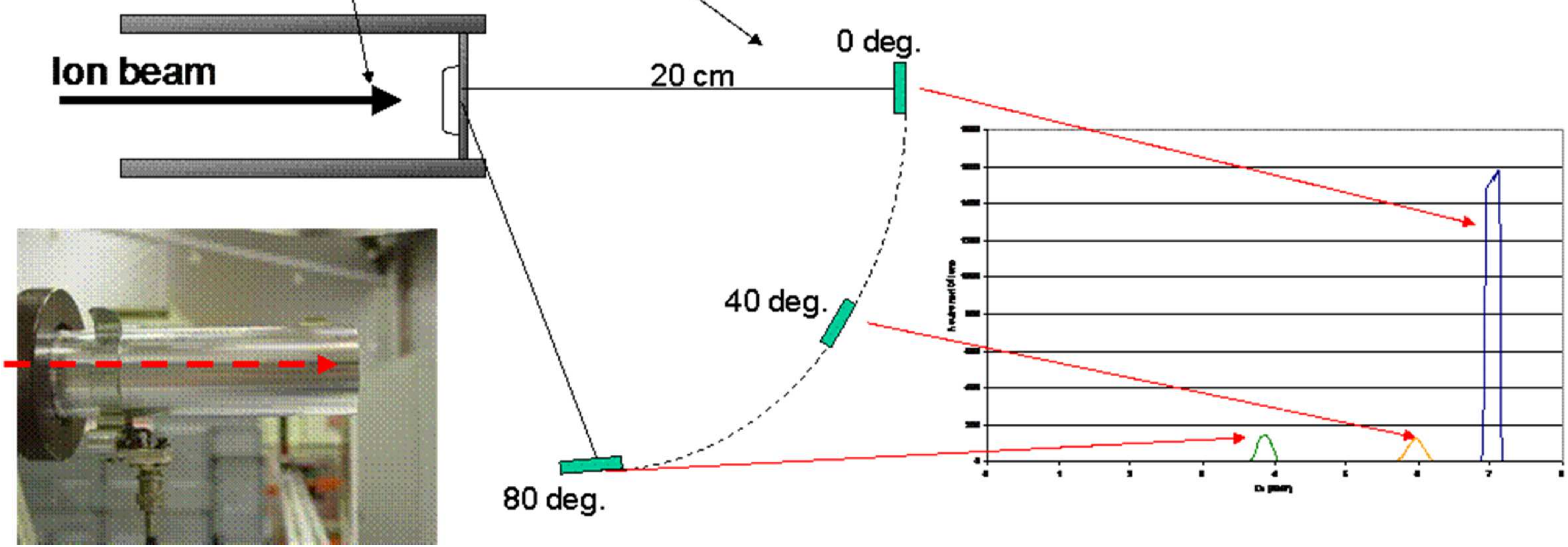


^{7}Li(p,n)^{7}Be	E_n: 0 - 5.3 MeV
T(p,n)^{3}He	E_n: 0 - 6.2 MeV
D(d,n)^{3}He	E_n: 1.8 - 10.1 MeV
T(d,n)^{4}He	E_n: 12.1 - 24.1 MeV

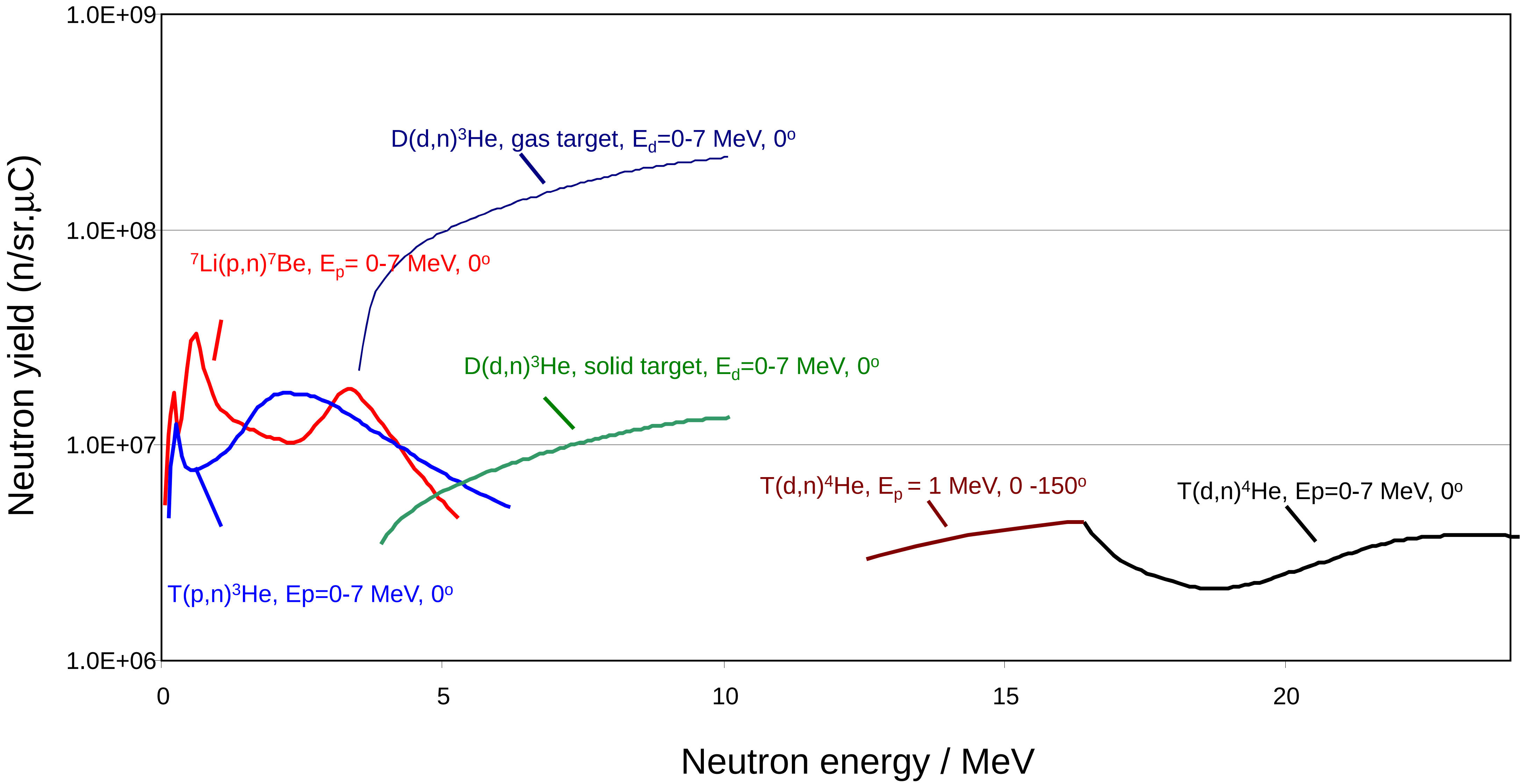
Mono-energetic neutron beams by (cp,n) reactions

- nuclear reaction,
- neutron emission angle,
- ion energy.

$^{7}Li(p,n)^{7}Be$ E_n: 0 - 5.3 MeV
$T(p,n)^{3}He$ E_n: 0 - 6.2 MeV
$D(d,n)^{3}He$ E_n: 1.8 - 10.1 MeV
$T(d,n)^{4}He$ E_n: 12.1 - 24.1 MeV



Mono-energetic neutron beams by (cp,n) reactions



Time-of flight facility GELINA

- Pulsed white neutron source

  (10 meV < E_n < 20 MeV)

- Neutron energy : time – of – flight (TOF)

- Multi-user facility: 10 flight paths (10 m – 400 m)

- Measurement stations with special equipment:
  - Total cross section measurements
  - Reaction cross section measurements

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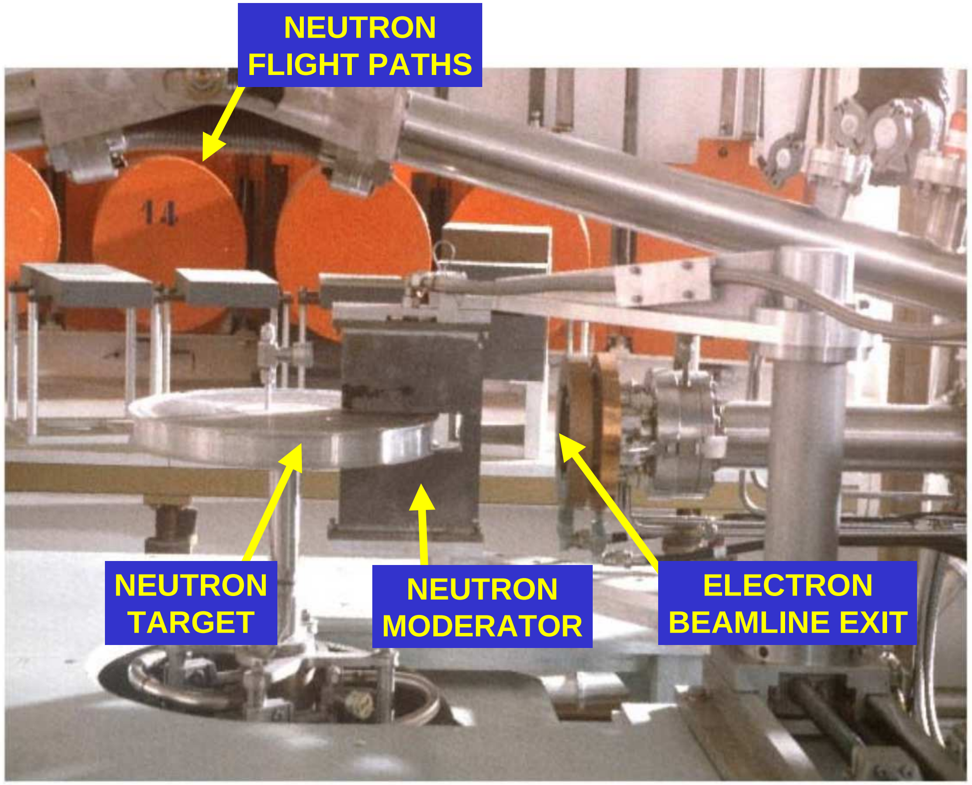
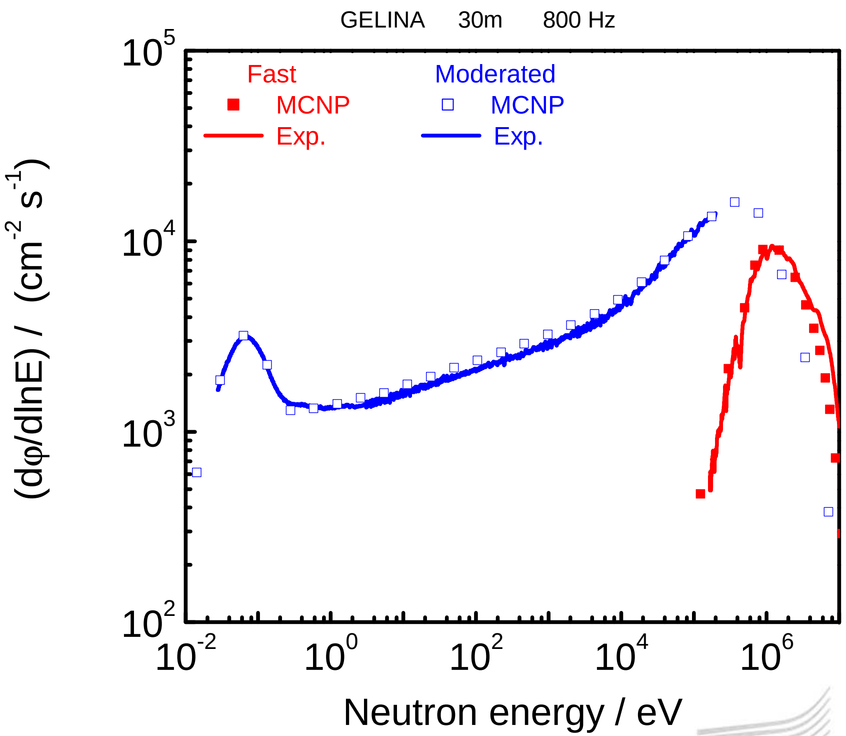
GELINA : neutron production

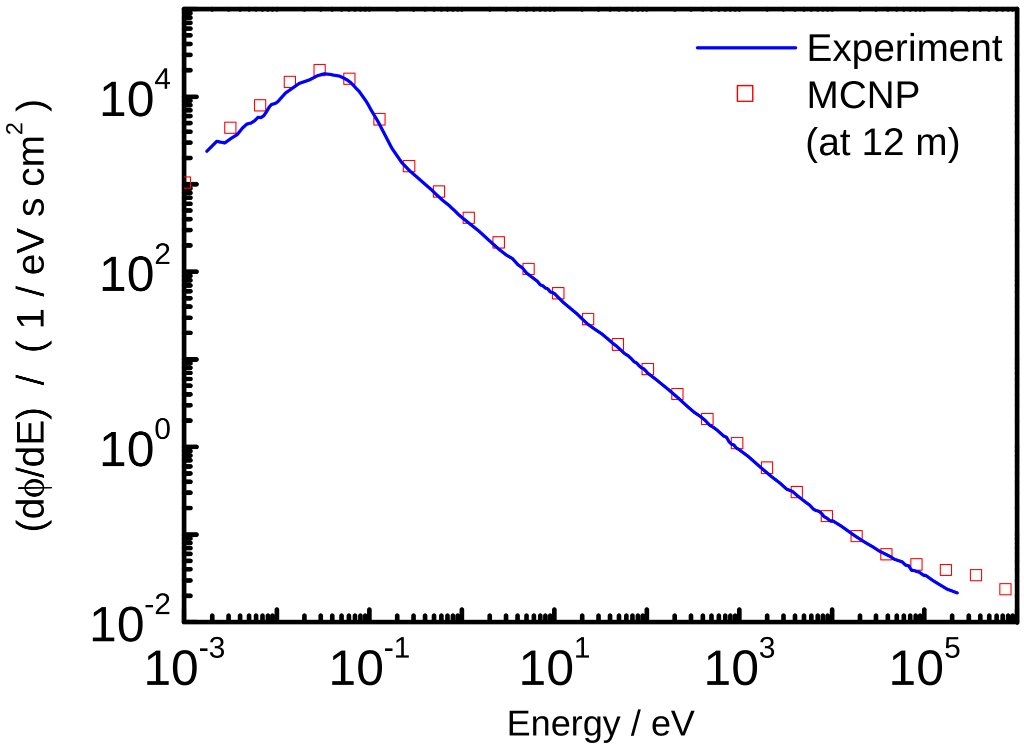


Neutron production:

- Bremsstrahlung in U-target
- (γ, n) and (γ, f) in U-target
- Low energy part enhanced by moderator (water in Be-canning)



Characteristics of neutron source



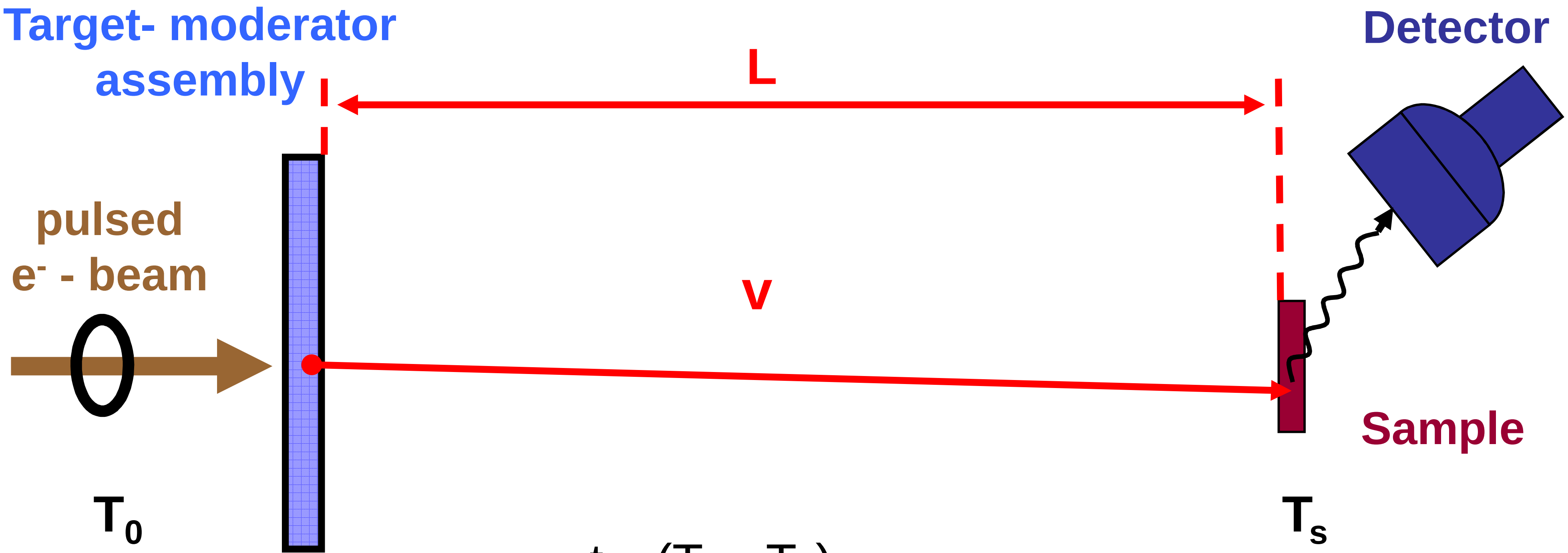
- Isotropic emission

$$\varphi_n(L) \propto \frac{1}{L^2}$$

- Moderated Spectrum

Maxwellian + 1/E

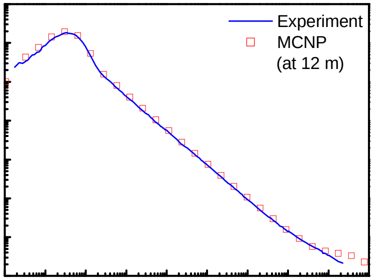
TOF - measurements

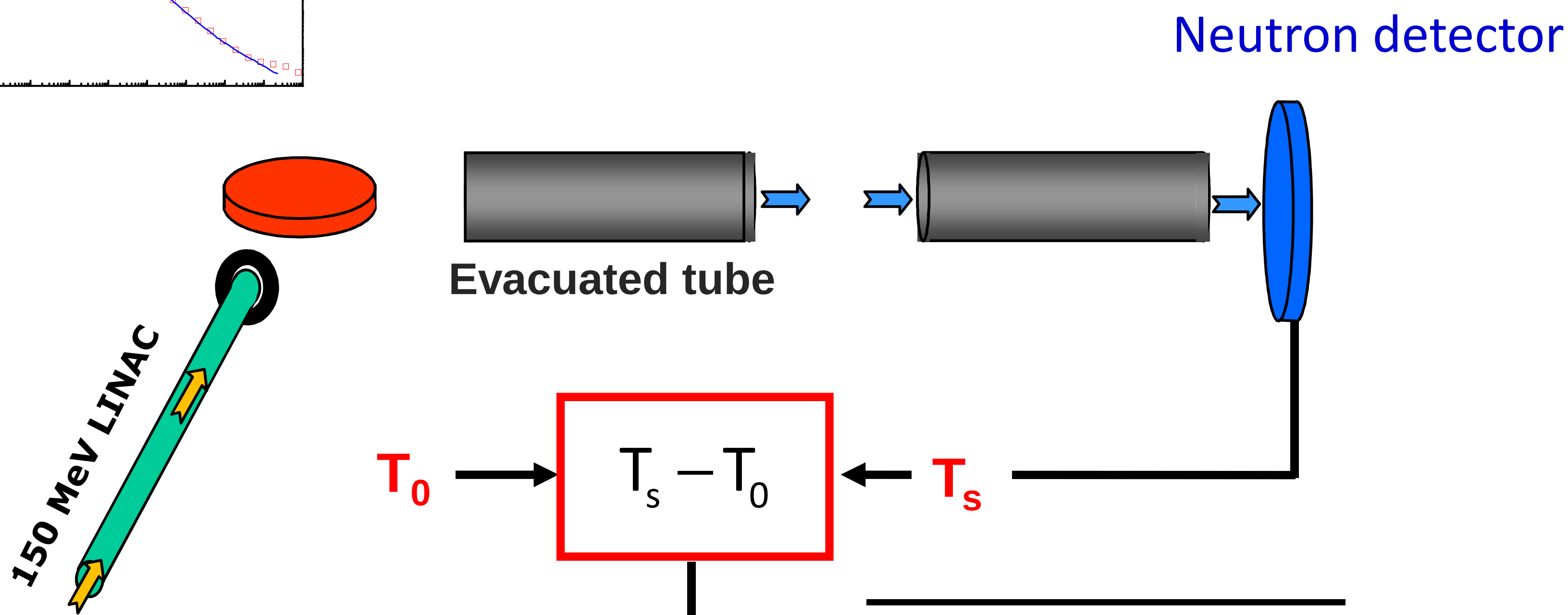


$$t \approx (T_s - T_0)$$

$$v = \frac{L}{t} \quad \Rightarrow \quad E = mc^2(\gamma - 1) \cong \frac{1}{2}mv^2$$

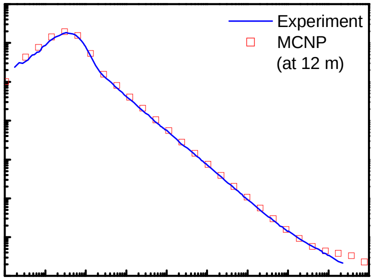
TOF - measurements

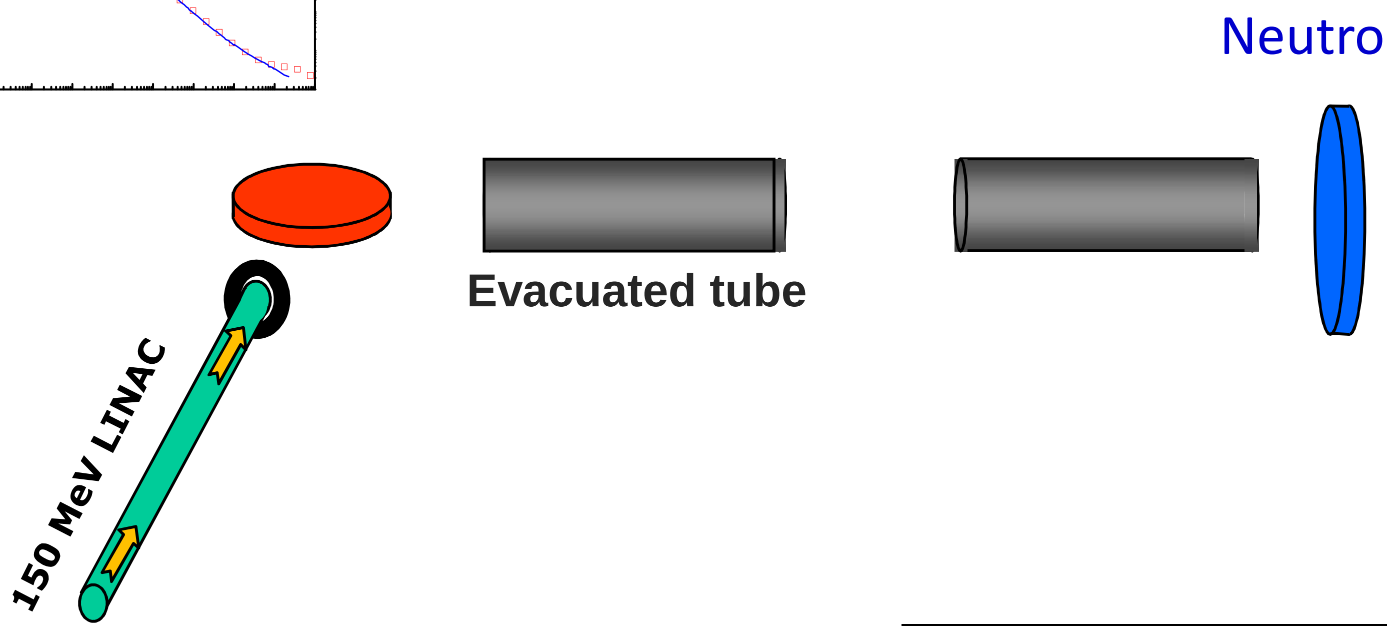


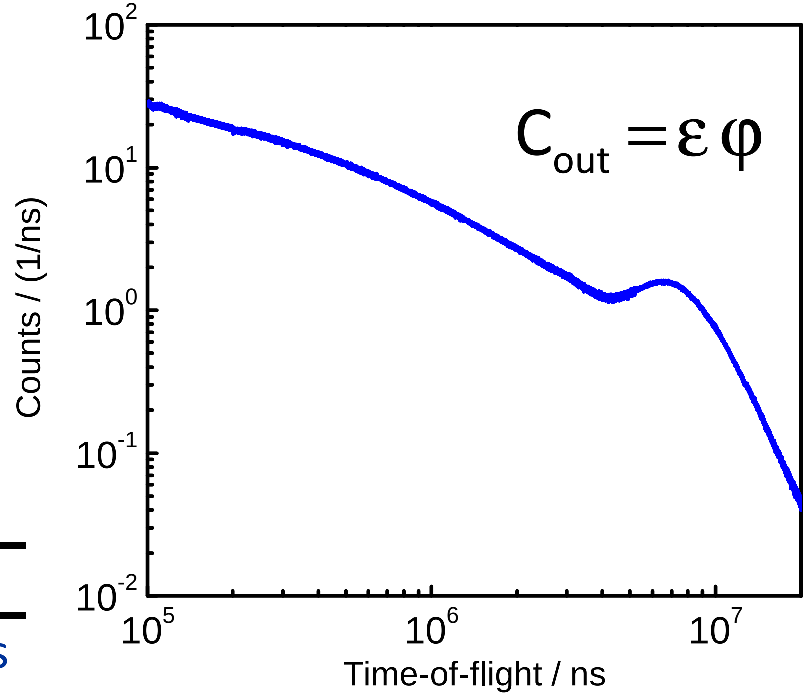


Event	Time
1	4000 ns

TOF - measurements

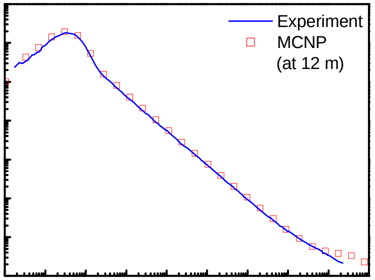


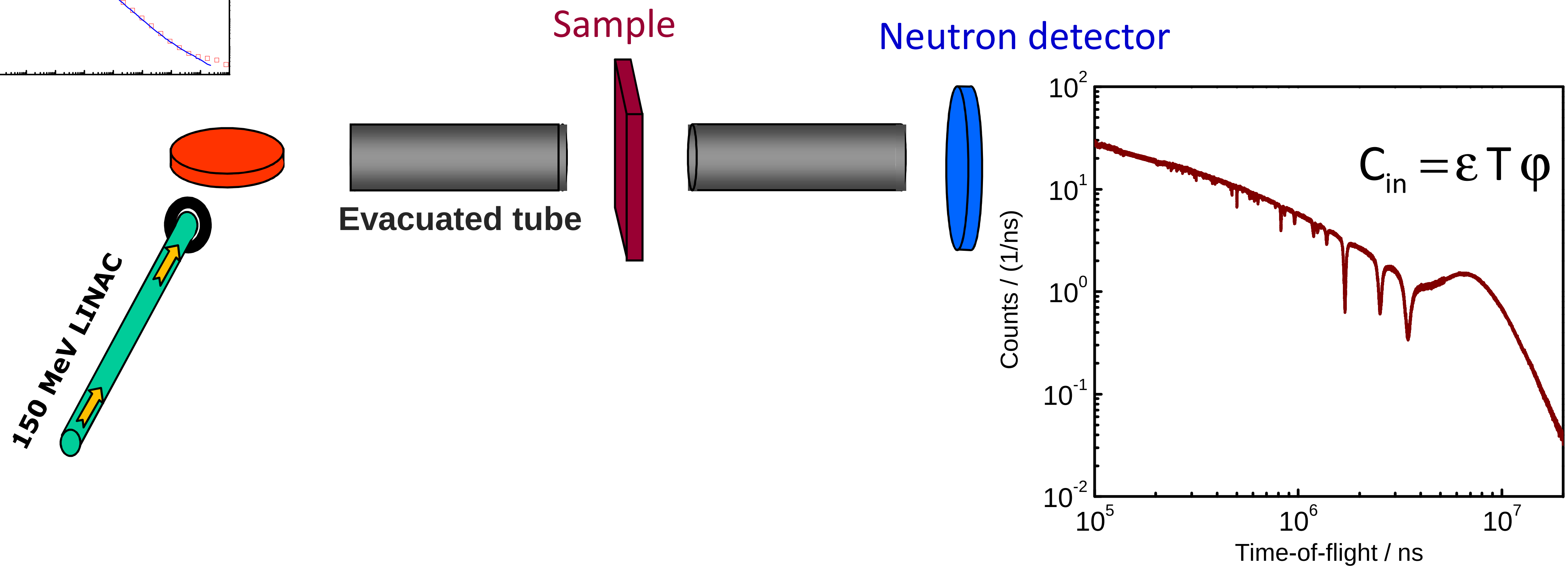




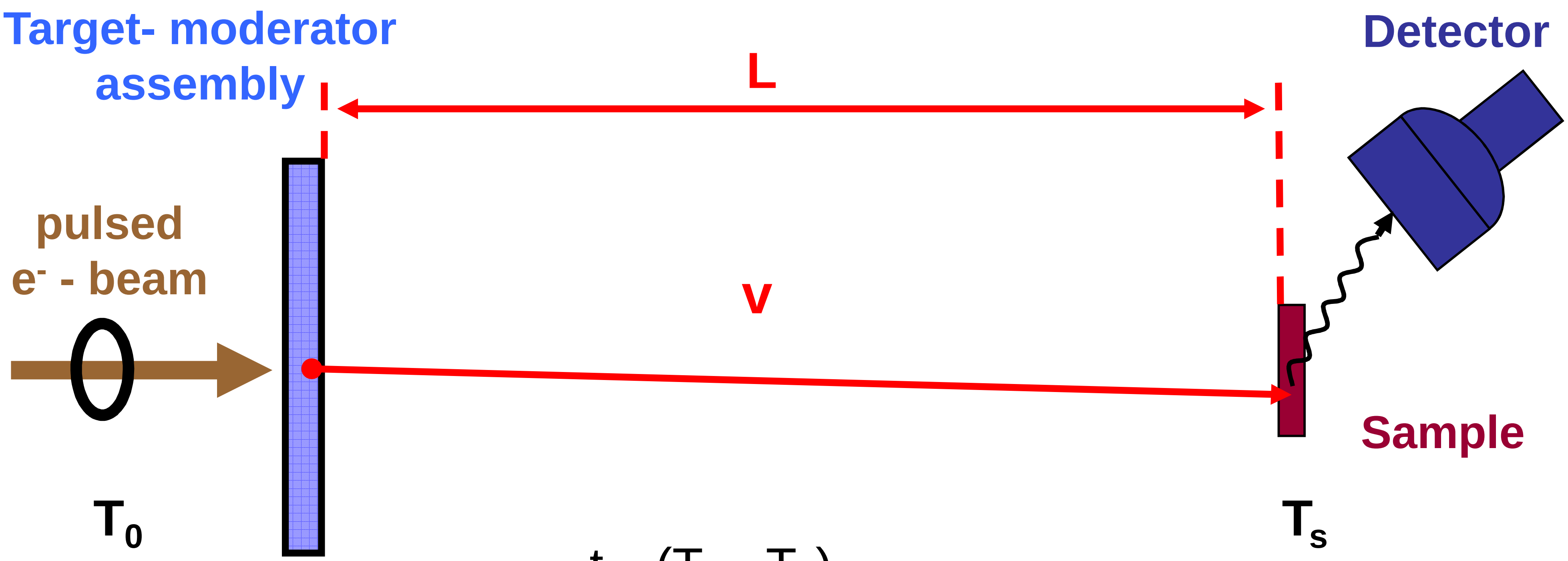
Event	Time
1	4000 ns
2	50000 ns
3	750000 ns
4	500 ns
.	.
.	.

TOF - measurements





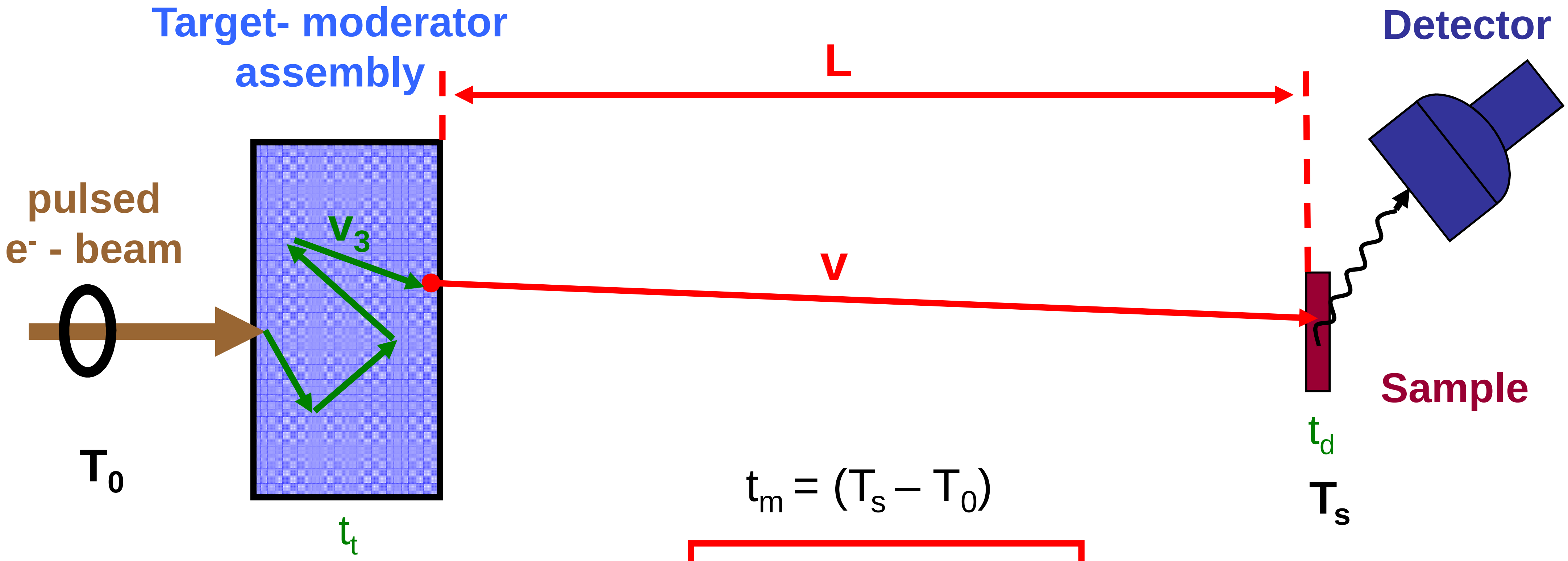
TOF - measurements



$$t \approx (T_s - T_0)$$

$$v = \frac{L}{t} \quad \Rightarrow \quad E = mc^2(\gamma - 1) \;\cong \frac{1}{2}mv^2$$

TOF - measurements



$$t_m = (T_s - T_0)$$

$$t = t_m - (t_t + t_d)$$

$$v = \frac{L}{t}$$

TOF - measurements

$$v = \frac{L}{t}$$

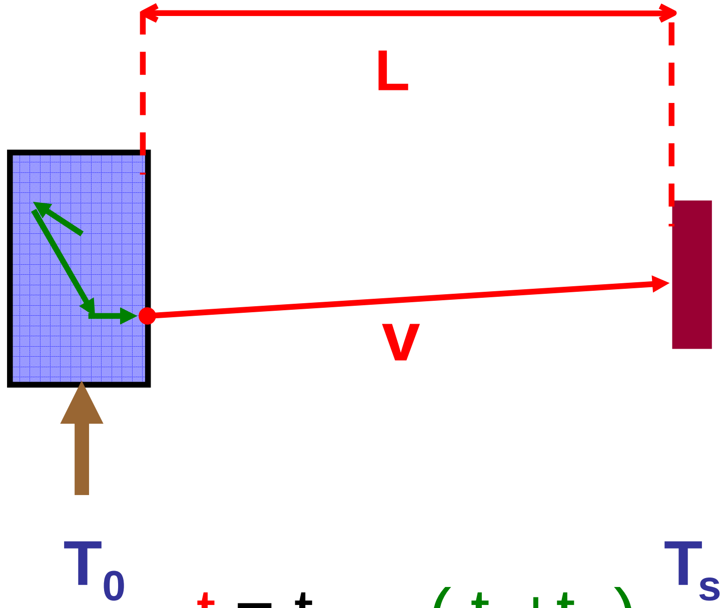
$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}}$$

$$E = mc^2(\gamma - 1)$$

$$\frac{\Delta E}{E} = (1+\gamma)\gamma\frac{\Delta v}{v}$$

$$E \cong \frac{1}{2}mv^2$$

$$\frac{\Delta E}{E} \cong 2\frac{\Delta v}{v}$$



$$t = t_m - (t_t + t_d)$$

$$E \cong \left(72.298\frac{L}{t}\right)^2$$

E : eV

t : μs

L : m

$\Rightarrow$ 1 eV neutron : $v \cong 13.8 \times 10^3$ m/s

$\Rightarrow$ γ-ray : $c \cong 3 \times 10^8$ m/s $\cong 300$ m/μs

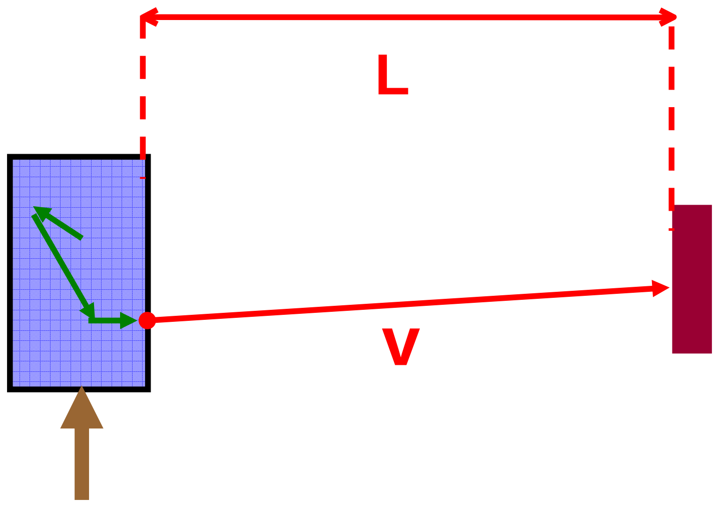
Response of TOF-spectrometer

$$v = \frac{L}{t}$$

$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}}$$

$$\frac{\Delta v}{v} = \frac{1}{L}\sqrt{v^2 \Delta t^2 + \Delta L^2}$$

$$\frac{\Delta v}{v} \searrow \qquad L \nwarrow$$



T_0 $\quad t = t_m - (t_t + t_d) \quad$ T_s

Response of TOF-spectrometer

$$v = \frac{L}{t}$$

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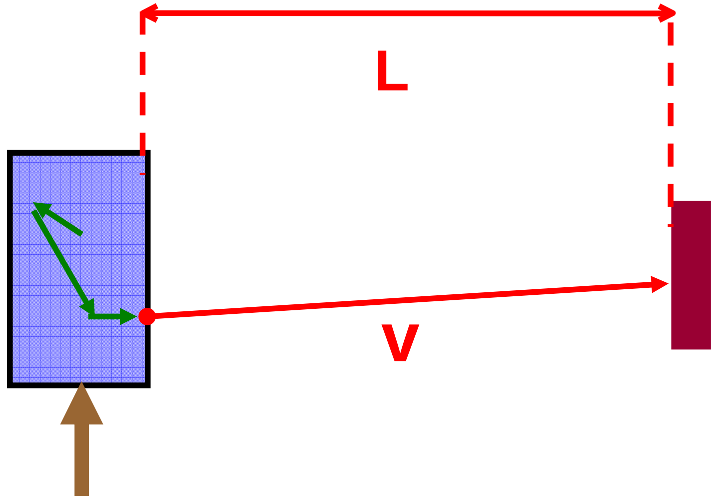


T_0 T_s

$t = t_m - (t_t + t_d)$

$t_m = (T_s - T_0)$

- **ΔL (~ 1 mm)**
- **Δt**
  - Initial burst width ΔT_0
  - Time jitter detector & electronics ΔT_s
  - Neutron transport in target - moderator Δt_t
  - Neutron transport in detector Δt_d

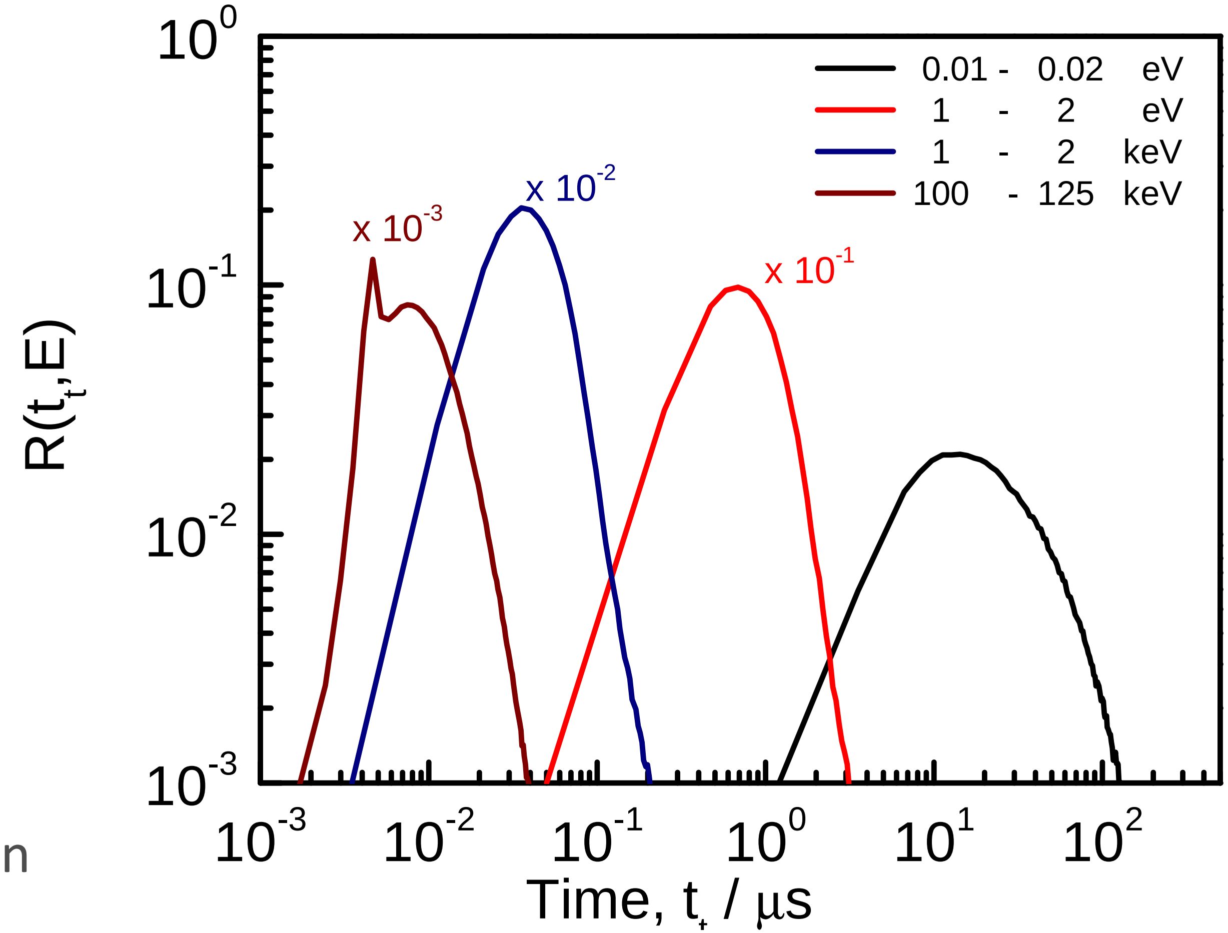
Probability distribution of t_t : GELINA

$$R(t_t,E) = R'(L(t_t),E)\left|\frac{dL}{dt}\right|$$

Transformation of variables :

$L_t = v\, t_t$

- L_t : equivalent distance
- v : neutron velocity when leaving the moderator
- t_t : time difference between neutron creation and moment it leaves the moderator



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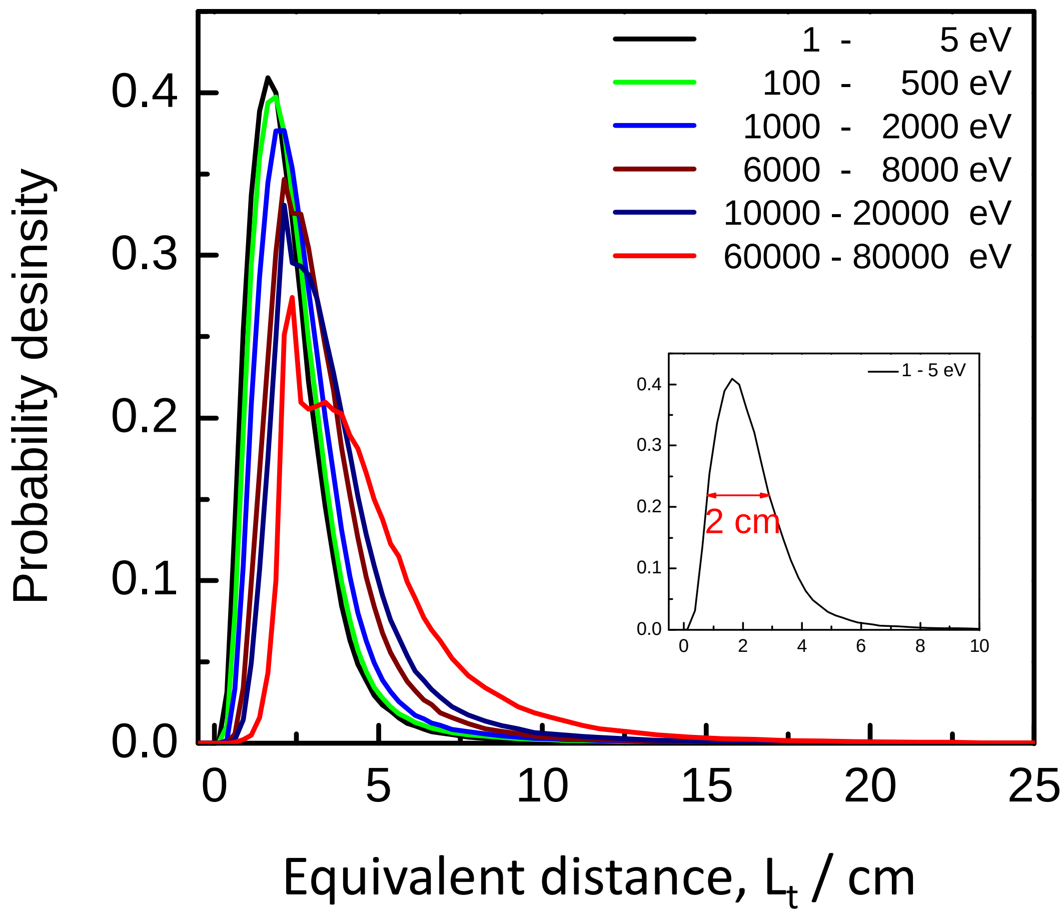


Probability distribution of L_t : GELINA

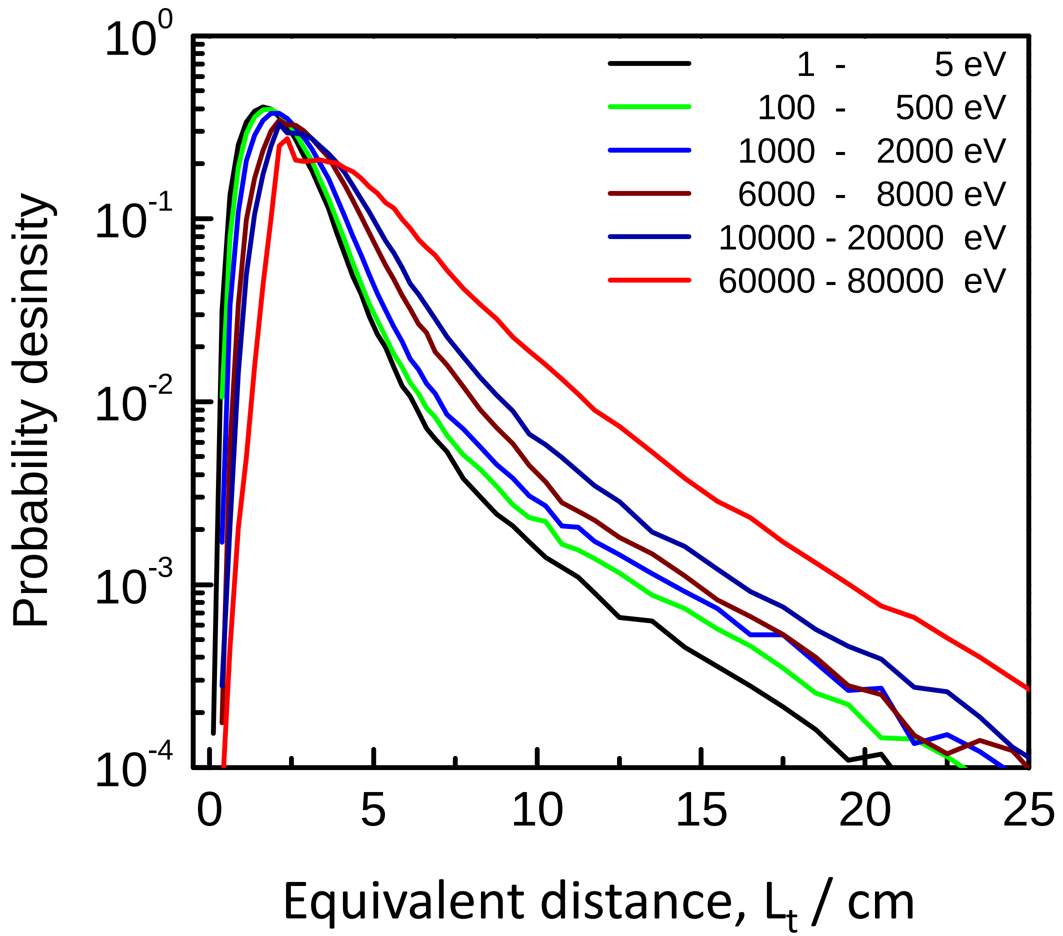
$$R(t_t, E) = R'(L(t_t), E)\left|\frac{dL}{dt}\right|$$

- Between 0.5 eV and 1000 eV: χ^2

  R'(L_t,E_n) dominated by χ^2 due to moderation process and almost independent of E_n

- Below 0.5 eV : χ^2 + storage

- Above 1000 keV : more complex



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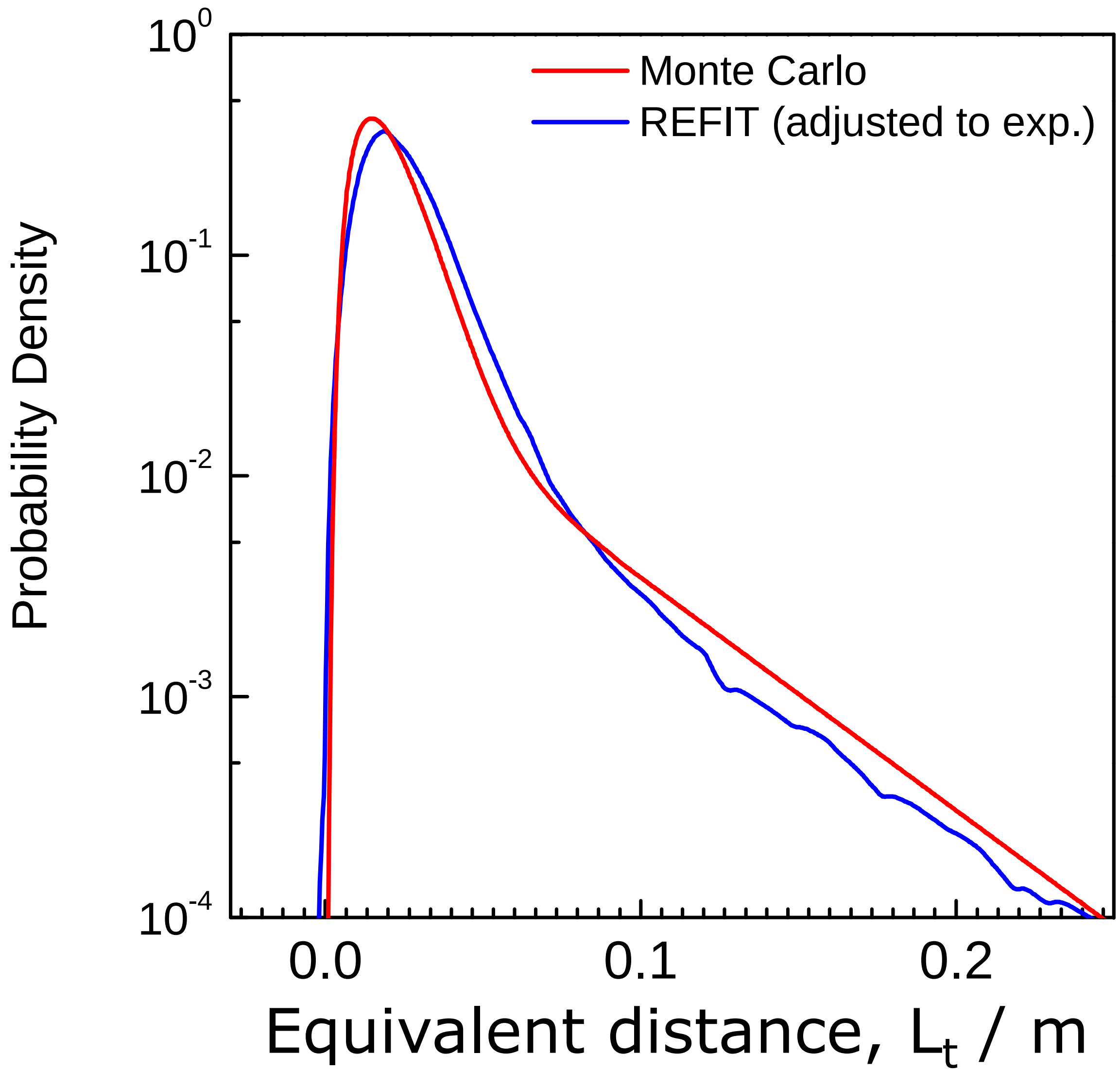
Probability distribution of L_t : GELINA



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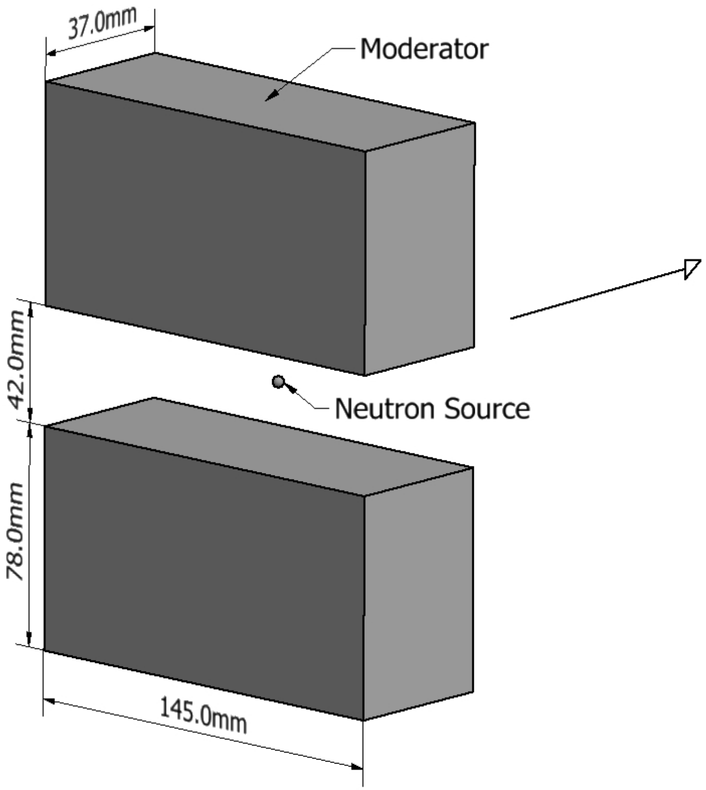
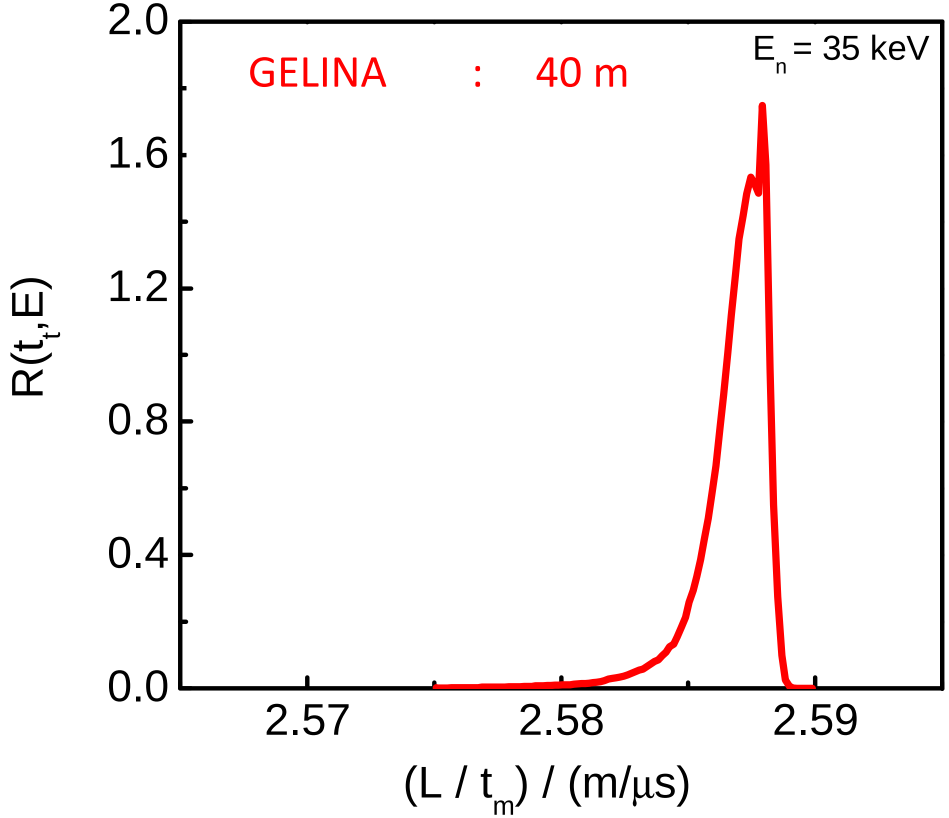
$P(t_t, E)$: photonuclear



ΔL (FWHM) = 2 cm

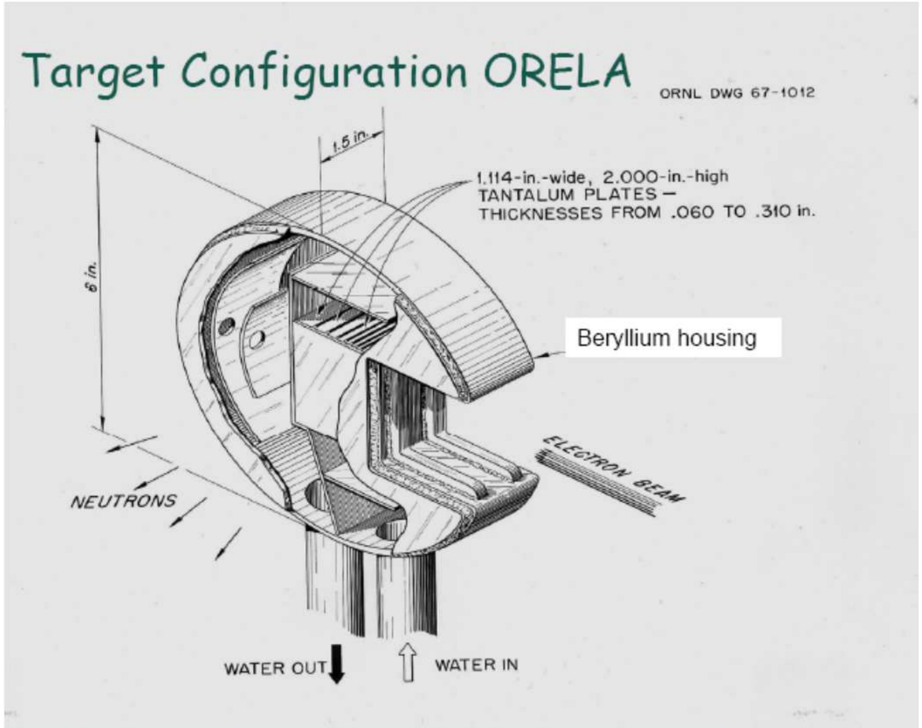
$\Rightarrow$ about half of the moderator thickness

E_n = 35 keV

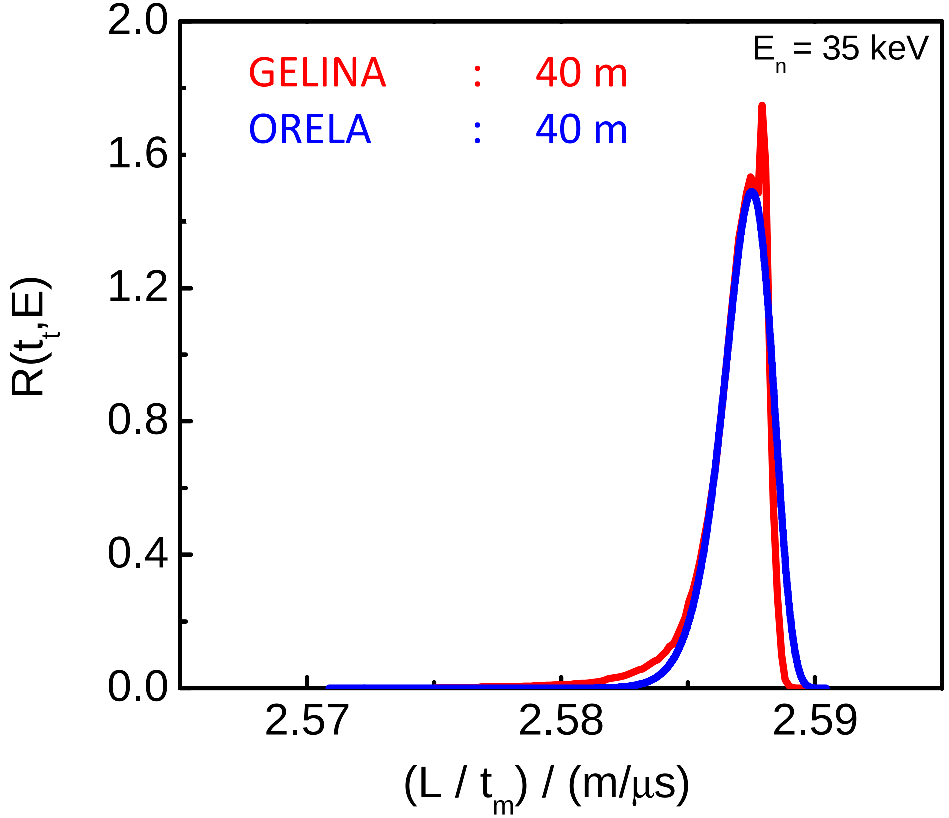


Resolution	:	ΔL (FWHM)
GELINA	:	2 cm

P(t_t, E) : photonuclear

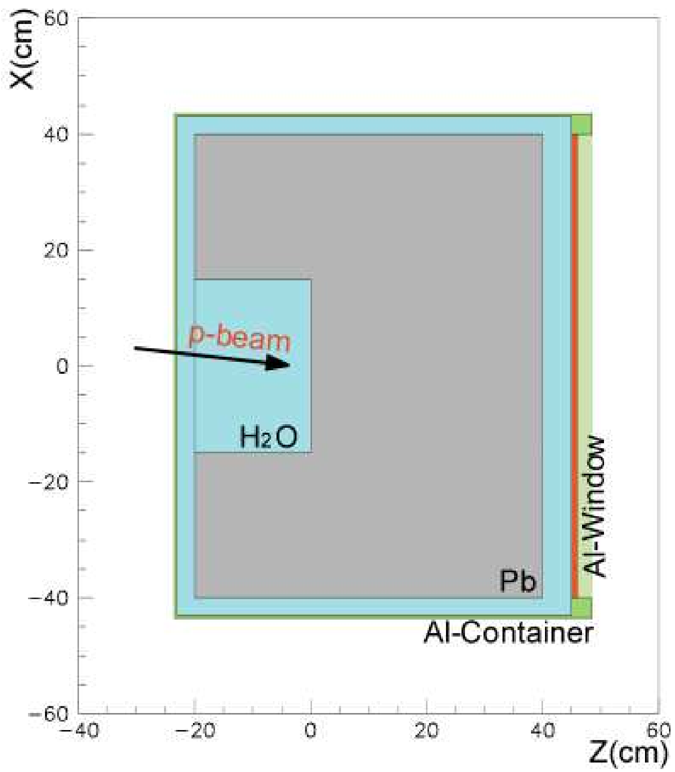


E_n = 35 keV



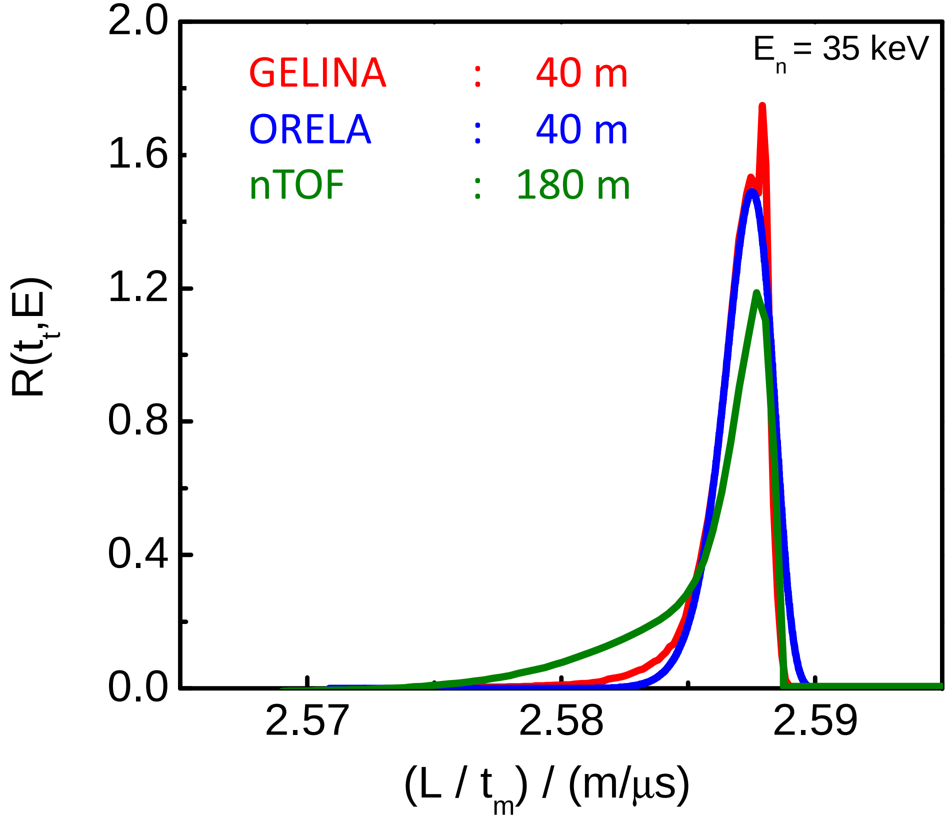
Resolution	:	ΔL (FWHM)
GELINA	:	2 cm
ORELA	:	2 cm

$P(t_t, E)$: photonuclear ⇔ spallation reactions



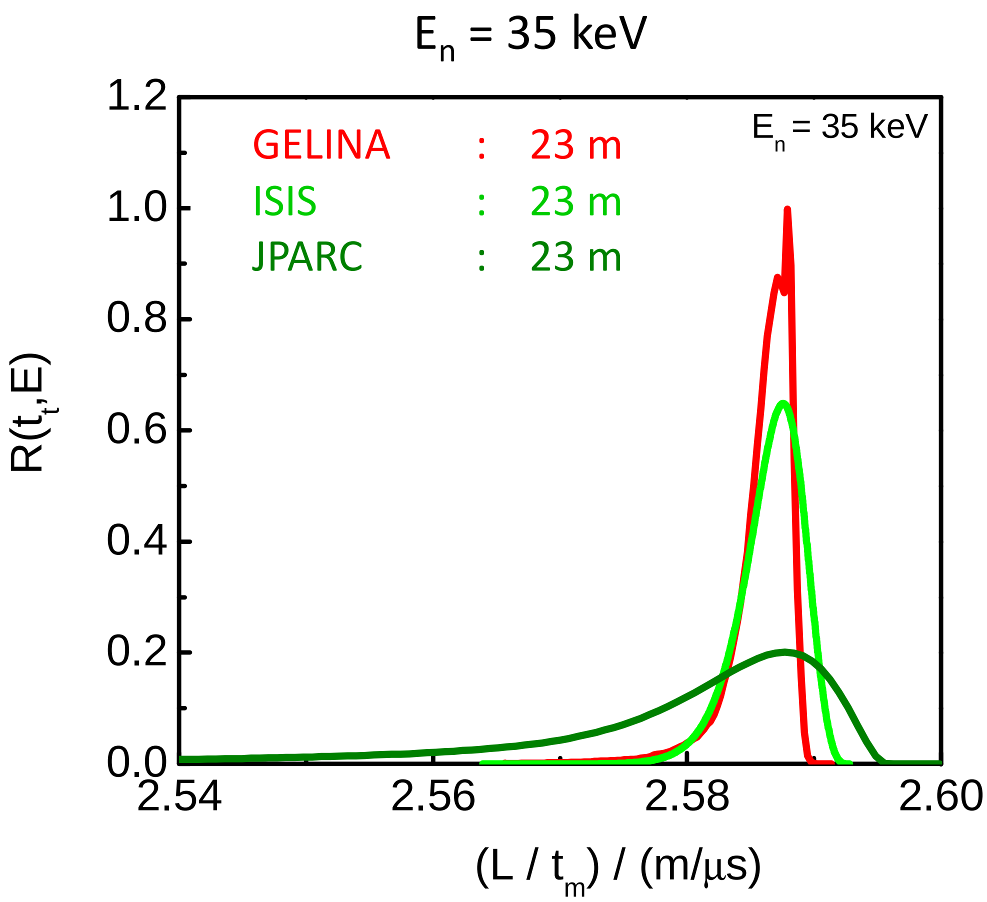
Dimensions : 80 × 80 × 60 cm^3
Pure Lead : 4 t
H_2O moderator : 5 cm
Al-window : 1.6 mm
Al-container : 140 l

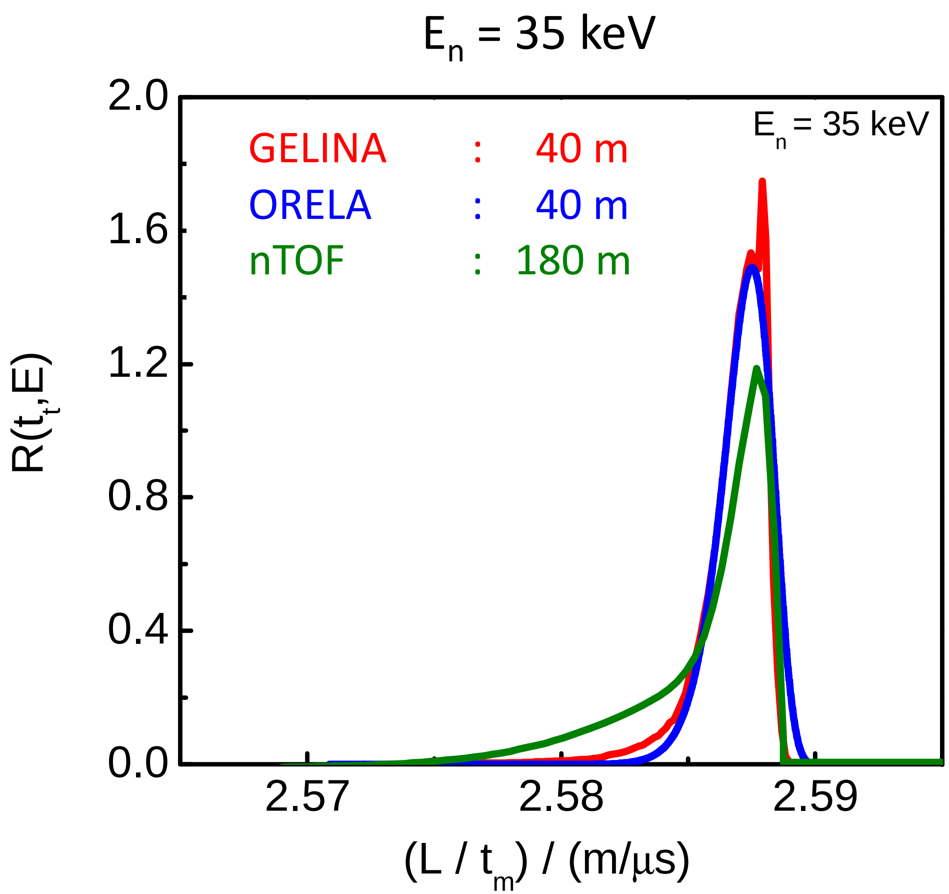
E_n = 35 keV



Resolution	:	ΔL (FWHM)
GELINA	:	2 cm
ORELA	:	2 cm
nTOF	:	10 cm

$P(t_t, E)$: photonuclear ⇔ spallation reactions





Resolution : ΔL (FWHM)
- ISIS (INES) : 5 cm
- J-PARC (MLF/ANNRI) : 13 cm

Strongly depend on target/moderator configuration (coupled/decoupled)

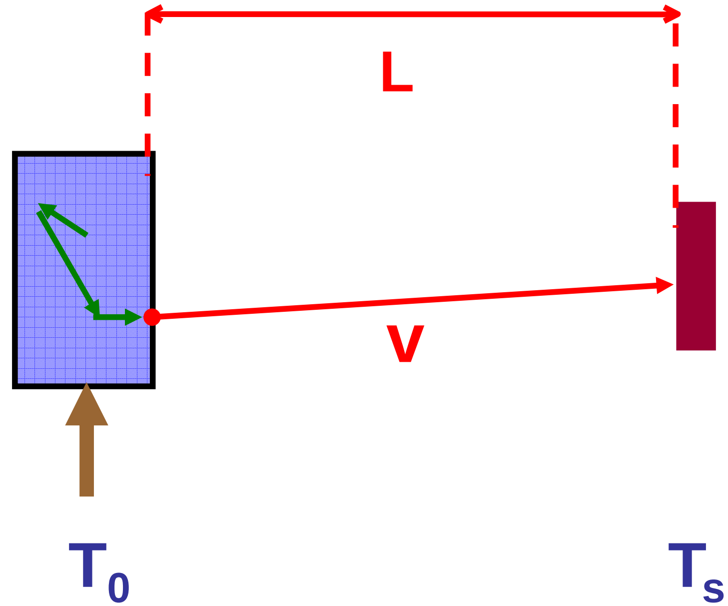
Resolution : ΔL (FWHM)
- GELINA : 2 cm
- ORELA : 2 cm
- nTOF : 10 cm

Response of TOF-spectrometer

$$v = \frac{L}{t}$$

$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}}$$

- **ΔL (~ 1 mm)**
- **Δt**
  - Initial burst width ΔT_0
  - Time jitter detector & electronics ΔT_s
  - Neutron transport in target - moderator Δt_t
  - Neutron transport in detector Δt_d



$$t = t_m - (t_t + t_d)$$

$$t_m = (T_s - T_0)$$

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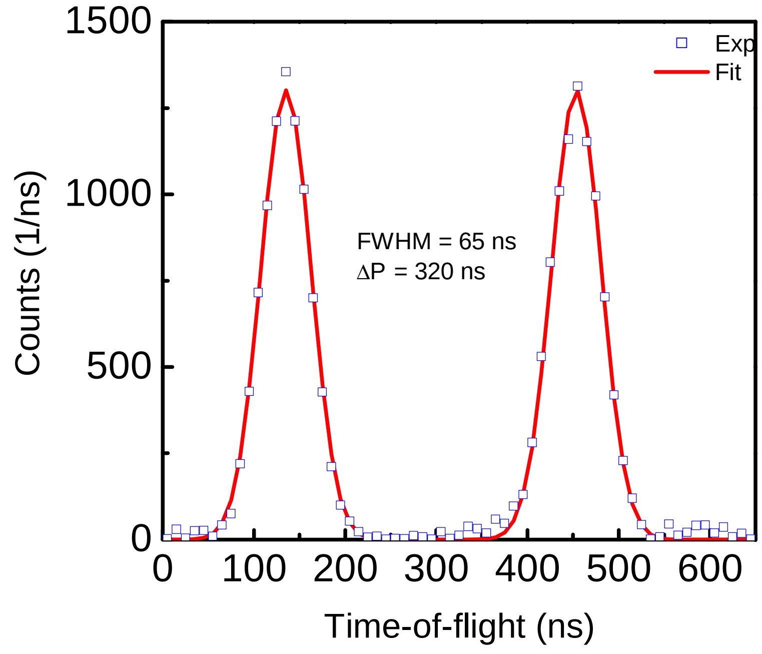
Initial burst (T_0)

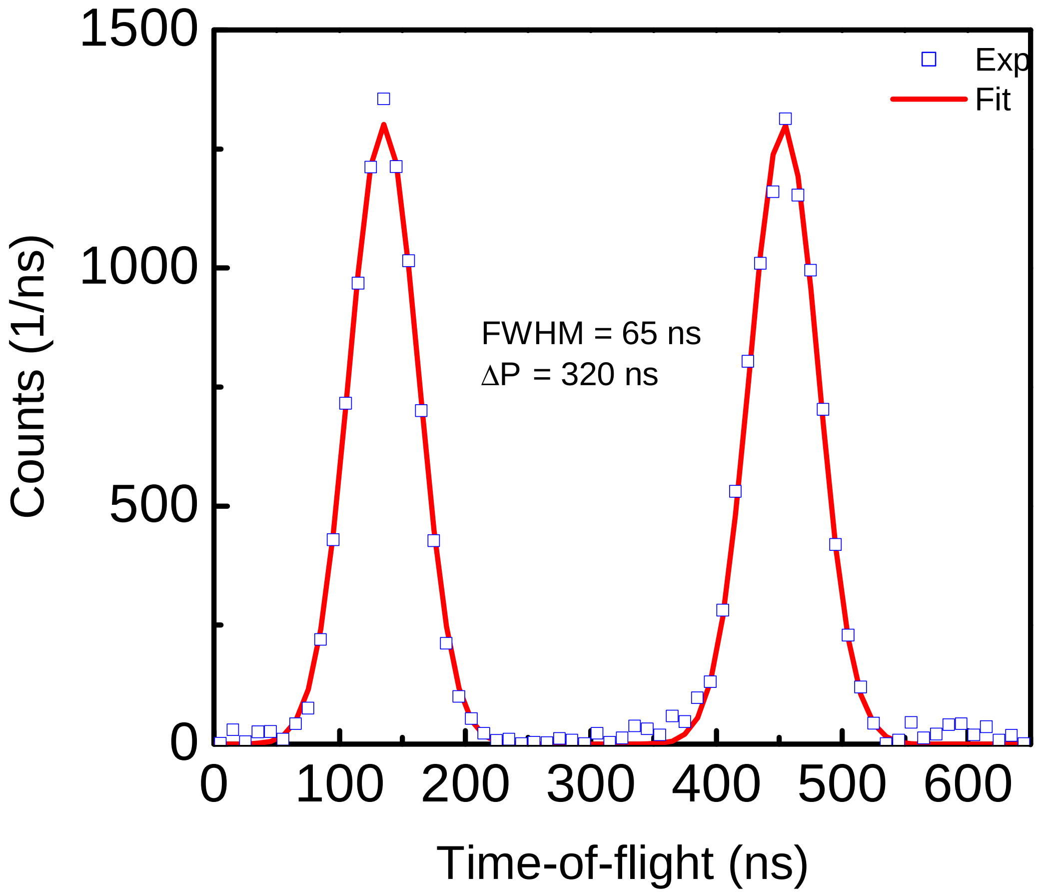
- Single burst : mostly normal (Gaussian) distribution
  - GELINA : ΔT_0 = 1 ns (FWHM)
  - ORELA : ΔT_0 = 4 ns (FWHM)
  - nTOF : ΔT_0 = 10 ns (FWHM)

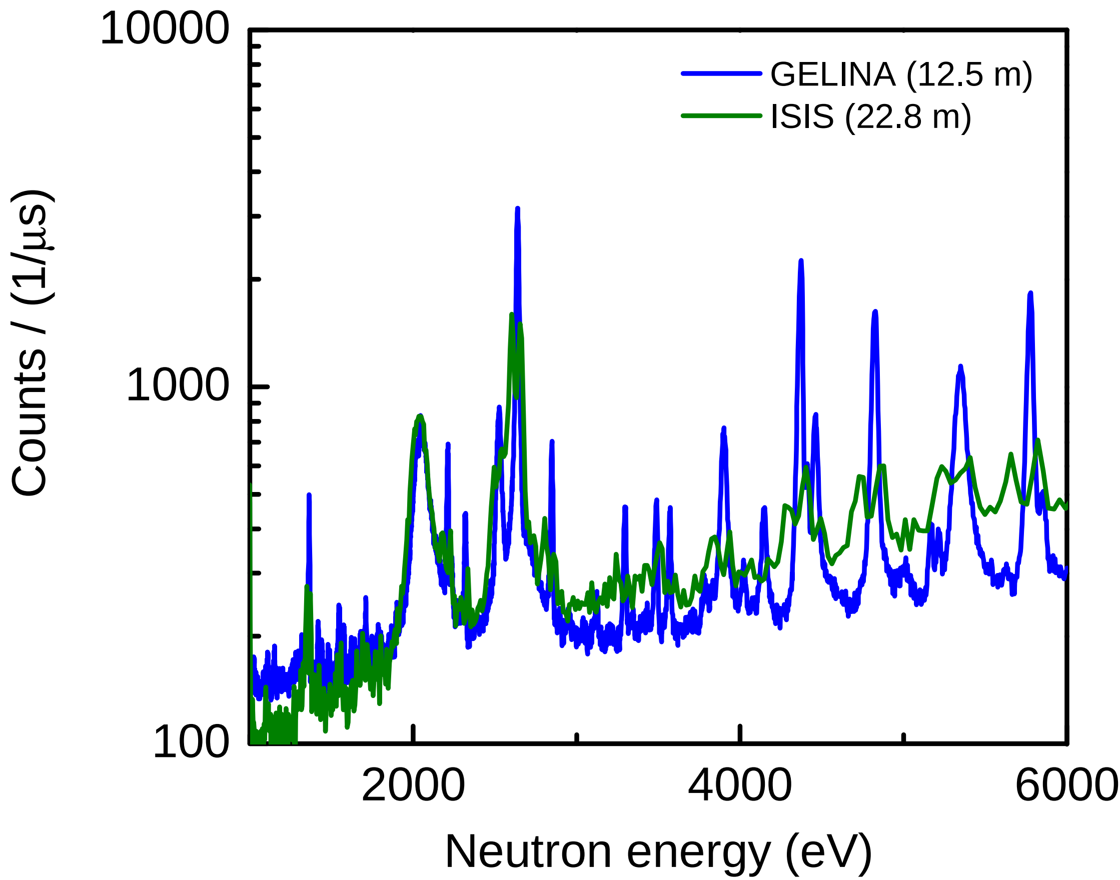
- Double pulse structure :
  - ISIS
  - J-PARC



Response GELINA (12.5 m) < - > ISIS (22.8 m)

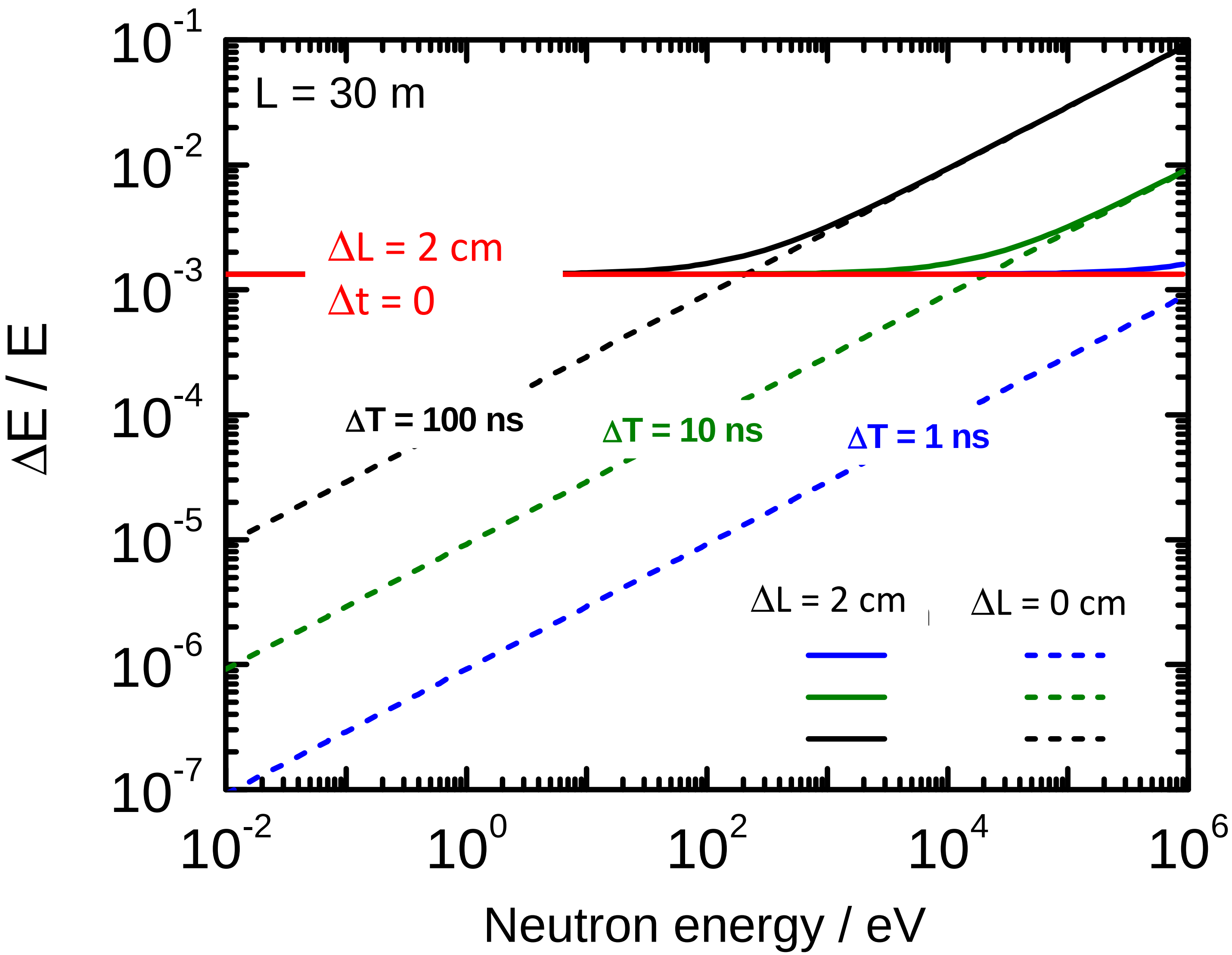
Double pulsed proton beam





Double pulsed proton beam also at J-PARC

TOF : resolution components



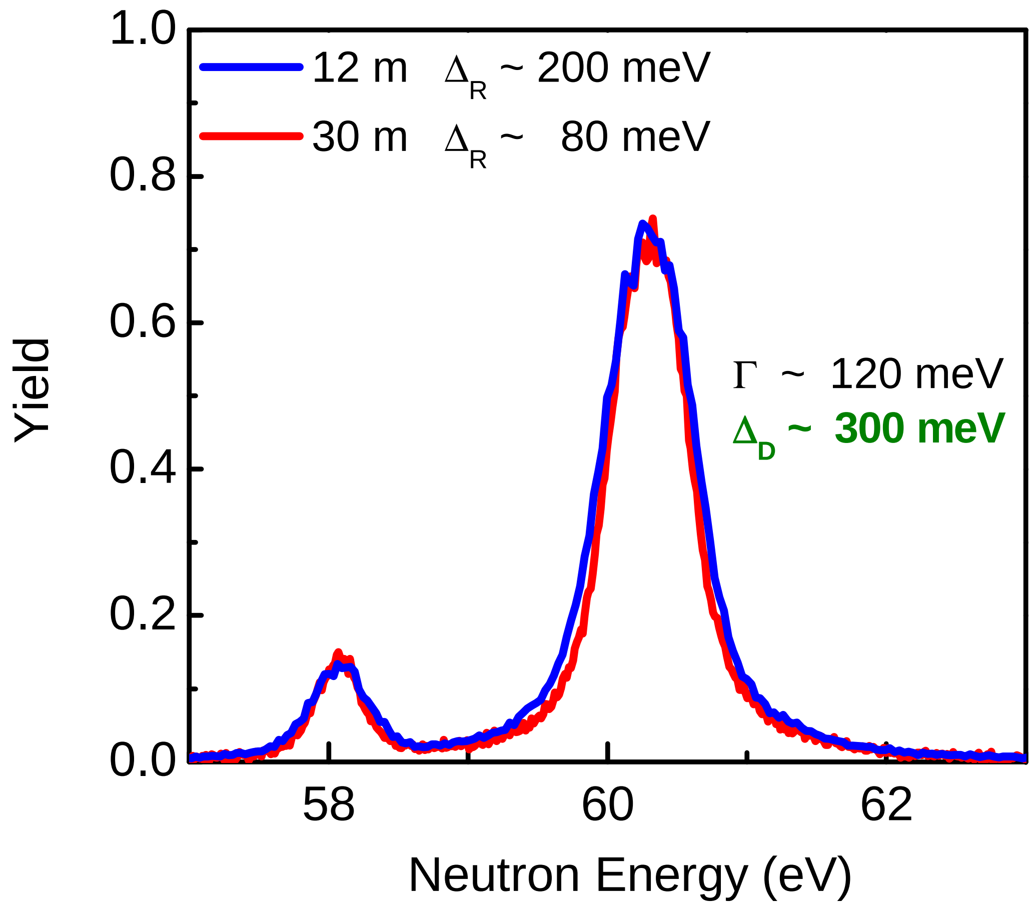
$$\frac{\Delta v}{v} = \frac{1}{L}\sqrt{v^2 \Delta t^2 + \Delta L^2}$$

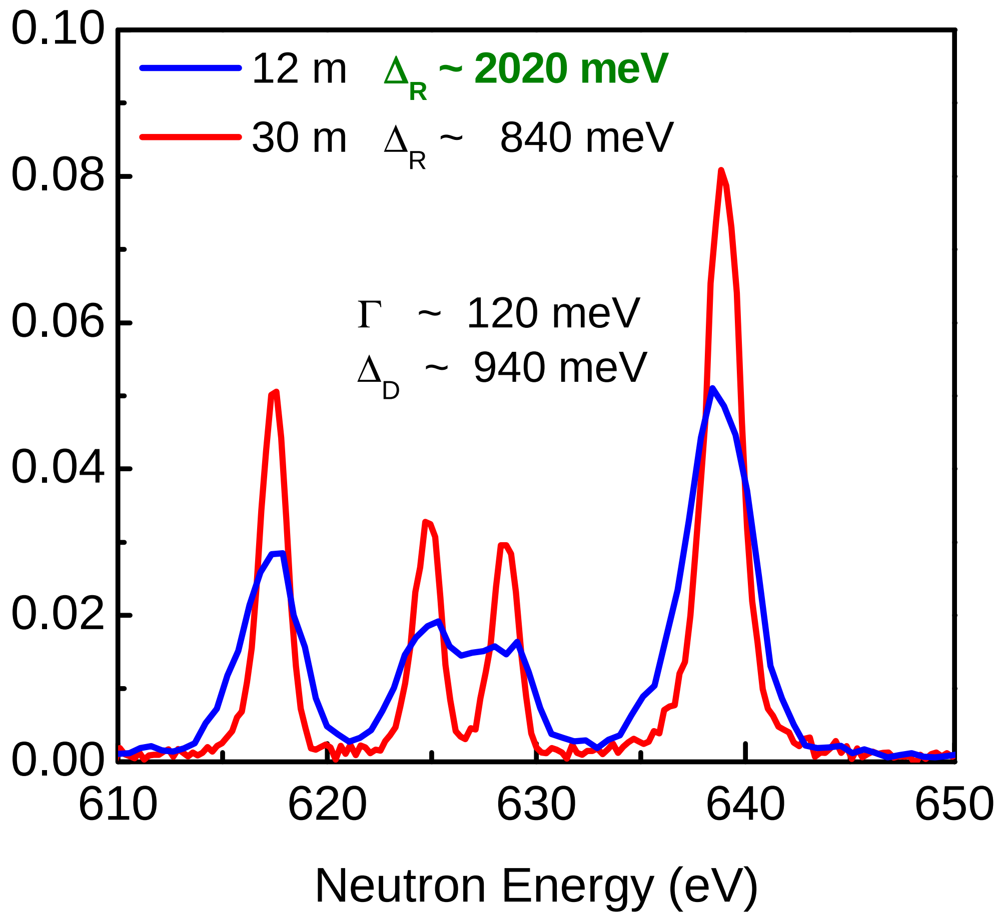
$$\frac{\Delta E}{E} \cong 2\frac{\Delta v}{v}$$

^{197}Au(n,γ) at L = 12 m and 30 m

$$\frac{\Delta E}{E} \cong 2\sqrt{\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

$$\Delta_D = \sqrt{\frac{4\,E\,k_B T}{m_X / m_n}} \qquad FWHM = 2\sqrt{\ln 2}\,\Delta_D$$





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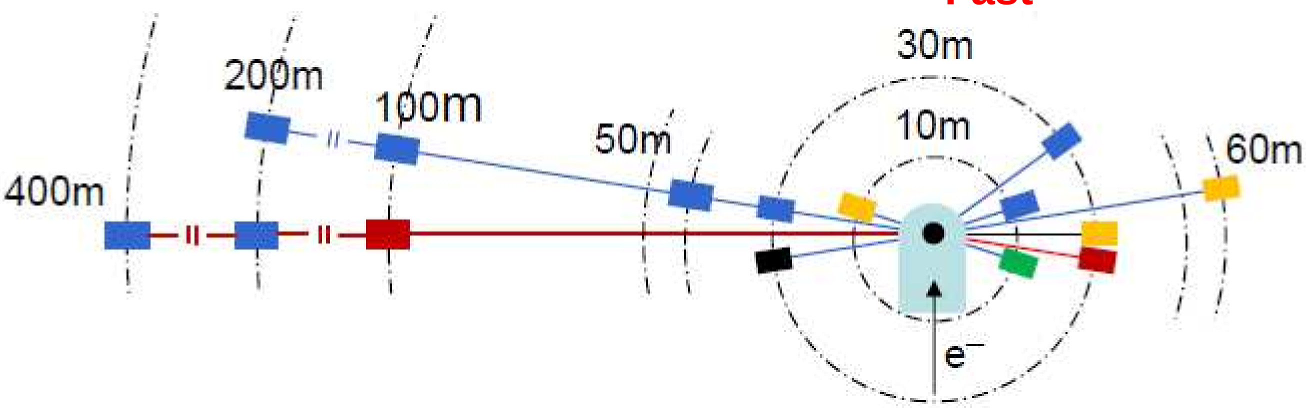
TOF – measurements at GELINA

Moderated

Fast



(n,γ)

(n,tot)

(n,f) and (n,cp)

(n,n'γ)

(n,n)

Velocity from TOF

$$v = \frac{L}{t}$$

- Neutron fluence rate $\Rightarrow L$ ↘

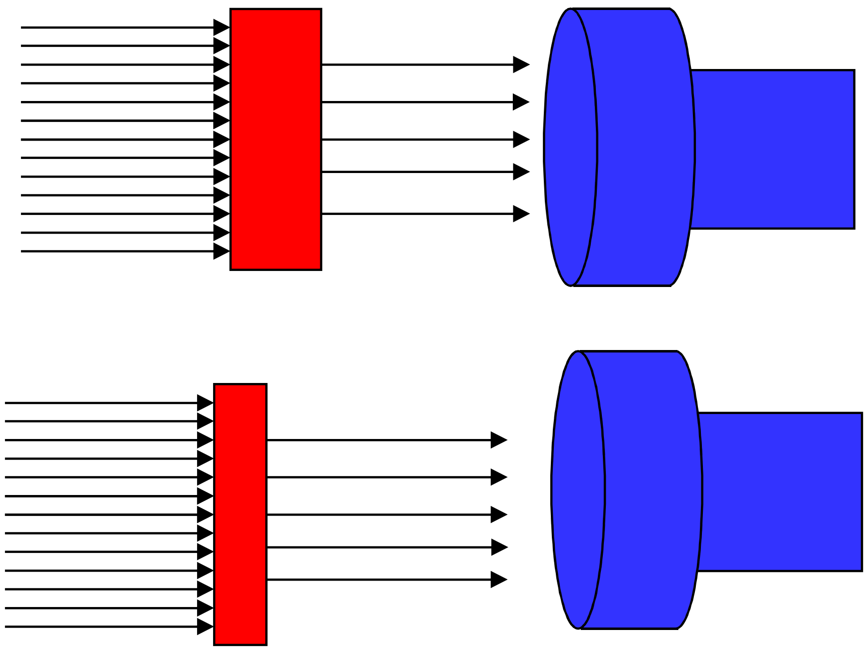
$$\varphi(L) \propto \frac{1}{L^2}$$

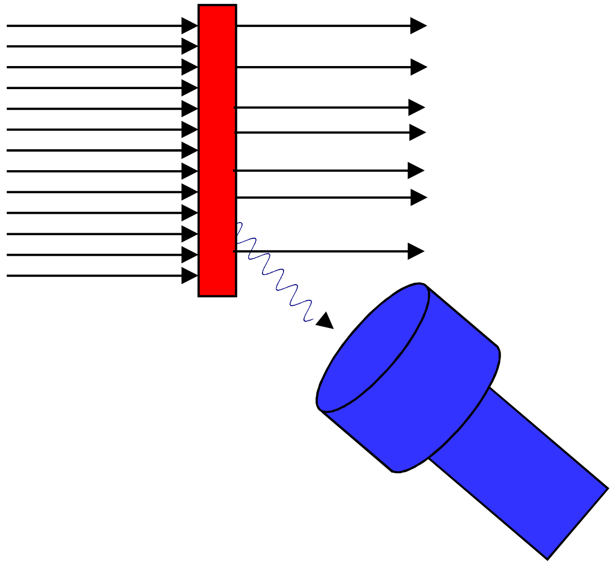
- Resolution $\Rightarrow L$ ↗

$$\frac{\Delta v}{v} = \frac{1}{L}\sqrt{v^2 \Delta t^2 + \Delta L^2}$$

Resonance parameters

- Determination of resonance parameters is a complex process and requires a set of complementary data
- Combine reaction cross section measurements on thin samples with transmission measurements on samples with different thicknesses





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Transmission measurements

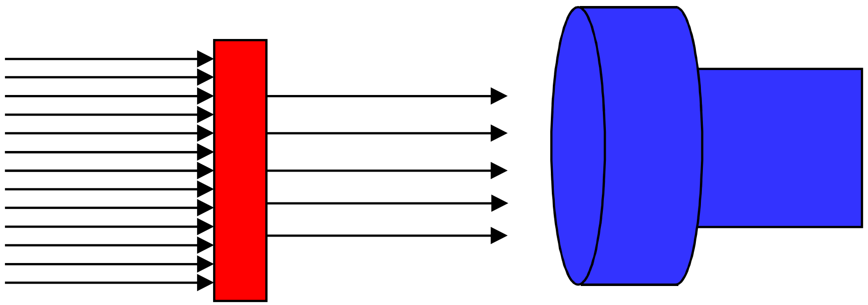
- Basic principles
- Background measurements (black resonance filters)
- Resolved resonance region
- Unresolved resonance region

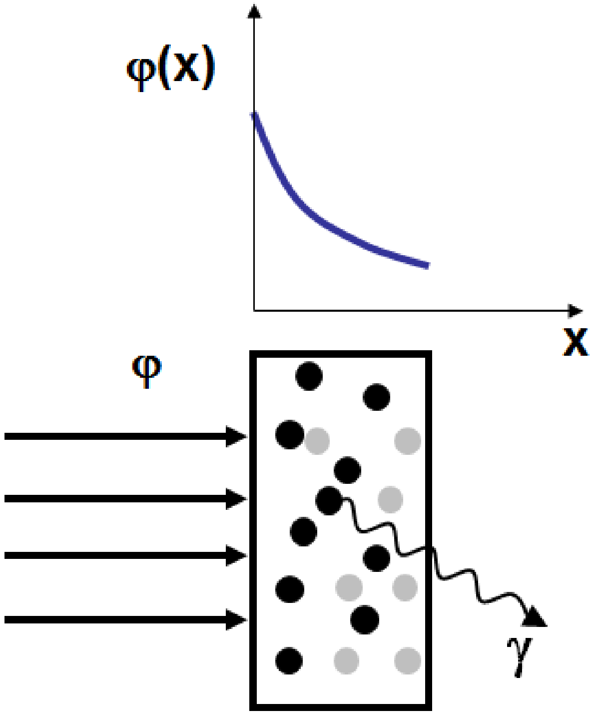
Cross section measurements

Transmission

$$T \cong e^{-n\bar{\sigma}_{tot}}$$

T : transmission
Fraction of the neutron beam traversing the sample without any interaction





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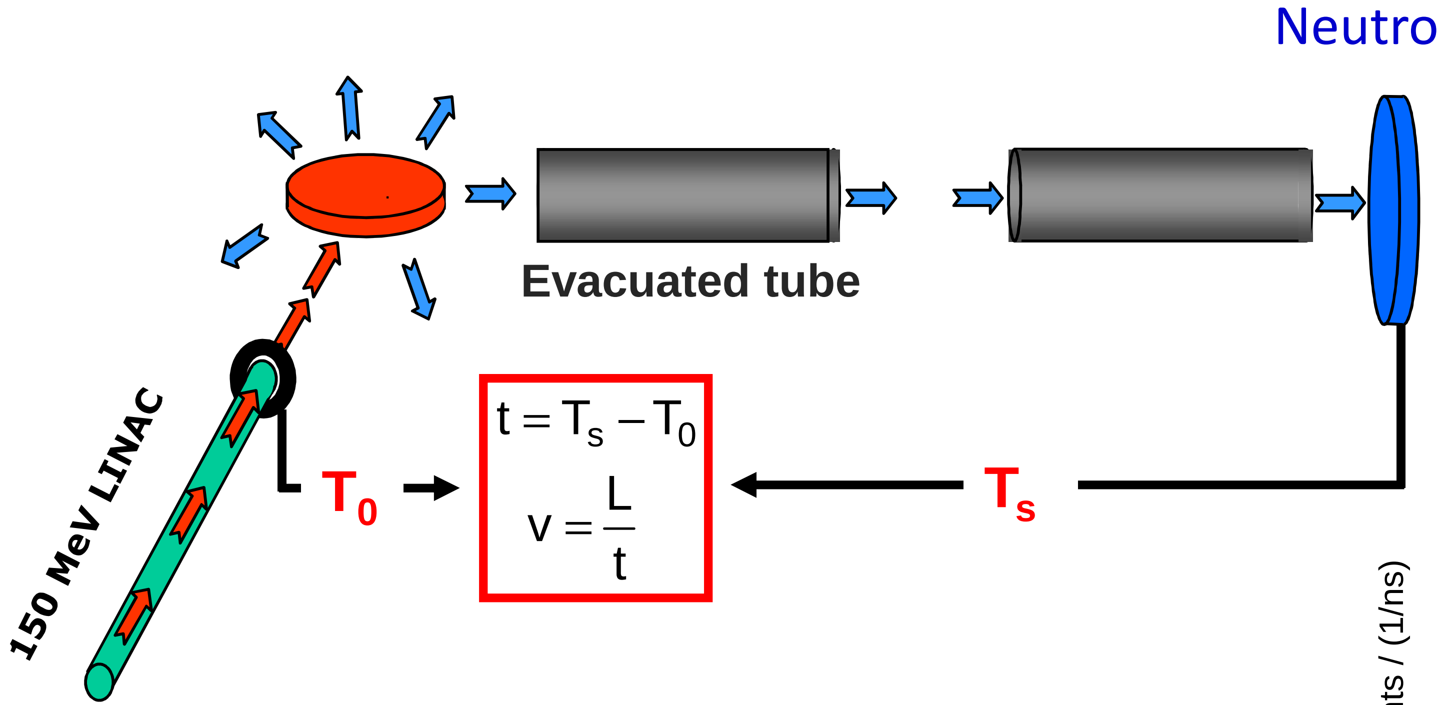
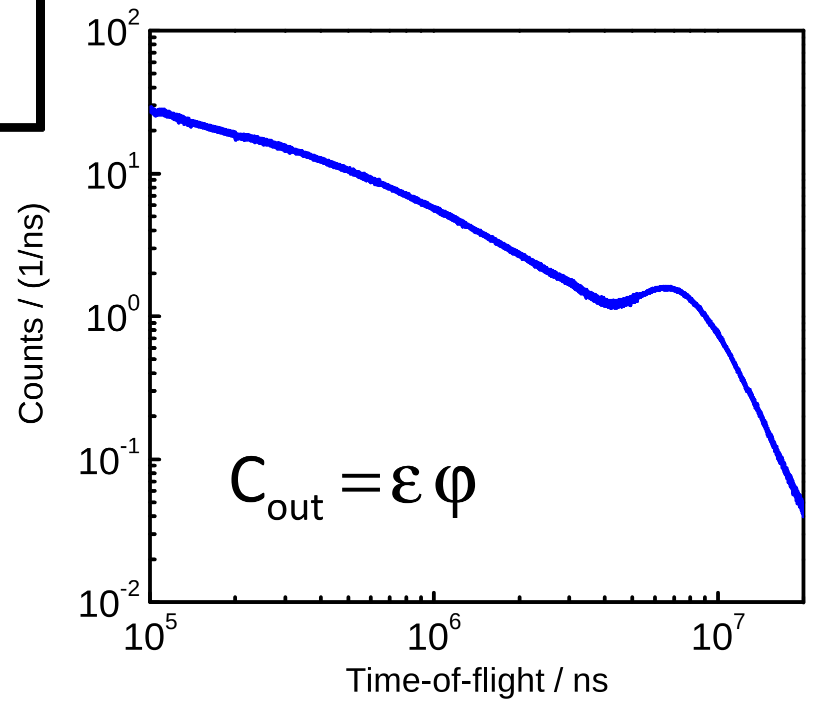
TOF-cross section measurements

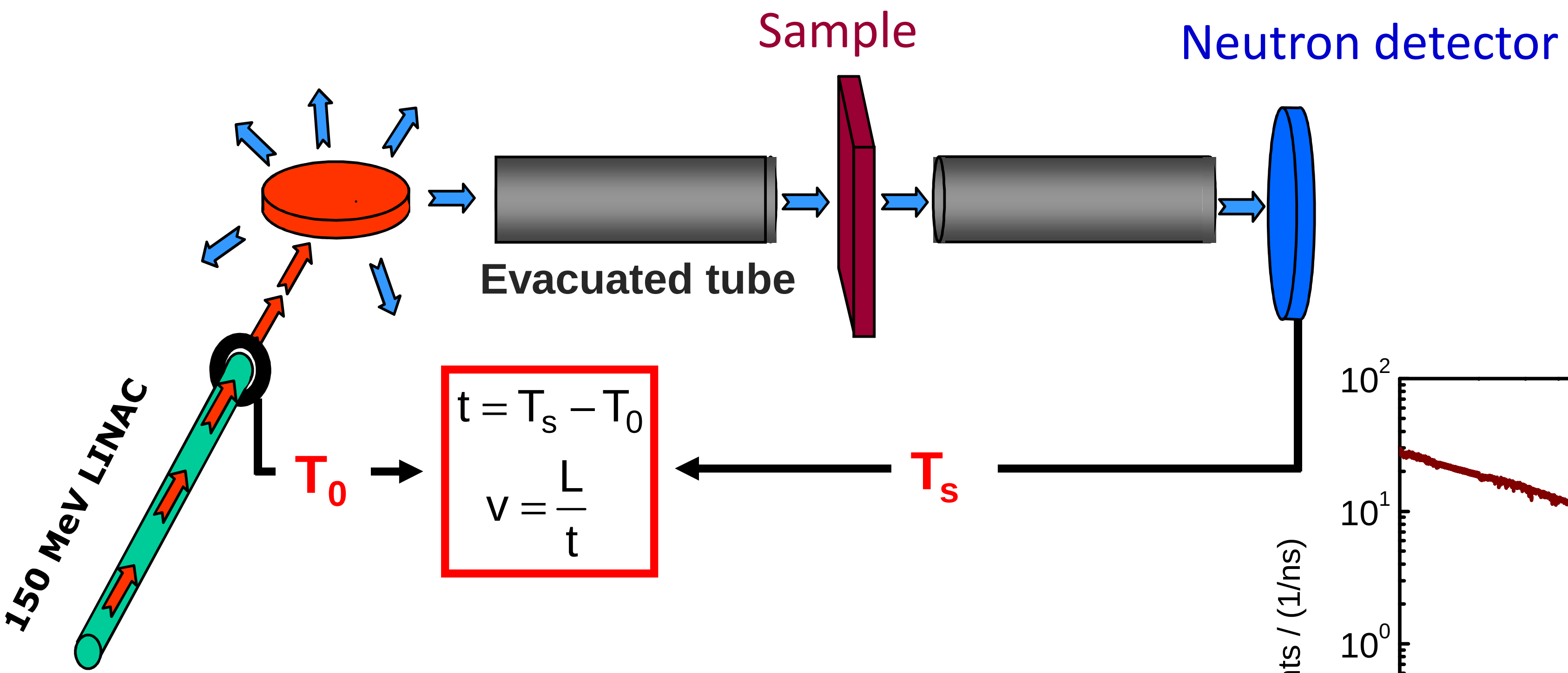


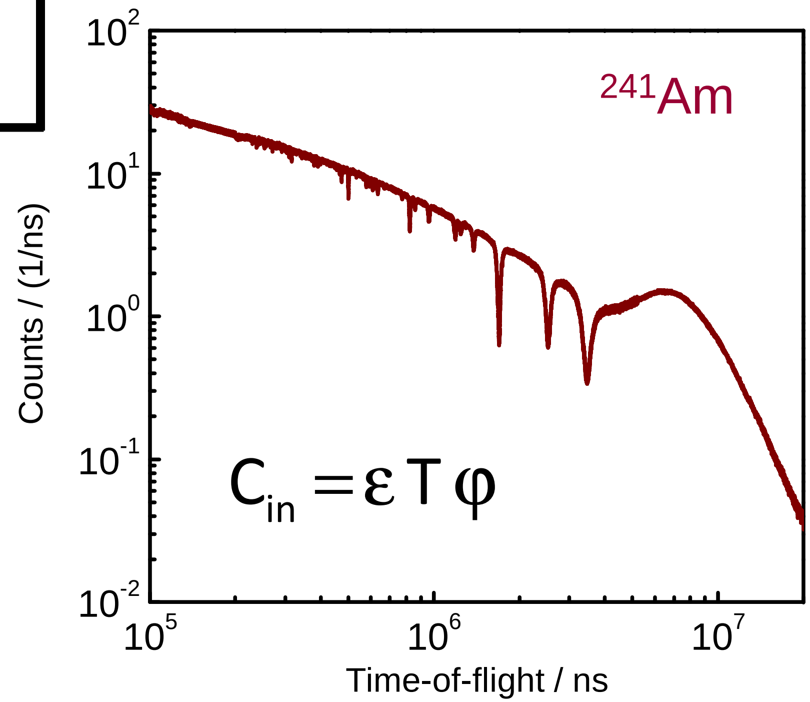
L : distance between target and detector

t : time-of-flight



TOF-cross section measurements





L : distance between target and detector

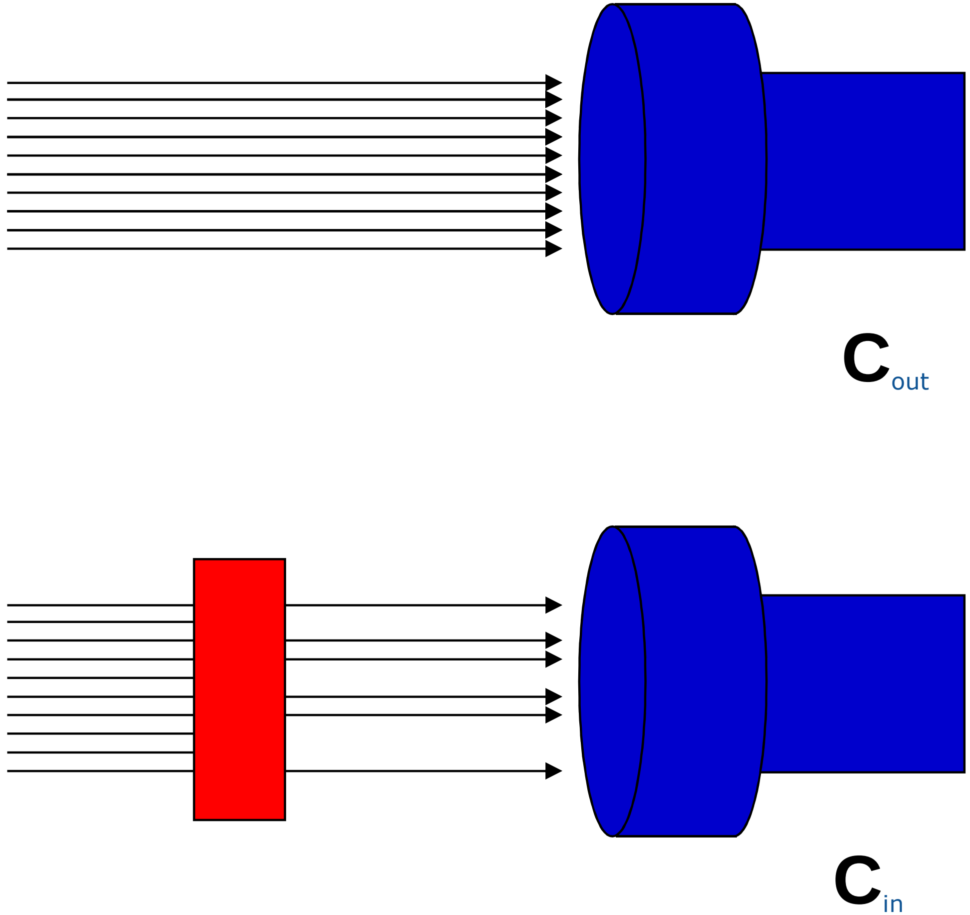
t : time-of-flight

Transmission measurements

Transmission

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

- Incoming neutron flux cancels
- Detection efficiency cancels



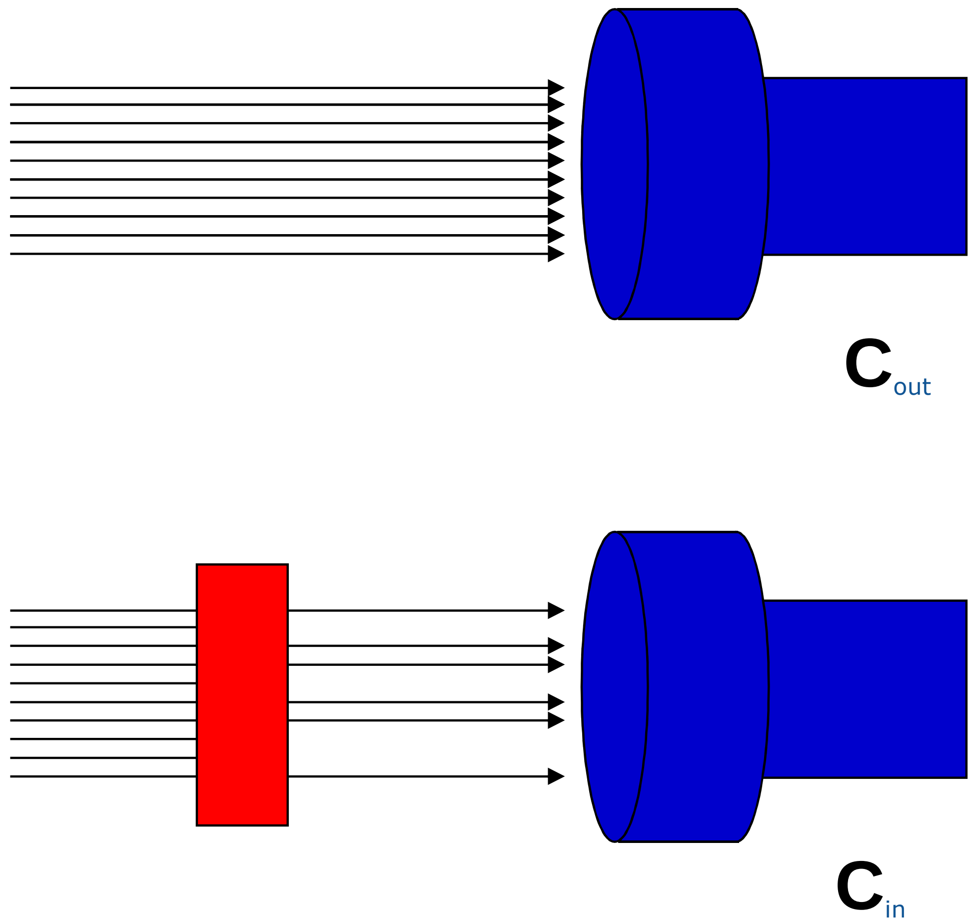
Transmission measurements

Transmission

$$T_{exp} = \frac{C_{in}}{C_{out}} \propto e^{-n\bar{\sigma}_{tot}}$$

- Incoming neutron flux cancels
- Detection efficiency cancels

⇒ Direct relation between T_{exp} and σ_{tot}



Transmission : principle

$$T_{exp} = \frac{C_{in}}{C_{out}} \propto e^{-n\overline{\sigma}_{tot}}$$

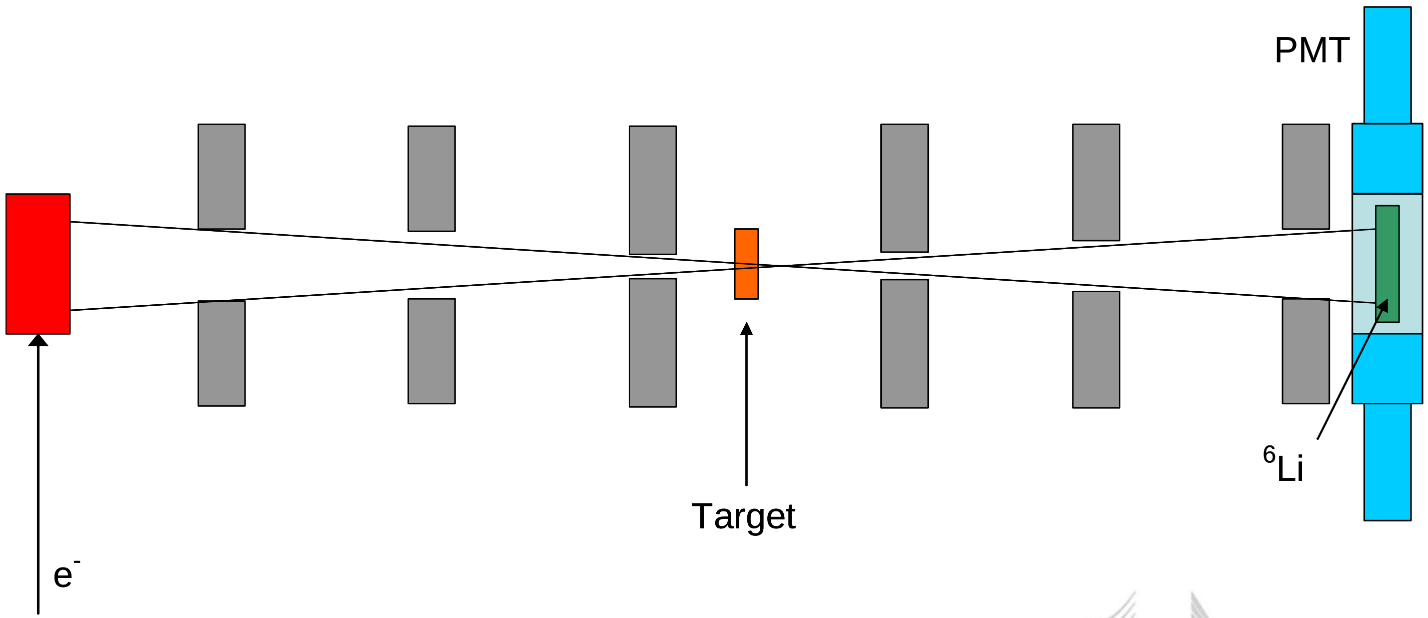
(1) All detected neutrons passed through the sample

(2) Neutrons scattered in the target do not reach detector

(3) Sample perpendicular to parallel neutron beam

$\Rightarrow$ Good transmission geometry (collimation)

(4) Homogeneous target (no spatial distribution of n)



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Transmission measurements

$$T_{exp} = \frac{C_{in}}{C_{out}} \propto e^{-n\overline{\sigma}_{tot}}$$

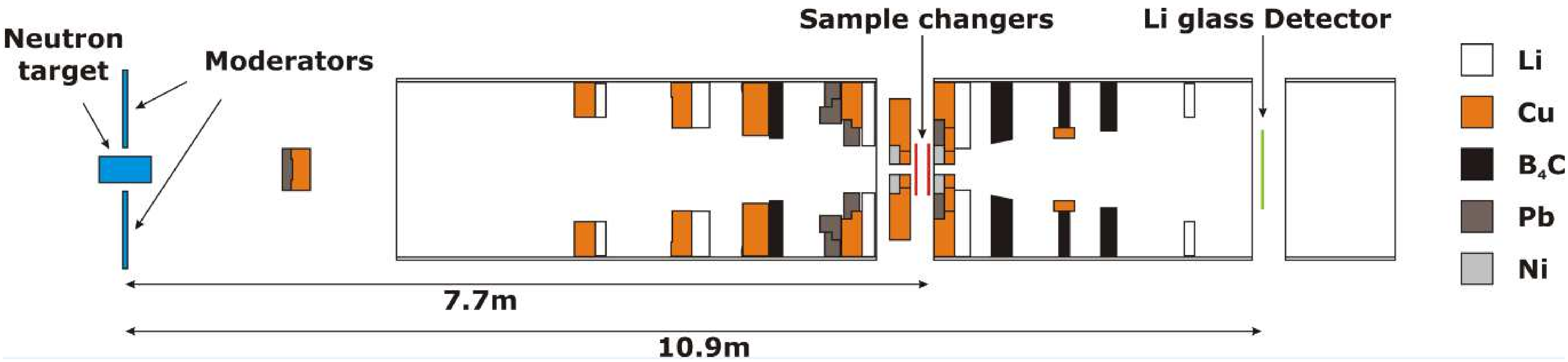
(1) All detected neutrons passed through the sample

(2) Neutrons scattered in the target do not reach detector

(3) Sample perpendicular to parallel neutron beam

$\Rightarrow$ Good transmission geometry (collimation)

(4) Homogeneous target (no spatial distribution of n)



Transmission station at GELINA

^{6}Li detector

Castle

Neutron target + moderators

European Commission

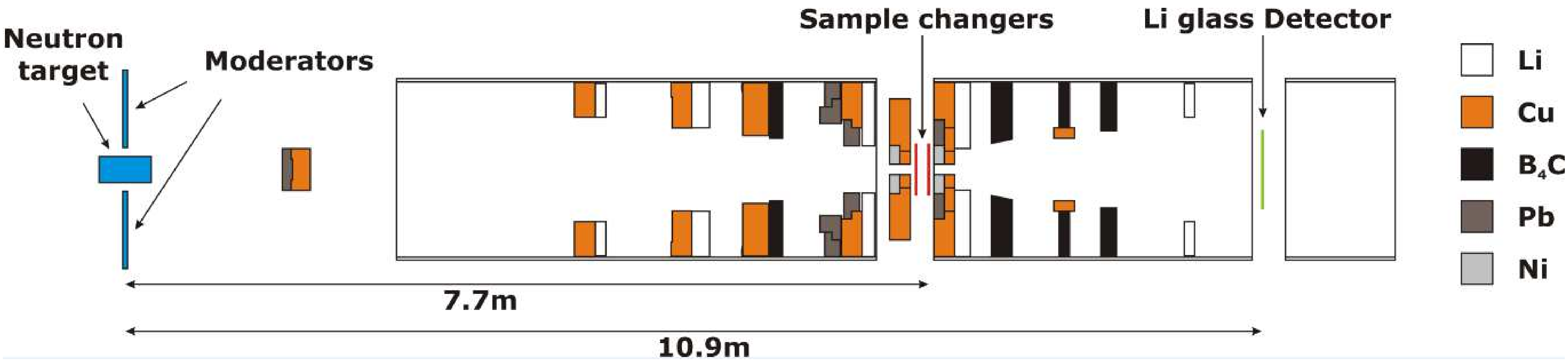
Transmission : principle

$$T_{exp} = \frac{C_{in}}{C_{out}} \propto e^{-n\overline{\sigma}_{tot}}$$

Detectors

Low energy : $^{6}Li(n,t)\alpha$ Li-glass

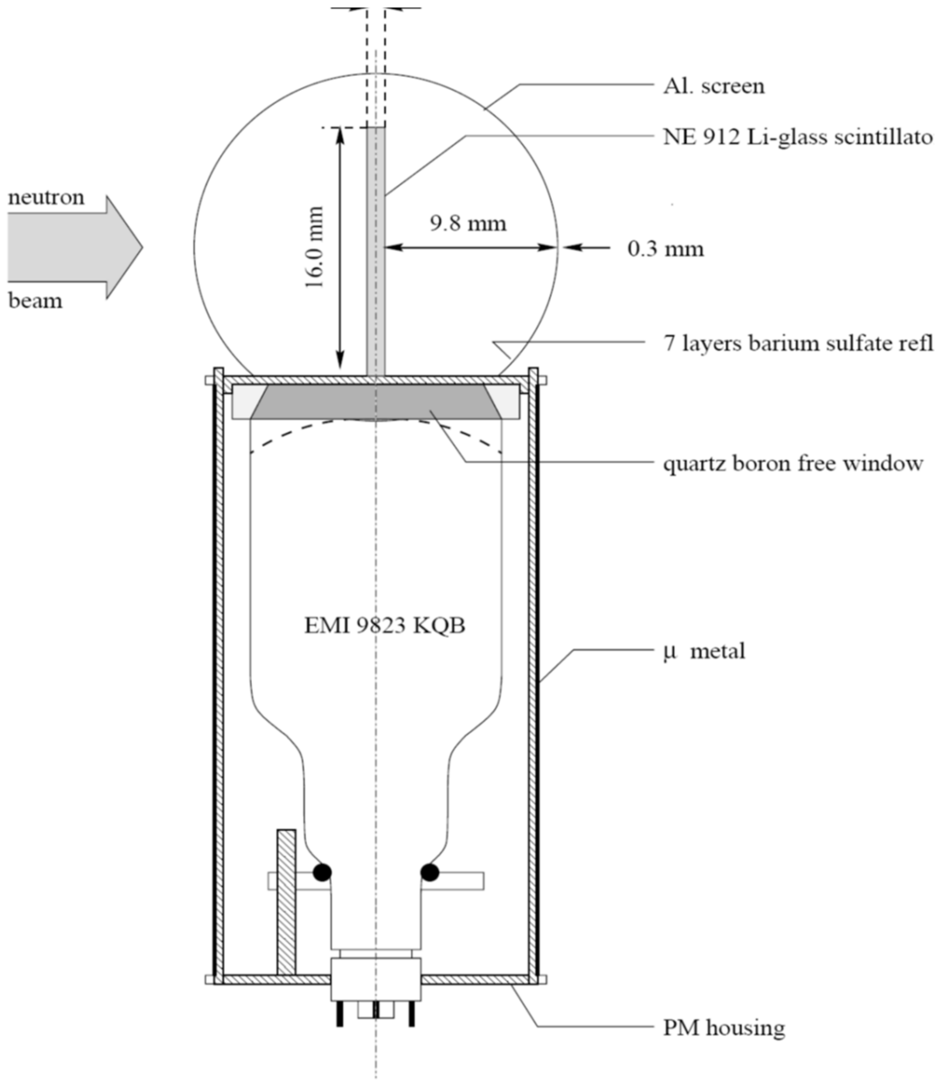
High energy : H(n,n)H Plastic scintillator

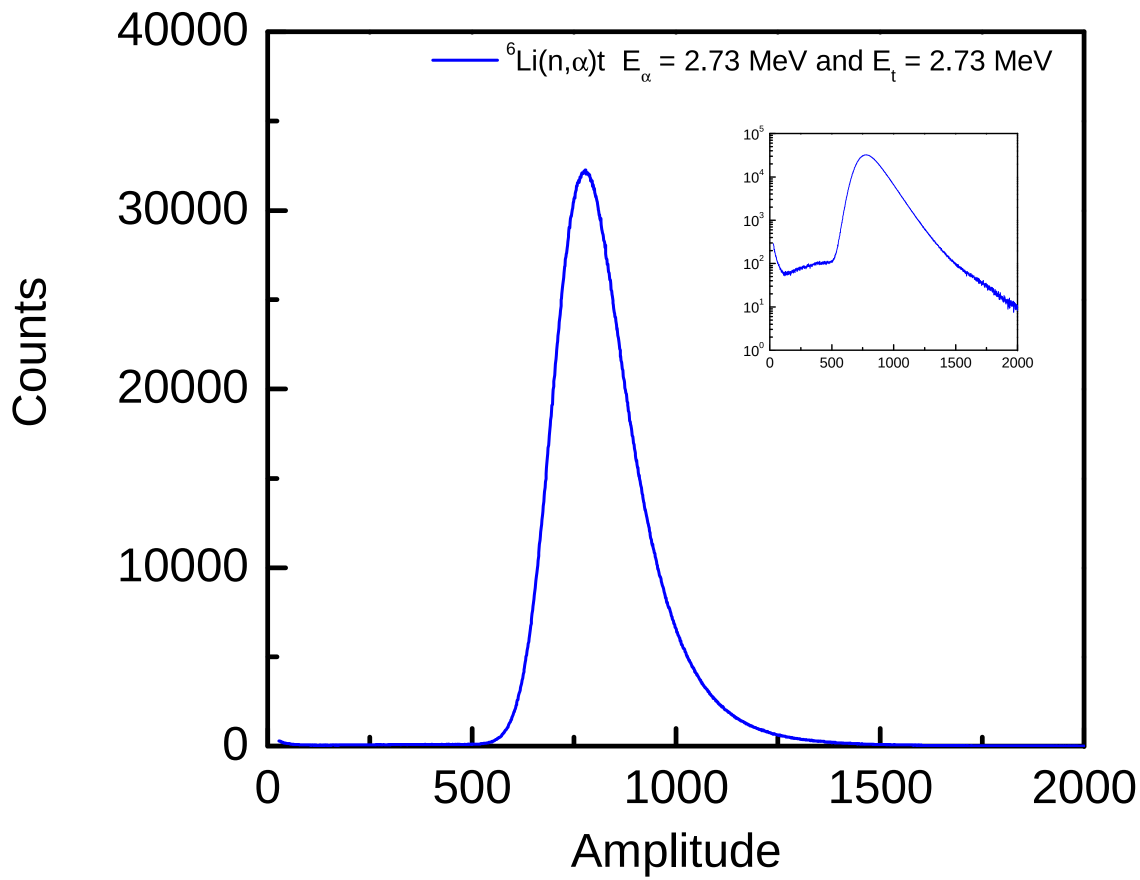


Lithium-glass scintillator : energy deposition

$^{6}Li(n,t)\alpha$

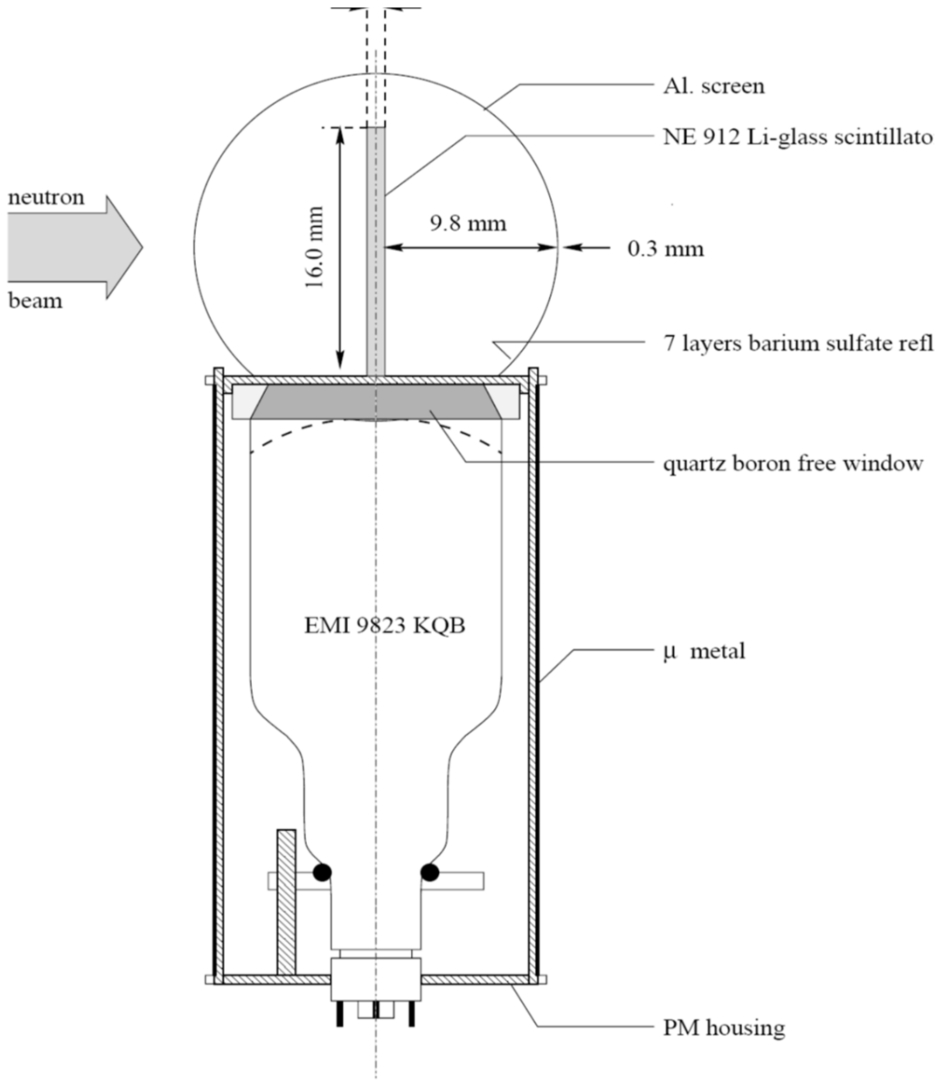
Scintillator + PMT

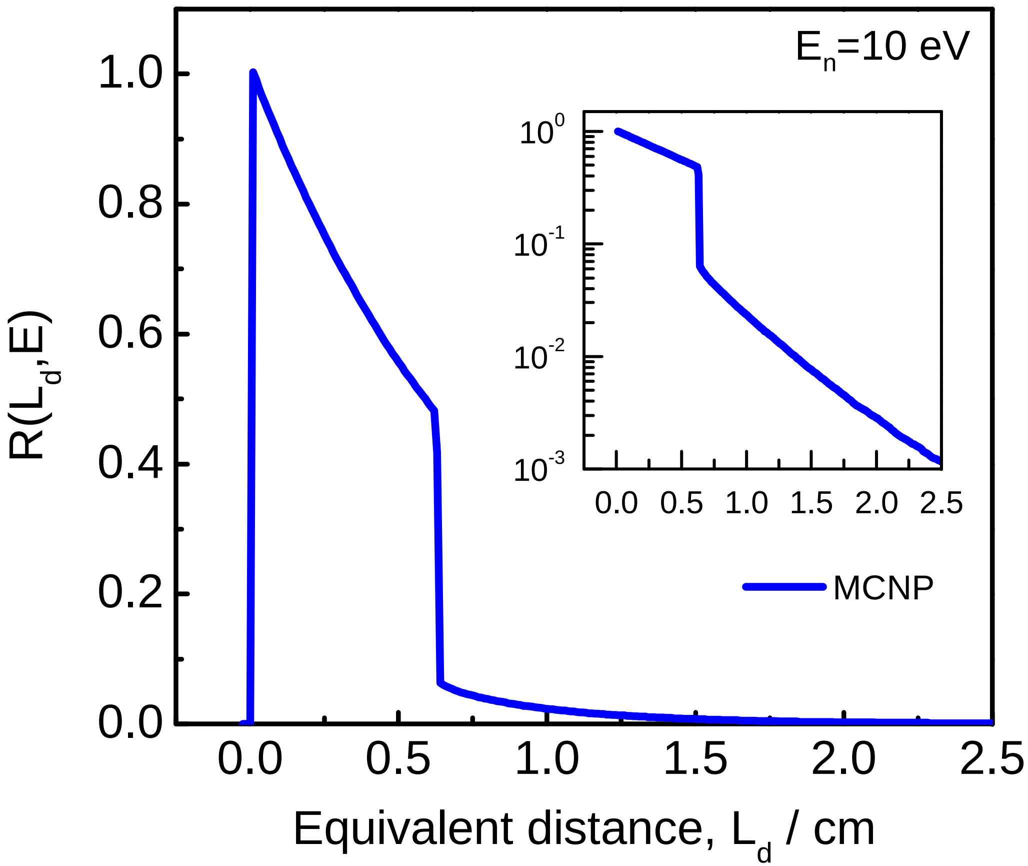




Lithium-glass scintillator : resolution

$^{6}Li(n,t)\alpha$
Scintillator + PMT





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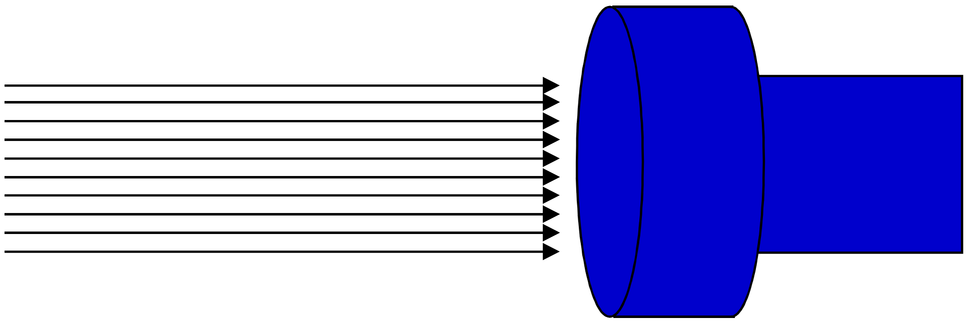
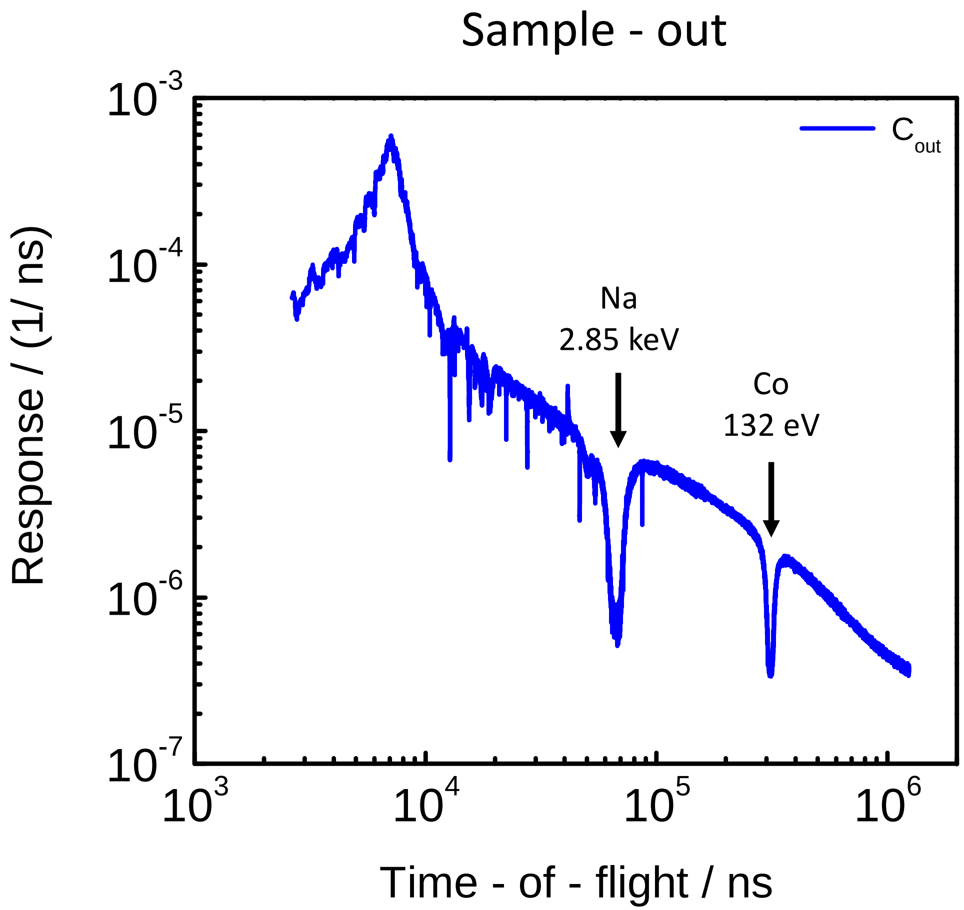
Transmission : sample-out

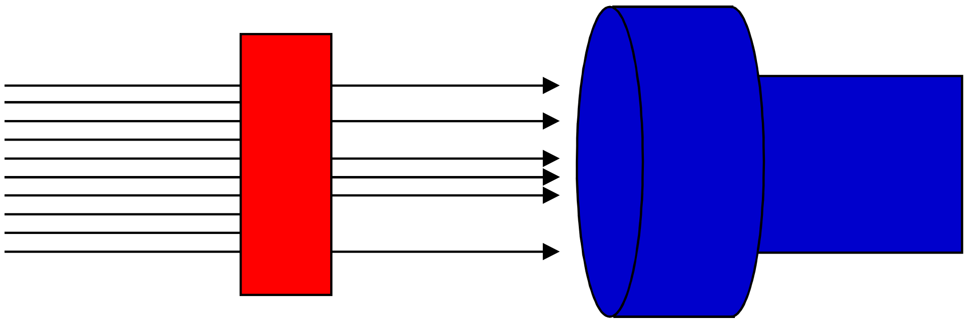
- Detector
  - NE912 Li-glass scintillator, 95% enriched in ^{6}Li
    diameter : 101.1 mm
    thickness : 6.35 mm
  - at 49.34 m from neutron source



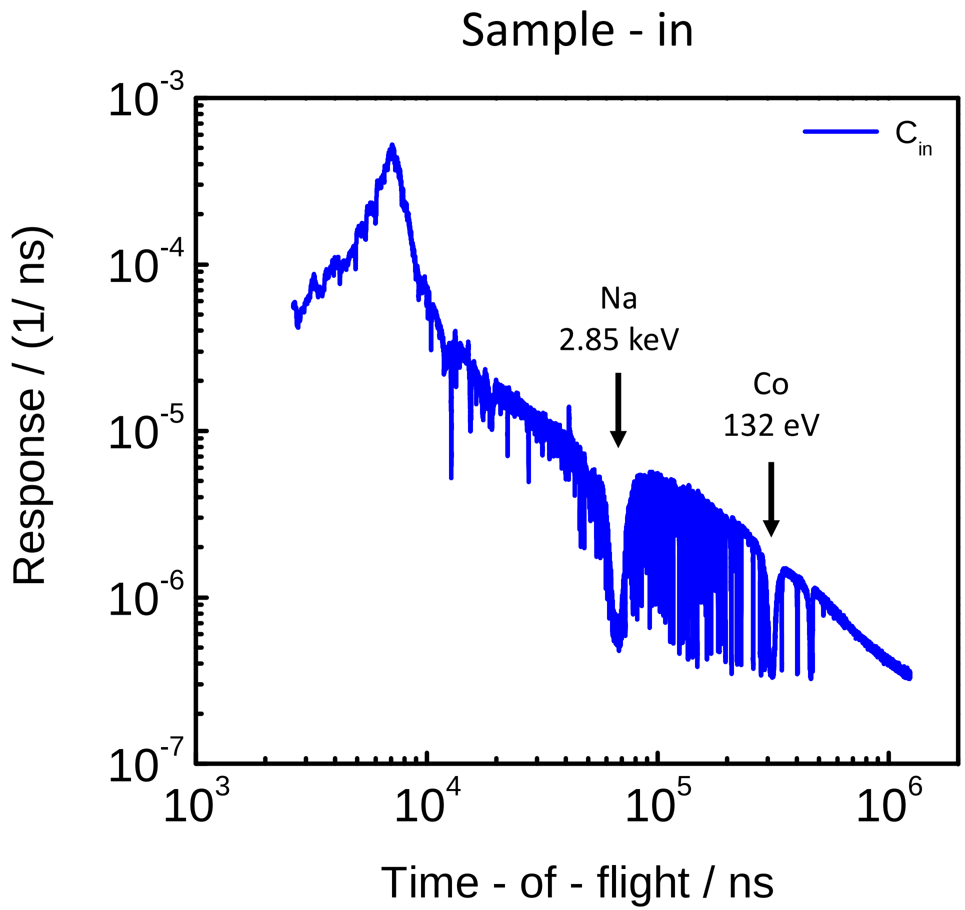


Transmission : sample-in

- Detector
  - NE912 Li-glass scintillator, 95% enriched in ^{6}Li
    diameter : 101.1 mm
    thickness : 6.35 mm
  - at 49.34 m from neutron source



- Sample
  - Au metal foil
    50 mm x 50 mm x 3 mm
    1.757 (0.004) 10^{-2} at/b
  - at 23.78 m from neutron source



Background: black resonance technique

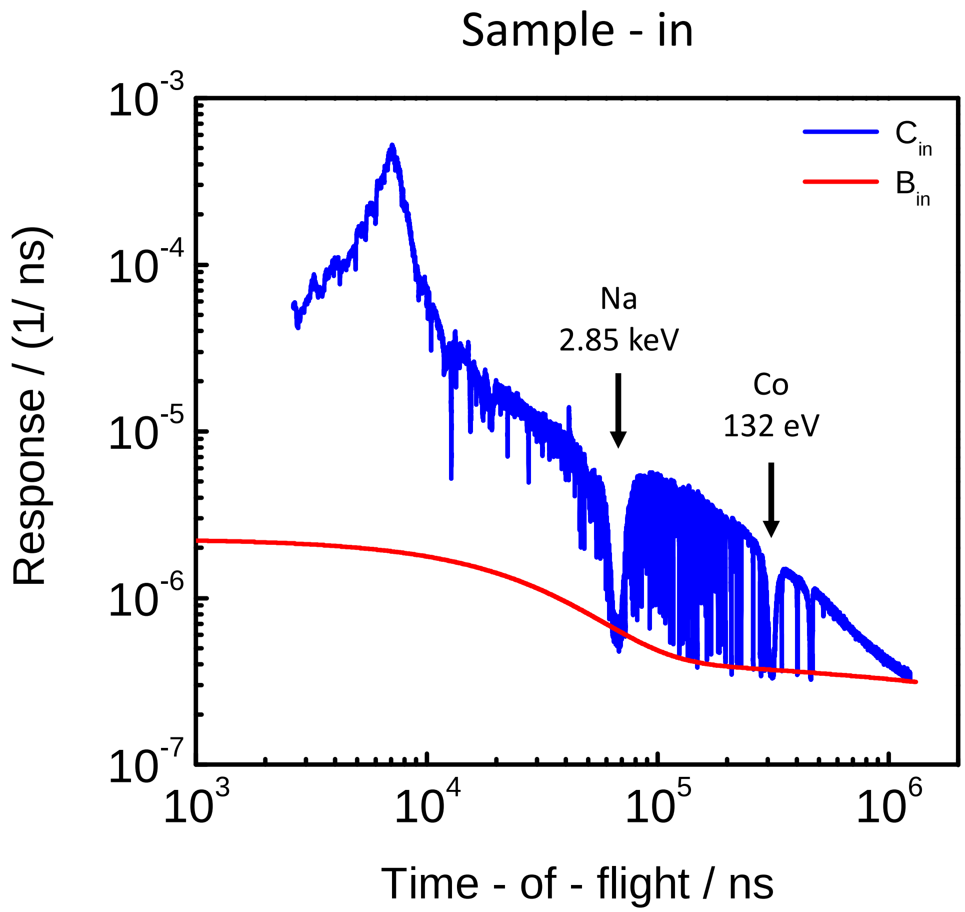
Black resonance filter

- strong resonance at E_r

$$T = e^{-n\bar{\sigma}_{tot}} \approx 0$$

- removes all neutrons at TOF corresponding to E_r

$\Rightarrow$ Remaining counts are due to background



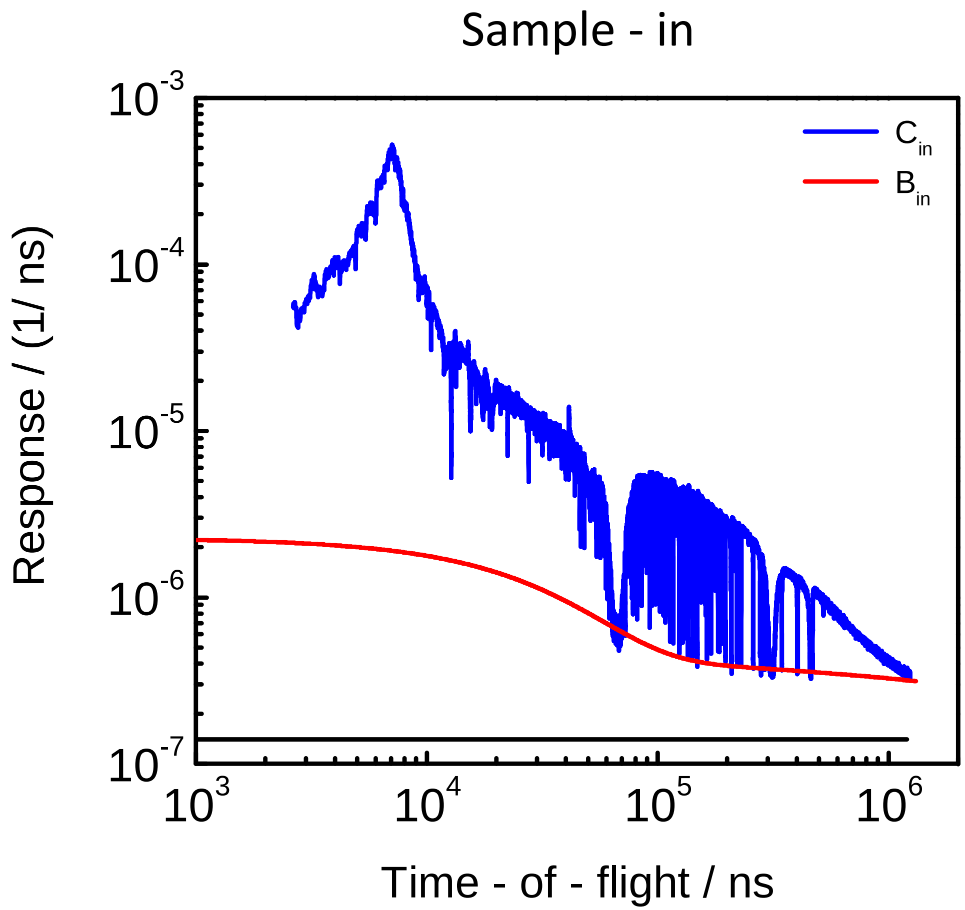
European Commission

Background: black resonance technique

$B(t) = B_0$

- B_o time independent

From measurement with no beam

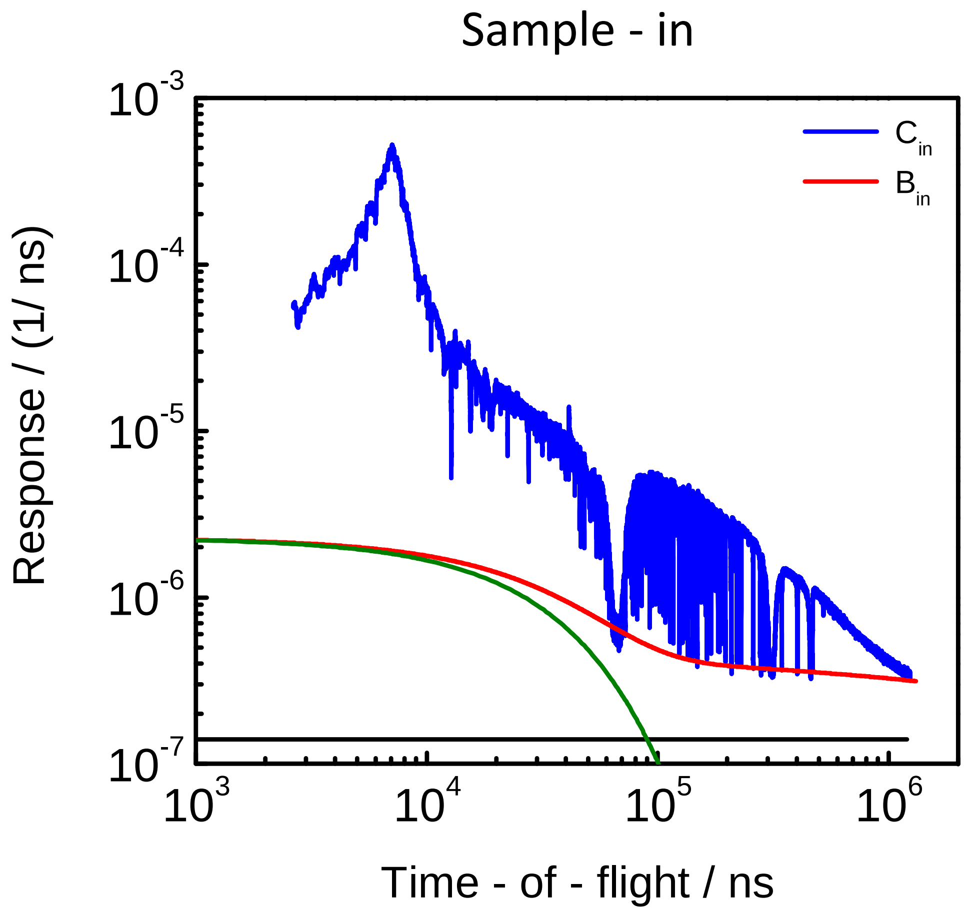


Background: black resonance technique

$B(t) = B_0 + B_\gamma(t)$

- B_o time independent
- $B_\gamma(t)$ $^1H(n, \gamma)$ $E_\gamma = 2.2$ MeV
  $b_1 e^{-\lambda_1 t}$

Shape from measurement with thick poly-ethylene filter in the beam to remove neutrons



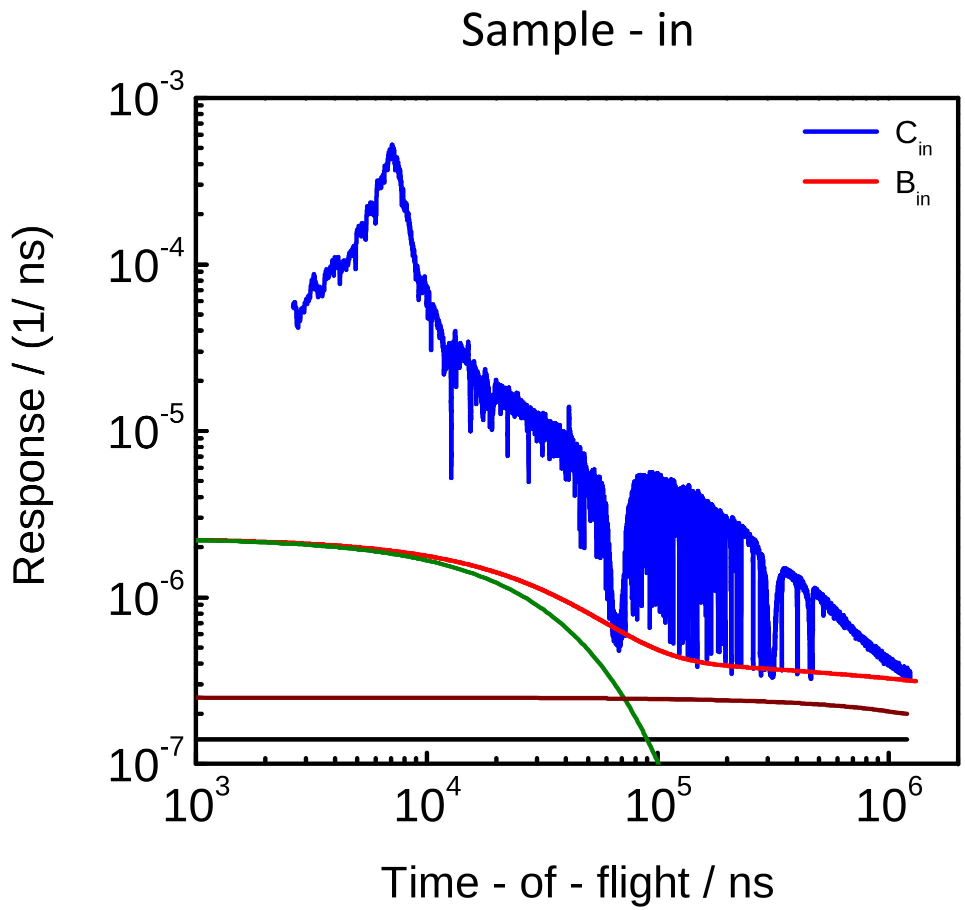
Background: black resonance technique

$B(t) = B_0 + B_\gamma(t) + B_n(t)$

- B_o time independent
- $B_\gamma(t)$ $^1H(n, \gamma)$ $E_\gamma = 2.2$ MeV
  $b_1 e^{-\lambda_1 t}$
- $B_n(t)$ scattered neutrons
  $b_2 e^{-\lambda_2 t}$

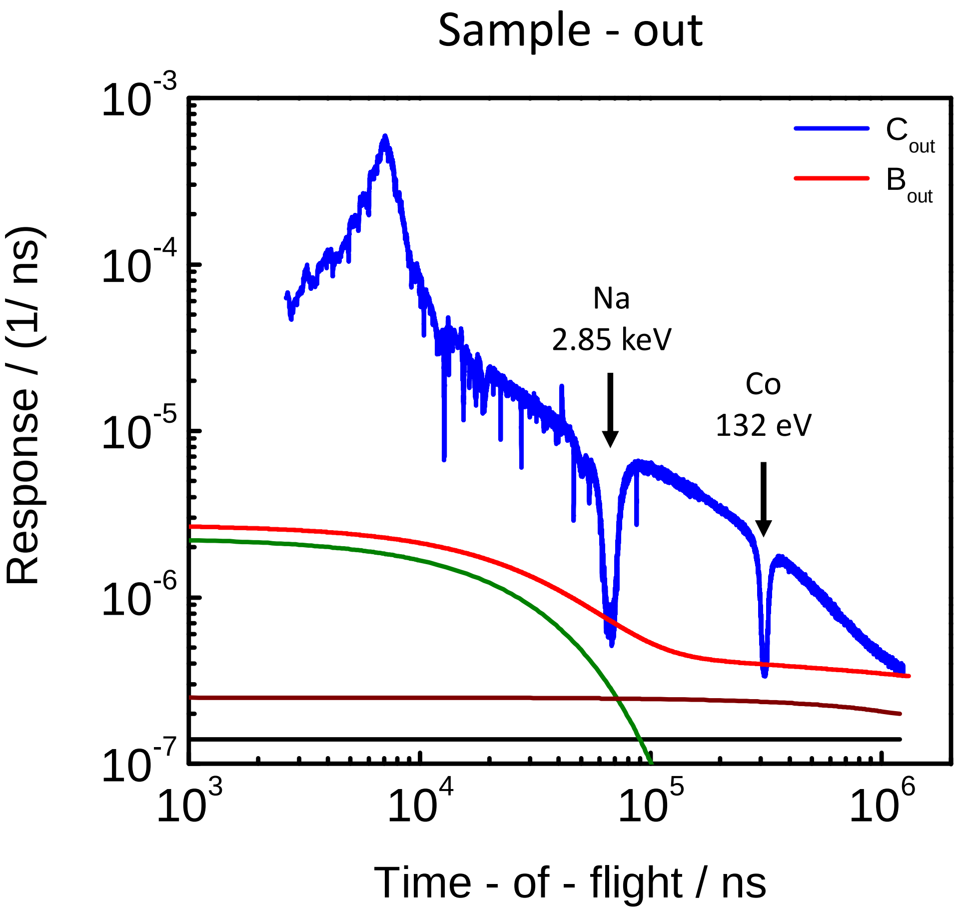
Shape from measurement with

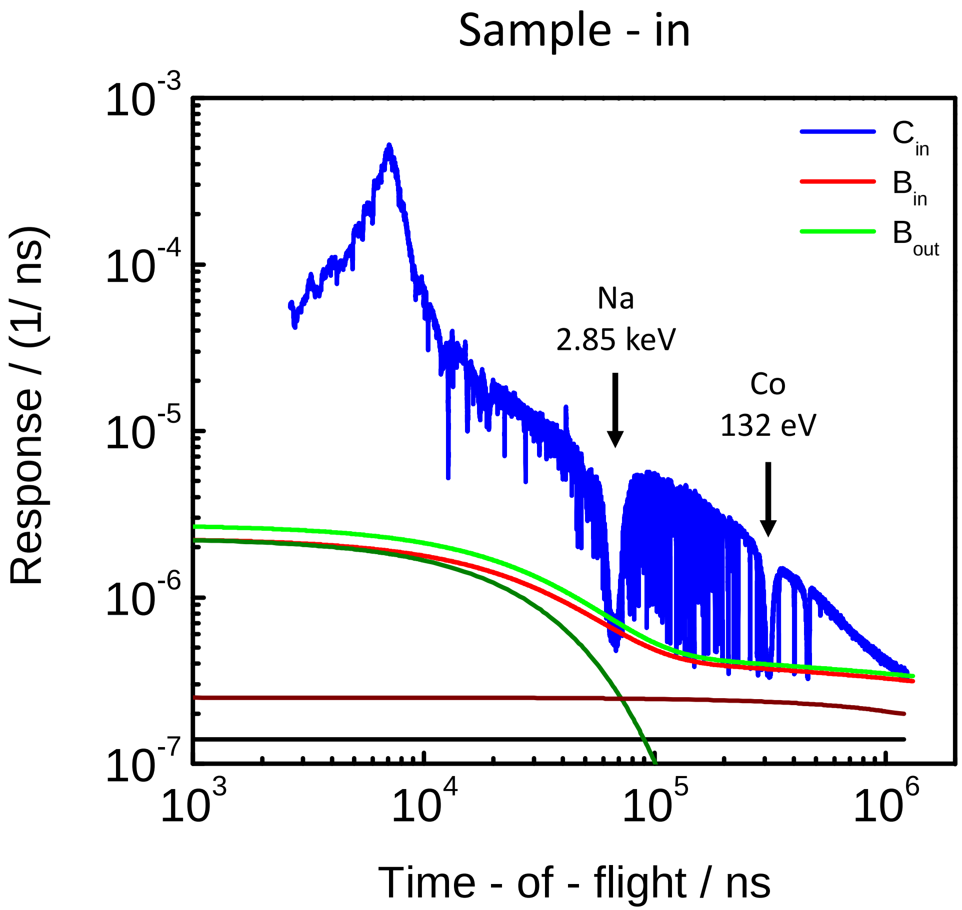
Pb-filter + black resonance filters



European Commission

Background: black resonance technique





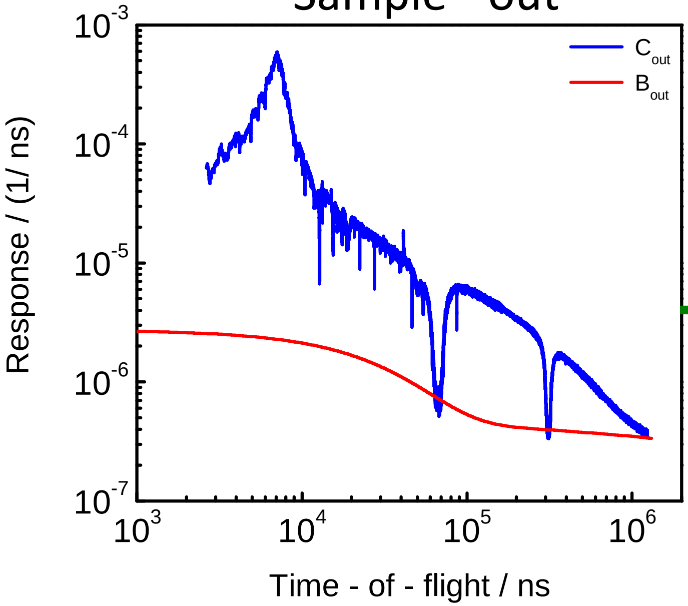
Background influenced by sample

$\Rightarrow$ use of fixed background filters to adjust b_1 and b_2

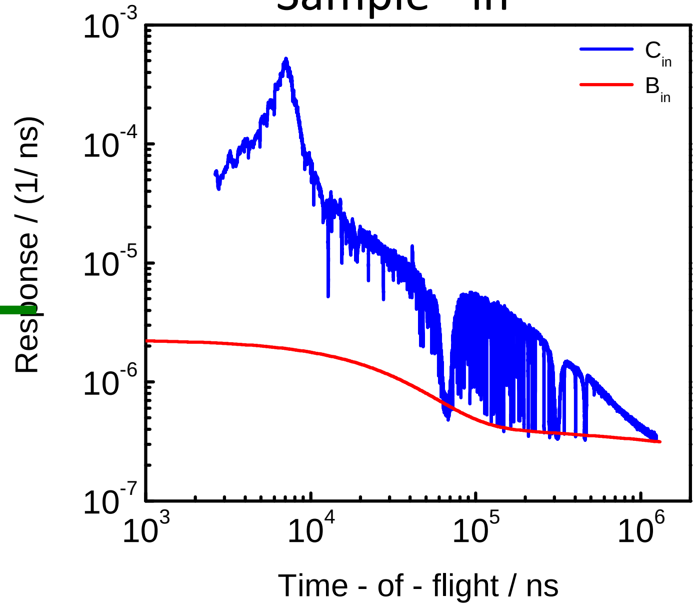
$$B = b_0 + b_1 e^{-\lambda_1 t} + b_2 e^{-\lambda_2 t}$$

TOF-spectra $\Rightarrow T_{exp}$

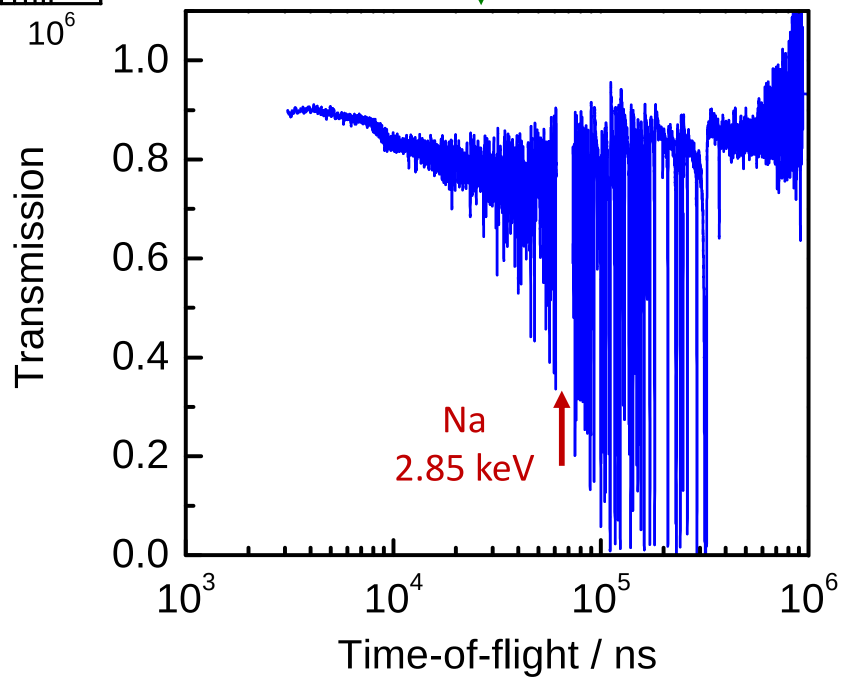
Sample - out



Sample - in



$$T_{exp} = \frac{C_{in} - K B_{in}}{C_{out} - K B_{out}}$$

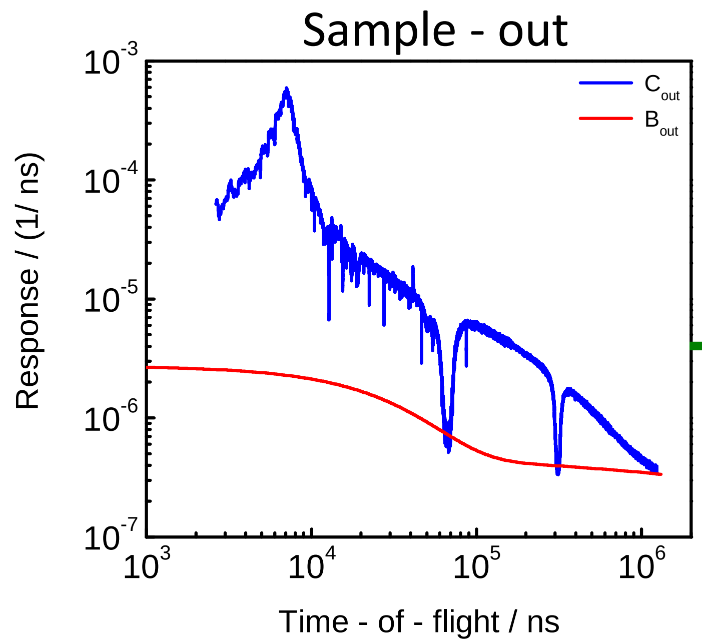


Factor K introduces a correlated uncertainty due to the background model

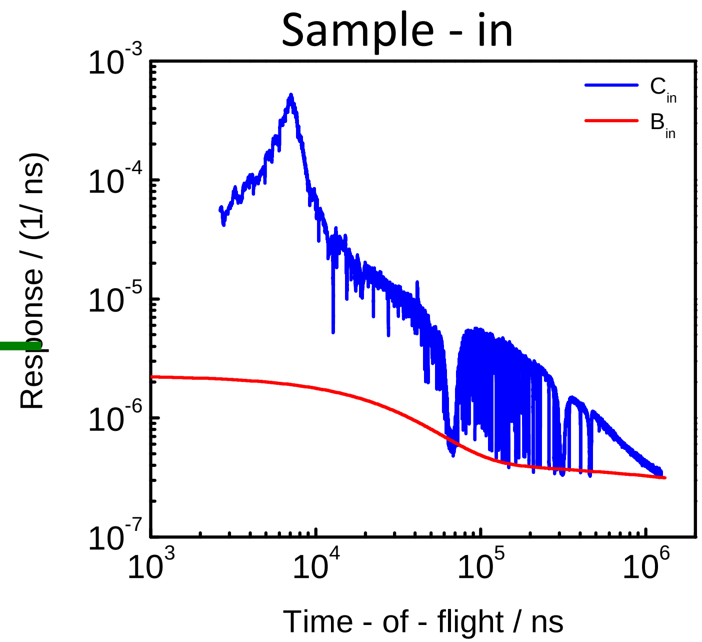
Sample - in

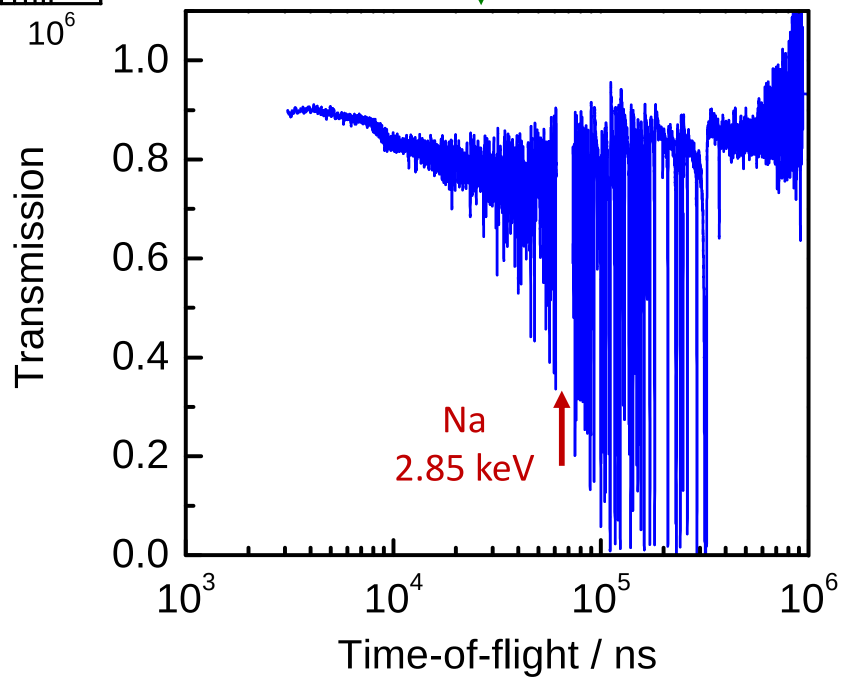
K = 1.00 ± 0.03

TOF-spectra $\Rightarrow T_{exp}$



$$T_{exp} = \boxed{N} \frac{C_{in} - K\,B_{in}}{C_{out} - K\,B_{out}}$$





Factor N introduces a correlated uncertainty due to the normalisation

Sample - in

$K = 1.00 \pm 0.03$

$N = 1.0000 \pm 0.0025$

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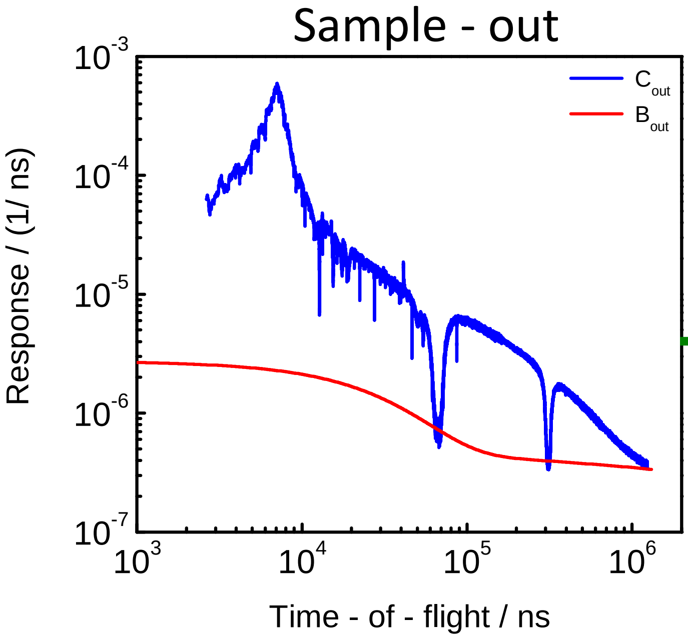
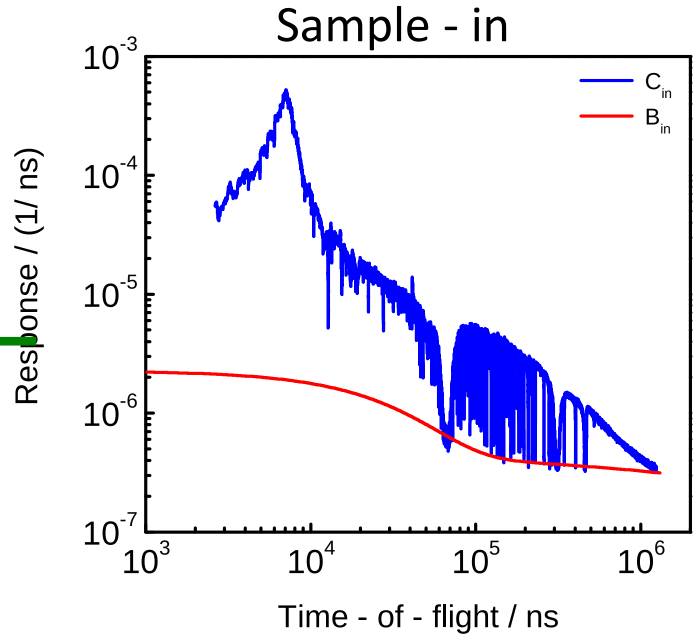
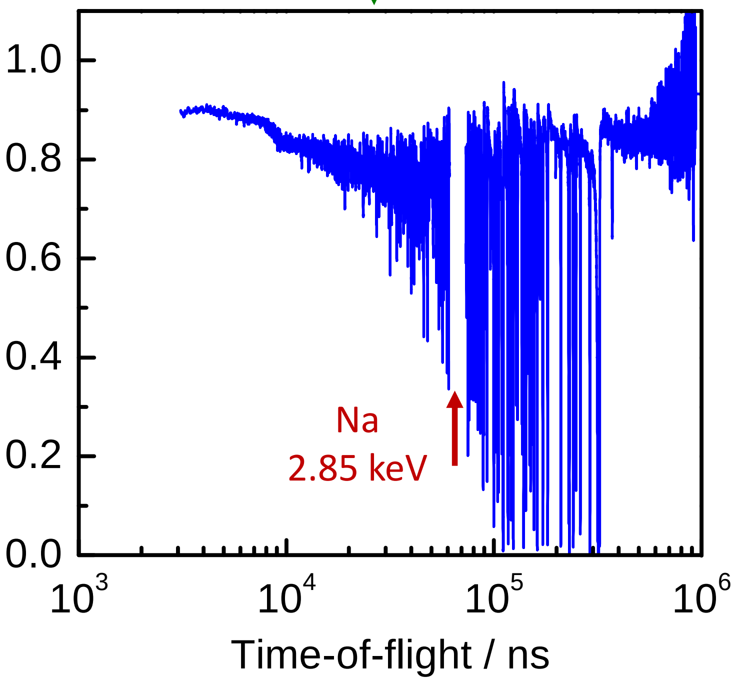
TOF-spectra $\Rightarrow T_{exp}$



$$T_{exp} = N \frac{C_{in} - K B_{in}}{C_{out} - K B_{out}}$$





Repeated measurements of sample-in and sample-out cycles to avoid impact of:

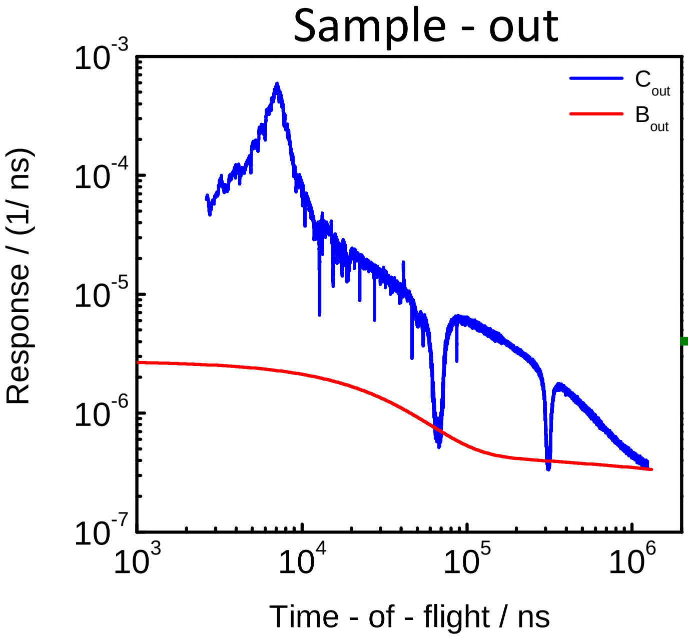
- Electronic drifts
- Variations in beam intensity

Sample - in

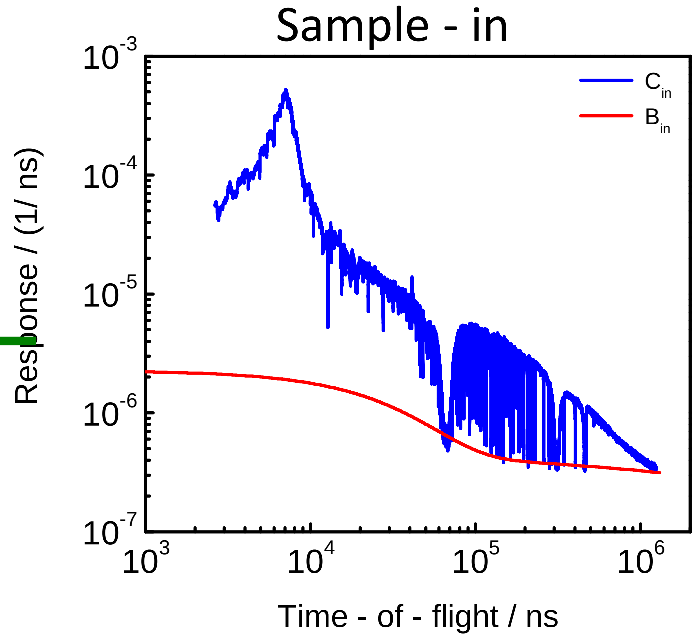
$K = 1.00 \pm 0.03$

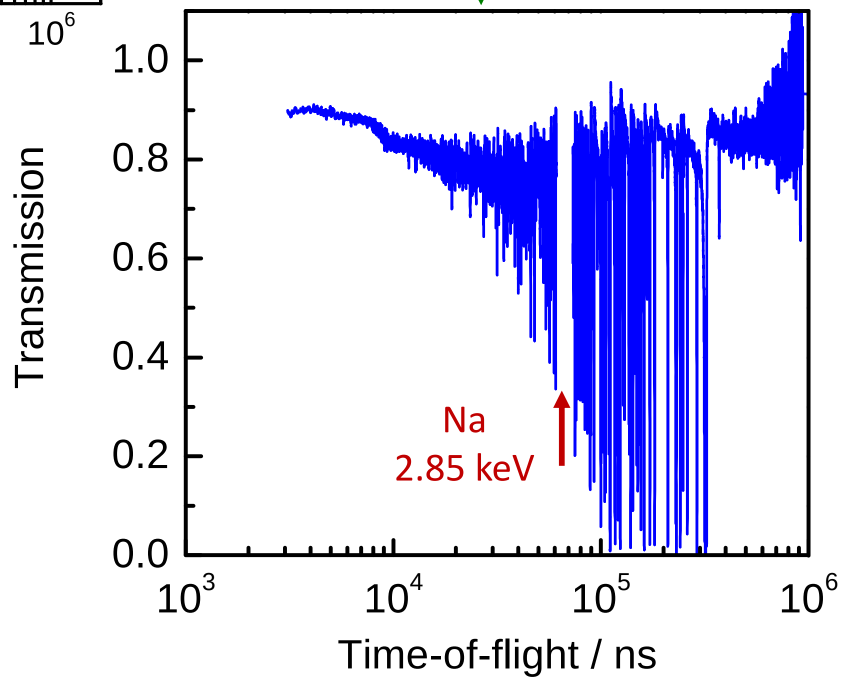
$N = 1.0000 \pm 0.0025$

TOF-spectra $\Rightarrow T_{exp}$



$$T_{exp} = N \frac{C_{in} - K\,B_{in}}{C_{out} - K\,B_{out}}$$





Sample - in

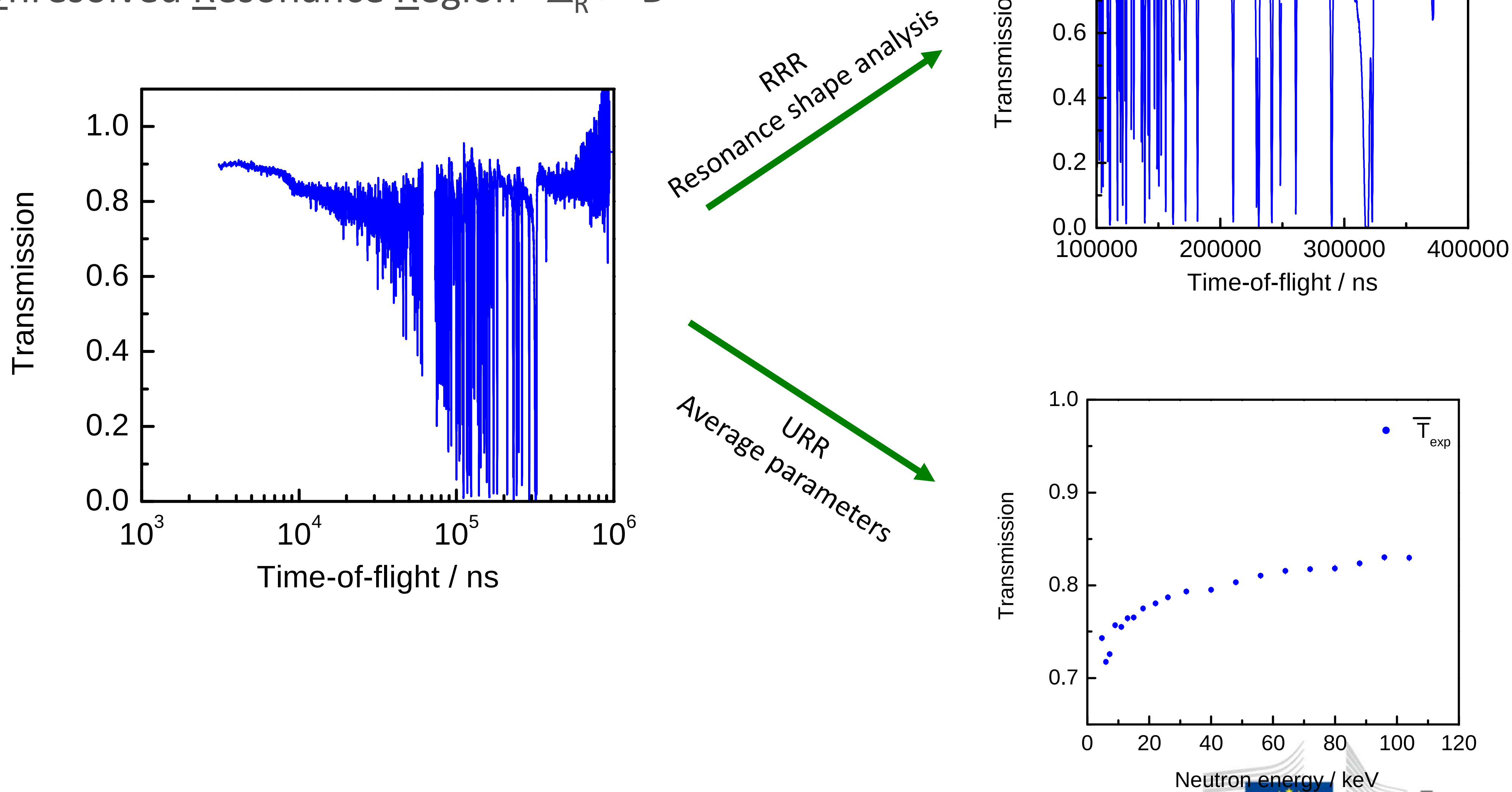
$$\frac{u_K}{K} \approx 3\%$$

$$\frac{u_N}{N} \approx 0.25\%$$

Resonance region

Resonance Region   D > Γ

- Resolved Resonance Region $\Delta_R <$ D
- Unresolved Resonance Region $\Delta_R >$ D



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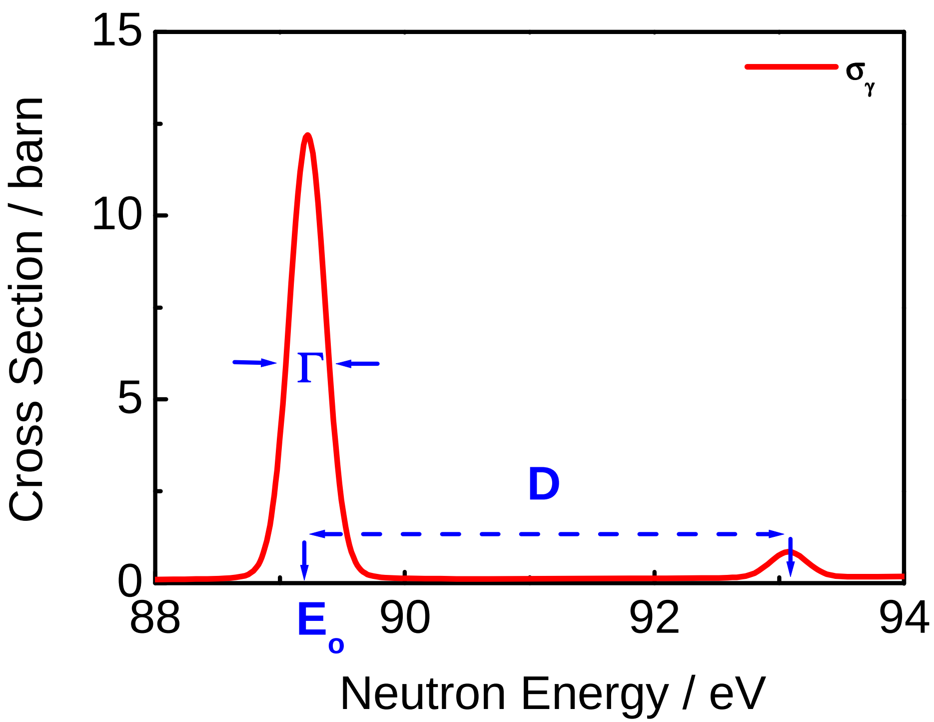
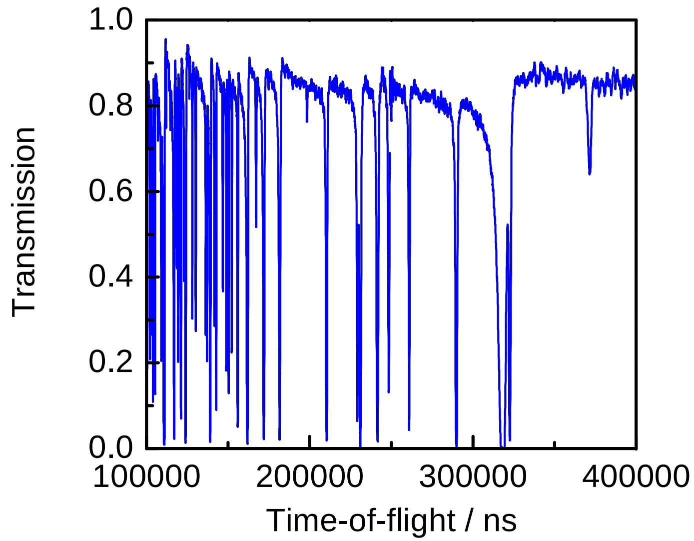
Data analysis

Resonance Region D > Γ

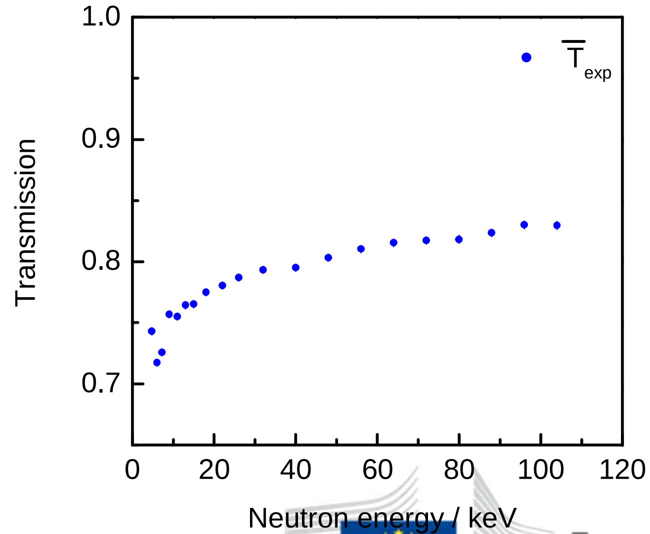
- **Resolved Resonance Region** $\Delta_R < D$
- Unresolved Resonance Region $\Delta_R > D$



RRR
Resonance shape analysis



URR
Average parameters



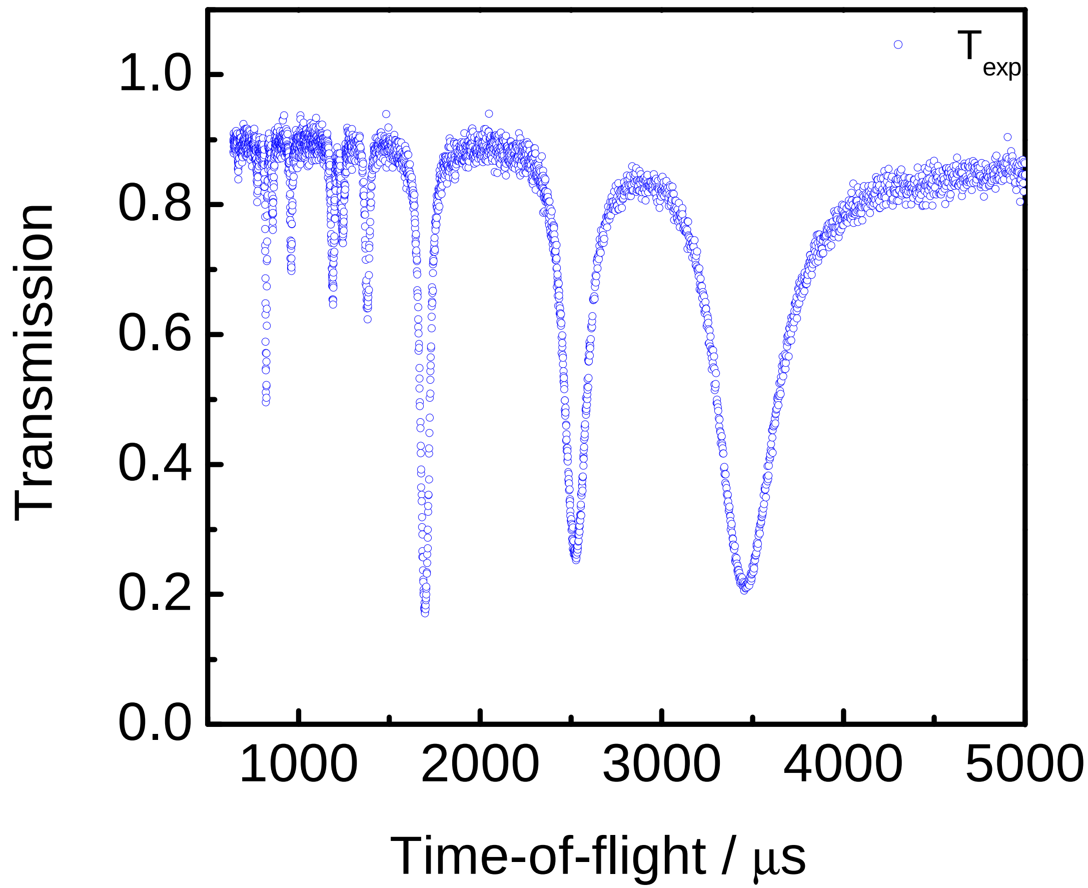
Transmission data : $^{241}Am + n$

Determine resonance parameters from a GLSQ fit to the experimental data

$$T_{exp} = \frac{C_{in} - B_{in}}{C_{out} - B_{out}} \qquad \frac{u_{T_{exp}}}{T_{exp}} < 0.25\%$$

$$\chi^2 (RP) = (T_{exp} - T_M)^T V_{T_{exp}}^{-1} (T_{exp} - T_M)$$

$$T_M(t) = \int R(t, E)\, e^{-n\, \bar{\sigma}_{tot}(E)}\, dE$$



$R(t_m,E)$	:	response of TOF-spectrometer
σ_{tot}	:	total cross section
n	:	areal number density
		total number of atoms per unit area

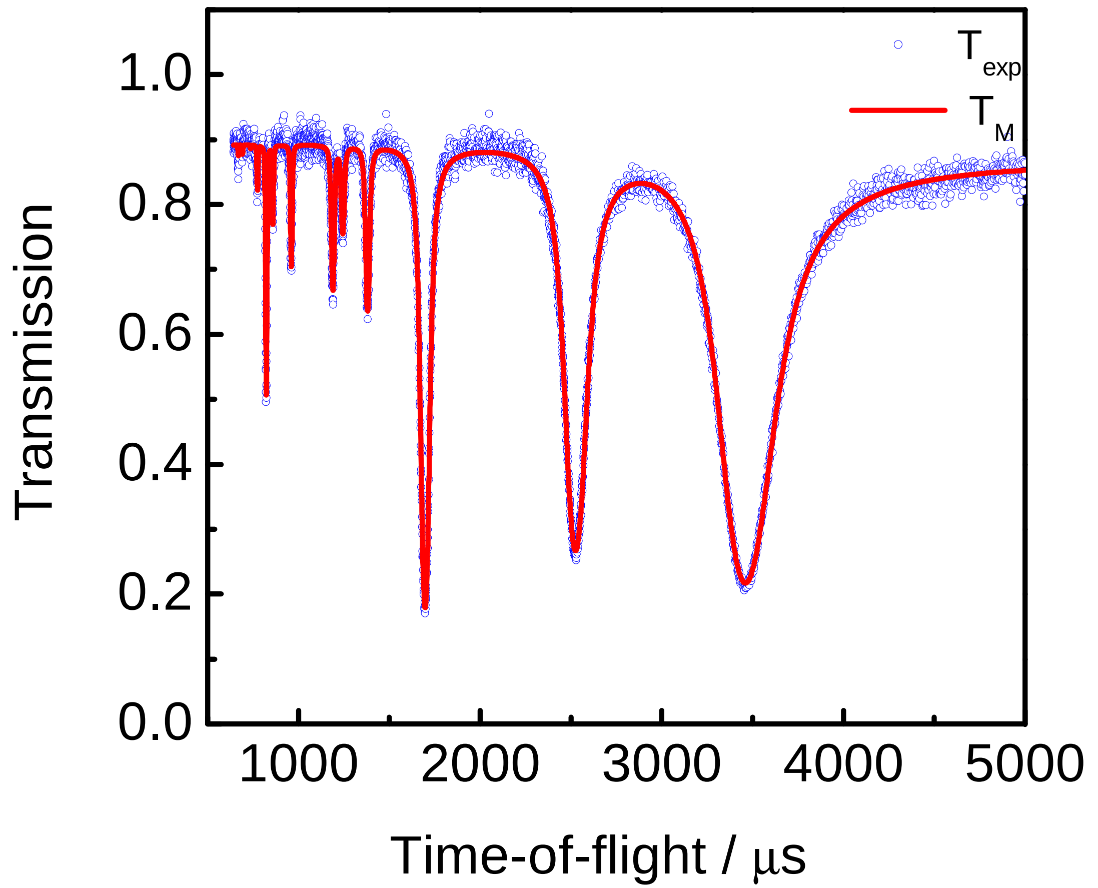
Transmission data : ^{241}Am + n

Determine resonance parameters from a GLSQ fit to the experimental data
Resonance shape analysis (RSA) with **REFIT**

$$\chi^2(RP) = \left(T_{exp} - T_M\right)^T V_{T_{exp}}^{-1} \left(T_{exp} - T_M\right)$$

$$T_{exp} = \frac{C_{in} - B_{in}}{C_{out} - B_{out}} \qquad \frac{u_{T_{exp}}}{T_{exp}} < 0.25\%$$

$$T_M(t) = \int R(t, E)\, e^{-n\,\bar{\sigma}_{tot}(E)}\, dE$$



$R(t_m,E)$: response of TOF-spectrometer
σ_{tot} : total cross section
n : areal number density
total number of atoms per unit area

European Commission

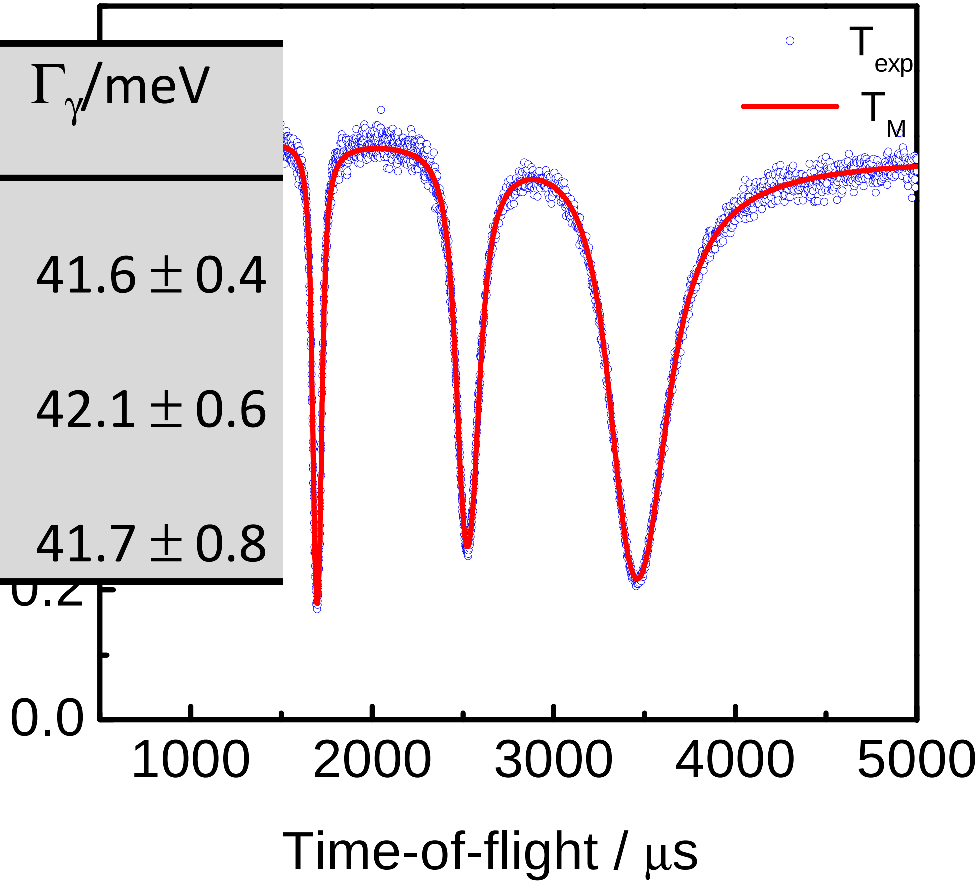
Transmission data : ^{241}Am + n

Determine resonance parameters from a GLSQ fit to the experimental data
Resonance shape analysis (RSA) with **REFIT**

^{241}Am : I^{π} =5/2- ℓ = 0 from shape

$\Delta_D \sim$ 25 meV and $\Delta_R \sim$ 2.5 meV (L = 25 m)

Energy /eV	J	g	$g\Gamma_n$/meV	Γ_γ/meV
0.306	3	7/12	0.0373 ± 0.0002	41.6 ± 0.4
0.574	2	5/12	0.0629 ± 0.0004	42.1 ± 0.6
1.271	3	7/12	0.2176 ± 0.0023	41.7 ± 0.8



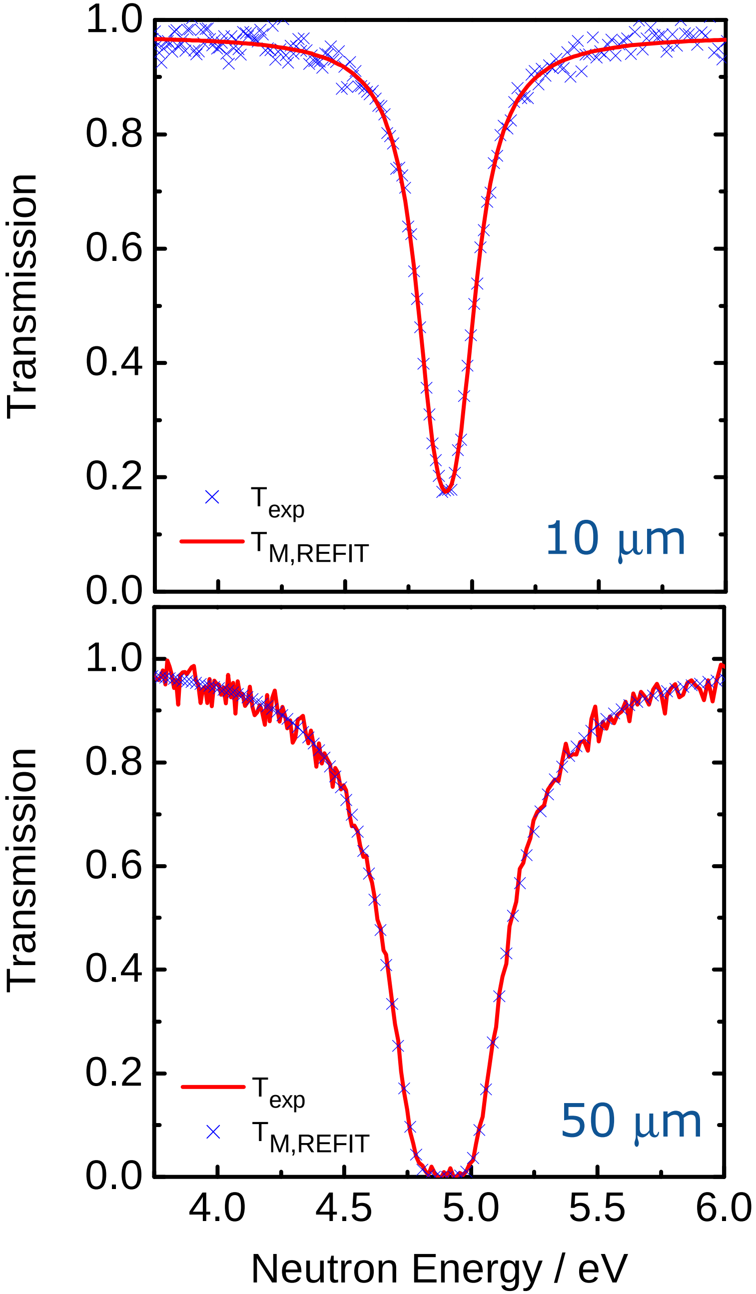
Uncertainties only due to counting statistics

⇒**absolute measurement**

⇒**no reference to any other cross section**

4.9 eV resonance for ^{197}Au+n

$^{197}Au : I^{\pi} = 3/2^{+}$



Resonance shape analysis with REFIT

ℓ = 0 from shape, *spin J = 2 from fit with capture data*

$\Delta_D \sim 80$ meV and $\Delta_R \sim 5$ meV (L = 50 m)

$\Rightarrow$

$\Gamma_n = (15.06 \pm 0.08)$ meV

$\Gamma_\gamma = (121.7 \pm 1.3)$ meV

$\Rightarrow$

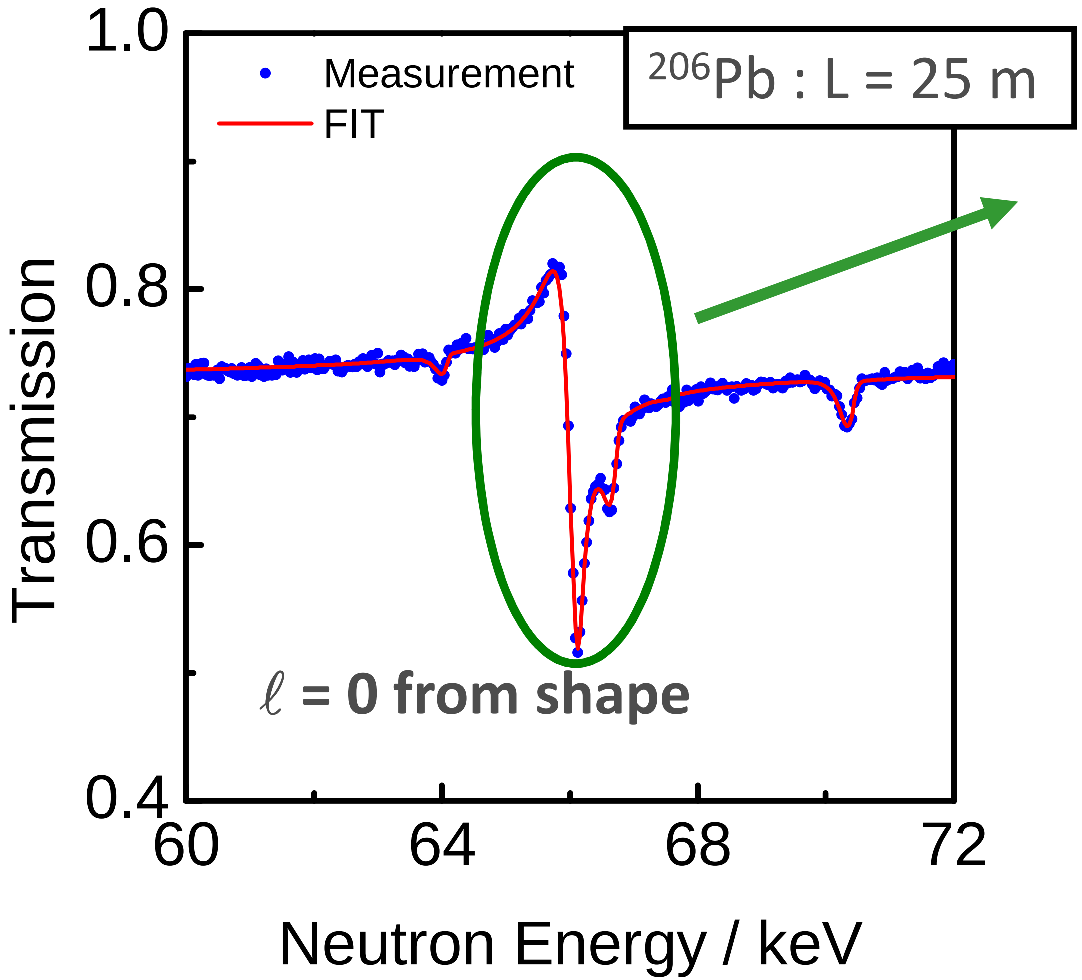
$\Gamma_n = (14.66 \pm 0.30)$ meV

$\Gamma_\gamma = (124.8 \pm 3.7)$ meV

Uncertainties only due to counting statistics

Determination of scattering radius

$$\sigma_{tot}(E_n) = g\frac{\pi}{k_n^2}\frac{\Gamma_n\Gamma}{(E_n - E_R)^2 + (\Gamma/2)^2} + g\frac{4\pi}{k_n}\frac{\Gamma_n(E_n - E_R)R}{(E_n - E_R)^2 + (\Gamma/2)^2} + g4\pi R^2$$



Interference

R = 9.55 (0.02) fm

Borella et al., Phys. Rev. C 76 (2007) 014605

Determination of statistical factor

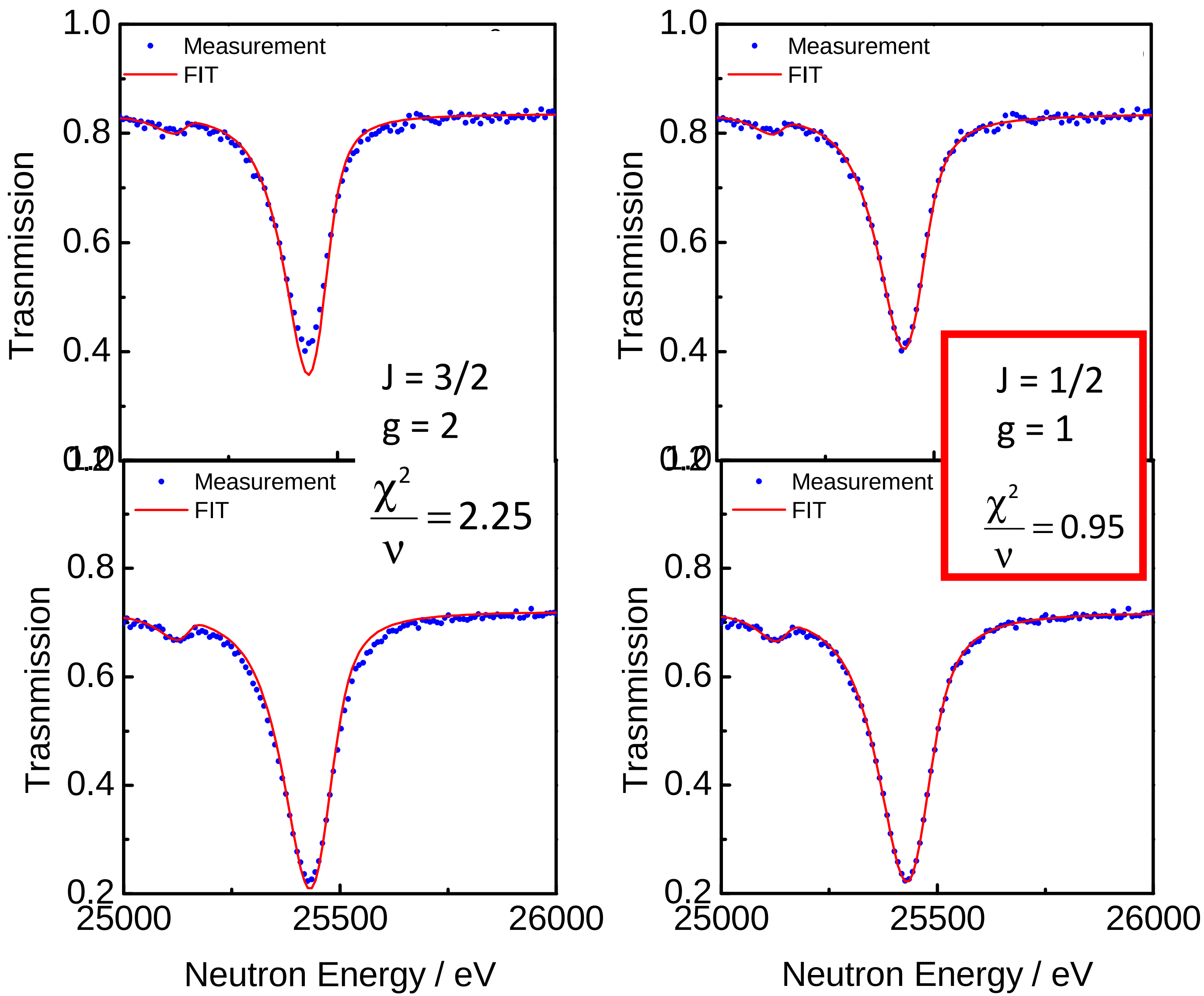
^{206}Pb ($I^{\pi} = 0^{+}$) + n

ℓ = 1 from shape

$$g = \frac{2J+1}{2(2I+1)}$$

⇒ **J = 1/2**

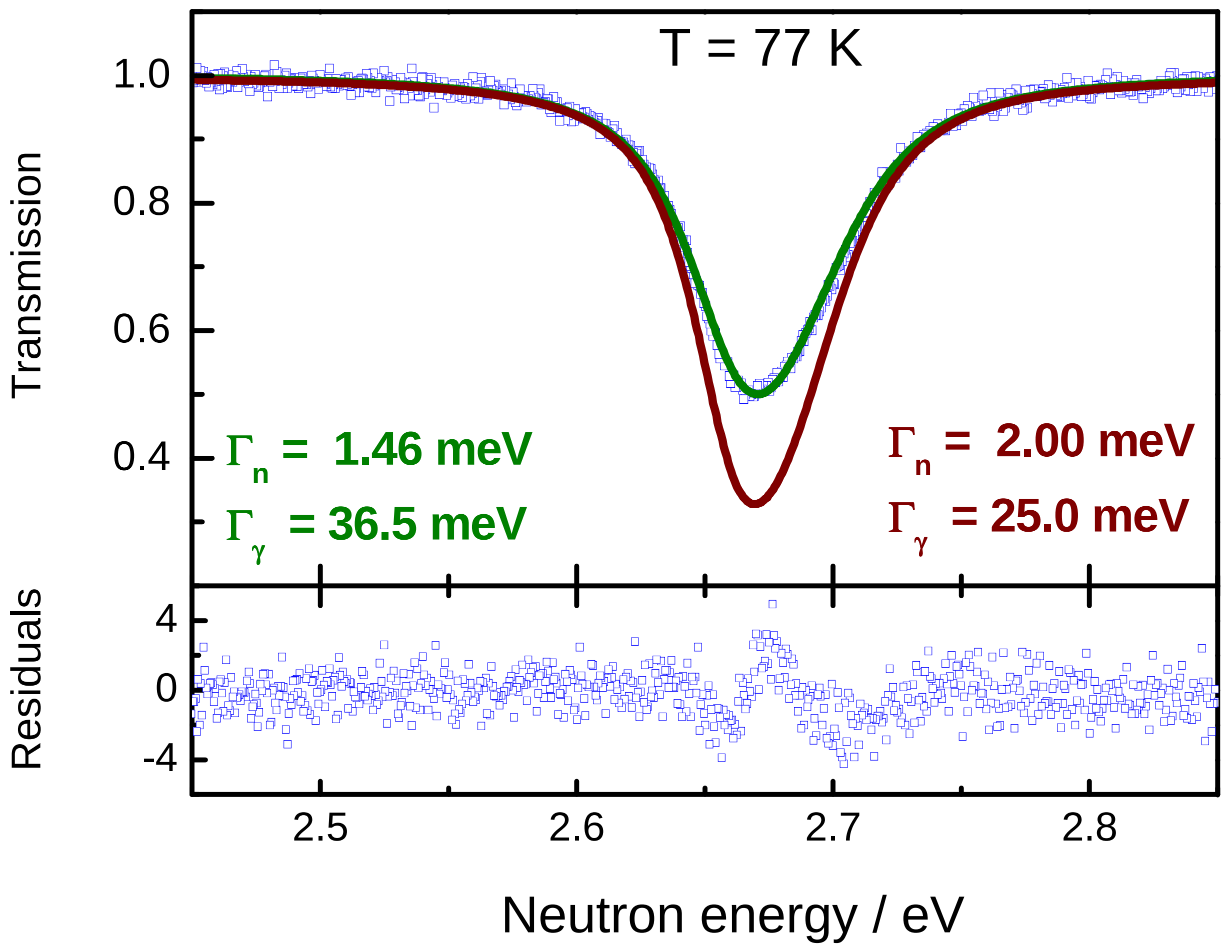
⇒ **g = 1**



Borella et al., Phys. Rev. C 76 (2007) 014605

REFIT : homogeneous sample

PuO$_2$ powder mixed with carbon powder



Homogeneous sample

$$T_M(t) = \int R(t,E)\, T(E, \overline{\sigma}_{tot}, n)\, dE$$

$$T(E, n, \overline{\sigma}_{tot}) = e^{-n\, \overline{\sigma}_{tot}(E)}$$

Peak cross section underestimated

Width overestimated

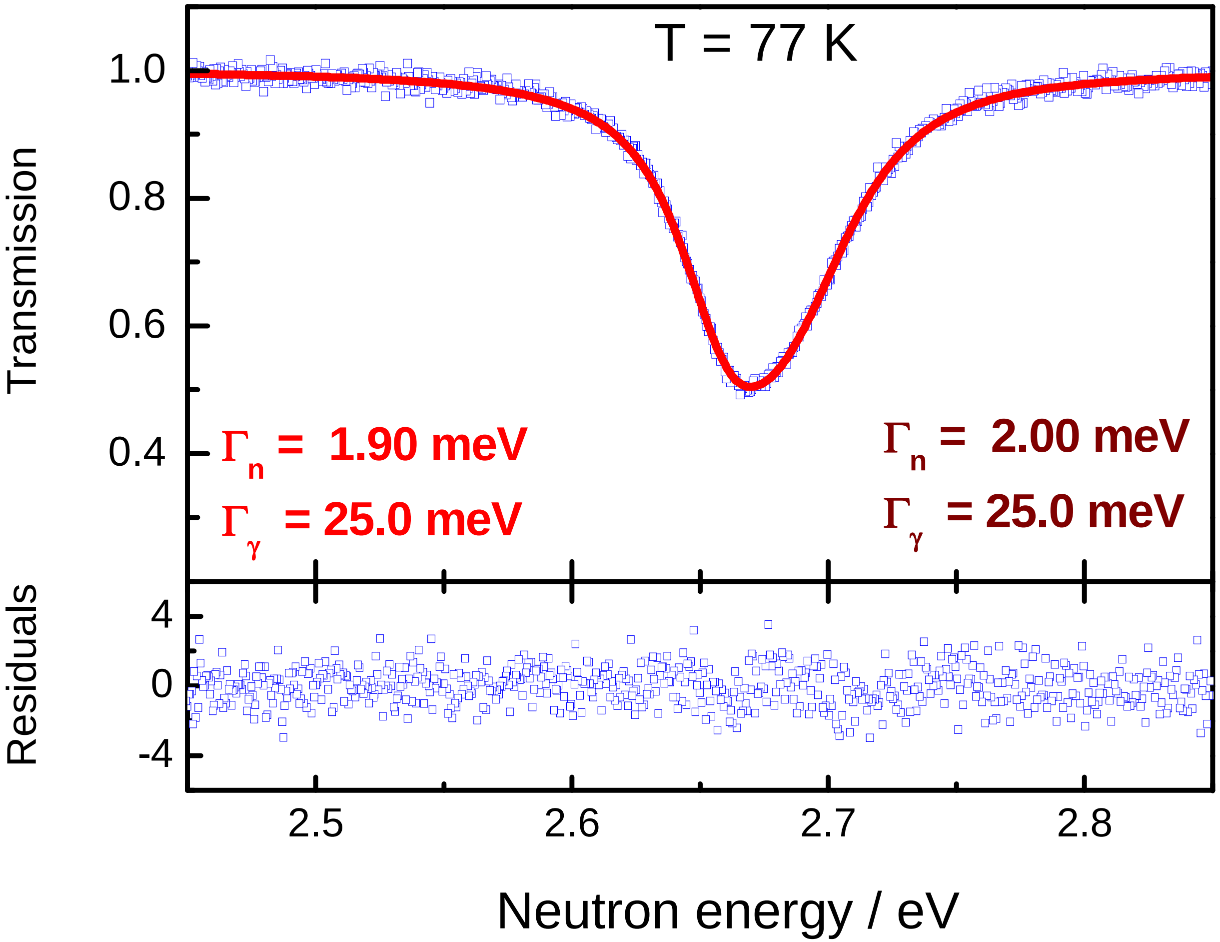
^{242}Pu

Γ_n underestimated

Γ_γ overestimated

REFIT : sample inhomogeneities

PuO_2 powder mixed with carbon powder



Account for particle size distribution

$$T_M(t) = \int R(t, E)\, T(E, \bar{\sigma}_{tot}, n, \ldots)\, dE$$

$$T(E, \bar{\sigma}_{tot}, n \ldots) = (1 - f_h) \int e^{-\sum_k x\, n'_k \bar{\sigma}_{tot,k}}\, p(x) dx + f_h$$

$$p(x) = \frac{1}{x\sqrt{2\pi s^2}} e^{-\frac{(\ln x + s^2/2)^2}{2s^2}}$$

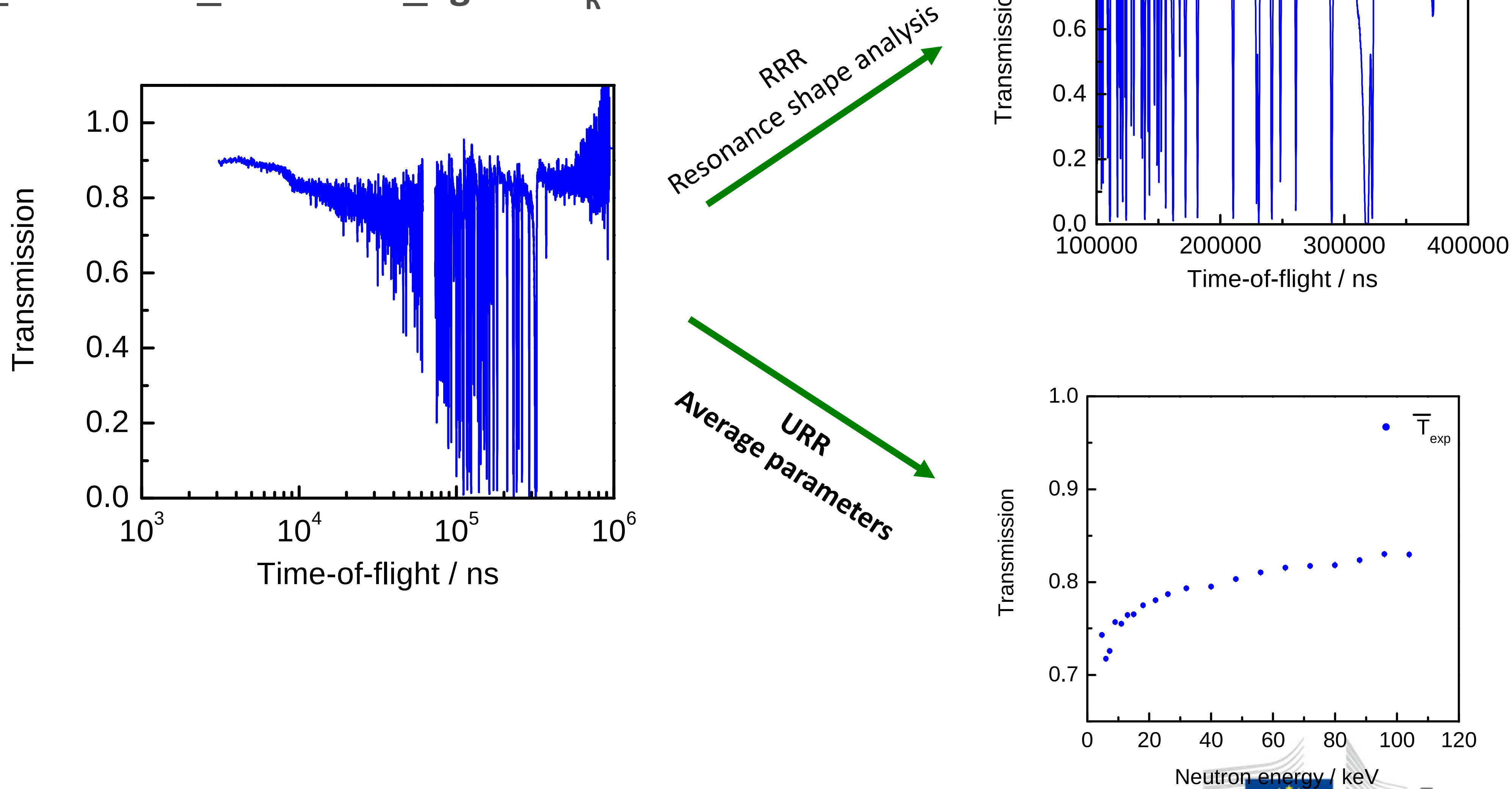
$$n'_k = \frac{n_k}{f_h}$$

See Becker et al.

Resonance region

Resonance Region D > Γ

- Resolved Resonance Region $\Delta_R <$ D
- **Unresolved Resonance Region $\Delta_R >$ D**



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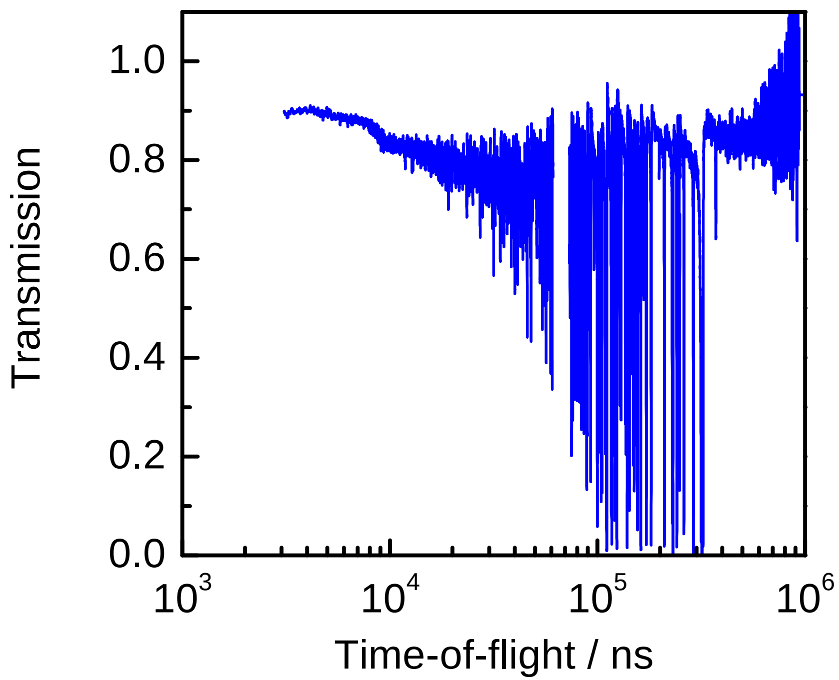
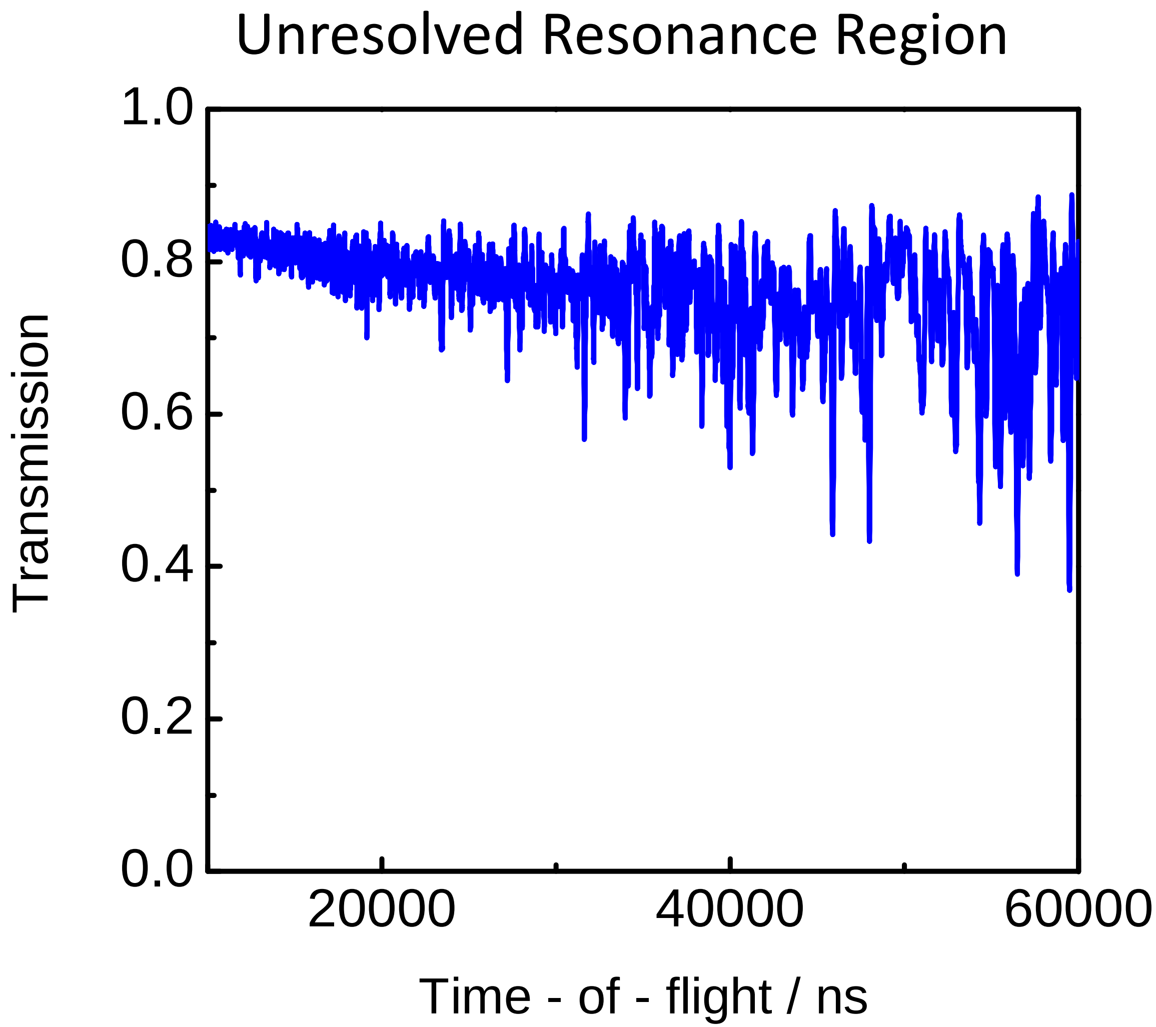
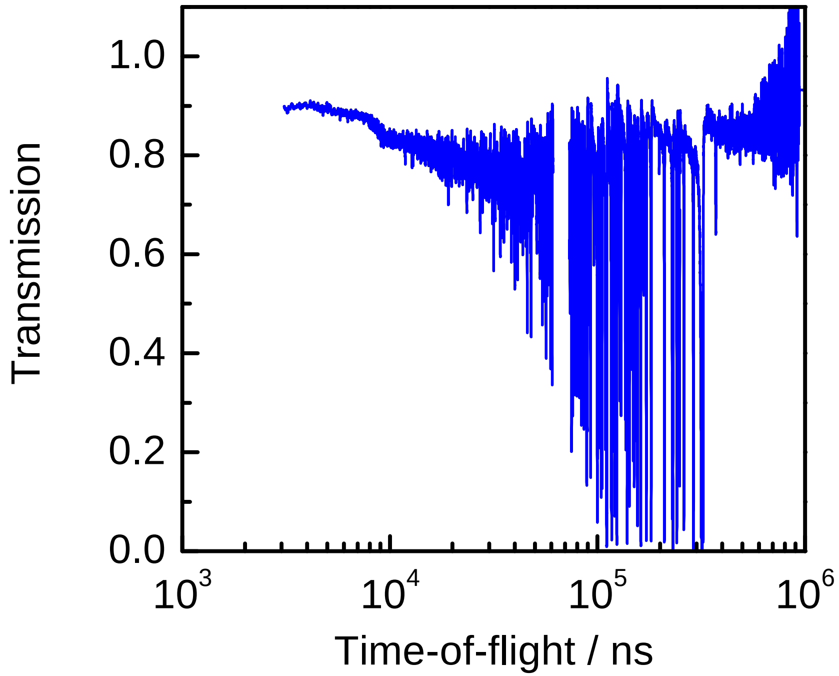
Unresolved resonance region

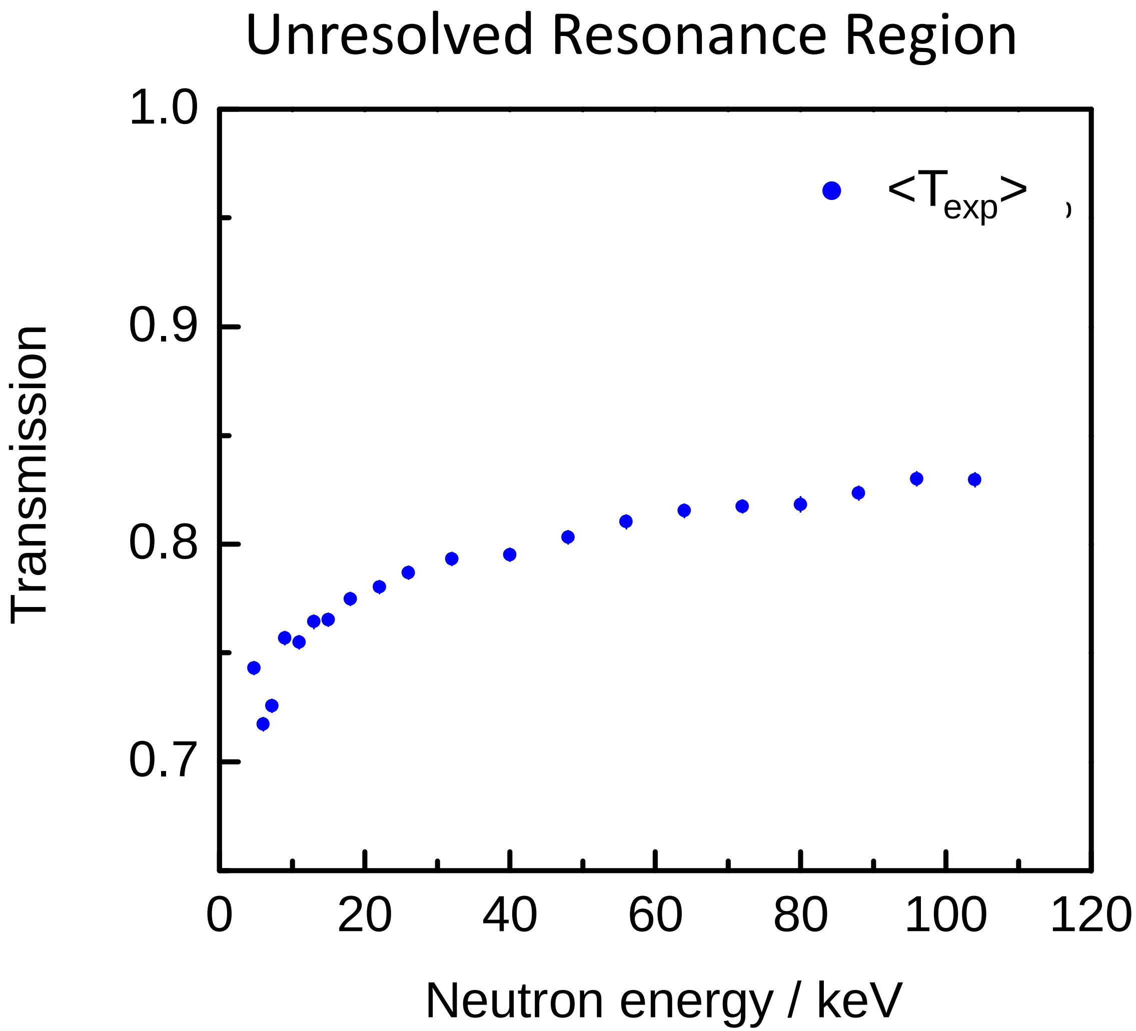




European Commission

From average T_{exp} to average σ_{tot}





From average T_{exp} to average σ_{tot}

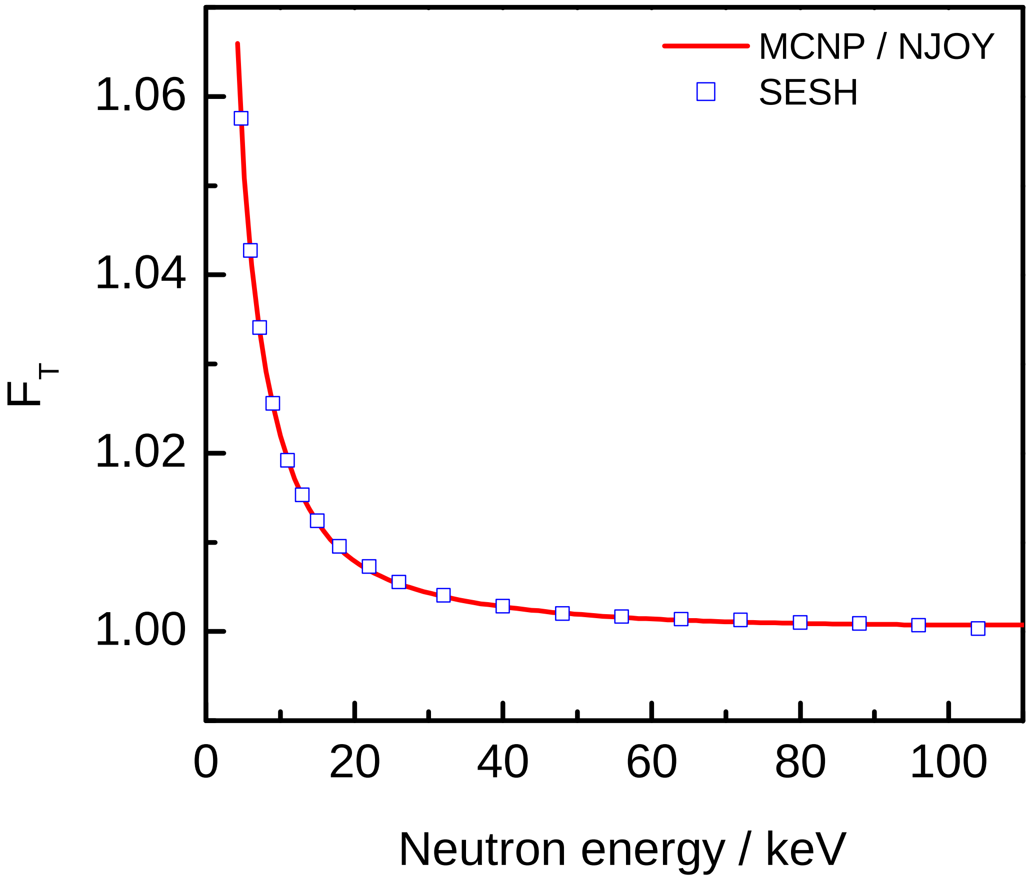
$$T = e^{-n\,\sigma_{tot}}$$

$$<T> = <e^{-n\sigma_{tot}}> = e^{-n<\sigma_{tot}>}\left(1 + \frac{n^2}{2}var(\sigma_{tot}) + \ldots\right)$$

$$<T> \neq e^{-n<\sigma_{tot}>}$$

$$<\sigma_{tot}> \neq \frac{-1}{n}\ln <T_{exp}>$$

From average T_{exp} to average σ_{tot}



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

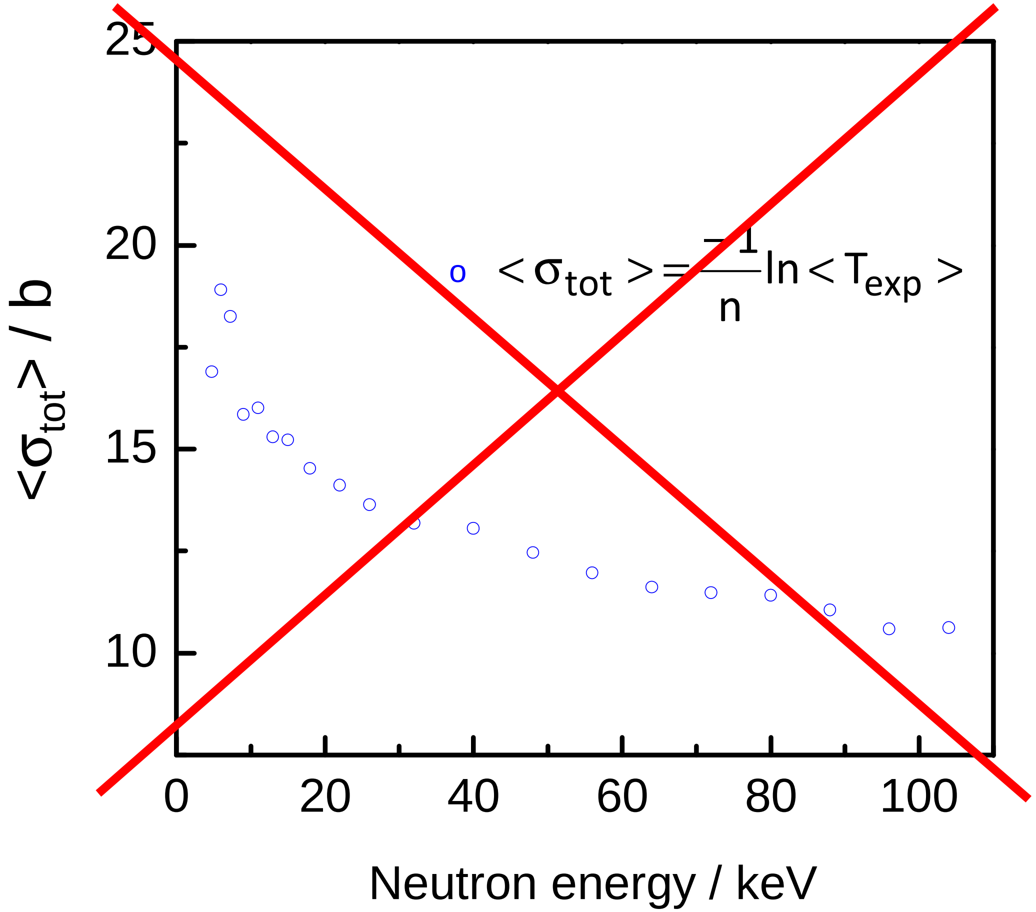
$$<T> = <e^{-n\sigma_{tot}}> = e^{-n<\sigma_{tot}>}\left(1 + \frac{n^2}{2}\mathrm{var}(\sigma_{tot}) + \ldots\right)$$

$$<T> = <e^{-n\sigma_{tot}}> \neq e^{-n<\sigma_{tot}>}$$

$$F_T = \frac{<e^{-n\sigma_{tot}}>}{e^{-n<\sigma_{tot}>}} = 1 + \frac{n^2}{2}\mathrm{var}(\sigma_{tot}) + \ldots$$

$$<\sigma_{tot}> = \frac{-1}{n}\ln\frac{<T_{exp}>}{F_T}$$

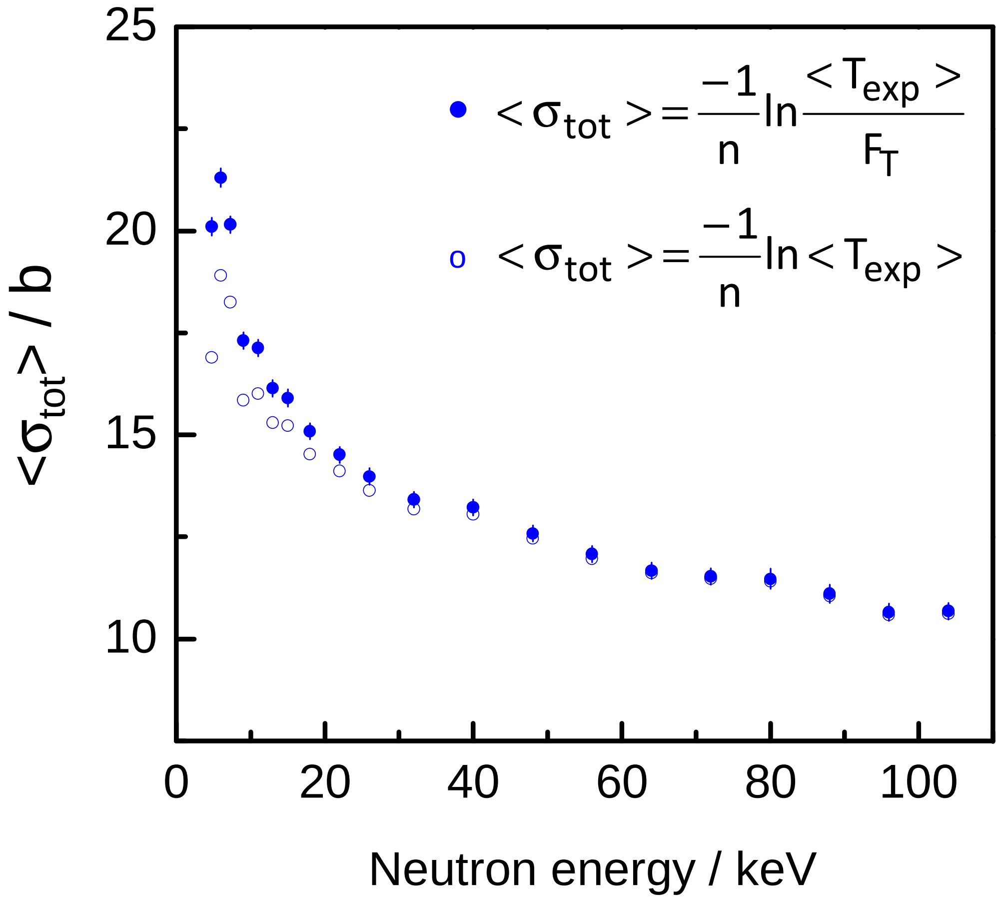
From average T_{exp} to average σ_{tot}



$$F_T = \frac{<e^{-n\sigma_{tot}}>}{e^{-n<\sigma_{tot}>}} = 1 + \frac{n^2}{2} var(\sigma_{tot}) + \ldots$$

$$<\sigma_{tot}> = \frac{-1}{n} \ln \frac{<T_{exp}>}{F_T}$$

From average T_{exp} to average σ_{tot}



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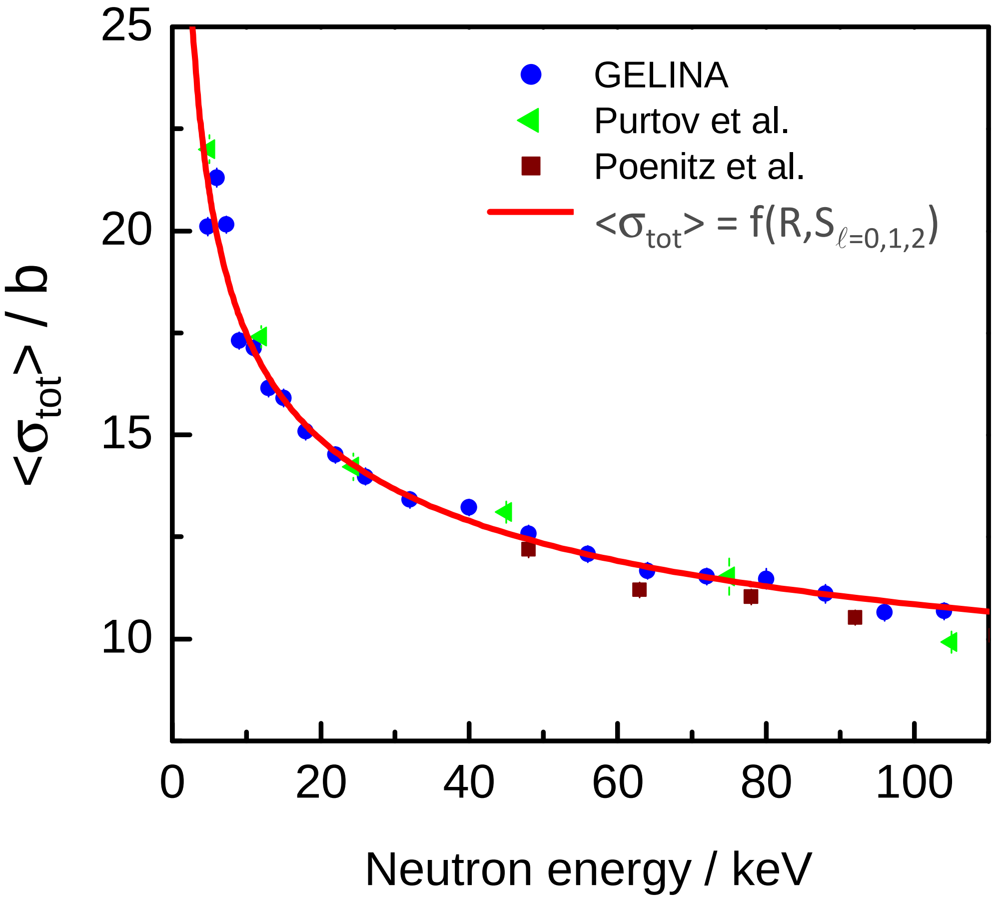
Parameterisation by average parameters



$$<\sigma_c>=\frac{2\pi}{k_c^2}g_c\left[1-\sqrt{1-T_c}\cos(2\psi_c)\right]$$

$$T_c(E)=\frac{2\pi\sqrt{E}P_cS_c}{k_ca_c}\times\left[\left(1+\frac{\pi\sqrt{E}P_cS_c}{2k_ca_c}-F_cR_c^\infty\right)^2+\left(P_cR_c^\infty+\frac{\pi\sqrt{E}F_cS_c}{2k_ca_c}\right)^2\right]^{-1}, \quad (7)$$

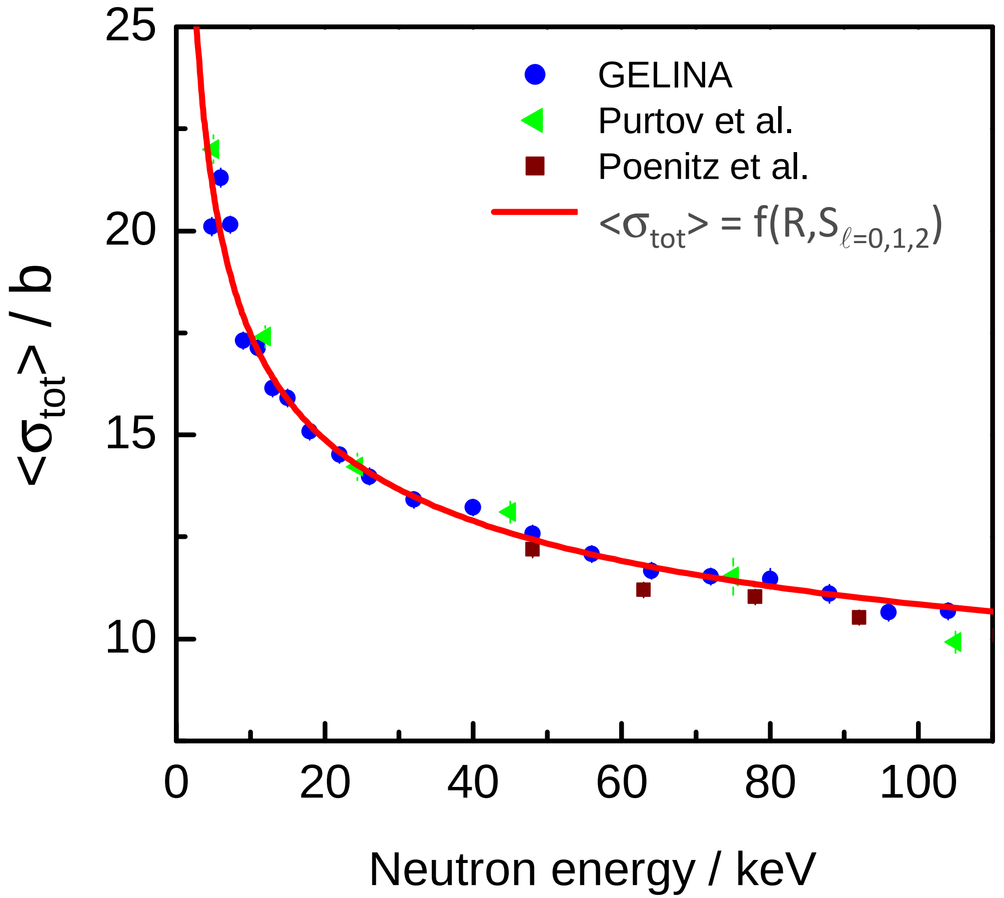
$$\psi_c(E)=\phi_c(k_ca_c)-\frac{1}{2}\left[\tan^{-1}\frac{P_cR_c^\infty-\pi\sqrt{E}F_cS_c/2k_ca_c}{1-\pi\sqrt{E}P_cS_c/2k_ca_c-F_cR_c^\infty}+\tan^{-1}\frac{P_cR_c^\infty+\pi\sqrt{E}F_cS_c/2k_ca_c}{1+\pi\sqrt{E}P_cS_c/2k_ca_c-F_cR_c^\infty}\right], \quad (8)$$

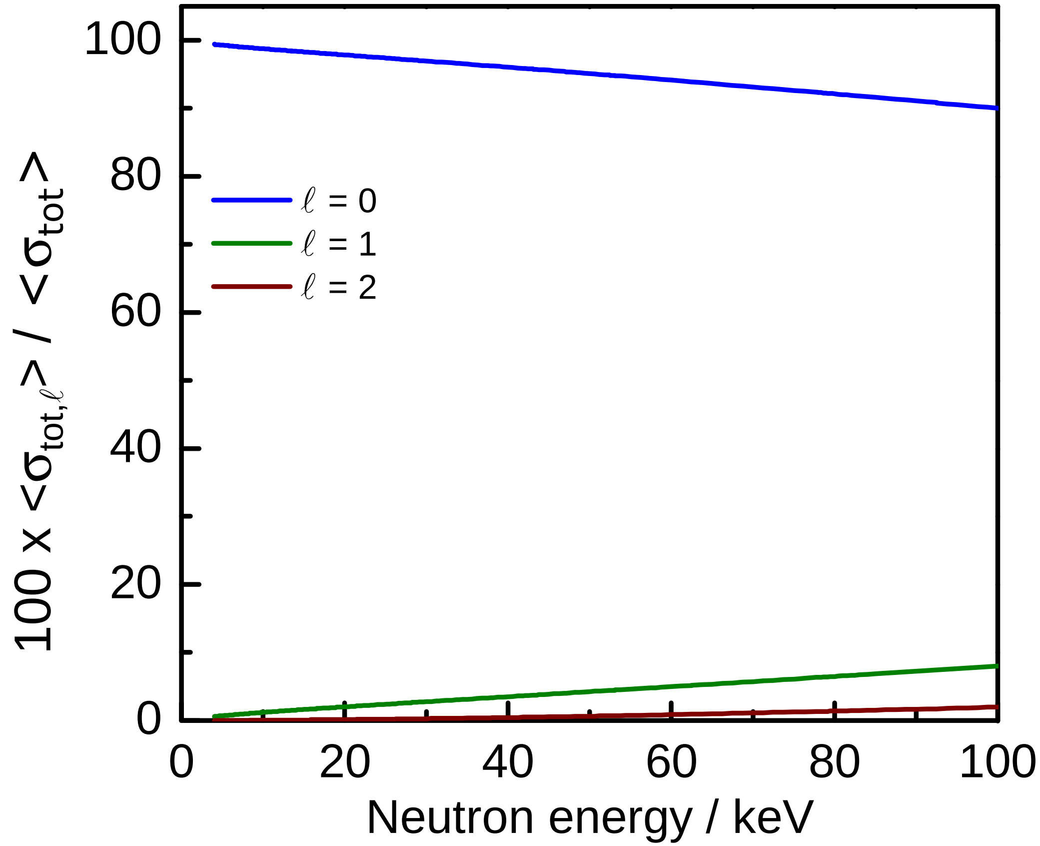
$$<\sigma_{tot}> = f(R,S_{\ell=0,1,2})$$

$$S_\ell=\frac{\sum_{j=1}^{N}(g\Gamma_n^\ell)_j}{(2\ell+1)\,\Delta E}$$

$$\Gamma_n^\ell=\frac{1}{\sqrt{E_n/1\text{eV}}}\frac{k_ca_c}{P_\ell}\Gamma_{n,\ell}$$

Parameterisation by average parameters





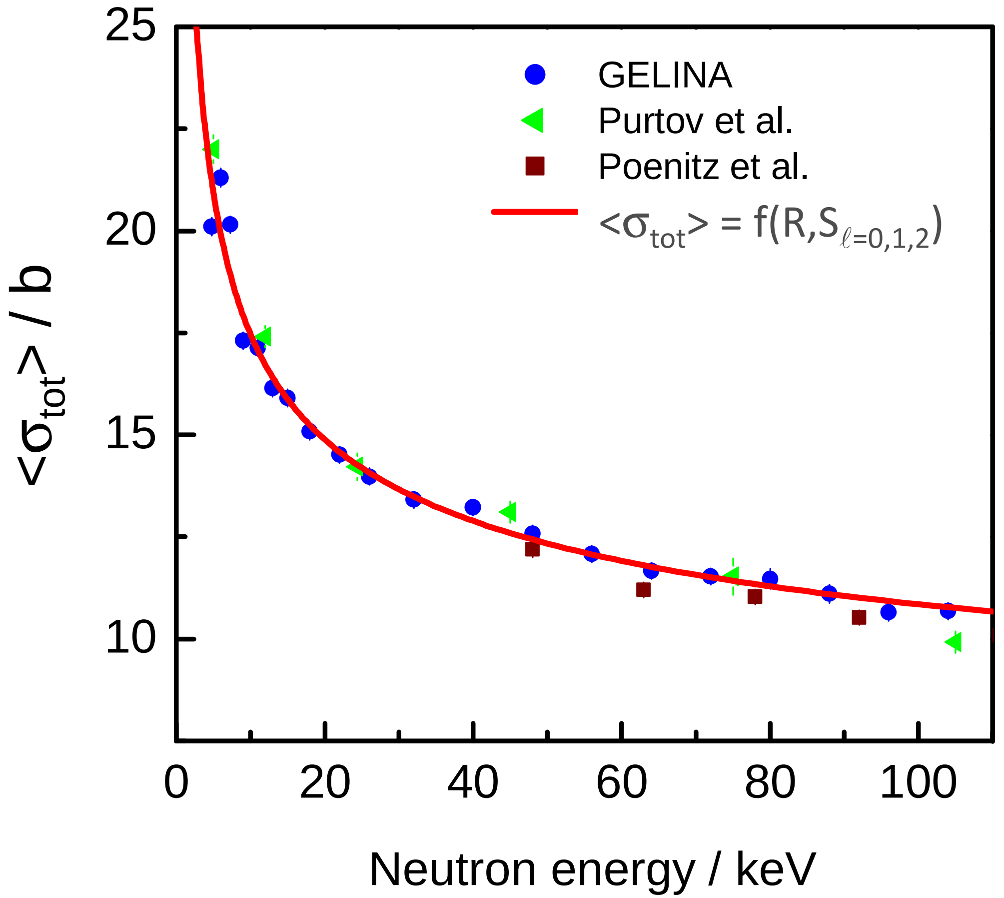
$$<\sigma_{tot}> = f(R, S_{\ell=0,1,2})$$

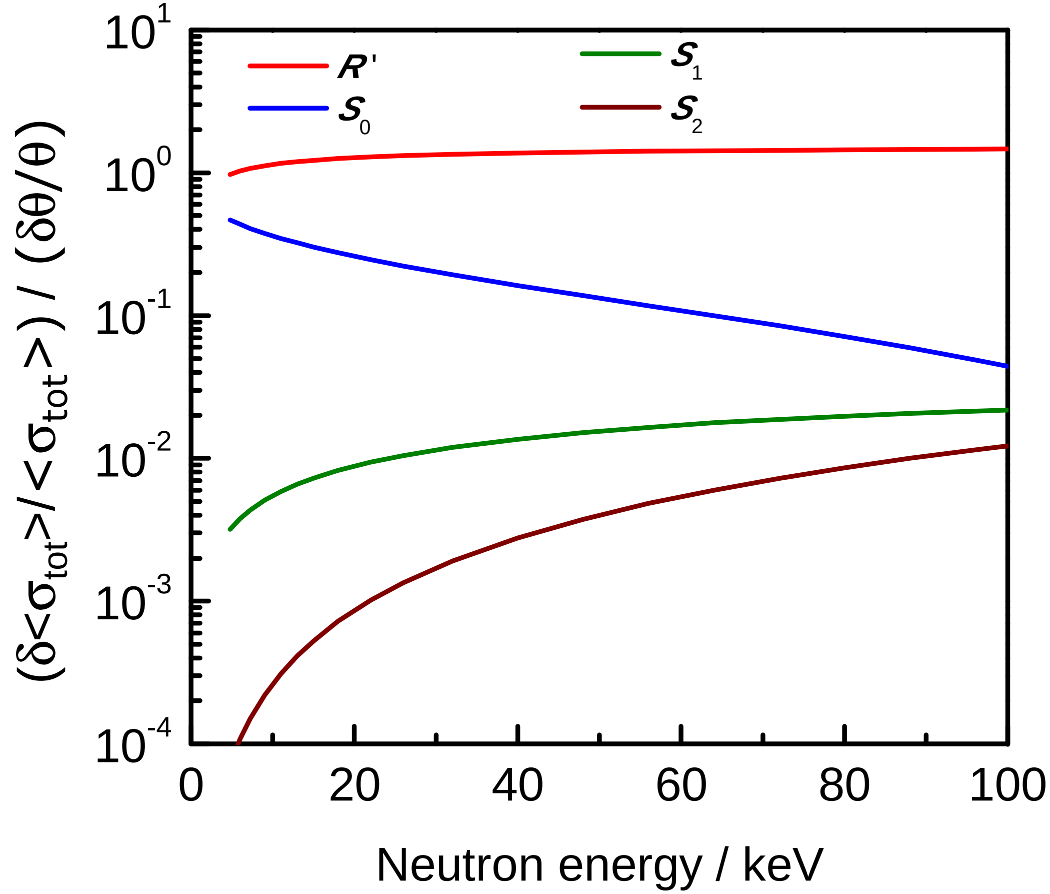
$$S_\ell = \frac{\sum_{j=1}^{N} (g\Gamma_n^\ell)_j}{(2\ell+1)\,\Delta E}$$

$$\Gamma_n^\ell = \frac{1}{\sqrt{E_n/1\text{eV}}} \frac{k_c a_c}{P_\ell} \Gamma_{n,\ell}$$

European Commission

Parameterisation by average parameters



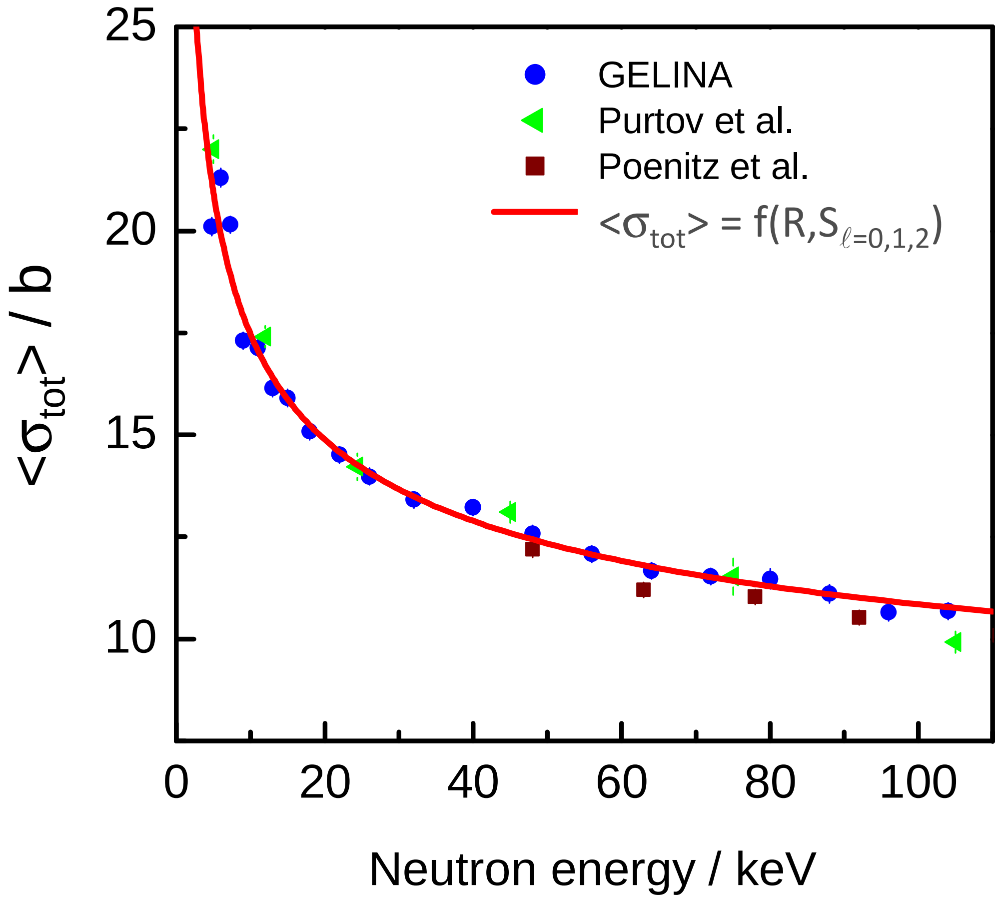


$$<\sigma_{tot}> = f(R, S_{\ell=0,1,2})$$

$$S_\ell = \frac{\sum_{j=1}^{N} (g\Gamma_n^\ell)_j}{(2\ell+1)\,\Delta E}$$

$$\Gamma_n^\ell = \frac{1}{\sqrt{E_n / 1\text{eV}}} \frac{k_c a_c}{P_\ell} \Gamma_{n,\ell}$$

Parameterisation by average parameters



		Correlation matrix	
R / fm	9.12 ± 0.09	1	-0.43
S_0 / 10^{-4}	1.93 ± 0.03	-0.43	1
S_1 / 10^{-5}	5.64	from OM	
S_2 / 10^{-4}	3.48		

Average parameters are essential for self-shielding calculations

ENDF file in URR:

- Average resonance parameters : required
- Average point wise cross section : optional

$$\langle\sigma_{tot}\rangle = f(R, S_{\ell=0,1,2})$$

$$S_\ell = \frac{\sum_{j=1}^{N} (g\Gamma_n^\ell)_j}{(2\ell+1)\,\Delta E}$$

$$\Gamma_n^\ell = \frac{1}{\sqrt{E_n / 1\text{eV}}} \frac{k_c a_c}{P_\ell} \Gamma_{n,\ell}$$

Literature

- "Experimental Neutron Resonance Spectroscopy", by J. Harvey
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- "Evaluation and Analysis of Nuclear Resonance Data", by F.H. Fröhner
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