Principles of neutron TOF cross section measurements

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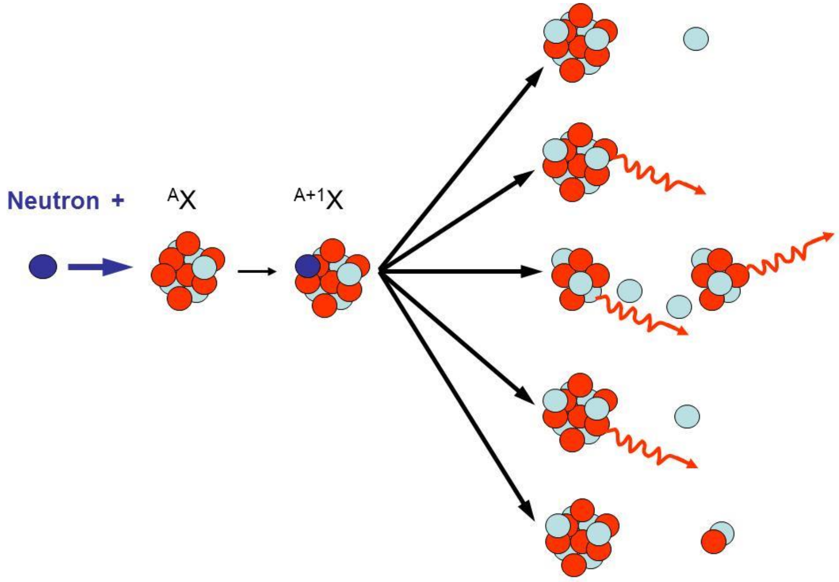
  - Principle : transmission geometry
  - Background: black resonance
  - Example
- **Reaction cross section measurements**
  - Principle
  - Reaction yield

Neutron Induced reaction cross sections



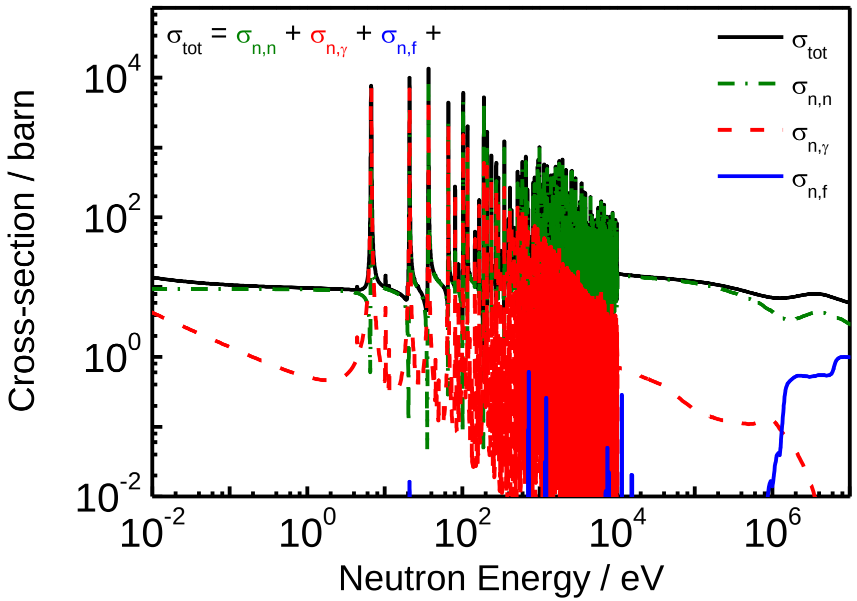
elastic scattering
(n,n)

radiative capture
(n,γ)

fission
(n,f)

inelastic scattering
(n,n'γ)

other reactions
(n,p), (n,d), (n,α)

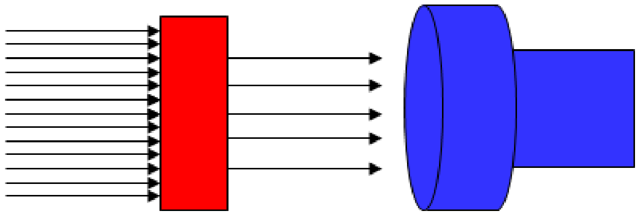


Cross section measurements

Transmission

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

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



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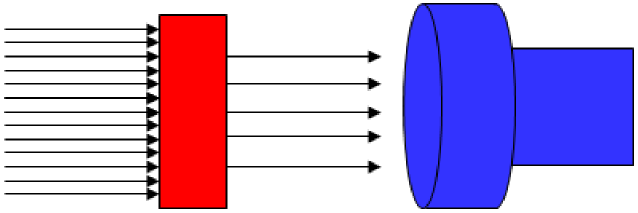
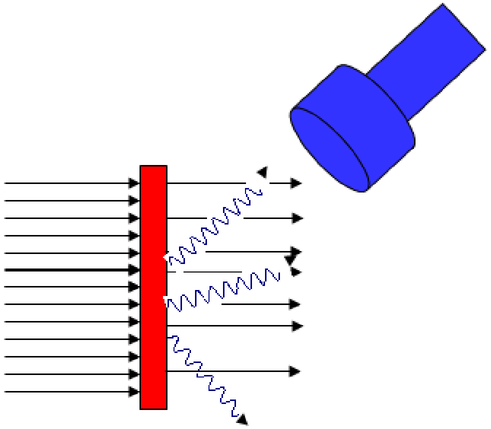


Reaction

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

Y_r : reaction **yield**

Fraction of the neutron beam creating a (n,γ) reaction in the sample

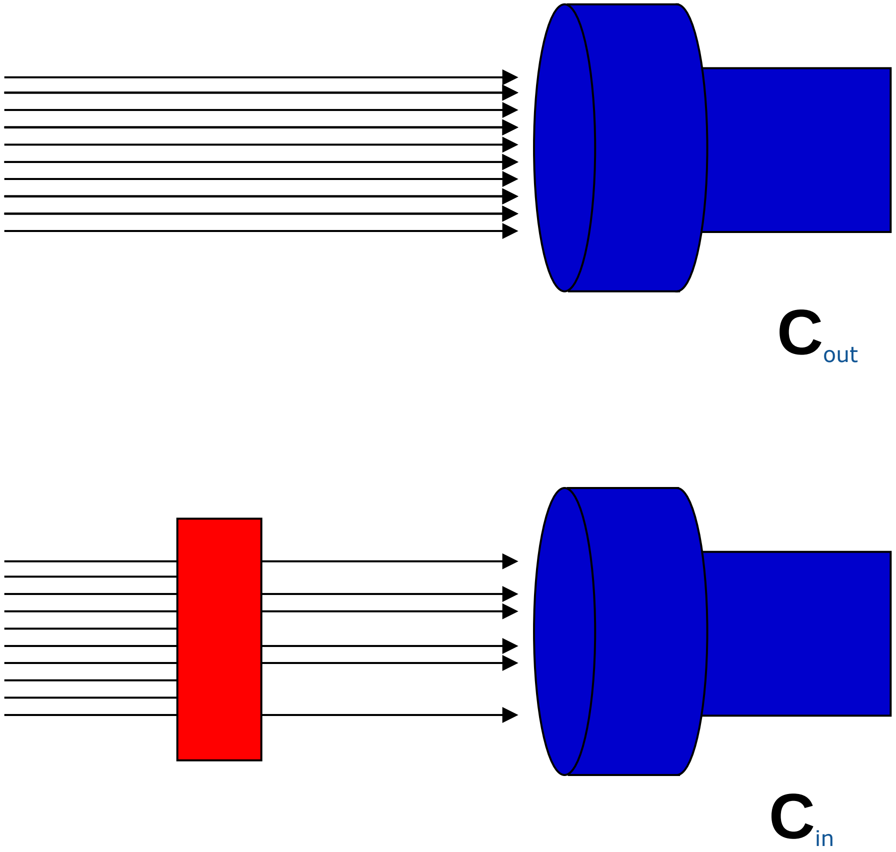


Transmission experiments

Transmission (n,tot)

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

- **Incoming neutron flux cancels**
- **Detection efficiency cancels**



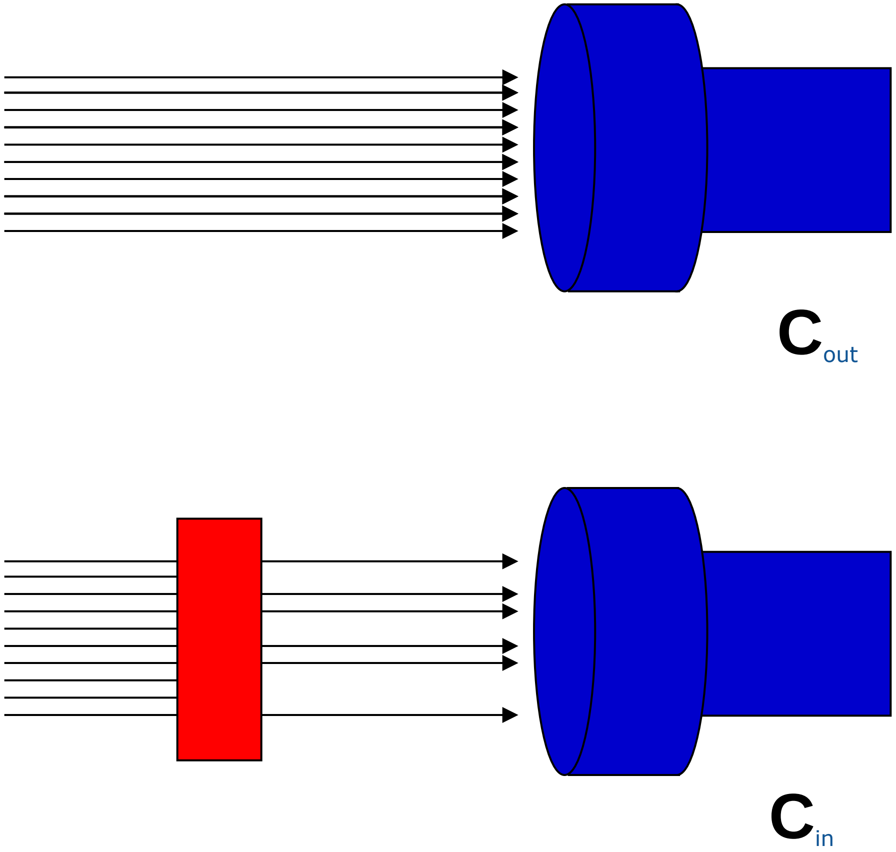
Transmission experiments

Transmission (n,tot)

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

- **Incoming neutron flux cancels**
- **Detection efficiency cancels**

$\Rightarrow$ Direct relation between T_{exp} and σ_{tot}



Transmission : principle

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

(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

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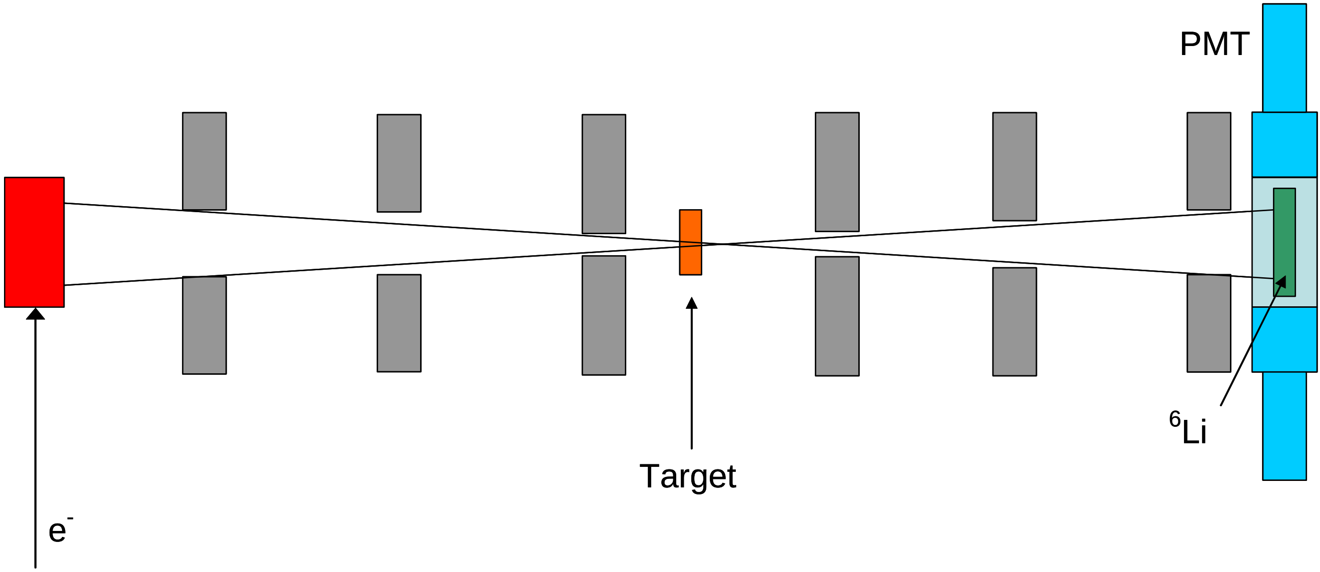
⇒ Good transmission geometry (collimation)



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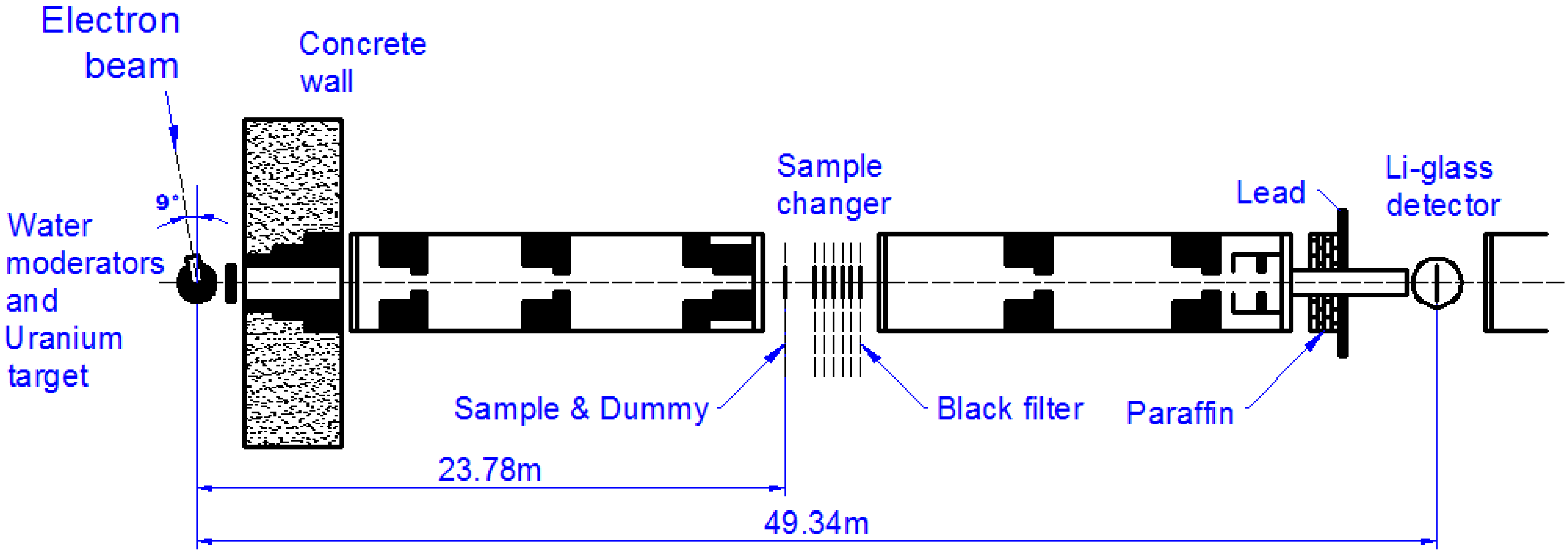

Electron beam
Concrete wall
9°
Water moderators and Uranium target
Sample changer
Lead
Li-glass detector
Sample & Dummy
Black filter
Paraffin
23.78m
49.34m

Transmission : principle

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

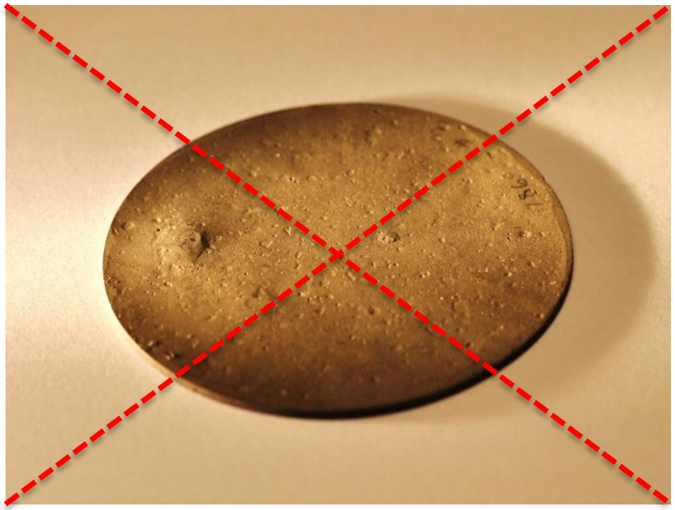
(1) All detected neutrons passed through the sample

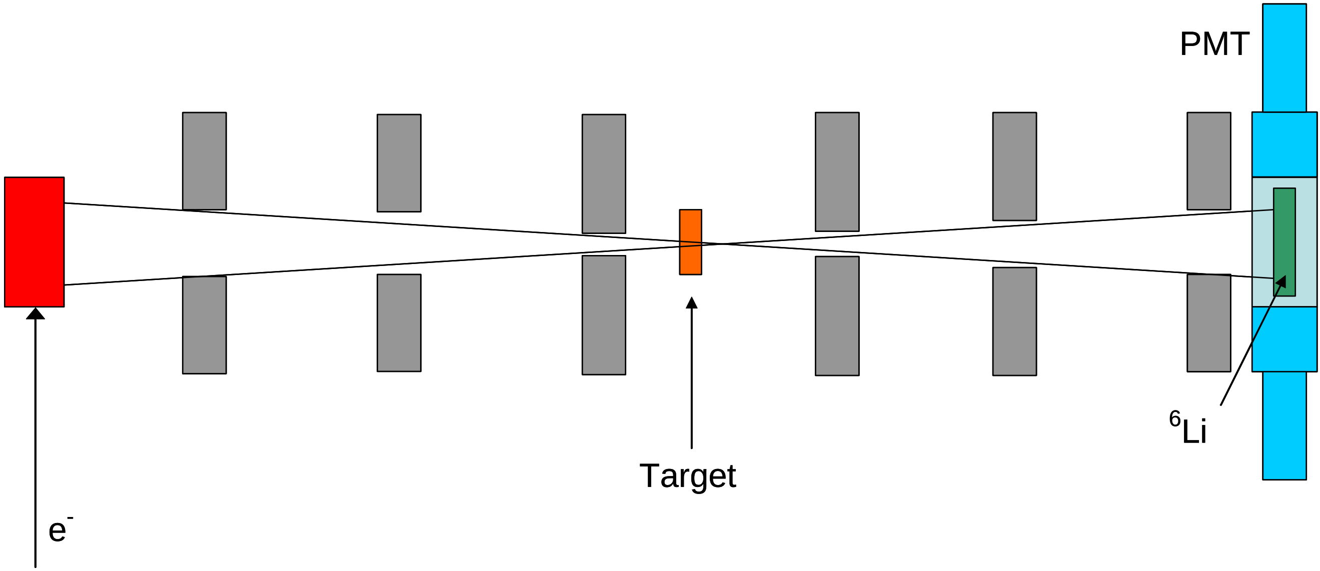
(2) Neutrons scattered in the target do not reach detector

(3) Sample perpendicular to parallel neutron beam

⇒ Good transmission geometry (collimation)

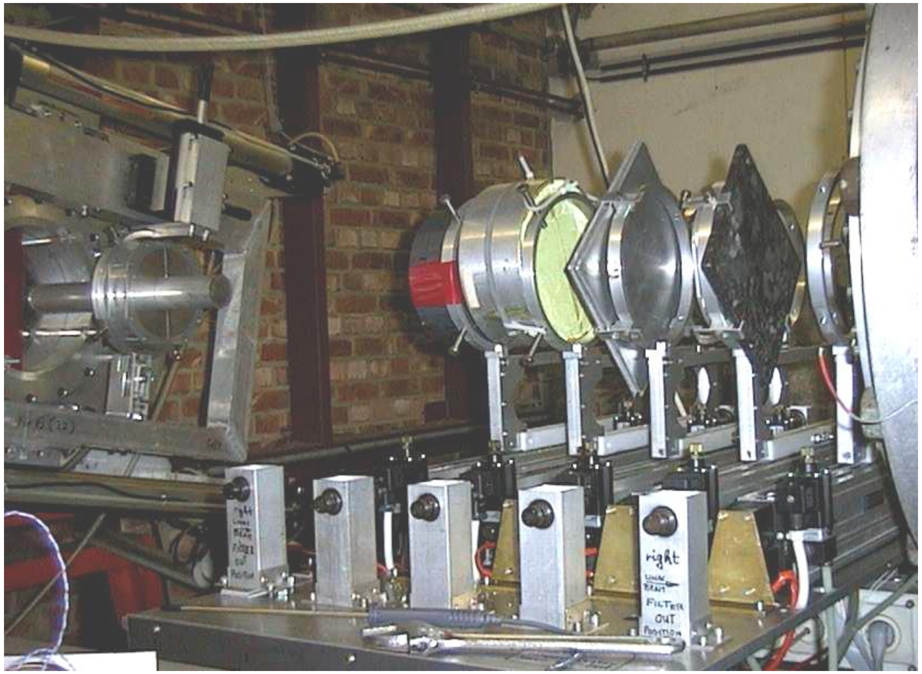
(4) Homogeneous target (no spatial distribution of n)





Transmission: experimental set-up (50 m)

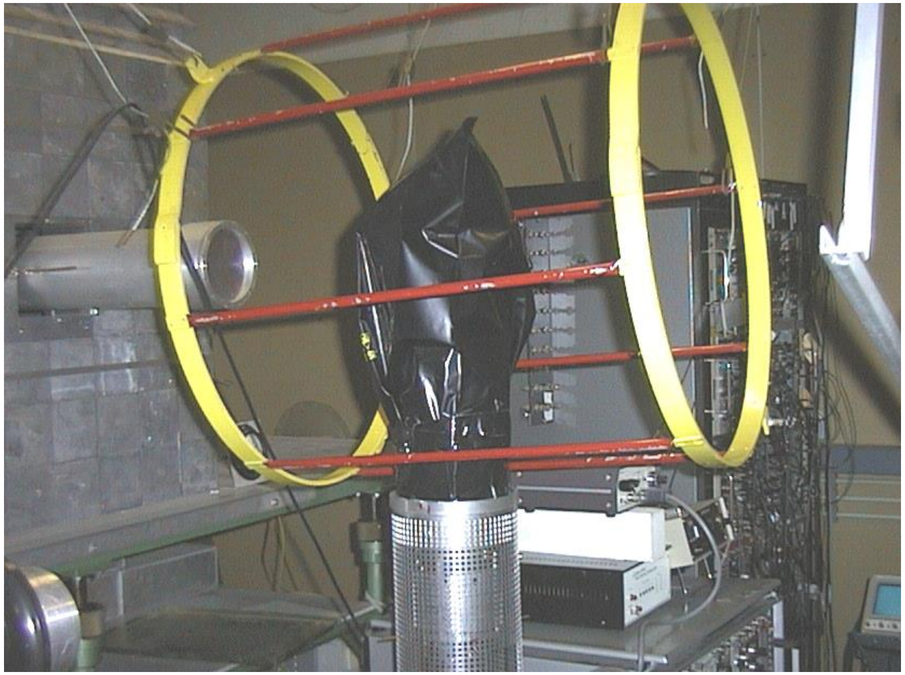
Sample & Background Filters
at 25 m


right
LINAC BEAM
FILTER OUT POSITION

Detector stations at GELINA

Moderated : at 10 m, 30 m, 50 m, 100 m
Fast : at 400 m

Neutron detector
at 50 m



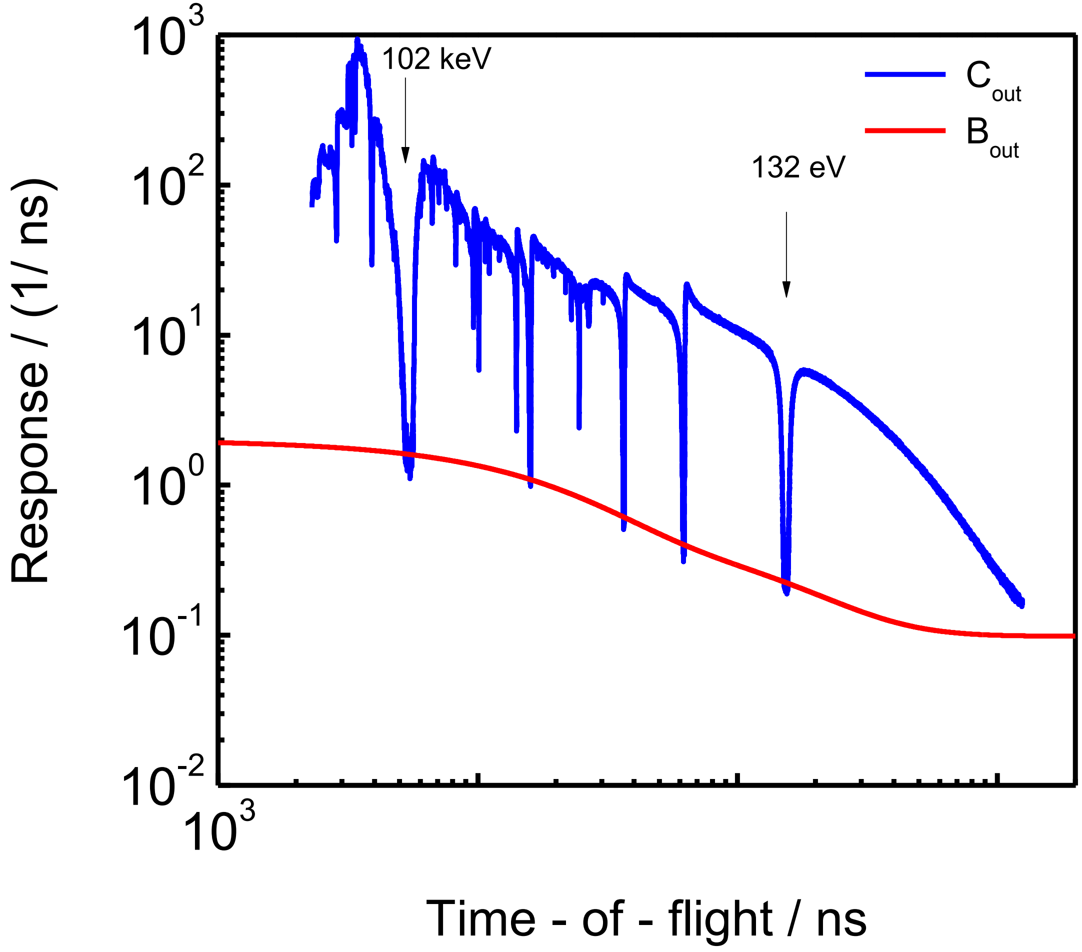
Detectors

Low energy : ^{6}Li(n,t)α Li-glass
High energy : H(n,n)H Plastic scintillator

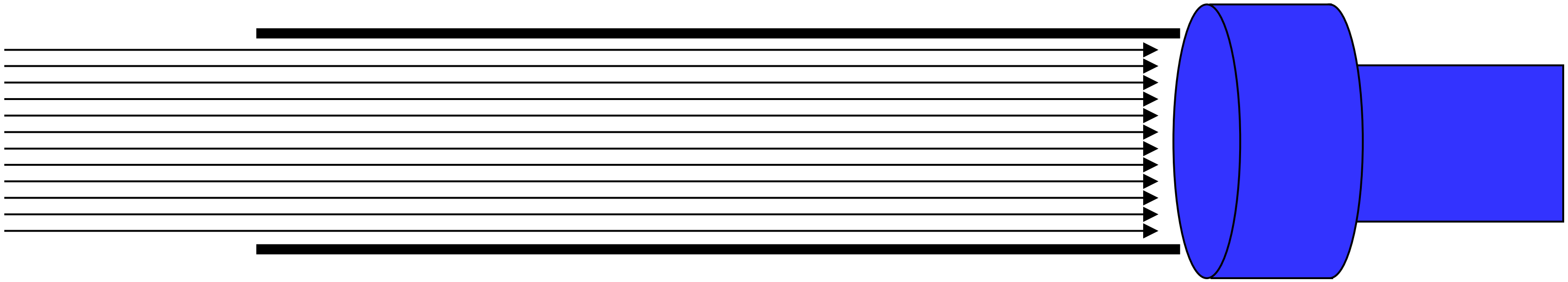
Background: black resonance technique

No Sample

Filters : S + Bi + Co



Background : black resonance filters



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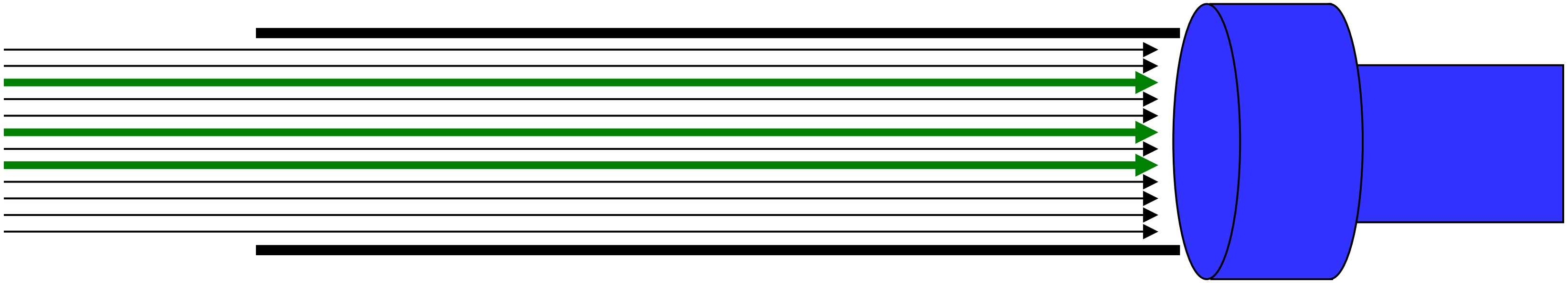
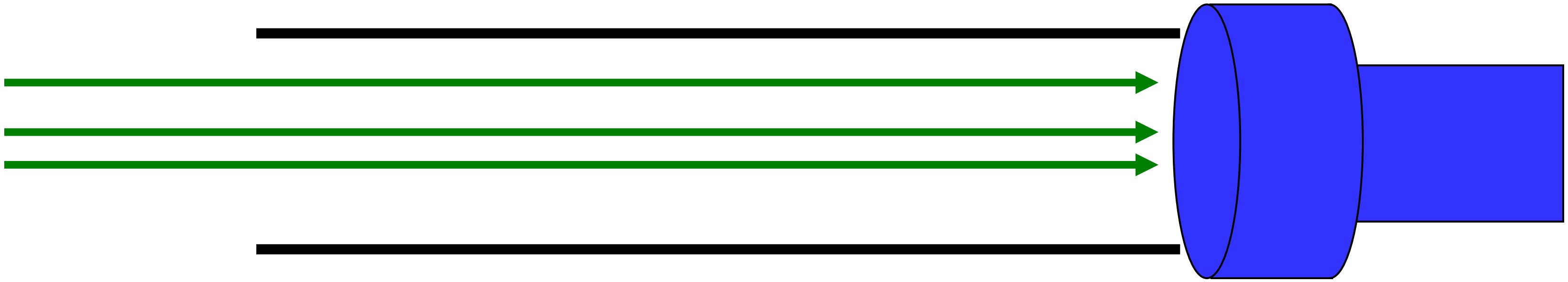


E_n = 132 eV

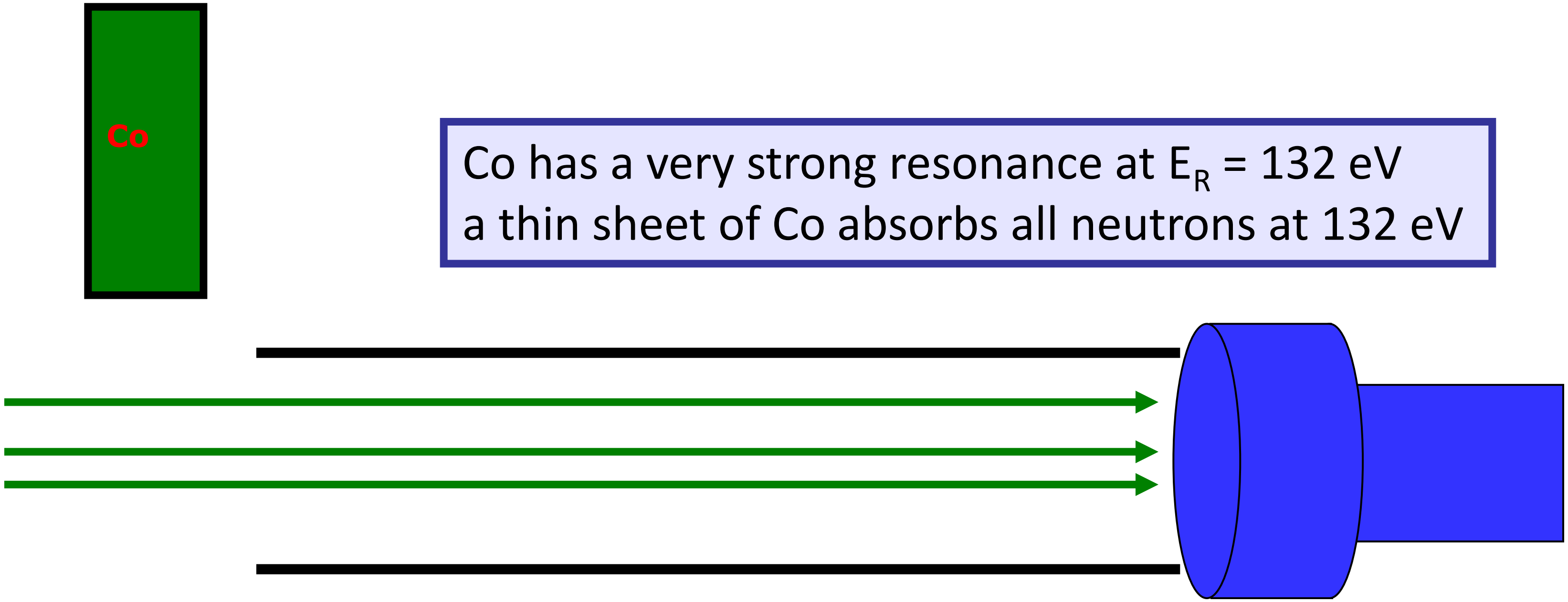
Background : black resonance filters



$E_n = 132$ eV

$$at \quad t = \frac{L}{v} \quad with \quad v = \sqrt{\frac{2E_n}{m_n}} \; and \quad E_n = 132\,eV$$

Background : black resonance filters



Co has a very strong resonance at E_R = 132 eV
a thin sheet of Co absorbs all neutrons at 132 eV

E_n = 132 eV

$$\text{at} \quad t = \frac{L}{v} \quad \text{with} \quad v = \sqrt{\frac{2E_n}{m_n}} \text{ and } \quad E_n = 132 \, eV$$

Background : black resonance filters

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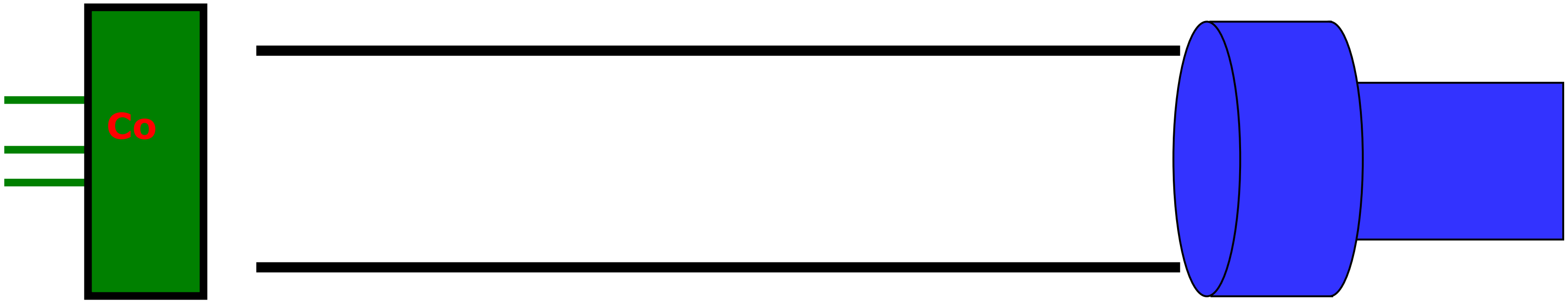
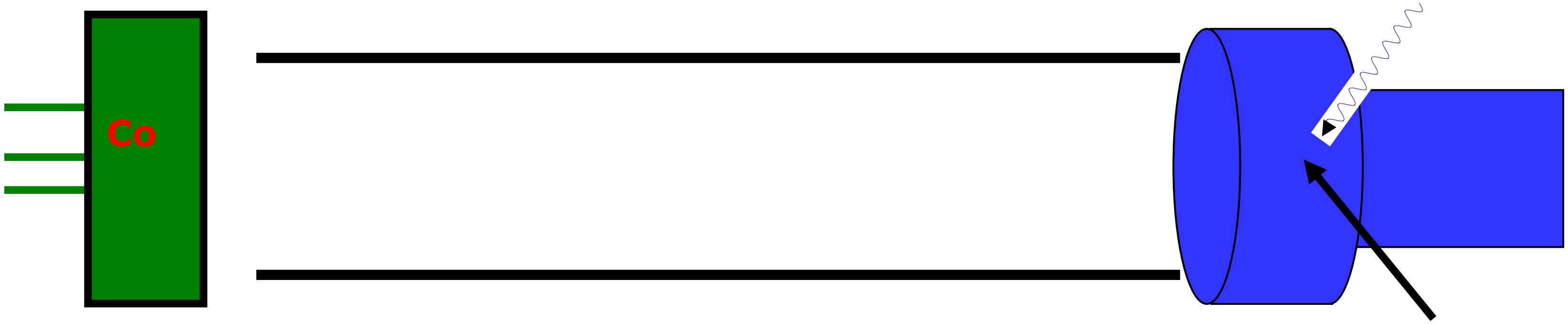
a thin sheet of Co absorbs all neutrons at 132 eV



E_n = 132 eV

$$at \quad t = \frac{L}{v} \quad with \quad v = \sqrt{\frac{2E_n}{m_n}} \; and \quad E_n = 132\, eV$$

Background : black resonance filters

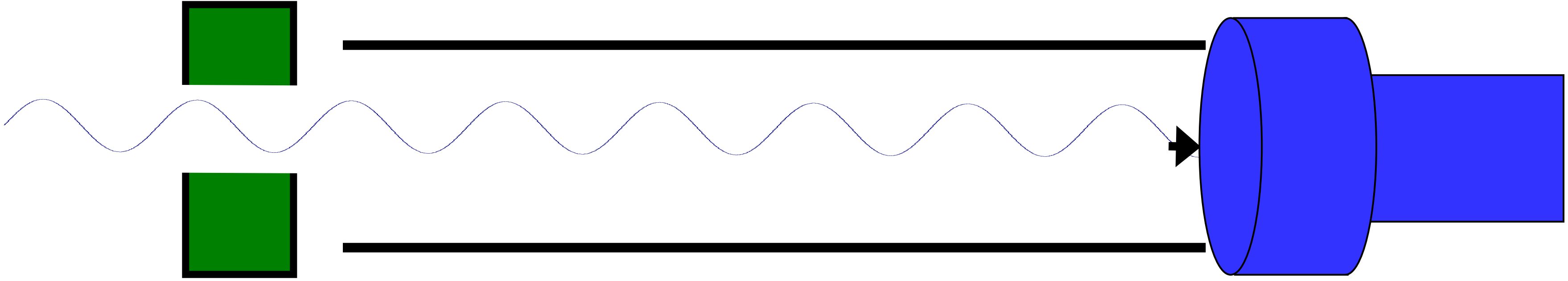


$$at \quad t = \frac{L}{v} \quad with \quad v = \sqrt{\frac{2E_n}{m_n}} \; and \quad E_n = 132\,eV$$

$B(t) = b_o$

Background : black resonance filters

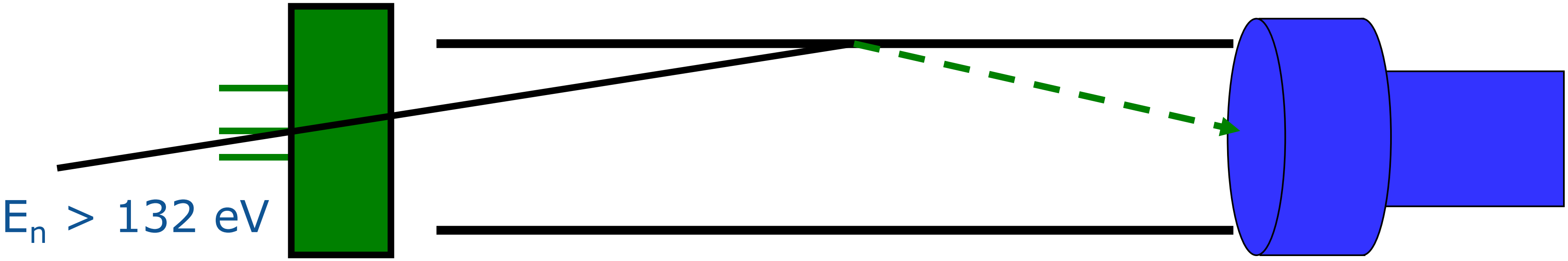
$^{1}H(n,\gamma)$
$E_{\gamma} = 2.2$ MeV



$$at \quad t = \frac{L}{v} \quad with \quad v = \sqrt{\frac{2E_n}{m_n}} \quad and \quad E_n = 132\, eV$$

$B(t) = b_o + B_{\gamma}(t)$

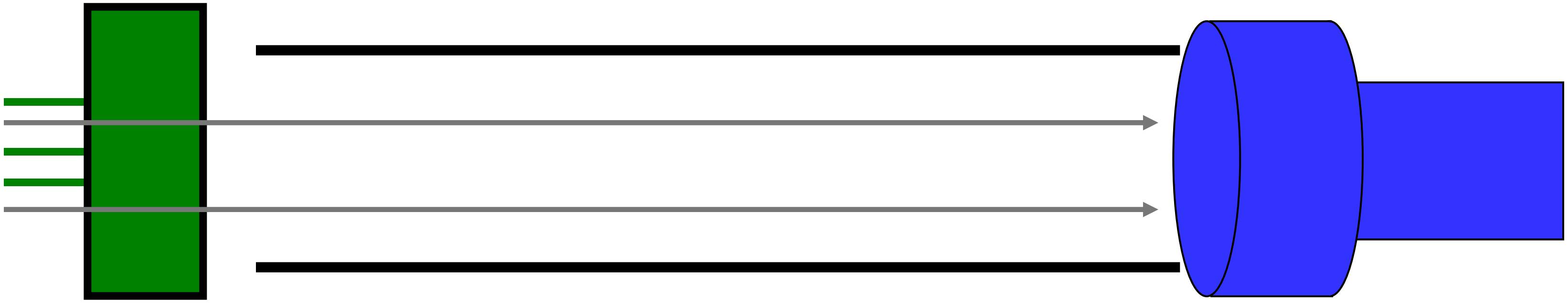
Background : black resonance filters



$$\text{at} \quad t = \frac{L}{v} \quad \text{with} \quad v = \sqrt{\frac{2E_n}{m_n}} \quad \text{and} \quad E_n = 132\, eV$$

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

Background : black resonance filters



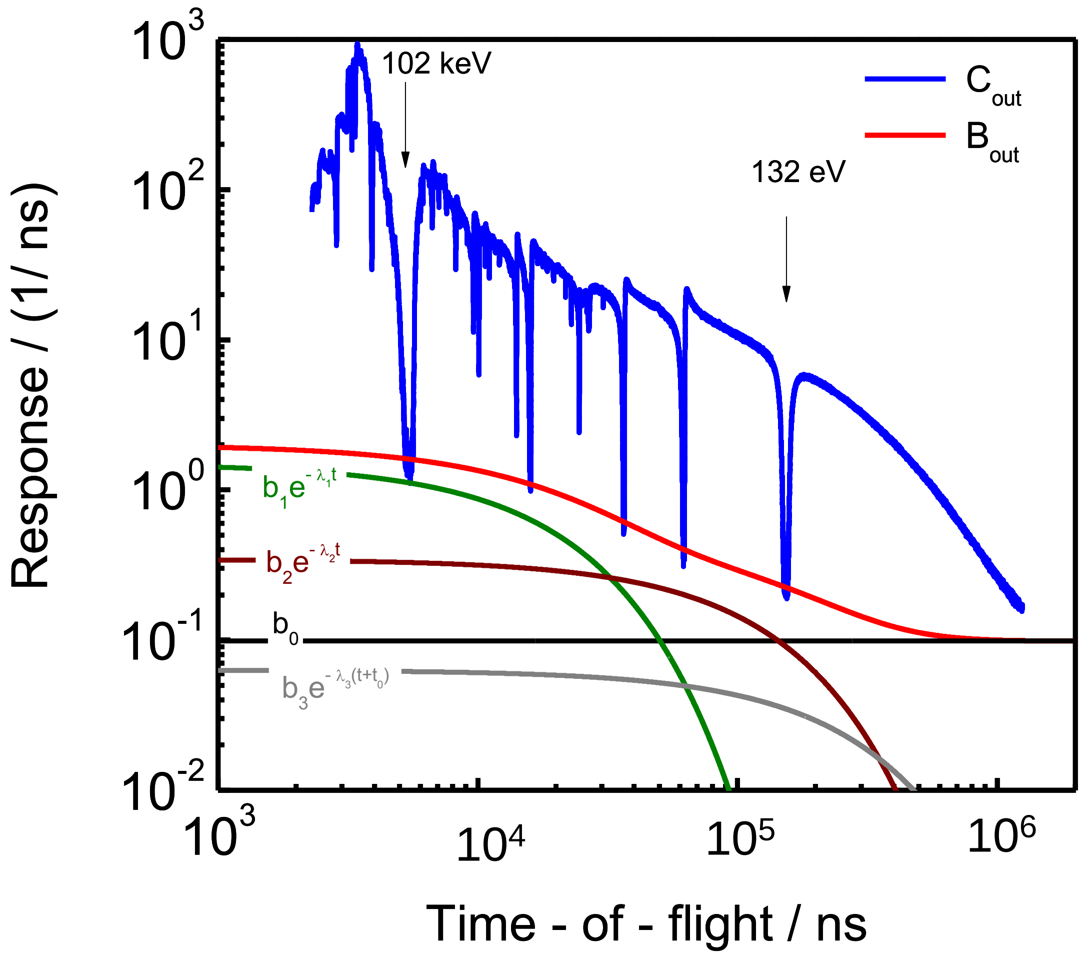
E_n : $t > 1/f$?? ($E_n < 132$ eV)

$$\text{at} \quad t = \frac{L}{v} \quad \text{with} \quad v = \sqrt{\frac{2E_n}{m_n}}$$

$B(t) = b_o + B_\gamma(t) + B_n(t) + B_{ov}(t)$

Background: black resonance technique

Filters : S + Bi + Co



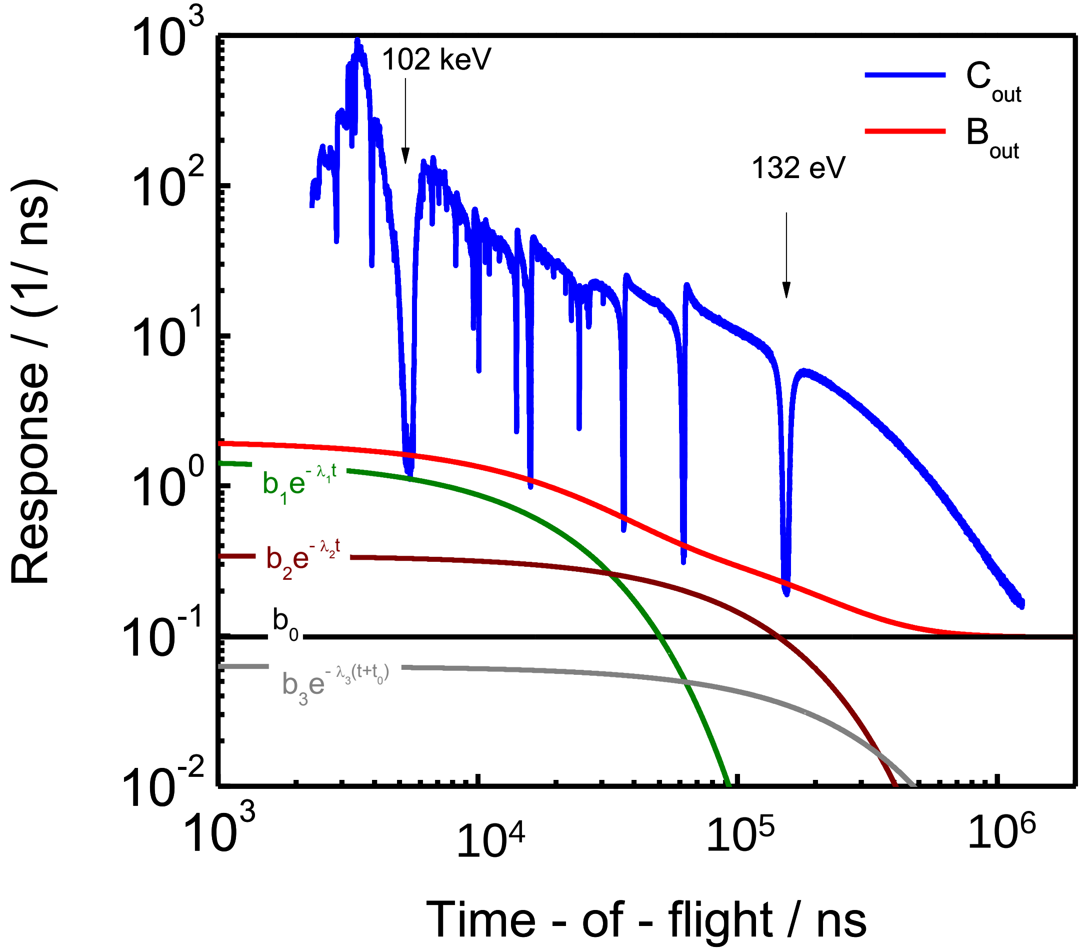
Background

B(t)

Background: black resonance technique

No Sample

Filters : S + Bi + Co



Background

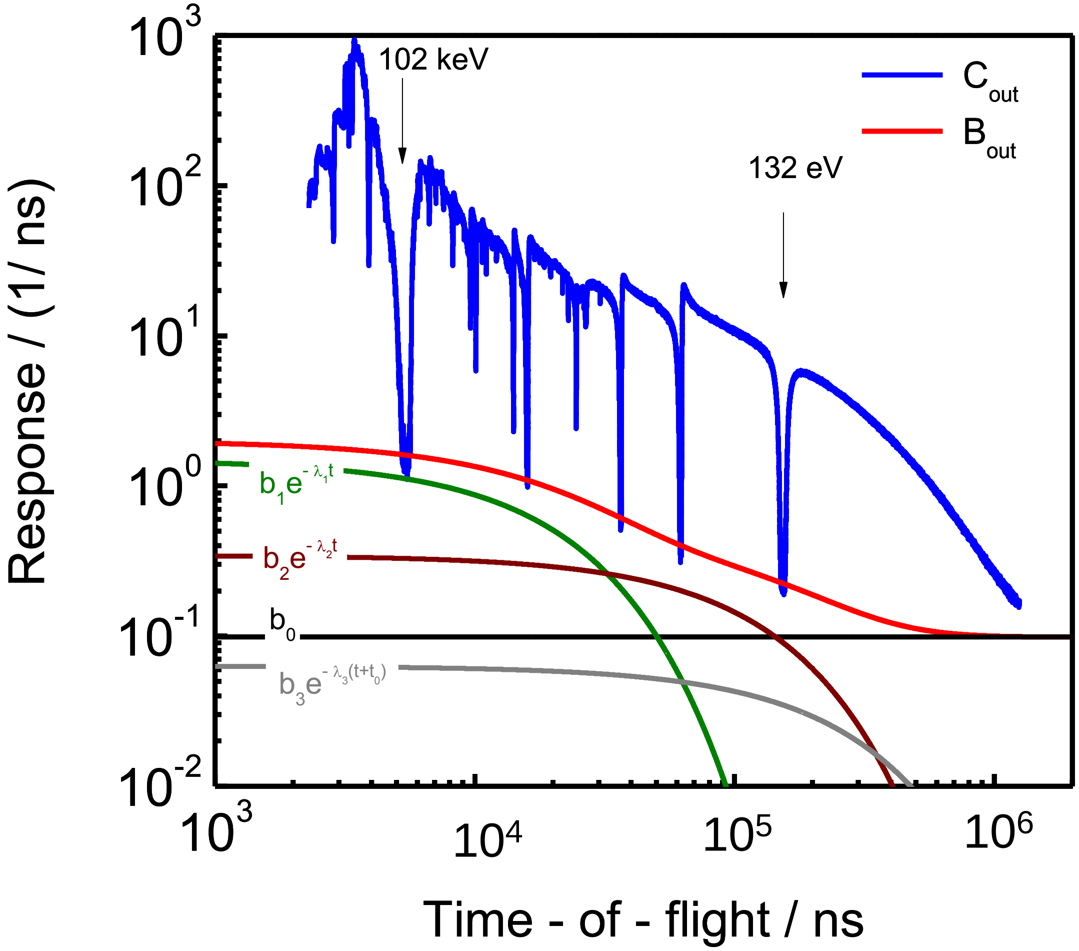
B(t) = b_0 +

- b_o time independent

Background: black resonance technique

No Sample

Filters : S + Bi + Co



Background

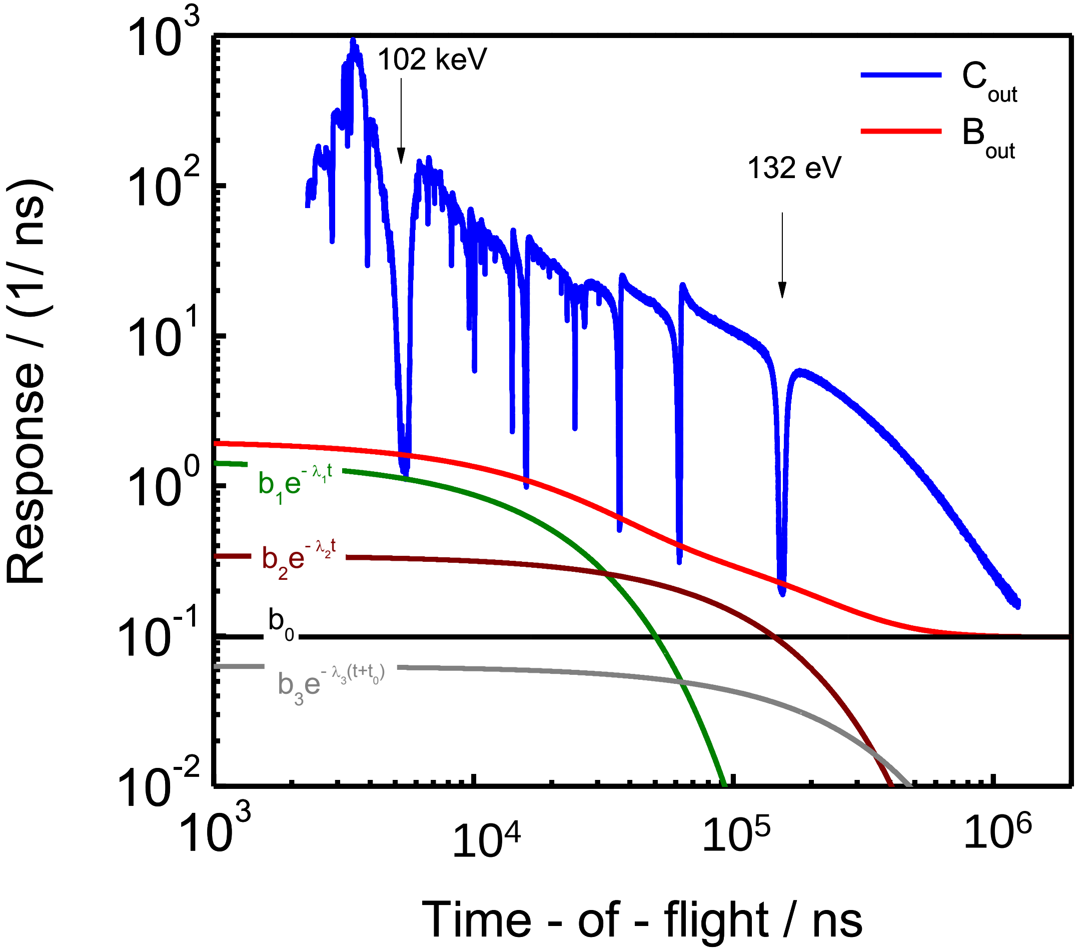
$B(t) = b_0 + B_\gamma(t)$

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

Background: black resonance technique

No Sample

Filters : S + Bi + Co

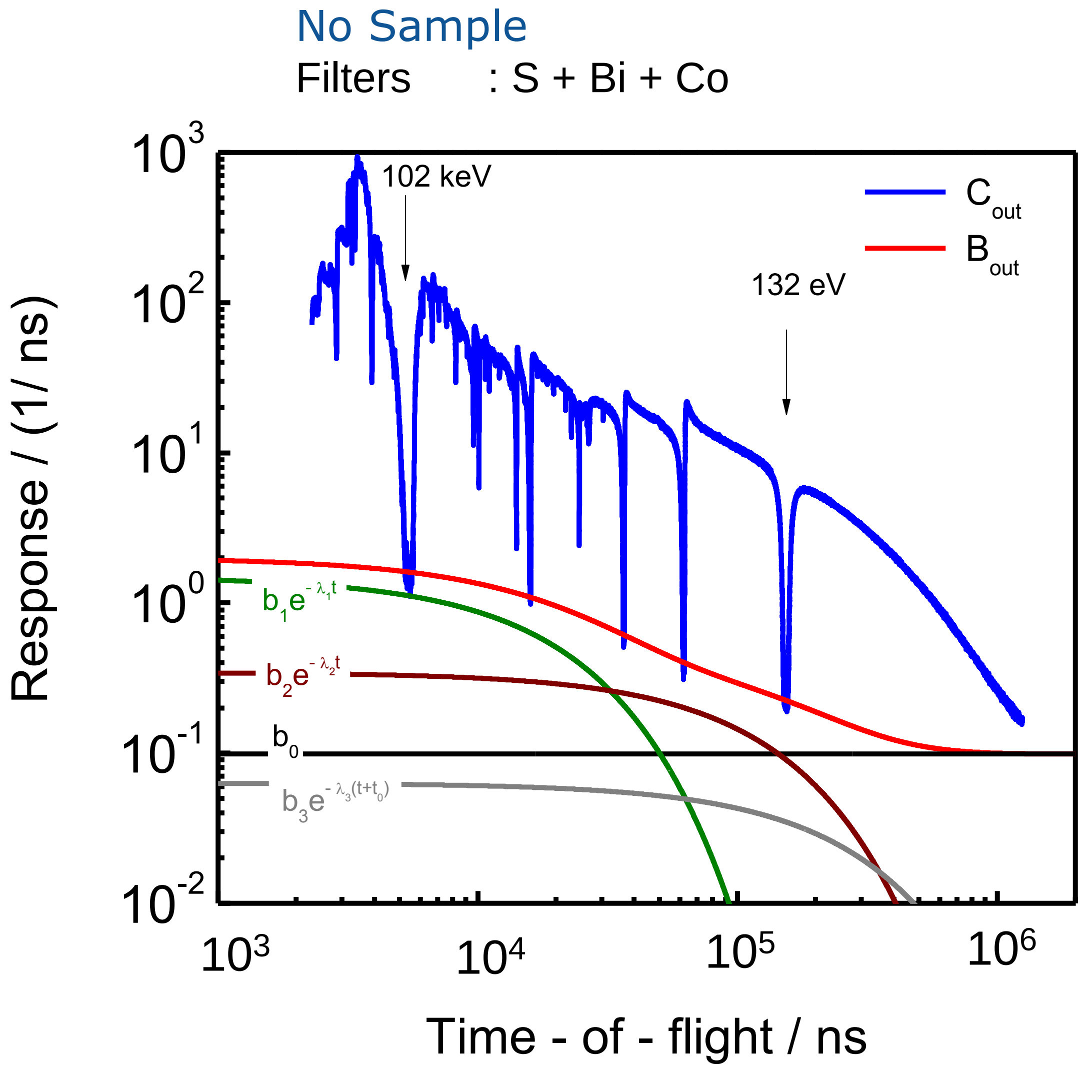


Background

$B(t) = b_0 + B_\gamma(t) + B_n(t)$

- b_o time independent
- $B_\gamma(t)$ $^1H(n, \gamma)$ $E_\gamma = 2.2$ MeV
  $b_1e^{-\lambda_1 t}$
- $B_n(t)$ scattered neutrons
  $b_2e^{-\lambda_2 t}$

Background: black resonance technique



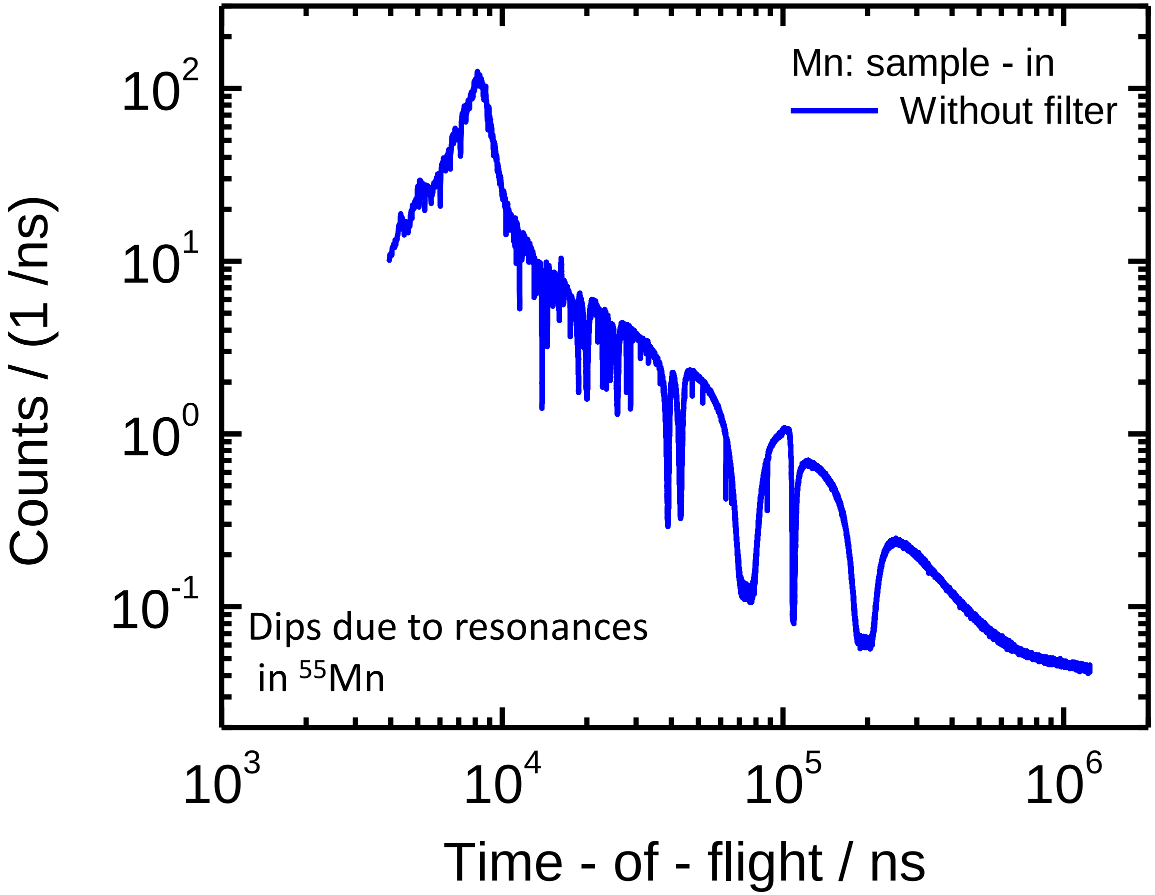
Background

$B(t) = b_0 + B_\gamma(t) + B_n(t) + B_{ov}(t)$

- 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
  $b_2 e^{-\lambda_2 t}$
- $B_{ov}(t)$ overlap neutrons
  $b_3 e^{-\lambda_3 (t+t_0)}$

Impact filter and sample thickness

Sample : ^{55}Mn
Filters : none

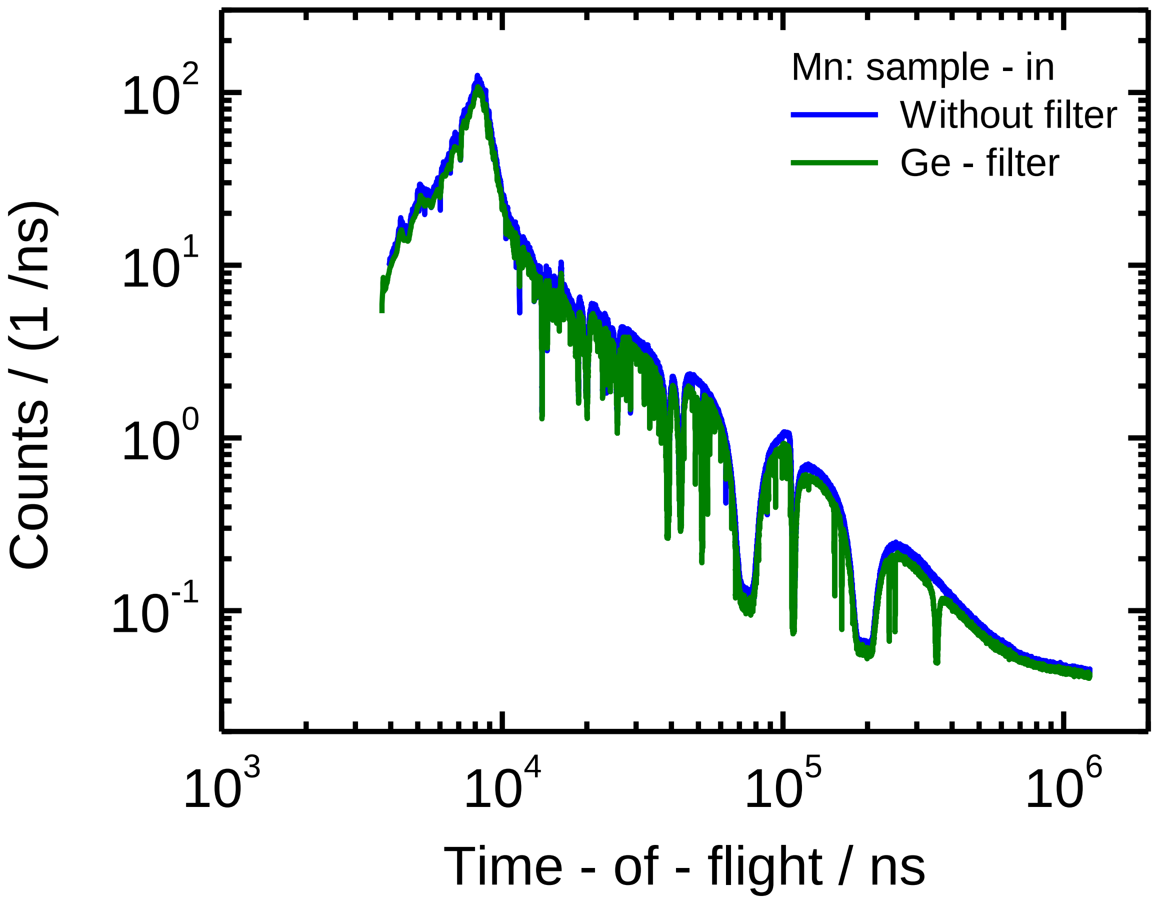


Dips due to resonances in ^{55}Mn

Background depends on sample and filter properties

Impact filter and sample thickness

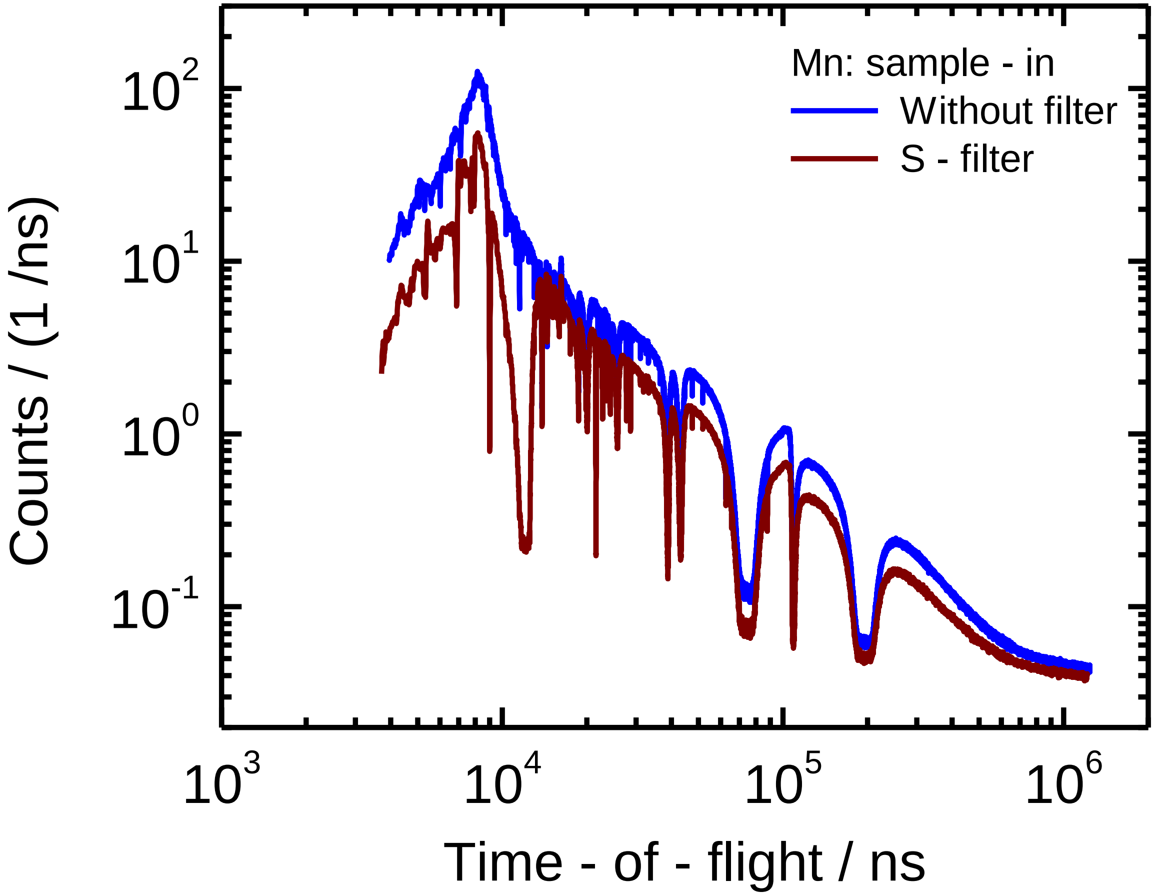
Sample : ^{55}Mn
Filters : Germanium



Background depends on sample and filter properties

Impact filter and sample thickness

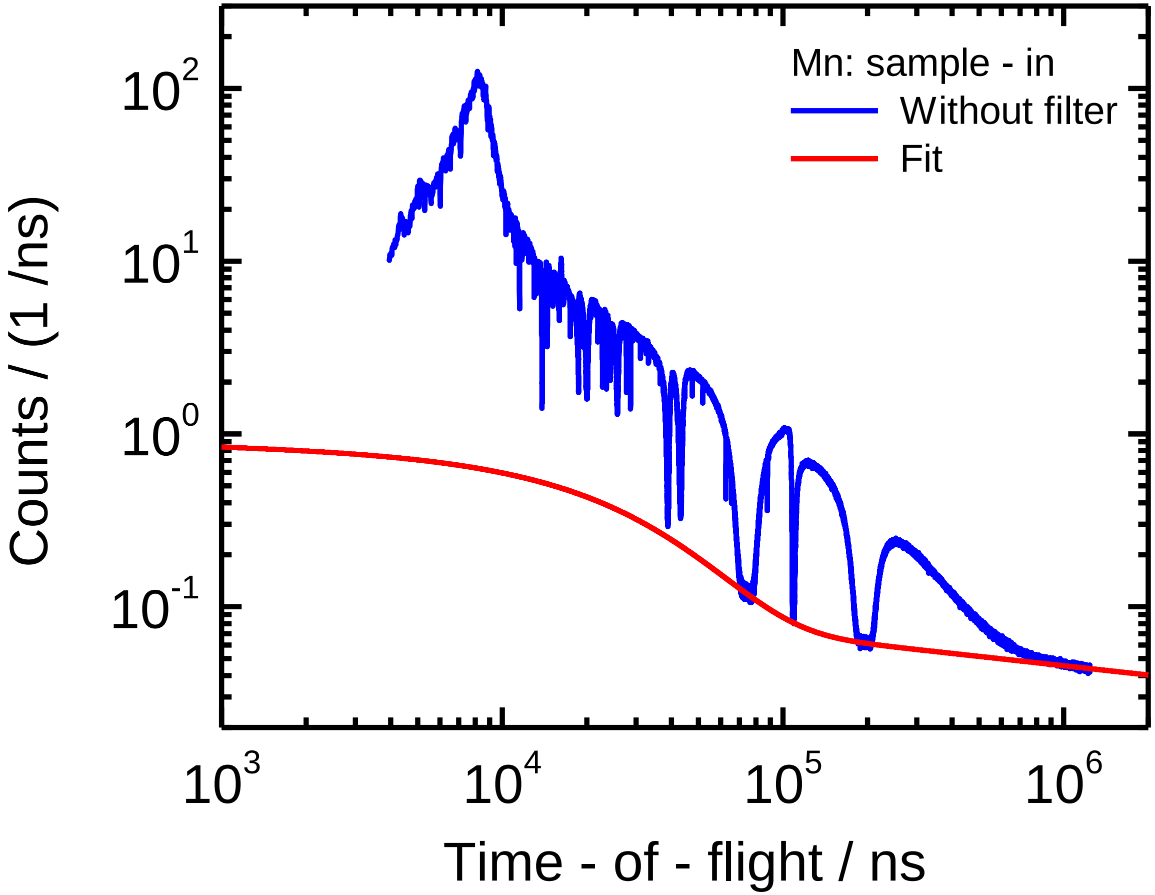
Sample : ^{55}Mn
Filters : Sulfur



Background depends on sample and filter properties

Impact filter and sample thickness

Sample : ^{55}Mn
Filters : none

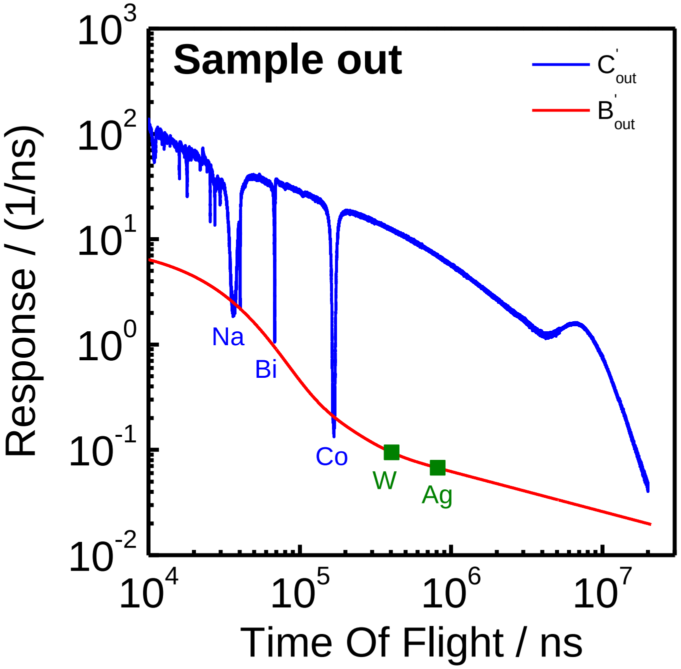


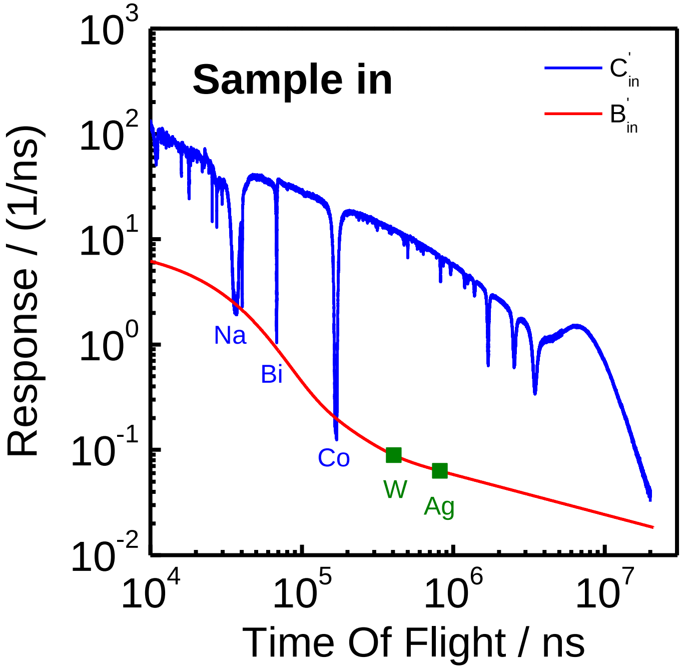
Background depends on sample and filter properties

Correct for impact of sample and filter thickness by

- extrapolation (to zero thickness)
- using black resonances from sample or fixed filters

Transmission data : ^{241}Am + n





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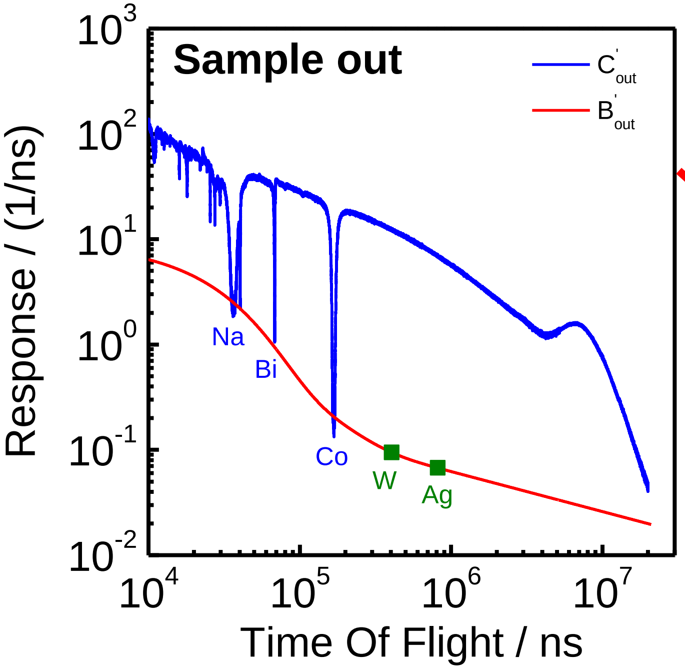
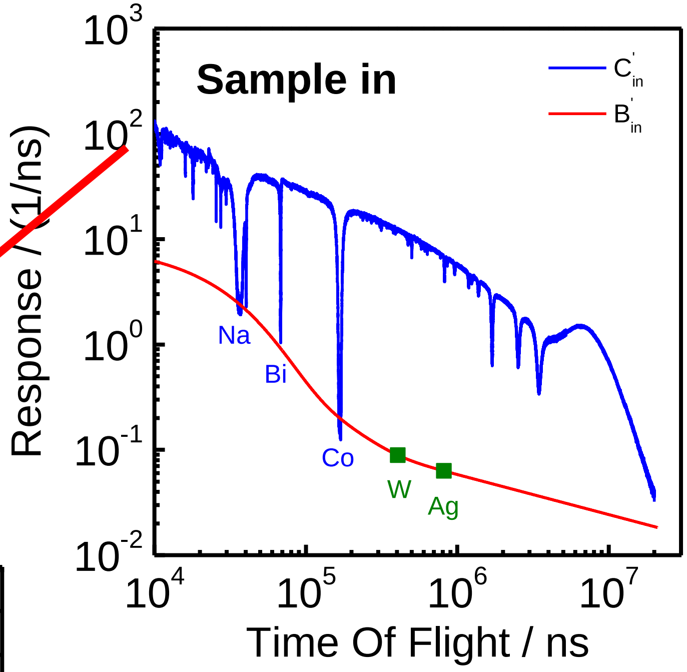
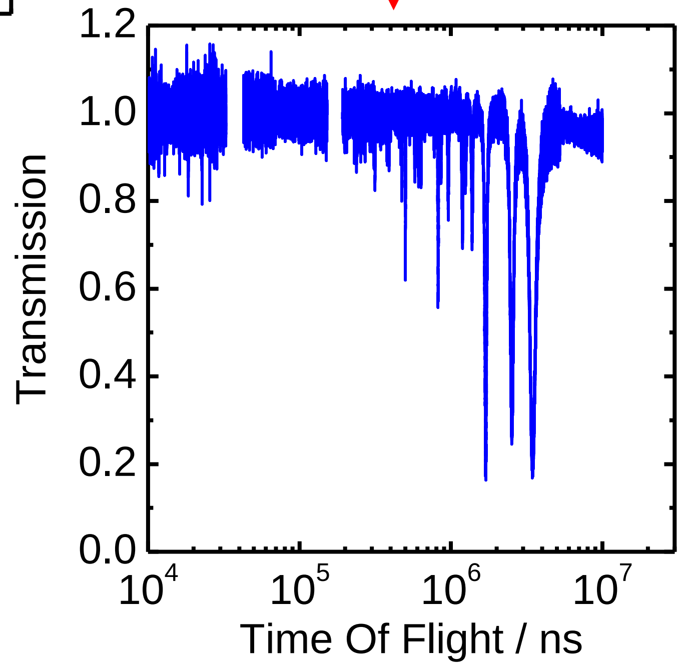


$$T_{exp} = \frac{C'_{in} - B'_{in}}{C'_{out} - B'_{out}}$$

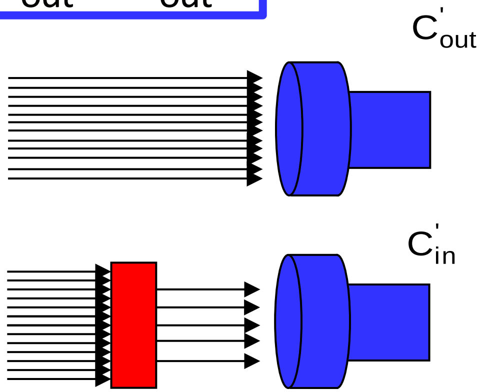


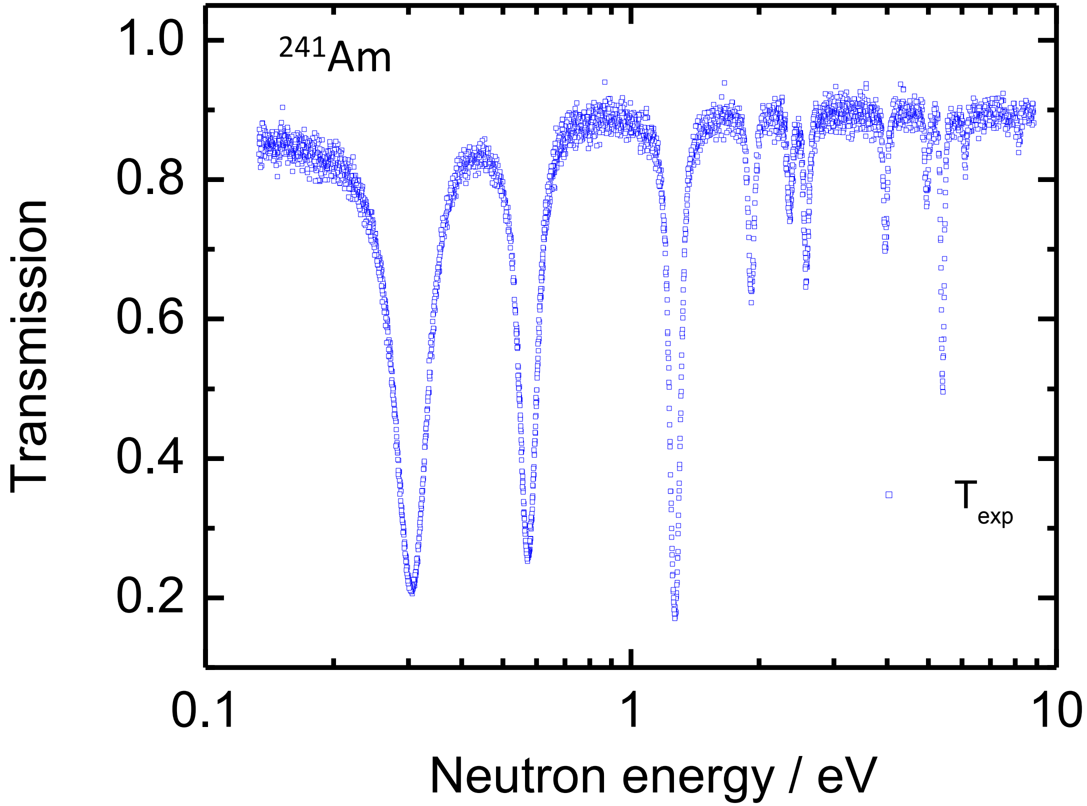


$$\frac{u_{T_{exp}}}{T_{exp}} \approx 0.25\%$$

Transmission measurement:
good geometry + homogeneous sample

$$T_{exp} = \frac{C'_{in} - B'_{in}}{C'_{out} - B'_{out}}$$





Transmission measurement: good geometry + homogeneous sample

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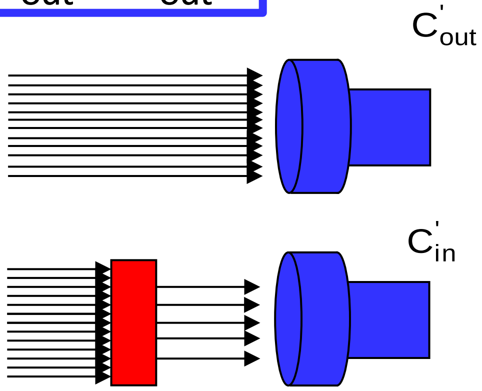
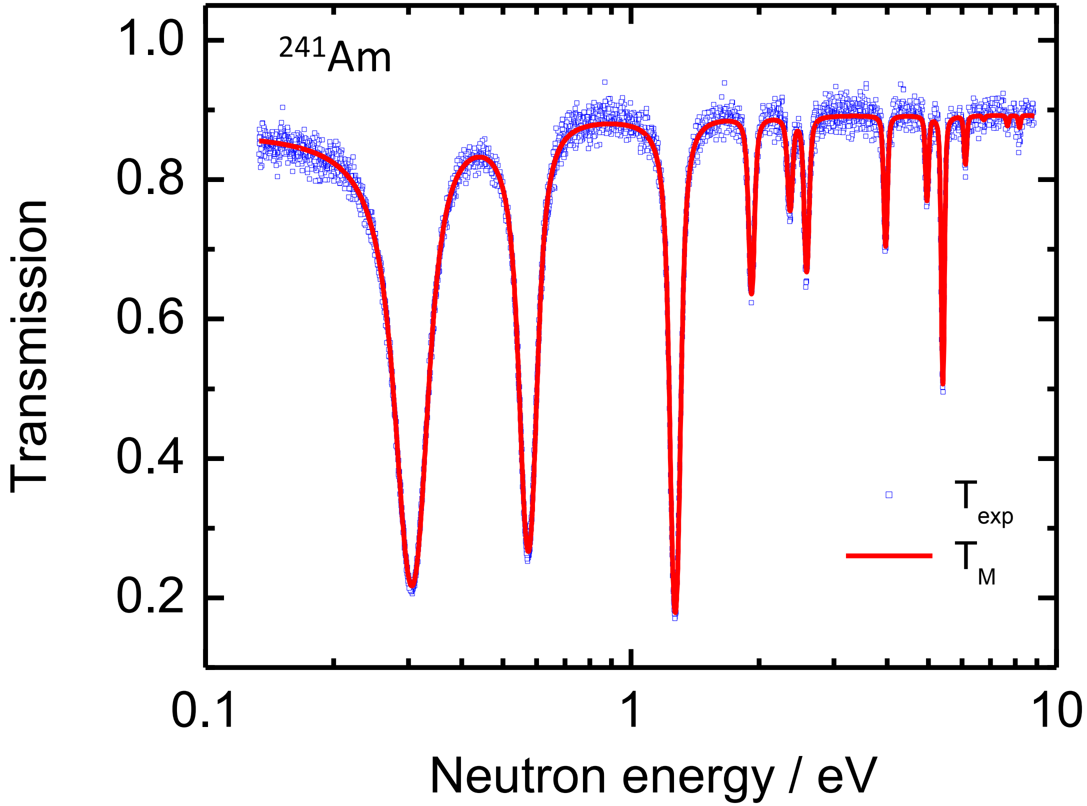




$$T_M(t,\bar{\theta}) = \frac{\int R(t,E)\, e^{-n\sigma_{tot}(E)} dE}{\int R(t,E)\, dE}$$

$$\chi^2(\vec{\theta}) = (T_{exp} - T_M(t,\vec{\theta}))^T\, V_{T_{exp}}^{-1}\, (T_{exp} - T_M(t,\vec{\theta}))$$

R(t,E) response of TOF-spectrometer + detector

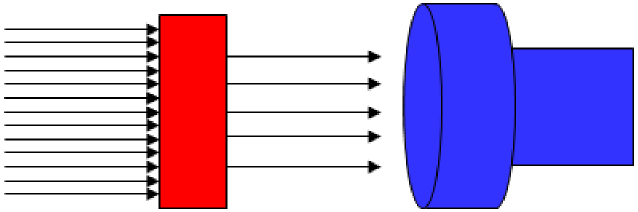
REFIT, M. Moxon

Cross section measurements

Transmission

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

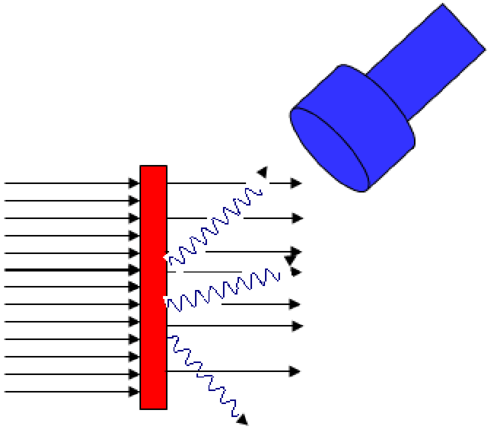
$$T_{exp} = \frac{C_{in}}{C_{out}}$$



Reaction

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

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

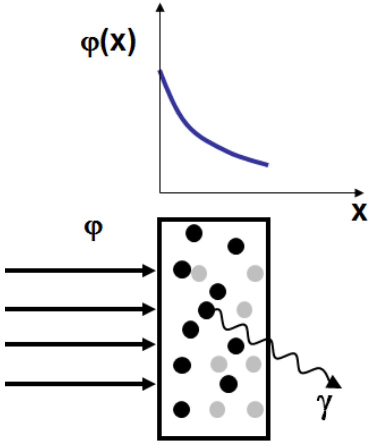


Reaction cross section measurement

- **Thin sample, no scattering, only self-shielding**

$$Y_{r,0} = (1 - e^{-n\,\sigma_{tot}})\,\frac{\sigma_r}{\sigma_{tot}}$$

⇒ $Y_r = f(\sigma_r, \sigma_{tot})$



- **Infinitely thin sample**

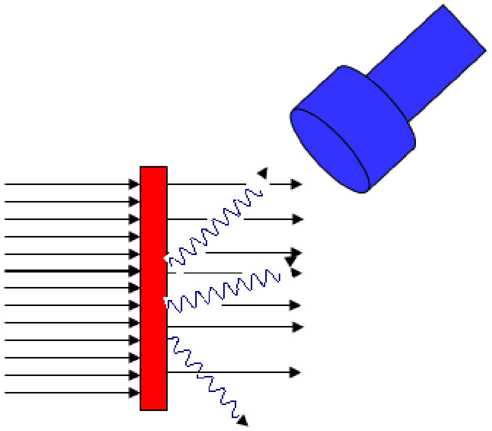
$$Y_r = n\,\sigma_r$$

⇒ Direct Relation : Y_r <--> σ_r

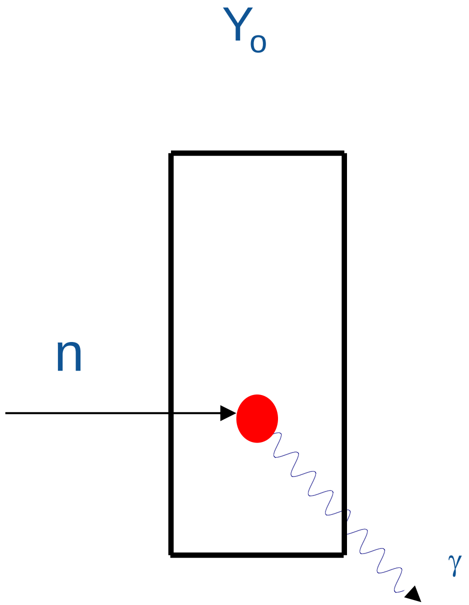
Reaction

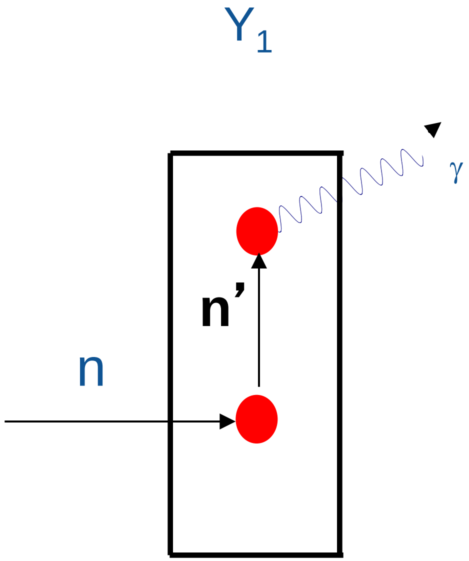
$$Y_r \cong (1 - e^{-n\sigma_{tot}})\,\frac{\sigma_r}{\sigma_{tot}} + \dots$$

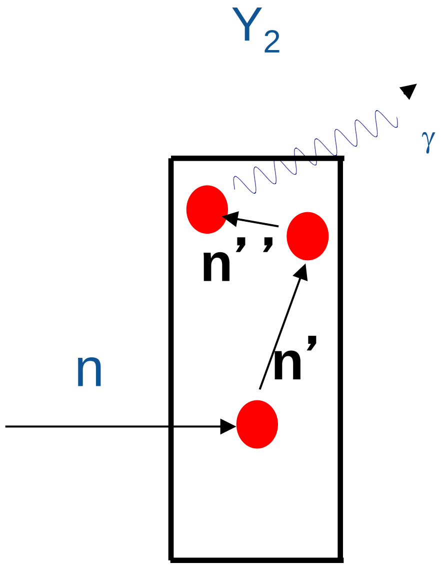
$$Y_{r,exp} = \frac{C_r}{\varepsilon_r\,\Omega\,P_r\,A_r\,\varphi}$$



Self-shielding + multiple scattering







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

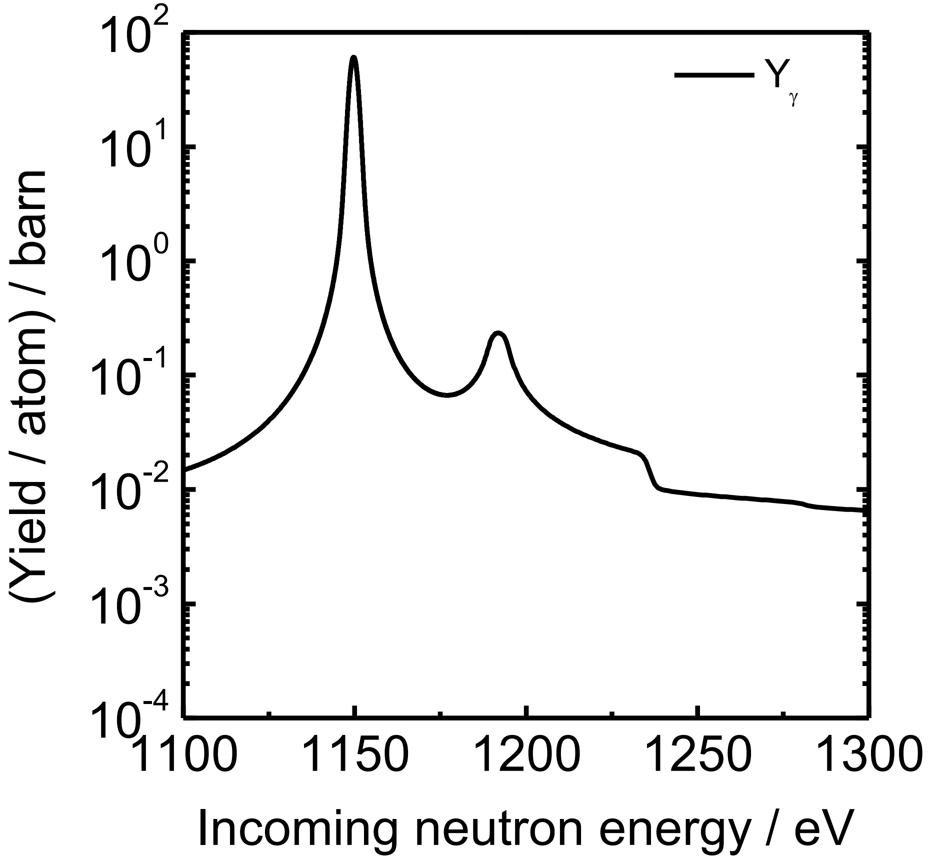
$$E_n^{'} = E_n\left(\frac{m_n}{m_A + m_n}\right)^2\left(\cos\theta + \sqrt{\left(\frac{m_A}{m_n}\right)^2 - \sin^2\theta}\right)^2$$

Correction for self-shielding and multiple scattering requires ⇒ σ_{tot} & σ_n

Reaction cross section

^{56}Fe(n,γ)

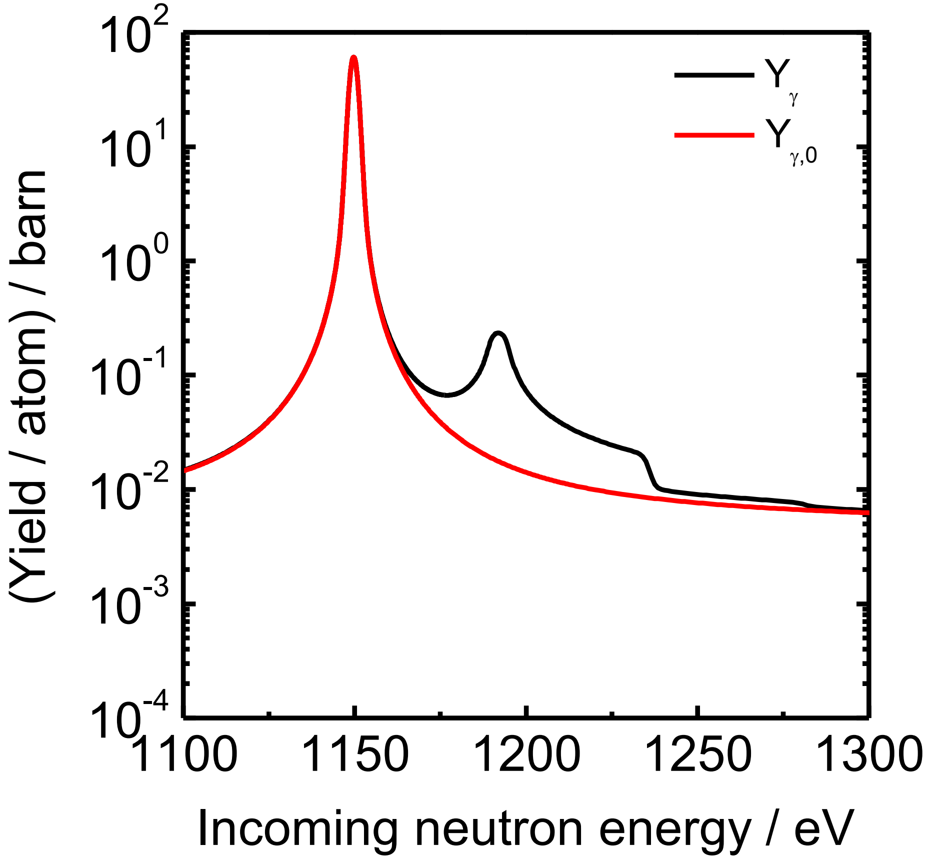
n_{Fe} = 1 10^{-3} at/b (0.12 mm thick)

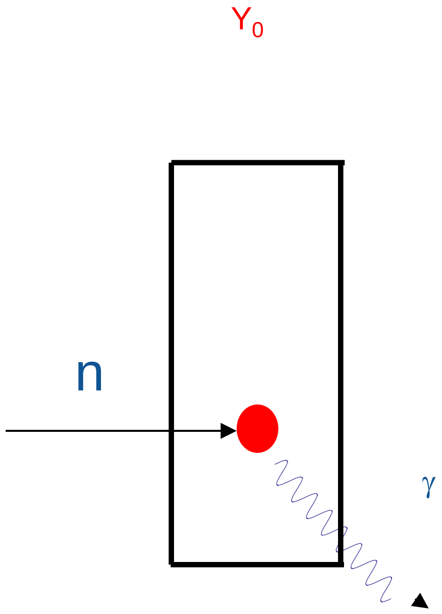


Reaction cross section

^{56}Fe(n,γ)

n_{Fe} = 1 10^{-3} at/b (0.12 mm thick)

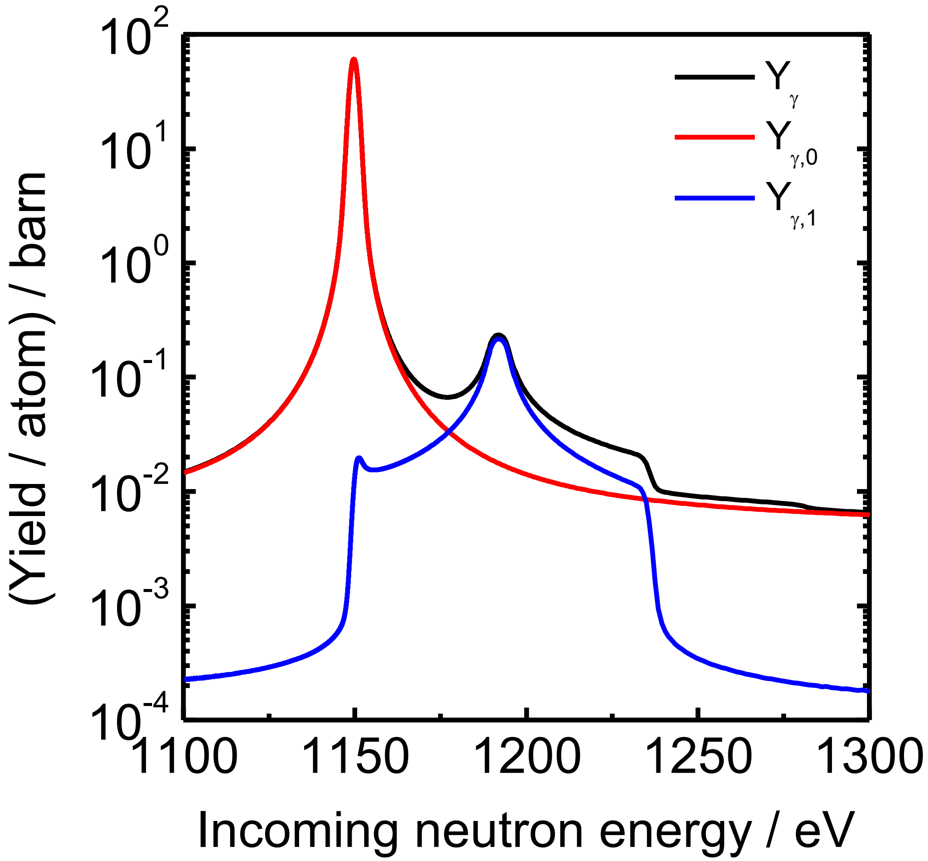


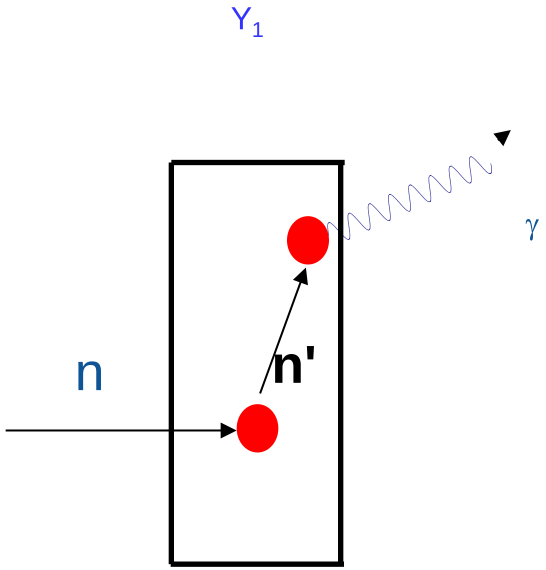


Reaction cross section

$^{56}Fe(n,\gamma)$

$n_{Fe} = 1\ 10^{-3}$ at/b (0.12 mm thick)

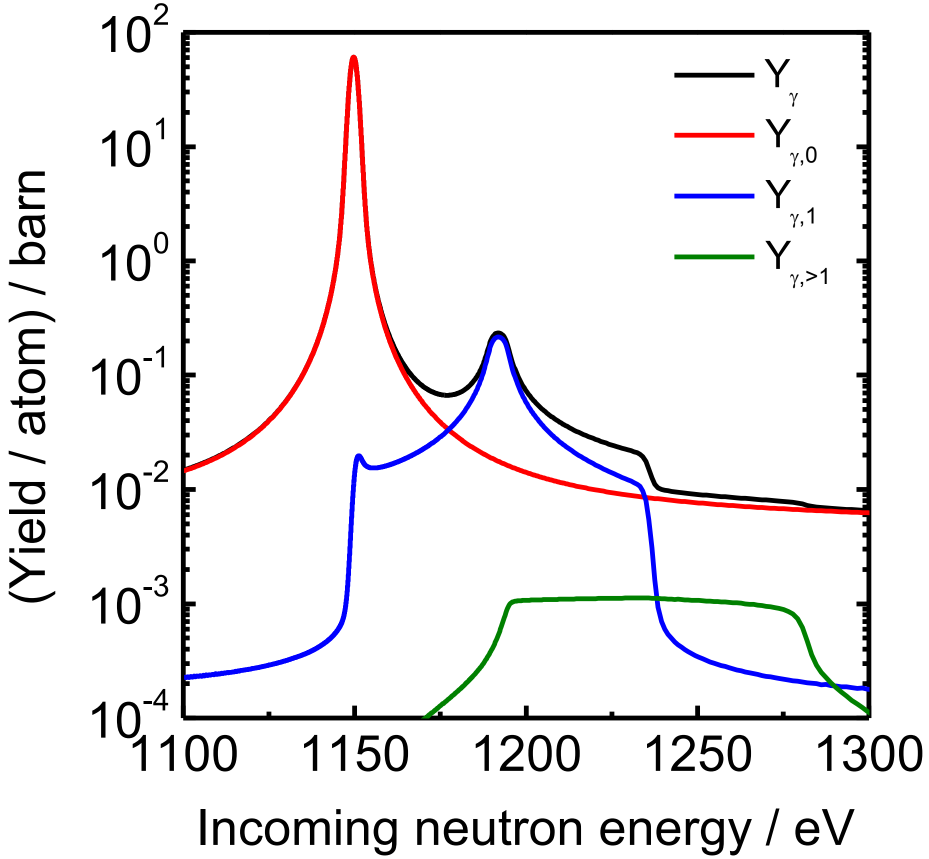


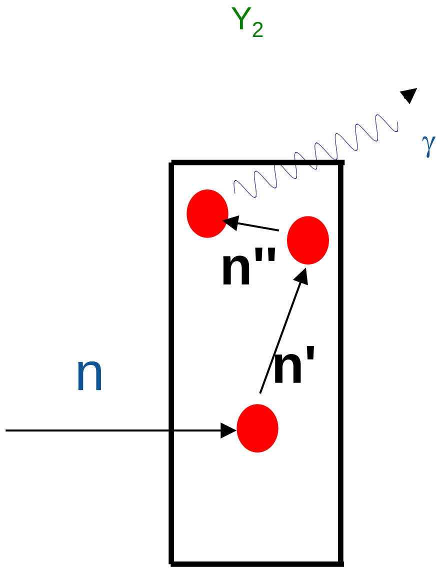


Reaction cross section

^{56}Fe(n,γ)

n_{Fe} = 1 10^{-3} at/b (0.12 mm thick)



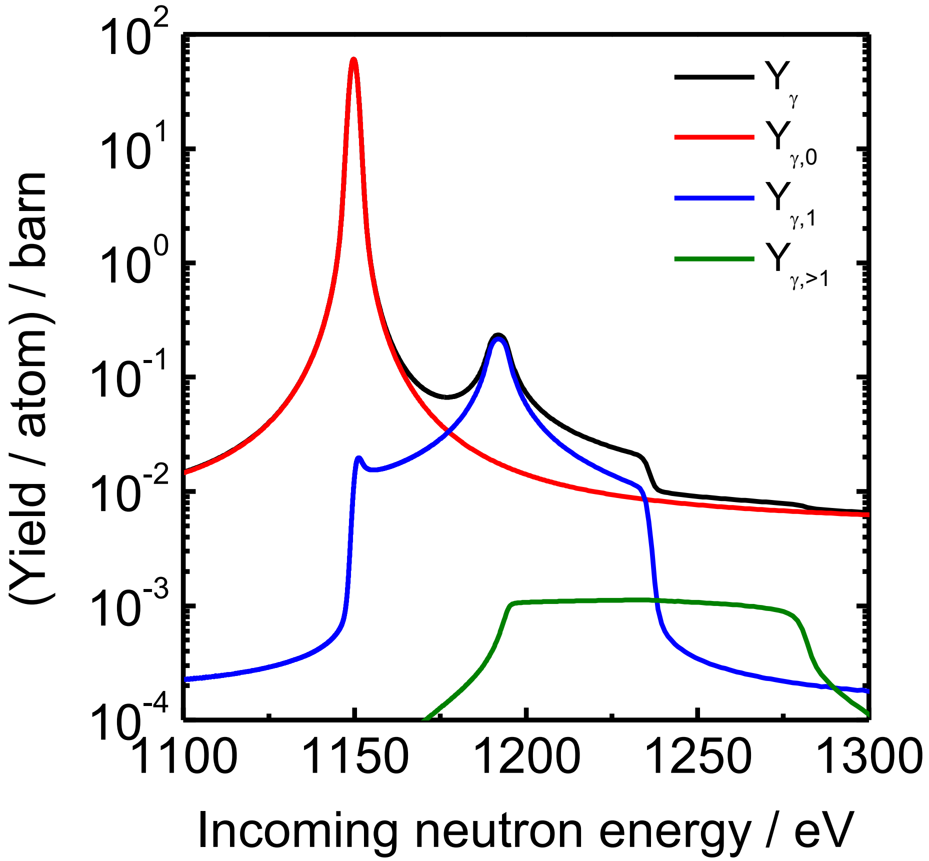


Y_2
γ
n''
n'
n

Reaction cross section

^{56}Fe(n,γ)

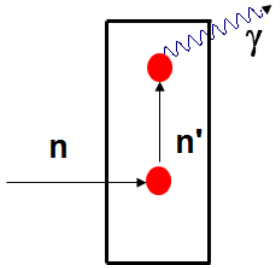
$n_{Fe} = 1\ 10^{-3}$ at/b (0.12 mm thick)



$$E' = E\left(\frac{m_n}{m_X + m_n}\right)^2 \left(\cos\theta + \sqrt{\left(\frac{m_X}{m_n}\right)^2 - \sin^2\theta}\right)^2$$

$$\theta = 90^\circ \quad \Rightarrow \quad E' = E\,\frac{m_X - m_n}{m_X + m_n}$$

$$\theta = 180^\circ \quad \Rightarrow \quad E' = E\left(\frac{m_X - m_n}{m_X + m_n}\right)^2$$

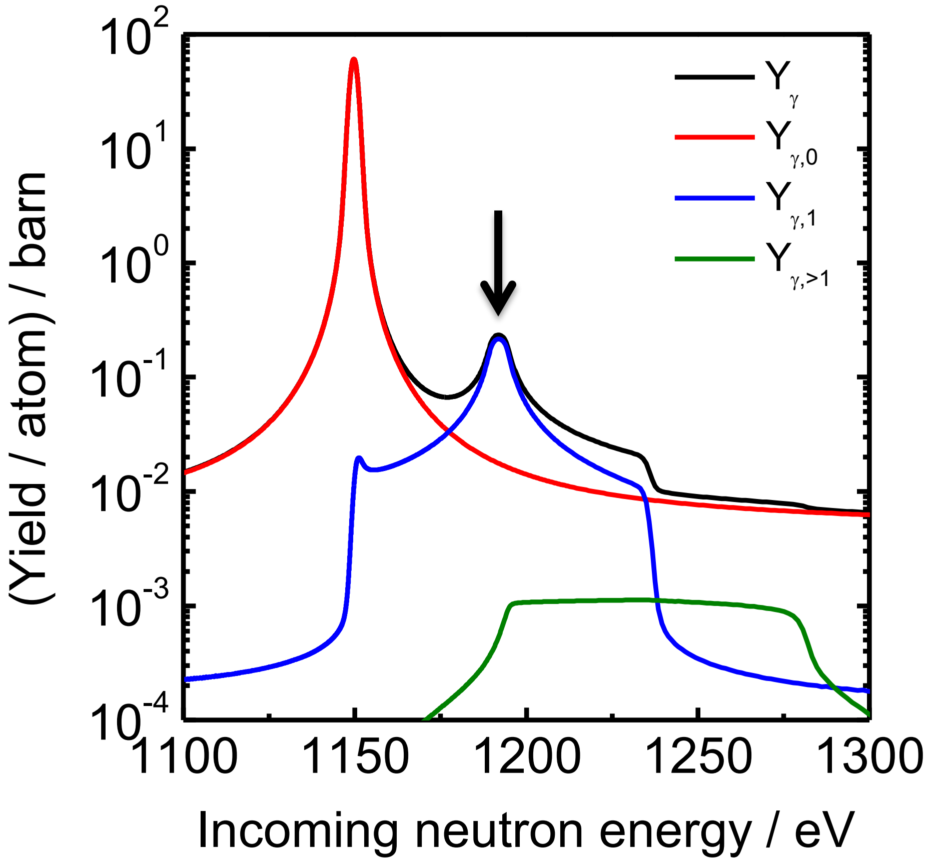


^{56}Fe E_r = 1.15 keV		
θ	**E / keV**	**E' / keV**
90°	**1.192**	**1.15**
180°	**1.235**	**1.15**
90° & 180°	**1.280**	**1.15**

Reaction cross section

^{56}Fe(n,γ)

n_{Fe} = 1 10^{-3} at/b (0.12 mm thick)



$$E' = E\left(\frac{m_n}{m_X+m_n}\right)^2\left(\cos\theta+\sqrt{\left(\frac{m_X}{m_n}\right)^2-\sin^2\theta}\right)^2$$

$$\theta = 90^o \quad \Rightarrow \quad E' = E\,\frac{m_X-m_n}{m_X+m_n}$$

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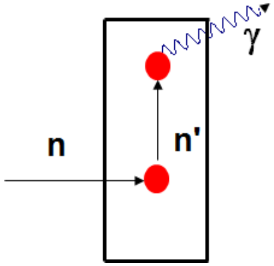


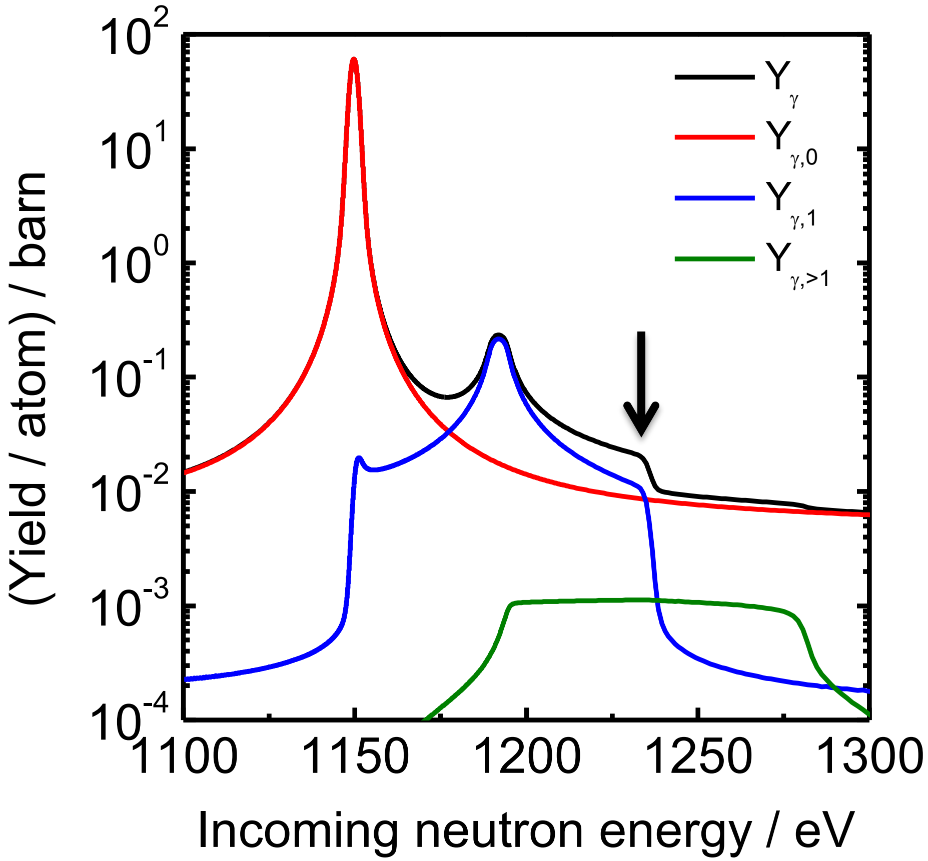
^{56}Fe E_r = 1.15 keV

θ	E / keV	E' / keV
90^o	1.192	1.15
180^o	1.235	1.15
90^o & 180^o	1.280	1.15

Reaction cross section

^{56}Fe(n,γ)

$n_{Fe} = 1\ 10^{-3}$ at/b (0.12 mm thick)



$$E' = E\left(\frac{m_n}{m_X+m_n}\right)^2\left(\cos\theta+\sqrt{\left(\frac{m_X}{m_n}\right)^2-\sin^2\theta}\right)^2$$

$$\theta=90^\circ \quad \Rightarrow \quad E' = E\,\frac{m_X-m_n}{m_X+m_n}$$

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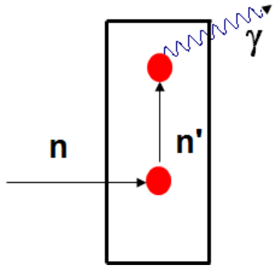
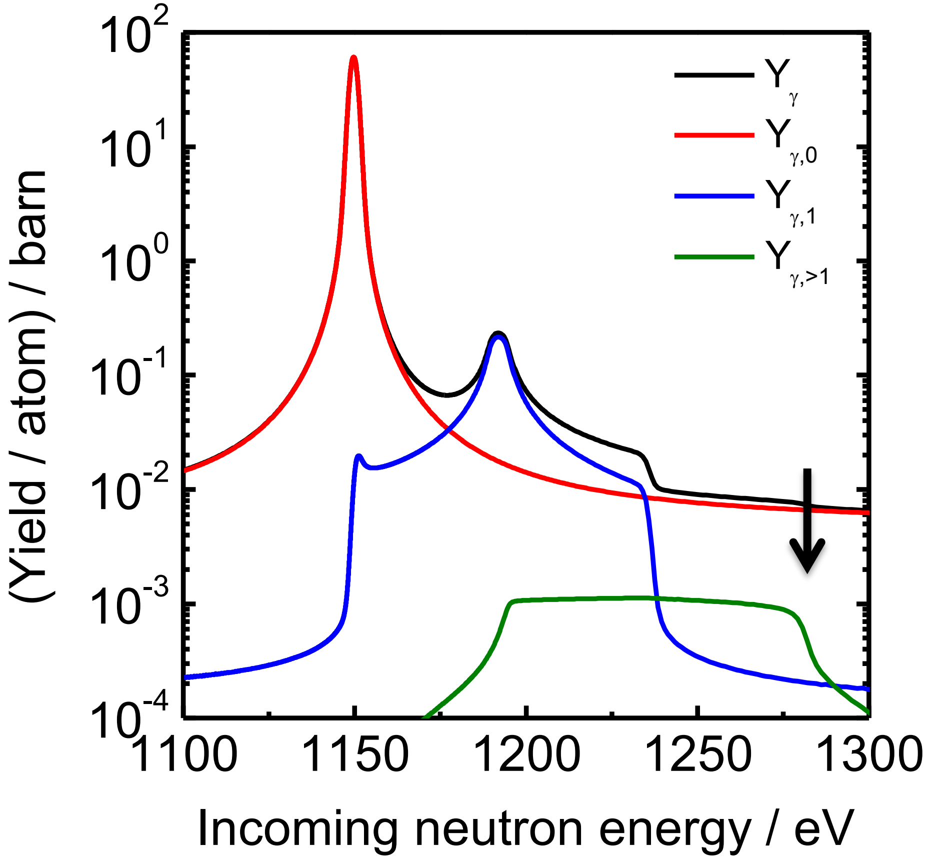


^{56}Fe E_r = 1.15 keV		
θ	E / keV	E' / keV
90°	1.192	1.15
180°	**1.235**	**1.15**
90° & 180°	1.280	1.15

Reaction cross section

^{56}Fe(n,γ)

$n_{Fe} = 1\ 10^{-3}$ at/b (0.12 mm thick)



$$E' = E\left(\frac{m_n}{m_X + m_n}\right)^2 \left(\cos\theta + \sqrt{\left(\frac{m_X}{m_n}\right)^2 - \sin^2\theta}\right)^2$$

$$\theta = 90^o \quad \Rightarrow \quad E' = E\frac{m_X - m_n}{m_X + m_n}$$

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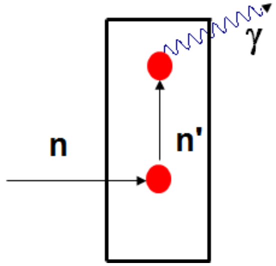


^{56}Fe E_r = 1.15 keV

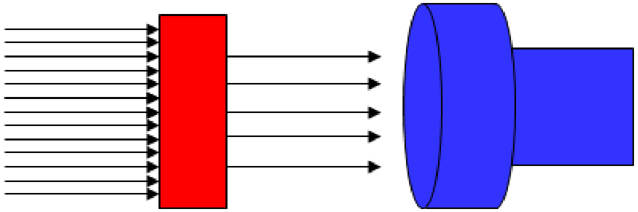
θ	E / keV	E' / keV
90°	**1.192**	**1.15**
180°	**1.235**	**1.15**
90° & 180°	**1.280**	**1.15**

Cross section measurements

Transmission

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

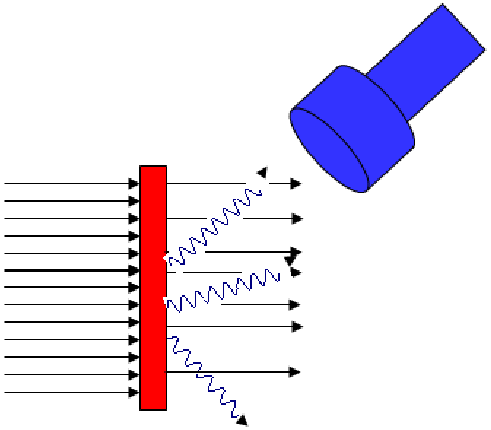
$$T_{exp} = \frac{C_{in}}{C_{out}}$$



Reaction

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

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



Reaction cross section measurements

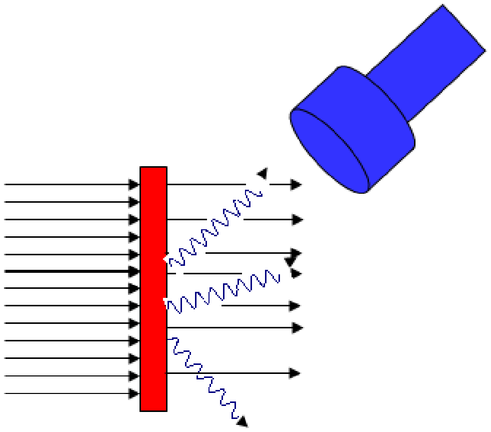
$$C_r = \varepsilon_r \, \Omega P_r \, Y_r \, A_r \, \varphi$$

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

Reaction

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

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



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 $n\sigma_{tot} \ll 1$: $Y_r \cong n\,\sigma_r$

Cross section measurements

Transmission

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

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

- Incoming flux cancels
- Detection efficiency cancels

Total cross sections:

Most accurate cross section

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 $n\sigma_{tot} \ll 1$: $Y_r \cong n\,\sigma_r$

Cross section measurements

Transmission

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

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

- Incoming flux cancels
- Detection efficiency cancels

Total cross sections:

Most accurate cross section

From transmission: ^{197}Au(n,γ)

$\sigma(n_{th}, \gamma) = (98.7 \pm 0.1)$ b

Reaction

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

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

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 $n\sigma_{tot} \ll 1$: $Y_r \cong n\,\sigma_r$