



# The European Commission's science and knowledge service

## Joint Research Centre

# Testing of resonance parameters of actinides

**S. Kopecky**

WONDER-2018

- Method
  - Measurement principle
  - Testing
- Testing of Actinides (CBRN standards)
- MINVERE samples
  - Model development

- **Method**
  - Measurement principle
  - Testing
- Testing of Actinides (CBRN standards)
- MINVERE samples
  - Model development

# GELINA - overview



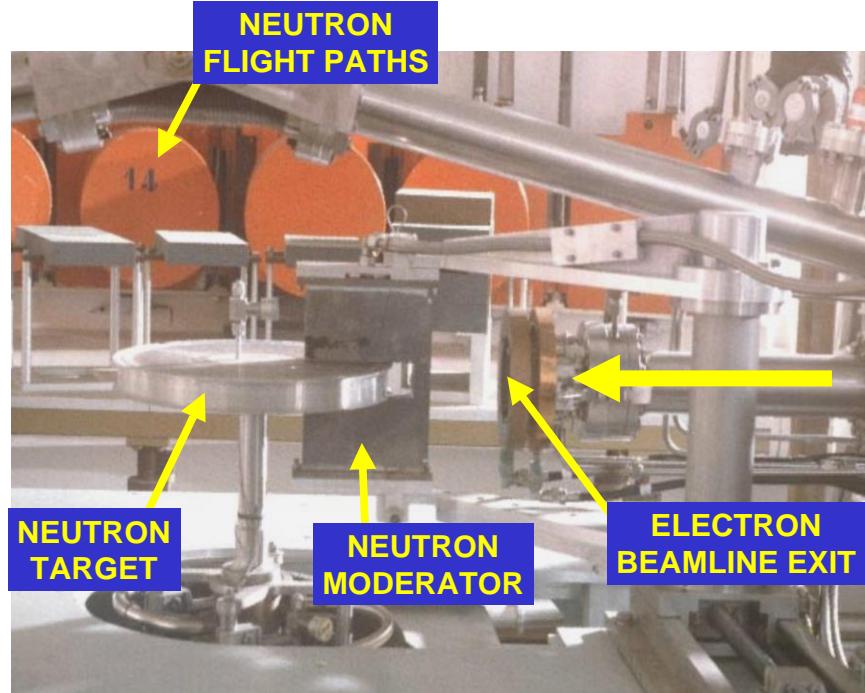
# GELINA - overview



- Pulsed white neutron source  
 $(10 \text{ meV} < E_n < 20 \text{ MeV})$
- Pulse frequency 50Hz – 800 Hz
- Neutron energy : time – of – flight (TOF)
- Multi-user facility: 12 flight paths  
 $(10 \text{ m} - 400 \text{ m})$
- Measurement stations with special equipment to perform:
  - Total cross section measurements
  - Partial cross section measurements

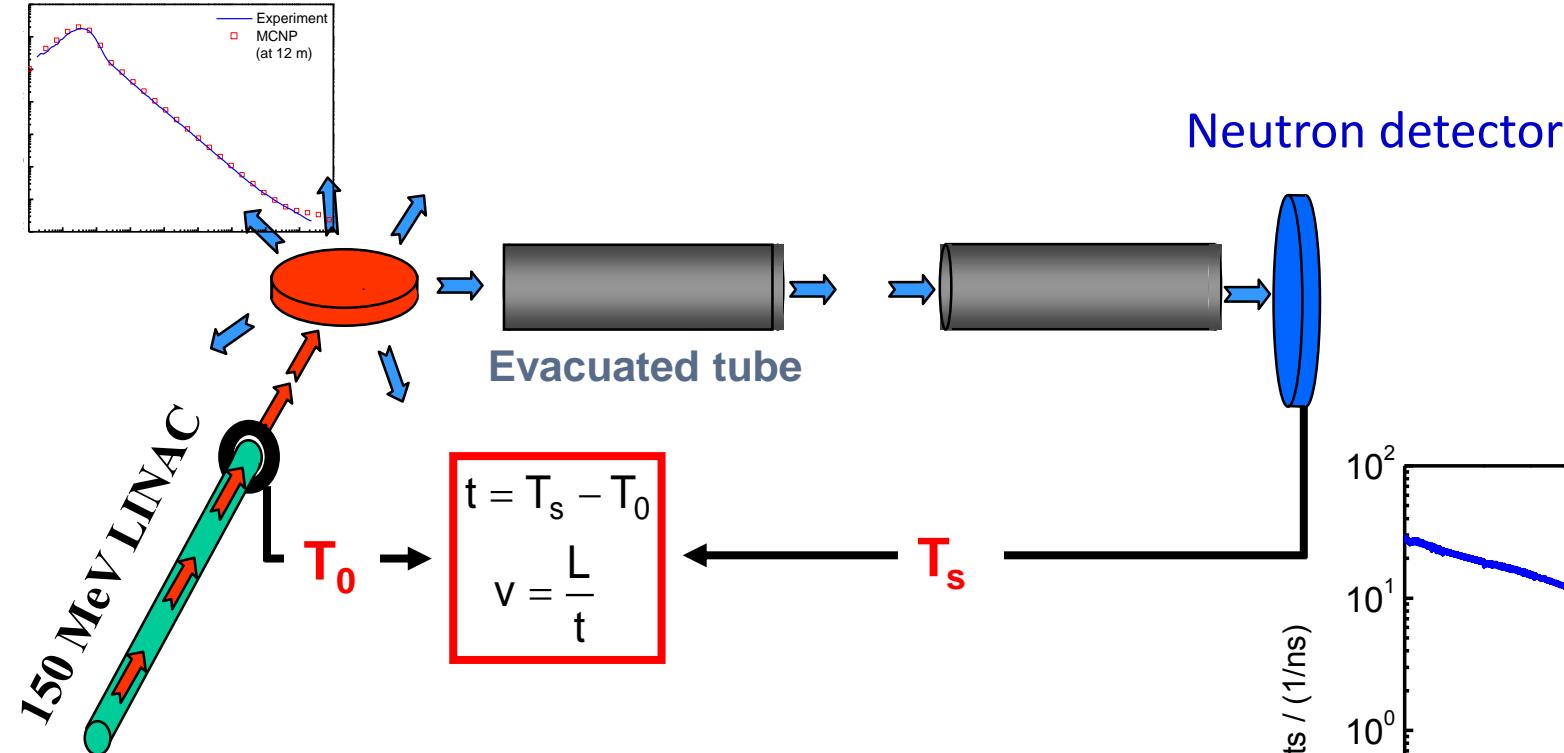


# GELINA - target

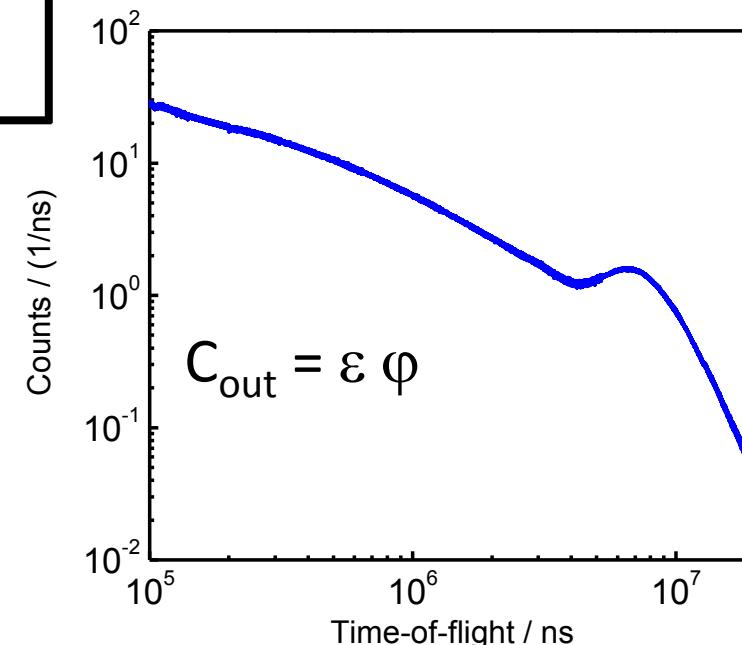


- $e^-$  accelerated to  $E_{e-,max} \approx 140$  MeV
- Bremsstrahlung in U-target  
(rotating & cooled with liquid Hg)
- $(\gamma, n)$ ,  $(\gamma, f)$  in U-target
- Low energy neutrons by moderation  
(water moderator in Be-canning)

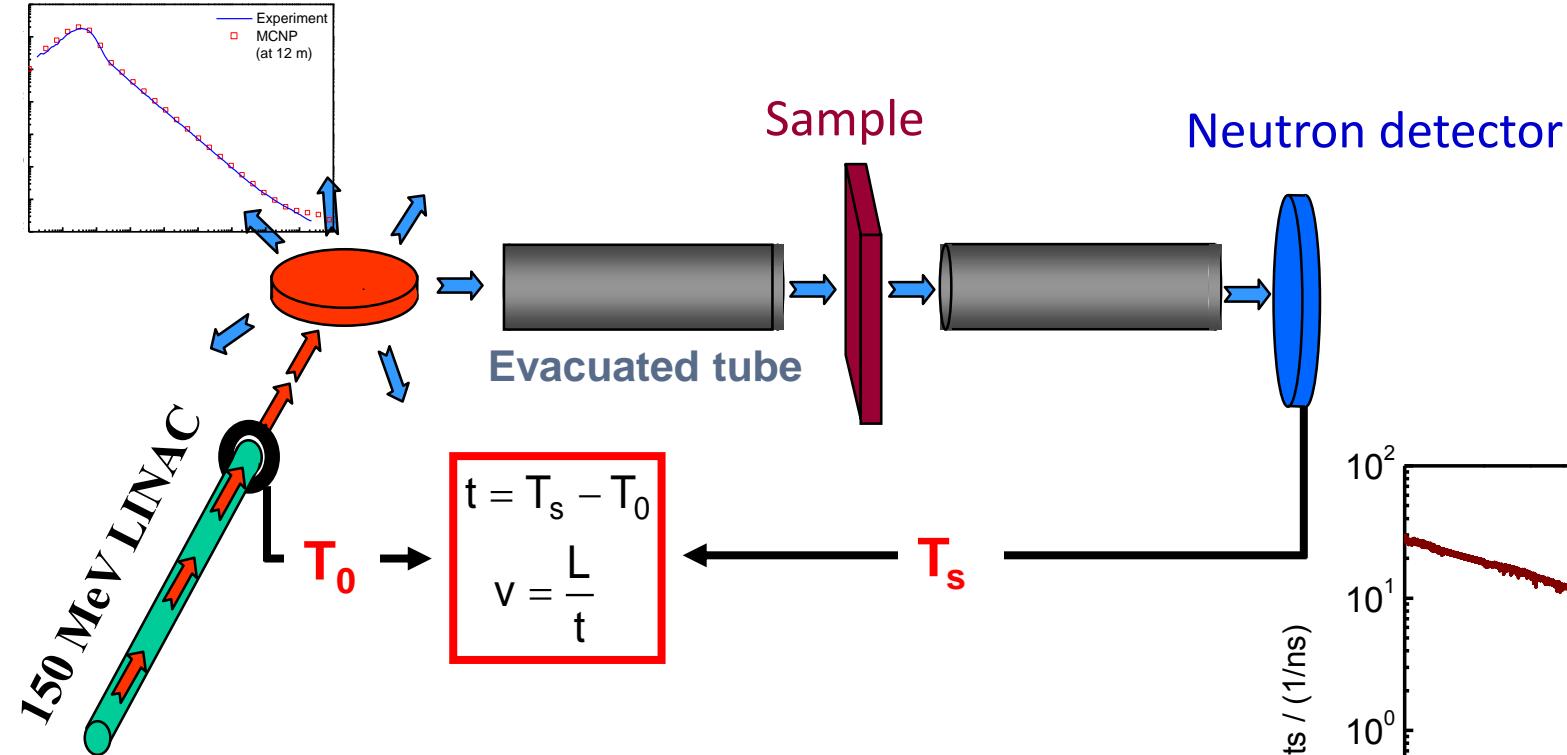
# Tof - principle



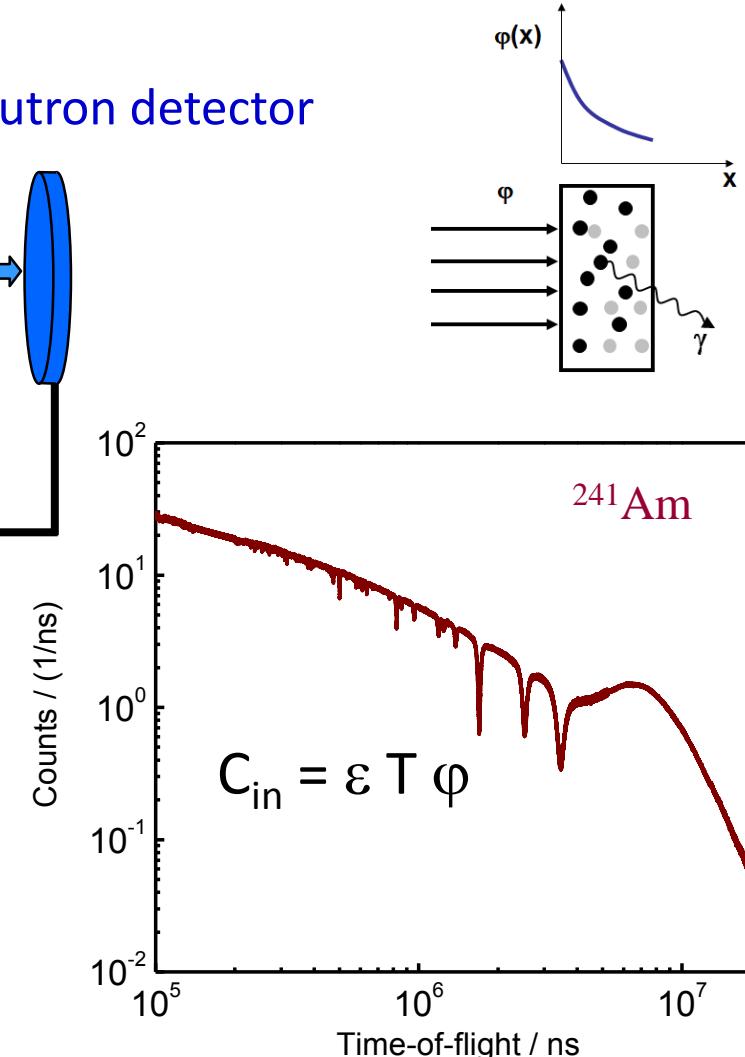
$L$  : distance between target and detector  
 $t$  : time-of-flight



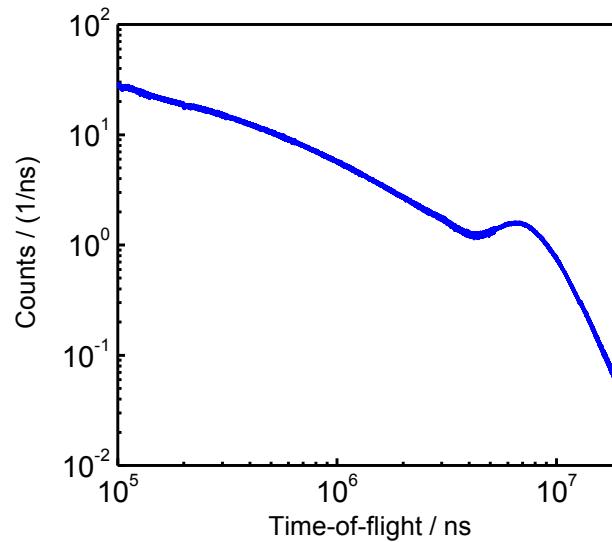
# Tof - principle



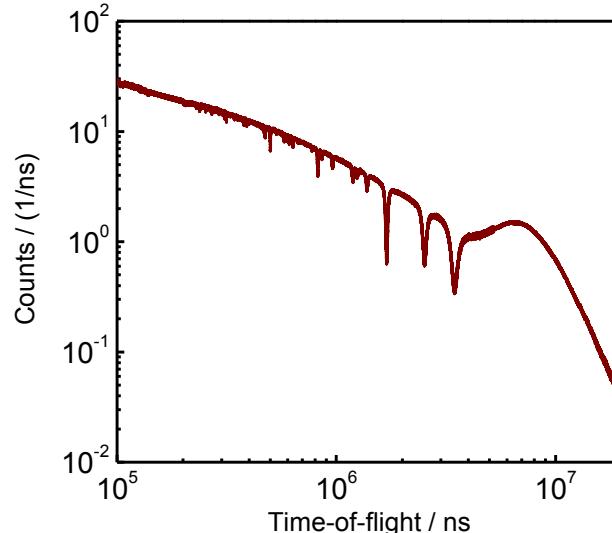
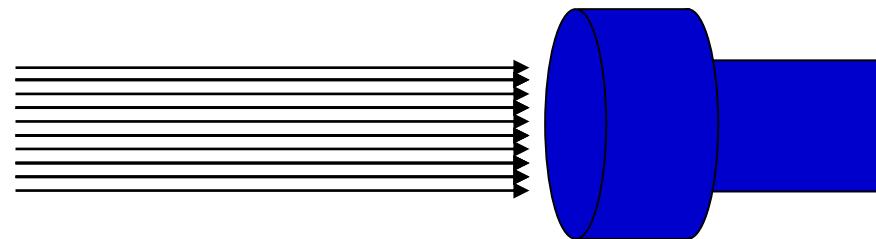
L : distance between target and detector  
 t : time-of-flight



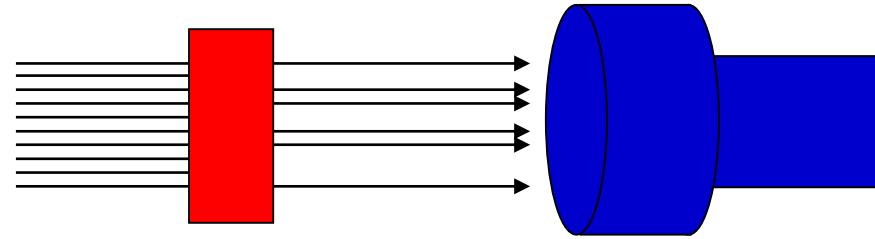
# Transmission - principle



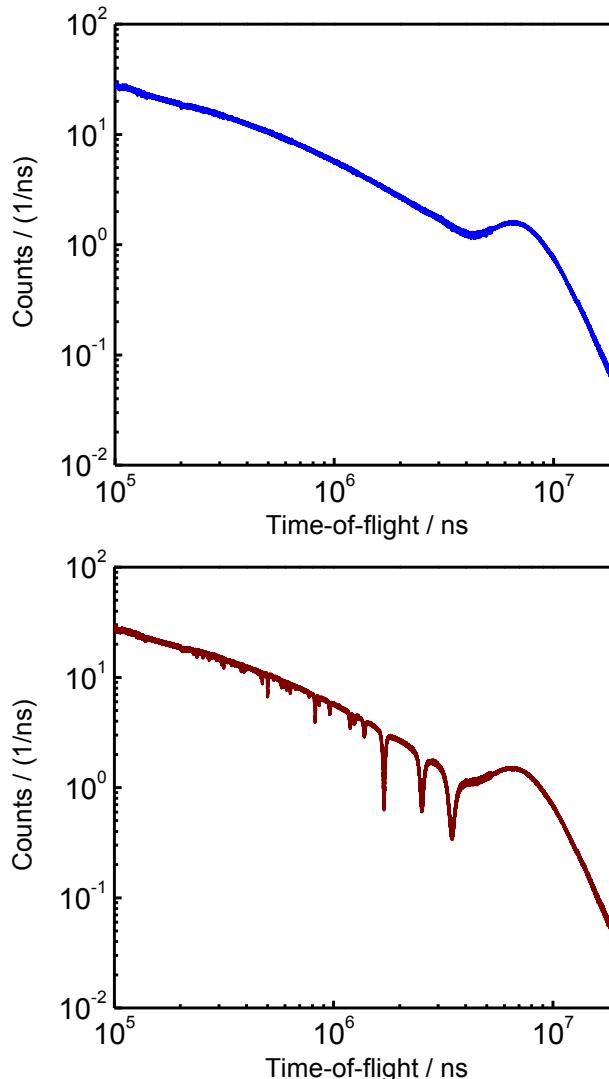
$$C_{\text{out}} = \epsilon \phi$$



$$C_{\text{in}} = \epsilon T \phi$$

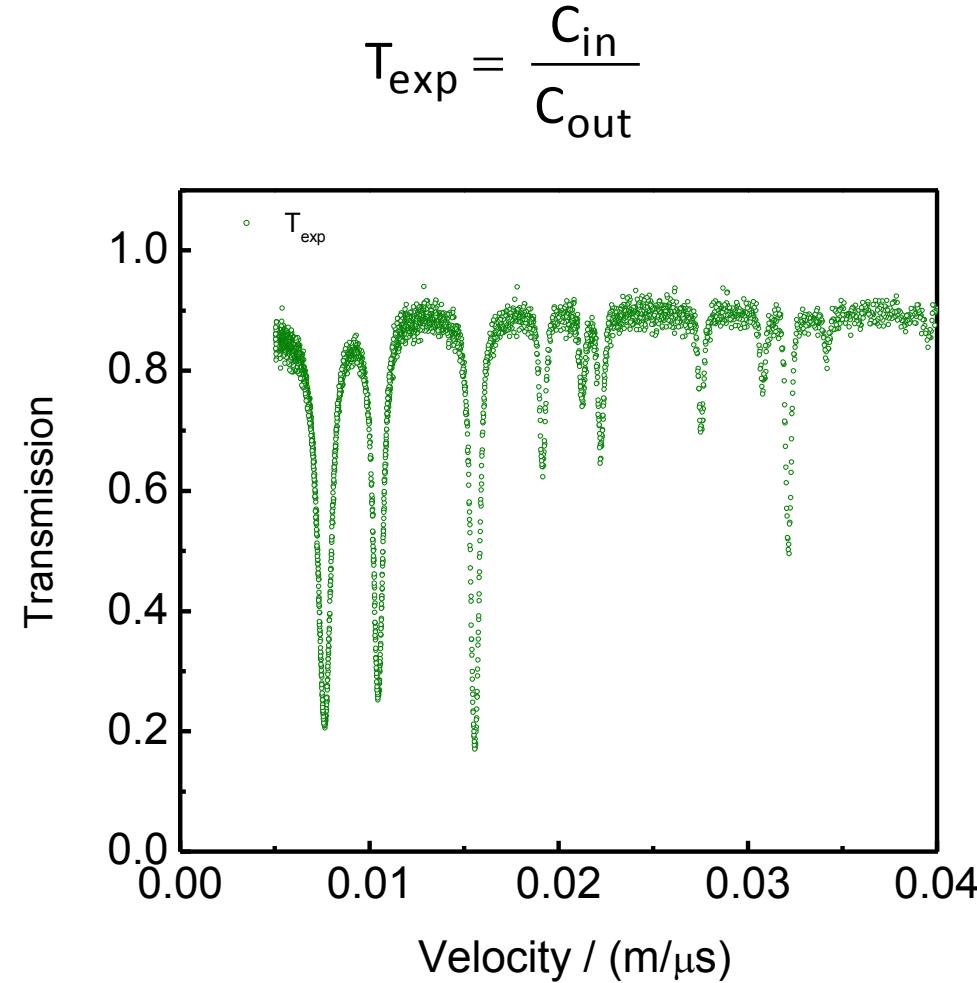


# Transmission - principle



$$C_{\text{out}} = \varepsilon \phi$$

$$C_{\text{in}} = \varepsilon T \phi$$

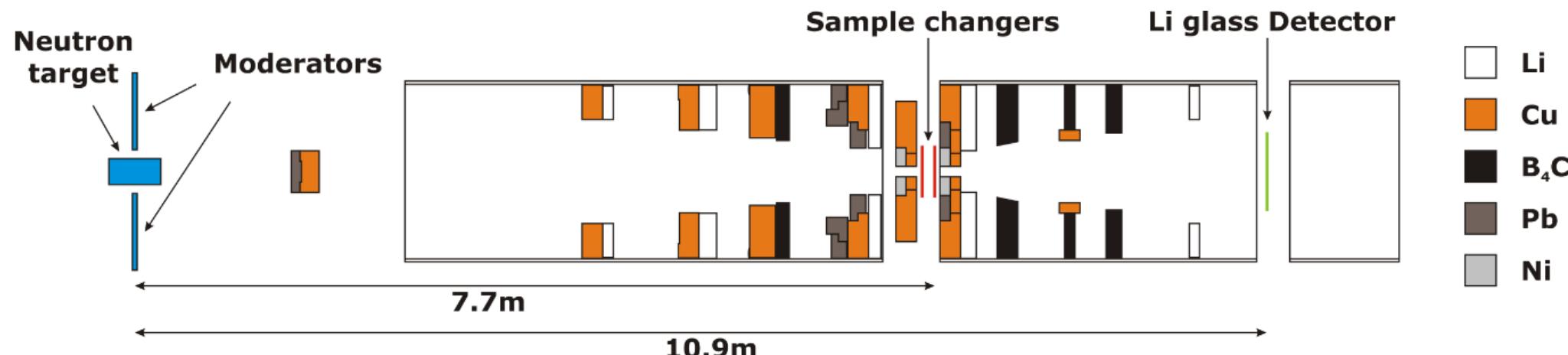


$$T_{\text{exp}} = \frac{C_{\text{in}}}{C_{\text{out}}}$$

# Transmission - principle

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

- (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)**



# NRTA

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

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

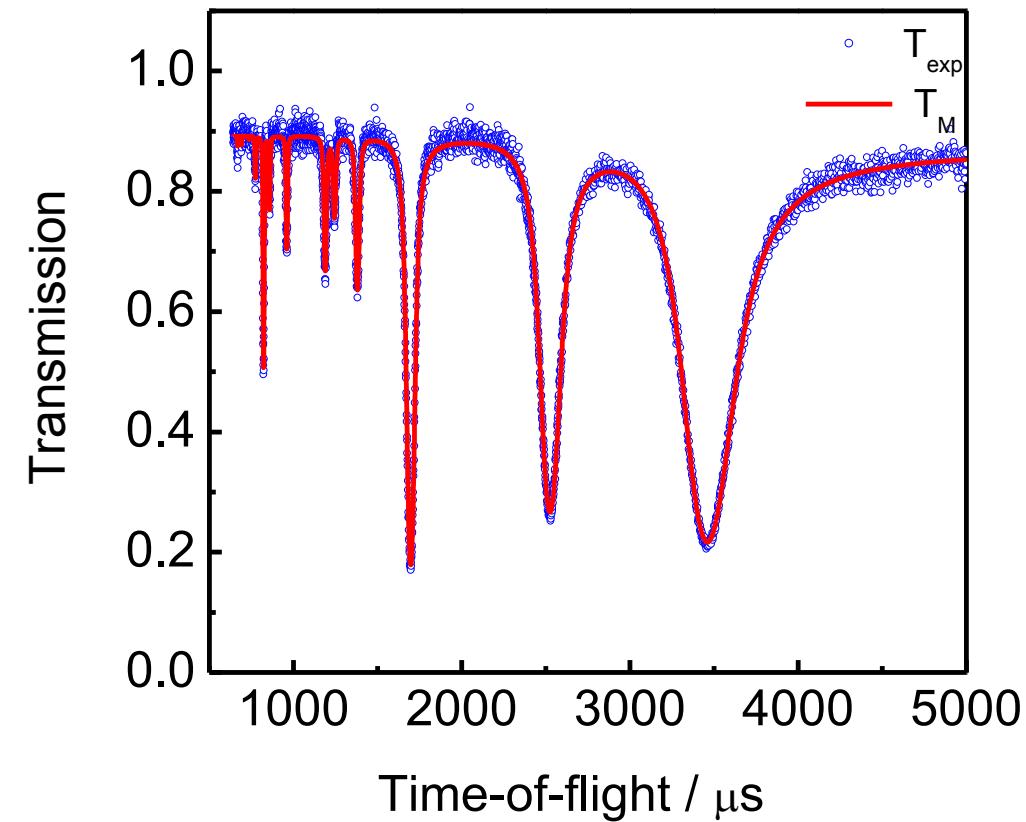
Resonance Shape Analysis: REFIT

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

$$T_M(t) = \int R(t, E) T(E) dE$$

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

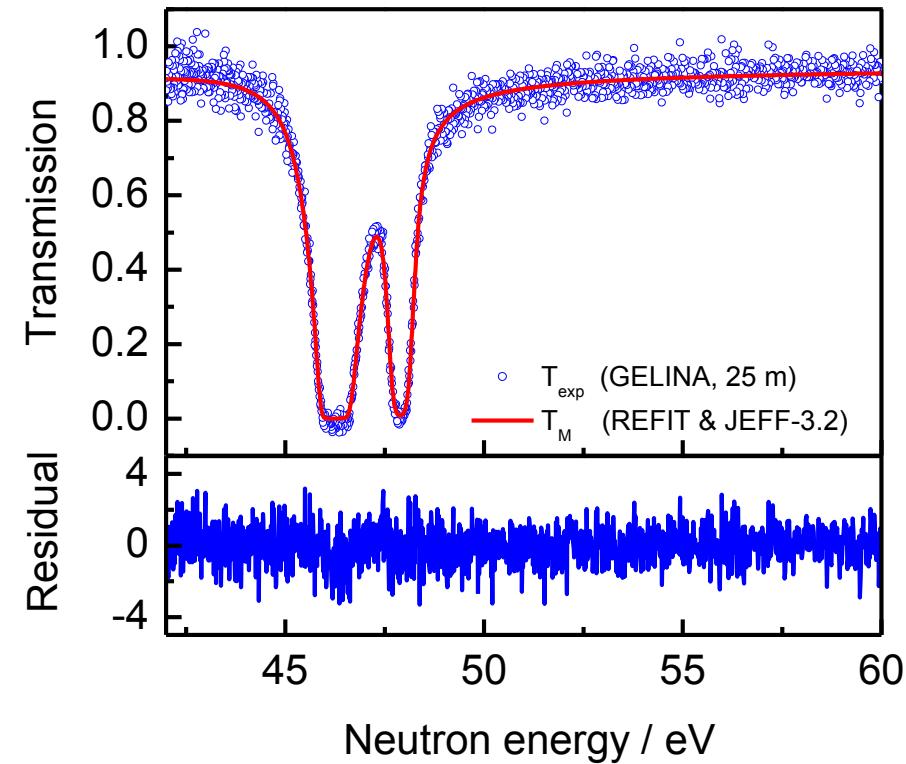
n : areal density  
total number of nuclei per unit area



# Example: Tungsten

- Transmission measurements
  - 25 m station of GELINA
  - ${}^6\text{Li}$  detector
- Sample:  ${}^{\text{nat}}\text{W}$  metal disc ( $u_n < 0.2\%$ )
- Determine areal density by RSA (REFIT)

$$\chi^2(n) = (Y_{\text{exp}} - Y_M(t_m, n))^T V_{Y_{\text{exp}}}^{-1} (Y_{\text{exp}} - Y_M(t_m, n))$$

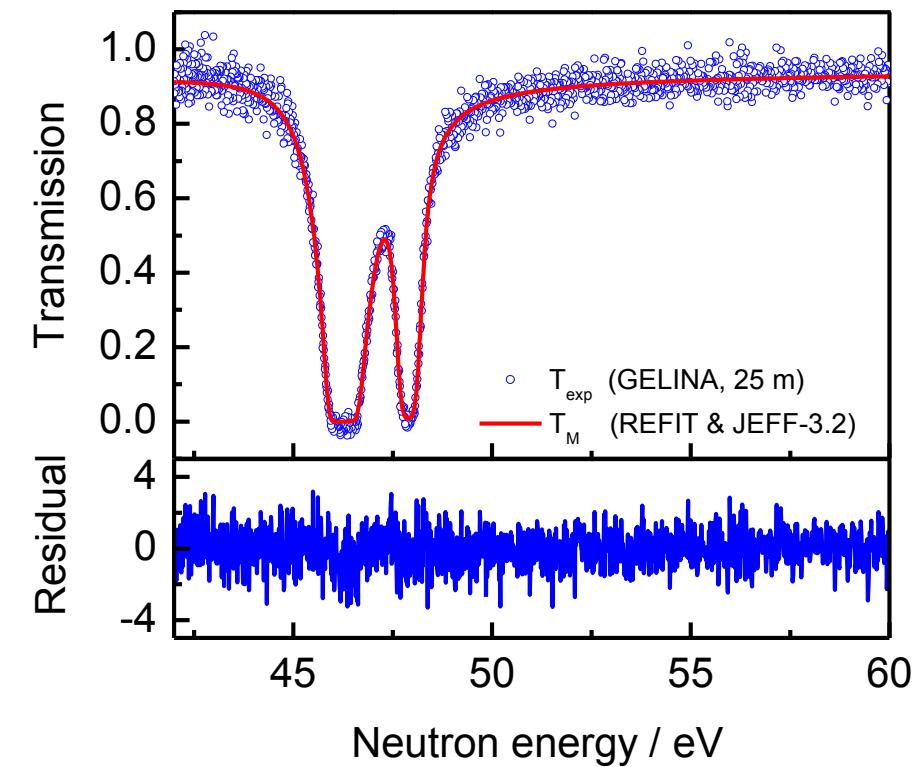


# Example: Tungsten

- Transmission measurements
  - 25 m station of GELINA
  - ${}^6\text{Li}$  detector
- Sample:  ${}^{\text{nat}}\text{W}$  metal disc ( $u_n < 0.2\%$ )
- Determine areal density by RSA (REFIT)

	$n_{\text{fit}}$ (at/b)	$100 \times n_{\text{fit}}/n_{\text{ref}}$
Reference	$(6.389 \pm 0.001) \times 10^{-3}$	
JEFF – 3.2	<b><math>(6.402 \pm 0.032) \times 10^{-3}</math></b>	<b><math>100.2 \pm 0.5</math></b>
ENDGF/B-VI.8	$(7.009 \pm 0.032) \times 10^{-3}$	$109.7 \pm 0.5$
JENDI – 3.3	$(7.111 \pm 0.032) \times 10^{-3}$	$111.3 \pm 0.5$
ENDF/B-VII.1	$(7.111 \pm 0.070) \times 10^{-3}$	$111.3 \pm 1.1$

$$\chi^2(n) = (\mathbf{Y}_{\text{exp}} - \mathbf{Y}_M(t_m, n))^T V_{Y_{\text{exp}}}^{-1} (\mathbf{Y}_{\text{exp}} - \mathbf{Y}_M(t_m, n))$$



# Example: Tungsten

Library	$E_R = 46.26 \text{ eV}$		$E_R = 47.80 \text{ eV}$		$100 \times n_{\text{ref}}/n_{\text{fit}}$
	$\Gamma_n / \text{meV}$	$\Gamma_\gamma / \text{meV}$	$\Gamma_n / \text{meV}$	$\Gamma_\gamma / \text{meV}$	
<b>JEFF-3.2</b>	<b>163.4</b>	<b>75.3</b>	<b>120.8</b>	<b>61.5</b>	<b>100.2 (0.5)</b>
ENDF/B-VI.8	154	69	115	78	109.7 (0.5)
JENDL – 3.3	154	46	119	81	111.3 (0.5)
ENDF/B-VII.1	154 (0.8)	46	119 (1.2)	81 (5.1)	111.3 (1.1)

Overestimation of  $n$  compensates for underestimation of  $\Gamma_n$

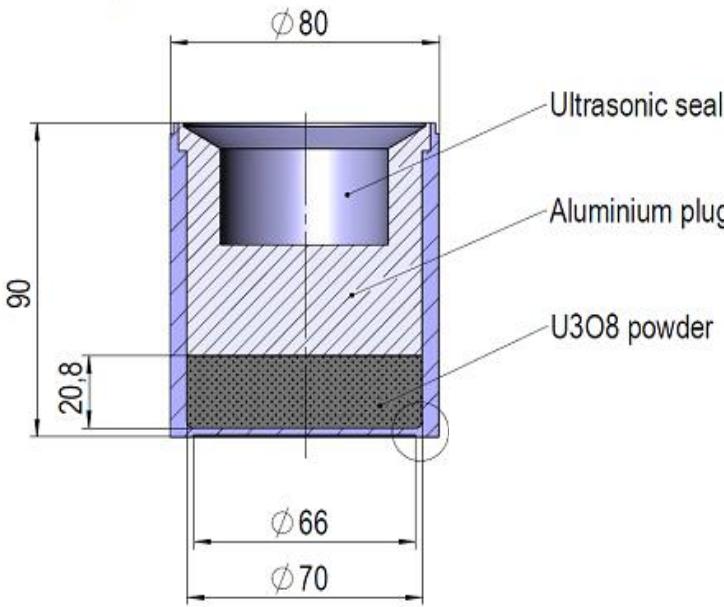
- Method
  - Measurement principle
  - Testing
- **Testing of Actinides (CBNM standards)**
- MINVERE samples
  - Model development

# FP13-setup

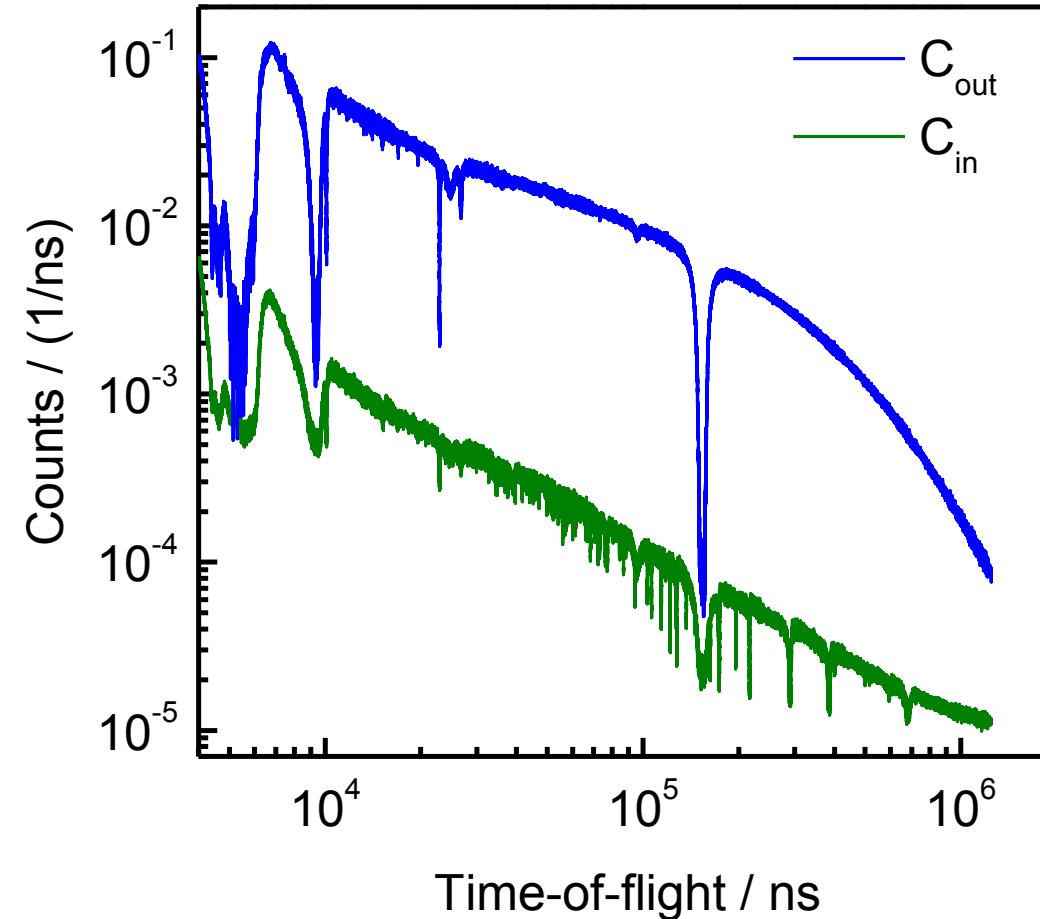


# CBNM standard: U

$\text{U}_3\text{O}_8$  reference sample  
EC NRM 171

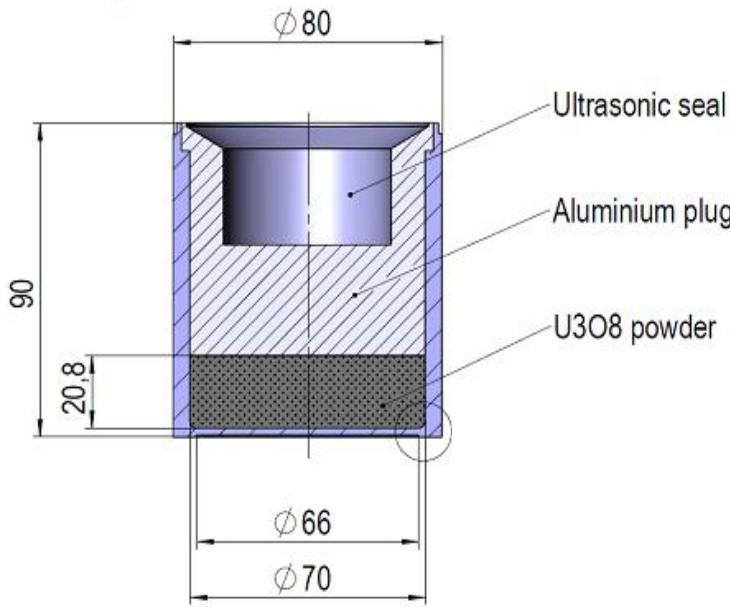


- Strong impact of matrix material
- Beam attenuation due to matrix ~ 97%

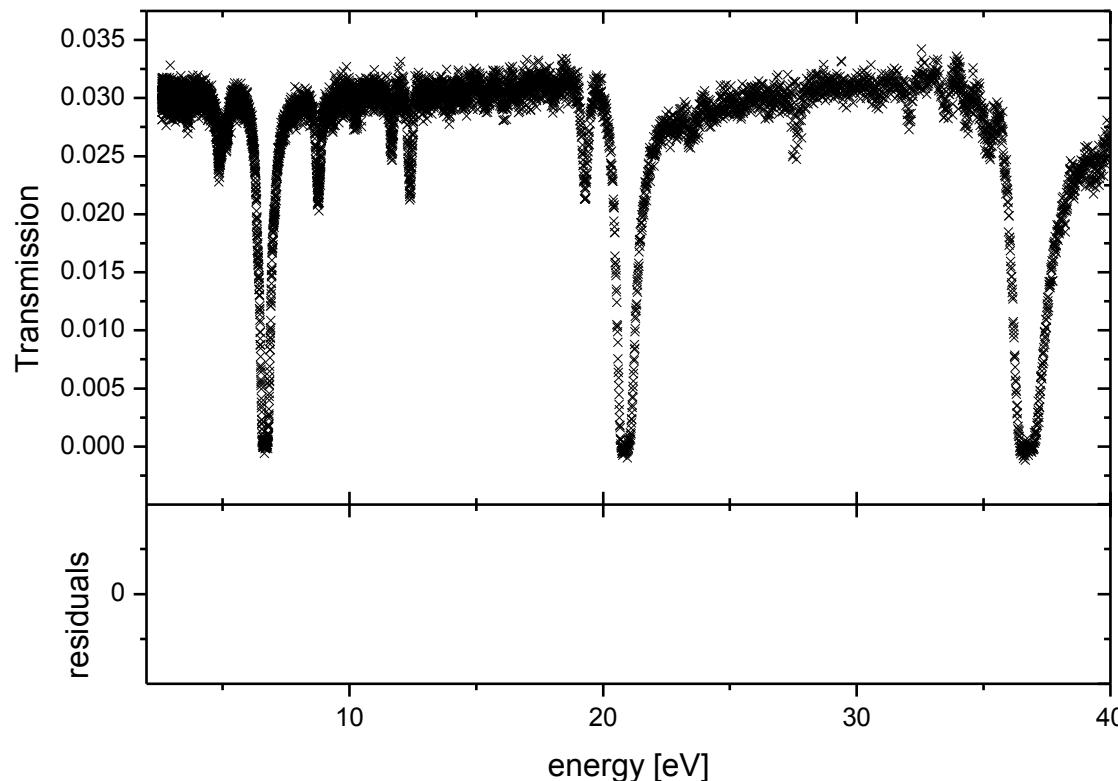


# CBNM standard: U

$\text{U}_3\text{O}_8$  reference sample  
EC NRM 171



- Strong impact of matrix material
- Beam attenuation due to matrix ~ 97%

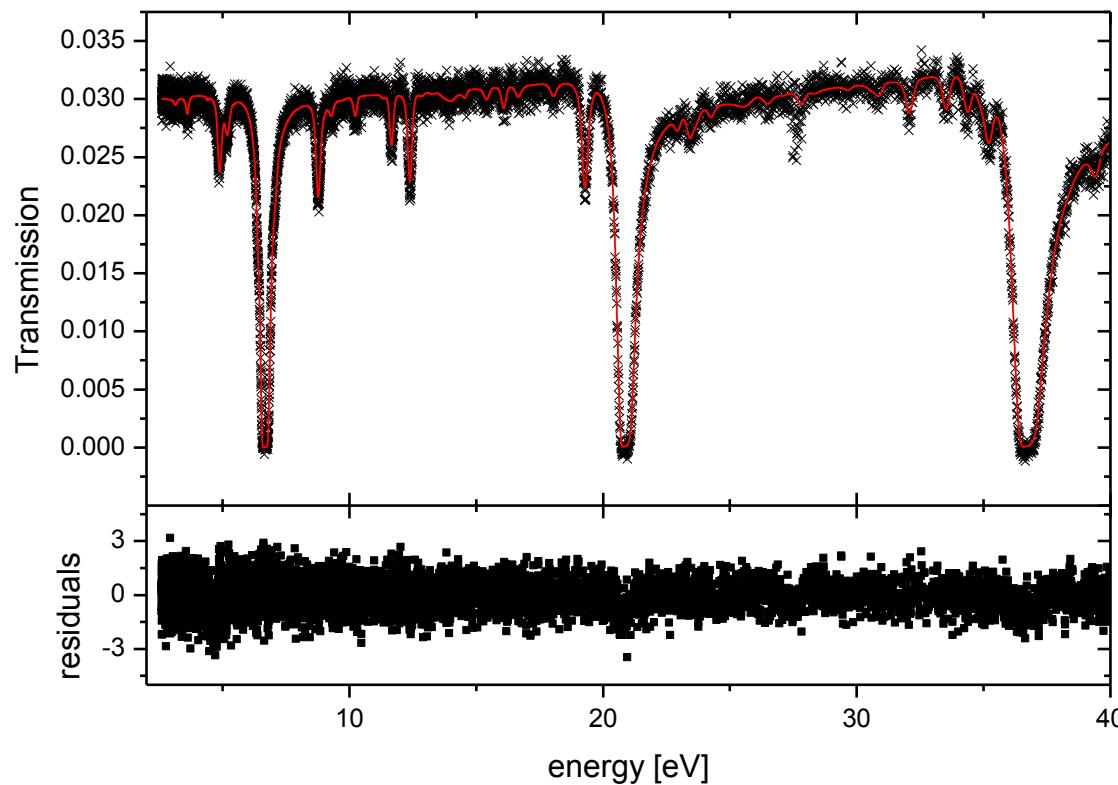


# CBNM standard: U

$\text{U}_3\text{O}_8$  reference sample  
EC NRM 171

Fit for  $^{235,238}\text{U}$  areal density  
+

$$n_X \sigma_{\text{tot},X}(E) = a_X + \frac{b_X}{\sqrt{E}}$$

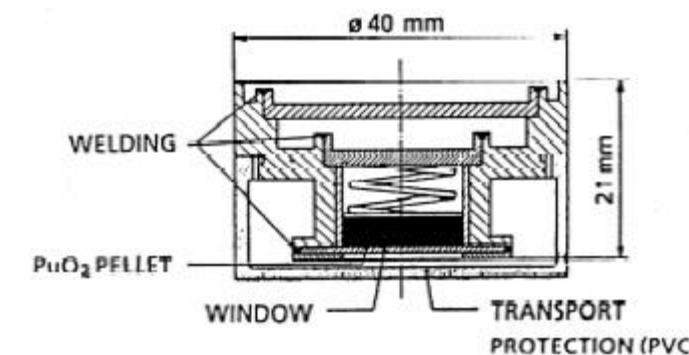
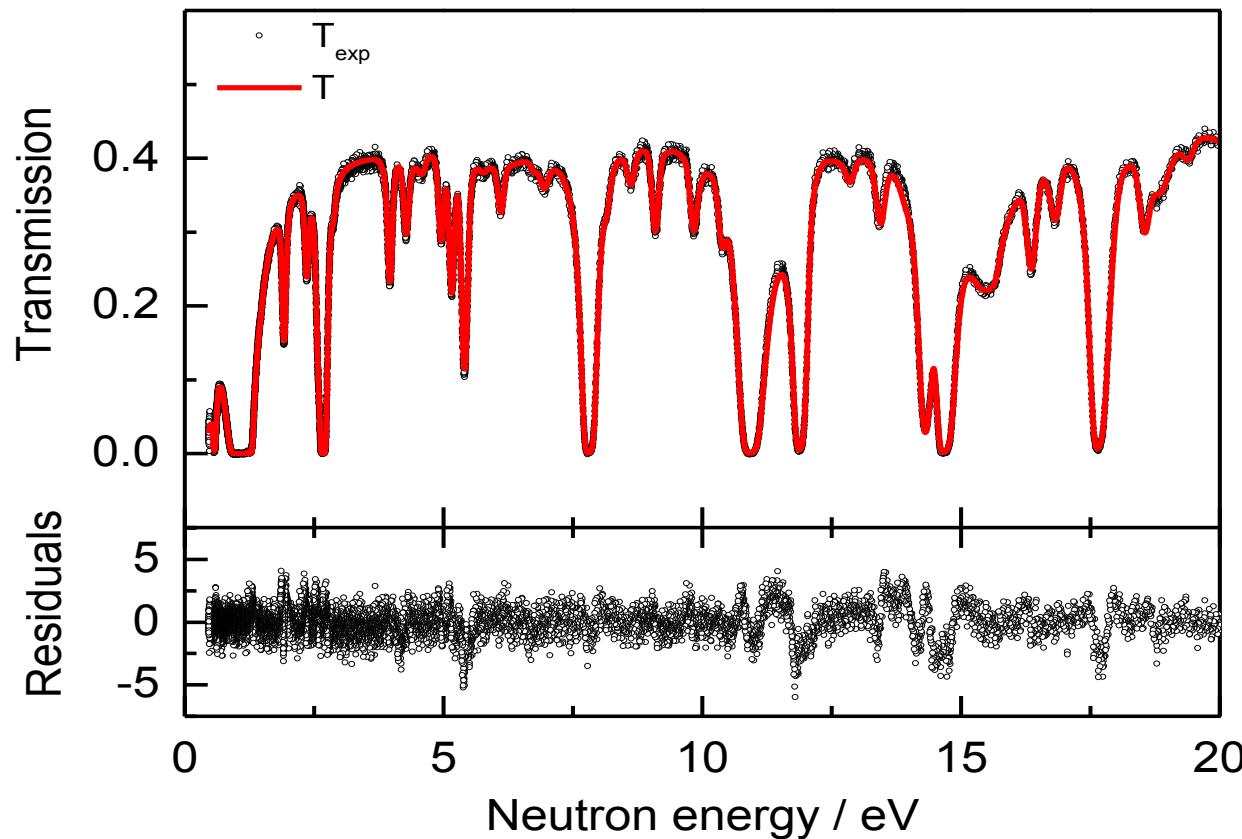


# CBNM standard: U

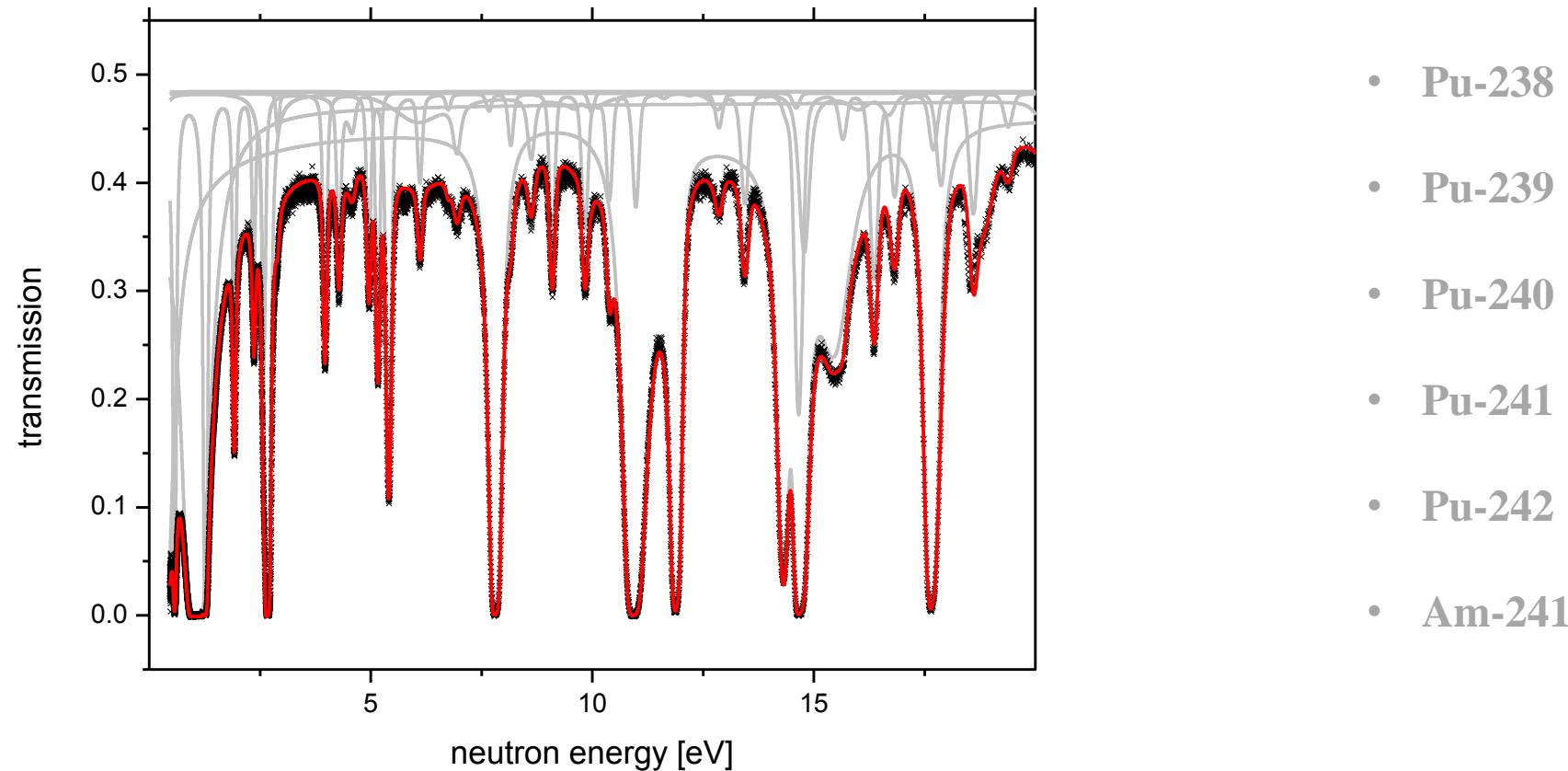
$\text{U}_3\text{O}_8$  reference sample  
EC NRM 171

	235U/238U Declared [%]	uncertainty Declared [%]	235U/238U NRTA [%]	uncertainty NRTA [%]	<i>NRTA declared</i>	Uncertainty ratio
U-031	0.3206	0.0002	0.313	0.03	0.976	0.100
U-070	0.7209	0.0005	0.812	0.08	1.127	0.110
U-194	1.9664	0.0014	2.012	0.02	1.023	0.012
U-295	2.9857	0.0021	3.012	0.03	1.009	0.009
U-445	4.5168	0.0032	4.627	0.07	1.024	0.015

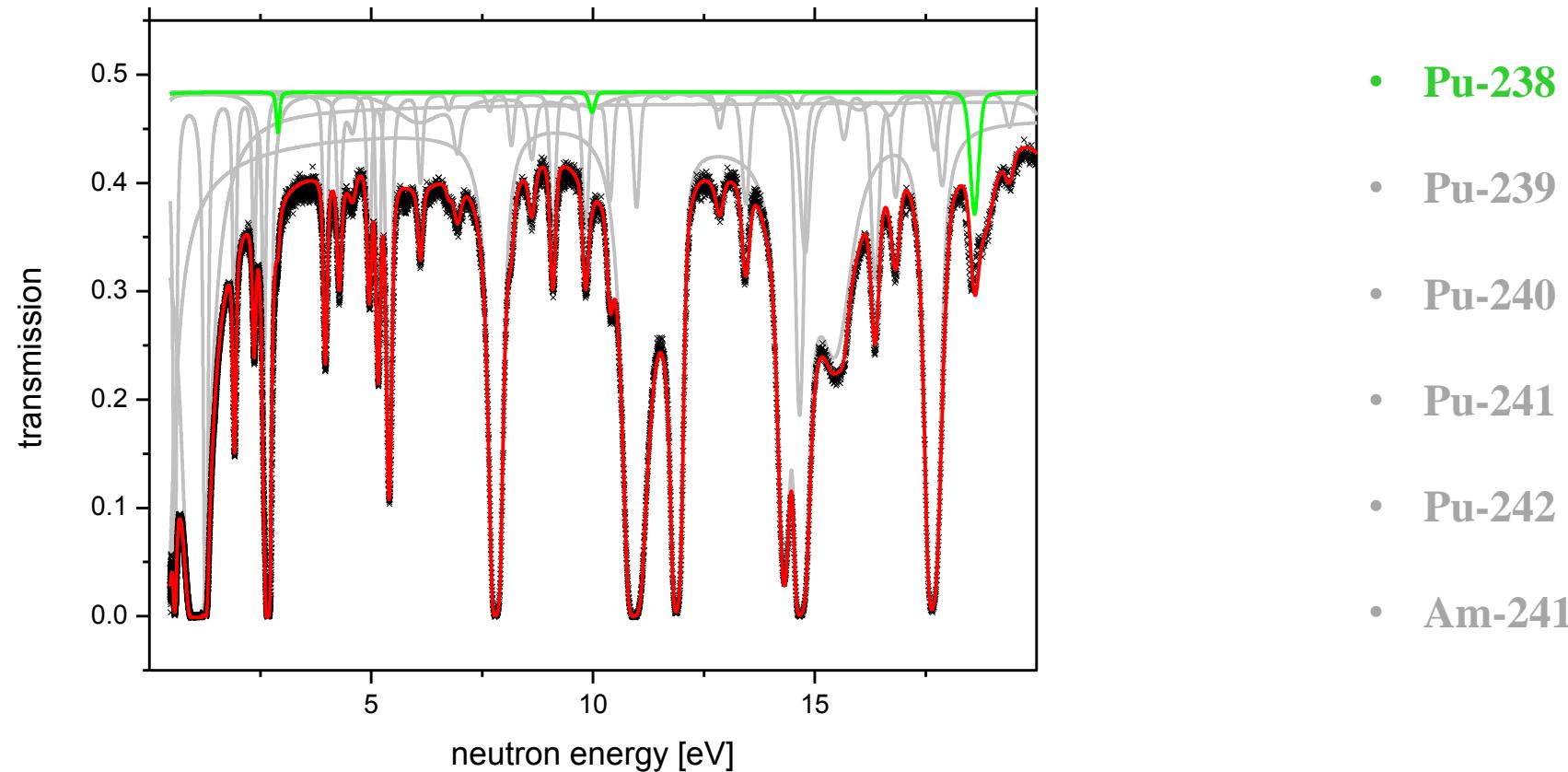
# CBNM standard: Pu



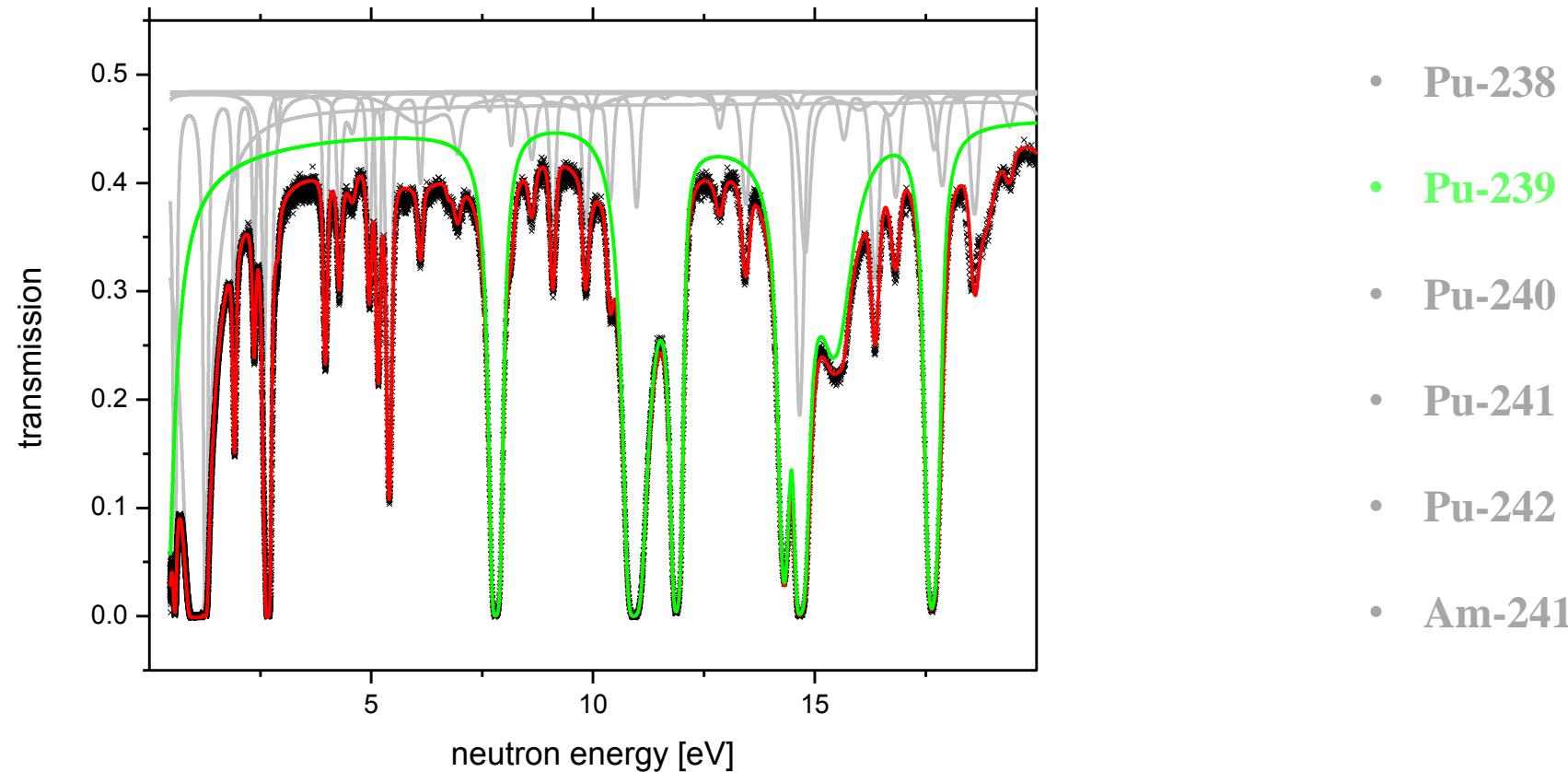
# CBNM standard: Pu - Contributions



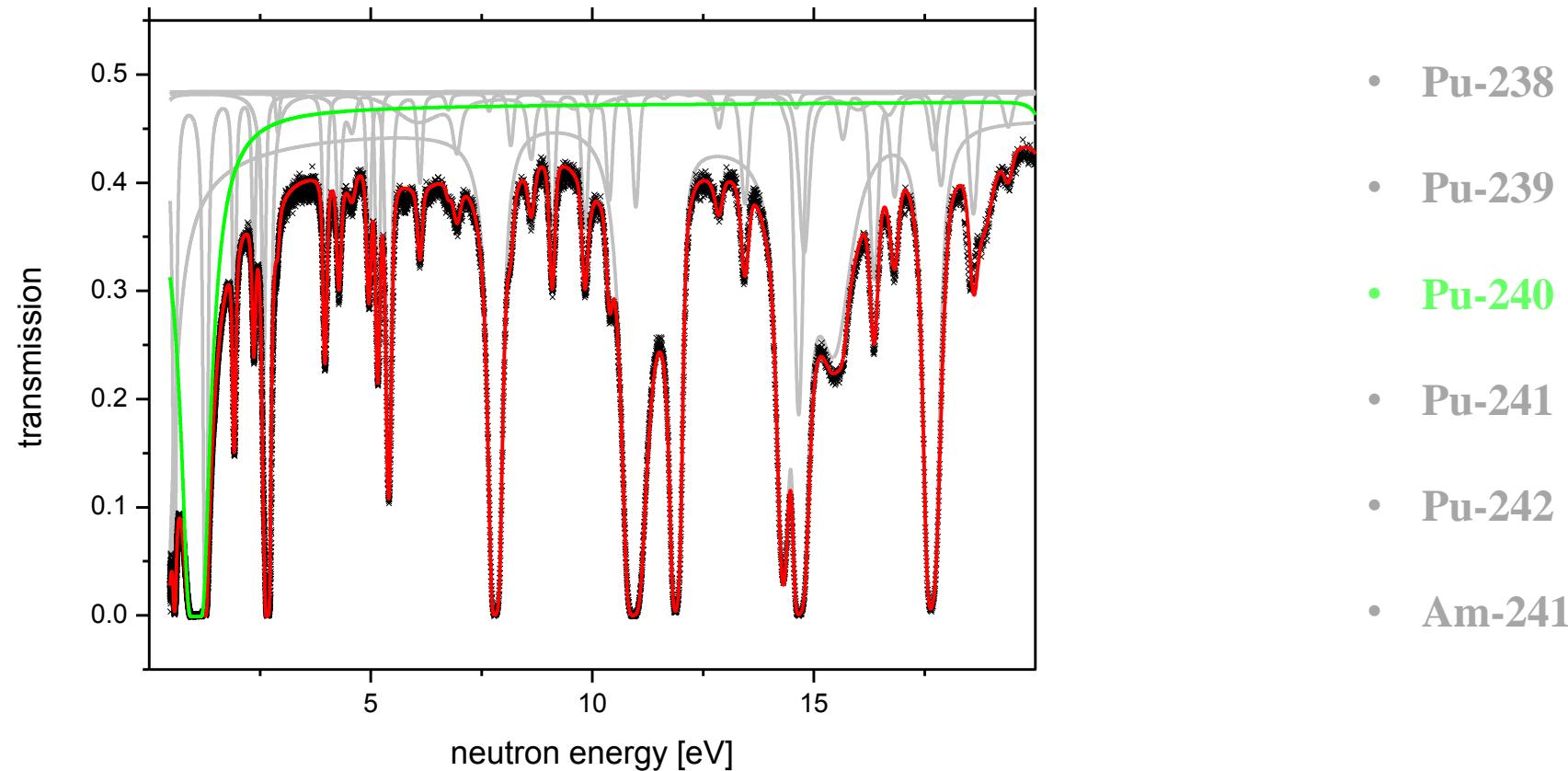
# CBNM standard: Pu - Contributions



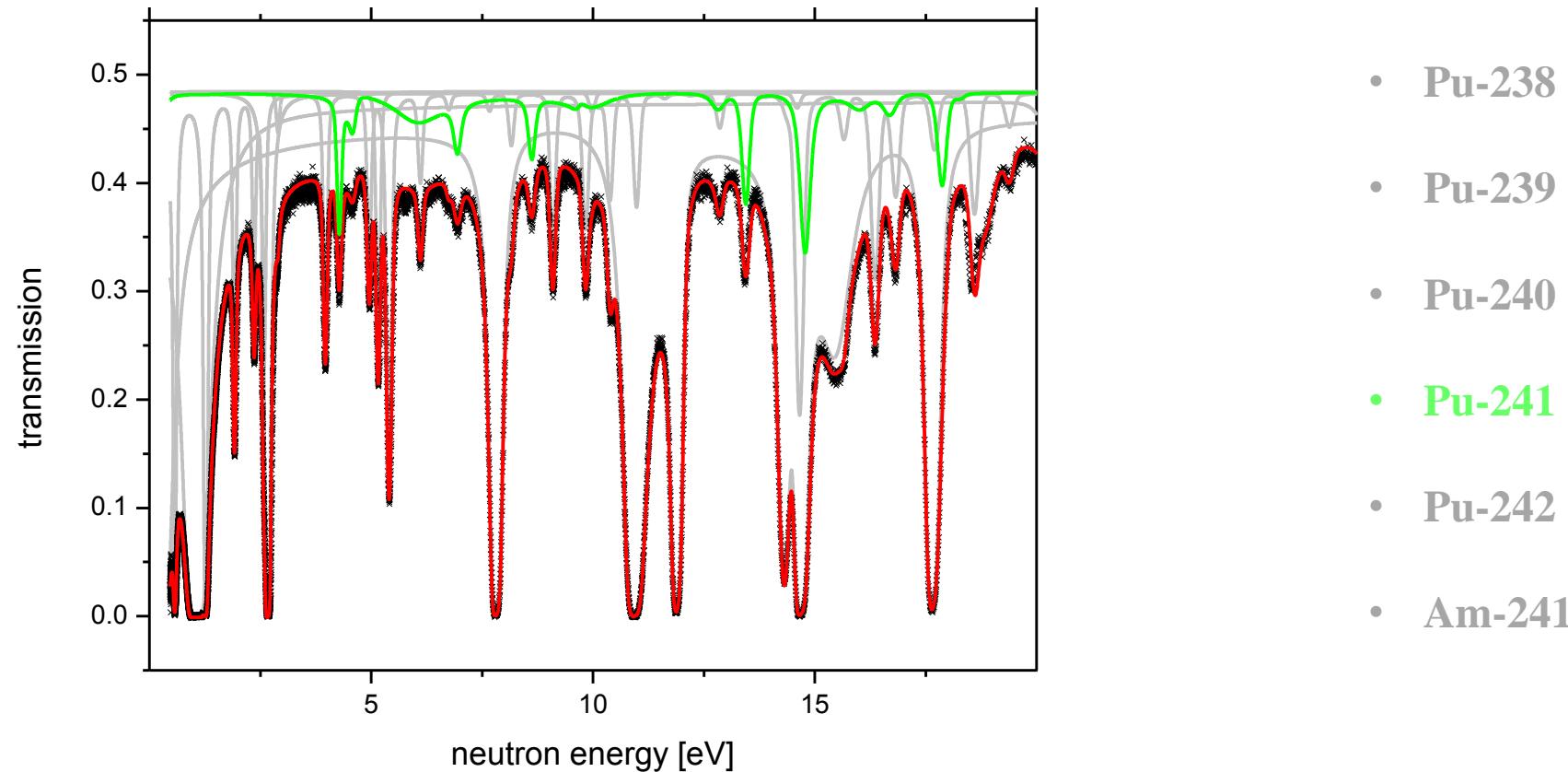
# CBNM standard: Pu - Contributions



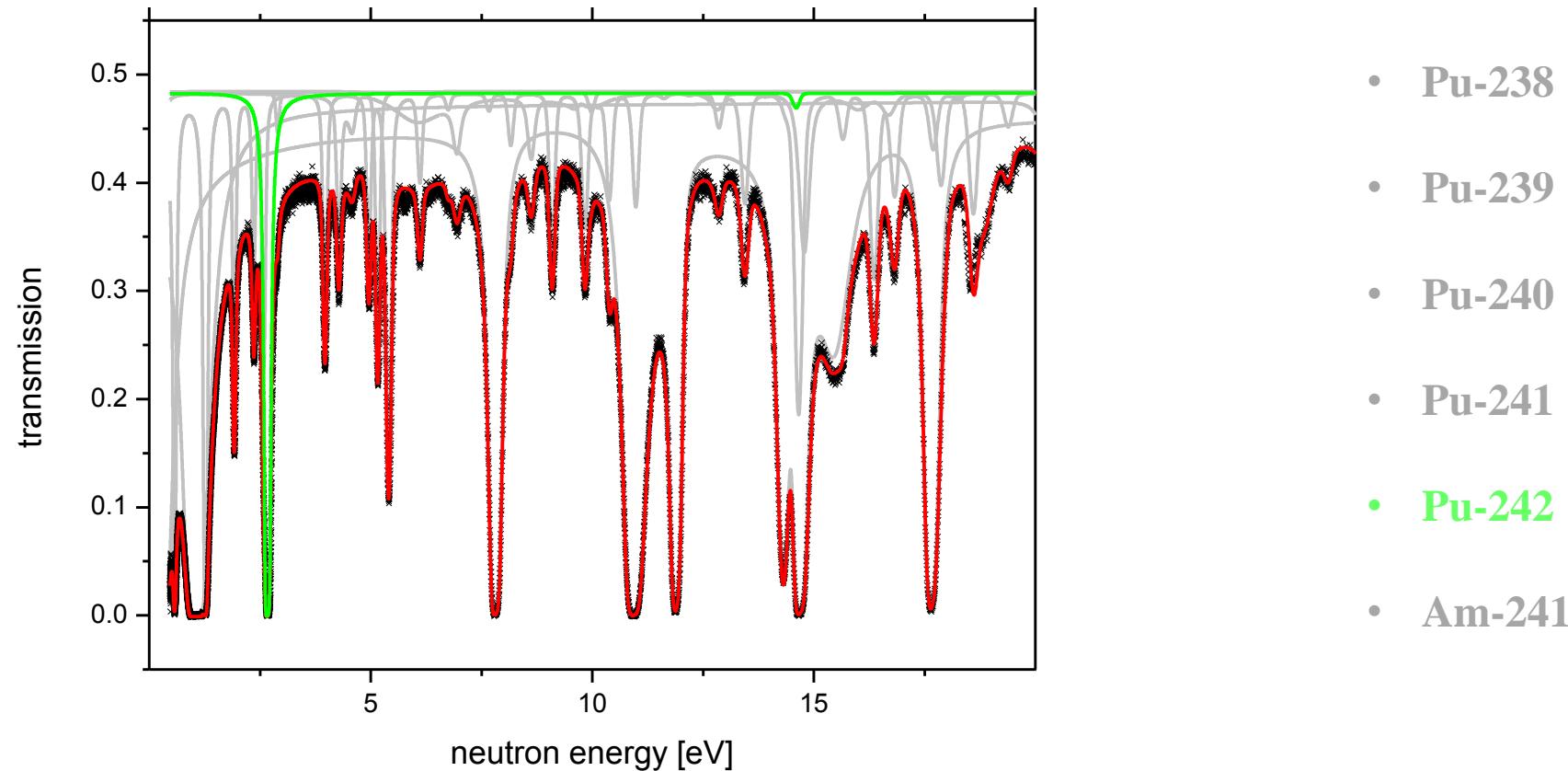
# CBNM standard: Pu - Contributions



# CBNM standard: Pu - Contributions

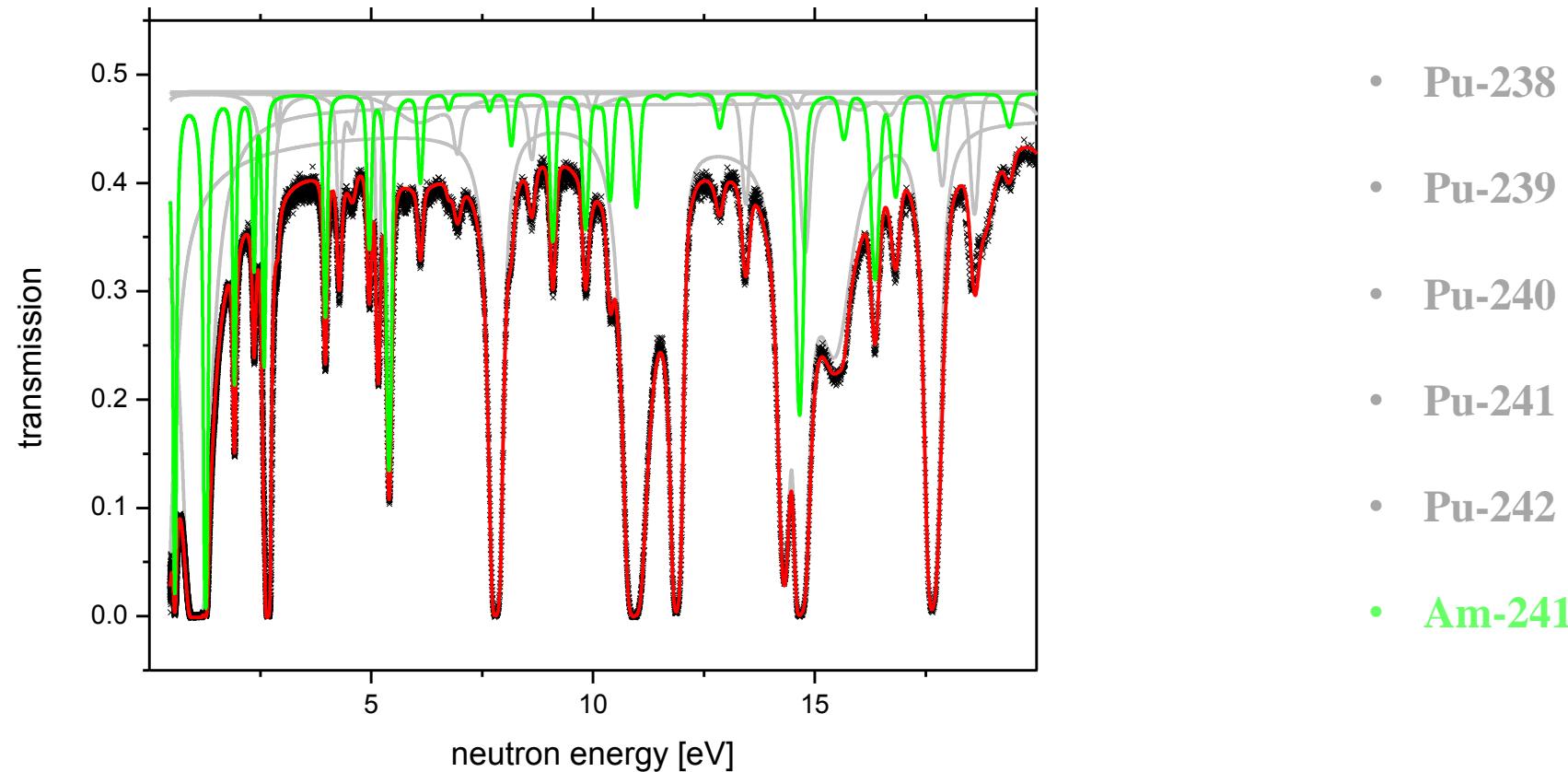


# CBNM standard: Pu - Contributions



- Pu-238
- Pu-239
- Pu-240
- Pu-241
- **Pu-242**
- Am-241

# CBNM standard: Pu - Contributions



# CBNM standard: Pu (JEFF3.3)

NRM2761			
	Certificate (at/b)	NRTA (at/b)	NRTA/Cert.
Pu-238	$(7.970 \pm 0.020)\text{E-}05$	$(7.600 \pm 0.180)\text{E-}05$	$0.954 \pm 0.023$
Pu-239	$(5.251 \pm 0.002)\text{E-}03$	$(5.217 \pm 0.005)\text{E-}03$	$0.993 \pm 0.001$
Pu-240	$(2.120 \pm 0.002)\text{E-}03$	$(2.211 \pm 0.002)\text{E-}03$	$1.043 \pm 0.001$
Pu-241	$(1.299 \pm 0.002)\text{E-}04$	$(1.318 \pm 0.007)\text{E-}04$	$1.014 \pm 0.005$
Pu-242	$(3.480 \pm 0.005)\text{E-}04$	$(3.601 \pm 0.007)\text{E-}04$	$1.035 \pm 0.002$
Am-241	$(5.285 \pm 0.013)\text{E-}04$	$(5.086 \pm 0.009)\text{E-}04$	$0.963 \pm 0.002$

NRTA uncertainties only due to counting statistics.

# CBNM standard: Pu

NRM2761			
	Certificate (at/b)	NRTA (at/b)	NRTA/Cert.
Pu-238	$(7.970 \pm 0.020)\text{E-}05$	$(7.600 \pm 0.180)\text{E-}05$	$0.954 \pm 0.023$
Pu-239	$(5.251 \pm 0.002)\text{E-}03$	$(5.217 \pm 0.005)\text{E-}03$	$0.993 \pm 0.001$
Pu-240	$(2.120 \pm 0.002)\text{E-}03$	$(2.211 \pm 0.002)\text{E-}03$	$1.043 \pm 0.001$
Pu-241	$(1.299 \pm 0.002)\text{E-}04$	$(1.318 \pm 0.007)\text{E-}04$	$1.014 \pm 0.005$
Pu-242	$(3.480 \pm 0.005)\text{E-}04$	$(3.601 \pm 0.007)\text{E-}04$	$1.035 \pm 0.002$
Am-241 (ENDF/B-VIII.0)	$(5.285 \pm 0.013)\text{E-}04$	$(6.326 \pm 0.009)\text{E-}04$	$1.197 \pm 0.002$

NRTA uncertainties only due to counting statistics.

- Method
  - Measurement principle
  - Testing
- Testing of Actinides (CBRN standards)
- **MINVERE samples**
  - Model development

# Minerve samples

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

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

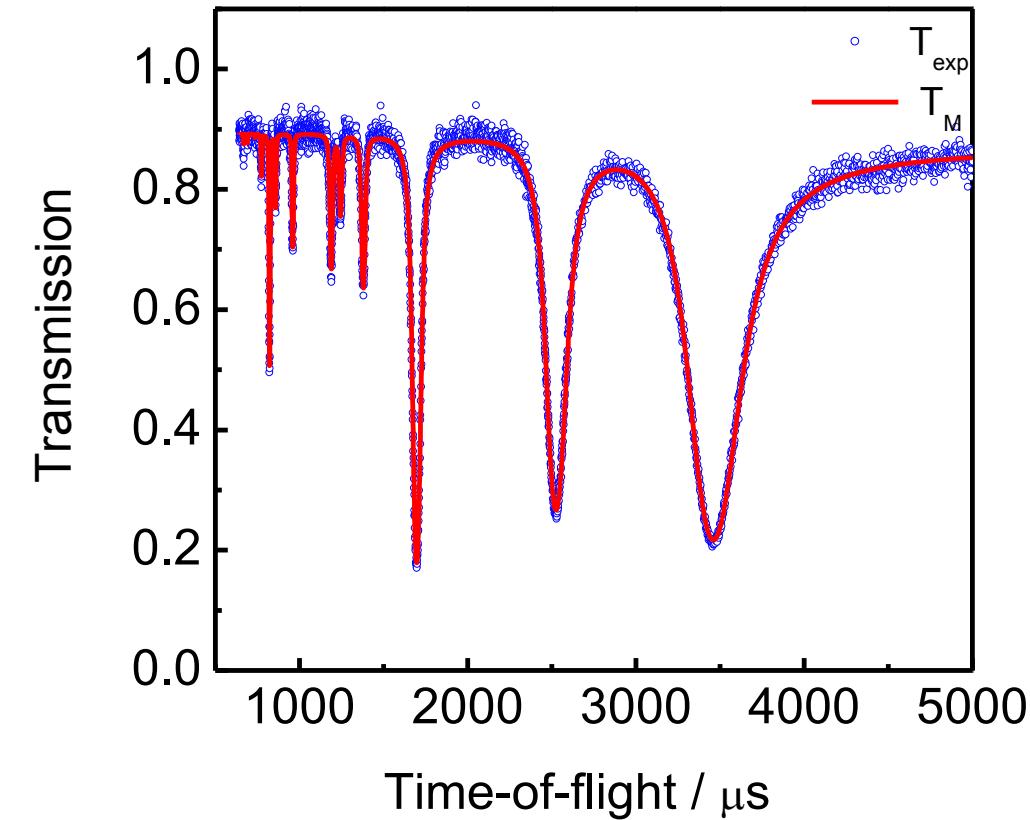
Resonance Shape Analysis: REFIT

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

$$T_M(t) = \int R(t, E) T(E) dE$$

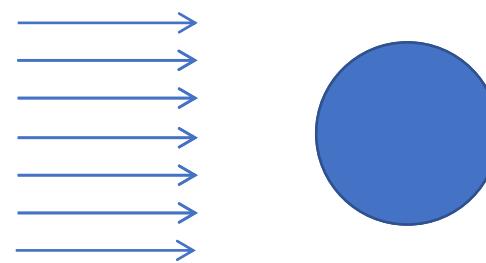
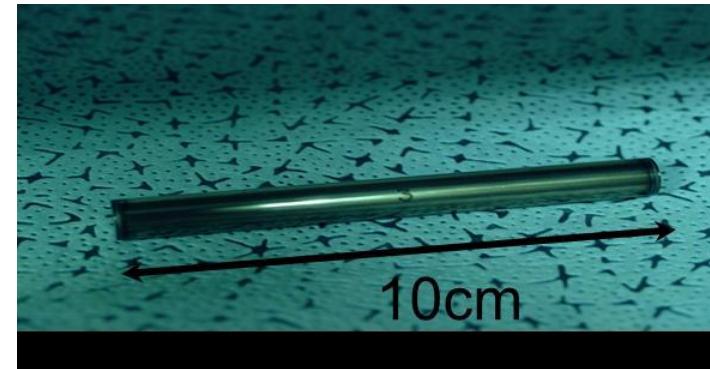
$$T(E) = e^{-n \sigma_{\text{tot}}}$$

n : areal density  
total number of nuclei per unit area



# Minerve samples

$$T(E) \neq e^{-n\sigma_{tot}}$$



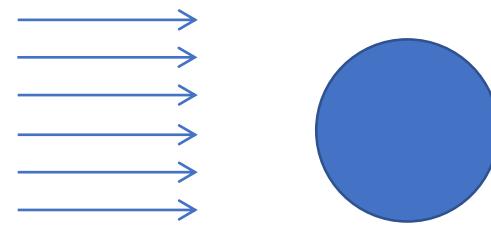
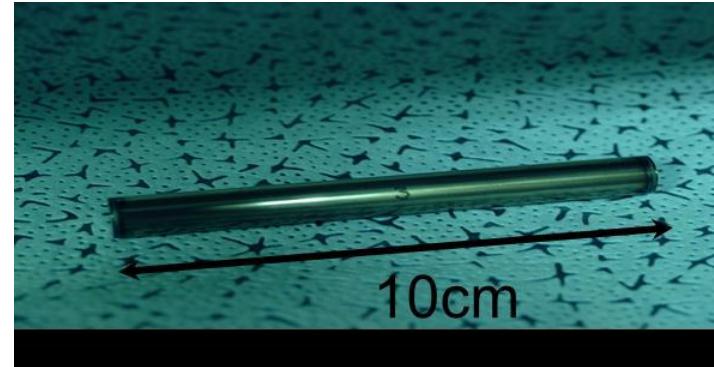
# Minerve samples

$$T(E) = e^{-n\sigma_{tot}}$$



$$T(E) = f + (1 - f) \int p(s) e^{-\rho s \sigma_{tot}(E)} ds$$

- Chord length distribution
- Hole fraction
- Flux profile?



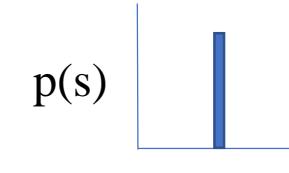
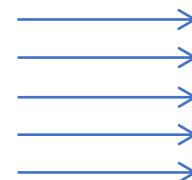
# Testing for Minerve samples

$$T(E) = e^{-n\sigma_{tot}}$$

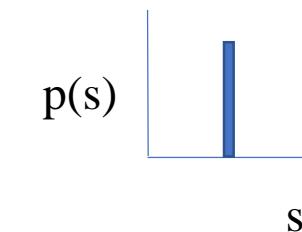
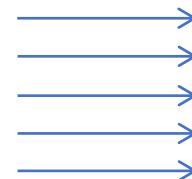


$$T(E) = f + (1 - f) \int p(s) e^{-\rho s \sigma_{tot}(E)} ds$$

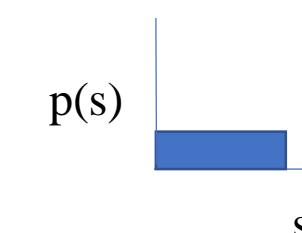
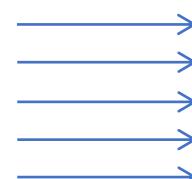
- Chord length distribution
- Hole fraction
- Flux profile?



$$f = 0$$

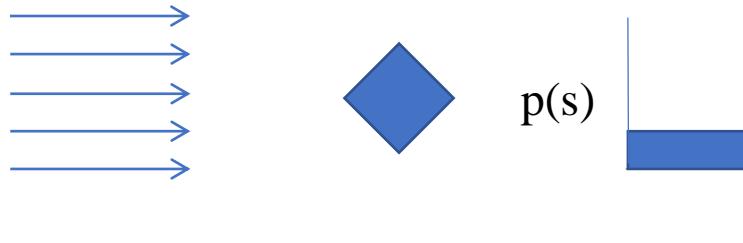


$$f \neq 0$$

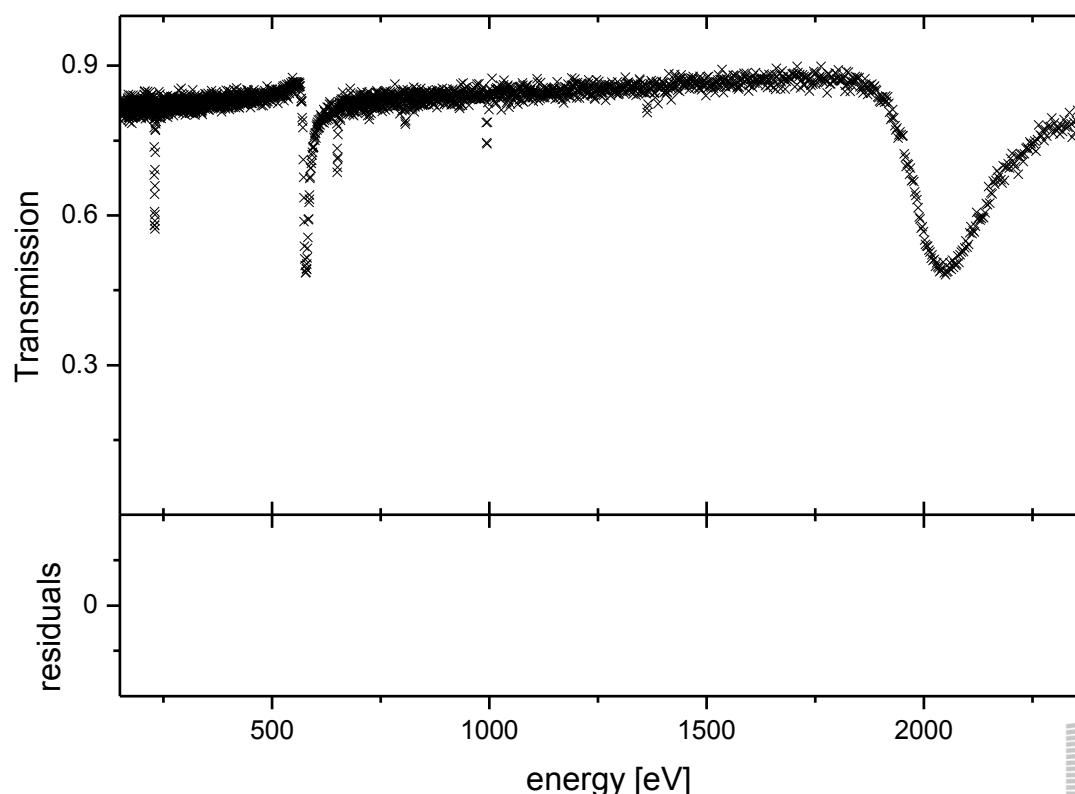


$$f \neq 0$$

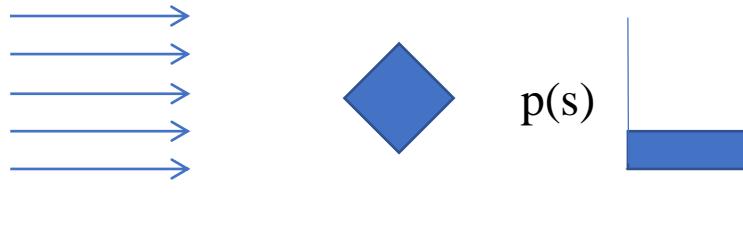
# Rod: Cu



$$f \neq 0$$

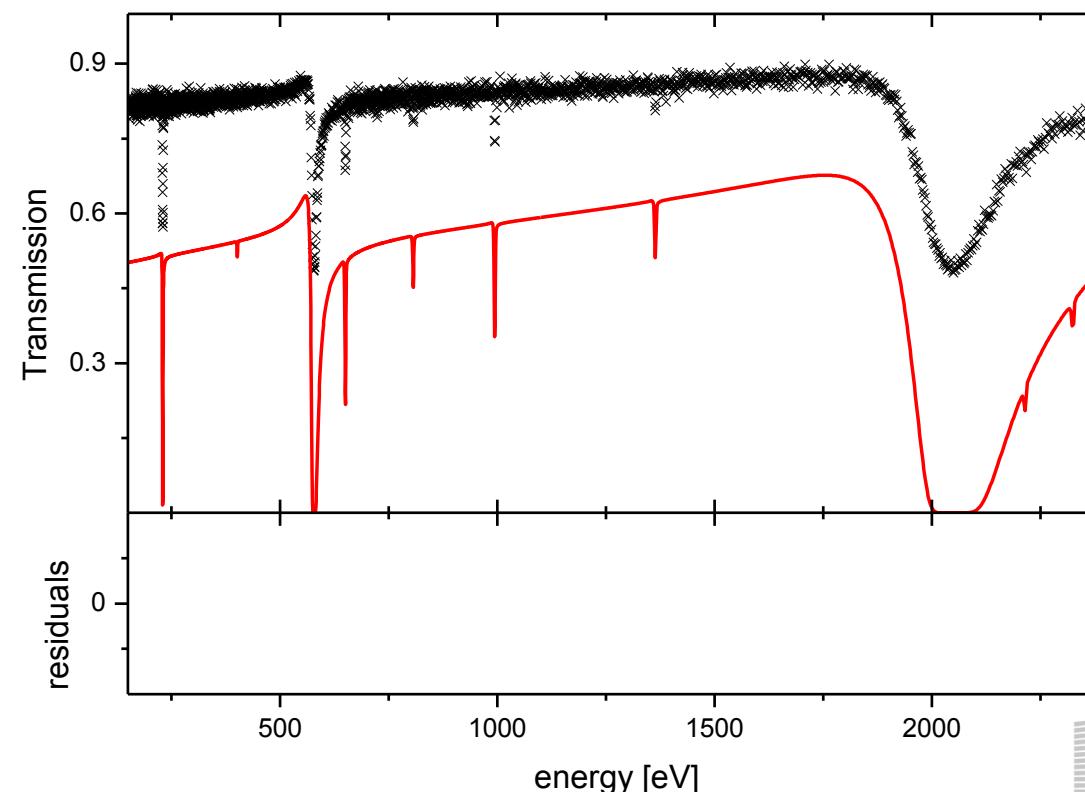


# Rod: Cu

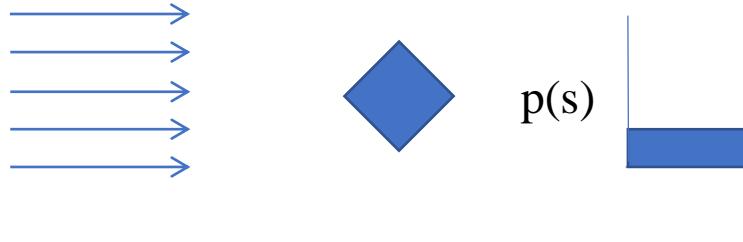


$$f \neq 0$$

homogenous and  $f = 0$



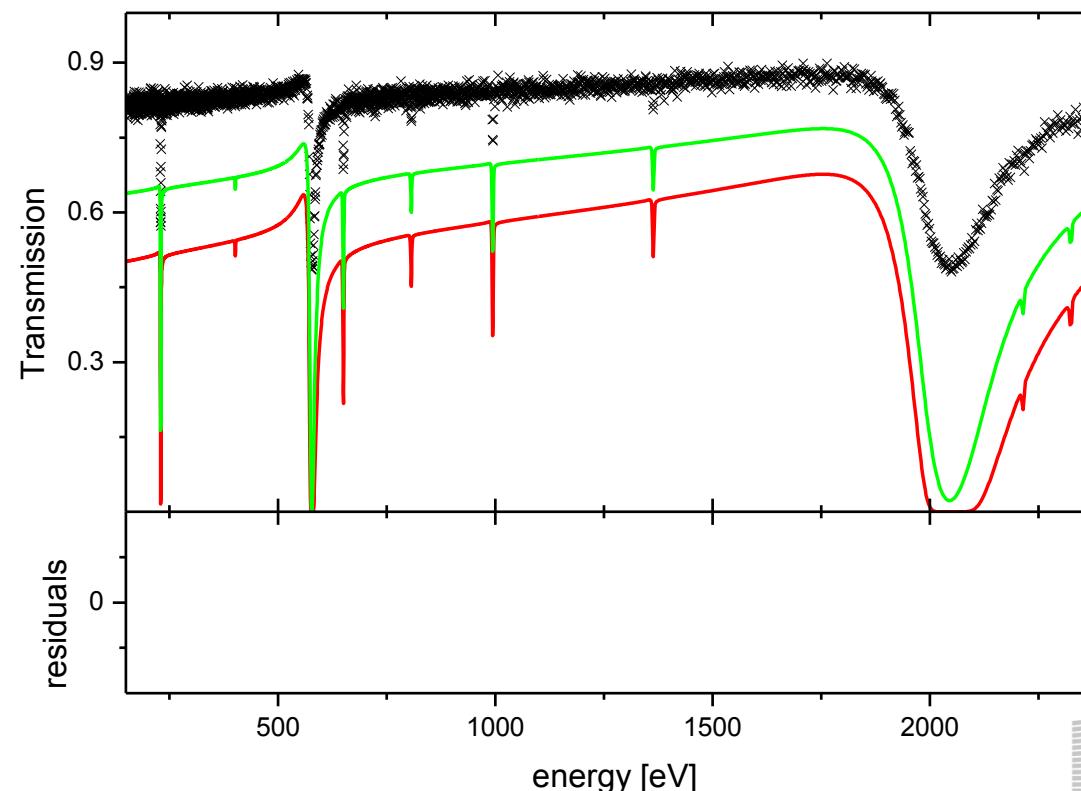
# Rod: Cu



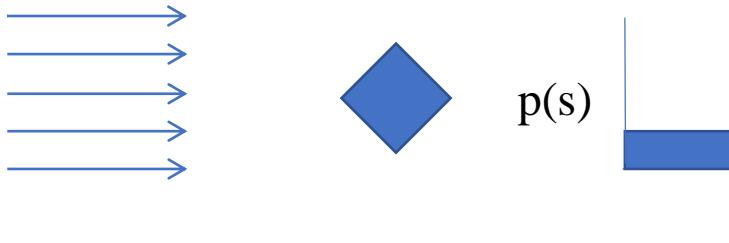
homogenous and  $f = 0$

45 deg rotated and  $f=0$

$$f \neq 0$$



# Rod: Cu

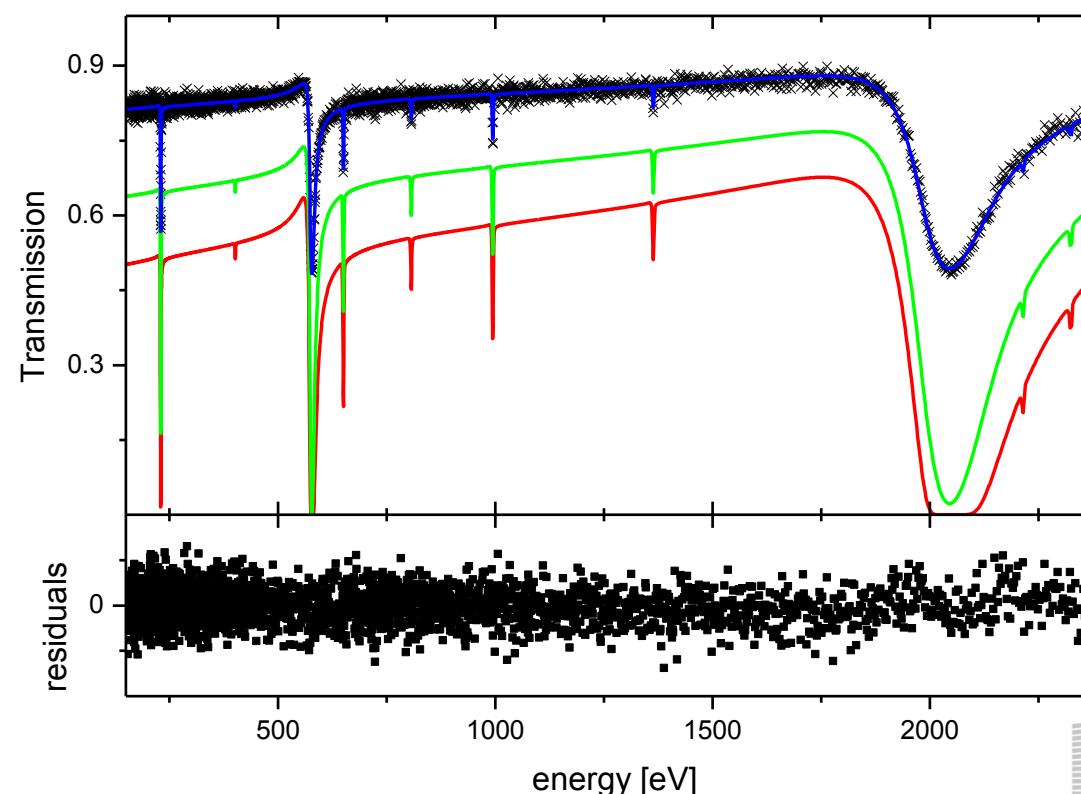


homogenous and  $f = 0$

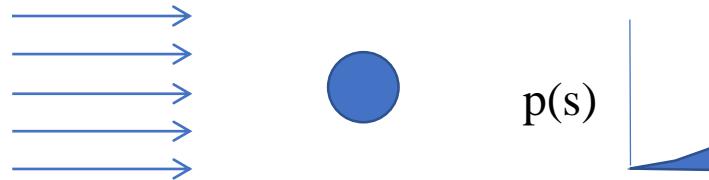
45 deg rotated and  $f=0$

45 deg rotated and  $f\neq 0$

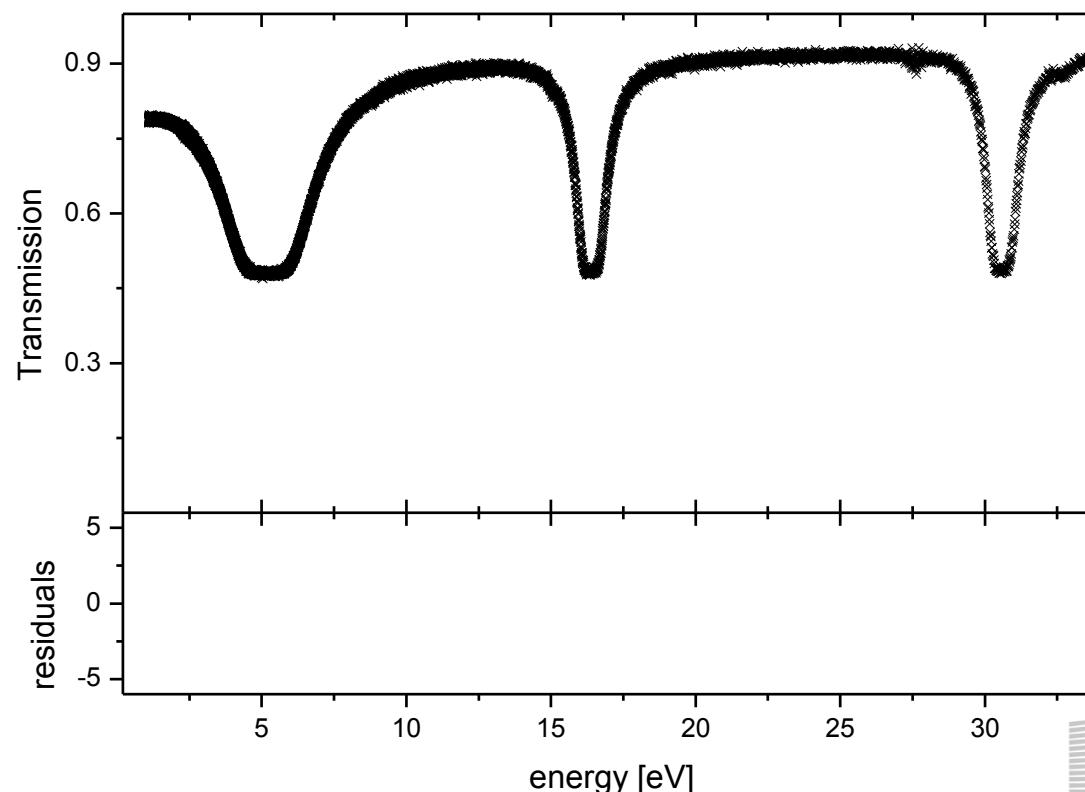
$$f \neq 0$$



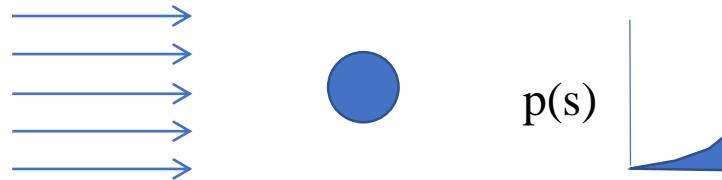
# Pellet: Ag



$$f \neq 0$$

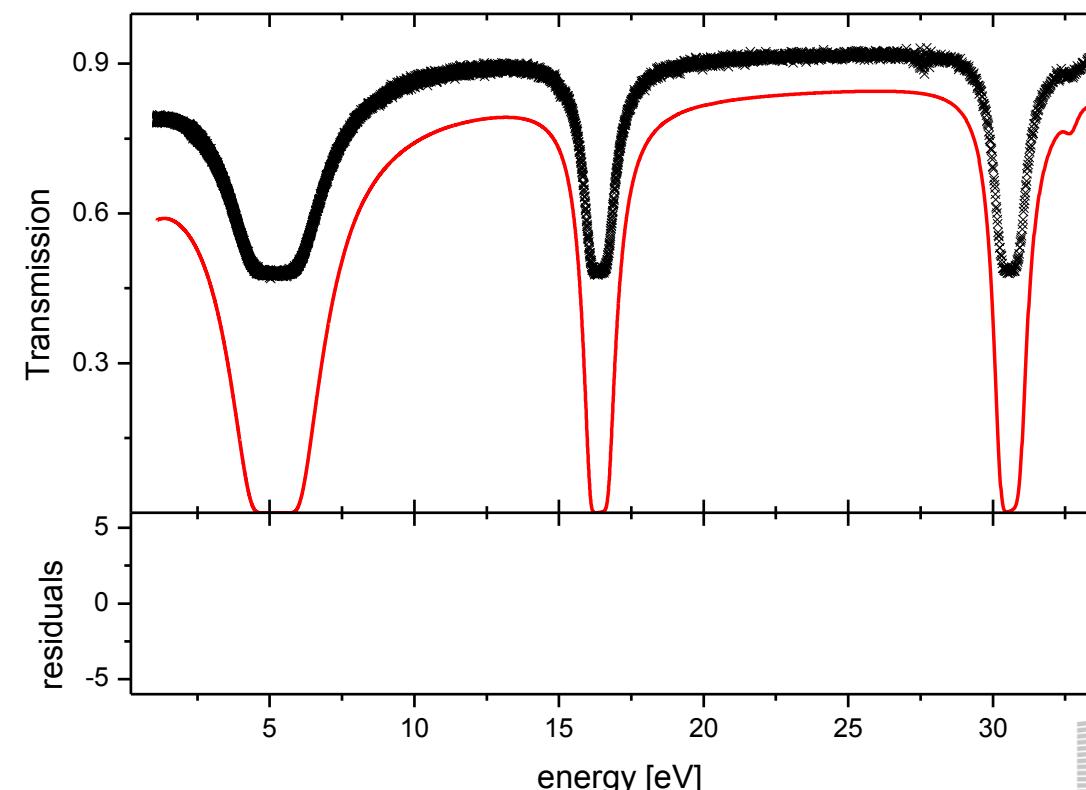


# Pellet: Ag

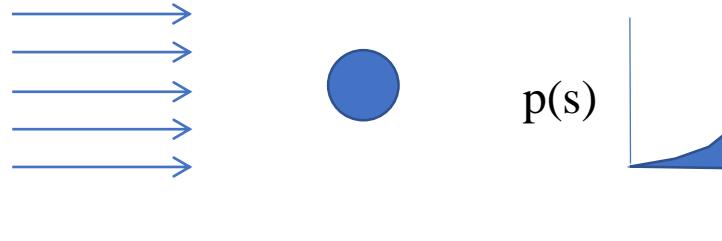


$$f \neq 0$$

homogenous and  $f = 0$



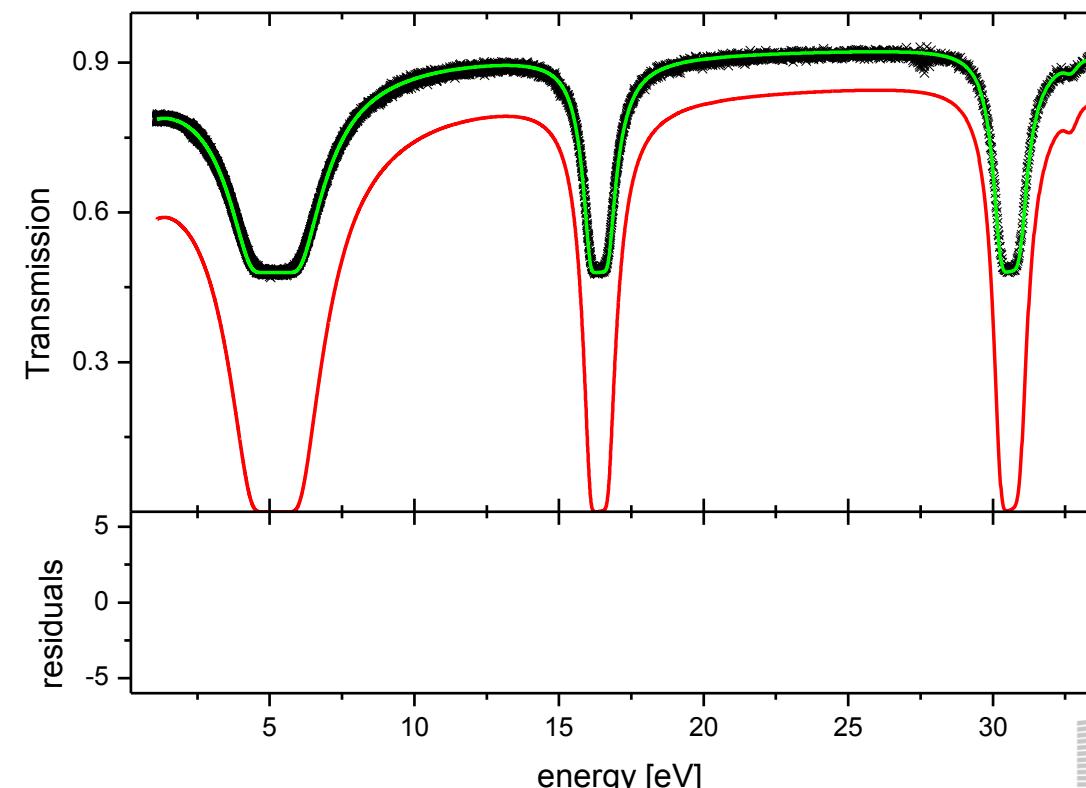
# Pellet: Ag



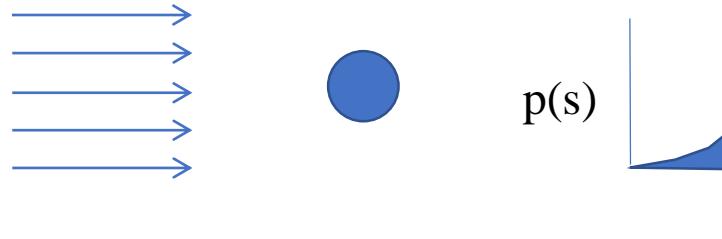
$$f \neq 0$$

homogenous and  $f = 0$

homogenous and  $f \neq 0$



# Pellet: Ag

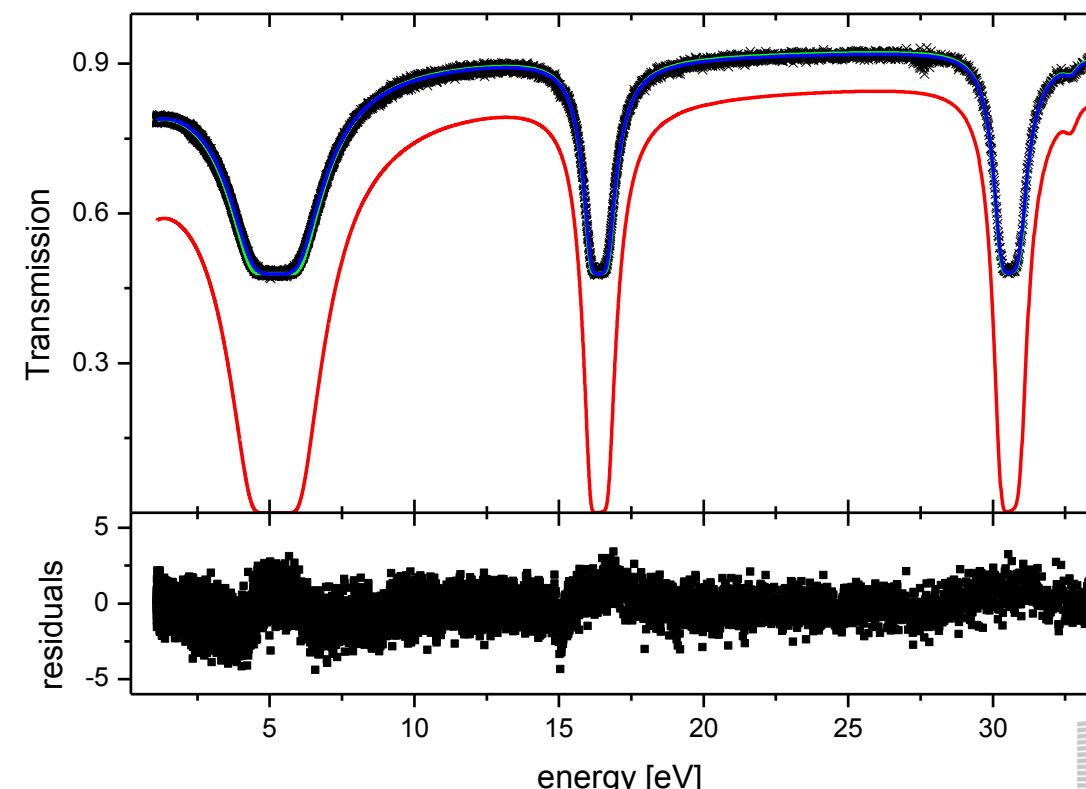


$$f \neq 0$$

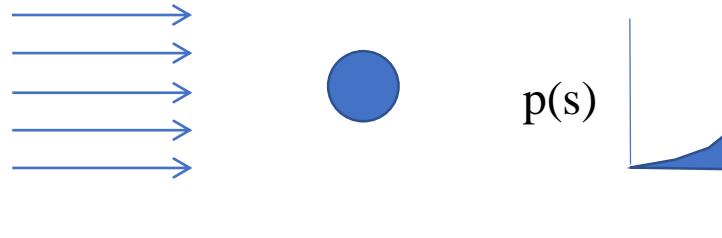
homogenous and  $f = 0$

homogenous and  $f \neq 0$

Cylinder and  $f \neq 0$



# Pellet: Ag

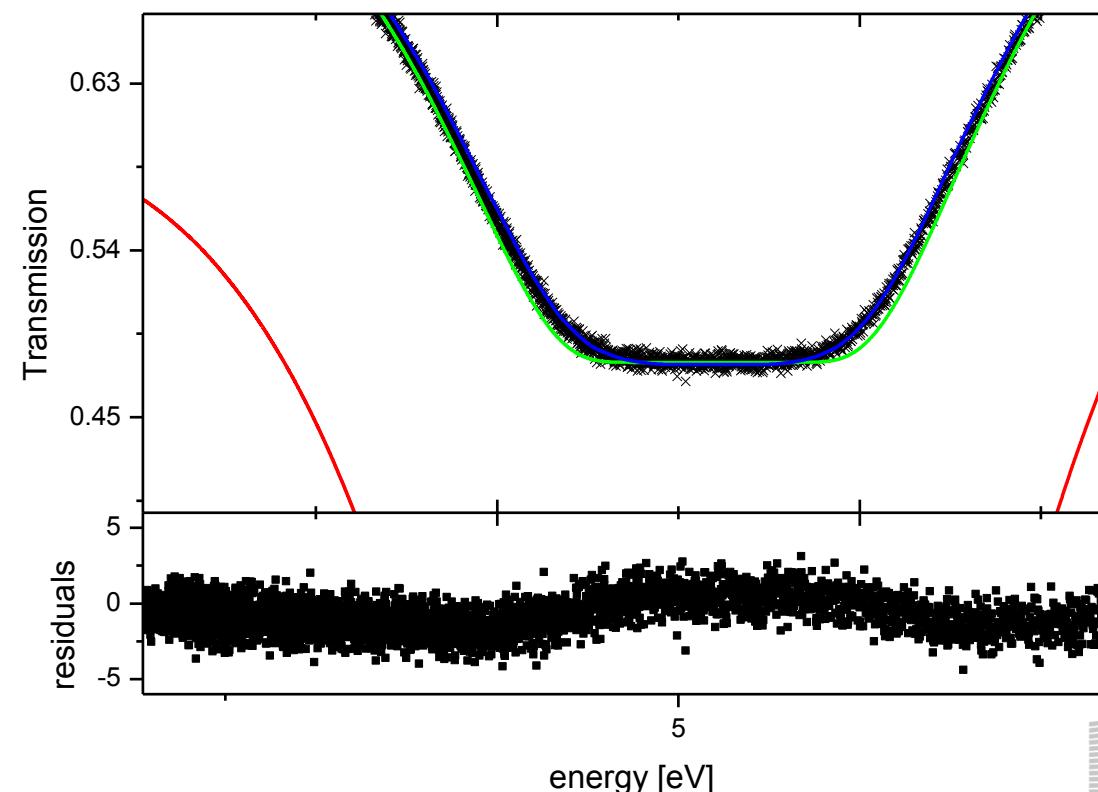


$$f \neq 0$$

homogenous and  $f = 0$

homogenous and  $f \neq 0$

Cylinder and  $f \neq 0$



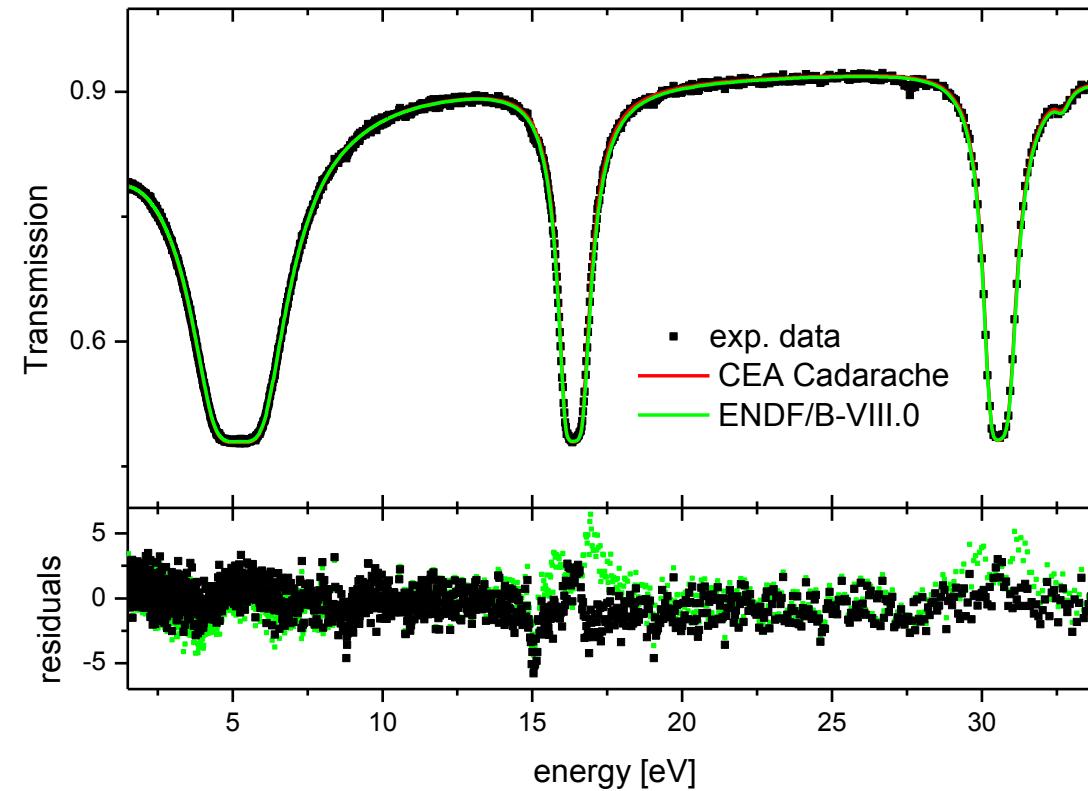
# Pellet: Ag

CEA/Cadarache

Transmission and capture measurements

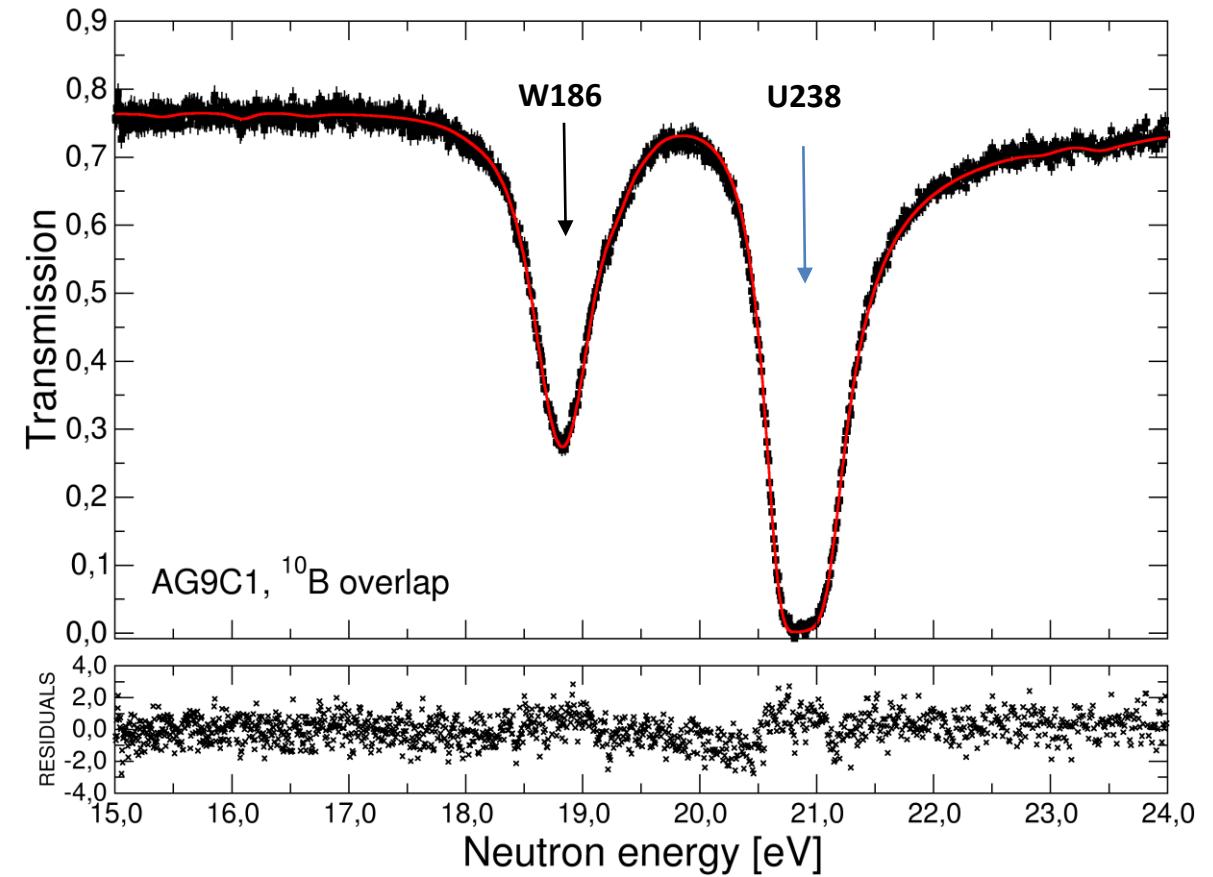
New Ag resonance parameters

Testing on new parameters on (pure) Ag pellet



# Minerve pellet: Ag

Transmission of a MINERVE sample ( $^{109}\text{Ag}$  in a  $\text{UO}_2$  matrix) with a strong Tungsten contamination ( $^{186}\text{W}$ )



# General Remarks

EUFRAT:

open access to facilities at JRC GEEL

ENEN+:

funding scheme for training (bachelor, master, PhD, postdoc )



# Any questions?

You can find me at [stefan.kopecky@ec.europa.eu](mailto:stefan.kopecky@ec.europa.eu)