EUROPEAN COMMISSION
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Neutron-induced reaction cross section studies at GELINA

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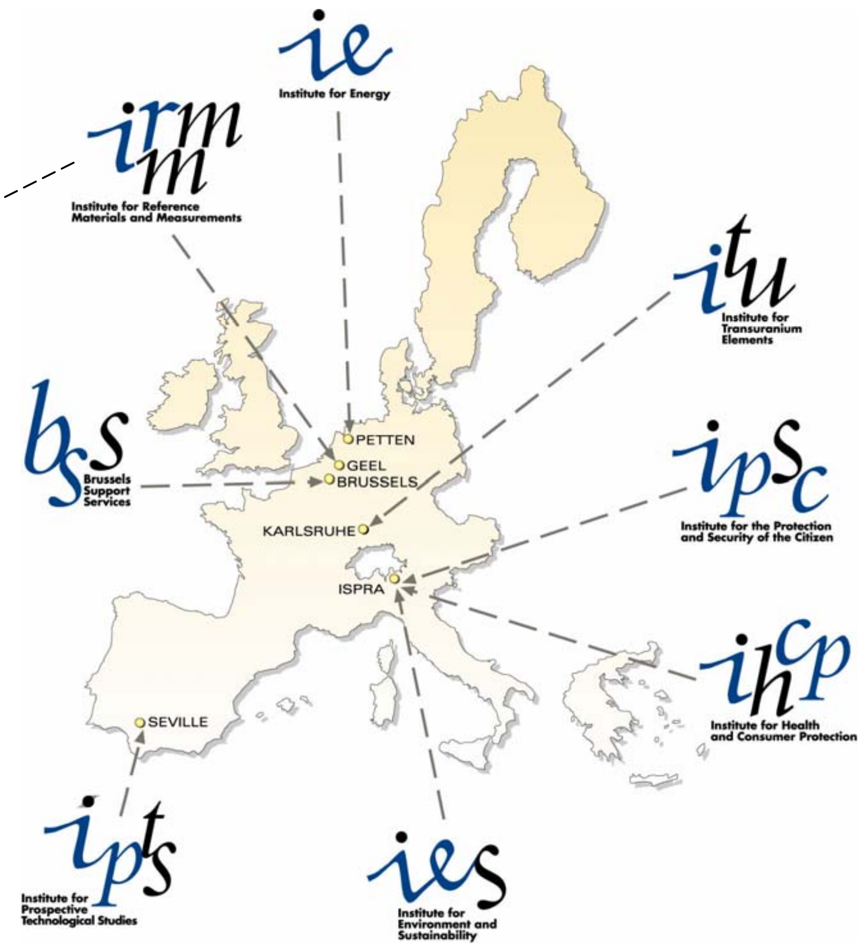
irmm

EC - JRC - IRMM

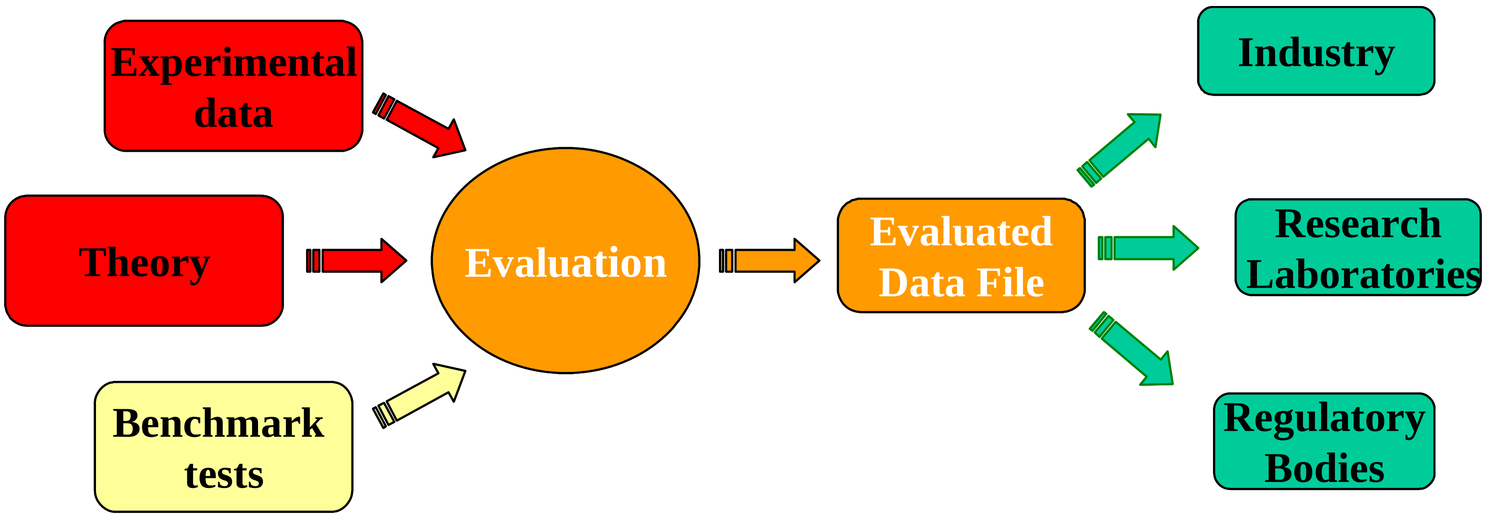
Institute for Reference Materials and Measurements



The Mission of the Neutron Physics Unit

Provide European <u>safety authorities</u> and <u>industry</u> with <u>neutron reaction data</u> for:

- **The *safety* assessment of nuclear installations and the nuclear fuel cycle**
- **The *feasibility* study and *development* of waste transmutation facilities and innovative reactor systems**



⇒ GELINA and VdG

7 MV Van de Graaff accelerator

- Single-user facility
- 6 different beam lines
- 100h/w
- 0.1 - 10 & 13-21 MeV
- Li(p,n), T(p,n), D(d,n), T(d,n)

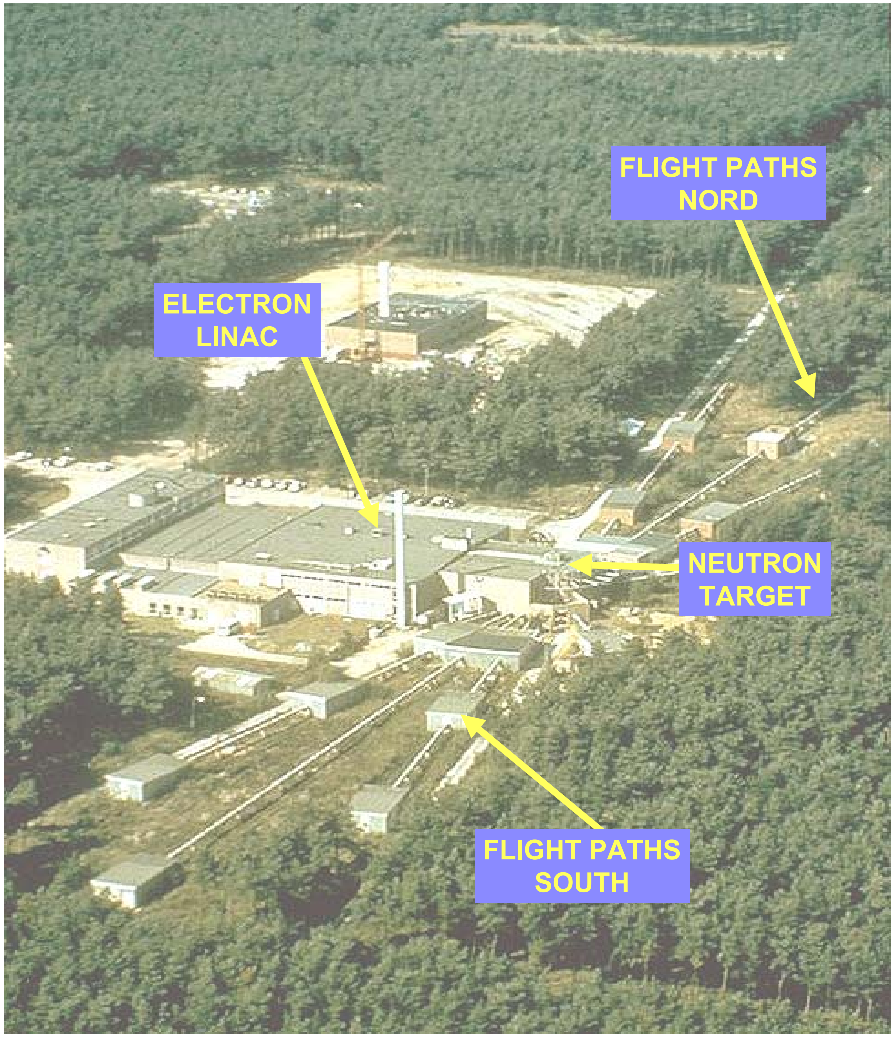
Measurement types

- Fission
- Activation measurements
  n → light charged particles
- Flux (BIPM)
- Inelastic scattering
- Calibration of detectors

GELINA TOF-facility

- GELINA – TOF Facility
- Measurement stations (capabilities)
- Research Activities
- Cross Section Measurements for Applications

GELINA

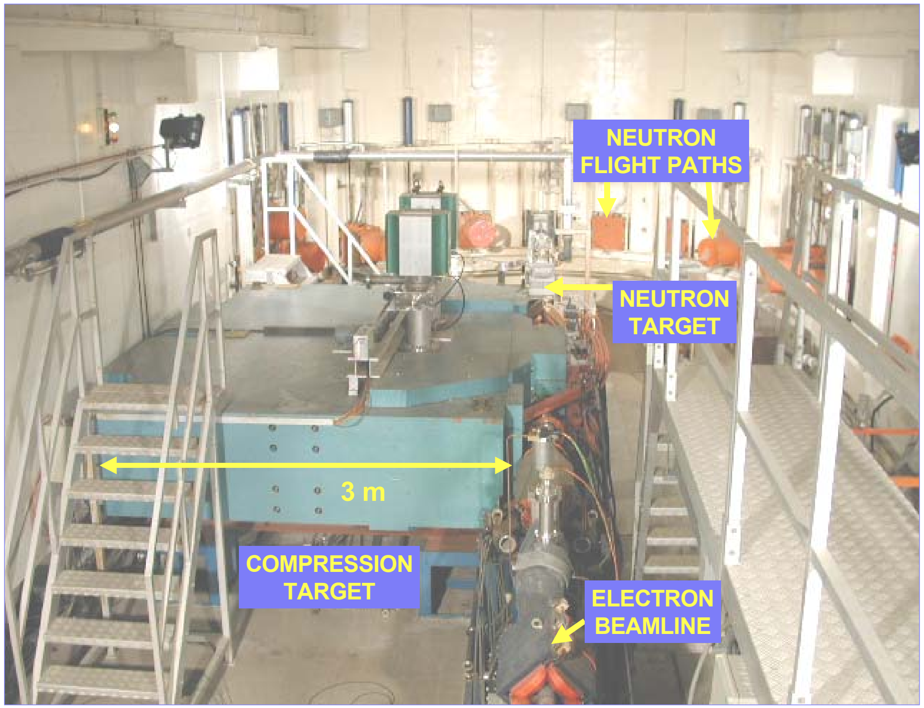


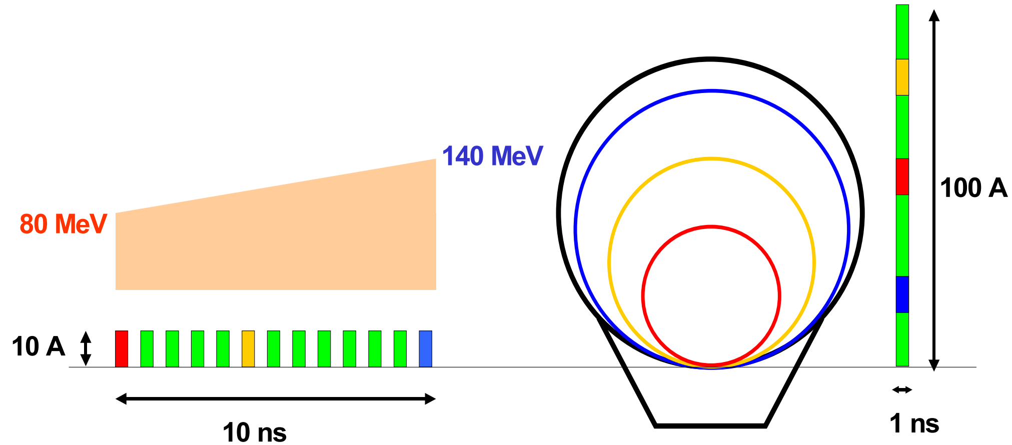
- **Time-of-flight facility**
- **Pulsed white neutron source**

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

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

Compression Magnet





$$B\rho = \frac{p}{q}; \; E \cong pc; \; q = e$$

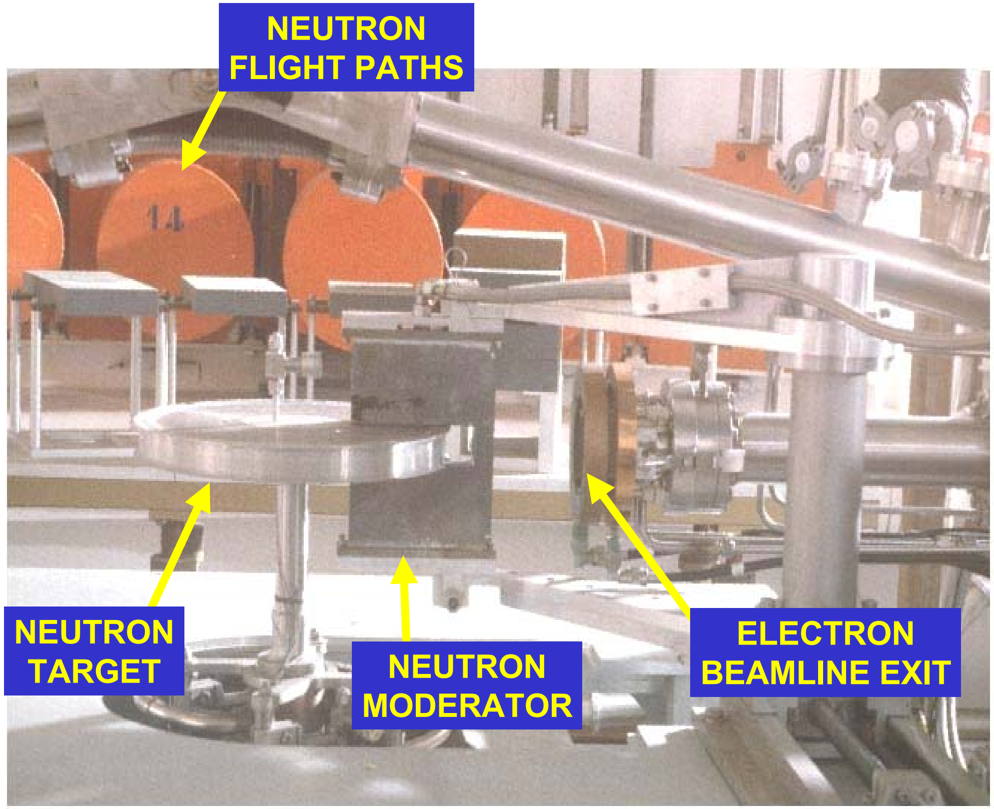
$$\Rightarrow \quad \rho = \frac{1}{B}\frac{E}{qc}$$

$$\Rightarrow \quad B = \frac{2\pi}{qc^2}\frac{\Delta E}{\Delta\tau}$$

ΔE = 60 MeV
$\Delta\tau$ = 10 ns

➔ compressed pulse length ~ 1 ns

Neutron Production

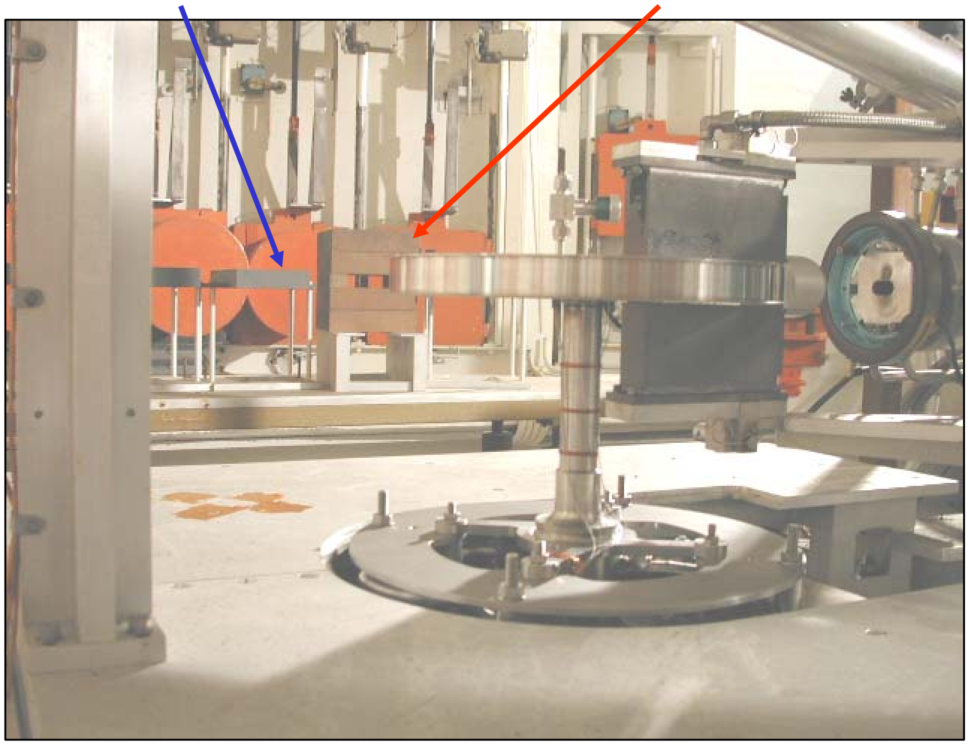


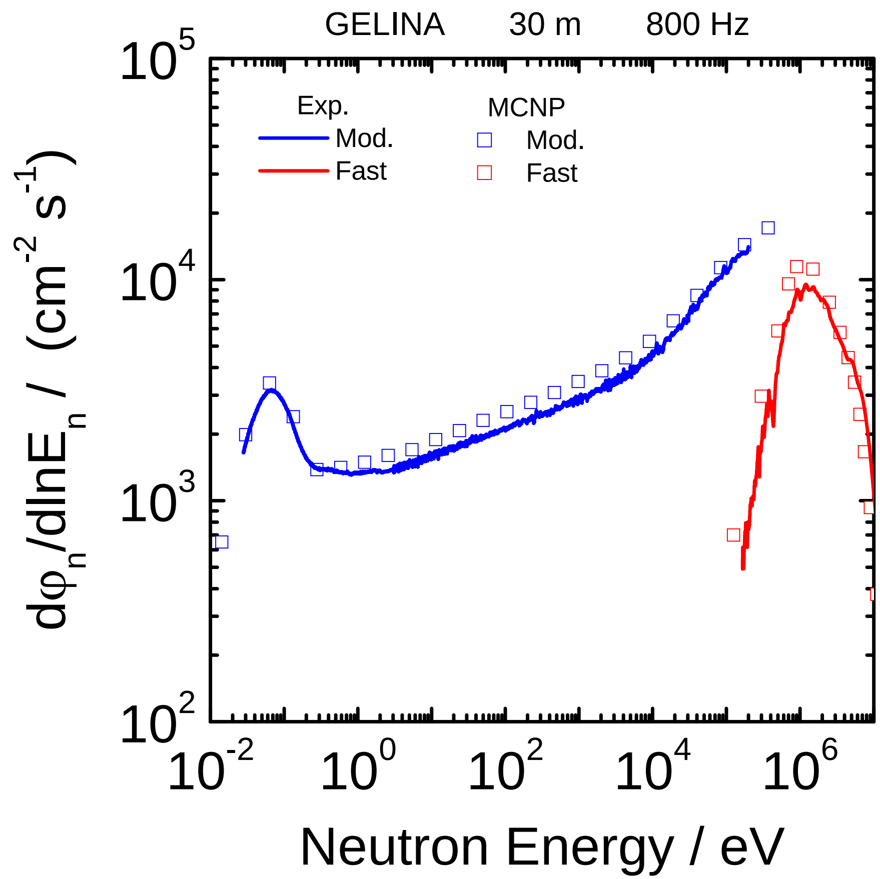
- e^- accelerated to $E_{e-,max} \approx 140$ MeV
- (e^-, γ) Bremsstrahlung in U-target (rotating & cooled with liquied Hg)
- (γ , n) , (γ , f) in U-target
- Low energy neutrons by water moderator in Be-canning

Neutron Production

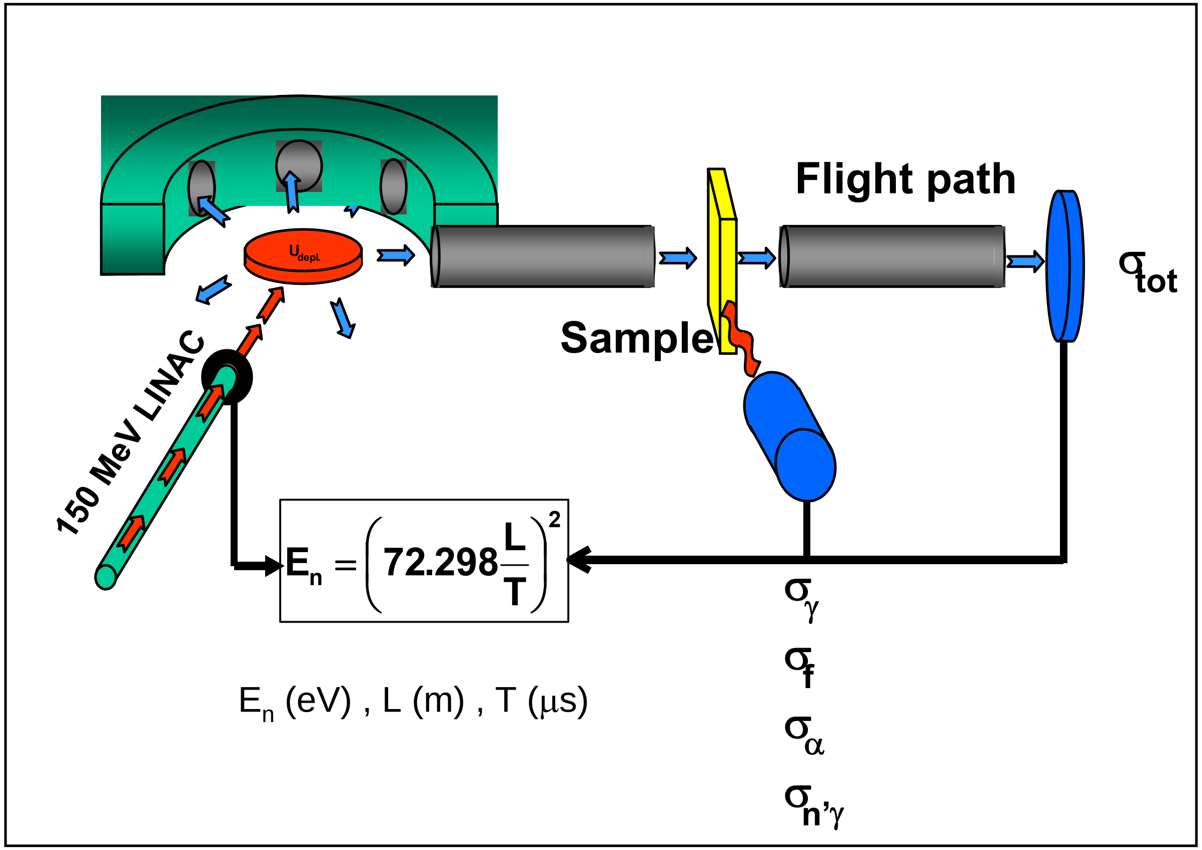
SHIELDING MODERATED SPECTRUM

SHIELDING FAST SPECTRUM





GELINA and ORELA TOF-Facilities for High Resolution Total and Partial Cross-Sections



- **Neutron Flux** ⇒ **L** ↘

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

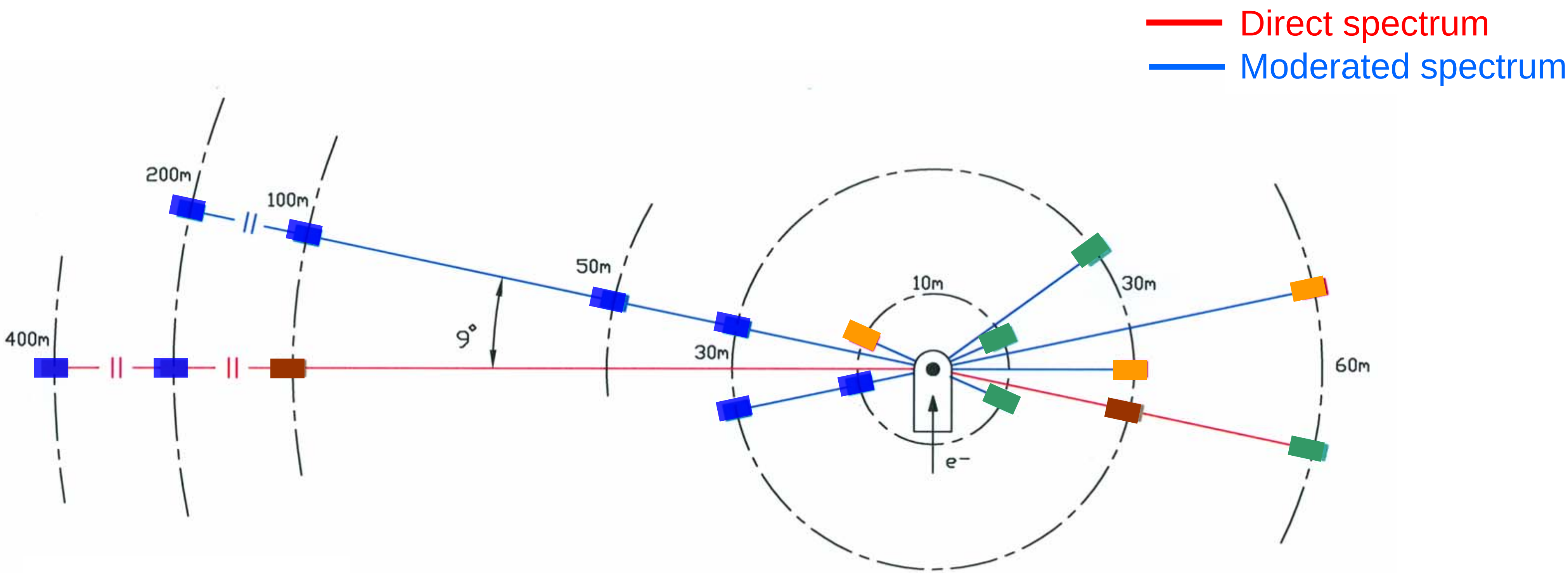
- **Resolution** ⇒ **L** ↗

$$\frac{\Delta E_n}{E_n} = \frac{1}{L}\sqrt{\frac{E_n \Delta T^2}{\alpha} + \Delta L^2}$$

We need to adapt the flight path length and operation conditions

to the required resolution and neutron flux

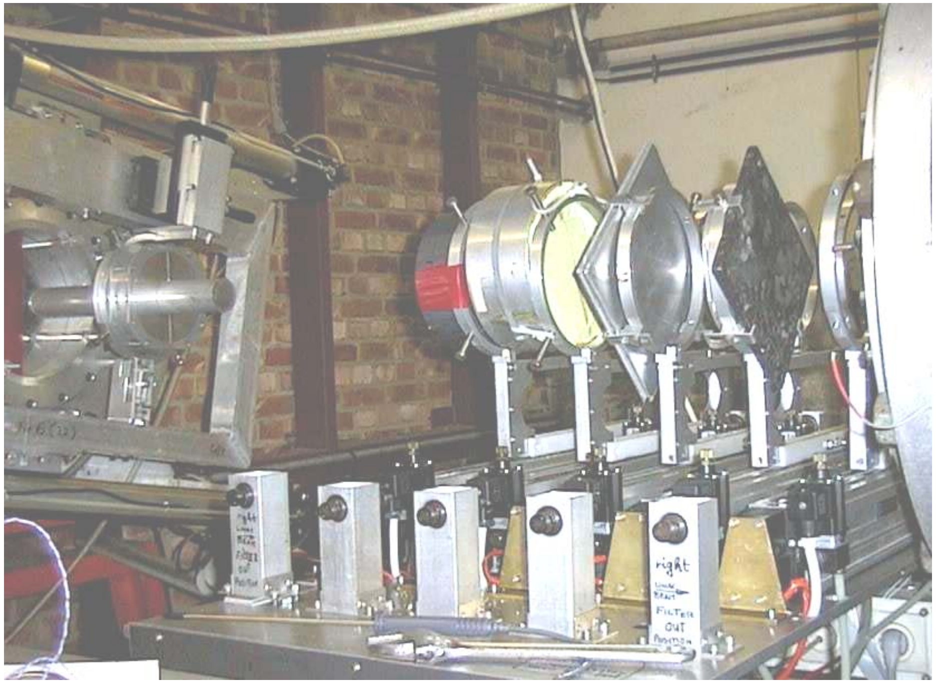
Measurement Stations



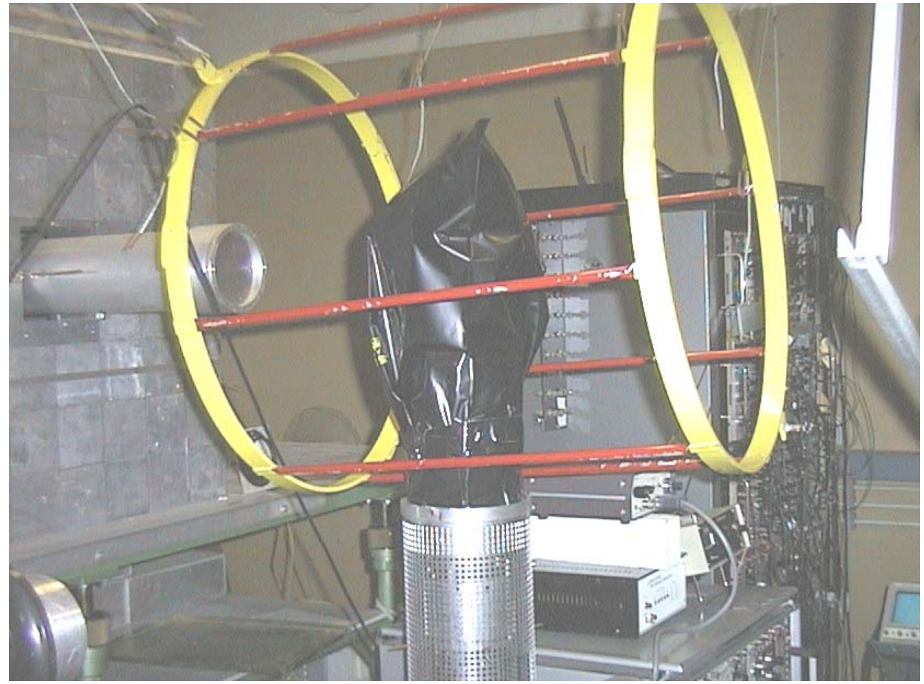
(orange)	(n,γ)	NIM, j.nima.2007.03.034
(blue)	(n,tot)	NP A 773, 173 (2006)
(green)	(n,f) and (n,cp)	NSE 156, 211 (2007)
(brown)	(n,n'γ)	NP A 786, 1 (2007)

Transmission Measurements

Sample & Background Filters



Detector



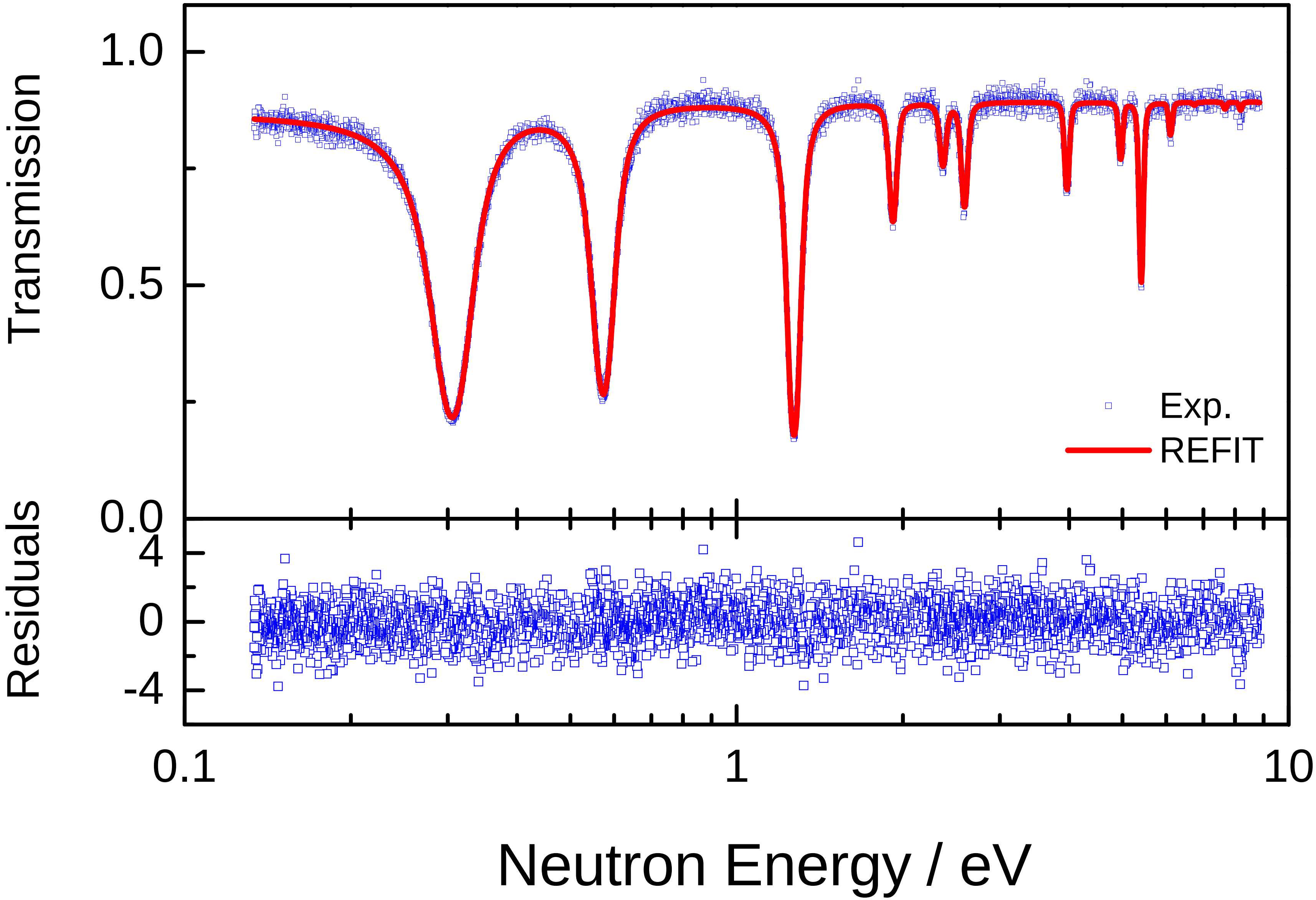
Detector stations
Moderated : L = 30 m, 50 m, (100 m, 200 m)
Fast : L = 400 m

Low energy : ^{6}**Li(n,t)**α **Li-glass**

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

$$T = \frac{C_{in}}{C_{out}} \cong e^{-n\sigma_{tot}}$$

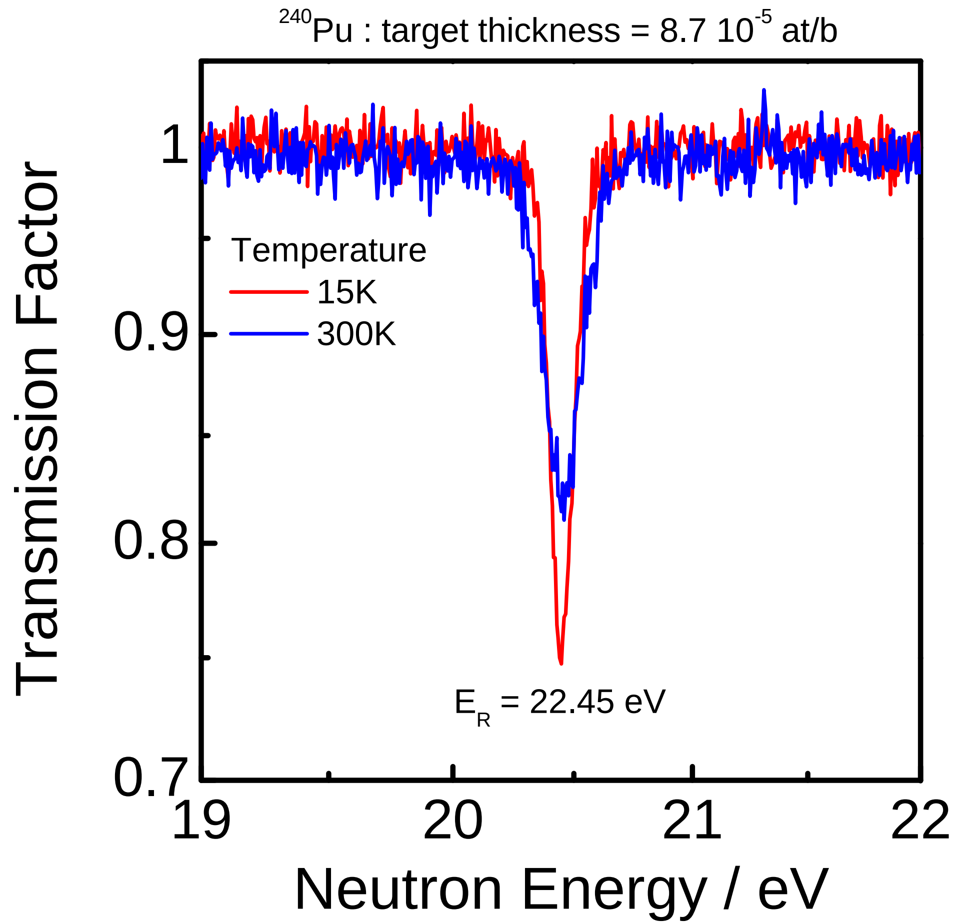
$^{241}Am(n,tot)$ at 30 m



Doppler Measurements

Detector station at : L = 30m

Temperatures from 10 K - 300 K



(n,f) and (n, cp) Measurements at 10 m and 30 m

- **Flux $^{10}B(n,\alpha)$ or $^{235}U(n,f)$**

$$C_\varphi = \varepsilon_\varphi n_\varphi \sigma_\varphi A_\varphi \varphi_\varphi$$

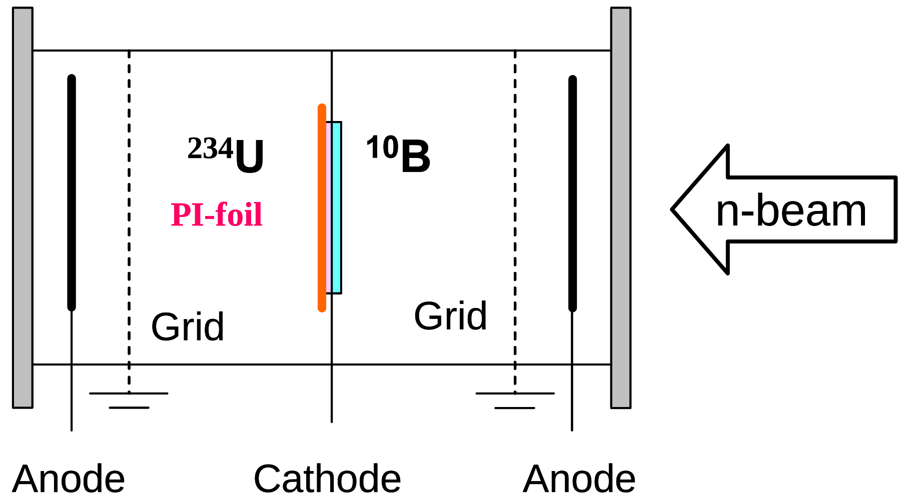
- **Fission**

$$C_f = \varepsilon_f n_f \sigma_f A_f \varphi_f$$

+ Back to back target : $A_\varphi = A_f$

+ Ionisation chamber : $\varepsilon_\varphi = 100\%$

$\varepsilon_f = 100\%$

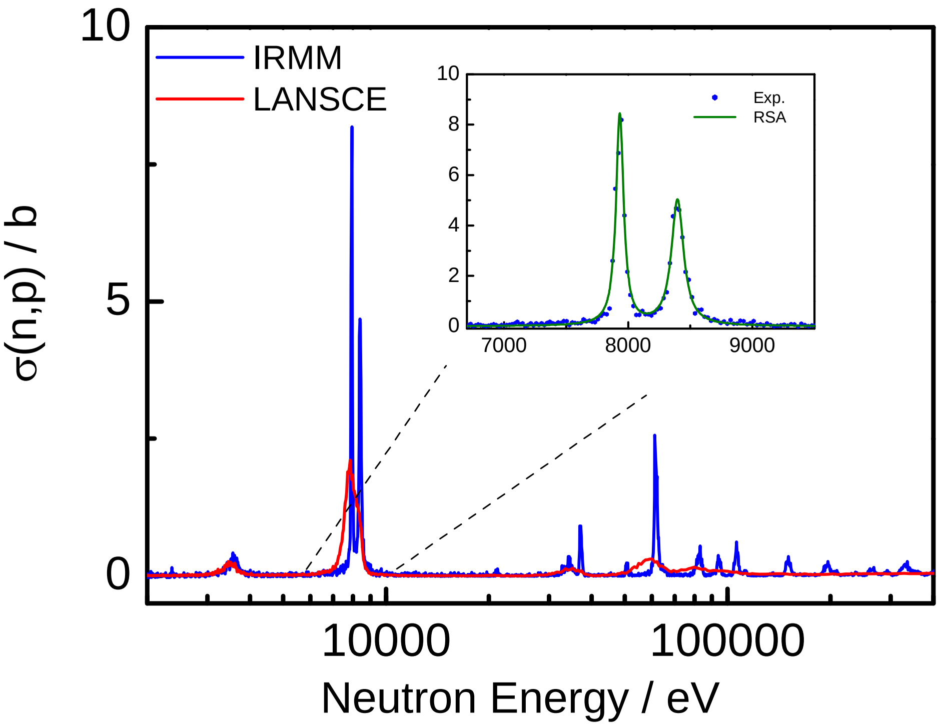


$$\Rightarrow \quad \sigma_f = \frac{C_f}{C_\varphi} \frac{n_\varphi}{n_f} \sigma_\varphi$$

Detector station at : L = 10 m and 30m
Moderated spectrum

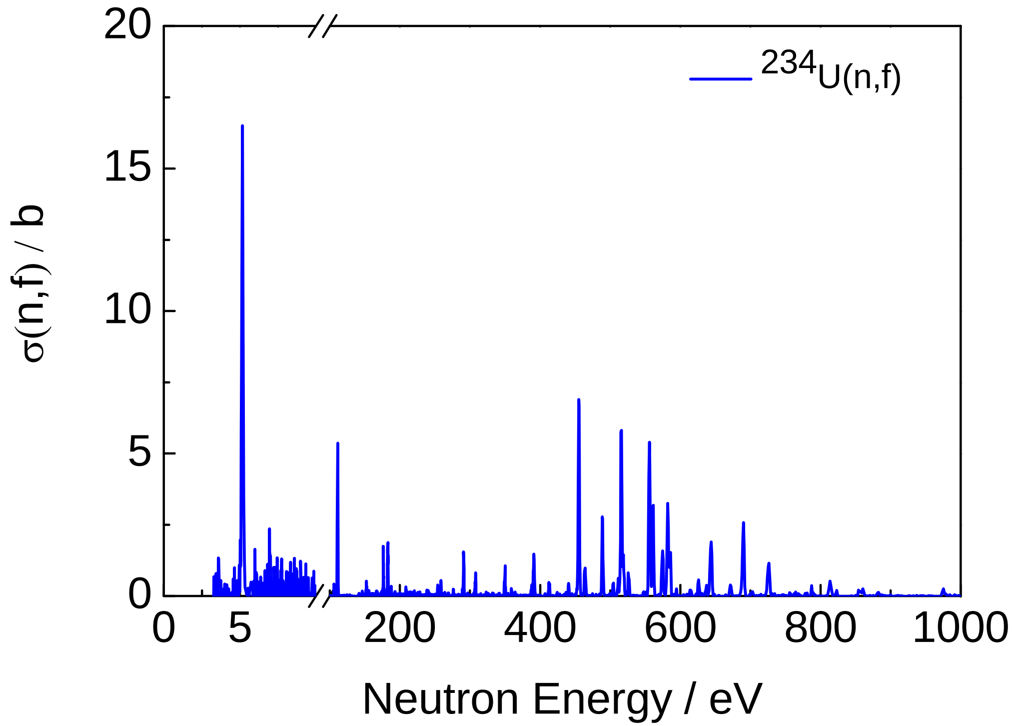
(n,f) and (n,cp) : IRMM - UGent

$^{36}Cl(n,p)^{36}S$



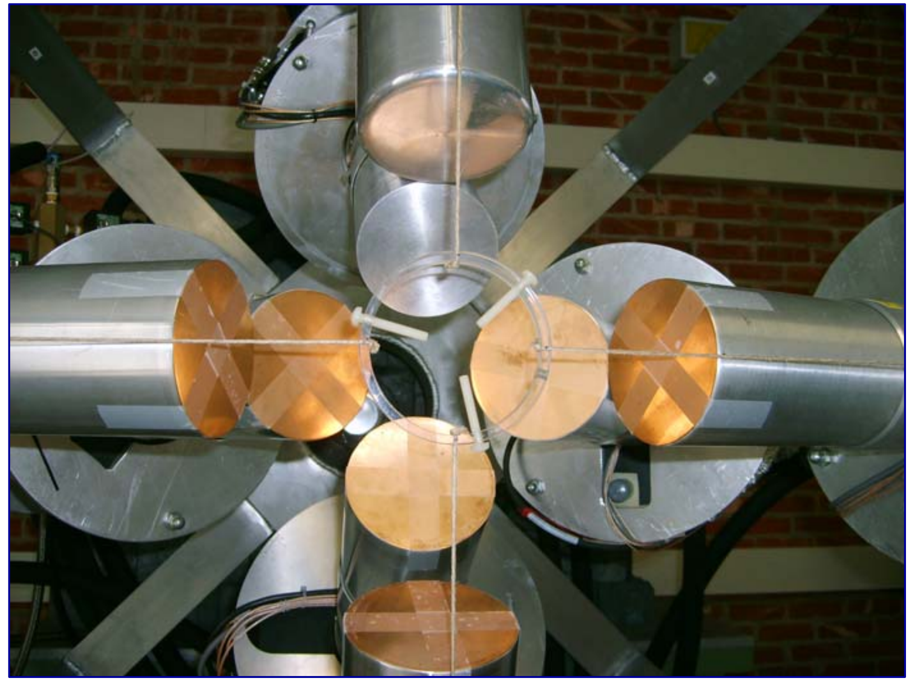
De Smet et al., Accepted PRC

$^{234}U(n,f)$



Heyse et al., NSE 156, 211 (2007)

In-elastic scattering at 30 m and 200 m
Direct spectrum



2001-2006 : 2 – 4 HPGe 100 %

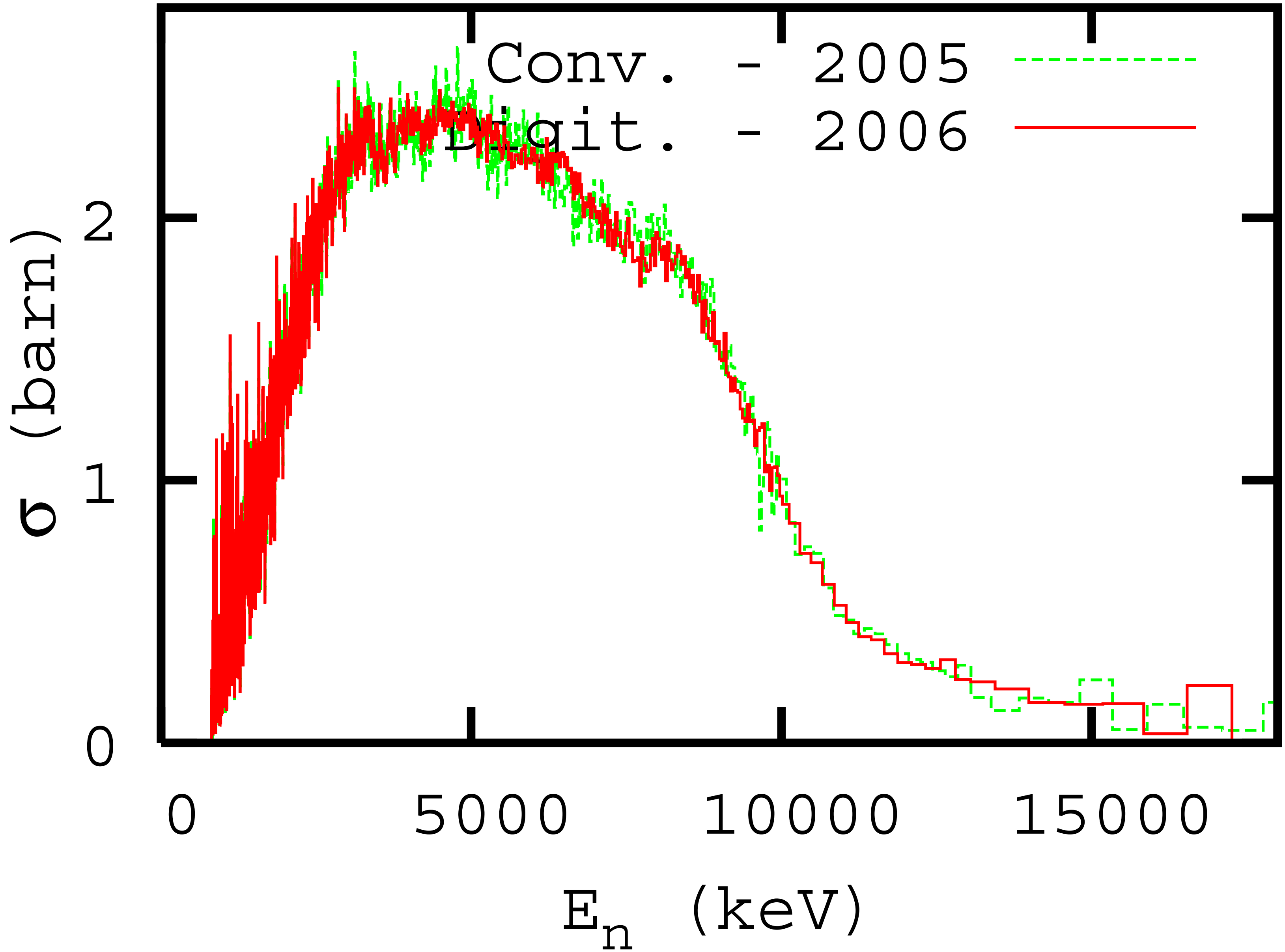
^{56}Ni, ^{52}Cr, ^{209}Bi, $^{206, 207, 208}$Pb

2006 – 2007 : 8 HPGe (100 %)

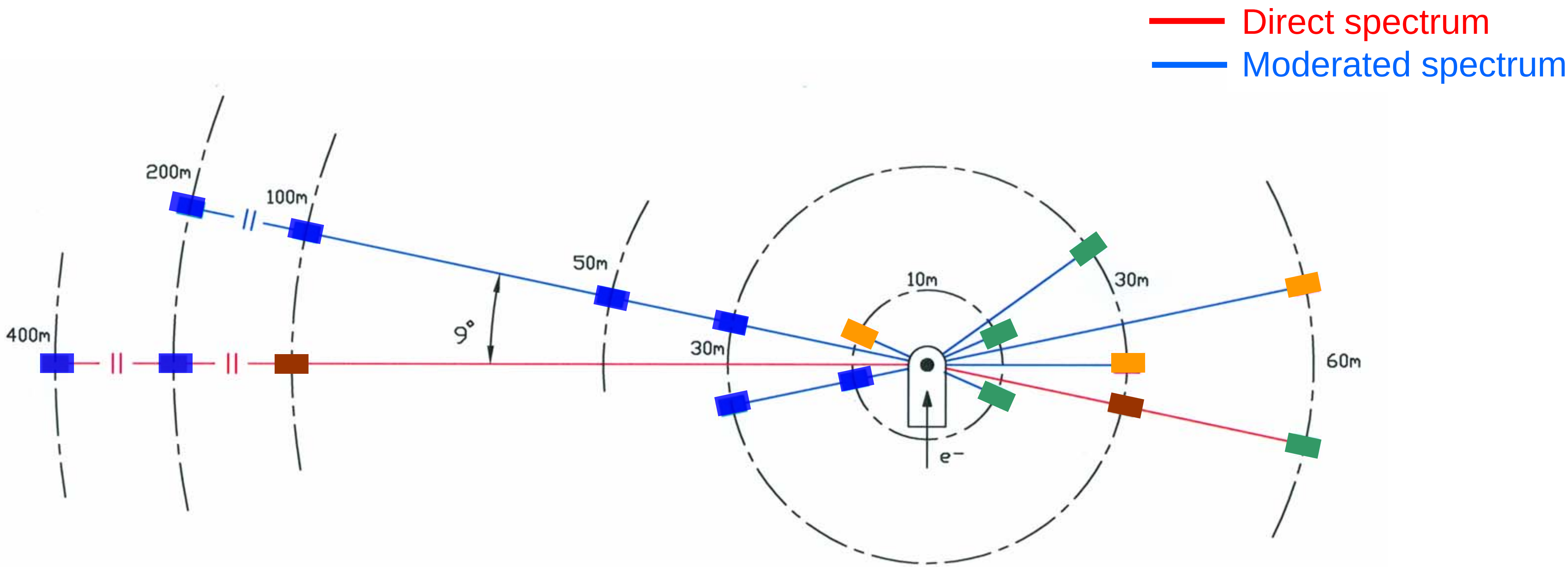
^{56}Fe, ^{28}Si

Mihailescu et al., NP A786, 1 (2007)

$^{206}Pb(n, n'\gamma)$ in-elastic scattering cross section

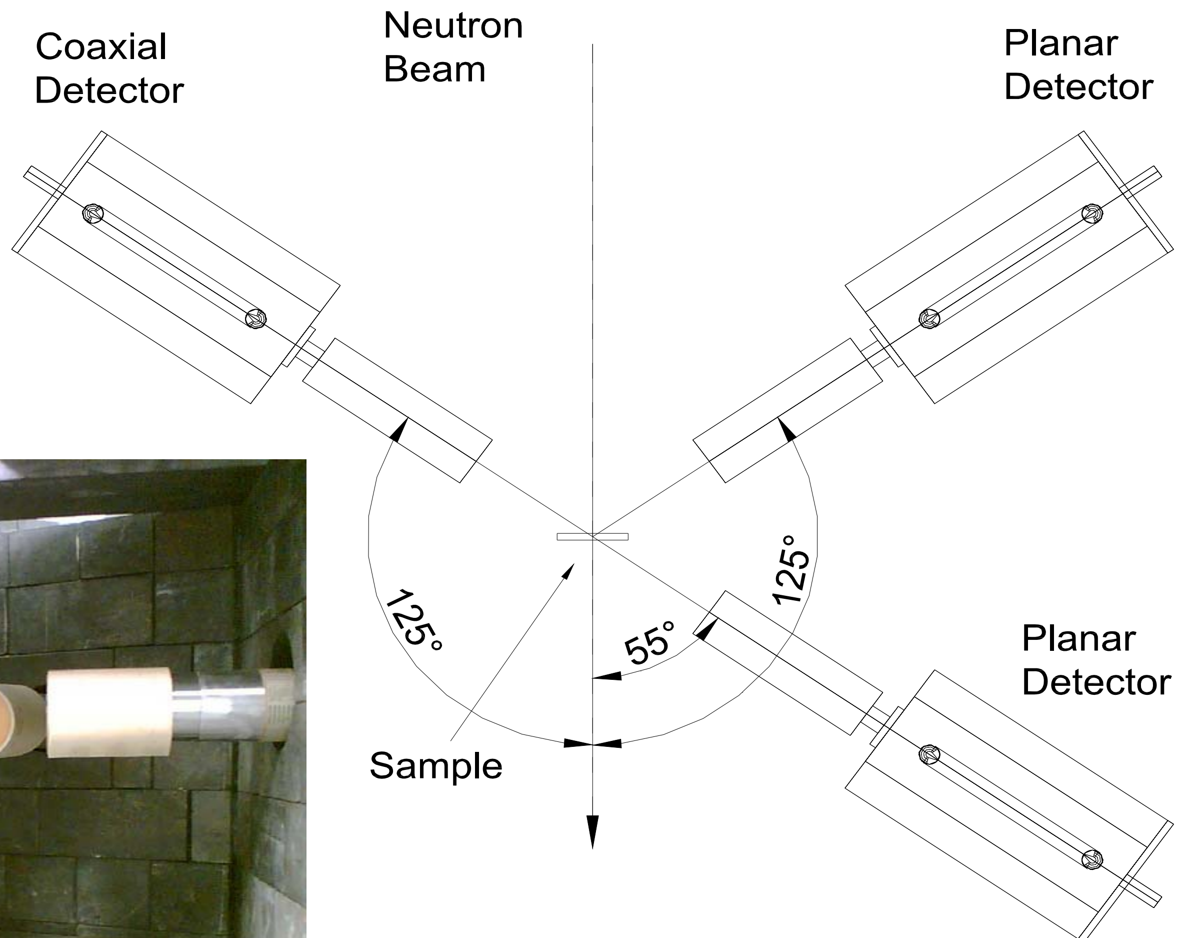


Capture Measurement Stations



- **C_6D_6 detectors (L = 10, 30 and 60 m)**
  - Study of resonance structured $\sigma(n,\gamma)$ from thermal up to 1 MeV
- **Ge-detectors (L = 10 m)**
  - Spin and parity PR C 61, 054616 (2000)
  - Partial capture cross sections & branching ratio
  - Isotope identification

Ge-detectors at L = 10 m



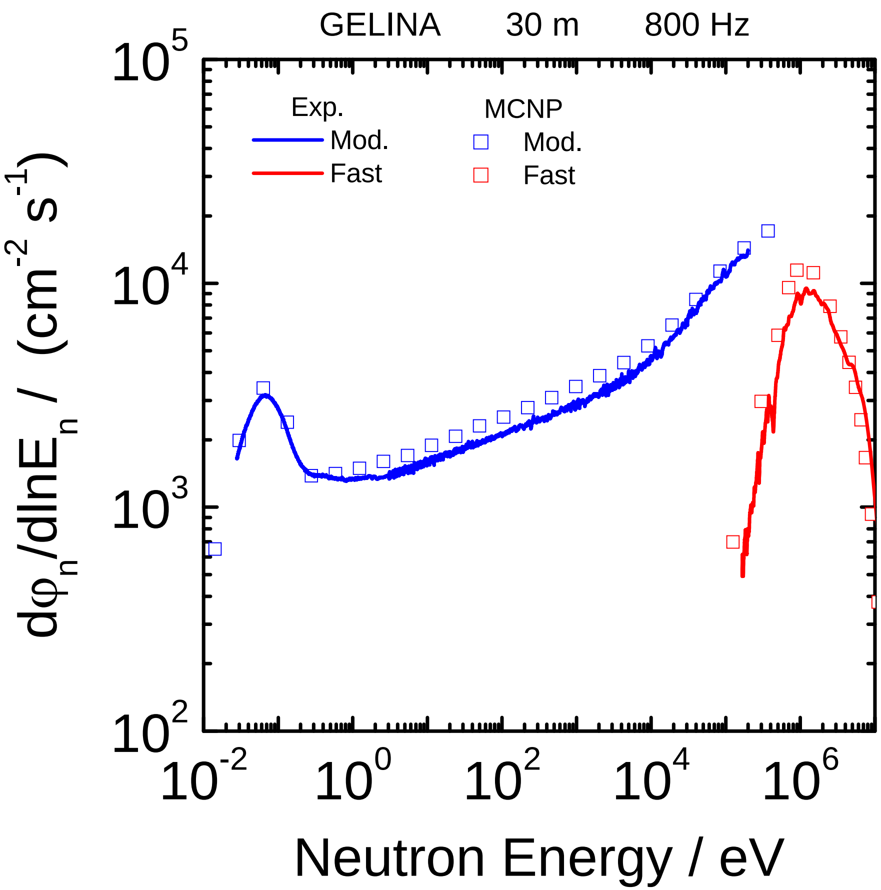
Research Activities

Improve the quality of the cross section data obtained at GELINA:

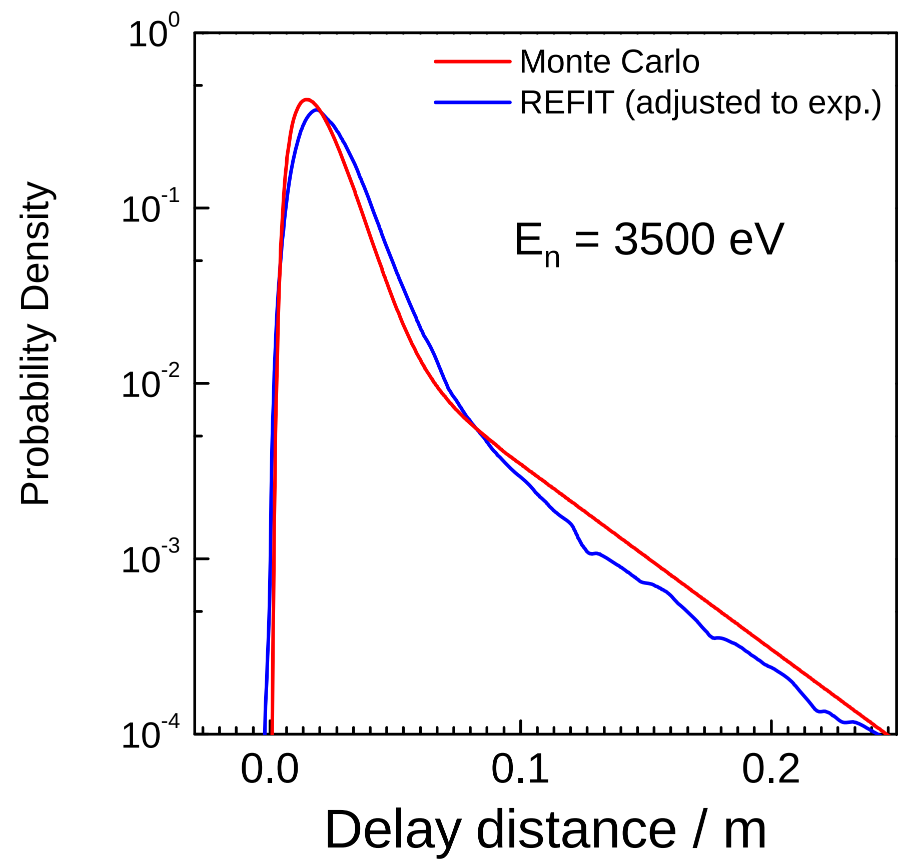
- **Better understanding of neutron producing target by MC-simulations**
- **Use of digitizers to replace conventional analog electronics**
- **Data reduction procedures with full covariance information**
- **Improved data reduction for capture measurements**
- **Improved RSA for thin sample transmission data**
- **Support the development of analysis codes for RRR and URR**

Characterisation of GELINA : TOF-Facility

Neutron Flux



Resolution Function

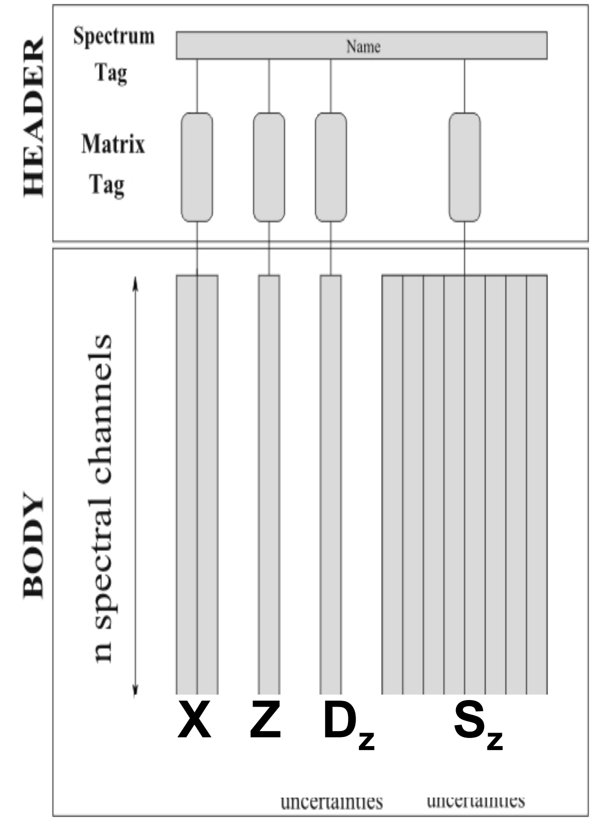


Flaska et al.,NIM , A531, 394 (2004)

Data reduction with full covariance information

Analysis of Generic tof_Spectra (AGS)

- Transform count rate spectra into observables (transmission factors, partial reaction yields)
- Full propagation of uncertainties starting from counting statistics
- Output: complete covariance matrix
- Special format for covariance matrix
- Due to the special format used in AGS:
  - **Reduce space for data storage (EXFOR)**
  - **Verify and document the sources of uncertainties in each step of the reduction process**



Observable Z (dim. n) with k sources of correlated uncertainties ⇒

$$C_Z = D_Z + S_Z S_Z^T$$

D_Z : uncorrelated part
n values

S_Z : correlated part
dim. (n x k)

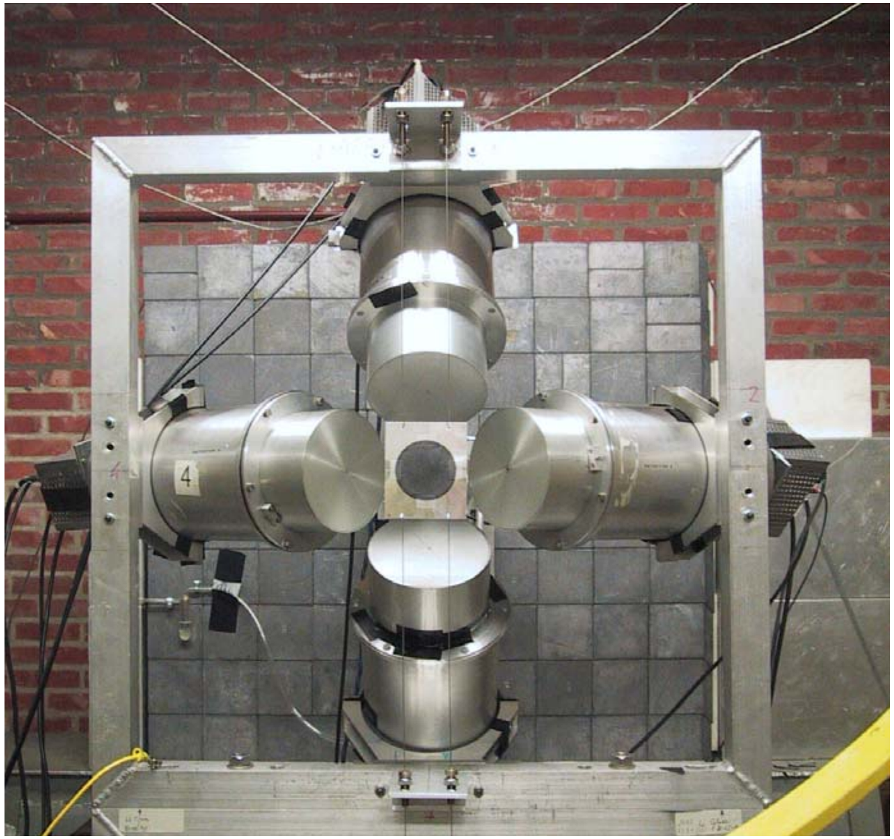
Bastian et al., PHYSOR 2006

Capture cross section measurements at GELINA

Total energy detection

- C_6D_6 liquid scintillators
  - 125°
  - PHWT $\int R(E_d, E_\gamma)\, WF(E_d)\, dE_d = kE_\gamma$
- Flux measurements (IC)
  - $^{10}B(n,\alpha)$
  - $^{235}U(n,f)$

L = 10 m, 30 m and 60 m



$$Y_{exp} = \sigma_\varphi \frac{C_w - B_w}{C_\varphi - B_\varphi}$$

WF : from MC simulations

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

Improved Data Reduction for (n,γ)

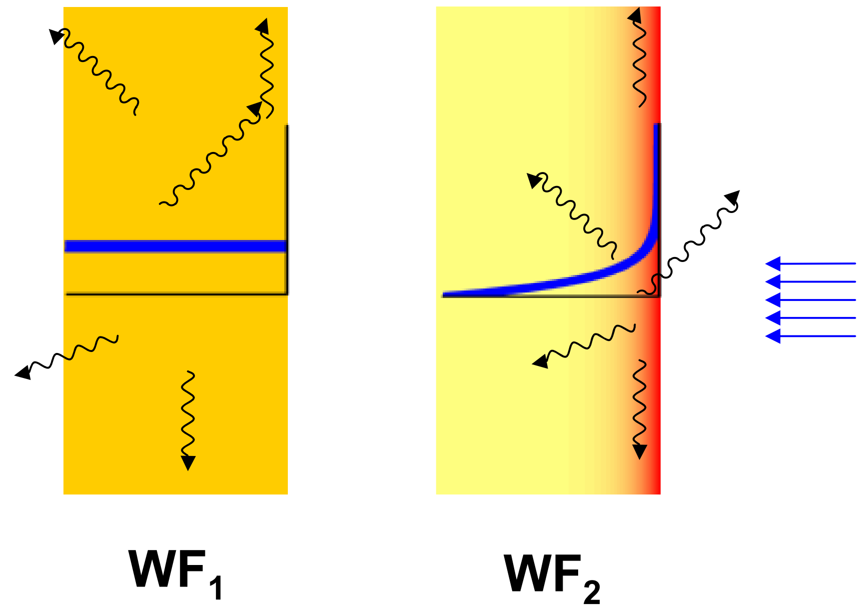
Reliable WF's can be obtained by Monte Carlo simulations provided that the geometry input reflects the experimental conditions, i.e. accounts for γ–ray transport in sample
(started with Perey et al. at ORELA)

⇒ **Weak resonance : WF1**

⇒ **Strong resonance : WF2**
(Affects also the observed shape)

Procedure :
(1) Apply WF1 on experimental data

(2) Correction factor on calculated yield

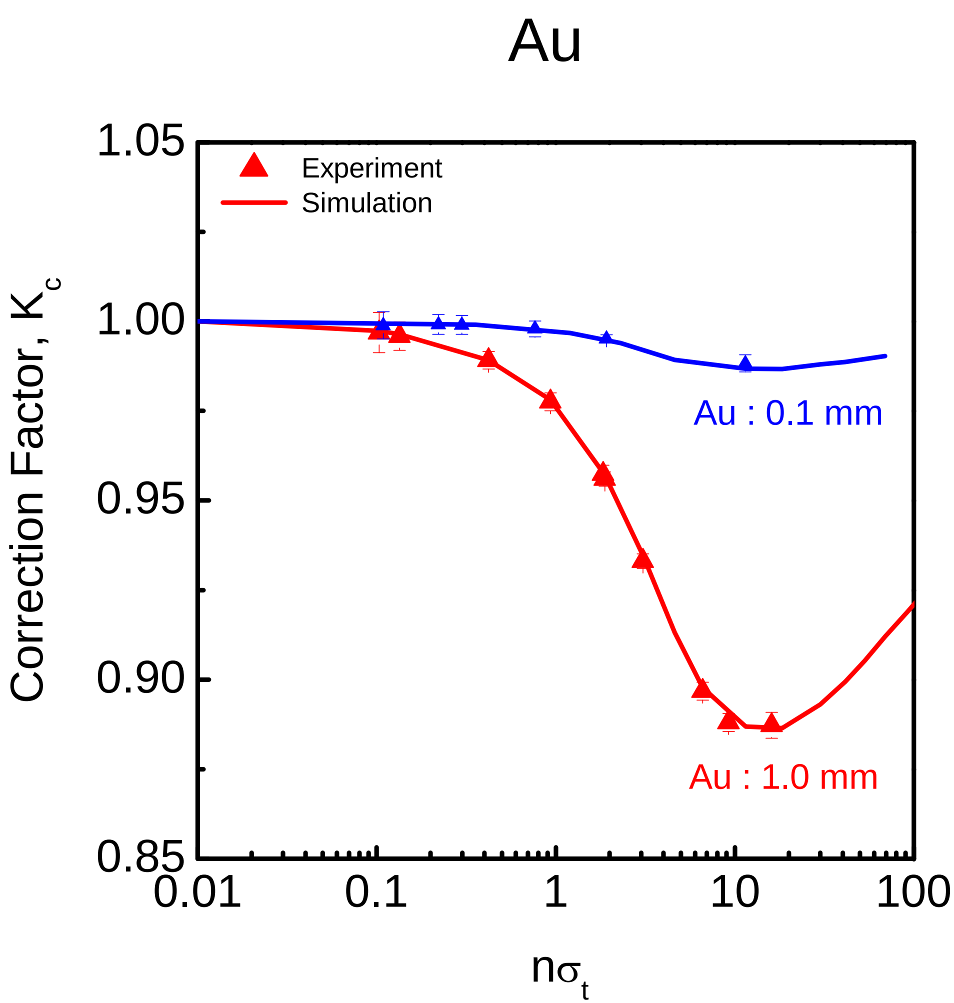


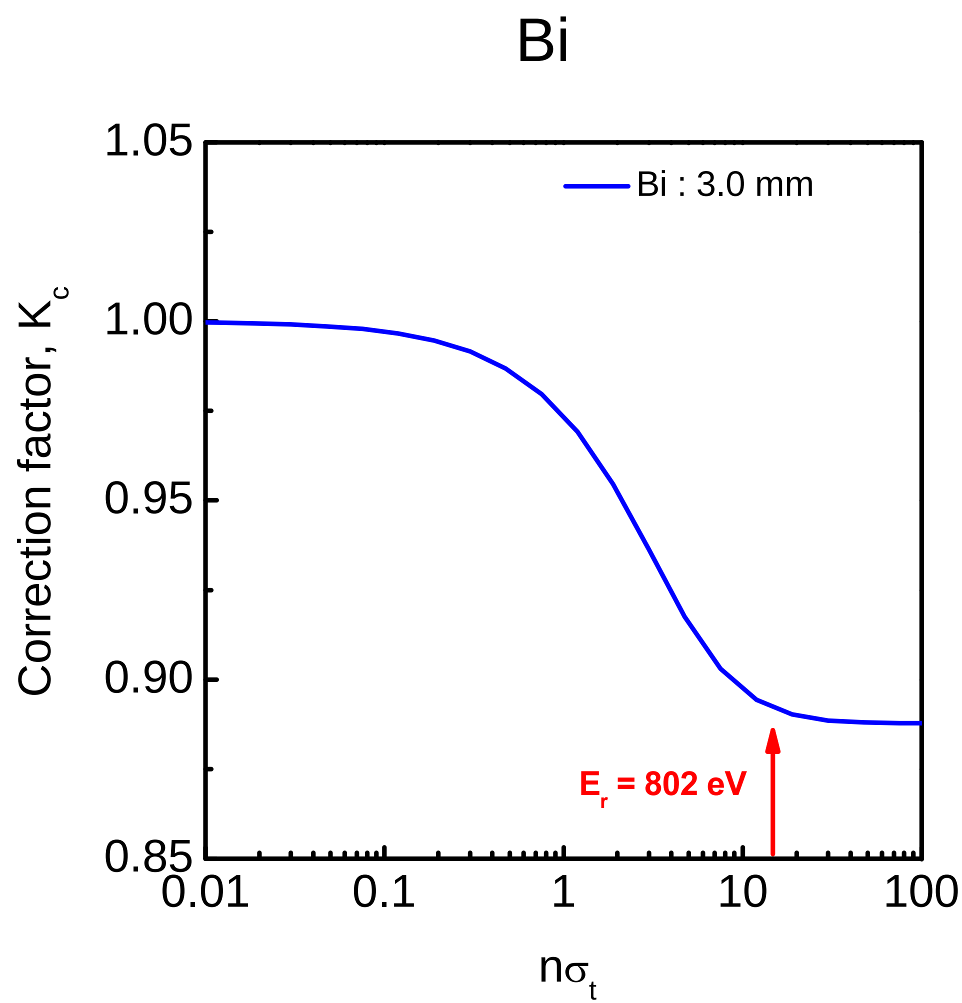
$$K_c(n\sigma_t) = \frac{< WF_1 >}{< WF_2 >}$$

$$Y_{exp} = N \int R(T_n, E_n)\,(K_c \varepsilon_{cw} Y_c + \varepsilon_{nw} Y_n)\, dE_n$$

Borella et al., NIMA 2007, j.nima.2007.03.034

Examples : Au & Bi





MC: γ-ray spectrum from DICEBOX

MC: γ-ray spectrum from measurements at BNC

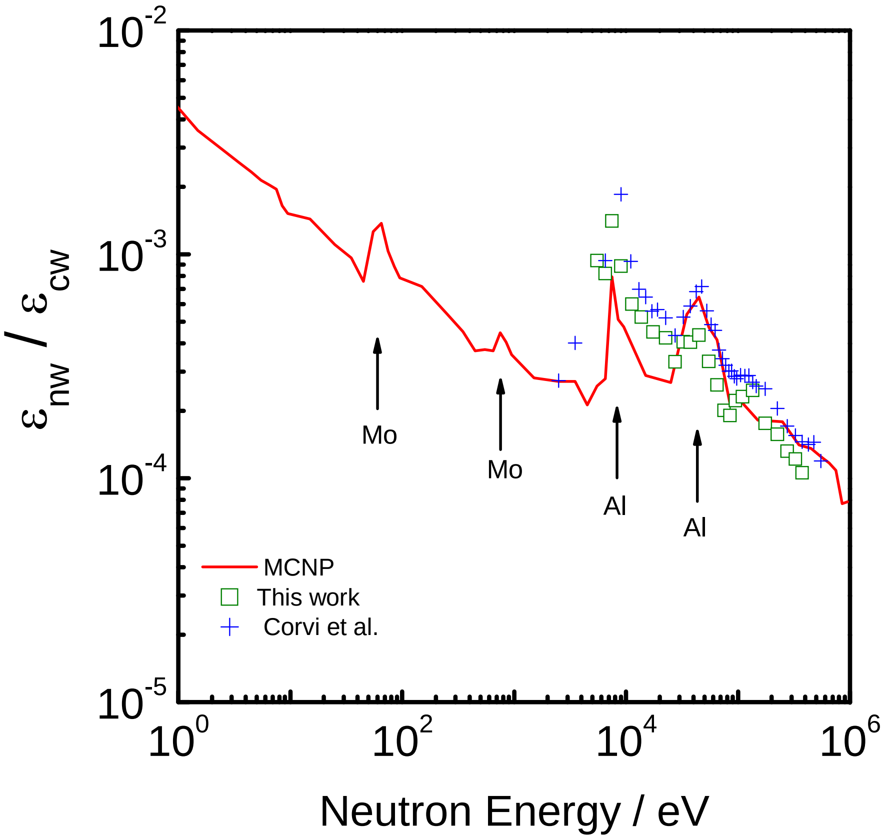
Borella et al., NIMA 2007, j.nima.2007.03.034

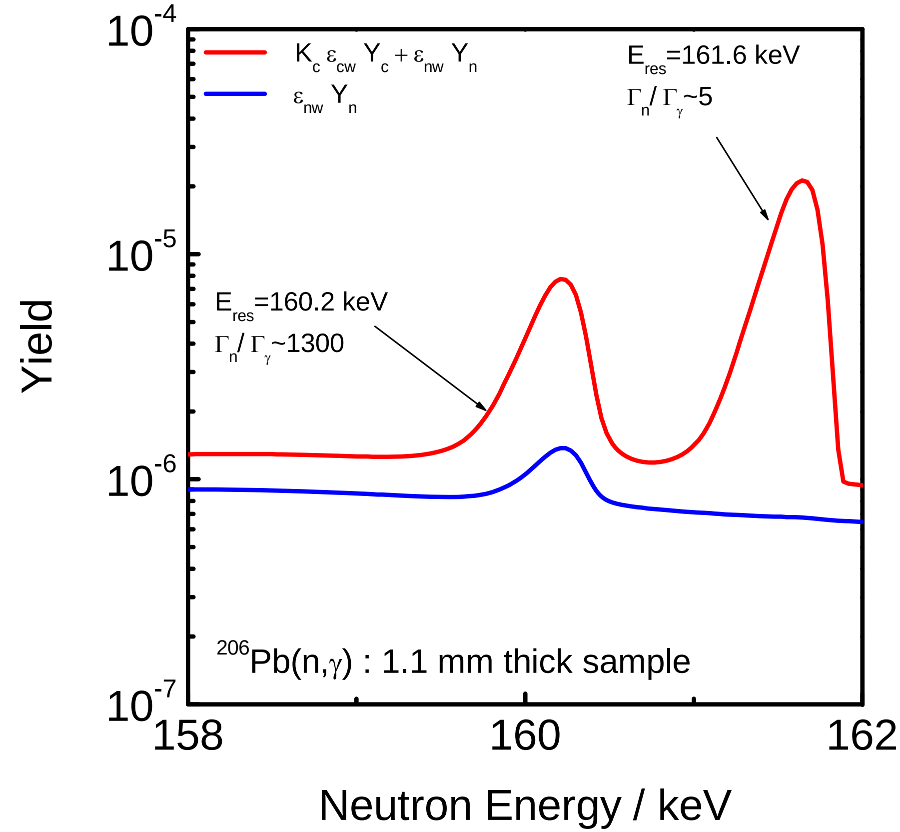
Neutron sensitivity

$$Y_{exp} = N \int R(T_n, E_n)\,(K_c \varepsilon_{cw} Y_c + \varepsilon_{nw} Y_n)\, dE_n$$

$$Y_c = (1 - e^{-n\sigma_t})\frac{\sigma_\gamma}{\sigma_t} + Y_m$$

$$Y_n = (1 - e^{-n\sigma_t})\frac{\sigma_n}{\sigma_t} - Y_m$$



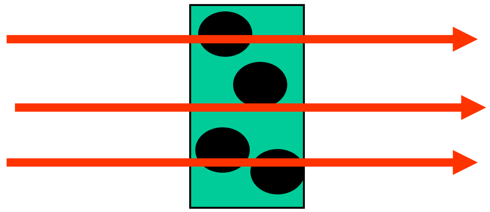


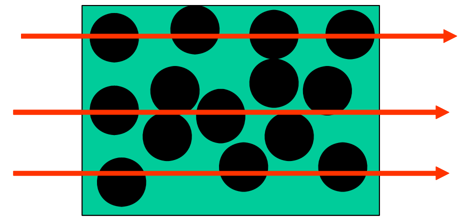
Borella et al., j.nima.2007.03.034

REFIT $\Rightarrow \Gamma_\gamma$ = 53.5 meV

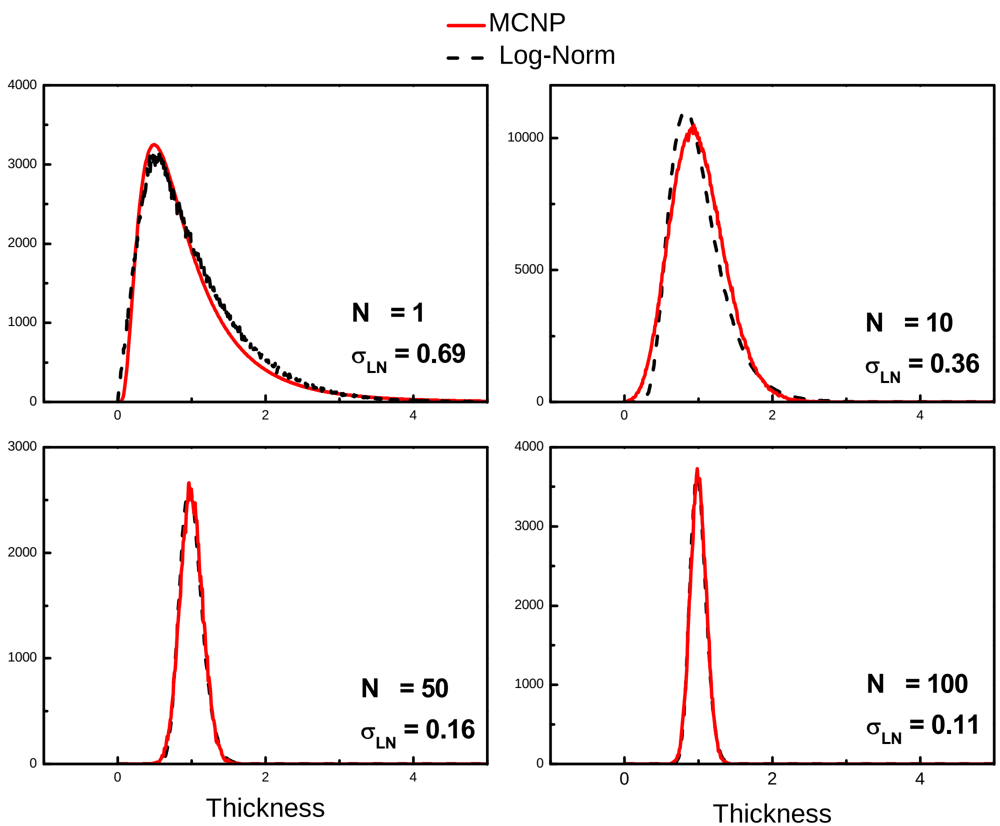
$$\Gamma_\gamma = \Gamma'_\gamma - \frac{\varepsilon_n}{\varepsilon_c}\Gamma_n \quad \Rightarrow \Gamma_\gamma = 48.3 \text{ meV}$$

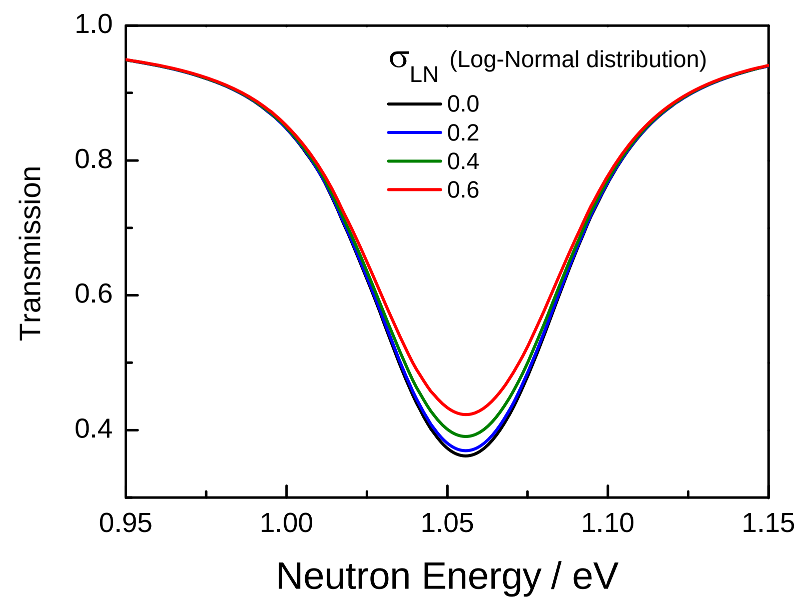
Improved RSA of thin sample transmission data





Variation of sample thickness can be described by a Log-Normal distribution with free parameter σ_{LN}





Kopecky et al., ND2007

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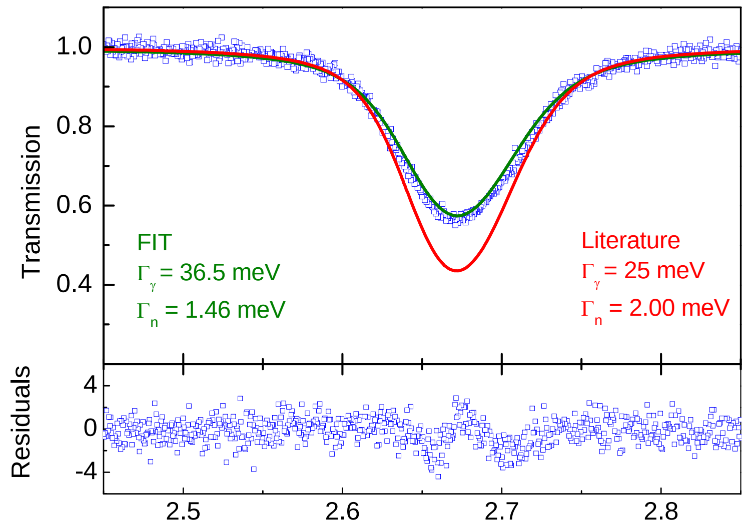
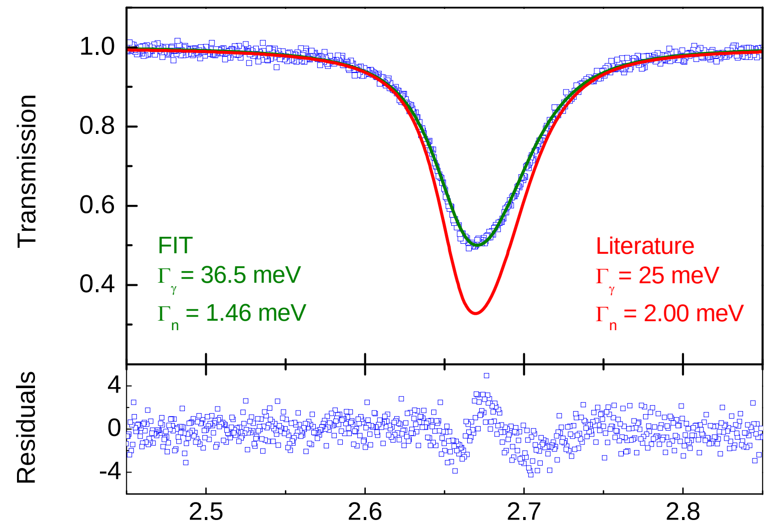
Thin sample transmission data : ^{242}Pu 2.5 10^{-5} at/b

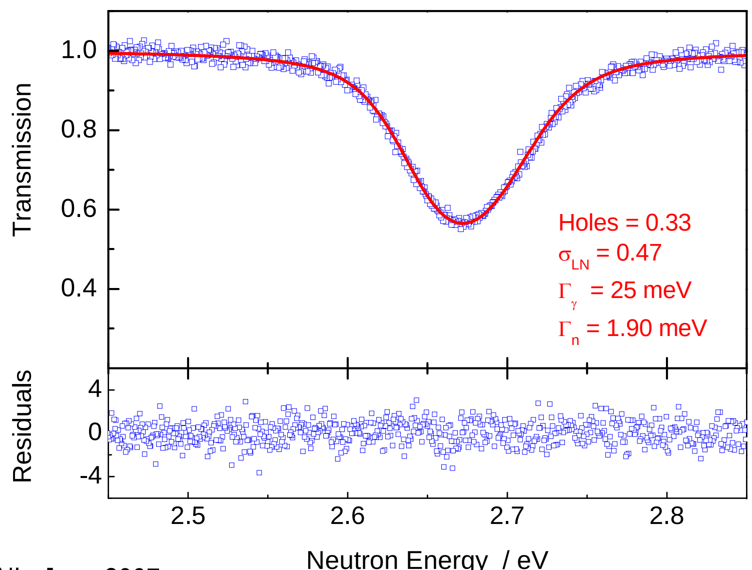
300 K

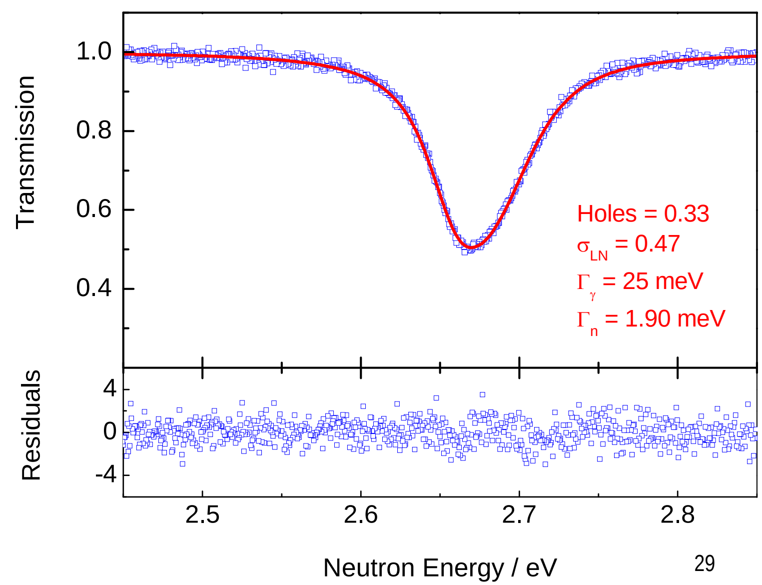


77 K



Variation of thickness described by Log-Normal distribution





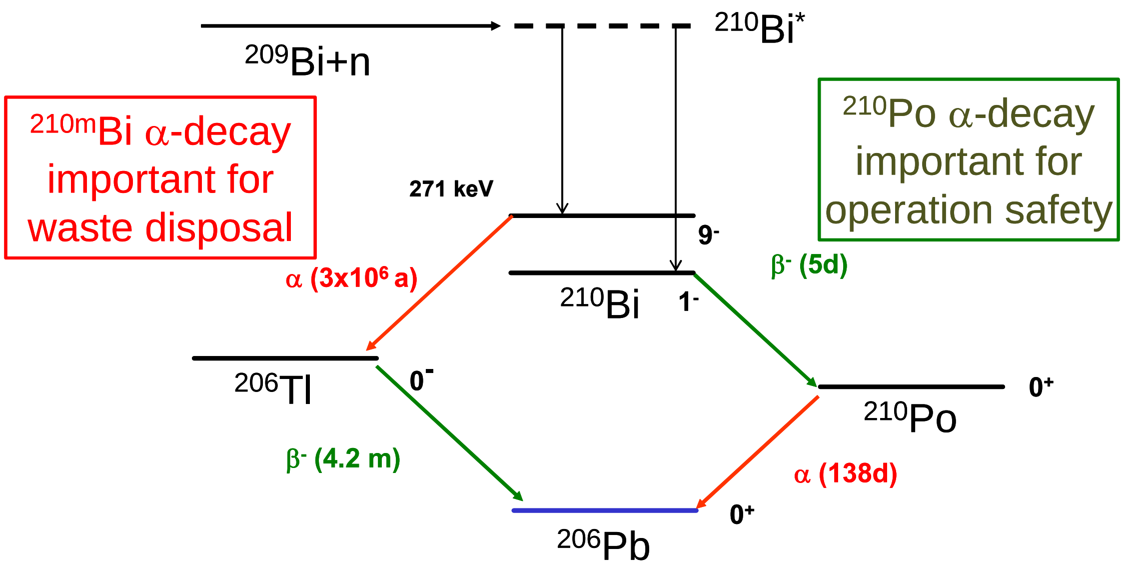
Support the development of analysis codes for the parameterisation of experimental data in terms of RP

- **Resolved resonance region : REFIT**
  (Moxon, WONDER 2006)
  - Tested and documented version
    (collaboration with Serco Assurance: C. Dean)
  - Implement improvements (EFNUDAT support for scientific visit M. Moxon)
    - Improved analysis of capture data
    - Treatment of variation in sample thickness for transmission
      (Kopecky et al. ND2007)
    - Accommodate different resolution functions
      (Kopecky et al., WONDER 2006)
- **Unresolved resonance region (collaboration with IAEA)**
  (Sirakov et al., WONDER 2006)
    - HF + WF
    - Link to optical model (DCCOM) (Capote et al.)
    - Covariance data
    - ENDF-6 compatible output

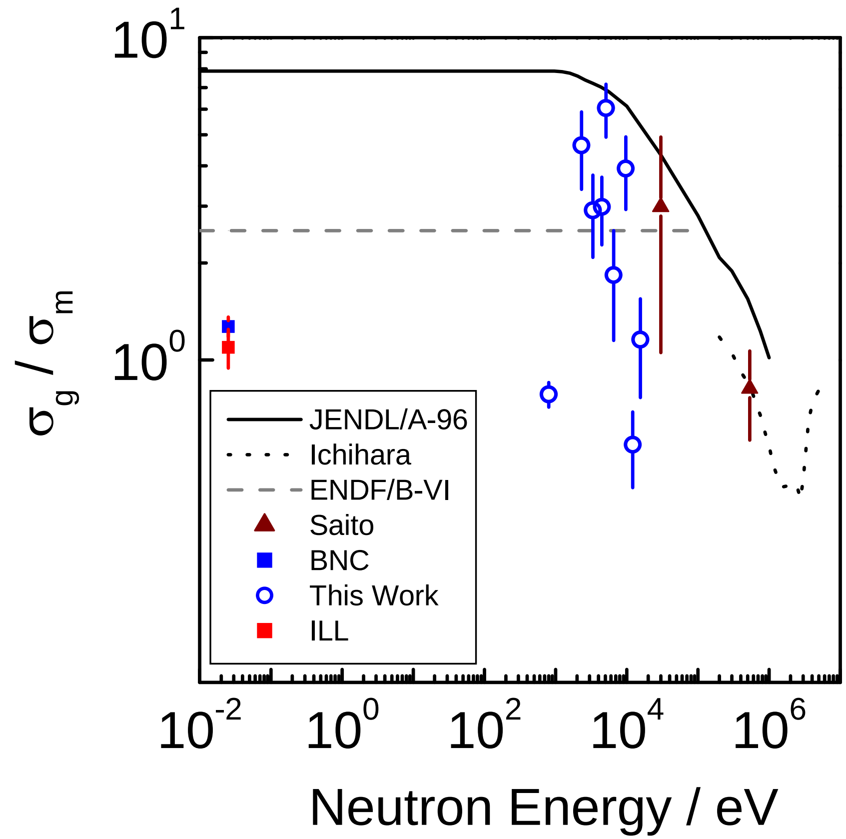
Neutron data in support to production of nuclear energy

- **Transmutation of nuclear waste**
  - RP for ^{99}Tc, ^{129}I, ^{237}Np, ^{241}Am
- **High Temperature Reactors**
  - ^{240,242}Pu – Doppler effect
- **Development of ADS systems**
  - ^{209}Bi-branching
  - ^{206,207,208}Pb and ^{209}Bi (n,tot), (n,γ), (n,n'γ)
- **Th-U fuel cycle**
  - ^{234,236}U(n,f)
  - RP for ^{232}Th (RRR + URR)
- **U-Pu fuel cycle**
  - Fission products
  - ^{55}Mn

$^{209}Bi(n,\gamma)$- branching ratio at L = 10 m with Ge-detectors



Important for any system using Bi as coolant, moderator or target (ADS)



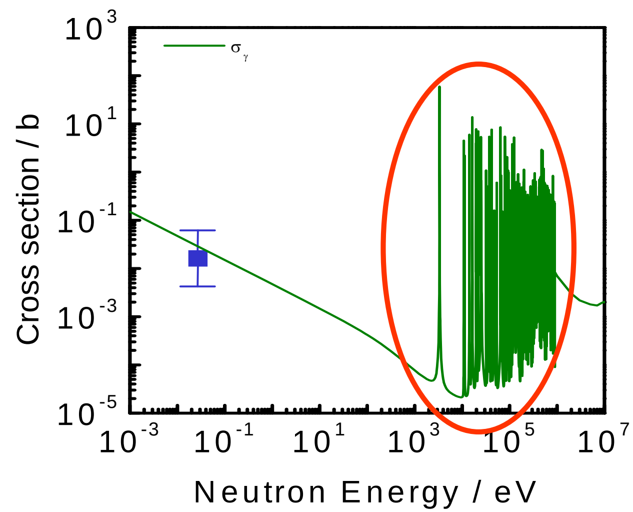
Borella et al., ND2007

ADS : ^{206}Pb + n resonance parameter file

Thermal neutron energy

BNC

$\sigma(n_{th},\gamma)$ = 27.3 (8) mb



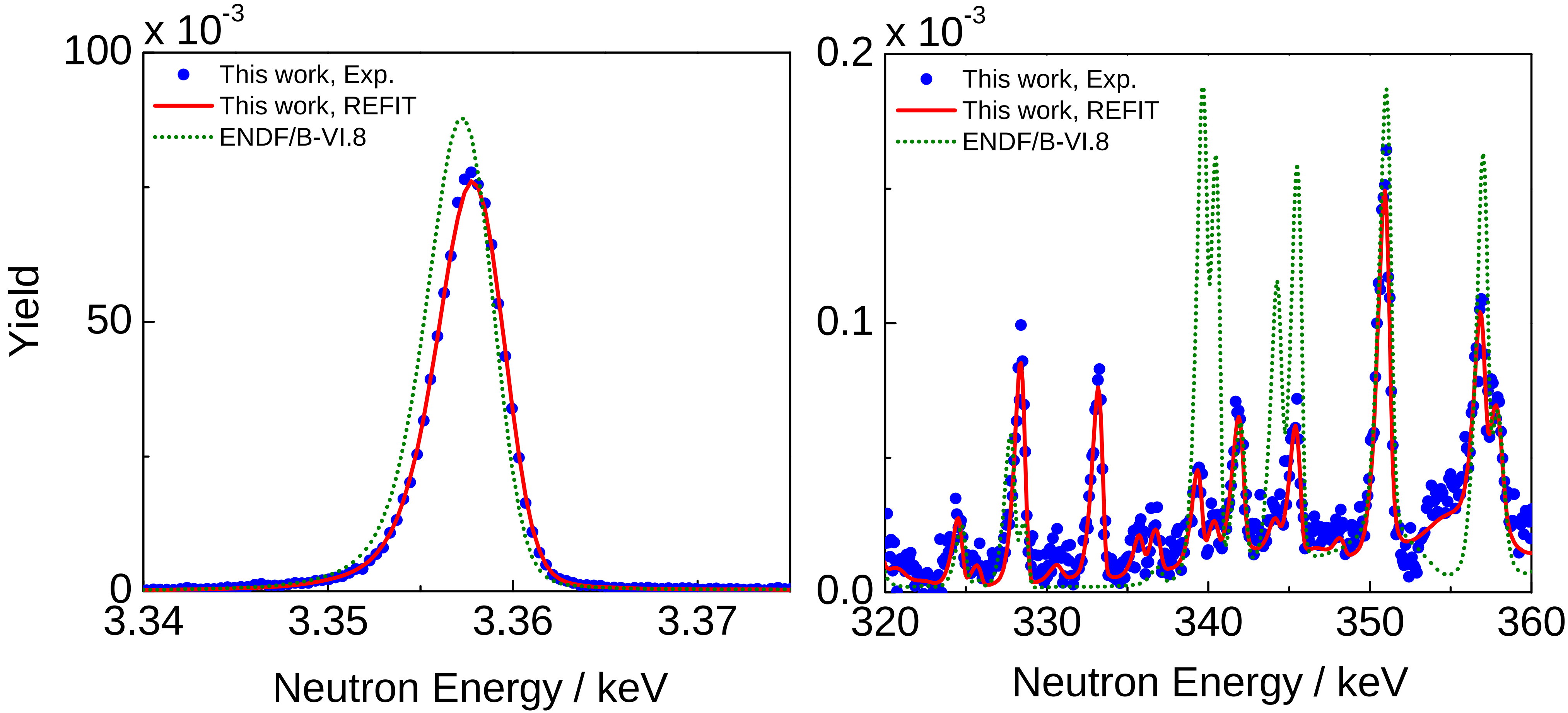
RRR

GELINA

- Resonance parameter file (matching thermal values)
  - 304 resonances up to 620 keV (221 in ENDF/B-VI.8)
  - R' = 9.54 (2) fm
  - E_o > 80 keV: Γ_n from ORELA, (Horen et al., PR C20, 478 (1979))
- MAC cross sections (based on 304 resonances !)
- Photon strength function from C_6D_6 spectra
  - f_{E1} < 225 (5) 10^{-9} MeV^{-3}
  - f_{M1} follows systematics (no M1 enhancement)
  - B(E2)↓

Borella et al., accepted PRC

$^{206}Pb + n$: results

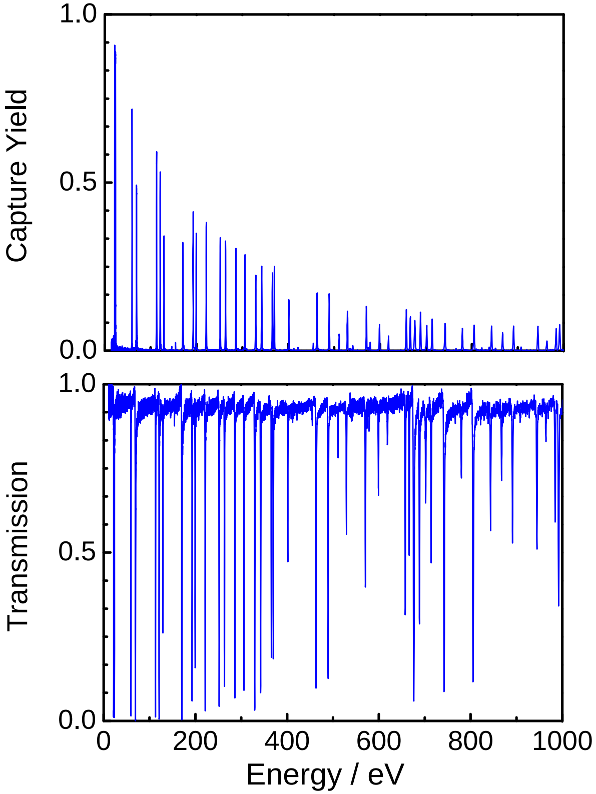


⇒ new evaluation : re-analyse together with ORELA data

(transmission and scattering)

Borella et al., accepted PRC

IAEA CRP: Thorium – Uranium Fuel Cycle
Resonance parameters (RRR & URR) for ^{232}Th + n



Facility	Measurement Type	Flight Path Length	Target Thickness at/b
ORELA	Transmission	180 m	1.68 10^{-4} 14.00 10^{-4} 38.70 10^{-4} 193.1 10^{-4}
GELINA	Transmission	50 m	8.00 10^{-4} 34.0 10^{-4} 61.0 10^{-4}
GELINA	Capture Borella et al., NSE 152, 1 (2006)	15 m 60 m	15.8 10^{-4} 34.0 10^{-4}
n-TOF	Capture	200 m	41.0 10^{-4}

RRR (ORNL) + URR (IRMM) ⇒ ENDF/B-VII

Optimise the U - Pu fuel cycle

More accurate nuclear data are needed for:

1) Tendency to operate conventional nuclear power plants at increased fuel burn-up

2) Fuel cycles based on reprocessed fuel

3) Spent fuel storages (ORNL – RADWASTE)

Nuclide	Priority Level	
	Storrer et al. Burnup	Salvatores Reprocessing
^{103}Rh	1	
^{133}Cs	1	
^{155}Gd		1
^{147}Sm		1
^{149}Sm	1	
^{152}Sm		1
^{143}Nd	2	1
^{145}Nd		1
^{153}Eu	2	1
^{155}Eu	1	

$\sigma_\gamma < 2\text{-}3\%$

1 & 2 : Collaboration with CEA Saclay (F)

3 : Collaboration with ORNL (US)

M. Salvatores, ND2002, J. Sci. & Techn. 2 (2002) p. 4
F. Storrer et al., ND2002, J. Sci. & Techn. 2 (2002) p. 1357
NEA High Priority List, March 2001

Collaboration ORNL – IRMM

sotope	Transmisson				Capture			
	Flight Path	Frequency	Target Thick.	Data Red.	Flight Path	Frequency	Target Thick.	Data Red.
^{55}Mn	30 m	800 Hz	1.2 10^{-1} at/b					
	50 m	800 Hz	4.4 10^{-4} at/b	Done	30 m	800 Hz	4.4 10^{-4} at/b	
	50 m	800 Hz	1.5 10^{-3} at/b	Done	30 m	800 Hz	1.9 10^{-2} at/b	
	50 m	800 Hz	1.0 10^{-2} at/b	Done	60 m	800 Hz	1.0 10^{-2} at/b	
	50 m	800 Hz	1.9 10^{-2} at/b	Done	60 m	800 Hz	1.9 10^{-2} at/b	Done
^{103}Rh	50 m	100 Hz	3.4 10^{-4} at/b	Done	15 m	40 Hz	1.8 10^{-3} at/b	Done
	50 m	100 Hz	2.2 10^{-3} at/b	Done	30 m	800 Hz	1.8 10^{-3} at/b	Done
	50 m	400 Hz	4.6 10^{-2} at/b	Done	30 m	800 Hz	3.4 10^{-4} at/b	Done
	50 m	800 Hz	4.6 10^{-2} at/b	Done	60 m	800 Hz	1.8 10^{-3} at/b	Done
^{133}Cs	30 m	800 Hz	2.3 10^{-4} at/b		15 m	50 Hz	3.8 10^{-4} at/b	
	30 m	800 Hz	1.0 10^{-2} at/b		15 m	50 Hz	1.5 10^{-3} at/b	
	50 m	800 Hz	2.3 10^{-4} at/b	Done	15 m	50 Hz	5.2 10^{-3} at/b	
	50 m	800 Hz	5.2 10^{-3} at/b	Done	30 m	800 Hz	2.3 10^{-4} at/b	Done
					30 m	800 Hz	3.8 10^{-4} at/b	
					30 m	800 Hz	1.5 10^{-3} at/b	
					30 m	800 Hz	5.2 10^{-3} at/b	
					30 m	800 Hz	1.0 10^{-2} at/b	Done
^{nat}Gd	30 m	800 Hz	1.5 10^{-3} at/b		15 m	50 Hz	6.0 10^{-4} at/b	
	50 m	800 Hz	6.0 10^{-4} at/b	Done	30 m	50 Hz	6.0 10^{-4} at/b	
	50 m	800 Hz	1.5 10^{-3} at/b	Done				
^{155}Gd	30 m	800 Hz	3.4 10^{-4} at/b		15 m	50 Hz	6.0 10^{-3} at/b	
	30 m	800 Hz	6.0 10^{-3} at/b		30 m	800 Hz	3.4 10^{-4} at/b	
					30 m	800 Hz	6.0 10^{-3} at/b	

Criticality safety

RADWASTE

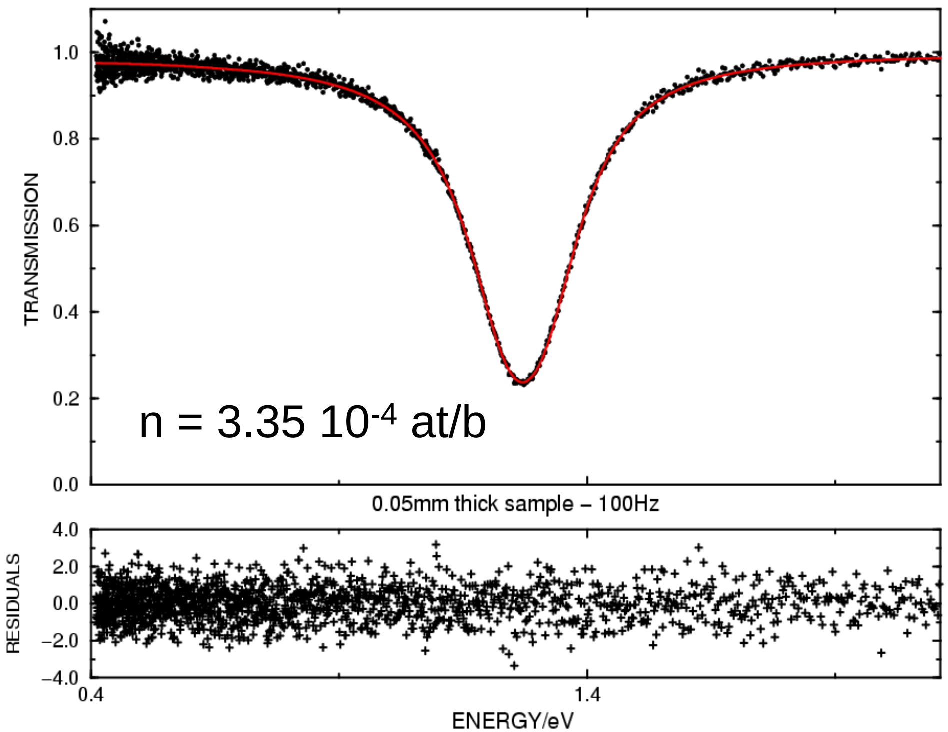
Combine transmission & capture
Different flight paths & facilities
Use of samples with different properties

⇒

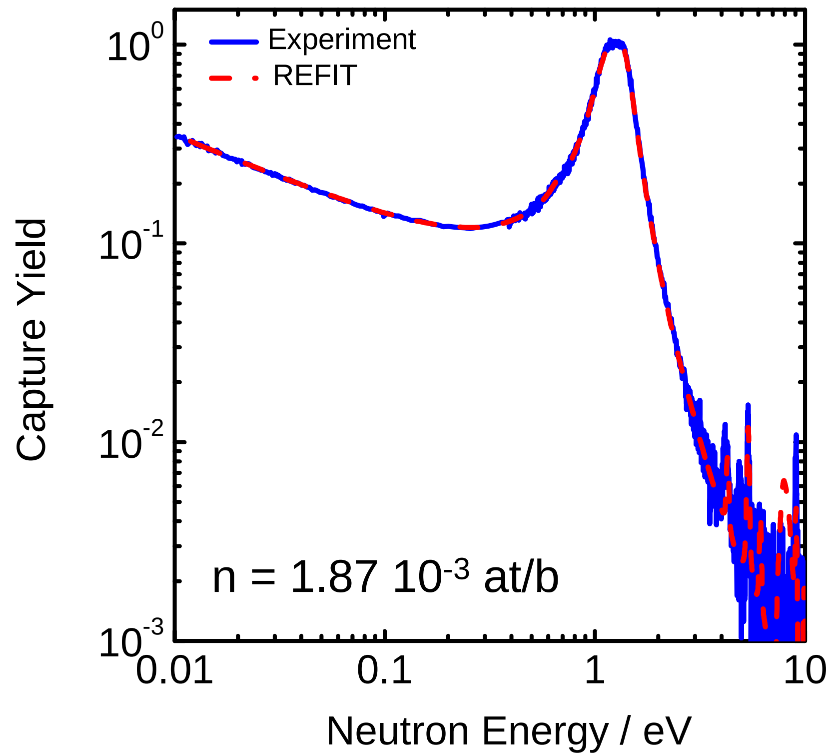
Reduction of bias effects due to:
- Resolution
- Sample properties
- Normalization of capture data

^{103}Rh: Thermal region

Transmission: 50 m 100 Hz



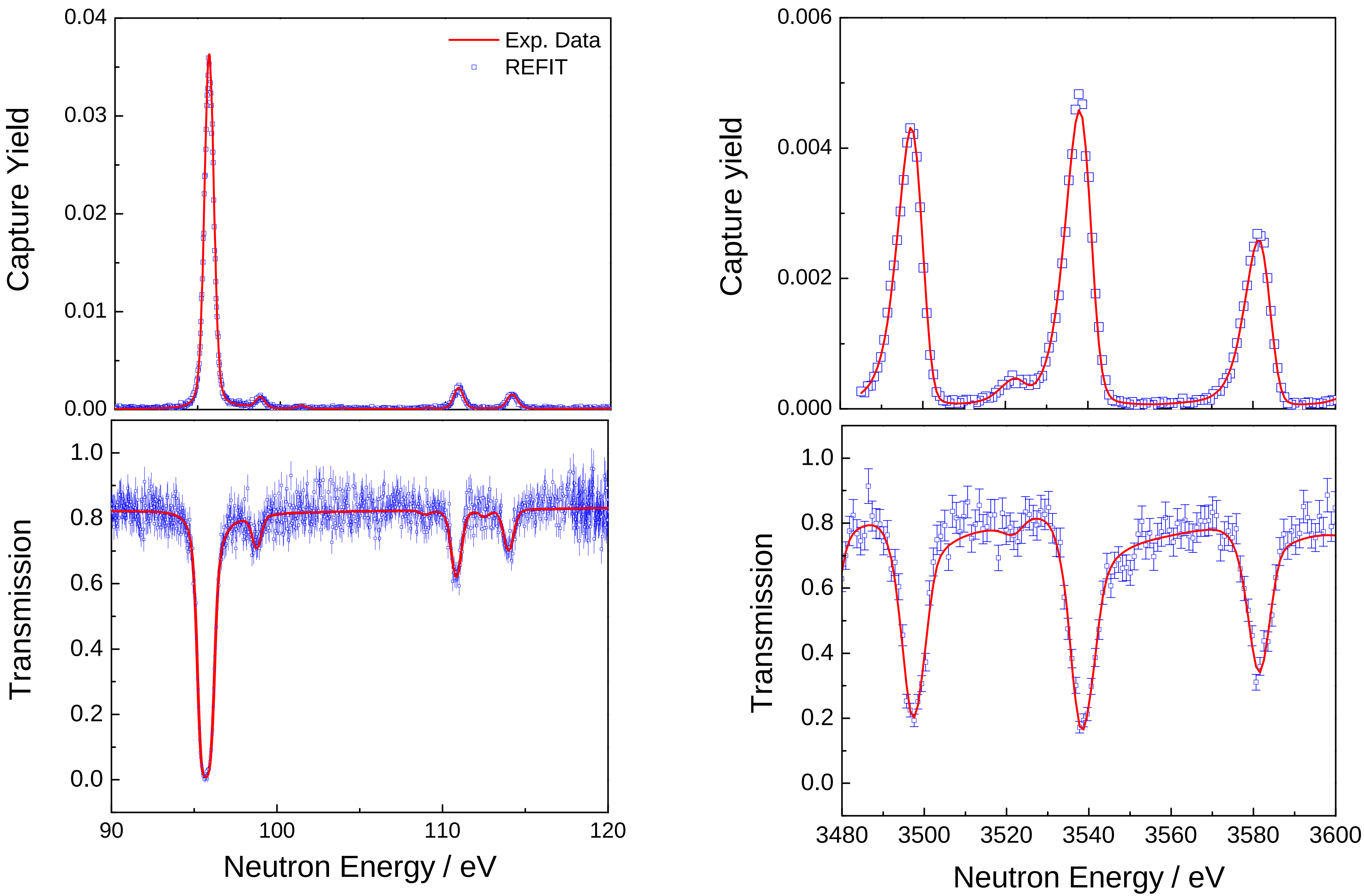
Capture : 15 m 40 Hz



E_r = 1.260 eV
Γ_n = 0.464 meV
Γ_γ = 156.0 meV
g = 3/4

$\sigma(n,\gamma)$ at 25.3 meV
WF : 142.0 (1.5) b
1.0 % normalization
0.5 % uncorrelated
Counts : 143.3 b

^{103}Rh : Resolved Resonance Region



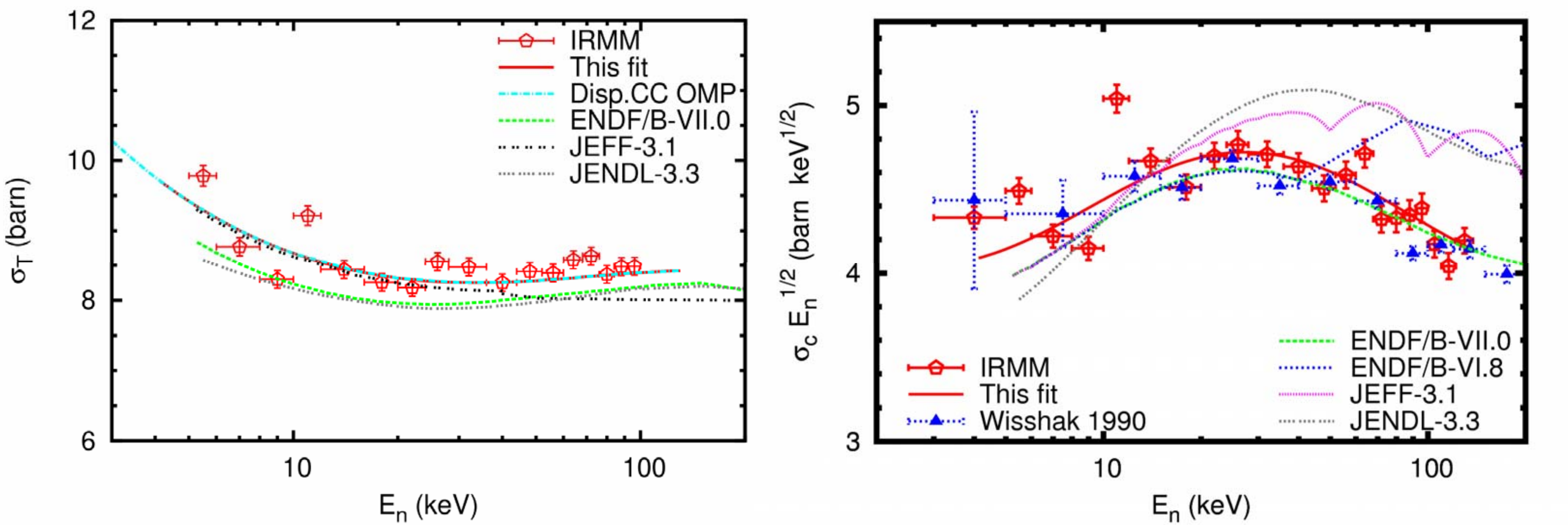
^{103}Rh : Unresolved Resonance Region

Improved the experimental data in URR :

- **Transmission : 50 m, 800 Hz, n = 4.49 10^{-2}**
- **Capture : 30 m, 800 Hz, n = 1.87 10^{-3}**

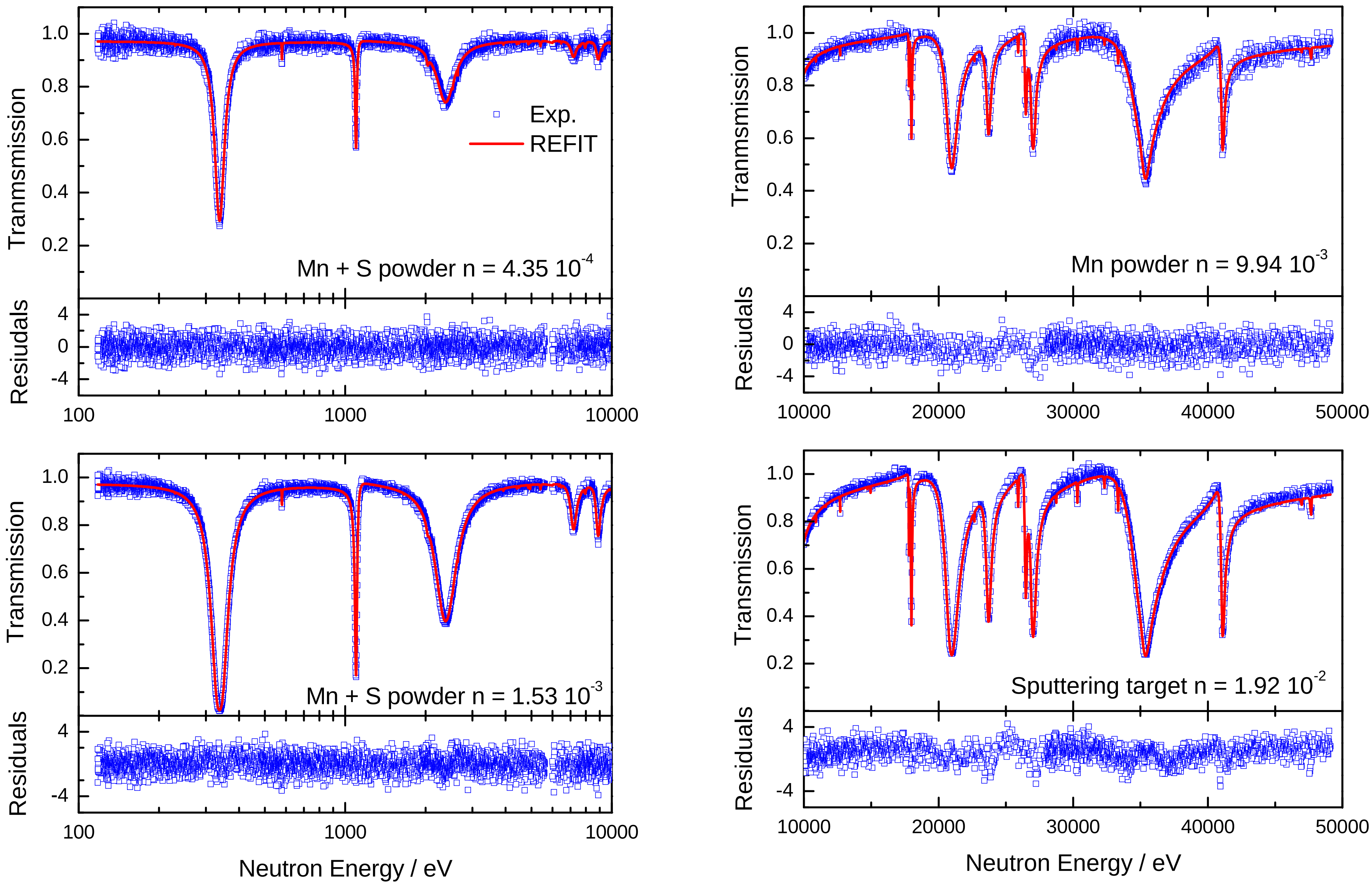
Analysis based on Sirakov et al. (WONDER 2006):

- **HF + WF with link to OM : Sirakov (IRMM) & Capote (IAEA)**
- **S_ℓ and R^∞ from Dispersive Coupled Channel Optical Model Potential**

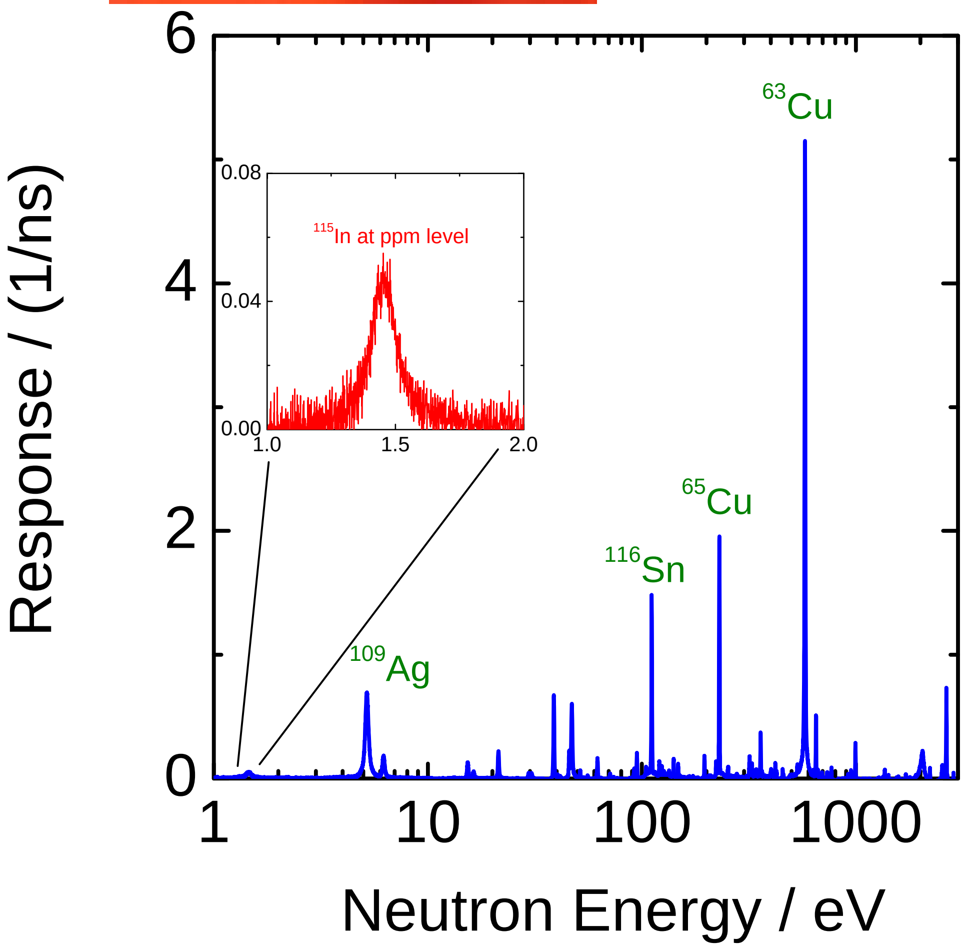


Mihailescu et al., ND2007

^{55}Mn Transmission measurements at 50 m



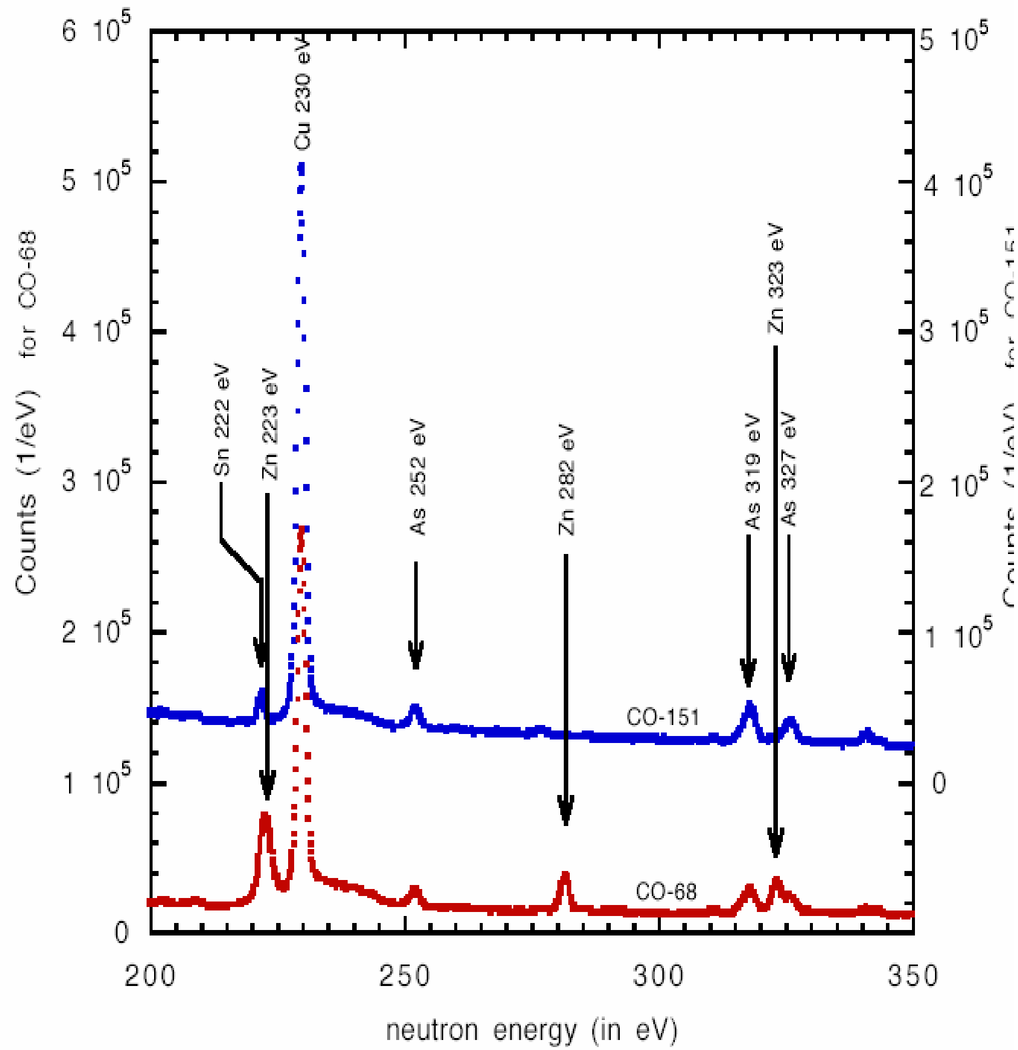
Neutron Resonance Capture Analysis : NRCA



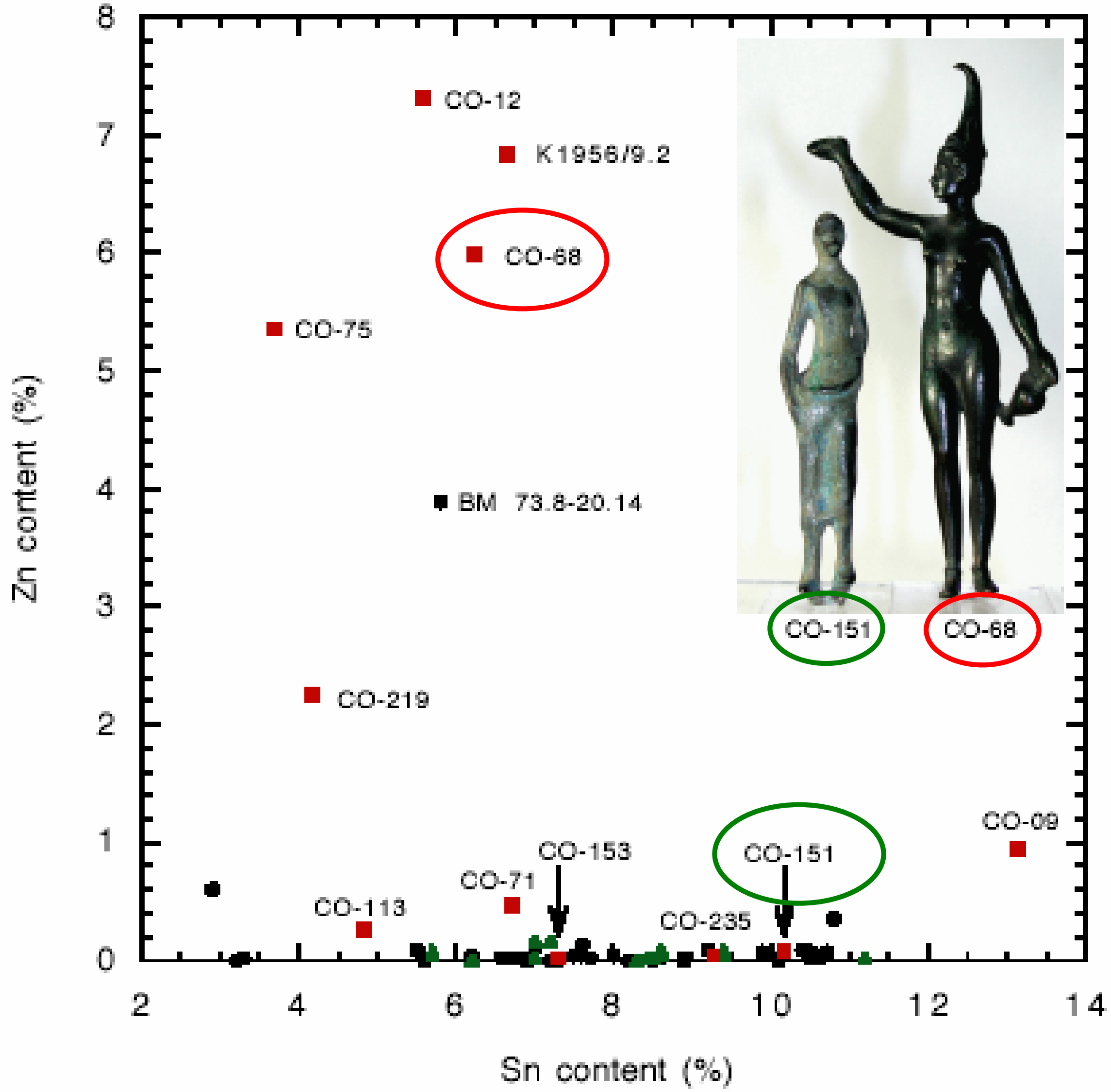
Element	Fractions (%)		Isotope	Resonance (eV)
Cu	77.76	(0.11)		
			^{63}Cu	579.0
			^{65}Cu	230.0
Sn	20.85	(0.10)		
			^{112}Sn	94.8
			^{116}Sn	111.2
			^{117}Sn	38.8
			^{118}Sn	45.7
			^{119}Sn	222.6
			^{120}Sn	427.5
			^{122}Sn	1756.0
			^{124}Sn	62.0
As	0.34	(0.01)		
			^{75}As	47.0
Sb	0.196	(0.021)		
			^{121}Sb	6.24
			^{123}Sb	21.4
Ag	0.090	(0.01)		
			^{107}Ag	16.3
			^{109}Ag	5.2
Fe	0.770	(0.09)		
			^{56}Fe	1147.4
In	0.0061	(0.0003)		
			^{115}In	1.46

NRCA : Authenticity of Etruscan artefacts

CO-151 CO-68



NRCA : Authenticity of Etruscan artefacts



Conclusions

- **GELINA : a TOF-facility similar to ORELA for high resolution cross section measurements in the resonance region.**
- **Importance of collaboration between ORNL and IRMM for production and analysis of cross section data in the resonance region.**
- **Progress in measurement capabilities, data reduction and analysis has improved the quality of the data.**
- **Accurate neutron induced cross section data, including full covariance information, can be obtained at these facilities from thermal up to the unresolved resonance region with improved uncertainty levels.**

EC-JRC-IRMM (B)
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