Neutron time-of-flight measurements at GELINA

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EFNUDAT Workshop
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Joint Research Centre (JRC)
IRMM - Institute for Reference Materials and Measurements
Geel - Belgium
http://irmm.jrc.ec.europa.eu/
http://www.jrc.ec.europa.eu/

Neutron resonance spectroscopy at GELINA

Efforts to produce accurate cross section data in the resonance region including full uncertainty information for nuclear energy applications:

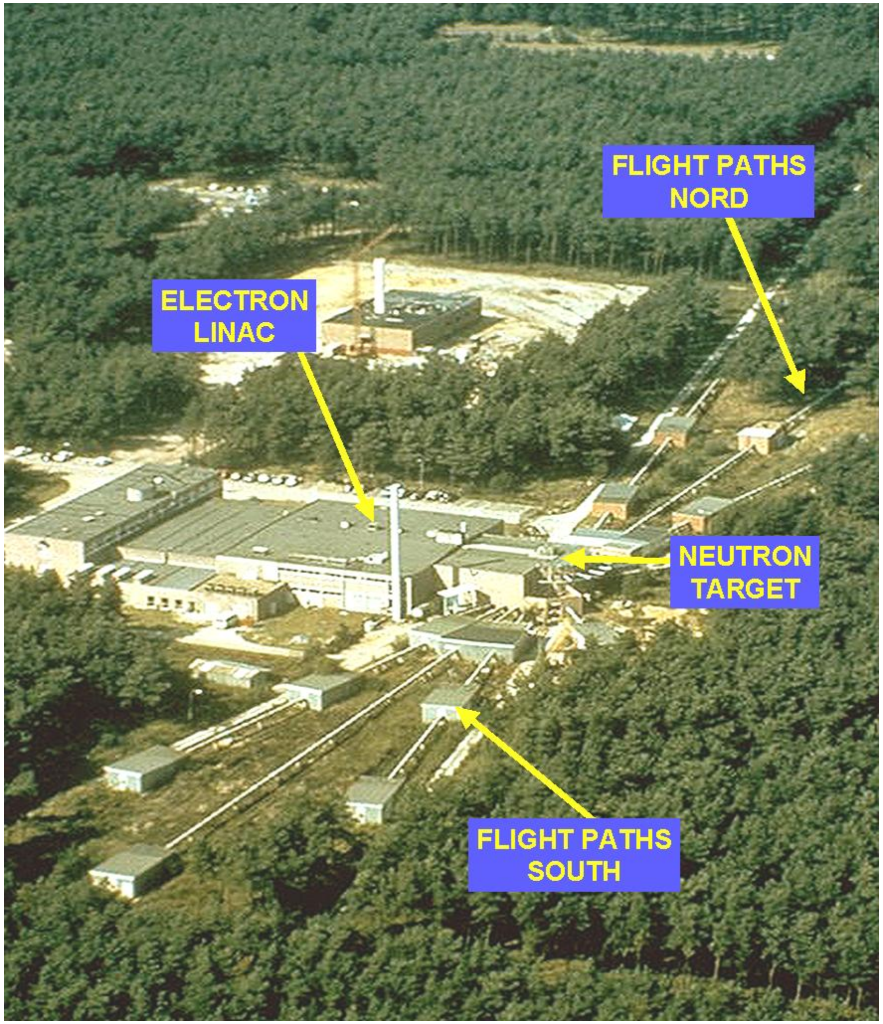
- **Accelerator performance**
- **Target characterization procedures**

  T. Belgya (EFNUDAT), Schillebeeckx et al. NIMA 613 (2010) 378 : α-spec. + NRCA & NRTA
- **Measurement capabilities**

  C. Massimi, EFNUDAT project reported at Budapest workshop
- **Data reduction procedures providing full covariance information**
- **Resonance analysis and evaluation in RRR and URR: production of ENDF-compatible files with covariances**

  S. Kopecky, EFNUDAT (Scientific visits I. Sirakov and M. Moxon)

TOF-facility GELINA

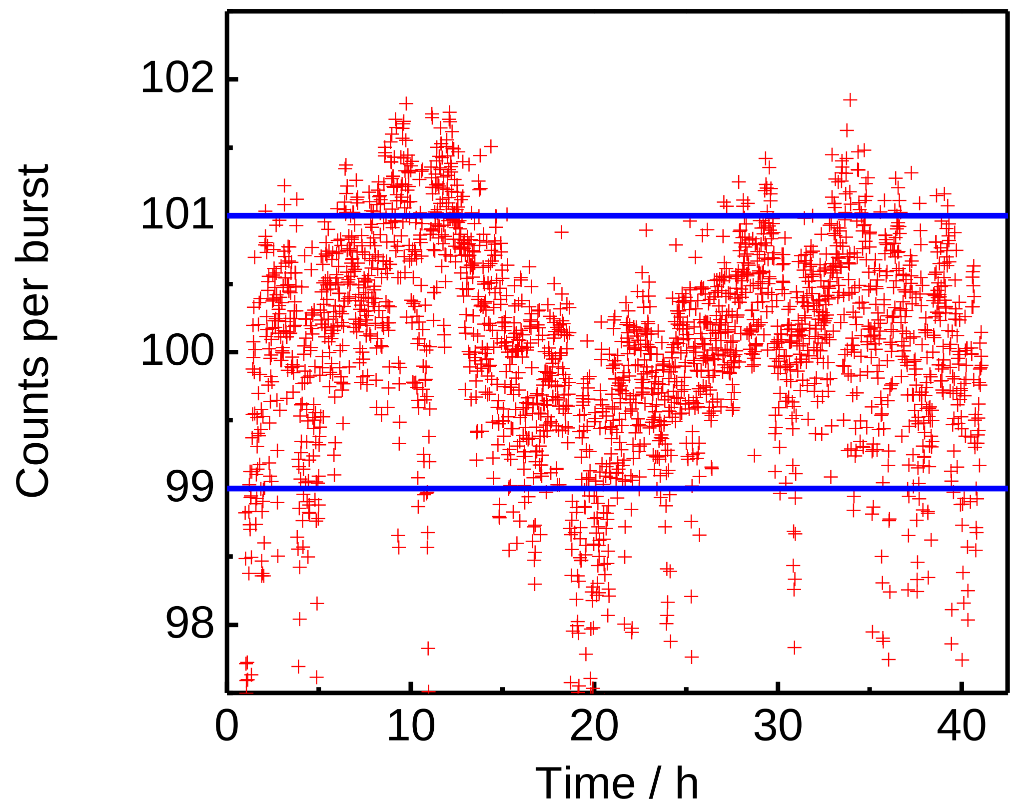


- **Pulsed white neutron source :**
  - 10 meV < E_n < 20 MeV
  - Δt = 1 ns (compression magnet)
- **Neutron energy by Time-Of-Flight**
- **Multi-user facility**
  10 Flight Paths (10 m - 400 m)
- **Measurement stations have special equipment to perform:**
  - Total cross section measurements
  - Partial cross section measurements

Accelerator refurbishment : started in 2001

Computer-controlled operation of accelerator and interlock system

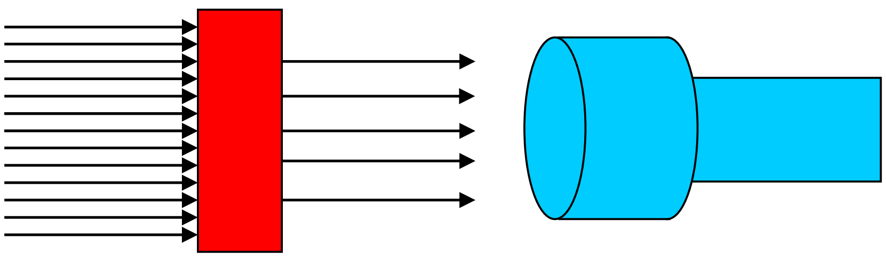
Stability at 1% level



Resonance parameters : $(E_r, J^{\pi}, \Gamma_n, \Gamma_{\gamma}, \Gamma_f)_j$ and R_{ℓ}

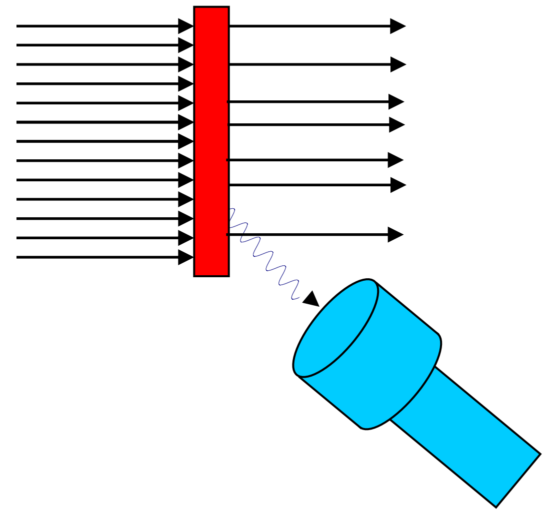
Transmission

$$T \propto e^{-n\sigma_t}$$



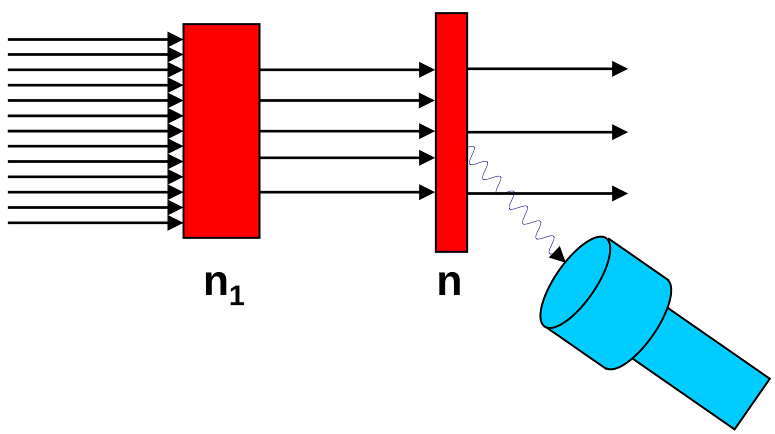
Capture, Fission

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



Self-indication

$$Y_{SI,\gamma} \propto e^{-n_1\sigma_t}((1 - e^{-n\sigma_t})\frac{\sigma_{\gamma}}{\sigma_t} + \ldots)$$



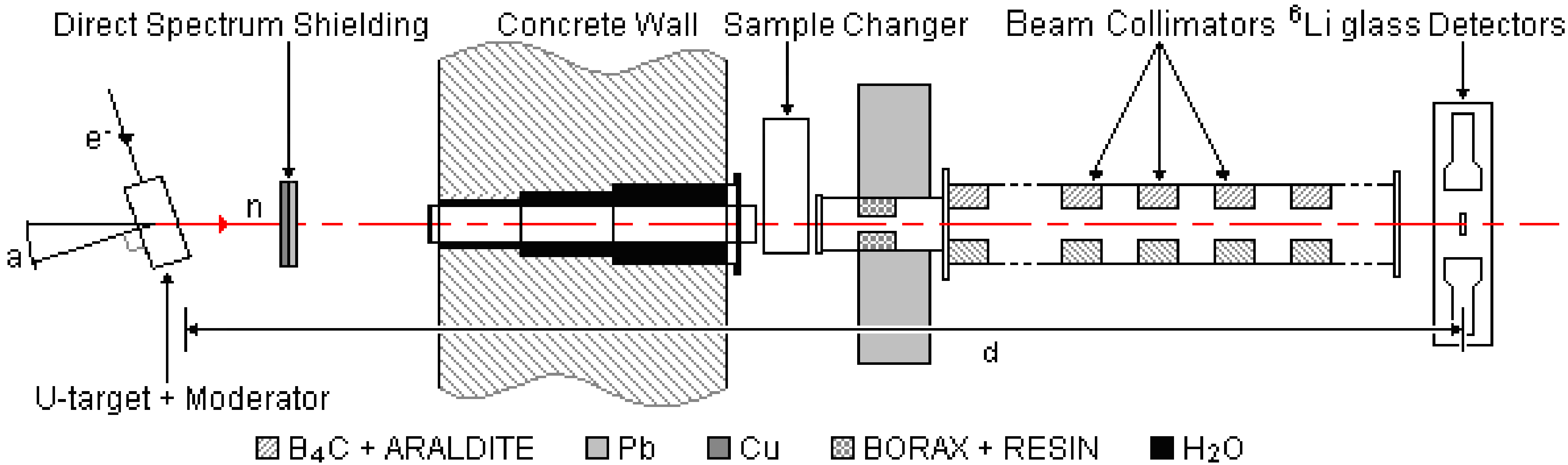
At GELINA
transmission, capture and self-indication data

Combine complementary experimental observables :

- **Reduce bias effects**
- **Traceable resonance energies from transmission**
- **Scattering radius**
- **Orbital angular momentum: $\ell = 0$ assignment (s-wave)**
- **Spin assignment**
  - **Thin - thick transmission data**
  - **Capture (thin) – transmission (thick) data**
  - **Self-indication data (C. Massimi EFNUDAT project)**
- **Normalization of capture data using $g\Gamma_n$ from transmission of strong capture resonances ($\Gamma_n < \Gamma_\gamma$)**

Transmission measurements at 25 m and 50 m

Moderated spectrum



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

$\Rightarrow (E_r, g\Gamma_n, \ell = 0, J, \Gamma,)$

$E_r = 6.6735 \pm 0.0030$ eV of ^{238}U+n

$L = 26.444 \pm 0.006$ m

$L = 49.345 \pm 0.012$ m

Capture and self-indication measurements at 12.5 m, 30m and 60 m

- **Flux measurements (IC)**
  - $^{10}B(n,\alpha)$ < 150 keV
  - $^{235}U(n,f)$ > 150 keV

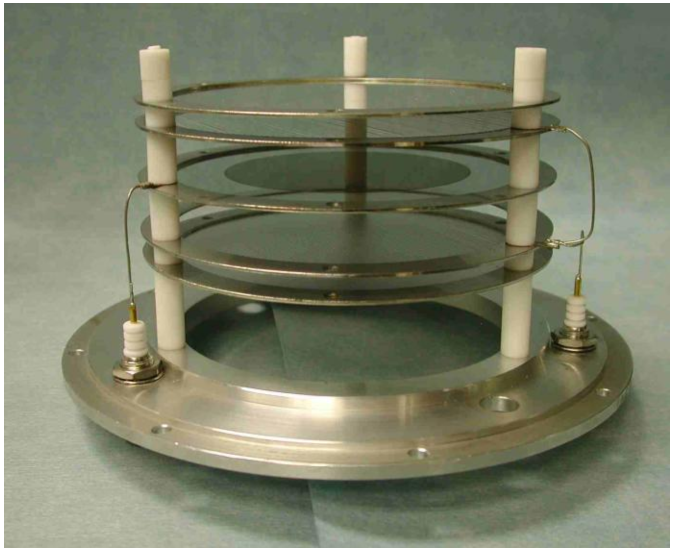
- **C_6D_6 liquid scintillators at 125°**
- **Total energy detection principle +PHWT**

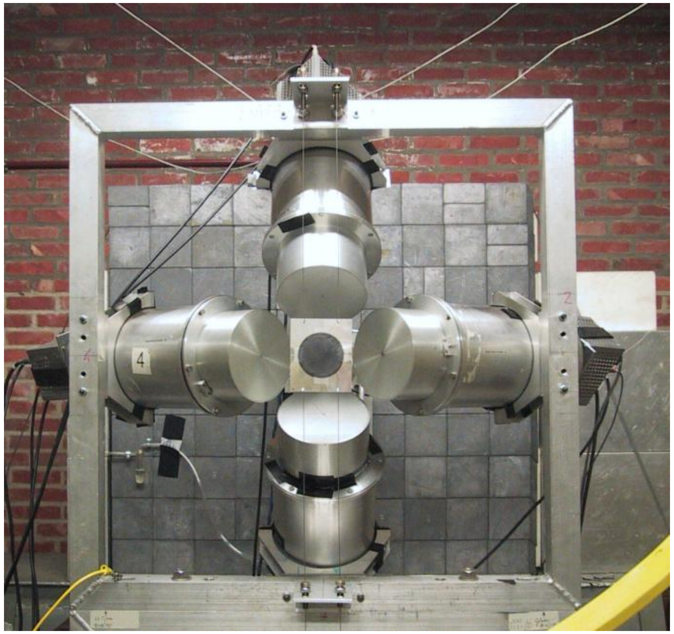
$$\int R(E_d,E_\gamma)\, WF\,(E_d)\, dE_d = kE_\gamma$$

WF : MC simulations (S. Kopecky)

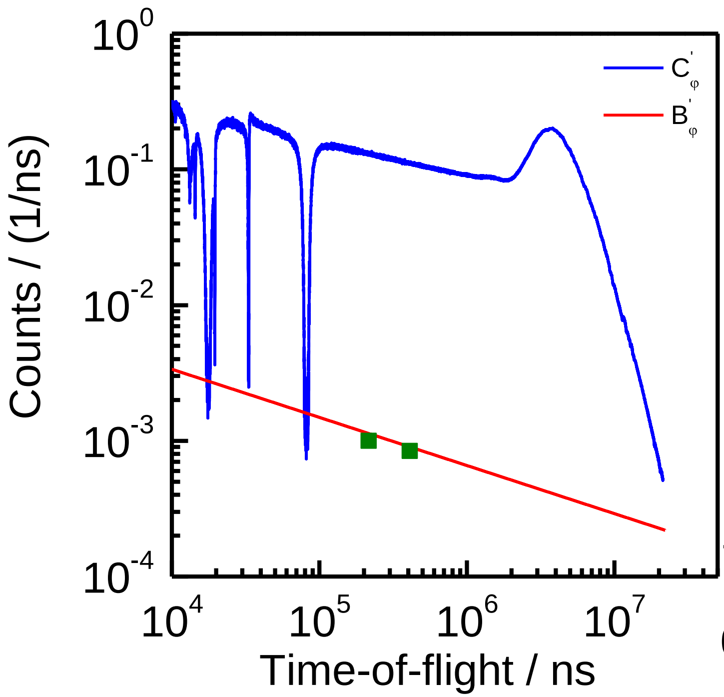
- For each target – detector combination
- γ-ray attenuation in sample (K_c in REFIT)
- WF's and K_c verified by experiment

Borella et al., NIMA 577(2007) 626

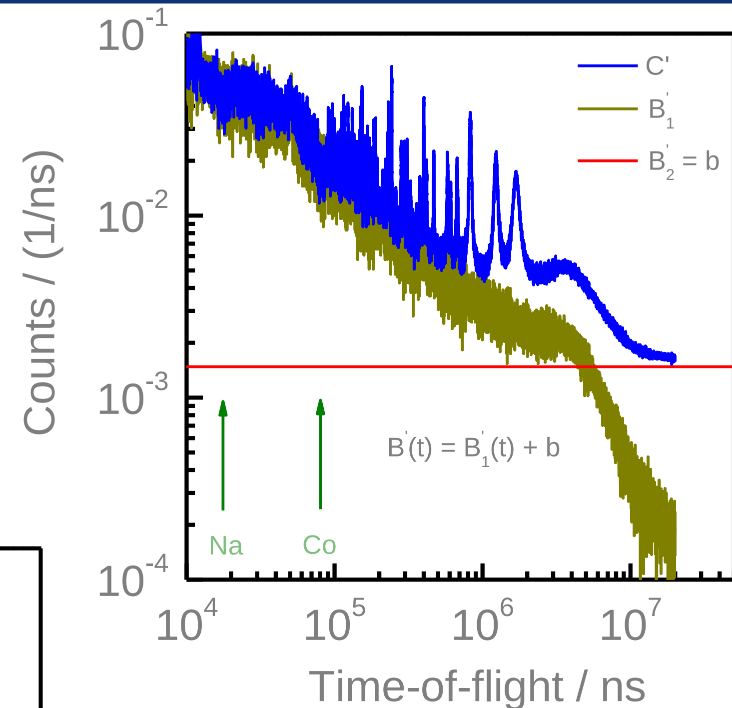


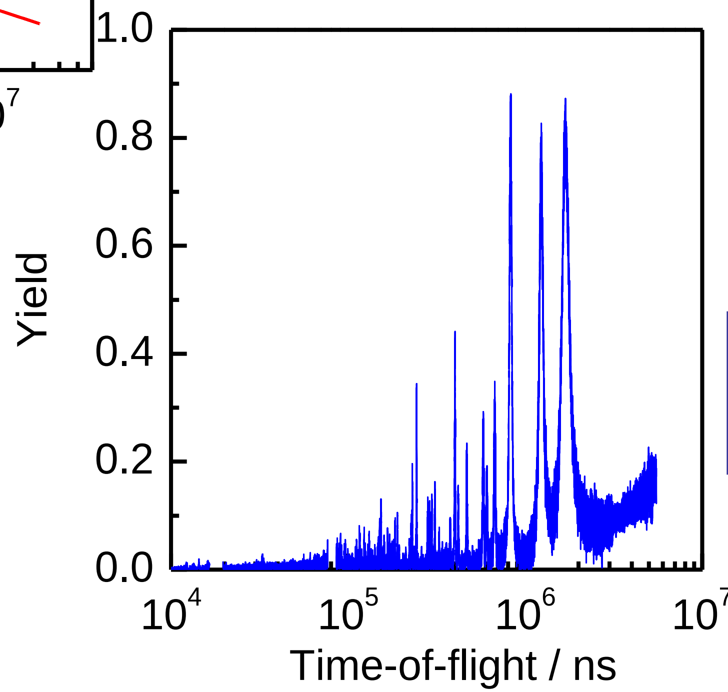


^{241}Am(n,γ) measurement at 12.5 m and 50 Hz



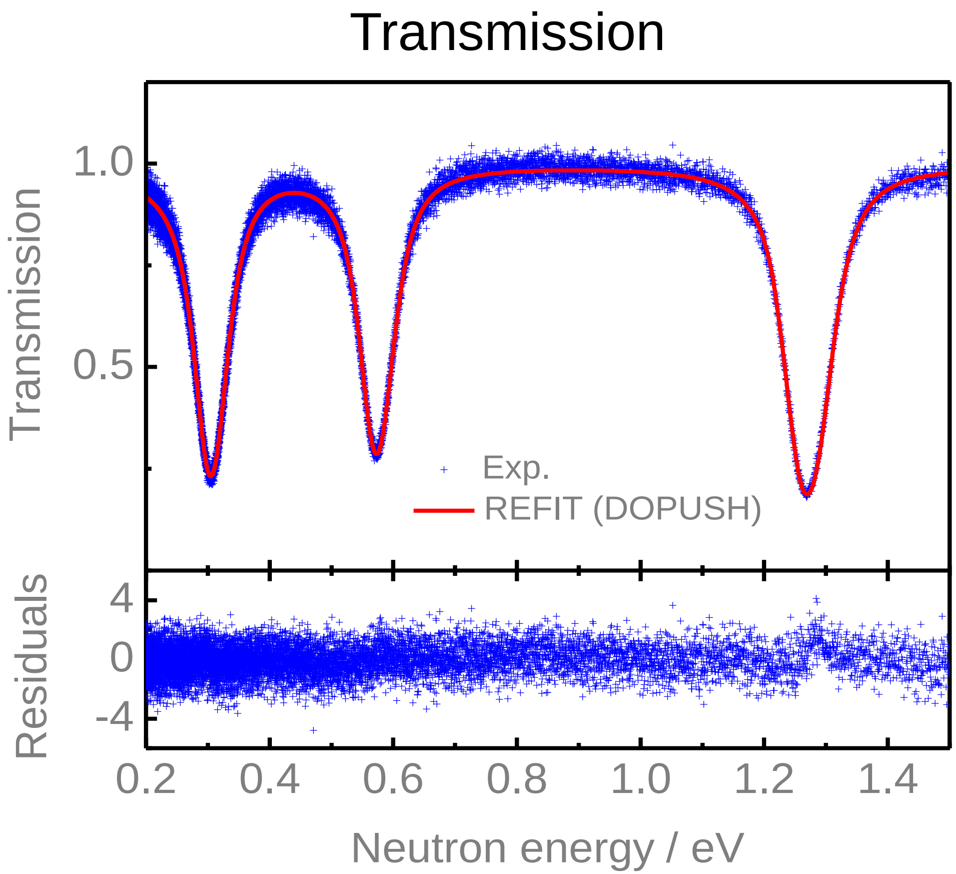
$$Y_{exp} = N \frac{C'_w - B'_w}{C'_\varphi - B'_\varphi} Y_\varphi$$

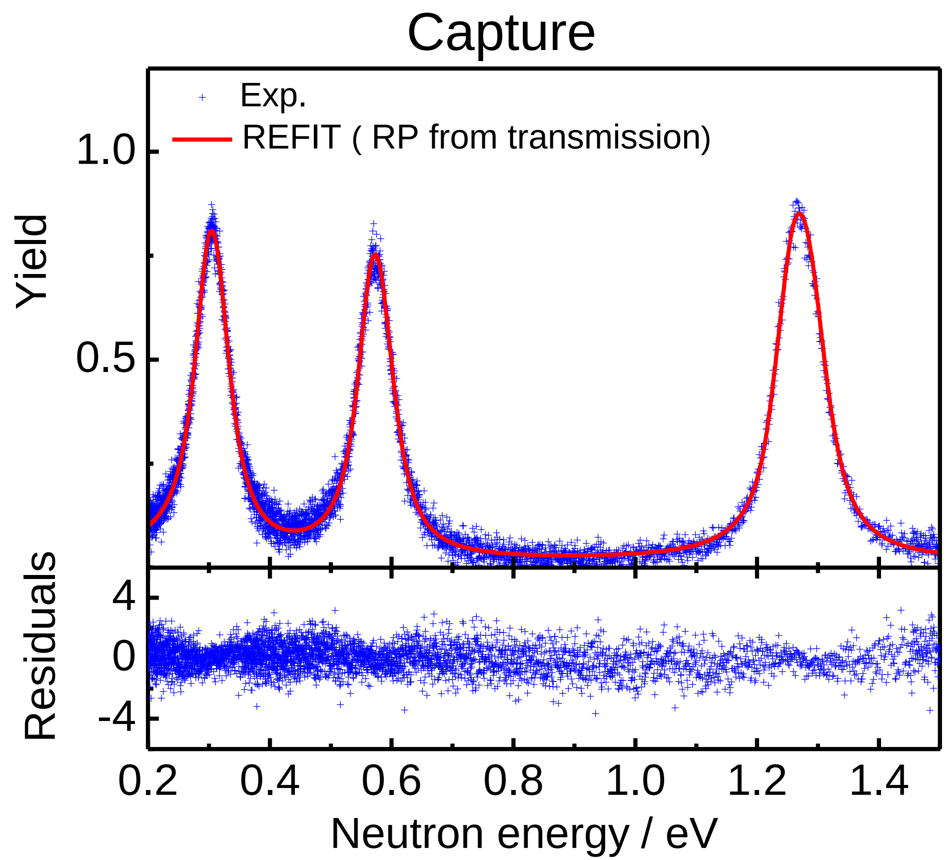




At least one fixed background filter

^{241}Am + n : transmission and capture ANDES project





Normalization capture data :

by simultaneous analysis of capture and transmission data with REFIT

Reduction of correction factors to be applied: e.g. for IC, flux profile, …

Data reduction with AGS (Analysis of Geel Spectra)

- **Transforms count rate spectra into observables (T, Y_{exp}, Y_{SI})**
- **Full uncertainty propagation starting from counting statistics**

$$V_Z = U_Z + S_{\vec{a}} S_{\vec{a}}^T$$

n : dimenstion of TOF-spectrum
k : number of correlated components

dim. (n x n)   dim. n S_a : dim. (n x k)

- **Reduction of space needed for data storage**
- **Document all uncertainty components involved in data reduction**
  - **Study the impact of uncertainty components on RP and cross sections**
  - **Provides full experimental details to evaluators**
- **Recommended by International Network of Nuclear Reaction Data Centres to store data in EXFOR**
- **WPEC sub-group 36**

  “Reporting and usage of experimental data for evaluation in the RRR ”

Uncertainty propagation in AGS

(1) Data reduction starts from spectra subject only to uncorrelated uncertainties

(2) Channel – channel operations (+, - , x , ÷) and log, exp, …

(3) Additional computations using parameters with well defined covariance matrix

$$Z = F(\vec{a}, Y) \quad \text{e.g.} \quad Z(t) = Y(t) - (a_1 + a_2 t^{a_3})$$

Covariance matrix V_a well defined

$\Rightarrow$ symmetric and positive definite

$\Rightarrow$ Cholesky transformation

V_Y only diagonal terms :

$\Rightarrow D_Y = V_Y \qquad v_{Y,i\neq j} = 0$

$$S_{\vec{a}} = \left(\frac{\partial F}{\partial \vec{a}}\right) L_{\vec{a}}$$

$$V_{\vec{a}} = L_{\vec{a}} L_{\vec{a}}^T \quad \longrightarrow \quad V_Z = U_Z + S_{\vec{a}} S_{\vec{a}}^T$$

L_a : lower triangular matrix

U_Z – diagonal : n values

$S_{\vec{a}}$ – dimension: n x k

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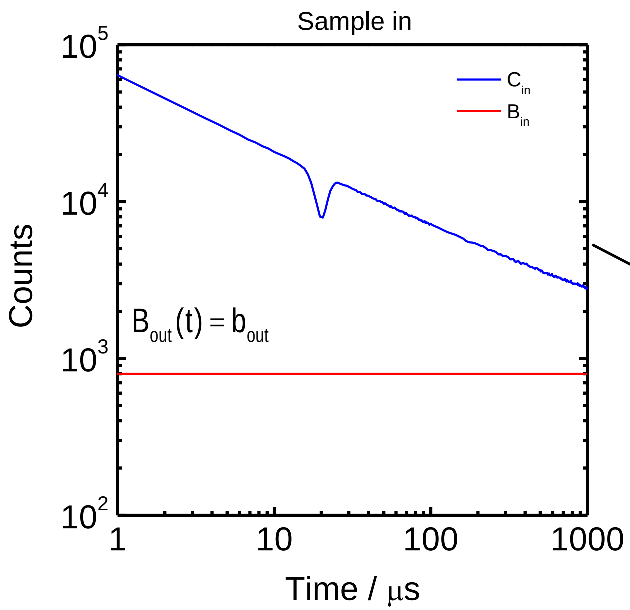
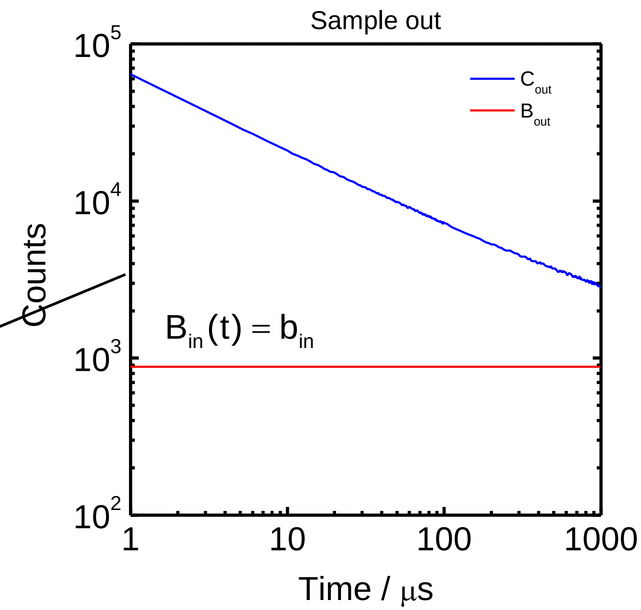
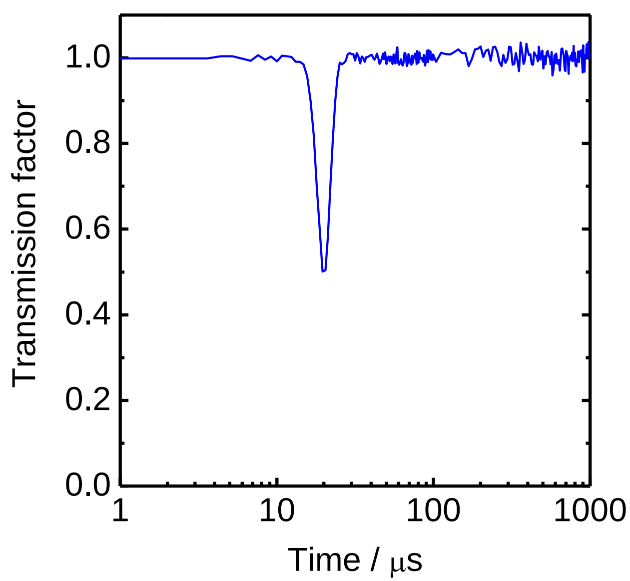
Data reduction of transmission : T_{exp}





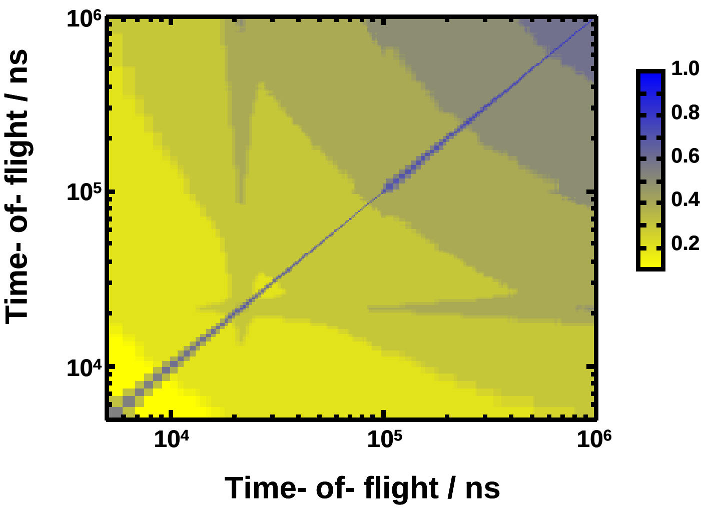
$$T_{exp} = N \frac{C_{in} - B_{in}}{C_{out} - B_{out}}$$



Output AGS_PUTX

$\delta N / N$: 0.5 %

$\delta B_{in} / B_{in}$: 10.0 %
$\delta B_{out} / B_{out}$: 5.0 %



X_L	X_H	Z	δZ	δZ_u	$C_Z = D_Z + S\,S^T$			
					D_Z	S		
					δZ_u^2	B_{in}	B_{out}	N
800	1600	0.999	0.79E-2	0.59E-2	0.35E-4	0.14E-2	-0.08E-2	0.50E-2
1600	2400	0.999	0.86E-2	0.67E-2	0.45E-4	0.18E-2	-0.10E-2	0.50E-2
2400	3200	0.999	0.92E-2	0.73E-2	0.54E-4	0.21E-2	-0.12E-2	0.50E-2
3200	4000	0.999	0.97E-2	0.78E-2	0.61E-4	0.24E-2	-0.13E-2	0.50E-2
.	.	.	.	.	.	.	.	.
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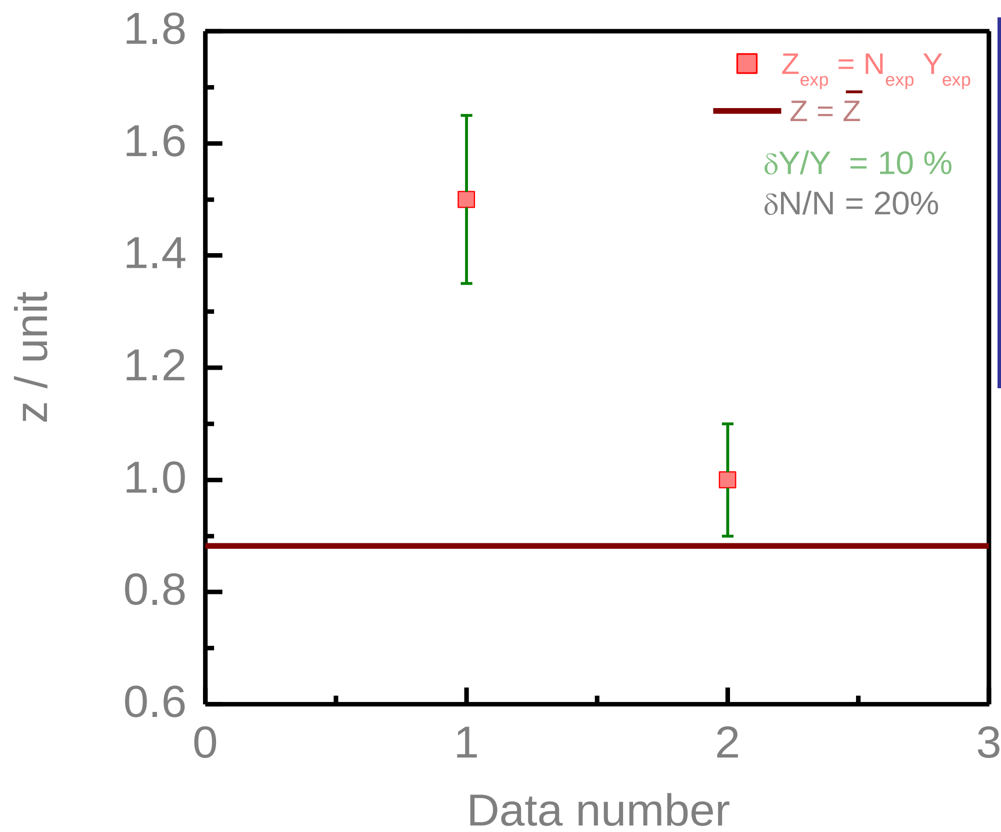
.	.	.	.	.	.	.	.	.
16000	16800	0.899	1.30E-2	1.07E-2	1.15E-4	0.51E-2	-0.25E-2	0.45E-2
16800	17600	0.818	1.24E-2	1.02E-2	1.04E-4	0.53E-2	-0.24E-2	0.41E-2
17600	18400	0.701	1.15E-2	0.93E-2	0.86E-4	0.54E-2	-0.21E-2	0.35E-2
18400	19200	0.594	1.06E-2	0.84E-2	0.71E-4	0.55E-2	-0.18E-2	0.30E-2
19200	20000	0.501	0.98E-2	0.76E-2	0.57E-4	0.56E-2	-0.15E-2	0.25E-2
20000	20800	0.504	1.00E-2	0.77E-2	0.59E-4	0.57E-2	-0.16E-2	0.25E-2
20800	21600	0.581	1.09E-2	0.85E-2	0.73E-4	0.58E-2	-0.19E-2	0.29E-2
21600	22400	0.707	1.22E-2	0.98E-2	0.97E-4	0.60E-2	-0.23E-2	0.35E-2
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
964000	972000	0.999	5.91E-2	3.75E-2	14.06E-4	3.98E-2	-2.18E-2	0.50E-2
972000	980000	1.037	6.09E-2	3.89E-2	15.13E-4	4.04E-2	-2.31E-2	0.52E-2
980000	988000	1.001	6.01E-2	3.80E-2	14.46E-4	4.05E-2	-2.23E-2	0.50E-2
988000	996000	1.010	5.92E-2	3.77E-2	14.23E-4	3.96E-2	-2.20E-2	0.50E-2

Peelle's Pertinent Puzzle



$$Z_{exp} = N_{exp} Y_{exp}$$

$$\frac{\delta N_{exp}}{N_{exp}} = 20\% \quad \text{and} \quad \frac{\delta Y_{exp}}{Y_{exp}} = 10\%$$

$$\vec{Z} = \bar{Z}$$

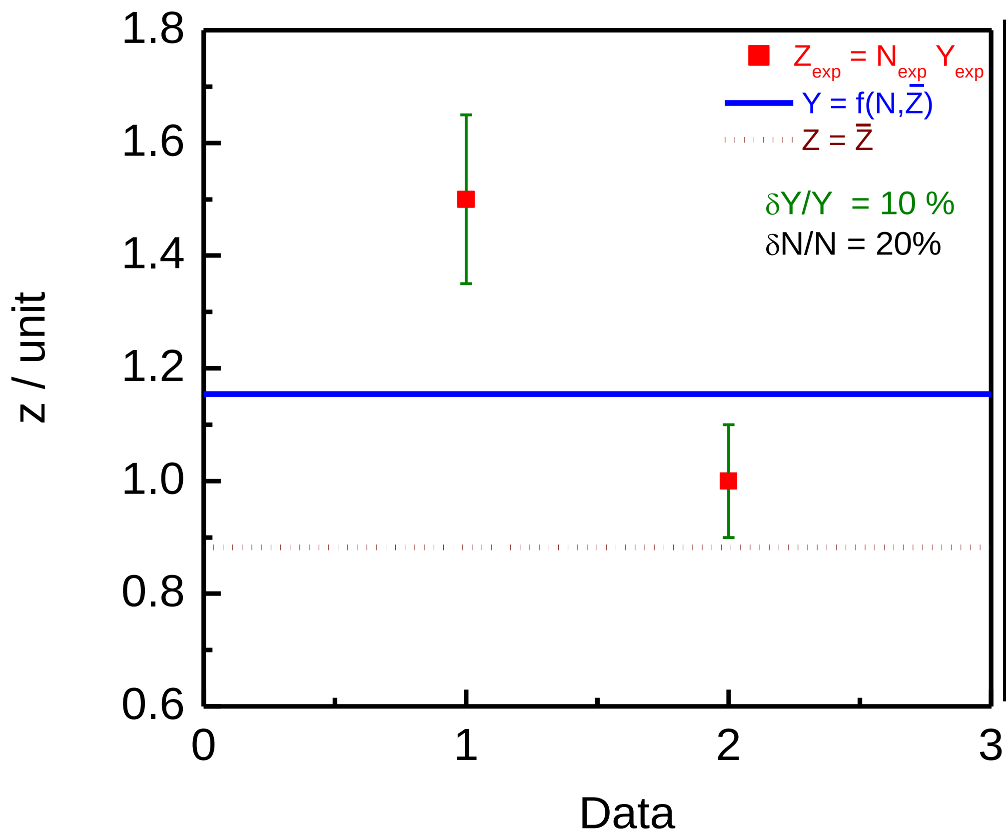
$$\chi^2(\bar{Z}) = (\vec{Z}_{exp} - \bar{Z})^T \, V_Z^{-1} \, (\vec{Z}_{exp} - \bar{Z})$$

⇒ Reporting Z_{exp} + V_Z does not provide enough experimental information to evaluate data

Solution : Fröhner, NSE 126 (1997) 1- 18

$$(N,\vec{Y}) = f(N,\overline{Z}) = (N,\frac{\overline{Z}}{N})$$

$$\chi^2(N,\overline{Z}) = ((N_{exp},\vec{Y}_{exp}) - f(N,\overline{Z}))^T\ V^{-1}_{(N,Y)}\ ((N_{exp},\vec{Y}_{exp}) - f(N,\overline{Z}))$$



⇒ **Detailed model of experiment required**

⇒ **Experimental details required**

⇒ **Recommendations NRDC:**

“Report data using AGS procedures”

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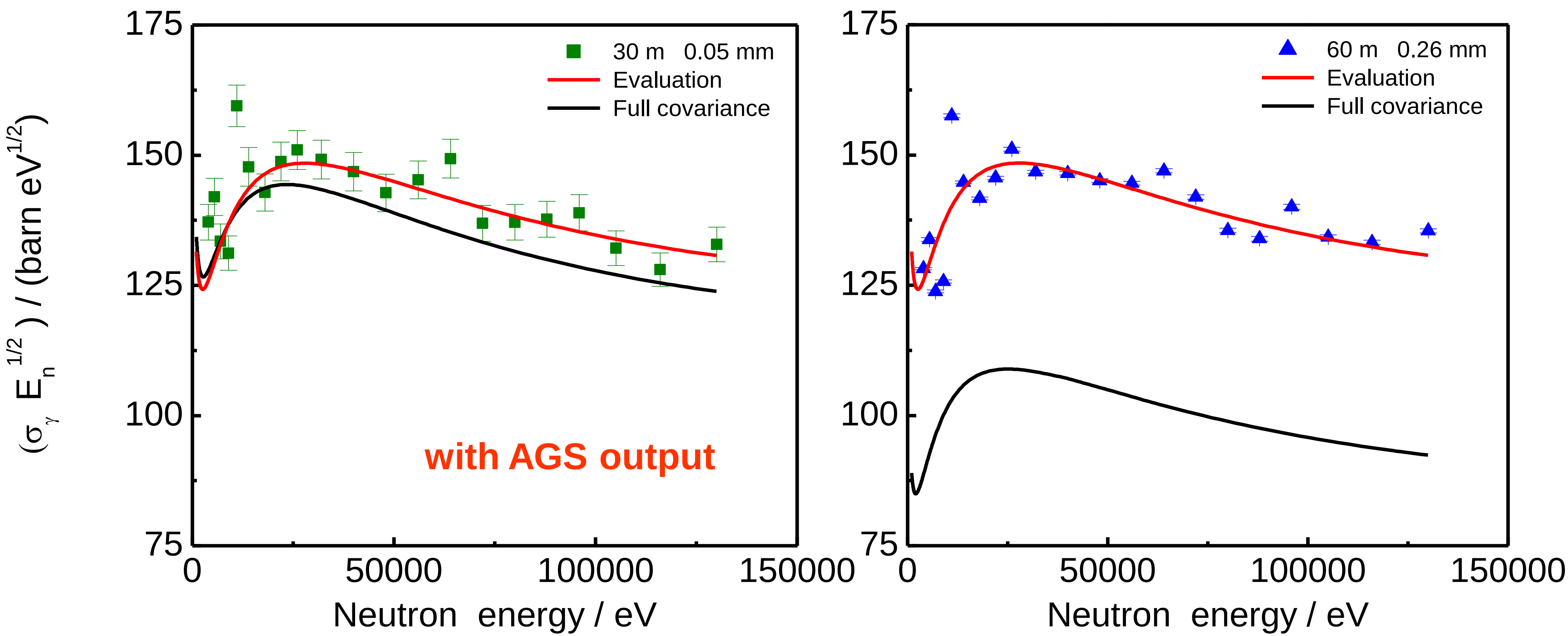
Peelle's Pertinent Puzzle: e.g. ^{103}Rh(n,γ) in URR (EFNUDAT project)



$$(N, \vec{Y}) = f(N, S_\ell, T_\ell) = (N, \frac{\vec{Z}_{HF}}{N})$$

$$\chi^2(N, \overline{Z}) = ((N_{exp}, \vec{Y}_{exp}) - f(N, S_\ell, T_\ell))^T \; V^{-1}_{(N,Y)} \; ((N_{exp}, \vec{Y}_{exp}) - f(N, S_\ell, T_\ell))$$

Evaluation for Cd + n
IAEA – IRMM NUDAME project

- **Capture measurements with enriched ^{111}Cd at ORELA**

  Wasson and Allen Phys. Rev. C 7 (1973) 780

- **Transmission measurements with enriched $^{110, 112, 114,116}$Cd and ^{nat}Cd at Columbia Univ. (NEVIS synchrocyclotron)**

  Liou et al. Phys. Rev. C 10 (1974) 709

- **Capture measurements with enriched $^{110, 112, 114,116}$Cd at ORELA**

  Musgrove et al. , J. Phys. G:Nucl. Phys., 4 (1978) 771

- **Capture measurements with enriched ^{113}Cd at LANL**

  Frankle et al., Phys. Rev. C 45 (1992) 2143

- **Transmission and capture measurements with enriched ^{113}Cd at ORELA**

  Frankle et al., Phys. Rev. C 50 (1994) 2774

- **Transmission and capture measurements with ^{nat}Cd at GELINA**

⇒ Simultaneous resonance shape analysis with REFIT

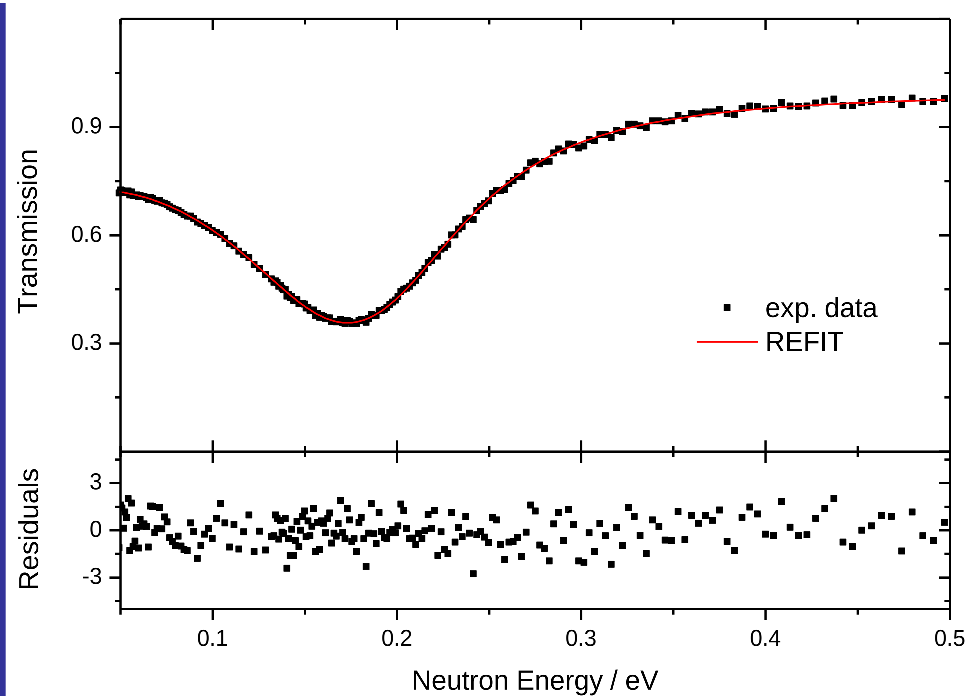
^{113}Cd+n : 0.179 eV resonance

Experiment ⇒ Data reduction with AGS ⇒ REFIT

Thin – Thick transmission
(1.3610^{-4} 2.2410^{-4} at/b)
Metal discs

$\ell = 0$ J =1 $\chi^2 = 0.98$
$\ell = 0$ J =0 $\chi^2 = 1.30$

Parameter	p / meV			$\rho(p_i,p_j)$	
E_R	178.7	± 0.1	1.00	0.53	0.28
Γ_γ	113.5	± 0.2		1.00	0.26
Γ_n	0.640	± 0.004			1.00



$\Delta_D \sim 20$ meV
$\Delta_R \sim 0.2$ meV (L = 50 m)

Kopecky et al., NIMB 267 (2009) 2345 - 2350

^{113}Cd : impact of uncertainty components (only transmission)

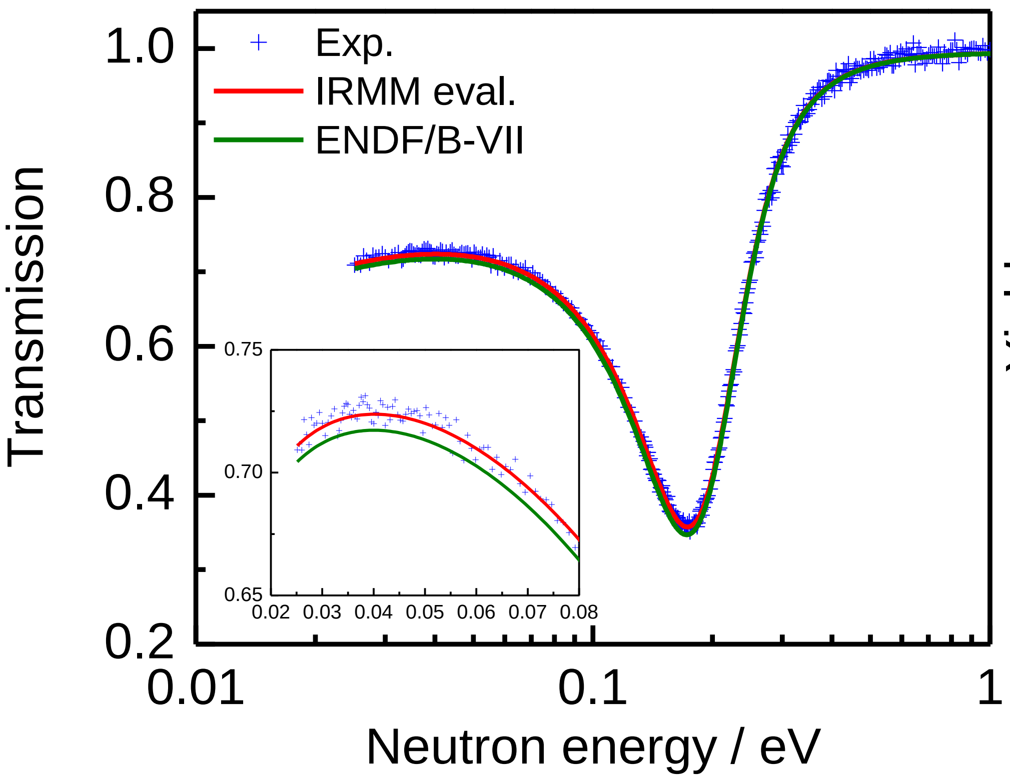
Parameter	δp_{ini}	p	δp	$\rho(p_i,p_j)$						
				E_R	Γ_γ	Γ_n	L	n	T_D	N
E_R / meV	-	178.7	± 0.074	1.00	0.53	0.28	0.13	0.00	0.00	-0.34
Γ_γ / meV	-	113.5	± 0.22		1.00	0.26	0.20	0.02	-0.04	-0.70
Γ_n / meV	-	0.640	± 0.0036			1.00	0.11	-0.91	-0.00	-0.28
L / m	0.006	26.4439	± 0.006				1.00	-0.00	0.01	-0.09
n / (at/b)	0.5 %		± 0.5 %					1.00	0.00	-0.00
T_D / meV	0.5 %	25.46	± 0.5 %						1.00	0.00
N (norm)	0.5 %	1.000	± 0.0013							1.00

Data reduction: counting statistics, dead time, background

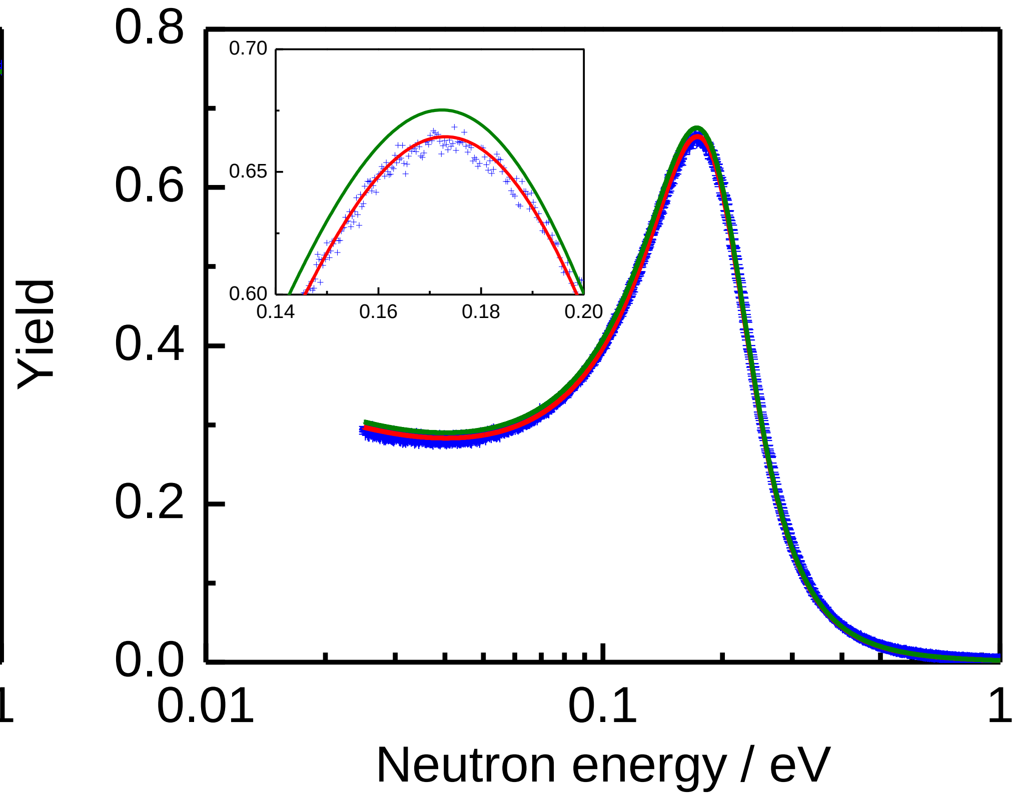
Parameter	p / meV	$\rho(p_i,p_j)$		
E_R	178.7 ± 0.069	1.00	0.43	0.64
Γ_γ	113.5 ± 0.16		1.00	0.31
Γ_n	0.640 ± 0.0011			1.00

Evaluation for $^{nat}Cd + n$

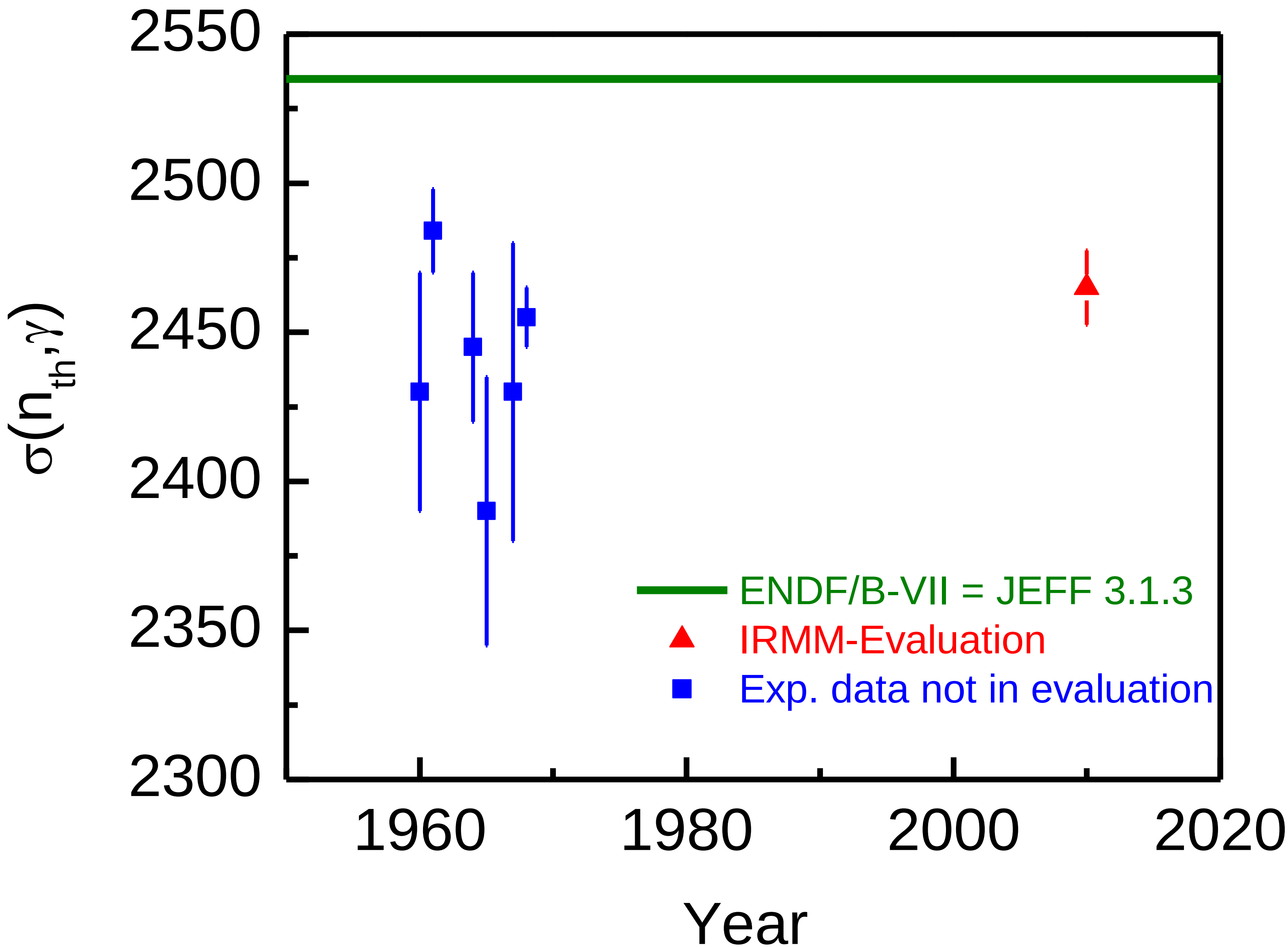
Transmission



Capture



$^{nat}Cd(n,\gamma)$ at 2200 m/s



Conclusions and outlook

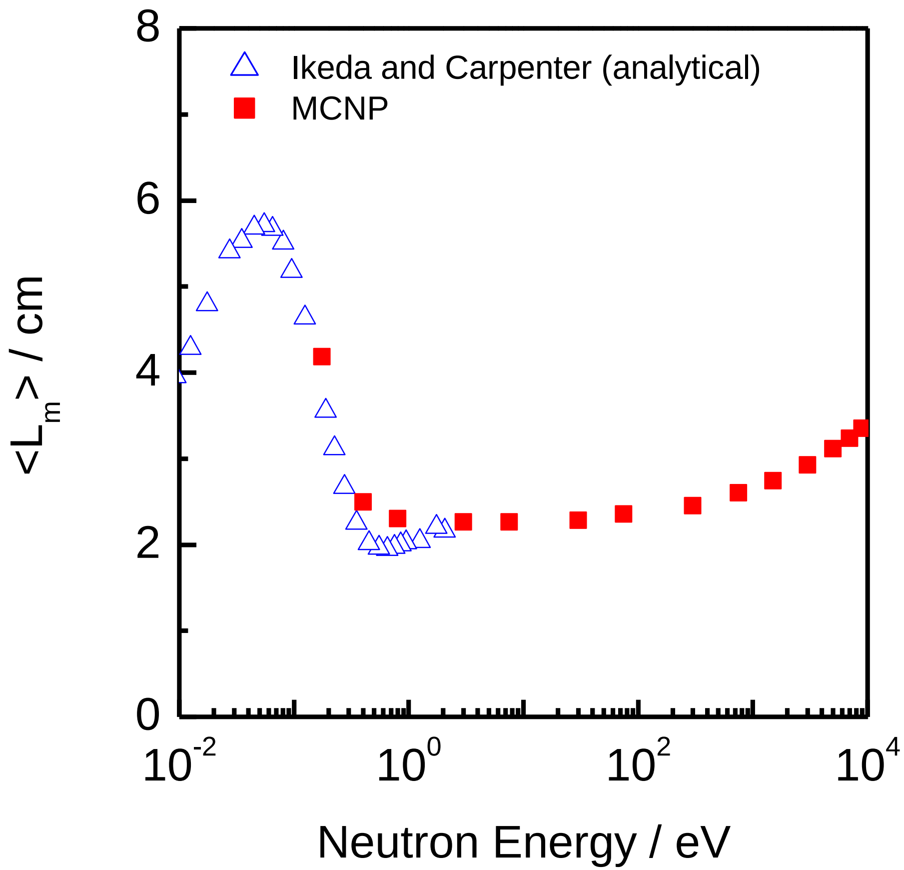
Continuous efforts to produce accurate cross section data in the resonance region together with full uncertainty information

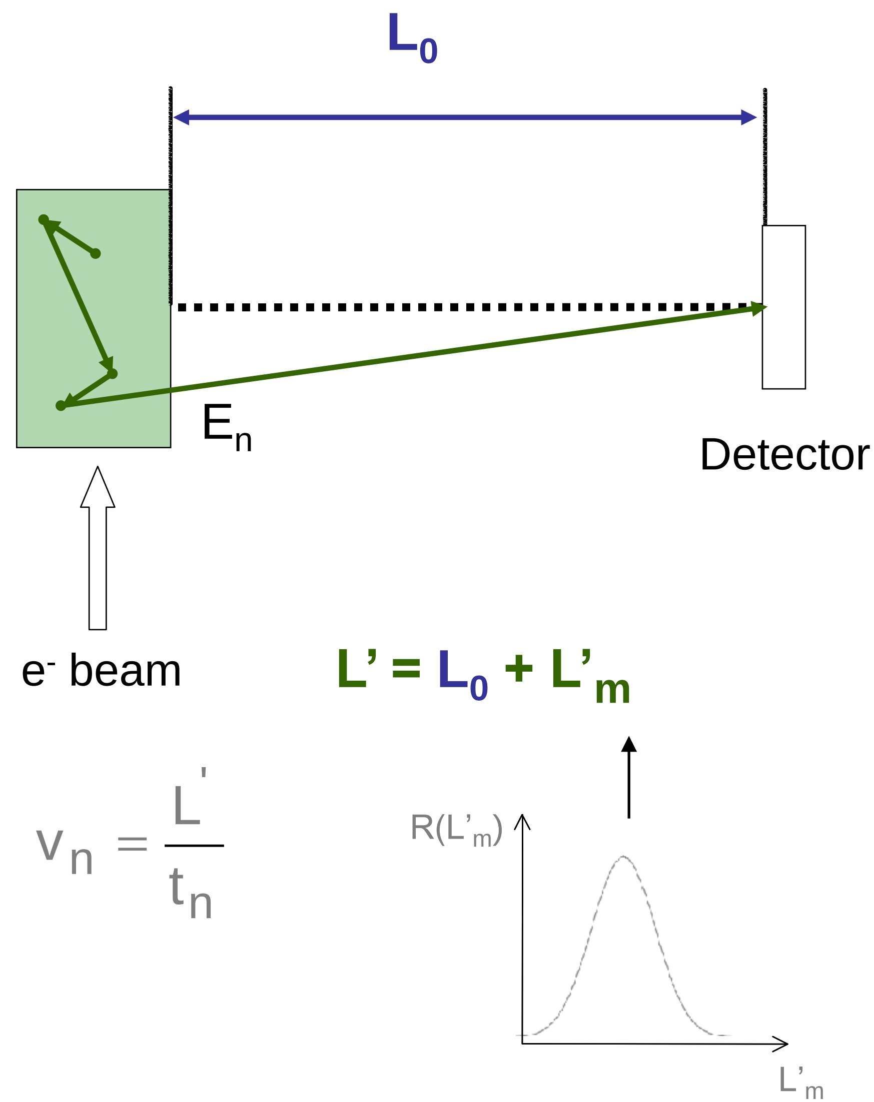
⇒ full ENDF compatible evaluation including covariances (EFNUDAT)

Outlook

- **Evaluation for Rh, W and Cu (collaboration with ORNL)**
- **^{197}Au + n : evaluation in URR and standard σ(n, γ) (IAEA CRP, nTOF)**
  Simultaneous analysis capture + transmission + link to OM (S. Kopecky)
- **^{238}U + n : evaluation in URR and σ(n, γ)**
  ANDES : GELINA & nTOF
- **^{241}Am + n : evaluation in RRR based on transmission and capture**
  ANDES : GELINA & nTOF
- **Resonance energies traceable to SI – units**

Resonance energies depend on response function of the TOF spectrometer

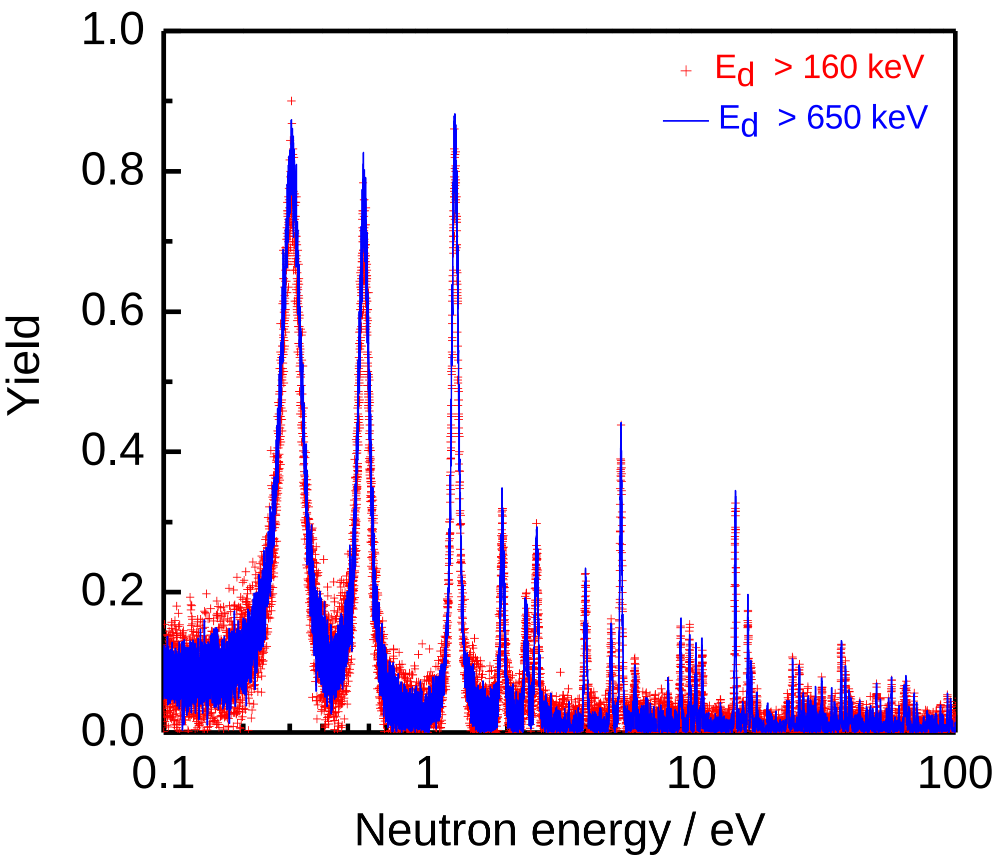


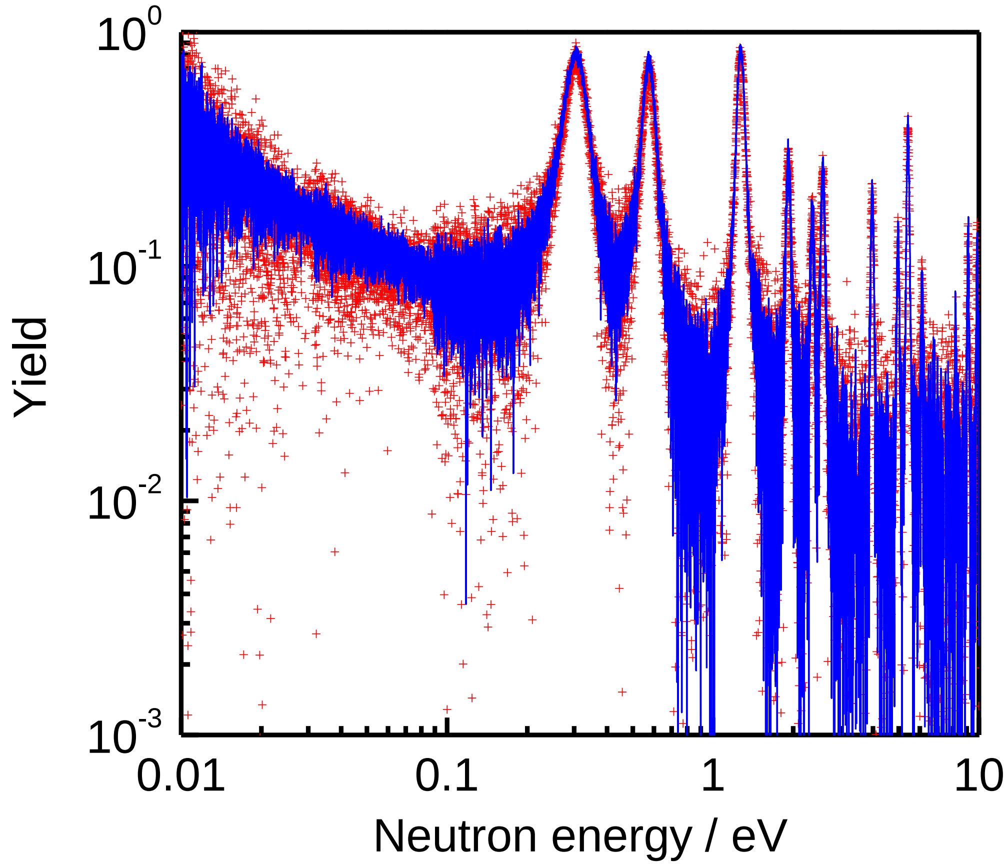


$$v_n = \frac{L'}{t_n}$$

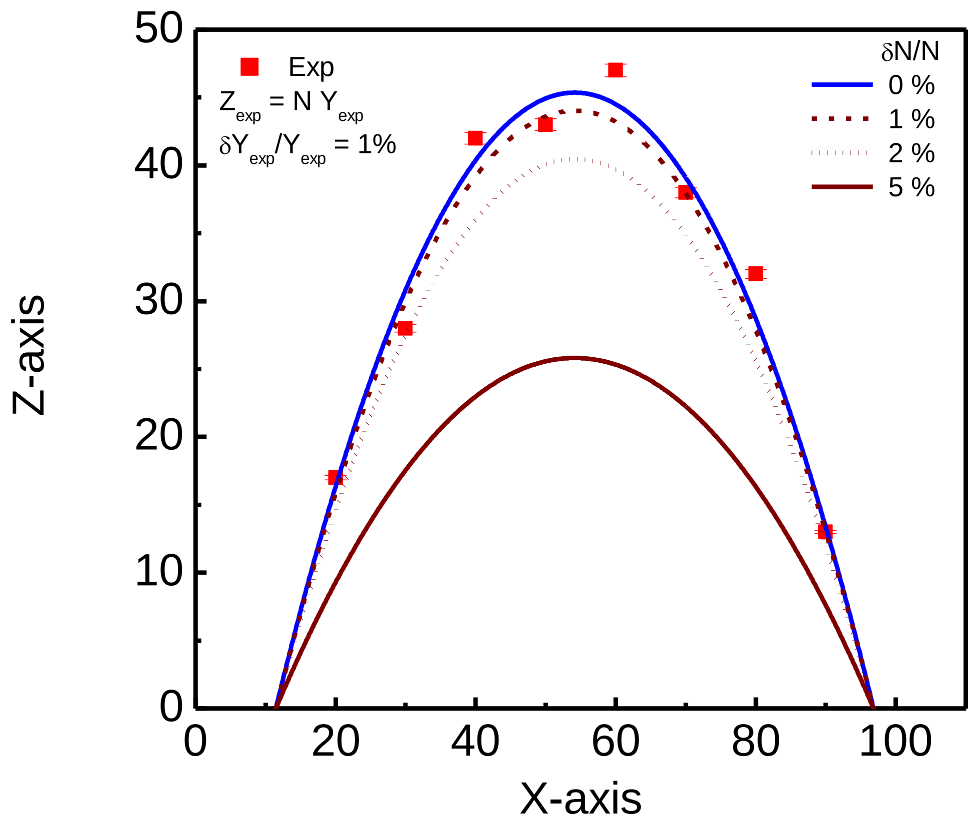
Resonance energy depends on response function of TOF-spectrometer
Storage term of Ikeda and Carpenter in REFIT (see S. Kopecky)

Capture yield: impact of threshold E_d > 160 and 650 keV





Peelle's Pertinent Problem



$$\vec{Z} = f(\vec{a}, X) = \sum_{i=0}^{2} a_i \; X^i$$

$$\chi^2(\vec{a}) = (\vec{Z}_{exp} - f(\vec{a}, X))^T \; V_Z^{-1} \, (\vec{Z}_{exp} - f(\vec{a}, X))$$