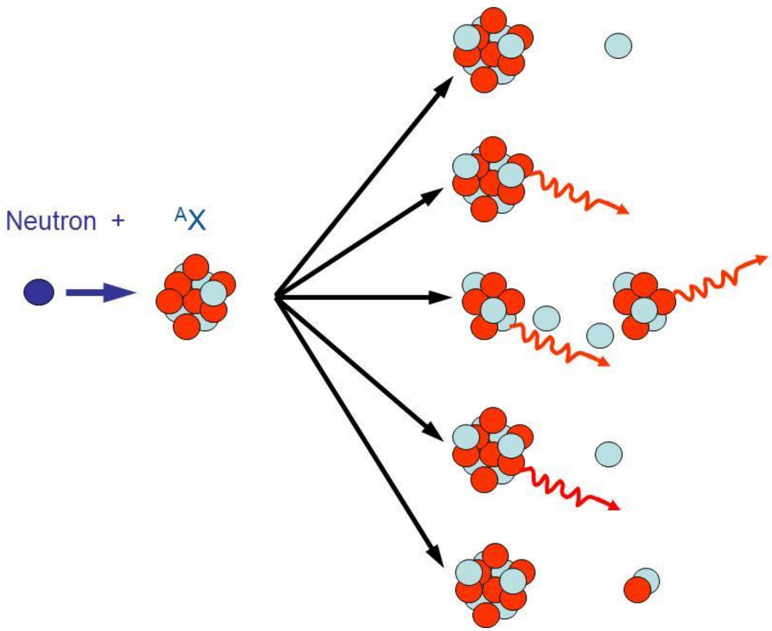
Nuclear data activities at JRC Geel in support to nuclear technology

1st RAON Users Workshop
3 – 5 April, 2019
Daejeon, South Korea

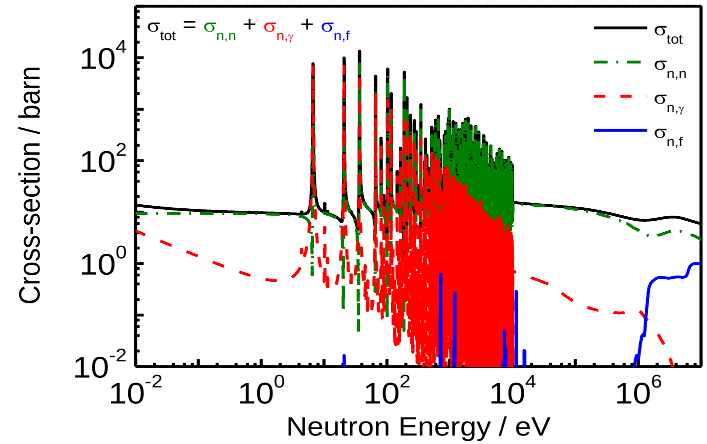
Peter Schillebeeckx
JRC Geel, SN3S
peter.schillebeeckx@ec.europa.eu

European Commission

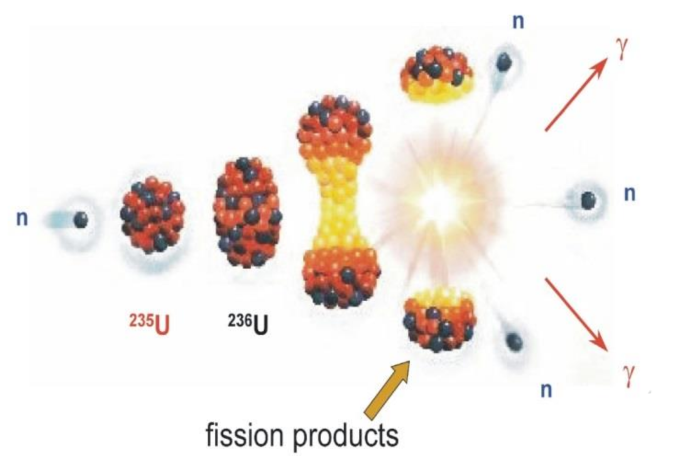
Nuclear data activities at JRC Geel ⇔ NDPS at RAON



- **Neutron induced interaction cross sections**



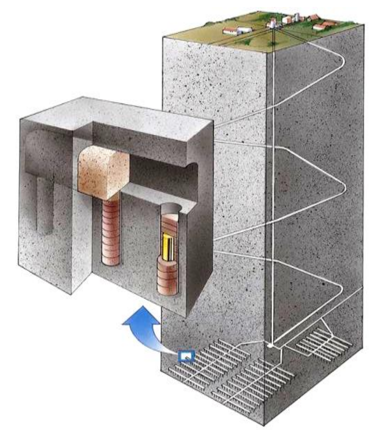
- **Nuclear fission process**



Applications

- **Nuclear data for nuclear energy technology**
  - Safety of current systems
  - Development of innovative systems (e.g. MYRRHA)
  - Spent Nuclear Fuel (Burn Up Credit, Decay heat)
    - *Transport of SNF*
    - *Reprocessing facilities*
    - *Disposal of SNF*

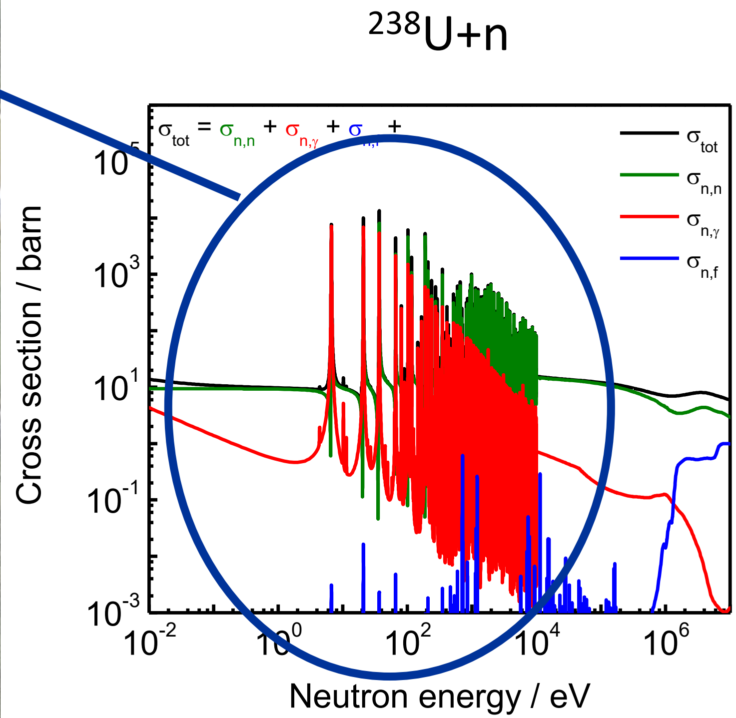
- Medical applications
- Nuclear data for astrophysics
- New detector development
- NRA for characterisation of materials
- Radiation hardness of electronic components



Neutron interaction cross sections

GELINA

White neutron source
Time-of-flight (TOF)

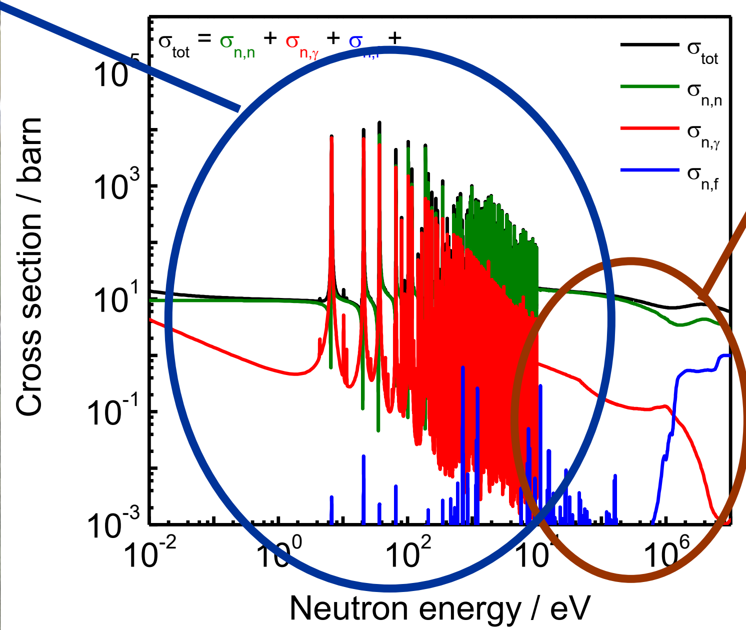


Neutron interaction cross sections

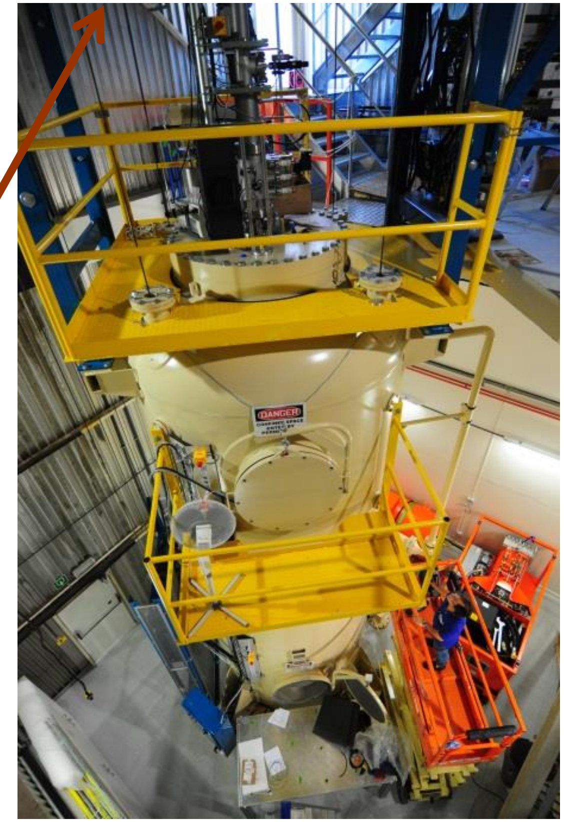
GELINA

White neutron source
Time-of-flight (TOF)

$^{238}U+n$



MONNET

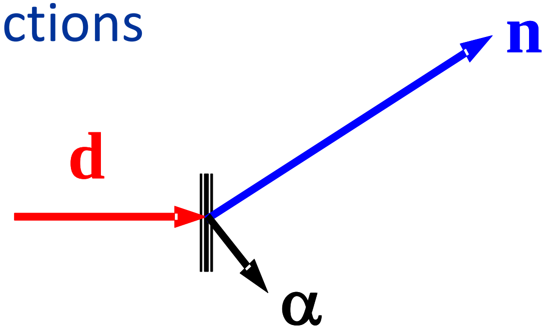


Mono-energetic neutrons
(cp,n) reactions

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

quasi mono-energetic neutrons produced via nuclear reactions

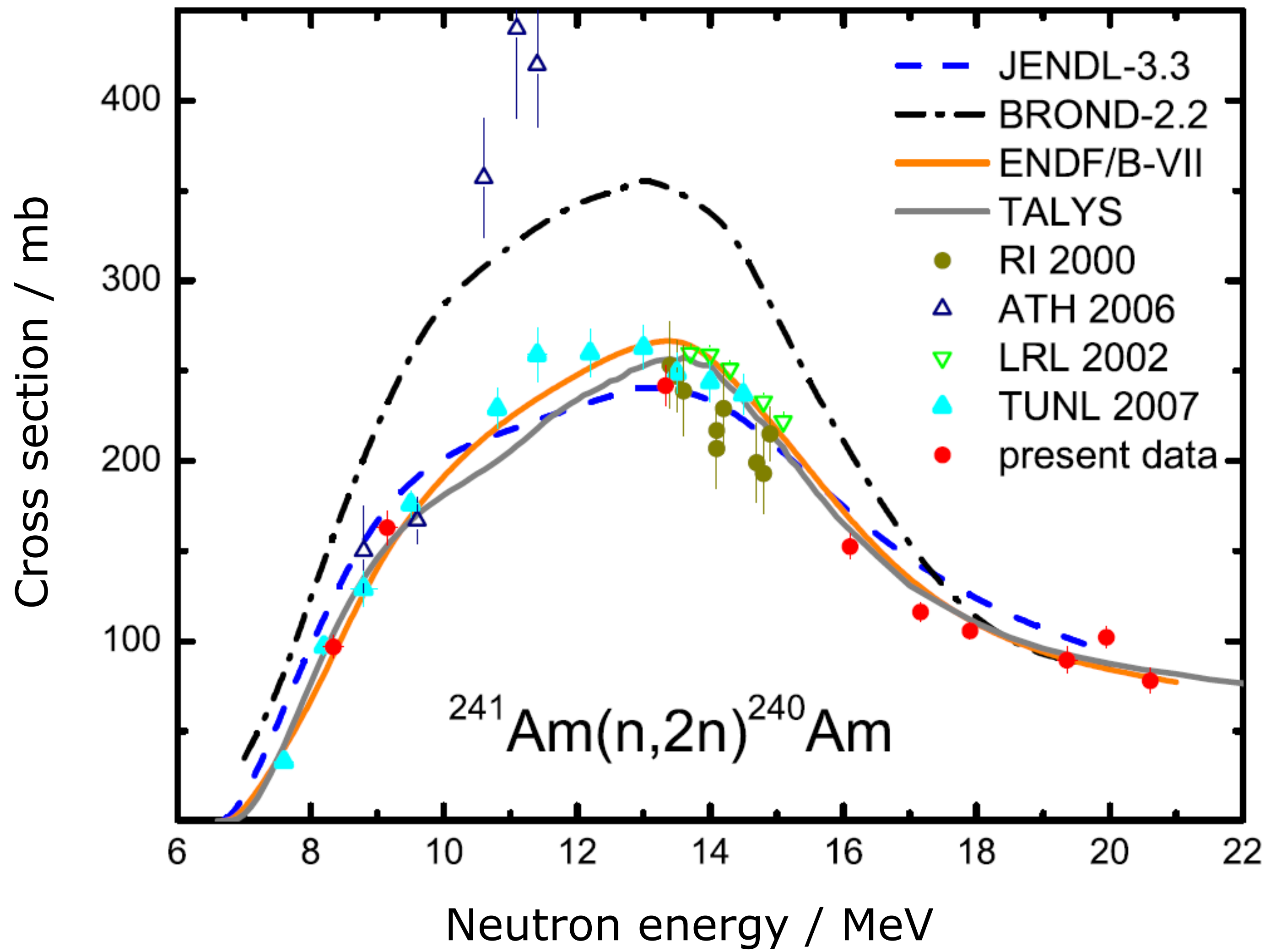
e.g. $T(d,n)^4He$



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

European Commission

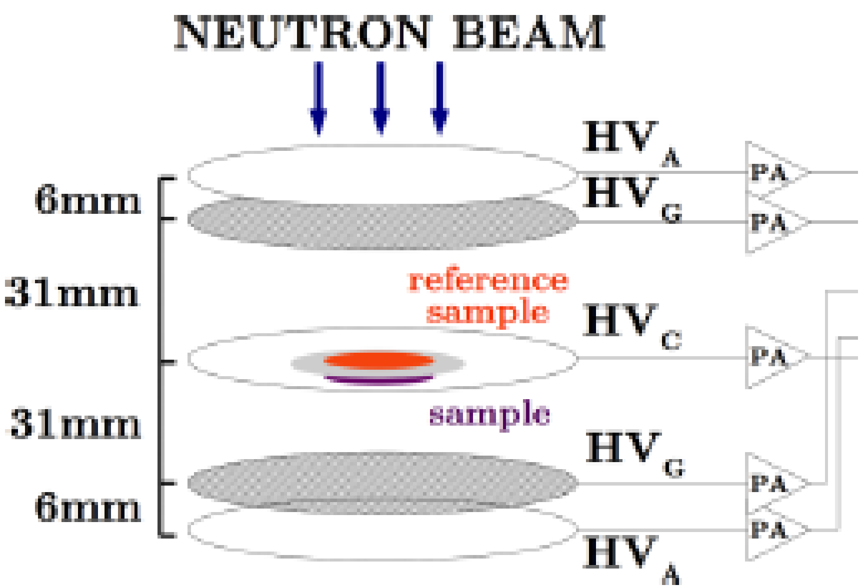
$^{241}Am(n,2n)$ cross section

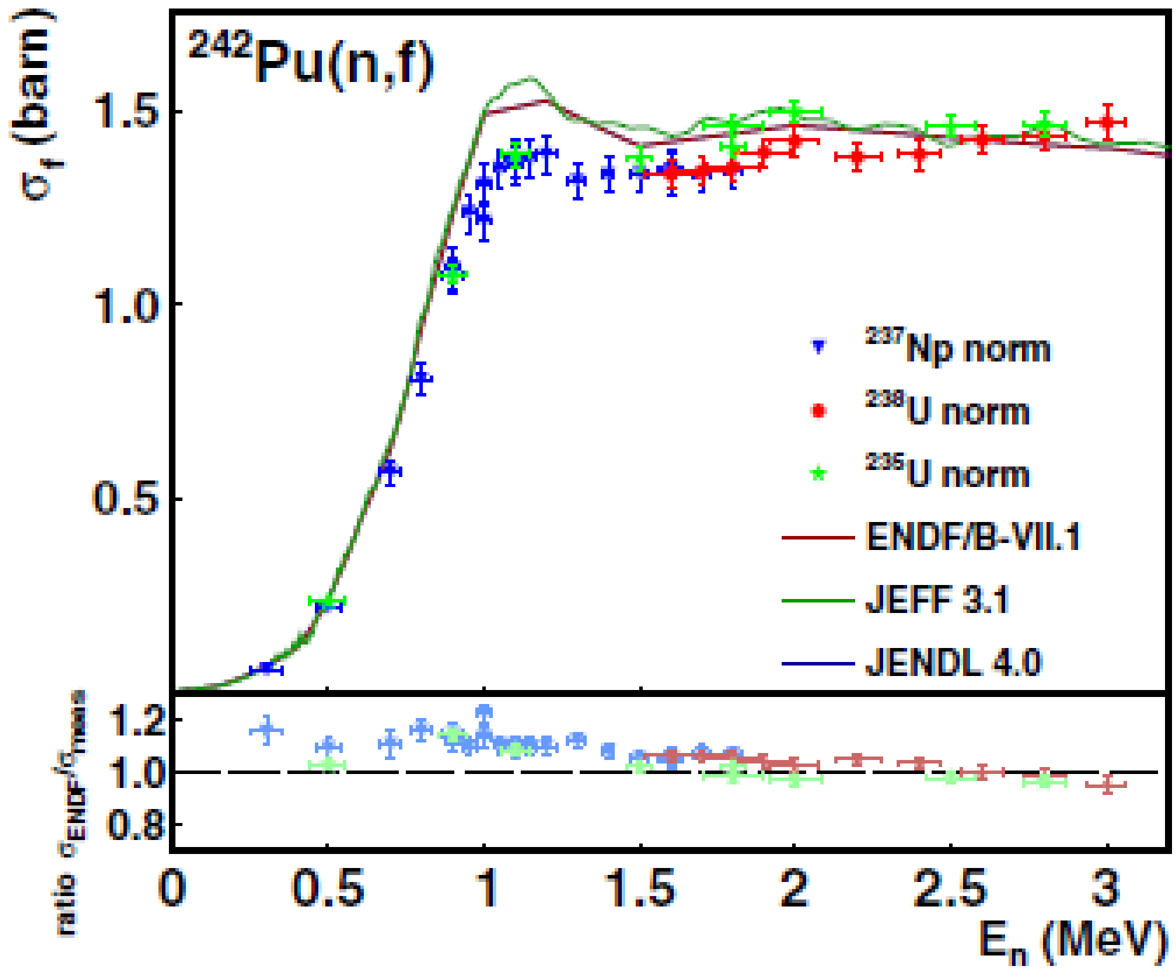


Sage et al., PR C 81 (2010) 064604

European Commission

$^{242}Pu(n,f)$ cross section



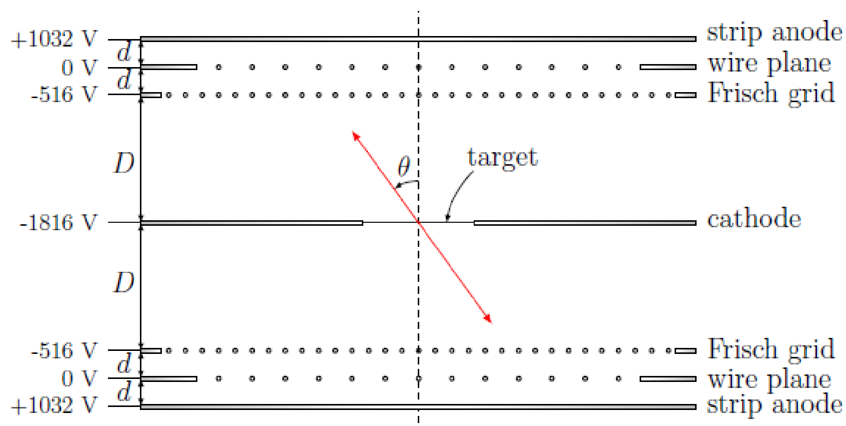


Salvador-Castiñeira et al., Phys. Rev. C **92** (2015) 044606

European Commission

Fission fragment properties, prompt fission neutrons & γ-rays

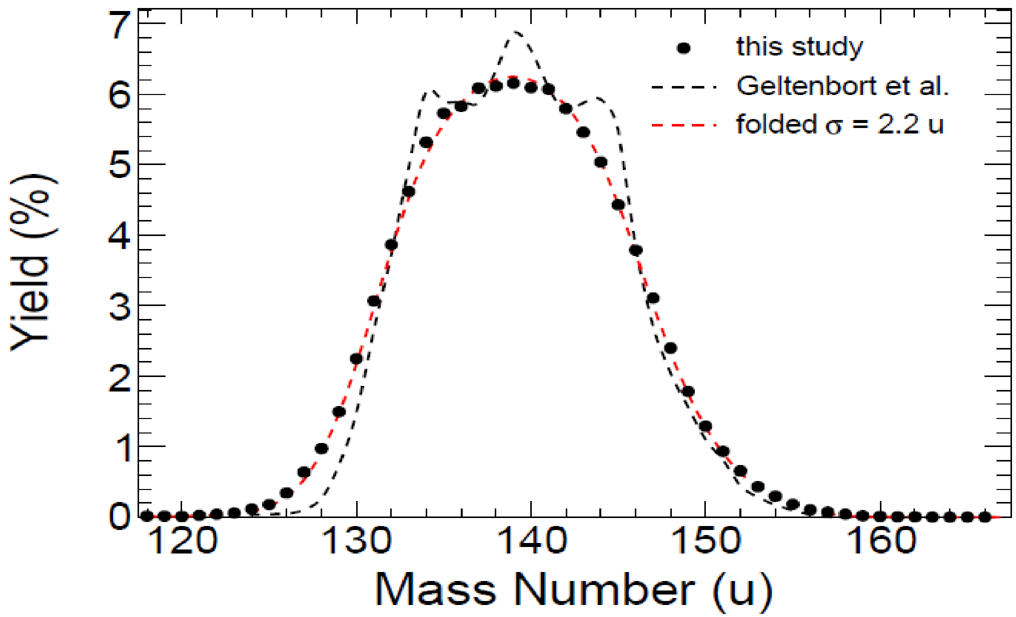
- Fission fragments by Twin Frisch-Gridded IC (position sensitive)
  - Fragment energy
  - Fragment mass: - 2E-technique
- Prompt fission neutrons
  - 12 x Scintillators (NE213 equivalent)
  - Energy : time-of-flight
- Prompt fission γ-rays
  - LaBr, CeBr scintillators



A.Göök et al., NIM A830 (2016) 366–374

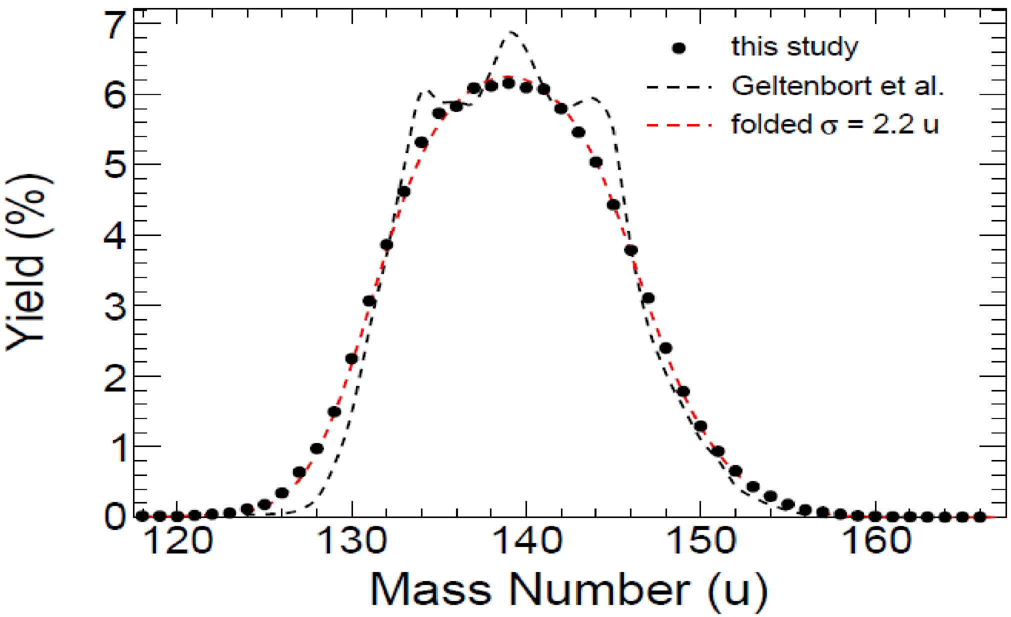
Position sensitive electrode

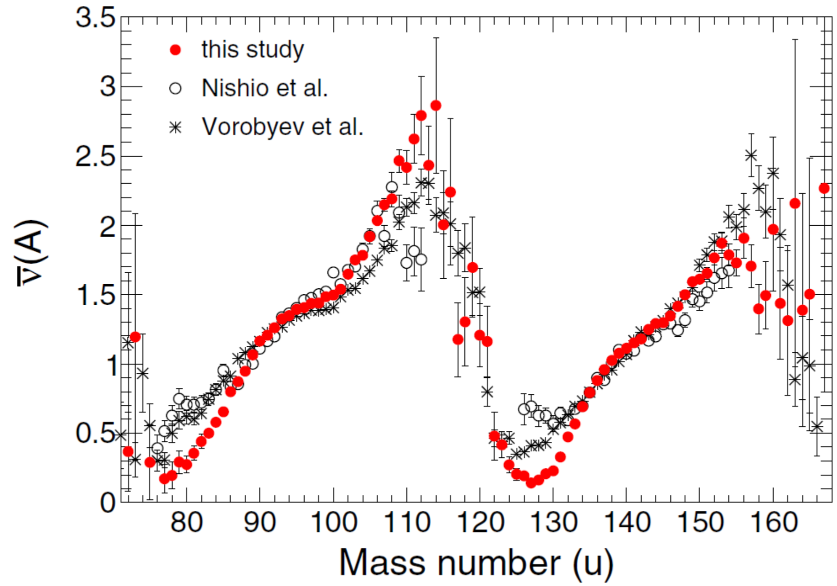
e.g. ^{235}U(n,f) FP + prompt fission neutrons

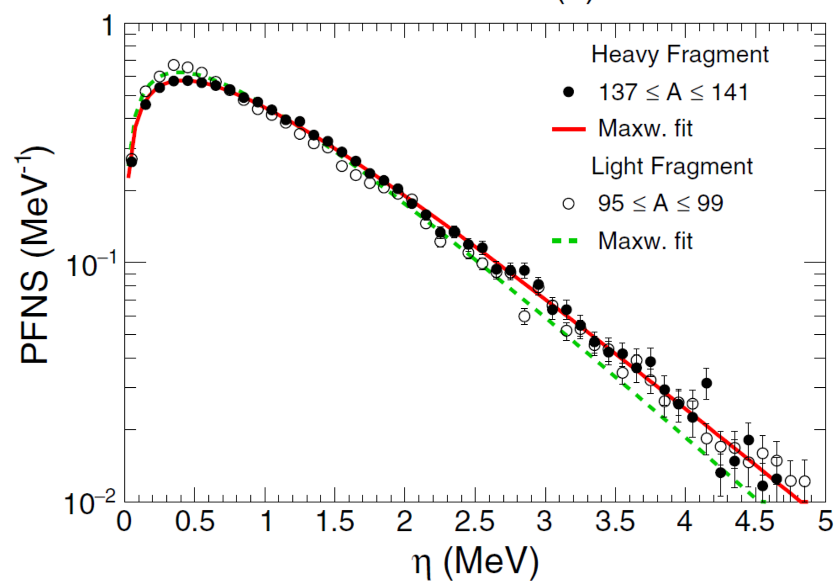


Göök et al., PRC98, 044615 (2018)

e.g. $^{235}U(n,f)$ FP + prompt fission neutrons



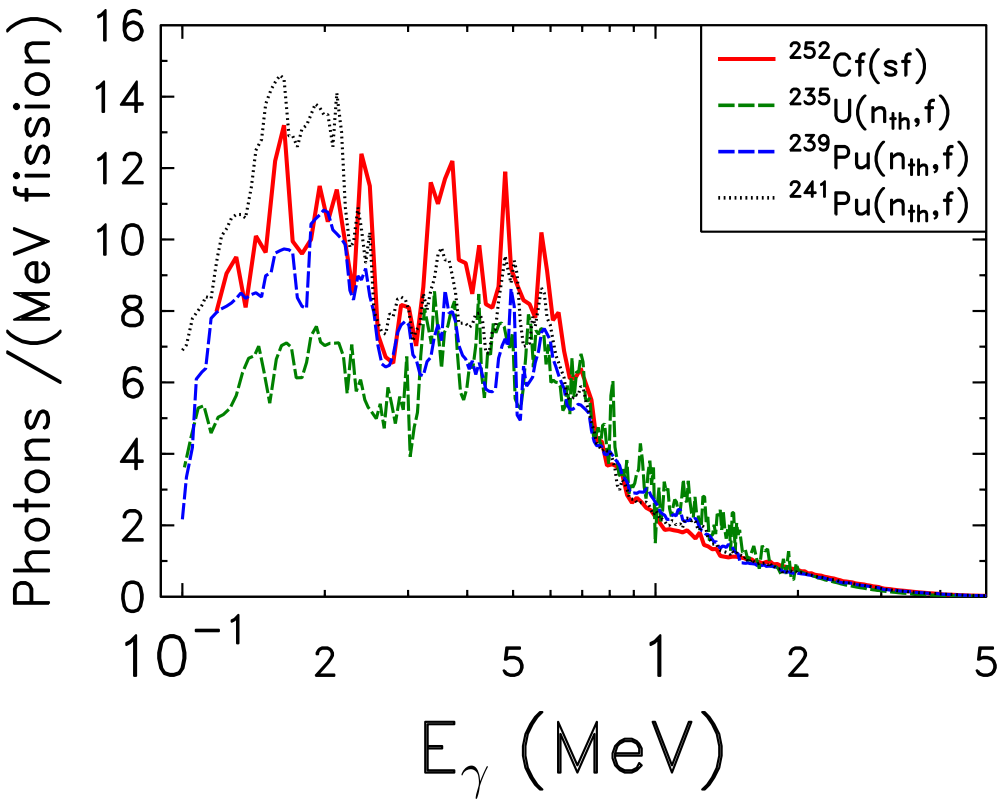


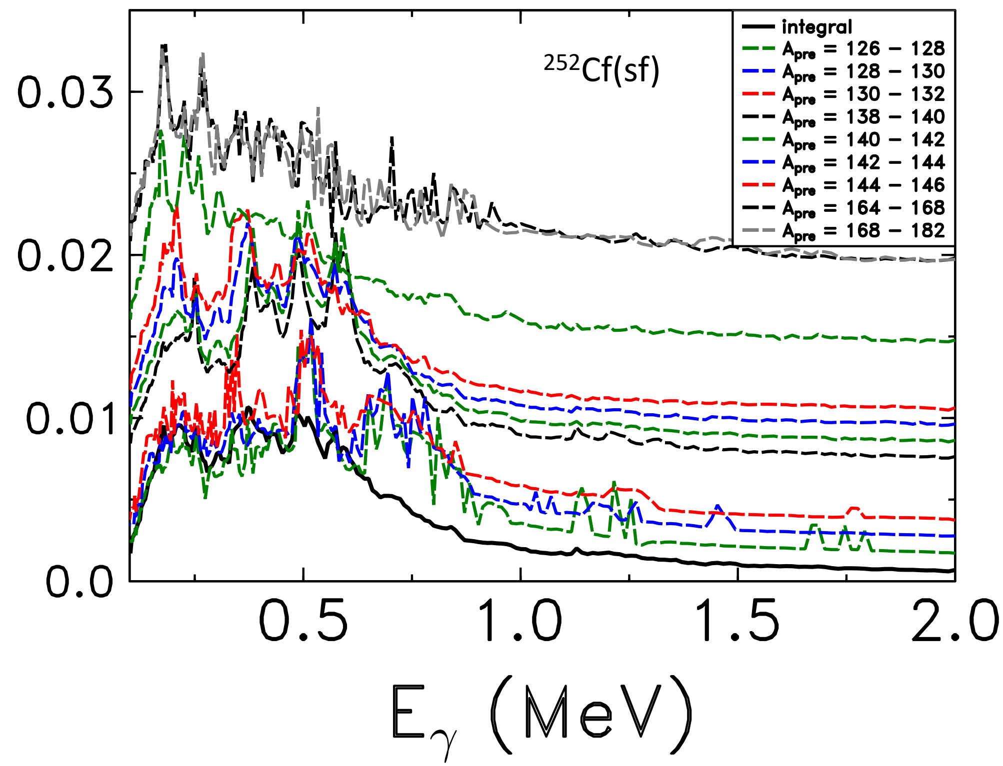


Göök et al., PRC98, 044615 (2018)

European Commission

e.g. FP + prompt fission neutrons + γ-rays

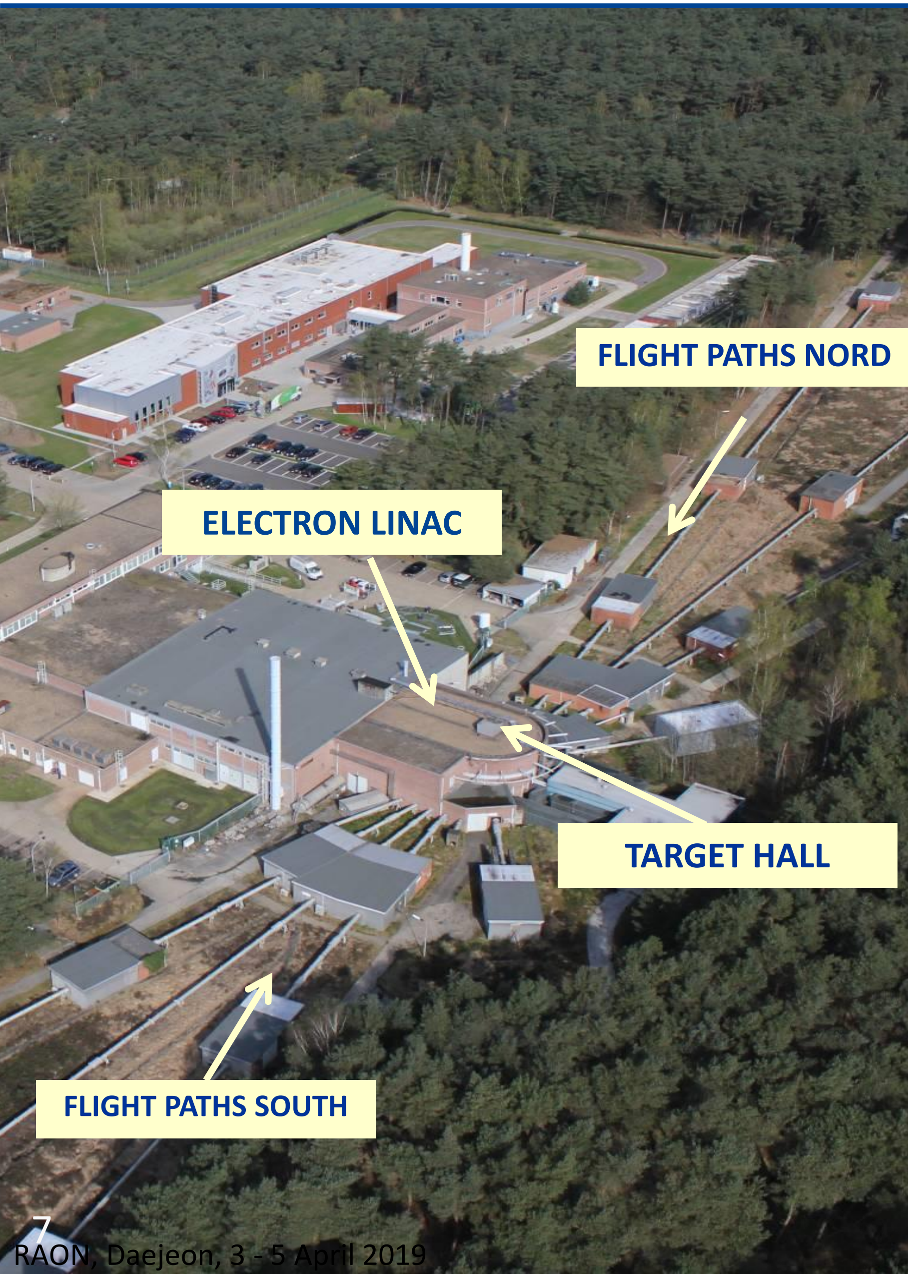




Oberstedt et al., EPJ A 51 (2015) 178

European Commission

TOF – facility GELINA



- Pulsed white neutron source

  (10 meV < E_n < 20 MeV)

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

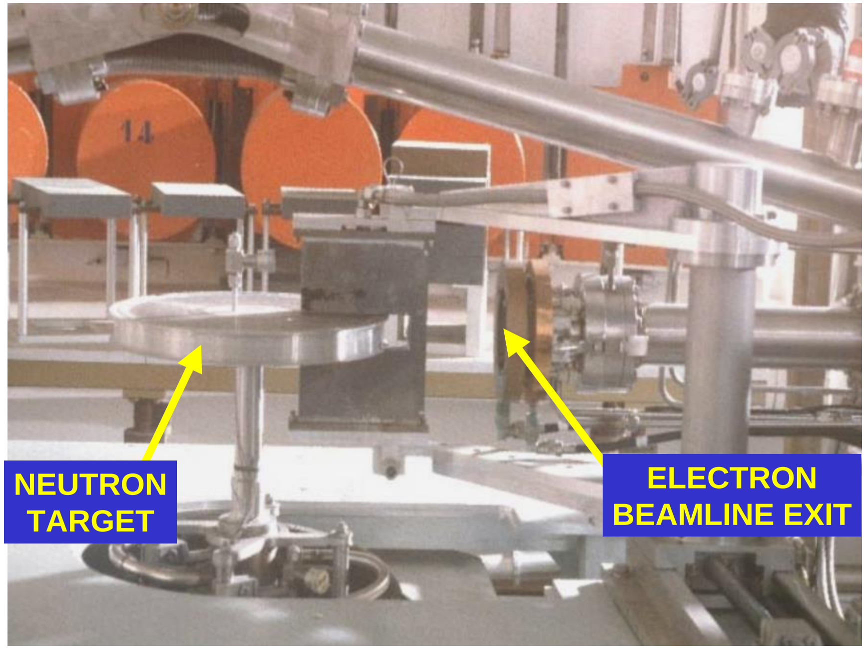
- Multi-user facility: 10 flight paths (10 m – 400 m)

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

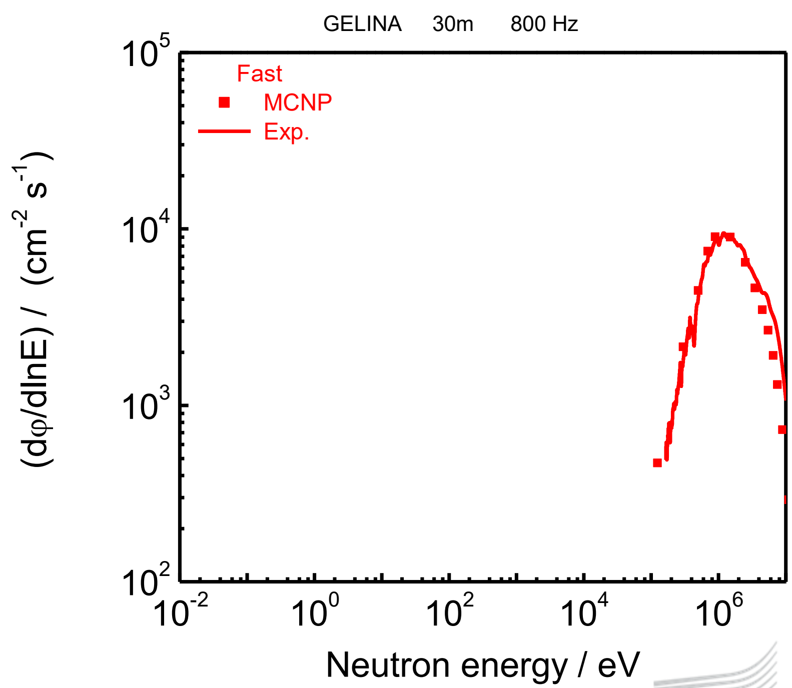
Mondelaers and Schillebeeckx,
Notizario Neutroni Luce Sincrotrone 11 (2006) 19

European Commission

GELINA : neutron production

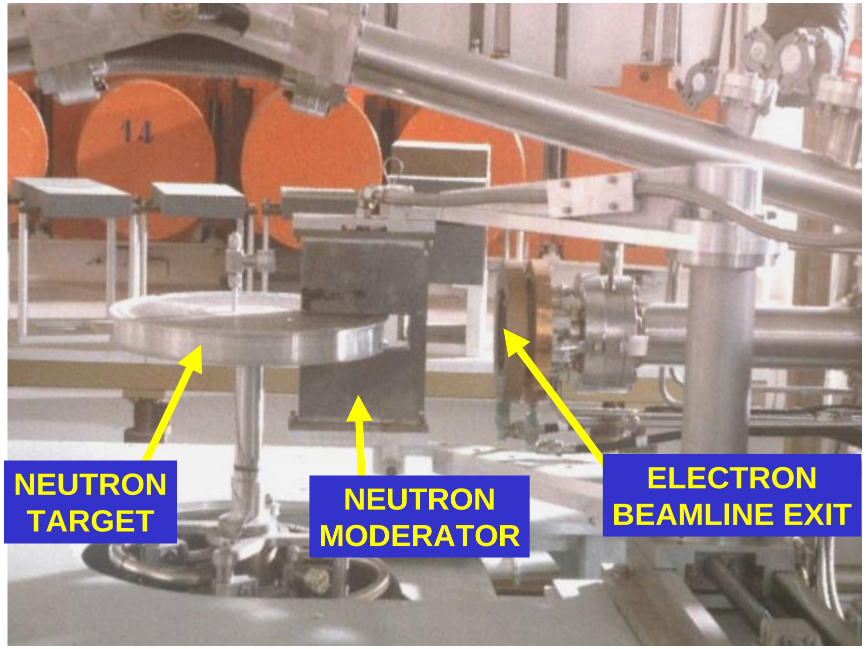


- e^{-} accelerated to $E_{e-,max}$ ≈ 140 MeV
- Bremsstrahlung in U-target
  (rotating & cooled with liquid Hg)
- (γ , n) , (γ , f) in U-target

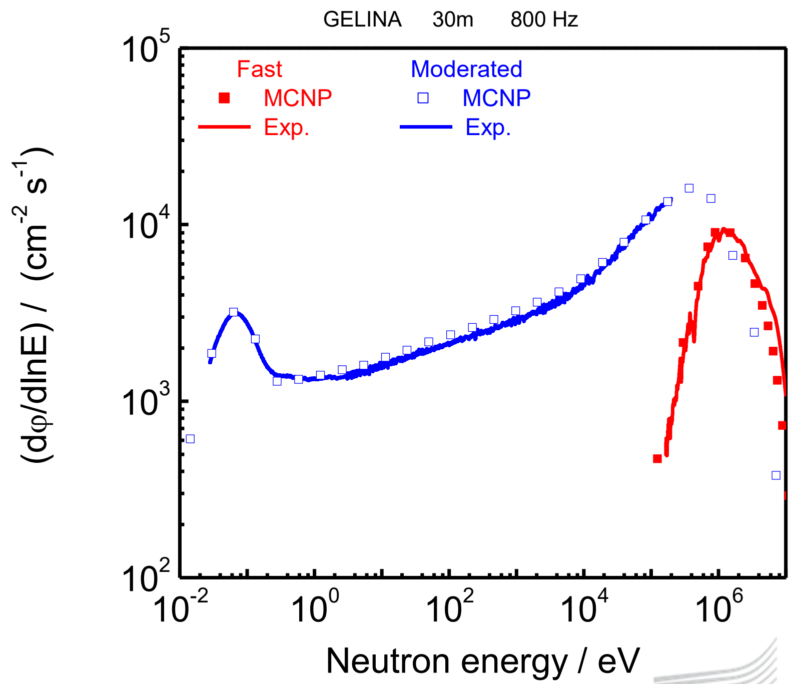


European Commission

GELINA : neutron production



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



European Commission

Experimental set-ups at GELINA

Direct (fast) neutron beam

- Elastic/inelastic scattering
  - 25 m
- In-elastic scattering
  - 25 m, 100 m

Moderated neutron beam

- Transmission (n,tot)
  - 10 m, *25 m*, 50 m, *200 m*
- Capture
  - 10 m, 30 m, 60 m
- Fission, (n,p), (n,α),
  - 10 m

European Commission

(n,n) and (n,n'): ELISA at 30 m

32 liquid organic scintillators

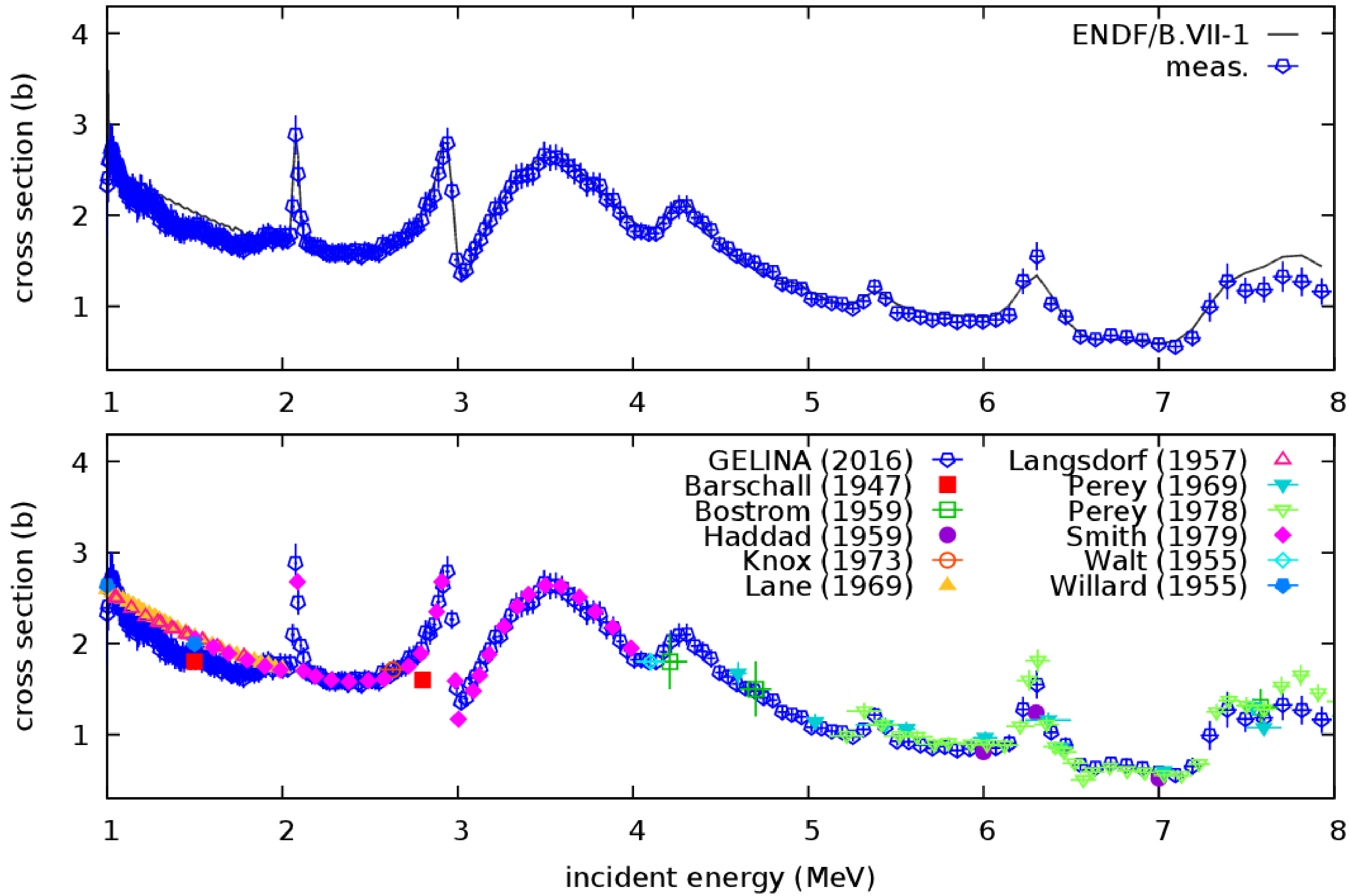
- 2×8 EJ301 (NE213 type)
- 2×8 EJ315 (C_6D_6)

Parallel plate ionisation chamber

- 8 $^{235}UF_4$ deposits
- 4.095(4) ^{235}U mg /cm^2

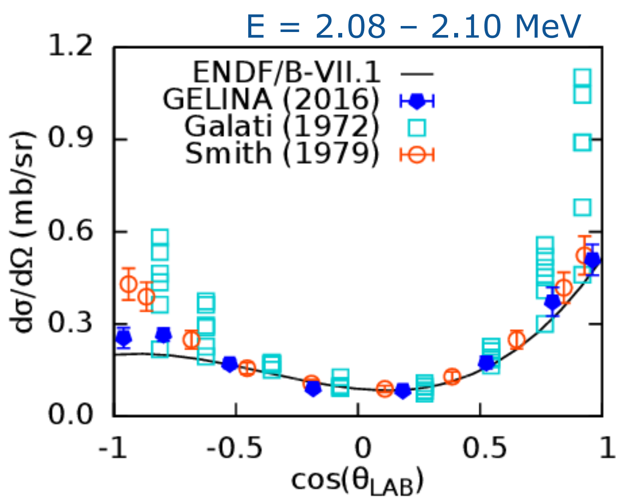
Pirovano et al., Phys. Rev. C 99 (2019) 024601

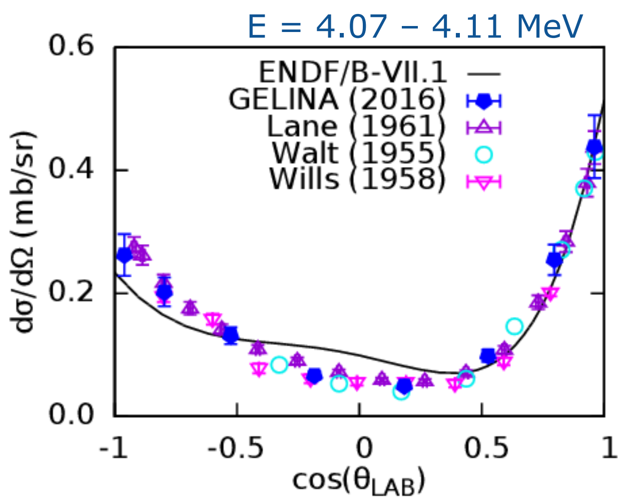
$^{nat}C(n,n)$: test set-up and procedures

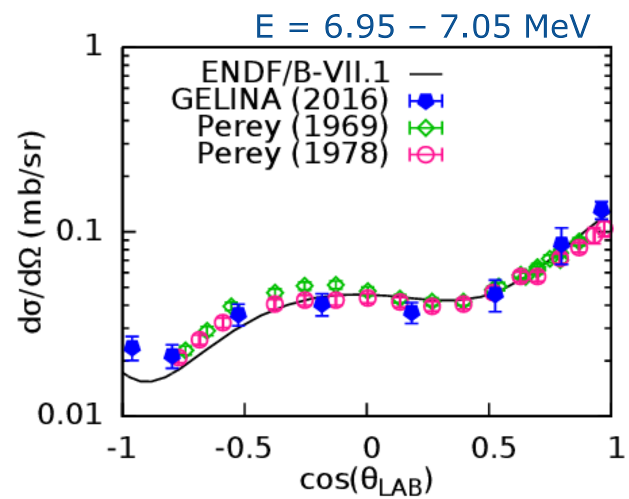


European Commission

$^{nat}C(n,n)$: test set-up and procedures

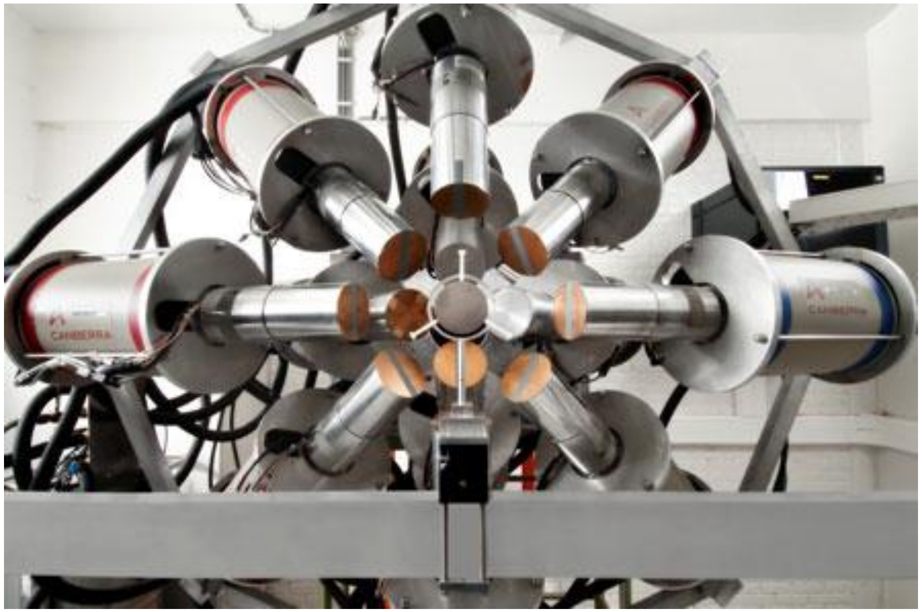






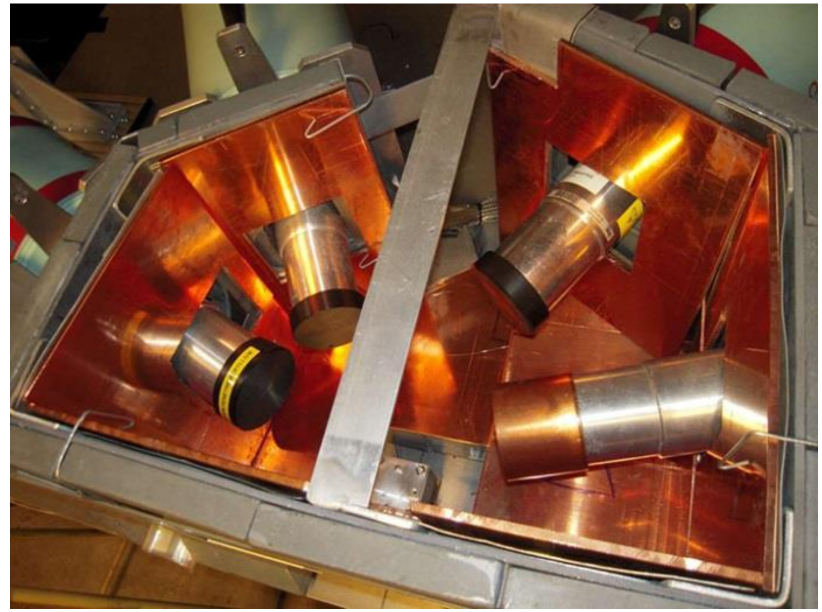
(n,n'γ) at GELINA

GAINS, at 100 m



- ^{235}U parallel plate chamber
- 12 coaxial HPGe detectors

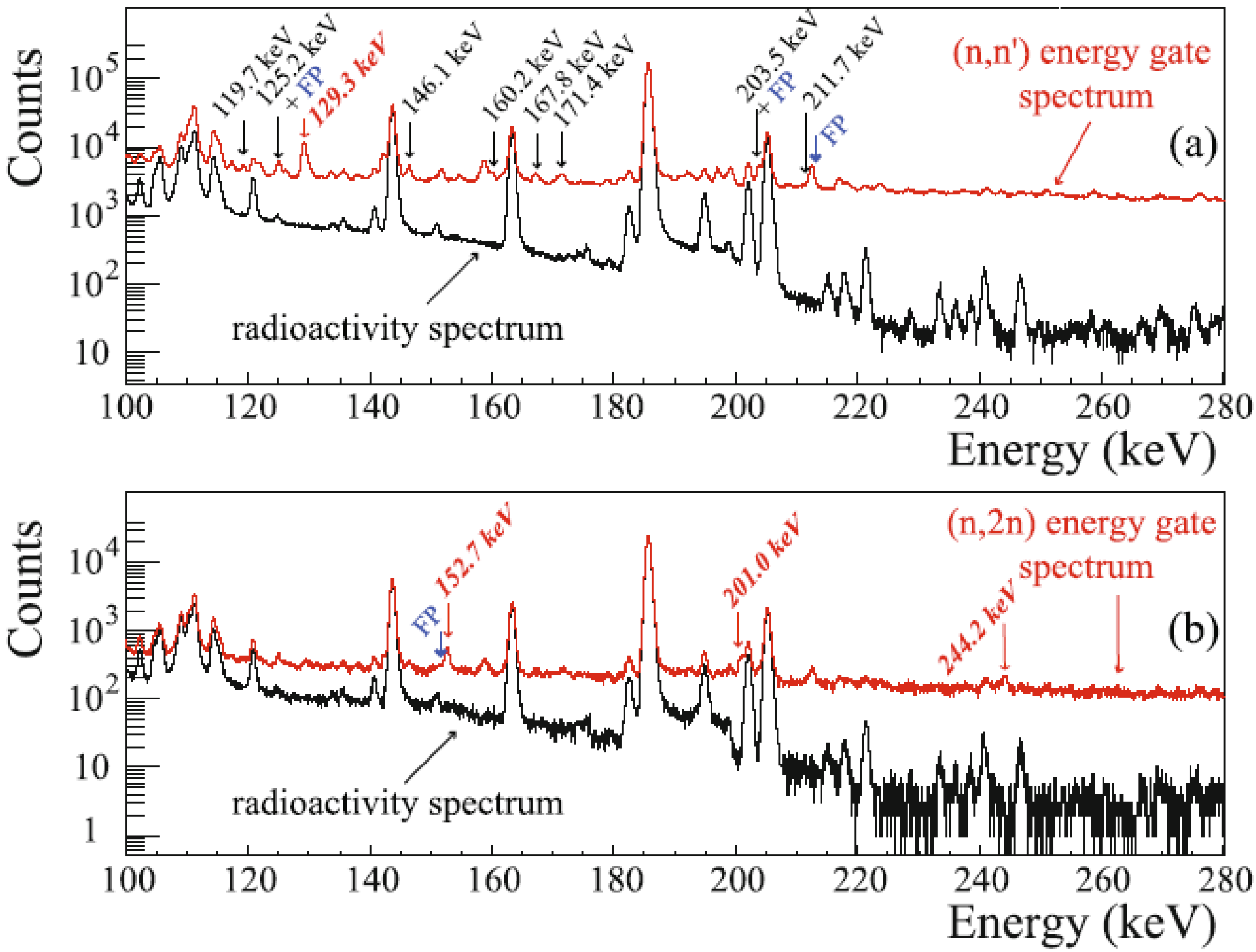
GRAPhEME, at 30 m

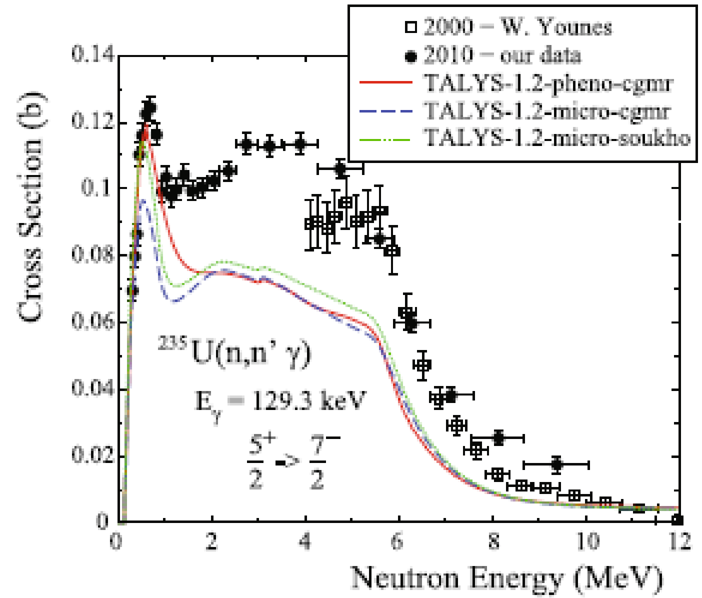


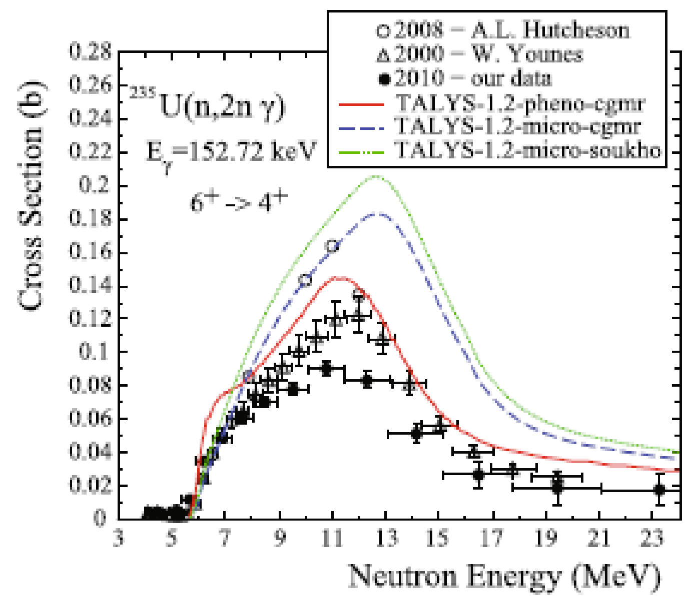
- ^{235}U parallel plate chamber
- 5 planar HPGe detectors
  1 segmented (36 planar 4x4x2 cm^3)

Kerveno et al., Eur. Phys. J. A 51 (2015) 167

$^{235}U(n,n'\gamma)$ at GELINA

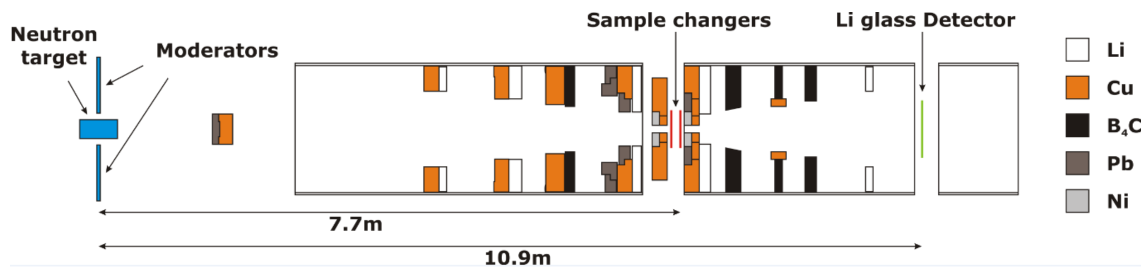






Experimental set-ups at GELINA

- Transmission
  - 10 m, 25 m, 50 m
  - *25 m: oven to study Doppler effect*
  - *200 m high energy*



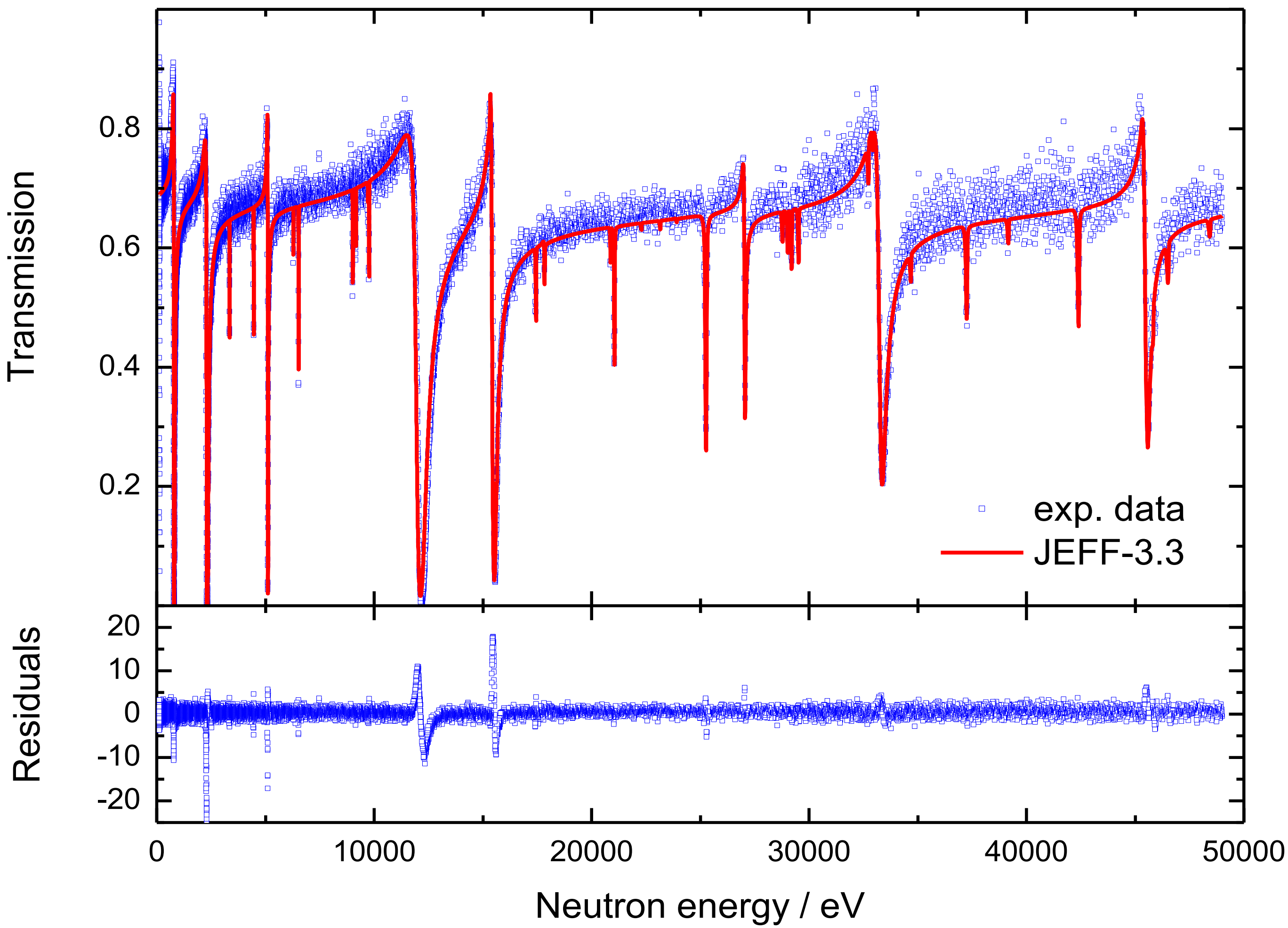
Detectors

Low energy : ^{6}Li(n,t)α Li-glass

High energy : H(n,n)H Plastic scintillator or NE213 type

European Commission

^{209}Bi(n,tot): verify RP (JEFF-3.3) for ^{209}Bi + n

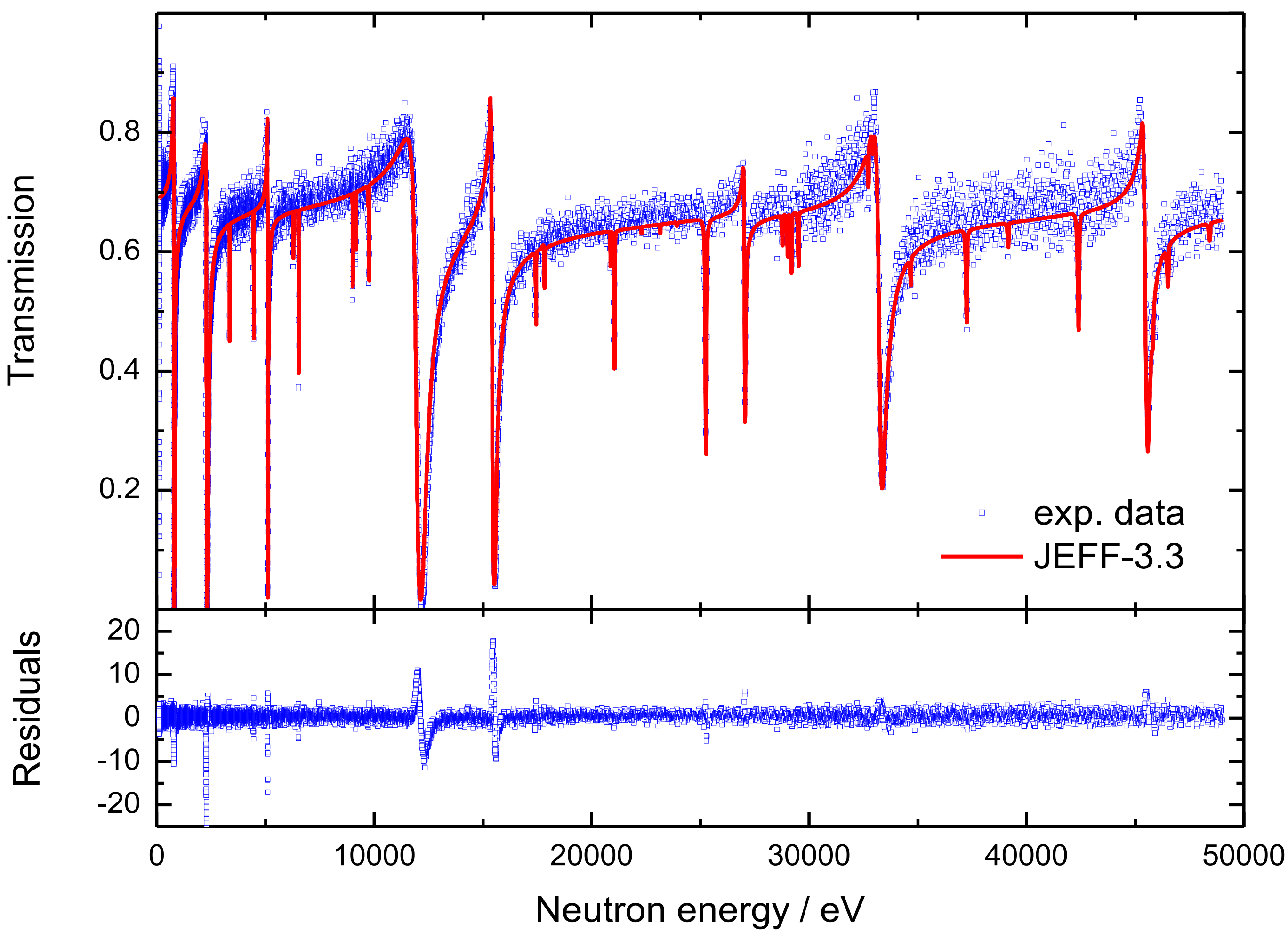


Project in collaboration with SCK•CEN and JAEA

- Improve RP for ^{209}Bi

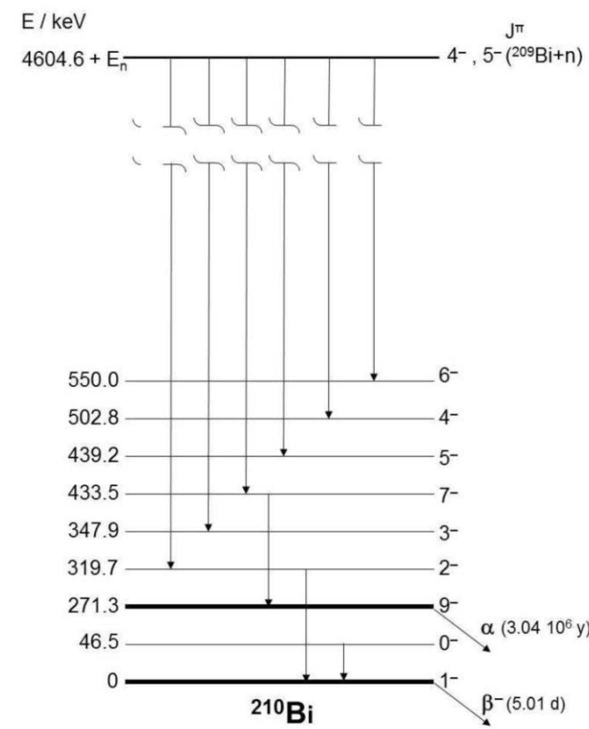
European Commission

New evaluation for ^{209}Bi + n



Project in collaboration with SCK•CEN and JAEA

- Improve RP for ^{209}Bi
- Capture at GELINA (60m)
- Determine branching ratio J-PARC: $\sigma_{\gamma,g} / \sigma_{\gamma,m}$

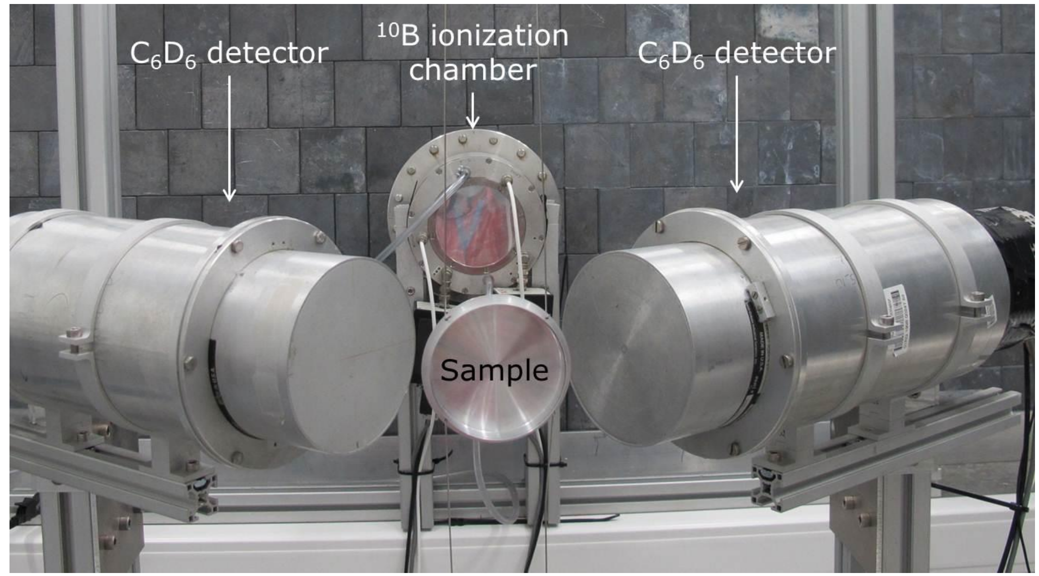


European Commission

Capture cross section measurements: σ_γ

- Total energy detection principle
  - C_6D_6 liquid scintillators
  - Pulse Height Weighting
  - 125°
- Fluence rate measurements (IC)
  - $^{10}B(n,\alpha)$: $E_n <$ 200 keV
  - $^{235}U(n,f)$: $E_n >$ 200 keV

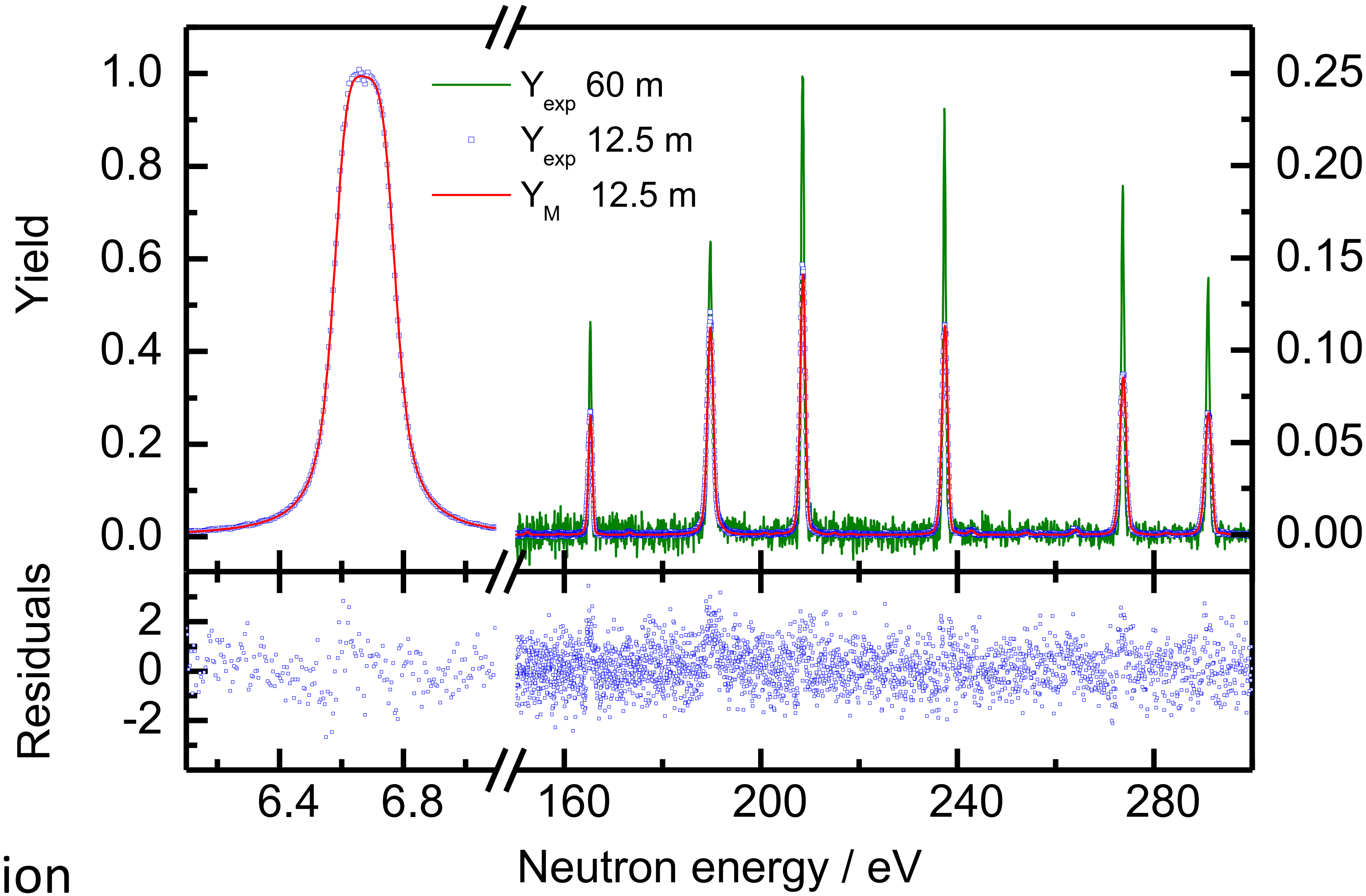
L = 12.5 m, 30 m and 60 m



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

Borella et al., NIMA 577 (2007) 626

$^{238}U(n,\gamma)$: Resonance shape analysis with REFIT (R-matrix code)

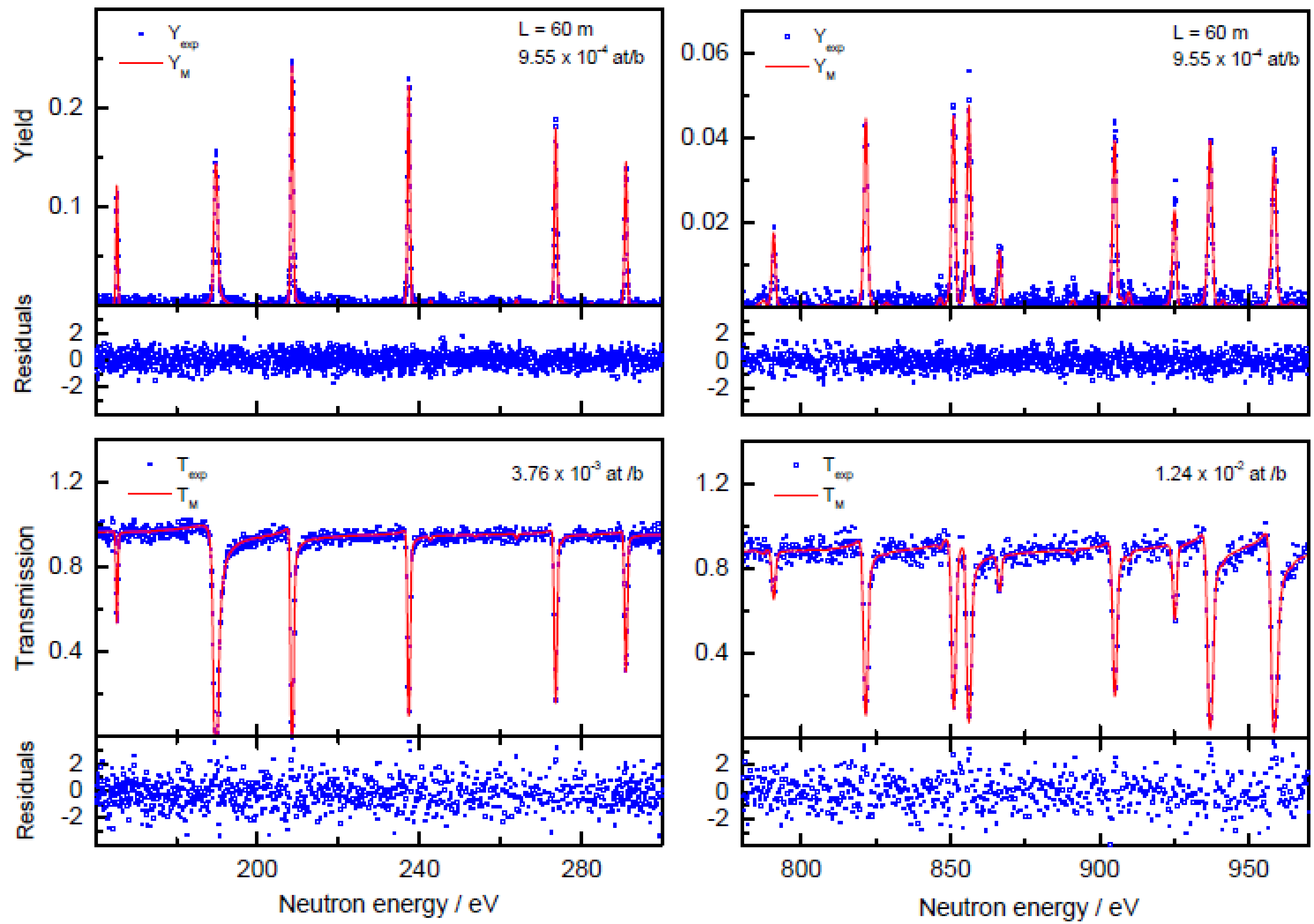


Collaboration
JRC / KAERI

Kim et al., EPJA 52 (2016) 170

European Commission

Capture (GELINA) + Transmission (ORELA)



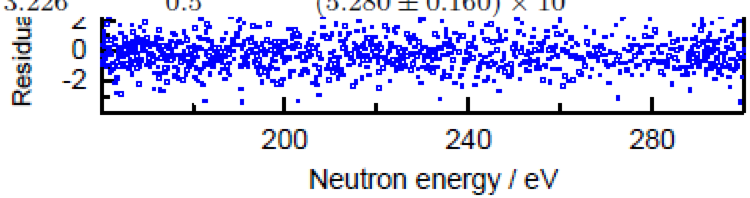
Kim et al., EPJA 52 (2016) 170

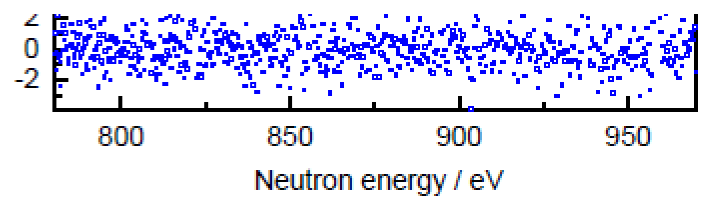
European Commission

Capture (GELINA) + Transmission (ORELA)

Table 5. Resonance parameters (E_r, J^π, $g\Gamma_n$, Γ_γ, Γ_f) for the neutron-induced reaction on ^{238}U below 1200 eV.

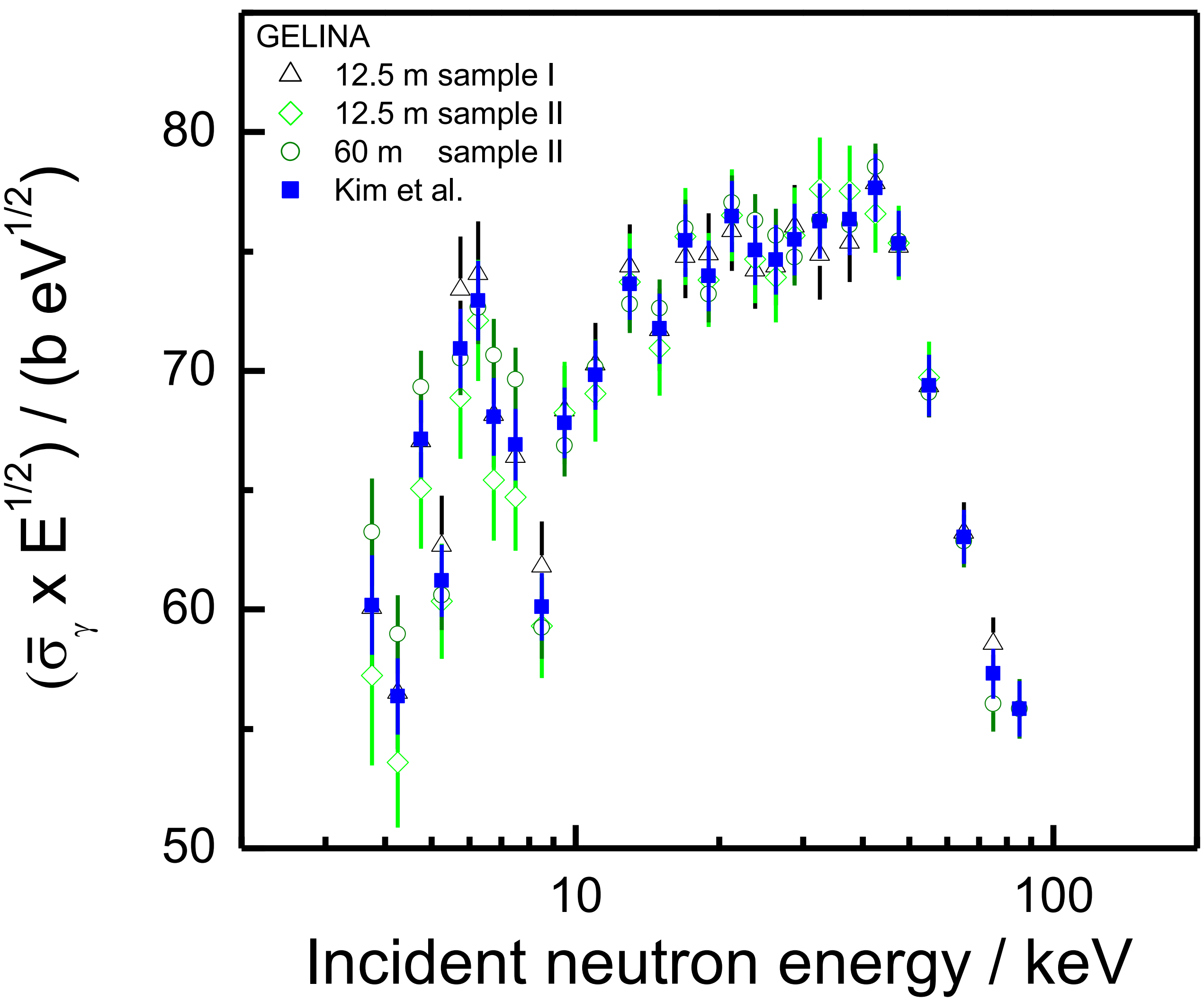
E_r/eV	J^π	$g\Gamma_n$/meV	Γ_γ/meV	$\rho(\Gamma_n, \Gamma_\gamma)$	Γ_f/μeV
−33.300	0.5^+	4.808	23.0		
−3.500	0.5^+	0.049	26.1		
6.674	0.5^+	1.4923 ± 0.0011	22.711 ± 0.019	−0.77	0.00988 ± 0.00039
10.240	1.5^-	$(1.698 \pm 0.010) \times 10^{-3}$			
19.525	1.5^-	$(1.570 \pm 0.021) \times 10^{-3}$			
20.872	0.5^+	10.076 ± 0.010	22.753 ± 0.024		0.0546 ± 0.0011
36.683	0.5^+	33.592 ± 0.020	22.264 ± 0.024	−0.47	0.00972 ± 0.00059
63.523	0.5^-	$(1.049 \pm 0.021) \times 10^{-2}$			
66.030	0.5^+	24.275 ± 0.031	22.415 ± 0.043	−0.40	0.0519 ± 0.0022
80.752	0.5^+	1.8559 ± 0.0041			0.0595 ± 0.0013
83.711	0.5^-	$(1.081 \pm 0.039) \times 10^{-2}$			
89.249	0.5^-	0.1038 ± 0.0012			
102.563	0.5^+	70.871 ± 0.080	23.173 ± 0.040	−0.26	0.0129 ± 0.0026
116.904	0.5^+	25.270 ± 0.071	21.445 ± 0.062	−0.18	
145.666	0.5^+	0.9306 ± 0.0035			
152.458	1.5^-	$(5.820 \pm 0.150) \times 10^{-2}$			
165.297	0.5^+	3.435 ± 0.010			
173.226	0.5^-	$(5.280 \pm 0.160) \times 10^{-2}$			





Kim et al., EPJA 52 (2016) 170

GELINA: from average Y_{exp} to average σ_γ



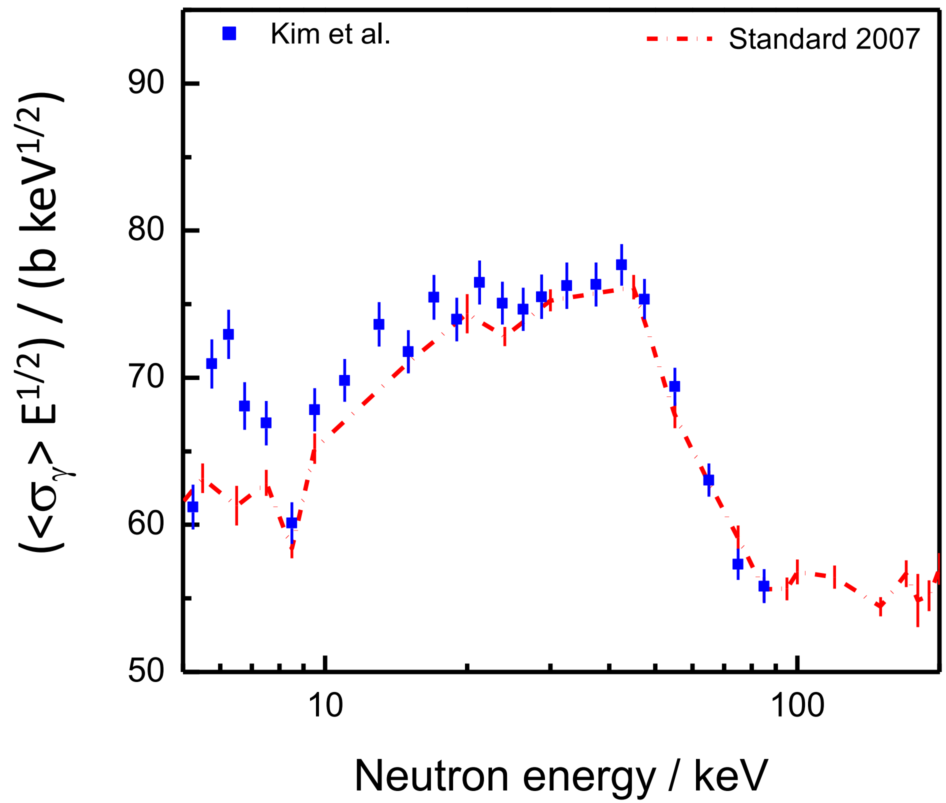
Kim et al., EPJA 52 (2016) 170

European Commission

Experimental data for ^{238}U+n: $\sigma(n,\gamma)$

Experimental data from :

- Standard 2007
- Kim et al. (GELINA) (~ 2%)

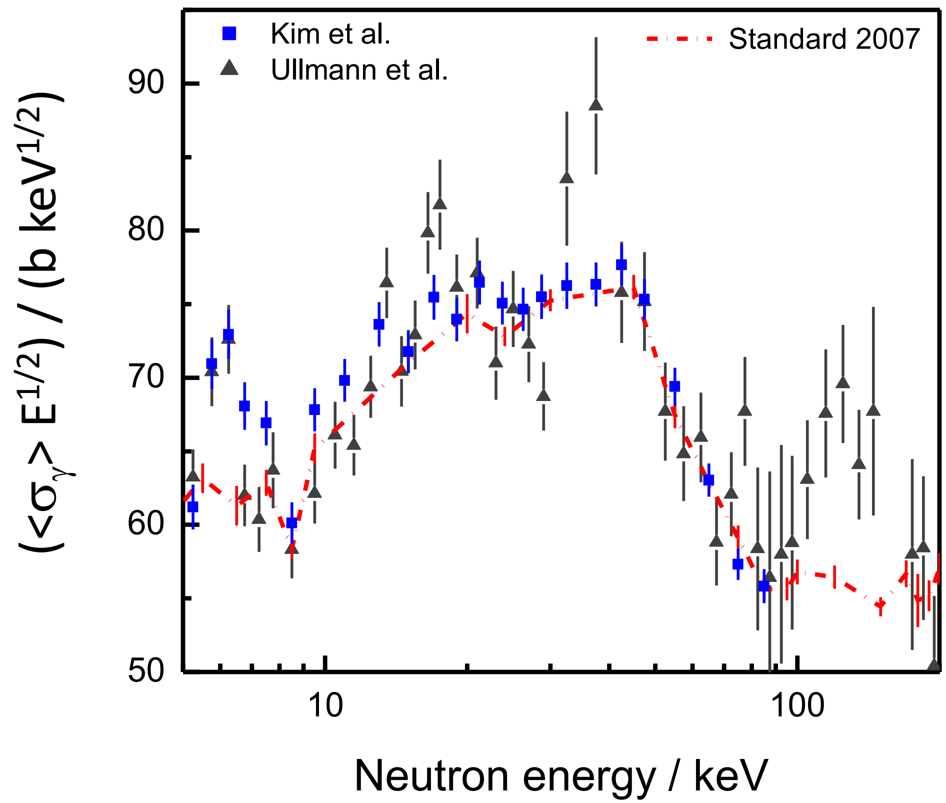


European Commission

Experimental data for ^{238}U+n: σ(n,γ)

Experimental data from :

- Standard 2007
- Kim et al. (GELINA) (~ 2%)
- Ullmann et al. (LANSCE)

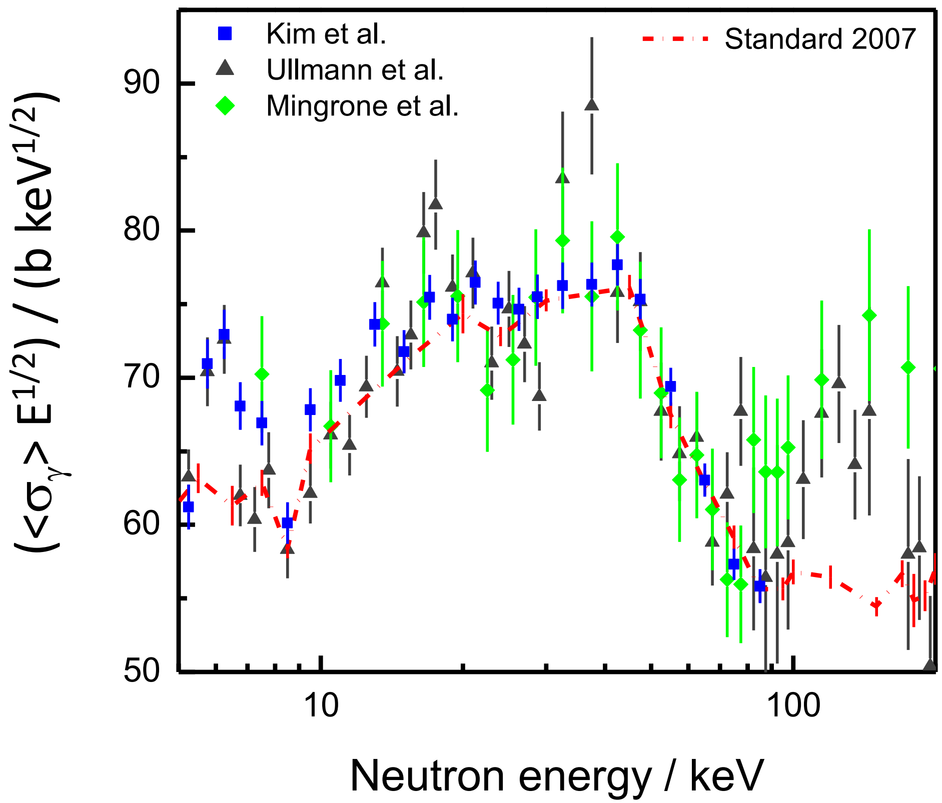


European Commission

Experimental data for ^{238}U+n: $\sigma(n,\gamma)$

Experimental data from :

- Standard 2007
- Kim et al. (GELINA) (~ 2%)
- Ullmann et al. (LANSCE)
- Mingrone et al. (n_TOF)

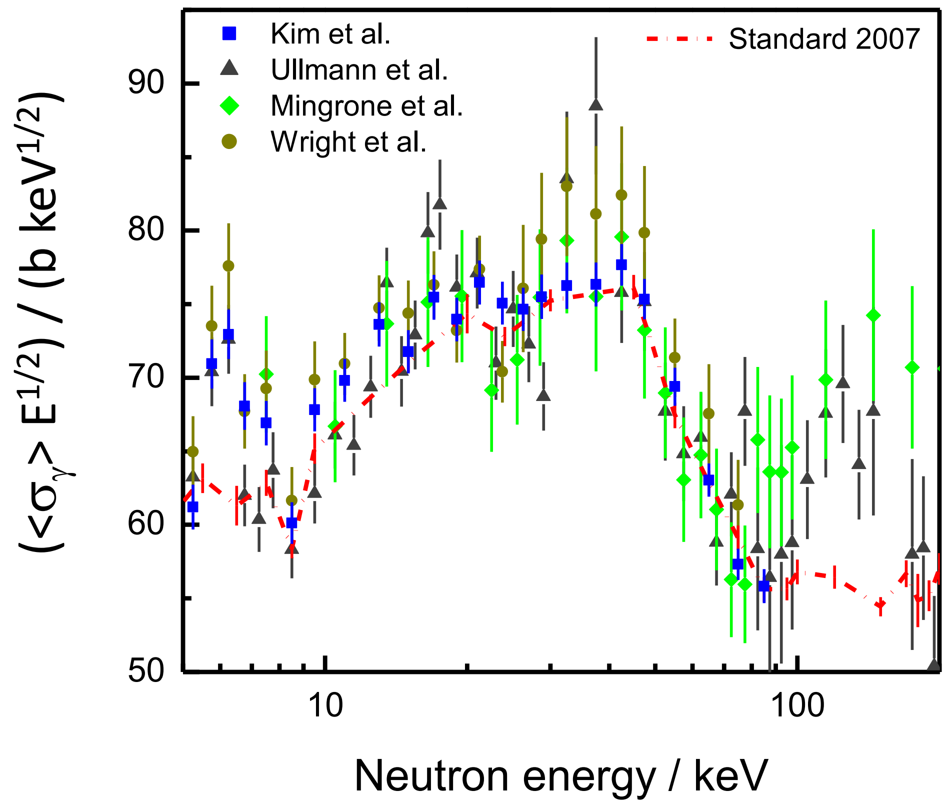


European Commission

Experimental data for ^{238}U+n: $\sigma(n,\gamma)$

Experimental data from :

- Standard 2007
- Kim et al. (GELINA) (~ 2%)
- Ullmann et al. (LANSCE)
- Mingrone et al. (n_TOF)
- Wright al. (n_TOF)



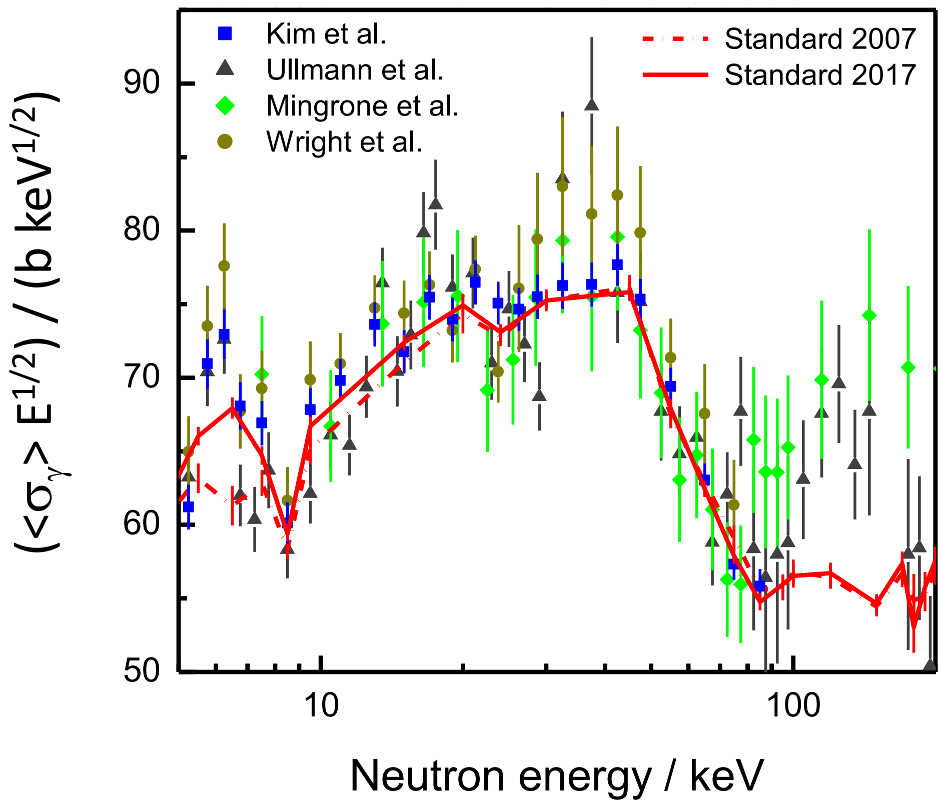
European Commission

GLSQ analysis for n + ^{238}U: $\sigma(n,\gamma)$

Experimental data from :

- Standard 2007
- Kim et al. (GELINA) (~ 2%)
- Ullmann et al. (LANSCE)
- Mingrone et al. (n_TOF)
- Wright al. (n_TOF)

⇒ GMA analysis (GLSQ)

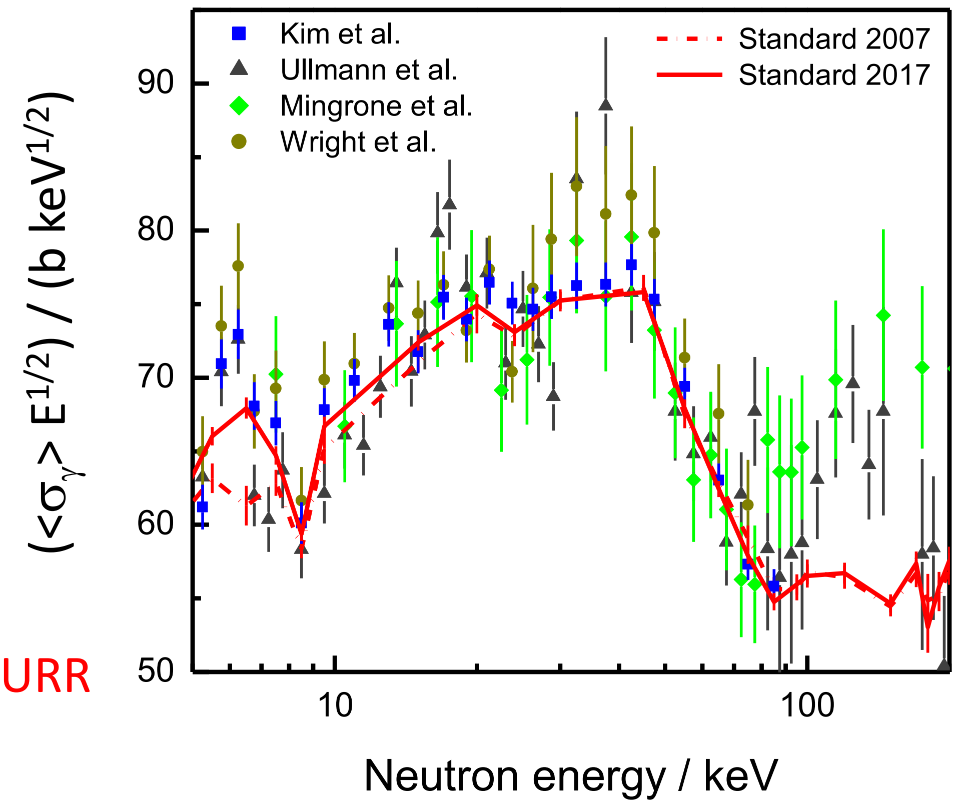


European Commission

GLSQ analysis for n + ^{238}U: $\sigma(n,\gamma)$

Experimental data from :

- Standard 2007
- Kim et al. (GELINA) (~ 2%)
- Ullmann et al. (LANSCE)
- Mingrone et al. (n_TOF)
- Wright al. (n_TOF)



⇒ GMA analysis (GLSQ)

⇒ New evaluation for ^{238}U + n in RRR and URR

Collaboration with:
KAERI, Nuclear Data Center, Daejeon
Dr. K. Kim, Dr. Y.-O. Lee

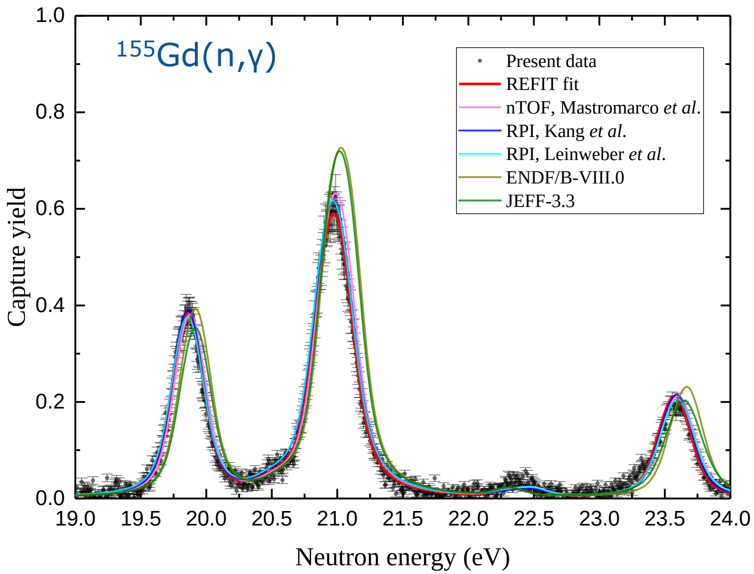
Kim et al., EPJA 52 (2016) 170
Sirakov et al., EPJA 53 (2017) 199

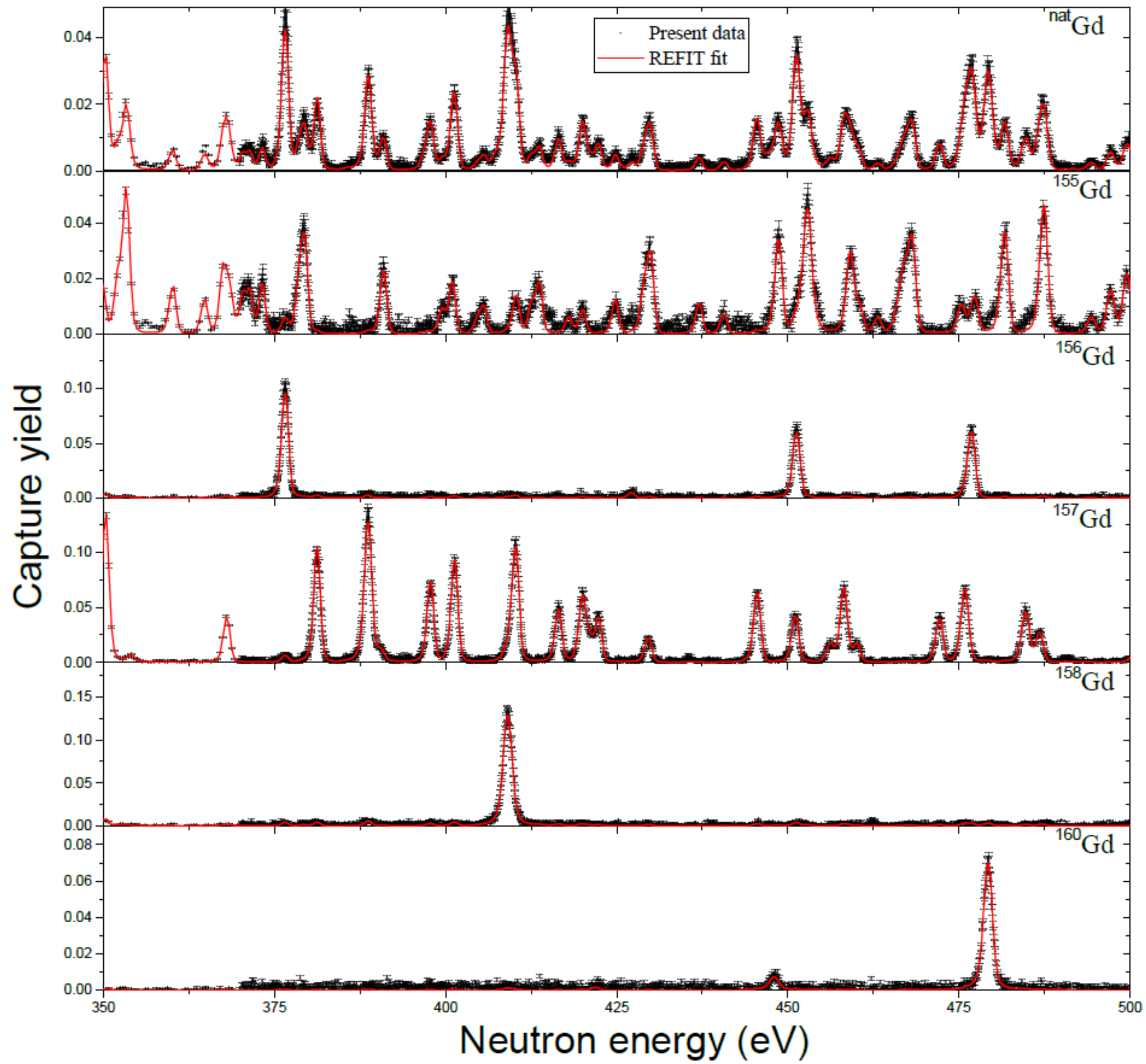
European Commission

$^{155,156,157,158,160}Gd + n$ (SNF, criticality safety)

Measurements at GELINA

- Capture at 12.5 m and 30 m





Collaboration with:
PhD of Y. Kye,
Pohang Accelerator Laboratory,
Pohang University of Science and Technology

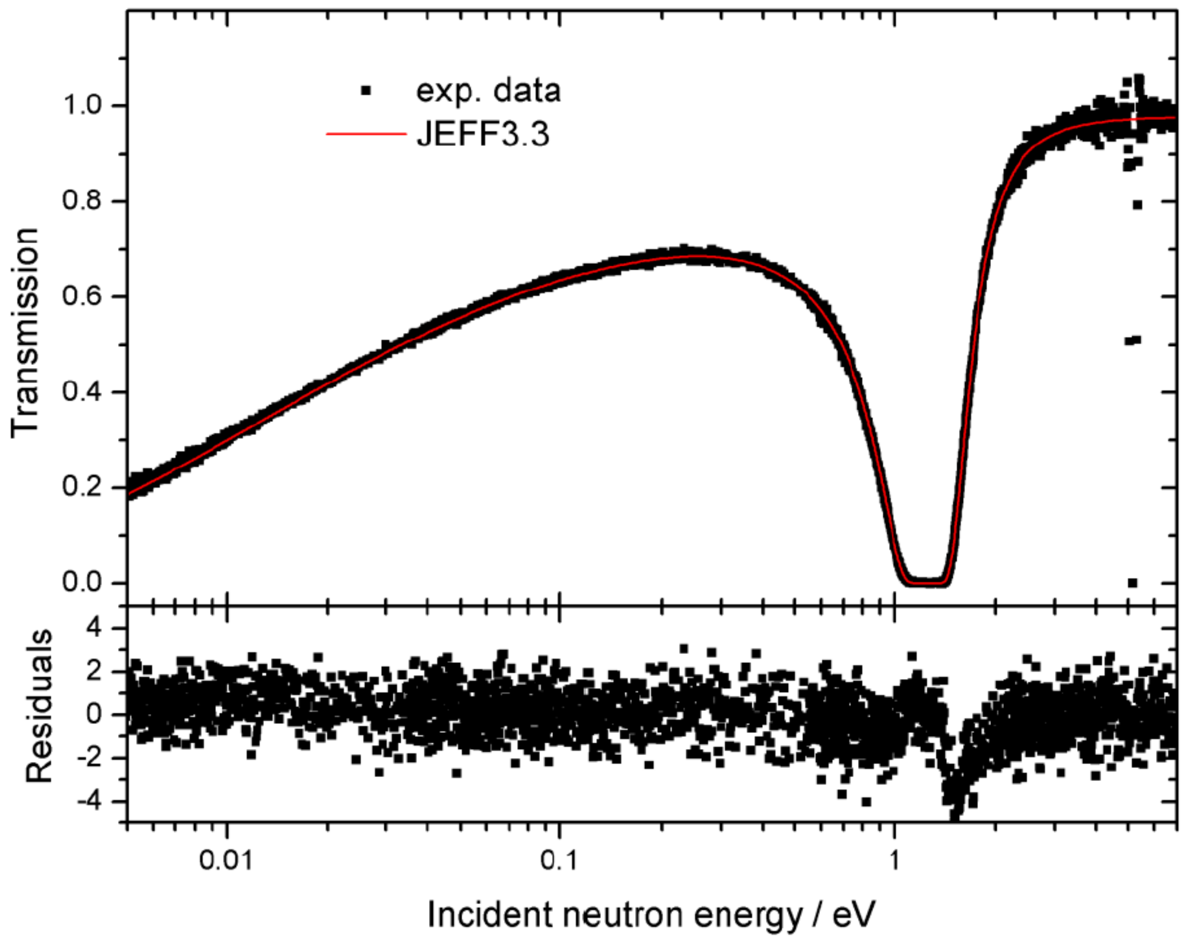
Prof. G. Kim,
Kyungpook National University

European Commission

^{103}Rh + n (SNF, criticality safety)

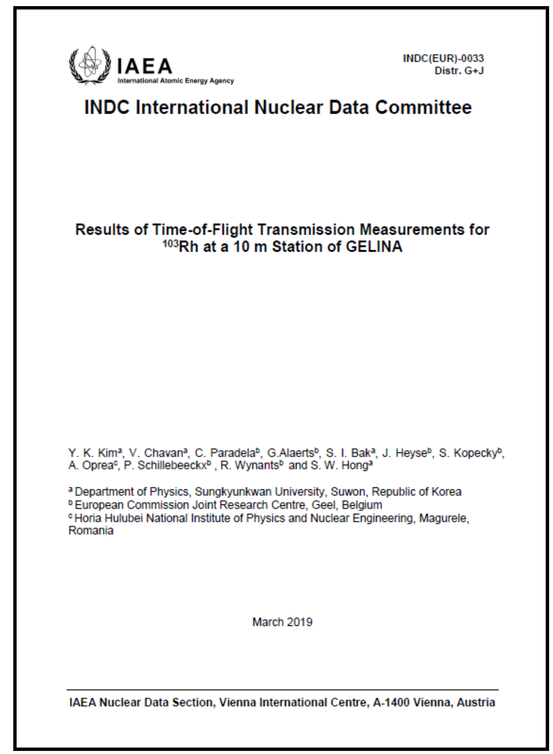
Measurements at GELINA

- Transmission at 10m and 50 m
- Capture at 12.5 m



Collaboration with:
Prof. S.W. Hong
Sungkyunkwan University, Suwon

See poster Dr. V. Chavan



IAEA International Atomic Energy Agency

INDC(EUR)-0033
Distr. G+J

INDC International Nuclear Data Committee

Results of Time-of-Flight Transmission Measurements for ^{103}Rh at a 10 m Station of GELINA

Y. K. Kim[a], V. Chavan[a], C. Paradela[b], G.Alaerts[b], S. I. Bak[a], J. Heyse[b], S. Kopecky[b], A. Oprea[c], P. Schillebeeckx[b] , R. Wynants[b] and S. W. Hong[a]

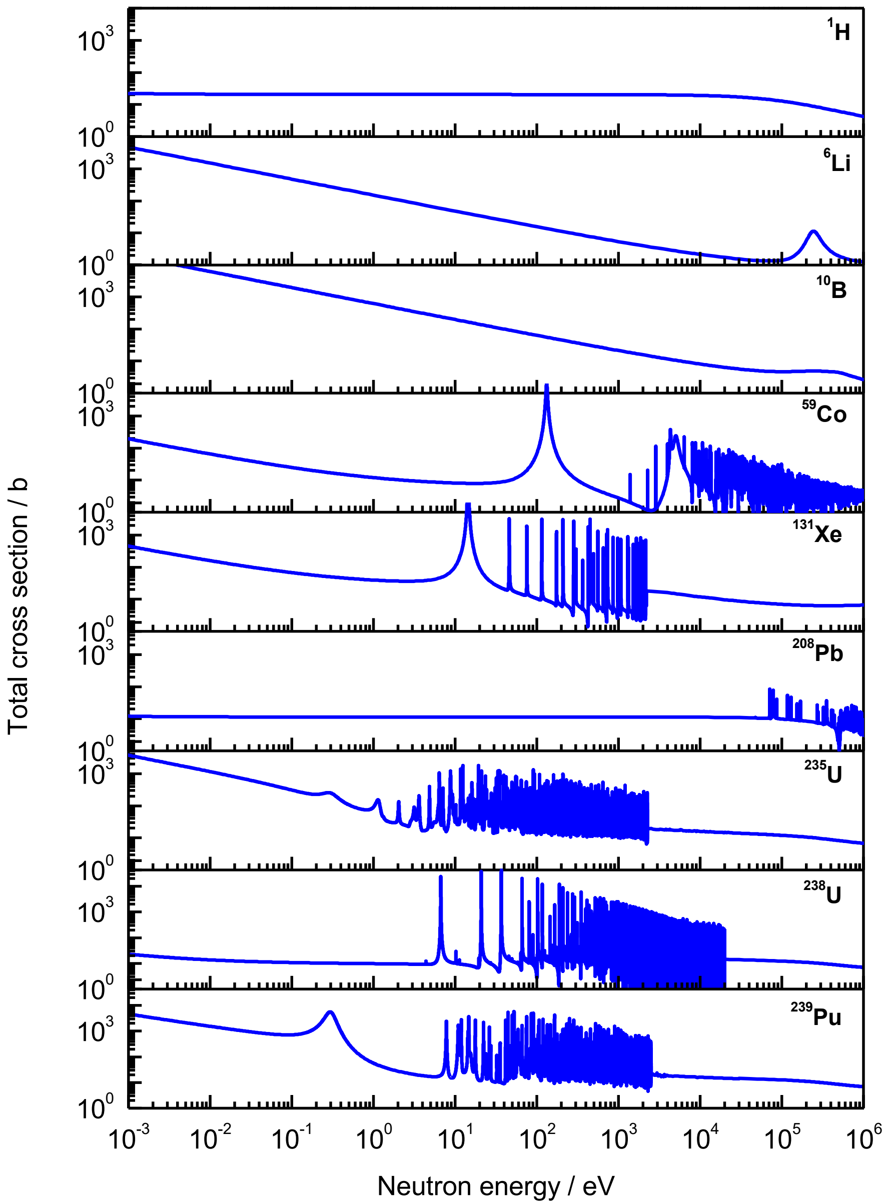
[a] Department of Physics, Sungkyunkwan University, Suwon, Republic of Korea
[b] European Commission Joint Research Centre, Geel, Belgium
[c] Horia Hulubei National Institute of Physics and Nuclear Engineering, Magurele, Romania

March 2019

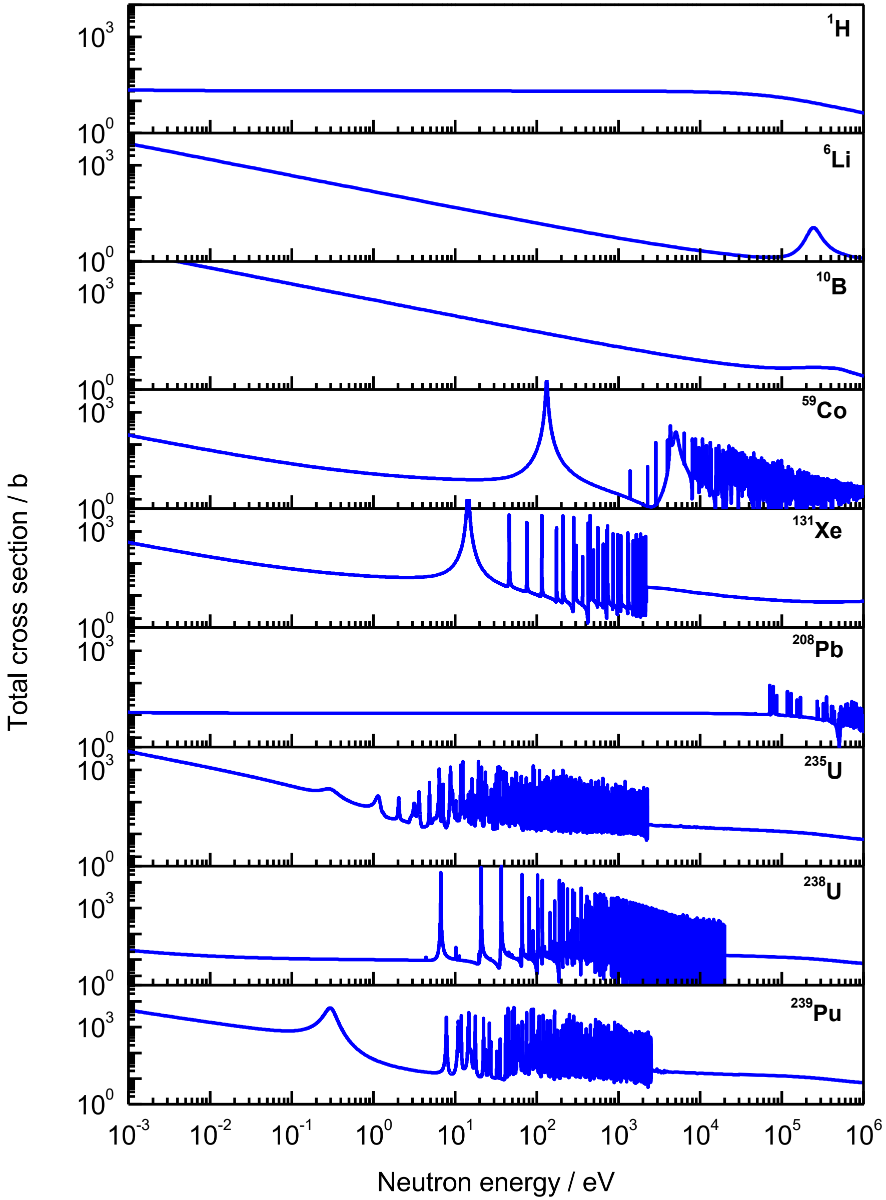
IAEA Nuclear Data Section, Vienna International Centre, A-1400 Vienna, Austria

European Commission

Neutron cross sections



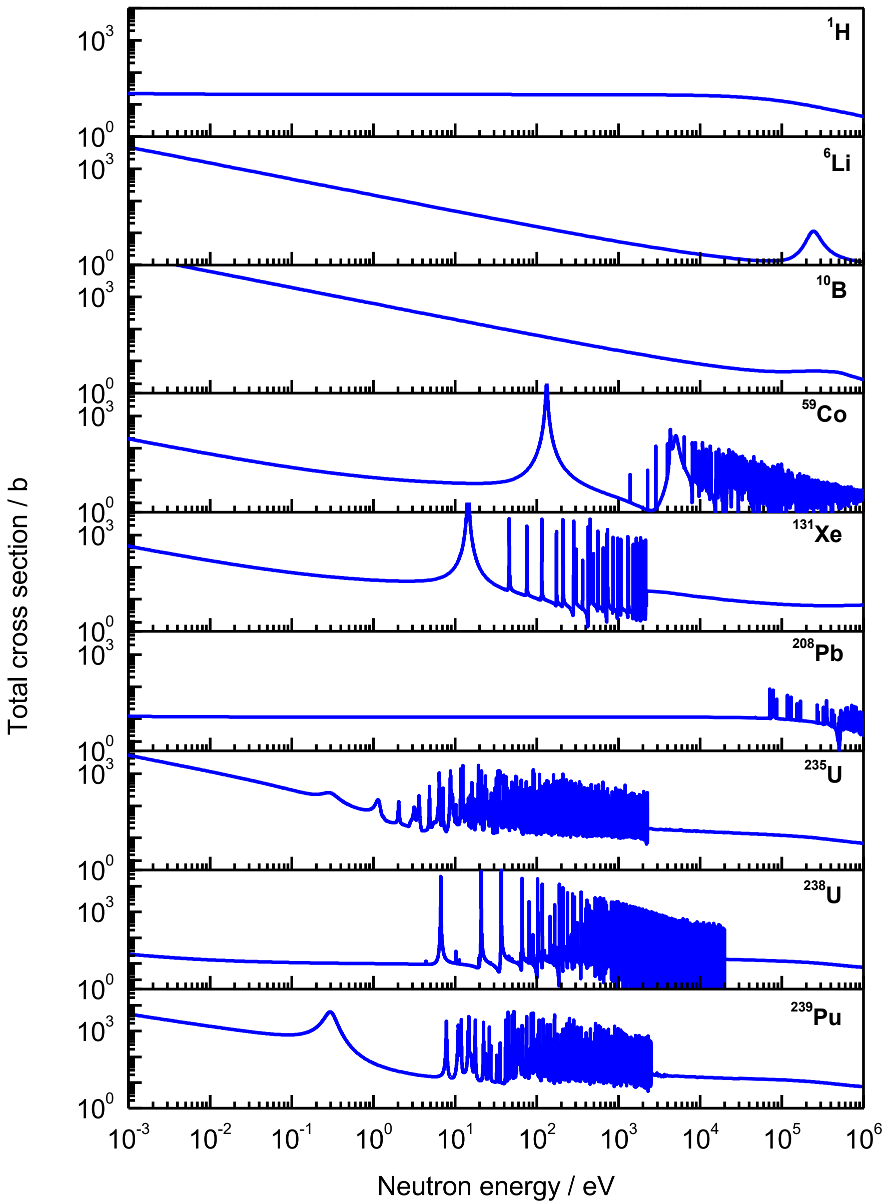
Neutron Resonance Analysis (NRCA&NRTA)



- Resonances appear at energies that are specific for each nuclide
- Energy and amplitude of resonances can be used as fingerprints to
  - identify and quantify nuclides
  - elemental & isotopic composition

Schillebeeckx et al., Report EUR 26848-EN (2014)

Neutron Resonance Analysis (NRCA&NRTA)



- Resonances appear at energies that are specific for each nuclide
- Energy and amplitude of resonances can be used as fingerprints to
  - identify and quantify nuclides
  - elemental & isotopic composition
- Neutron Resonance Analysis (developed at JRC) NRTA and NRCA
  - Non-Destructive Analysis (NDA)
  - no sample taking or preparation required
  - sensitive to almost all nuclides (except light)
  - requirements:
    TOF-measurements at a **white neutron source e.g. GELINA**

Schillebeeckx et al., Report EUR 26848-EN (2014)

European Commission

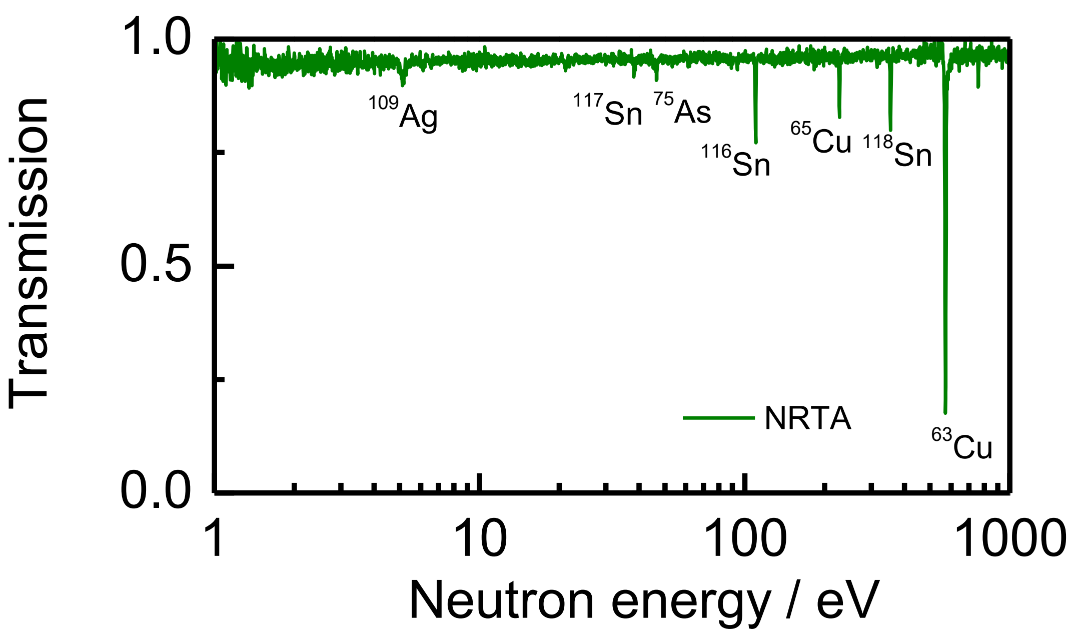
NRTA

- Element ratio

Uncertainties: only counting statistics

	NRTA
– Ag/Cu	1.112 (10) x 10^{-3}
– Sn/Cu	0.243 (7) x 10^{-3}

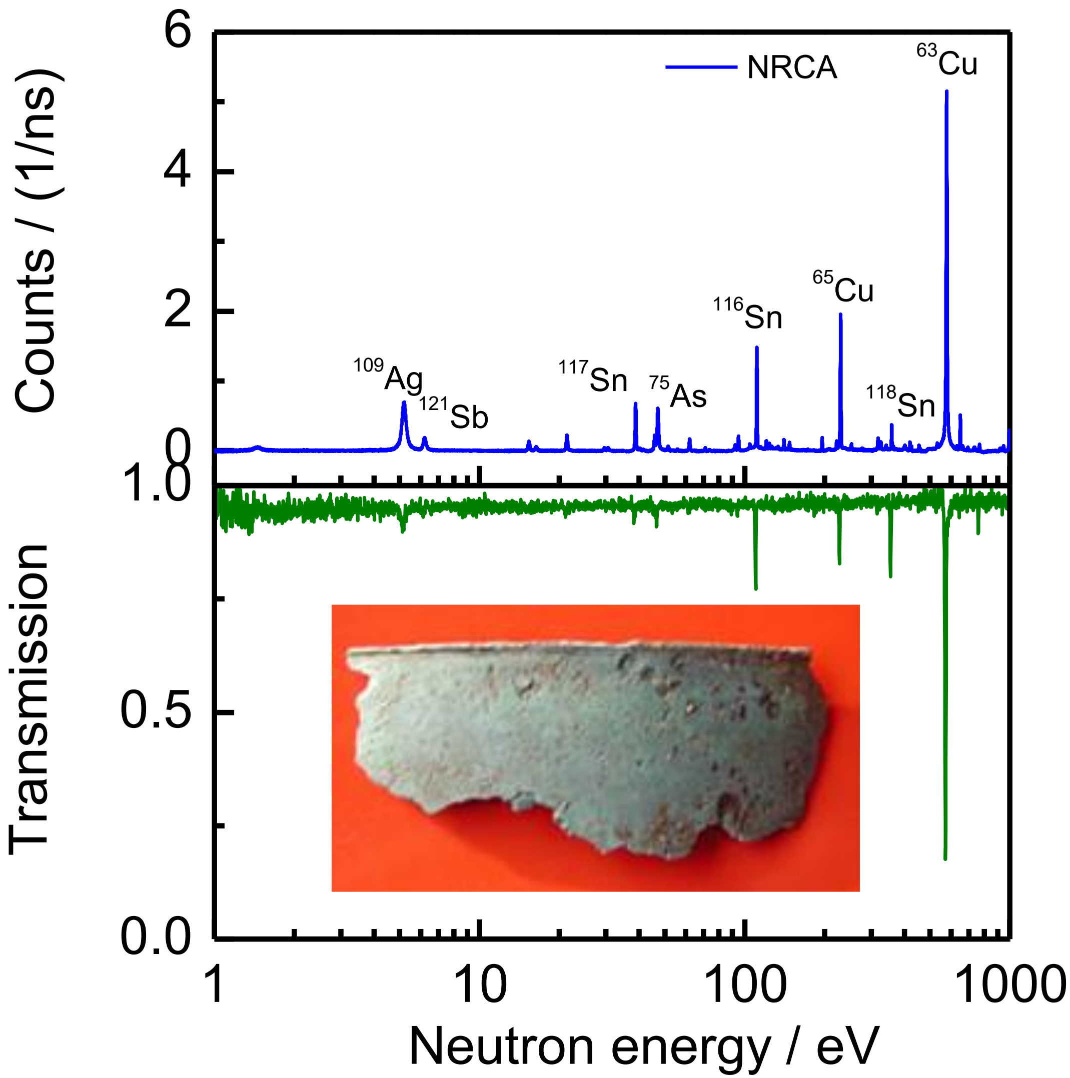
- Areal density of Cu
  - NRTA 0.55 (2) g/cm²



 Postma and Schillebeeckx, in Neutron Methods for Archaeology and Cultural Heritage (Springer)

European Commission

NRTA and NRCA

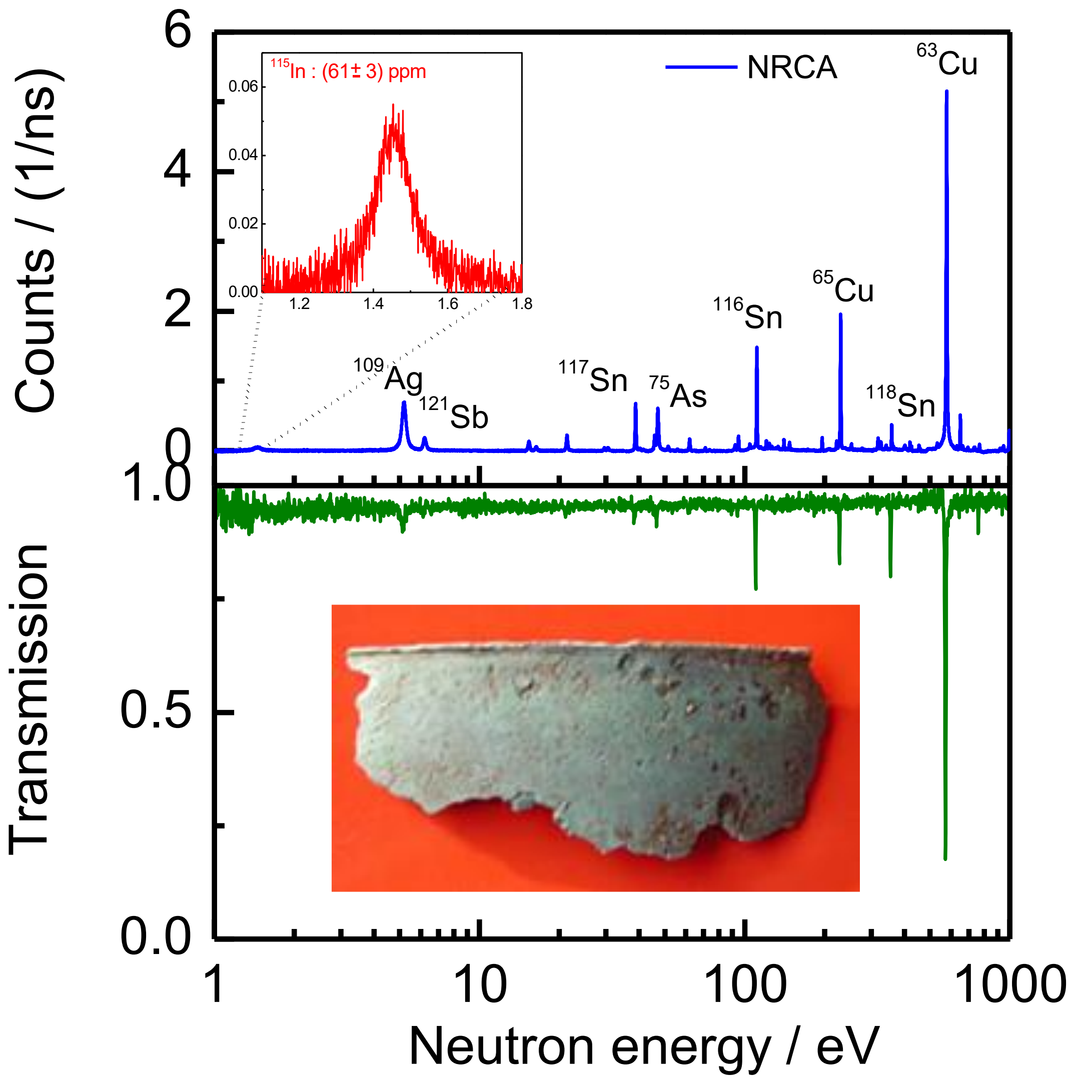


Areal density Cu: 0.55 (2) g/cm^2

Element	wt%			Isotope	E_r / 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
				^{124}Sn	62.0
As	**0.34**	±	**0.01**	^{75}As	47.0
Sb	**0.20**	±	**0.02**	^{121}Sb	6.24
				^{123}Sb	21.4
Ag	**0.09**	±	**0.01**	^{107}Ag	16.3
				^{109}Ag	5.2
Fe	**0.77**	±	**0.10**	^{56}Fe	1147.4
In	**0.0061**	±	**0.0003**	^{115}In	1.46

 Postma and Schillebeeckx, in Neutron Methods for Archaeology and Cultural Heritage (Springer)

NRTA and NRCA

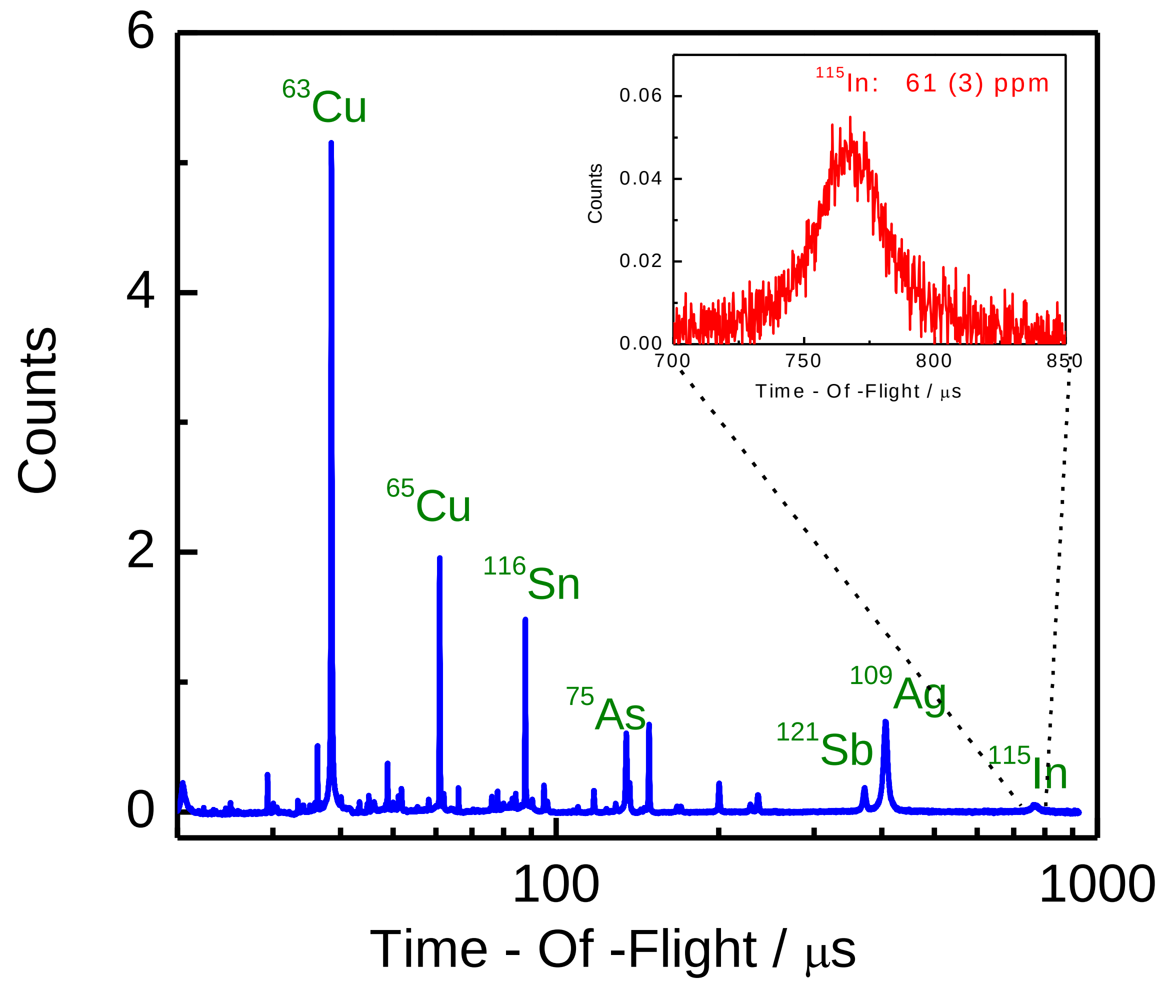


Areal density Cu: 0.55 (2) g/cm^2

Element	wt%			Isotope	E_r / 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
				^{124}Sn	62.0
As	**0.34**	±	**0.01**	^{75}As	47.0
Sb	**0.20**	±	**0.02**	^{121}Sb	6.24
				^{123}Sb	21.4
Ag	**0.09**	±	**0.01**	^{107}Ag	16.3
				^{109}Ag	5.2
Fe	**0.77**	±	**0.10**	^{56}Fe	1147.4
In	**0.0061**	±	**0.0003**	^{115}In	1.46

Postma et al., Czech. J. Phys. 53 (2003) A233

NRCA ⇔ PGAA

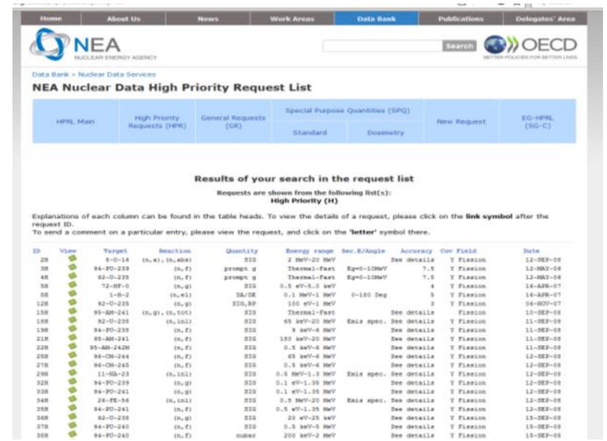


⇒ detection of In is not hindered by strong resonances of other elements (e.g. Cu)

Postma et al., Czech. J. Phys. 53 (2003) A233

Final remarks

- There is still a need of nuclear data in various fields of nuclear technology (see HPRL of NEA/OECD)

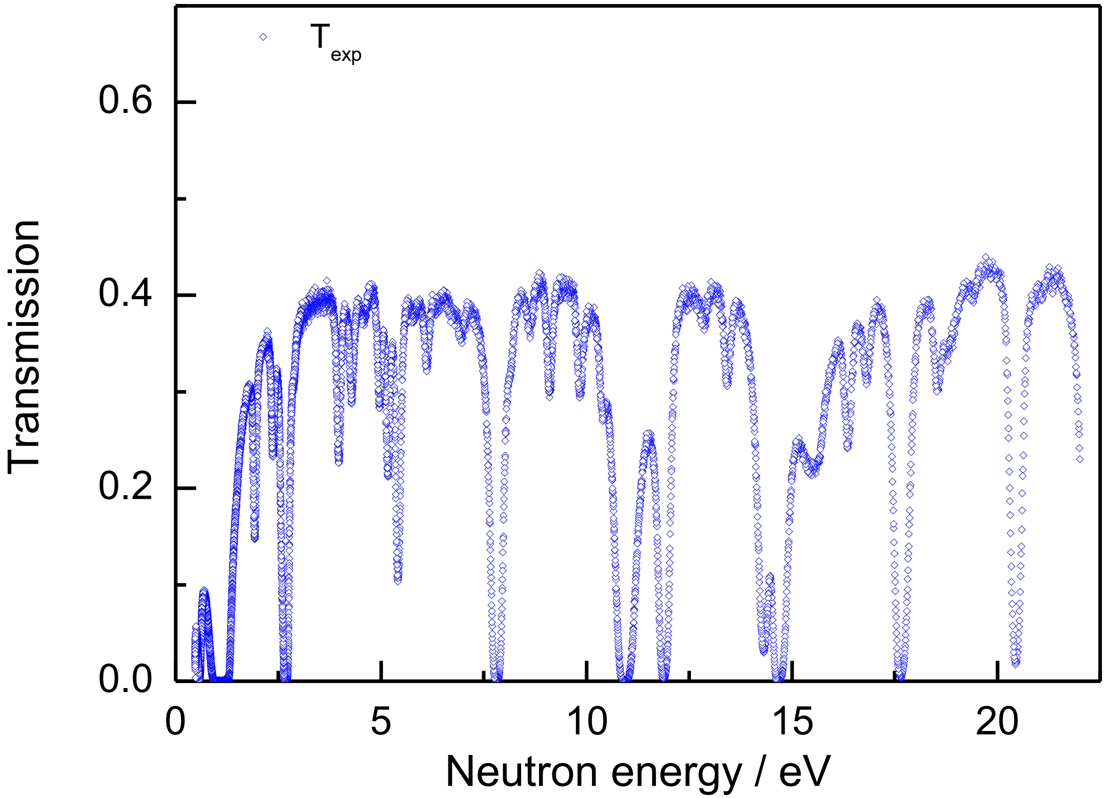


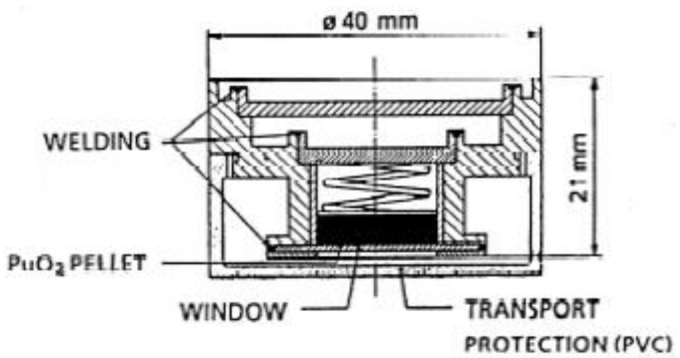
- Installations to produce accurate nuclear data are being closed (e.g. ORELA)

- Initiatives to construct new facilities and install new nuclear data programmes such as NDPS at RAON are welcome

Thank you for your attention

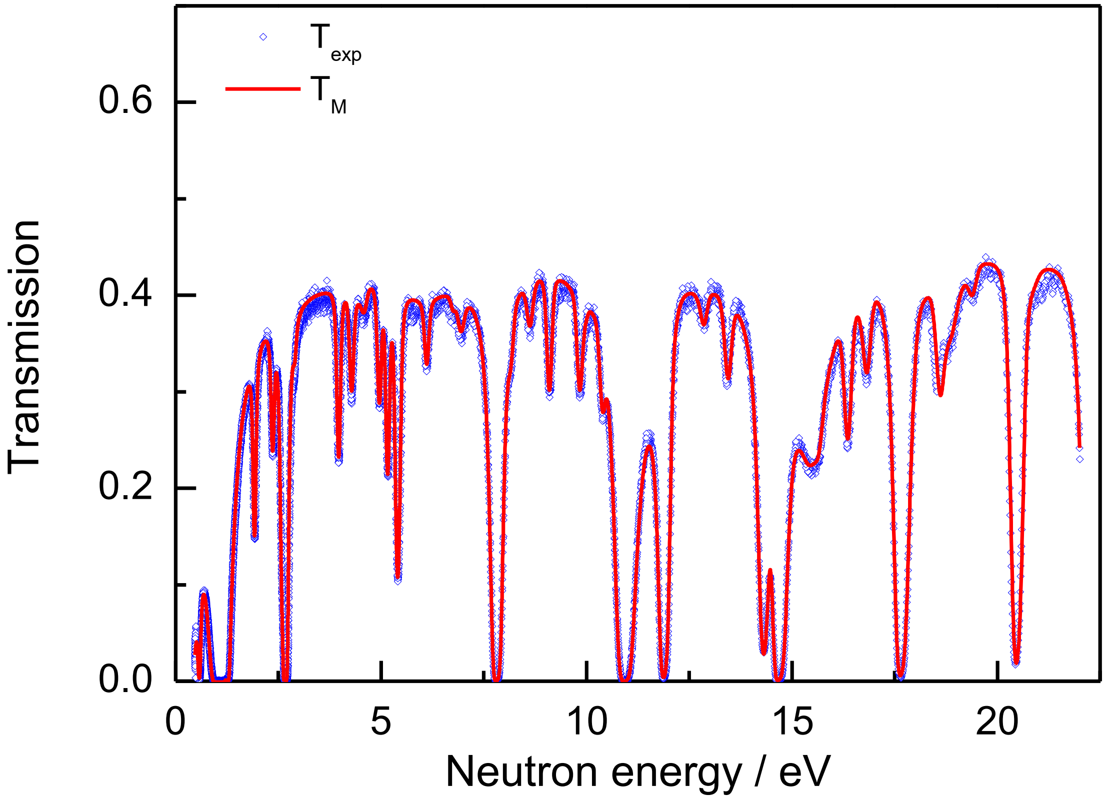
NRTA of PuO_2 sample at GELINA (CBNM – 271)





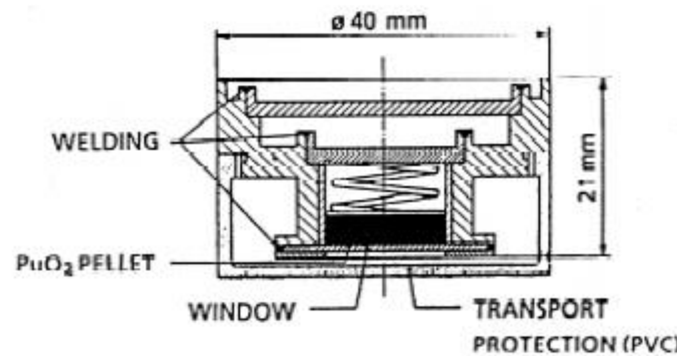
European Commission

NRTA of PuO_2 sample at GELINA (CBNM – 271)



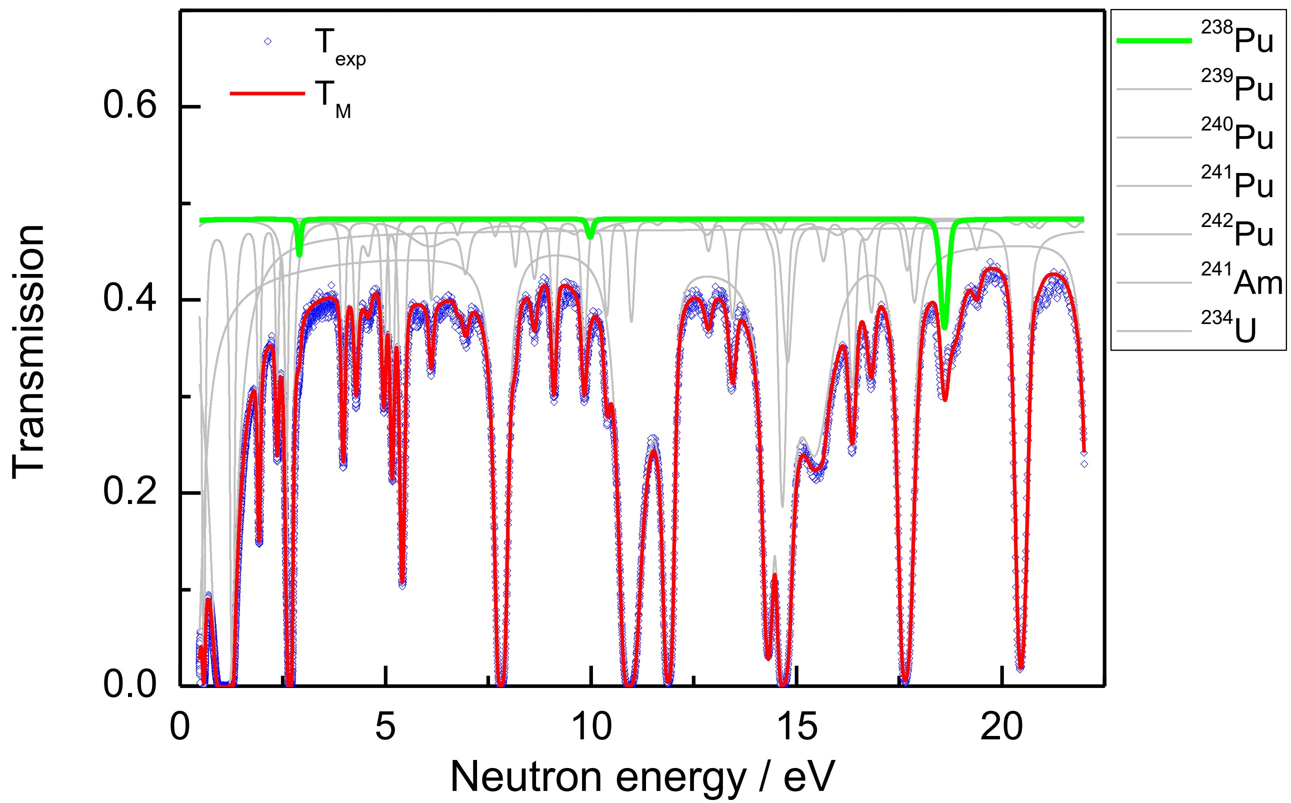
$$T_M(t_m, n) = \int R(t_m, E)\, e^{-n\,\sigma_{tot}(E)} dE$$

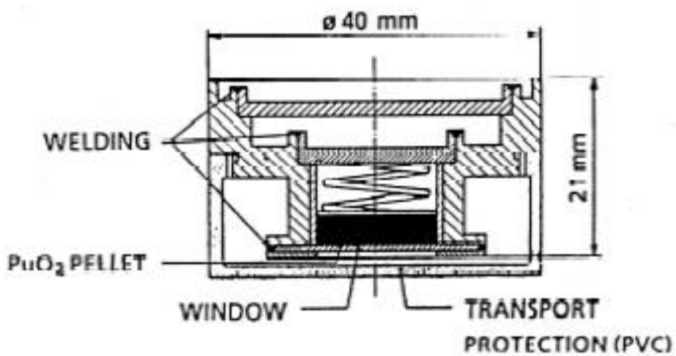
$$\chi^2(n) = \left(T_{exp} - T_M(t_m, n)\right)^T V_{T_{exp}}^{-1} \left(T_{exp} - T_M(t_m, n)\right)$$



European Commission

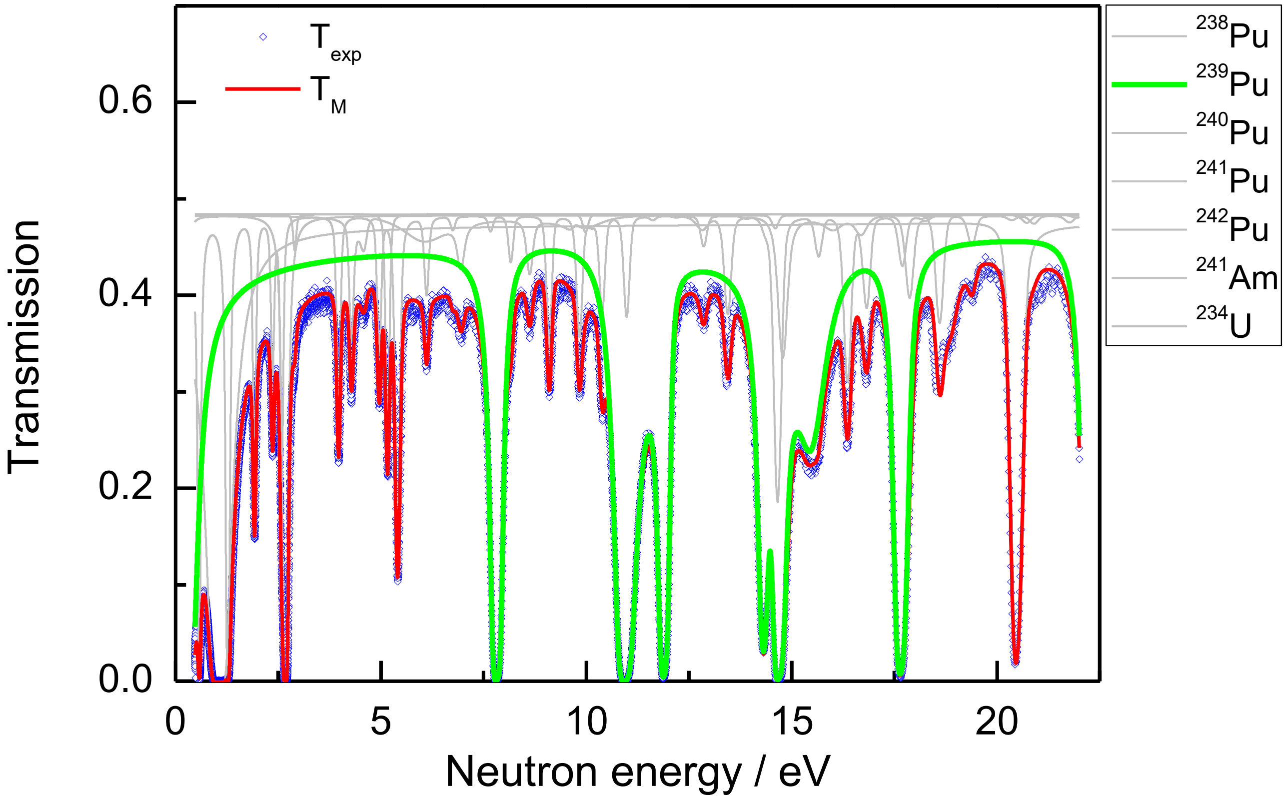
NRTA of PuO_2 sample at GELINA (CBNM – 271)

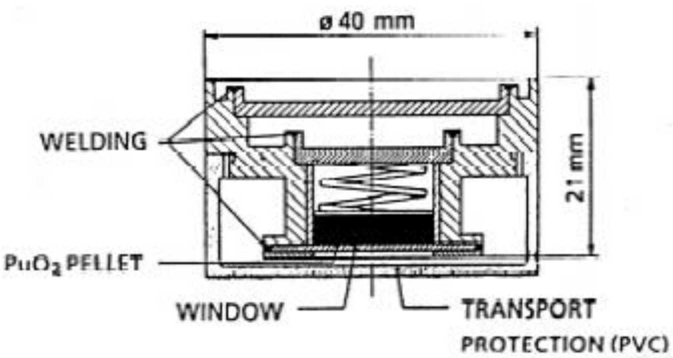




European Commission

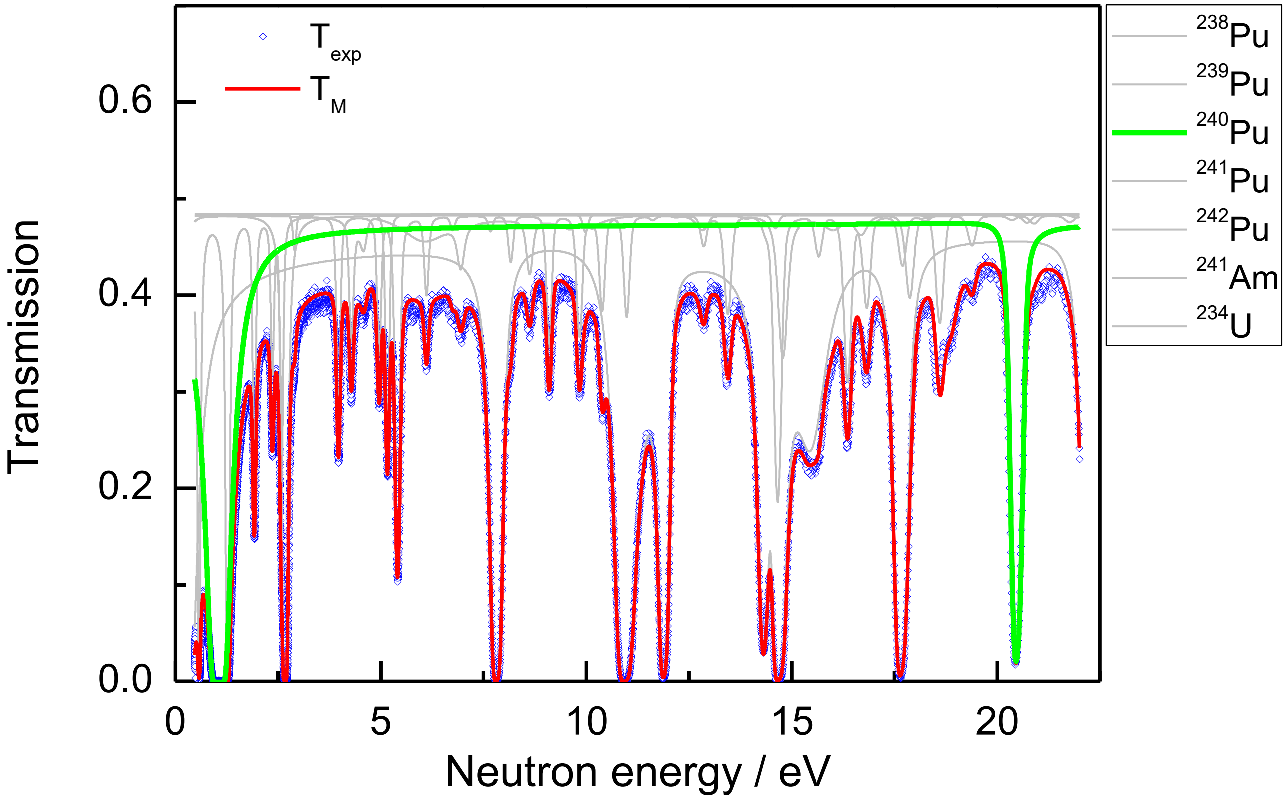
NRTA of PuO_2 sample at GELINA (CBNM – 271)

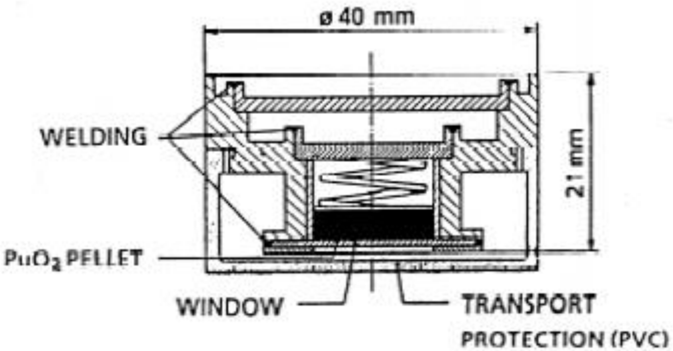




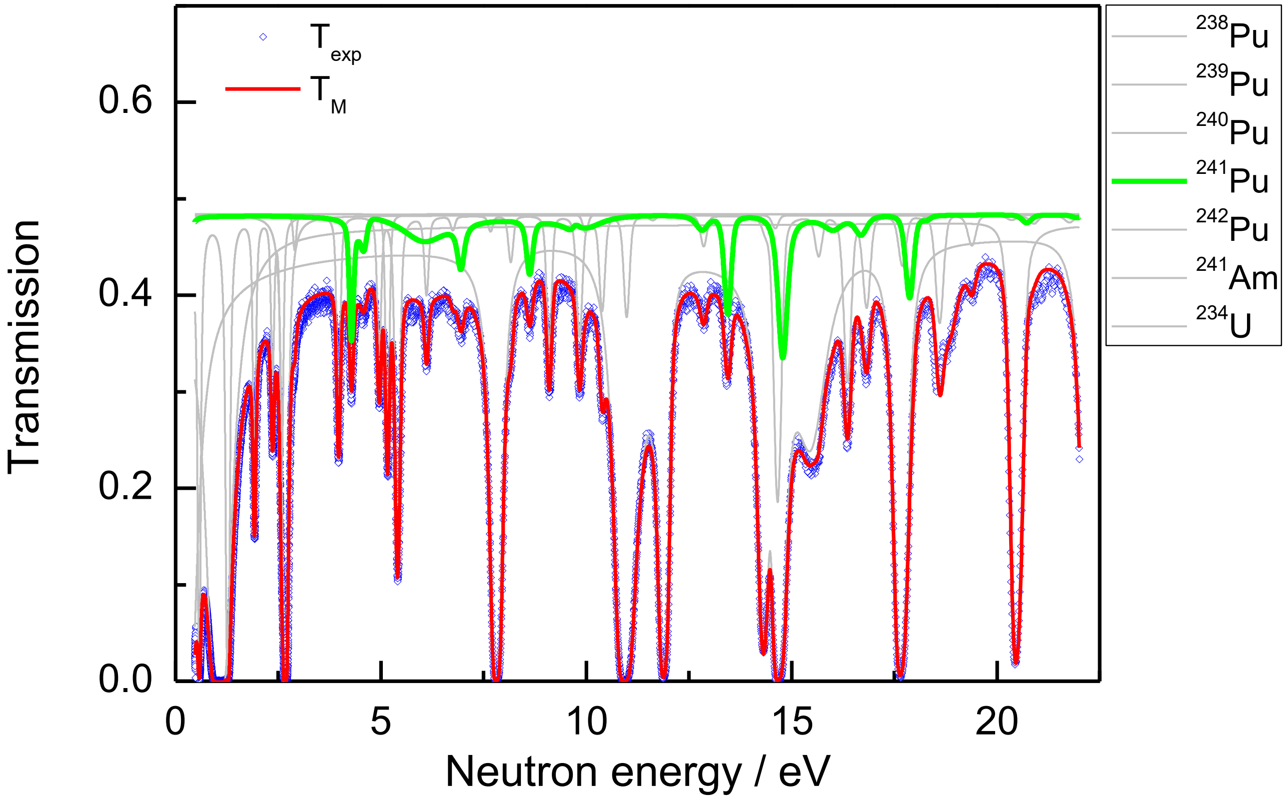
European Commission

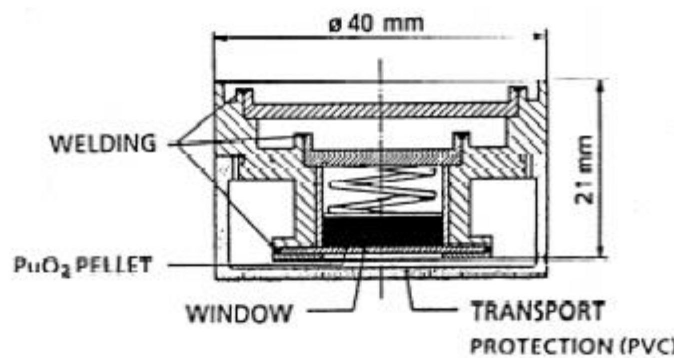
NRTA of PuO_2 sample at GELINA (CBNM – 271)



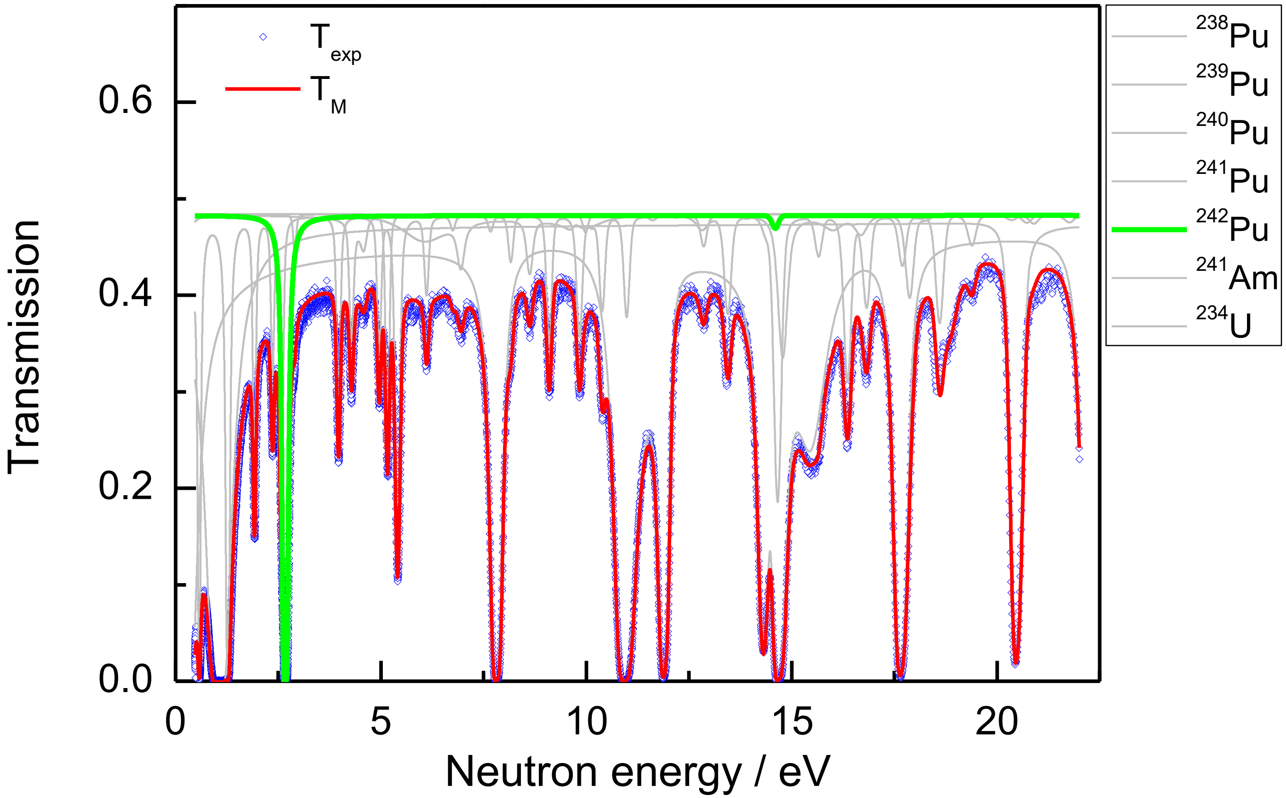


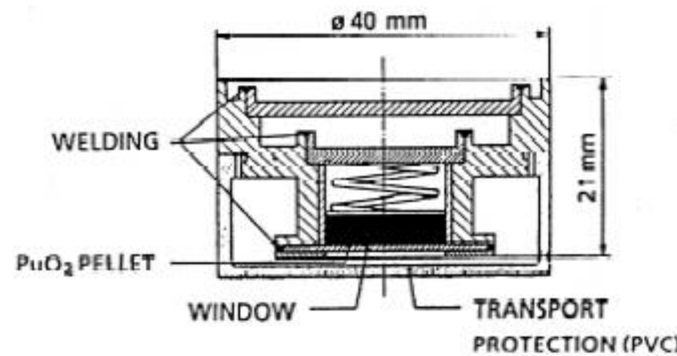
NRTA of PuO_2 sample at GELINA (CBNM – 271)





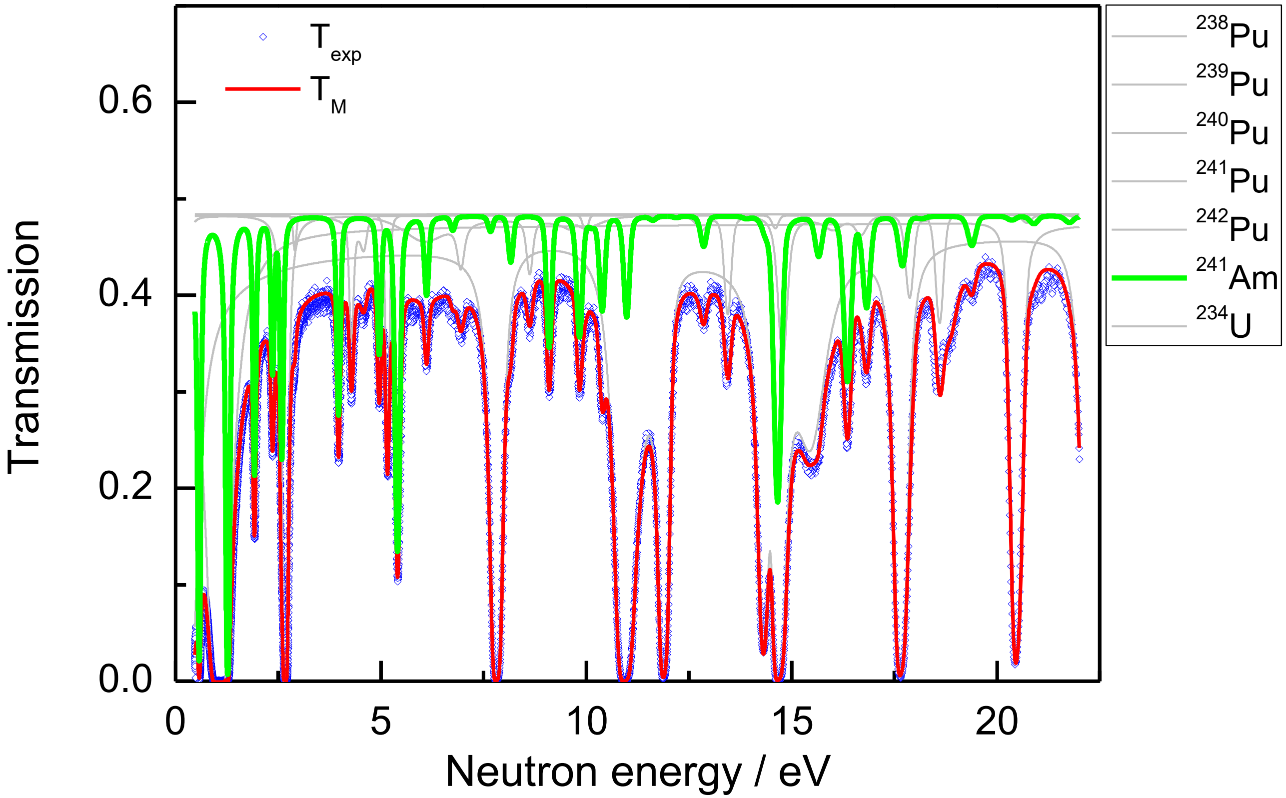
NRTA of PuO_2 sample at GELINA (CBNM – 271)

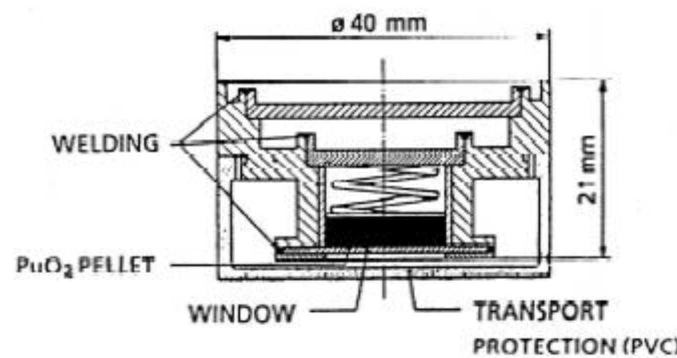




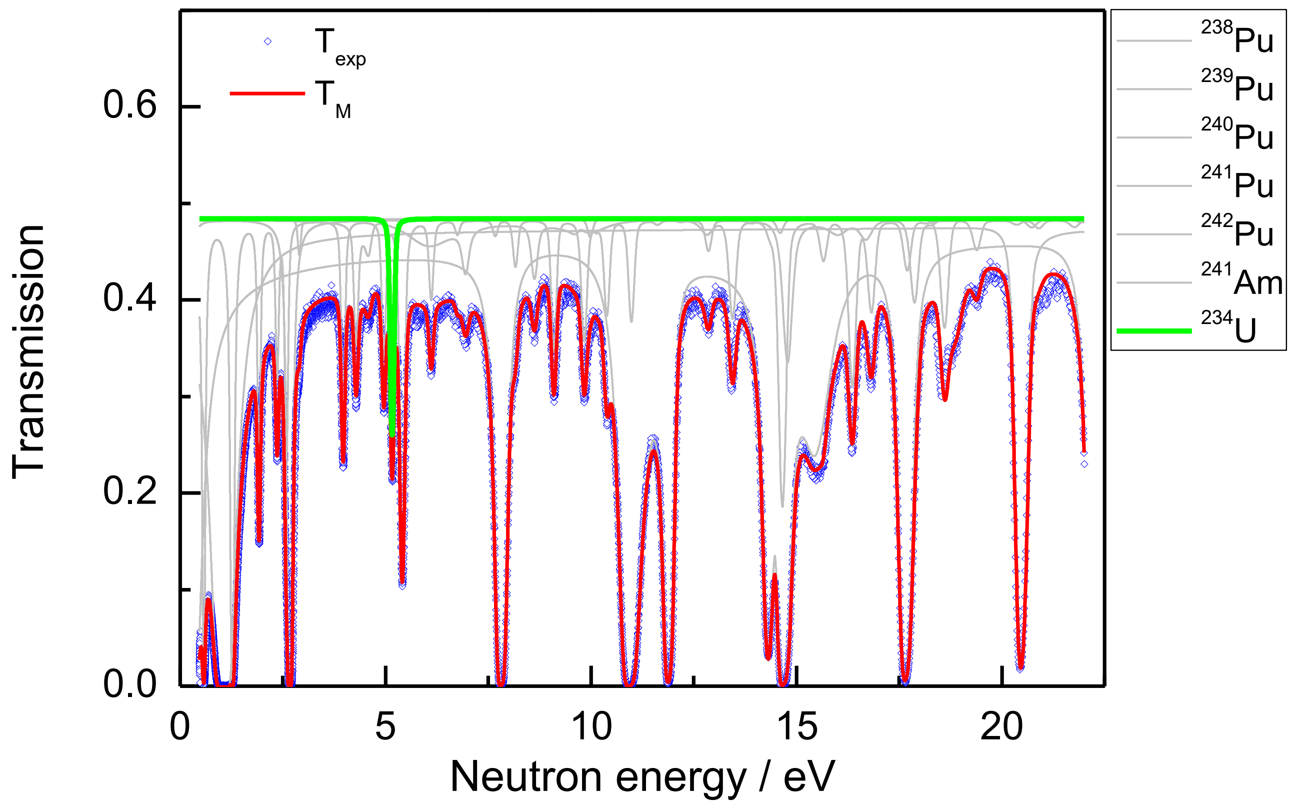
European Commission

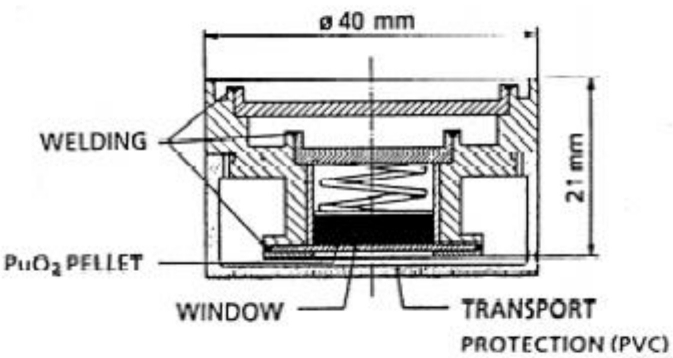
NRTA of PuO_2 sample at GELINA (CBNM – 271)





NRTA of PuO_2 sample at GELINA (CBNM – 271)





European Commission

NRTA of PuO_2 sample at GELINA (CBNM – 271)

Nuclide	n_{NRTA}		n_{REF}		n_{NRTA}/n_{REF}	
^{238}Pu	0.0098	(2)	0.009500	(20)	0.979	(20)
^{239}Pu	0.6236	(6)	0.62602	(28)	0.996	(1)
^{240}Pu	0.2593	(4)	0.25272	(24)	1.026	(2)
^{241}Pu	0.0157	(1)	0.015490	(20)	1.014	(7)
^{242}Pu	0.0427	(2)	0.041490	(60)	1.029	(5)
^{241}Am	0.0612	(9)	0.06300	(63)	0.971	(17)
^{234}U	0.00289	(3)	0.00293	(1)	0.986	(5)

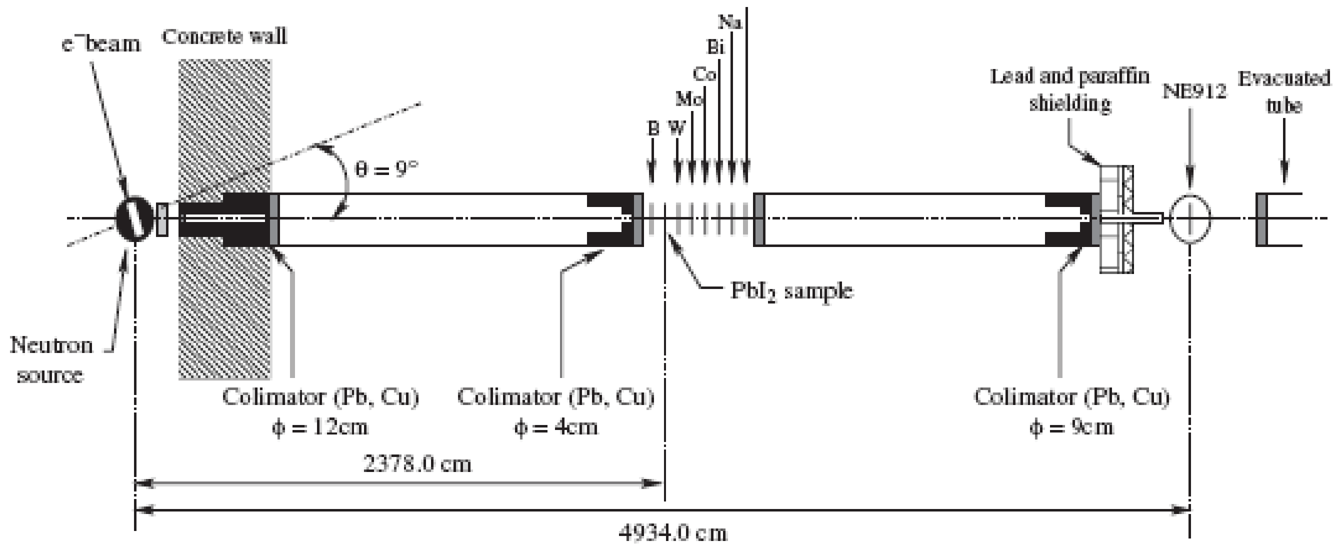
NRTA uncertainties only due to counting statistics

European Commission

Characterisation of PbI_2 by NRTA at GELINA

- JRC Geel preparation group extracted:
  - 150 g Iodine (powder) from 210 liter from **reprocessed waste** (Le Hague)
  - (1.3 g/l Iodine and 40 MBq/l)
- Sample characterisation: by mass spectrometry , NAA and **NRTA**

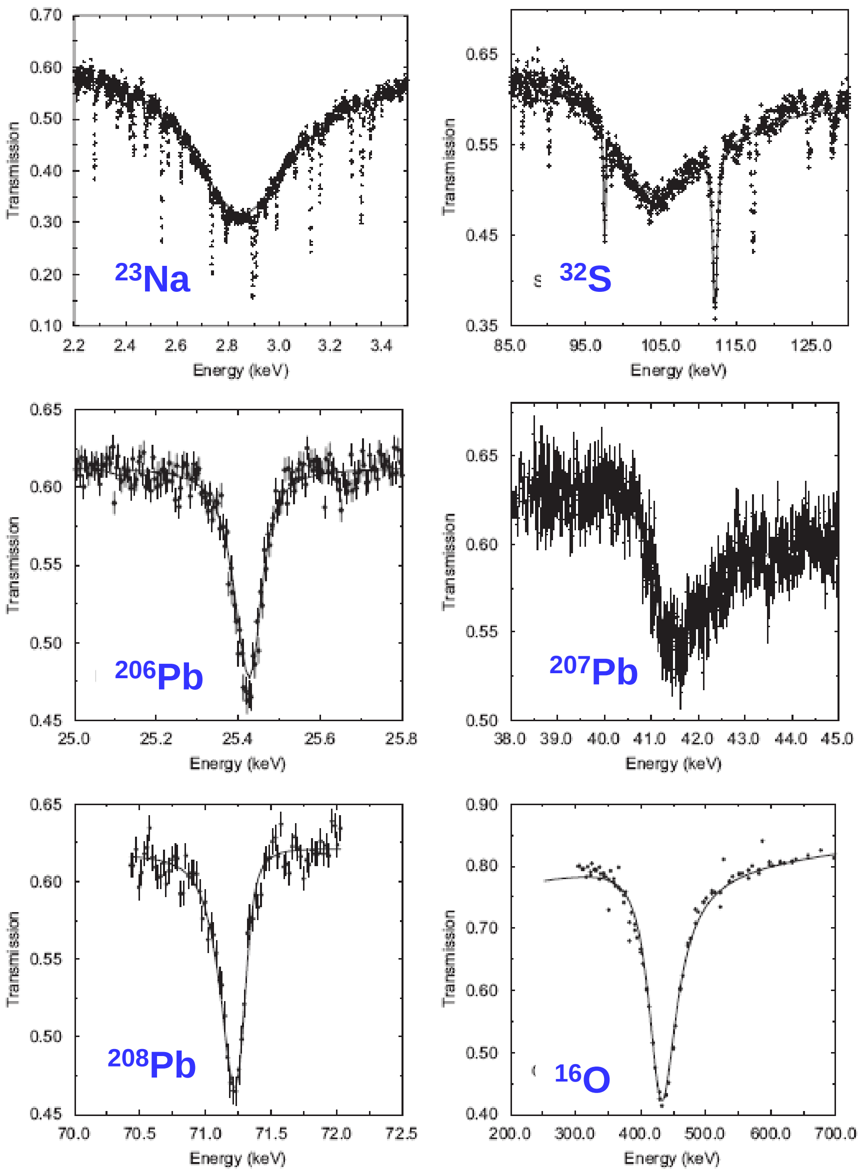
Fig. 3. Addition of $Pb(NO_3)_2$ to the iodide solution to precipitate lead iodide.



Noguere et al., Nucl. Instr. Meth. Phys. Res. A 575 (2007) 476

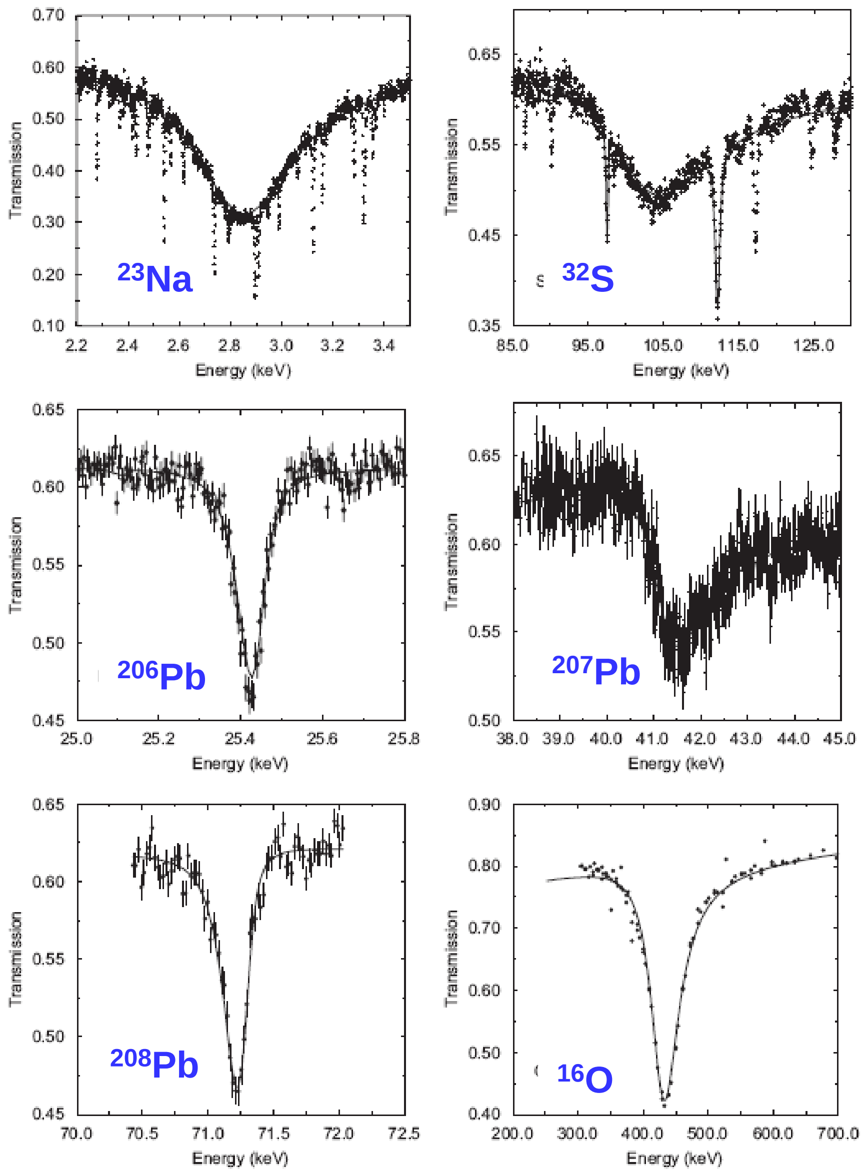
European Commission

Characterisation of PbI_2 by NRTA at GELINA



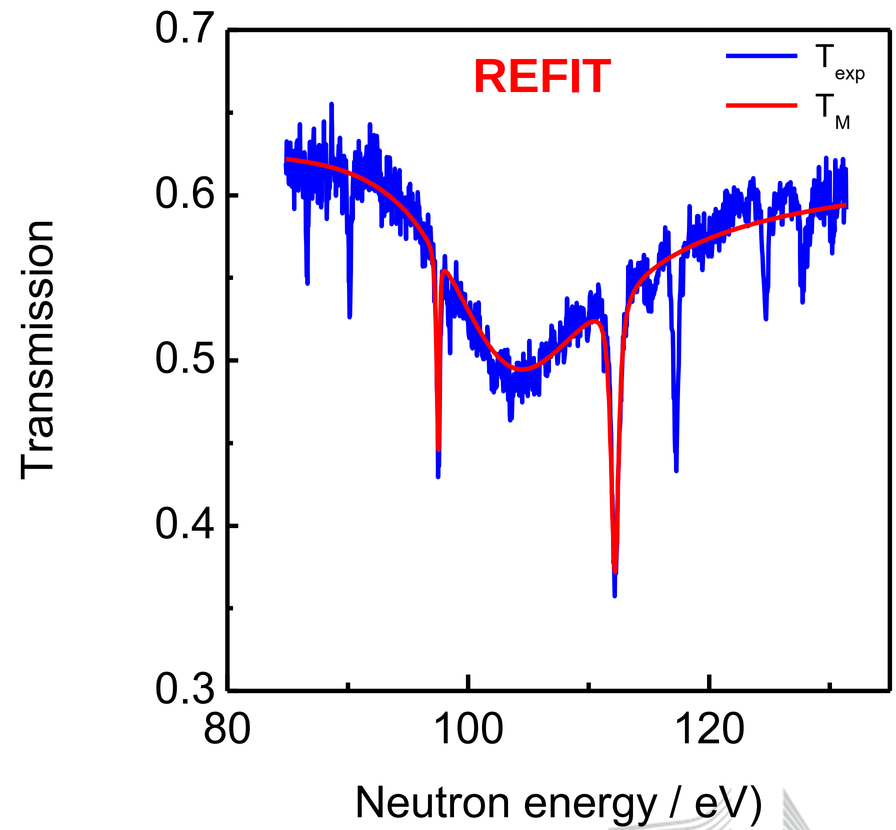
Noguere et al., Nucl. Instr. Meth. Phys. Res. A 575 (2007) 476

Characterisation of PbI_2 by NRTA at GELINA



$$T_M(t_m, n) = \int R(t_m, E)\, e^{-n\,\sigma_{tot}(E)}\, dE$$

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



Noguere et al., Nucl. Instr. Meth. Phys. Res. A 575 (2007) 476

European Commission

NRTA compared with NAA and ICP-MS

Element		NRTA (GELINA)		NAA		Mass spectrometry (PSI)	
Iodine	total	20.24	(0.41)	19.75	(0.61)	19.86	(0.41)
	^{127}I	3.44	(0.05)	3.35	(0.10)	3.36	(0.08)
	^{129}I	16.80	(0.40)	16.40	(0.60)	16.50	(0.40)
Lead	total	52.30	(1.70)	51.10	(1.80)		
	^{206}Pb	12.80	(0.50)				
	^{207}Pb	11.50	(0.10)				
	^{208}Pb	27.10	(1.70)				
Sulfur		5.44	(0.03)				
Sodium		0.72	(0.02)			1.00	(0.15)
Oxygen		13.92	(0.05)			14.50	(1.50)
Hydrogen		< 0.13				0.02	(0.002)
Nitrogen						1.20	(0.40)

NRTA :

- more elements have been analysed
- isotopic composition of Pb

Noguere et al., Nucl. Instr. Meth. Phys. Res. A 575 (2007) 476

European Commission

Cross section measurements

Total cross section

$$T \cong e^{-n\sigma_{tot}}$$

Capture cross section

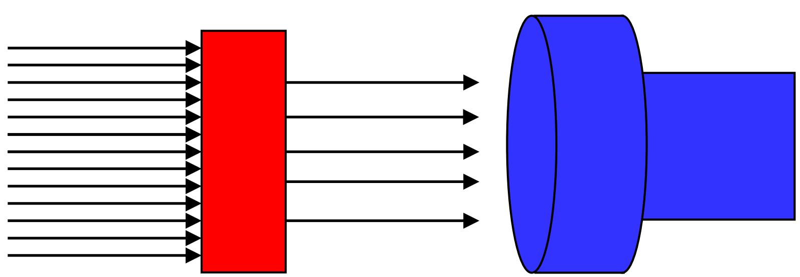
$$Y_\gamma \approx (1 - e^{-n\,\sigma_{tot}})\frac{\sigma_\gamma}{\sigma_{tot}}$$

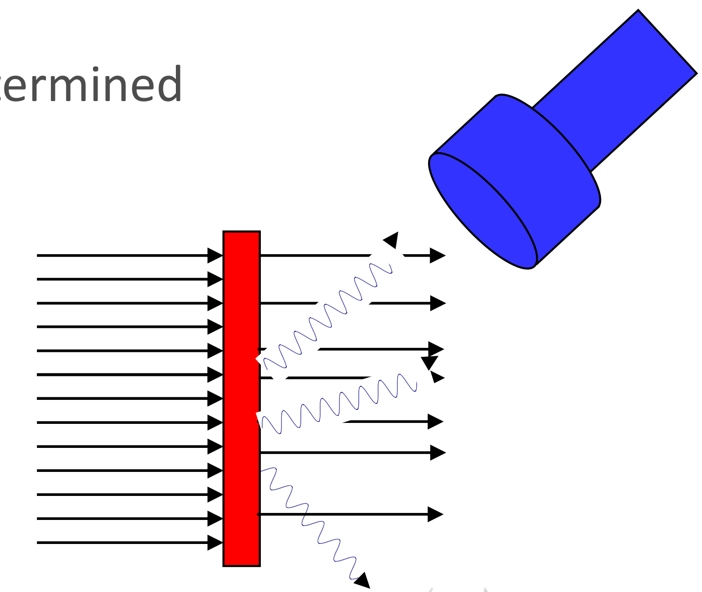
Well-characterised samples

n: areal density (total number of atoms per unit area) is well-known

$\Downarrow$

accurate cross-sections can be determined





Schillebeeckx et al., NDS 113 (2012) 3054

Neutron resonance analysis

NRTA

$$T \cong e^{-n\sigma_{tot}}$$

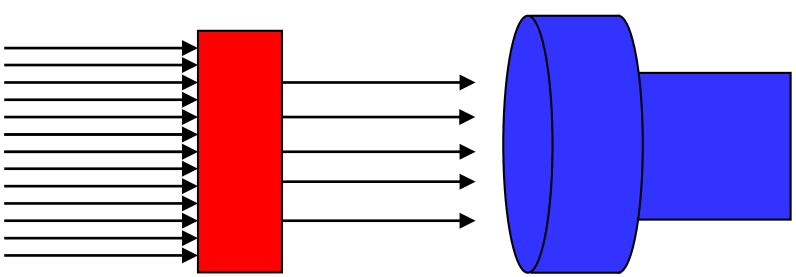
NRCA

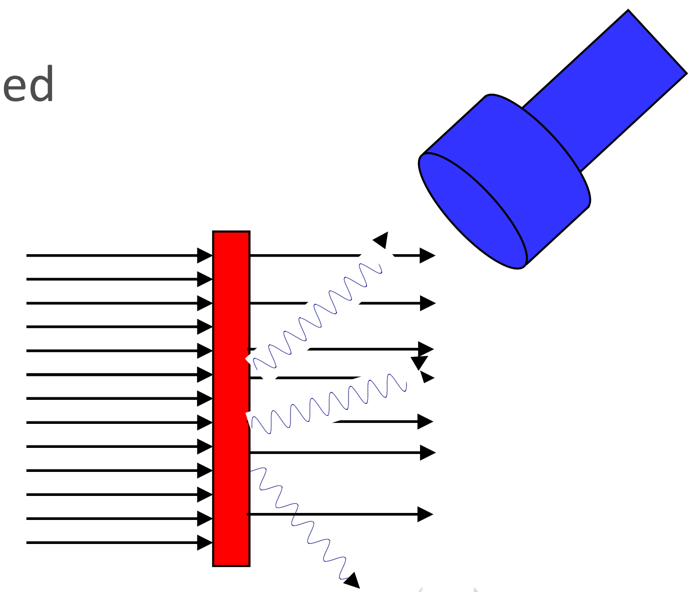
$$Y_\gamma \approx (1 - e^{-n\sigma_{tot}})\frac{\sigma_\gamma}{\sigma_{tot}}$$

Well-known cross sections

$\Downarrow$

areal density can be determined





Schillebeeckx et al., Report EUR 26848-EN (2014)

VERDI: 2E – 2v spectrometer

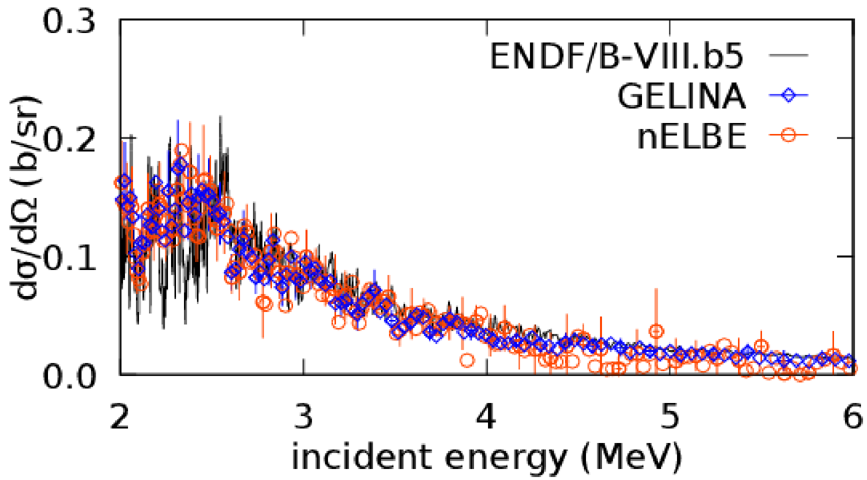
- Energy (E)
  - 2 arrays of 16 Si detectors
  - Each detector 450 mm^2
- Time-of-Flight (v)
  - **Start**: Electrons emitted from target detected by Micro Channel Plate (MCP)
  - **Stop**: Si detector

- Maximum solid angle coverage (0.5% of 4π) at relatively short flight path (50 cm)
- Energy (0.5%) and timing (150 ps) resolution
- Energy losses only in target backing and silicon detector dead layer

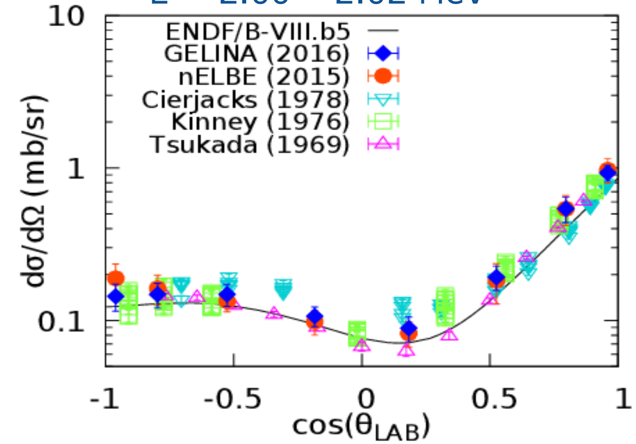
Frégeau, et al., NIM A817 (2016) 35–41

$^{nat}Fe(n,n)$

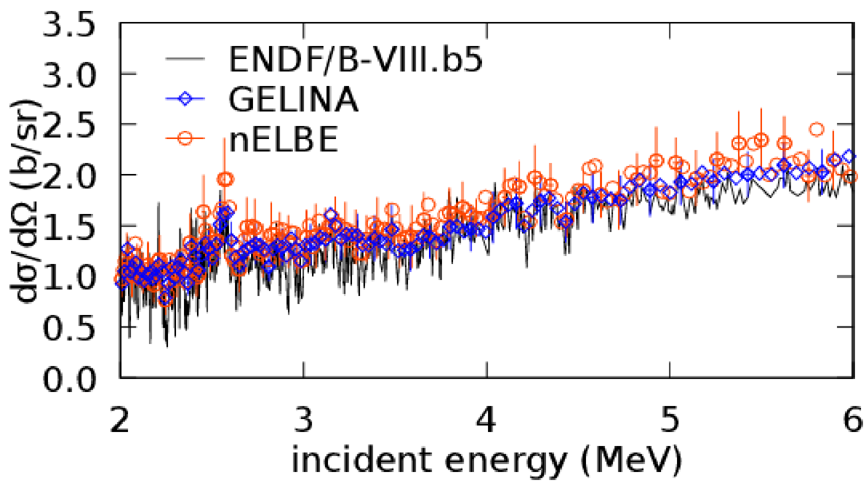
142.8°



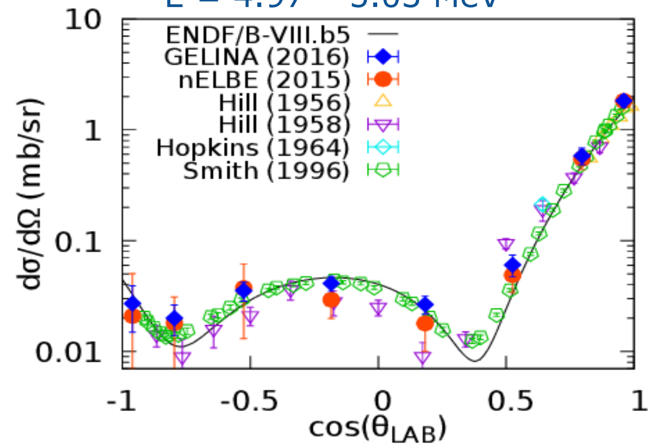
E = 2.00 – 2.02 MeV



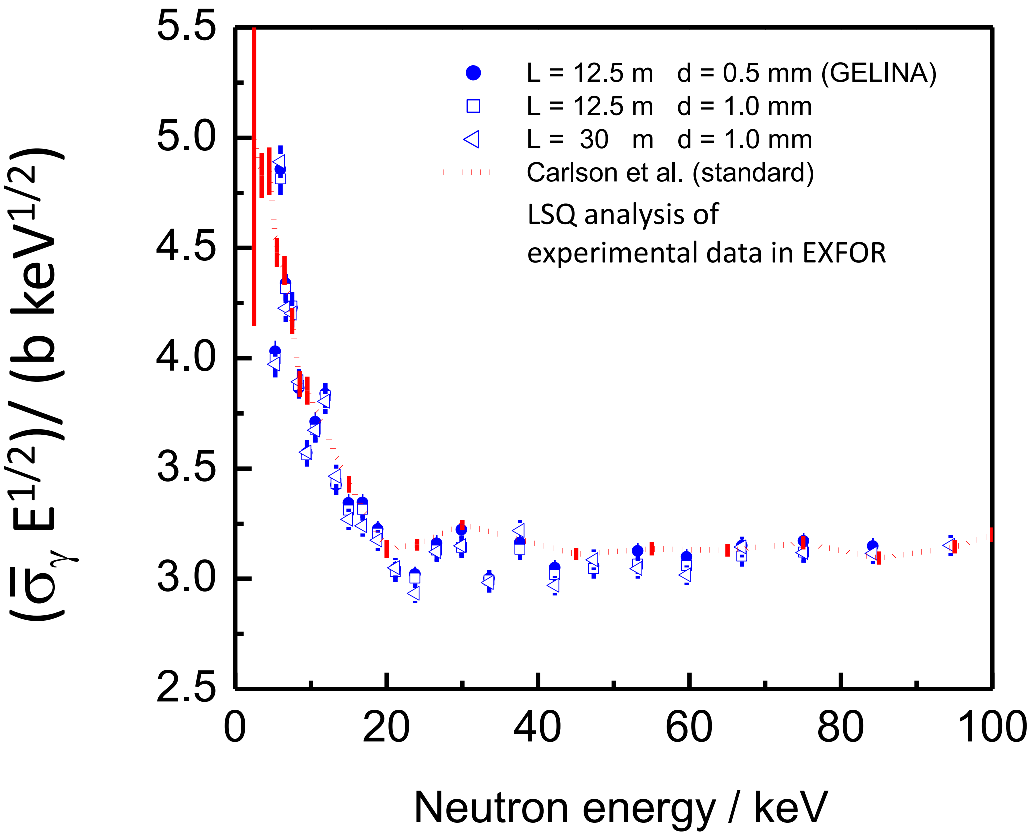
16.2°



E = 4.97 – 5.03 MeV



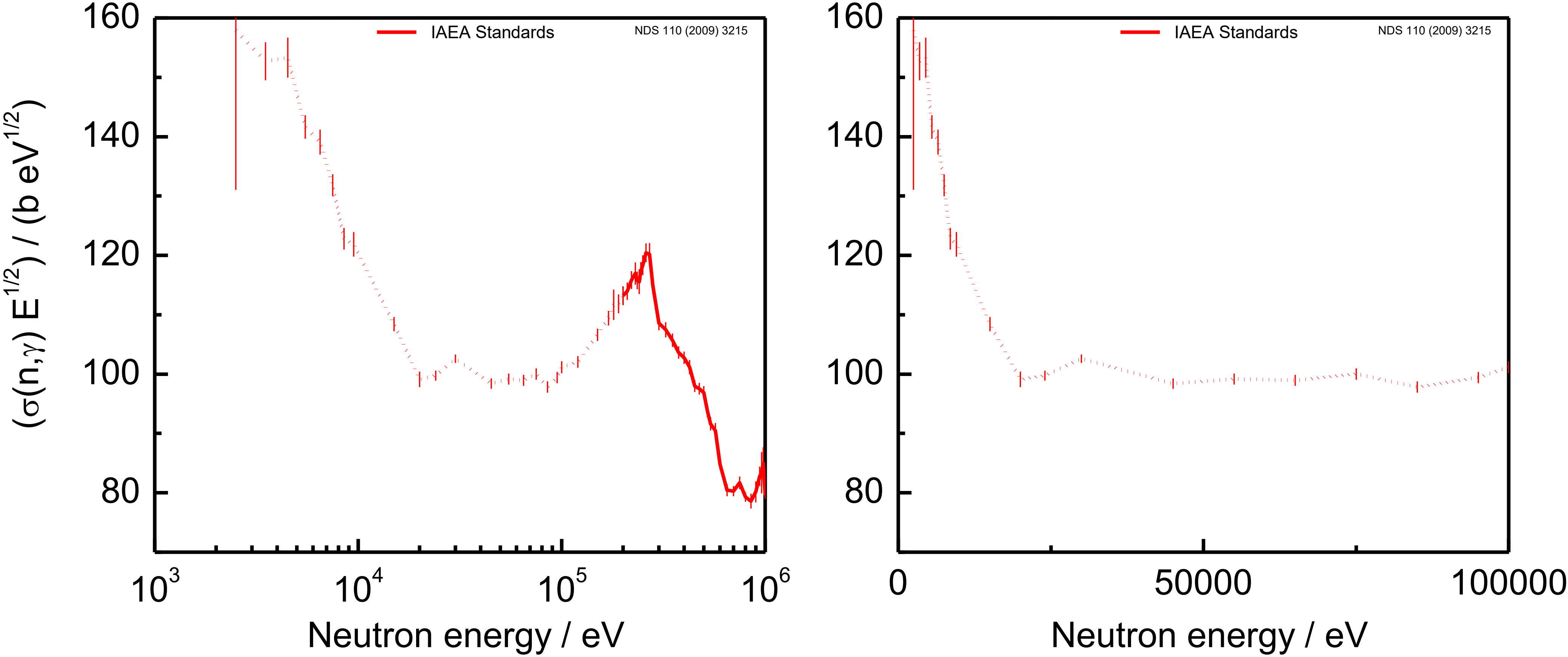
Comparison with data in the literature



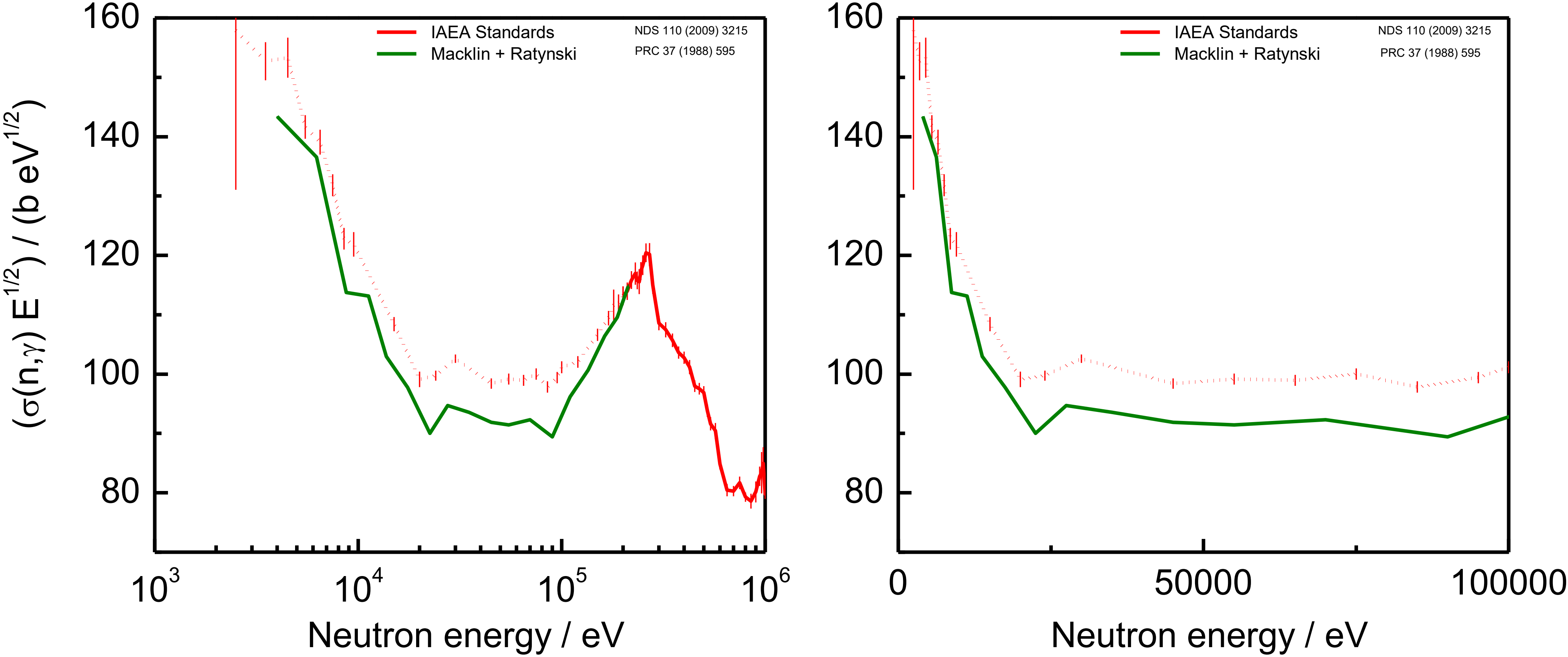
$$\boxed{\frac{u_{\sigma_\gamma}}{\sigma_\gamma} \approx 1.2\%}$$

European Commission

$^{197}Au(n,\gamma)$ in URR



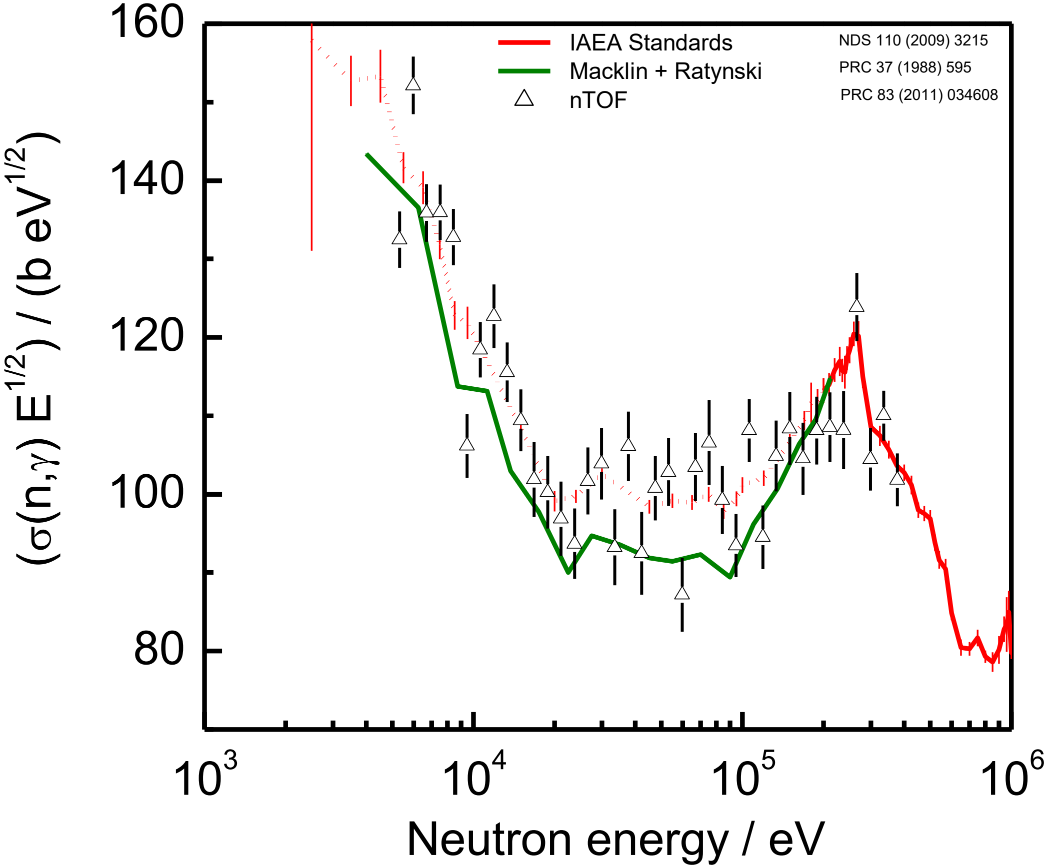
$^{197}Au(n,\gamma)$ in URR

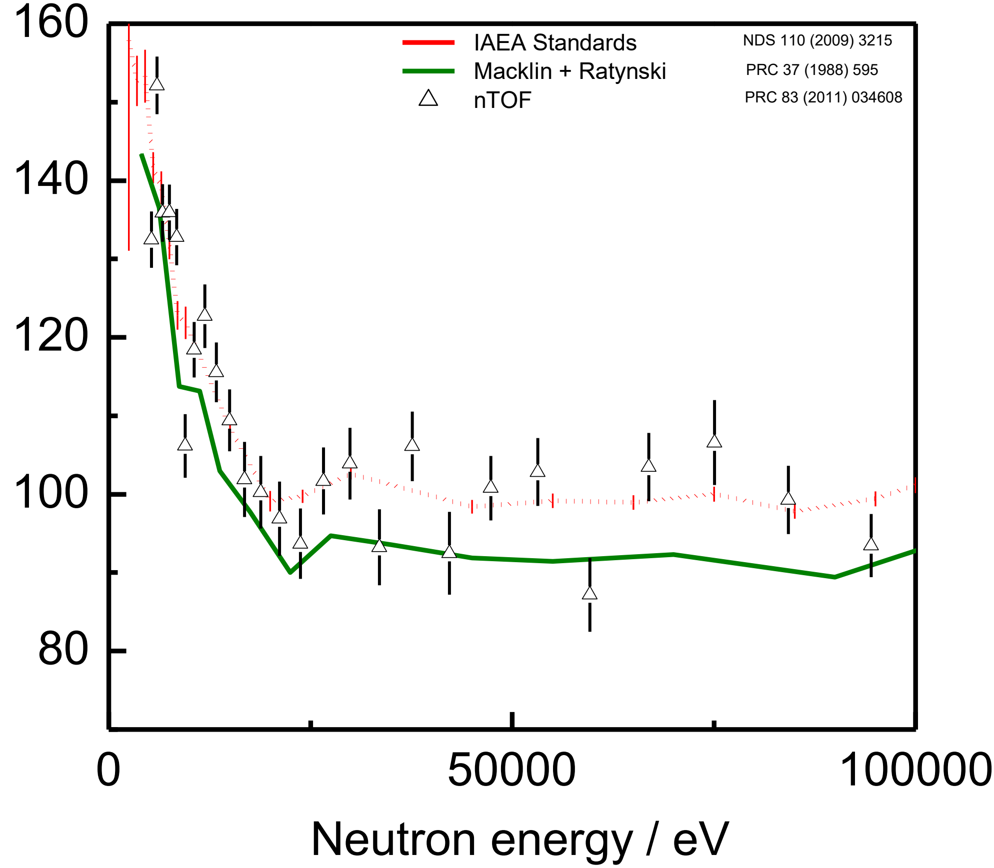


Between 5 and 100 keV : difference of about 8 %
in the region of interest for stellar calculations

European Commission

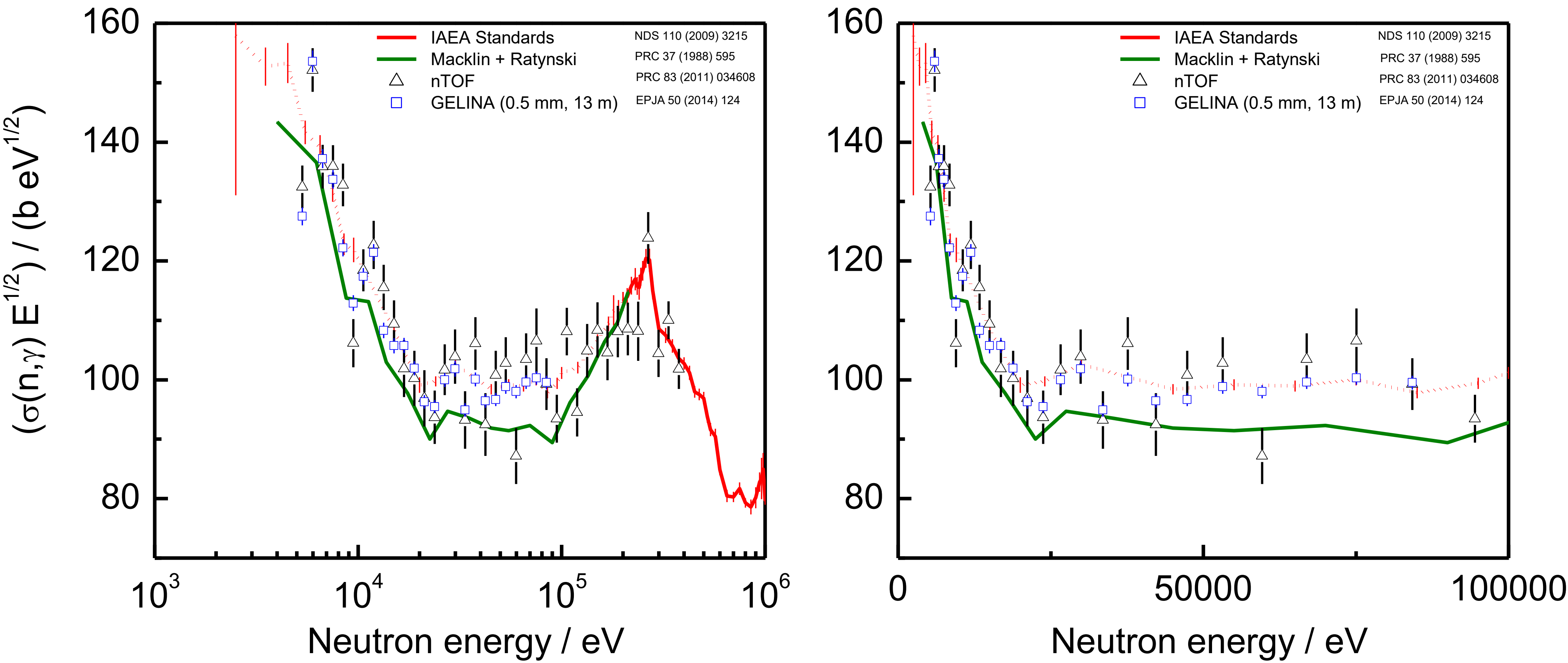
$^{197}Au(n,\gamma)$ in URR





European Commission

$^{197}Au(n,\gamma)$ in URR

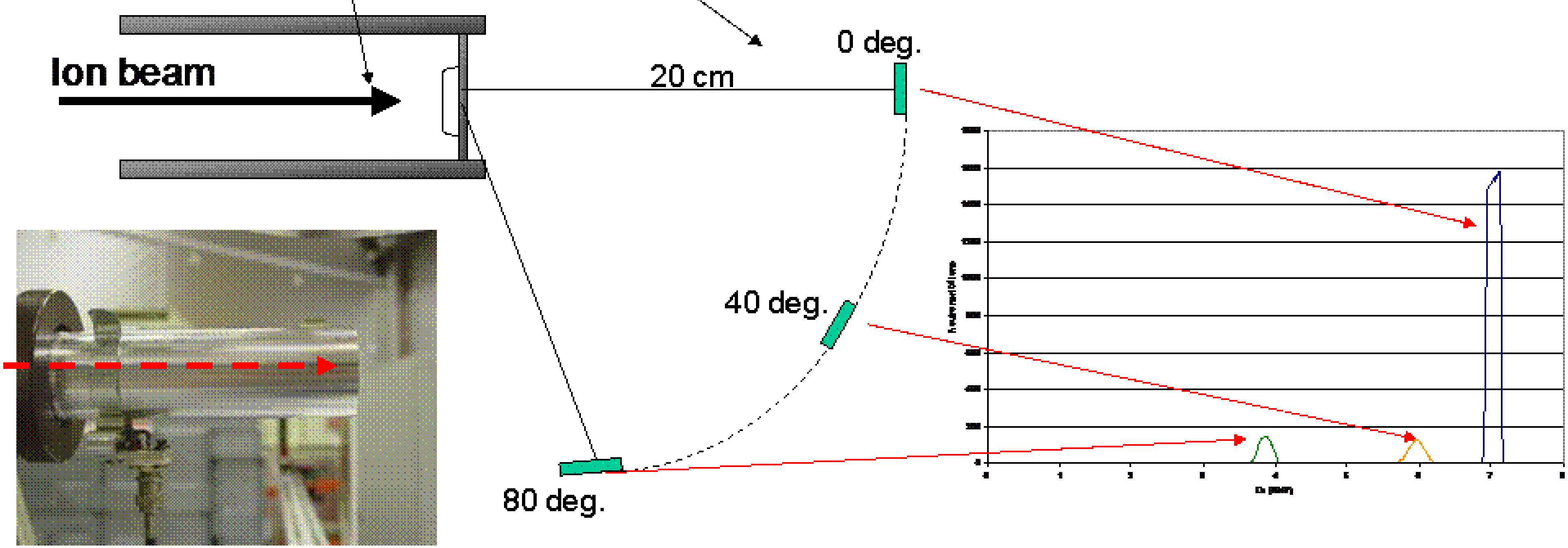


GELINA : uncertainty < 1.2 %

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

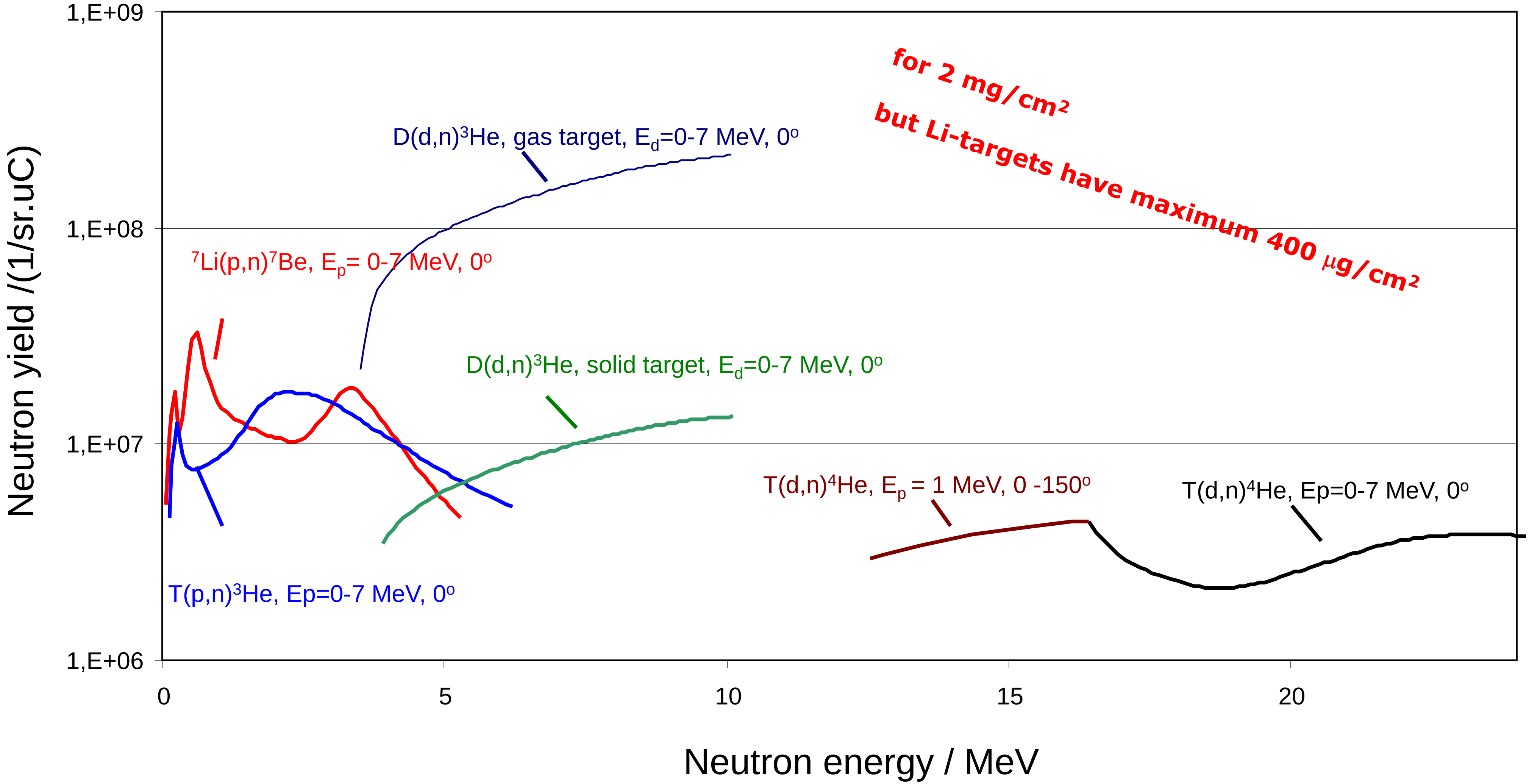
- nuclear reaction,
- neutron emission angle,
- ion energy.

$^{7}Li(p,n)^{7}Be$ 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



European Commission

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



European Commission

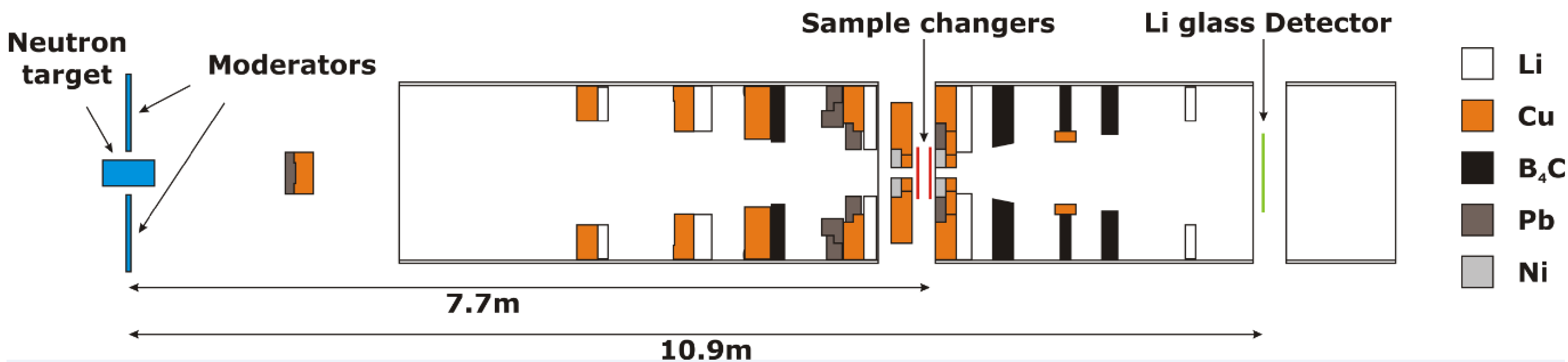
Transmission : good transmission geometry

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

Detectors

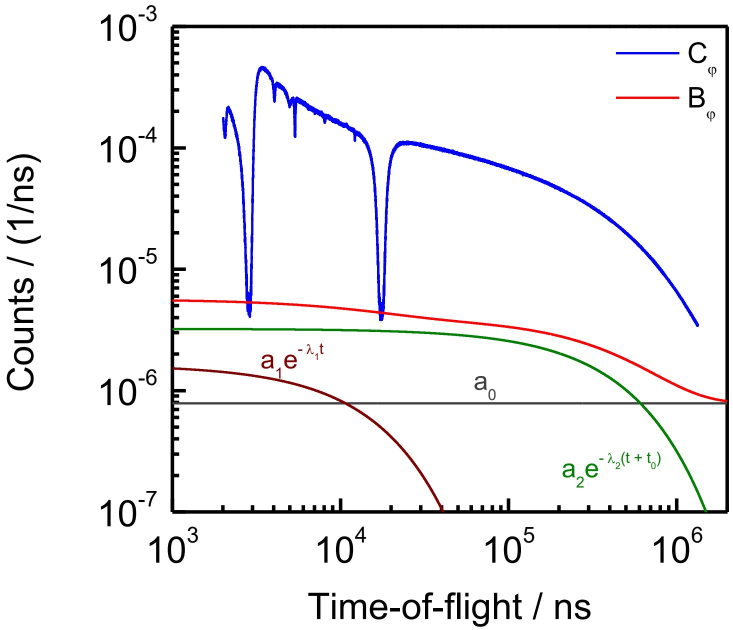
Low energy : $^{6}Li(n,t)\alpha$ Li-glass

High energy : H(n,n)H Plastic scintillator or NE213 type

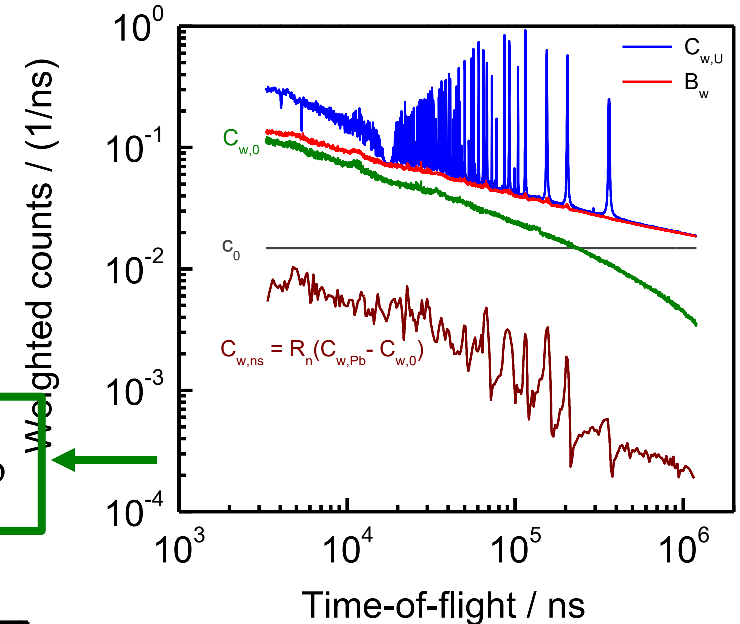


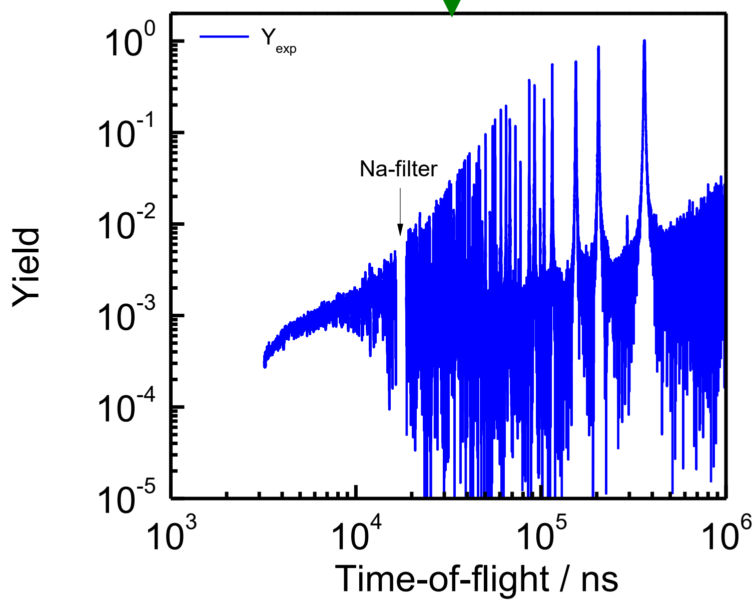
European Commission

$^{238}U(n,\gamma)$ measurements



$$Y_{\gamma,exp} = N\,\frac{C_w - B_w}{C_\varphi - B_\varphi}\,Y_\varphi$$



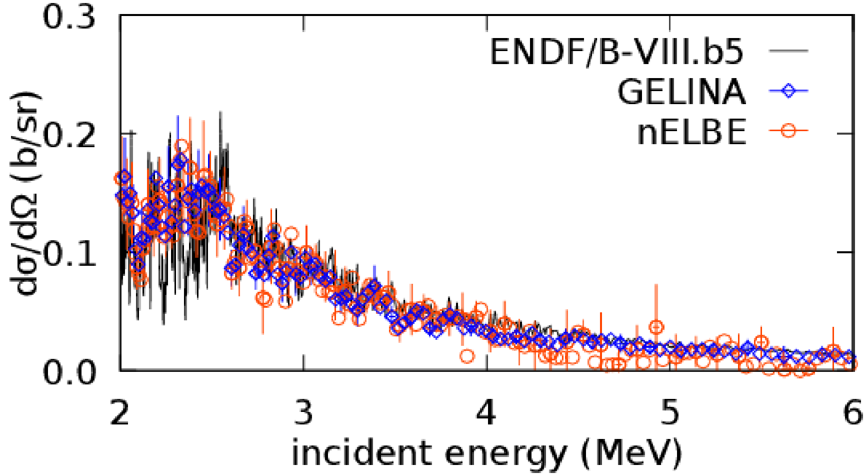


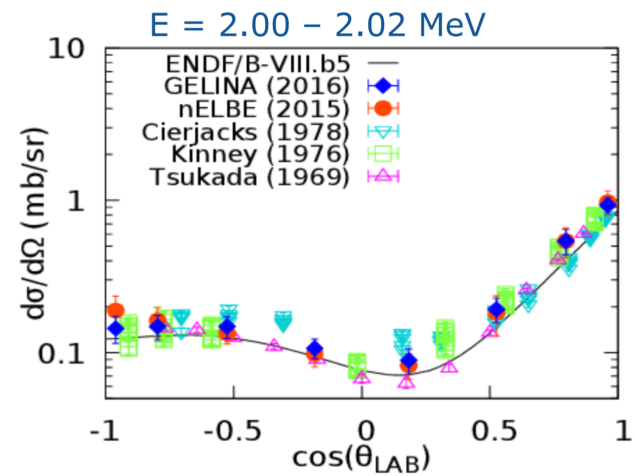
Kim et al., EPJA 52 (2016) 170

European Commission

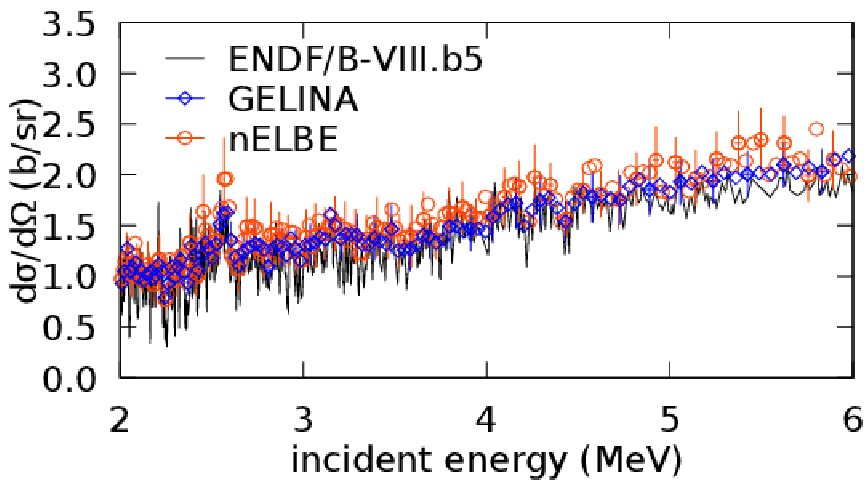
$^{nat}Fe(n,n)$

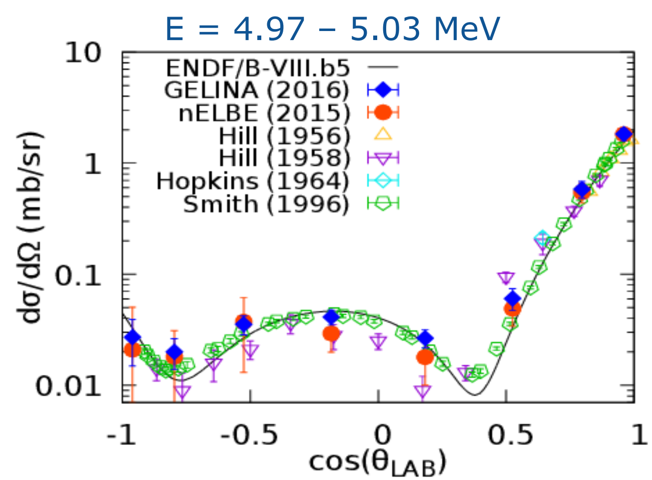
142.8°





16.2°



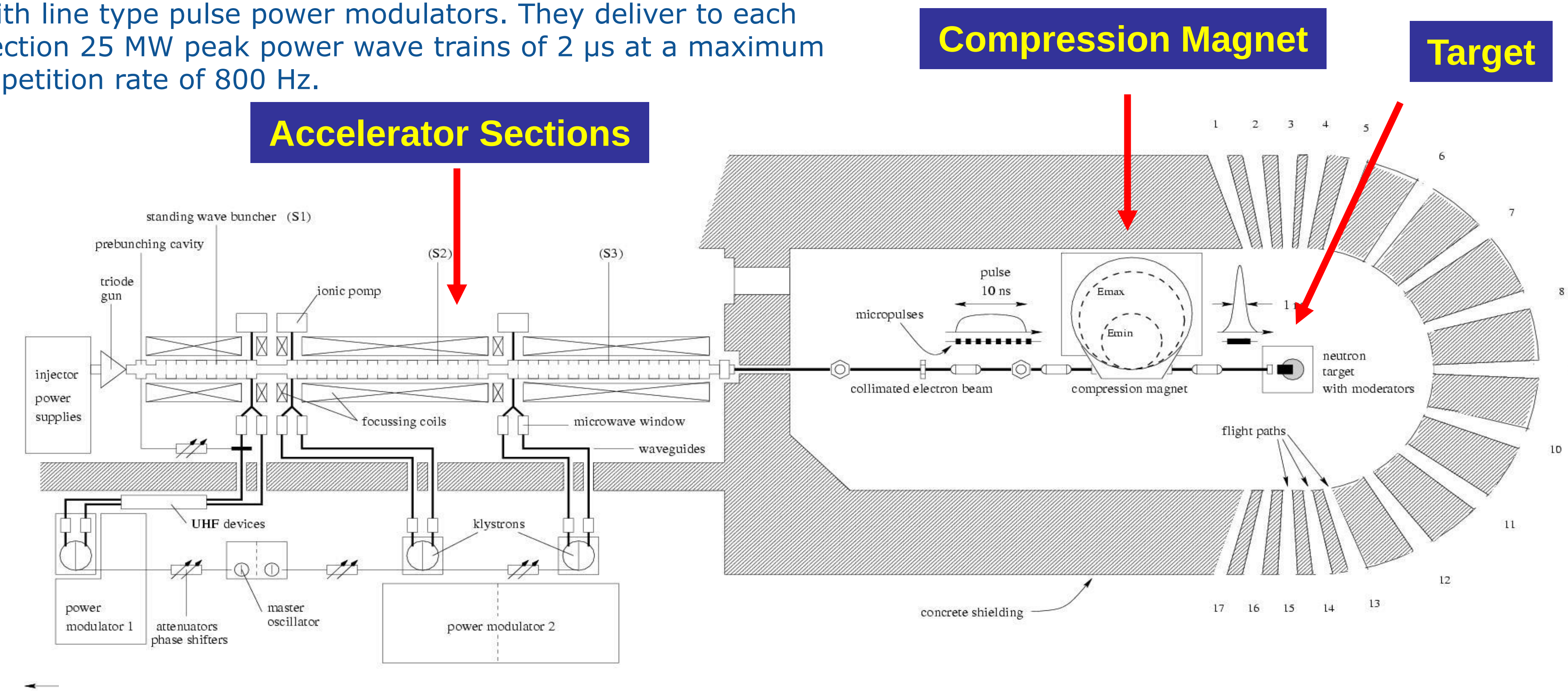


European Commission

Accelerator

three S-band accelerator sections operating at a frequency of 2999 MHz.

The accelerating waves in the sections are produced with three pulsed high power klystrons. The klystrons are powered with line type pulse power modulators. They deliver to each section 25 MW peak power wave trains of 2 μs at a maximum repetition rate of 800 Hz.

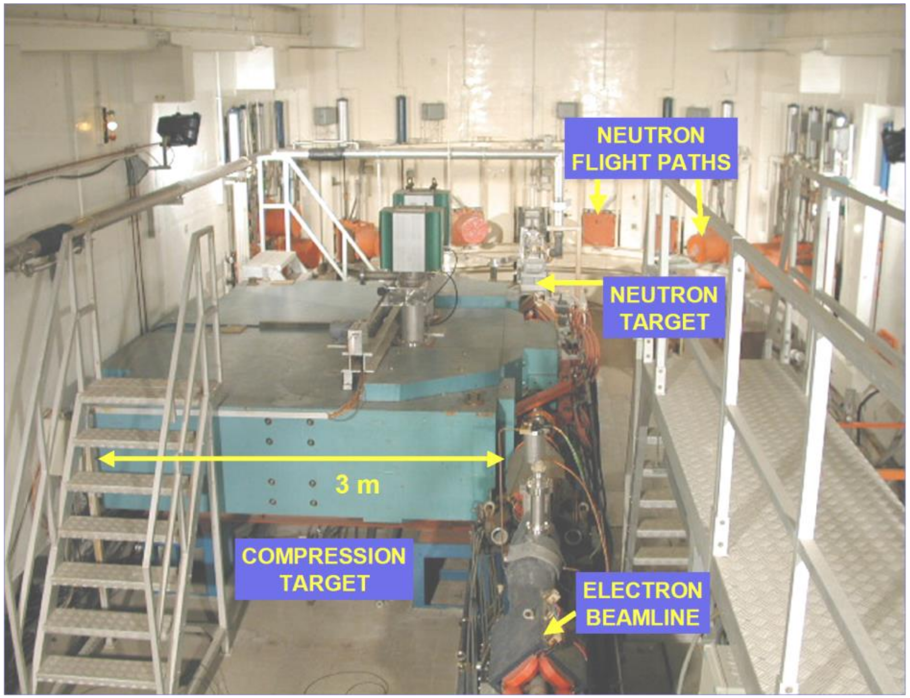


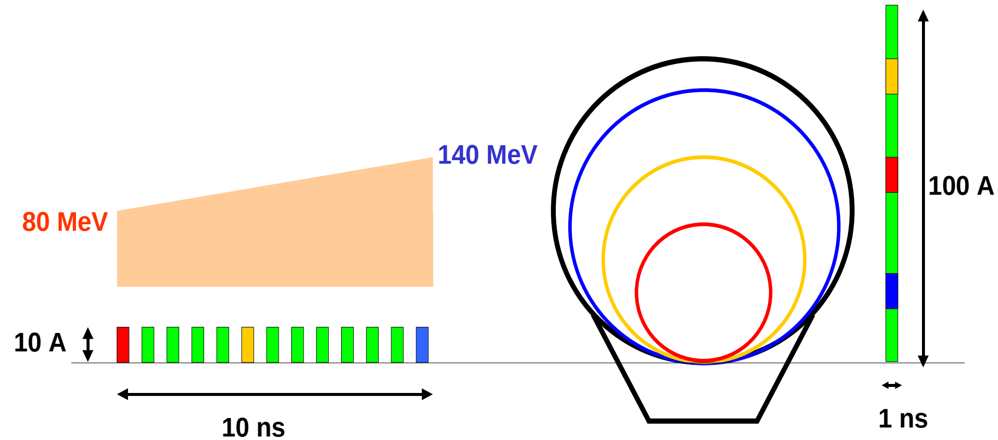
Normal operating parameters

Average Current	: 40 μA	Frequency	: 400 Hz
Average Electron Energy	: 100 MeV	Pulse Width	: 1.5 ns
Mean Power	: 4.0 kW	Neutron Flux	: 1.5 x 10^{13} 1/s

European Commission

Compression magnet





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

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

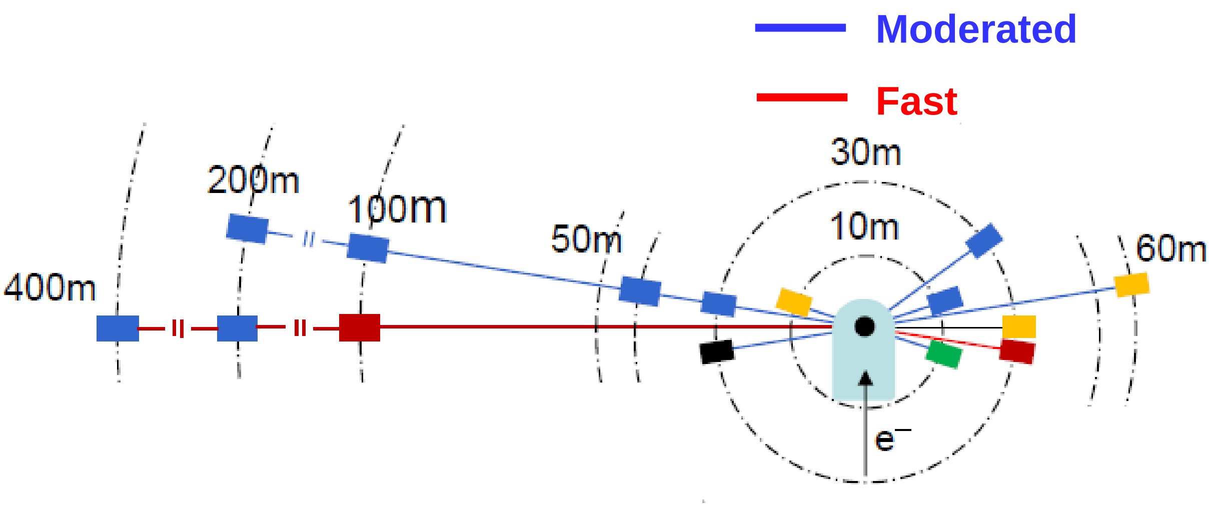
$$\Rightarrow \quad B = \frac{2\pi}{qc^2}\frac{\Delta E}{\Delta\tau}$$

$\Delta E = 60$ MeV

$\Delta\tau = 10$ ns

$\Rightarrow$ compressed pulse width ~ 1 ns

TOF – measurements at GELINA



(n,γ)

(n,tot)

(n,f) and (n,cp)

(n,n'γ)

(n,n)

Velocity from TOF

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

- Neutron fluence rate $\Rightarrow L \searrow$

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

- Resolution $\Rightarrow L \nearrow$

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

European Commission

Cross section measurements

Total cross section

$$T \cong e^{-n\sigma_{tot}}$$

Capture cross section

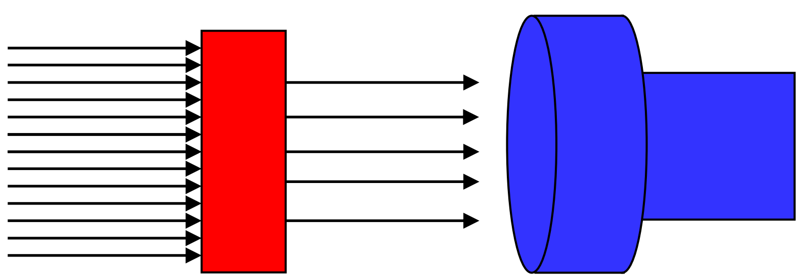
$$Y_\gamma \approx \left(1 - e^{-n\sigma_{tot}}\right)\frac{\sigma_\gamma}{\sigma_{tot}}$$

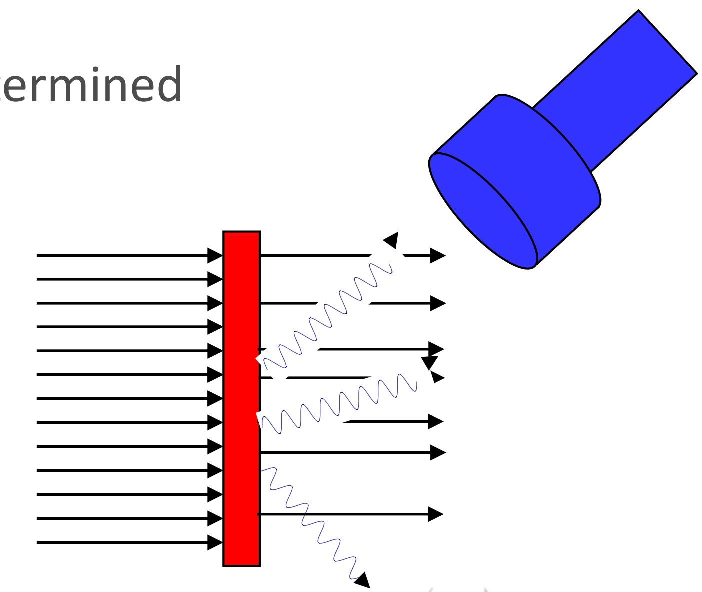
Well-characterised samples

n: areal density (total number of atoms per unit area) is well-known

$\Downarrow$

accurate cross-sections can be determined





Schillebeeckx et al., NDS 113 (2012) 3054

Neutron resonance analysis

NRTA

$$T \cong e^{-n\sigma_{tot}}$$

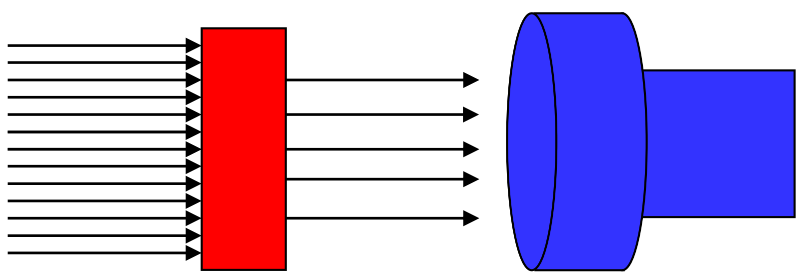
NRCA

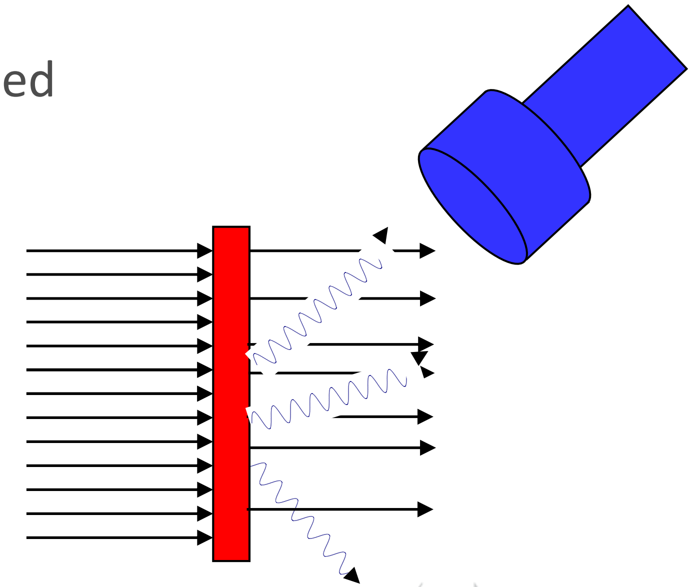
$$Y_\gamma \approx (1 - e^{-n\sigma_{tot}})\frac{\sigma_\gamma}{\sigma_{tot}}$$

Well-known cross sections

$\Downarrow$

areal density can be determined





Schillebeeckx et al., Report EUR 26848-EN (2014)

European Commission