European Commission

Post – Fukushima
Characterization of melted fuel

University of Bologna

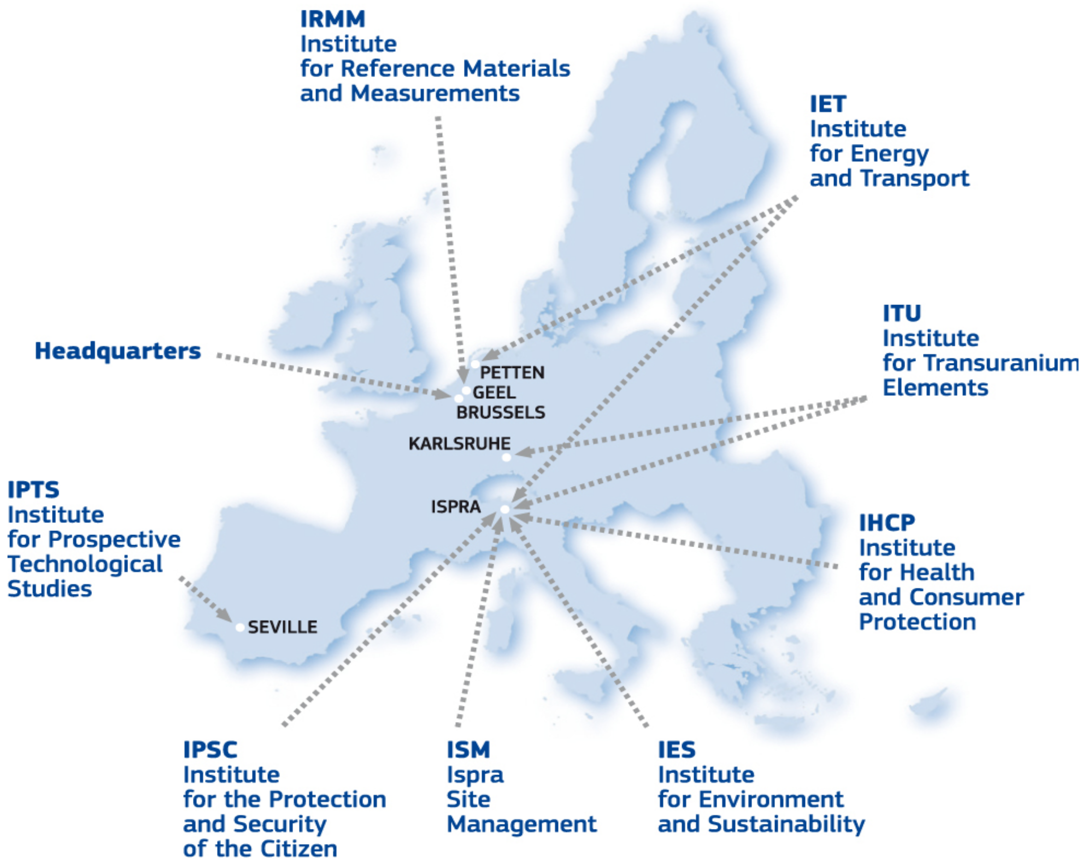
5 April 2013

P. Schillebeeckx

EC – JRC – IRMM

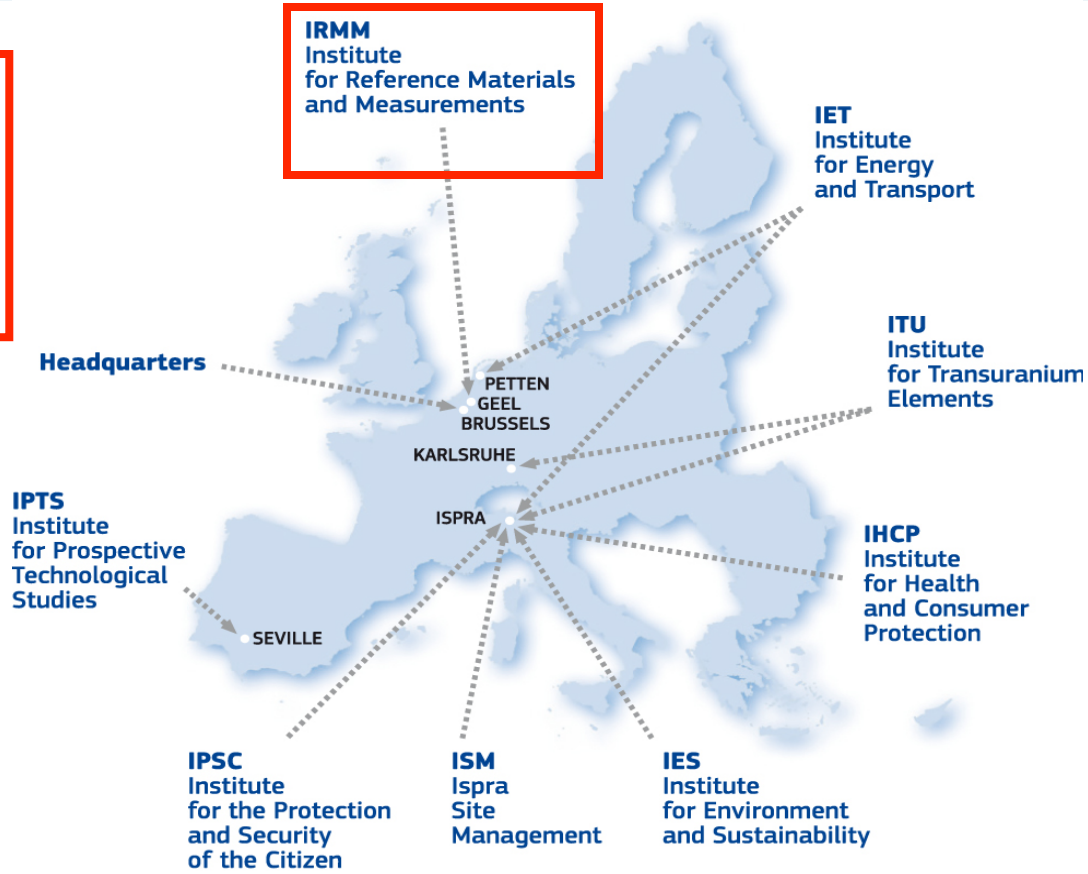
Standards for Nuclear Safety, Security and Safeguards (SN3S)

EC – JRC – IRMM
Institute for Reference Materials & Measurements

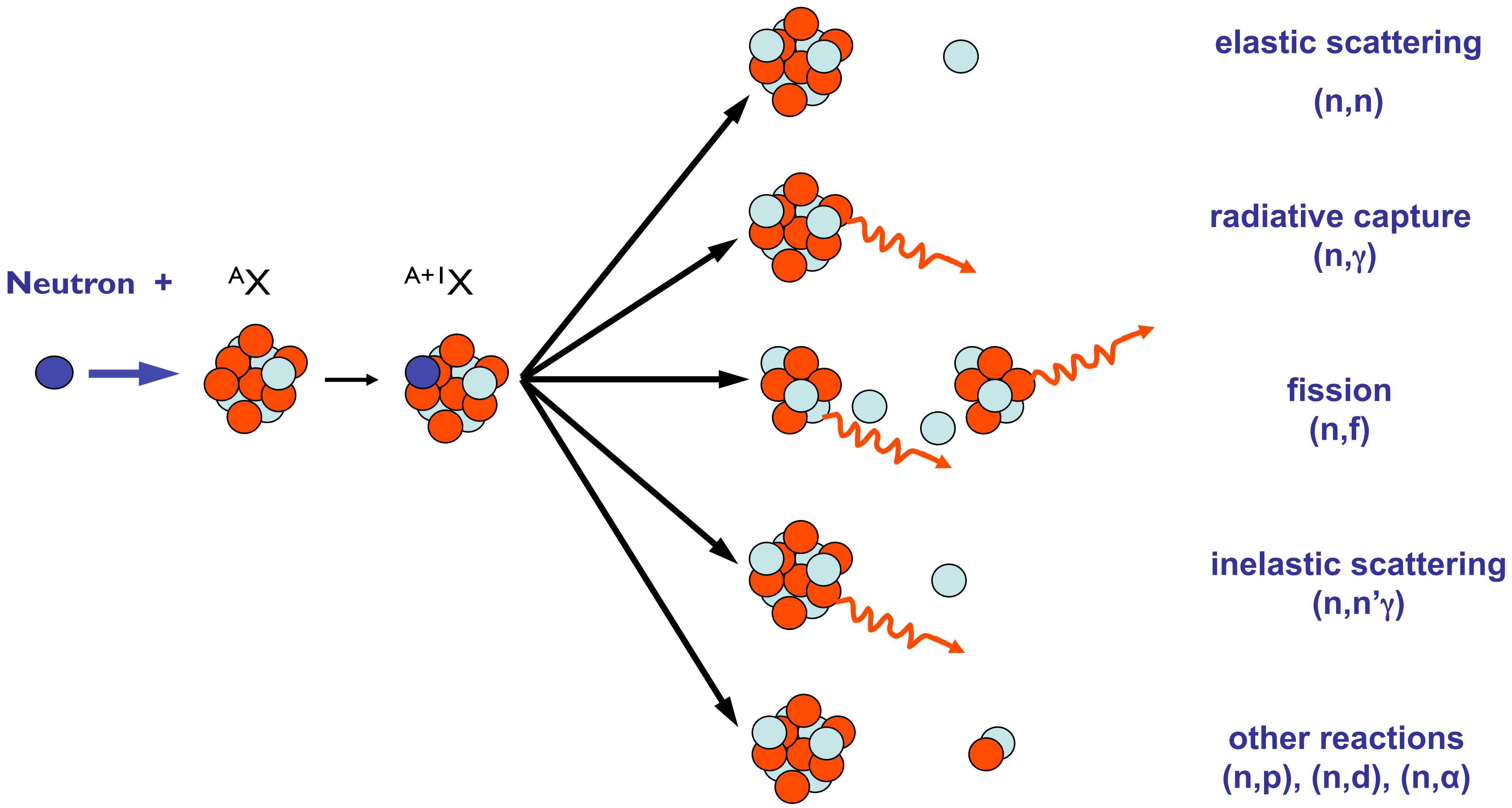


EC – JRC – IRMM
Institute for Reference Materials & Measurements

Mission:
to promote a common and reliable European measurement system in support of EU policies

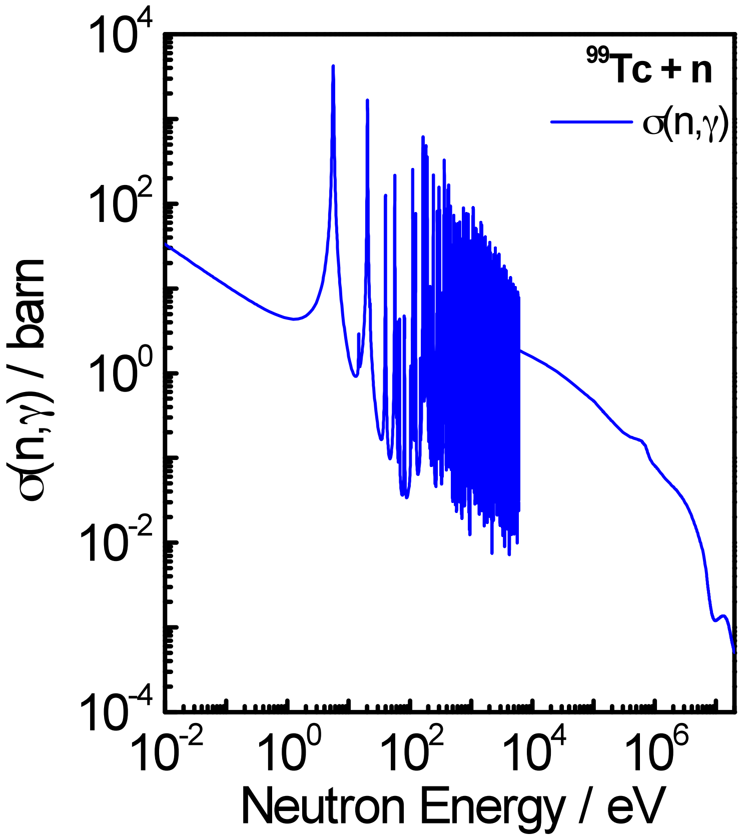


Neutron induced reactions



Experimental facilities at IRMM

^{99}Tc(n,γ) cross section



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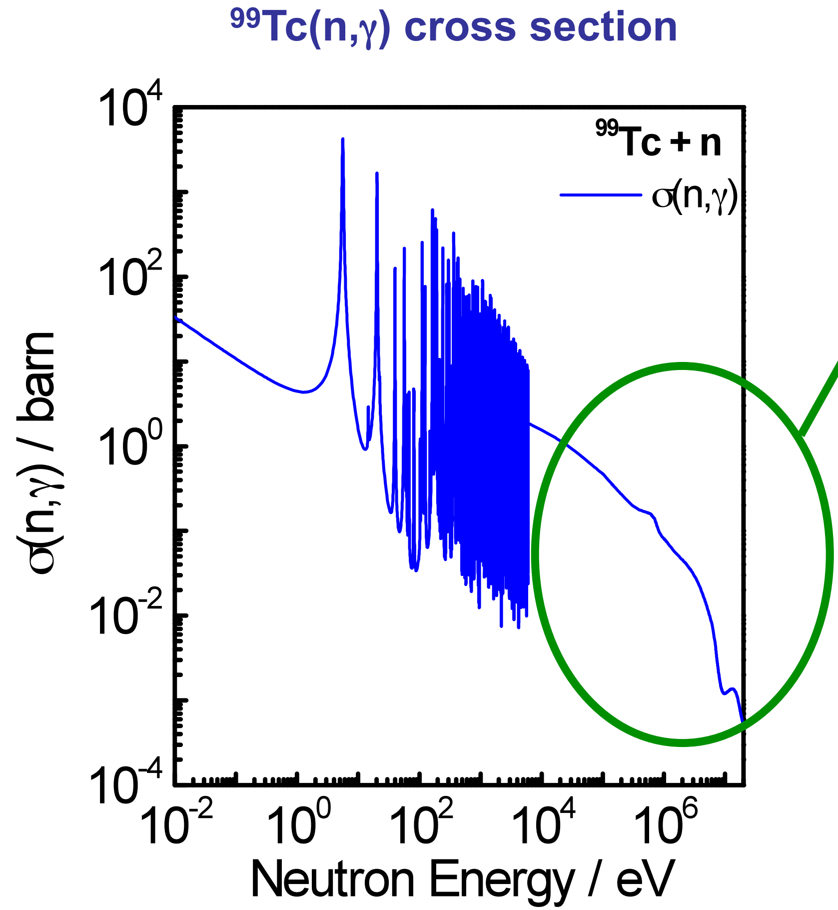
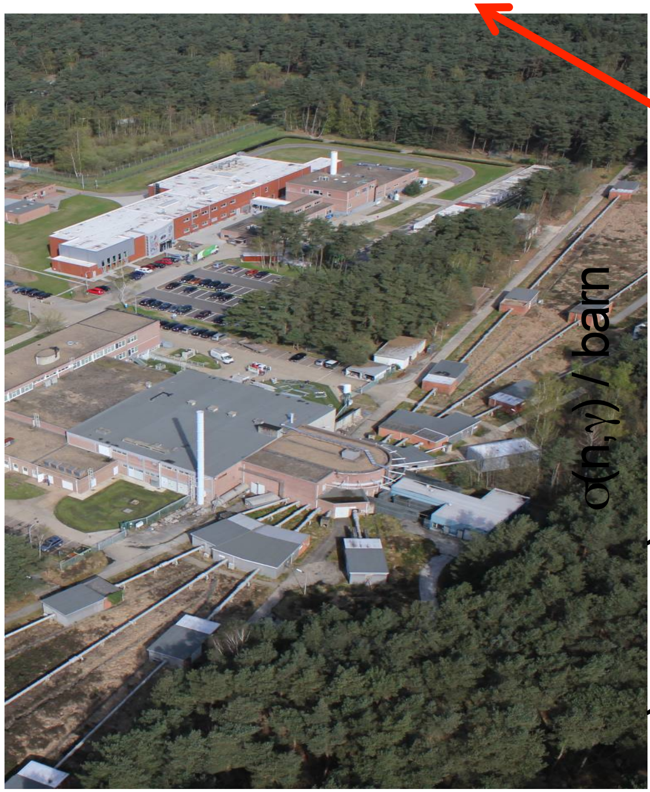


Van de Graaff

Mono-energetic neutrons
(cp,n) reactions

Experimental facilities at IRMM

GELINA



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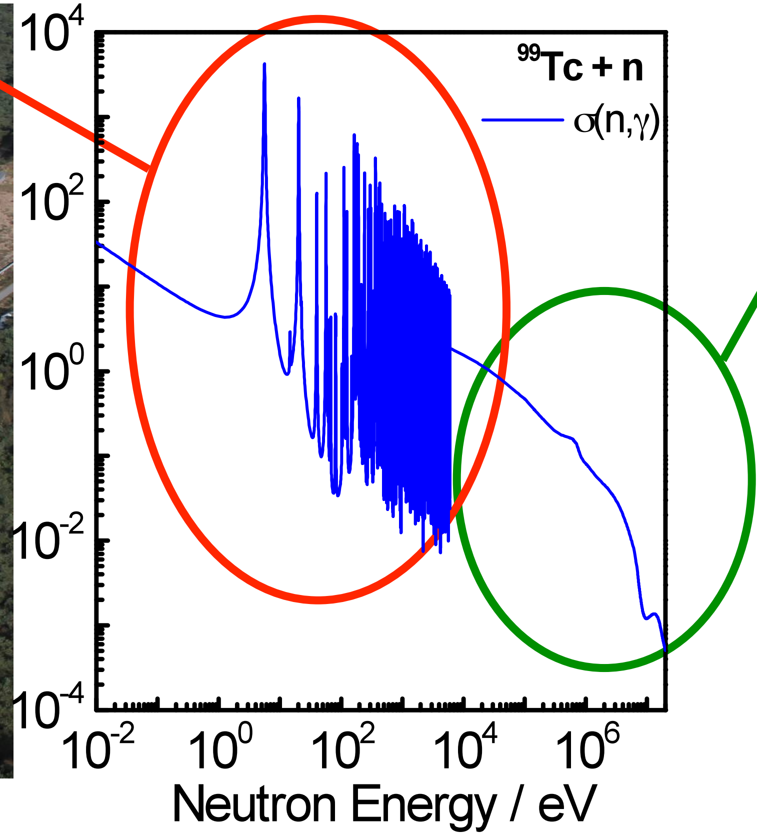


Van de Graaff

White neutron source
+
Time-of-flight (TOF)

Mono-energetic neutrons
(cp,n) reactions

TOF - Facility GELINA

Mondelaers and Schillebeeckx, Notizario 11 (2006)

TOF - Facility GELINA

- **Pulsed white neutron source**

  (10 meV < E_n < 20 MeV)

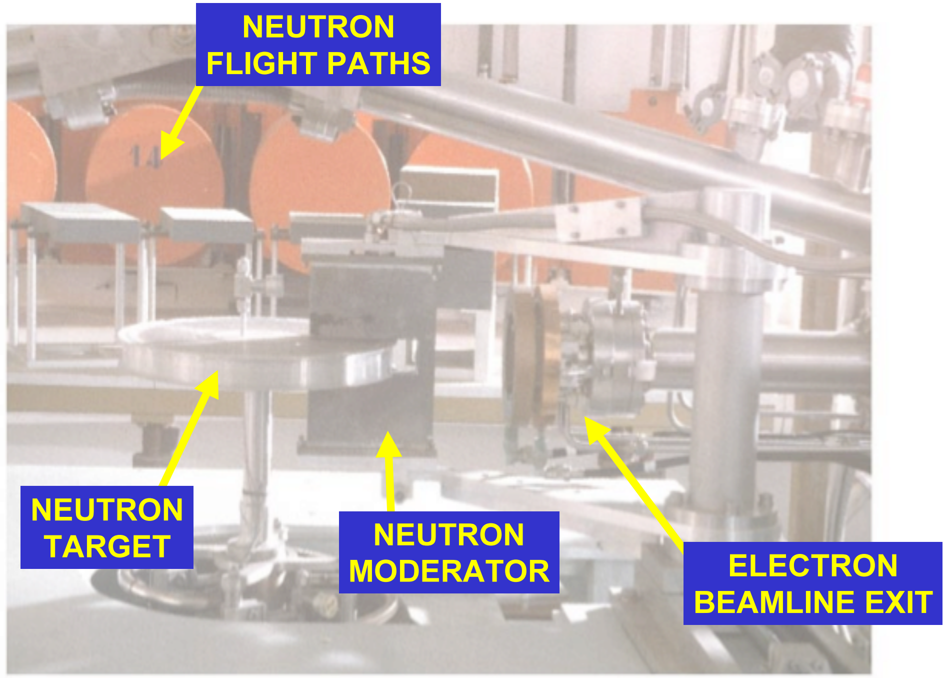
- **Neutron energy : time-of-flight (TOF)**

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

- **Measurement stations with special equipment to perform:**
  - **Total cross section measurements**
  - **Partial cross section measurements**

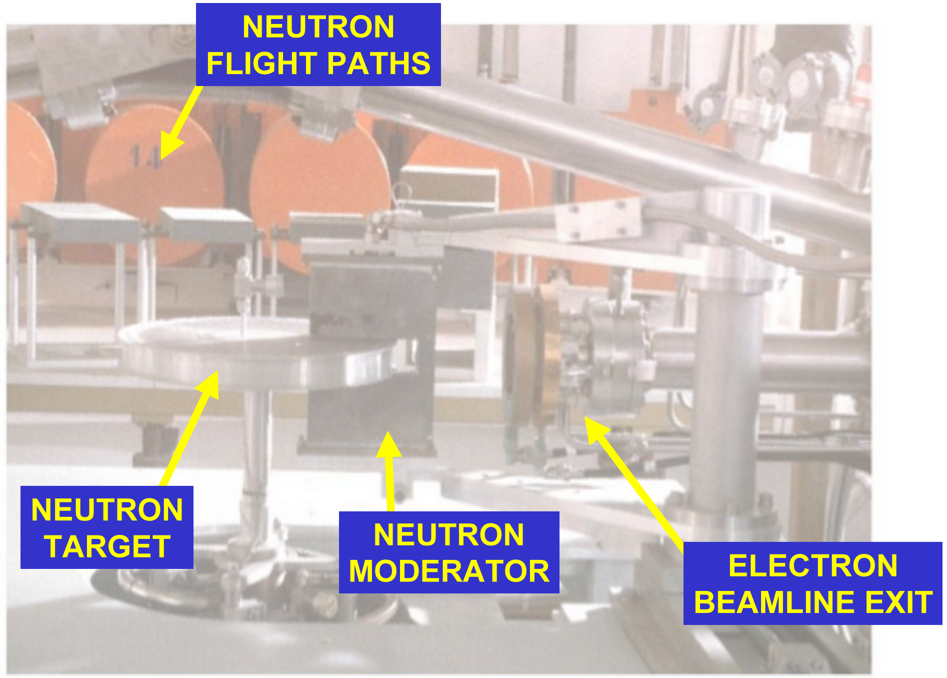
Mondelaers and Schillebeeckx, Notizario 11 (2006)

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
- Low energy neutrons by moderation (water moderator in Be-canning)

Neutron production



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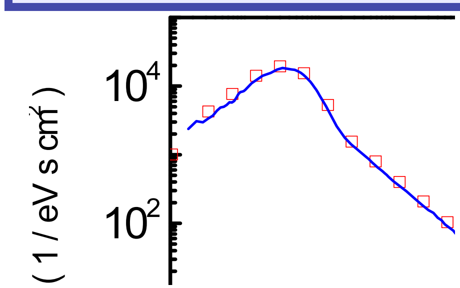
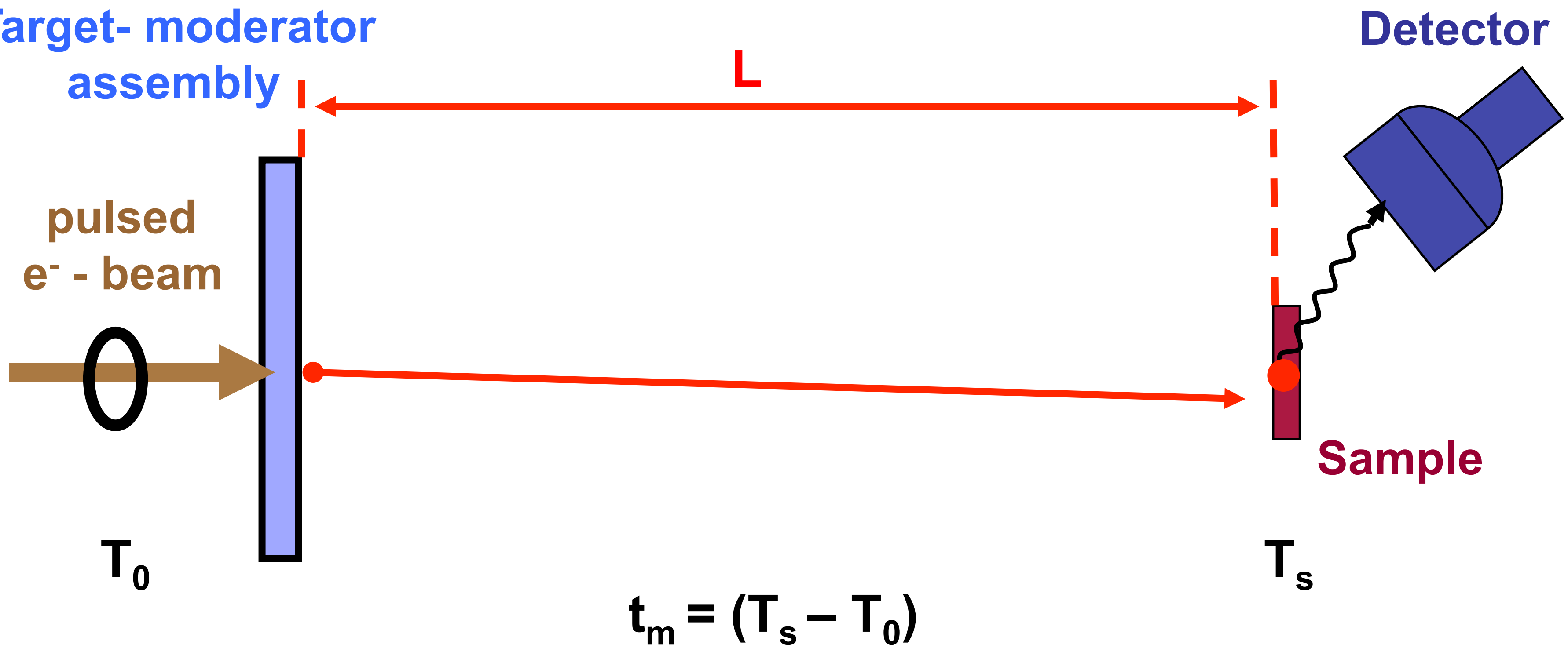


Time – of – flight technique



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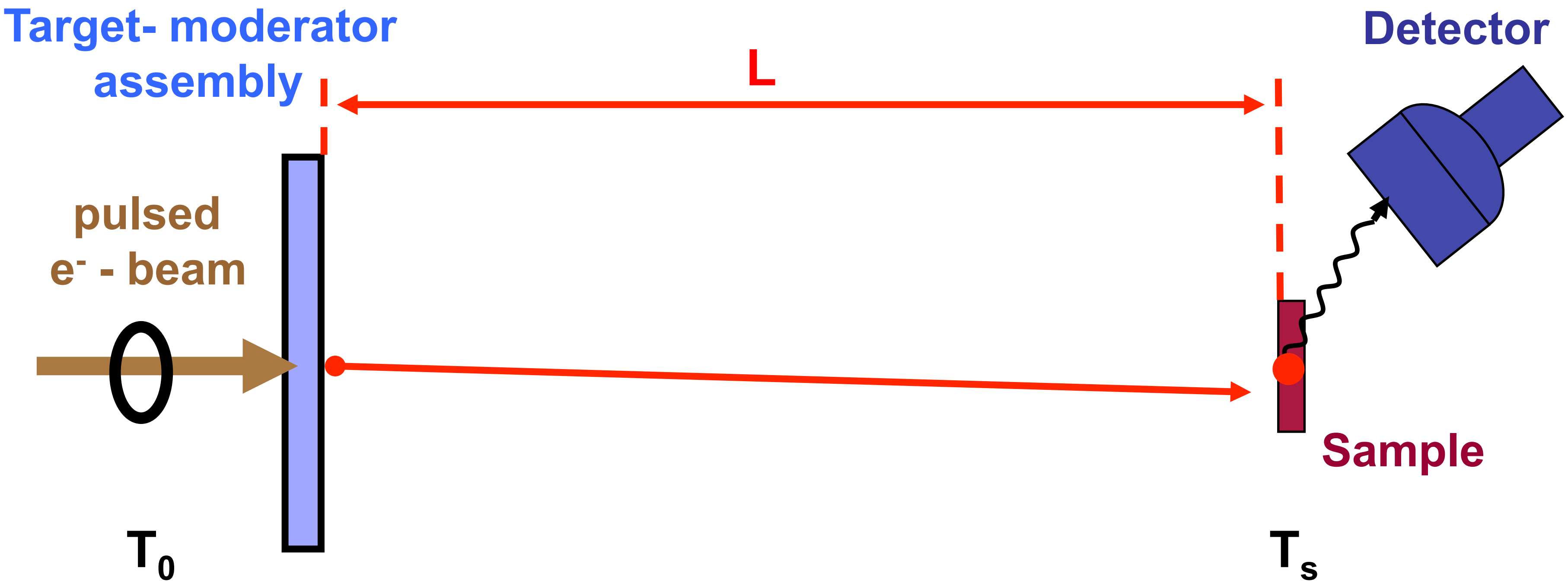
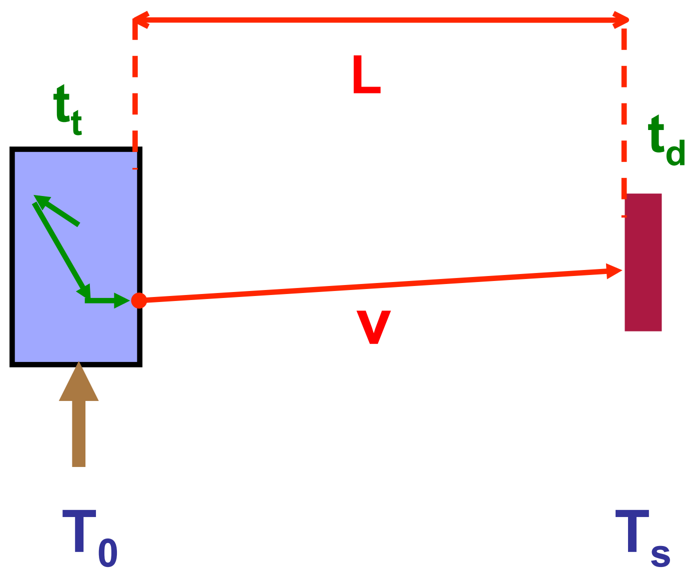


$$t_m = (T_s - T_0)$$

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

$$E = mc^2\left(\frac{1}{\sqrt{1-(v/c)^2}} - 1\right)$$

Response of TOF-spectrometer



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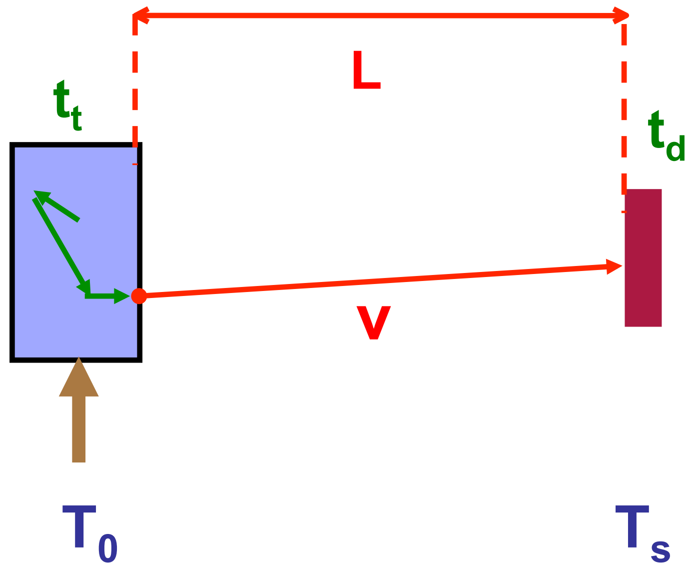


$$t_m = T_s - T_0$$

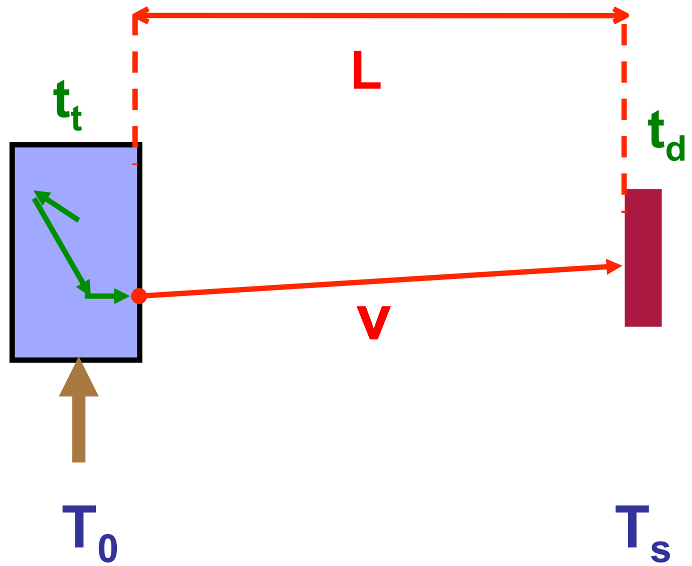
$$t = t_m - (t_t + t_d)$$

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

Response of TOF-spectrometer

$$\frac{\Delta v}{v} = \sqrt{\frac{\Delta t^2}{t^2} + \frac{\Delta L^2}{L^2}} \quad \Rightarrow \quad \frac{\Delta E}{E} = (\gamma + 1)\gamma \frac{\Delta v}{v}$$

- **ΔL (~ 1 mm)**
- **Δt**



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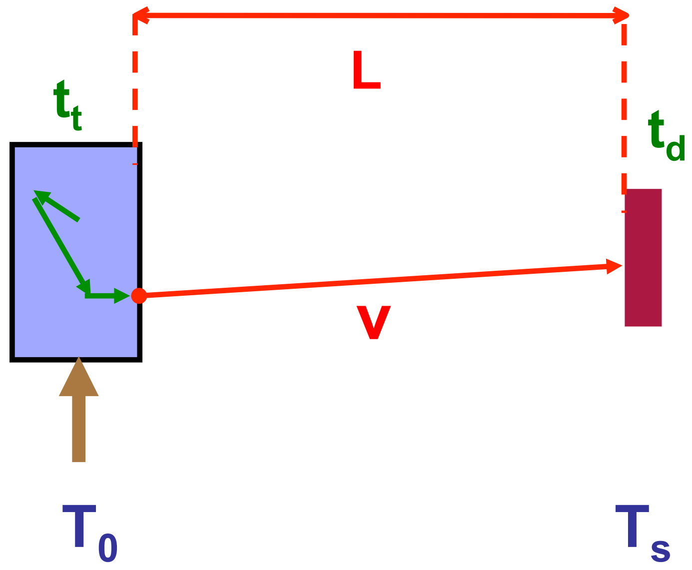

- ΔL (~ 1 mm)
- Δt
  - Initial burst width ΔT_0
  - Time jitter detector & electronics ΔT_s
  - Neutron transport in target - moderator Δt_t
  - Neutron transport in detector Δt_d

$$t_m = T_s - T_0$$

$$t = t_m - (t_t + t_d)$$

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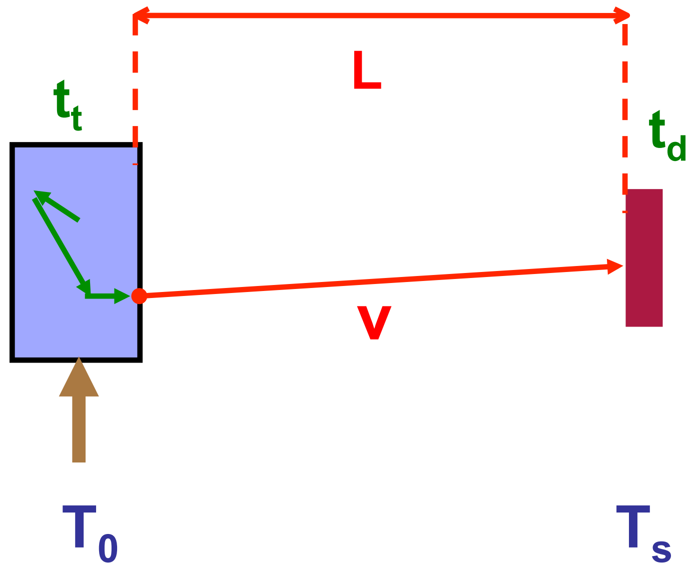

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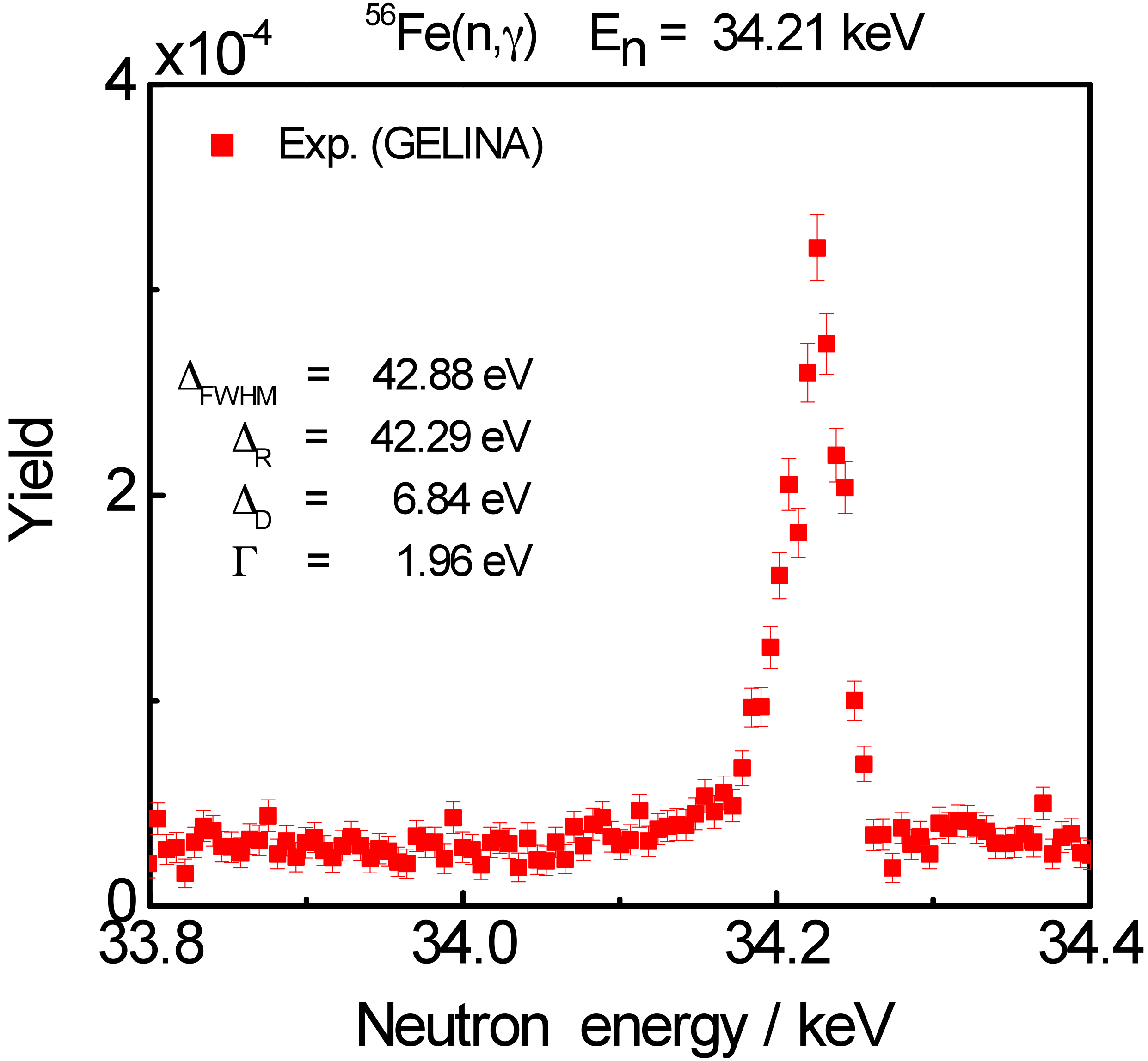
Response GELINA (60 m)



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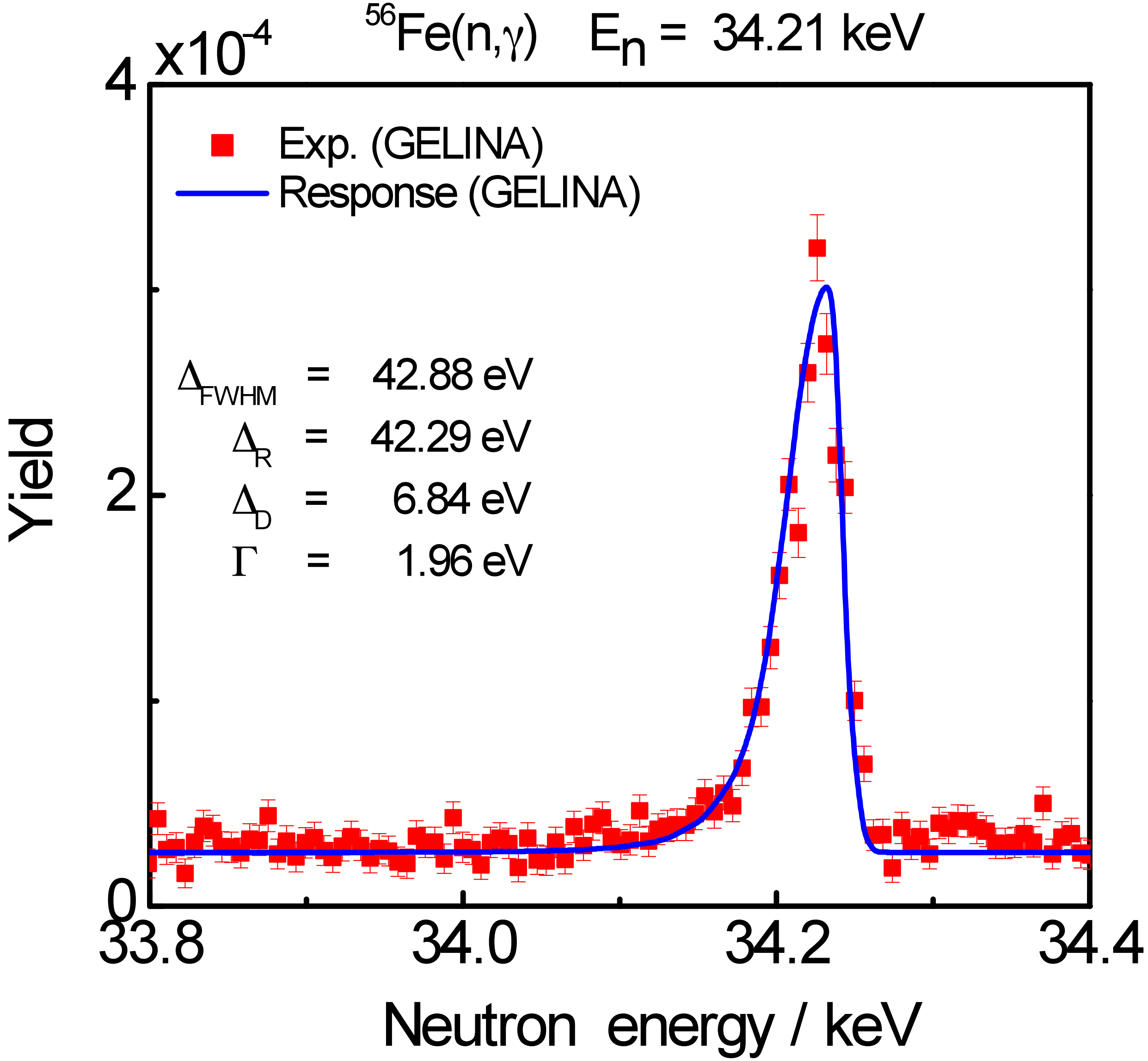
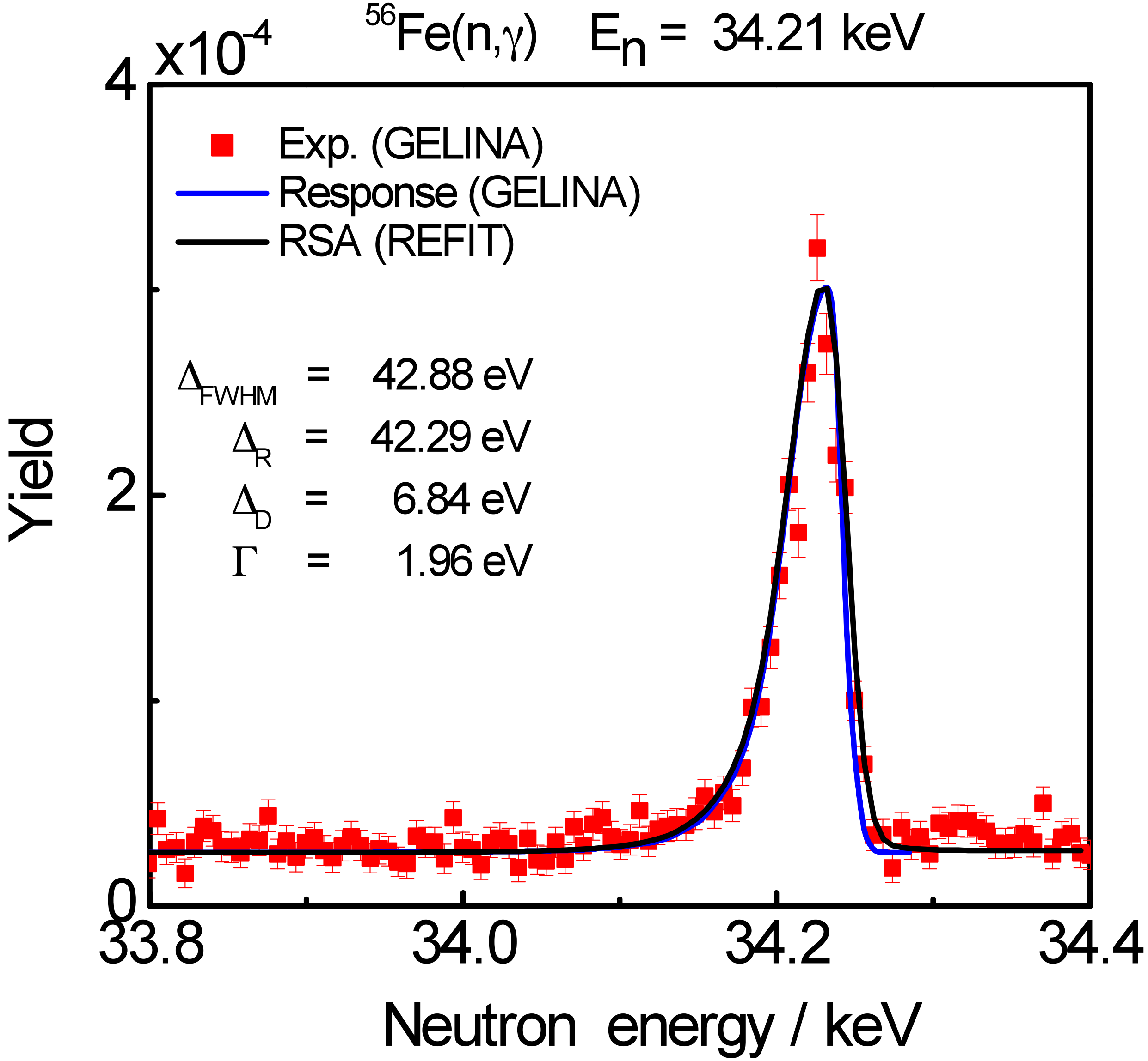
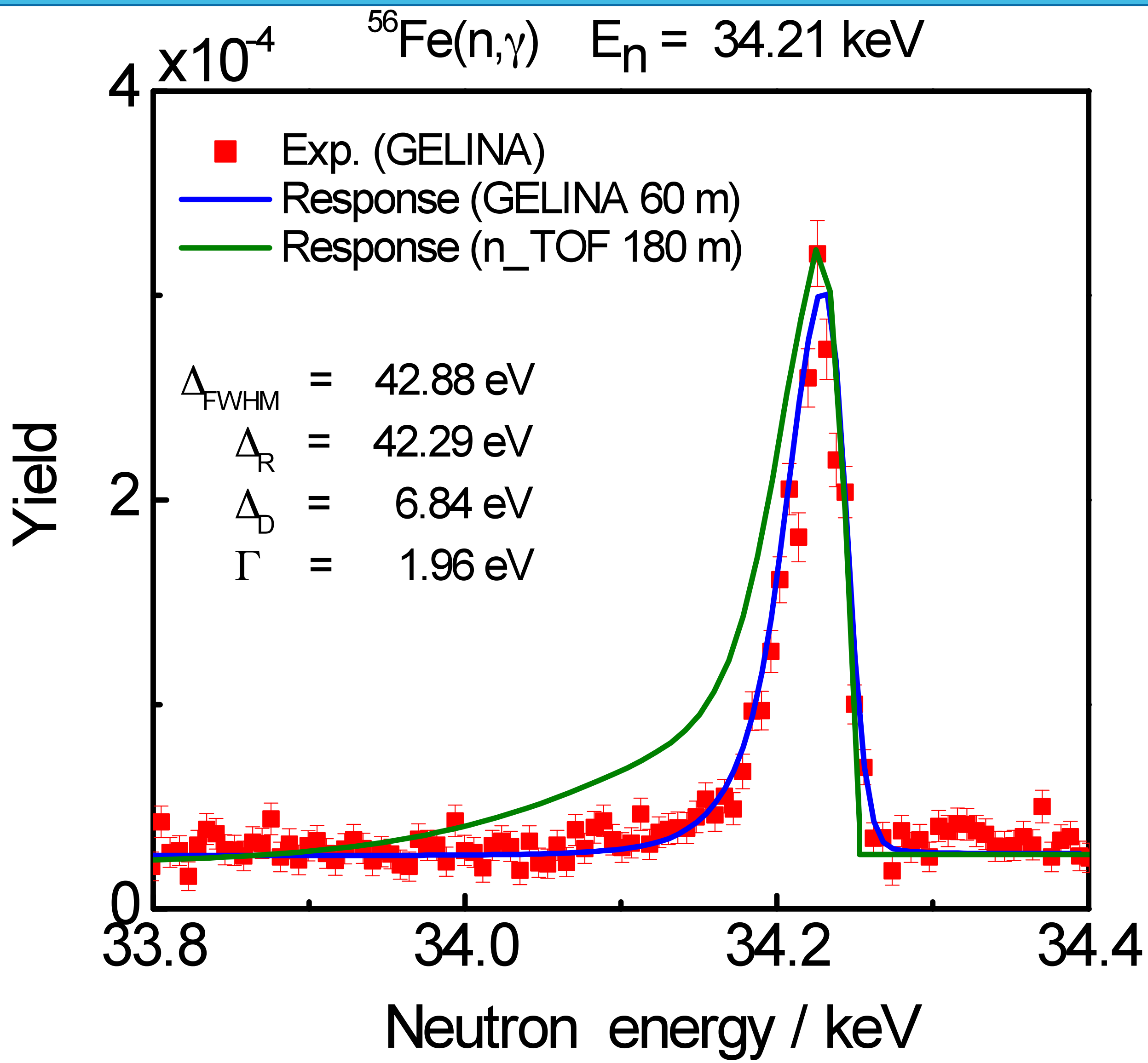


Response GELINA (60 m)

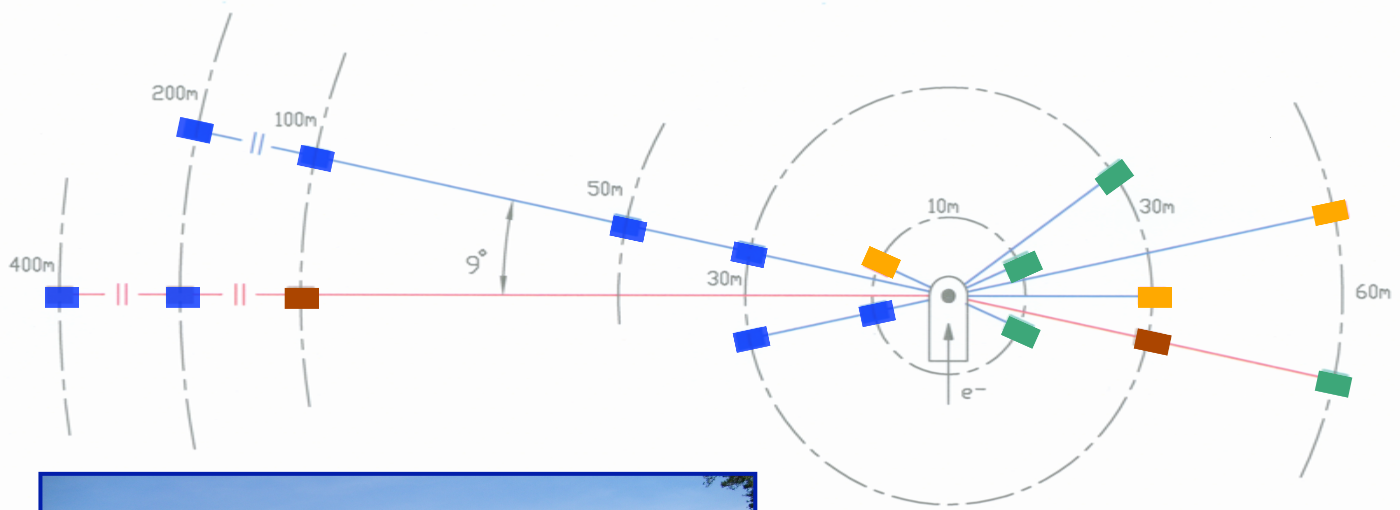


Response GELINA (60 m) < - > n_TOF (180 m)



Schillebeeckx et al., JINST 7 (2012) C03009

TOF - measurements



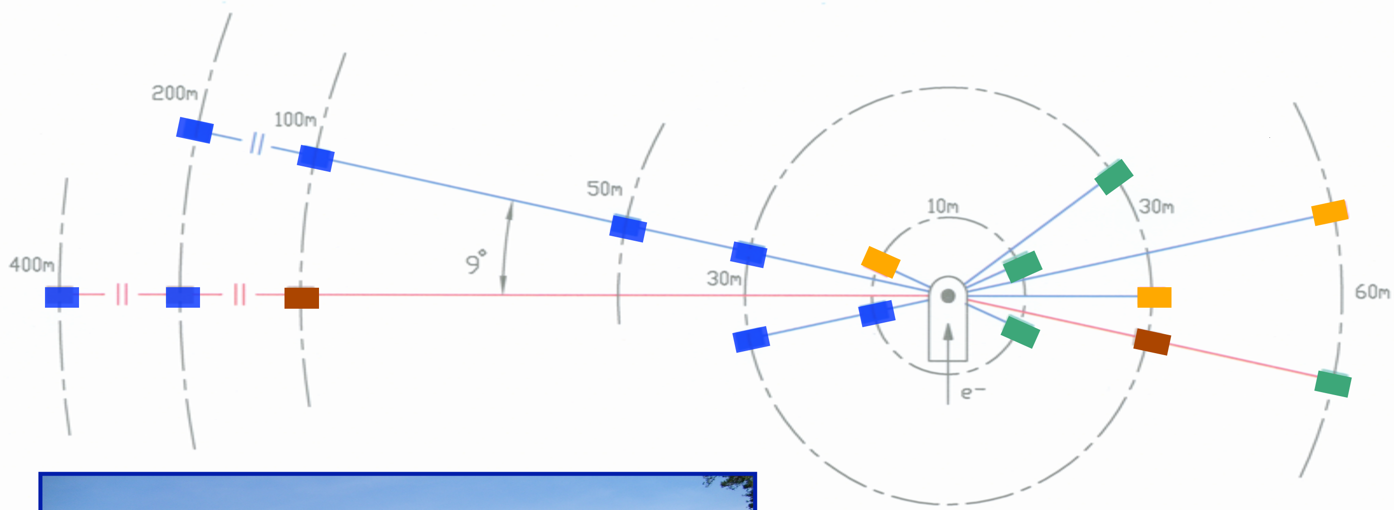
(n,γ)

(n,tot)

(n,f) and (n,cp)

(n,n'γ)

TOF - measurements



- (n,γ)
- (n,tot)
- (n,f) and (n,cp)
- (n,n'γ)

- **Velocity from TOF**

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

- **Neutron flux** ⇒ L ↘

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

- **Resolution** ⇒ L ↗

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

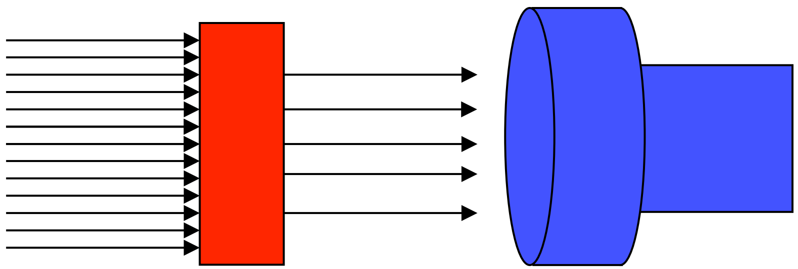
$$= \frac{1}{L}\sqrt{v^2 \Delta t^2 + \Delta L^2}$$

Cross section measurements

Transmission : $\sigma(n,tot)$

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

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



Schillebeeckx et al., Nuclear Data Sheets, 113 (2012) 3054 - 3100

Cross section measurements

Transmission : σ(n,tot)

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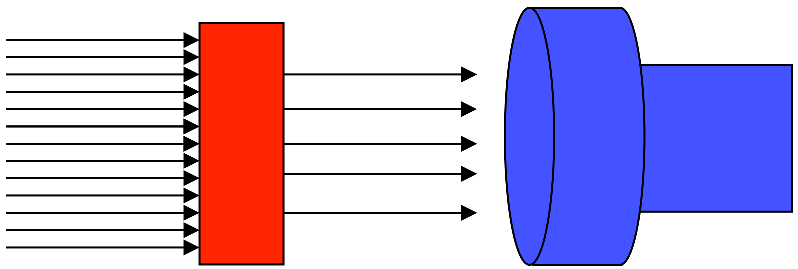
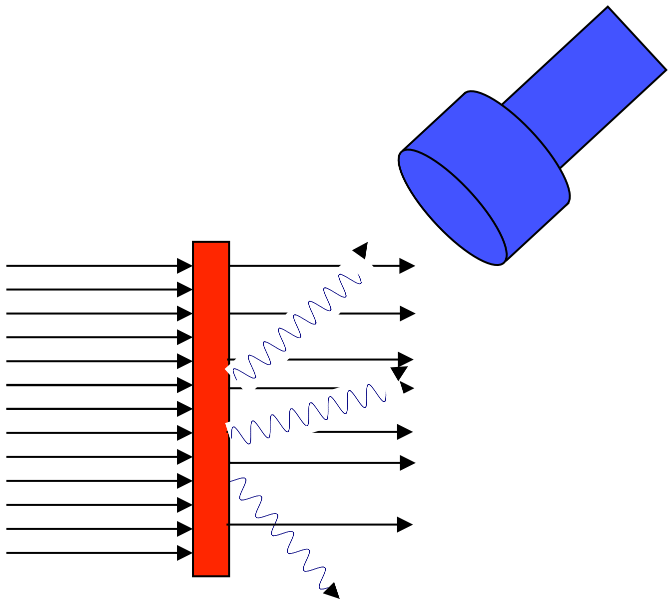
T : transmission
Fraction of the neutron beam traversing the sample without any interaction

Reaction yield : σ(n,r)

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

Y_r : reaction yield
Fraction of the neutron beam creating a (n,r) reaction in the sample





Schillebeeckx et al., Nuclear Data Sheets, 113 (2012) 3054 - 3100

Transmission measurements at GELINA

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

(1) All detected neutrons passed through the sample

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

(3) Sample perpendicular to parallel neutron beam

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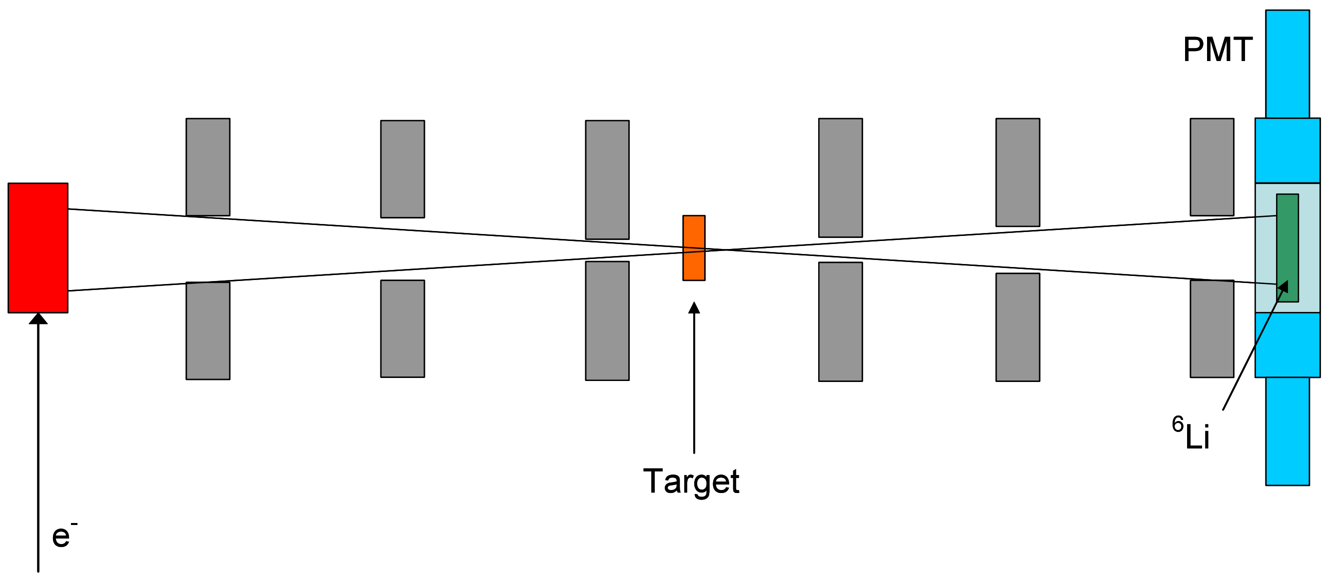
⇒ **Good transmission geometry (collimation)**

⇒ **Homogeneous target**



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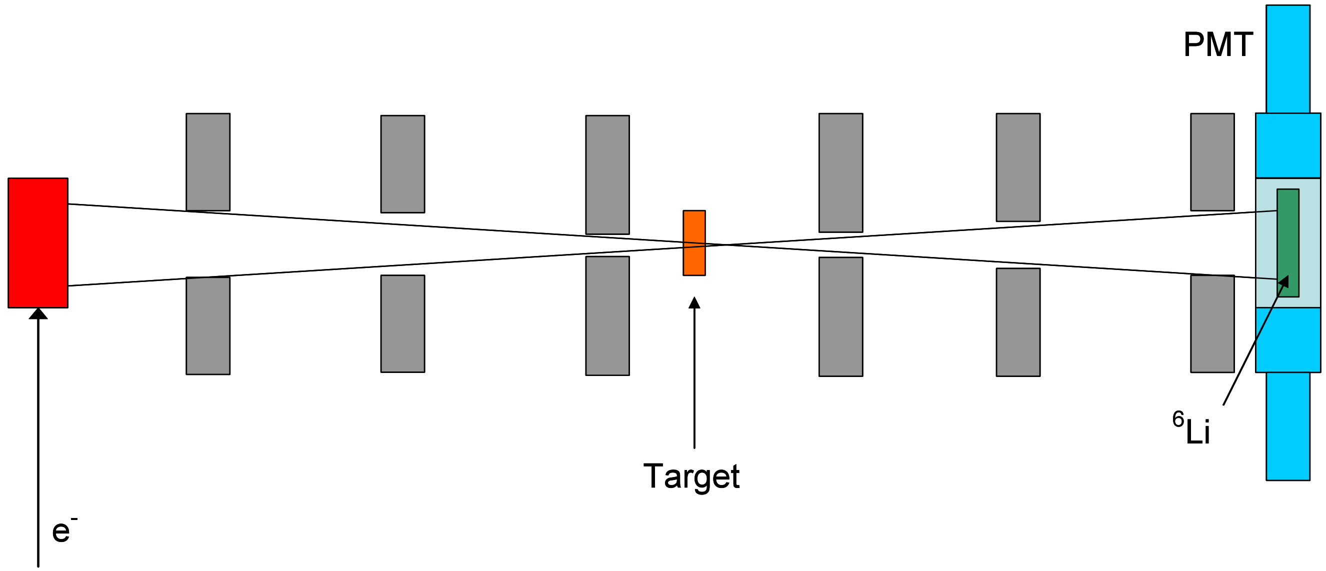
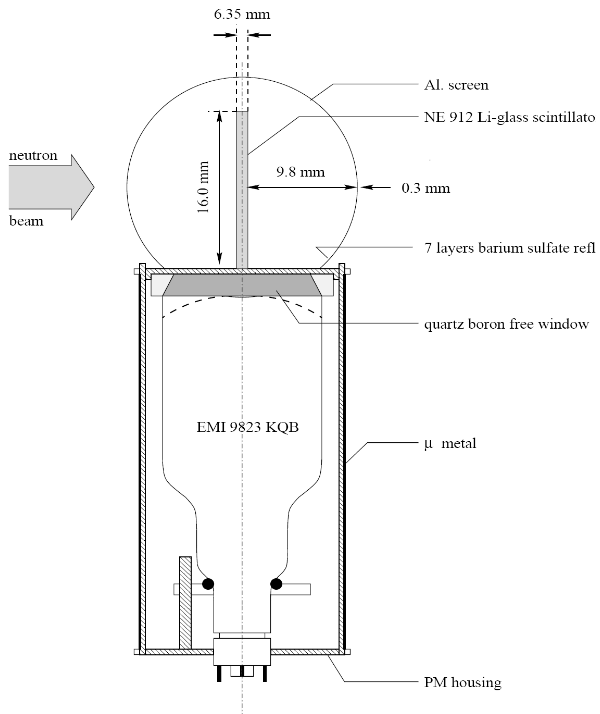


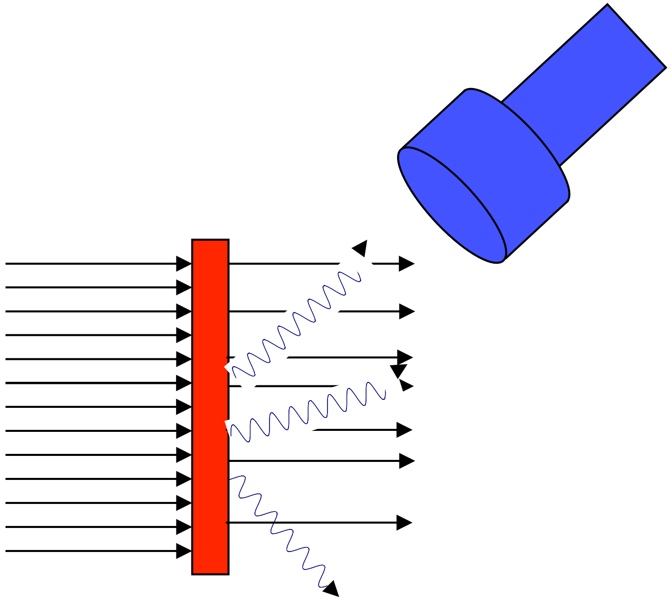


Reaction cross section measurements

Reaction e.g. (n,γ)

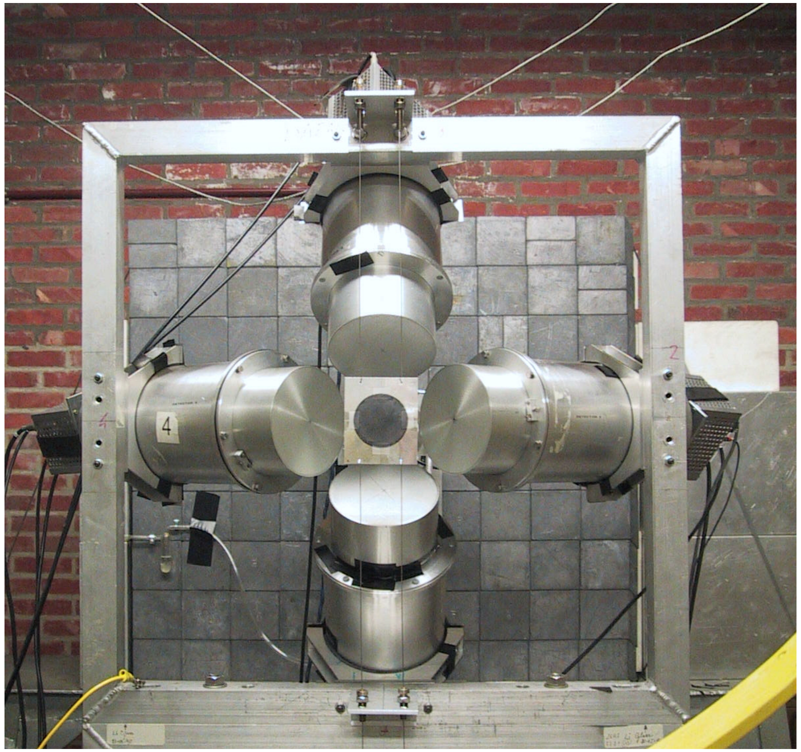
$$Y_\gamma \approx (1 - e^{-n\,\sigma_{tot}}) \frac{\sigma_\gamma}{\sigma_{tot}}$$

$$Y_{\gamma,exp} = \frac{C_\gamma}{\varepsilon_\gamma^{eff}\,\varphi}$$



σ(n,γ) measurements at GELINA

L = 10 m, 30 m and 60 m



Total energy detection principle

- **C_6D_6 liquid scintillators**
  - **125°**
  - **PHWT**

Collaboration INFN Legnaro (P. Mastinu)
Improvement of C_6D_6 detectors

Borella et al., Nucl. Inst. Meth. A 577 (2007) 626

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Total energy detection principle

- **C_6D_6 liquid scintillators**
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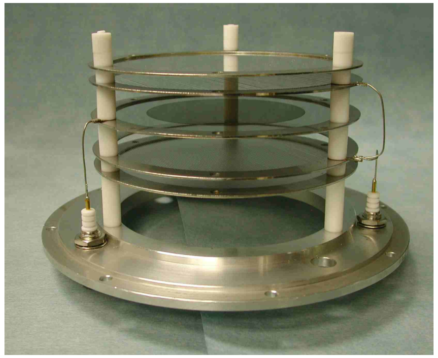
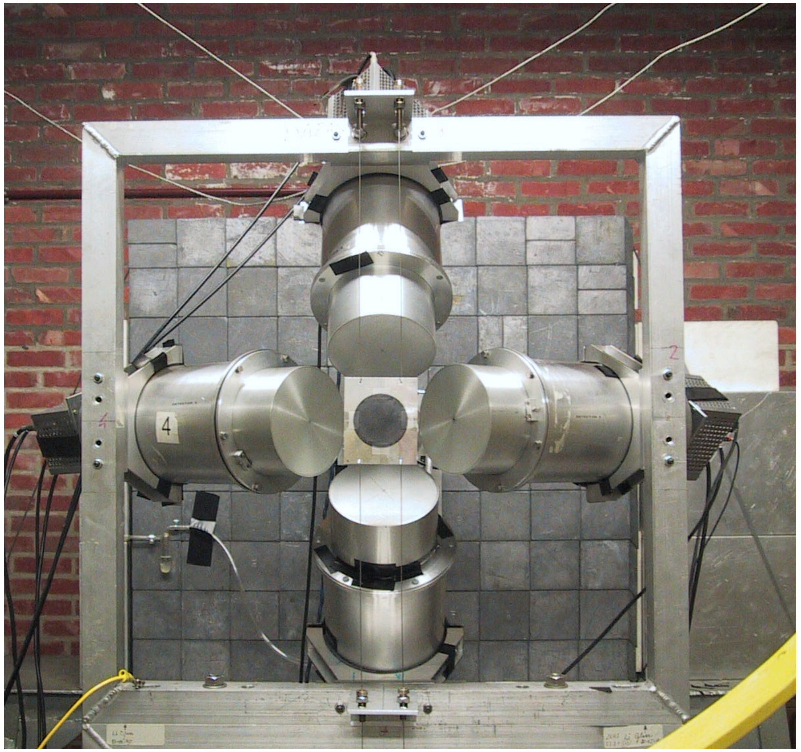
  - **PHWT**
- **Flux measurements (IC)**
  - **$^{10}B(n,\alpha)$**
  - **$^{235}U(n,f)$**





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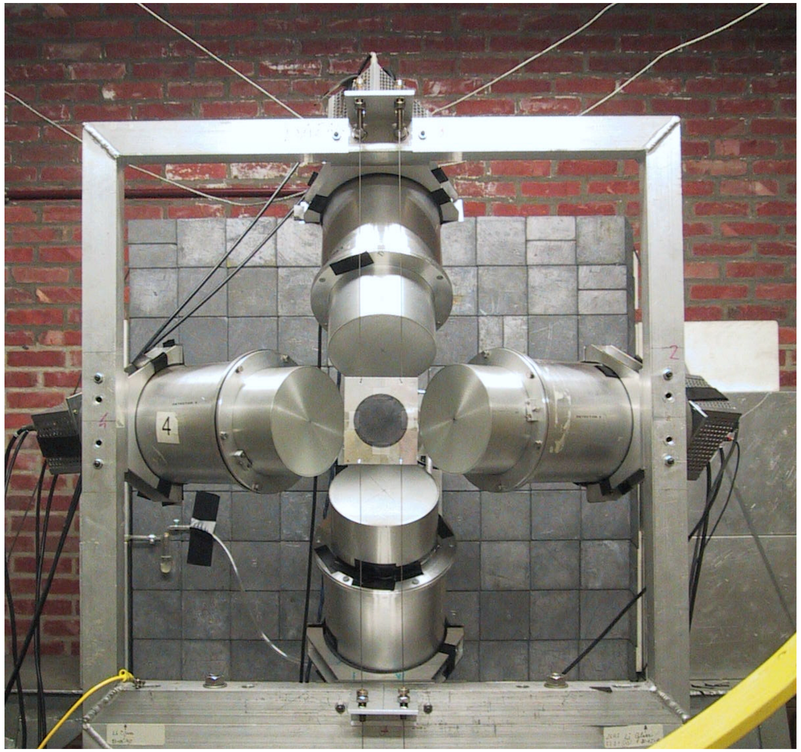

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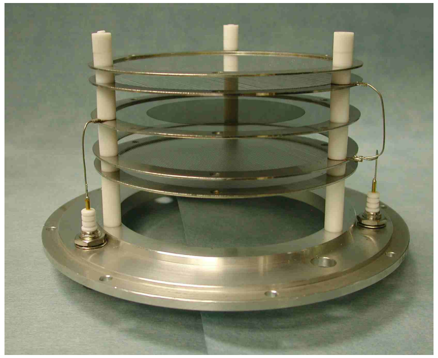
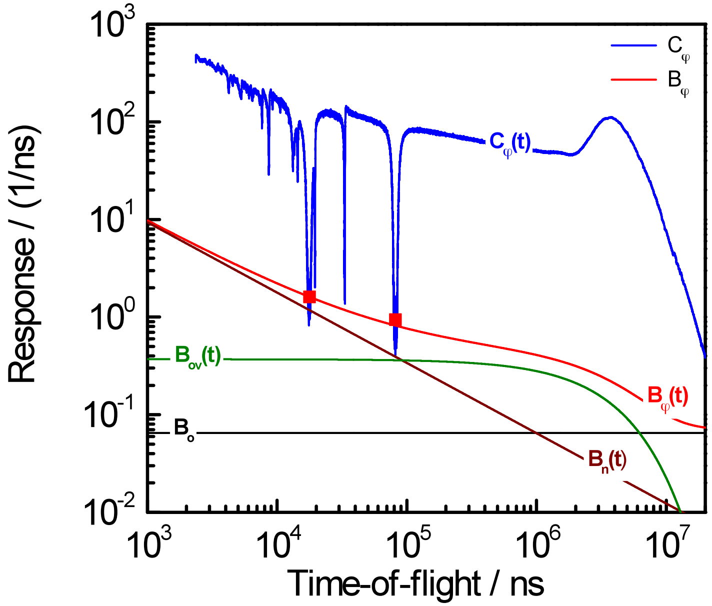


$$Y_{exp} = N\,Y_{\varphi} \frac{C_w - B_w}{C_{\varphi} - B_{\varphi}}$$

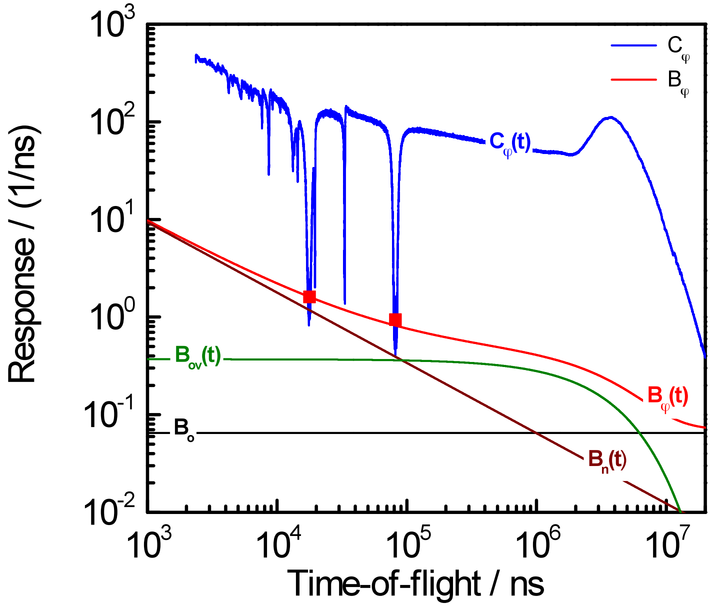
Becker et al., JINST 7 (2012) P11002

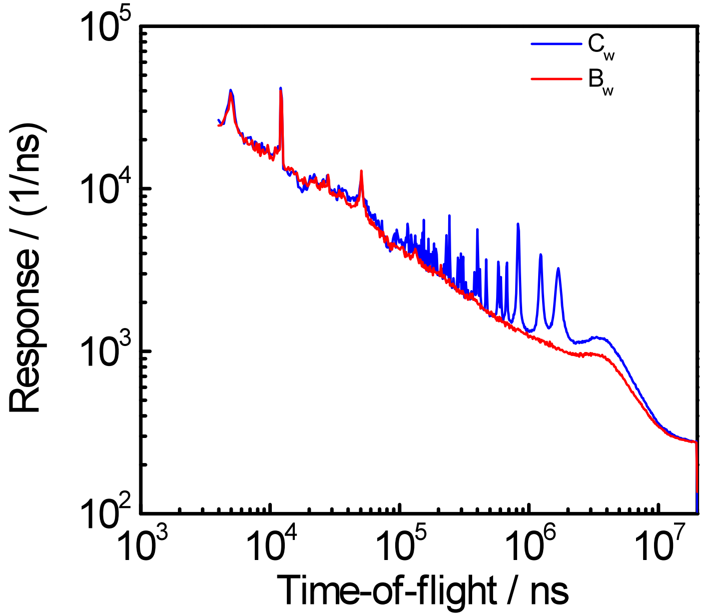
^{241}Am + n capture at GELINA

European Commission



$^{241}Am + n$ capture at GELINA





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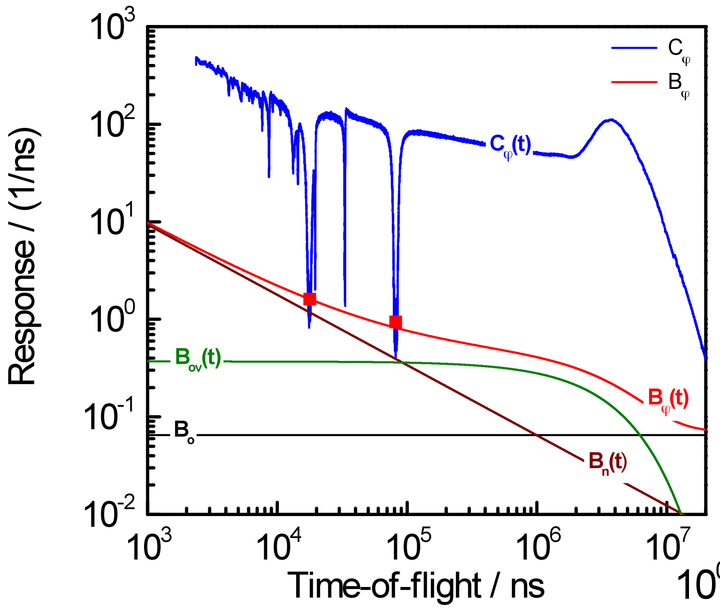
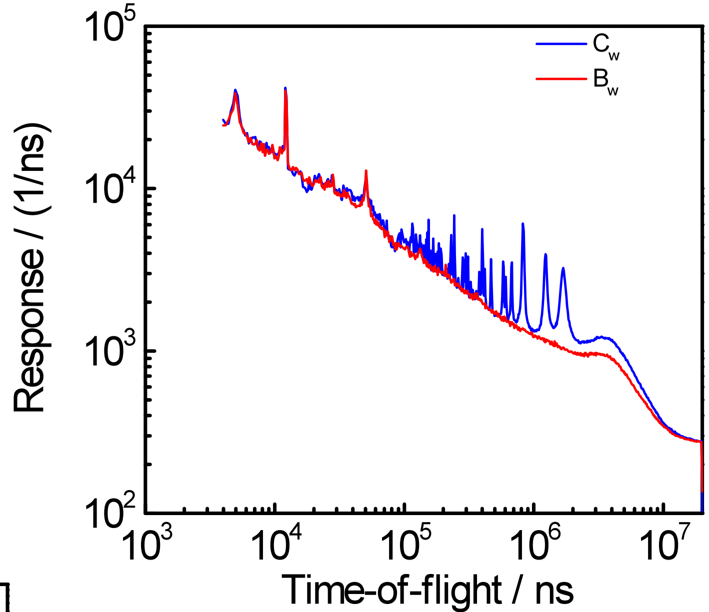
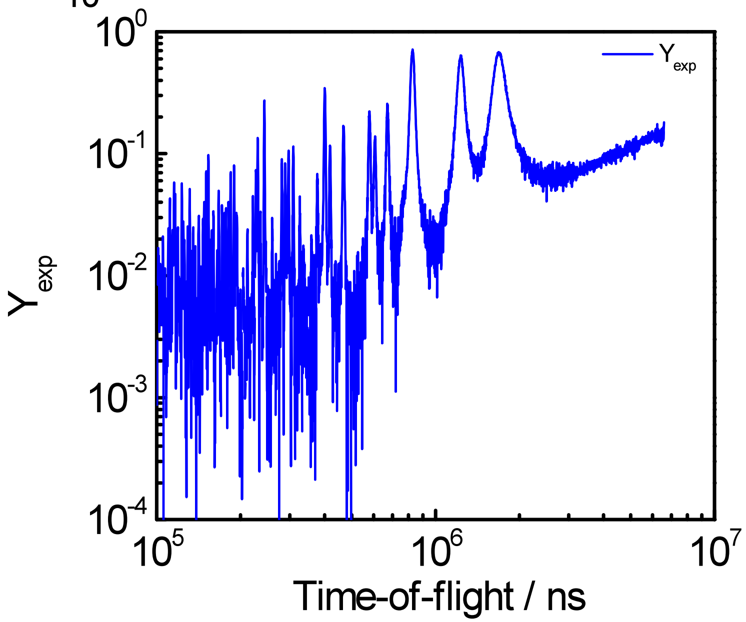


$$Y_{exp} = N \frac{C_w - B_w}{C_\varphi - B_\varphi} Y_\varphi$$





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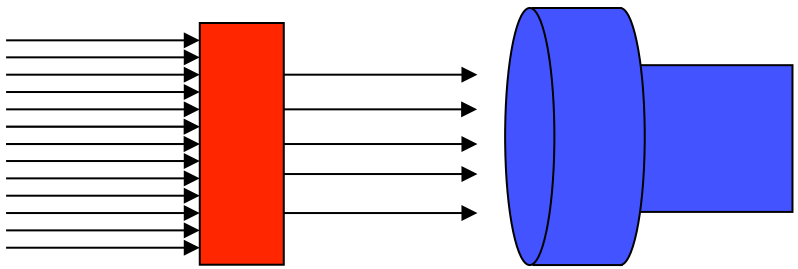

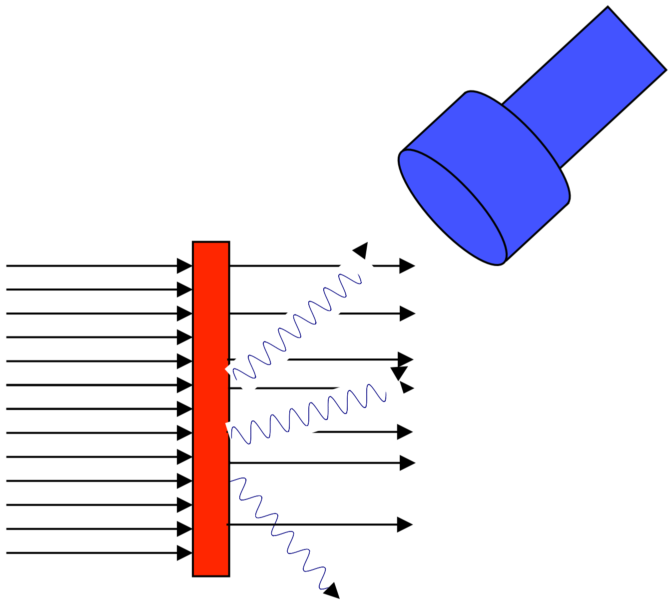

Fitting model parameters to experimental data

$$\chi^2(\vec{\eta}, \vec{\kappa}) = (\vec{Z}_{exp} - \vec{Z}_M(\vec{\eta}, \vec{\kappa}))^T \, \underline{V}_{Z_{exp}}^{-1} \, (\vec{Z}_{exp} - \vec{Z}_M(\vec{\eta}, \vec{\kappa}))$$

Z_{exp} : experimental observable

$Z_M(\vec{\eta}, \vec{\kappa})$: model prediction

$$Z_M(t_m) = \int R\,(t_m, E_n)\, Z(E_n)\, dE_n$$

$\vec{\eta}$ = resonance parameters

- R_J
- J^{π}
- $(E_R, \Gamma_{n,j}, \Gamma_{\gamma,j}, \Gamma_{f,j}, \ldots)$ j = 1,…,n

$\vec{\kappa}$ = experimental parameters

- Flight Path length
- Resolution
- Sample characteristics
- Doppler (sample temperature)
- Detector characteristics
- …

Schillebeeckx et al., Nuclear Data Sheets, 113 (2012) 3054 - 3100

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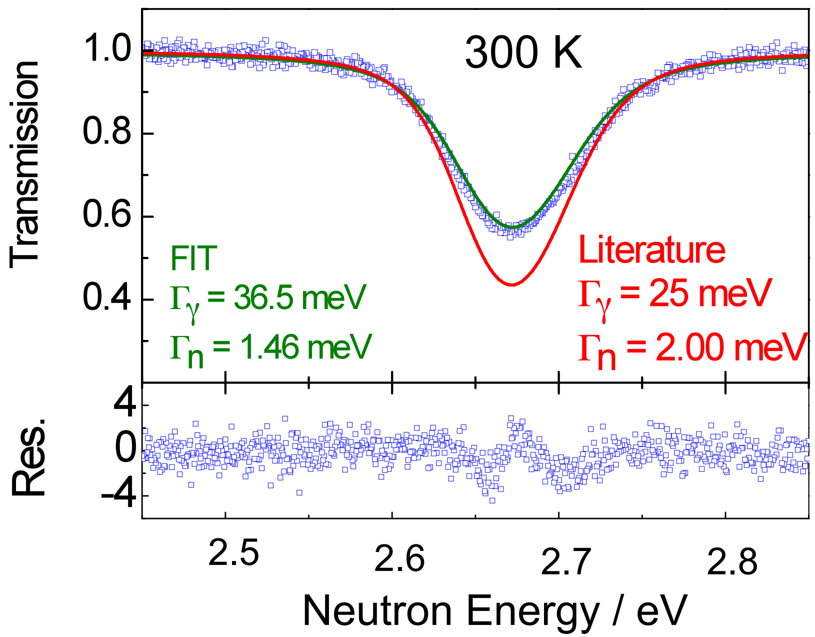
Sample properties: $^{242}PuO_2$ + carbon powder



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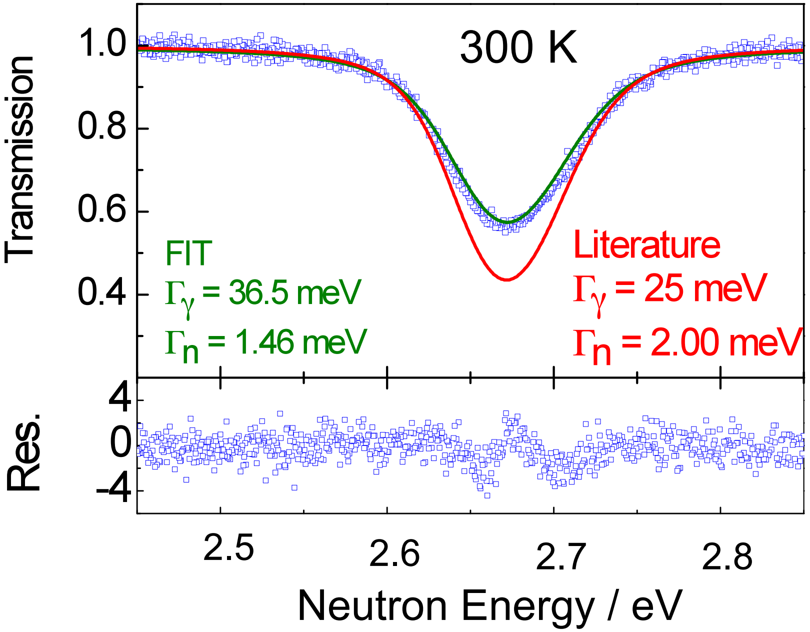
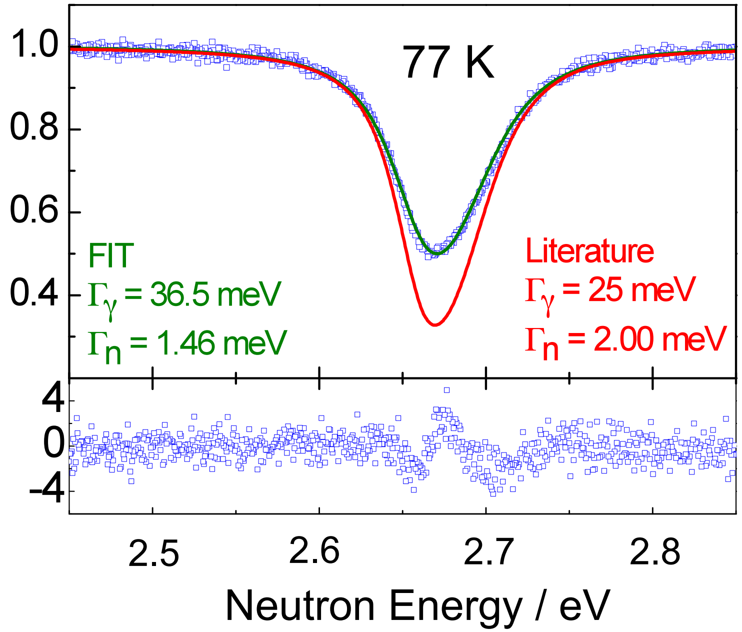


Γ_n underestimated

Γ overestimated



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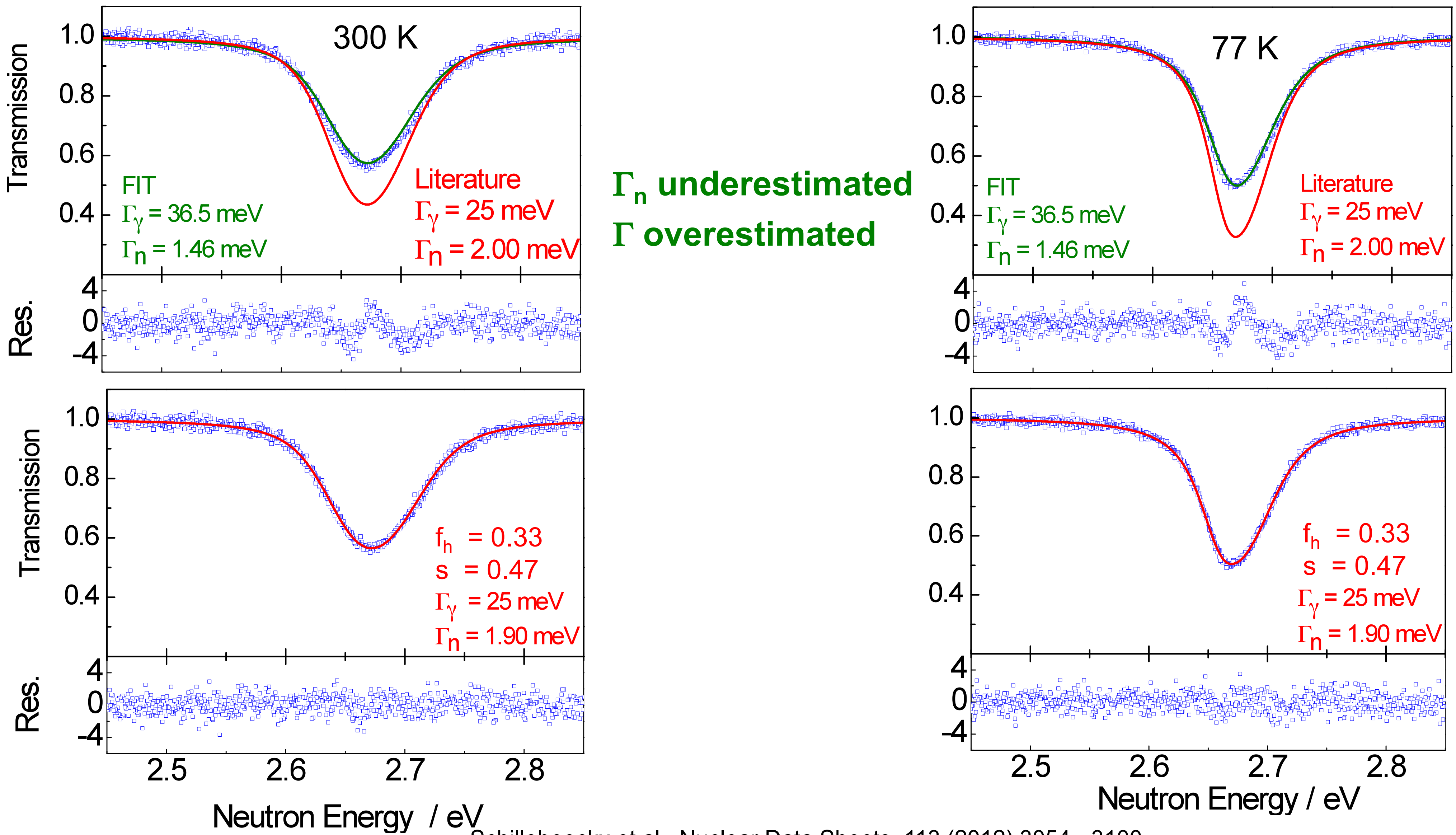
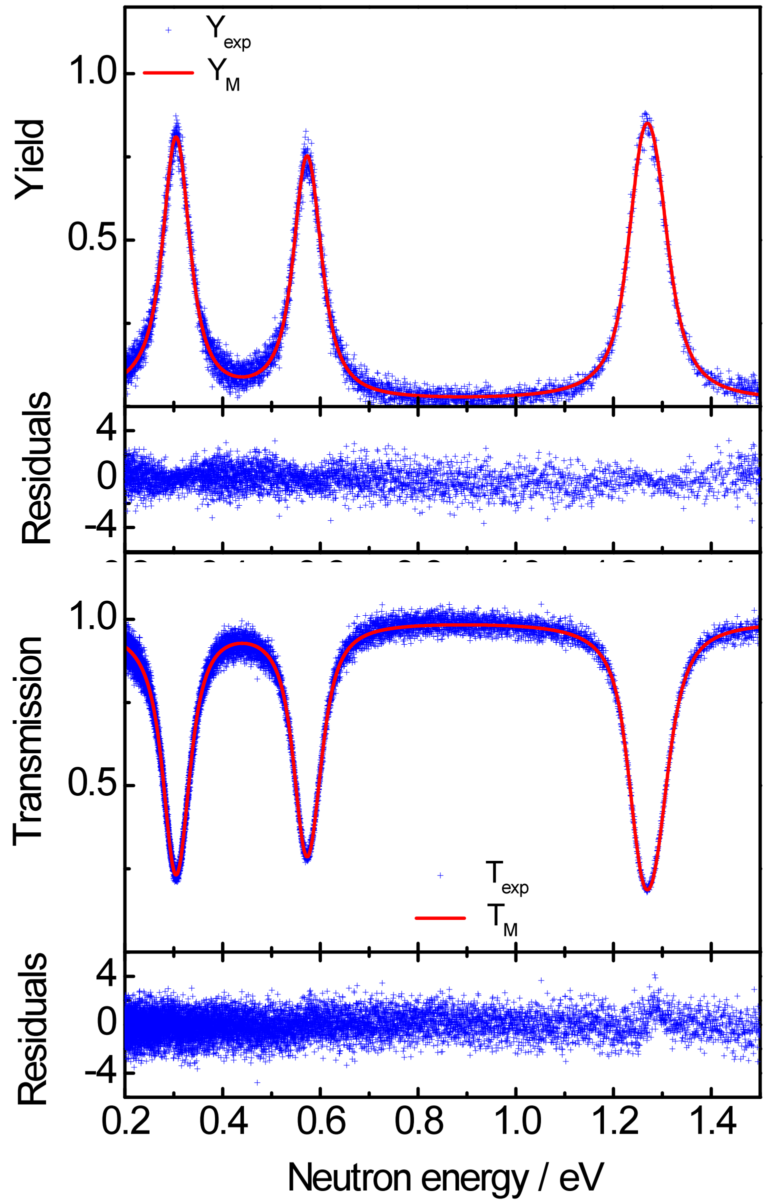


Schillebeeckx et al., Nuclear Data Sheets, 113 (2012) 3054 - 3100

Resonance parameters for $^{241}Am + n$



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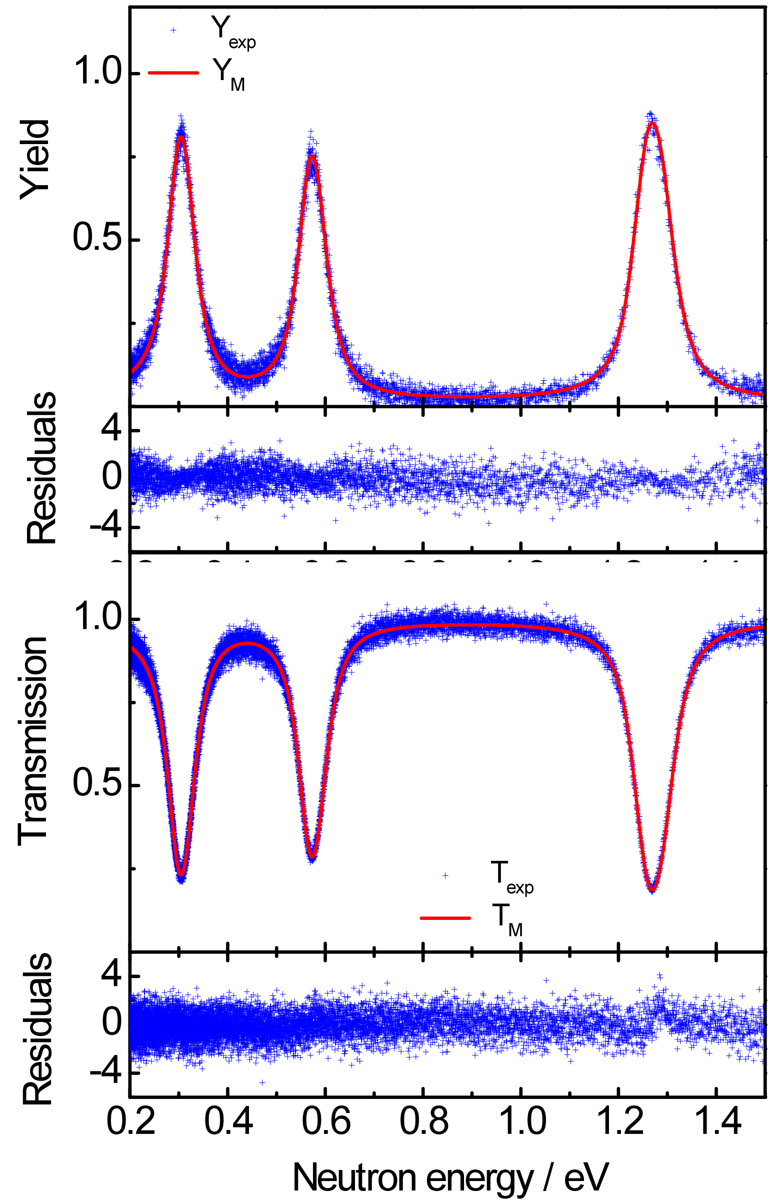
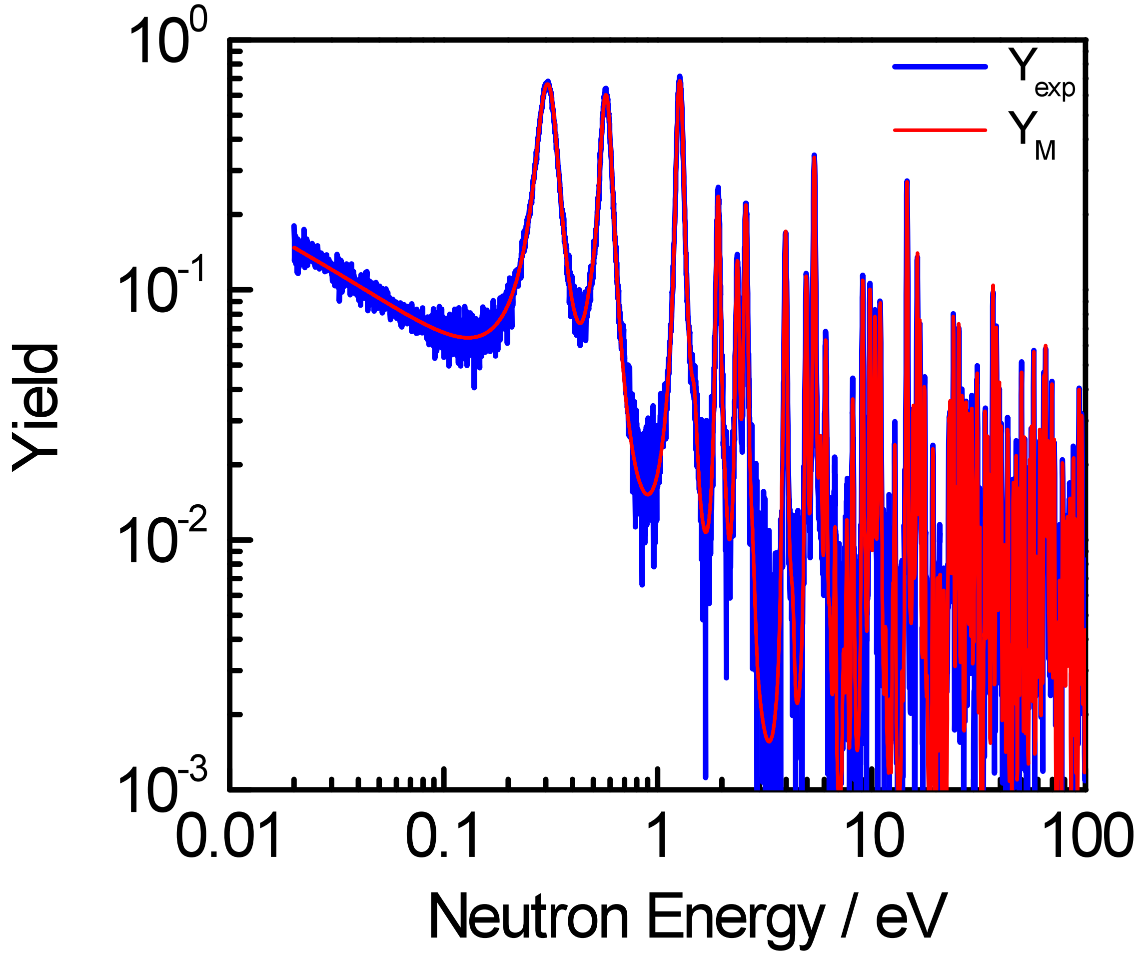
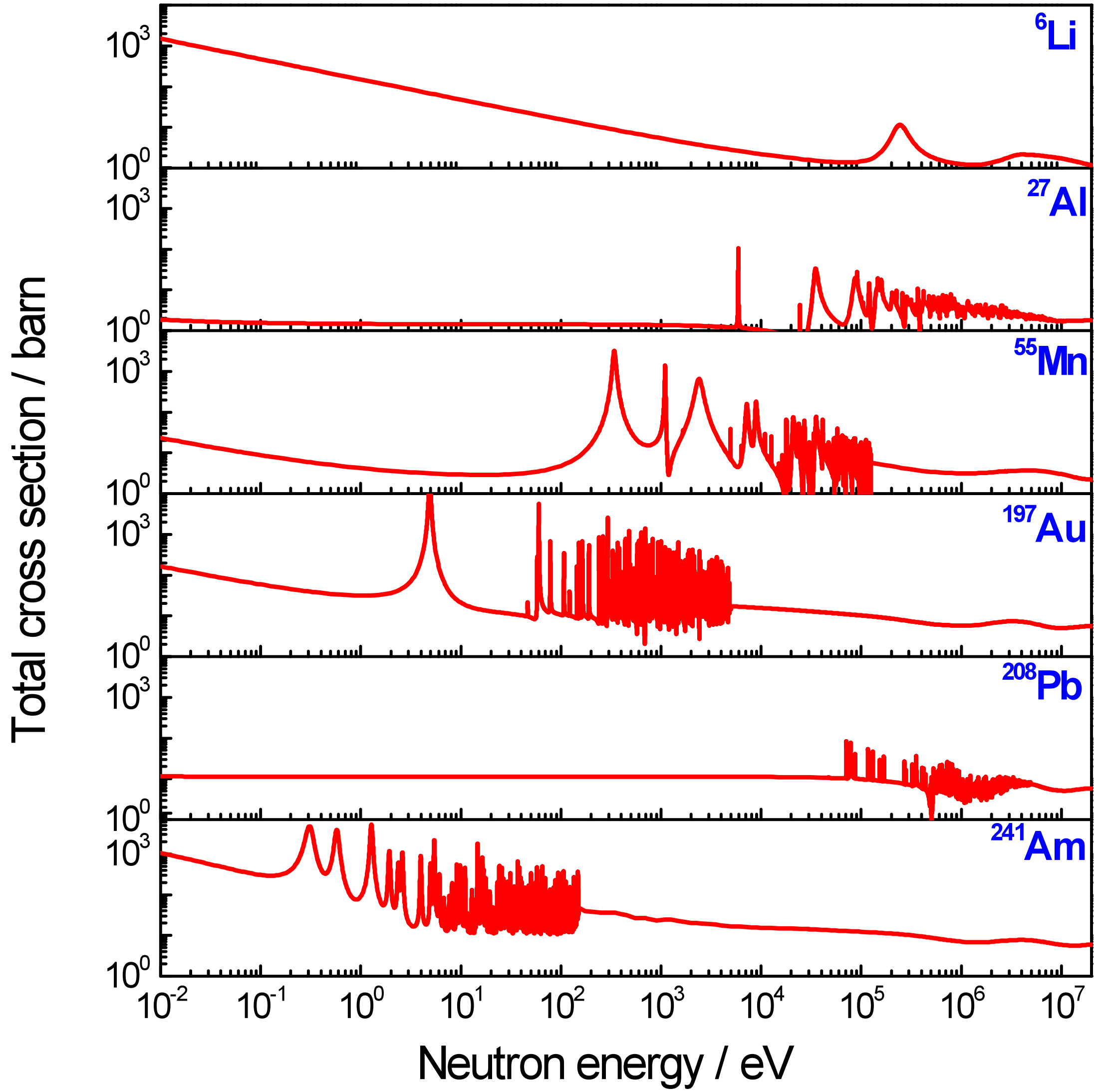
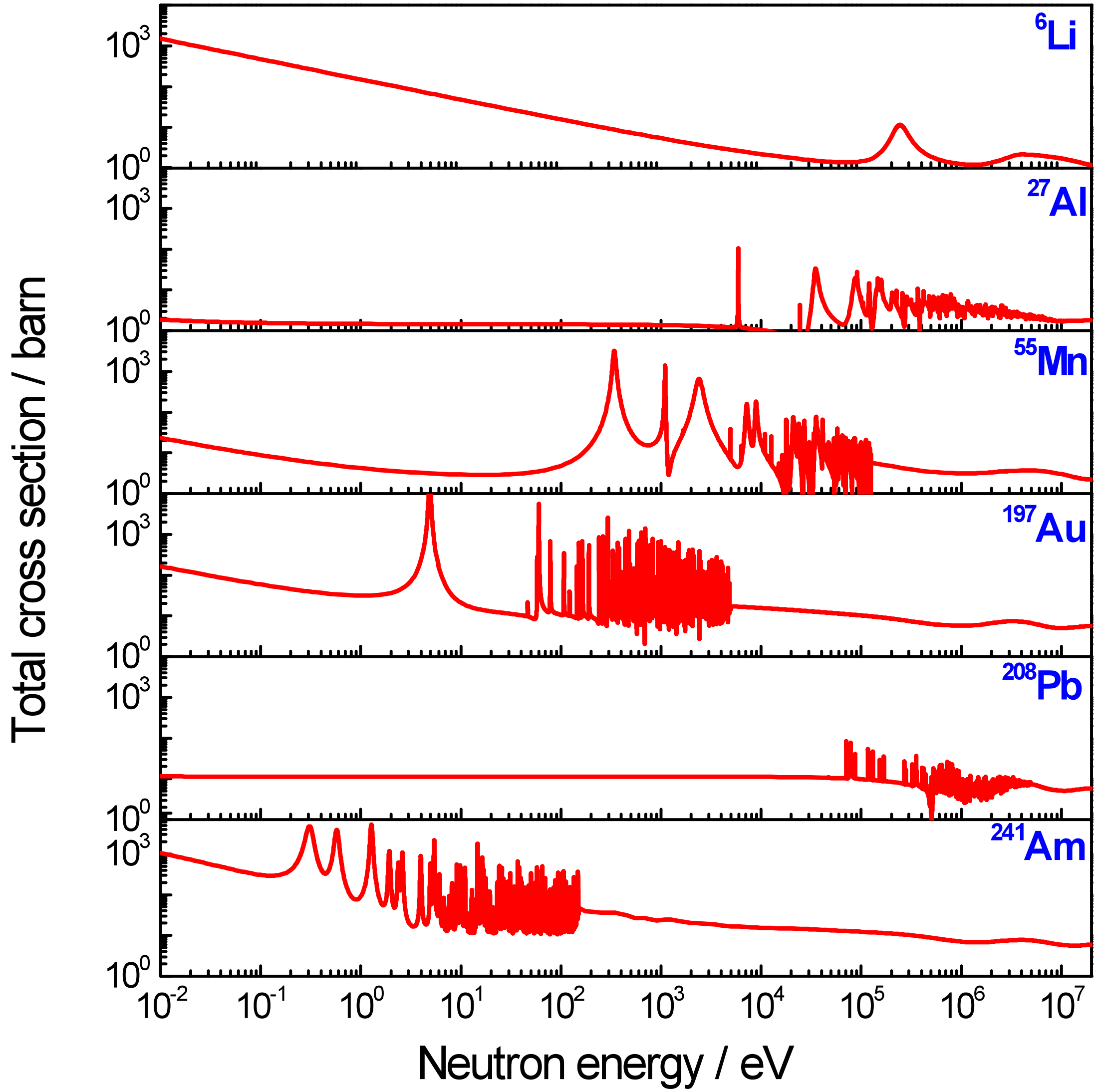




Resonance structured cross sections

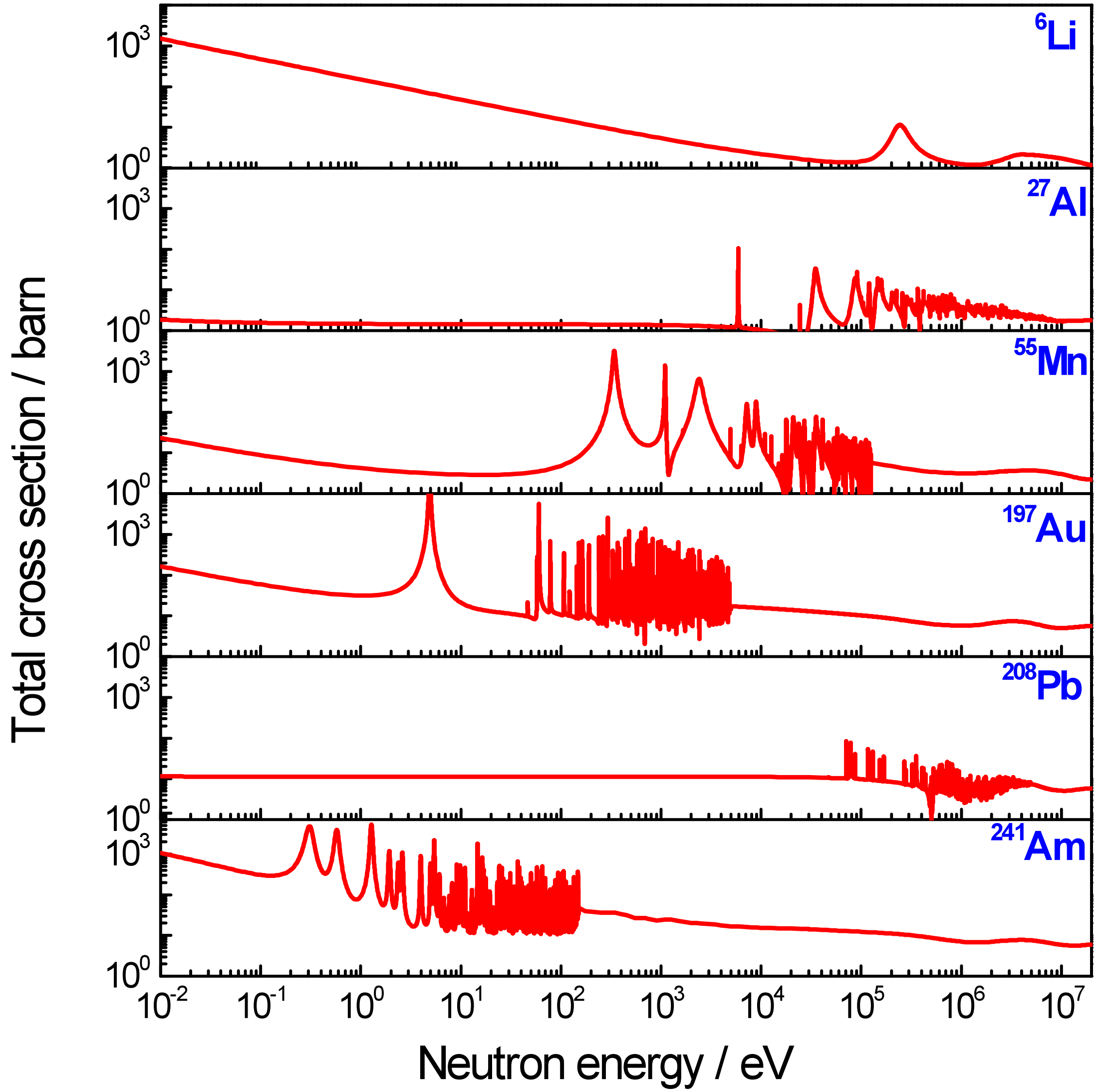


Resonance structured cross sections



Resonances appear at energies, which are specific for each nuclide

Neutron resonance analysis

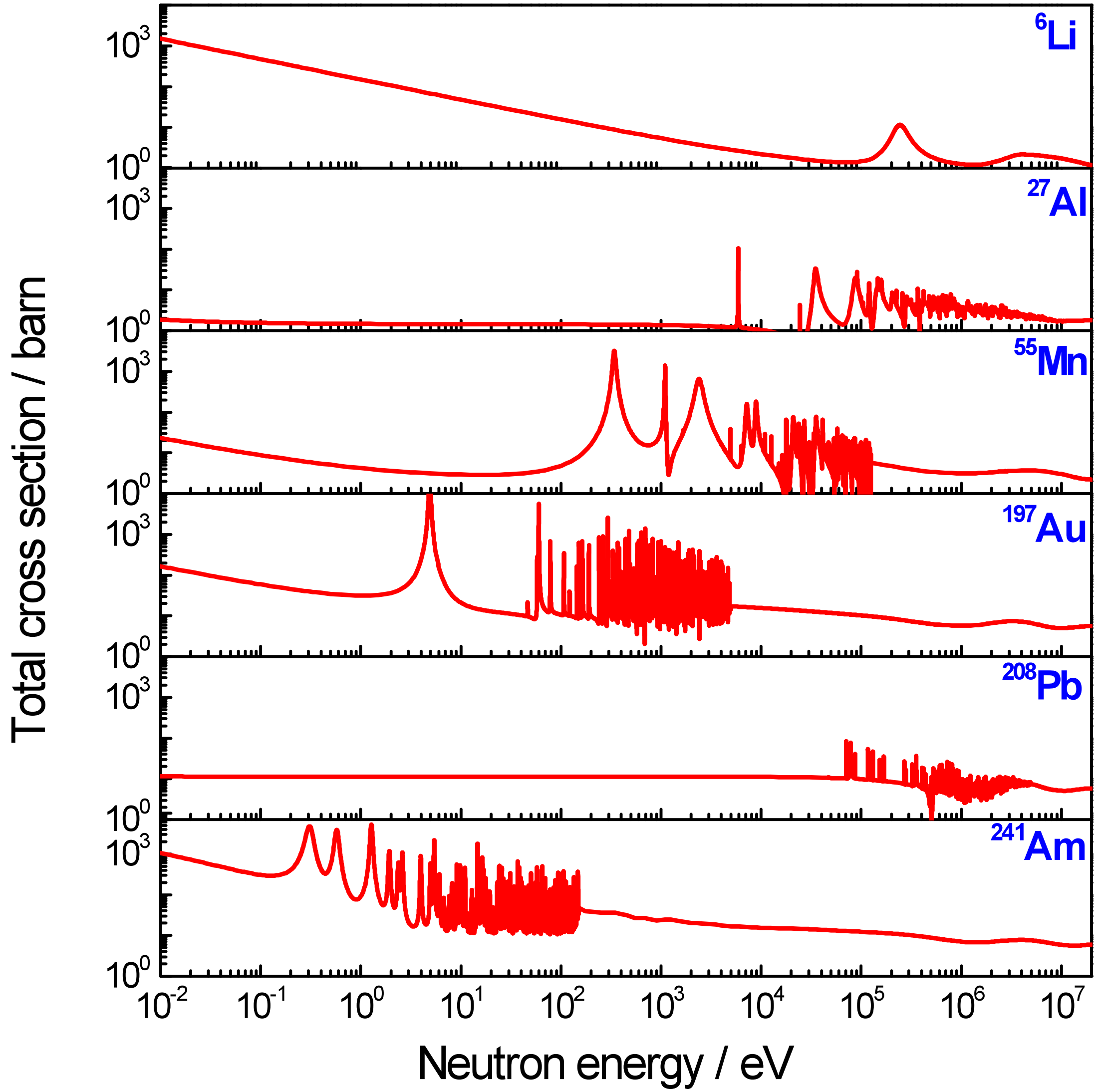


Resonances appear at energies, which are specific for each nuclide

- **Resonances can be used to**
  - **Identify and quantify nuclides**
  - **Elemental (& isotopic) composition**

Postma and Schillebeeckx, Encyclopedia of Analytical Chemistry, “Neutron resonance capture and transmission analysis'”

NRCA & NRTA



Resonances appear at energies, which are specific for each nuclide

- **Resonances can be used to**
  - **Identify and quantify nuclides**
  - **Elemental (& isotopic) composition**

- **NRCA & NRTA**
  - **Non - Destructive**
  - **No sample preparation required**
  - **Negligible residual activation**

Postma and Schillebeeckx, Encyclopedia of Analytical Chemistry, "Neutron resonance capture and transmission analysis'"

Cross section measurements

Transmission

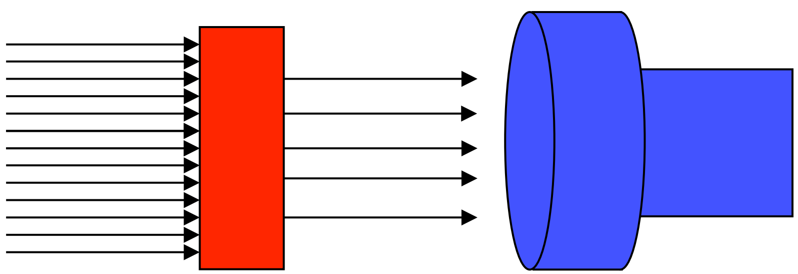
$$T_{exp} = \frac{C_{in}}{C_{out}}$$

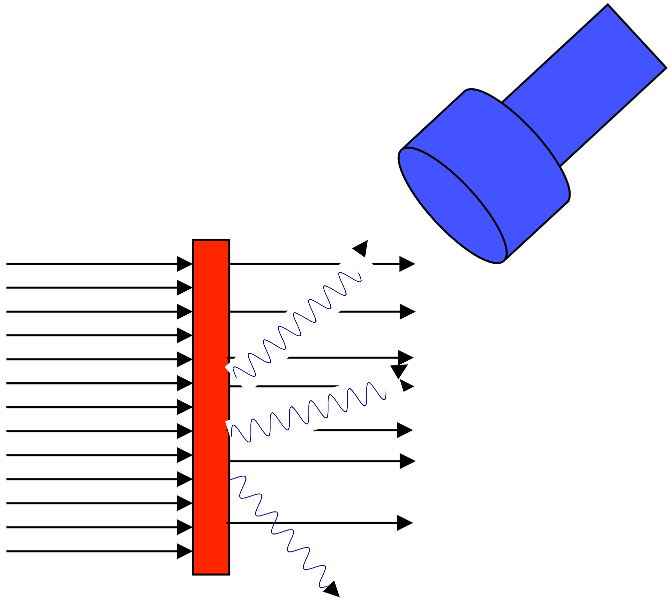
$$T \cong e^{-n\,\sigma_{tot}}$$

Capture

$$Y_{\gamma,exp} = \frac{C_\gamma}{\varepsilon_\gamma\ \varphi}$$

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





NRTA and NRCA

NRTA

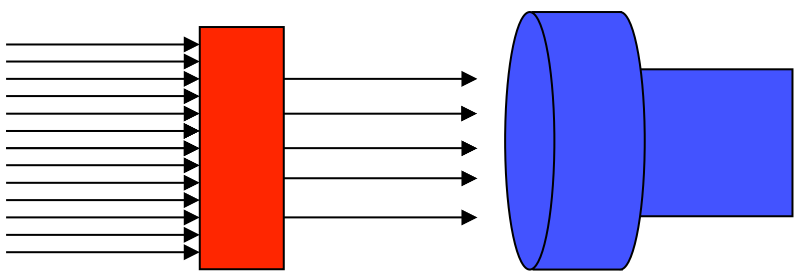
$$T_{exp} = \frac{C_{in}}{C_{out}}$$

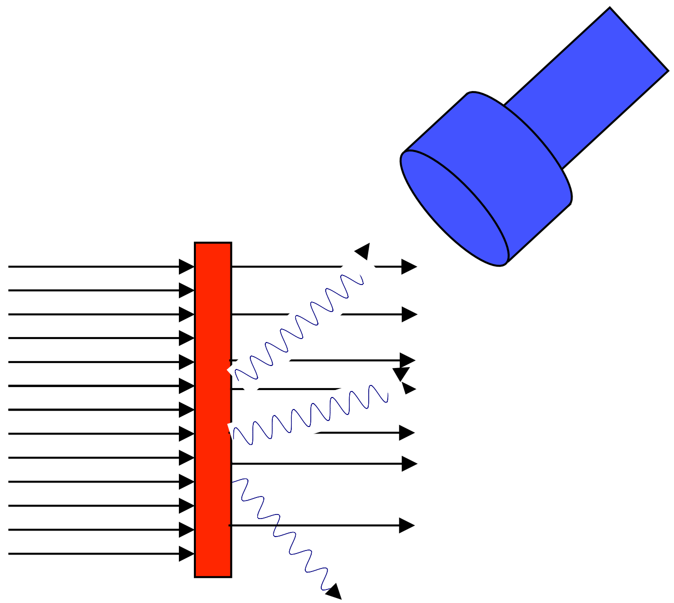
$$T \cong e^{-n\sigma_{tot}}$$

NRCA

$$Y_{\gamma,exp} = \frac{C_{\gamma}}{\varepsilon_{\gamma}\ \varphi}$$

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





NRTA and NRCA

European Commission

NRTA

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

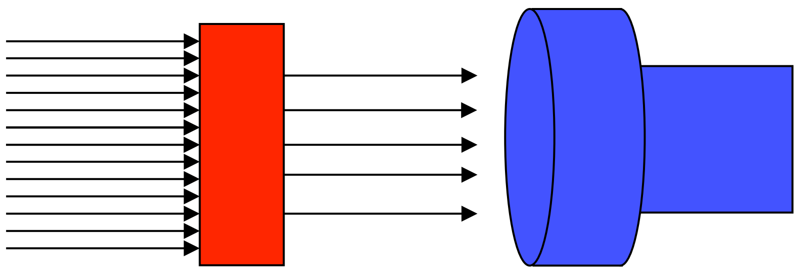
$$T \cong e^{-n\,\sigma_{tot}}$$

NRCA

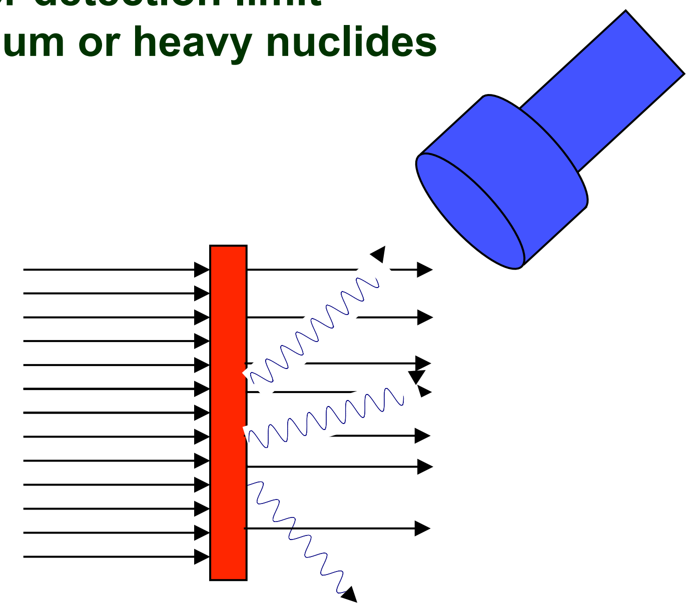
$$Y_{\gamma,exp} = \frac{C_\gamma}{\varepsilon_\gamma \; \varphi}$$

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

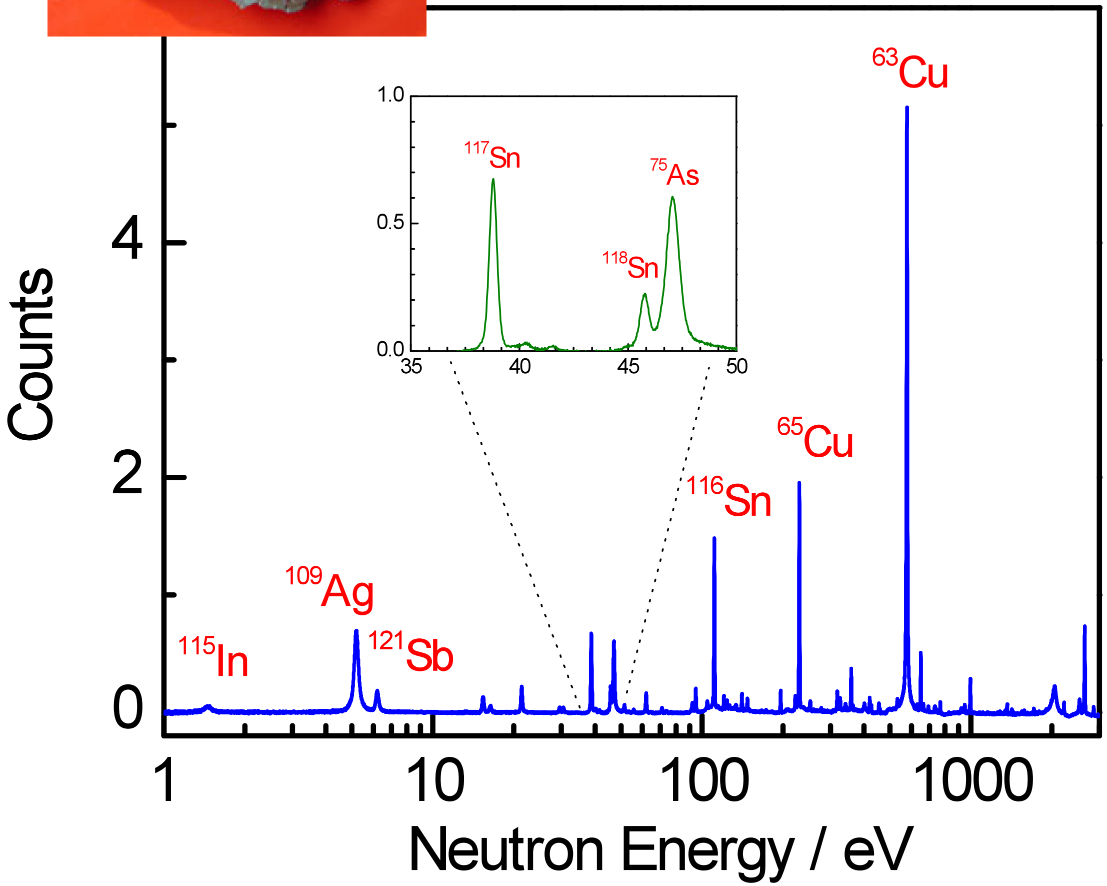
+ no calibration
+ radioactive samples
+ light nuclide or close to magic shells



+ better detection limit
+ medium or heavy nuclides



NRCA : example

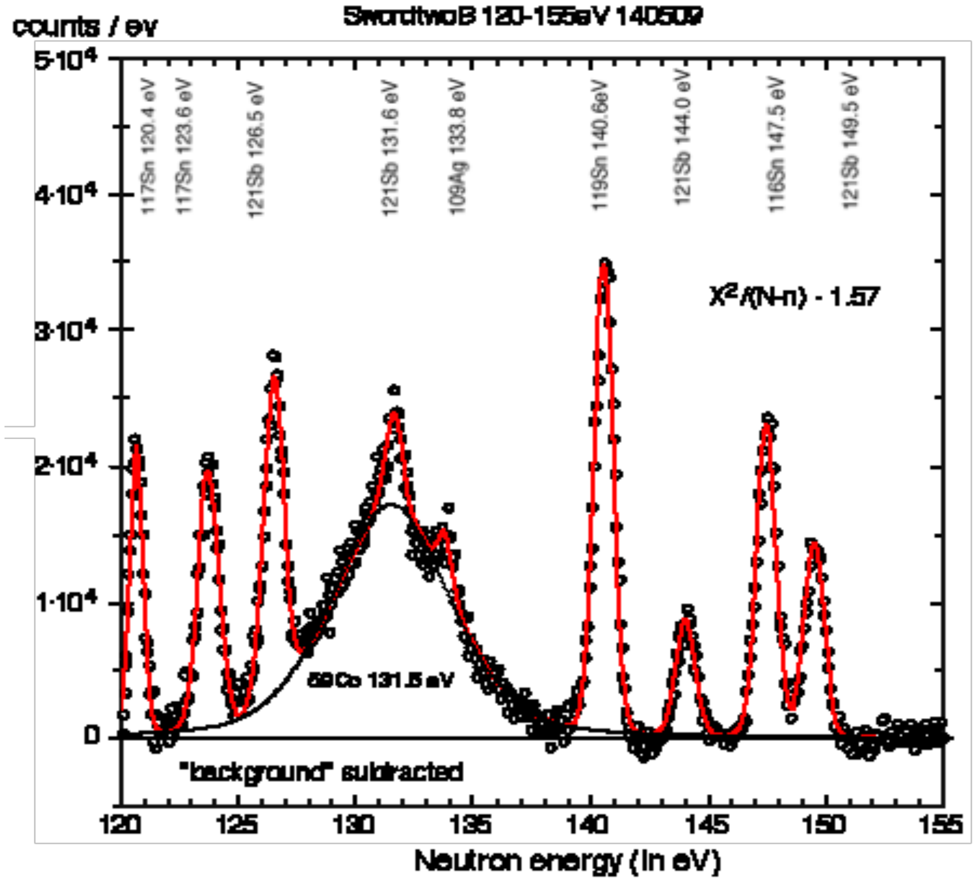


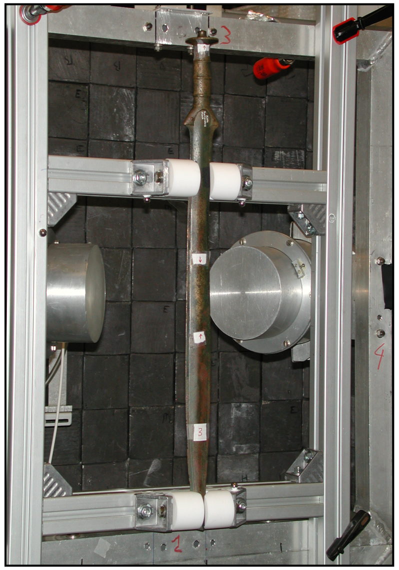
Element	Fractions (%)		Isotope	Resonance (eV)
Cu	77.76	(0.11)		
			^{63}Cu	579.0
			^{65}Cu	230.0
Sn	20.85	(0.10)		
			^{112}Sn	94.8
			^{116}Sn	111.2
			^{117}Sn	38.8
			^{118}Sn	45.7
			^{119}Sn	222.6
			^{120}Sn	427.5
			^{122}Sn	1756.0
			^{124}Sn	62.0
As	0.34	(0.01)		
			^{75}As	47.0
Sb	0.196	(0.021)		
			^{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

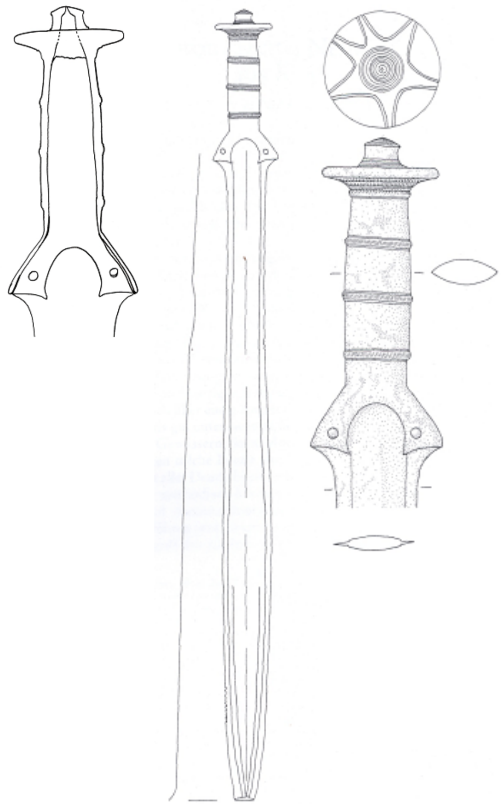
m_{NRCA} = 13.0 (0.5) g

m_{weight} = 13.25 g

Bronze age sword



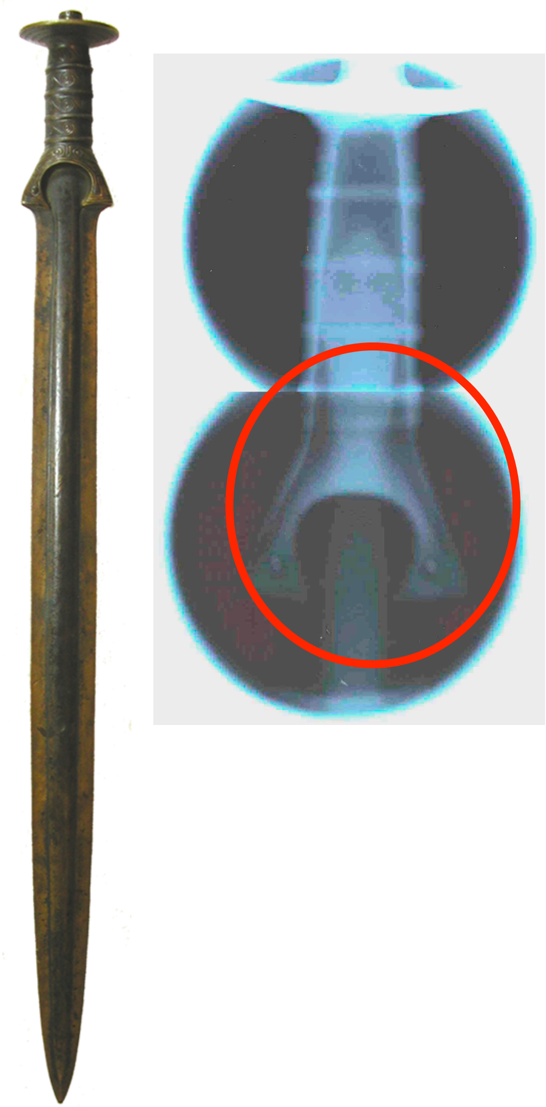


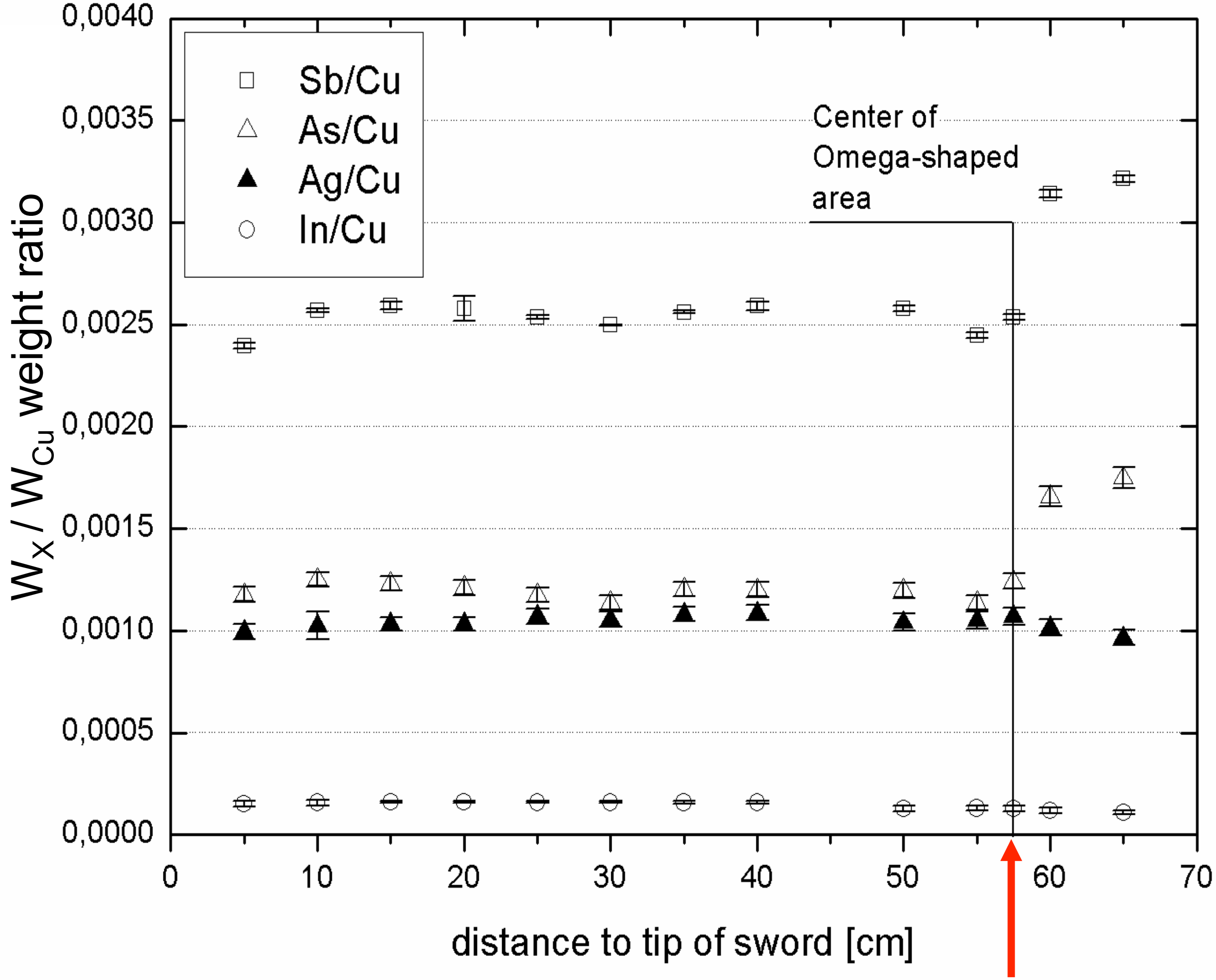


Tin – bronzes containing Sb, As and Ag

Presence of In and/or Co (not in all cases nor along all spots)

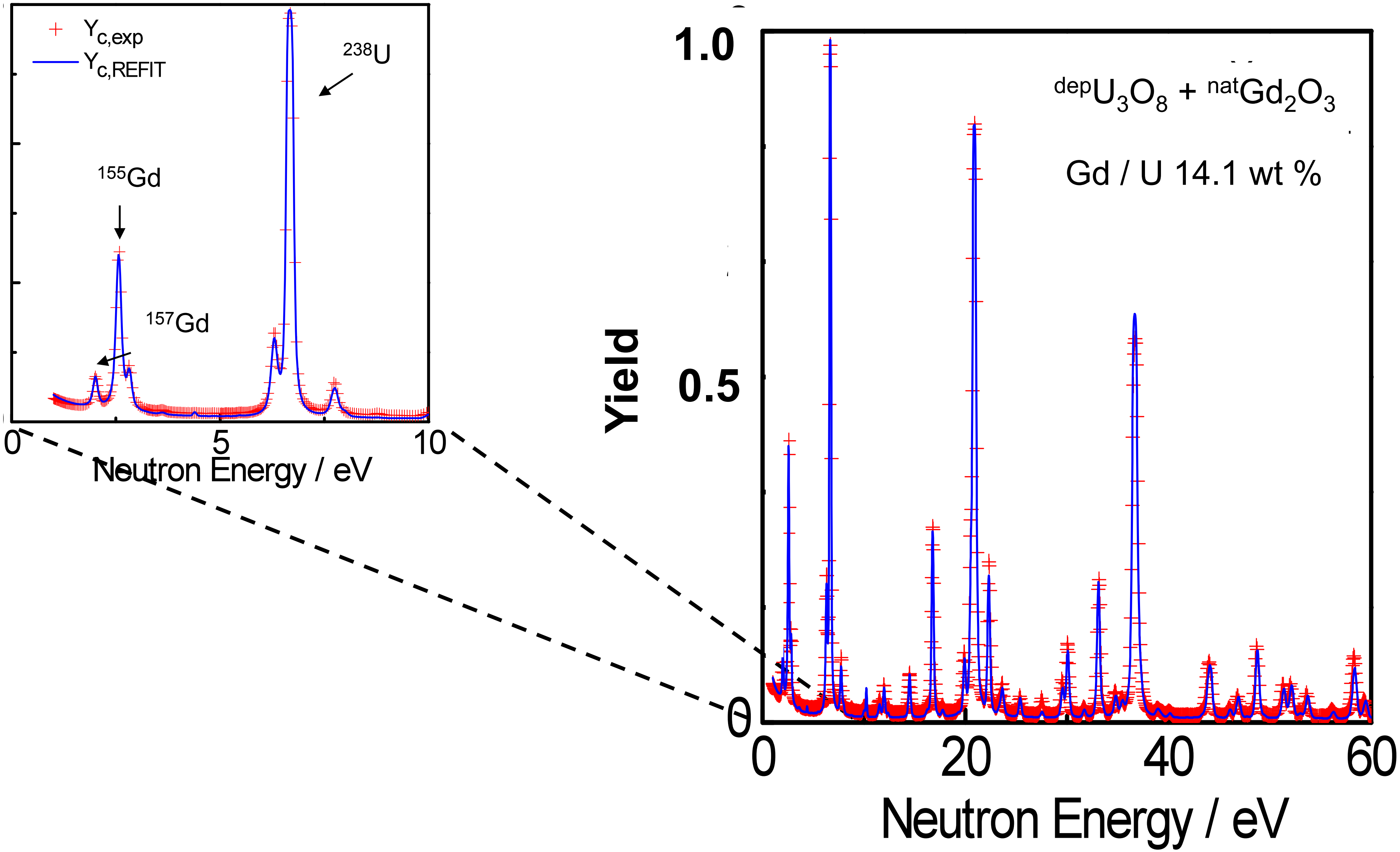
NRCA + γ-ray radiography





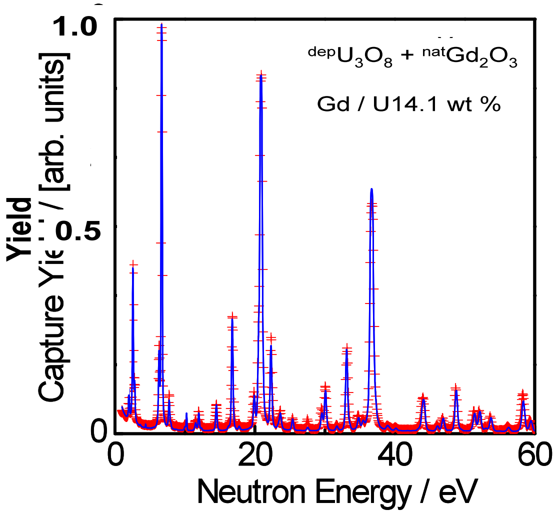
Postma et al., J. Radioanal. Nucl. Chem. 283 (2010) 641

NRCA on nuclear materials



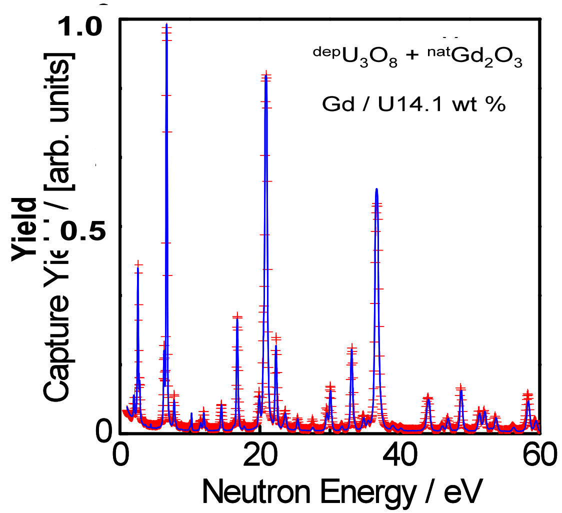
NRCA : RSA with REFIT

U / g	Gd / g	$n(^{155}Gd) / n(^{238}U)$ nat. abundance	$n(^{155}Gd) / n(^{238}U)$ NRCA	$n(^{157}Gd) / n(^{238}U)$ nat. abundance	$n(^{157}Gd) / n(^{238}U)$ NRCA
20.888	0.0636	$5.77\ 10^{-4}$		$6.10\ 10^{-4}$	
20.608	0.6206	$5.71\ 10^{-3}$		$6.03\ 10^{-4}$	
16.656	2.6240	$3.13\ 10^{-2}$		$3.36\ 10^{-2}$	



NRCA : RSA with REFIT

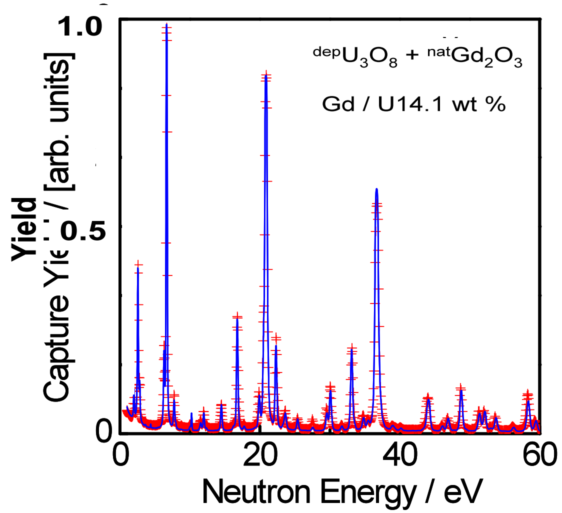
U / g	Gd / g	$n(^{155}Gd) / n(^{238}U)$		$n(^{157}Gd) / n(^{238}U)$	
		nat. abundance	NRCA	nat. abundance	NRCA
20.888	0.0636	$5.77 \cdot 10^{-4}$	$(5.78 \pm 0.04) \cdot 10^{-4}$	$6.10 \cdot 10^{-4}$	
20.608	0.6206	$5.71 \cdot 10^{-3}$	$(5.73 \pm 0.01) \cdot 10^{-3}$	$6.03 \cdot 10^{-3}$	
16.656	2.6240	$3.13 \cdot 10^{-2}$	$(3.14 \pm 0.01) \cdot 10^{-2}$	$3.36 \cdot 10^{-2}$	



NRCA : RSA with REFIT

European Commission

U / g	Gd / g	$n(^{155}Gd) / n(^{238}U)$ nat. abundance	$n(^{155}Gd) / n(^{238}U)$ NRCA	$n(^{157}Gd) / n(^{238}U)$ nat. abundance	$n(^{157}Gd) / n(^{238}U)$ NRCA
20.988	0.0636	$5.77\ 10^{-4}$	$(5.78 \pm 0.04)\ 10^{-4}$	$6.10\ 10^{-4}$	$(6.59 \pm 0.07)\ 10^{-4}$
20.608	0.6206	$5.71\ 10^{-3}$	$(5.73 \pm 0.01)\ 10^{-3}$	$6.03\ 10^{-4}$	$(6.53 \pm 0.02)\ 10^{-3}$
16.656	2.6240	$3.13\ 10^{-2}$	$(3.14 \pm 0.01)\ 10^{-2}$	$3.36\ 10^{-2}$	$(3.51 \pm 0.03)\ 10^{-2}$

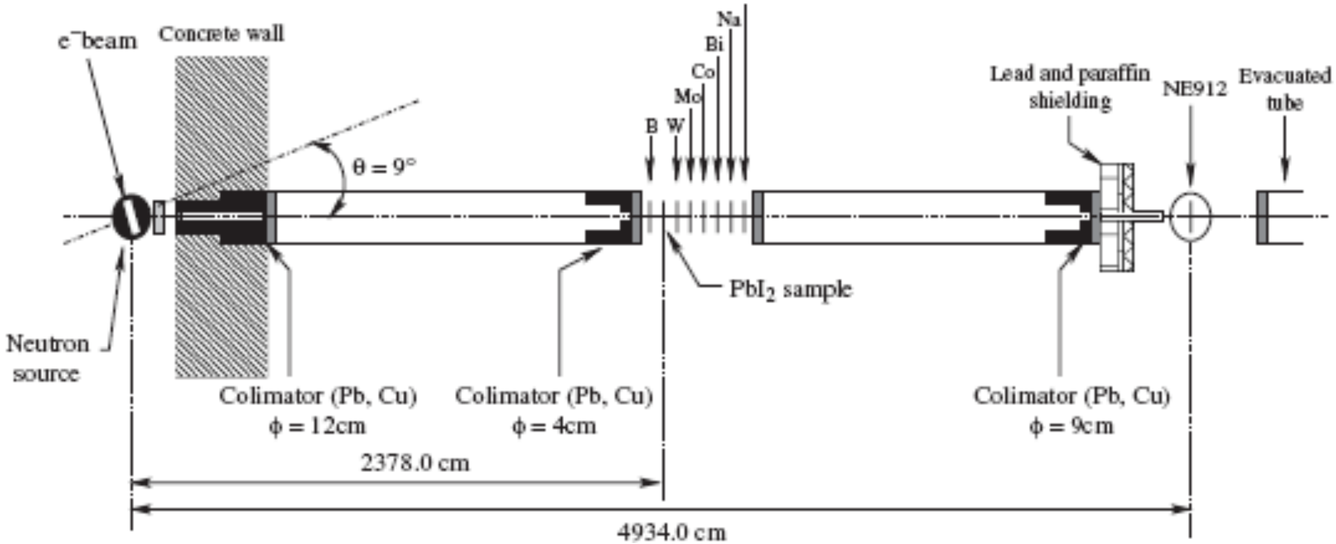


Schillebeeckx et al., Nucl. Inst. Meth. A613 (2010) 378

Characterisation of PbI_2 sample by NRTA

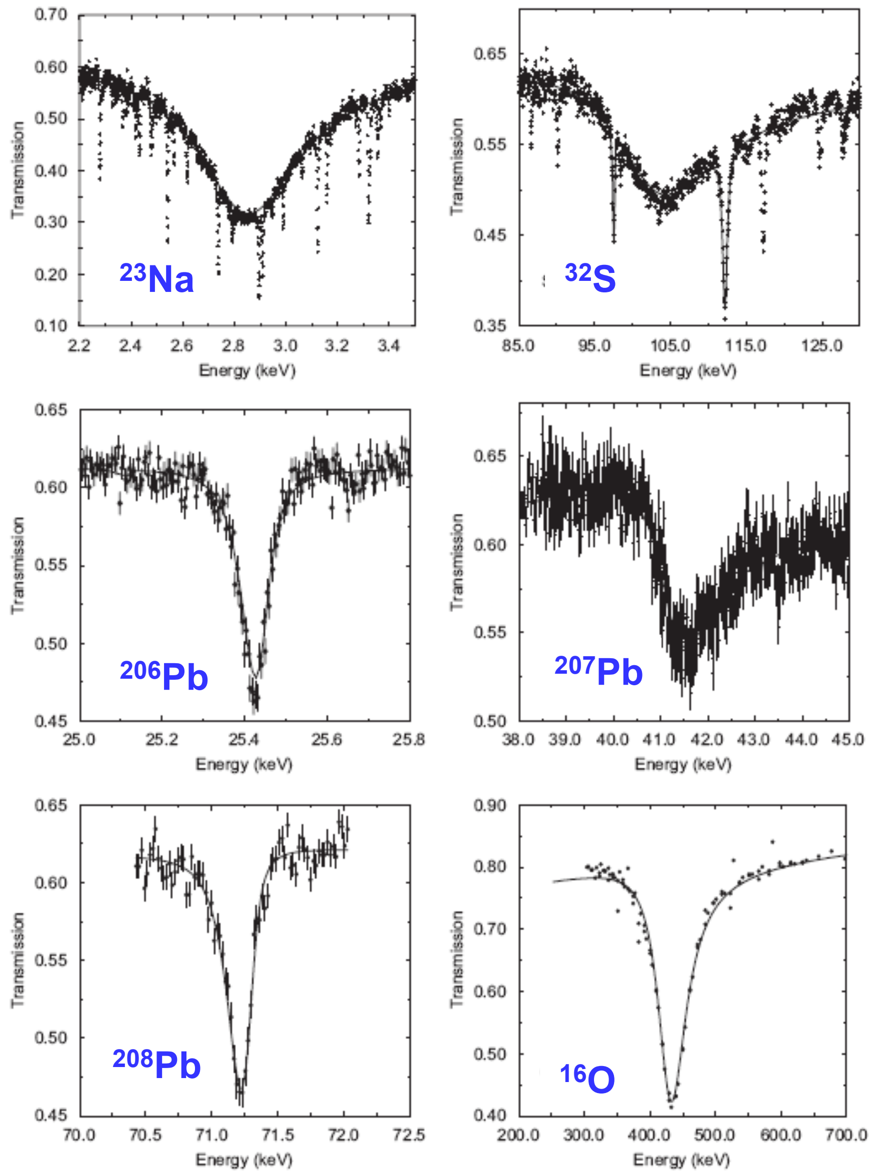
- **IRMM sample preparation group extracted** (NIMA 480 (2002) 204) :
  - 150 g Iodine (powder) from 210 liter reprocessed waste
  - (1.3 g/l Iodine and 40 MBq/l)
- **Sample characterisation: by mass spectrometry , (N)AA and NRTA**

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



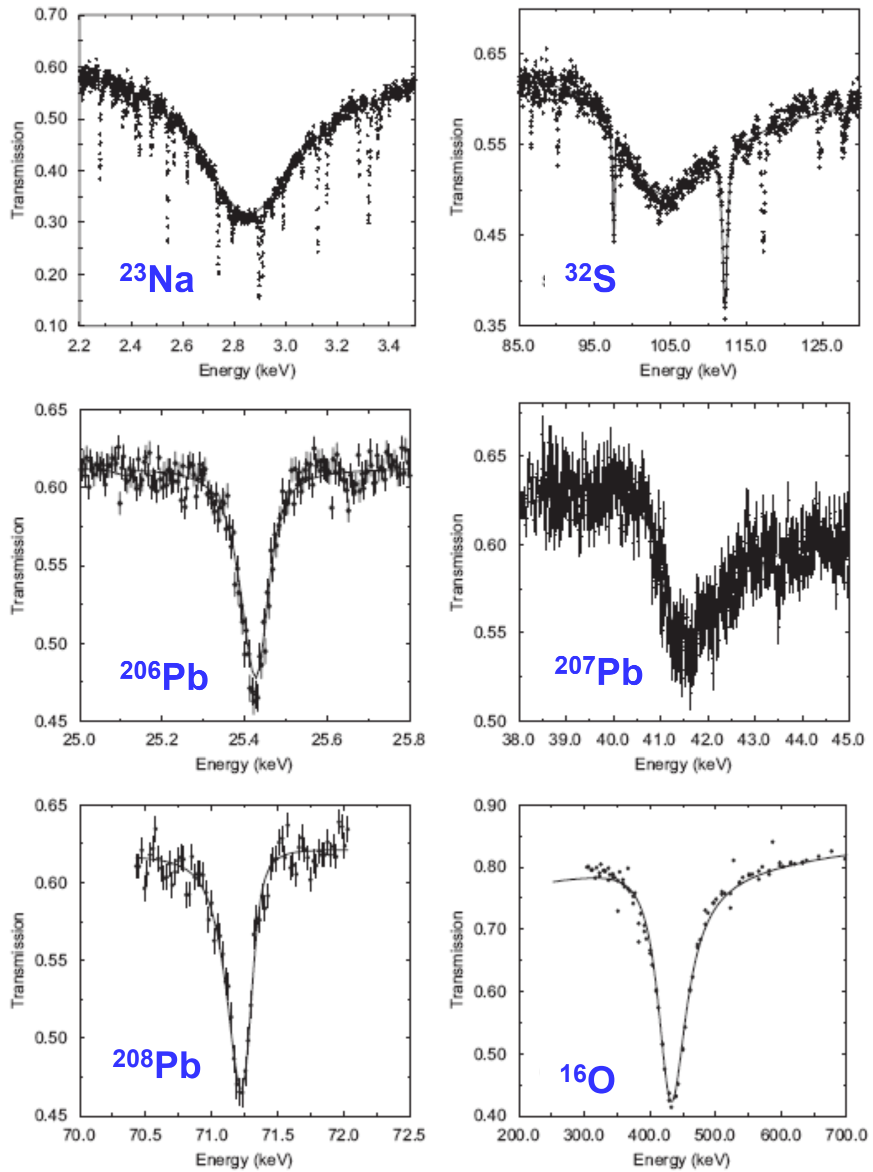
Ingelbrecht et al., Nucl. Inst. Meth. A 480 (2002) 204

Characterisation of PbI_2 by NRTA

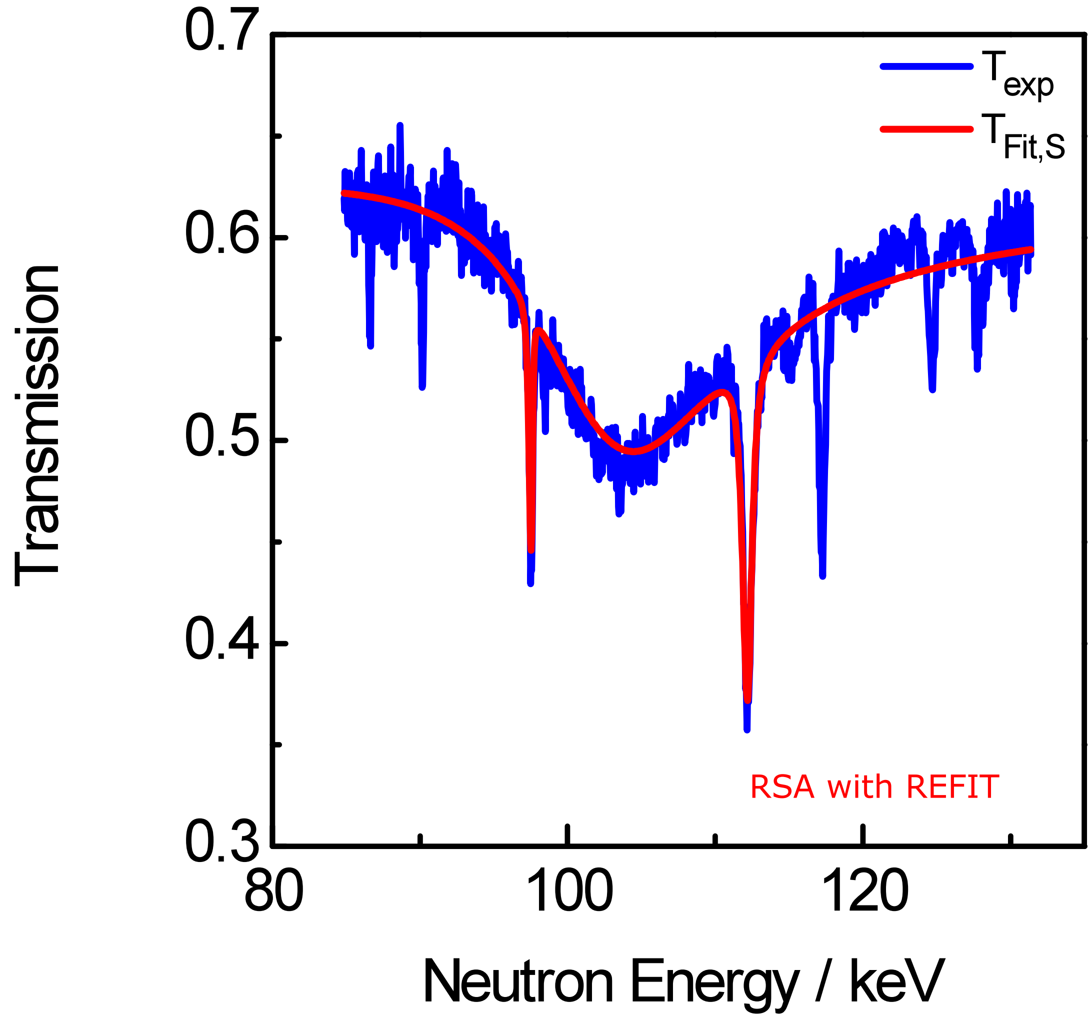


Characterisation of PbI_2 by NRTA

European Commission



RSA with REFIT



Advantages of NRTA

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)

Almost all elements present in the sample have been analyzed
Isotopic composition of Pb

Noguere et al., NIM A 575 (2007) 476

From Analysis to Imaging

European Commission

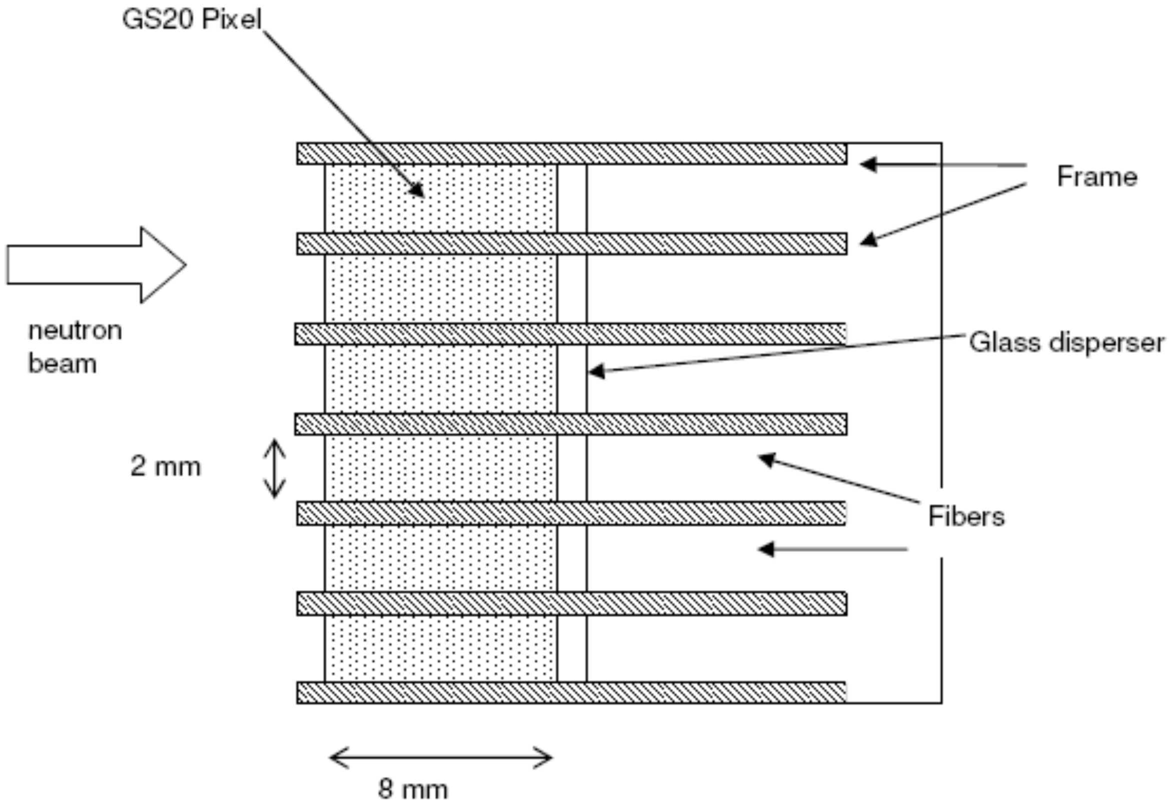
GELINA at IRMM

ISIS at RAL

PSND for imaging at ISIS

10 x 10 pixelated neutron detector, 100 ^{6}Li-glass scintillators (2 x 2 x 8 mm^{3})

7 position sensitive 16 channel PMT



Detection efficiency

25 % at 10 eV

4 % at 1 keV

Schooneveld et al., J. Phys. D. 42 (2009) 152003

Test of PSND for NRTI at GELINA

Tested for

- **Time resolution**
- **Cross talk**
- **Procedure to determine T_{exp} and deduce n in non-ideal geometry**

Test of PSND for NRTI at GELINA

Tested for

- **Time resolution**
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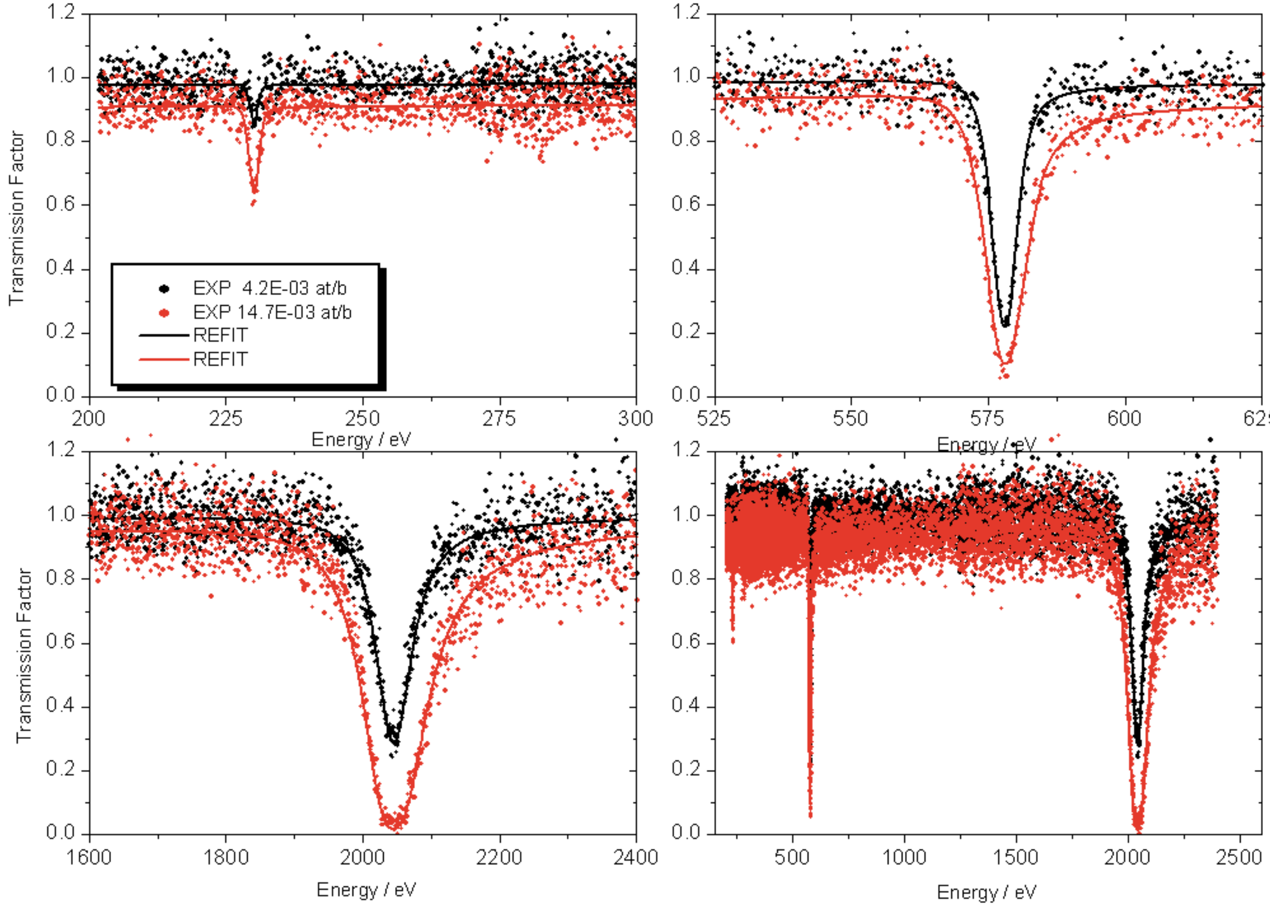
Measurements on Cu-discs



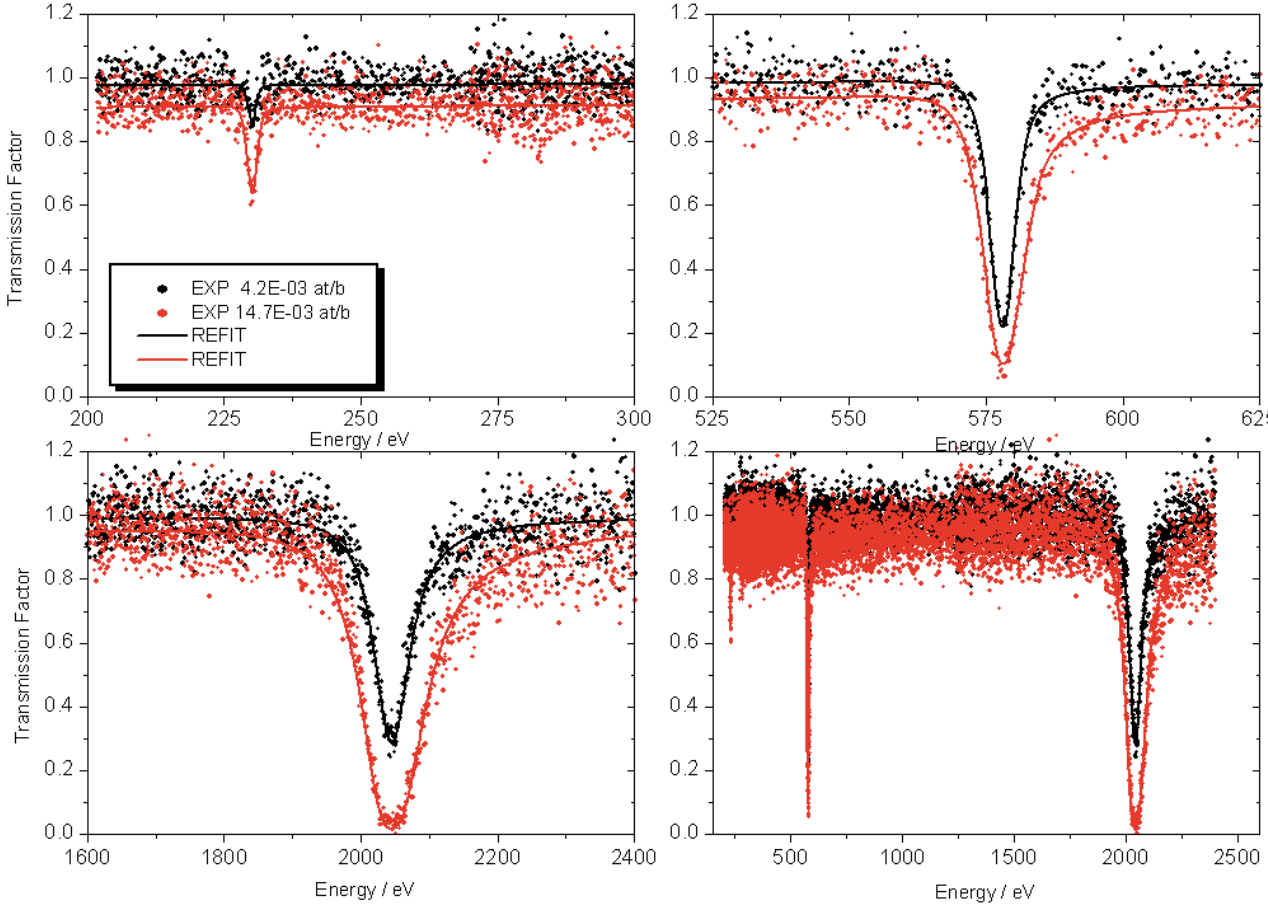
Schillebeeckx et al., JINST 7 (2012) C03009

Test of PSND for NRTI at GELINA

Tested for

- **Time resolution**
- **Cross talk**
- **Procedure to determine T_{exp} and deduce n in non-ideal geometry**

Measurements on Cu-discs



NRTA with REFIT

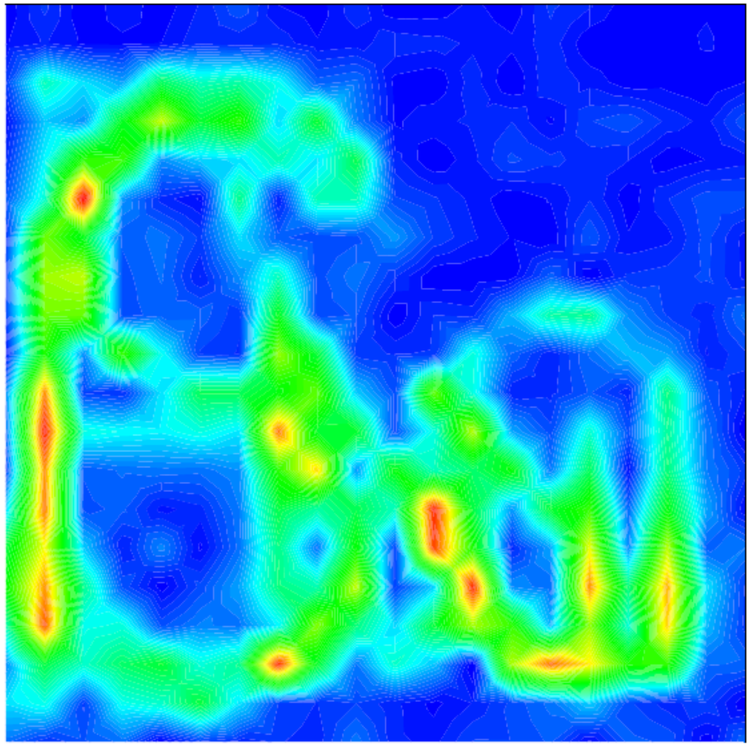
n_{Cu} = (4.29 ± 0.05) 10^{-3} at/b ↔ 4.22 10^{-3} at/b

n_{Cu} = (1.49 ± 0.01) 10^{-2} at/b ↔ 1.47 10^{-2} at/b

Schillebeeckx et al., JINST 7 (2012) C03009

NRTI with PSND at ISIS

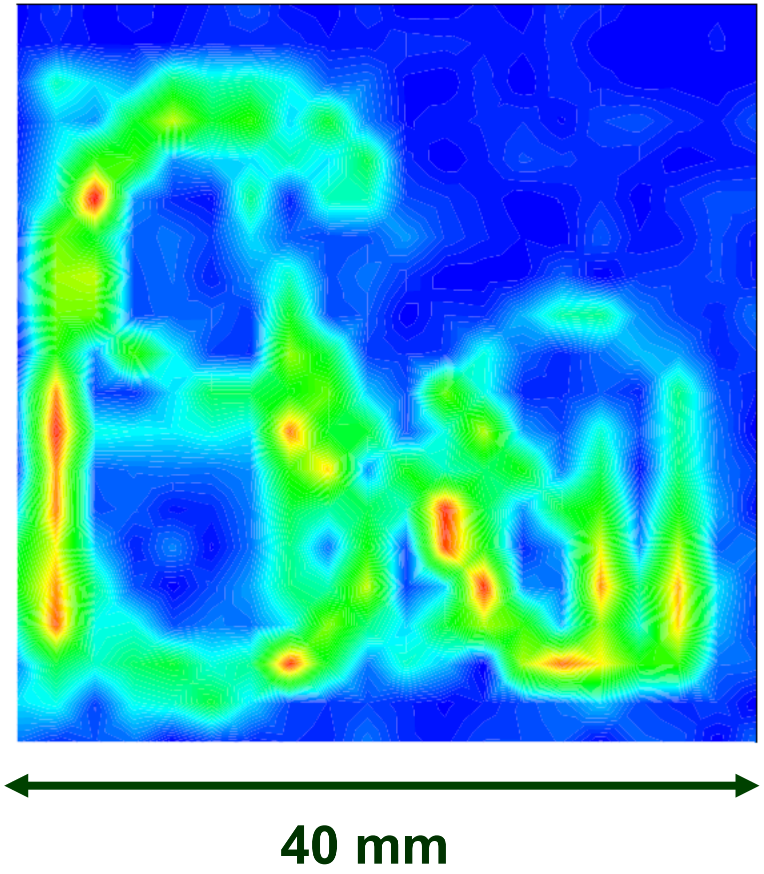
Total counts in TOF spectrum



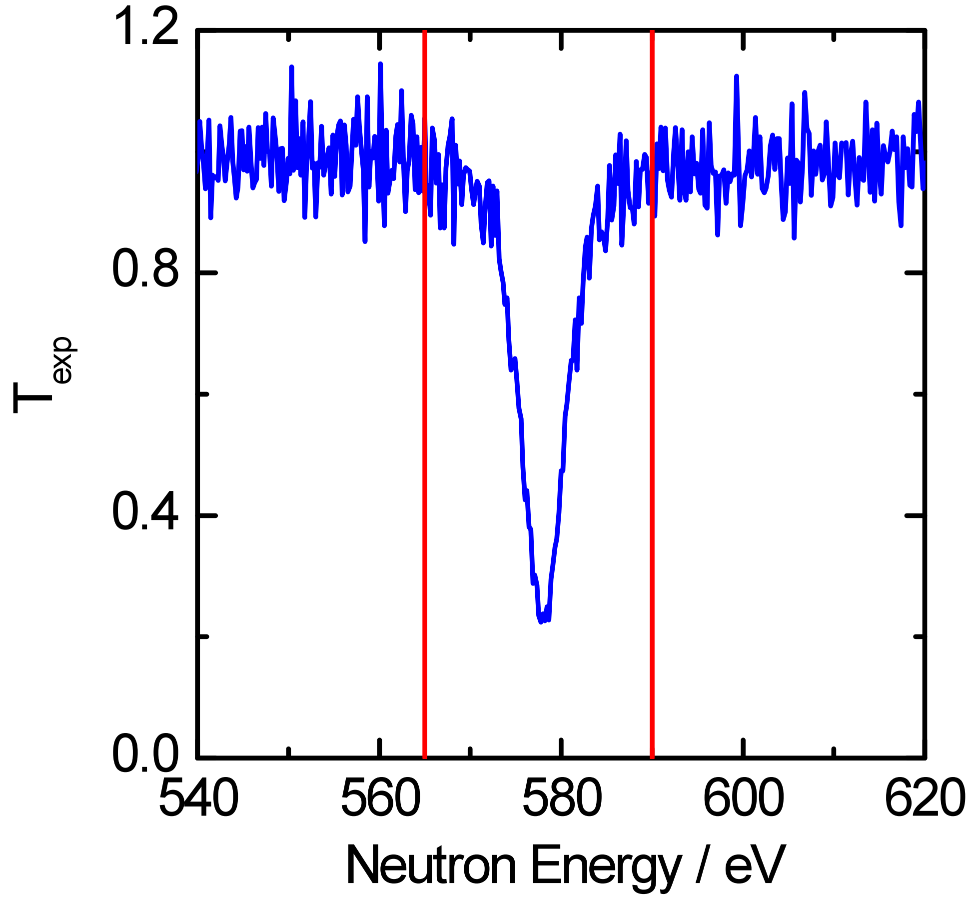
40 mm

NRTI with PSND at ISIS

Total counts in TOF spectrum



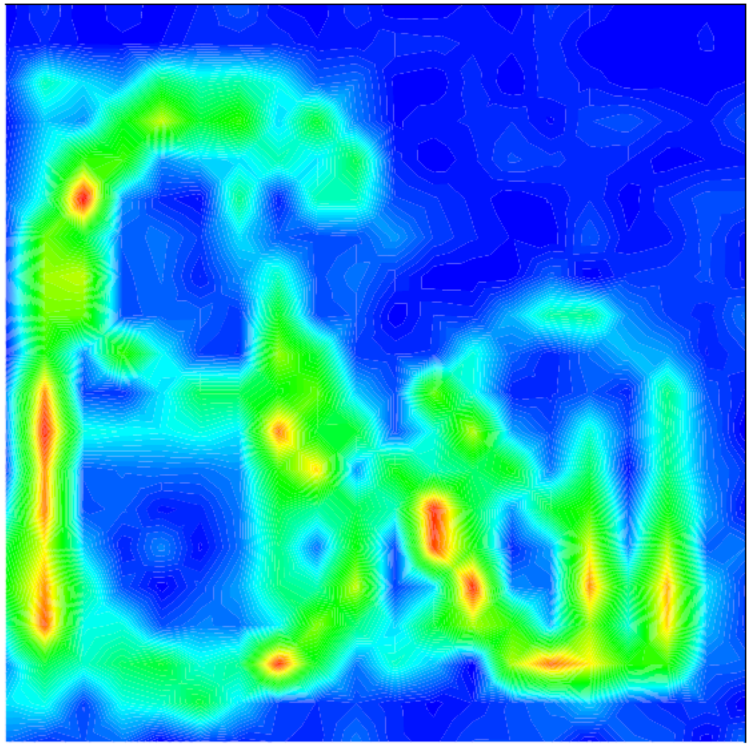
Select region : E_{μ} = 230 eV for ^{65}Cu + n



NRTI with PSND at ISIS

European Commission

Total counts in TOF spectrum



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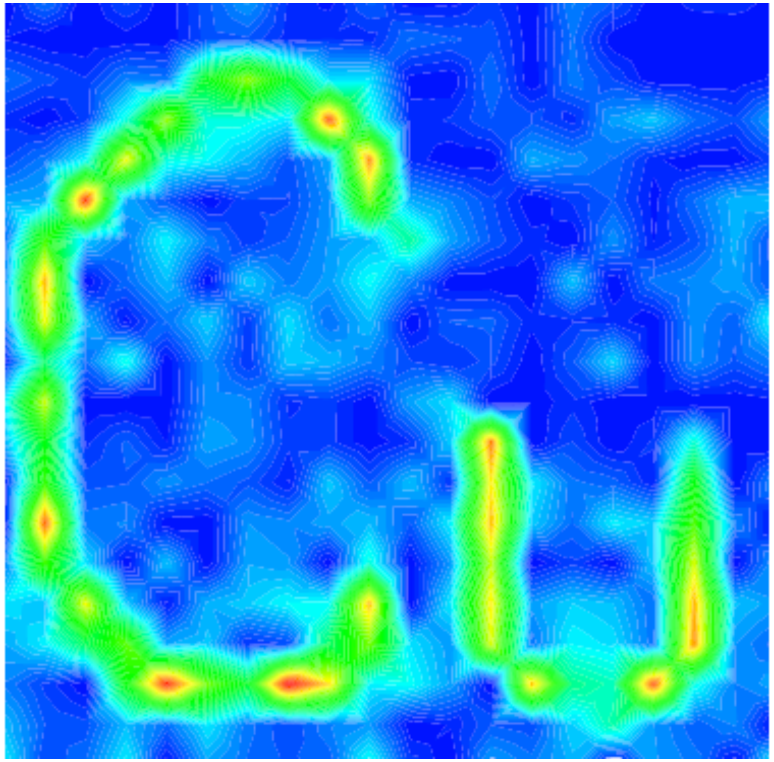
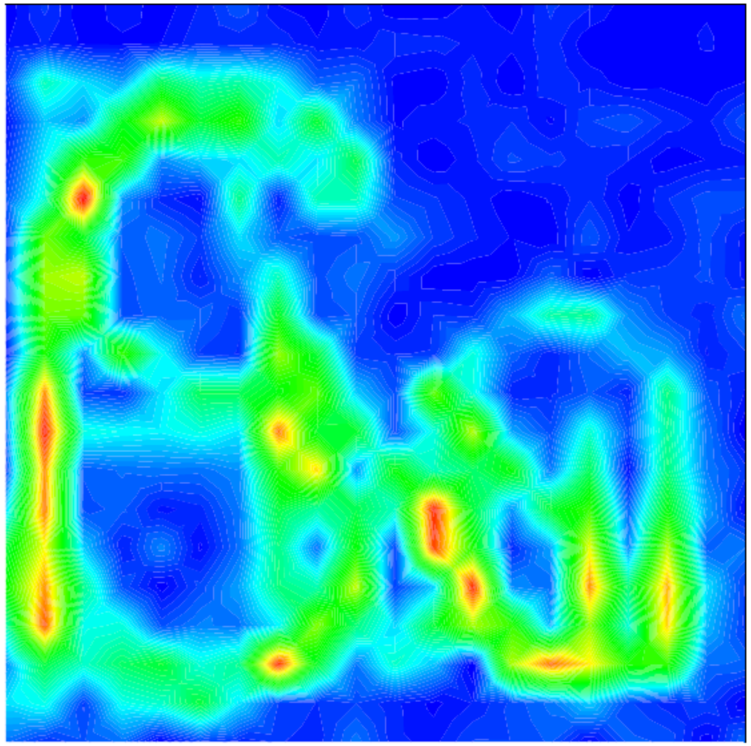


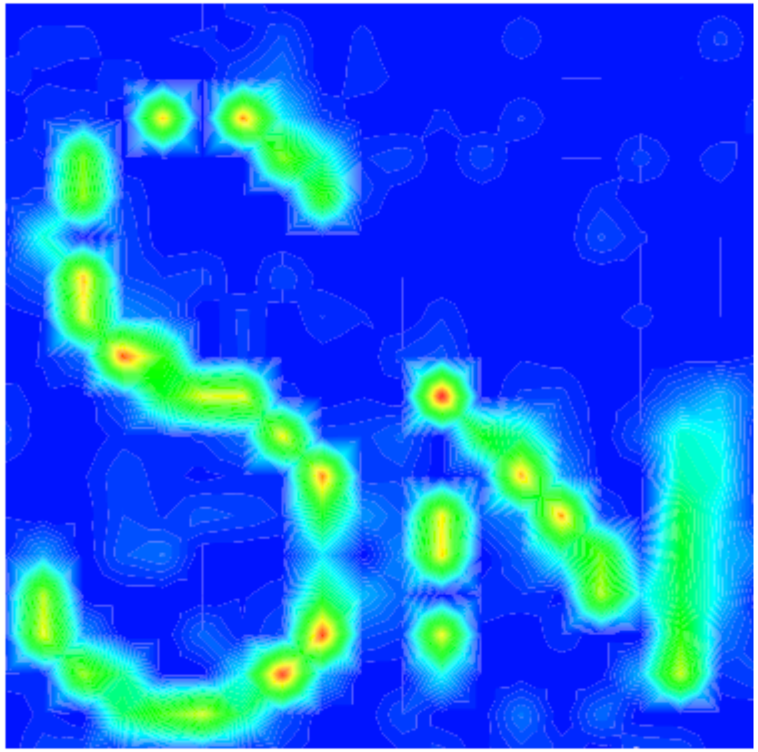
NRTI with PSND at ISIS

Total counts in TOF spectrum



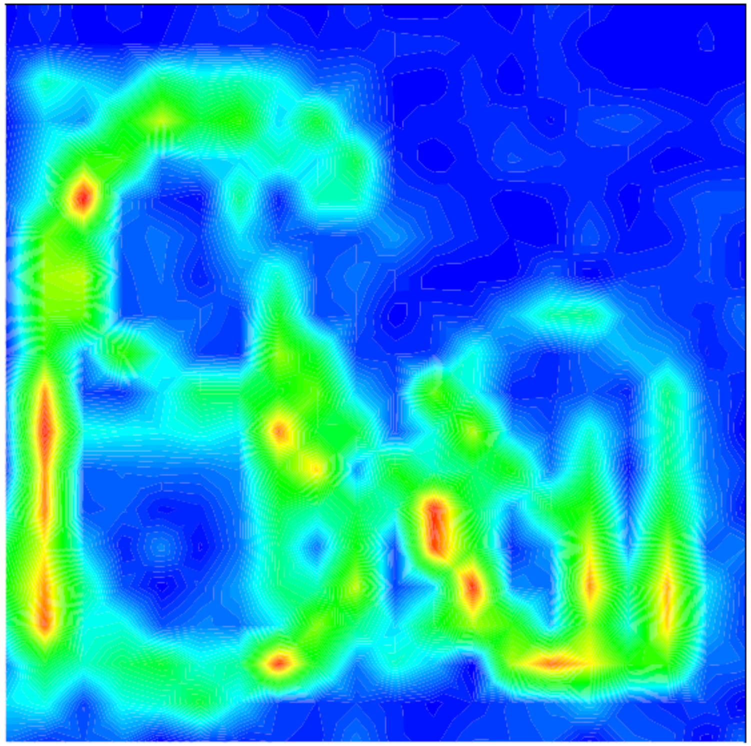
40 mm

Select region : E_μ = 111.2 eV for ^{116}Sn + n



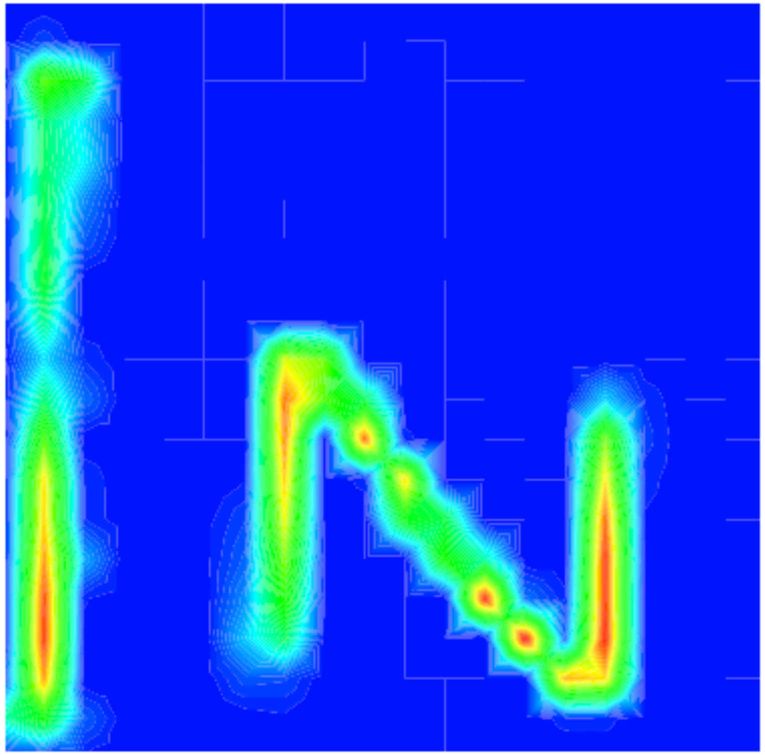
NRTI with PSND at ISIS

Total counts in TOF spectrum

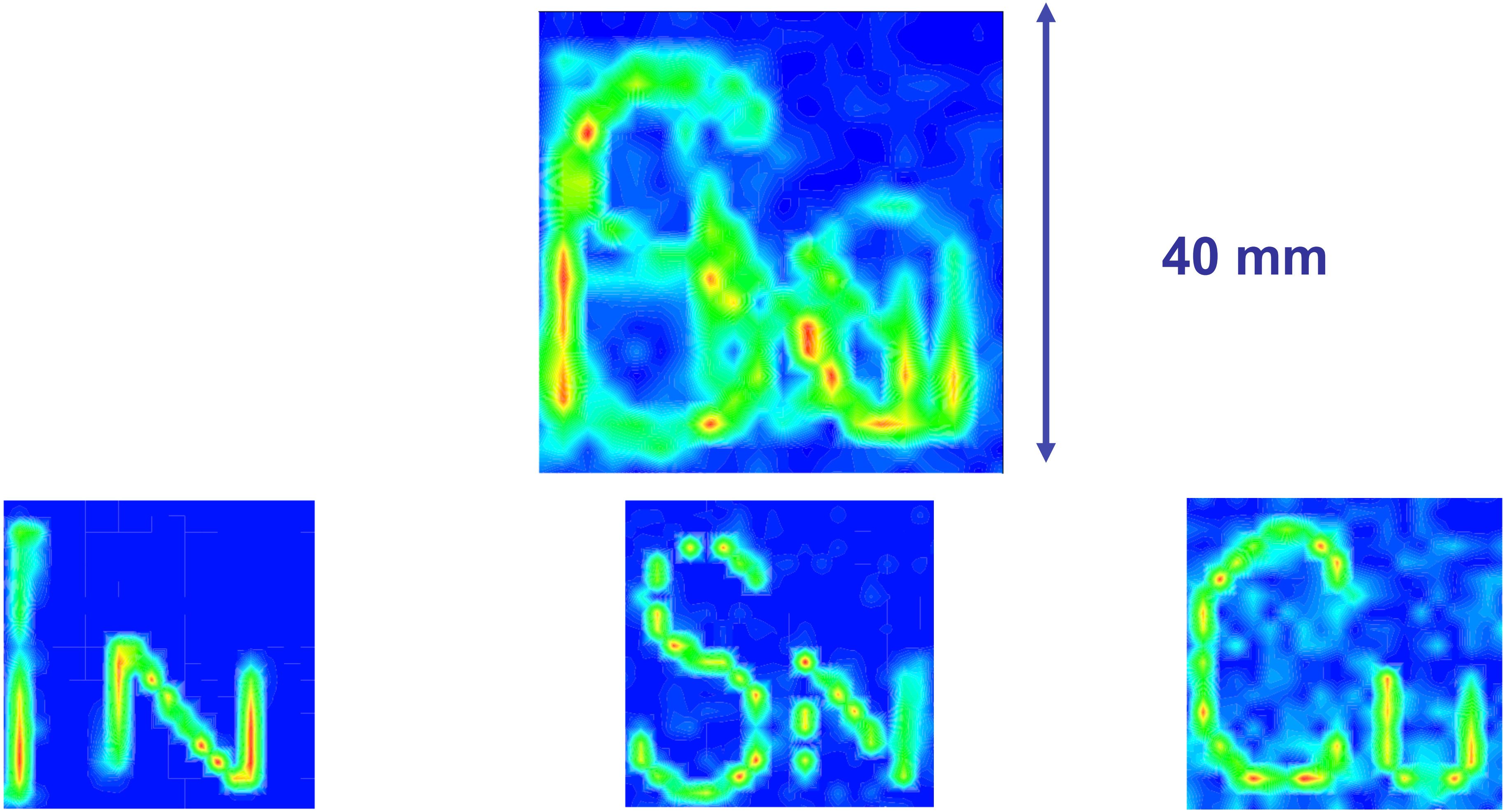


40 mm

Select region : E_{μ} = 1.46 eV for ^{115}In + n



NRTI with PSND at ISIS



E_n = 1.46 eV

E_n = 111.2 eV

E_n =230 eV

Schillebeeckx et al., JINST 7 (2012) C03009

NRTI with PSND at ISIS

10 x 10 pixelated neutron detector, 100 ^{6}Li-glass scintillators (2 x 2 x 9 mm^{3})

7 position sensitive 16 channel PMT

Perelli Cippo et al., J. Anal. At. Spectrom., 26 (2011) 992

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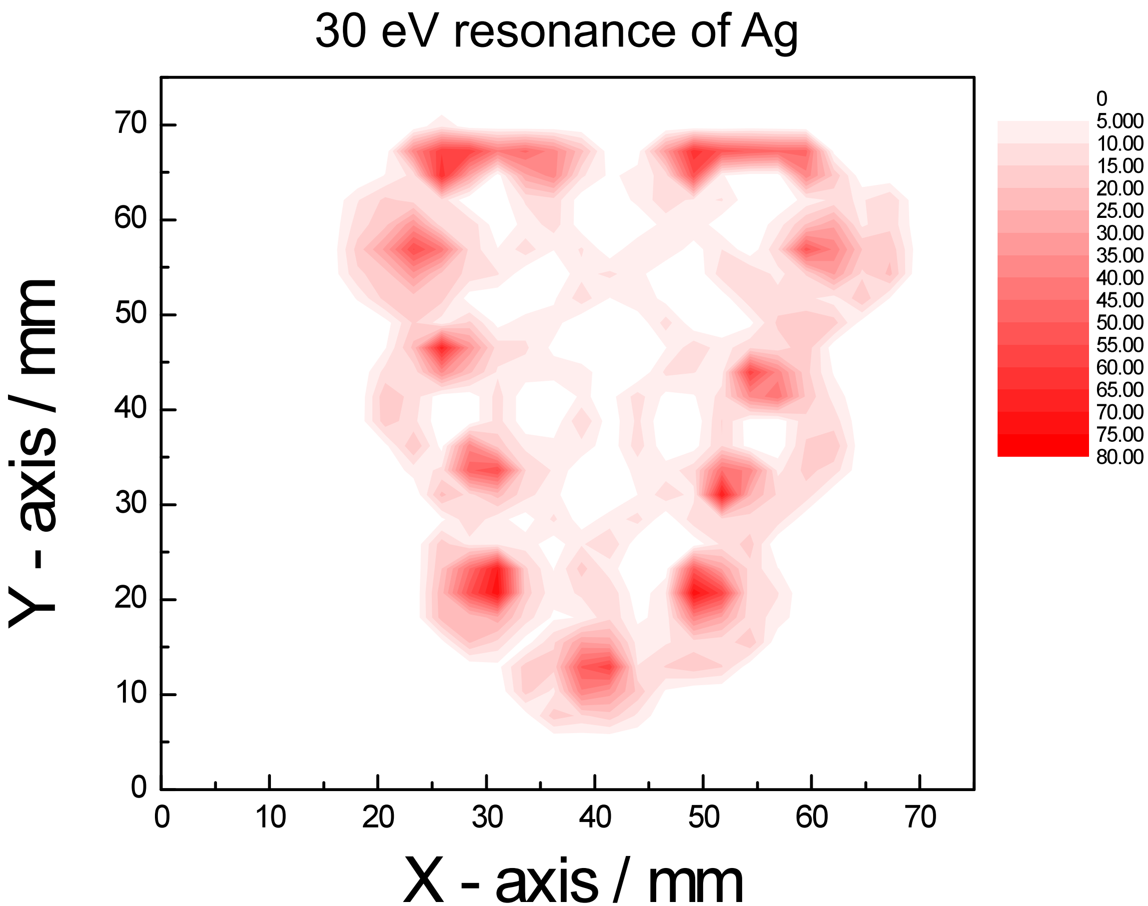
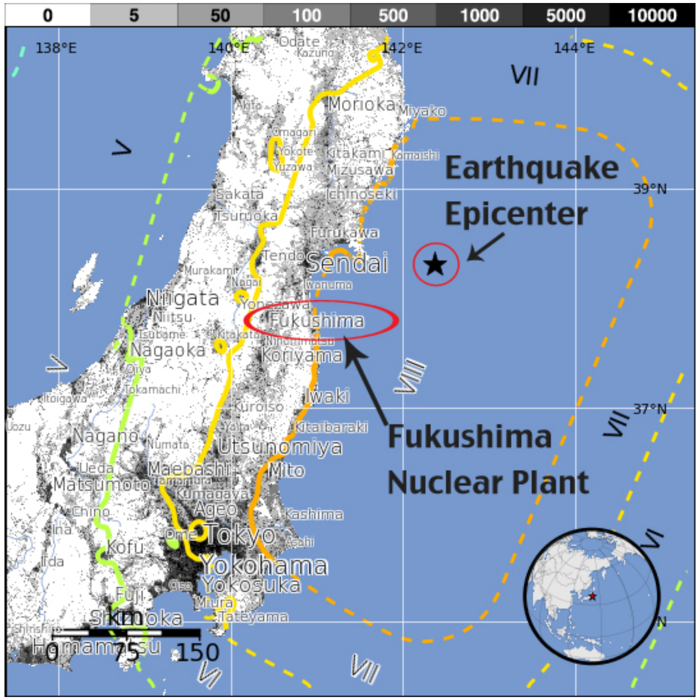


Perelli Cippo et al., J. Anal. At. Spectrom., 26 (2011) 992

Collaboration JAEA – JRC

Characterization of melted fuel formed in severe nuclear accidents, such as the one at the Fukushima Daiich nuclear power plants



Collaboration JAEA – JRC

Characterization of melted fuel formed in severe nuclear accidents, such as the one at the Fukushima Daiich nuclear power plants

Background

- **Accident at Fukushima following the earthquake on 11/03/2011**
- **Nuclear fuel (NF) will be removed after a cooling period of ~ 10 year**
- **Direct quantification of nuclear materials (NM) in melted fuel (MF) on the site**
- **Quantifying of NM in debris of MF is very complex due to the radioactivity, temperature and variety in size and shape**

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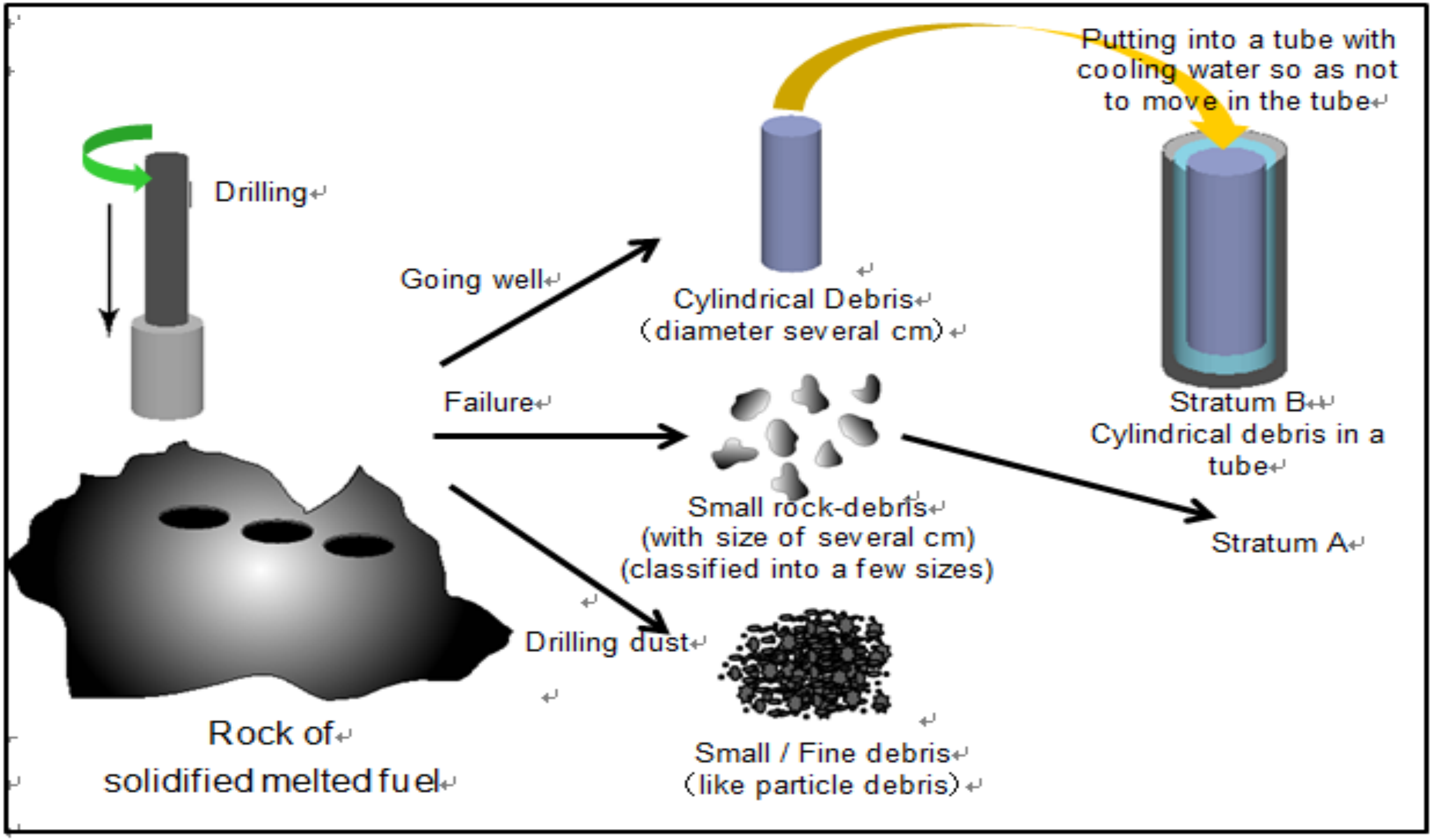
- **Quantifying of NM in debris of MF is very complex due to the radioactivity, temperature and variety in size and shape**

⇒ JAEA proposes to develop Neutron Resonance Densitometry (NRD)

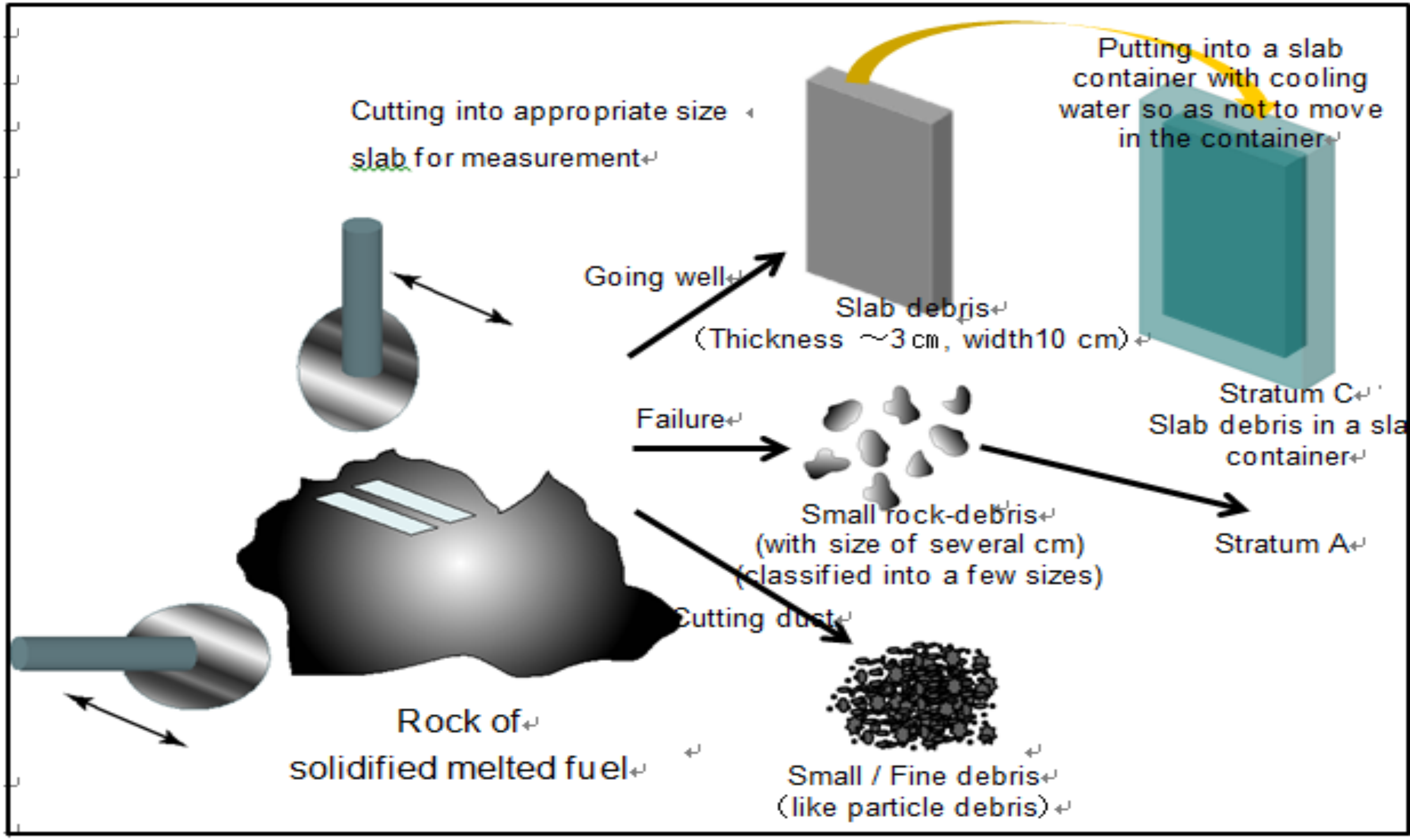
A method based on NRTA combined with NRCA

Drilling



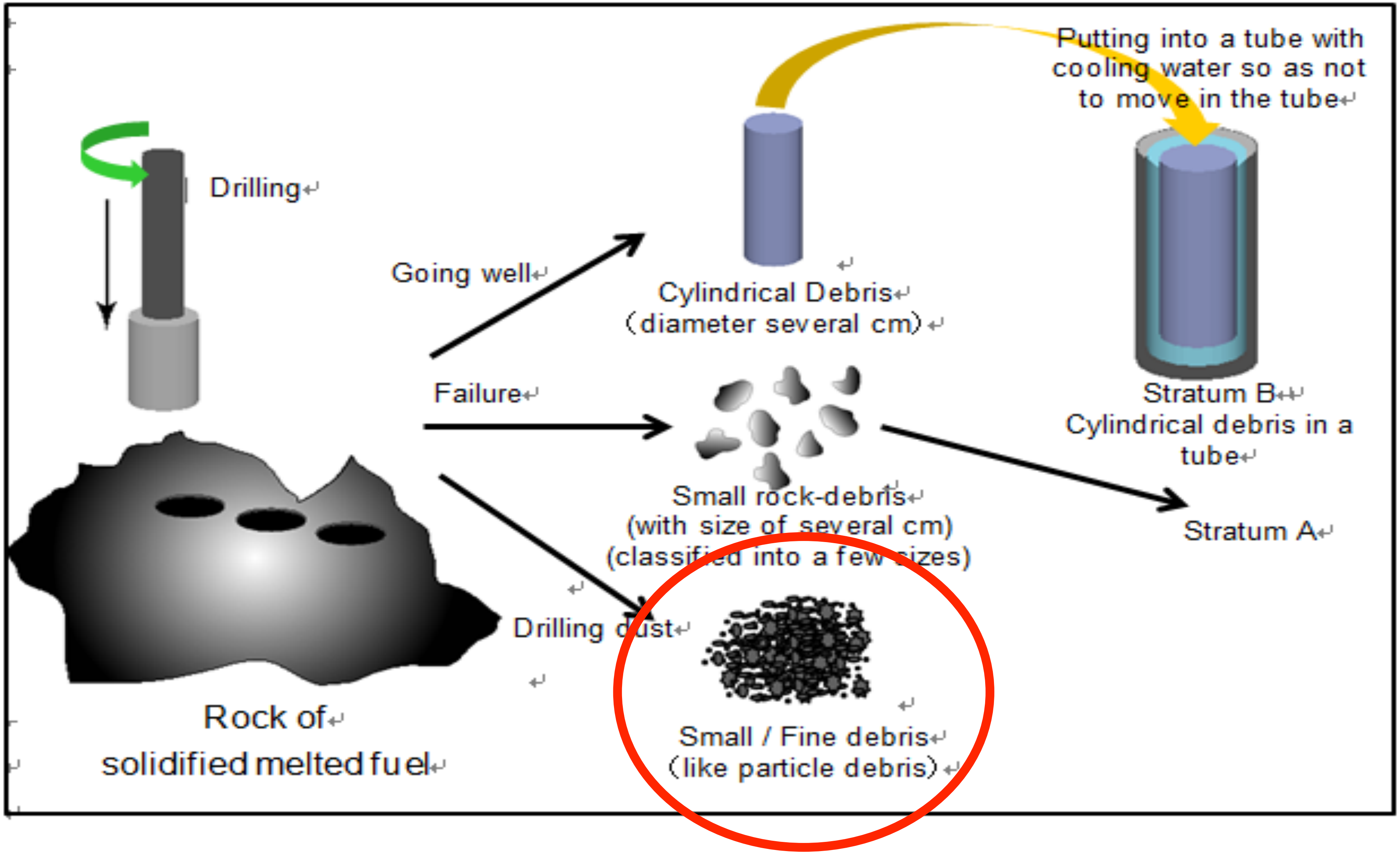
Putting into a tube with cooling water so as not to move in the tube
Drilling
Going well
Cylindrical Debris (diameter several cm)
Failure
Stratum B
Cylindrical debris in a tube
Small rock-debris (with size of several cm) (classified into a few sizes)
Stratum A
Drilling dust
Small / Fine debris (like particle debris)
Rock of solidified melted fuel

Cutting

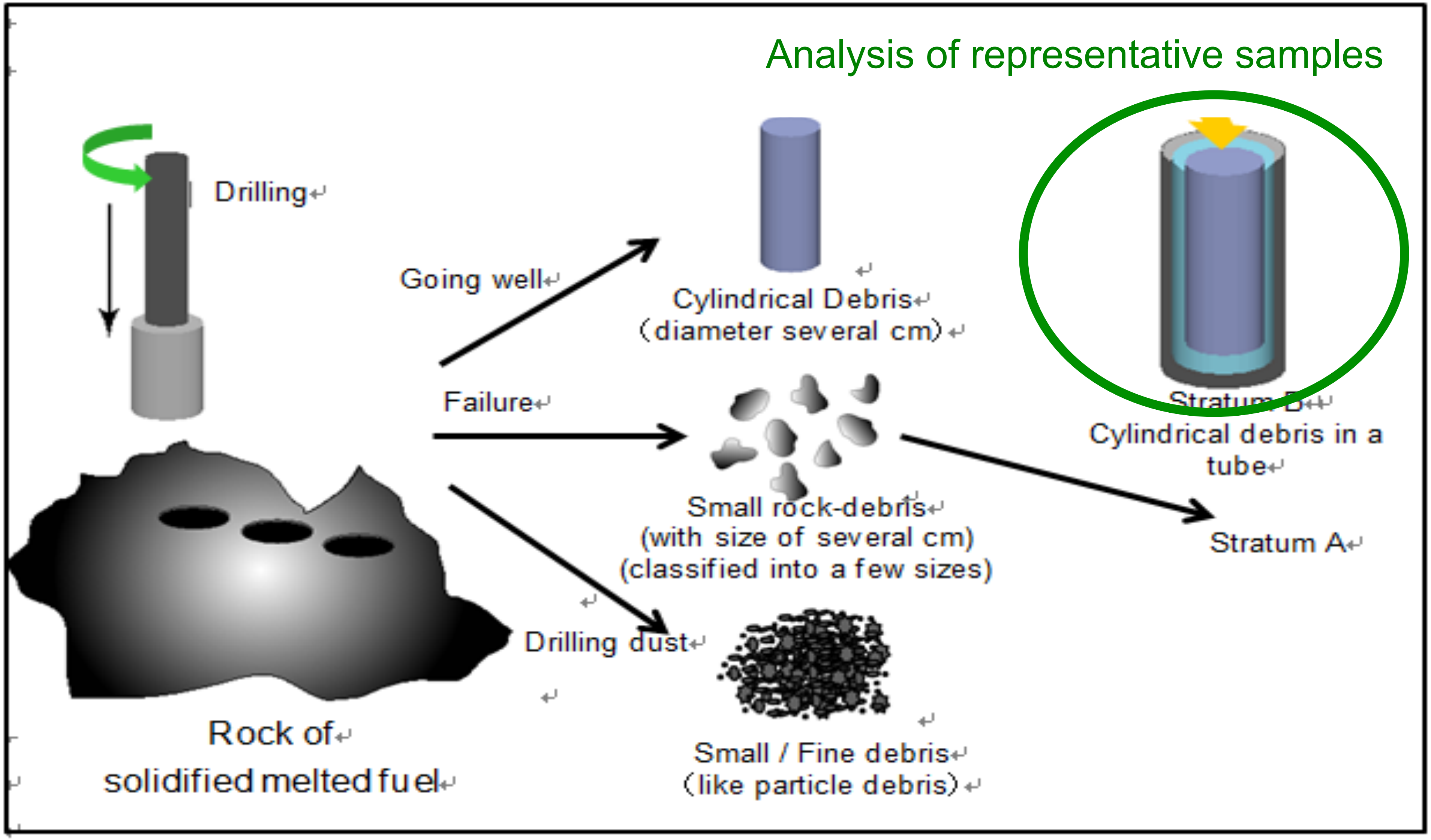


Putting into a slab container with cooling water so as not to move in the container
Cutting into appropriate size slab for measurement
Going well
Slab debris
(Thickness ~3 cm, width10 cm)
Stratum C
Slab debris in a slab container
Failure
Small rock-debris
(with size of several cm)
(classified into a few sizes)
Stratum A
Cutting dust
Rock of
solidified melted fuel
Small / Fine debris
(like particle debris)

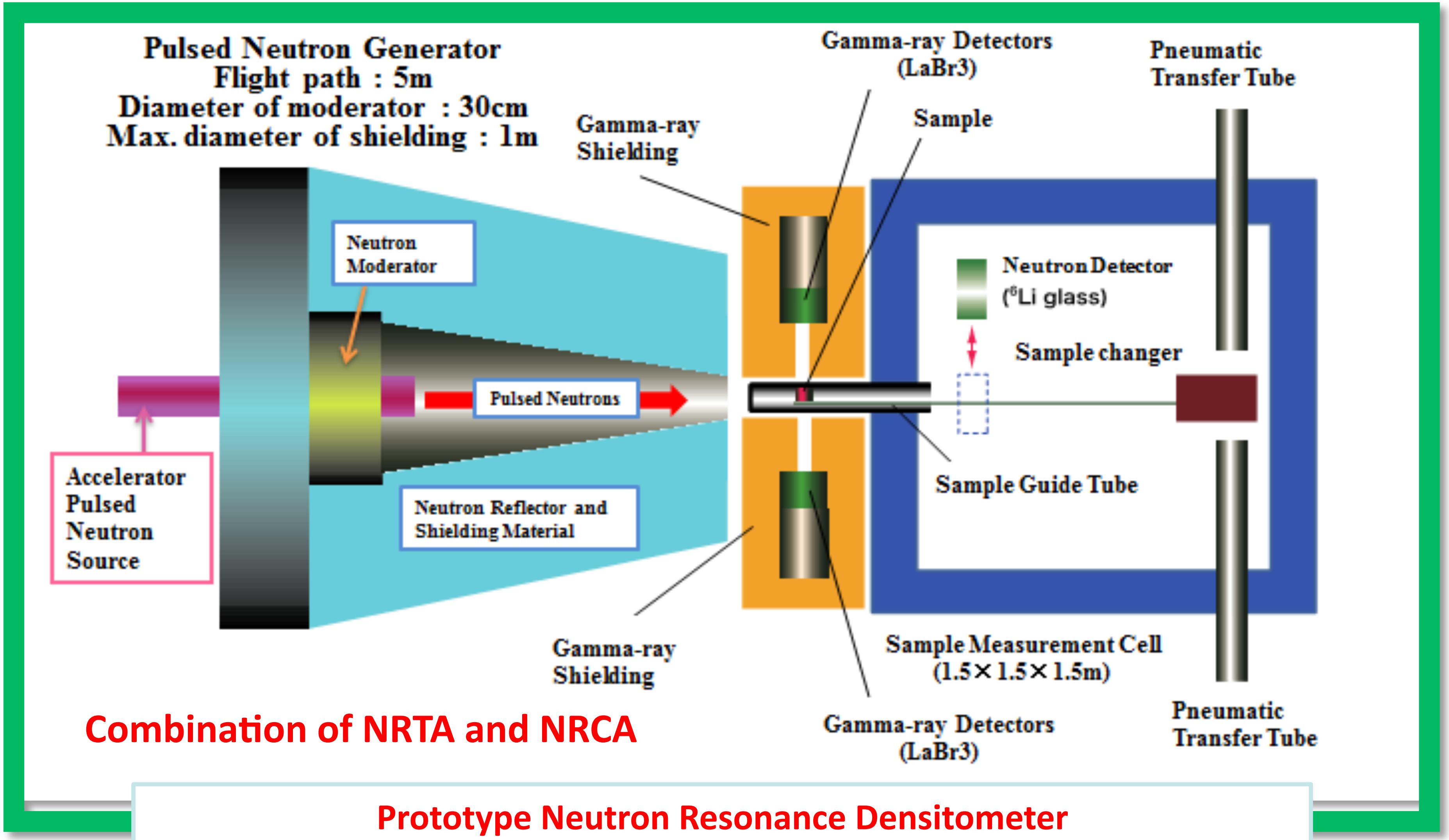
Characterization of debris by NRD



Characterization of debris by NRD



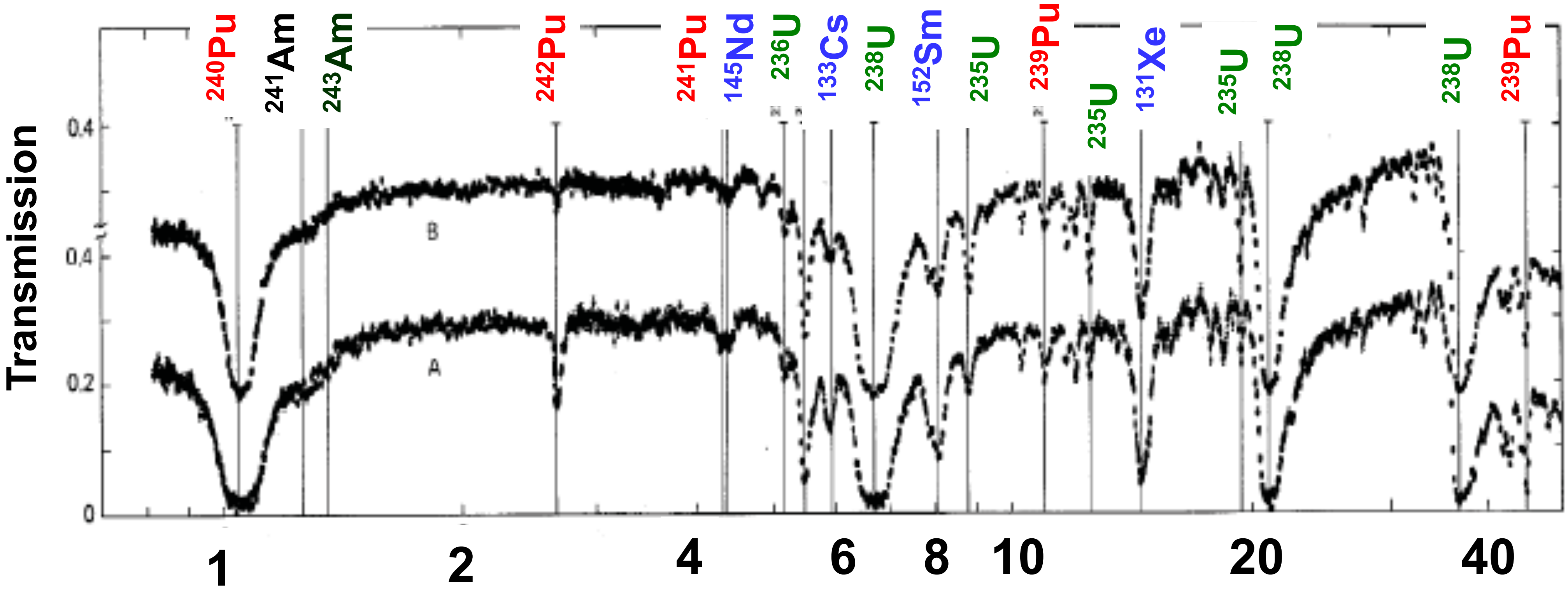
Neutron Resonance Densitometry (NRD)



Prototype Neutron Resonance Densitometer
Designed by JAEA/NSTD

NRTA of nuclear fuel

Use of NRTA to characterize nuclear fuel



A : centre of fuel pin
B : end of fuel pin

Behrens et al., Nucl. Techn. 67 (1984) 162

Work programme

- **Study of methodology**
  - Effect of particle size (• JRC , o JAEA)
  - Effect of sample temperature (• JRC , o JAEA)
  - Effect of sample thickness (• JAEA , o JRC)
  - Effect of contaminated materials (• JAEA , o JRC)
  - Study of detection systems (• JAEA , o JRC)
  - Generalization of resonance analysis code (REFIT) (• JRC , o JAEA)

- **Study of relevant nuclear data**
  - Survey of current nuclear data (• JAEA , o JRC)
  - Measurement of nuclear data and reference TOF-spectra (• JRC , o JAEA)

- **Study of neutron source**
  - Electron linear accelerator design (• JAEA , o JRC)
  - Neutron source study (• JAEA , o JRC)
  - Study of TOF- response function (• JRC , o JAEA)

A. Brusegan[†], F. Corvi, J.C. Drohe, J. Heyse, S. Kopecky, A. Moens, W. Mondelaers, A. Plompen, P. Siegler, D. Vendelbo, R. Wynants and the operators of GELINA

EC - JRC - IRMM (B)

B. Becker, A. Borella, F. Emiliani, K. Kauwenberghs, C. Lampoudis, C. Mihailescu and K. Volev

Current and ex-grantholders, EC - JRC - IRMM (B)

C. Massimi (INFN), M. Moxon, H. Postma and I. Sirakov

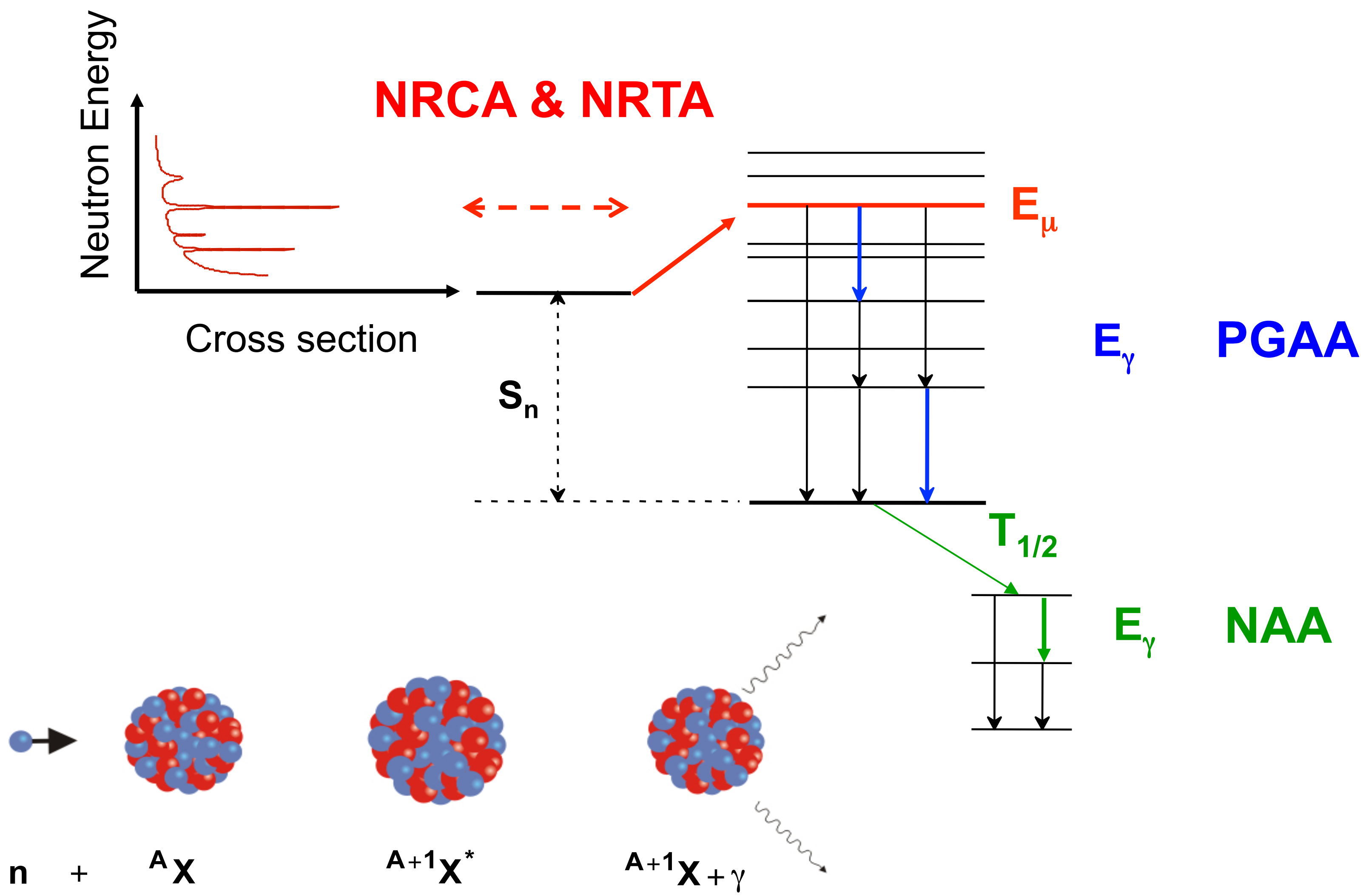
Scientific visitors, EC - JRC - IRMM (B)

H. Harada and M. Seya

JAEA (Japan)

Thank you for your attention

Use of resonances as fingerprints



Use of resonances as fingerprints

- **NAA**
  - Intense thermal neutron flux (irradiation in core, Mol, Delft, NIST, Budapest,..)
  - Gamma detector: gamma - ray energy resolution ⇒ Ge-detectors
- **PGNAA**
  - Intense neutron beam, (guided cold neutron beam Budapest, NIST, FRM-II)
  - Gamma detector: gamma - ray energy resolution ⇒ Ge-detectors
- **NRCA & NRTA**
  - Pulsed white neutron beam (GELINA, ISIS)
  - Gamma/Neutron detector: good time resolution ⇒ scintillators

Comparison: NRCA vs. PGAA

- **PGAA**

$$k_o = a\ \beta_\gamma\ \sigma_\gamma$$

σ_γ **thermal capture cross section**

β_γ **gamma-ray emission probability**

a **isotopic abundance**

$$S_\mu = a\, A_{\gamma,\mu}\, \frac{1}{E_\mu}$$

- **NRCA**

$$A_{\gamma,\mu} = 4.097\,10^6\, \frac{g\Gamma_n\Gamma_\gamma}{E_\mu \Gamma} (b\ eV)$$

$A_{\gamma,\mu}$ **capture area**

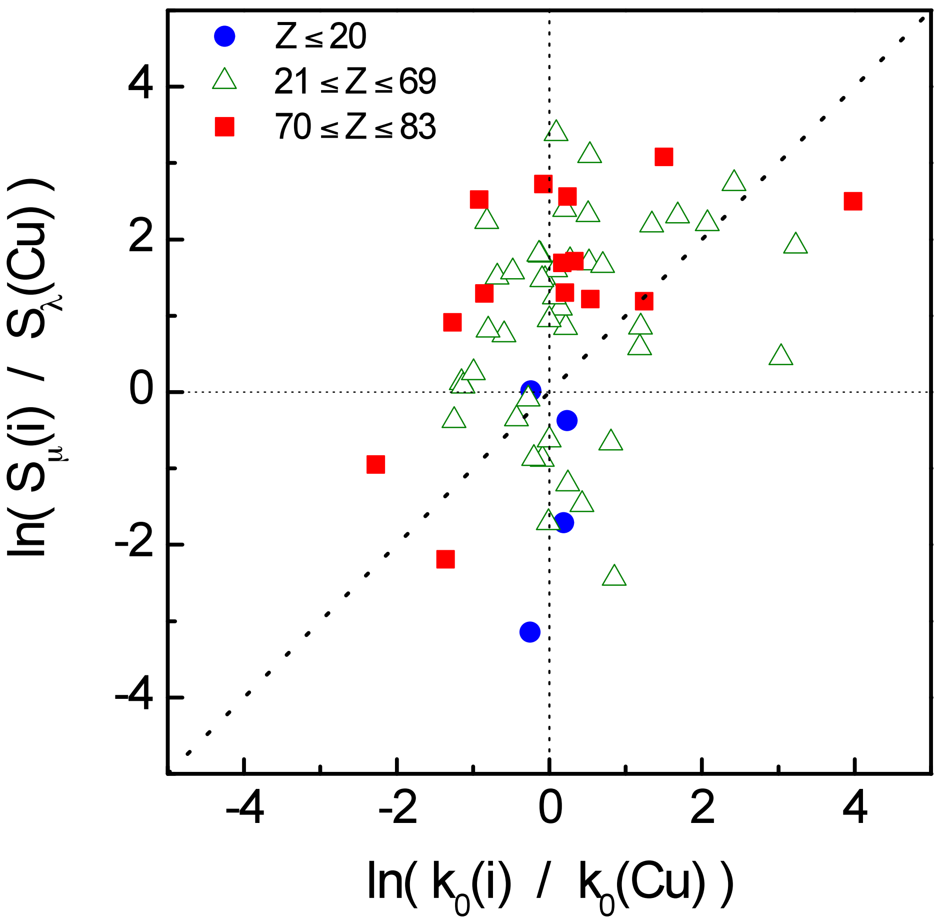
$1/E_\mu$ **flux shape**

H. Postma and P. Schillebeeckx, Journal of Radioanalytical and Nuclear Chemistry 265 (2005) 297 – 302

Comparison: NRCA vs. PGAA

PGAA (at Budapest) and NRCA (GELINA)
Comparable performance for Cu (uncertainty about 1%)

⇒ k_o and S_μ relative to Cu



PGAA best for light elements

- H, S, P, and K

NRCA best for heavy elements

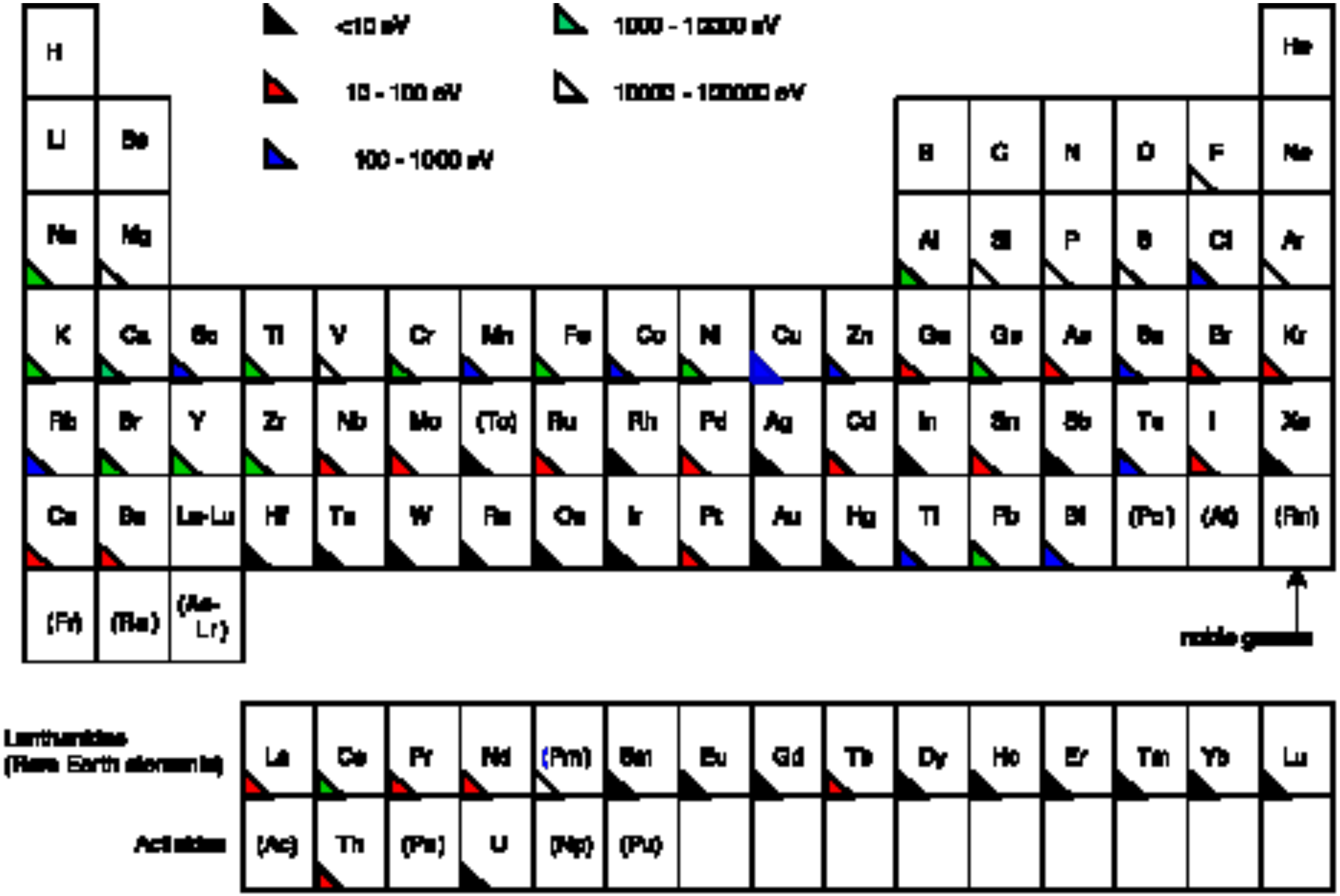
- As, Ag, Sb, Au and (Pb)

NRTA for light elements + magic

- C, N, O, Na, S and Pb

Postma et al., Journal of Radioanalytical and Nuclear Chemistry 271 (2007) 95 – 99

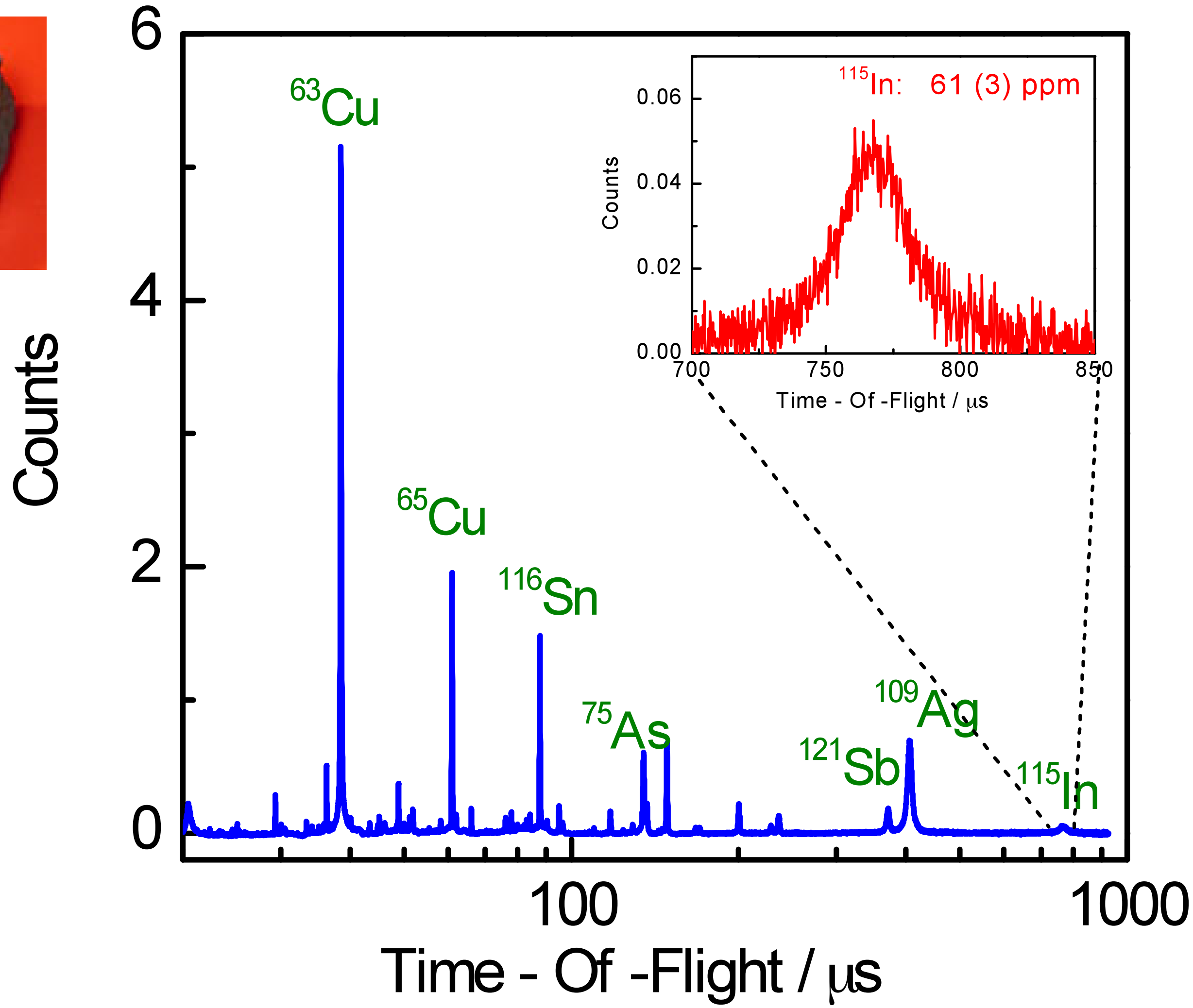
NRCA & NRTA : applicability



NRCA : example of TOF-spectrum

Typical dead time : 2.5 μs

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



Neutron Production

SHIELDING for MODERATED SPECTRUM

SHIELDING for FAST SPECTRUM