European
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Cross Section Measurements and Uncertainties of Cross Section Data

Arjan Plompen

European Commission, Joint Research Centre,
Institute for Reference Materials and Measurements - SN3S unit
ec.europa.eu/jrc/en/institutes/irmm

Joint
Research
Centre

Measurement design

Quantity to measure (measurand)

cross section(s)
reaction parameter(s)

Measurement principle

activation, emitted particle detection, …

Expression of the quantity in terms of control and influence quantities

Identification of possible influence quantities (sources of error)

Method of measurement

Sequence of logical steps

how to fix control quantities
how to correct for other influence quantities

Measurement procedure

Detailed prescription

Physical operations
Data manipulations

Arriving at *Measurement value, corrected for all important effects, with complete standard uncertainties, and correlations*

Evaluation of measurement uncertainty – Guide to the expression of uncertainty in measurement, JCGM 100:2008, www.bipm.org (2008)

Method of measurement

'Hardware'

Neutron source/collimation

Sample

Detection equipment fluence or normalization

Detection equipment process rate

Data acquisition

Peripheral control

Ancillary measurements

'Software'

Measurement sequence

Foreground, background, iterate over samples, other experimental conditions, sample characterization, calibration

Evaluation of data

Selection criteria

Data reduction

Determination of values, uncertainties and correlations

Measurements

There is a large variety even for one particular quantity

Specific examples will be used to illustrate these points

Highlights to show the range of possibilities

Specific examples

Transmission in the resonance range

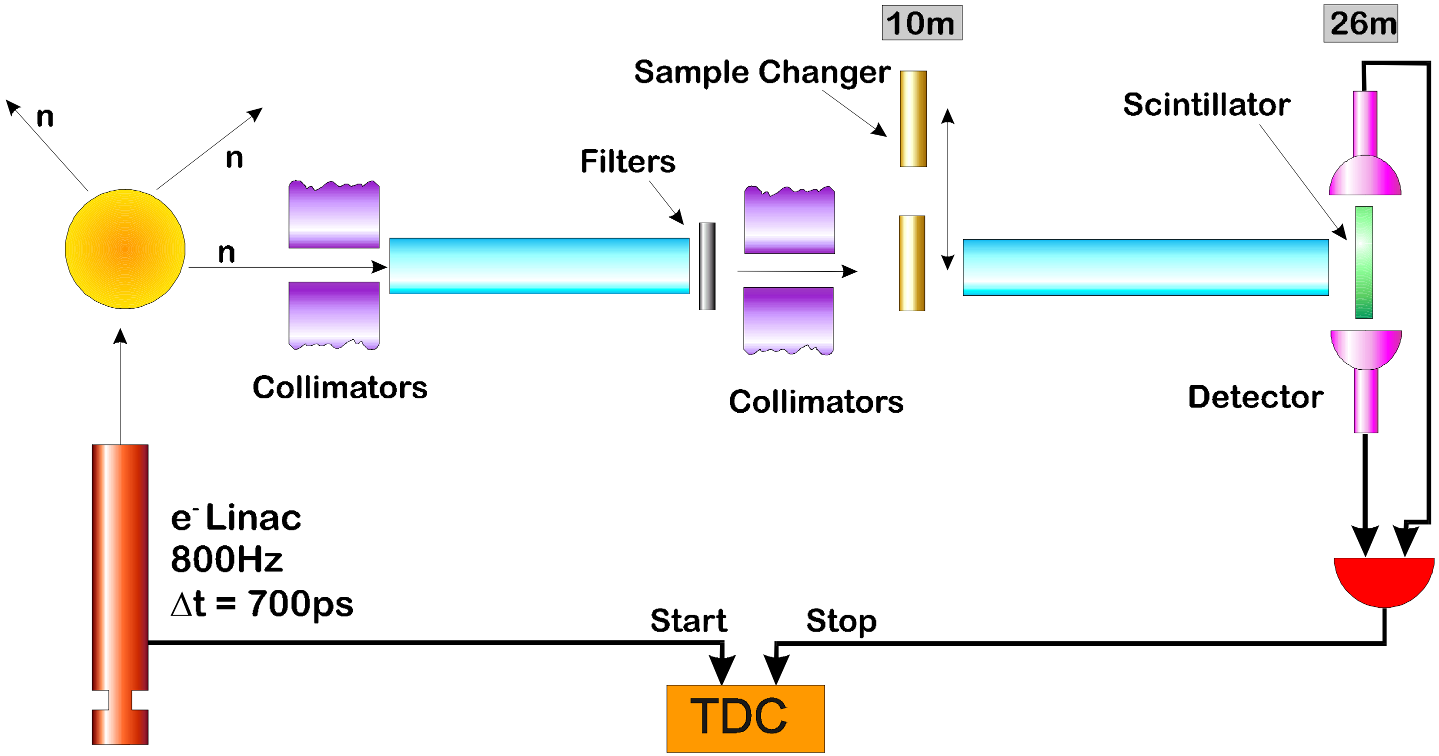
Capture

Inelastic scattering by the (n,n′γ)-technique

Activation
Uncertainties for activation

Drawn from experience at the IRMM neutron sources GELINA and the 7 MV VdG accelerator

Transmission for total cross section



Attenuation measurement

$$T \equiv \frac{C_{\text{sample in}}}{C_{\text{sample out}}} = e^{-Nd\sigma_T}$$

Mono-energetic neutron source

White neutron source with time-of-flight

$K_n = E_n - m_n c^2 = m_n c^2(\gamma-1) = m_n v^2\gamma^2/(1+\gamma)$

$v = L/T$ (L from flight path T from start-stop signal)

$\gamma = 1/\text{sqrt}(1-v^2/c^2)$, Lorentz factor

Total cross section: transmission

$$T \equiv \frac{C_{\text{sample in}}}{C_{\text{sample out}}} = e^{-Nd\sigma_T} = \frac{Y^c_{\text{in}} - B^c_{\text{in}}}{Y^c_{\text{out}} - B^c_{\text{out}}}$$

Attenuation measurement

σ_T = the total cross section

T = the transmission factor

C = Corrected counts in the detector

N = the nuclide concentration

d = the sample thickness

Y^c = Total counts

B^c = Background counts

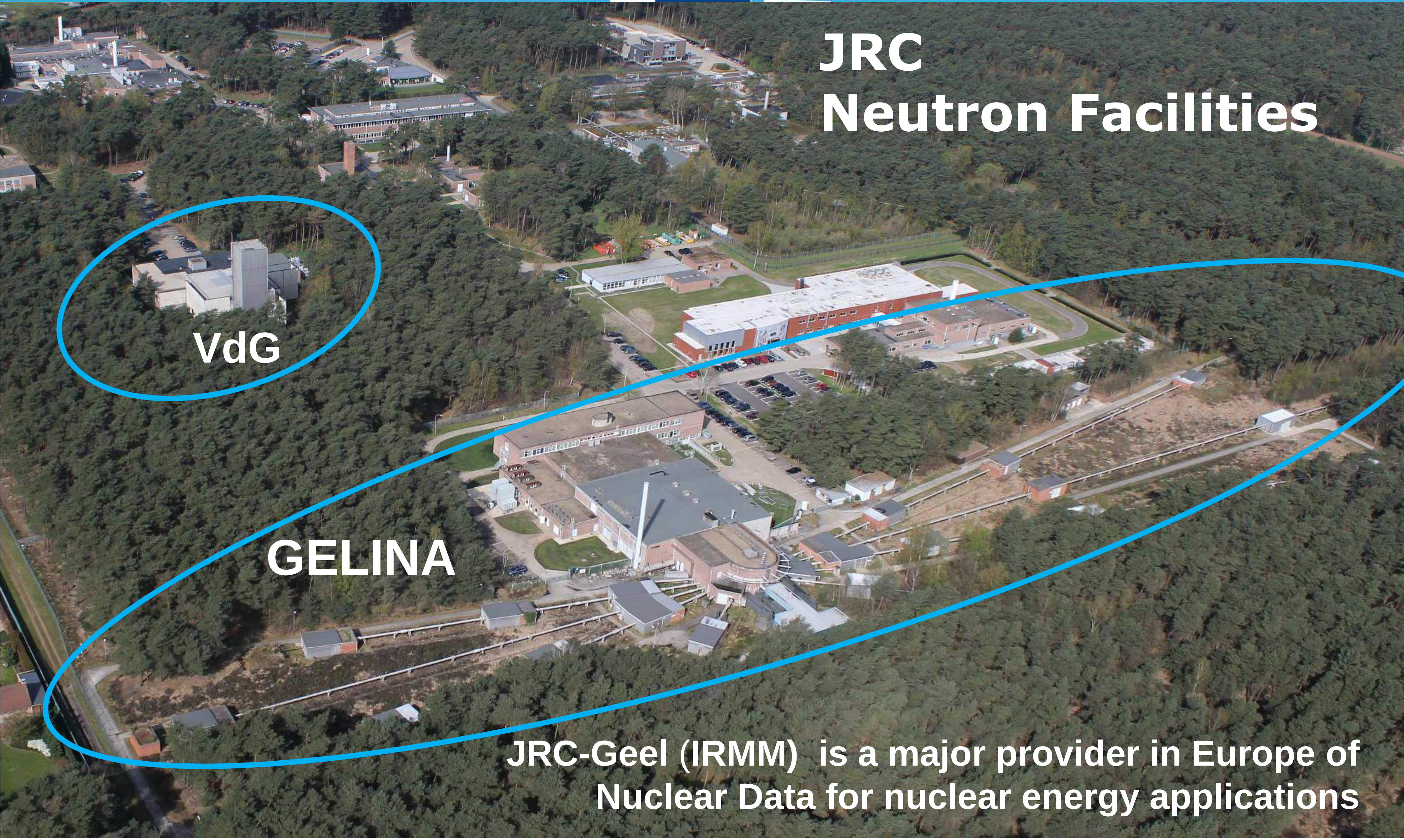
$\circ^c$ = deadtime corrected&normalized

Influence quantities

N d: nuclides per unit area
other nuclides in sample
sample container, homogeneity
collimation, background
temperature, stability equipment
flight path length
resolution (functions for time-of-flight)
- neutron source
- detector

deadtime

JRC Neutron Facilities



JRC-Geel (IRMM) is a major provider in Europe of Nuclear Data for nuclear energy applications

European Commission

GELINA, a multi-user facility

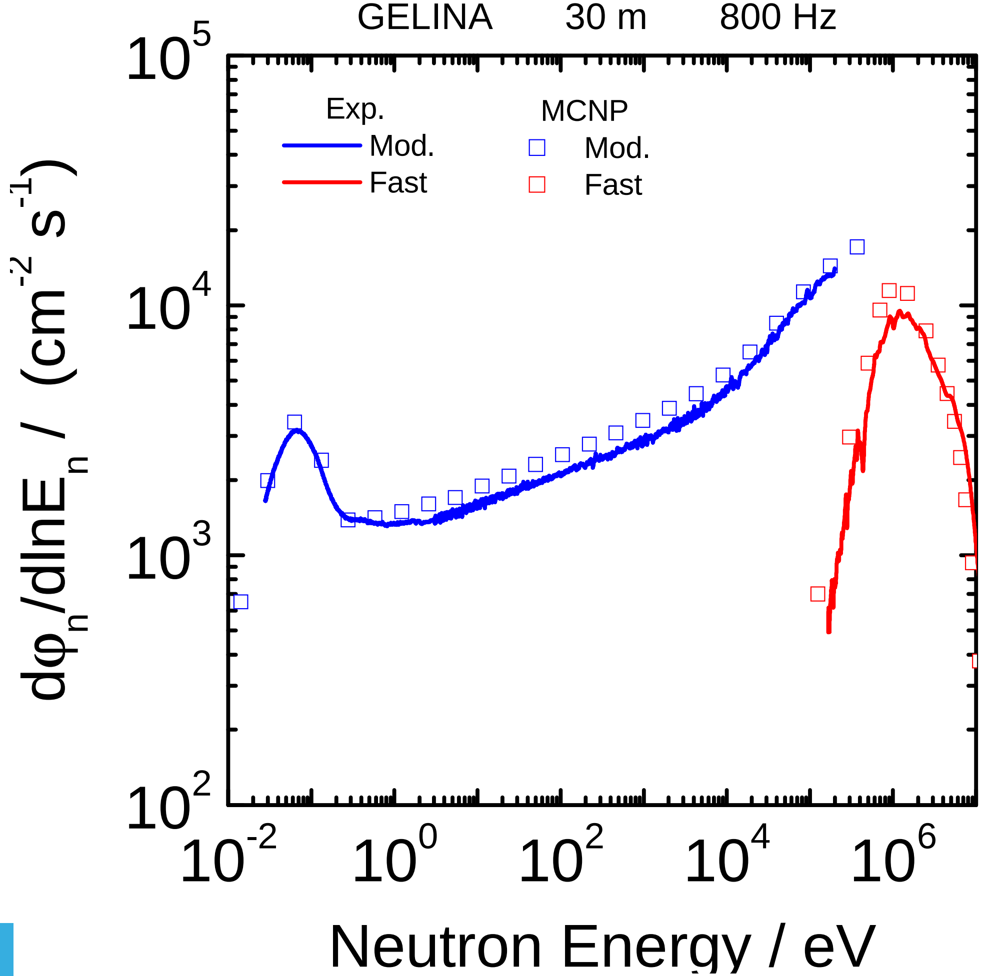
Uranium target $(e^- \Rightarrow \gamma \Rightarrow n)$
rotating, mercury cooled
$4\ 10^{10}$ neutrons / burst
Moderated or fast neutron spectrum
24 h/d, 100h/w, 12 parallel FPs

Joint Research Centre

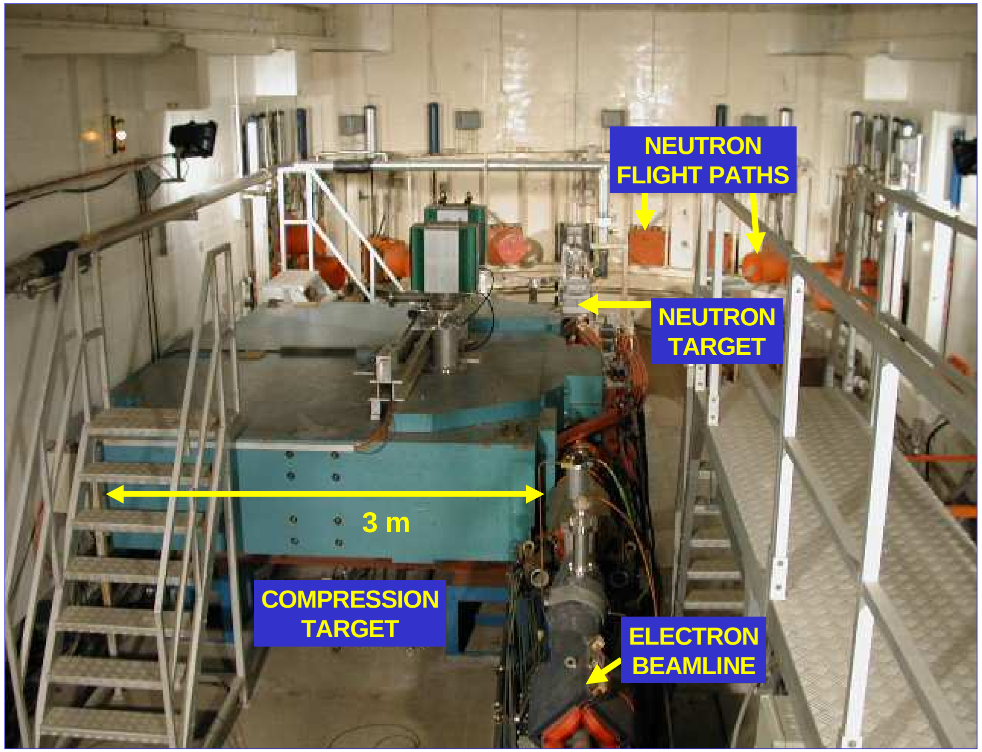
Neutron Production

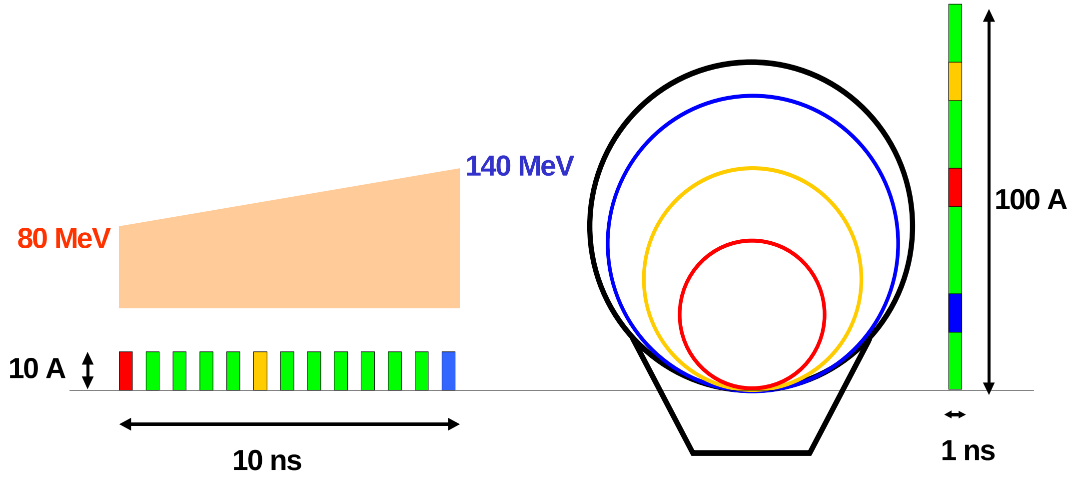
SHIELDING for
MODERATED
SPECTRUM

SHIELDING for
FAST
SPECTRUM



Compression Magnet





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

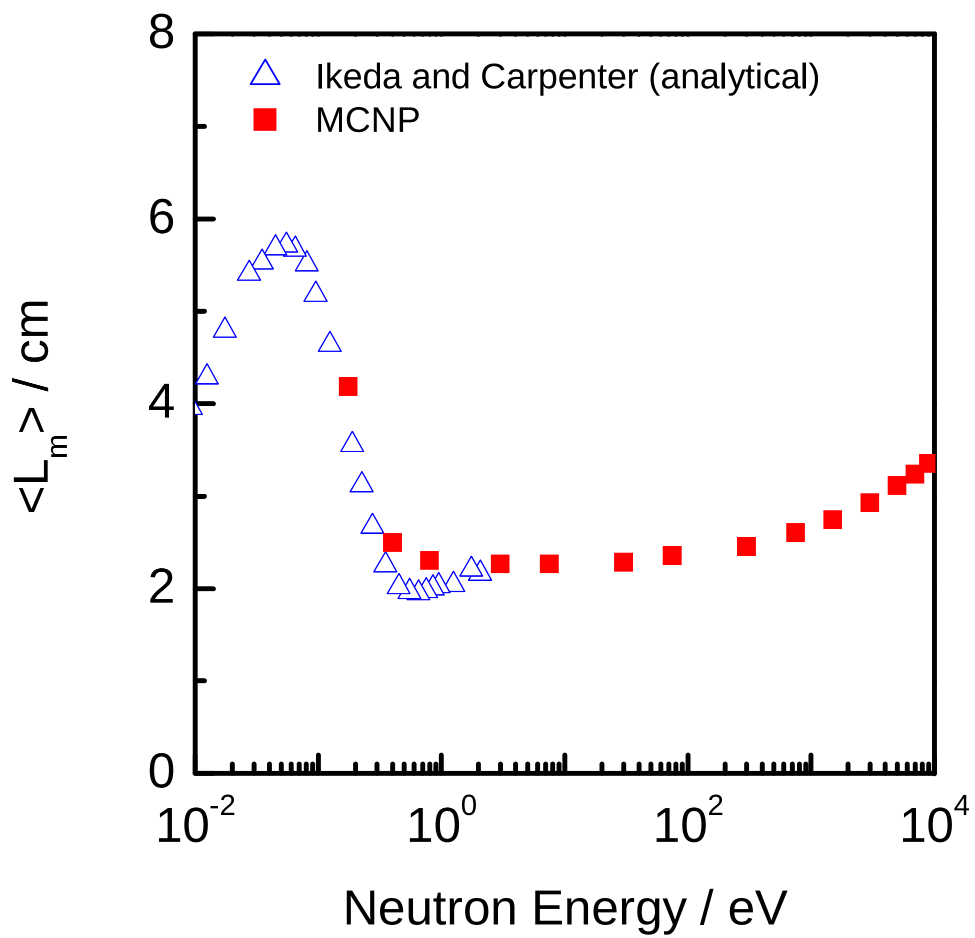
$$\Rightarrow \quad \rho = \frac{1}{B}\frac{E}{qc}$$

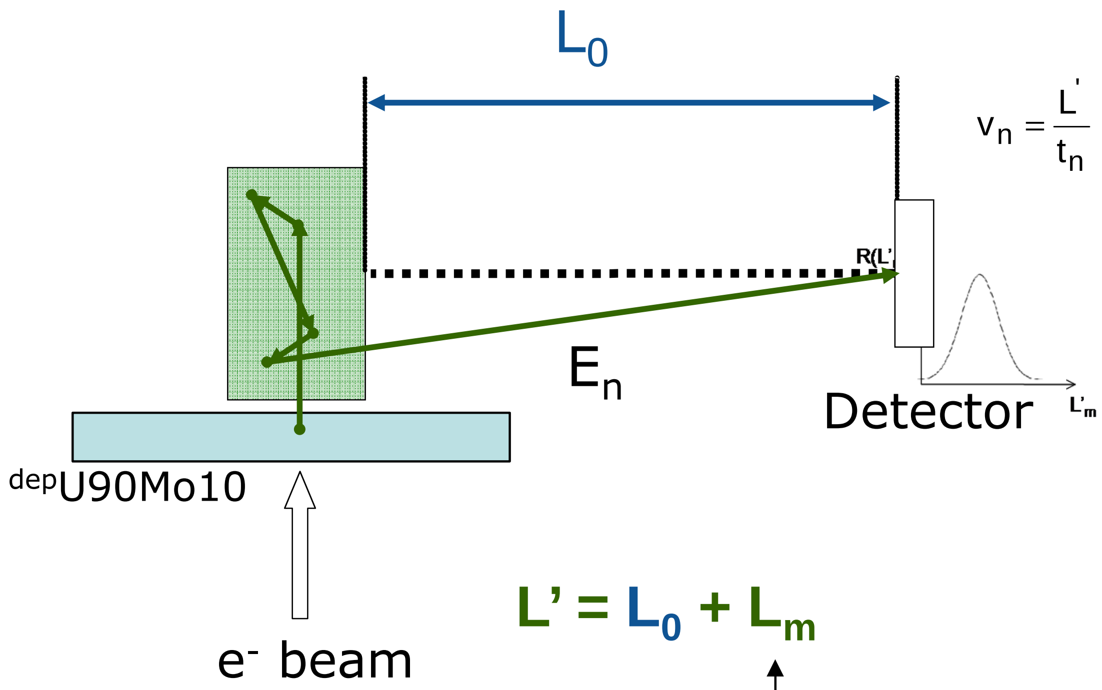
$$\Rightarrow \quad B = \frac{2\pi}{qc^2}\frac{\Delta E}{\Delta\tau}$$

ΔE = 60 MeV
$\Delta\tau$ = 10 ns

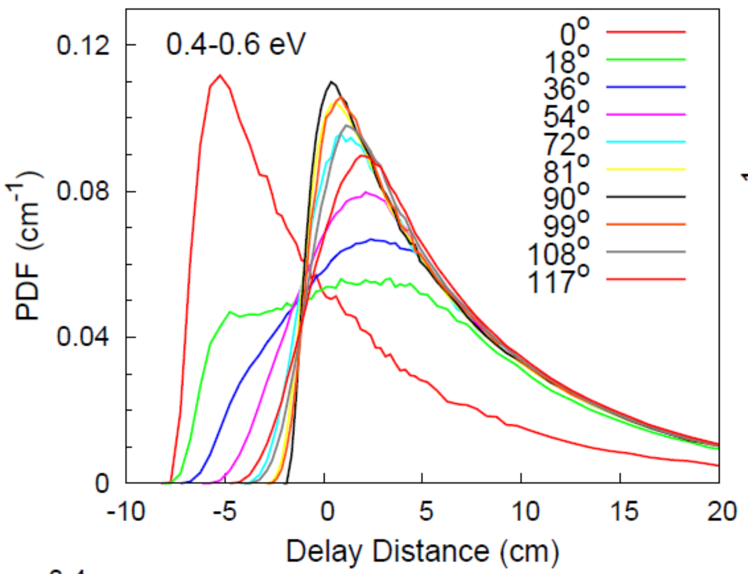
➔ compressed pulse length ~ 1 ns

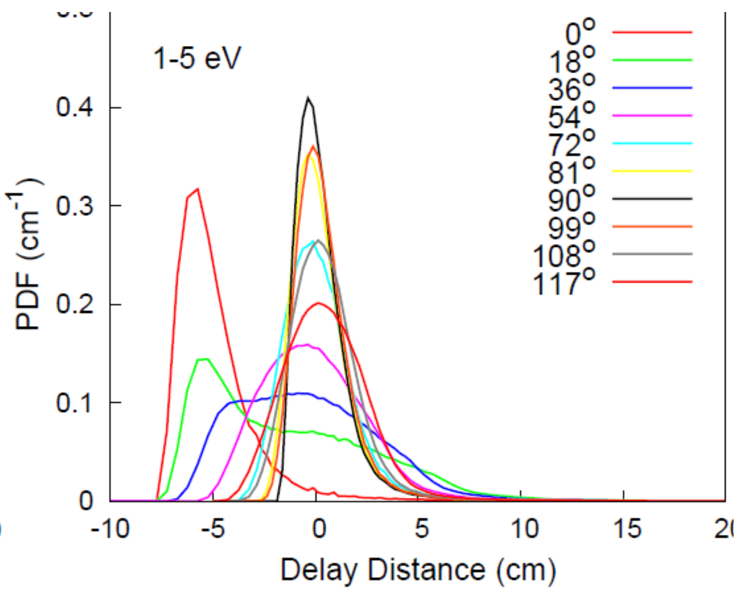
From time-of-flight to energy
The effective flight path

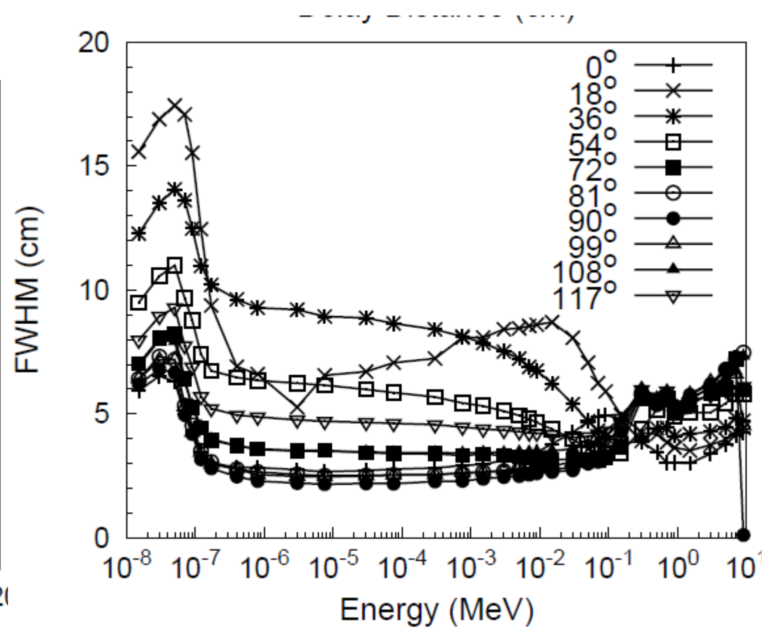


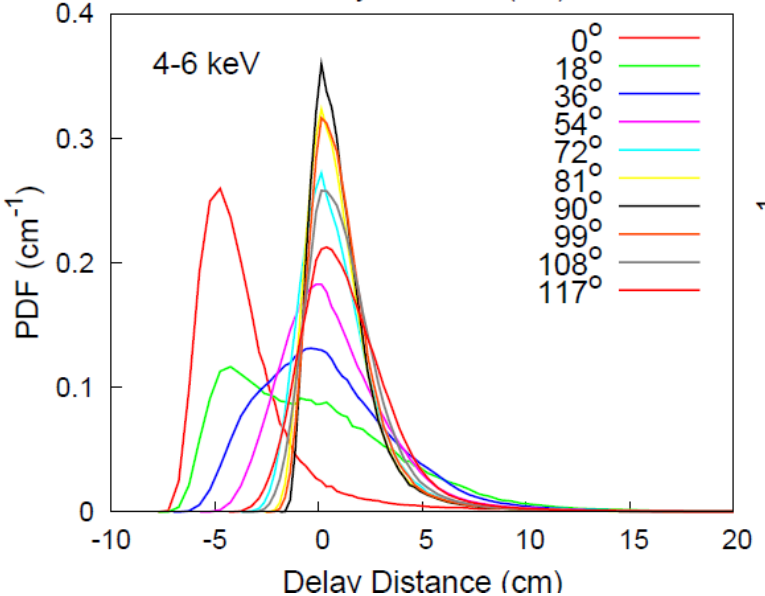


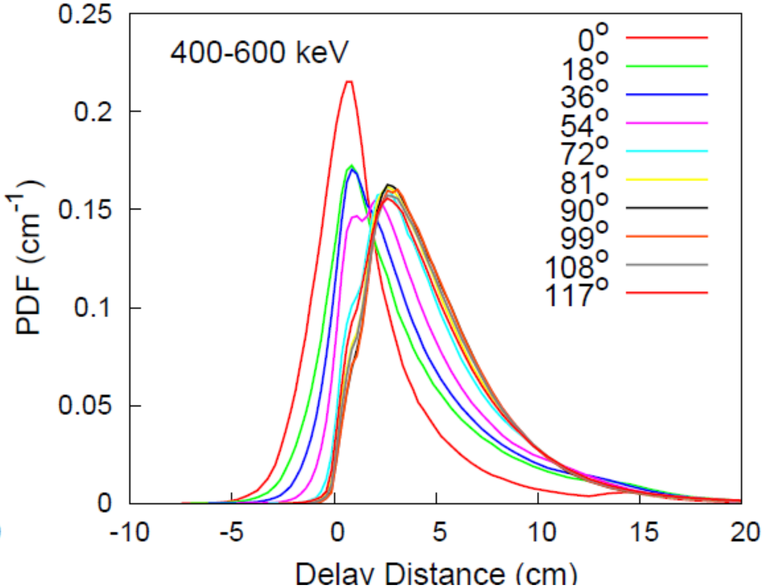
Analytical expressions in REFIT include storage term of Ikeda & Carpenter





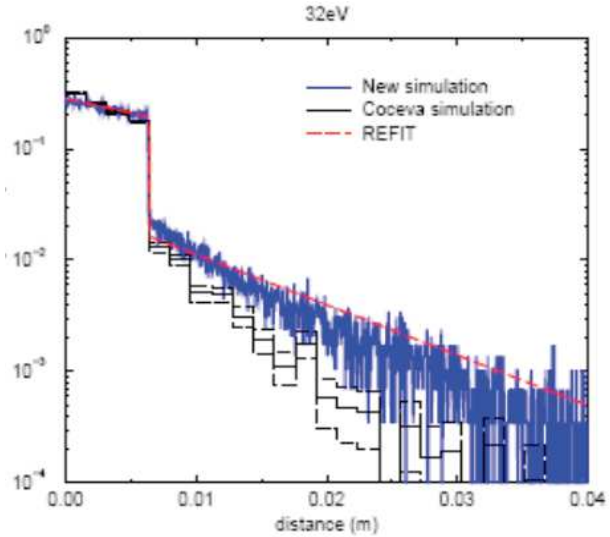






Ene et al. NIM A618 (2010)54
Monte Carlo simulations

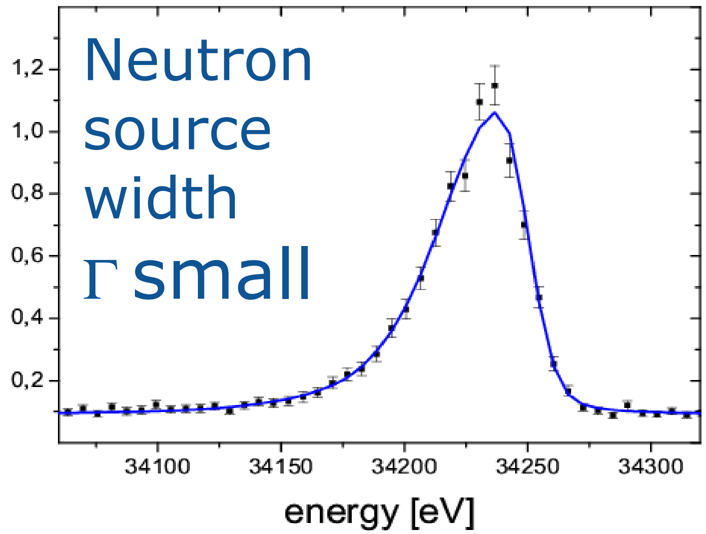
Resonance broadening



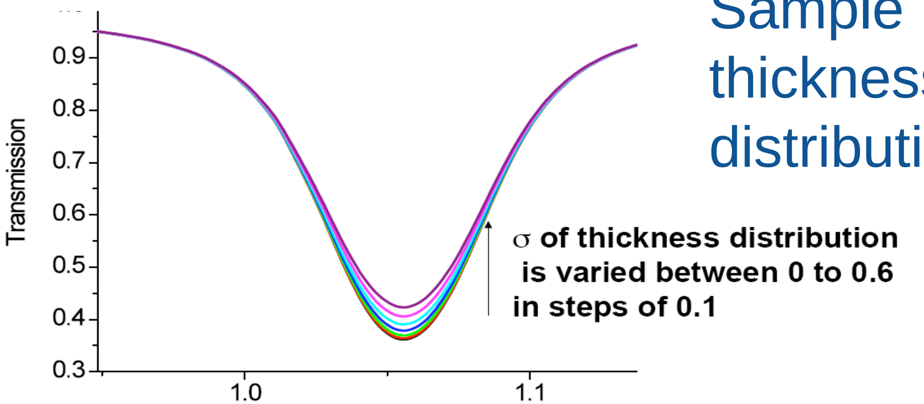
Detector Resolution

Neutron source width

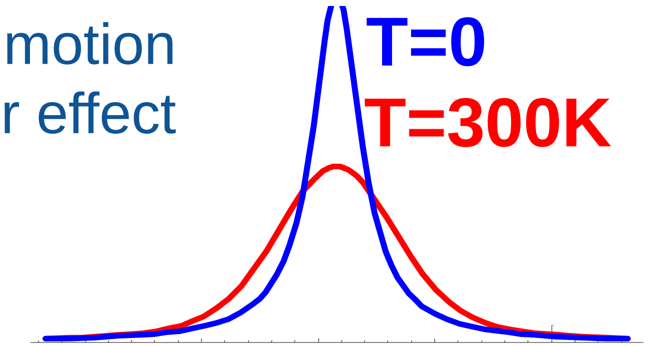
Γ small



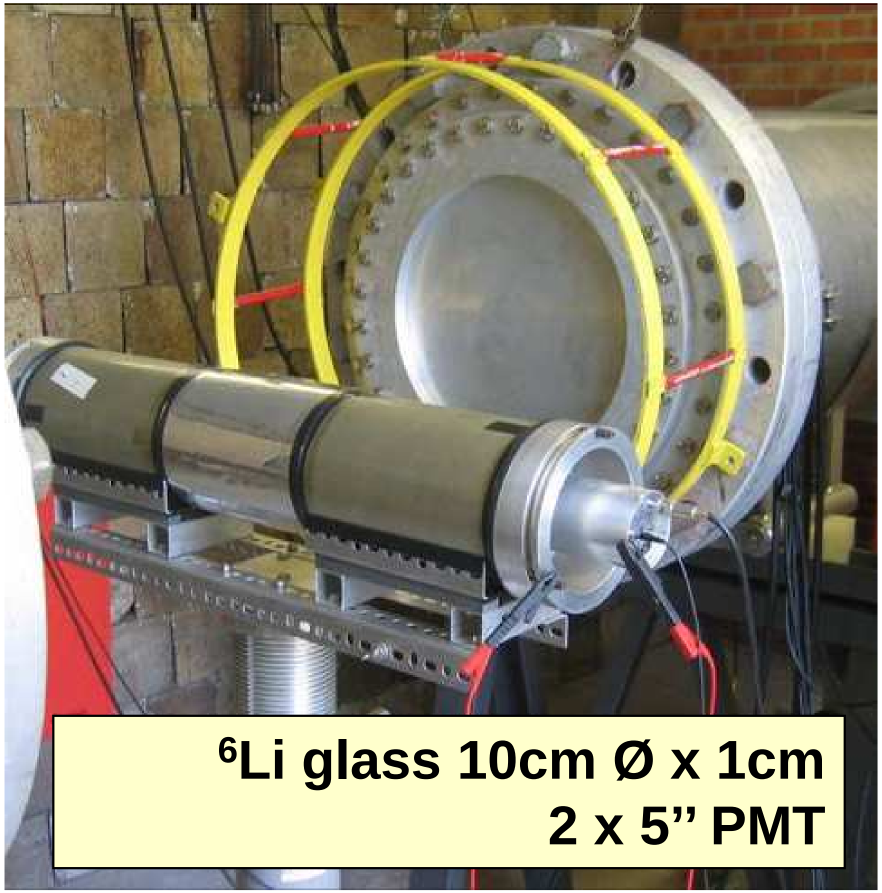
Sample thickness distribution



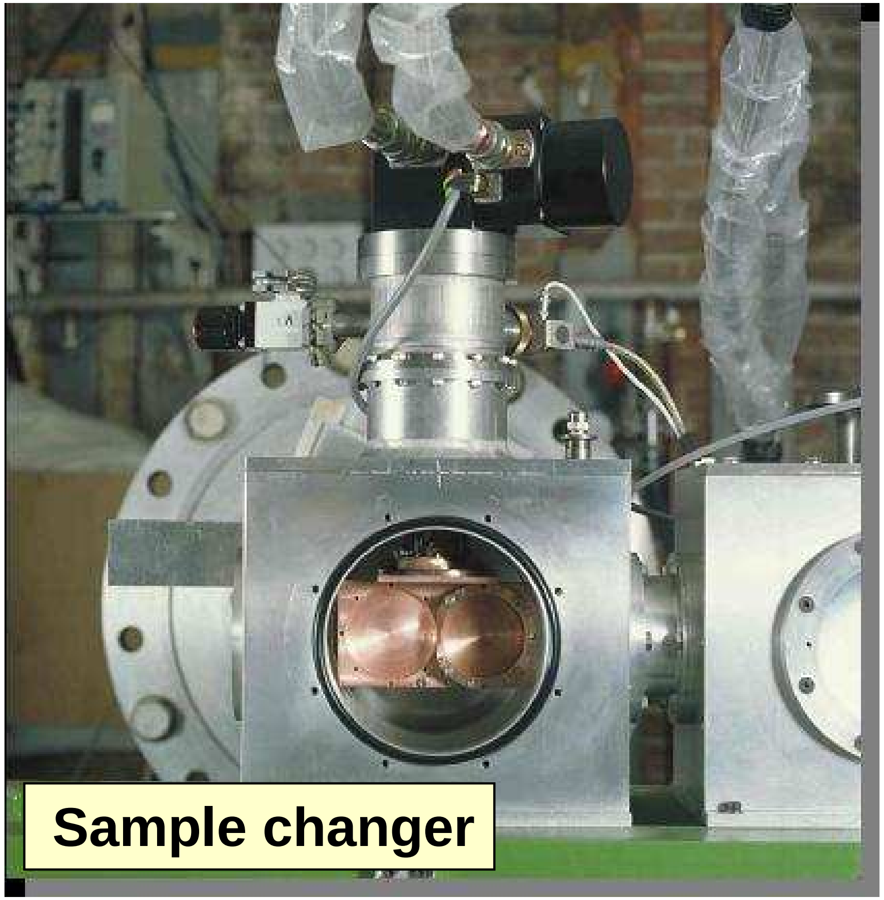
Thermal motion
Doppler effect



Transmission setup, sample holder and neutron detector



^{6}Li glass 10cm Ø x 1cm
2 x 5'' PMT

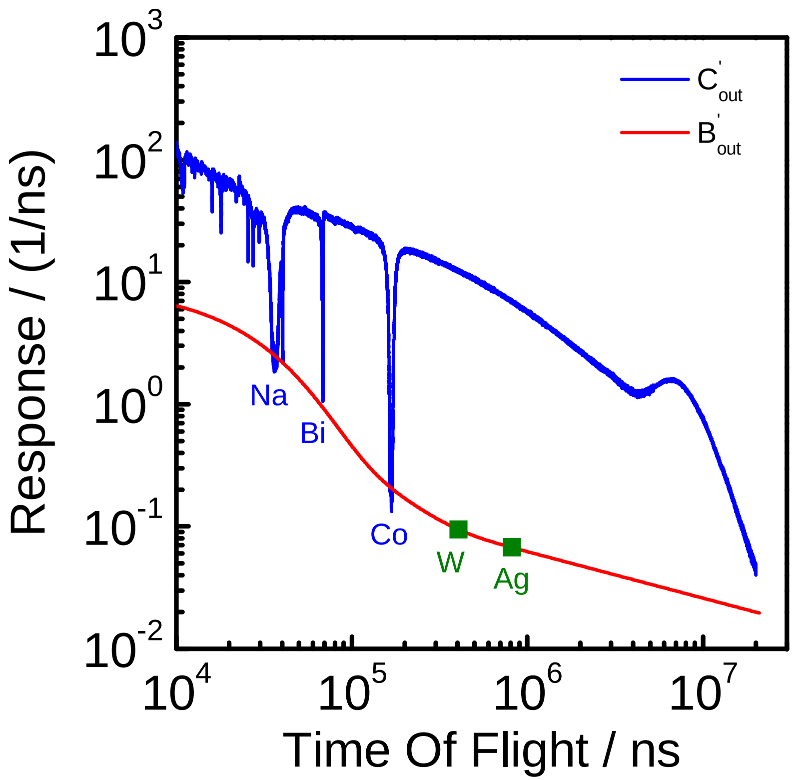


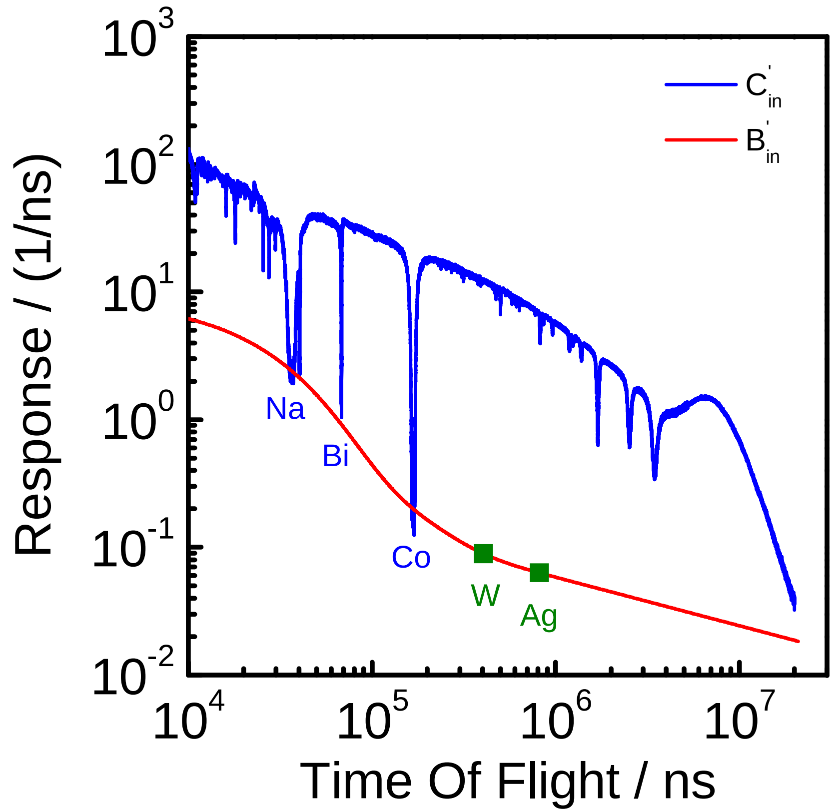
Sample changer

Background determination

Fixed and variable filters

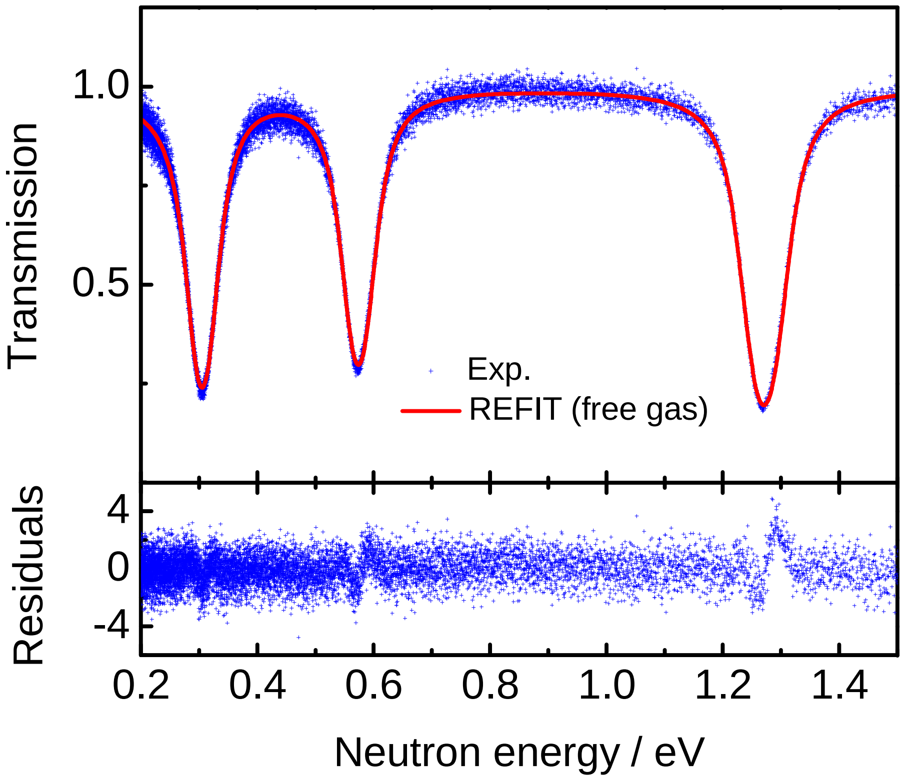
Black resonance technique



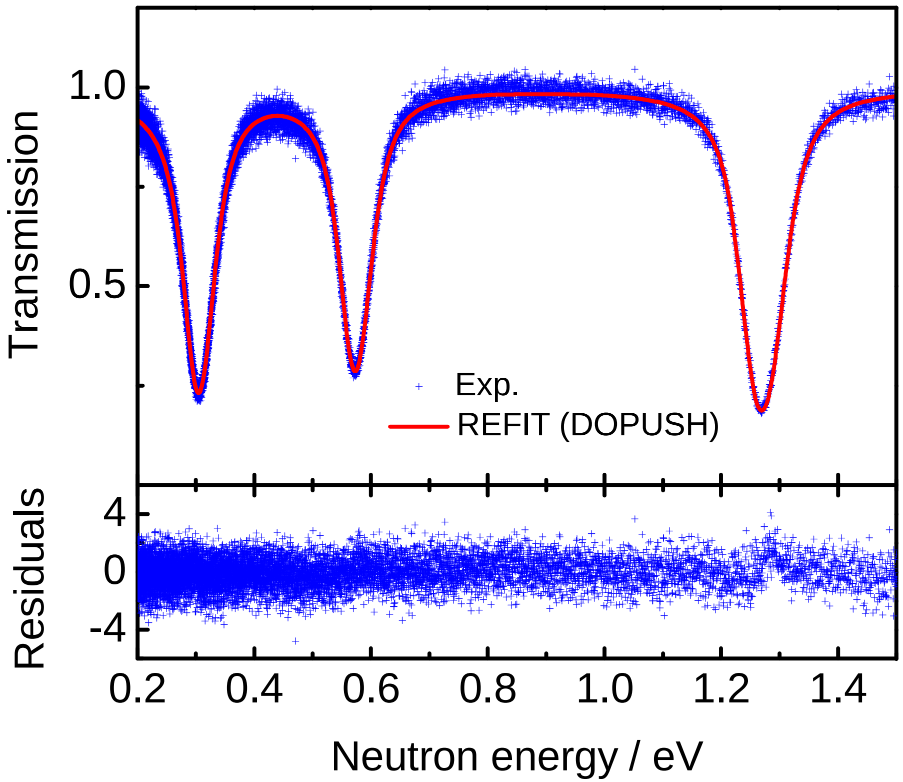


Transmission data and (REFIT, ^{241}Am)

Resonance analysis to obtain resonance parameters from which cross section may be reproduced under any required circumstances

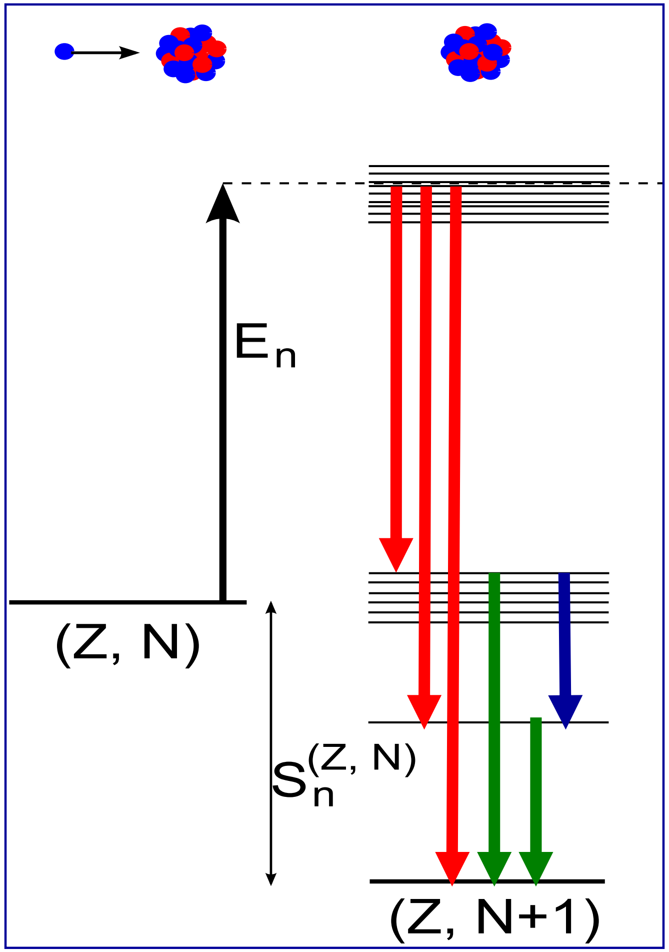


Gas model



Crystal lattice

Neutron capture



A neutron is absorbed

Nucleus decays by a cascade of gamma-rays

Detection of gamma-rays

gamma detectors, detection efficiency

Concerns:

Gamma-cascades vary with energy

Gamma-ray angular distribution

Normalization/fluence measurement

Fluence distribution as function of energy

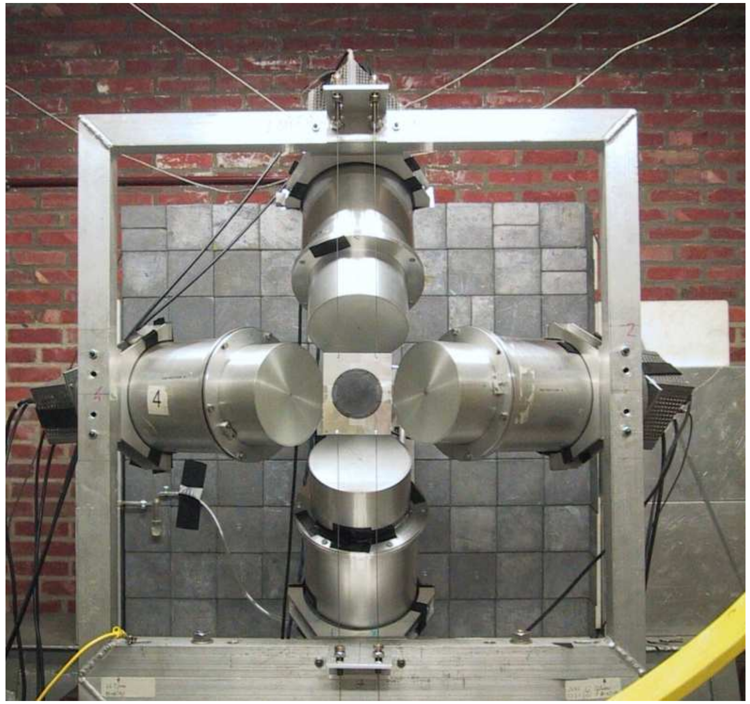
Reference cross section or black resonance

As for transmission: background, deadtime, etc.

$\sigma(n,\gamma)$ measurements

European Commission

L = 12.5 m and 60 m



Total energy detection principle

- C_6D_6 (low neutron-sensitivity)
- Pulse height weighing technique (PHWT, insensitive to cascade)
- 125^o (minimize effect ang. dist.)

Flux measurements (IC)

- < 120 keV : $^{10}B(n,\alpha)$
- > 120 keV : $^{235}U(n,f)$

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

$$\frac{\delta Y_{exp}}{Y_{exp}} \leq 2\%$$

WF : from MC simulations
Validated by experiment

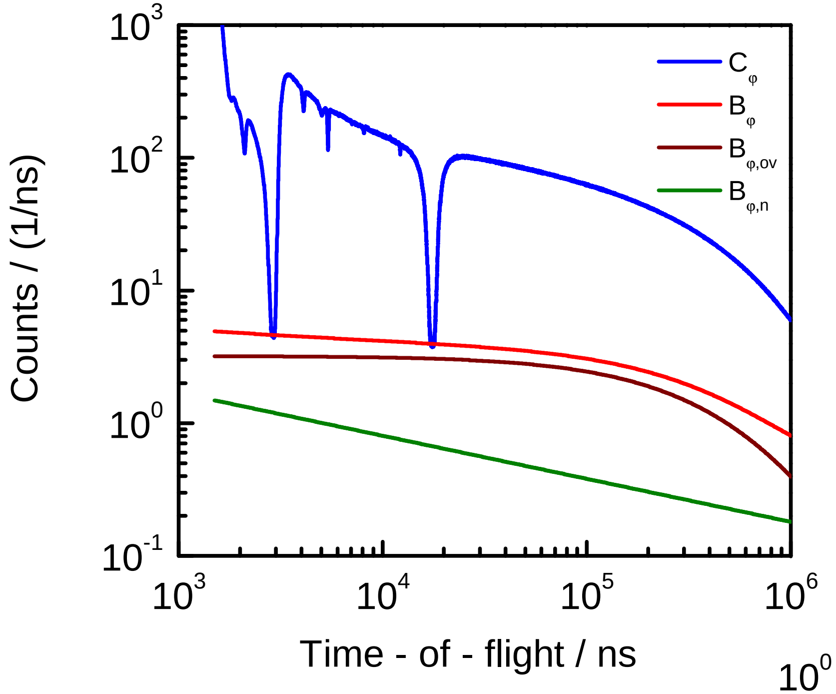
$$\int R(E_d, E_\gamma)\, WF\,(E_d)\, dE_d = kE_\gamma$$

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

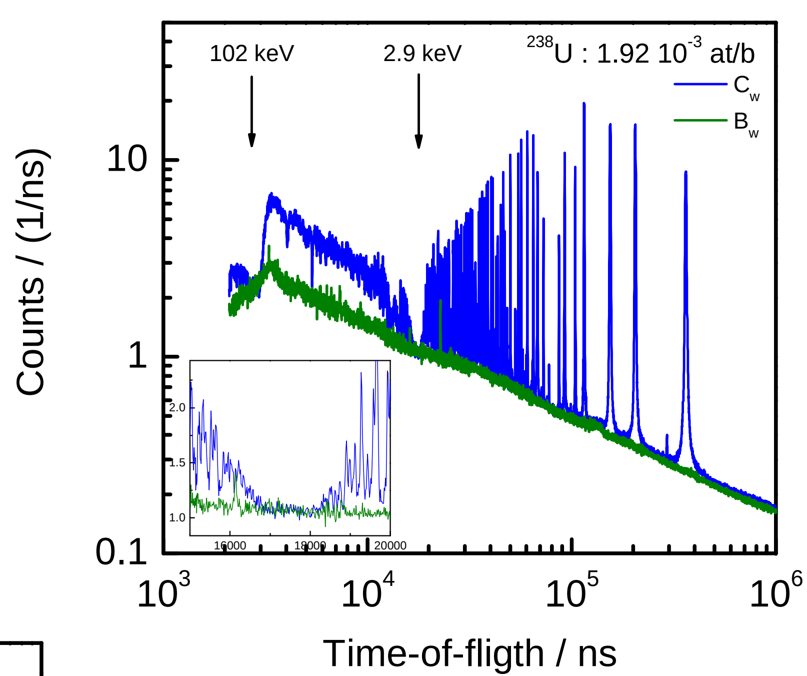
Borella et al., NIM A 577 (2007) 626

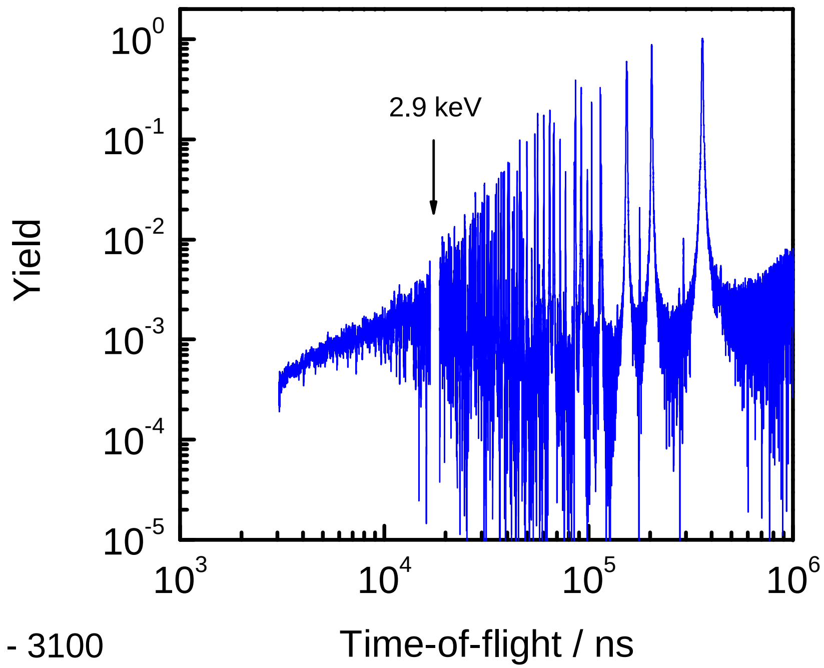
Schillebeeckx et al., Nuclear data sheets, 113 (2012) 3054 - 3100

σ(n,γ) measurements for ^{238}U at 12.5 m



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



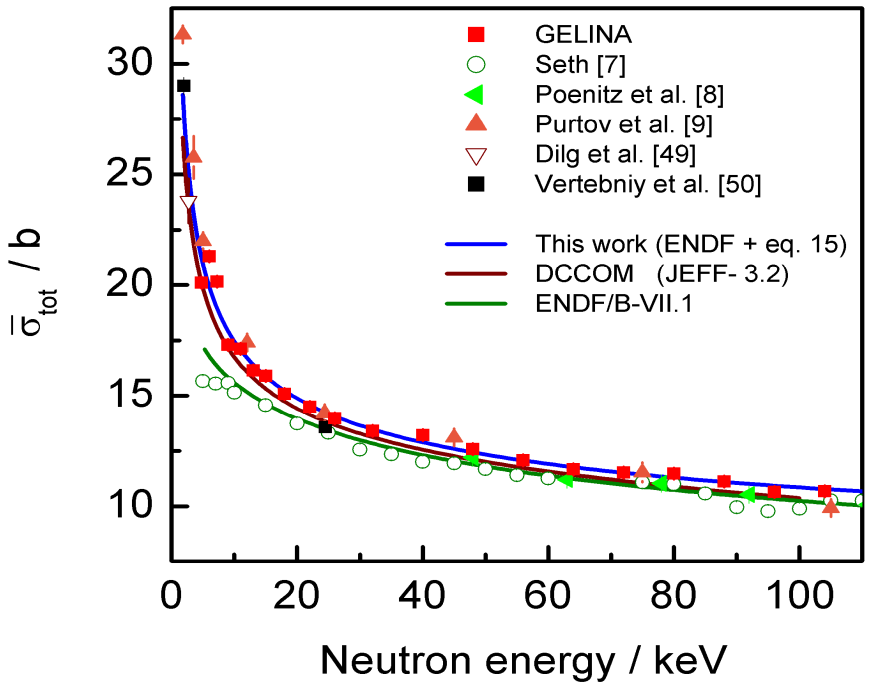


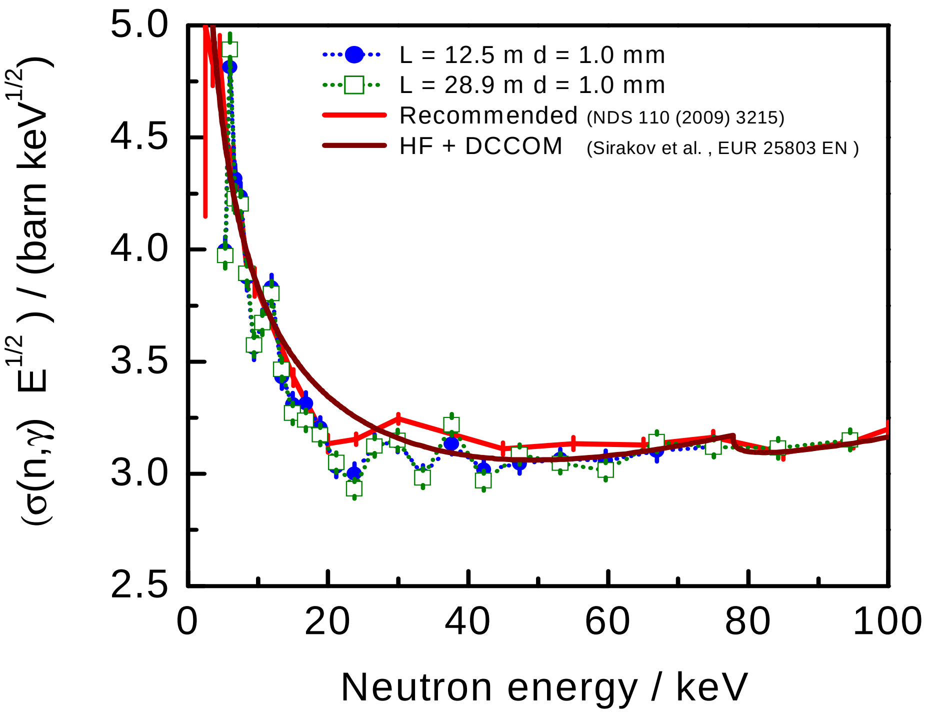
Fixed background filters

$\Rightarrow$ $\delta Y_{exp}/Y_{exp}$ ~ 2.5 % due to B_w

Schillebeeckx et al., NDS, 113 (2012) 3054 - 3100

^{197}Au(n,tot) & ^{197}Au(n,γ) cross section





- **Both results will be used in the parameterization of the URR**
- **(R', $S_{n,l=0,1,2}$, $T_{\gamma,0}^{2+}$, $T_{\gamma,0}^{2-}$)**
- **+ HZDR nELBE data (100 keV to 10 MeV)**

Normalization of capture data

C_6D_6 liquid scintillators : $C'_w - B'_w$

Flux measurements (IC): $C'_\varphi - B'_\varphi$

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

$$Y_{exp} = \frac{C'_w - B'_w}{C'_\varphi - B'_\varphi} \frac{\varepsilon_\varphi}{\varepsilon_r} \frac{\Omega_\varphi}{\Omega_r} \frac{F_\varphi}{F_r} \frac{A_\varphi}{A_r} \sigma_\varphi$$

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

Normalization constant N

1) Saturated resonance
   - ^{197}Au : 4.9 eV
   - ^{109}Ag : 5.2 eV
   - ....

2) Resonance with : $\Gamma_n << \Gamma_\gamma$
   - Γ_n from transmission
   - ^{56}Fe : 1.15 keV

Internal normalization:

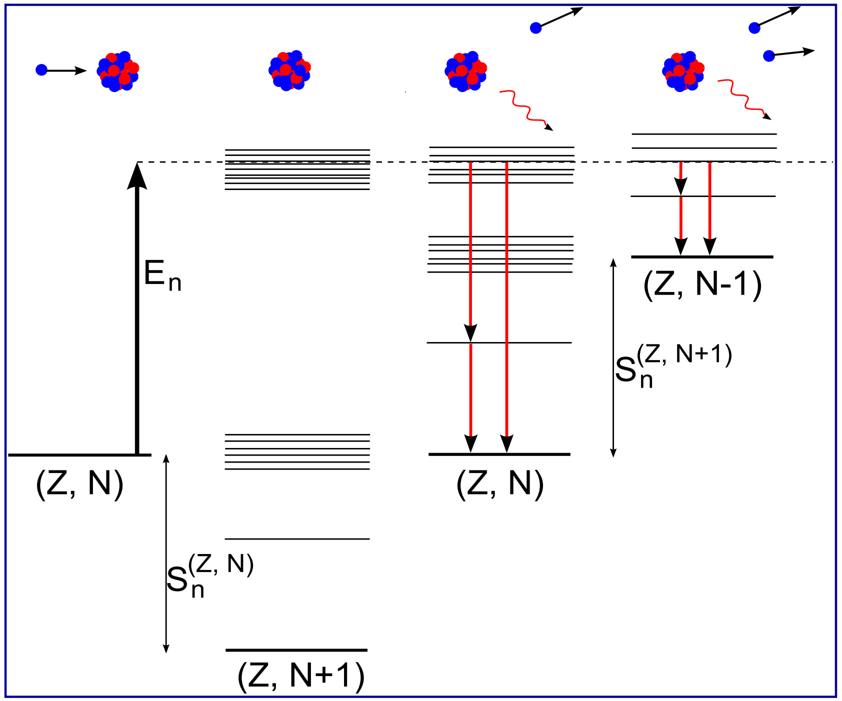
⇒Reduction of systematic effects

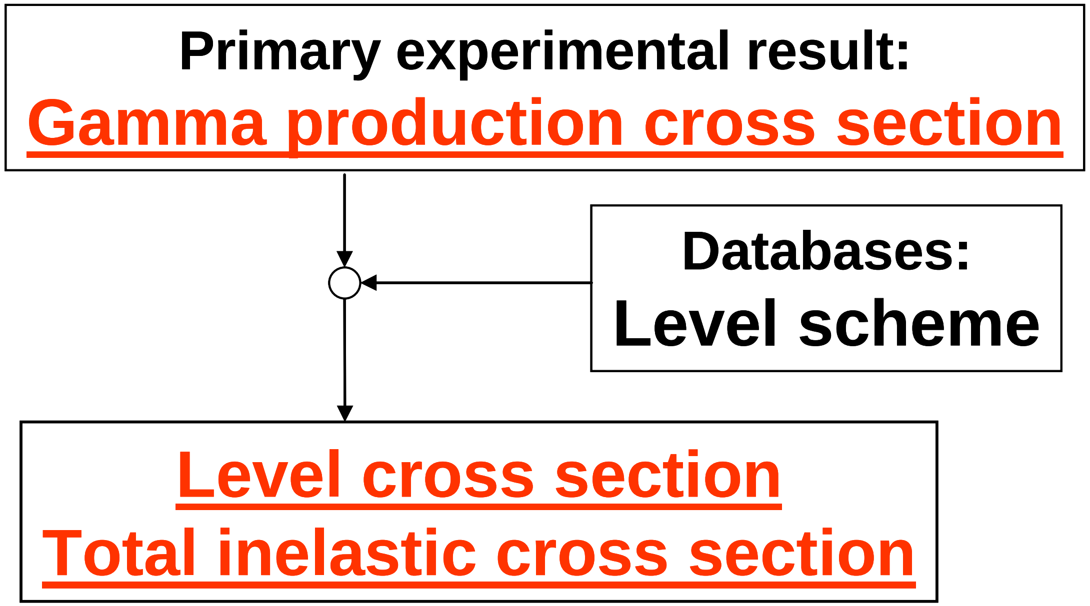
Borella et al., NIM A, 577 (2007) 626

Measurement of neutron inelastic scattering

Measurement of the associated gamma-rays

Very selective with access to angle-integrated cross section





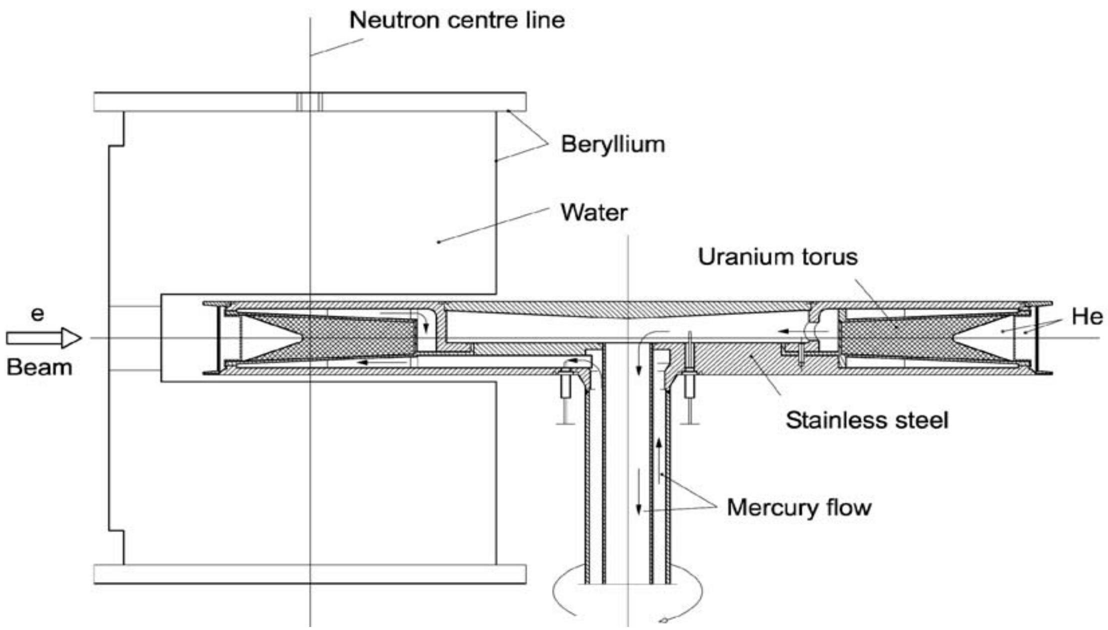
Germanium Array for Inelastic Neutron Scattering

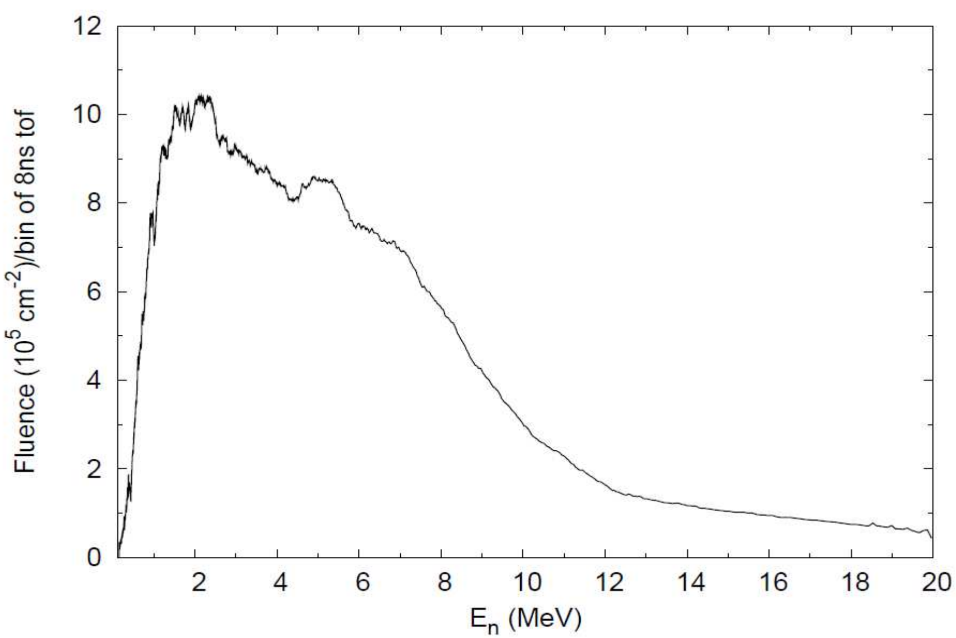
GAINS @ FP3/200m

12 HPGe 80 mm ø x 80 mm L
1 keV resolution at 1 MeV (neutrons)
Cross sections 3-5 %

The GELINA target

- Fast and moderated neutron spectra available for different flight paths
- Inelastic scattering: threshold reactions, so fast spectrum (right)





GAINS

Angle integration: $\lambda \leq 3$
Efficiency: calib+MC
Time-response
  12bit 440 MSPS dig.
Flux: U-235(n,f)

L.C. Mihailescu et al. NIMA531(2004)375

L.C. Mihailescu et al. NIMA578(2007)298

D. Deleanu et al. NIMA624(2010)130

A. Plompen et al. KPS59(2011)1581

^{52}Cr: L.C. Mihailescu et al. NPA786(2007)1

^{209}Bi: L.C. Mihailescu et al. NPA799(2008)1

^{208}Pb: L.C. Mihailescu et al. NPA811(2008)1

^{23}Na: C. Rouki et al. NIMA672(2012)82

^{235}U: M. Kerveno et al. PRC87(2013)024609

$0\nu2\beta$ bgs: A. Negret et al. PRC…(2013)…

^{12}C, ^{24}Mg, ^{28}Si, ^{56}Fe, ^{58}Ni, ^{76}Ge, ^{206}Pb, ^{207}Pb, ^{232}Th, ^{238}U: conf.

Ongoing: ^{57}Fe, ^{63}Cu, ^{65}Cu, Mo, Zr

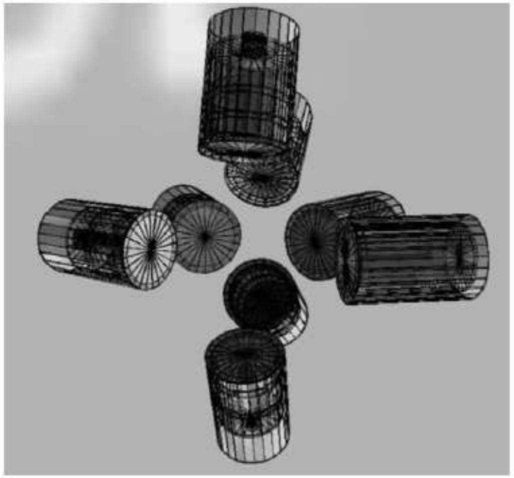


Fig. 1. GAINS. Drawing of the simulated geometry.

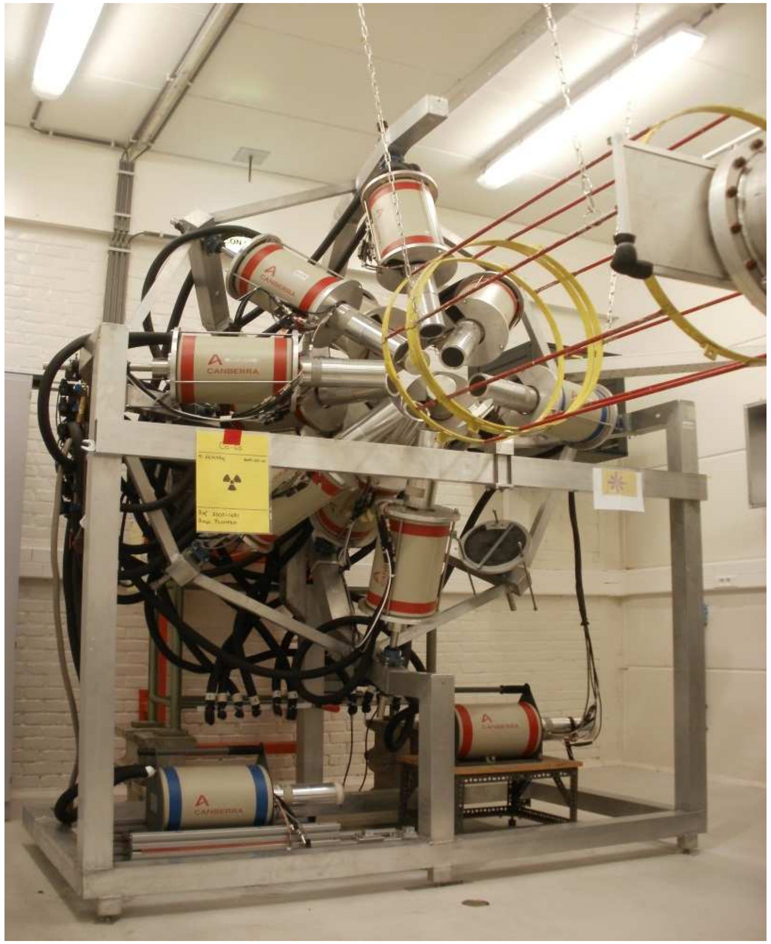
$$\sigma = 2\pi \int_{-1}^{1} \frac{d\sigma}{d\Omega}(x)dx = 2\pi \sum_{i=1}^{2} w_i \frac{d\sigma}{d\Omega}(x_i)$$

SS: SINGLE-SIDED
DS: DOUBLE-SIDED

European Commission

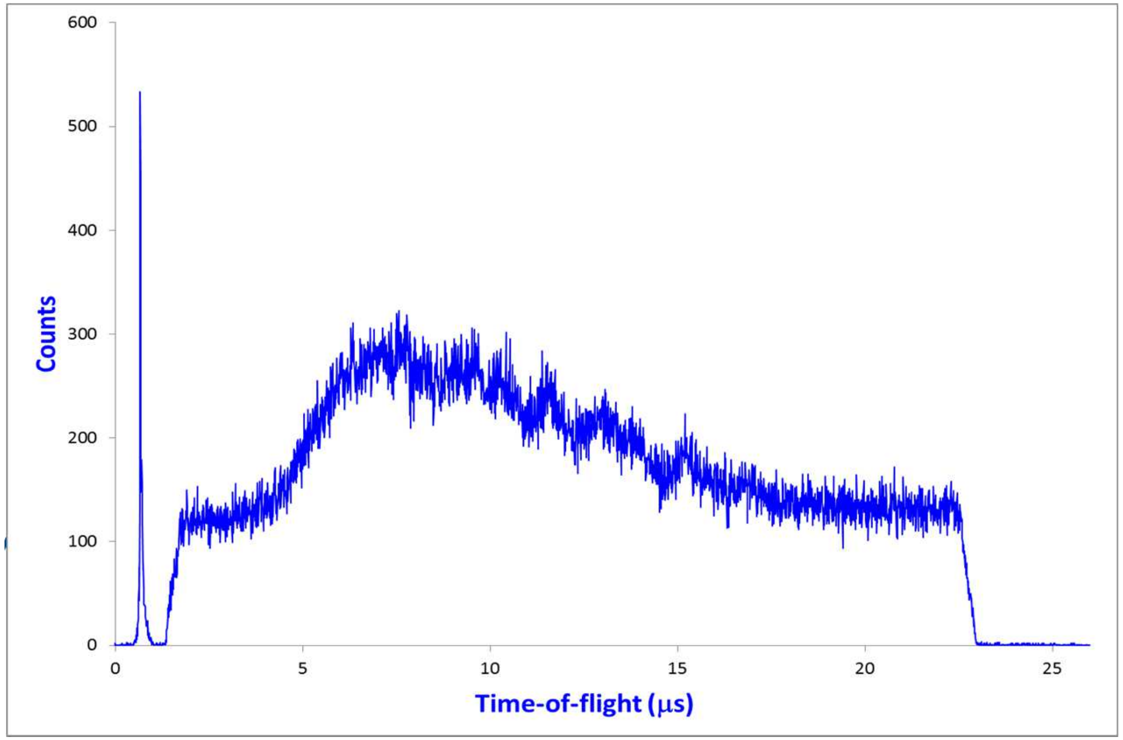
Gamma Array for Inelastic Neutron Scattering

- 200 m FP for resolution
- Recently upgraded to 12 HPGe detectors, about 100% relative efficiency
- Detectors at 110, 125, and 150 degrees, four detectors at each angle
- Fission chamber 1.3 m upstream from the sample position to monitor neutron flux
- 8 UF_4 deposits (Ø 70 mm) on 5 Al foils (20 μm)
- 3 Acquiris DC440 digitizers, 12 bit amplitude resolution, 440 MS/s



The (n,n'γ) technique

- E_n from the time-of-flight between the electron beam hitting the target and the detection of γ rays from inelastic scattering
- At 200 m tof = 3.3 – 20.5 μs for E_n = 20 – 0.5 MeV
- Time resolution of about 10 ns corresponds to a neutron energy resolution of about 1 keV at 1 MeV

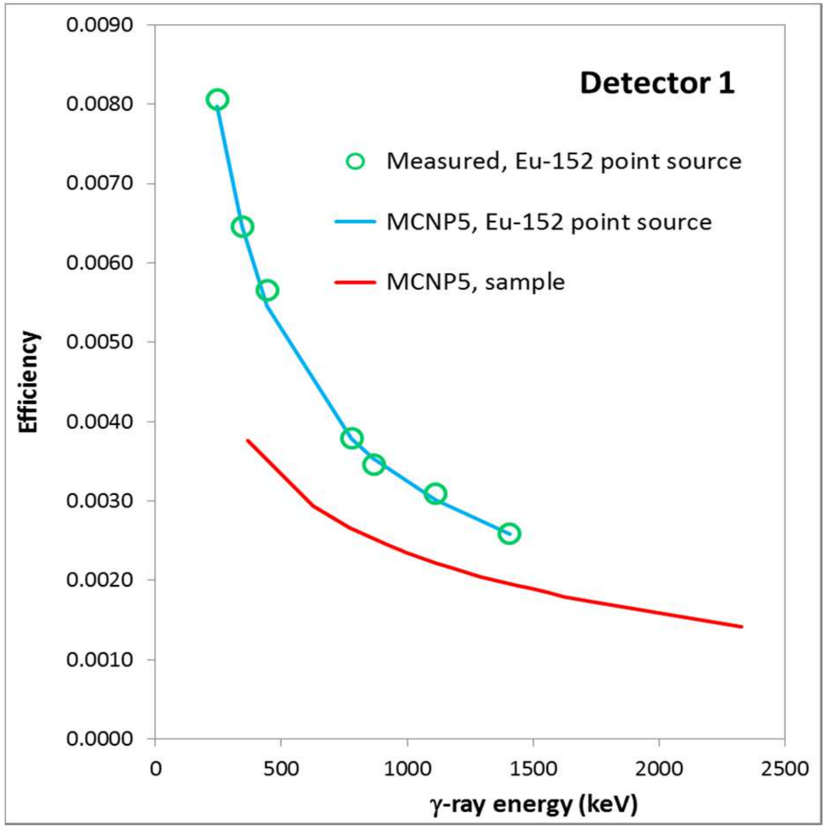


Data analysis

- Data is sorted into tof vs. E_γ matrices
- The primary experimental quantities are the differential γ-ray production cross sections
- These can be angle integrated to give the total γ-ray production cross sections
- Level cross sections are determined from σ_γ by subtracting feeding from higher levels
- As long as at least one γ ray per level is observed, the total inelastic cross section can be deduced
- Knowledge of the level scheme is necessary

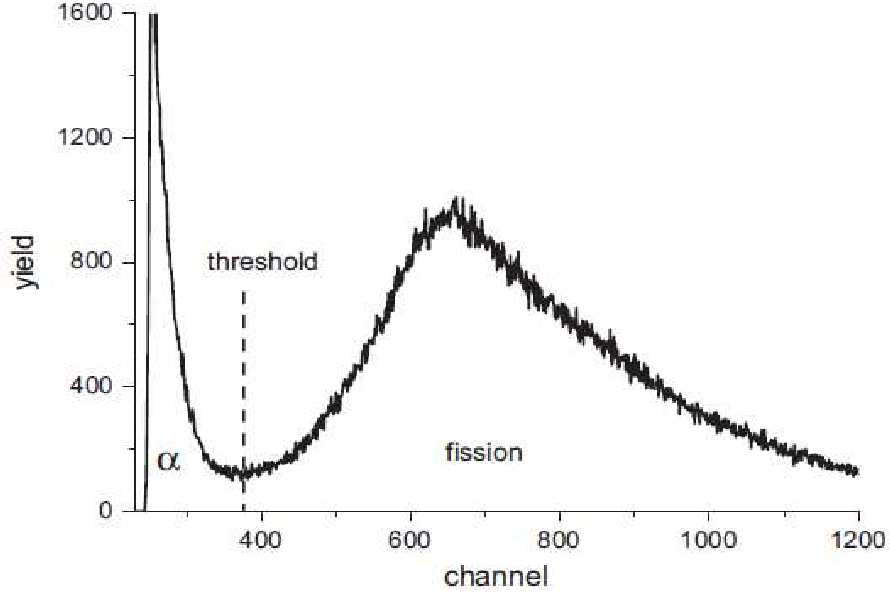
HPGe efficiency calibration

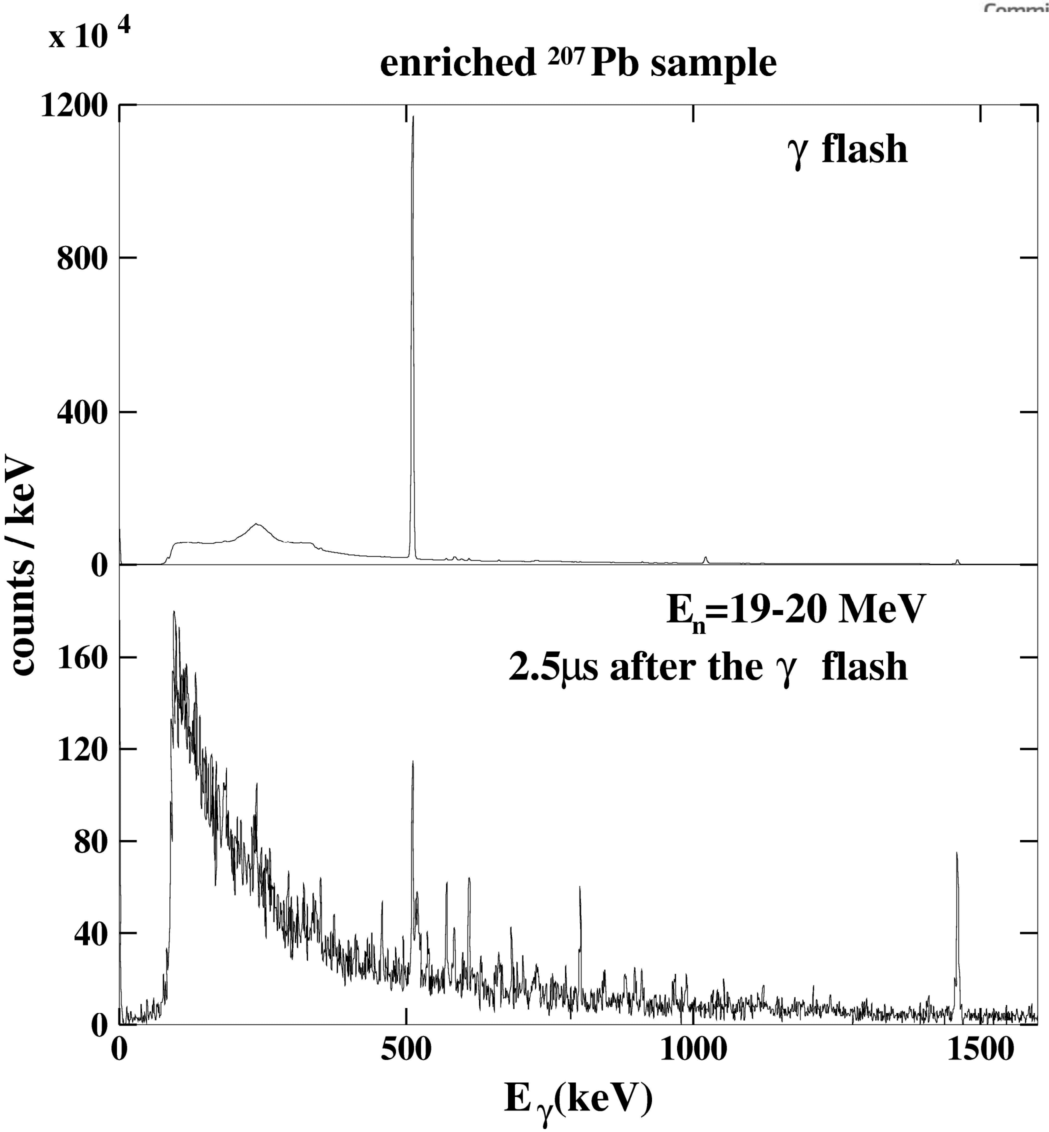
- An accurate efficiency calibration for the HPGe detectors is essential
- The calibration procedure:
  - An Eu-152 point source is used to determine ε in that geometry
  - MCNP5 simulation is the used to fix a model of the setup until ε_{SIM} matches ε_{EXP} for the point source
  - After this the point source in the simulation is replaced with the measured sample and the MCNP5 simulation is repeated
  - For details: D. Deleanu et al., Nucl. Inst. and Meth. A 624 130 (2010)

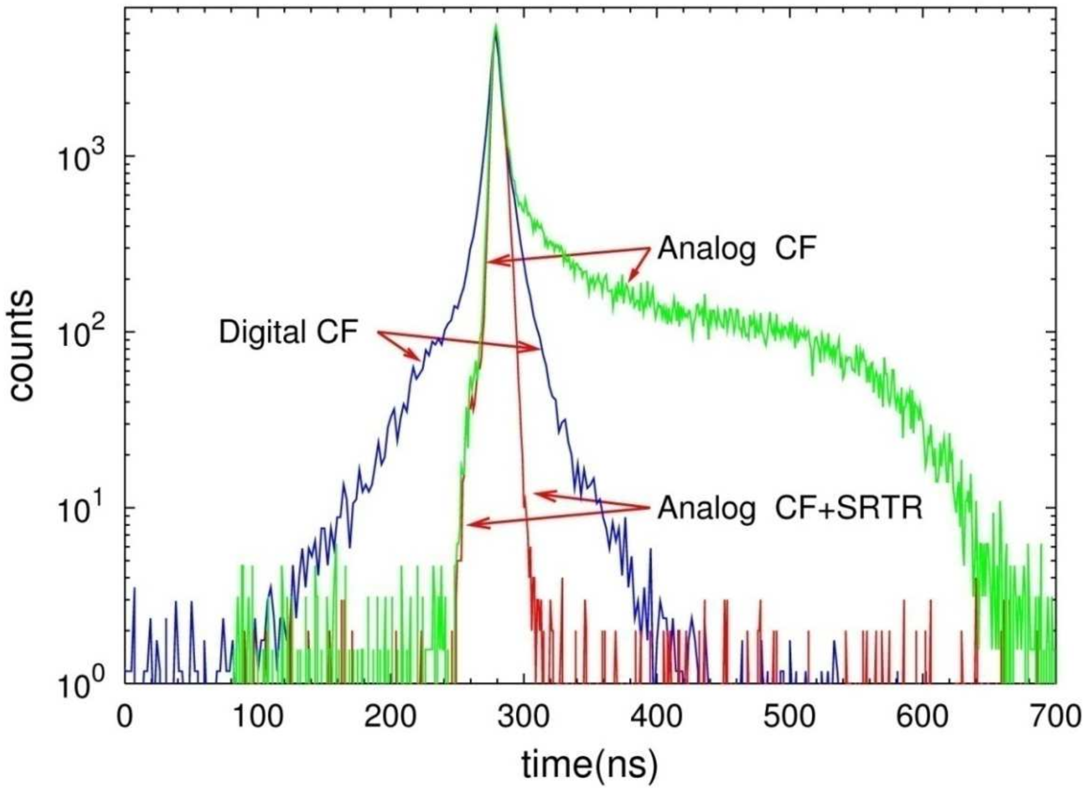


Fission chamber efficiency

- An accurate efficiency calibration for the fission chamber is essential
- Corrections are made to account for the following:
  - Number of fission fragments below threshold
  - Polarity effect
  - Inhomogeneity of the UF_4 foils
  - Number of fission fragments stopping in the foil
  - For details: C. Rouki et al., Nucl. Inst. and Meth. A 672 82 (2012)







Dead time reduction (< 2.5 μs)

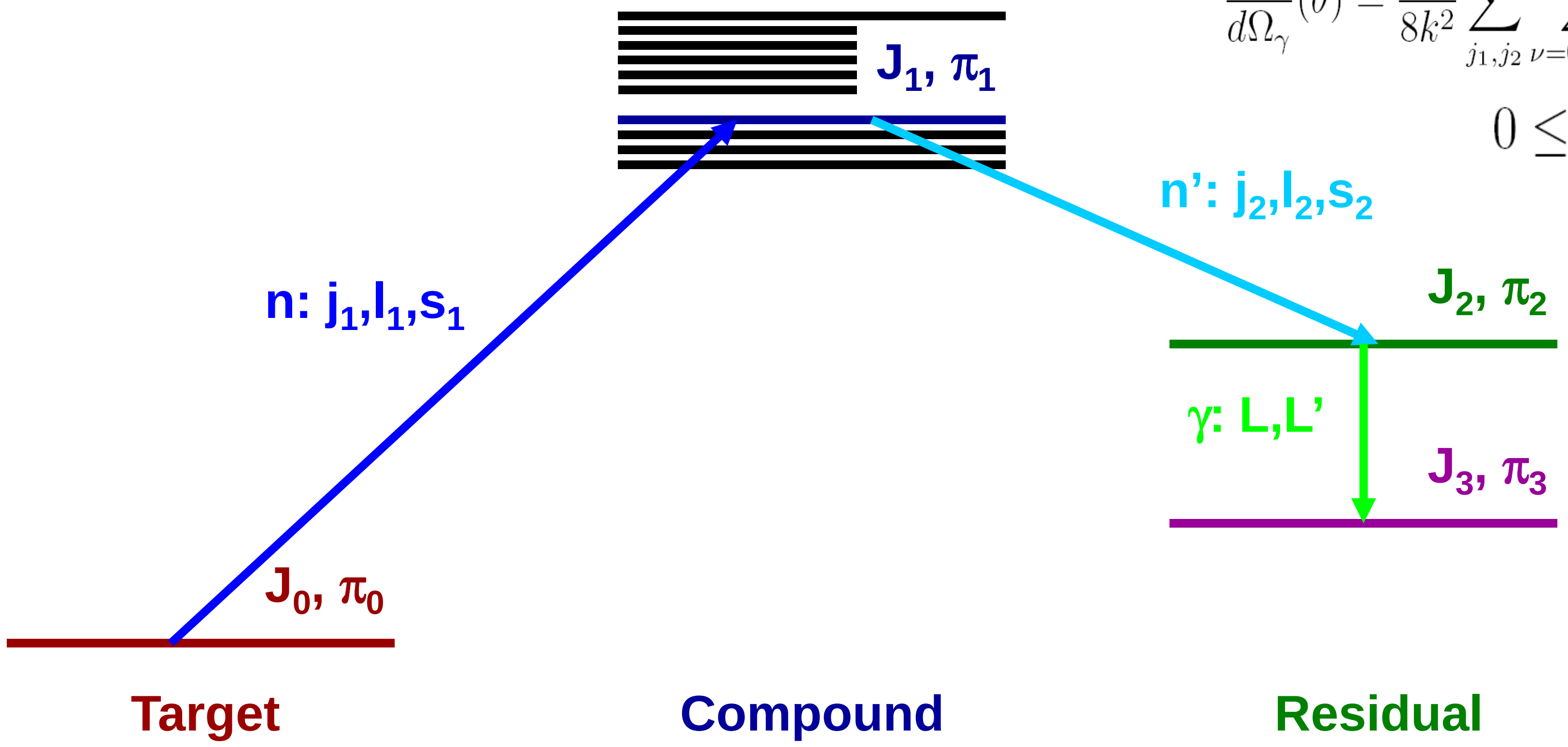
Time response improvement

Time range: 22 μs

Inelastic angular distributions

$$\frac{d\sigma}{d\Omega_\gamma}(\theta) = \frac{1}{8k^2}\sum_{j_1,j_2}\sum_{\nu=0,even}^{\nu_{max}} N'C'W'M(\delta)\tau P_\nu(\cos\theta_\gamma)$$

$$0 \leq \nu \leq 2j_1, 2J_1, 2J_2, 2L'$$



E. Sheldon and D.M. van Patter, Rev.Mod.Phys. 38(1966)143

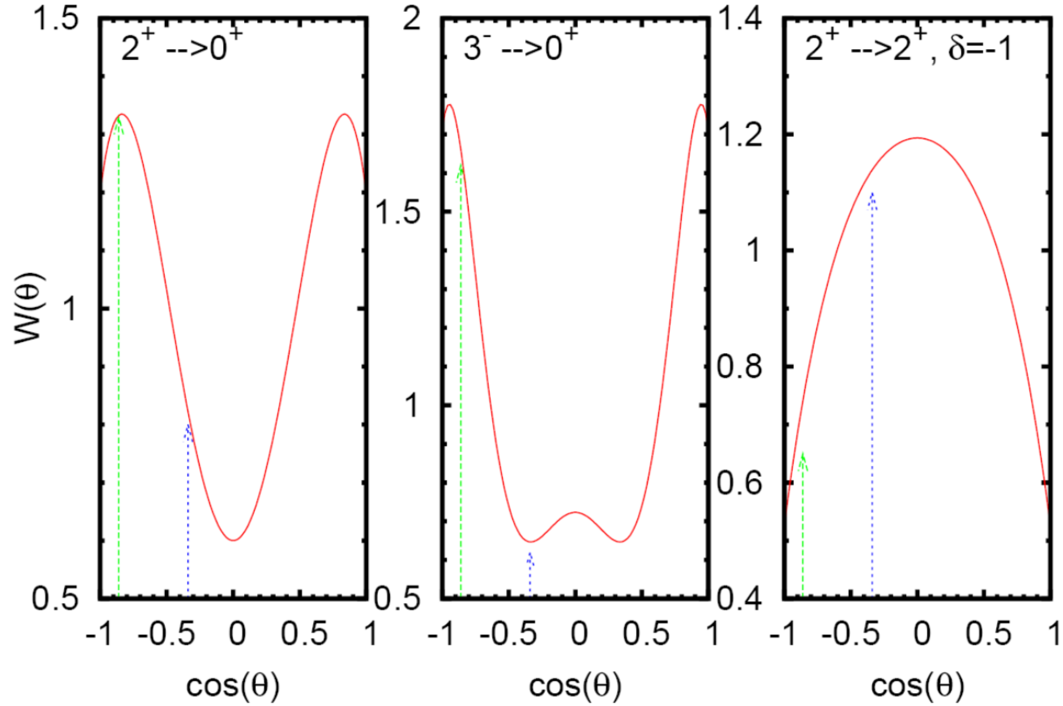
Angular distribution of gammas

Exact angle integration $1 \leq L \leq 3$

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{\sigma}{4\pi} W(\theta) = \frac{\sigma}{4\pi} \sum_{k=0}^{k_{max}} c_{2k} P_{2k}(\cos(\theta))$$

$$\sigma = 2\pi \int_{-1}^{1} \frac{d\sigma}{d\Omega}(x)dx = 2\pi \sum_{i=1}^{2} w_i \frac{d\sigma}{d\Omega}(x_i)$$

$$x_i = \cos(\theta_i)$$



θ_1=110º, 70º → w_1=1.30429
θ_2=150º, 30º → w_2=1.69571

European Commission

Metrological information Na disc Ø80 x 4mm (Can N°2)

Total mass:	19,44± 0.04 g
Ø	79,80 ± 0.08 mm
Thickness:	4.23 ± 0.08 mm
Area:	50,01 cm^2
Mass/area	0,389 g/cm^2
Density	0,92 g/cm^3 (Theoretical density: 0.97 g/cm^3)

Metallic sodium sample prepared by André Moens at IRMM

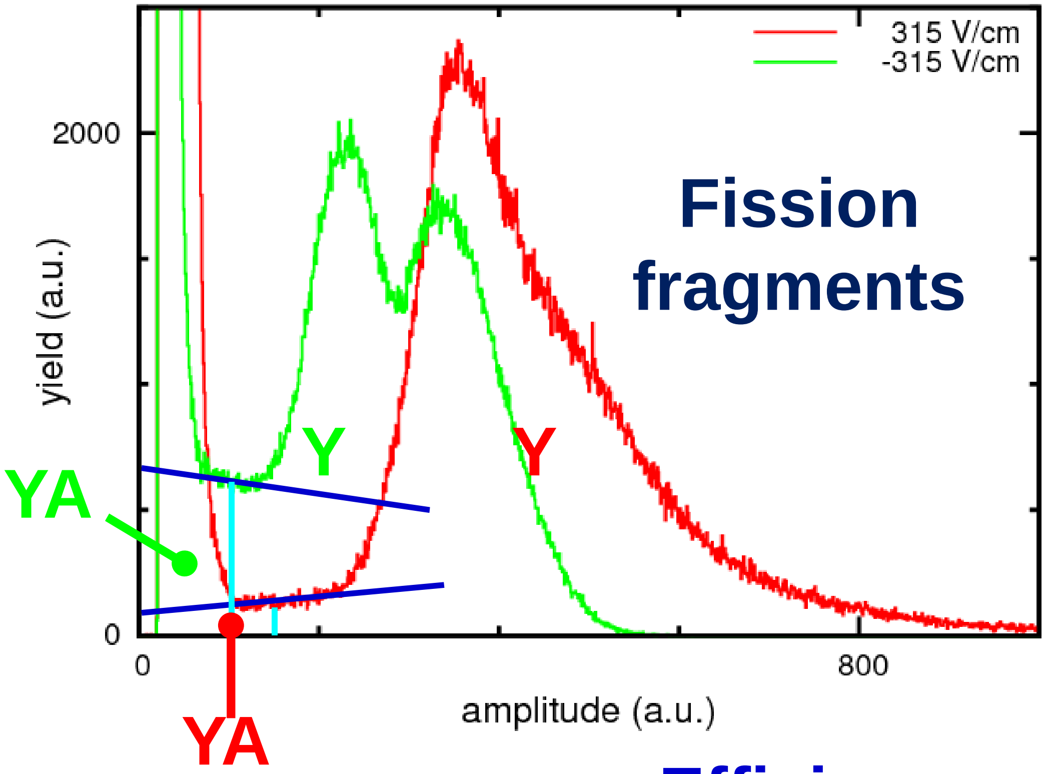
Preparation method

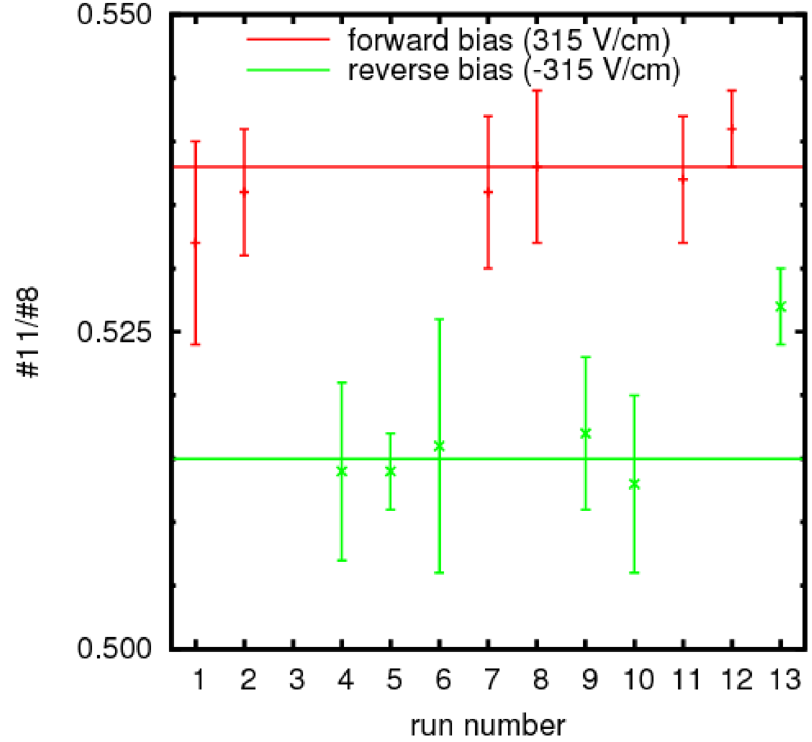
Cutting, Pressing, Mechanical Rolling (sandwich-method) and Punching.
Note: All mechanical transformations done under petrol.
Determination dimensions + weighing under inertgas atmosphere.
Canning Na-disc in Al-can under Ar-atmosphere. Closure of the cans was performed by a gluing method using "UHU plus".

Chemical analyses

Alfa Aesar, Lot D11S201 – Sodium ingot, 99.8% (metals basis)

Normalization to fission





Efficiency = Y / (Y+YA+YB)

Y+YA forward versus backward bias

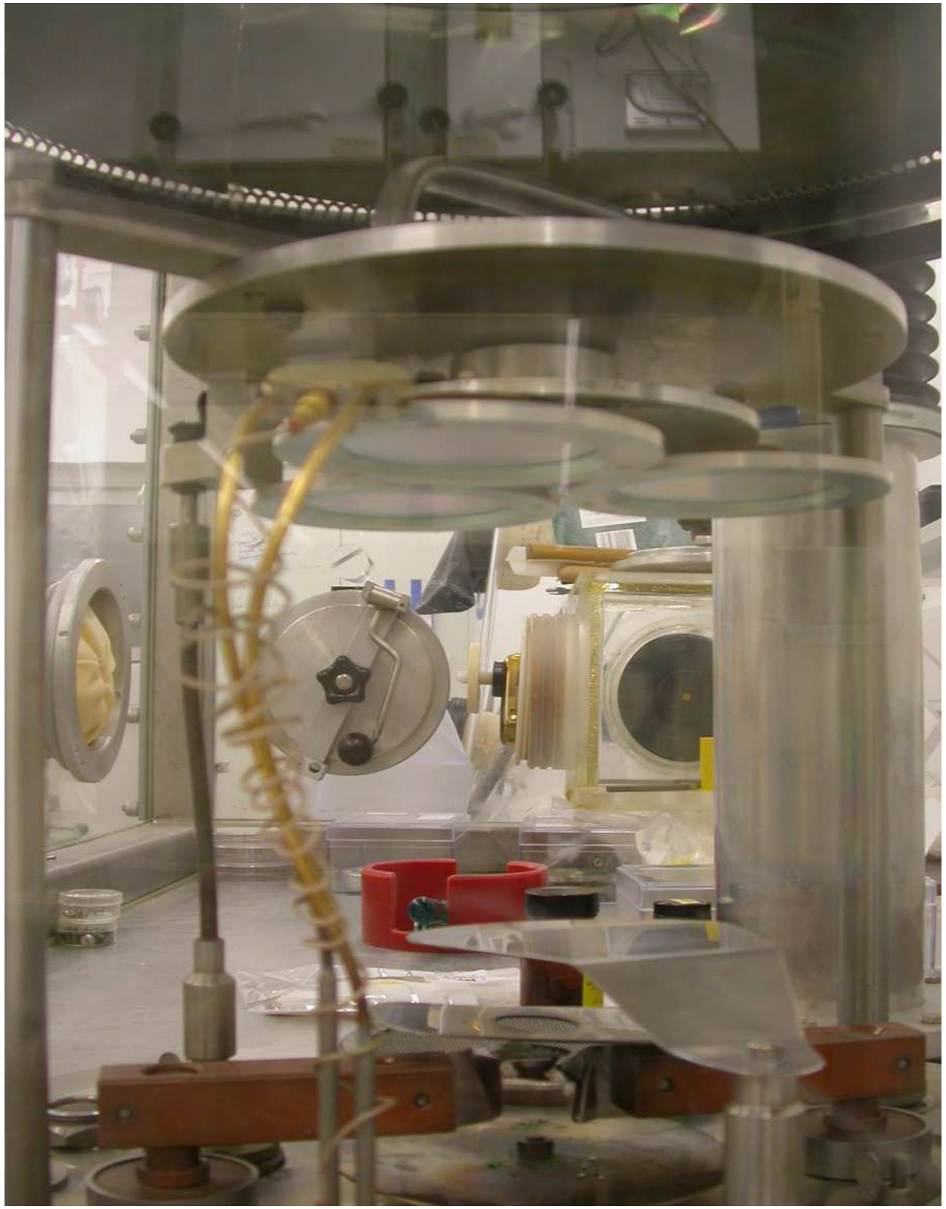
4.4% effect for 0.475 mg/cm^2 UF_4 evaporated

Y: yield above threshold, YA: yield below threshold (linear extrapolation)

YB: fragments stopped in the deposit (not shown) YB/(Y+YA+YB) = 0.105(7) t/(mg/cm2)

YB: measured by Budtz-Jörgensen Nucl.Instrum.Meth. 236(1985)630

Normalization: sample preparation



^{235}U

Fission deposit

Evaporated UF_4

Alpha-counting

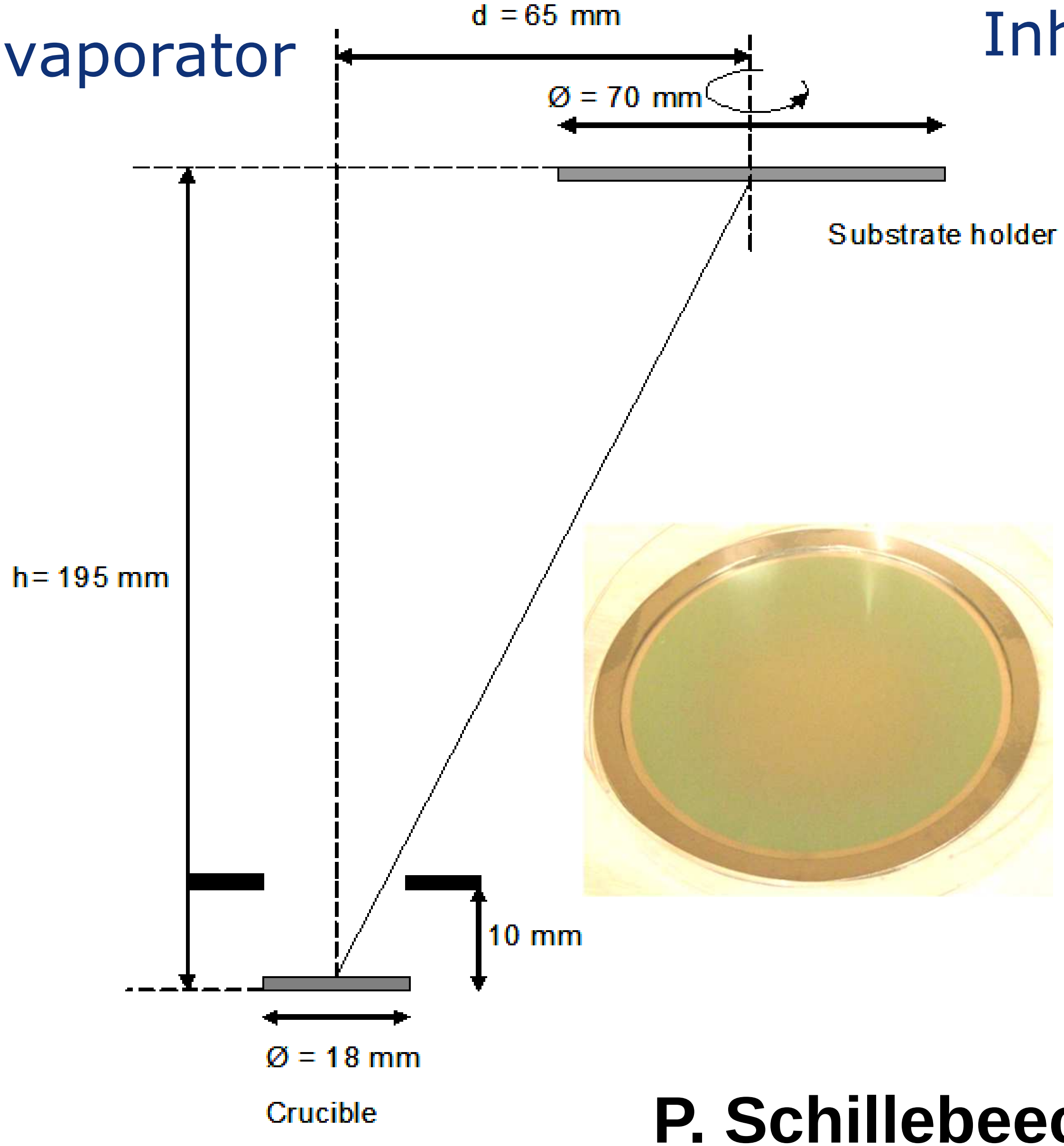
High purity

Roger Eykens
Andre Moens
Marc Peeters
Anna Stolarz

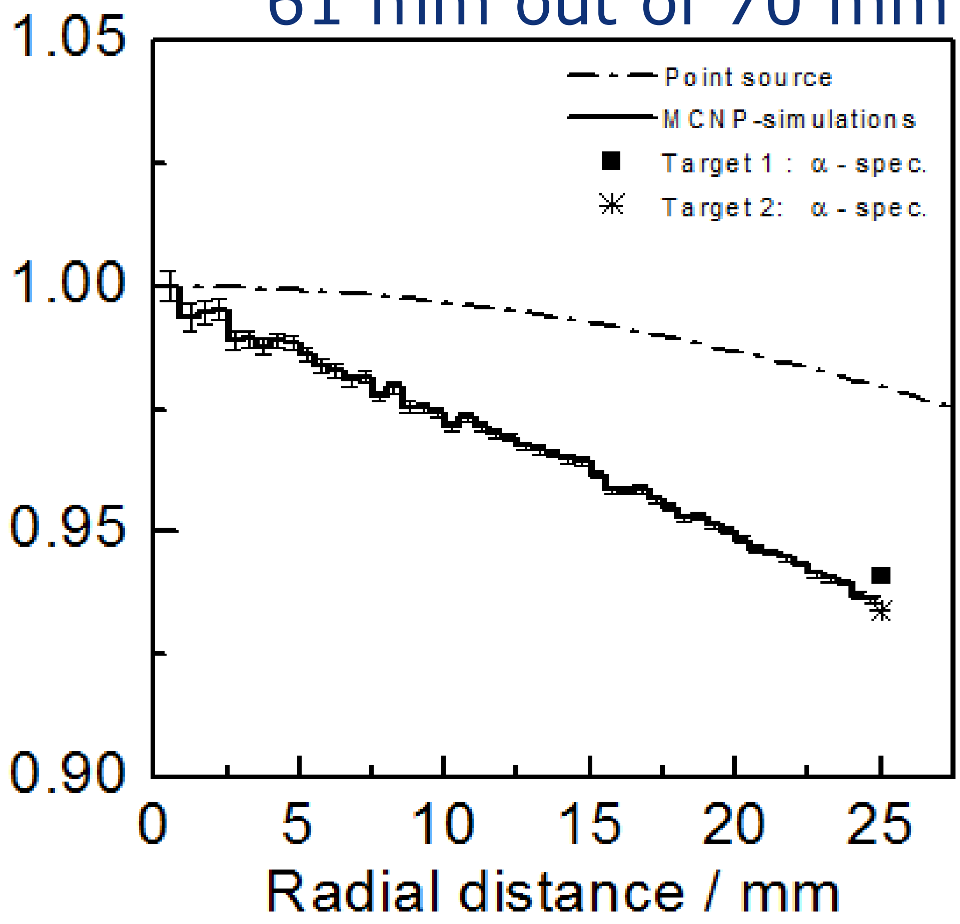
Peter Schillebeeckx

Sample preparation and characterization

Evaporator



Inhomogeneity: +2% areal mass density
61 mm out of 70 mm



P. Schillebeeckx et al., NIM A 613(2010)378

Sample production and characterization

Callet& De Bièvre 15 November 1985	Atom%	Acc (2s)
U-234	0.0626	0.0025
U-235	99.8266	0.0044
U-236	0.0365	0.0027

Richter 23 March 2009	Atom%	Acc (2s)
U-234	0.06389	0.00014
U-235	99.82275	0.00020
U-236	0.03768	0.00007
U-238	0.07568	0.00013

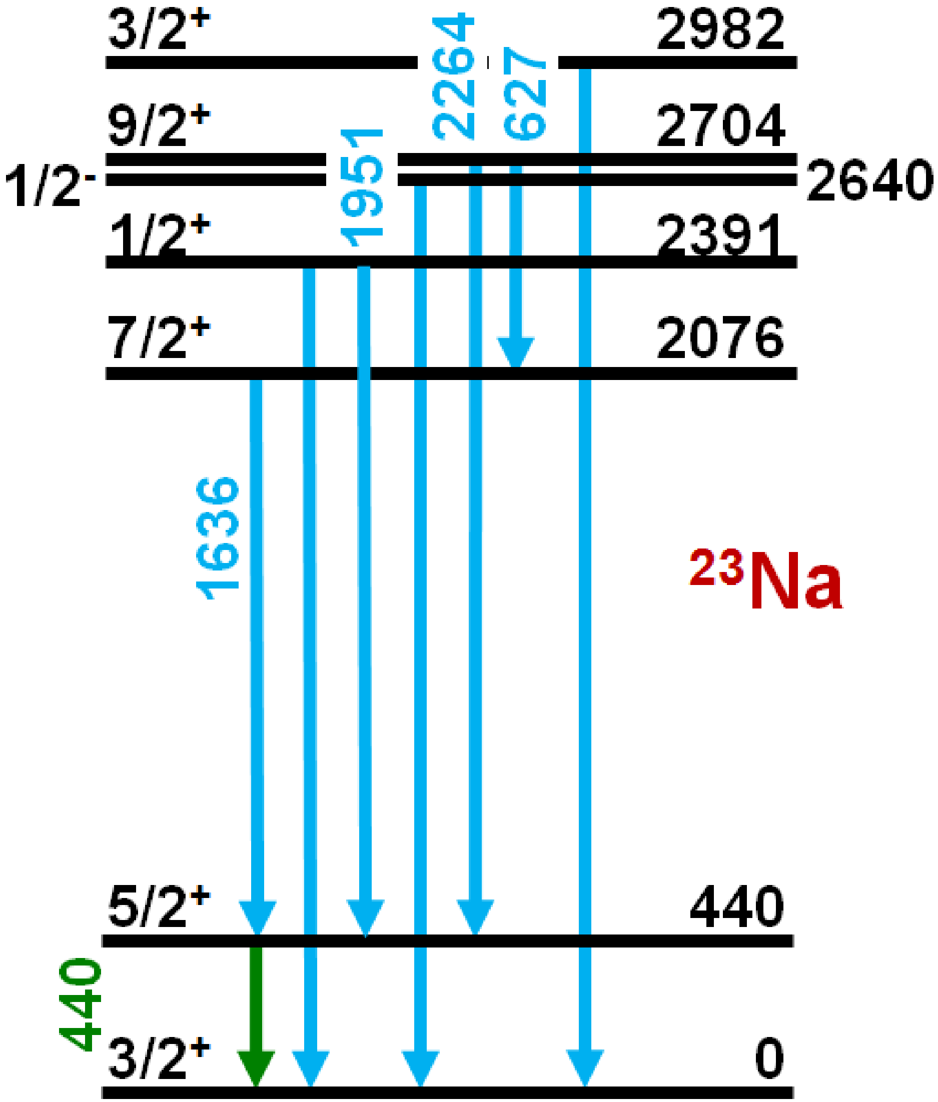
Activity to atoms
Mass spectrometry
65% activity: U-234

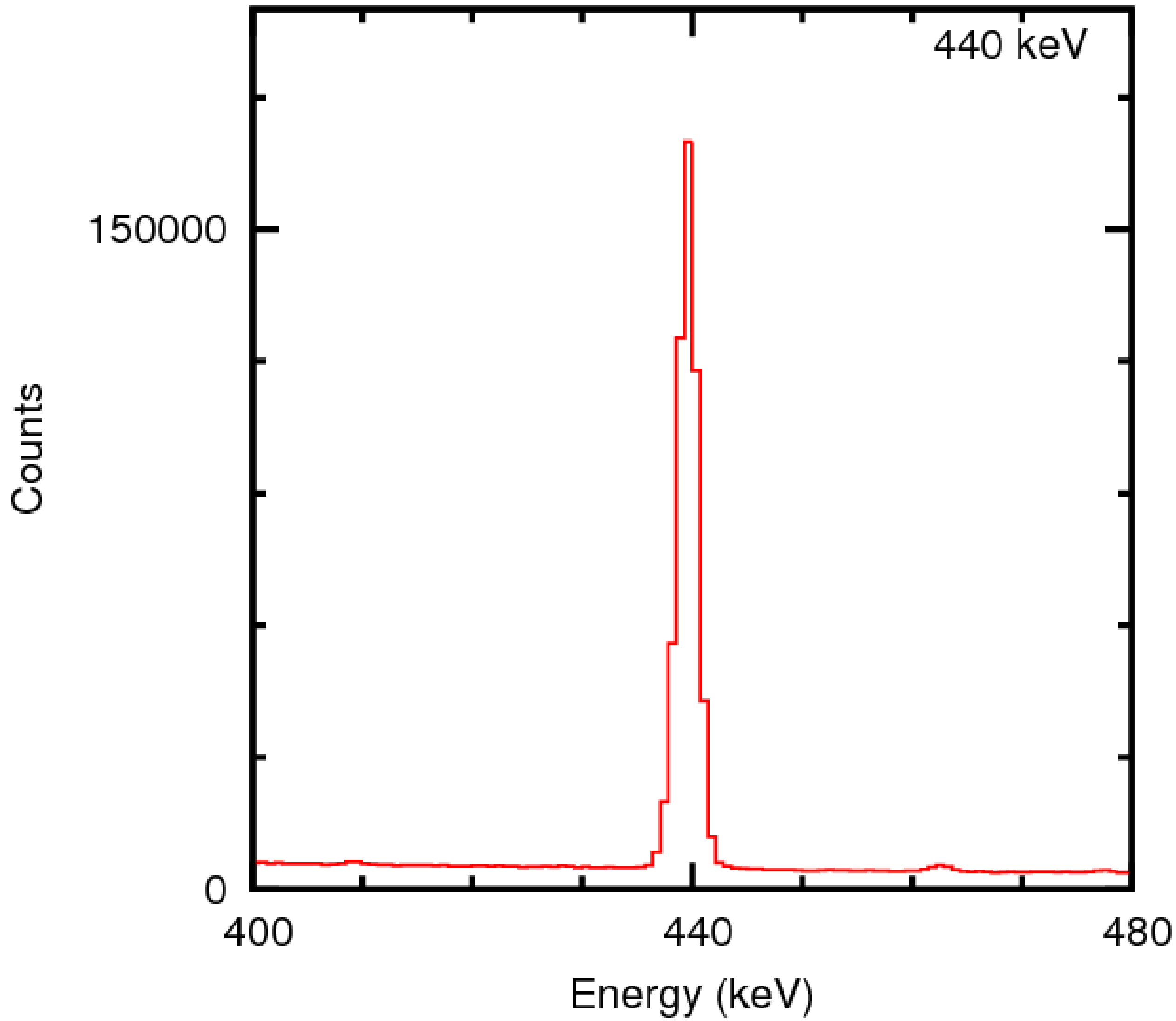
Quantity	Value (1s)
Decay constant	8.78(10) 10^{-17} U/s

Quantity	Value (1s)
Decay constant	8.88(2) 10^{-17} U/s

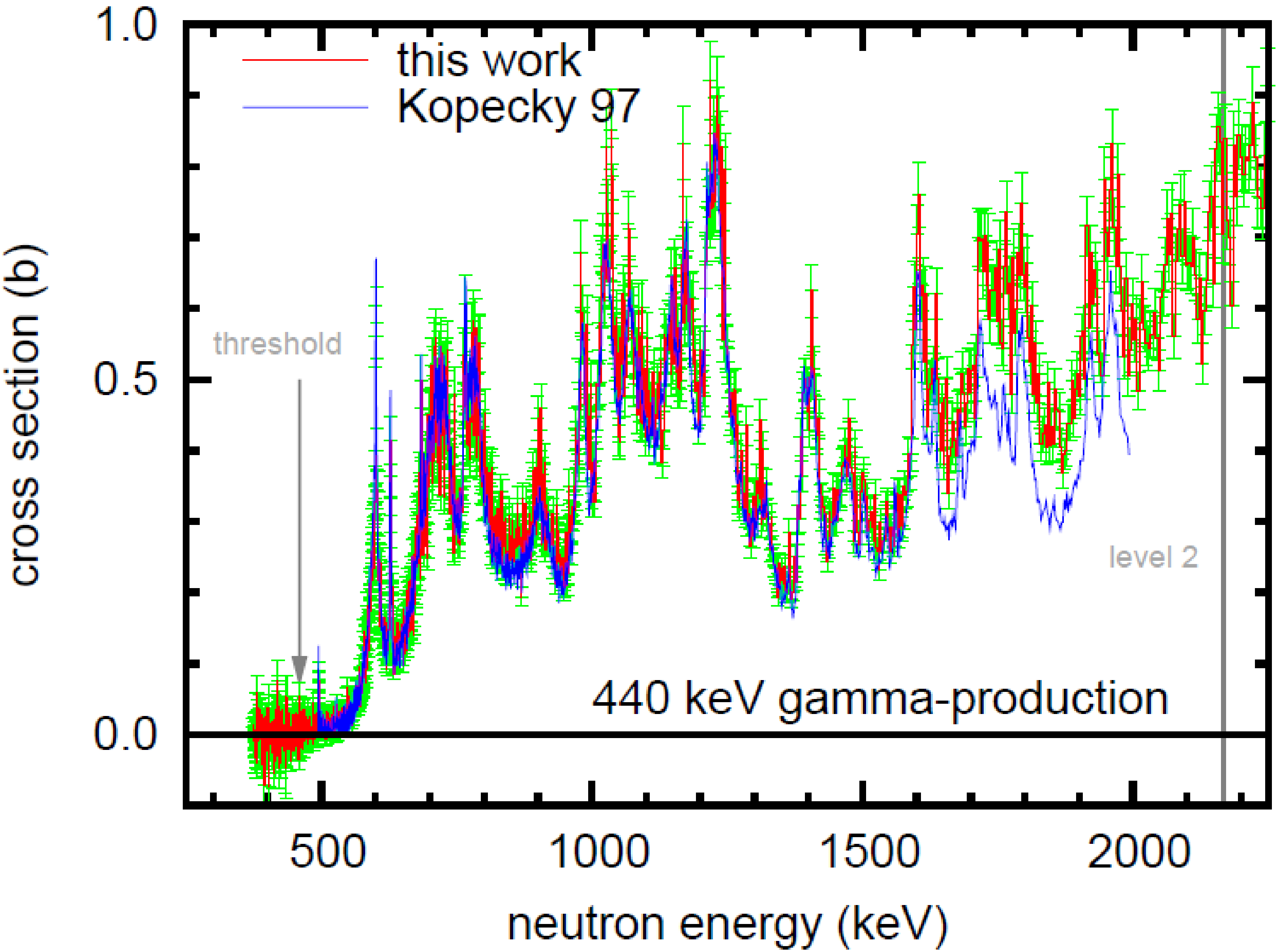
More accurate new value: +1% and 0.3% uncertainty

European Commission



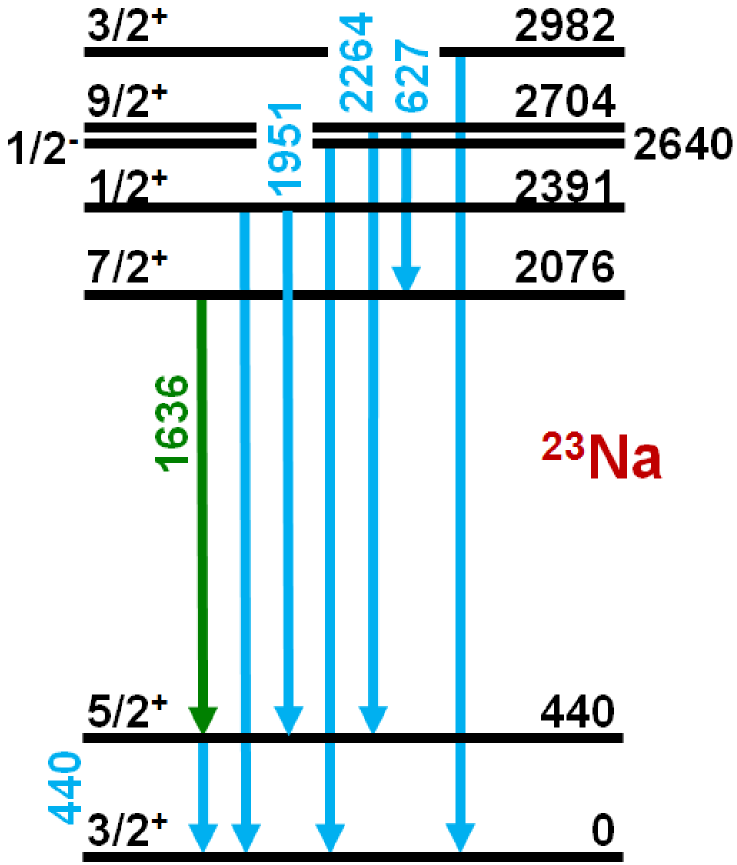


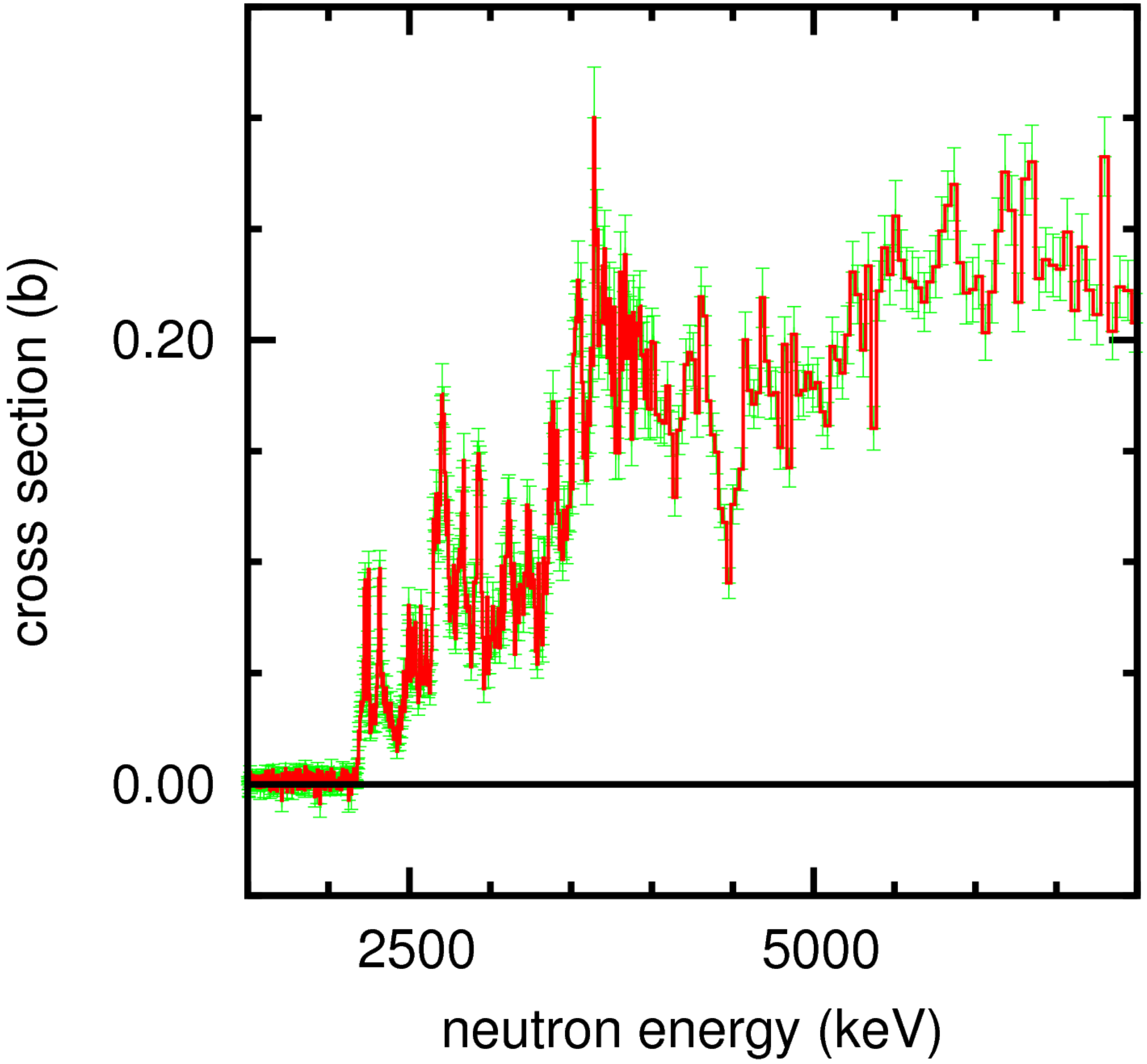
Joint Research Centre



Example ^{23}Na, 440 keV

Example ^{23}Na, 1636 keV





Activation cross section measurements

European Commission

Neutron source

- 7MV Van de Graaff accelerator
- Binary reactions for quasi mono-energetic neutrons $^{7}Li(p,n)^{7}Be$, $^{3}H(p,n)^{3}He$, $^{3}H(d,n)^{4}He$ reaction
- High intensity compared with time-of-flight, but only one energy per measurement
- Solid-state Ti/T

Samples

- Both natural and enriched

Example $^{241}Am(n,2n)^{240}Am$

Neutron energy and flux monitoring

- The neutron fluence rate was determined by the $^{27}Al(n,\alpha)^{24}Na$ ENDF/B-VI standard cross section
-

The neutron flux density distribution were determined by the spectral index method

$^{115}In(n,n')^{115m}In$, $^{58}Ni(n,p)^{58}Co$,

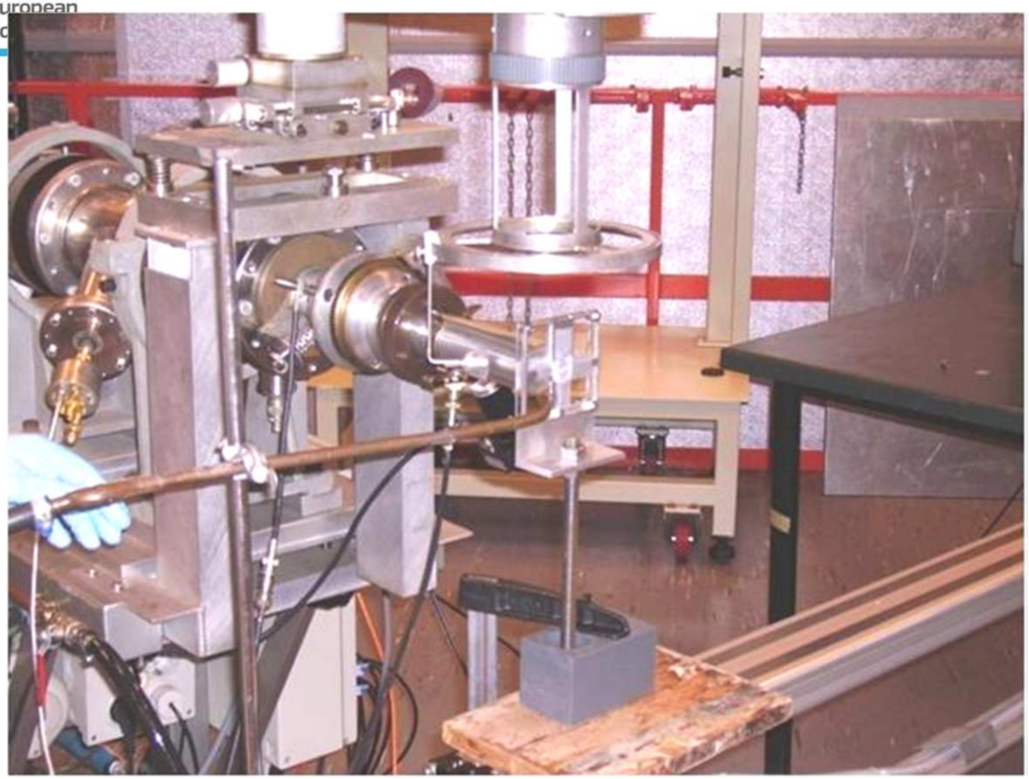
$^{27}Al(n,p)^{27}Mg$, $^{27}Al(n,\alpha)^{24}Na$, $^{56}Fe(n,p)^{56}Mn$, and $^{93}Nb(n,2n)^{92m}Nb$

distinct energy thresholds

time-of-flight spectrum

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

Fission
Activation measurements
light charged particles
Flux (BIPM)
Calibration of detectors



Irradiation setup
L3 beamline with Ti/T target
Light weight sample holder

7 MV Van de Graaff accelerator

Joint Research Centre

Sample preparation

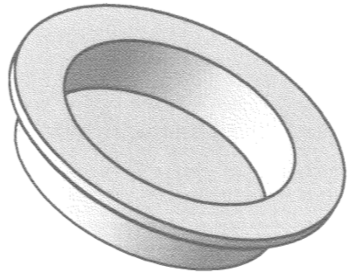
9 samples

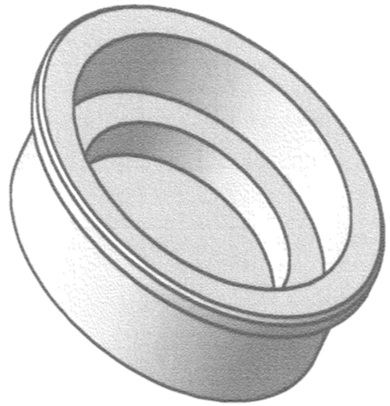
- **32.2 to 42.2 mg ^{241}Am (AmO_2)**
- **0.3 to 0.4 g Al_2O_3 matrix**
- **Ø =12.2 mm, height=1.6 to 2.1 mm**
- **5 GBq/piece, 10 mSv/h contact**

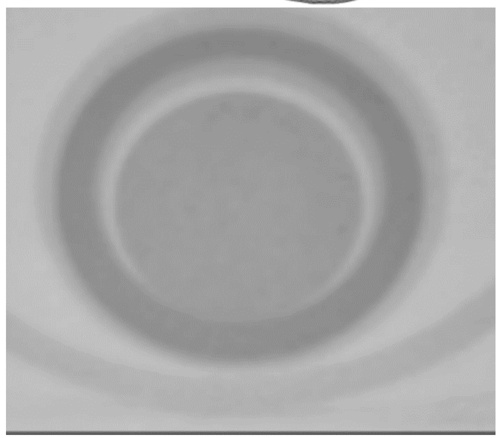
Infiltration technique (JRC-ITU, Karlsruhe) :

- **Porous alumina granules made by powder metallurgy**
- **Am infiltration with a nitrate solution**
- **Drying/calcination**

Nästren, Holzhäuser, Fernandez, Brossard, Wastin, Ottmar, Somers

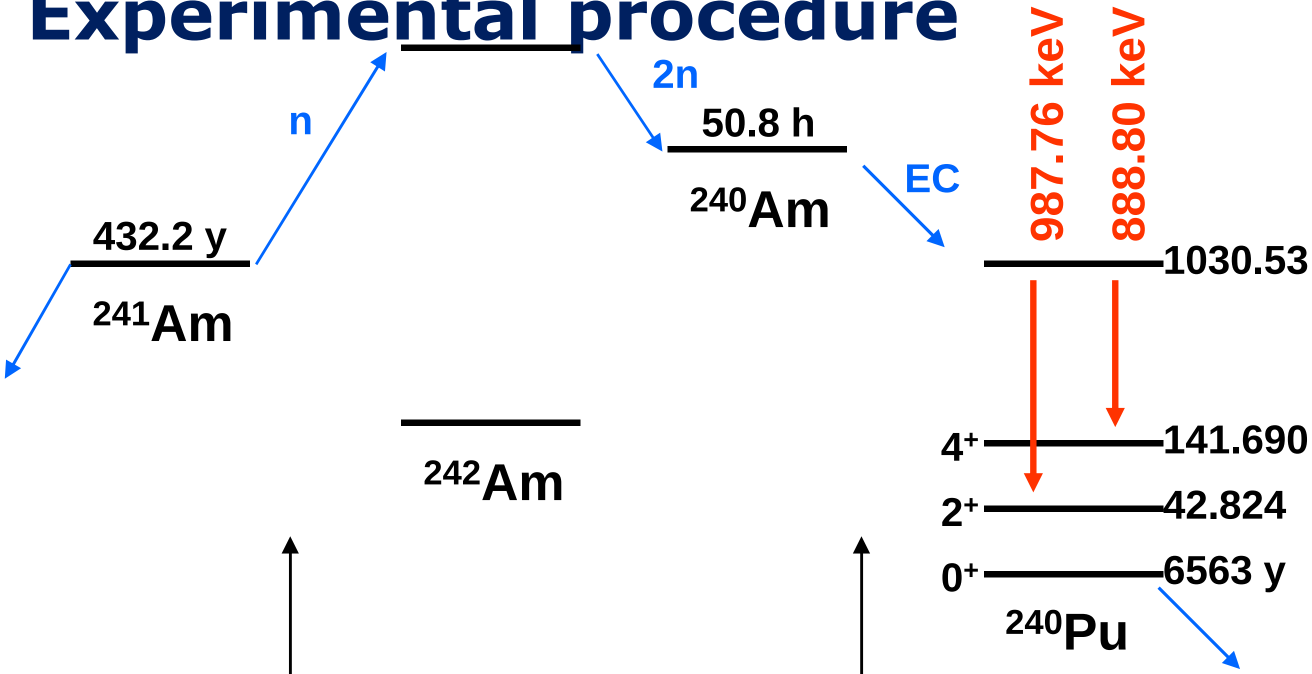






Schematic (n,2n) process and level scheme

Experimental procedure



n-source
n-flux measurement
Activation foil technique

Activity determination
sample
monitor foils
HPGe

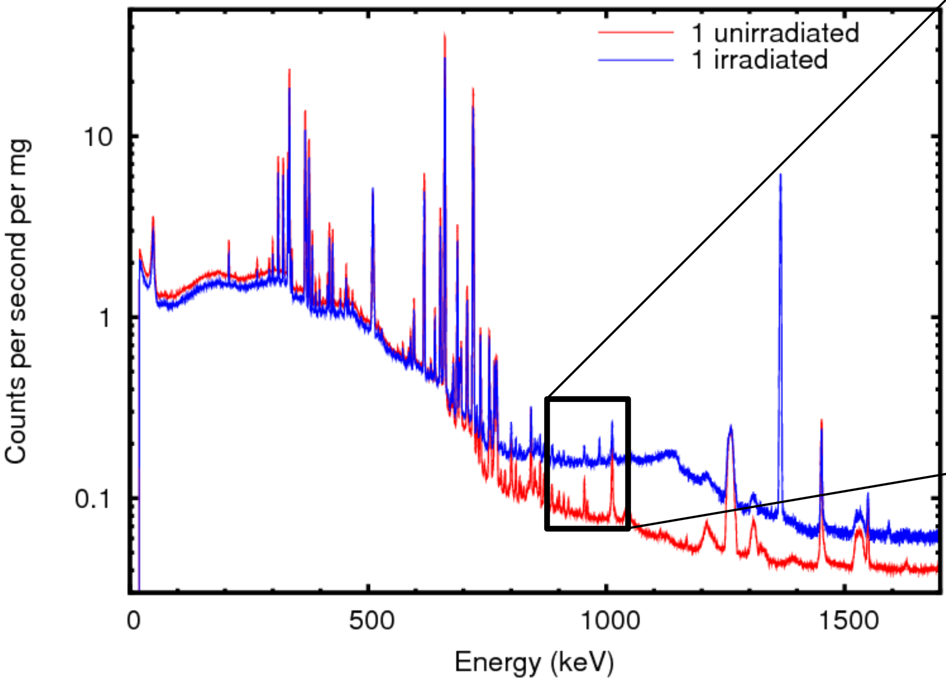
Relevant gamma rays

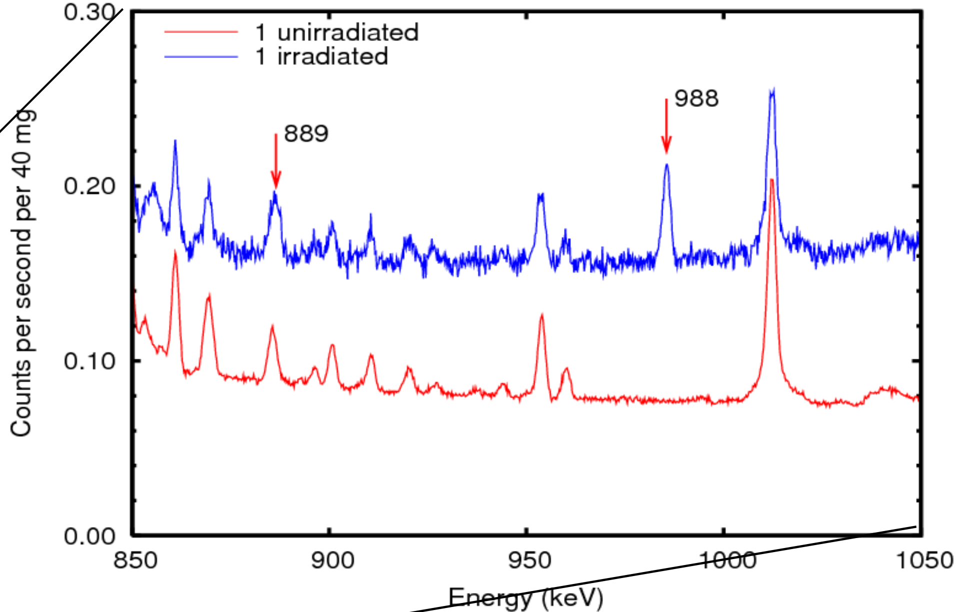
Nucleus	Half life	E_γ	I_γ
		(keV)	(%)
^{239}Am	11.9(1) h	278	15.0(17)
		228	11.3(13)
^{240}Am	50.8(3) h	**988**	**73(4)**
		889	**25.1(13)**
^{241}Am	432.1(7) y	60	35.9(5)
		233	$4.6(3)\ 10^{-6}$
		276	$6.6(4)\ 10^{-6}$
		278	$4.4\ 10^{-7}$
		887	**$2.2(5)\ 10^{-7}$**
		922	$1.9(4)\ 10^{-7}$

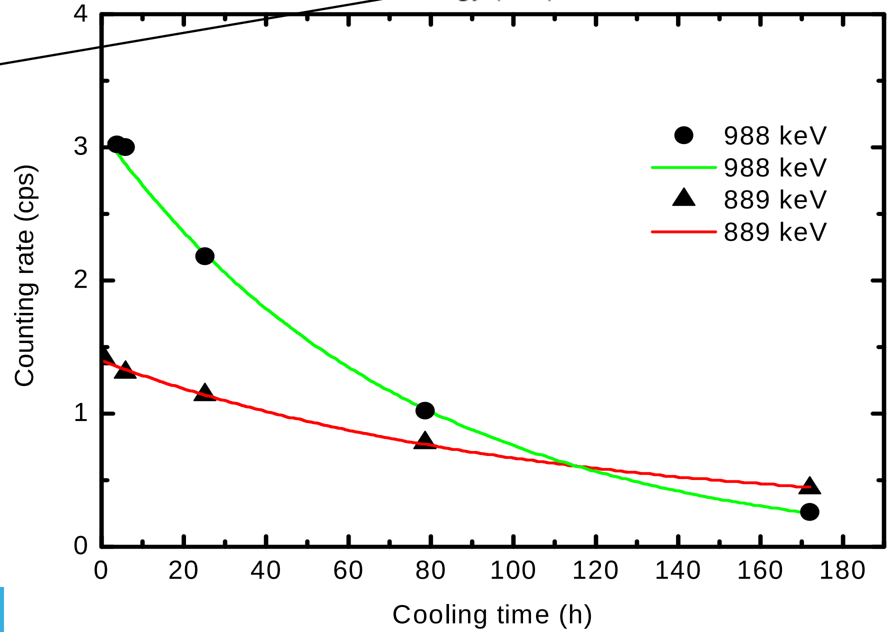
Activity determination

^{240}Am $T_{1/2}$ 50.8(3) h

- 988 keV 73(4)%
- 889 keV 25.1(1.3)%
- fitted $T_{1/2}$(988 keV)= 50.88 h





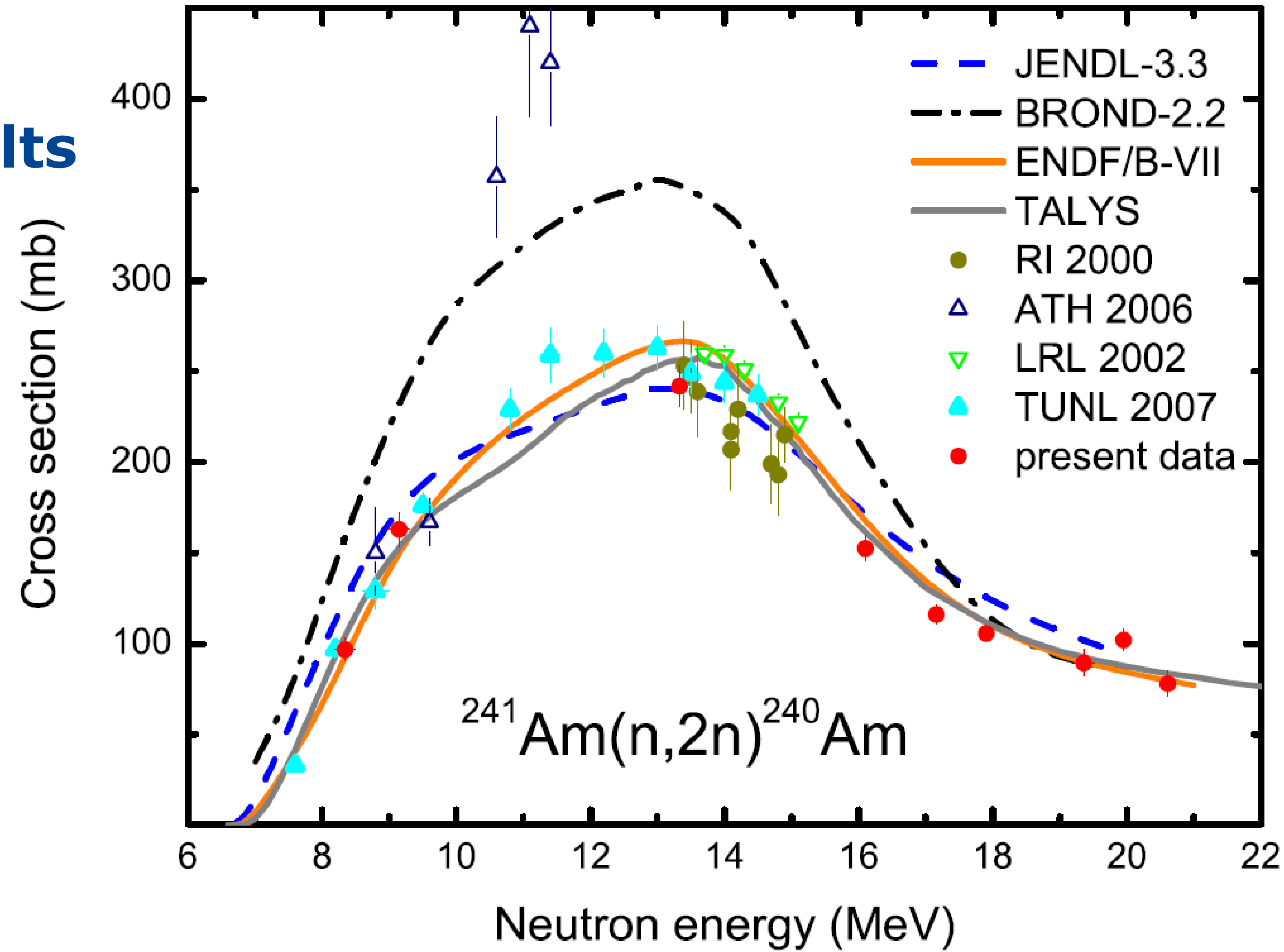


Shielding: 5 mm Pb + 2 mm Sn + 1 mm Cu

^{27}Al(n,α)^{24}Mg from container and matrix

Dead time ~ 10%

Results



Cross section (mb)
100
200
300
400
6
8
10
12
14
16
18
20
22
Neutron energy (MeV)
JENDL-3.3
BROND-2.2
ENDF/B-VII
TALYS
RI 2000
ATH 2006
LRL 2002
TUNL 2007
present data
$^{241}Am(n,2n)^{240}Am$