Using neutron resonances for non-destructive material analysis: the ANCIENT CHARM project

Enrico Perelli Cippo and the ANCIENT CHARM Collaboration

Departement of physics "Giuseppe Occhialini",

University of Milan-BICOCCA

ANCIEN CHARM is an EU funded adventure project under the *New and Emerging Science and Technology (NEST)* program of FP6.

http://ancient-charm.neutron-eu.net/ach

Partner	Country
Università degli Studi di Milano-Bicocca	Italy
Università degli Studi di Roma Tor Vergata	Italy
Leiden University	the Netherlands
Hungarian National Museum	Hungary
Universität Bonn	Germany
Technical University Delft	the Netherlands
Institute of Isotopes – Chemical Research Centre	Hungary
Universität Köln	Germany
Central Laboratory of the Research Councils	United Kingdom
EC - JRC - IRMM	Belgium

And the expertise in neutron physics and instrumentation: H. Postma, M. Moxon

Aim of the project is to conjugate *" ....Neutron resonant Capture Imaging and other Emerging Neutron Techniques...."* for non-destructive analysis of material.

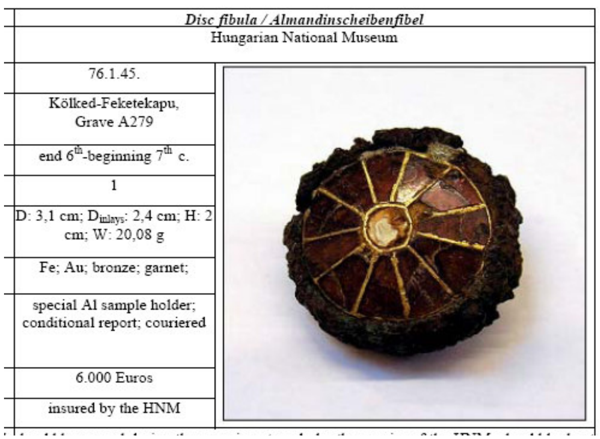
Neutron Resonance Capture Imaging combined with
Neutron Resonance Transmission Imaging
non-invasive techniques for element-sensitive imaging

Aim of the project is to conjugate *“ ....Neutron resonant Capture Imaging and other Emerging Neutron Techniques....”* for non-destructive analysis of material.

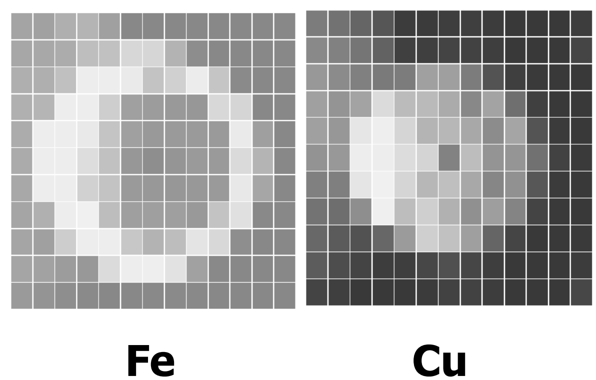
Neutron Resonance Capture Imaging combined with Neutron Resonance Transmission Imaging

In addition, related imaging methods:

Prompt Gamma Activation Imaging **(FRM II, IKI)**



Disc fibula / Almandinscheibenfibel
Hungarian National Museum
76.1.45.
Kölked-Feketekapu, Grave A279
end 6th-beginning 7th c.
1
D: 3,1 cm; D inlays: 2,4 cm; H: 2 cm; W: 20,08 g
Fe; Au; bronze; garnet;
special Al sample holder; conditional report; couriered
6.000 Euros
insured by the HNM



Images thanks to T. Belgya, IKI

Aim of the project is to conjugate *" ....Neutron resonant Capture Imaging and other Emerging Neutron Techniques...."* for non-destructive analysis of material.

Neutron Resonance Capture Imaging combined with Neutron Resonance Transmission Imaging

In addition, related imaging methods:

Prompt Gamma Activation Imaging (FRM II, IKI)

Neutron Tomography (FRM II, IKI)

Images thanks to FRM II ANTARES NT station

NRCA and NRT make use of epithermal neutrons

E_n up to 1 keV

- No sample preparation needed
- Non - destructive
- Negligible residual activation

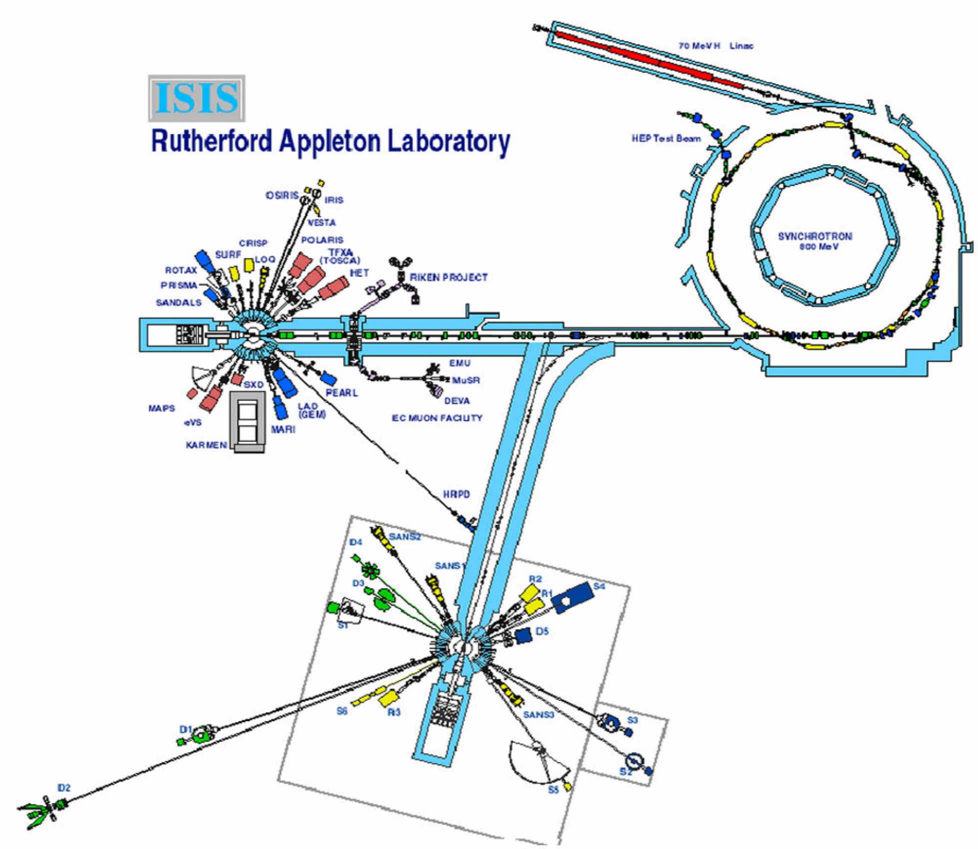
Neutron absorption resonances can be used for:

- Nuclide identification and quantification
- Elemental (& isotopic) composition

NRCA and NRT make use of epithermal neutrons

E_n up to 1 keV

Pulsed white neutron beam (GELINA, ISIS)



INES beamline at the ISIS spallation source	
Average current	150 – 180 μA (p)
Neutron pulse width	300 ns
Flight path length	23.0 m
Beam dimensions	50 x 50 mm
Flux at sample pos.	10^3 n/eV s cm2 at 10 eV

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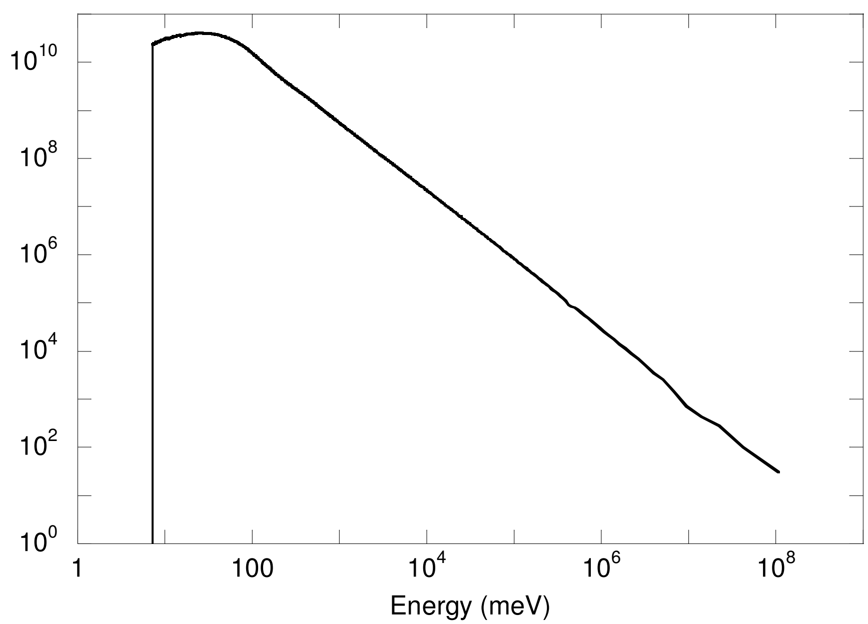

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"Undermoderated" beam at INES

NRCA and NRT make use of epithermal neutrons

E_n up to 1 keV

Pulsed white neutron beam (GELINA, ISIS)

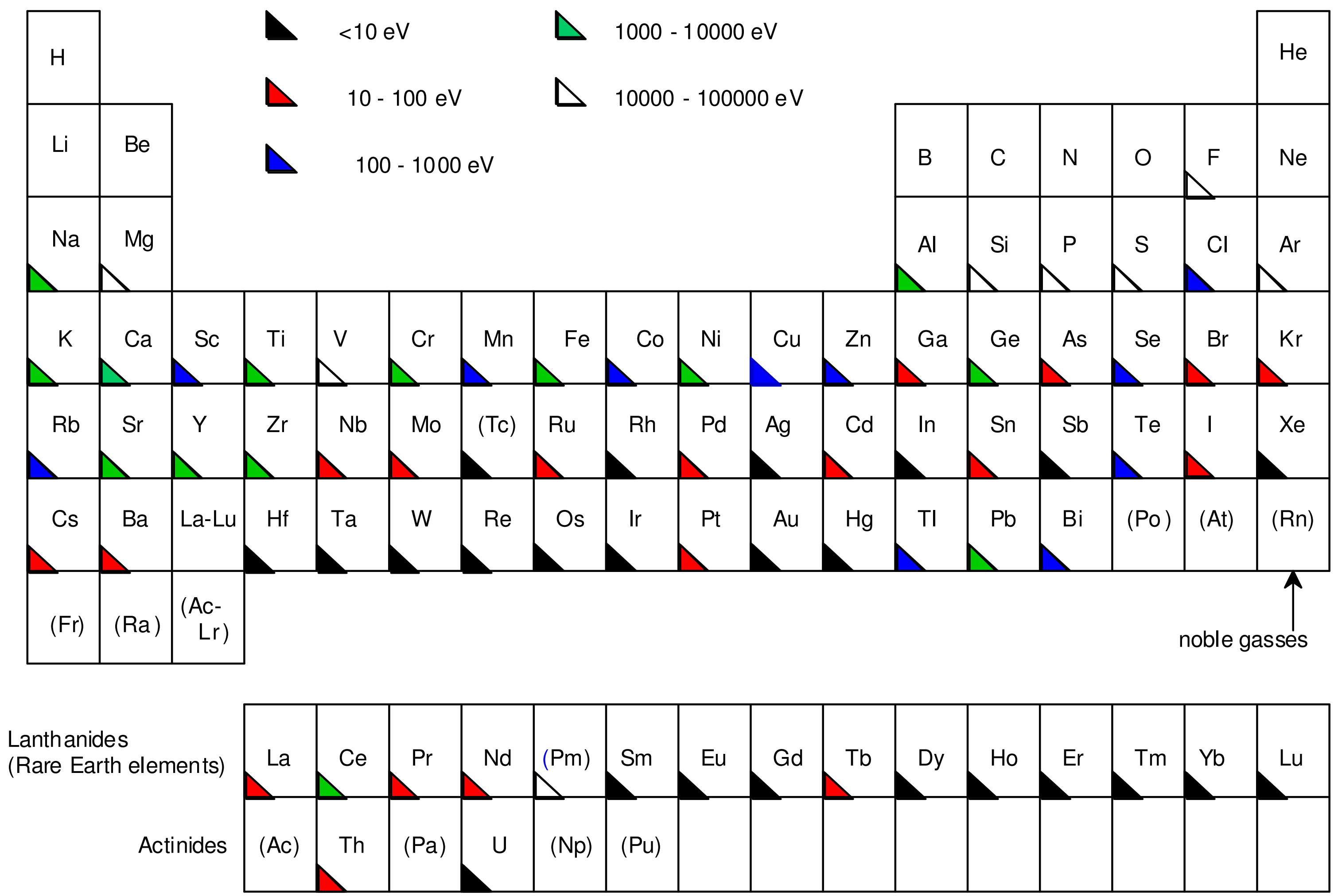
Absorption resonances are identified with the TOF technique

$$E_n = \left(\frac{72.2985 L}{t + t_0} \right)^2$$

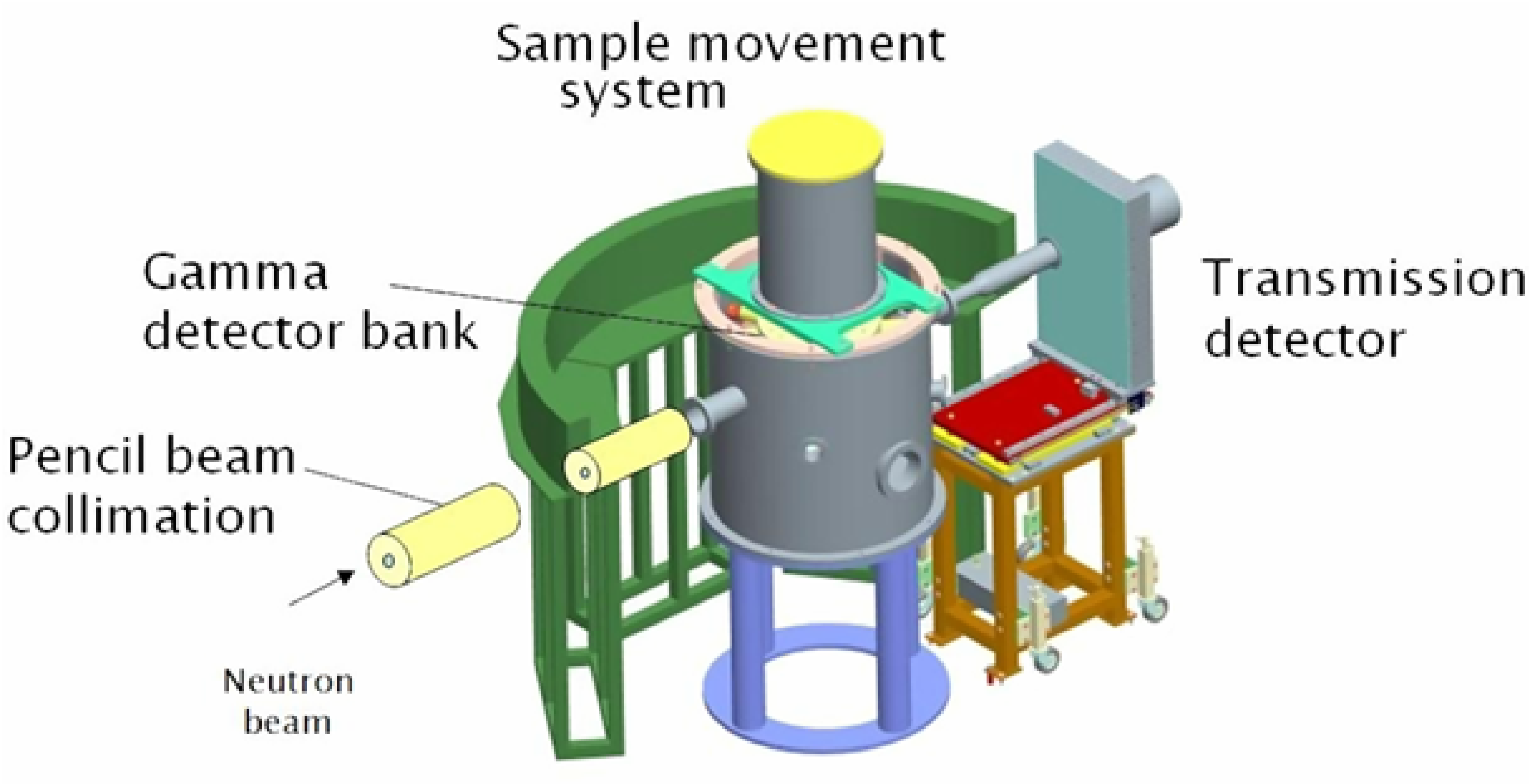
FAST detectors and electronics are crucial

NRCA and NRT make use of epithermal neutrons

E_n up to 1 keV



The neutron resonance transmission set-up



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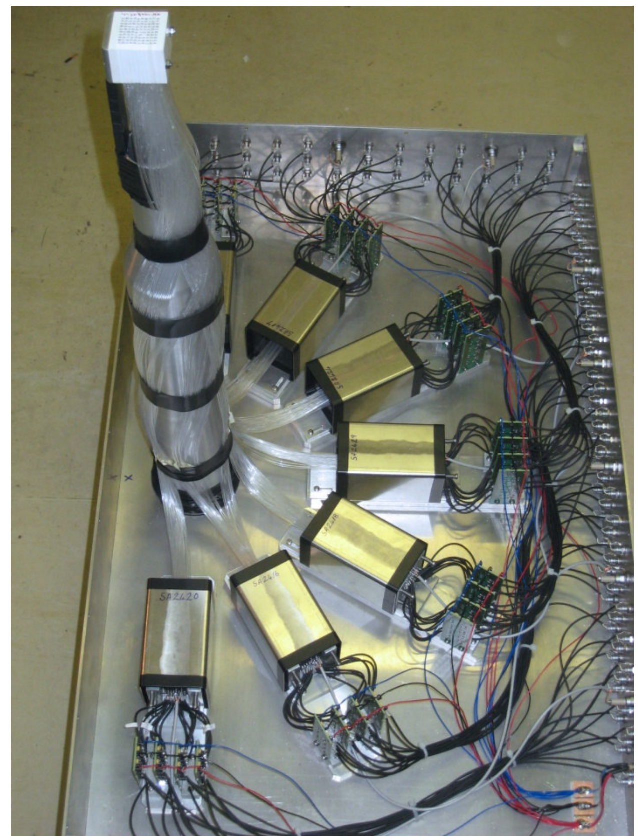

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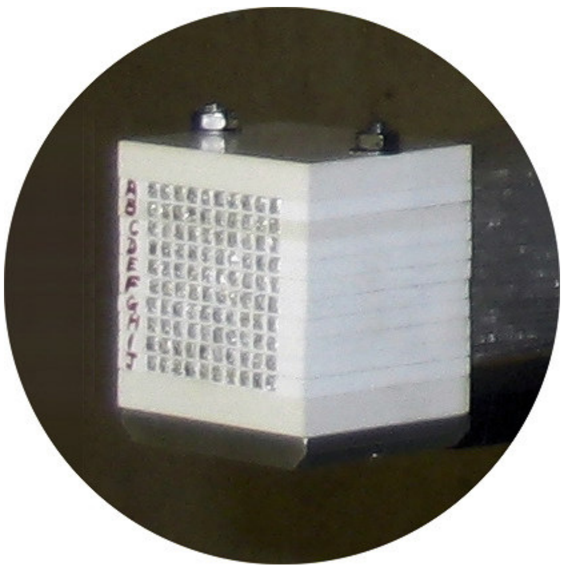
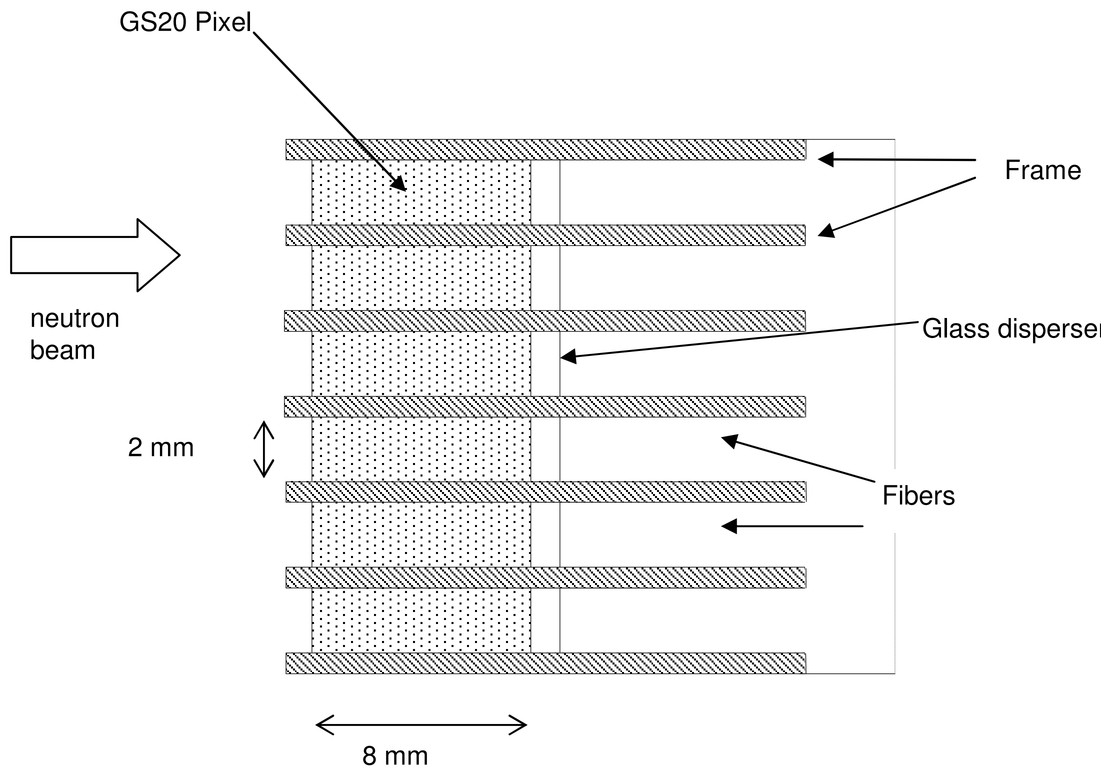




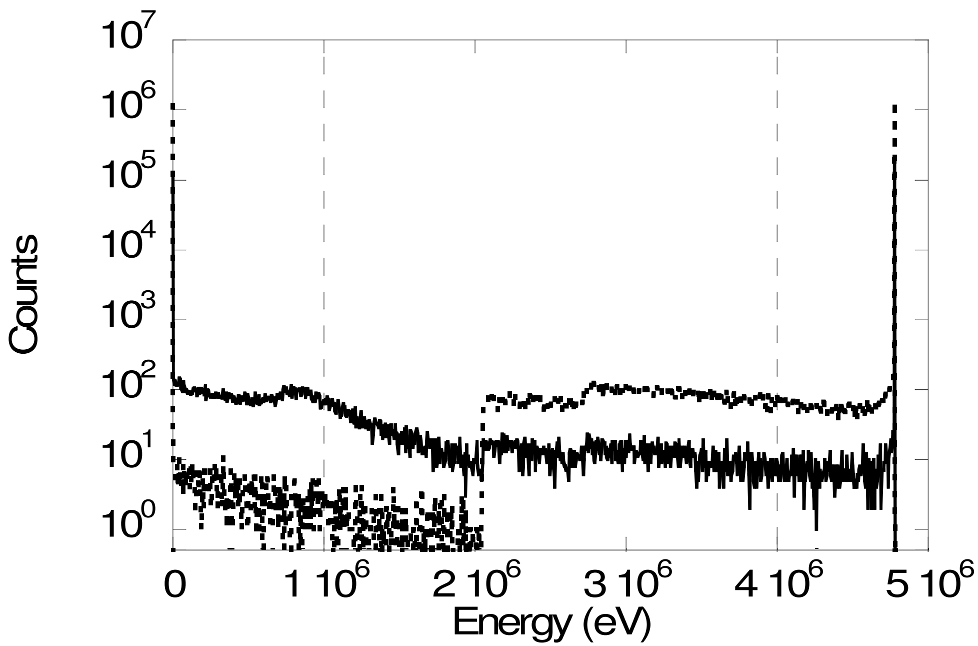
PSND

10 x 10 GS20 Li-enriched scintillator pixels

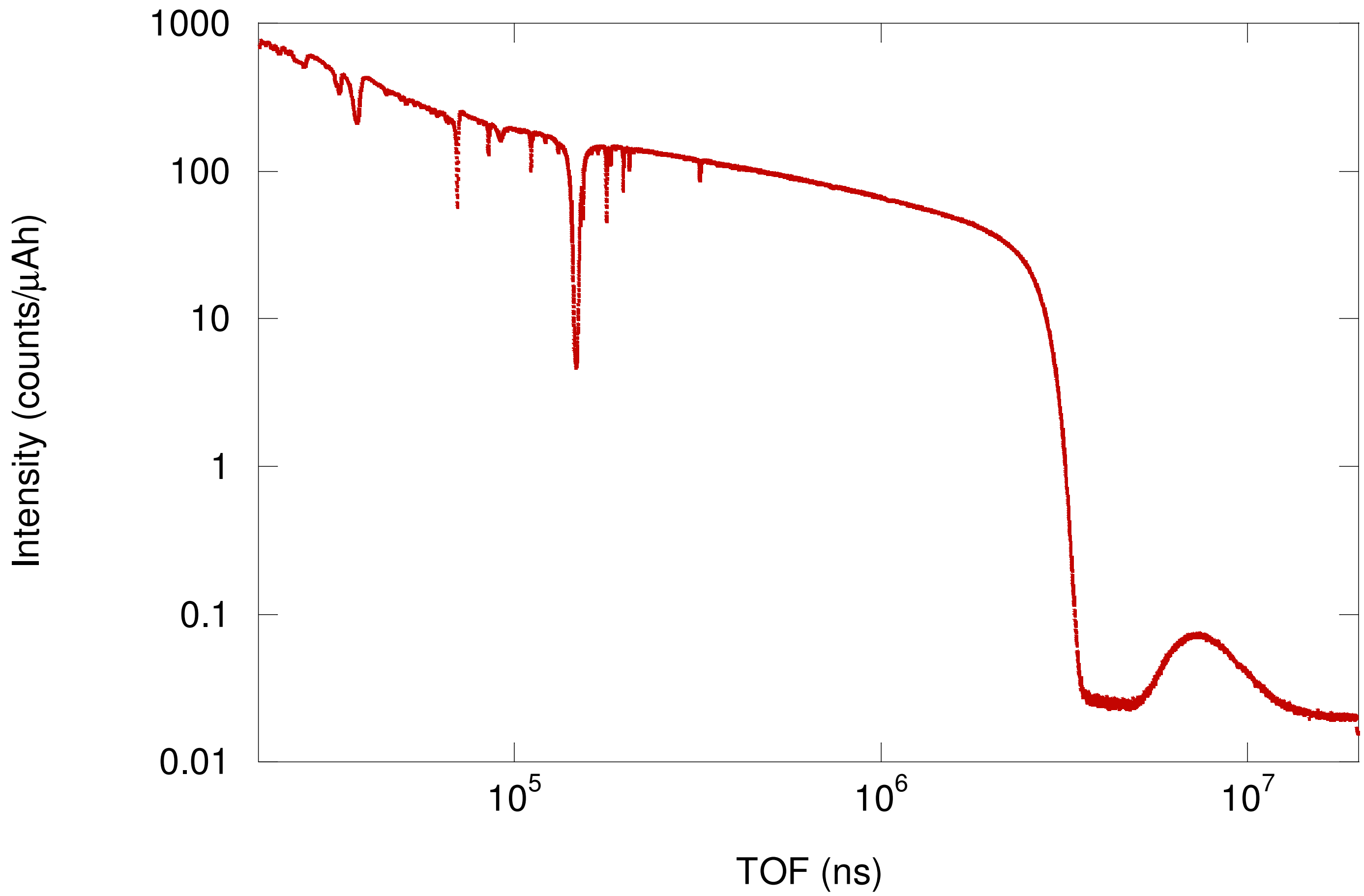
25% efficiency at 10 eV

4 % efficiency at 1 keV

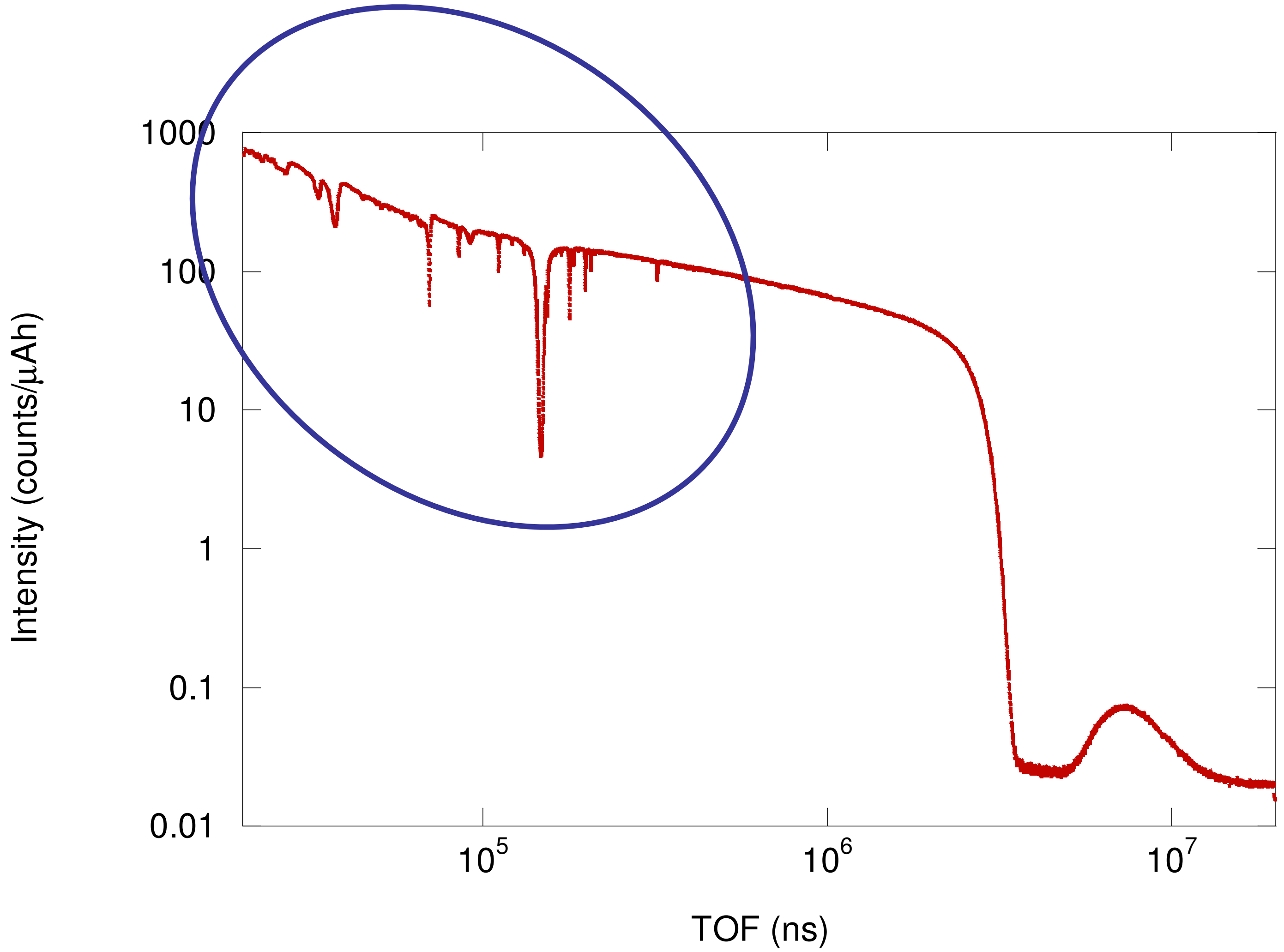
Neutron spectrum from a GS20 pixel



The transmission TOF spectrum



The transmission TOF spectrum



The physical quantity measured is the transmission factor:

$$T(E) = \frac{C_{in}}{C_{out}} = e^{-\sum_{X} n_x \sigma_{tot}(E)} R(E)$$

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$$T_{\exp}(t) = N \frac{S_{in}(t) - B_{in}(t)}{S_{out}(t) - B_{out}(t)}$$

where $S_{in,\ out}$ are the signal obtained from the sample-in and sample-out for the flux, and $B_{in,\ out}$ are the background levels in the two cases. N is a normalisation constant.

This is valid for all the values of t (in and off-resonances).

S_{in} is the TOF transmission spectrum of the sample that has undergone

- Dead time correction:

$$DTCF = \frac{C_o}{(1 - \beta_0)} \quad ; \qquad \beta_0 = \sum_{i=(2t-1)/2}^{((2t-1)/2)+\Delta t} N(t)$$

$\Delta t \approx 275$ ns

DT correction function is an integral function in t

M. S. Moore, "Rate dependence of counting losses in neutron time-of-flight measurements", *Nucl. Instr. Meth.* **169** 245 (1980)

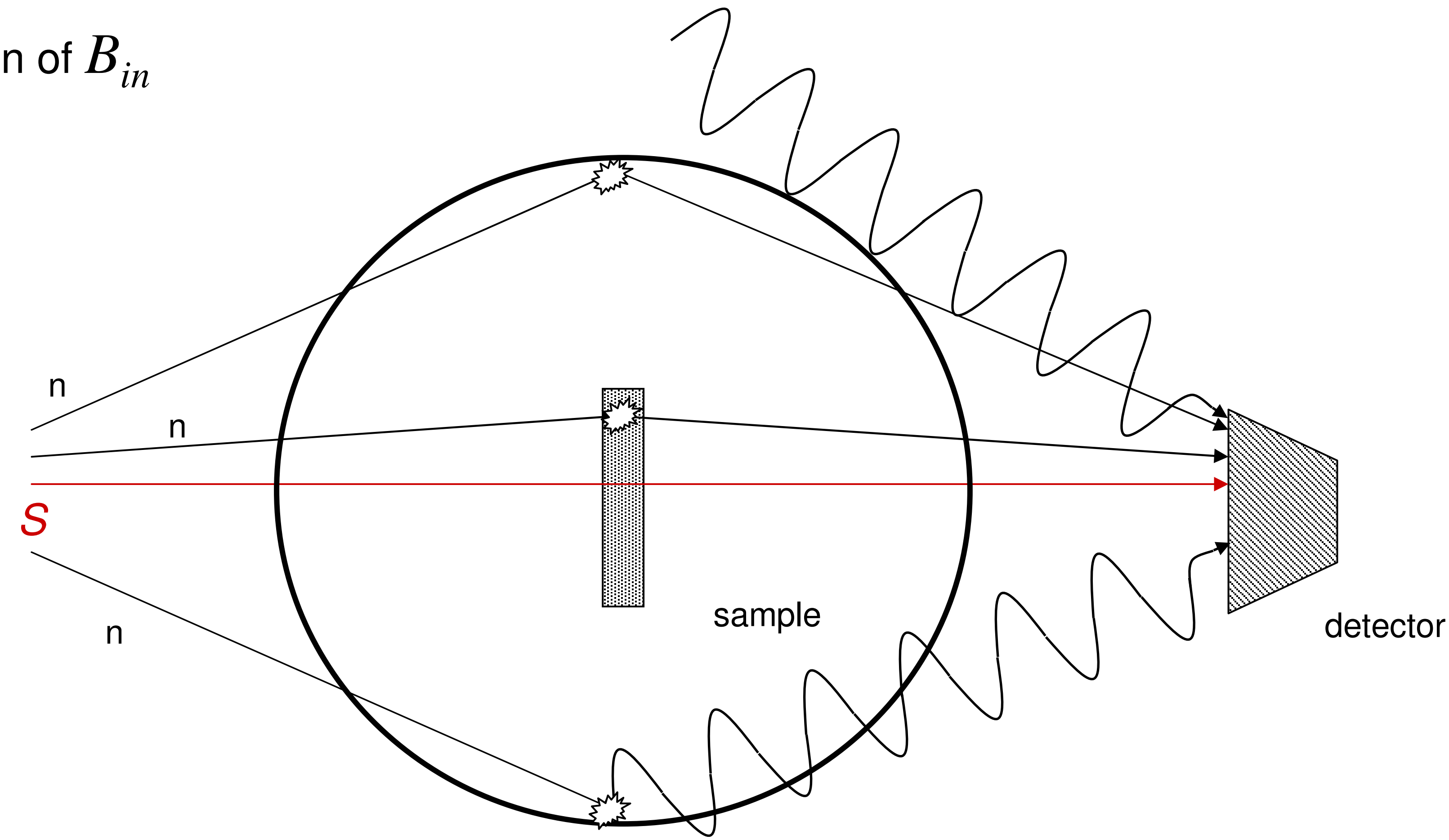
S_{in} is the TOF transmission spectrum of the sample that has undergone

- Dead time correction
- Normalisation to neutron flux

S_{in} is the TOF transmission spectrum of the sample that has undergone

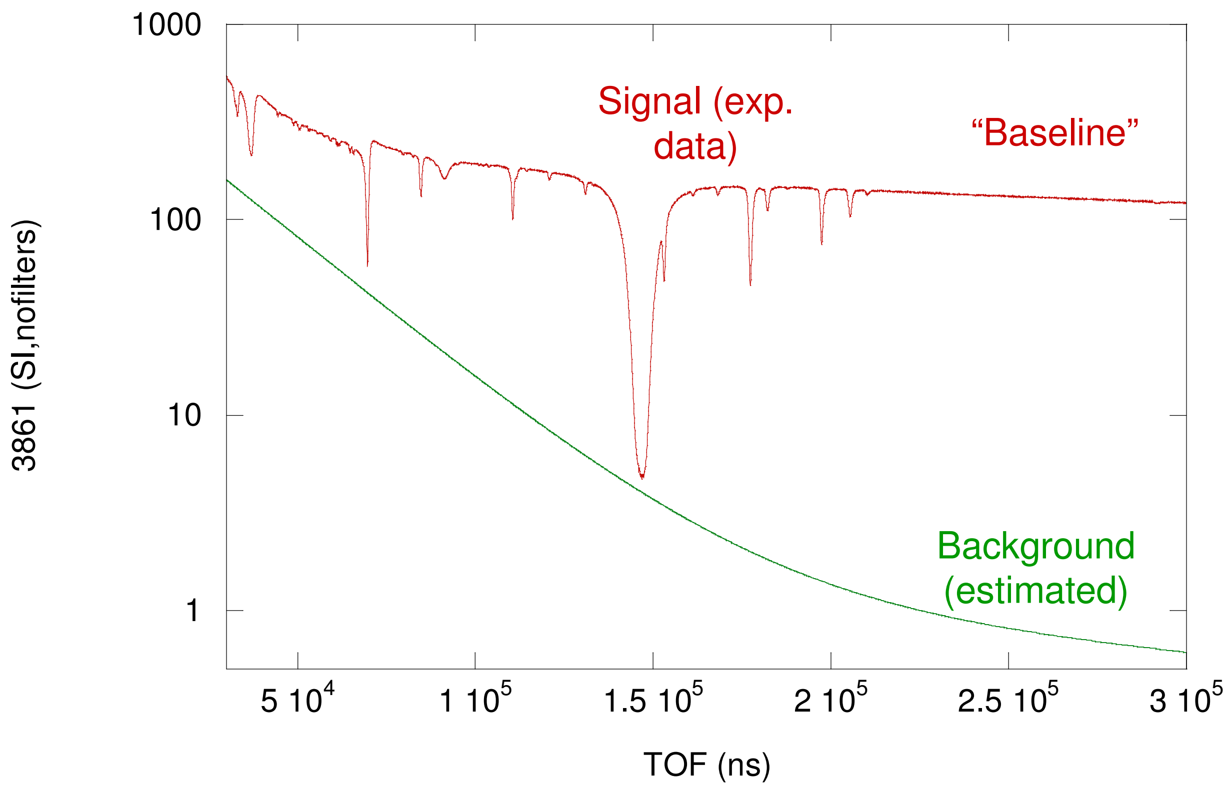
- Dead time correction
- Normalisation to neutron flux
- Normalisation to bin width

Definition of B_{in}

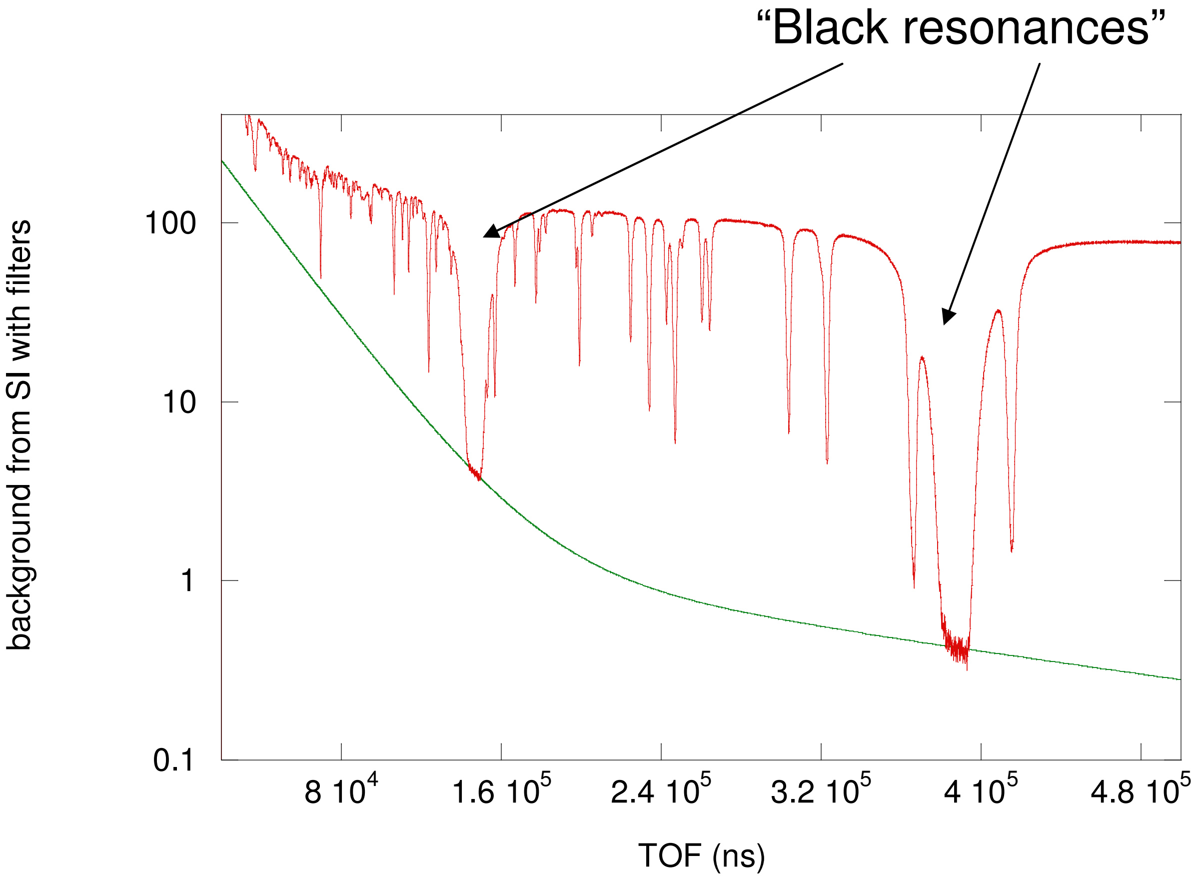


Only direct neutron passed through the sample give “Signal”.

Definition of B_{in}



How to determine B_{in}



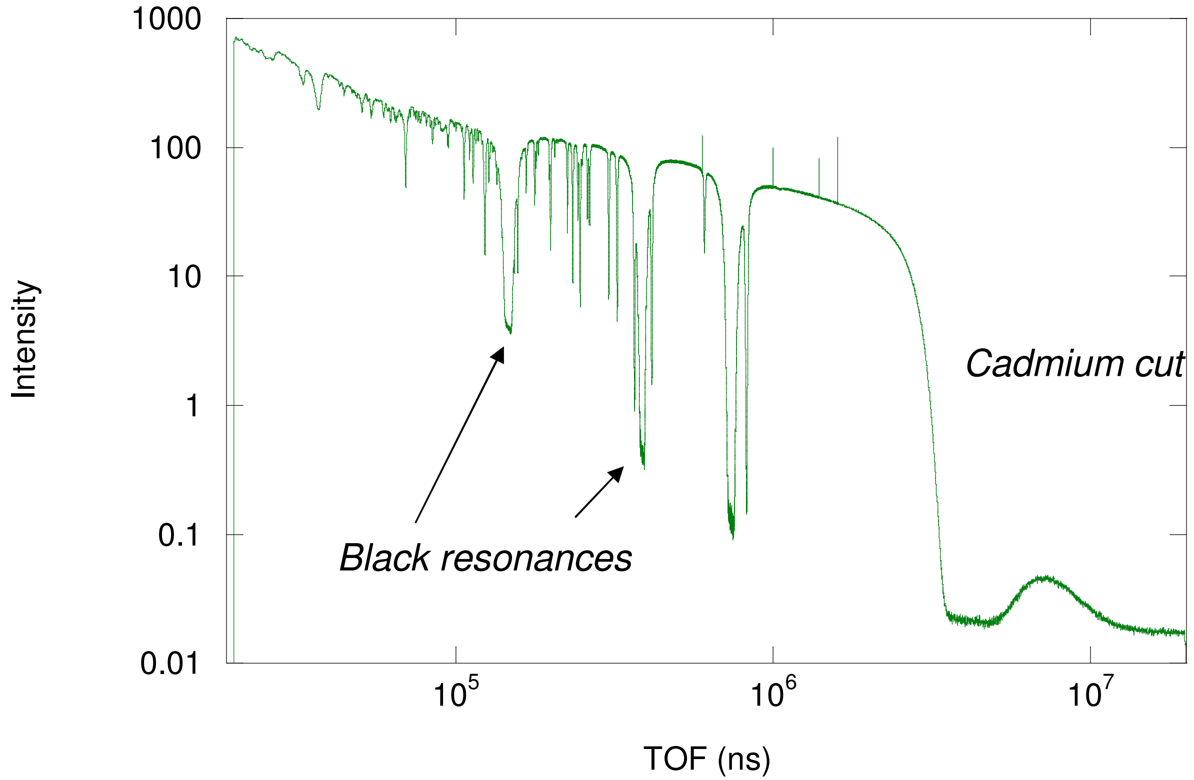
How to determine B_{in}

Resonances used:

Bi	800 eV	59 μs	
Co	132 eV	150 μs	
W	19 eV	390 μs	
Ag	5 eV	750 μs	
Cd	0.5 eV	3000 μs	(also for reducing activitation by thermal neutrons)

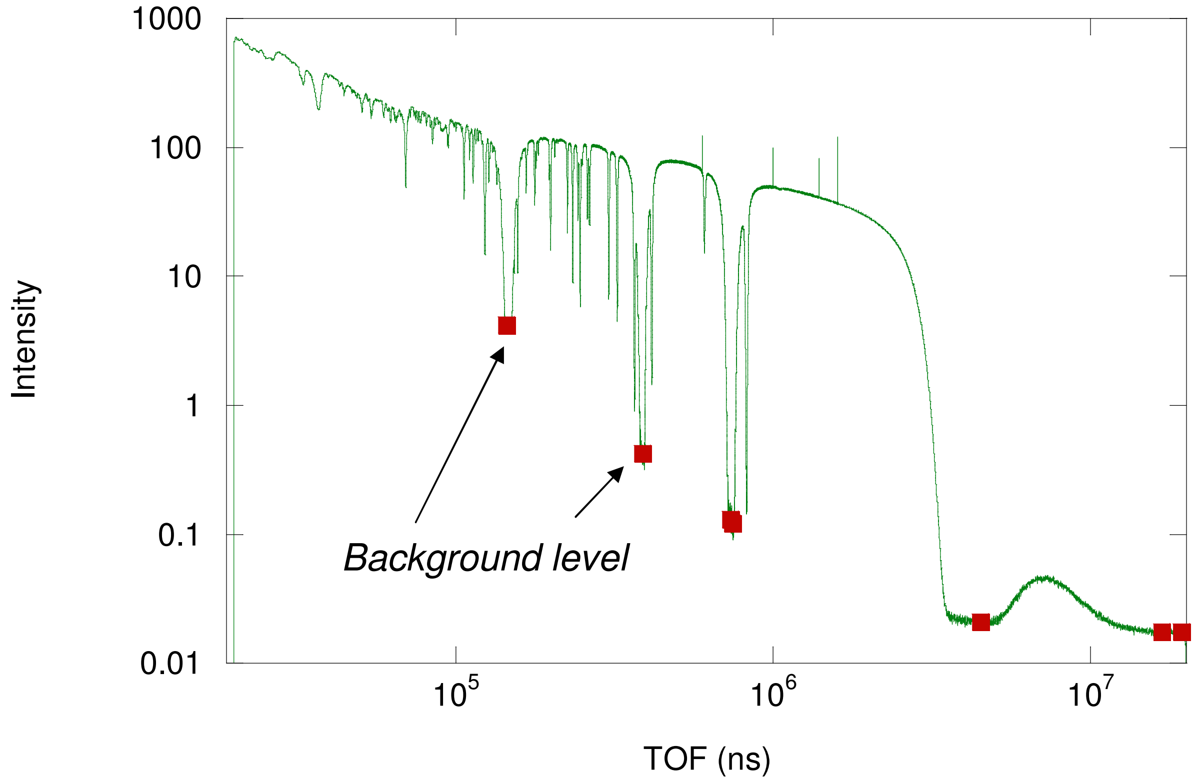
How to determine B_{in}

Spectrum from a sample-in + black resonances run



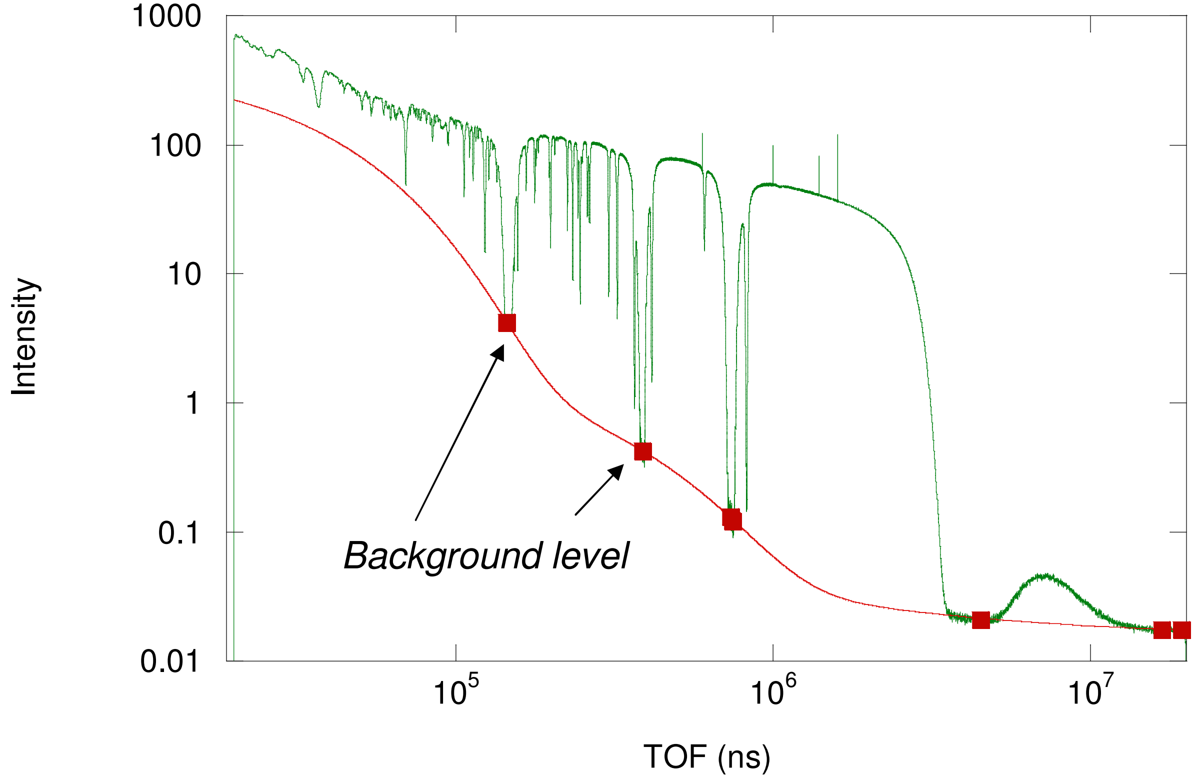
How to determine B_{in}

Estimated background level



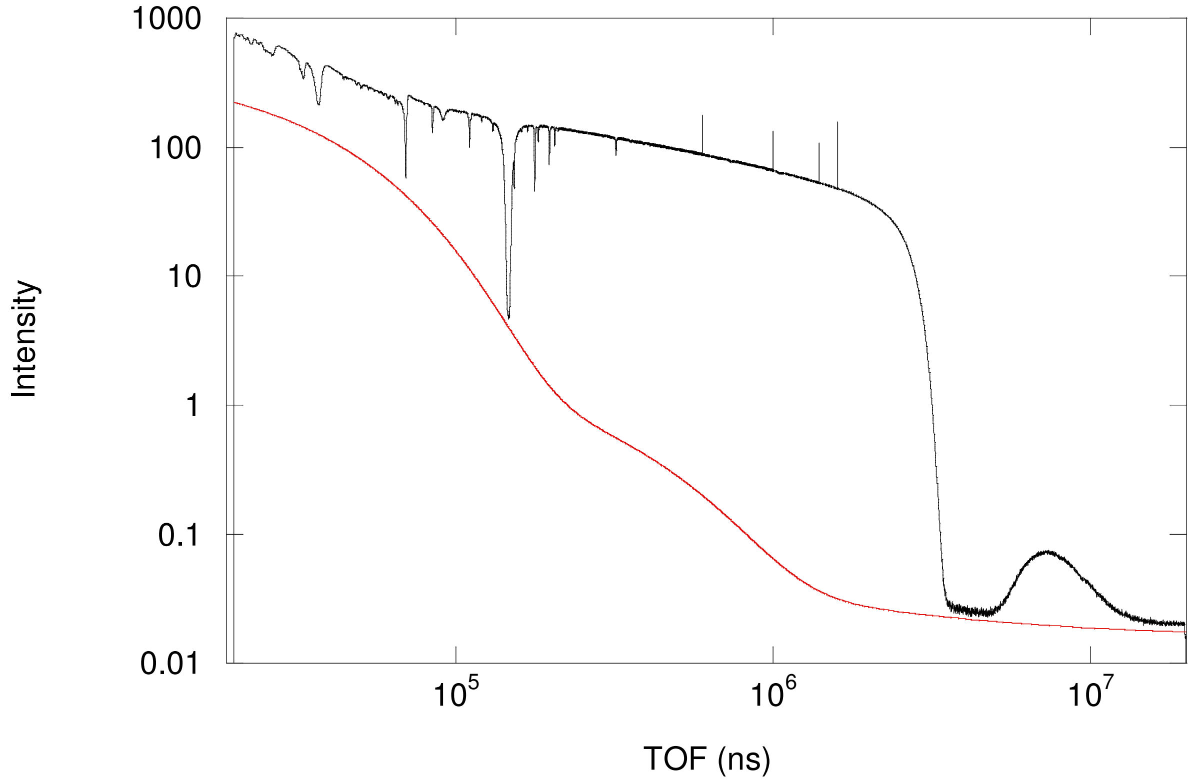
How to determine B_{in}

Estimated background interpolation



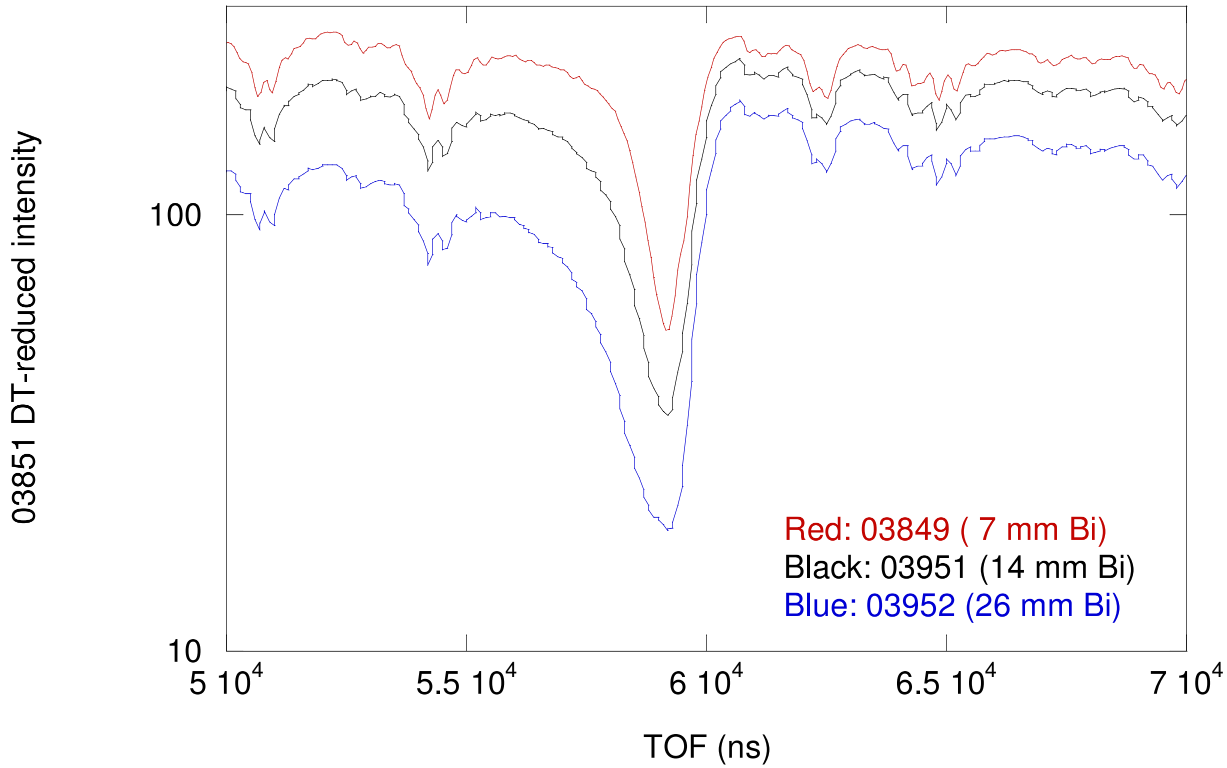
How to determine B_{in}

Estimated background level B_{in} compared with Sample-in (no filters) S_{in}



Bismuth problem:

Resolution problems make the bismuth black resonance to be not a strightforward background point. Moreover, bismuth is itself a source of background



How to determine B_{in}

The background is given by the interpolation of the background points whith the function:

$$a + b\ exp(-ct) + d\ exp(-et) + f\ t^{g}$$

How to determine B_{in}

$$T(t) = N\frac{S_{in}(t) - B_{in}(t)}{S_{out}(t) - B_{out}(t)}$$

experimental data

evaluated analytical function

AGS: a code for manipulation of TOF spectra

Step 1: DT correction and normalisation to all spectra, calculation of background points

Input: all the TOF spectra from INES DAE (in special format)

N. B. Step 1 macro needs information about time channels and time offset: it has to be adapted to every different ISIS cycle

AGS: a code for manipulation of TOF spectra

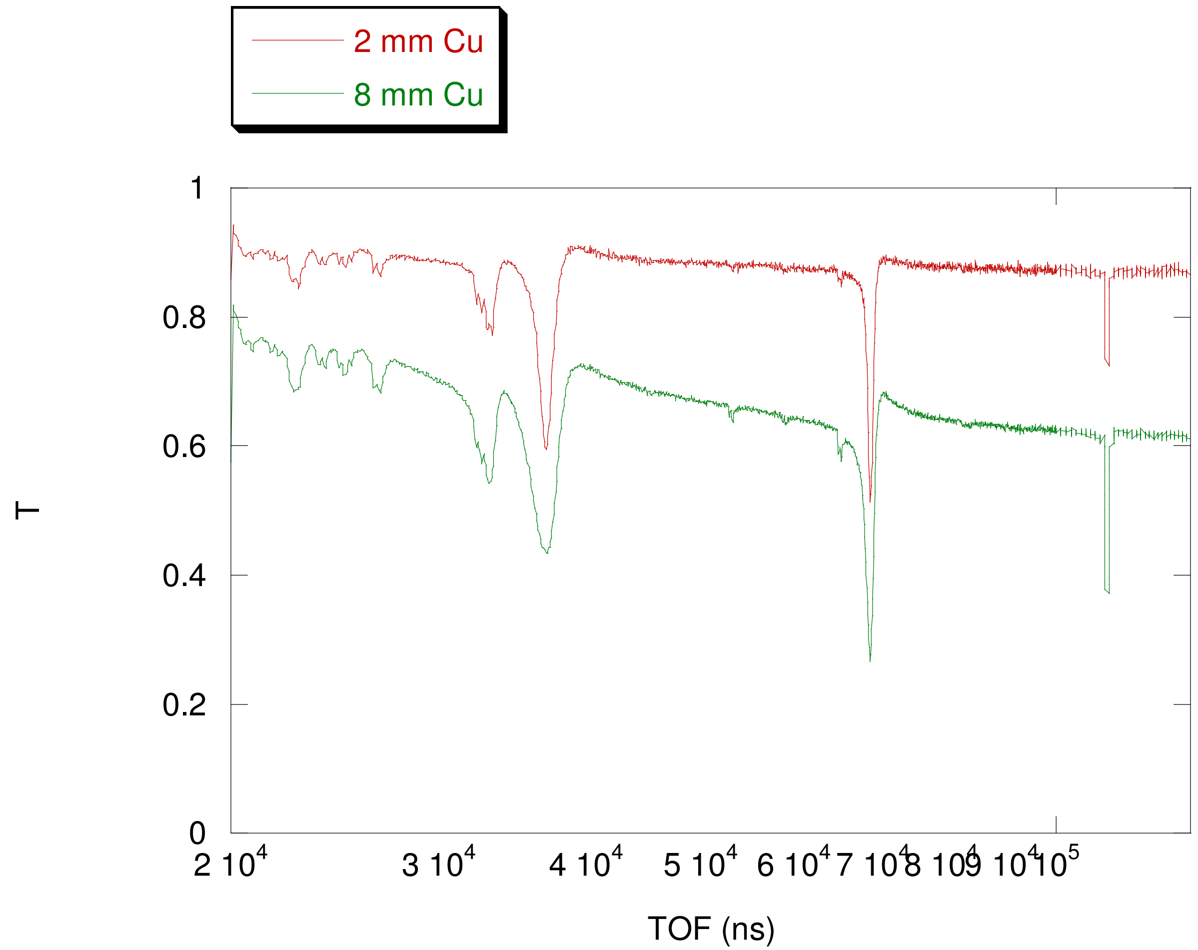
Step 1: DT correction and normalisation to all spectra, calculation of background points

Step 2: calculation of the transmission factor and production of a REFIT-compatible file

Input: $S_{in,\ out}$, $B_{in,\ out}$ spectra from Step 1, and *7* x *2 guess parameters (calculated outside AGS)*

Output: transmission factor in REFIT format and in text format

Transmission factor for Cu samples (INES, may – june 2009)



Optimum NRT analysis approach: REFIT

REFIT is a toolkit for analysis of transmission (and capture) neutron resonances spectra.

Advantage: fully quantitative

Resonaces are Doppler broadened

$$T(E) = \frac{C_{in}}{C_{out}} = e^{-\sum_{X} n_x \sigma_{tot}(E)} R(E)$$

Data do not have infinitely good resolution

Optimum NRT analysis approach: REFIT

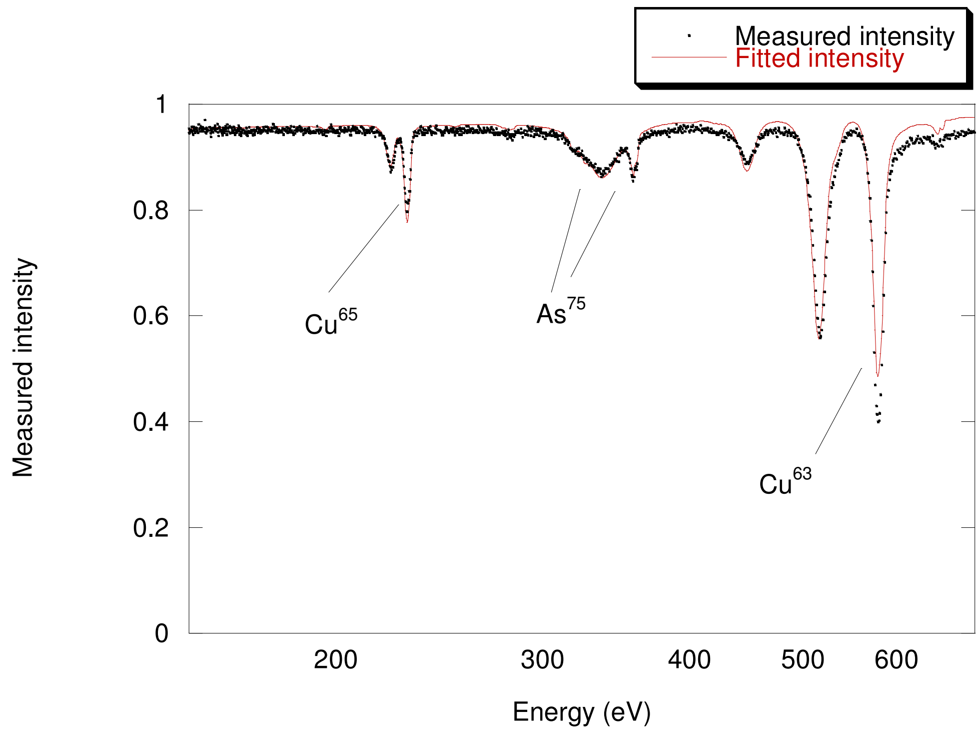
REFIT is a toolkit for analysis of transmission (and capture) neutron resonances spectra.

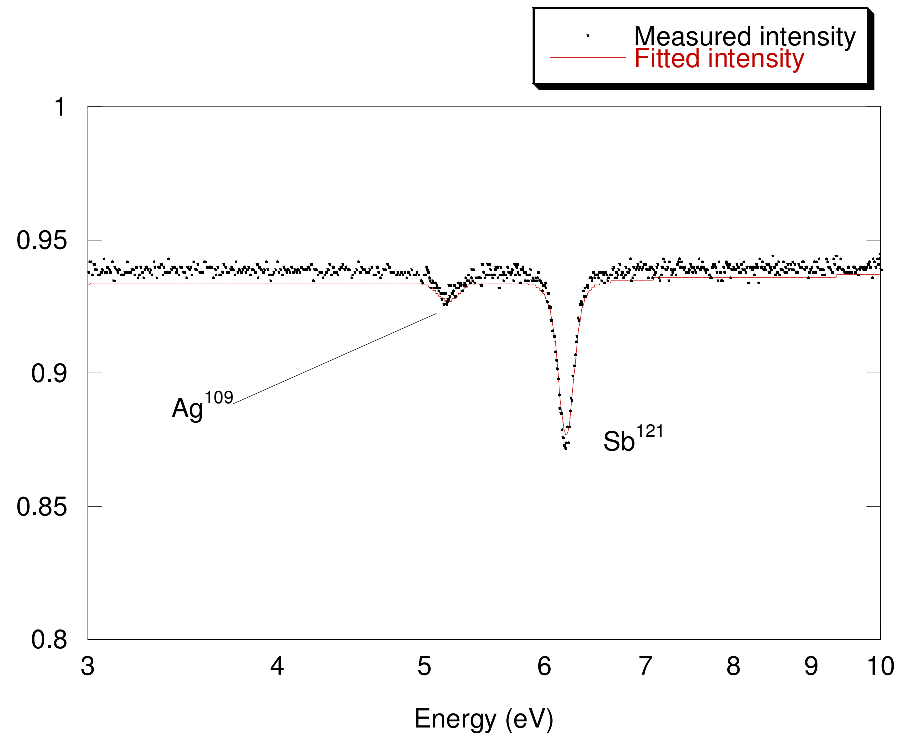
Calculation of Doppler broadening (various models)

energy dependence of the nuclear cross-section from the resonance parameters

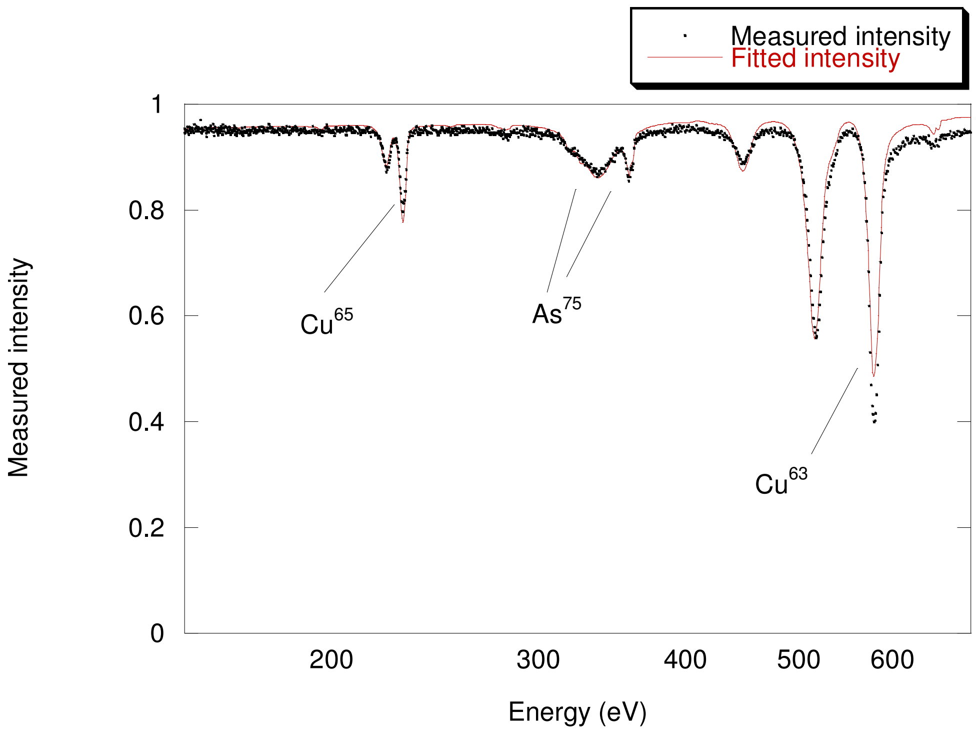
Calculation of resolution

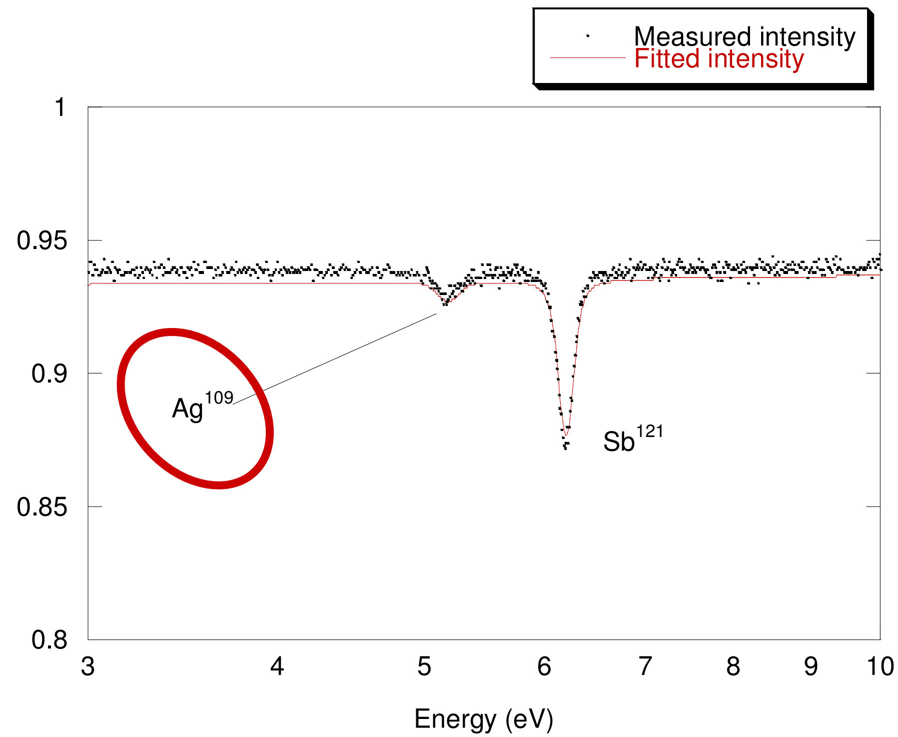
Fitting of the simulated spectra with experimental data to find $n(x)$





Element	Certified %wt	Estimated %wt
As	0.194	0.20
Sn	7.2	7.65
Zn	6.02	6.97
Sb	0.5	0.45
Mn	0.2	0.21
Ag	-	$12e^{-3}$





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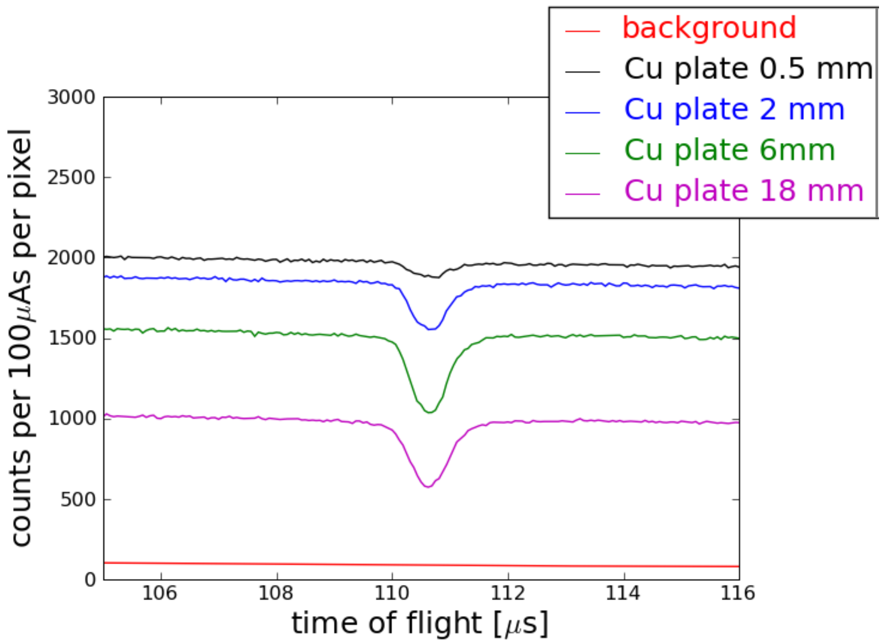
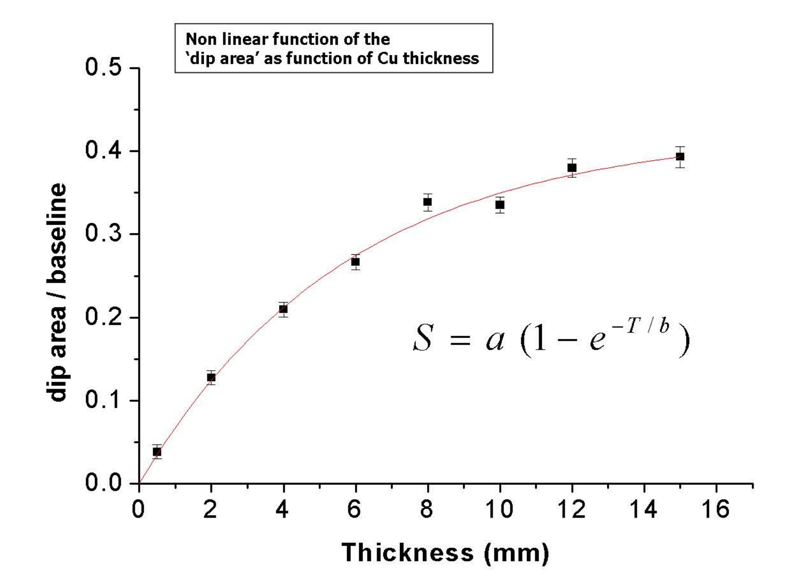
Simplified NRT analysis approach: area calibration

REFIT is ideal but quite long

Imaging requres the analysis of > 1000 spectra

Simplified NRT analysis approach: area calibration





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Some previous NRT applications

Investigations on nuclear fuel

Priesmeyer and Harz, “Isotopic content determination in irradiated fuel by neutron transmission analysis” *Atomkernenergie* **25** 109 (1975)

Schrack et al.,”Resonance neutron radiography using an electron linac”

IEEE Trans. Nucl. Scie. **28** 1640 (1981)

“

ISIS

Some previous NRT applications

Investigations on nuclear fuel

Detecion of explosives

C. Chen and R.C. Lanza, *IEEE Trans. Nucl. Scie*. **49** 1919 (2002)

Some previous NRT applications

Investigations on nuclear fuel

Detecion of explosives

Detection of diamonds in rocks

Watterson and Ambrosi, *Nucl. Instr. Meth. A* **513** 367 (2003)

ANCIENT CHARM gives IMAGES

Imaging

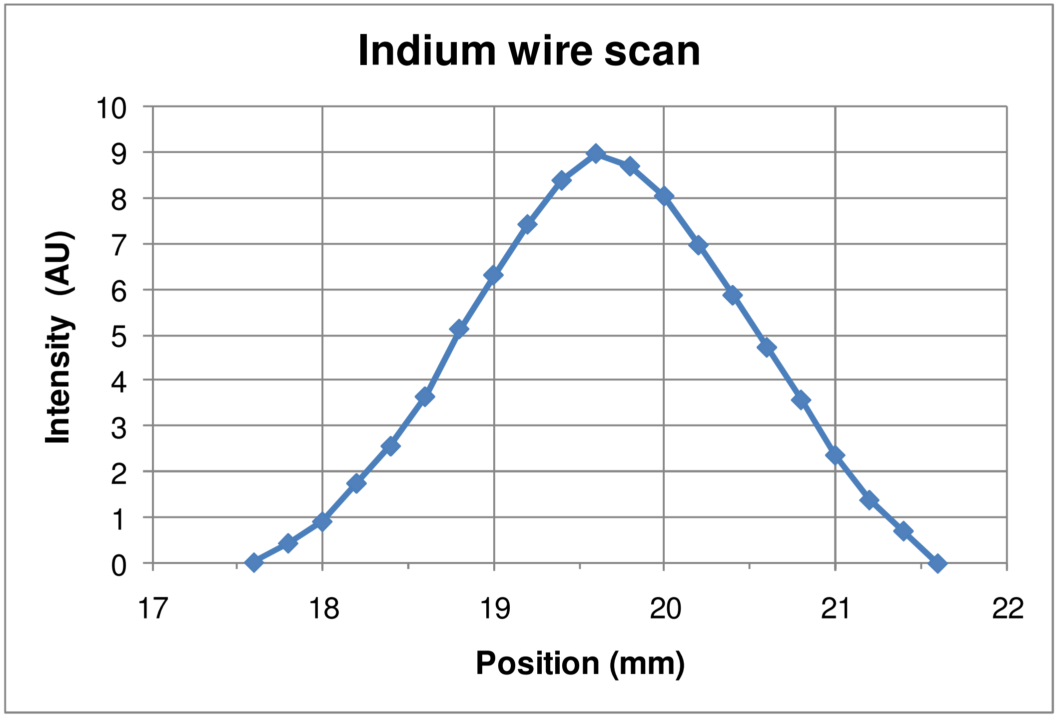
Non-destructive

No sample preparation needed

Negligible residual activation

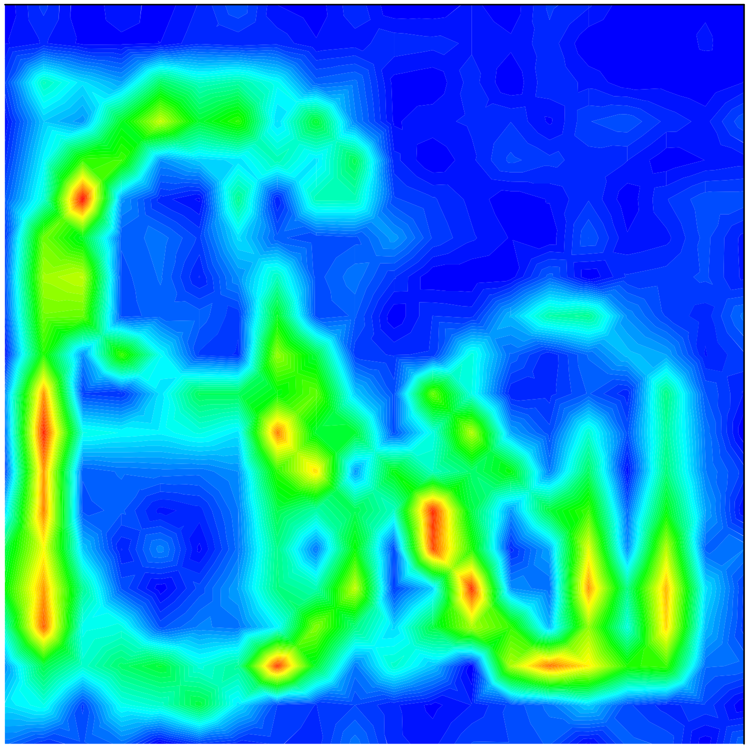
→ Cultural Heritage

Spatial resolution in NRT



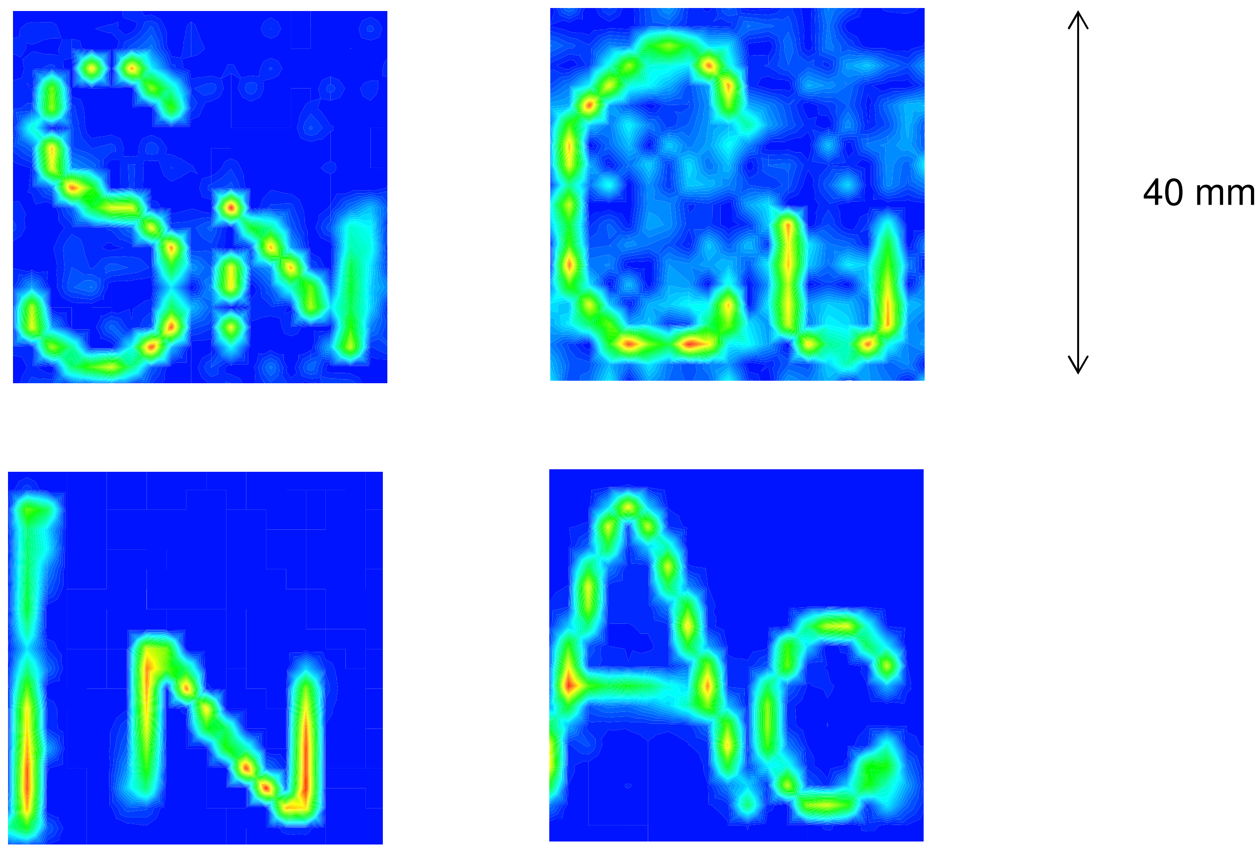
Space resolution of about 2.5 mm FWHM

Spatial resolution in NRT



A “mistery” stack of many layers folded in a closed metal sheet…..

Spatial resolution in NRT



….. Is revealed as thin (1 mm) wires of different materials)

ELEMENT-SENSITIVE IMAGING

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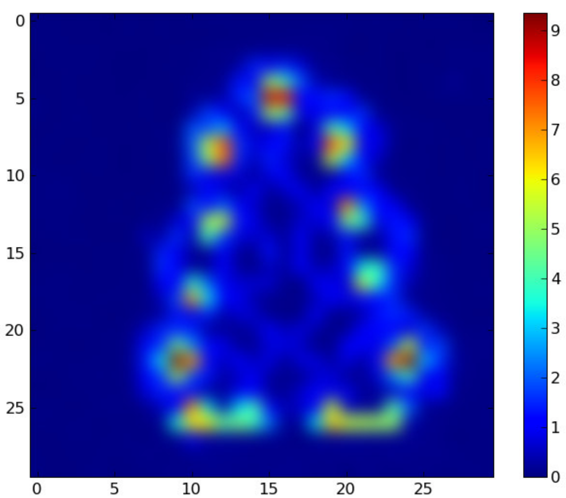
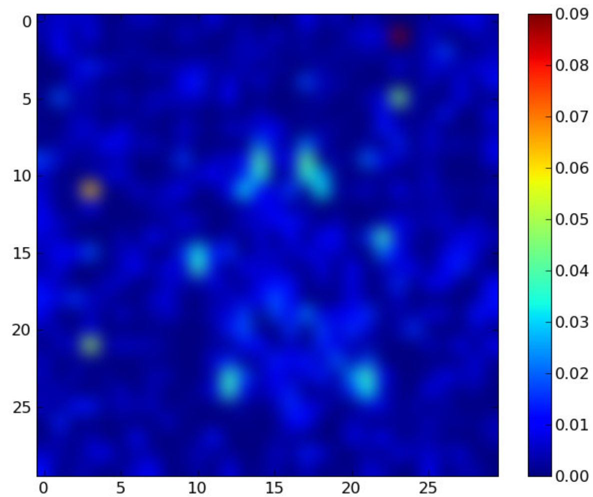
ELEMENT-SENSITIVE IMAGING

Ancient *gegenbeschlag* belt mount from
the National Hungarian Museum,
with glass and metal inlaying

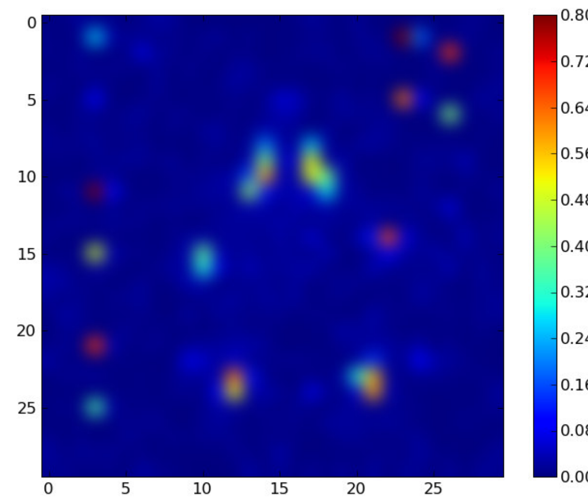
3 x 3 pictures element-sensitive radiography



Ag (16 eV)



Cu (230 eV)



Zn (514 eV)

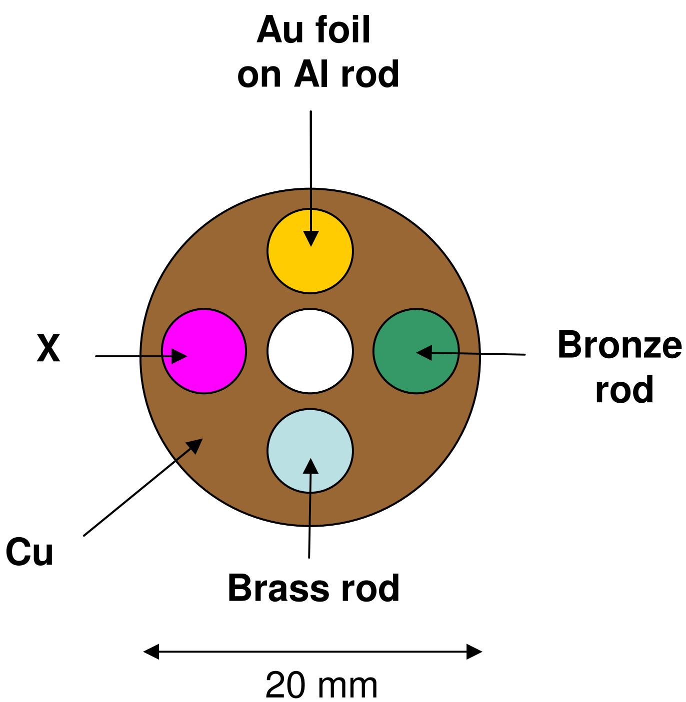
Images thanks to T. Materna and the AC collaboration

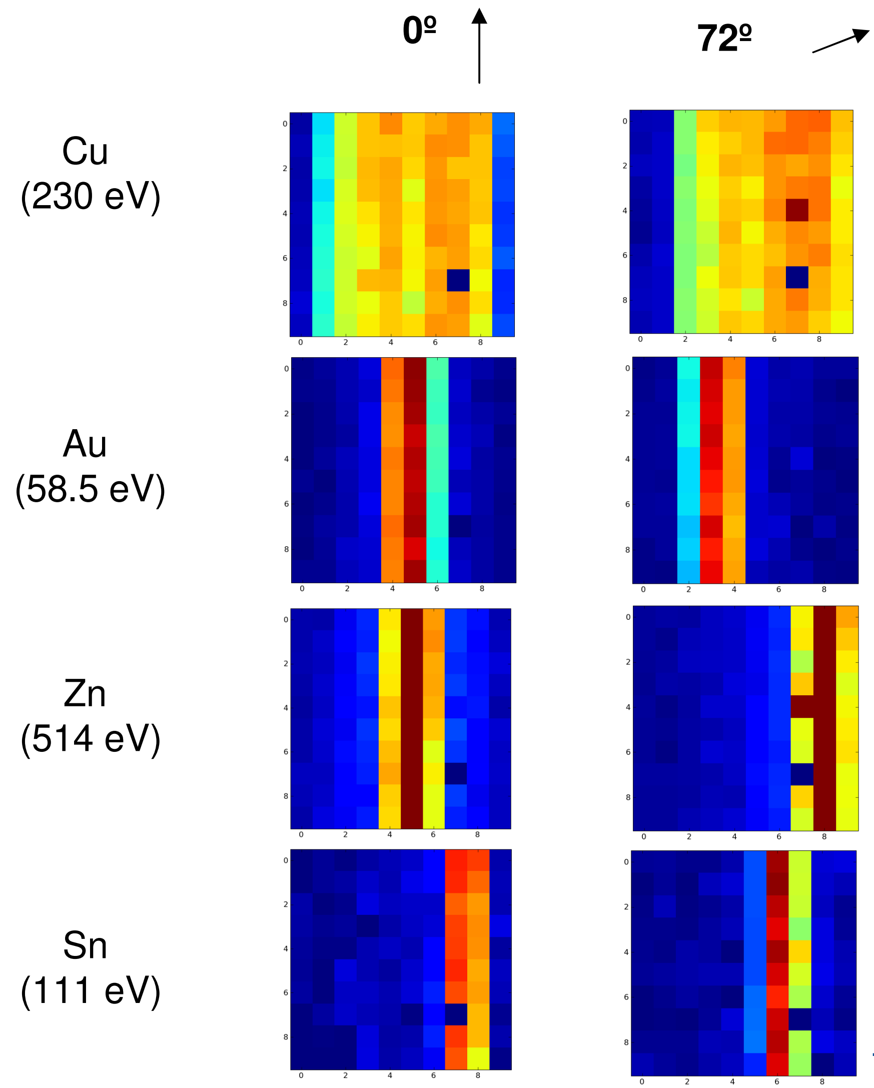
ISIS

ELEMENT-SENSITIVE IMAGING

2D radiographies can be developed in 3D images with standard tomographic methods

work in progress……





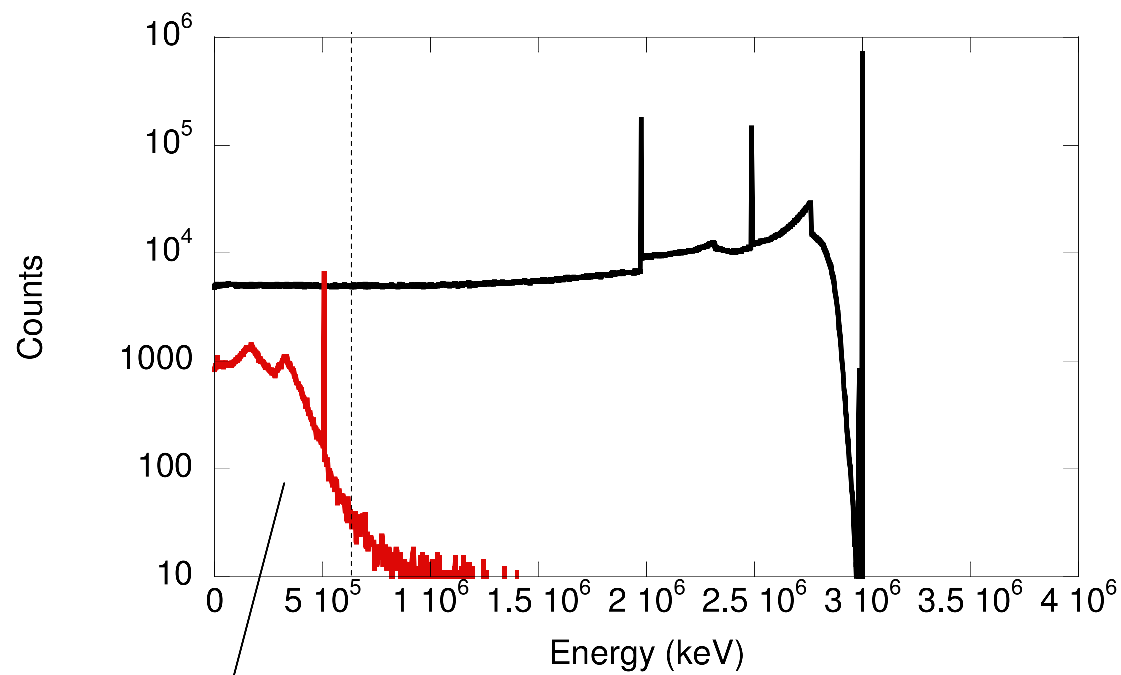
NEUTRON RESONANT CAPTURE IMAGING SET-UP

Array of 28 γ-detectors

YAP scintillator:
51mm ø, 25mm thick

~20% solid angle coverage

NEUTRON RESONANT CAPTURE IMAGING SET-UP



Simulated background spectrum

YAP scintillators

Fast τ = 27 ns

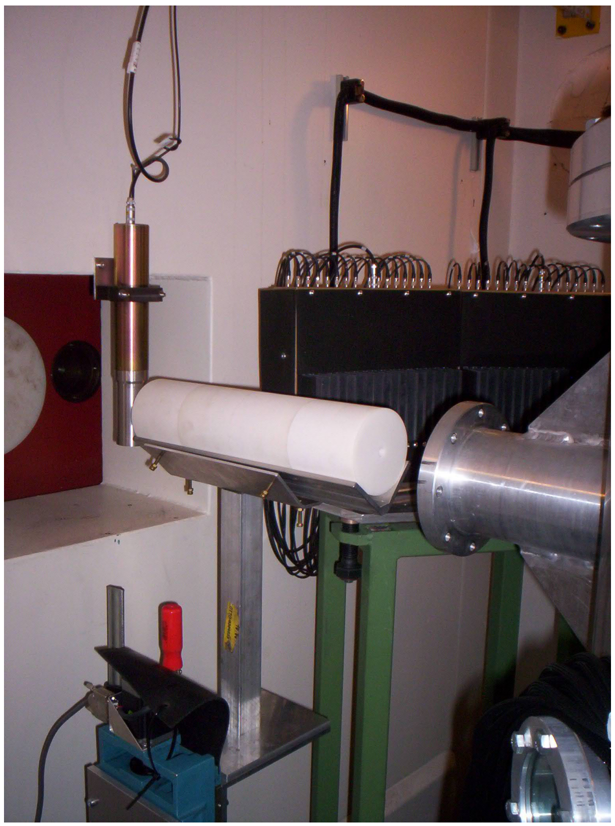
Neutron-insensitive

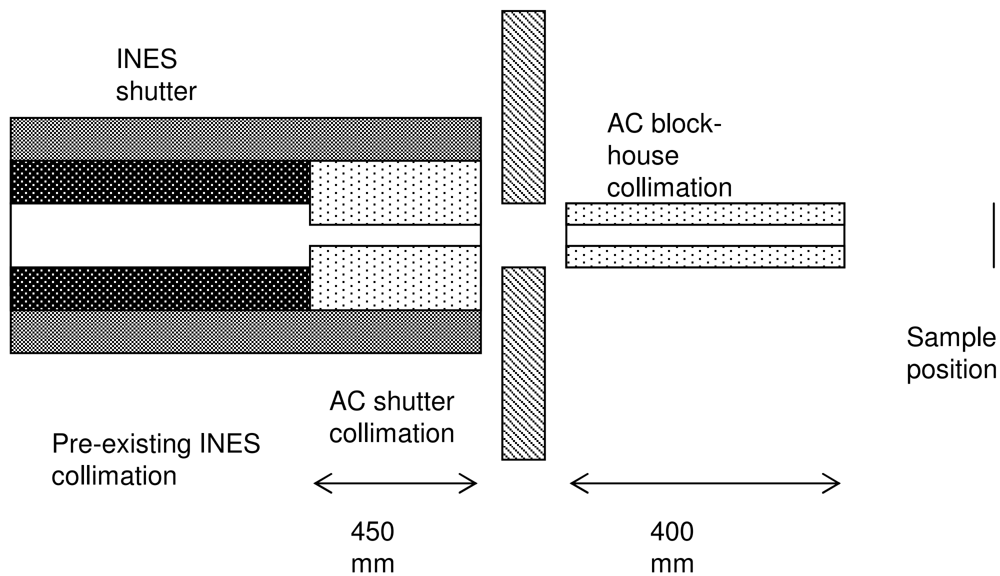
Efficiency about 35 % at 5 MeV

Energy treshold to optimise S/B

NEUTRON RESONANT CAPTURE IMAGING SET-UP

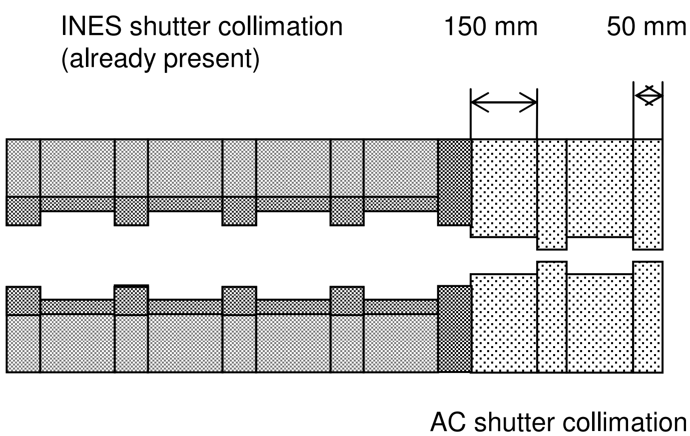
Lithium carbonate collimators for “pencil neutron beam”

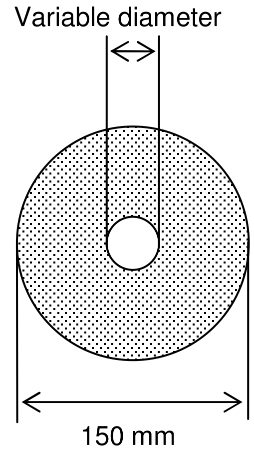


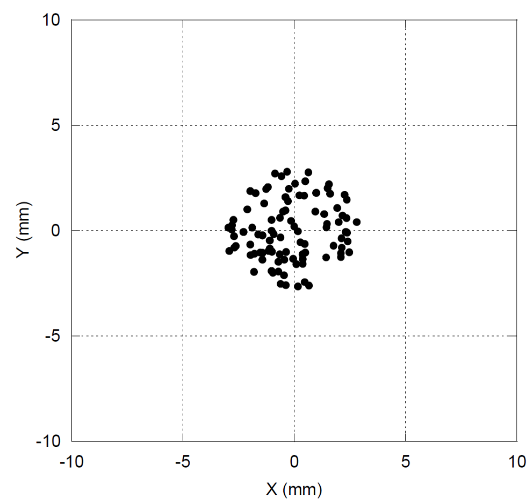


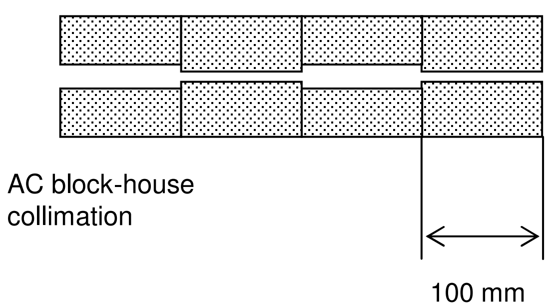
NEUTRON RESONANT CAPTURE IMAGING SET-UP

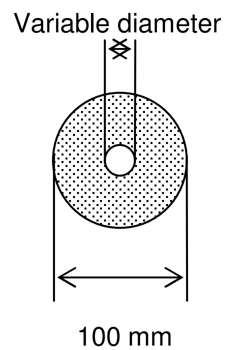
Lithium carbonate collimators for “pencil neutron beam”







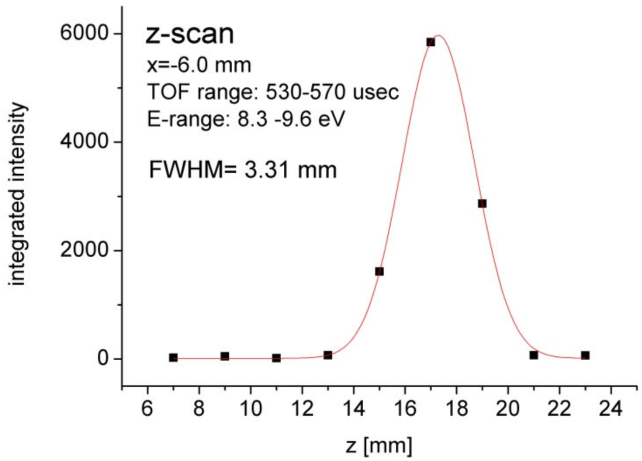


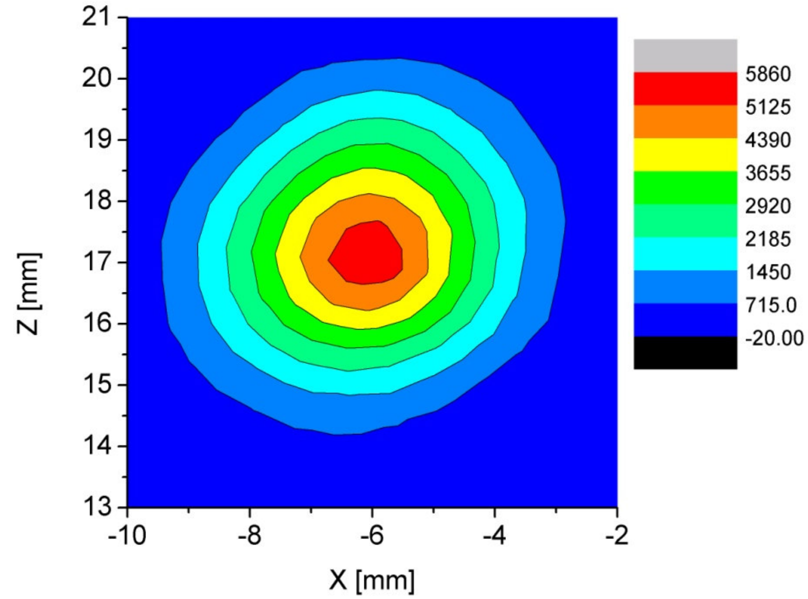


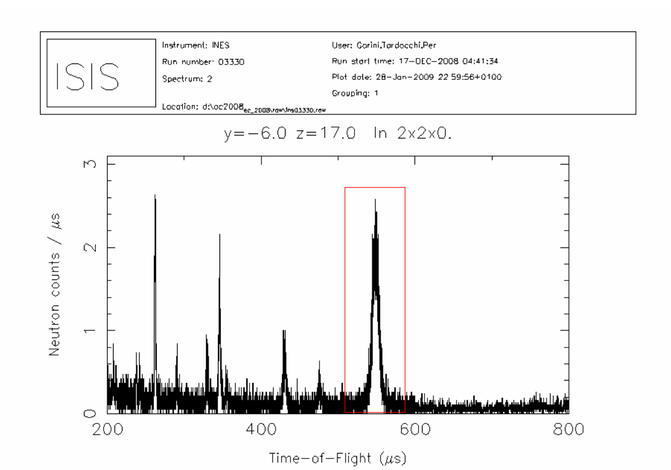
Pencil beam : full collimation

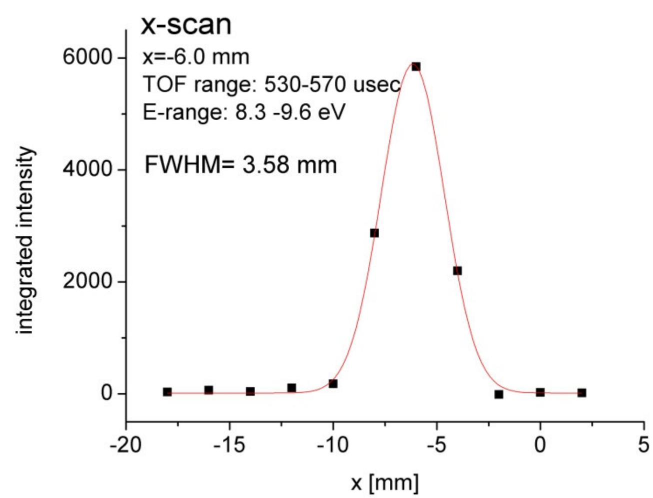
In – sample: 2x2x0.5 mm

scan step: 2.5 mm, 20 μamps









Conclusions and future perspectives

Aim of ANCIENT CHARM is to conjugate *" ....Neutron resonant Capture Imaging and other Emerging Neutron Techniques...."* for non-destructive analysis of material.

NRT offers element-sensitive imaging possibility

Fast, non destructive

Flexible

Possibility of developing a 3D tomographic technique

Future integration in the "phase 2" ISIS TS2 plan