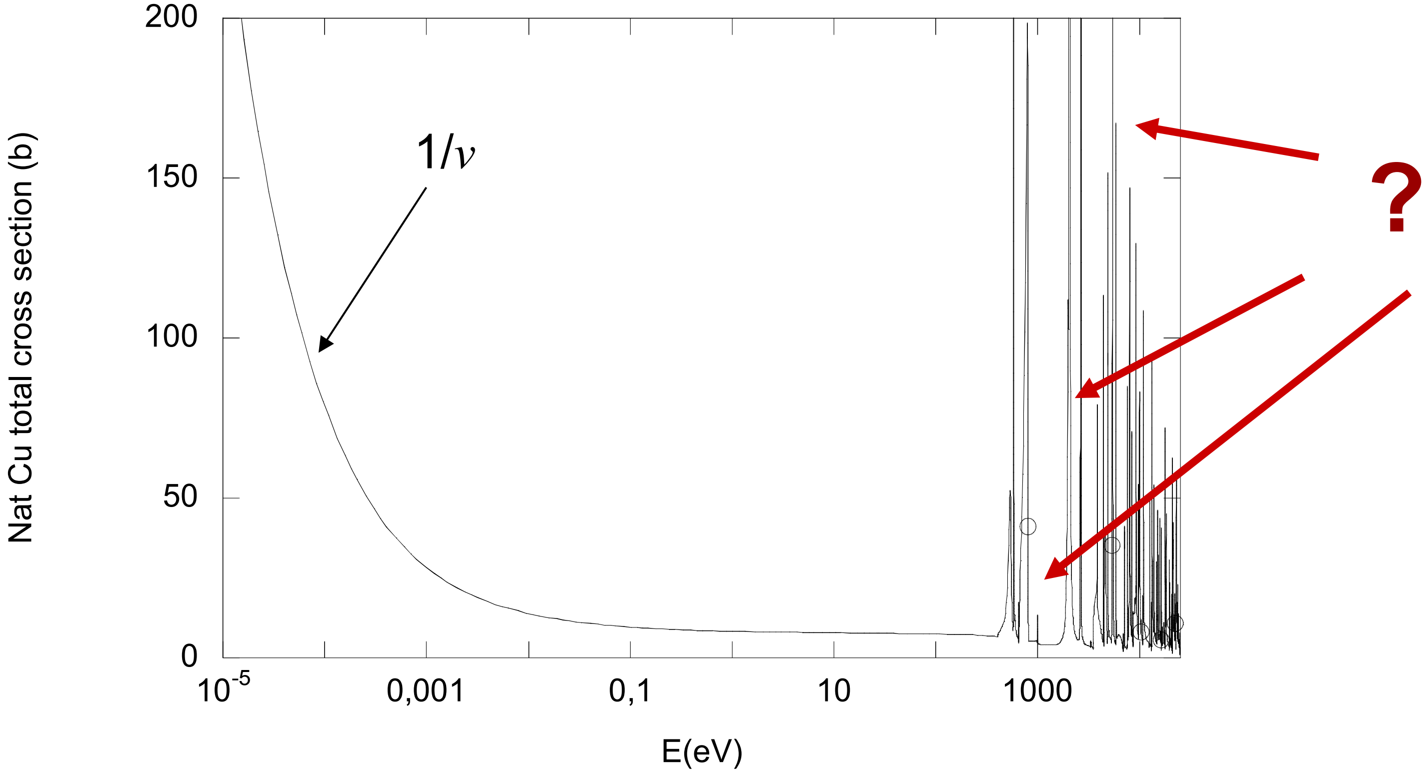
Non-scattering neutron techniques: NRT and NRCA

Enrico Perelli Cippo

"Piero Caldirola" Institut for Plasma Physics – CNR

Neutron Resonances: what happens here?



Neutron resonances

better: resonances in neutron absorption and scattering cross-section

Resonance cross-section for the reaction

A + X → B + Y

$$\sigma = \frac{\pi}{k^2}\, g\, \frac{\Gamma_{AX}\,\Gamma_{BY}}{(E-E_R)^2 + \Gamma^2/4}$$

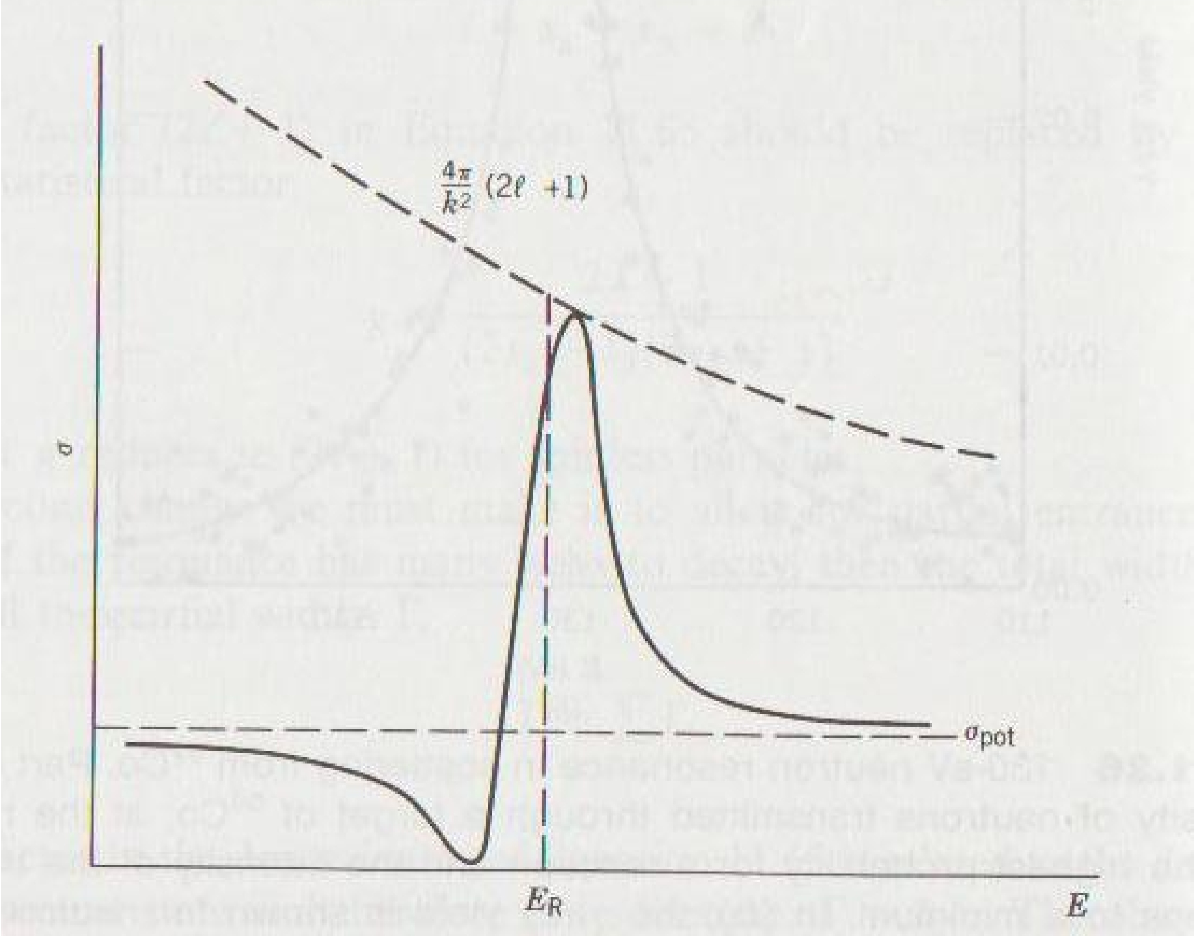
"Breit-Wigner curve"

It is related to the existence of a "compound nucleus".

$\sigma \sim 1/v$ off resonance

Neutron resonances

Interference with potential scattering (not related to a compound nucleus) results in slightly asymmetrical total cross secion resonances.



Neutron Resonances: who cares about neutron resonances?

Neutron absorption resonances are UNIQUE for every atom and isotope

Neutron absorption resonances can be used for:

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

Neutron Resonance Transmission (NRT)

Neutron absorption resonances can be used for:

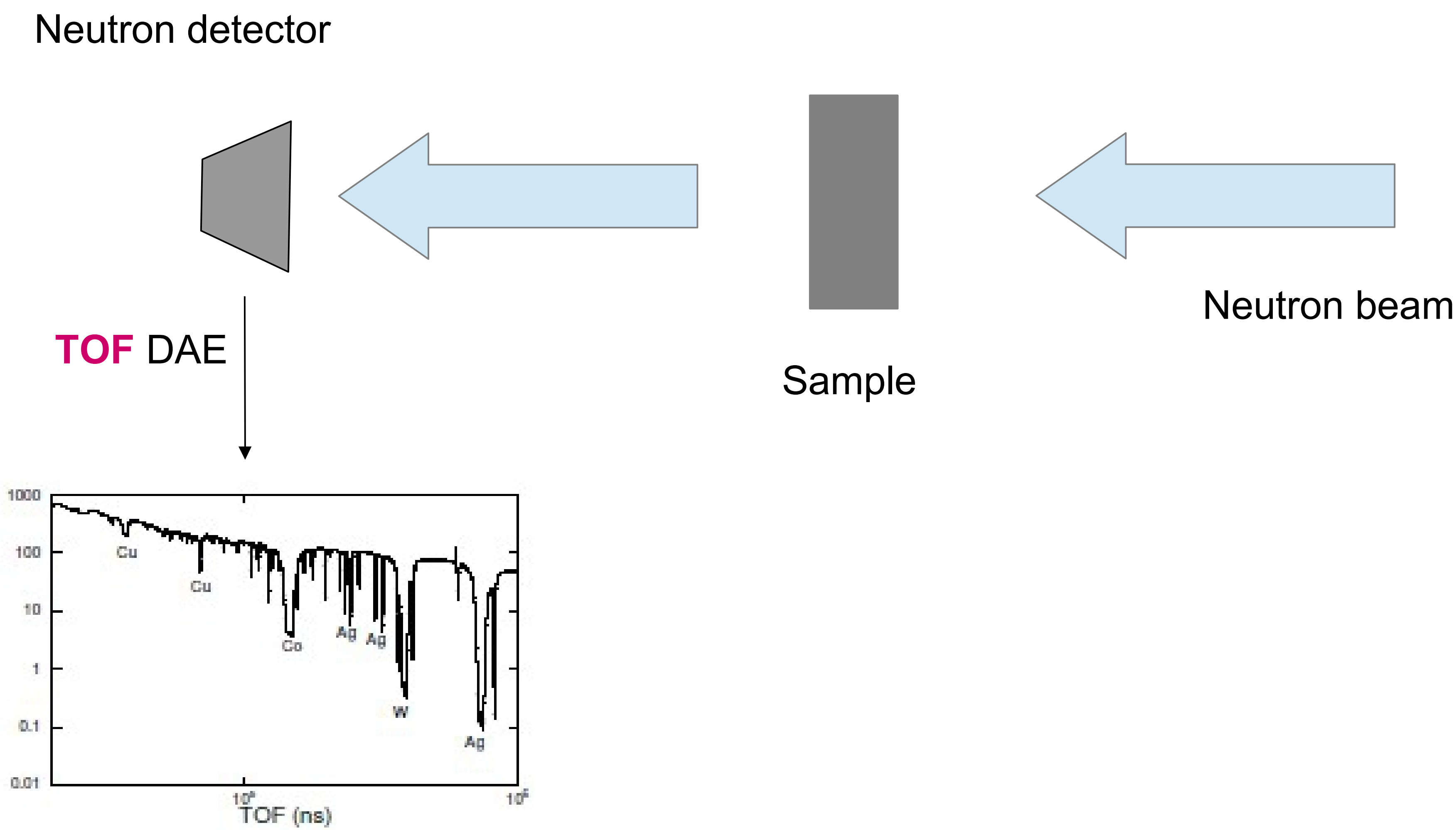
Nuclide identification and quantification
Elemental (& isotopic) composition

NRT makes use of epithermal neutrons

E_n up to 1 keV

No sample preparation needed
Non - destructive
Negligible residual activation
It can naturally lead to an imaging technique

Neutron Resonance Transmission (NRT)



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)

“

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

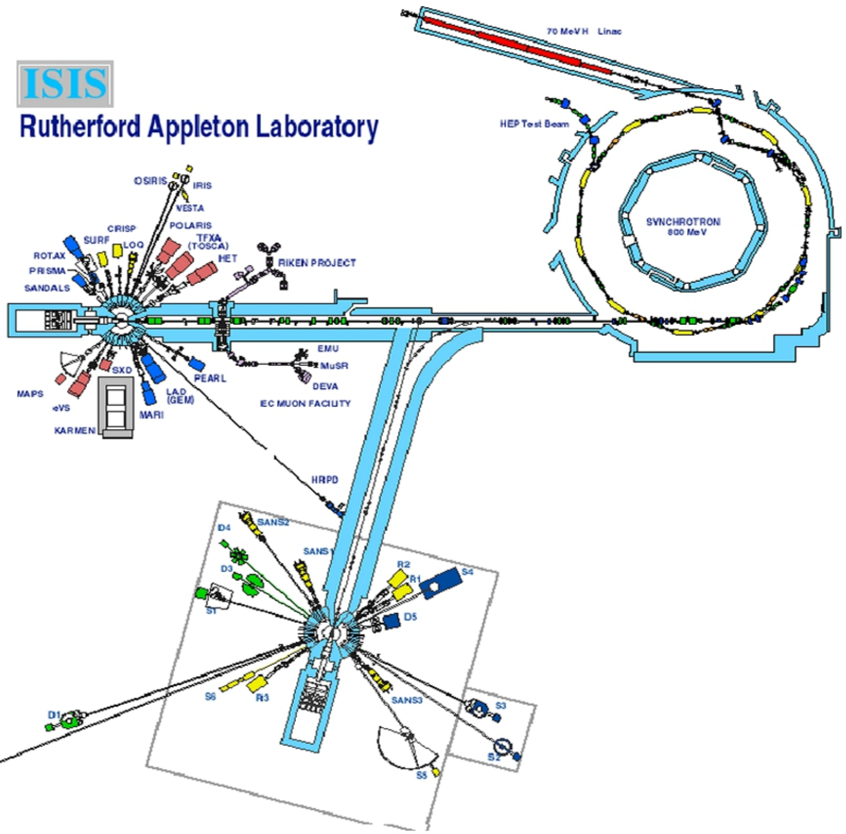
Detection of diamonds in rocks

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

NRT makes use of epithermal neutrons

E_n up to 1 keV

Pulsed white neutron beam (GELINA, ISIS)

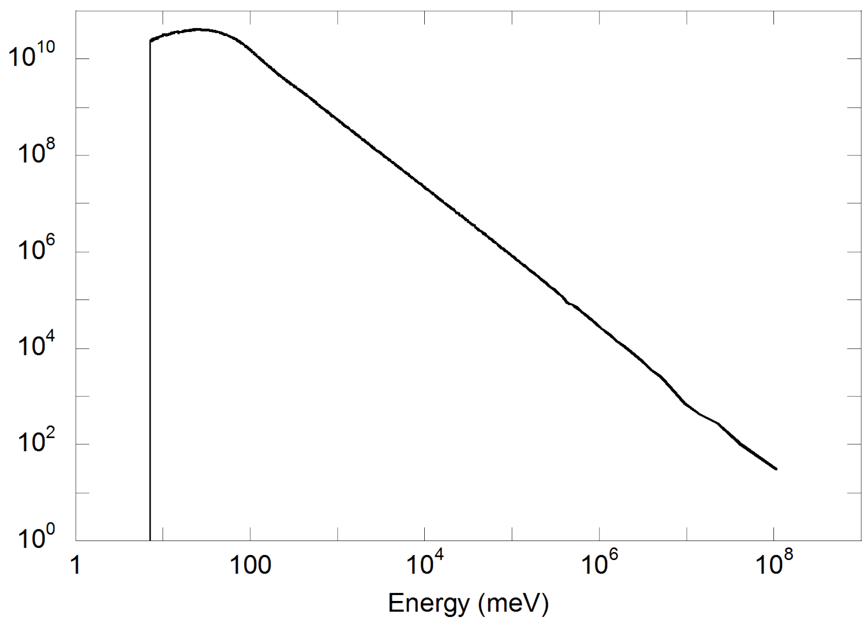


INES beamline at the ISIS spallation source	
Average current	150 – 180 μA (p)
Neutron pulse width	300 ns
Flight path length	23.0 m
Beam dimensions	50 x 50 mm
Flux at sample pos.	10^3 n/eV s cm2 at 10 eV

NRT makes use of epithermal neutrons

E_n up to 1 keV

Pulsed white neutron beam (GELINA, ISIS)



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Flux at sample pos.	10^3 n/eV s cm2 at 10 eV

"Undermoderated" beam at INES

NRT makes use of epithermal neutrons

E_n up to 1 keV

Pulsed white neutron beam (GELINA, ISIS)

Absorption resonances are identified with the TOF technique

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

FAST detectors and electronics are crucial

And if you want images, you als must conside spatial resolution

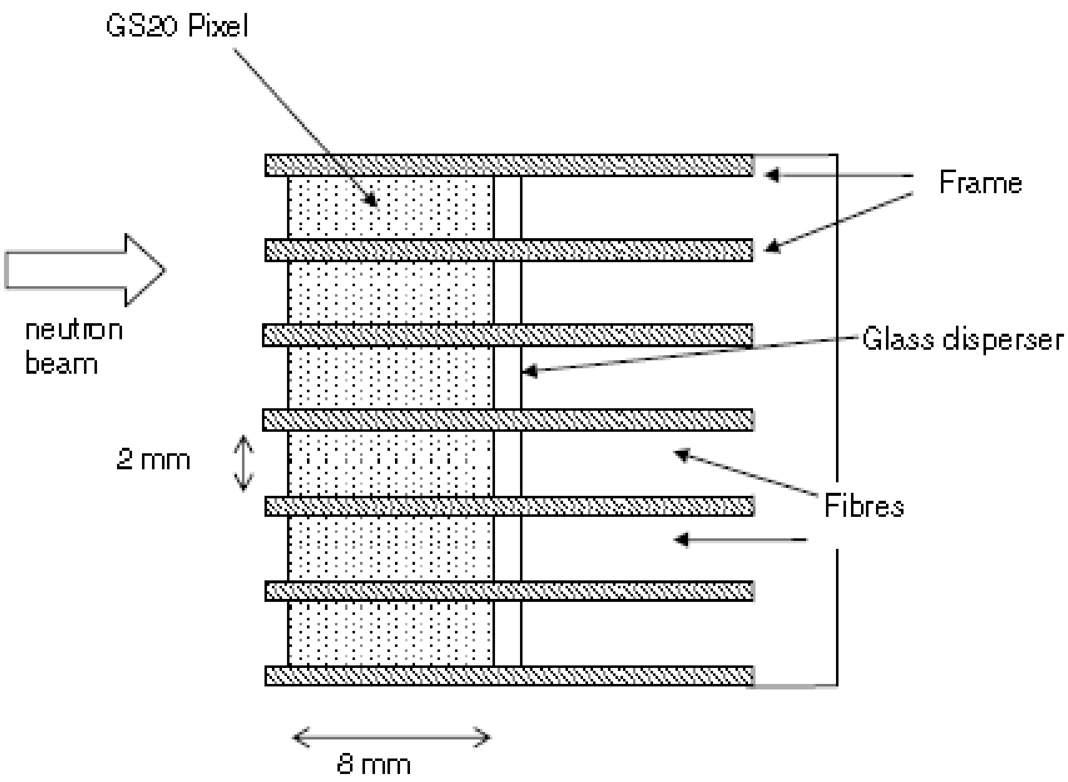
PSND

10 x 10 *GS20* Li-enriched scintillator pixels

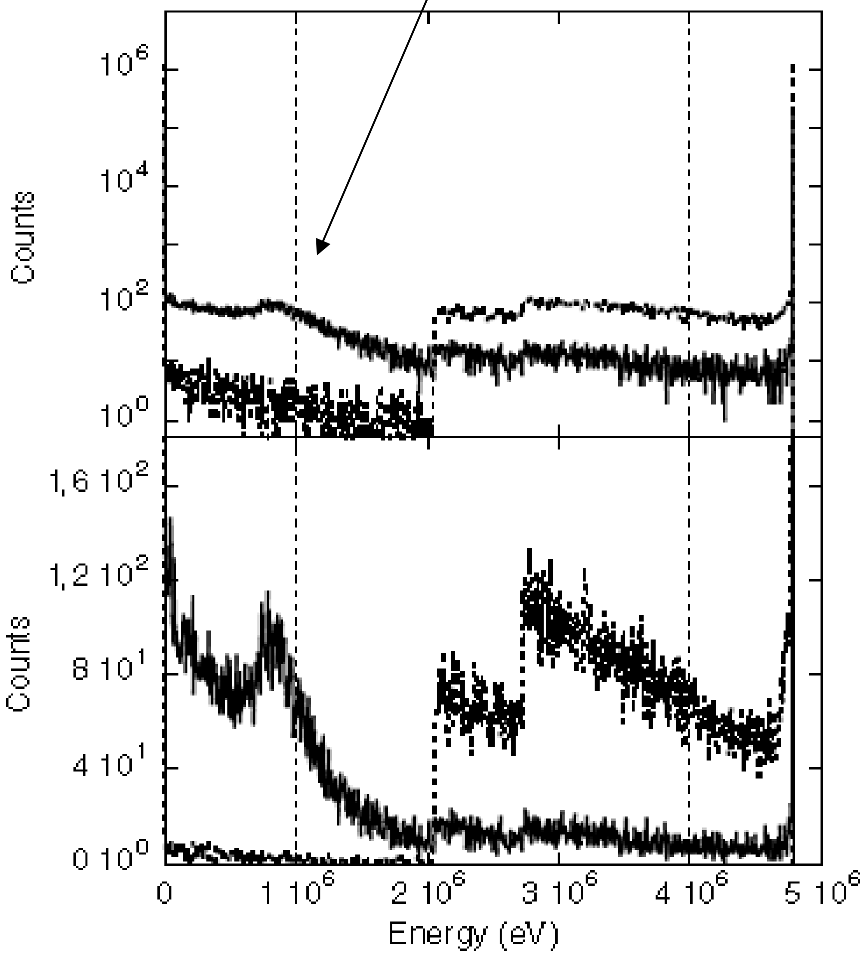
25% efficiency at 10 eV

4 % efficiency at 1 keV

FAST response

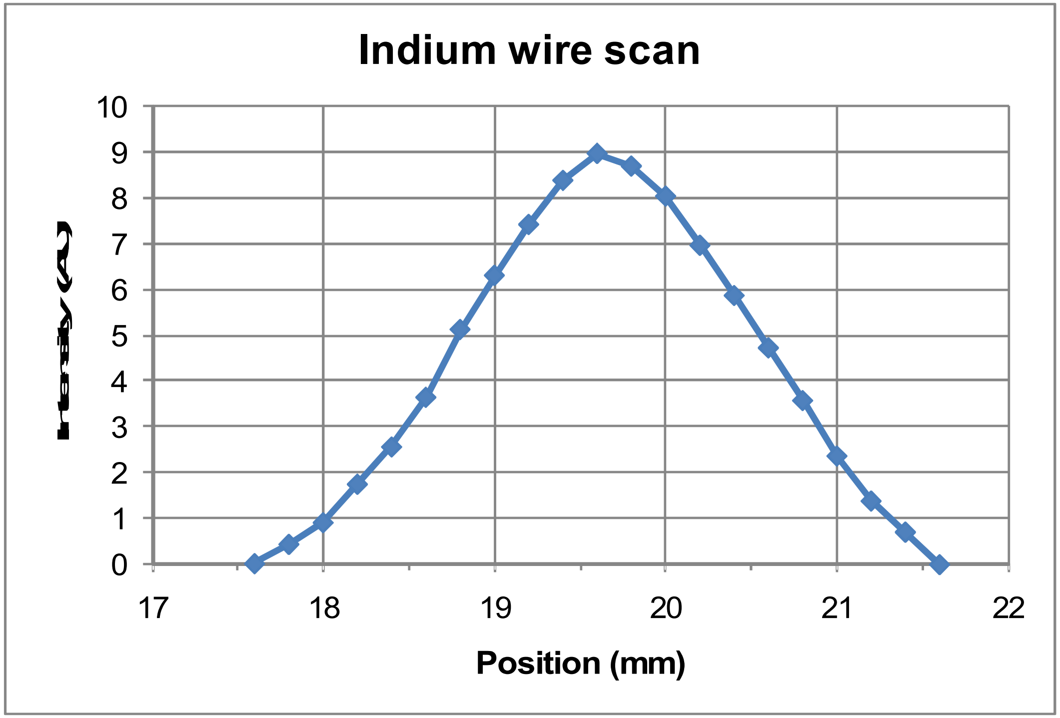


"Inverted wall effect" causes cross-talk between pixels



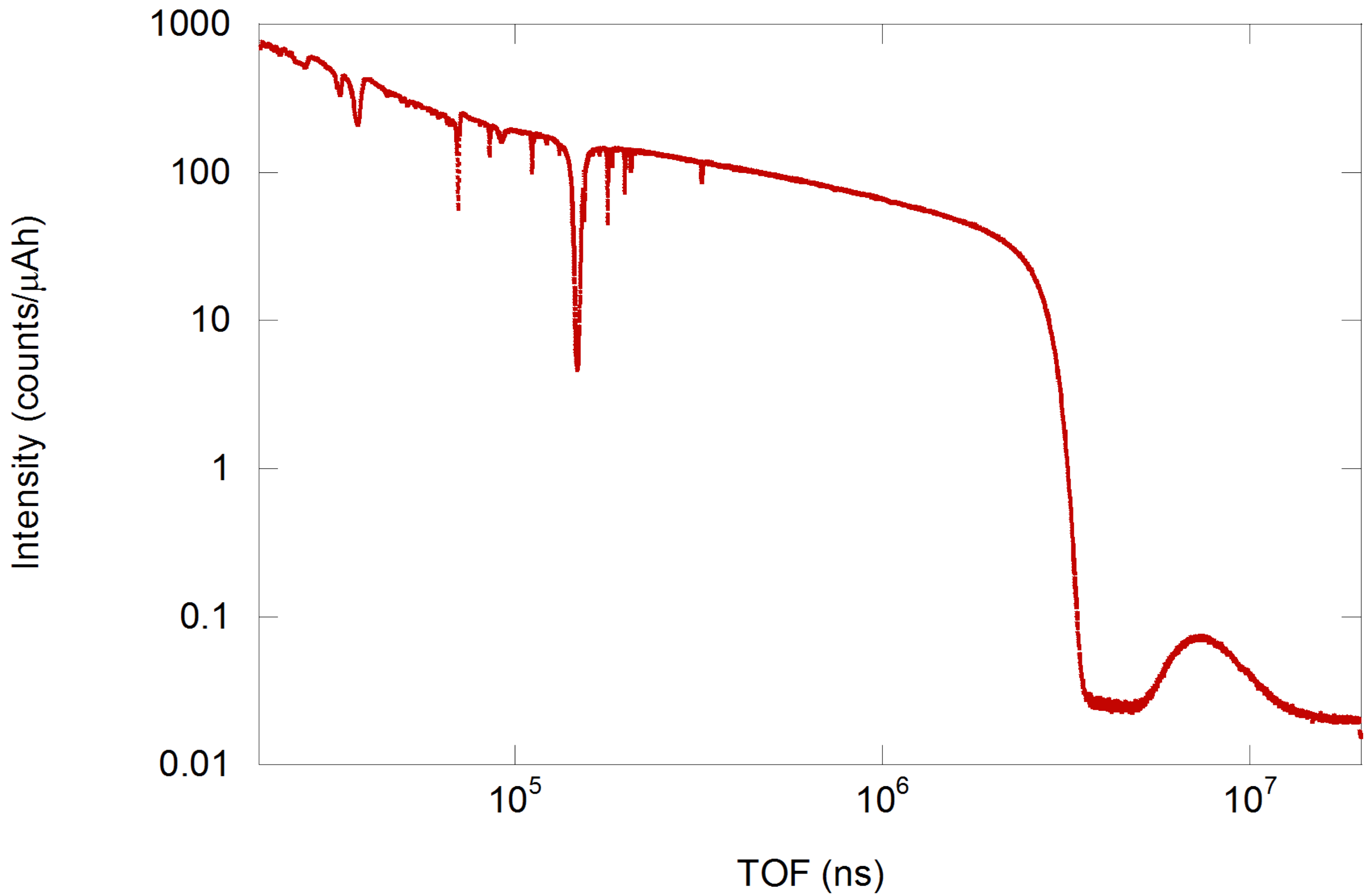
$$ {}^{6}_{3}\mathrm{Li} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{4}_{2}\alpha \frac{Q\text{-value}}{4.78\ \mathrm{MeV}}, $$

Spatial resolution



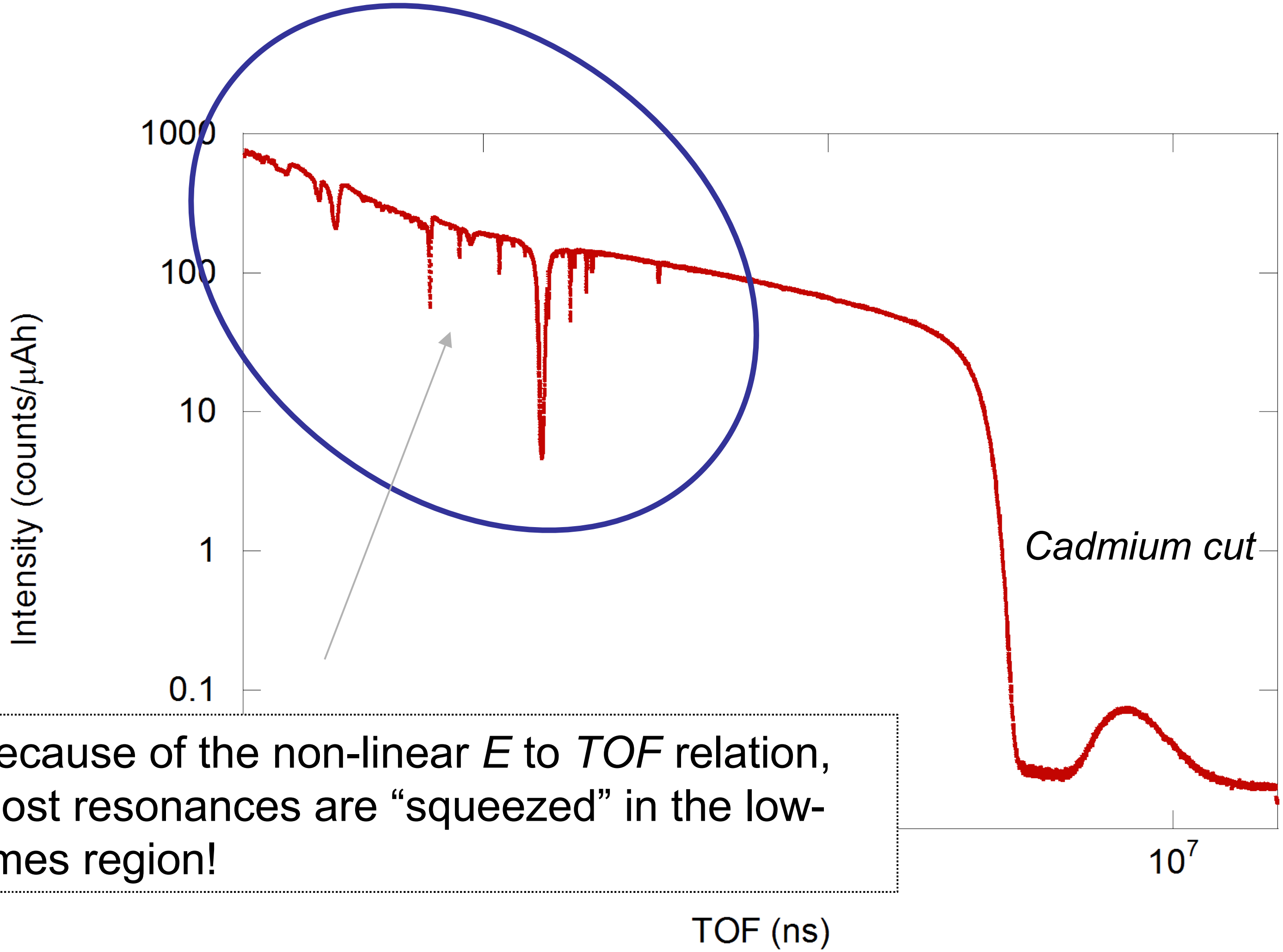
Space resolution of about 2.5 mm FWHM

The transmission TOF spectrum



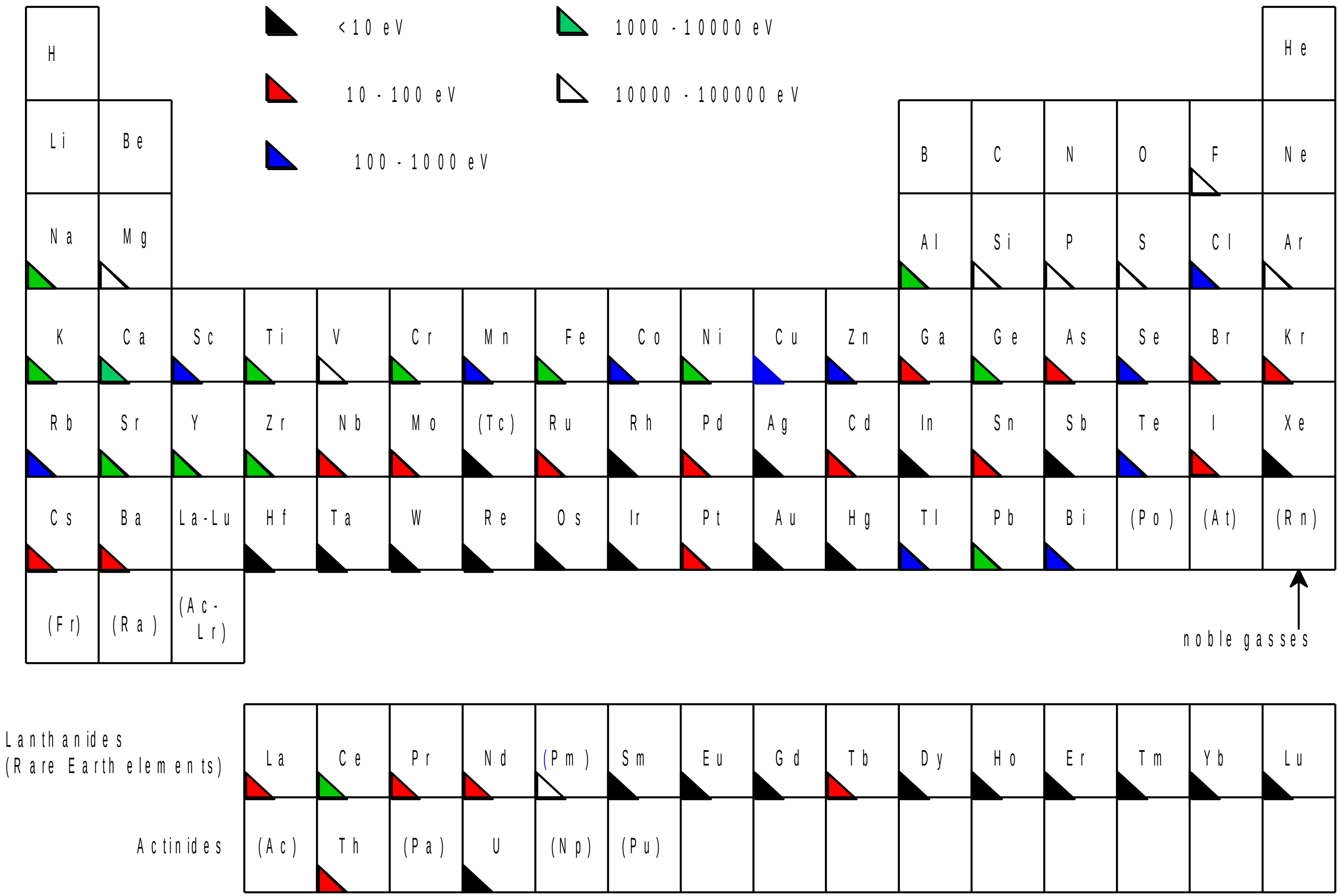
NRT Time of Fligth spectrum recorded at the INES beamline at ISIS

The transmission TOF spectrum

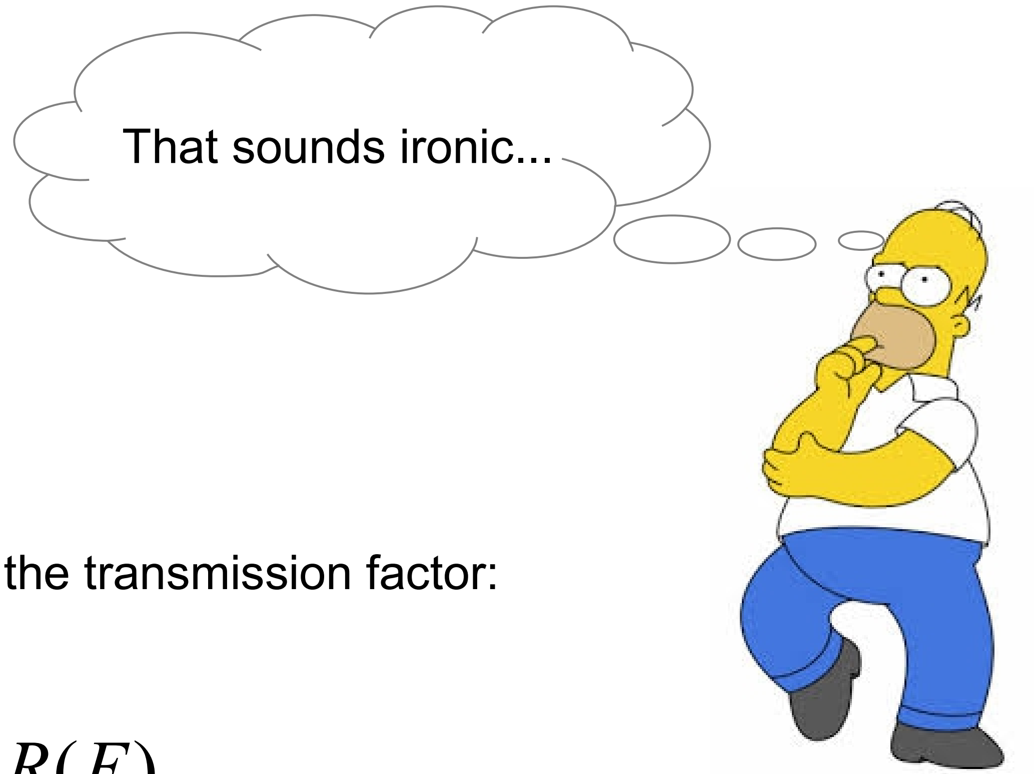


Because of the non-linear *E* to *TOF* relation, most resonances are “squeezed” in the low-times region!

Many elements of CH interest have resonances in the slightly lower energy (slightly longer TOF....) region......



The *optimum* NRT analysis approach



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

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

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).

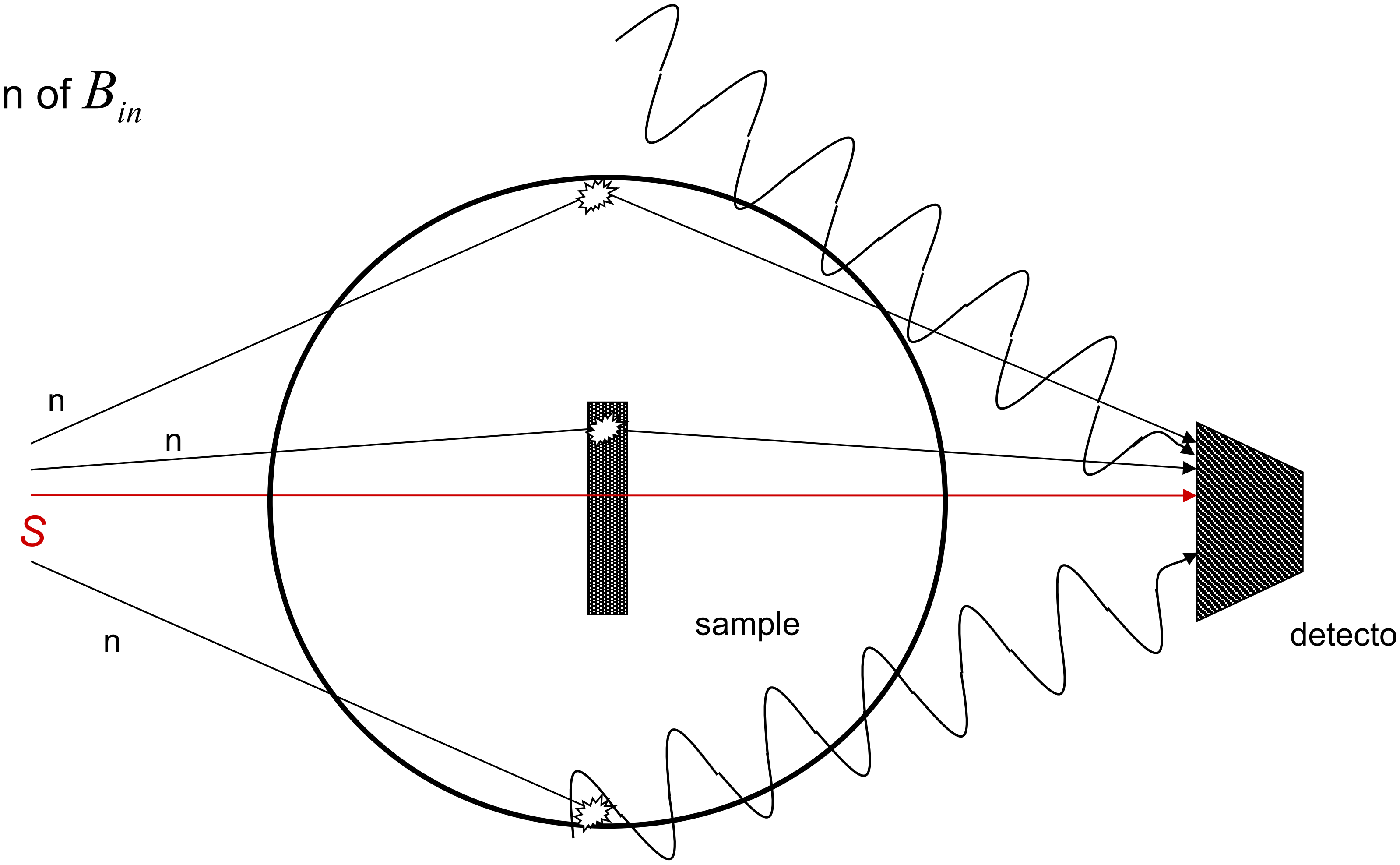
The physical quantity measured is the transmission factor:

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

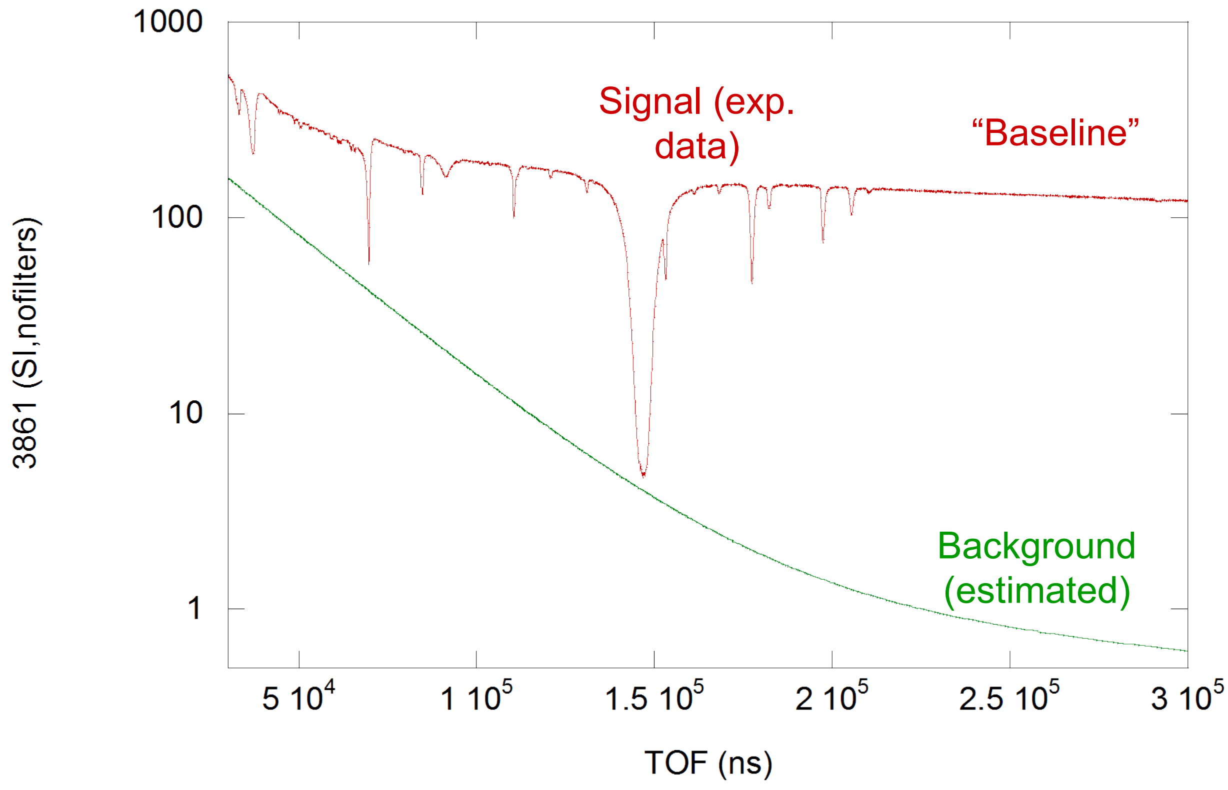
experimental data

evaluated analytical function

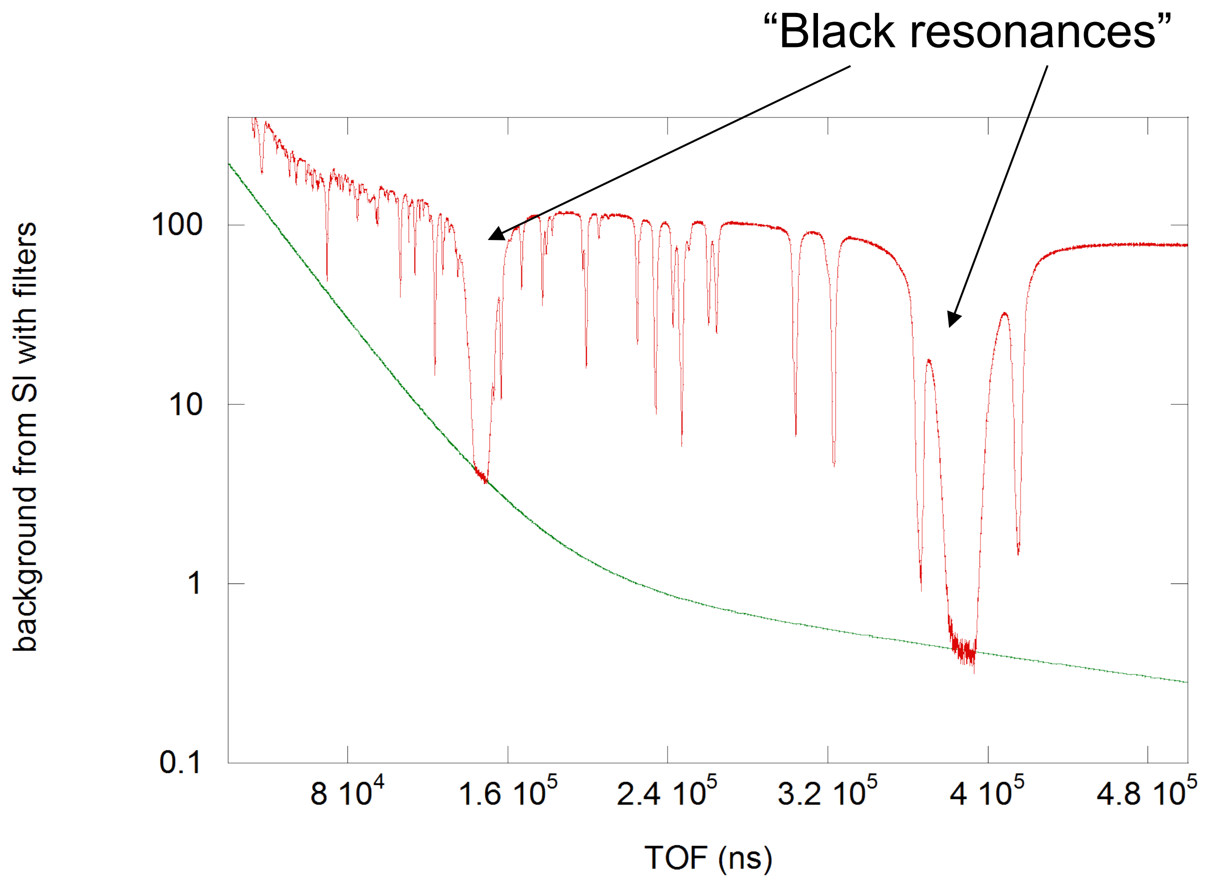
Definition of B_{in}



Definition of B_{in}



How to determine B_{in}



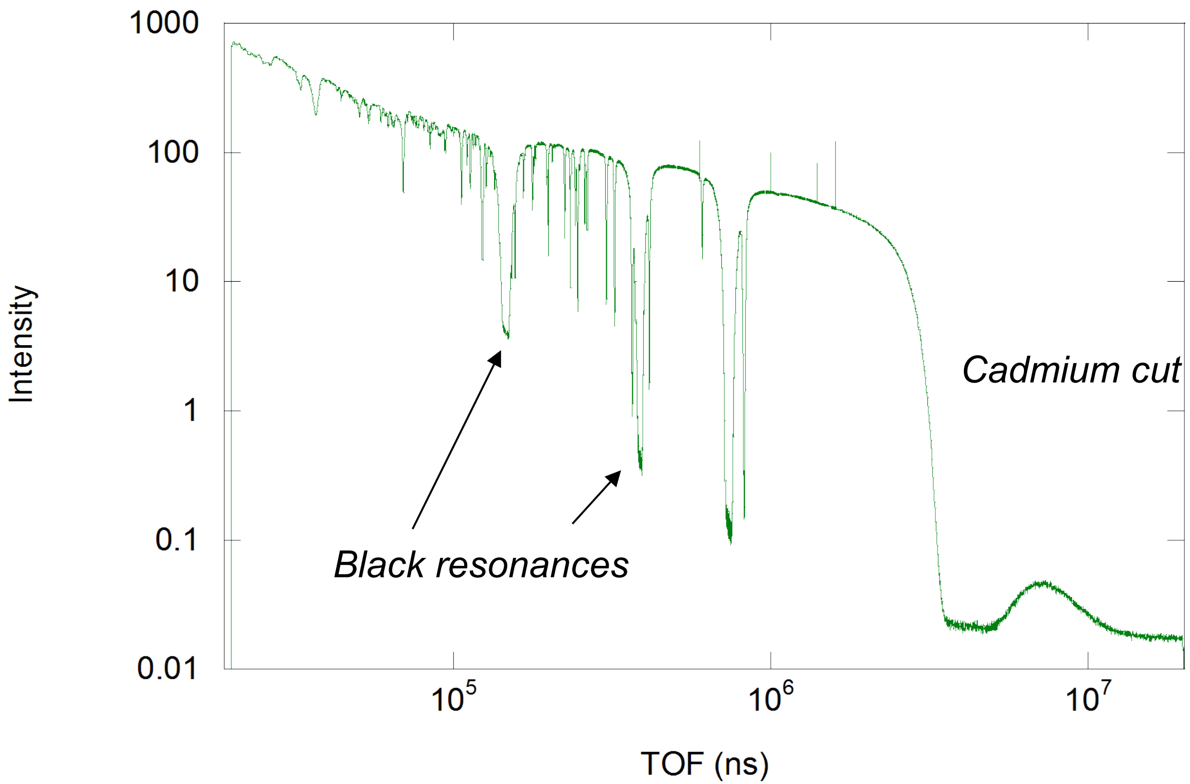
How to determine B_{in}

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)

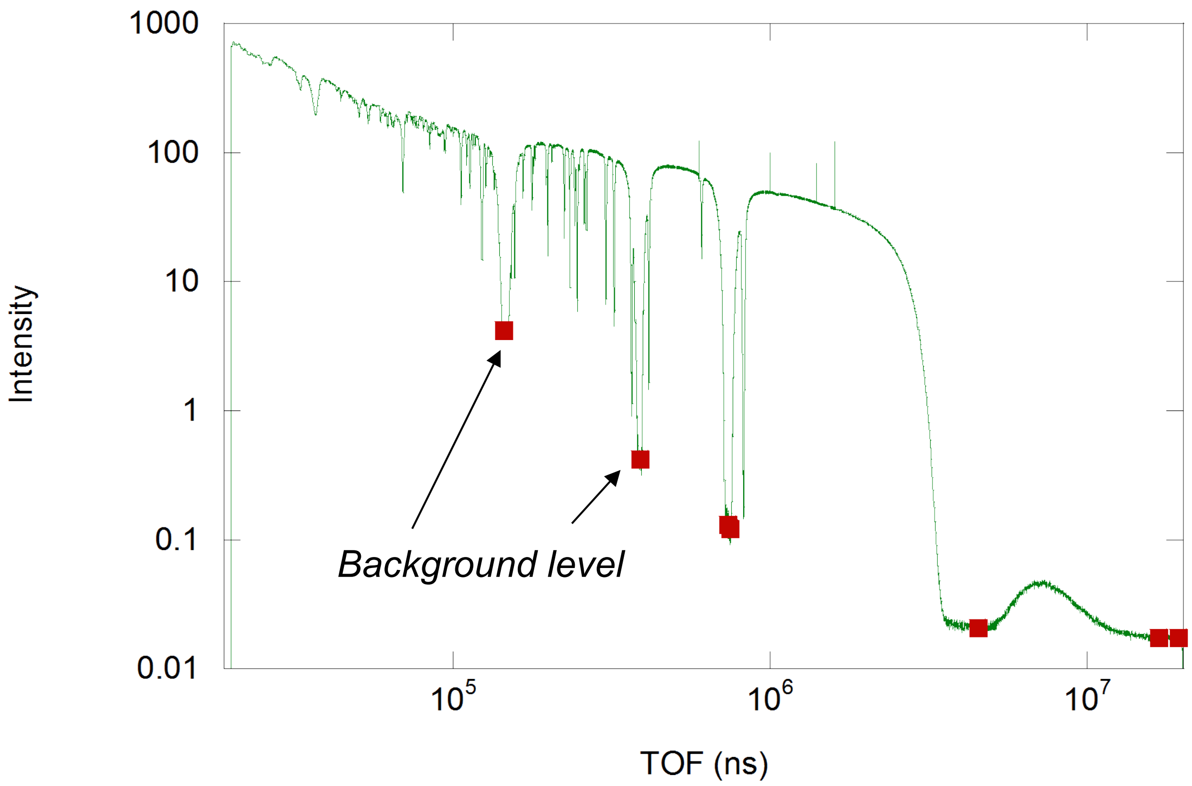
How to determine B_{in}

Spectrum from a sample-in + black resonances run



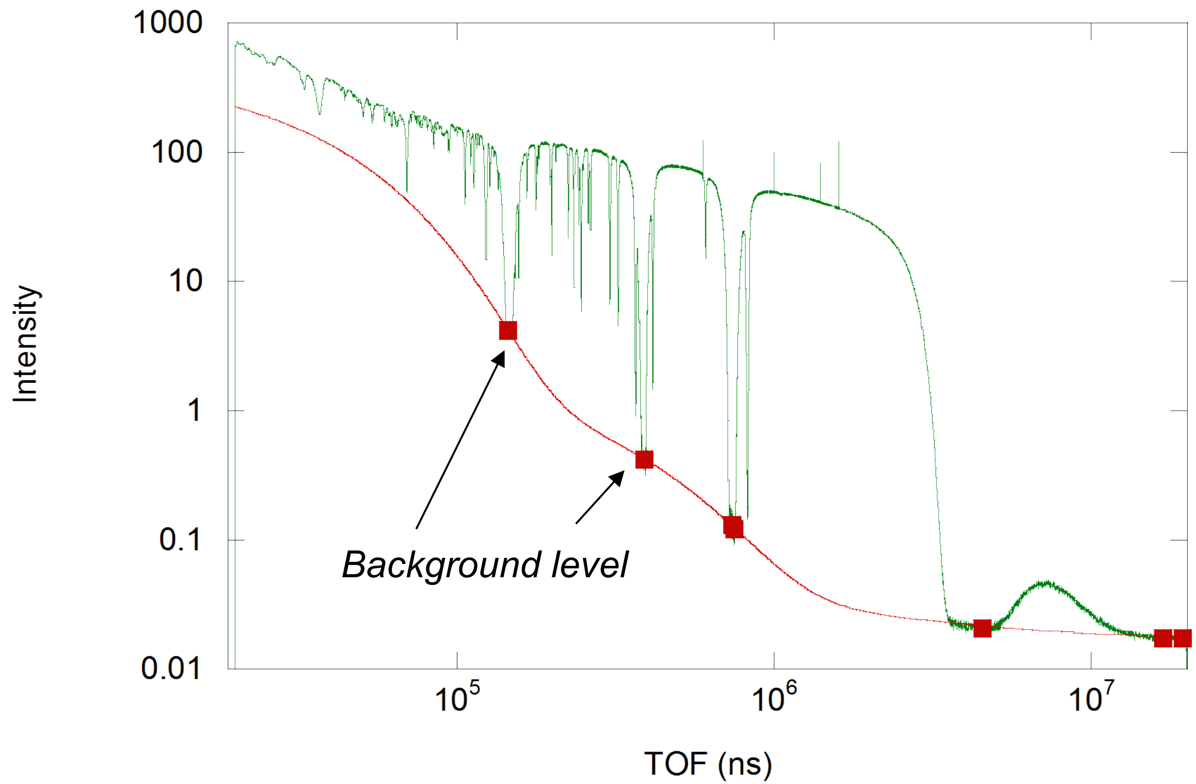
How to determine B_{in}

Estimated background level



How to determine B_{in}

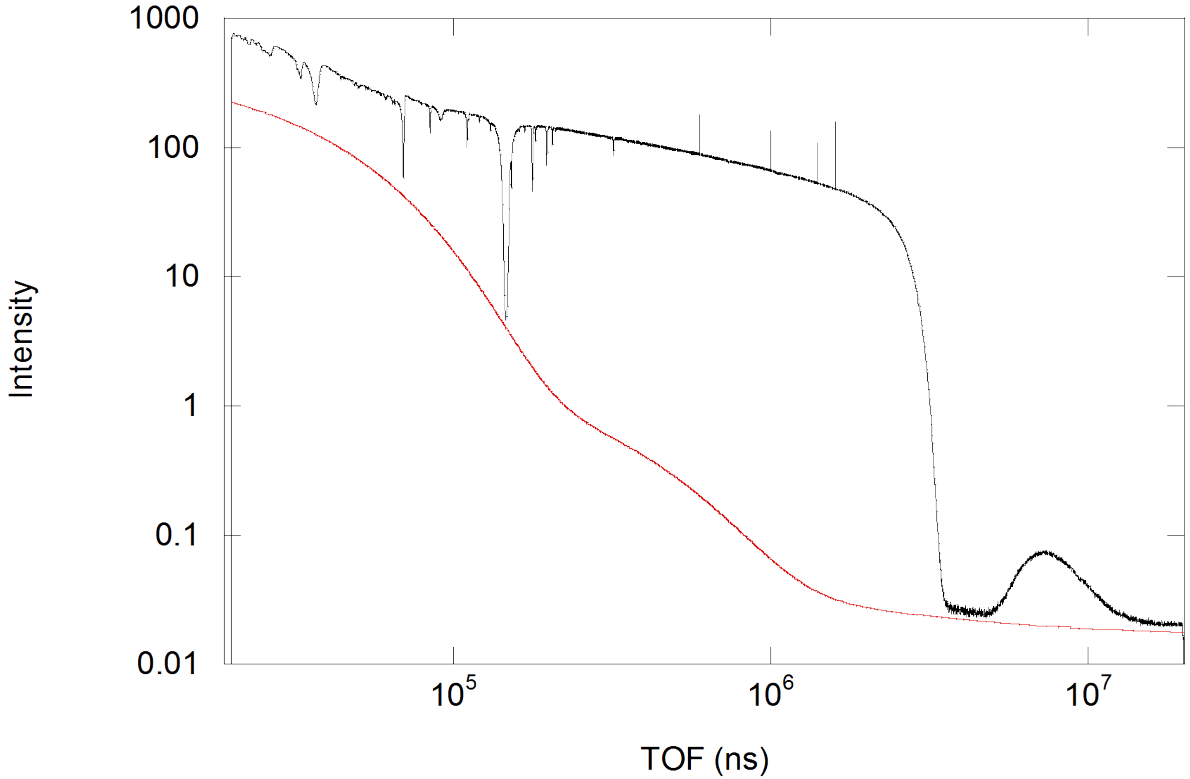
Estimated background interpolation



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

How to determine B_{in}

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



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

- Dead time correction:

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

$\Delta t \approx 275$ 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)

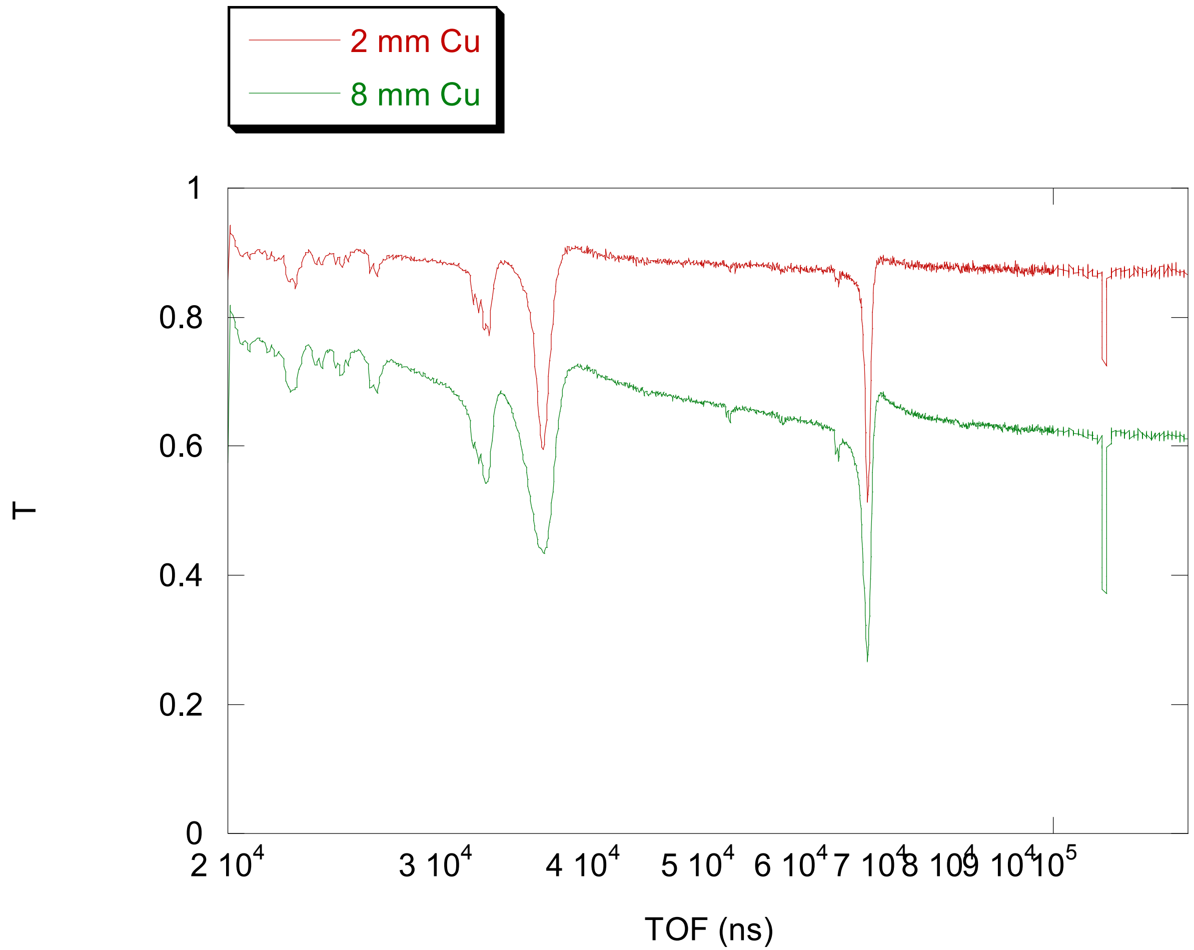
S_{in} is the TOF transmission spectrum of the sample that has undergone

- 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

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

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

Resonaces are Doppler broadened

Data do not have infinitely good resolution

Optimum NRT analysis approach: REFIT

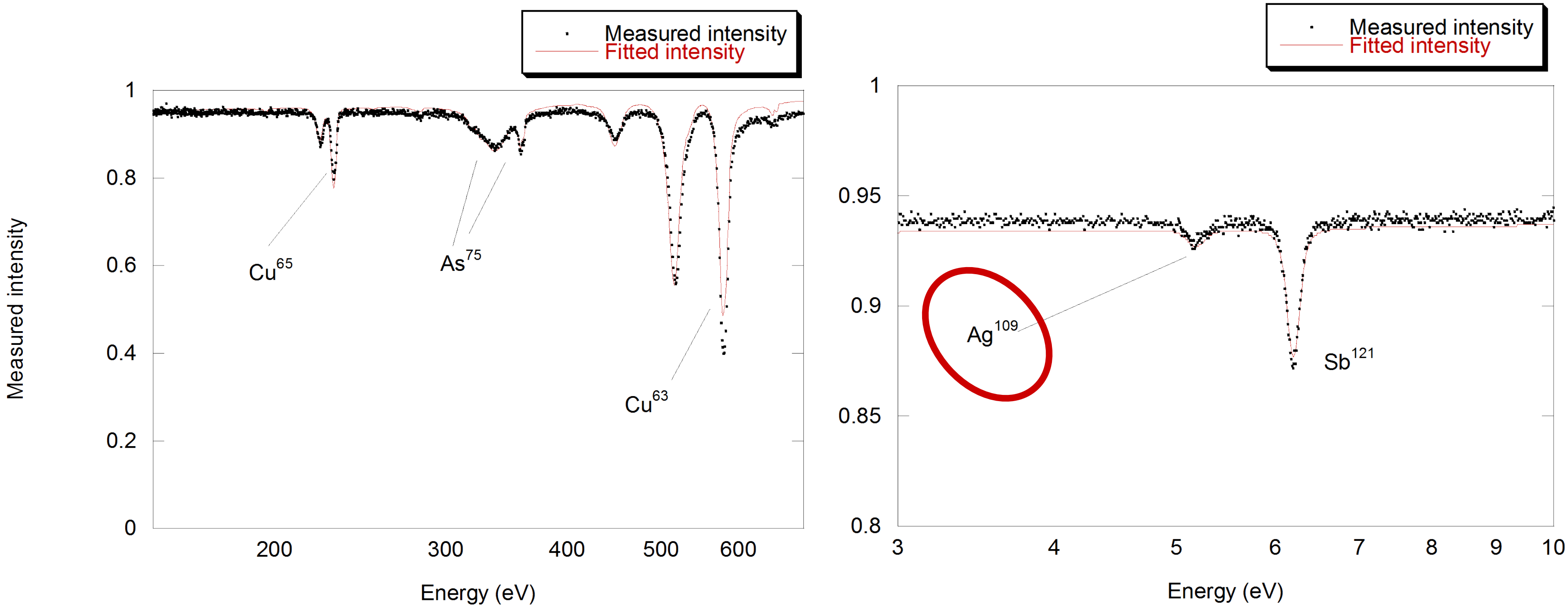
REFIT is a toolkit for analysis of transmission (and capture) neutron resonances spectra.

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	-	$12e^{-3}$

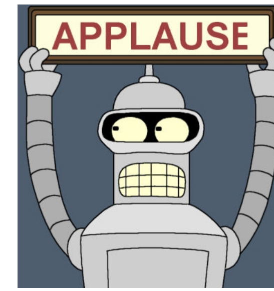
E. M. Schooneveld and the ANCIENT CHARM collaboration, *J. Phys.* D 42 No. 15 152003 (2009)

Simplified NRT analysis approach: area calibration

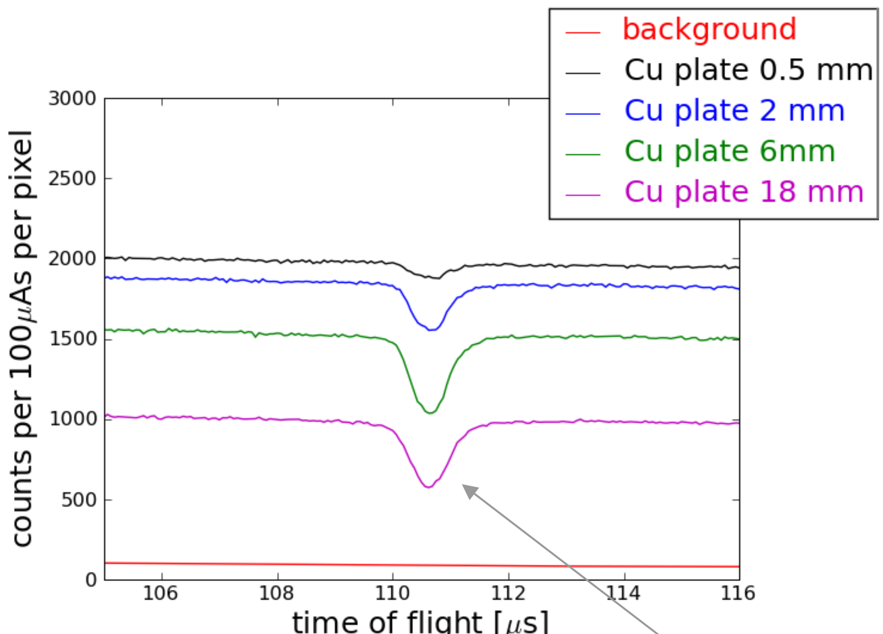
The optimum approach is ideal but quite long (both in terms of machine time and operator time)

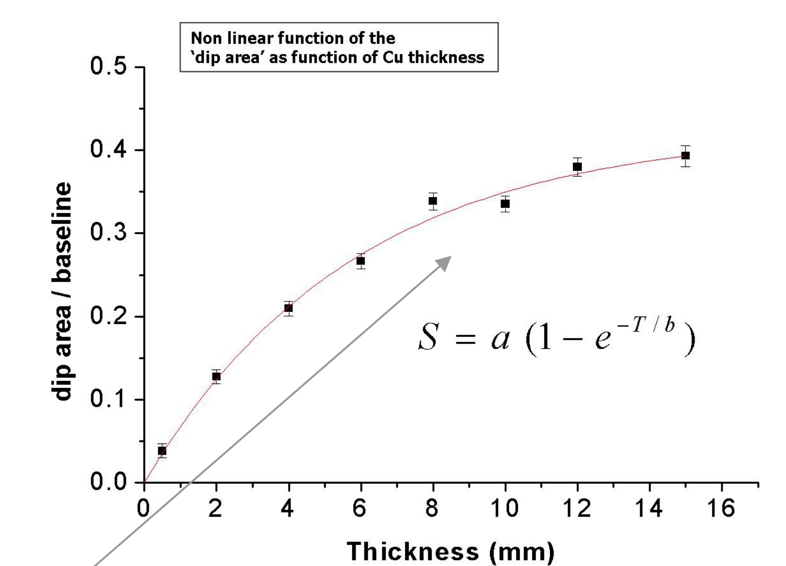
Images require the analysis of hundreds of spectra......

Simplified NRT analysis approach: area calibration



A suitable series of calibrated samples (for instance metal plates) can lead to an approximated but much simpler analysis





Saturation effect

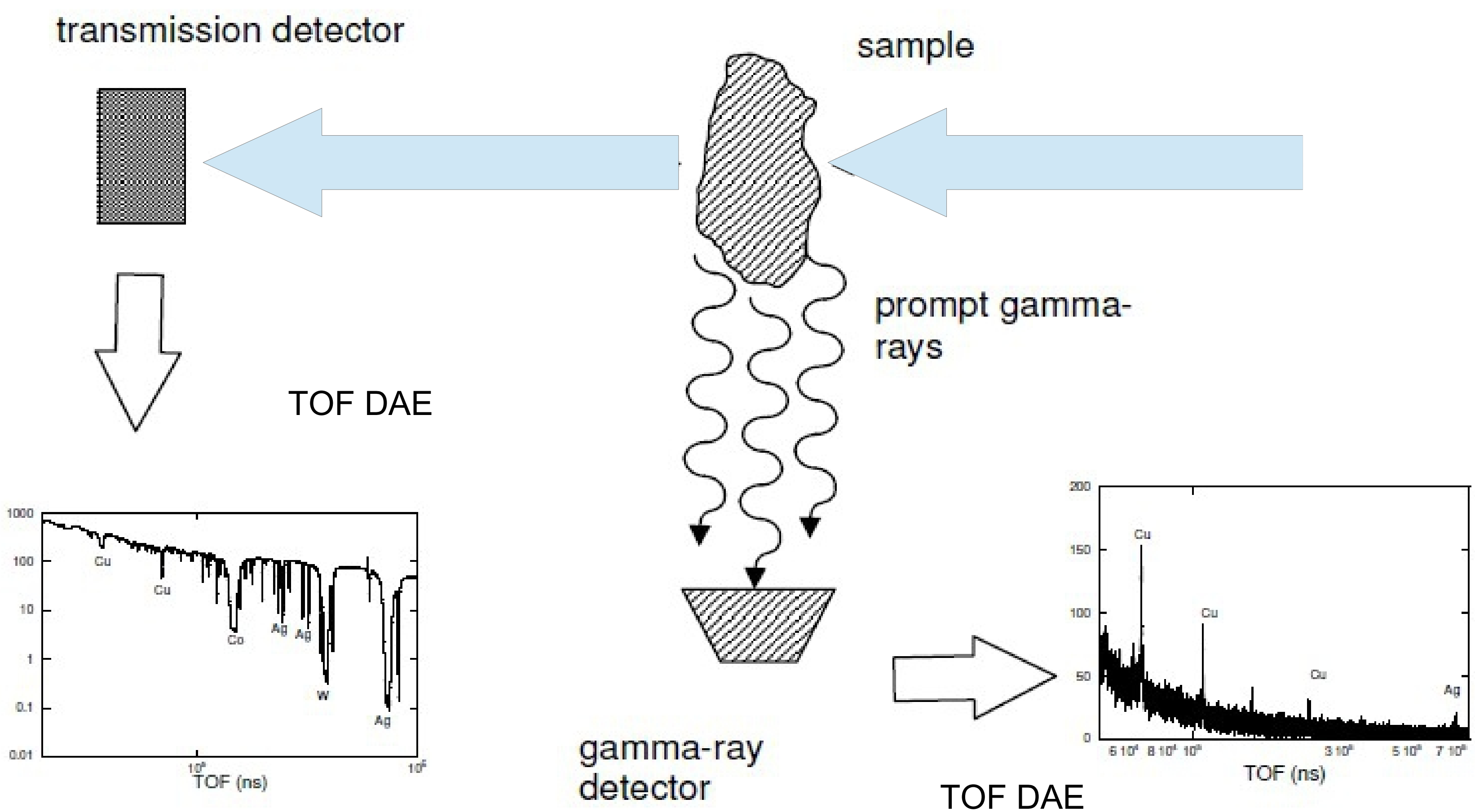
And what happens once the neutrons are adsorbed?

After neutron capture, most (not all....) isotopes deexcite via a PROMPT gamma emission

Prompt means “with characteristic times of the order of ps or less”

From the point of view of epthermal neutrons, that means IMMEDIATLY

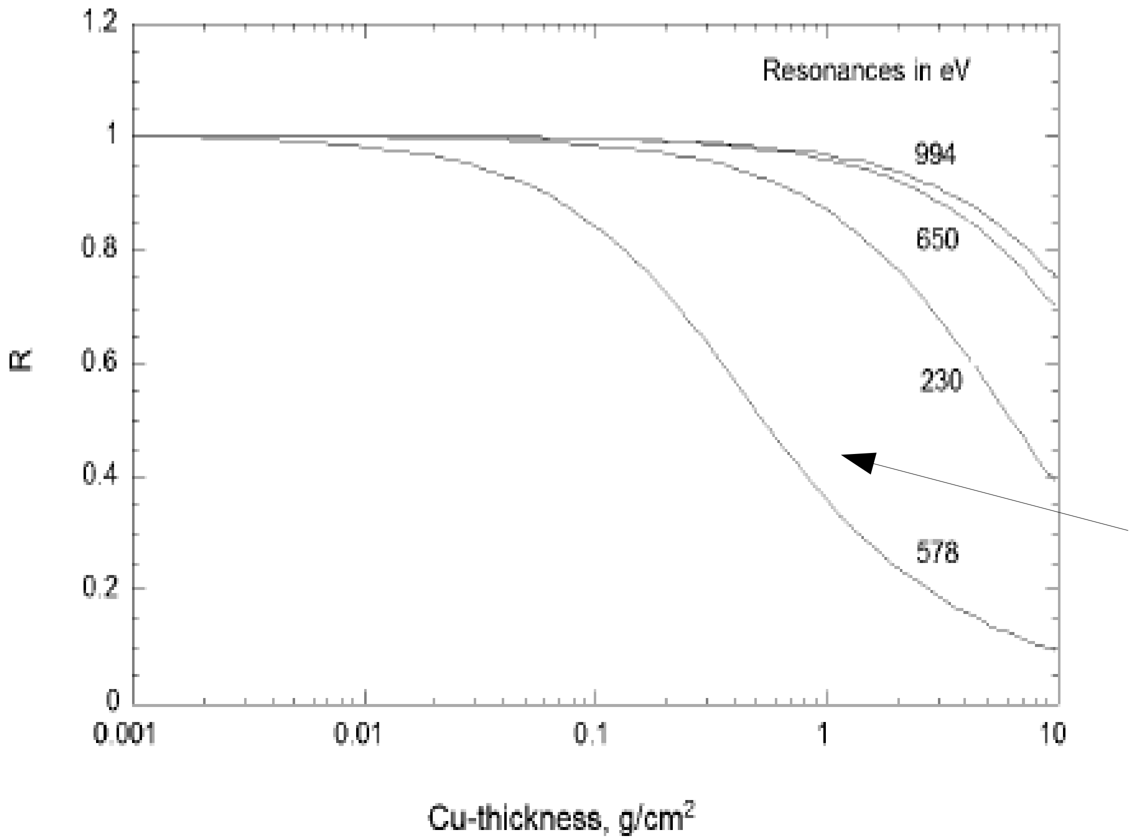
Thus the time information is preserved



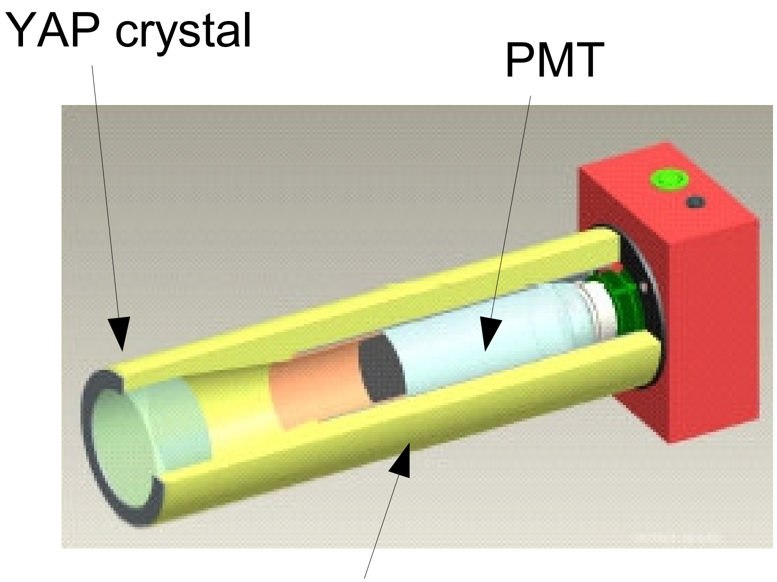
transmission detector
sample
TOF DAE
prompt gamma-rays
gamma-ray detector
TOF DAE
TOF (ns)
Cu
Co
Ag
W
TOF (ns)
Cu
Ag

Again, a fully quantitative approach is not simple.....

But NRCA has the advantage that a gamma detector is always simpler than a neutron detector!



Advanced set-up for NRCA



YAP is the ideal detector for NRCA

FAST
Neutron-insensitive

YAP scintillator:
51mm ø, 25mm thick

Array of 28 γ-detectors

~20% solid angle coverage

Application to Cultural Heritage

Selection of bronze axes from GIA University of Groningen (the Netherlands). H. Postma *et al.* 2005

Non-destructive material analysis of findings and museum objects

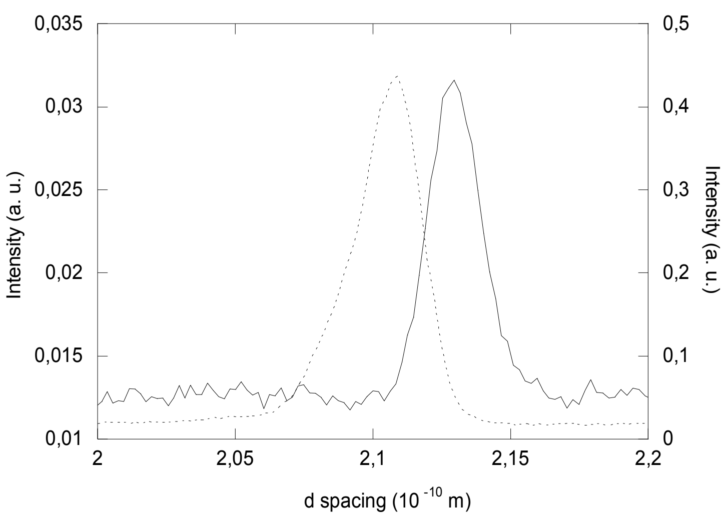
axe	Cu	Sn	As	Sb	Ag	Fe	Co	Zn	Pb	In (ppm)
1	100*	9.42 ±0.11	0.0774 ±0.0011	0.0736 ±0.0010	0.1004 ±0.0010	≤0.32	n.u.l.	0.100 ±0.011	≤1.3	17.4 ±0.3
2	100	15.68 ±0.19	0.292 ±0.004	0.0727 ±0.0010	0.0143 ±0.0005	0.50 ±0.02	0.067 ±0.002	0.224 ±0.014	≤1.2	23.2 ±0.4
3	100	4.96 ±0.06	0.183 ±0.004	0.355 ±0.005	0.153 ±0.002	≤0.03	0.052 ±0.003	≤0.05	≤2.4	7.5 ±0.4
4	100	3.79 ±0.06	0.189 ±0.027	0.0395 0.0008	0.0076 ±0.0007	≤0.03	n.u.l.	≤0.09	≤2.3	4.1 ±0.7
5	100	0.082 ±0.015	1.012 ±0.018	2.225 ±0.045	0.662 ±0.005	≤0.08	n.u.l.	≤0.29	≤2.2	4.4 ±1.0

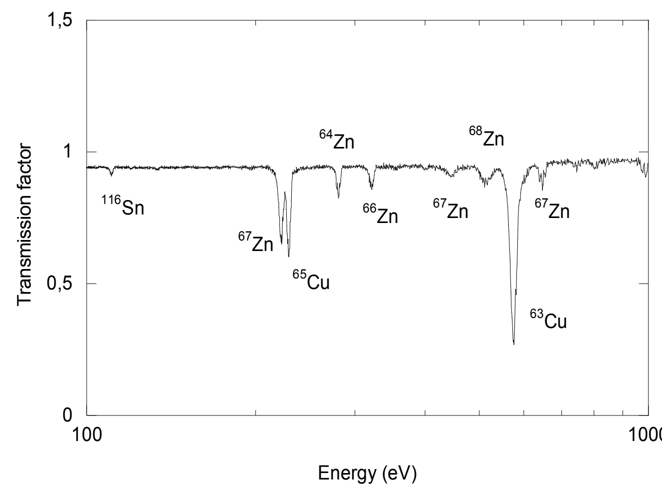
Application to Cultural Heritage

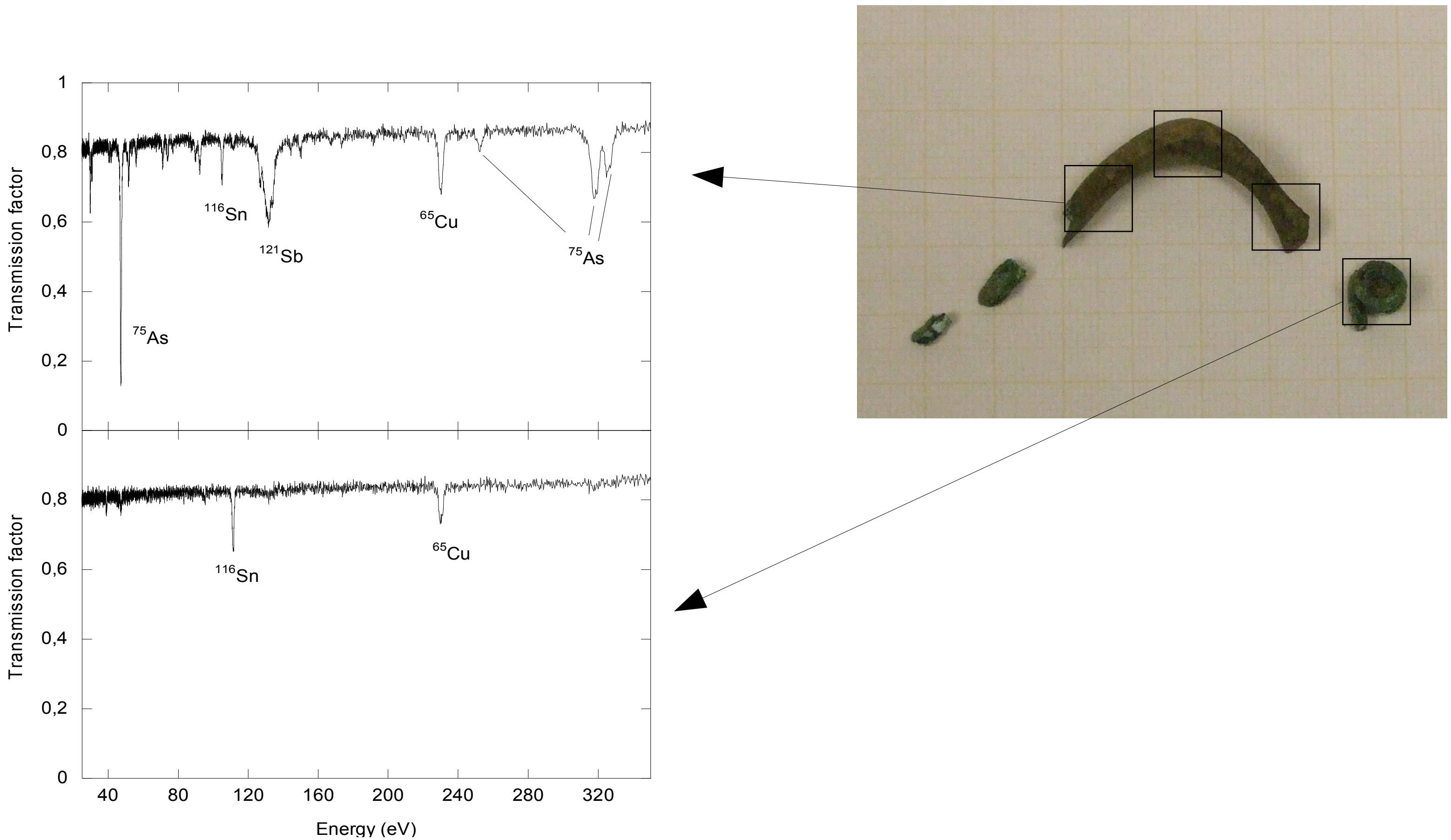
Natural complement to Vegard's law

$$a = a^0_A (1 - X_B) + a^0_B (X_B)$$

...but this just in the case of binary alloys.....

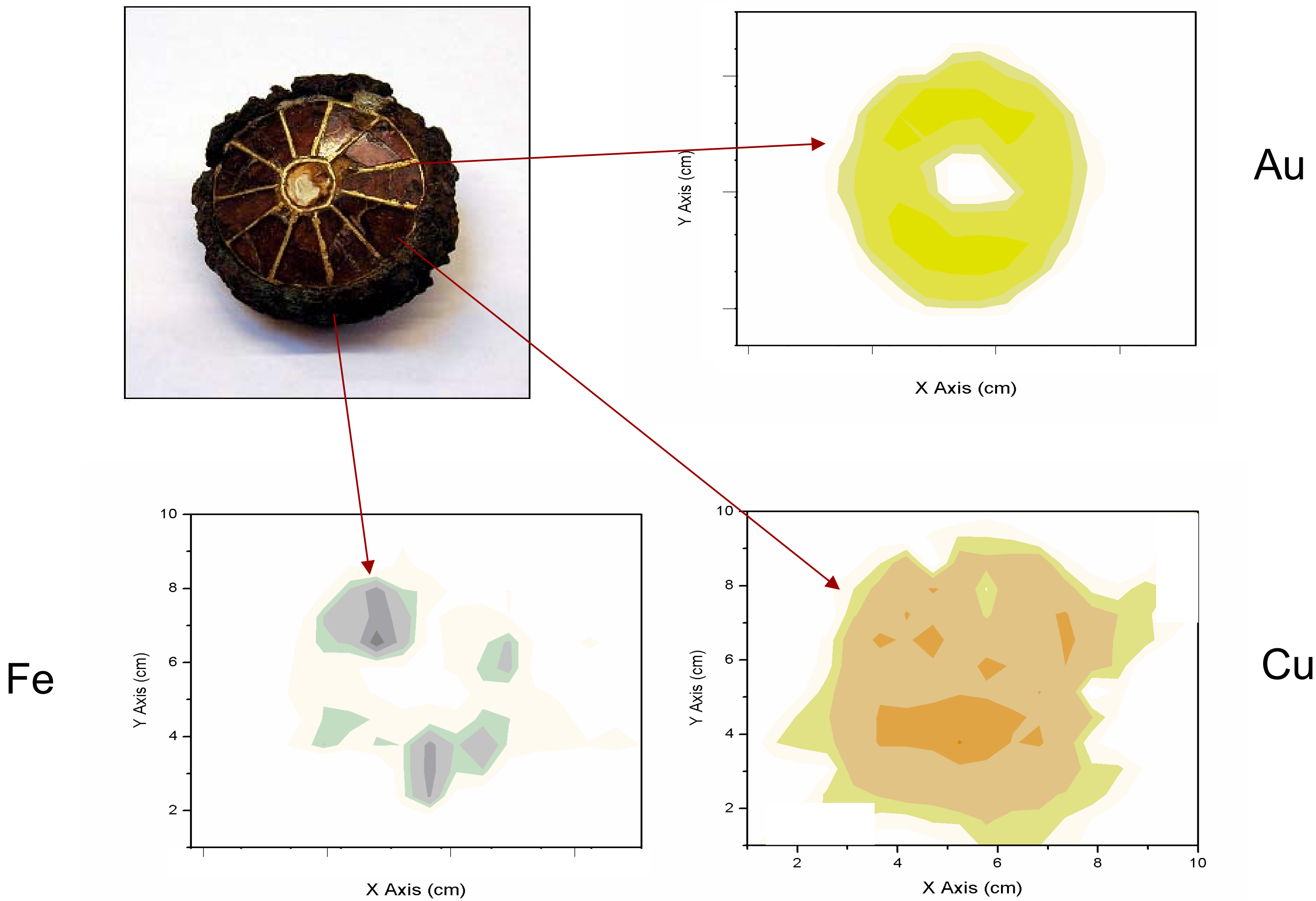




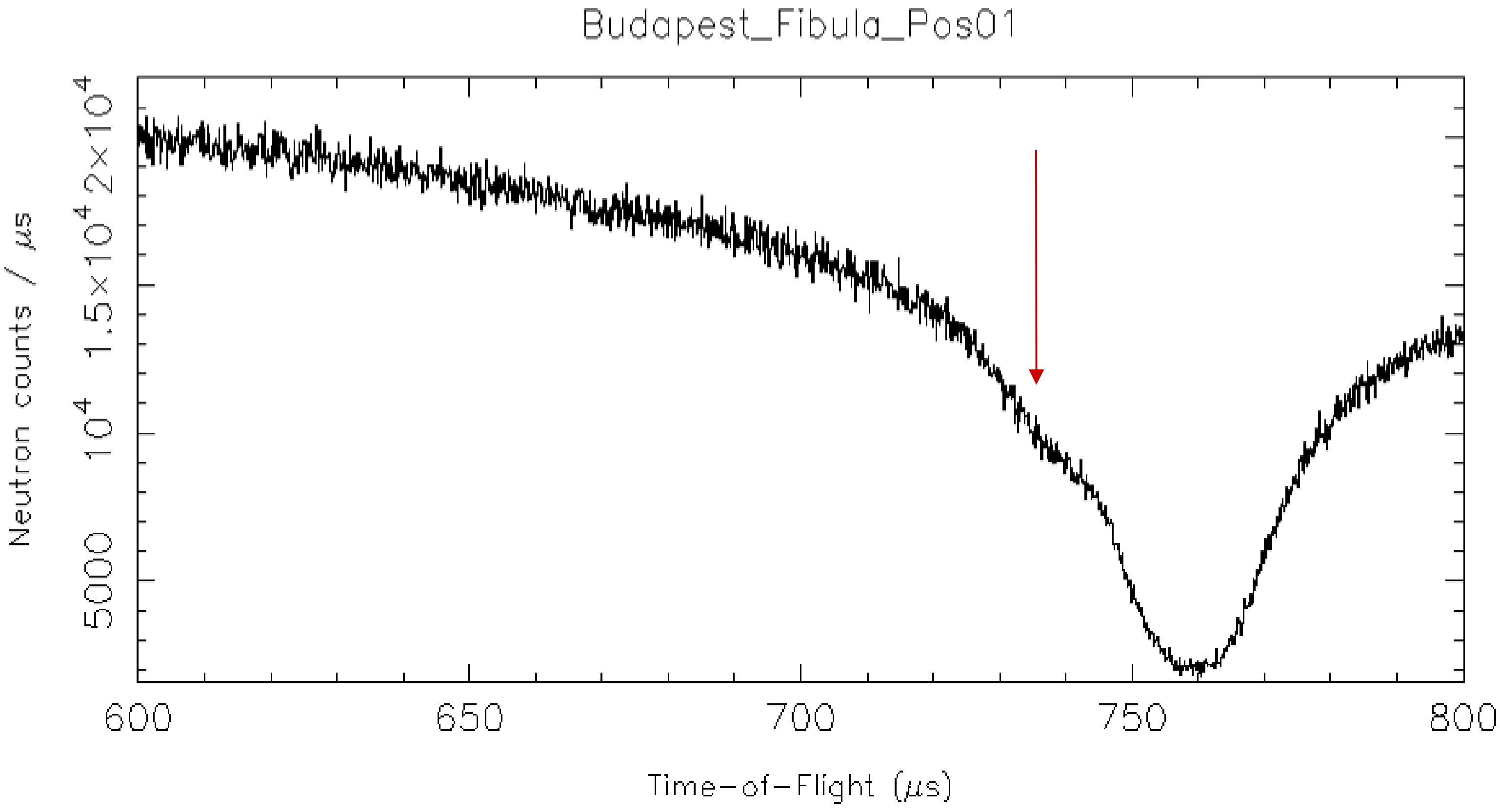


1
0,8
0,6
0,4
0,2
0
Transmission factor
75As
116Sn
121Sb
65Cu
75As
0,8
0,6
0,4
0,2
0
Transmission factor
116Sn
65Cu
40
80
120
160
200
240
280
320
Energy (eV)

Fibula VI - VII century C. E. From the Kölked-Feketekapu site
(National Hungarian Museum, Budapest)



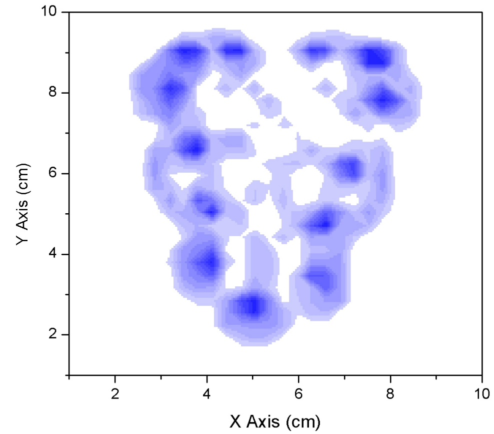
The distribution of gold "follows" the one of silver (the 5.1 eV resonance of silver is always visible as an edge of the 4.9 eV resonance of gold).

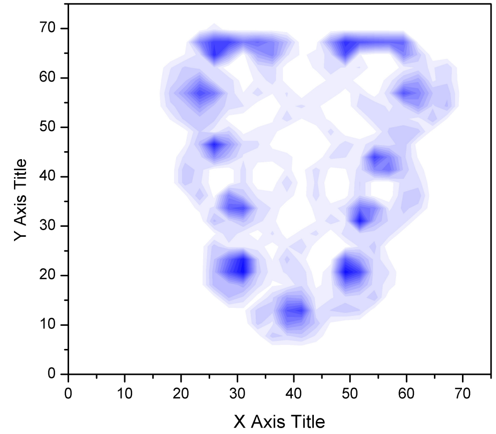


Conclusion: silver is significantly present in the gold alloy of the inlaying but not into the copper alloy of the base plate.

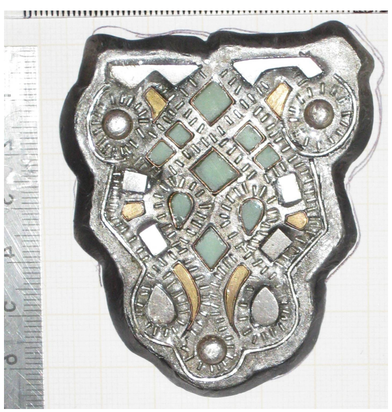
Belt mount VII century C. E. From the Kornye site (National Hungarian Museum, Budapest)

Ag

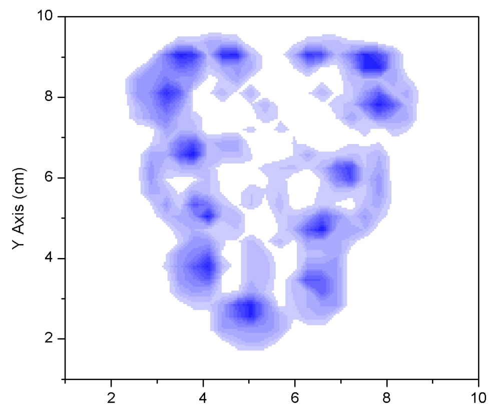


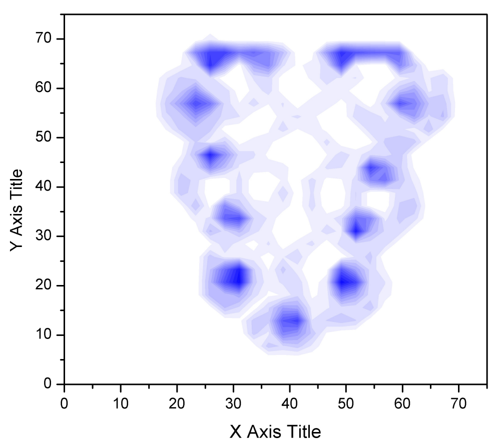


Borchia di cintura VII sec. d. C. dal sito di Kornye (Museo Nazionale Ungherese, Budapest)

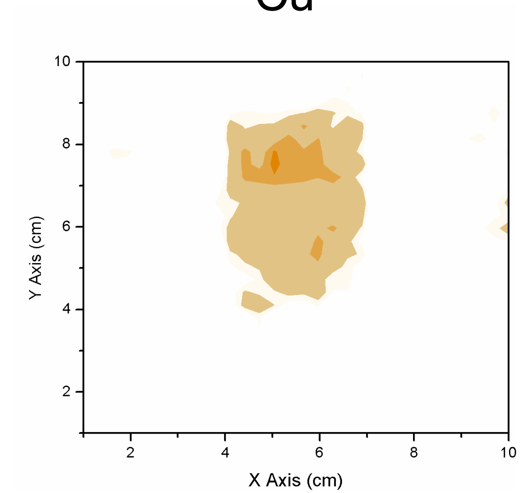


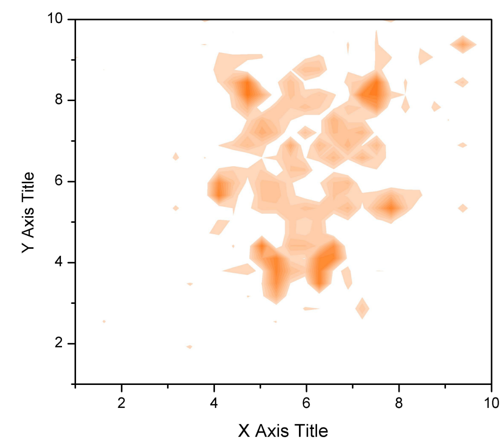
Ag





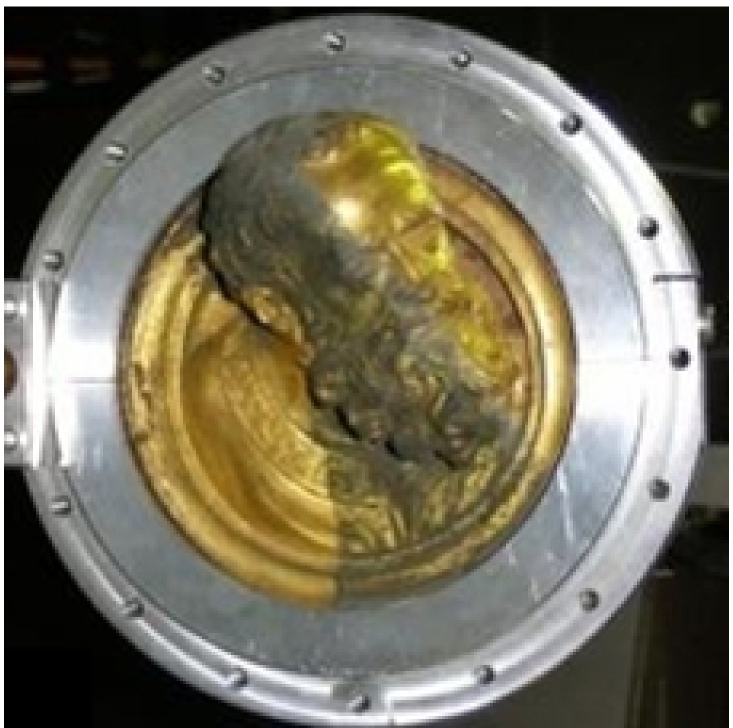
Cu

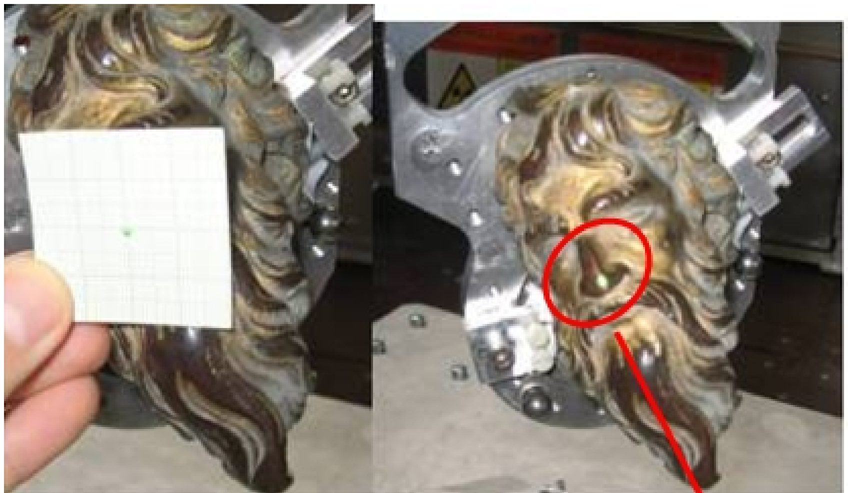




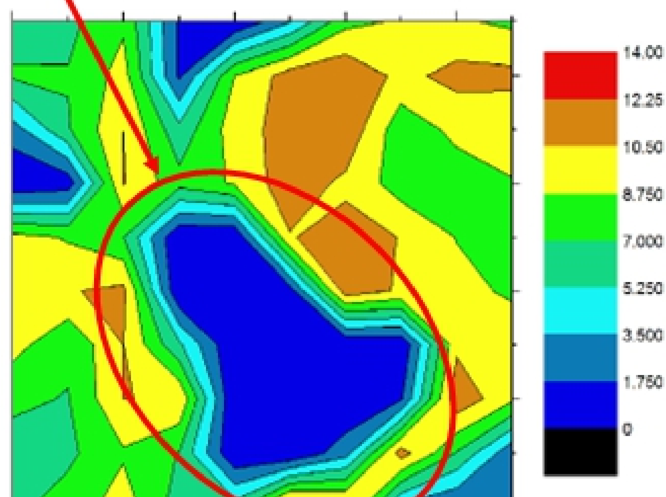
Lorenzo Ghiberti, Heads opf Prophets, from the gates of Florence baptistry (Opificio delle Pietre Dure, Firenze)

Gold glided bronze





In the North gate head, the gold leaf was completely removed by the effect of time form the most exposed parts (nose, eyebrows)



On the other hand, in the head from the “Gate of Heavens” the gold leaf is still present in exposed parts (beard) even under a heavy patina.