Prompt Gamma Activation Analysis

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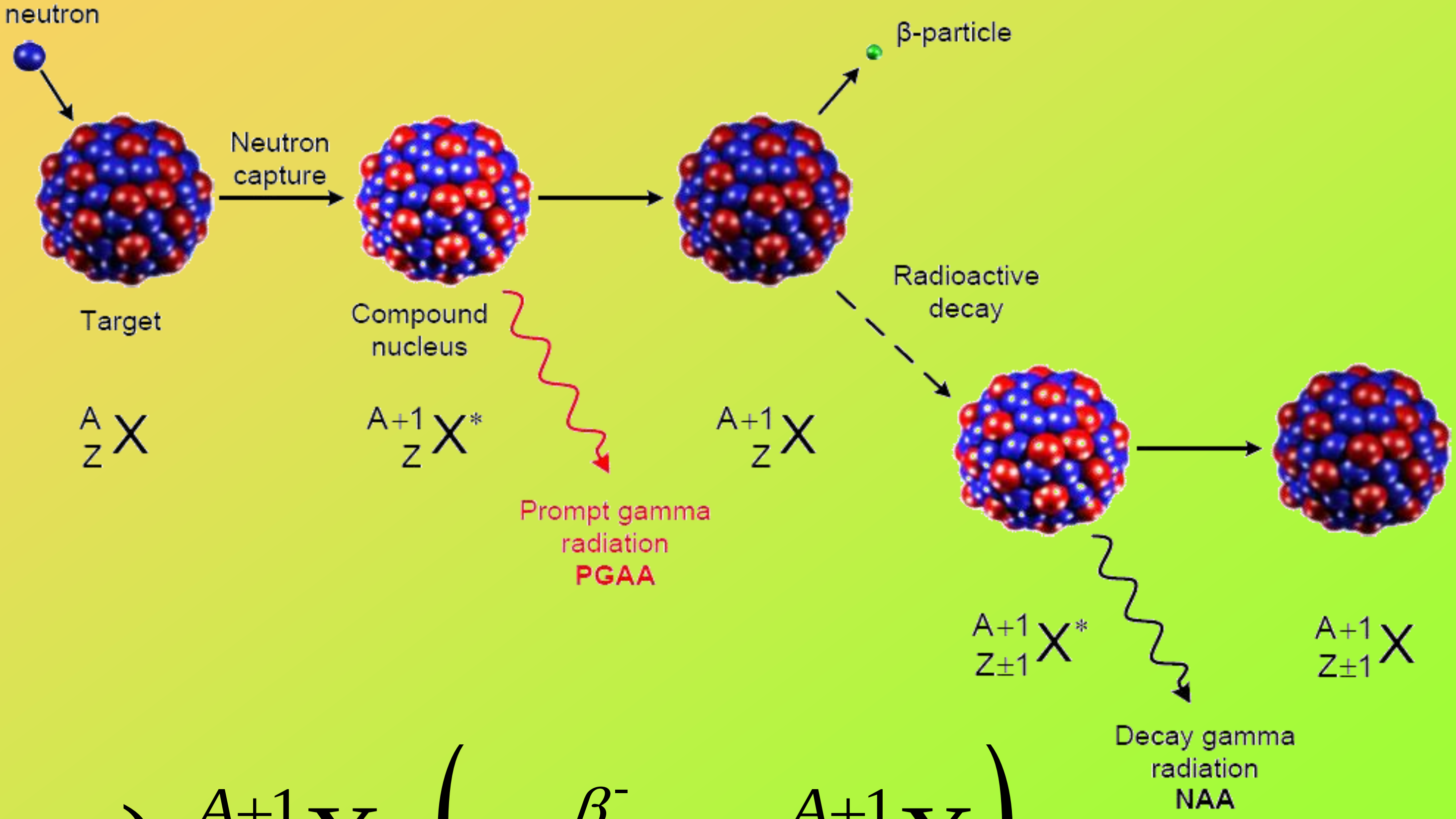
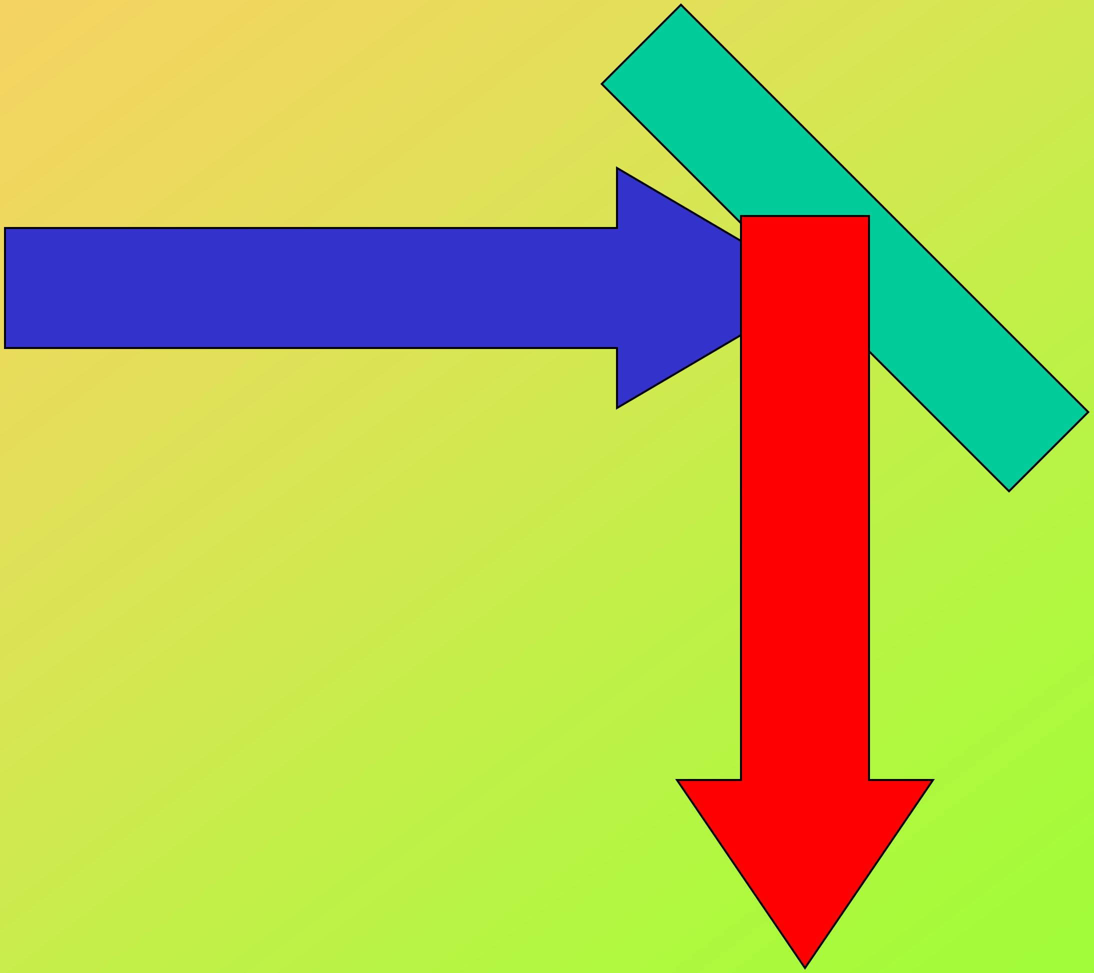
PGAA and NAA: based on radiative neutron capture



$$ {}^{A}_{Z}\mathrm{X}(\mathrm{n},\gamma)\ {}^{A+1}_{Z}\mathrm{X}\left(\xrightarrow{\beta^{-}}{}^{A+1}_{Z-1}\mathrm{X}\right) $$

Beam geometry



Neutrons and gamma rays

- both are highly penetrating
  - neutrons illuminate the sample in whole depth
  - high E gammas: almost no attenuation

- “double” shielding
  - massive lead shielding
  - ^{6}Li or B containing shielding

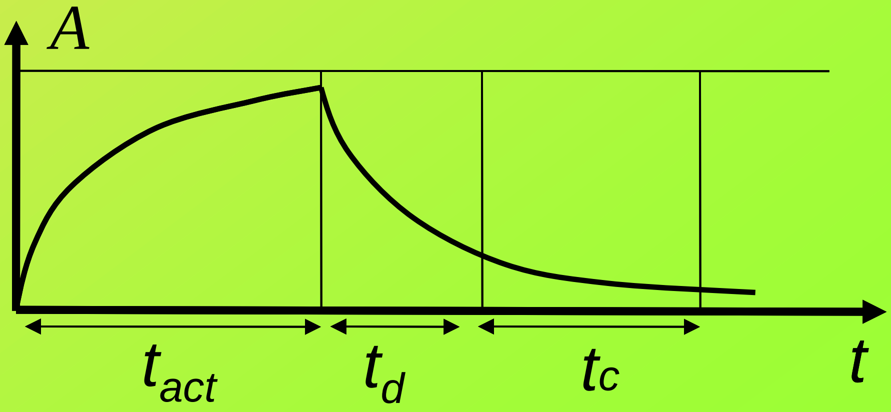
Principles

- Activation equation (peak count rate)

$$\frac{A}{t} = \overbrace{\varepsilon \underbrace{\frac{m}{M} N_A}_{n} \Phi \, \sigma_\gamma}^{\text{PGAA}} \quad \underbrace{S\,D\,C}_{\text{Correction for decay (NAA)}}$$

$$S = 1 - e^{-\lambda t_{act}} \qquad D = e^{-\lambda t_d} \qquad C = \frac{1 - e^{-\lambda t_c}}{\lambda t_c}$$

$$S\,D\,C \approx 0.01$$



Cross section differences

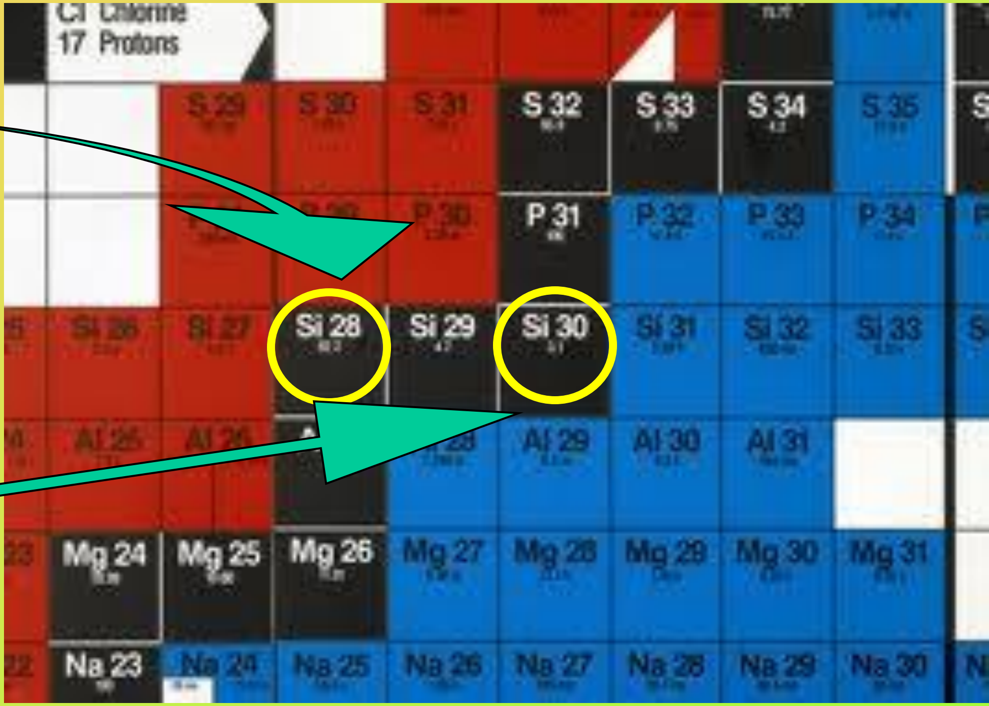
PGAA

$(\sigma_\gamma)_{max}$

NAA

$(\sigma_\gamma)_{last}$

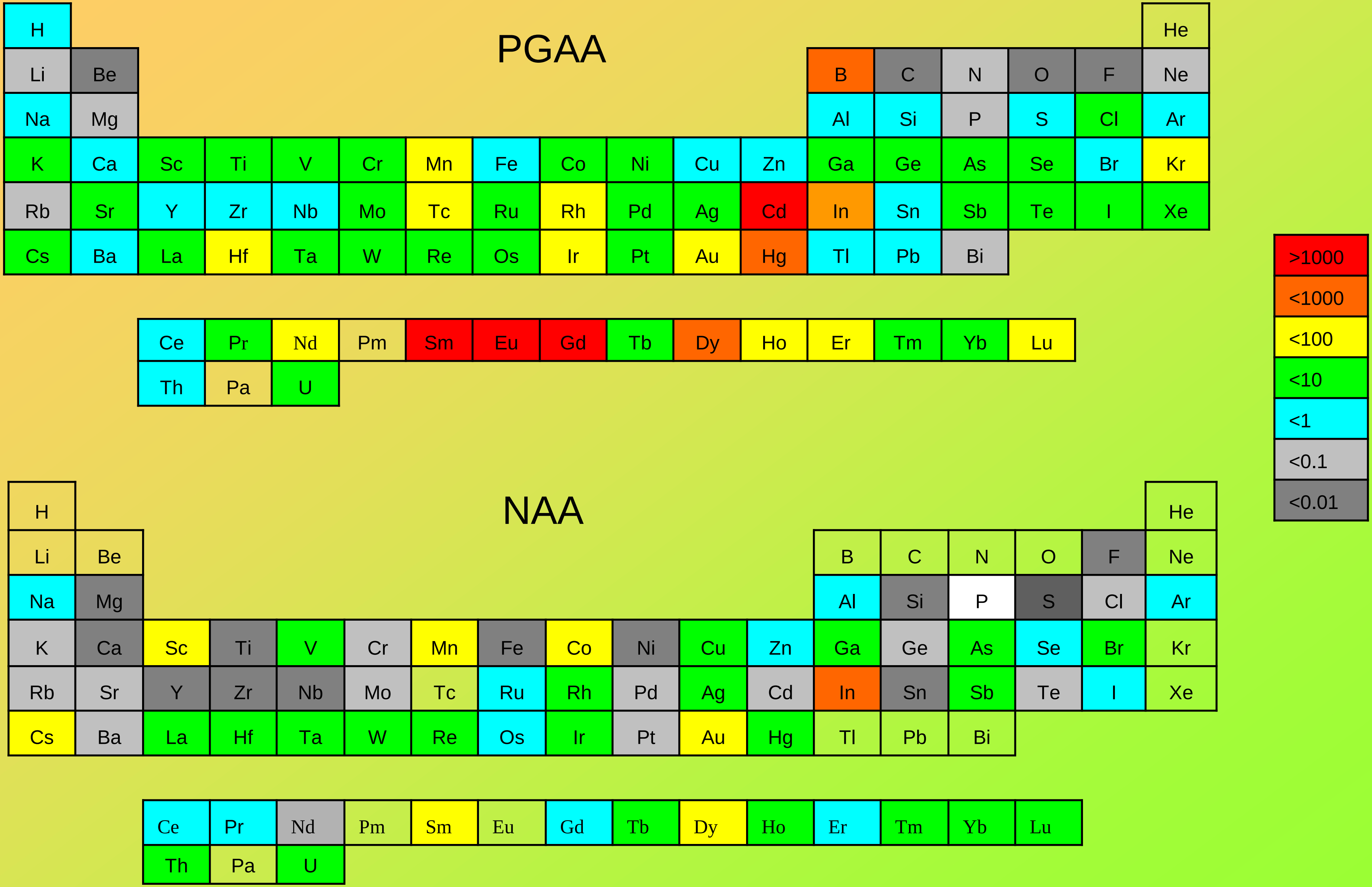
(Not always the last)



$(\sigma_\gamma)_{last} < (\sigma_\gamma)_{max}$

(by an order of magnitude)

Partial cross sections for PGAA and NAA



PGAA

🟦 H																	He
▒ Li	▓ Be											🟧 B	▓ C	▒ N	▓ O	▓ F	▒ Ne
🟦 Na	▒ Mg											🟦 Al	🟦 Si	▒ P	🟦 S	🟩 Cl	🟦 Ar
🟩 K	🟦 Ca	🟩 Sc	🟩 Ti	🟩 V	🟩 Cr	🟨 Mn	🟦 Fe	🟩 Co	🟩 Ni	🟦 Cu	🟦 Zn	🟩 Ga	🟩 Ge	🟩 As	🟩 Se	🟦 Br	🟨 Kr
▒ Rb	🟩 Sr	🟦 Y	🟦 Zr	🟦 Nb	🟩 Mo	🟨 Tc	🟩 Ru	🟨 Rh	🟩 Pd	🟩 Ag	🟥 Cd	🟧 In	🟦 Sn	🟩 Sb	🟩 Te	🟩 I	🟩 Xe
🟩 Cs	🟦 Ba	🟩 La	🟨 Hf	🟩 Ta	🟩 W	🟩 Re	🟩 Os	🟨 Ir	🟩 Pt	🟨 Au	🟧 Hg	🟦 Tl	🟦 Pb	▒ Bi			
		🟦 Ce	🟩 Pr	🟨 Nd	Pm	🟥 Sm	🟥 Eu	🟥 Gd	🟩 Tb	🟧 Dy	🟨 Ho	🟨 Er	🟩 Tm	🟩 Yb	🟨 Lu		
		🟦 Th	Pa	🟩 U													

NAA

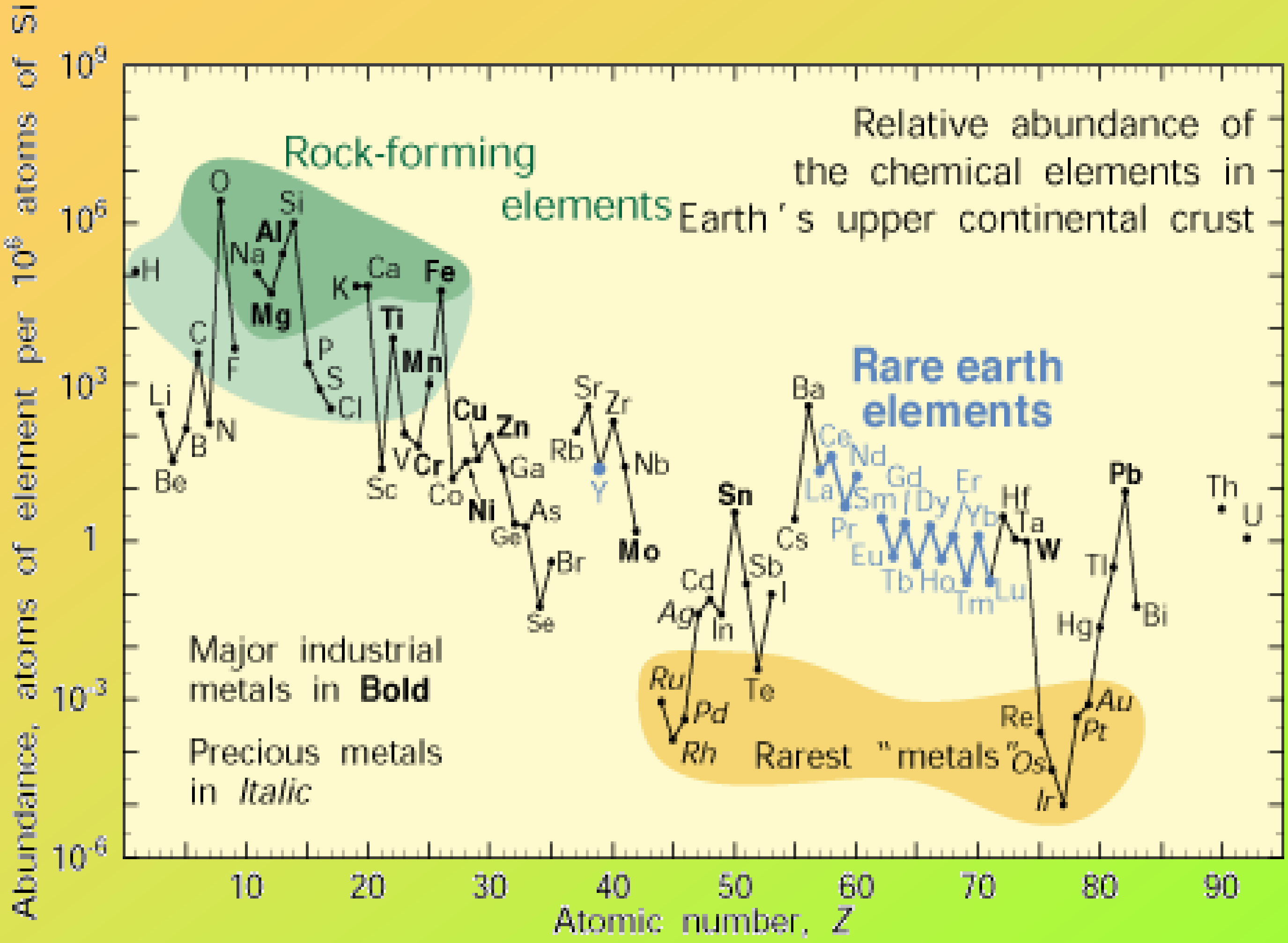
H																	He
Li	Be											B	C	N	O	▓ F	Ne
🟦 Na	▓ Mg											🟦 Al	▓ Si	□ P	▓ S	▒ Cl	🟦 Ar
▒ K	▓ Ca	🟨 Sc	▓ Ti	🟩 V	▒ Cr	🟨 Mn	▓ Fe	🟨 Co	▓ Ni	🟩 Cu	🟦 Zn	🟩 Ga	▒ Ge	🟩 As	🟦 Se	🟩 Br	Kr
▒ Rb	▒ Sr	▓ Y	▓ Zr	▓ Nb	▒ Mo	Tc	🟦 Ru	🟩 Rh	▒ Pd	🟩 Ag	▒ Cd	🟧 In	▓ Sn	🟩 Sb	▒ Te	🟦 I	Xe
🟨 Cs	▒ Ba	🟩 La	🟩 Hf	🟩 Ta	🟩 W	🟩 Re	🟦 Os	🟩 Ir	▒ Pt	🟨 Au	🟩 Hg	Tl	Pb	Bi			
		🟦 Ce	🟦 Pr	▒ Nd	Pm	🟨 Sm	Eu	🟦 Gd	🟩 Tb	🟨 Dy	🟩 Ho	🟦 Er	🟩 Tm	🟩 Yb	🟩 Lu		
		🟩 Th	Pa	🟩 U													

🟥 >1000
🟧 <1000
🟨 <100
🟩 <10
🟦 <1
▒ <0.1
▓ <0.01

Total count rate in the spectrum

- If the total intrinsic efficiency ≈ 1
  - For large detectors 100 keV—12 MeV $\varepsilon > 0.5$ (minimum around 10 MeV)
- Below Q (=E_{max}) 1 cps (if the γ photon reaches the detector)
  - For prompt gamma spectra: Q ≈ 7MeV
  - For delayed gamma spectra: Q ≈ 1.5 MeV
- So PGAA spectra have ~5× more counts from similar cross section materials

Abundance of elements



(figure from http://pubs.usgs.gov/fs/2002/fs087-02/)

- PGAA
  - Light elements (H)
  - Matrix constituents
    - Certain trace elements (B, Cd, REE)
- NAA
    - Z>10
    - Really good Z>20
    - Trace elements

NAA vs. PGAA for natural samples

- Most elements in the matrix are invisible
  - Trace elements: × 10^{-3}
- Cross sections are smaller
  - × 10^{-1}
- Decay correction
  - × 10^{-2}
- Count rate
  - × 10^{-1}
- Counting efficiency
  - × $10^{1—3}$

NAA needs $10^{4—6}$ higher flux

Analysis

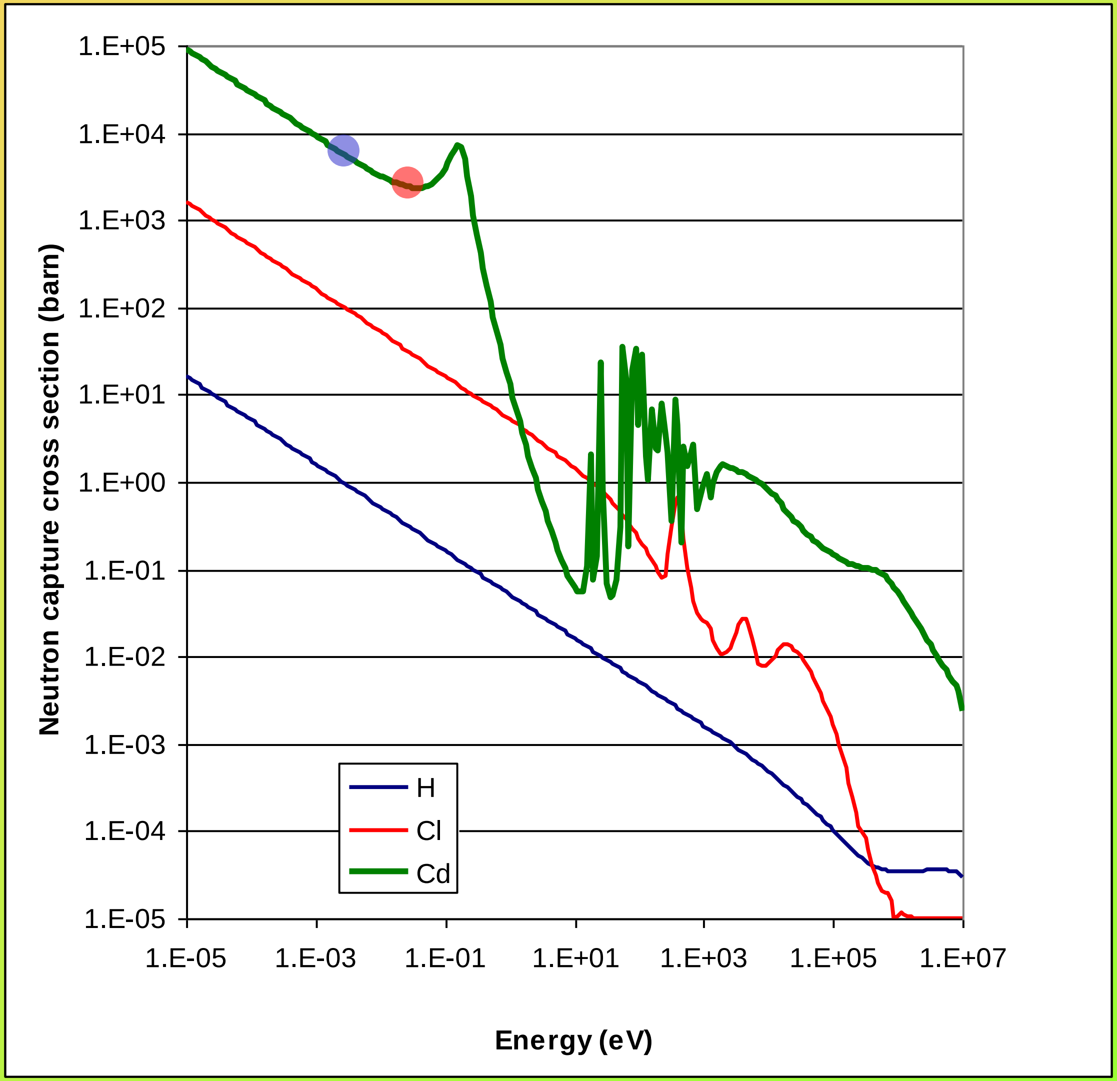
Gamma radiation is characteristic

- energy → elements (isotopes)
- intensity → quantity

Peak position	Peak area
Energy	Partial gamma-ray production cross section
2223.249 keV	0.3326 barn for H
…	…

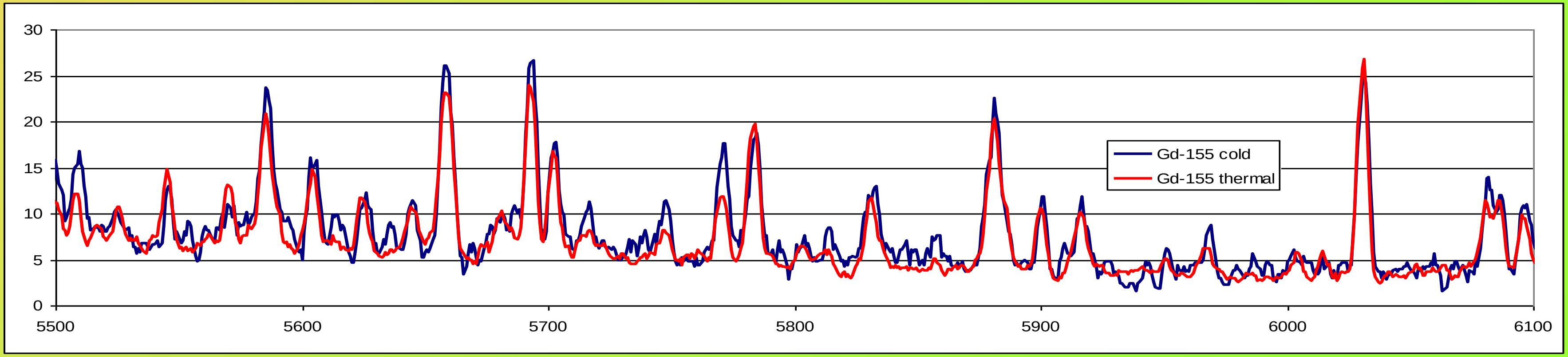
Cross section

- neutron capture cross section
- at low E: 1/*v* law
  - highest reaction rate for **cold neutrons**
- neutrons must be moderated
- resonance neutrons
  - RNCA (IRMM, Gel, Postma et al.)



Radiative neutron capture

- Kinetic energy of neutron (<eV) is negligible compared to binding energy (S_n~MeV), or the detector resolution (~keV)
- Prompt de-excitation from capture state
  - Is the de-excitation independent of the beam energy?
  - Mostly yes, but close-lying resonance(s) can also be excited, from which de-excitation **can** be be different
    - Emission probabilities (mainly below S_n) may differ in different beams
      - ^{149}Sm, ^{157}Gd, ^{151}Eu, 10—20% deviations in thermal/cold beam
      - but not ^{113}Cd
      - Epithermal neutrons may cause further deviations (collimated beams)



Heedong Choi, Zsolt Revay

Panorama analysis

- major components: Li, Be, **C, N**, O, Pb, Bi
- (at least) minor: **H**, F, Na, Mg, Al, Si, Ca, Sn
- above 10 ppm: halogenes, transition metals
- trace and above: **B**, Cd, Hg, rare-earths

Determination of masses

$$R_\gamma = N \sigma_\gamma \Phi$$

$$\sigma_\gamma = \theta \boldsymbol{\sigma} P_\gamma$$

$\boldsymbol{R_\gamma}$ - induced activity for a given gamma energy

$\boldsymbol{N}$ - number of atoms (~mass of component)

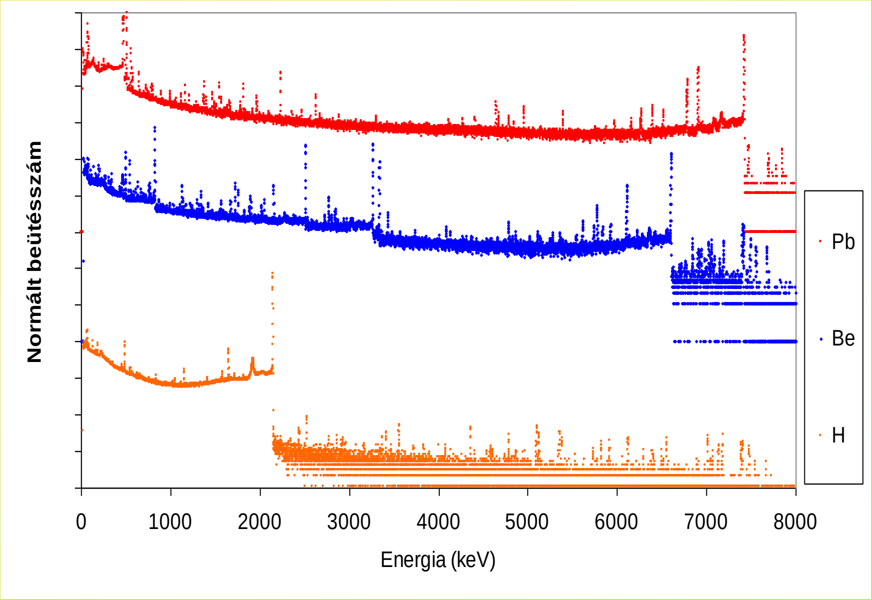
σ_γ - gamma ray production cross section

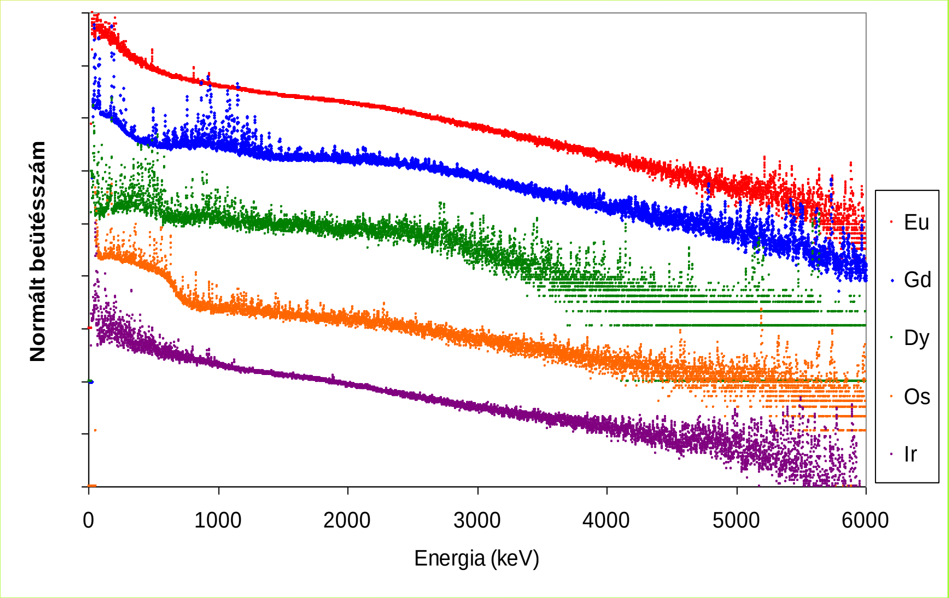
- θ – isotopic abundance
- $\boldsymbol{\sigma}$ – capture cross section
- $\boldsymbol{P_\gamma}$ – emission probability

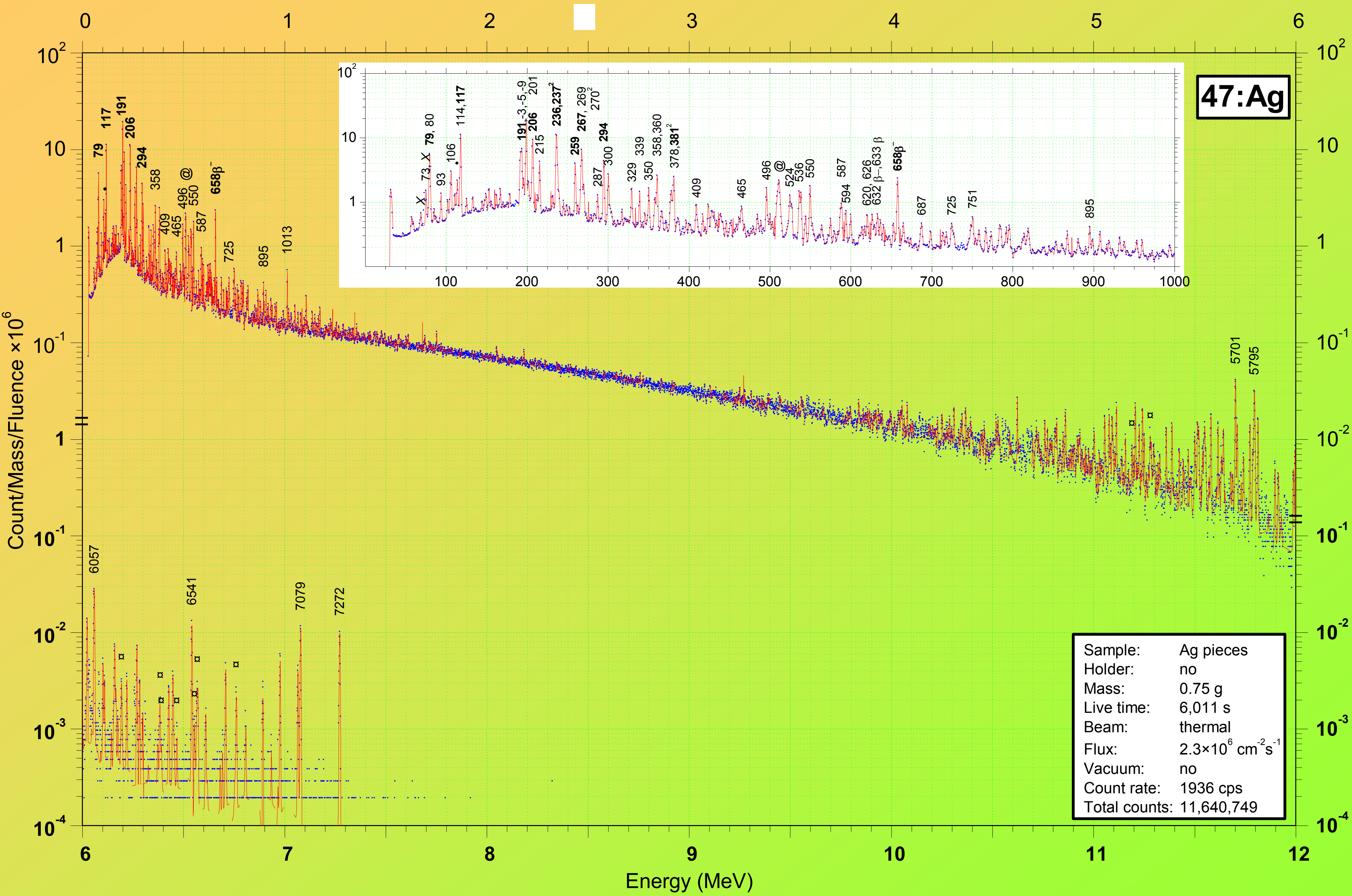
$\boldsymbol{\Phi}$ - neutron flux

PGAA spectra

- complicated gamma spectrum
  - Many known interferences
  - Many still unknown interferences
  - Peaks behave stochastic, can be handled using statistical techniques

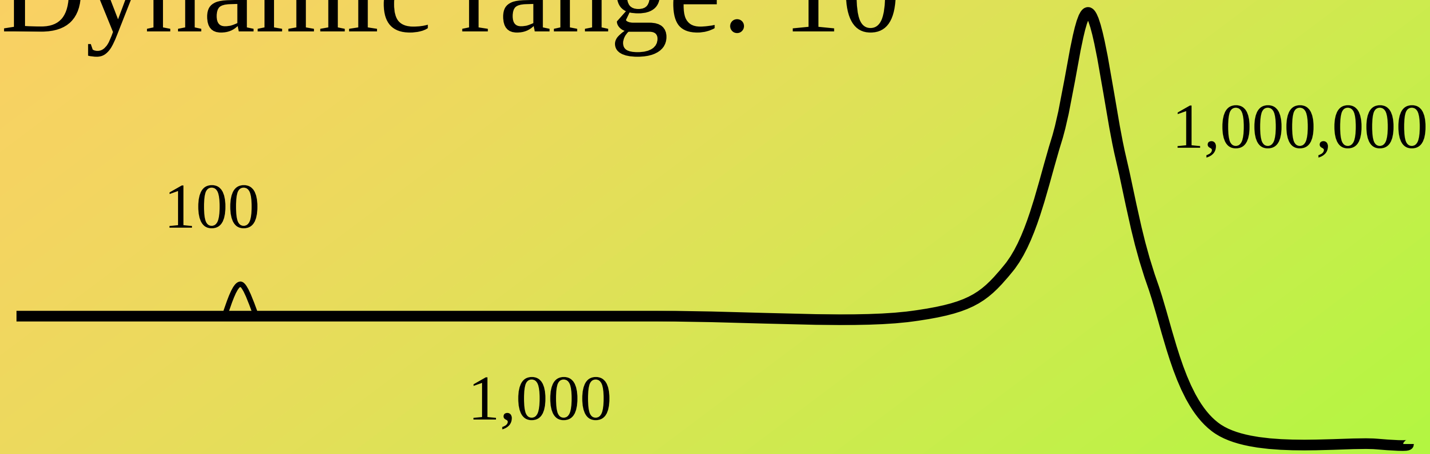






Sample:	Ag pieces
Holder:	no
Mass:	0.75 g
Live time:	6,011 s
Beam:	thermal
Flux:	2.3×10^6 cm^{-2}s^{-1}
Vacuum:	no
Count rate:	1936 cps
Total counts:	11,640,749

Dynamic range: $10^{3—4}$



bi-directional dynamic range: $10^{6—8}$

1 mg H together with 1 g Cl
(10 mg water in 1 g CCl_4)

1 mg Cl together with 1 g H
(1 mg Cl in 10 g water)

Properties of PGAA

- nondestructive
- no sample preparation, sample in any form
- independent from chemical environment
- all elements, isotopes: panorama analysis
  - light elements (H, B, C, N, F, Na, Al, Si, …)

- extremely different sensitivities

- complicated gamma spectrum

Components of the PGAA Instrument

Components of the instrument

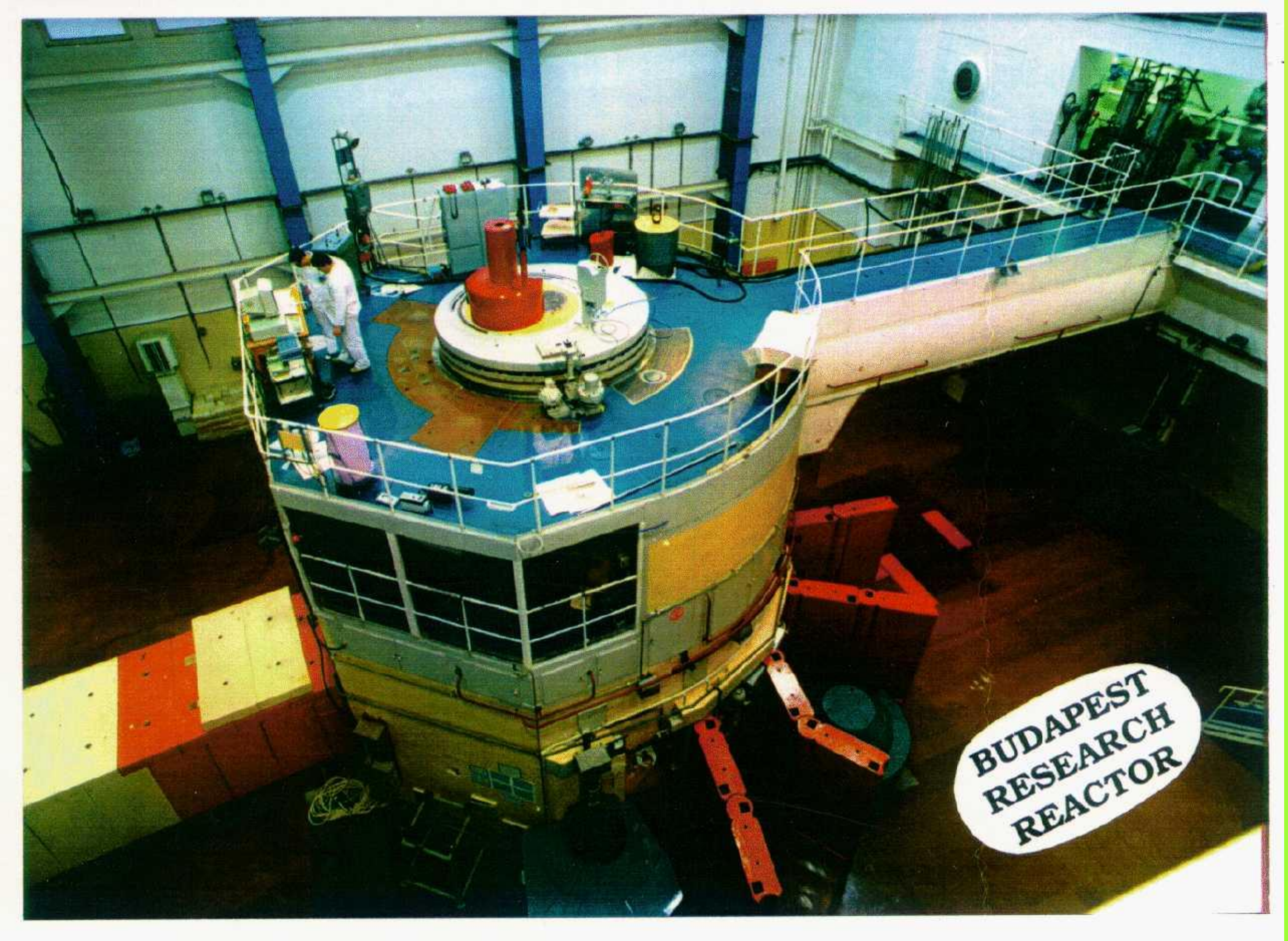
- Neutron source
  - spallation neutron source
  - nuclear reactor
  - neutron generator
  - isotopic neutron source (^{252}Cf, Pu-Be, ...)
- Moderator (H containing material)
- Shielding against ...
  - neutrons
  - gammas
- Detector
  - high-purity germanium (HPGe)
  - scintillator (NaI, ...)

Neutron sources

- Nuclear reactor
  - collimated neutron beams (NIST thermal system)
  - guided neutron beams (NIST cold, Budapest, Japan)
  - diffracted neutron beam (Korea)
- neutron generator

Research Reactor

- 10 MW
- water cooled
- water moderated
- thermal flux 10^{14} cm^{-2} s^{-1}



FRM II and the neutron guide hall

FRM II in Garching

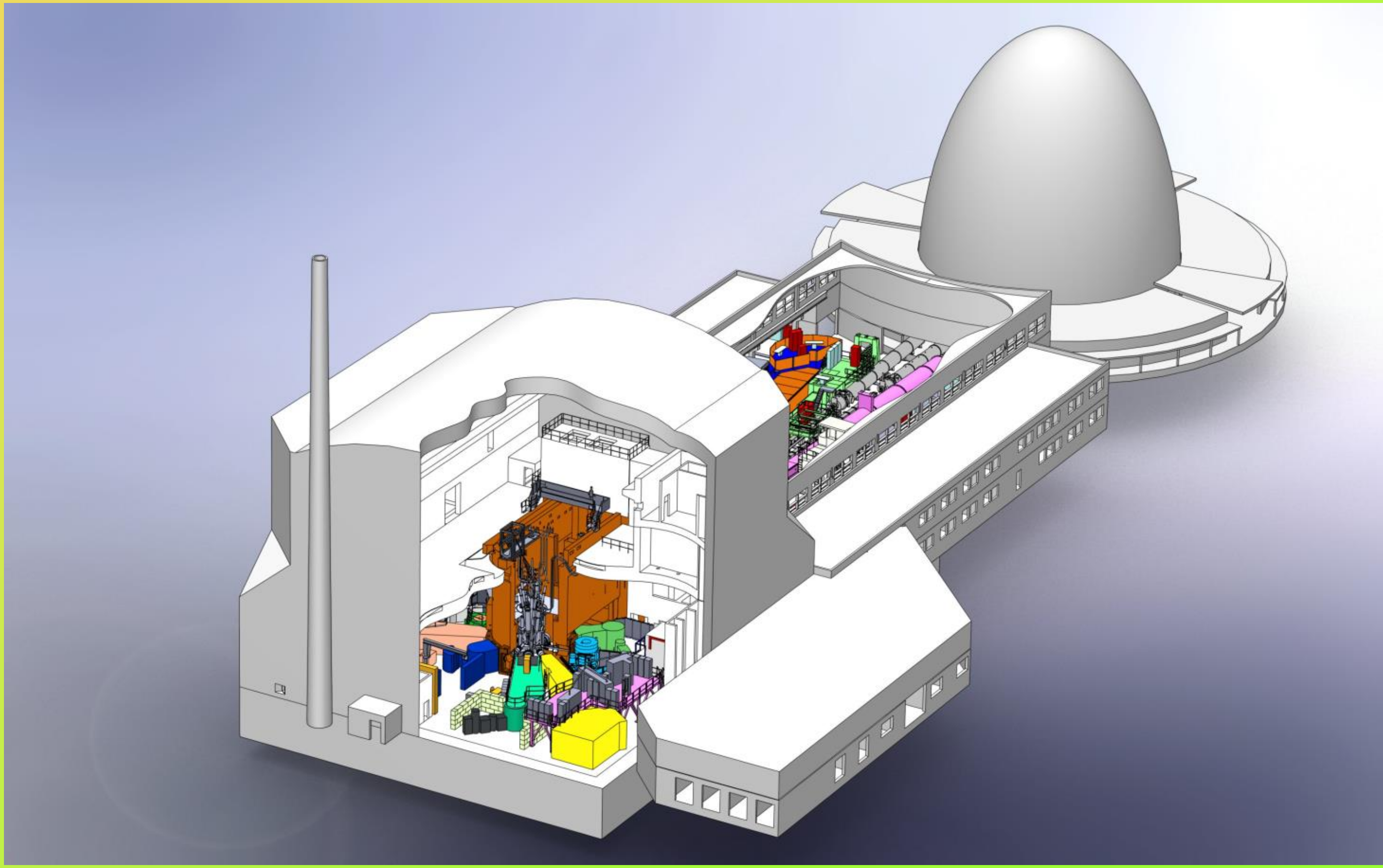
20 MW

water cooled

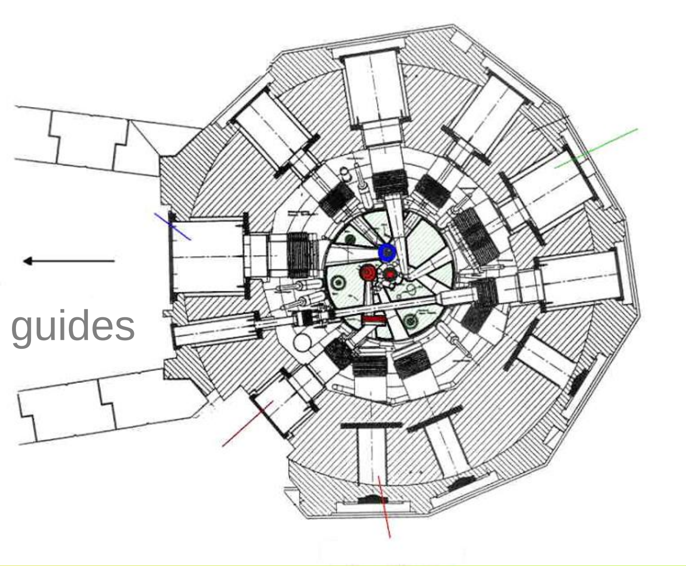
Heavy-water moderated

thermal flux

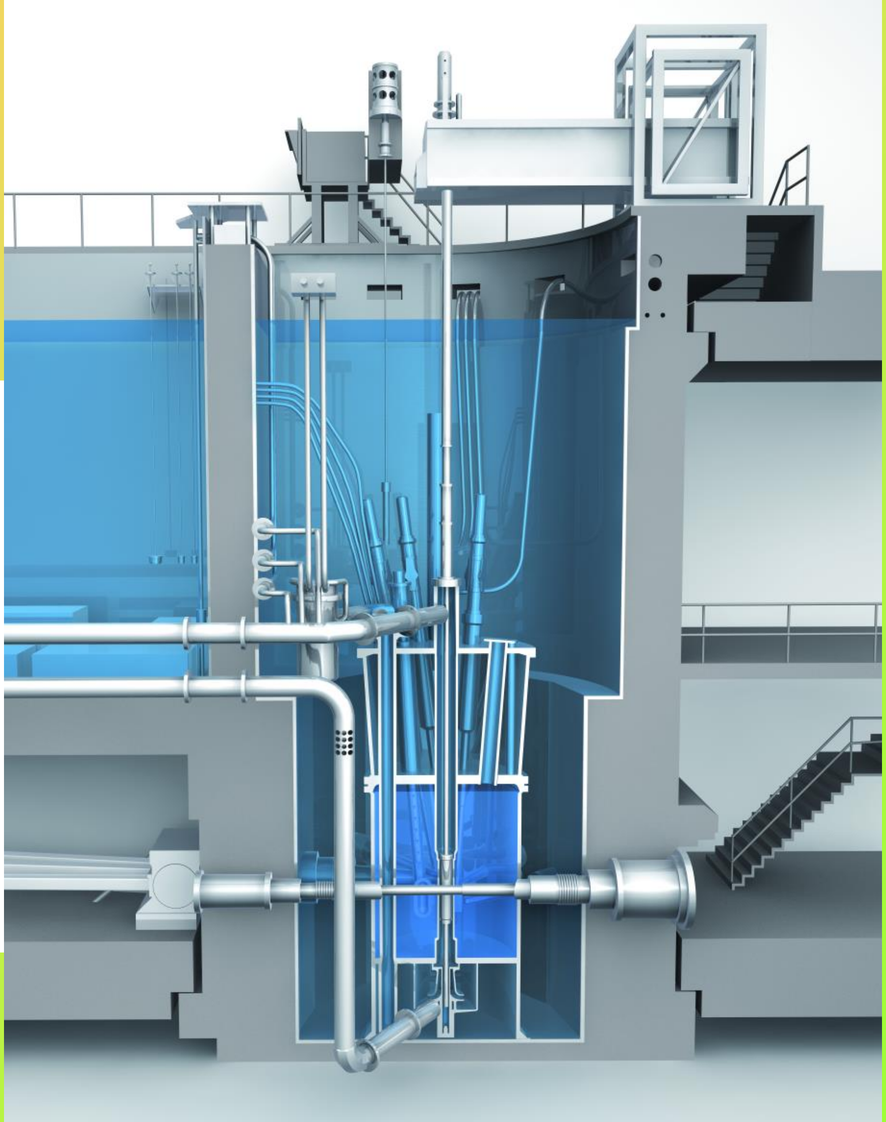
~10^{15} cm^{-2} s^{-1}



Cross section
primary circuit FRM II

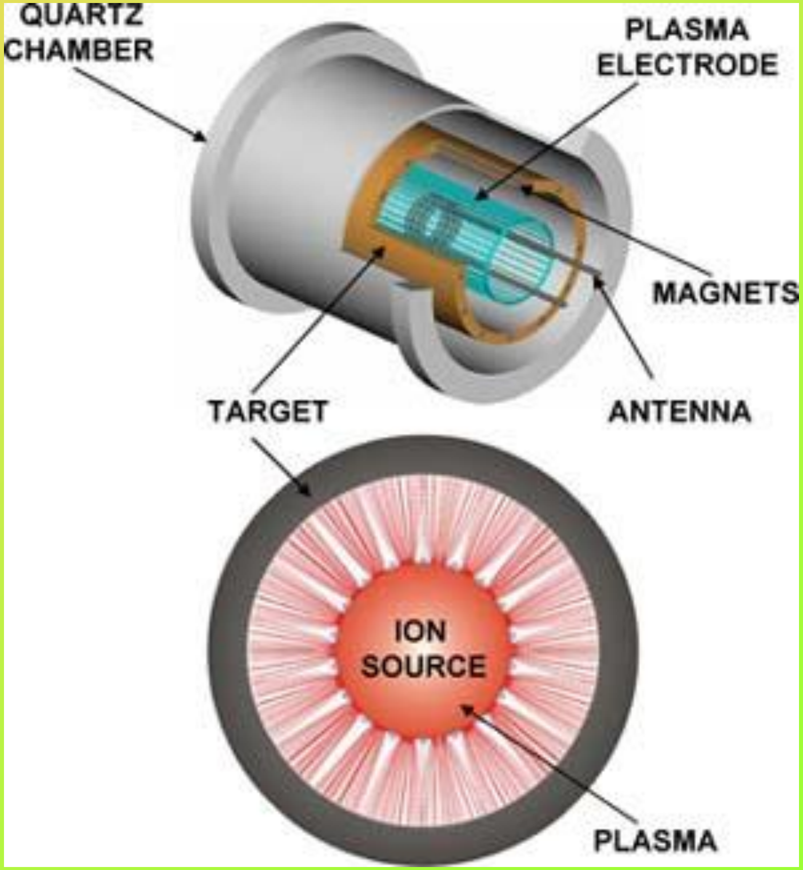


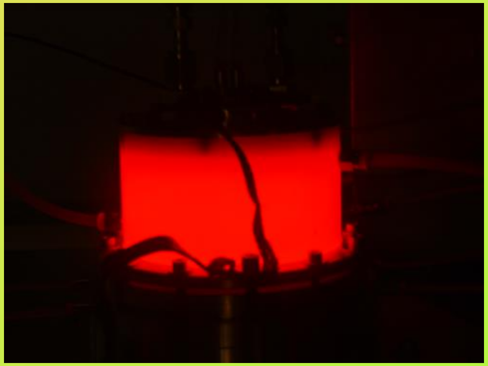
Neutron guides



Berkeley neutron generator

- D+D or D+T reaction
- $10^{9\text{-}11}$ fast n/s
- E = 2.4 or 14 MeV
- “desktop” instrument
- pulsed beam…





Moderators

- any H (maybe D) containing material
  - water (heavy water)
  - liquid hydrogen, deuterium

The cold neutron source (FRM II)

Liquid deuterium moderator

Volume moderator vessel	25 liters
Volume of liquid D_2	~ 13 liters
Temperature	25 K

3 beam tubes
for cold neutron experiments

1 vertical beam tube is not in use

Cooling power total	~ 6 kW
in liquid D_2	2.7 kW

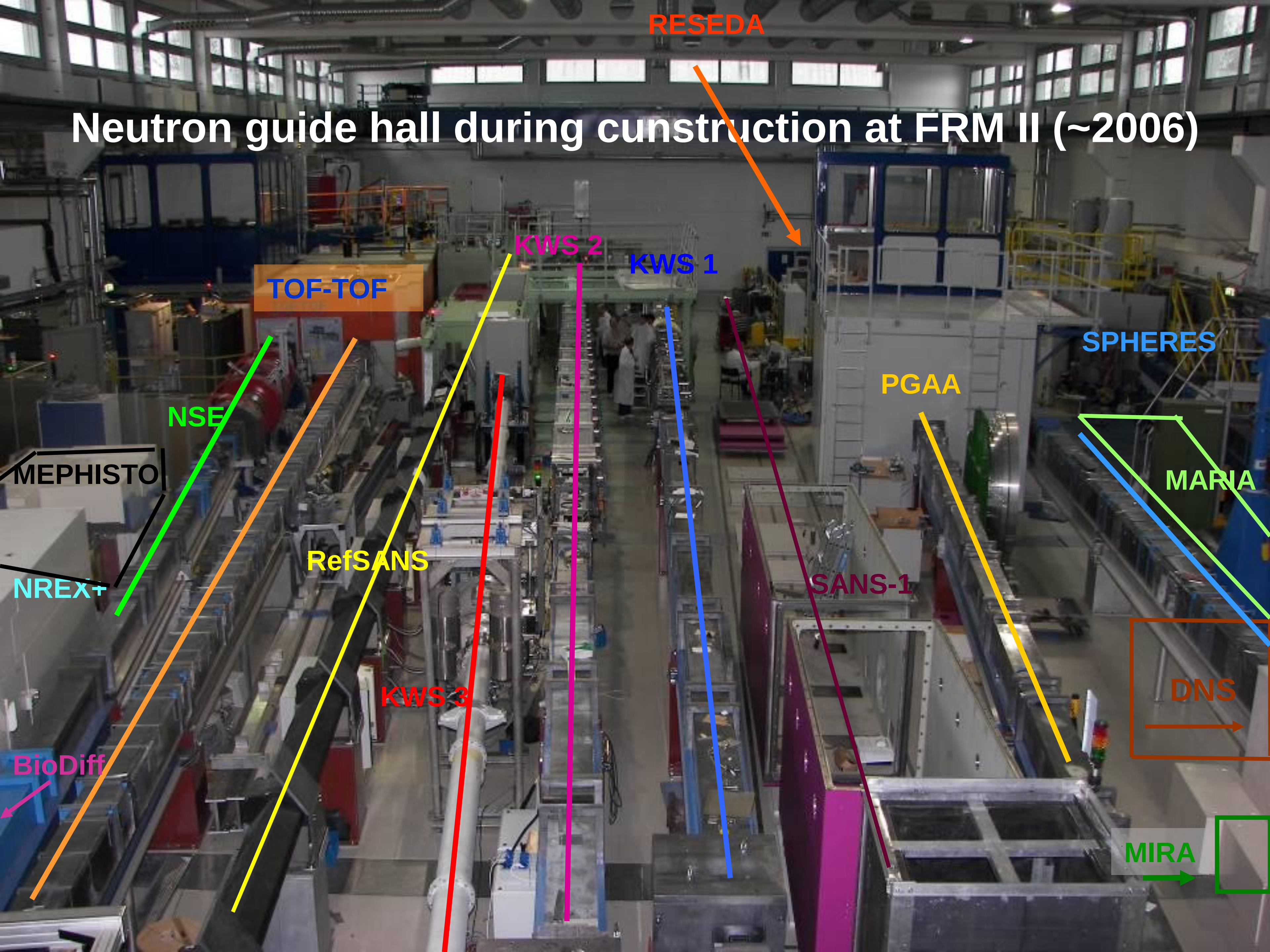
E. Gutsmiedl, Päthe, Chr. Müller, A. Scheuer

Neutron guides

- Ni or supermirror guides
- relatively small losses
- **low background**

Mirrotron Ltd.

Neutron guide hall during cunstruction at FRM II (~2006)



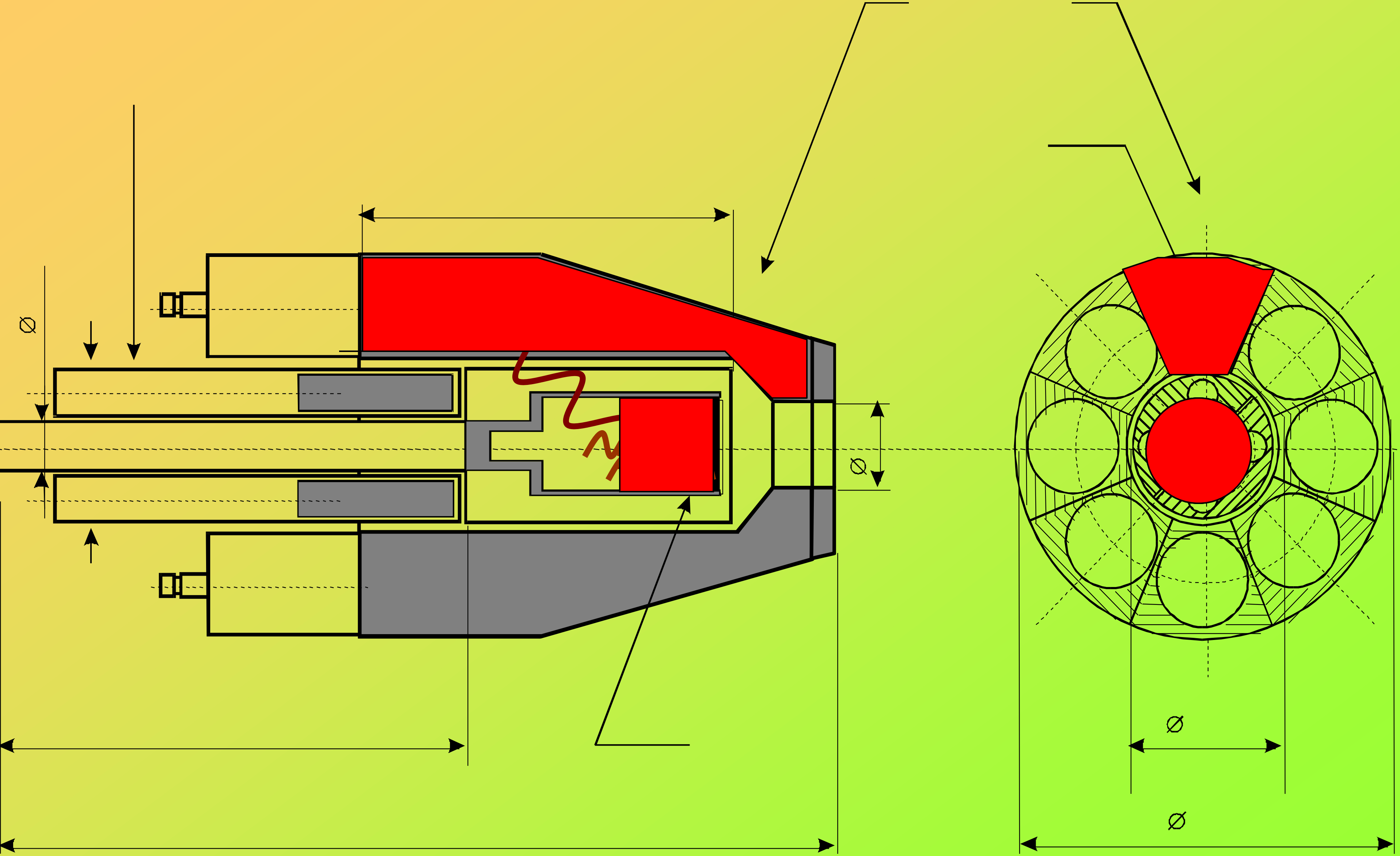
Detectors

- Scintillators (high count rate)
- high-purity germanium (high resolution)

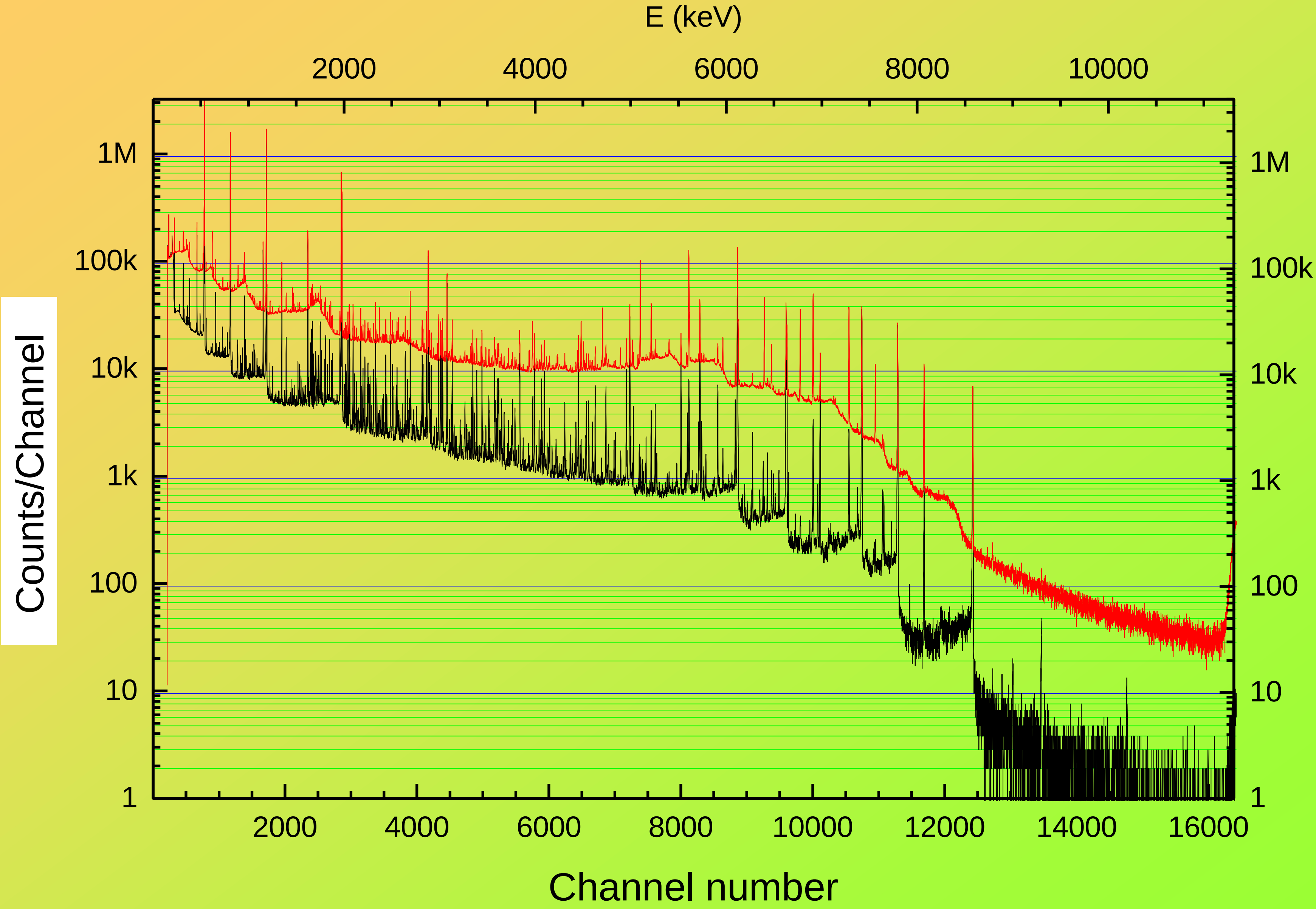
- Compton suppressed

composite detectors

Compton suppression



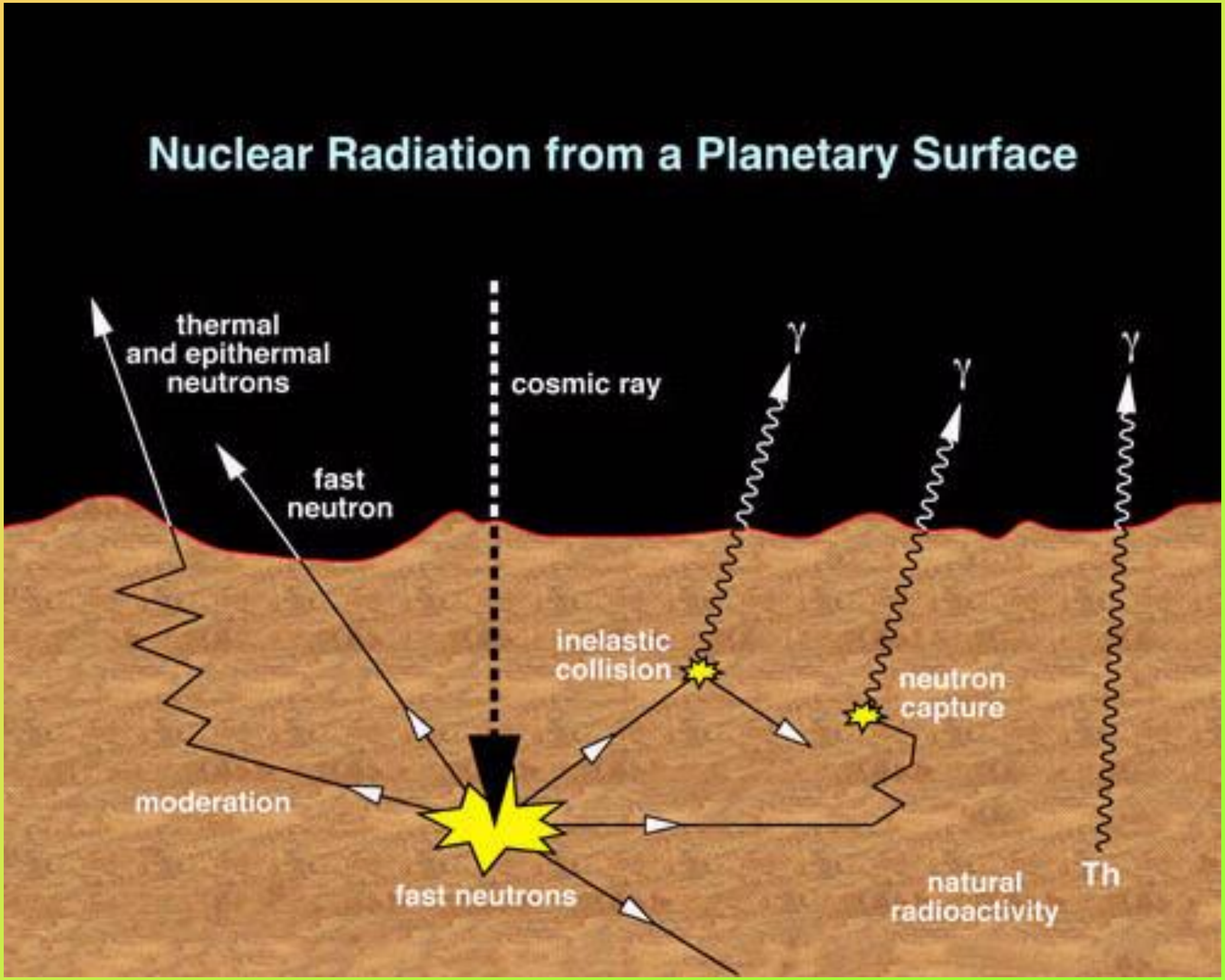
Compton suppression



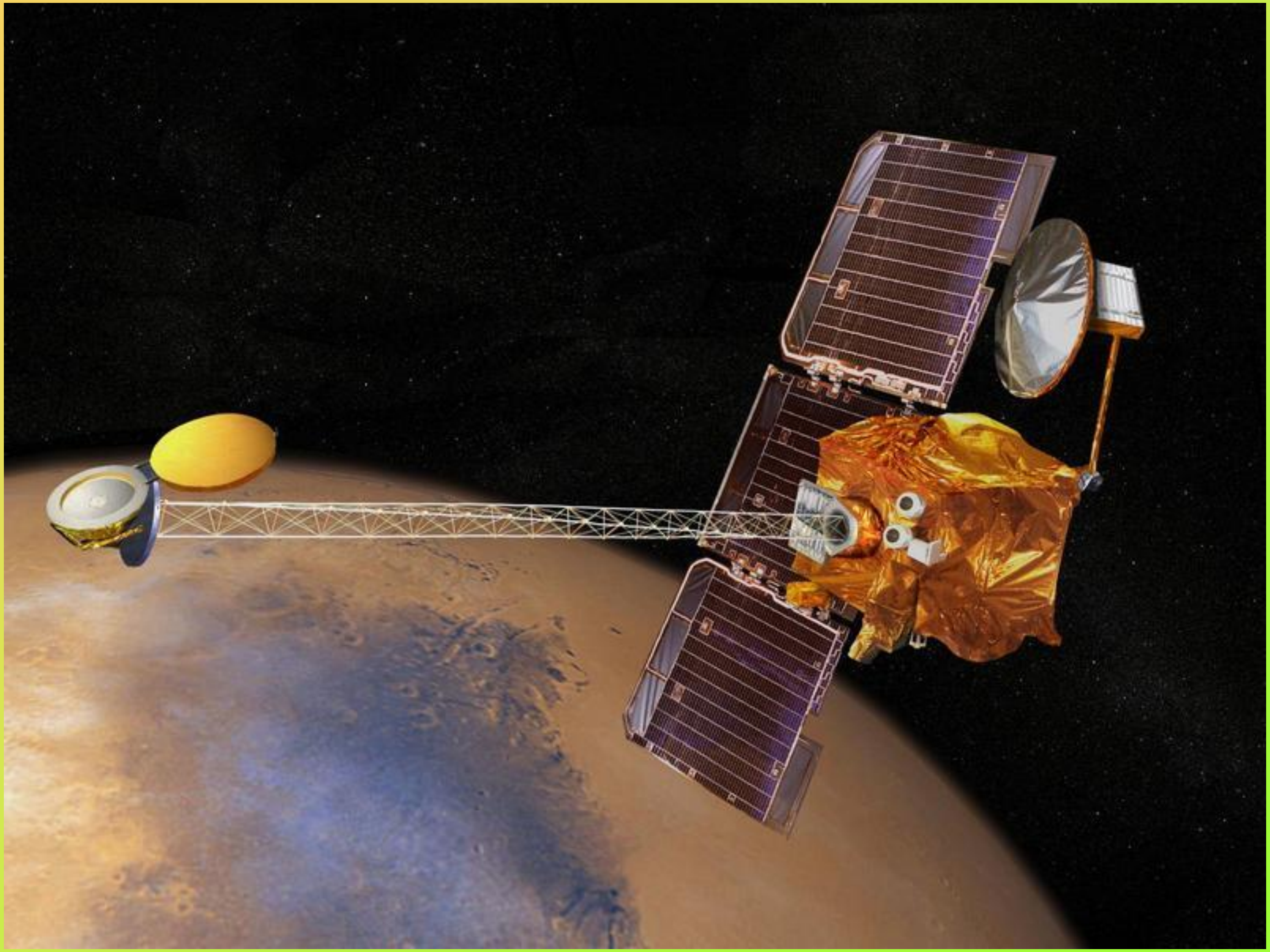
Facilities

The most exciting application ...

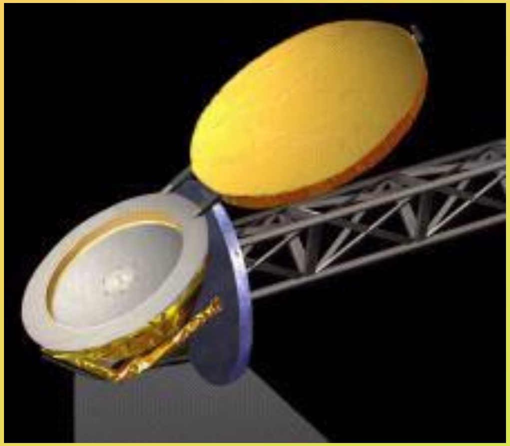
Production of prompt γ photons in the surface of Mars

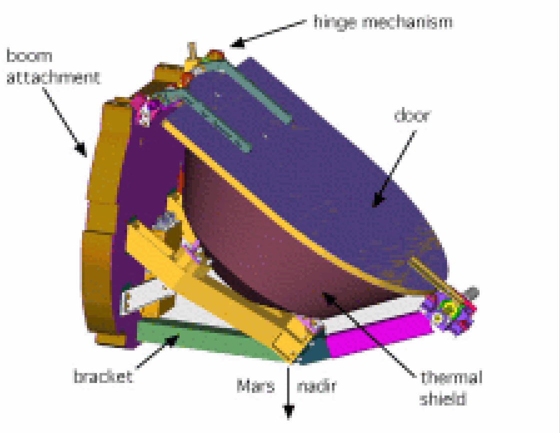


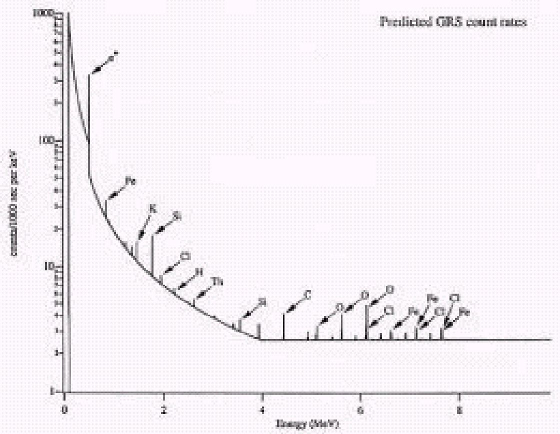
GRS instrument on satellite Odyssey



GRS
(Gamma Ray Spectrometer)







Robert Reedy
Los Alamos National Laboratory

Facilities on Earth

INDUSTRY

- on-line analyzers at conveyor belts
  - approx. 400 in cement factories
- bore hole logging
  - oil industry

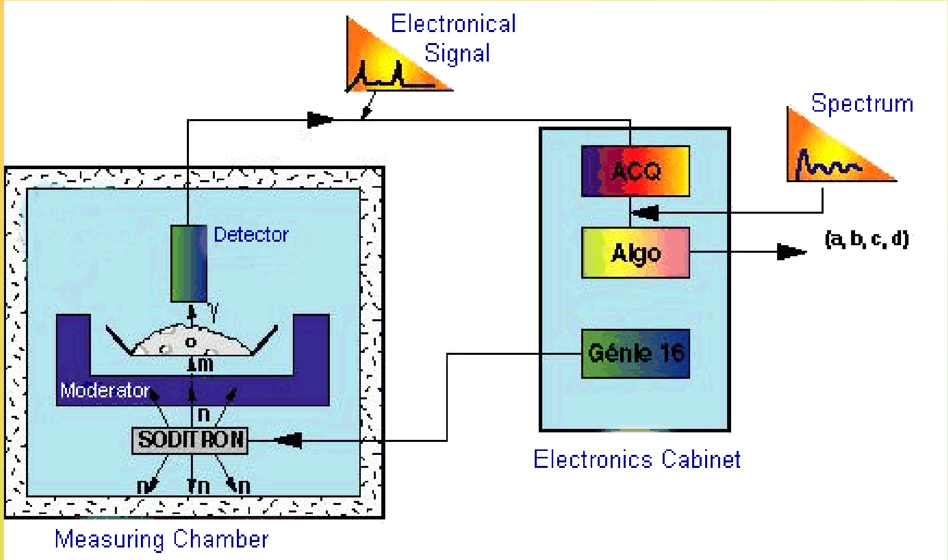
radioisotopic sources + scintillator

LABORATORY

- lab instrument using isotopic neutron source
- facilities at nuclear reactors

neutron beam + HPGe detector

Continuous Neutron Analyzer (CNA)

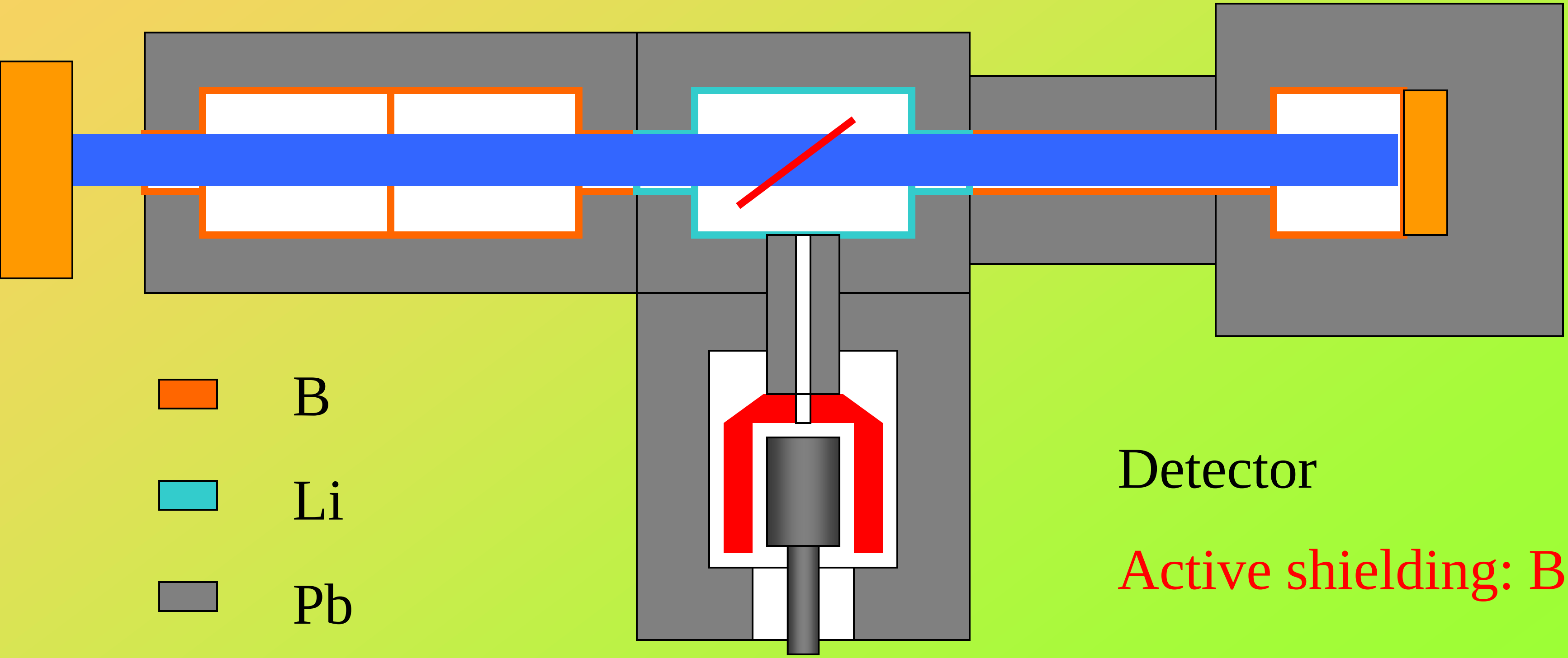


Figures from sodern.com

Guided neutron beam facilities at research reactors

- NIST (USA) cold beam
- JAERI (Japan) cold/thermal beam
- BNC (Budapest, Hungary) (thermal) cold beam
- Garching (Germany), cold beam,

Best arrangement: separate chambers



Collimator / guide

Sample

Beam stop

🟧 B

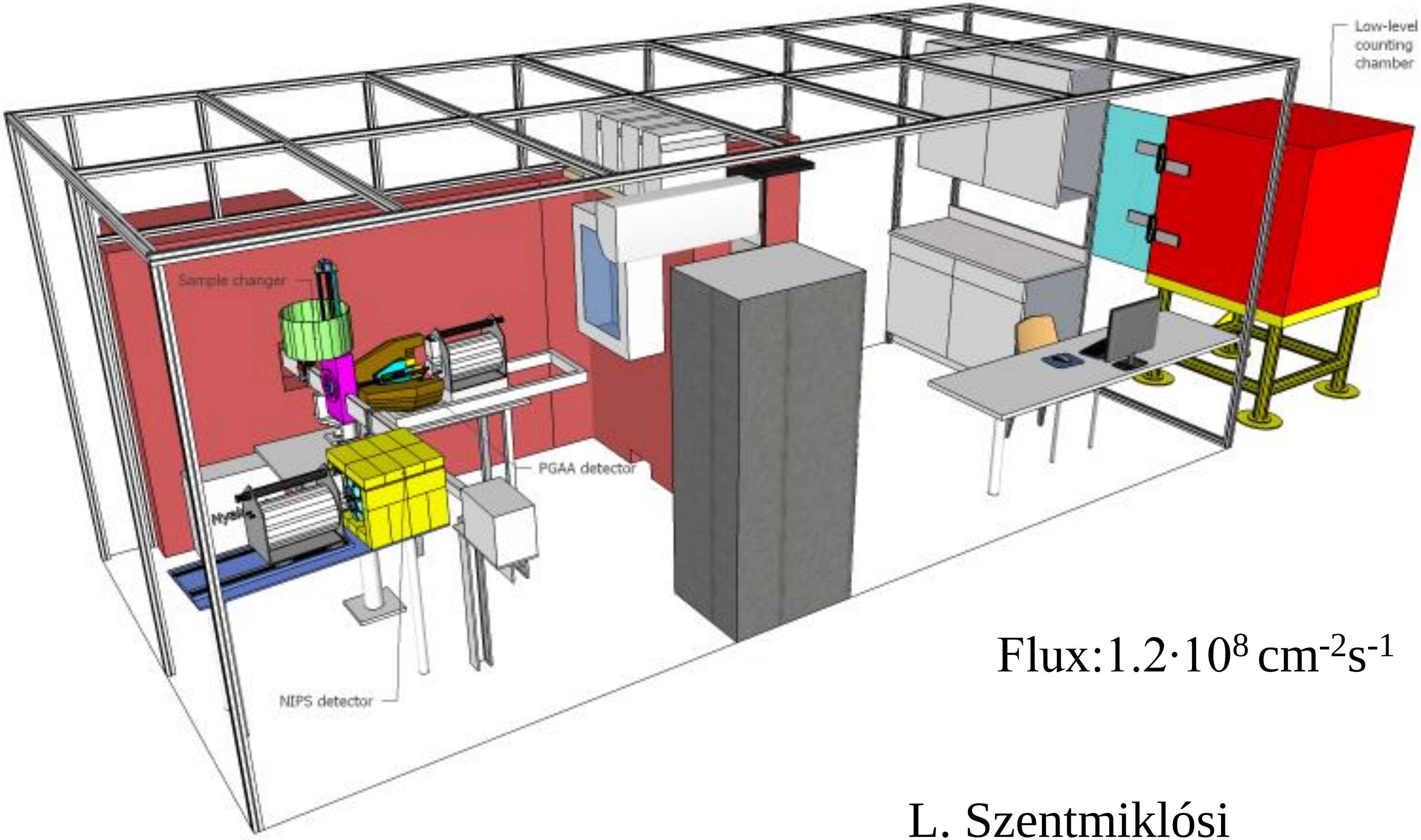
🟦 Li

⬛ Pb

Detector

Active shielding: BGO

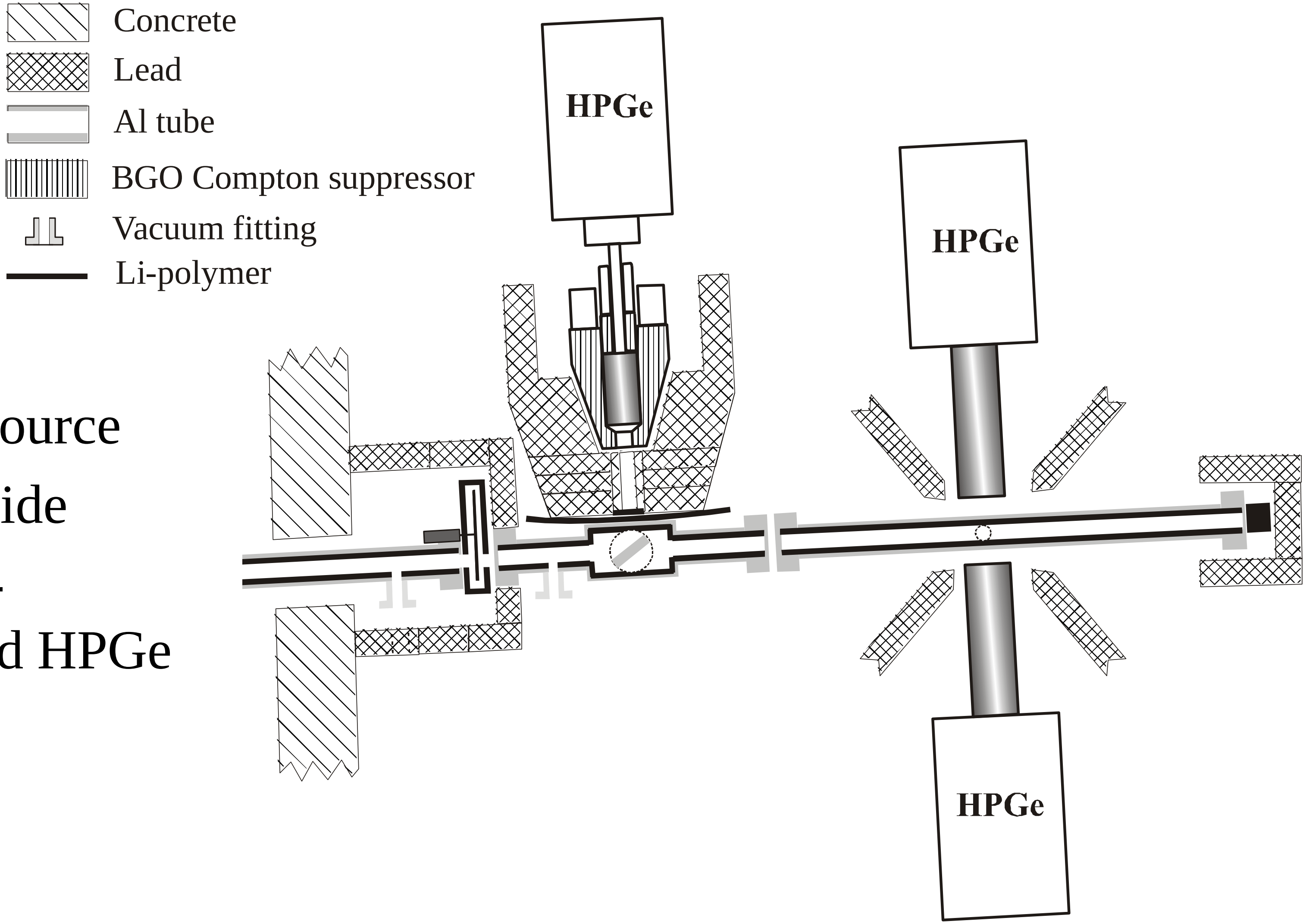
1) PGAA facilities at Budapest



Flux:$1.2 \cdot 10^{8}$ $cm^{-2}s^{-1}$

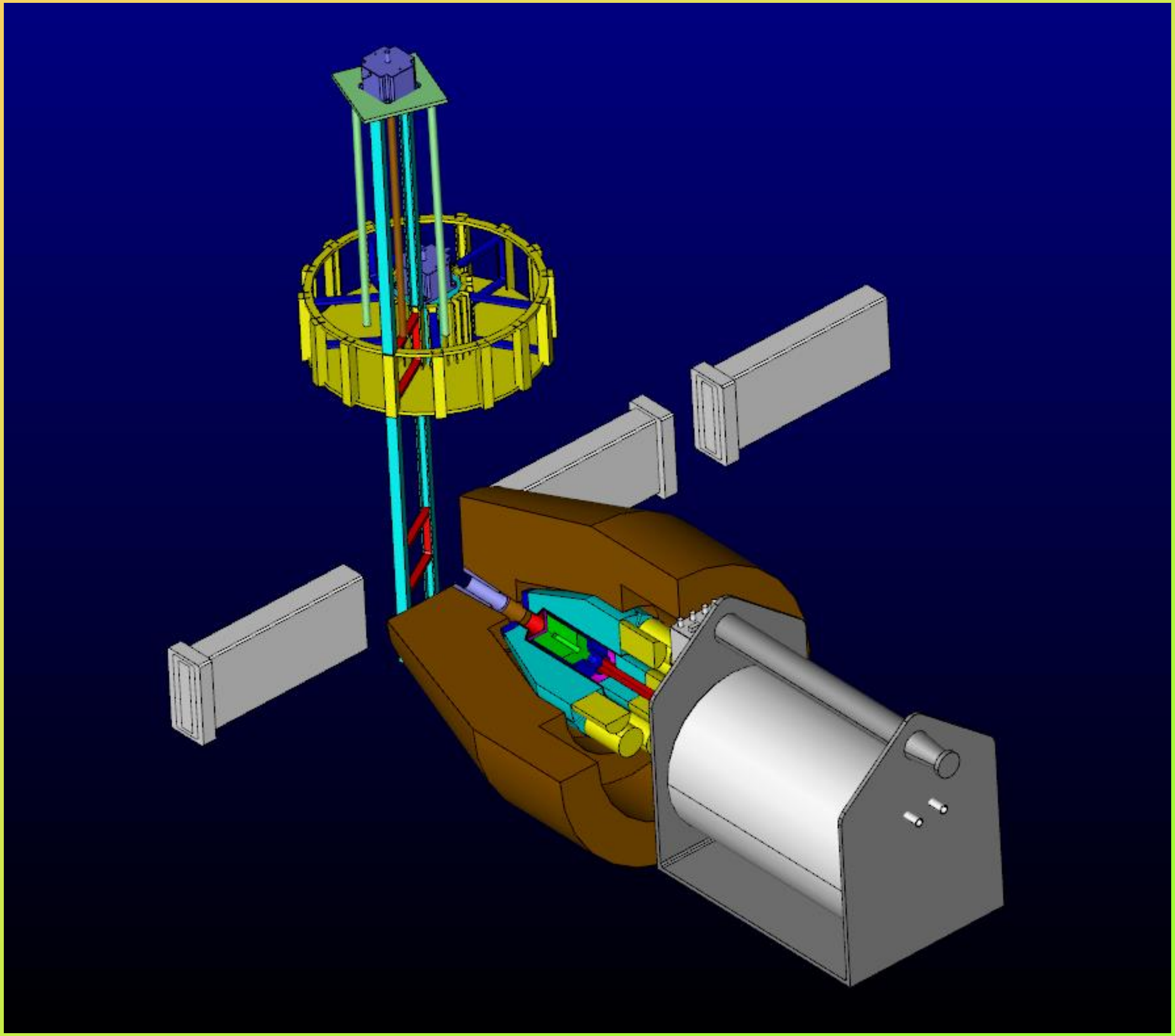
L. Szentmiklósi

Budapest PGAA facility



- 10 MW
- LH cold source
- curved guide
- Compton-suppressed HPGe
- chopper

Sample changer at PGAA



L. Szentmiklósi

Neutron radiography + PGAA

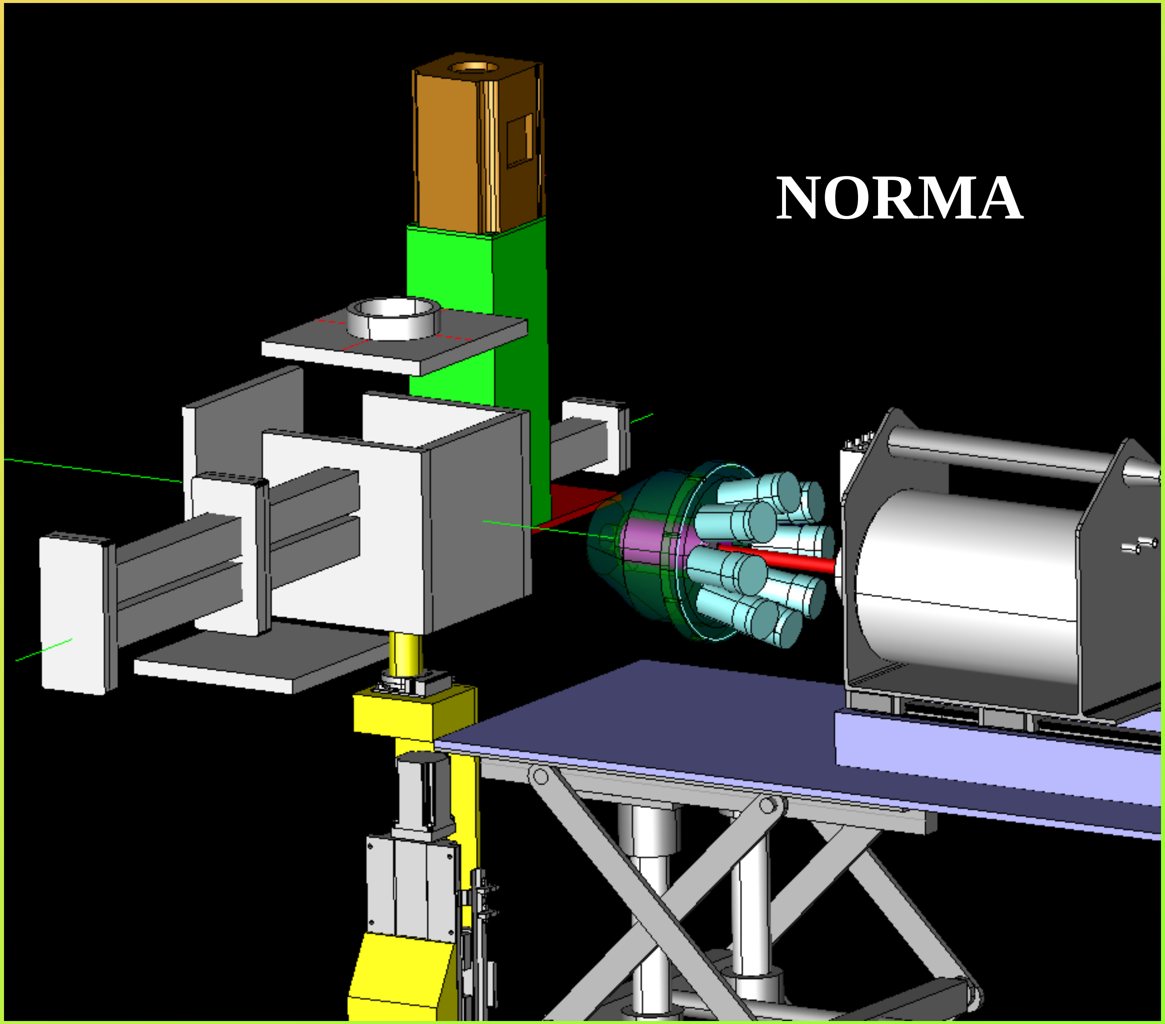
1) Full beam: neutron radiography and/or tomography

2) Sharp collimation of neutrons and gammas

Planned facilities

NORMA – Budapest

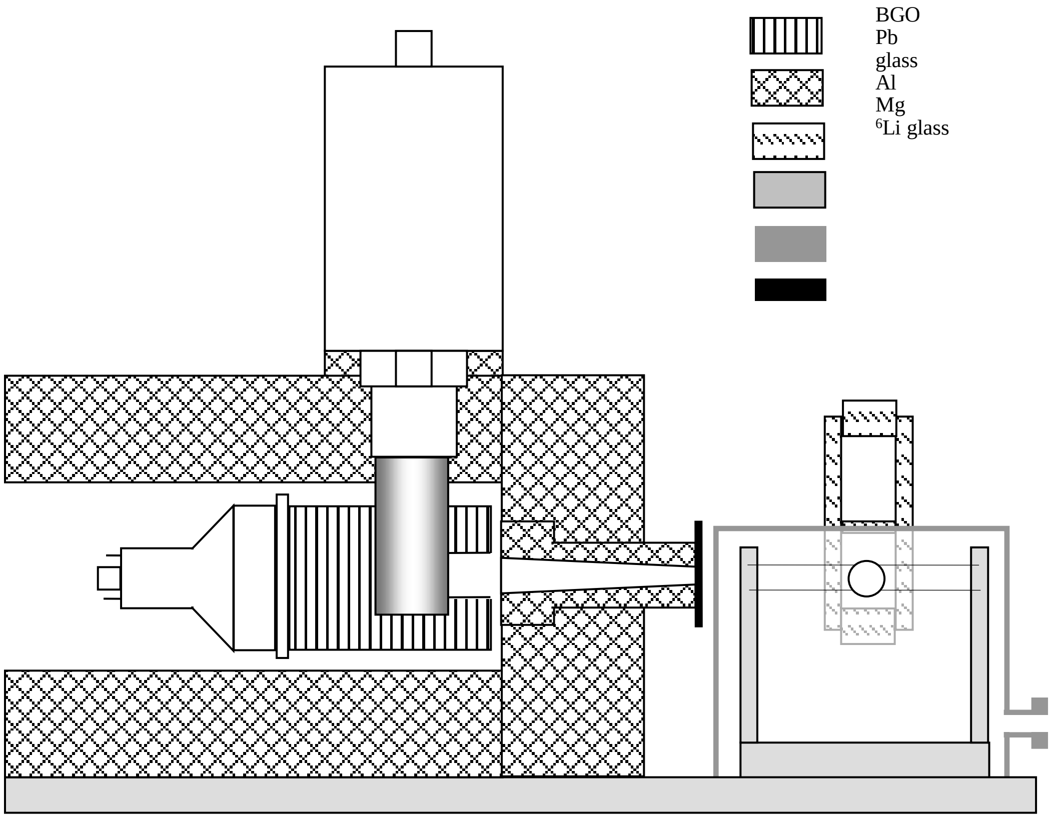
3D PGAA – Munich

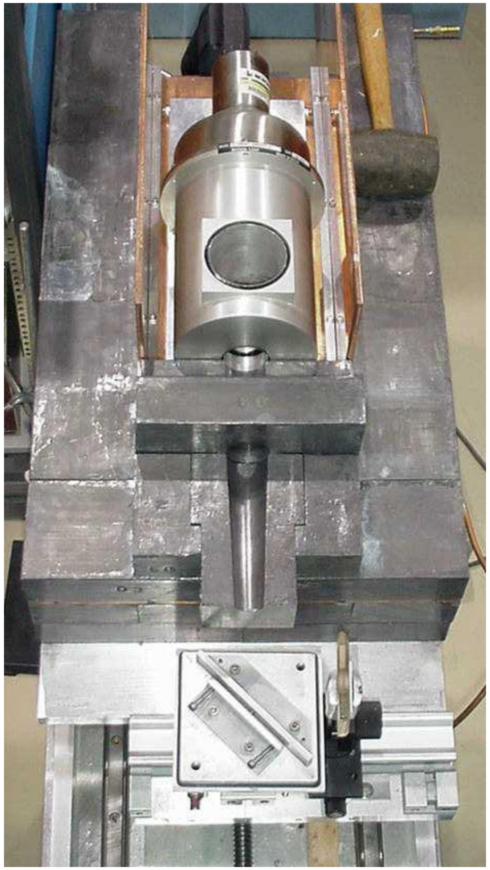


L. Szentmiklósi

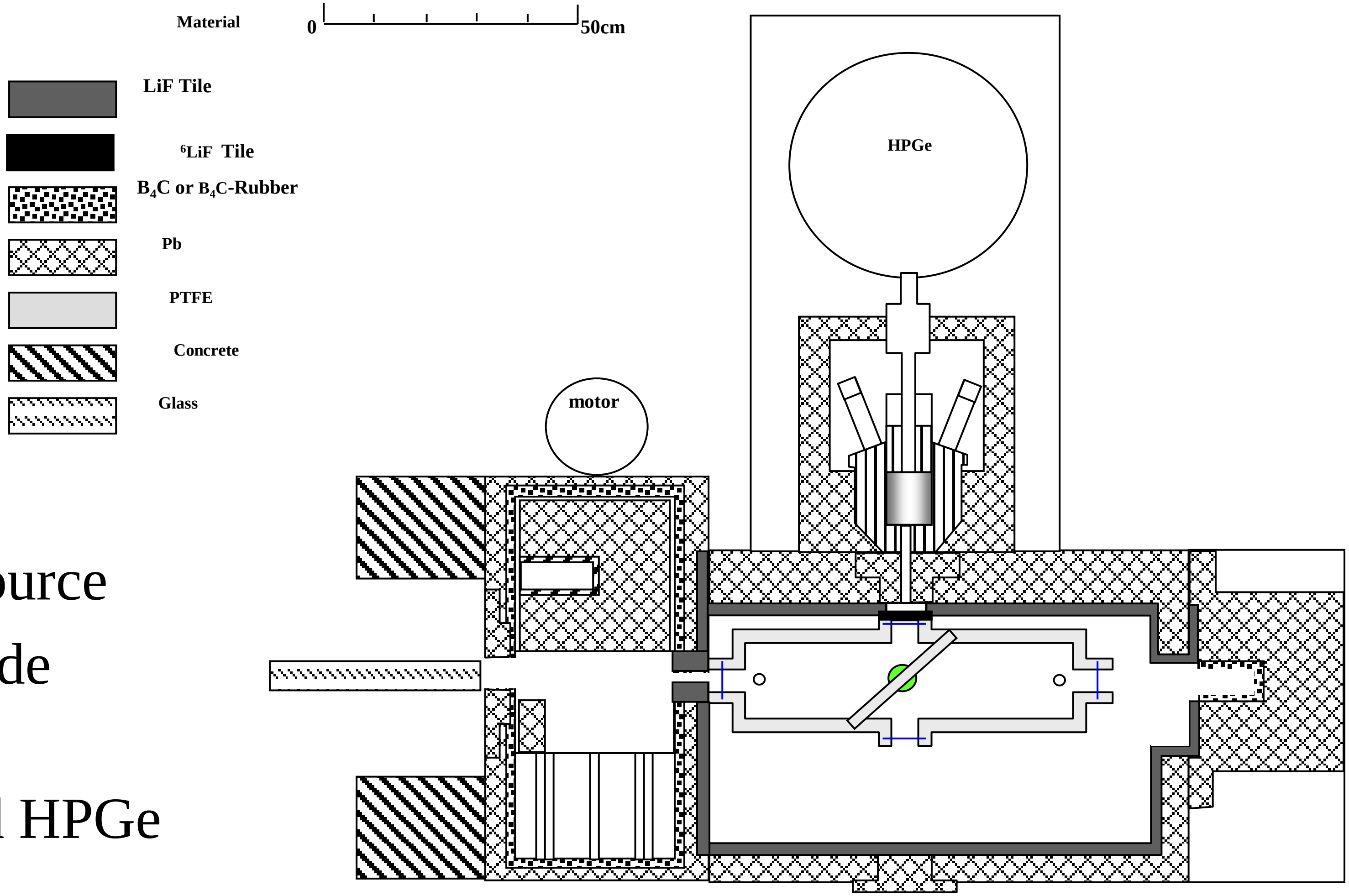
2) NIST cold beam PGAA facility

20 MW reactor, LH cold source, straight neutron guide, Compton-suppressed HPGe



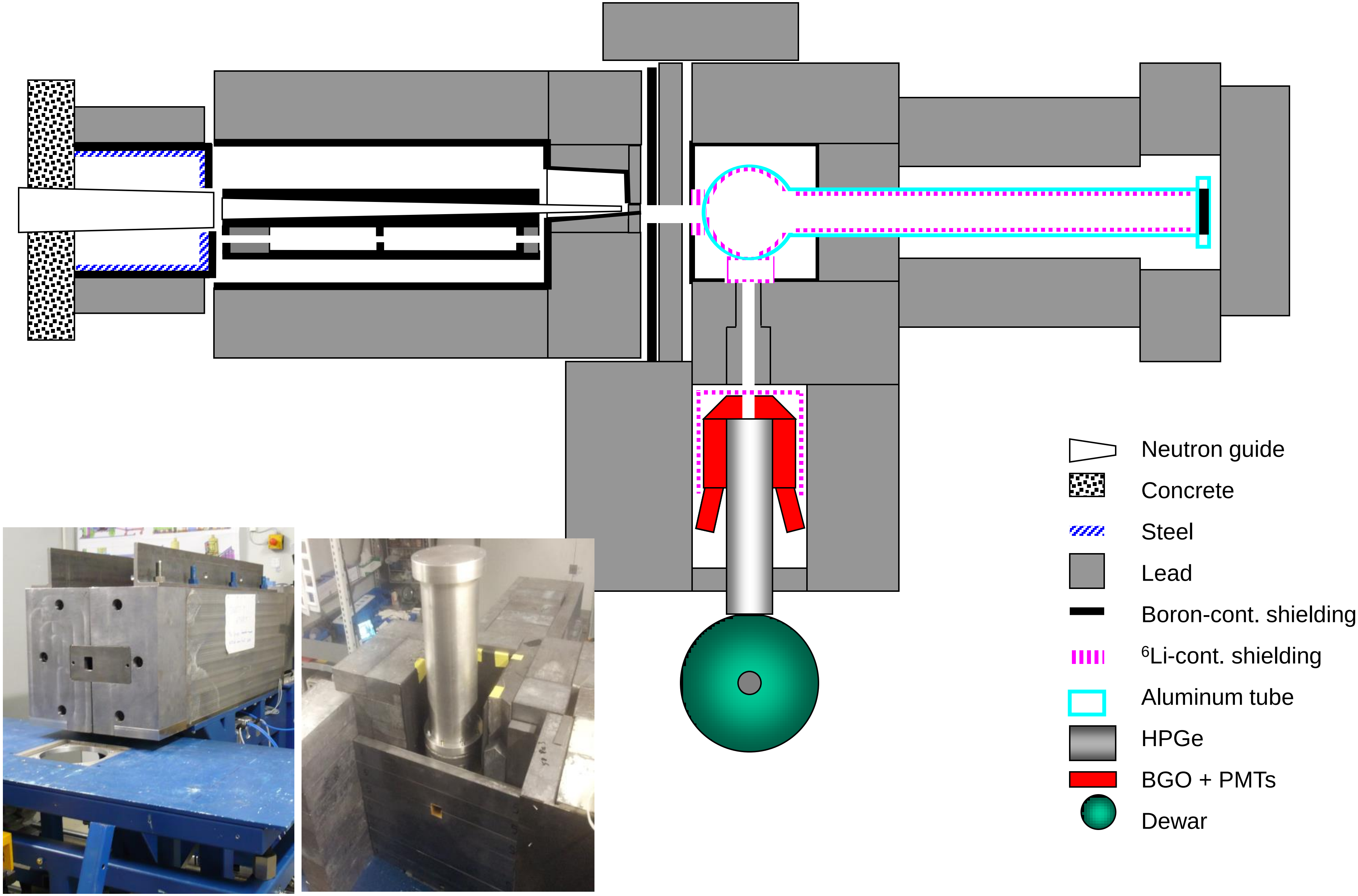


3) Japanese PGAA facility



- 10 MW
- LH cold source
- curved guide
- Compton-suppressed HPGe

4) PGAA facility at FRM II



Neutron guide

Concrete

Steel

Lead

Boron-cont. shielding

^{6}Li-cont. shielding

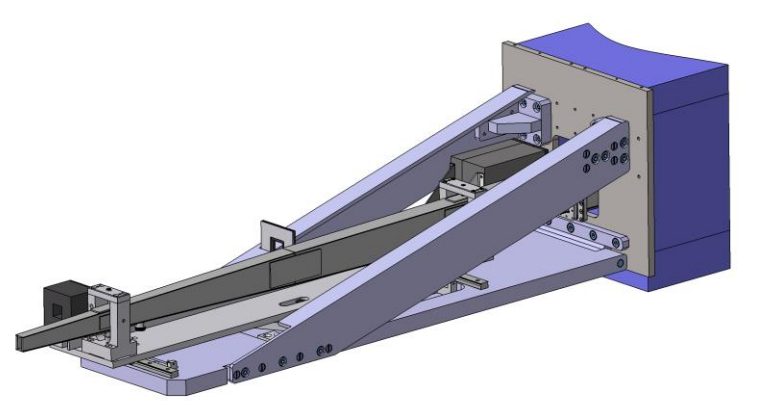
Aluminum tube

HPGe

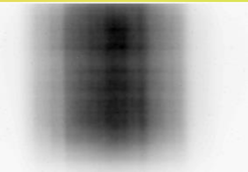
BGO + PMTs

Dewar

Neutron source: Collimator and elliptical guide interchangeable

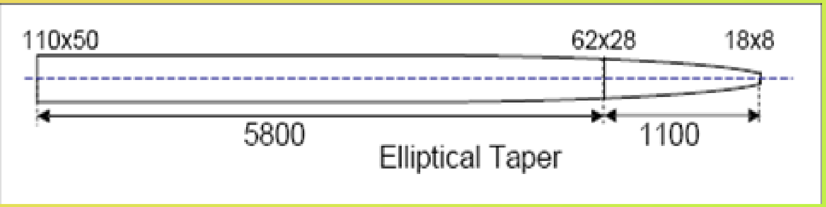


Collimated:
2×10^9 cm^{-2} s^{-1}

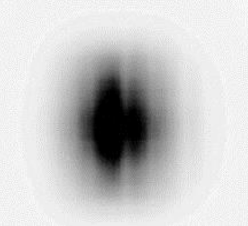


Area:
2 x 2 cm^2

5.8 m elliptical guide
1.1 m elliptical extension (removeable)



At focal point:
6×10^{10} cm^{-2} s^{-1}

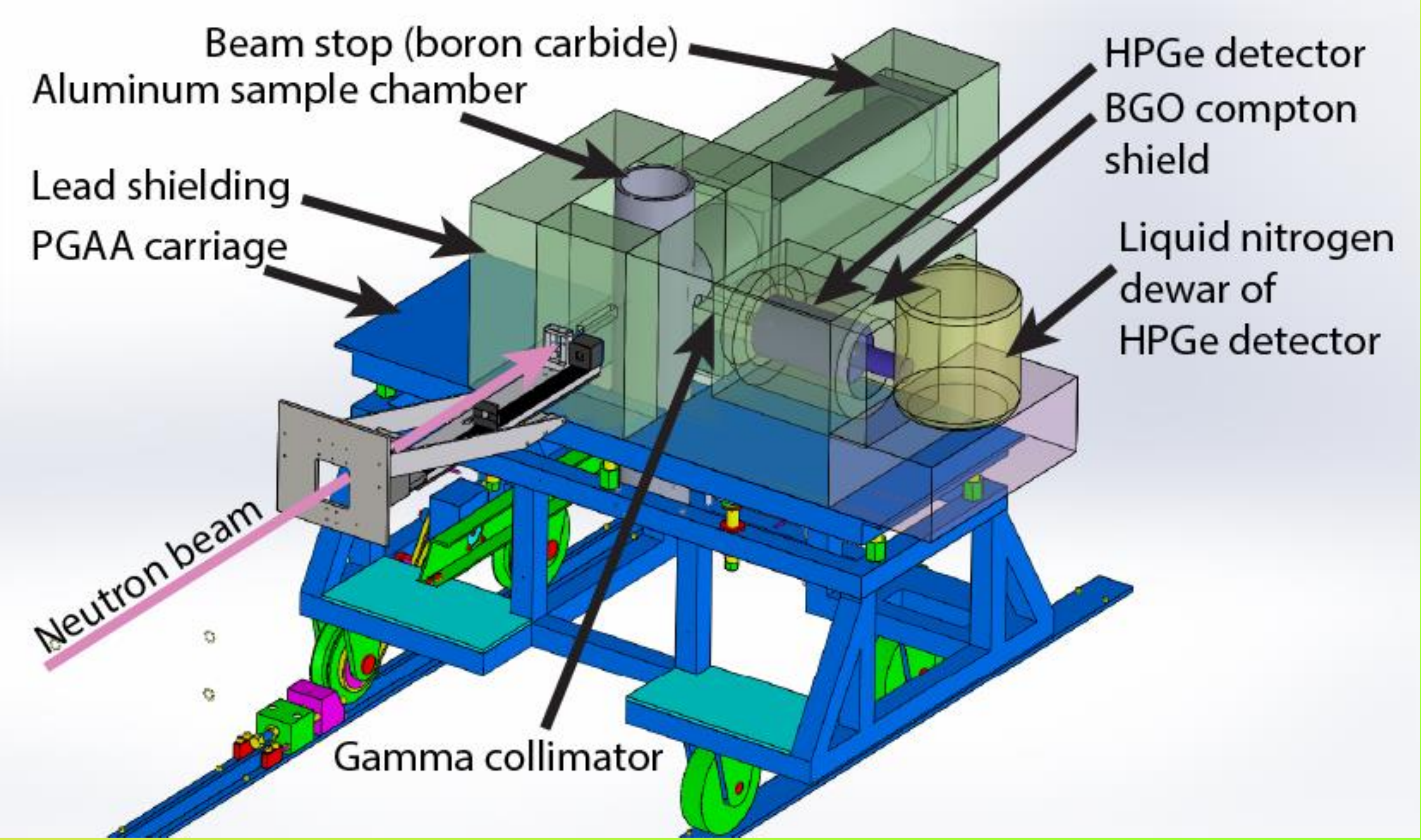


Area:
1.5 x 1 cm^2

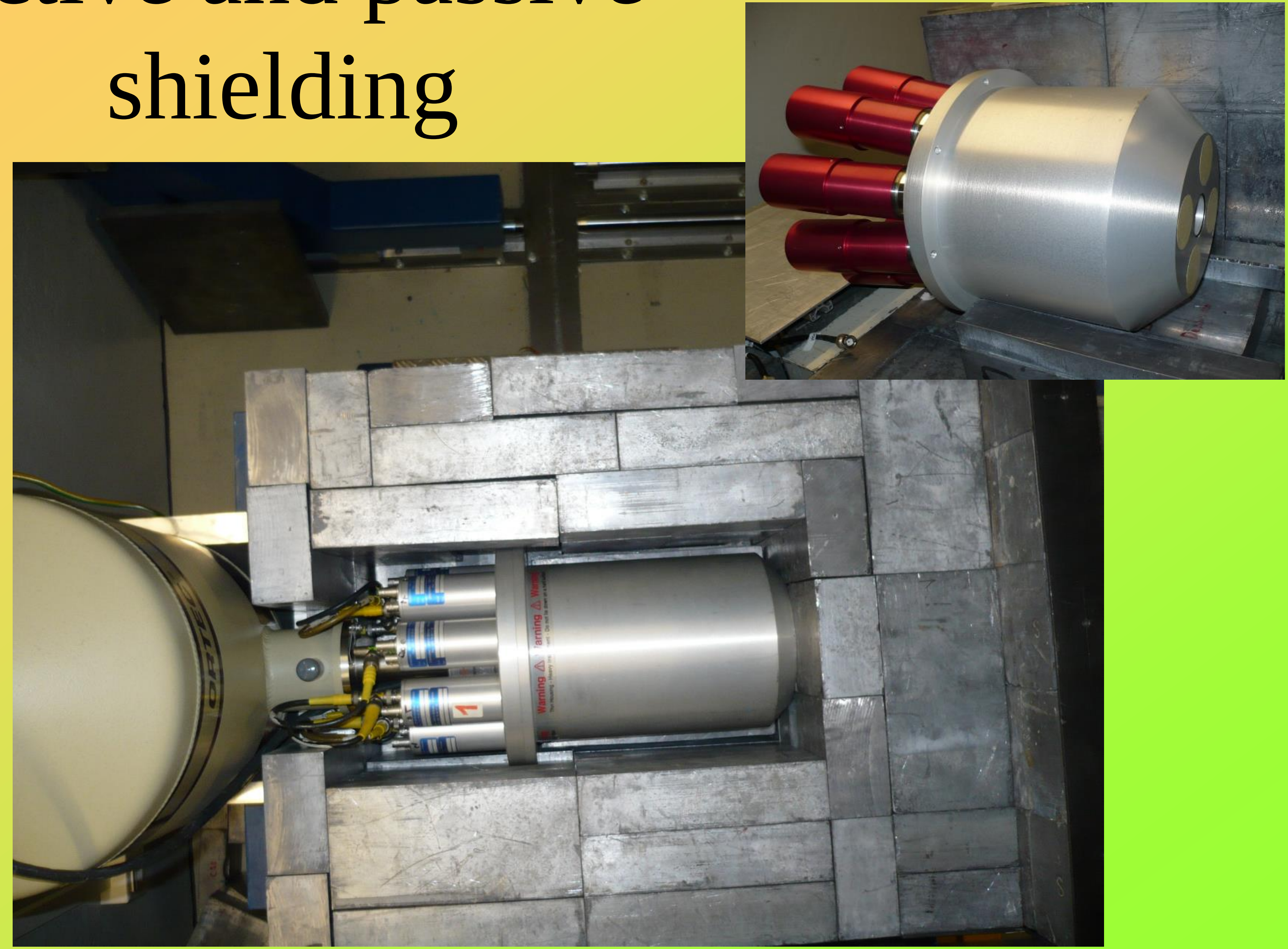
Other facilities
~10^8 cm^{-2} s^{-1}

New revised version of
the guide support

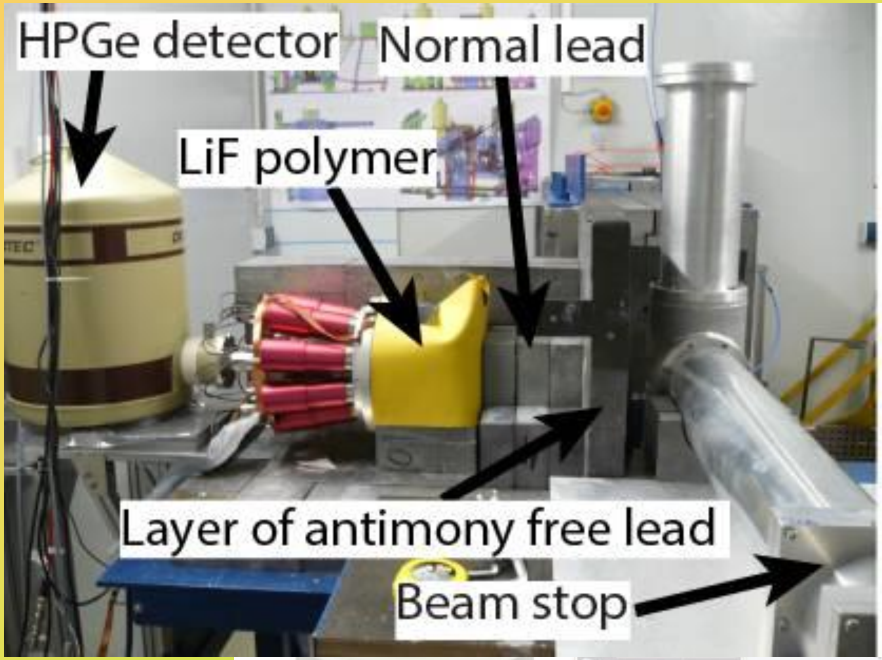
PGAA facility at Garching

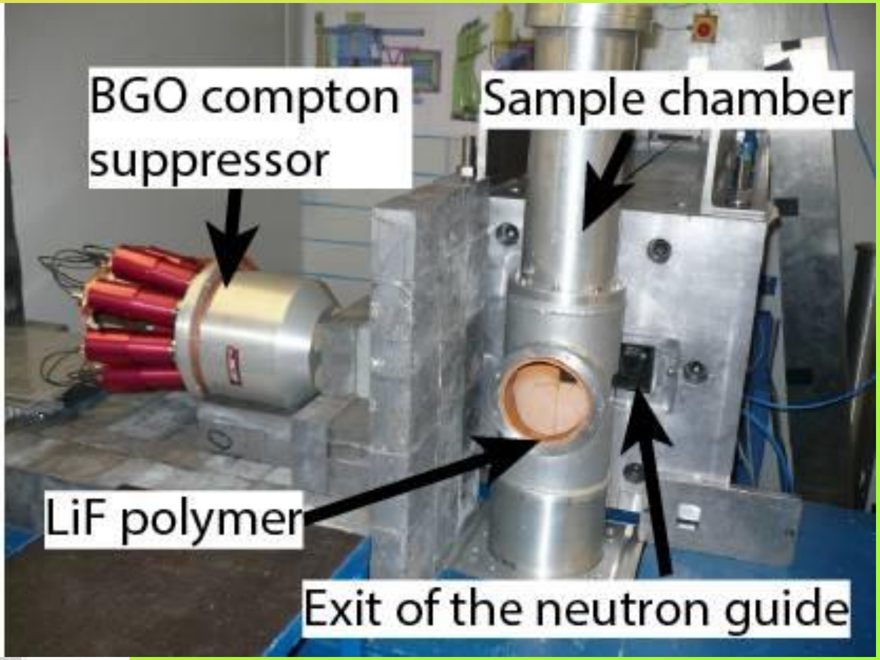


Active and passive shielding



Compton-suppressed detector and digital electronics

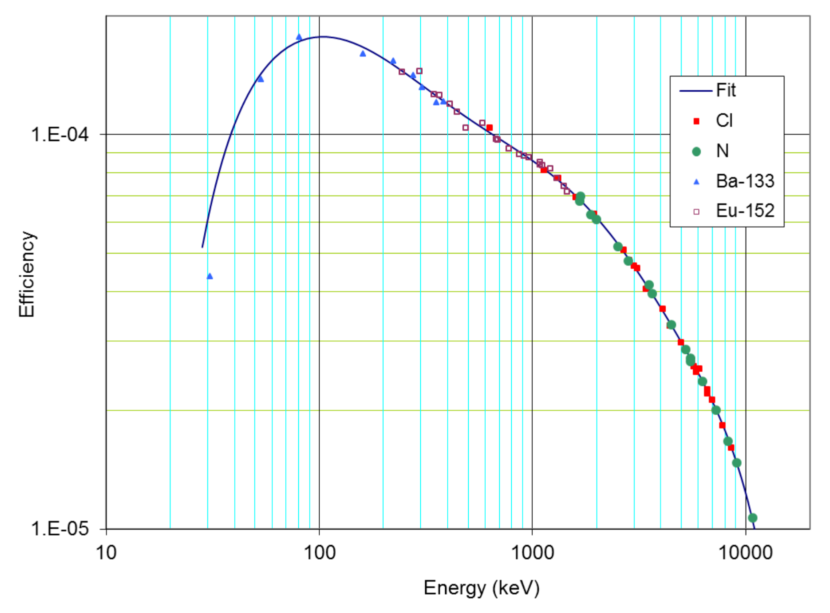




Max. rate = ~ 50,000 cps

Flux, Background in the Beam, Efficiency

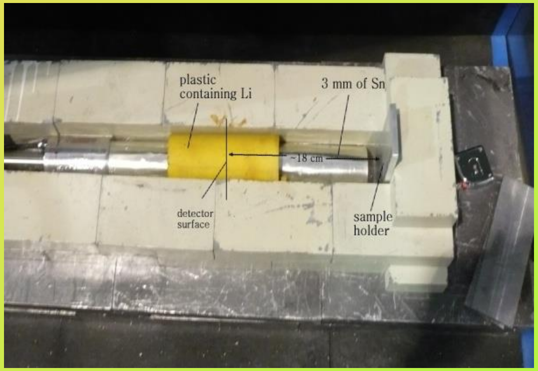
- Collimated beam
  - Flux: 1.35×10^{9} cm^{-2} s^{-1}
  - Beam background: 12 cps
- Focused beam
  - Flux: 2.7×10^{10} cm^{-2} s^{-1}
  - Beam background: 290 cps

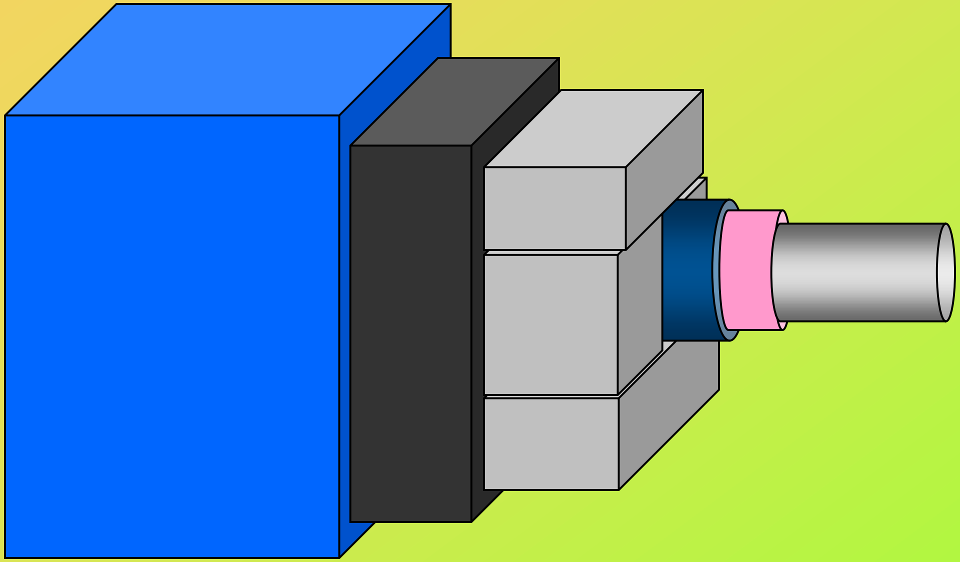


Element	collimated	focused
H	5.8×10^{-7}	3.5×10^{-7}
B	1.9×10^{-8}	1.5×10^{-8}
N	-	8.2×10^{-6}
Na*	-	9.3×10^{-6}
Al	2.2×10^{-5}	2.4×10^{-5}
Si*	-	4.0×10^{-5}
Ca*	-	3.1×10^{-6}
Ti*	-	5.6×10^{-7}
Cr	-	7.0×10^{-6}
Fe	1.0×10^{-6}	1.5×10^{-6}
Ni*	-	3.1×10^{-7}
Ge	-	1.8×10^{-6}
In	4.8×10^{-8}	5.6×10^{-8}
Pb	4.8×10^{-4}	4.6×10^{-4}

Low-background chamber next to neutron guides

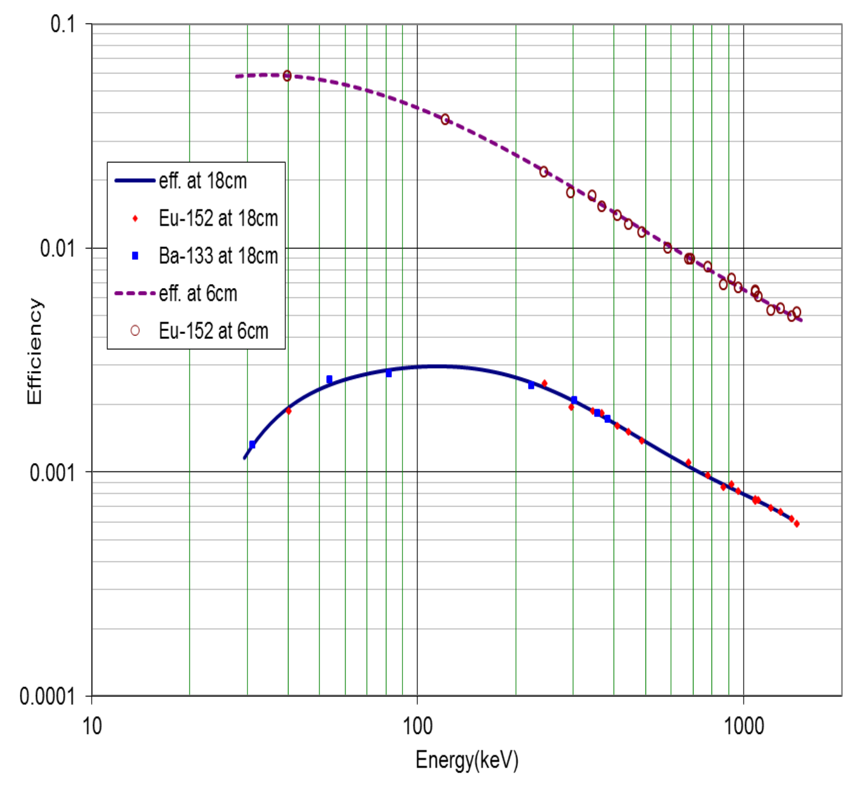
- ^{6}Li-containing plastic (2.5 mm)
- Sn sheets (4 mm) – instead of Cd
- 10 cm of lead
- 5mm boron rubber (40% B_4C)
- 5cm boron plastic (20% H_3BO_3)



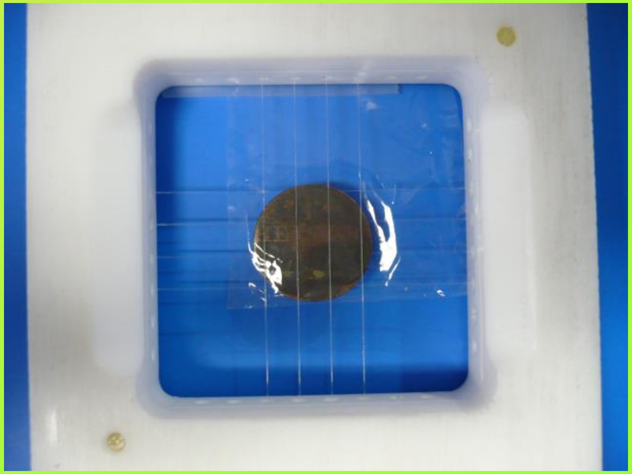


Characteristics of low-background chamber

- 2.5 cps during reactor operation
- 1.5 cps room background
- Background components from
    - 40K (1460 keV)
    - U, Th series
    - some neutron activation (Ge (n,γ) peaks, or with Cd)
    - 41Ar (1294 keV) – from reactor operation
    - 124Sb (601 keV, 1693 keV) – activated lead bricks
    - Cosmic muons
- No Compton suppression



What do we irradiate?



- PGAA in typical beams
  - Sample: 100mg—1g
  - Teflon bag: 50—200mg
- In high-flux
  - Sample: ~1mg
  - Packing???

Background in high flux

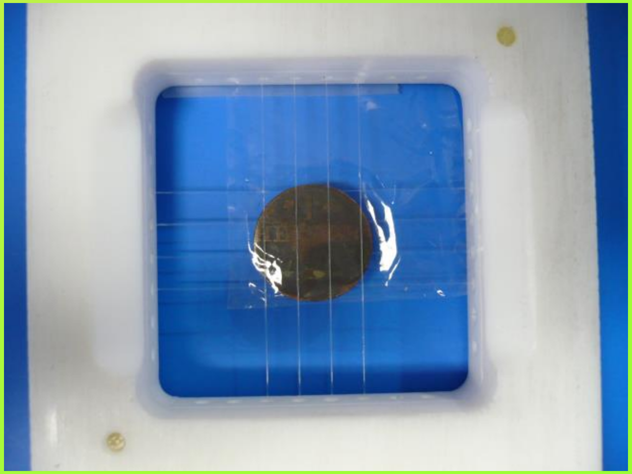
- No sample holder: 400 cps
- + Teflon sample holder: +150 cps
- + Teflon packing: +150 cps
- Air: +300 cps

- Bg peaks from stuctural components (like Al, Fe, Pb) depend on the scattering of the sample

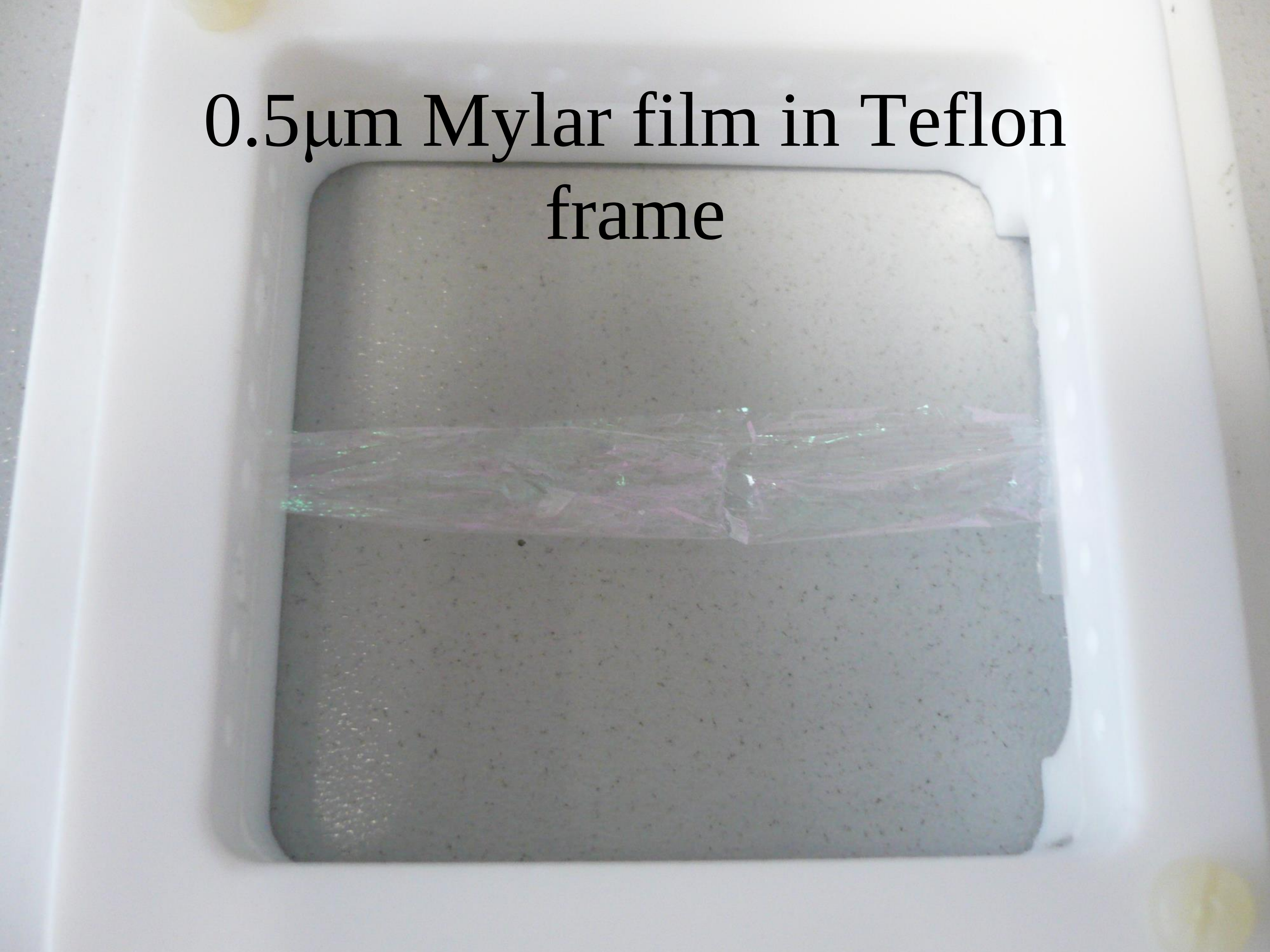
Traditional packing

- C: 3.8 mbarn, F: 9.6 mbarn
  - Teflon, FEP, PTFE
- Teflon bag: 0.025mm, heat sealed
- Teflon string:0.3mm diam

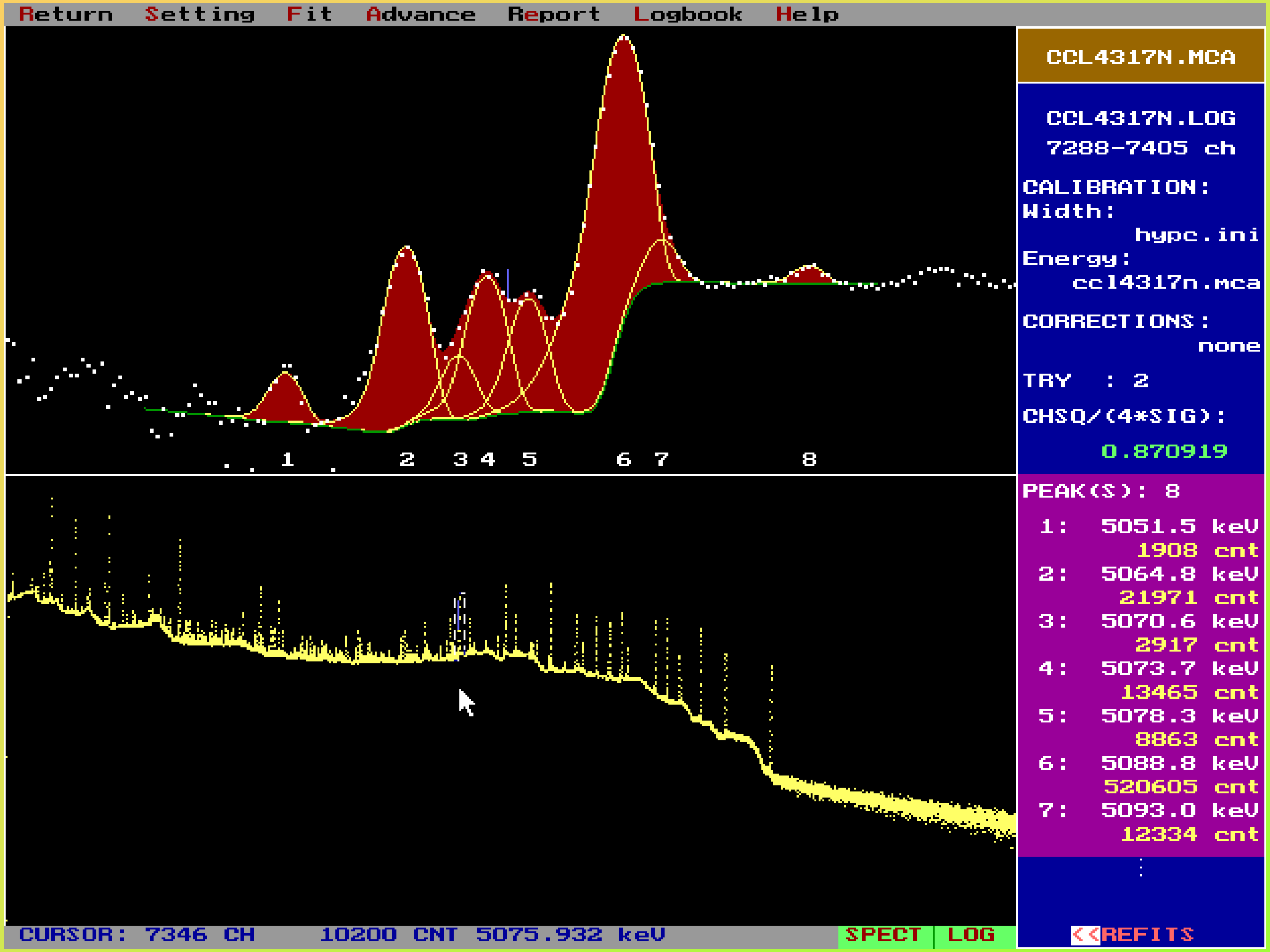
- Both approx. 50mg/cm^2



0.5μm Mylar film in Teflon frame



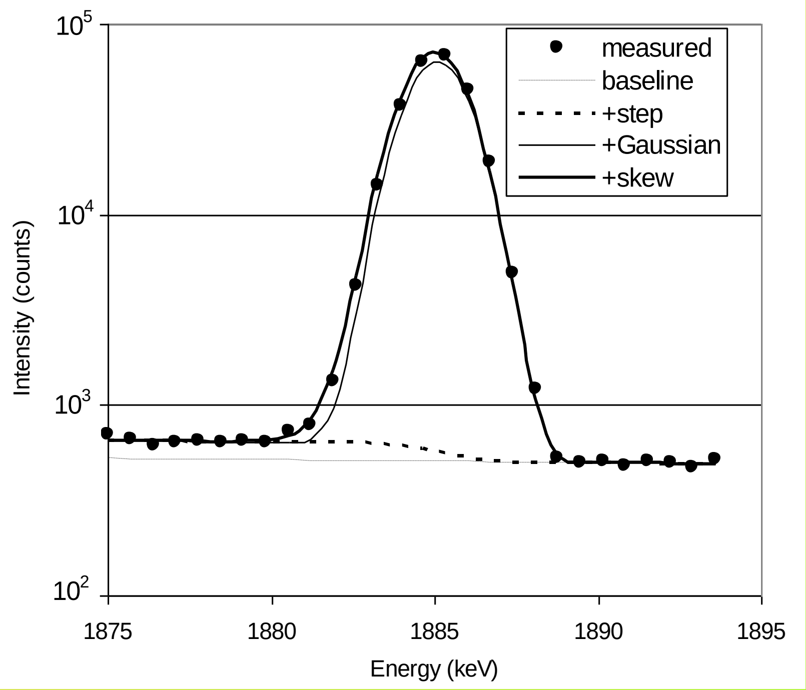
Spectrum evaluation (Hypermet-PC)

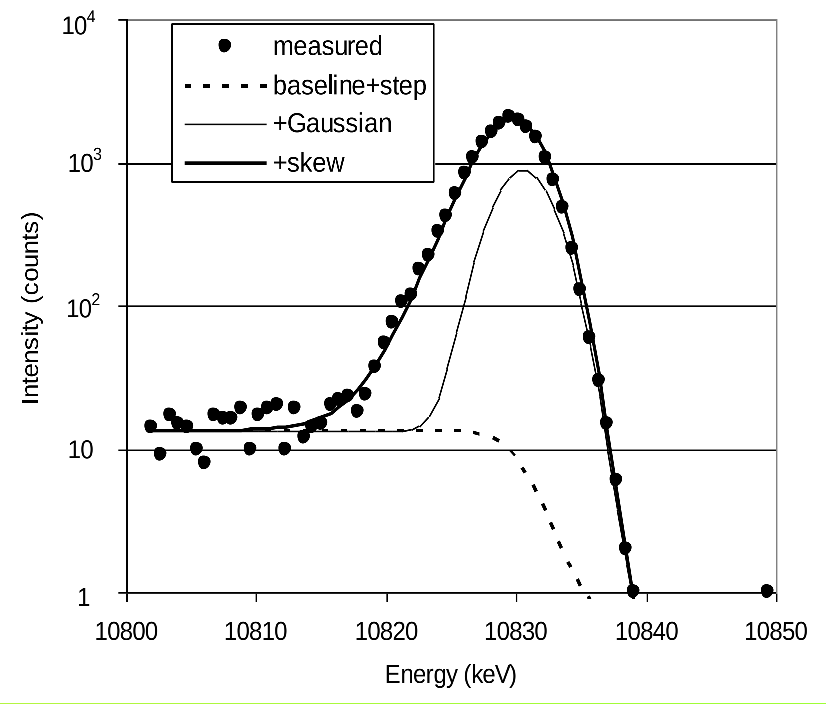


```
CCL4317N.MCA

CCL4317N.LOG
7288-7405 ch
CALIBRATION:
Width:
         hypc.ini
Energy:
     ccl4317n.mca
CORRECTIONS:
             none
TRY   : 2
CHSQ/(4*SIG):
       0.870919
PEAK(S): 8
 1:   5051.5 keV
        1908 cnt
 2:   5064.8 keV
       21971 cnt
 3:   5070.6 keV
        2917 cnt
 4:   5073.7 keV
       13465 cnt
 5:   5078.3 keV
        8863 cnt
 6:   5088.8 keV
      520605 cnt
 7:   5093.0 keV
       12334 cnt
        :
```

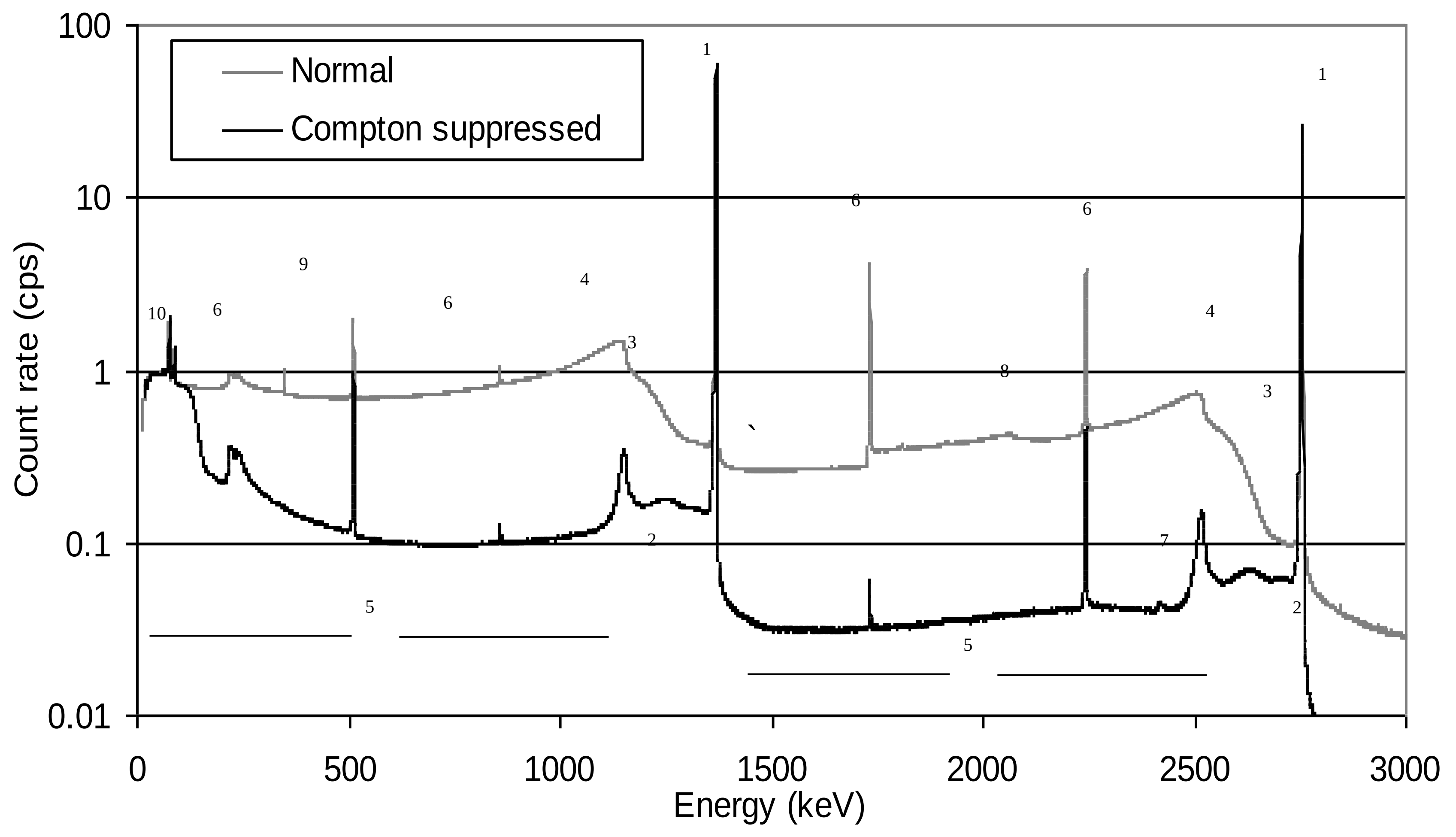
```
CURSOR: 7346 CH     10200 CNT 5075.932 keV
```

Accurate and reprodicible peak fitting – Hypermet-PC

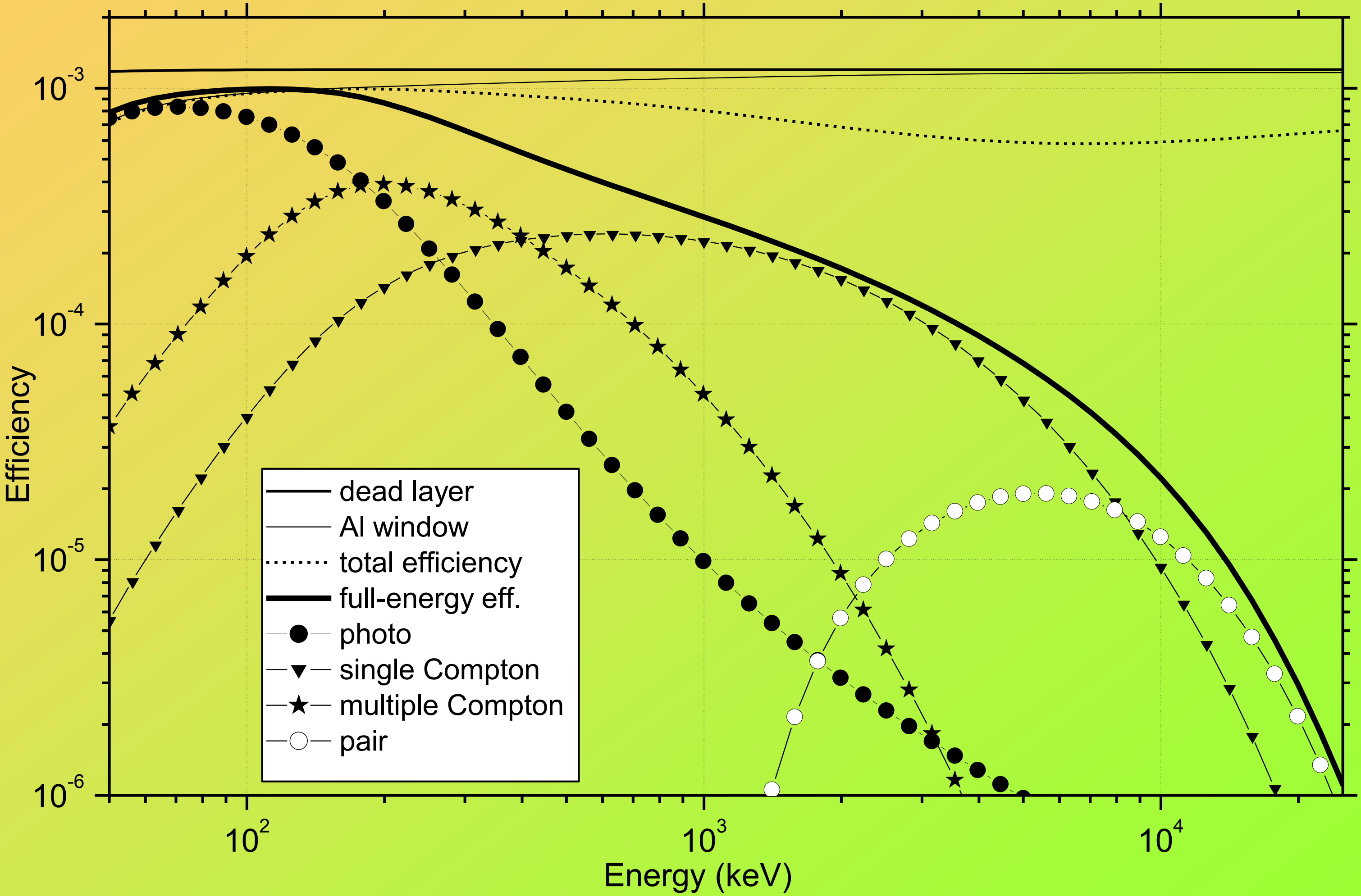




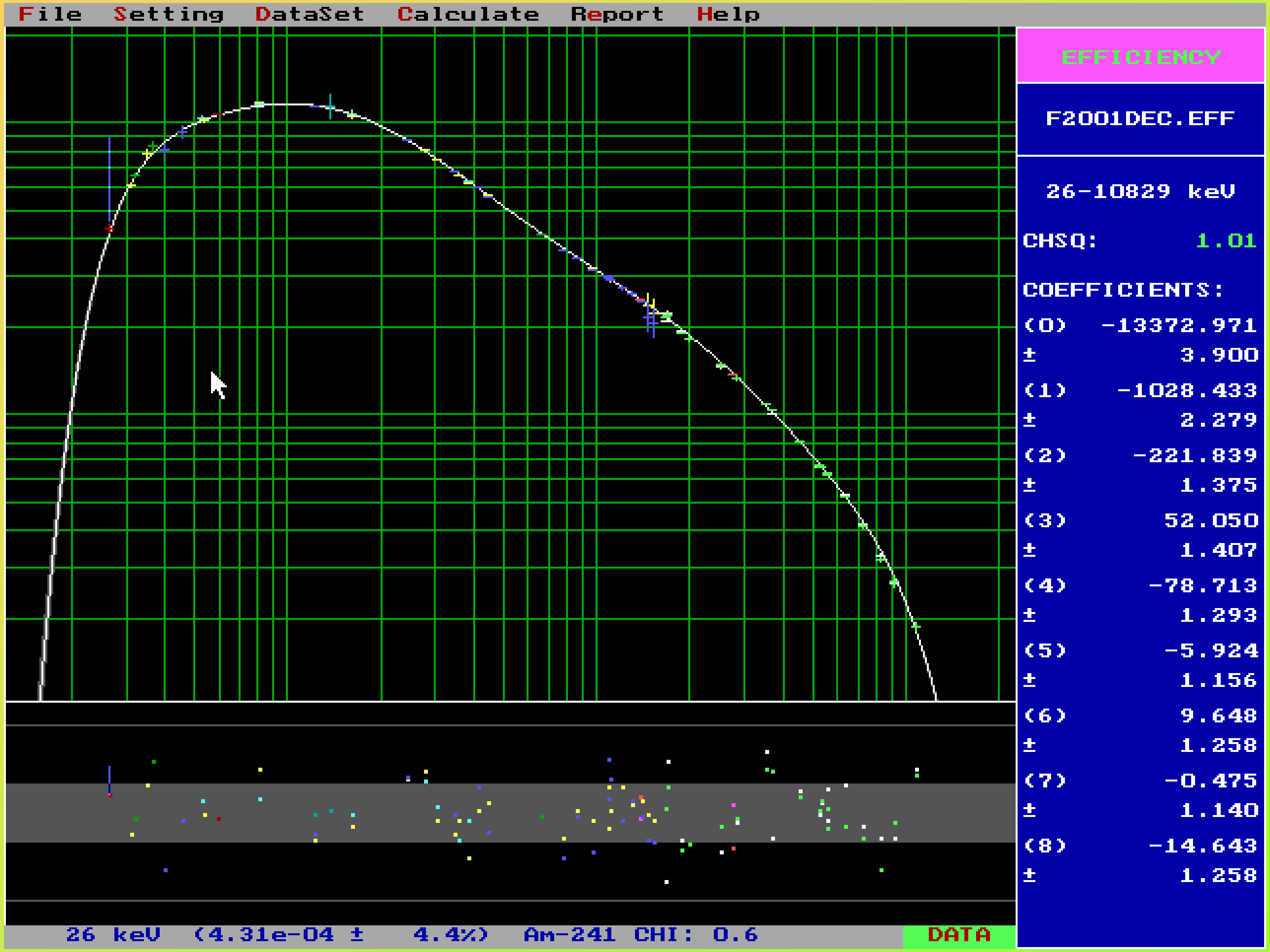
Response of the detector



Semiempirical efficiency



Measured efficiency 50 keV-11 MeV



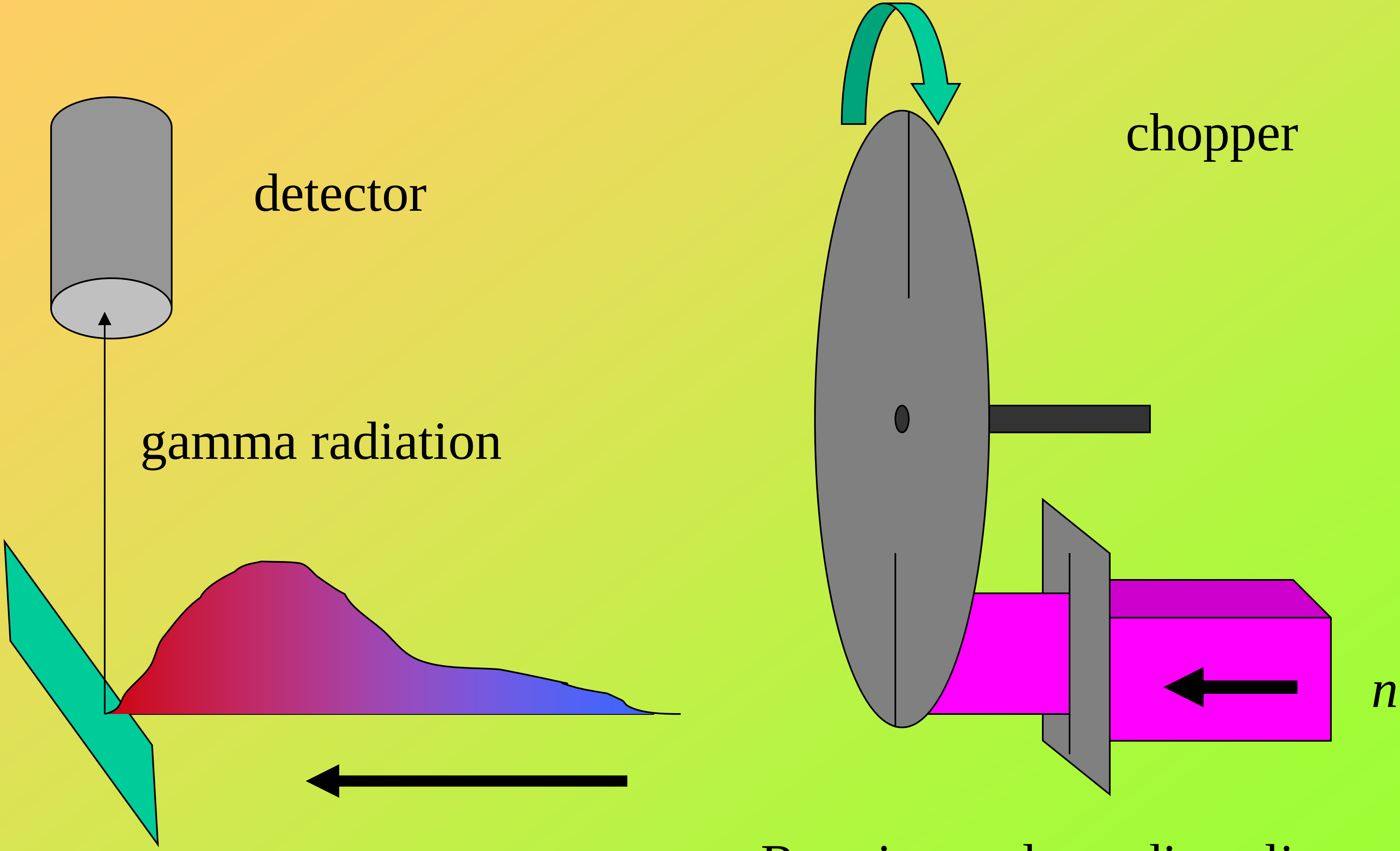
```
F2001DEC.EFF

26-10829 keV

CHSQ:          1.01

COEFFICIENTS:
(0)    -13372.971
±           3.900
(1)     -1028.433
±           2.279
(2)      -221.839
±           1.375
(3)        52.050
±           1.407
(4)       -78.713
±           1.293
(5)        -5.924
±           1.156
(6)         9.648
±           1.258
(7)        -0.475
±           1.140
(8)       -14.643
±           1.258
```

```
26 keV  (4.31e-04 ±   4.4%)  Am-241  CHI: 0.6
```

Tricks with PGAA

Methodological developments

1. Time of flight



detector

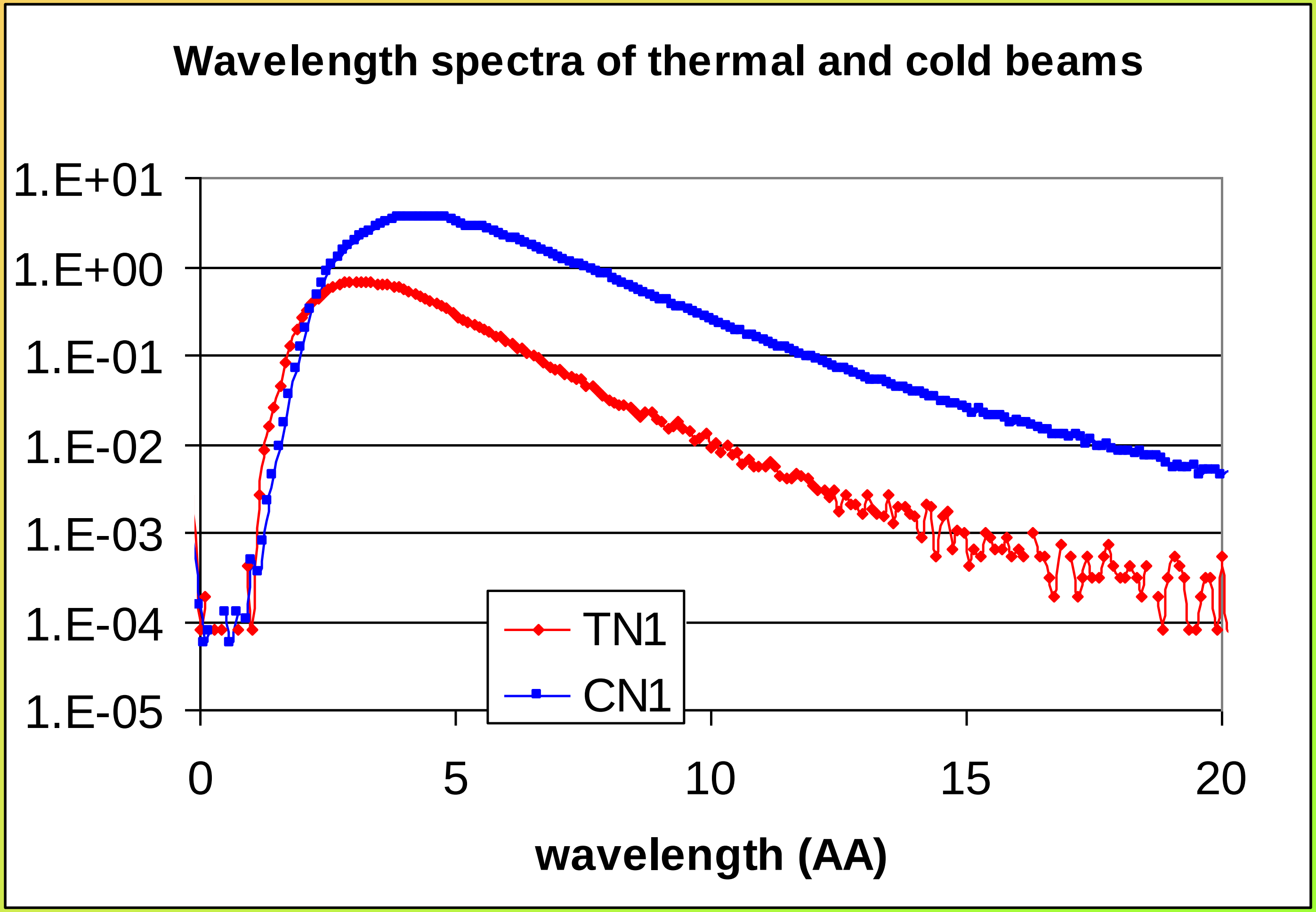
gamma radiation

chopper

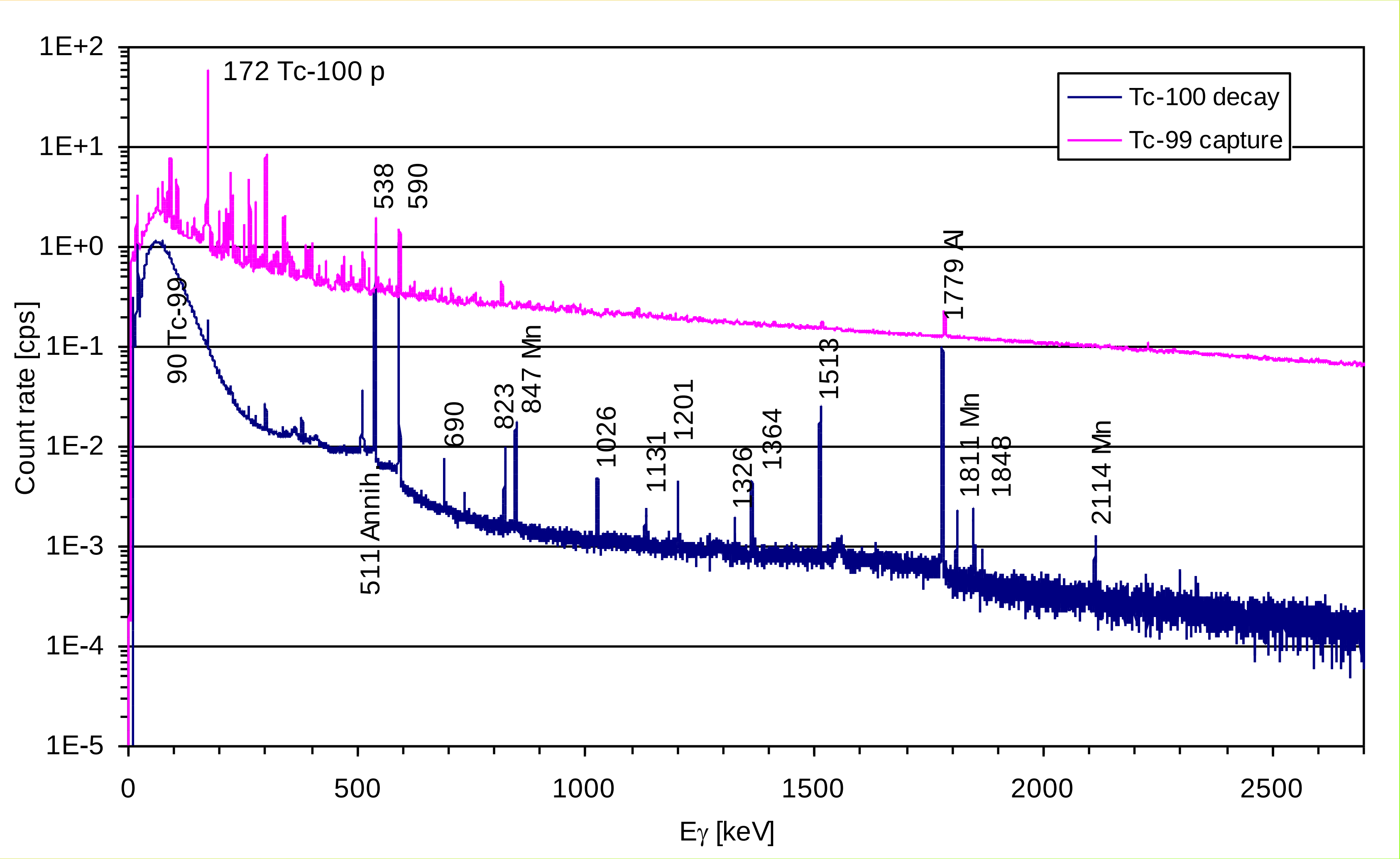
n

Rotating and standing slits

Cold and thermal neutron spectra



Prompt and decay spectrum of Tc-99



Simultaneous PGAA and NAA measurement with a chopper

- **Beam open**

prompt gamma rays

decay gamma rays

Usual PGAA spectrum

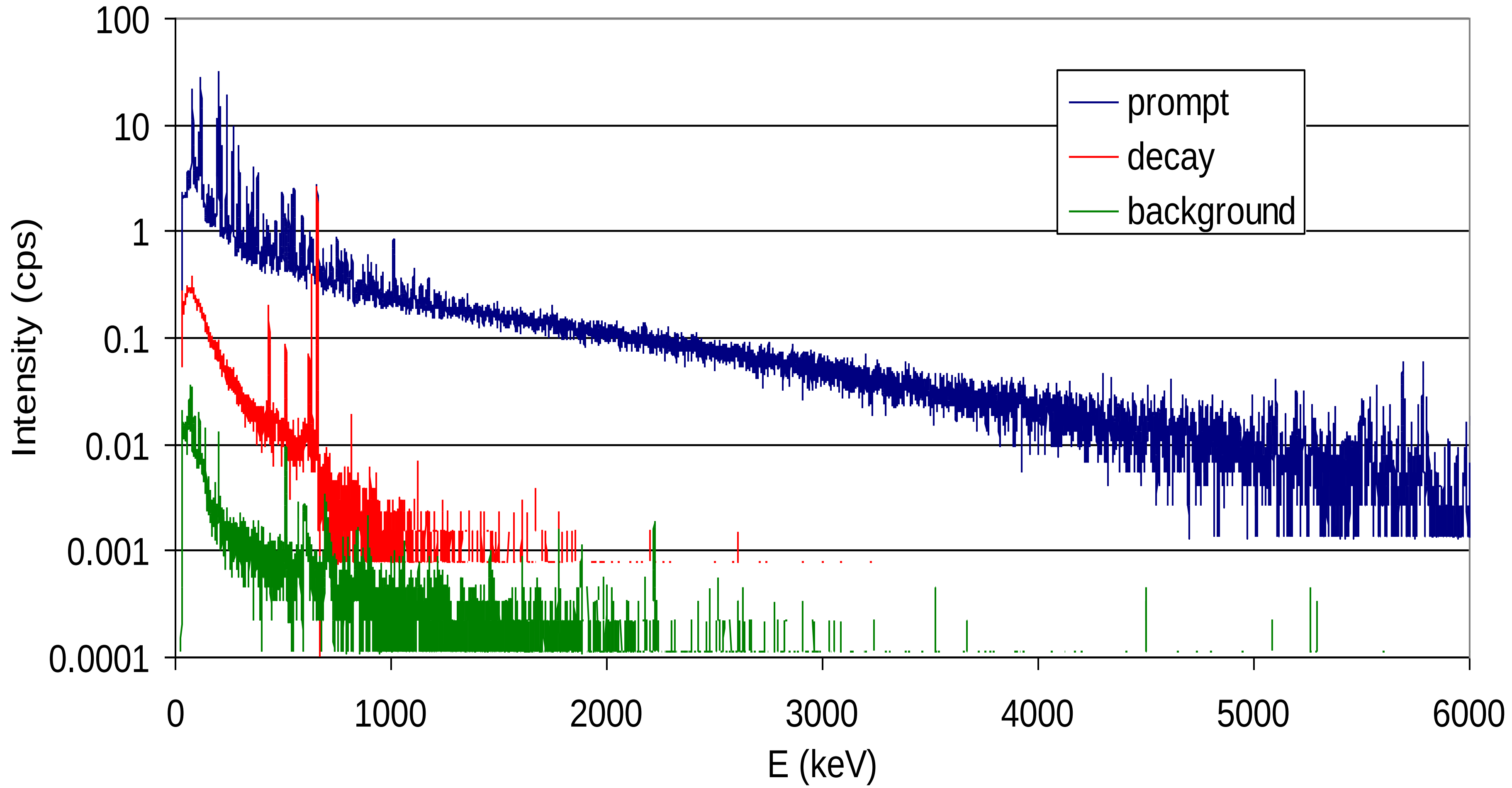
- **Beam closed**

only decay gamma rays

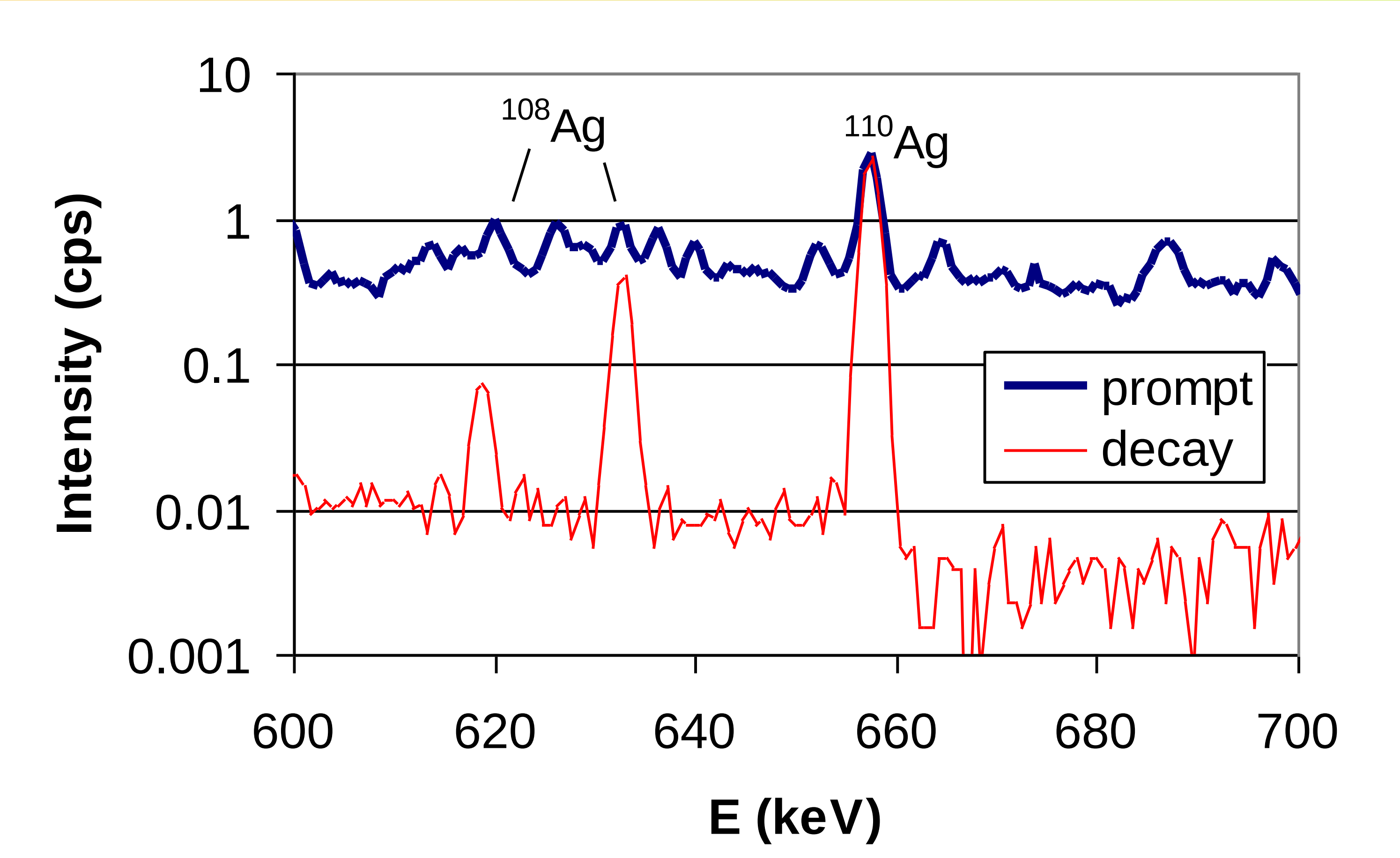
cyclic NAA spectrum

Increasing of the dynamic range

Prompt and decay spectra of Ag



Prompt and decay spectrum of Ag



Elements with visible decay lines in prompt spectra

< 1 s: Na,

< 1 min: F, Sc, Ge, Pd, Ag, In, Er, Hf, W,

< 10 min Mg, Al, V, Cr, Se, Br, Rh, Dy, Ir,

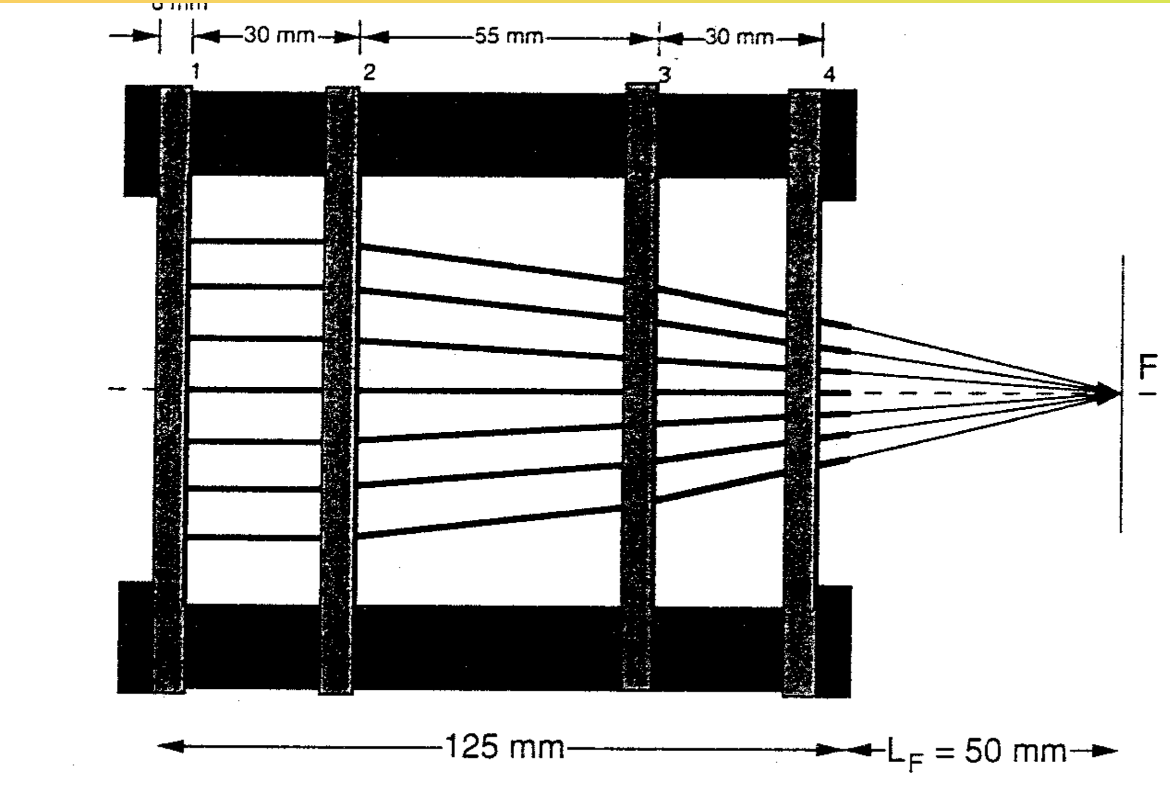
< 1 h: Ga, Rb, Sn, I, Pr, Nd, Ta, Re,

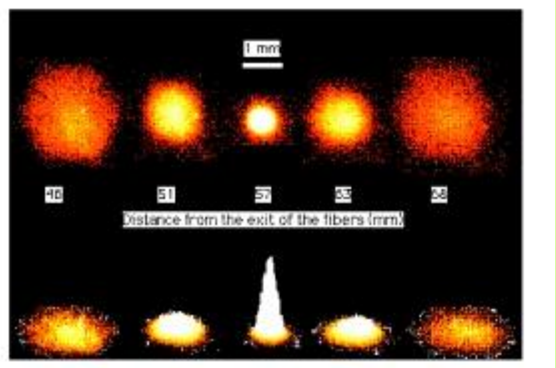
<1 day: Mn, Cu, Sr, Cs, Ba, Eu, Lu,

longer: As, Ru, La, Ce, Tb, Ho, Yb, Au,

2. Neutron lens for Cold Neutrons

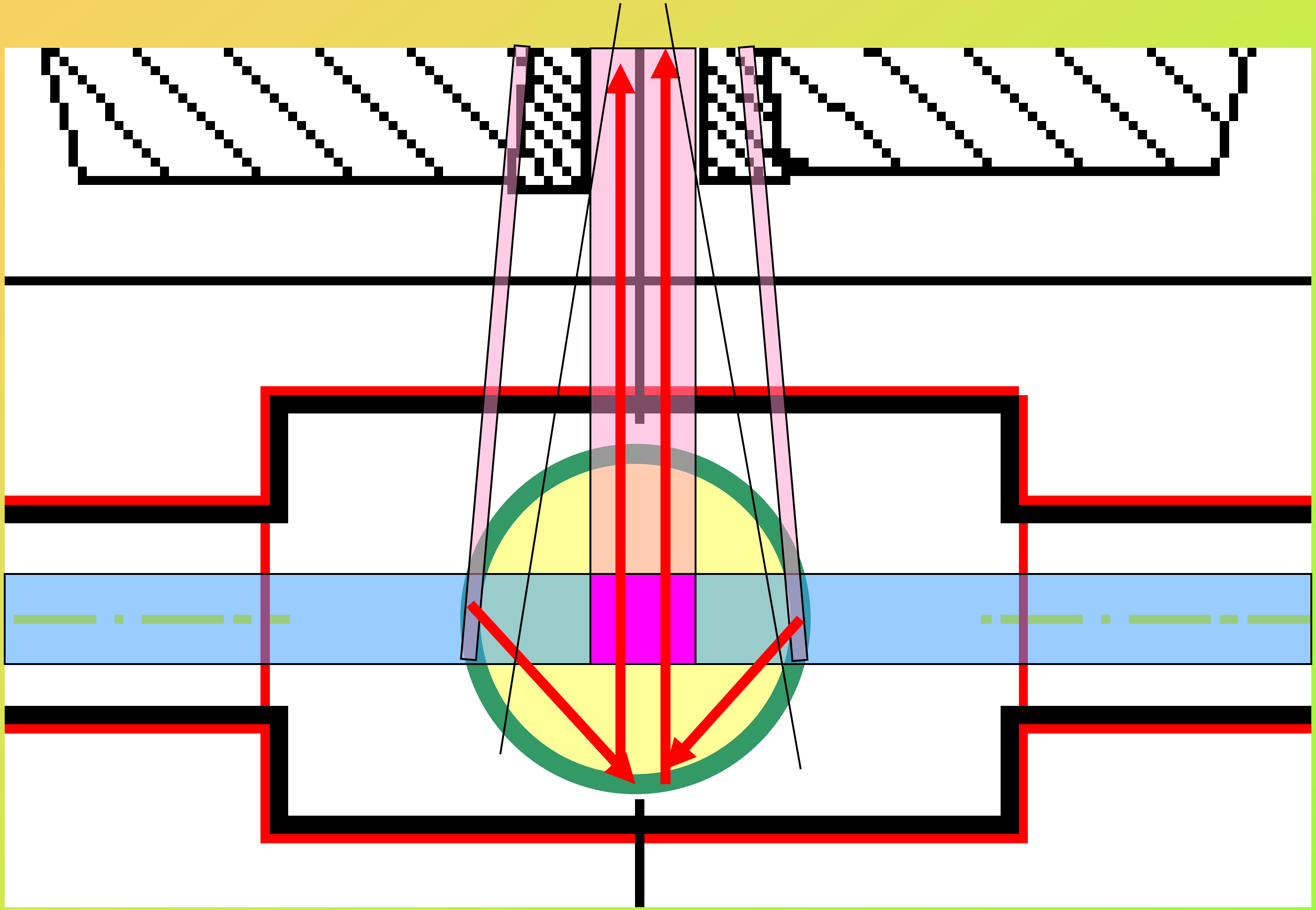
Polycapillary neutron lens (NIST). 1763 glass fibres (0.5 mm), each with 1657 channels (9 μm) focus neutrons to 0.5 mm spot.





source: NIST

3. Method of “invisible container”



Method of "invisible container"

Noble gases (Ne, Ar, Kr, Xe) were measured in this way

containers: borosilicate glass

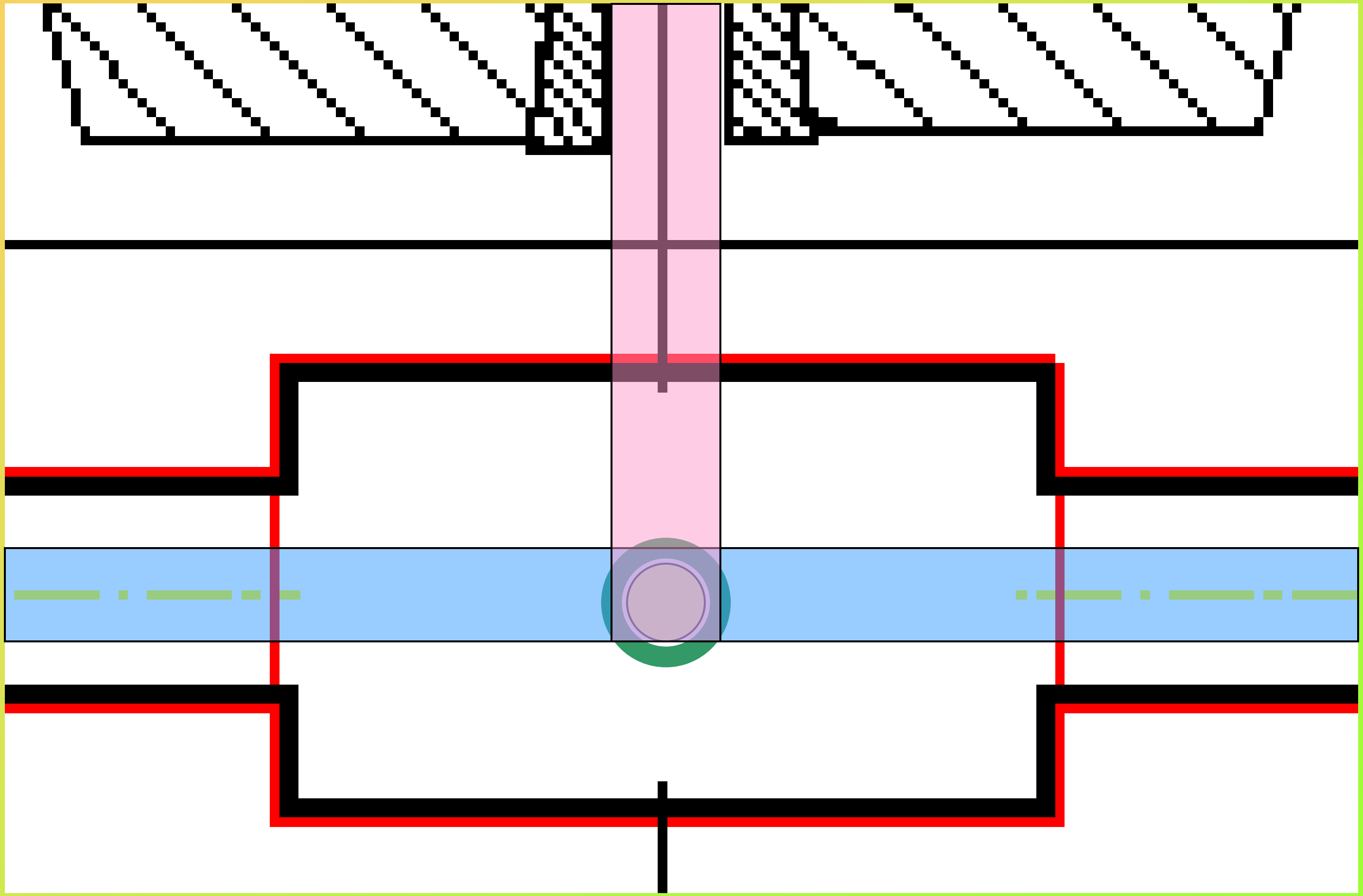
Al minican

When container has low cross-sec,

It should not be invisible

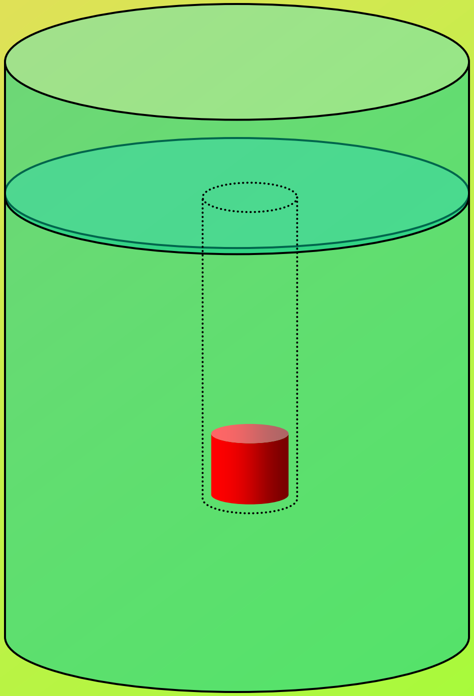
Figure: Linde

When the container is visible…

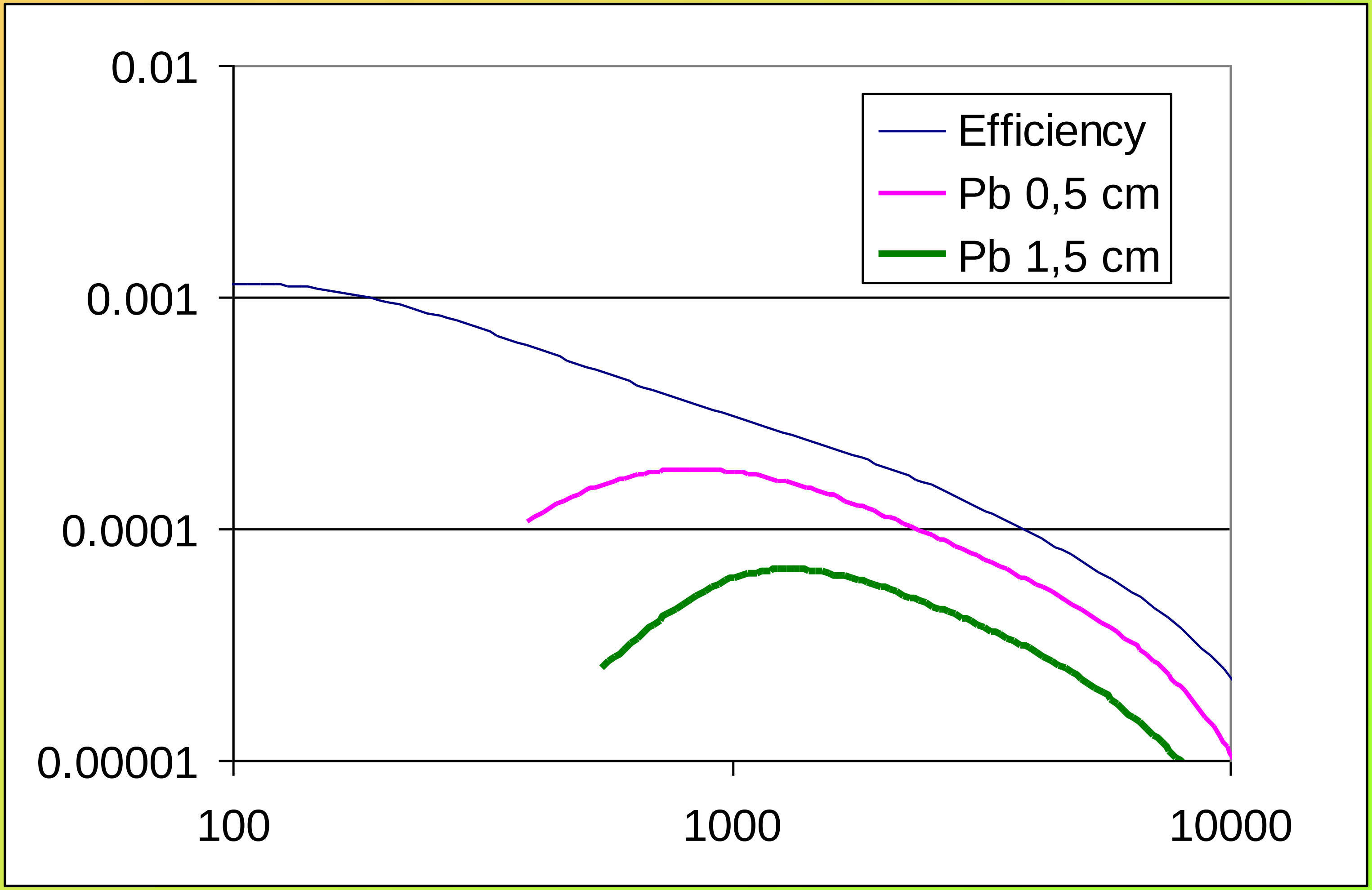


Detection of Material in Thick Containers

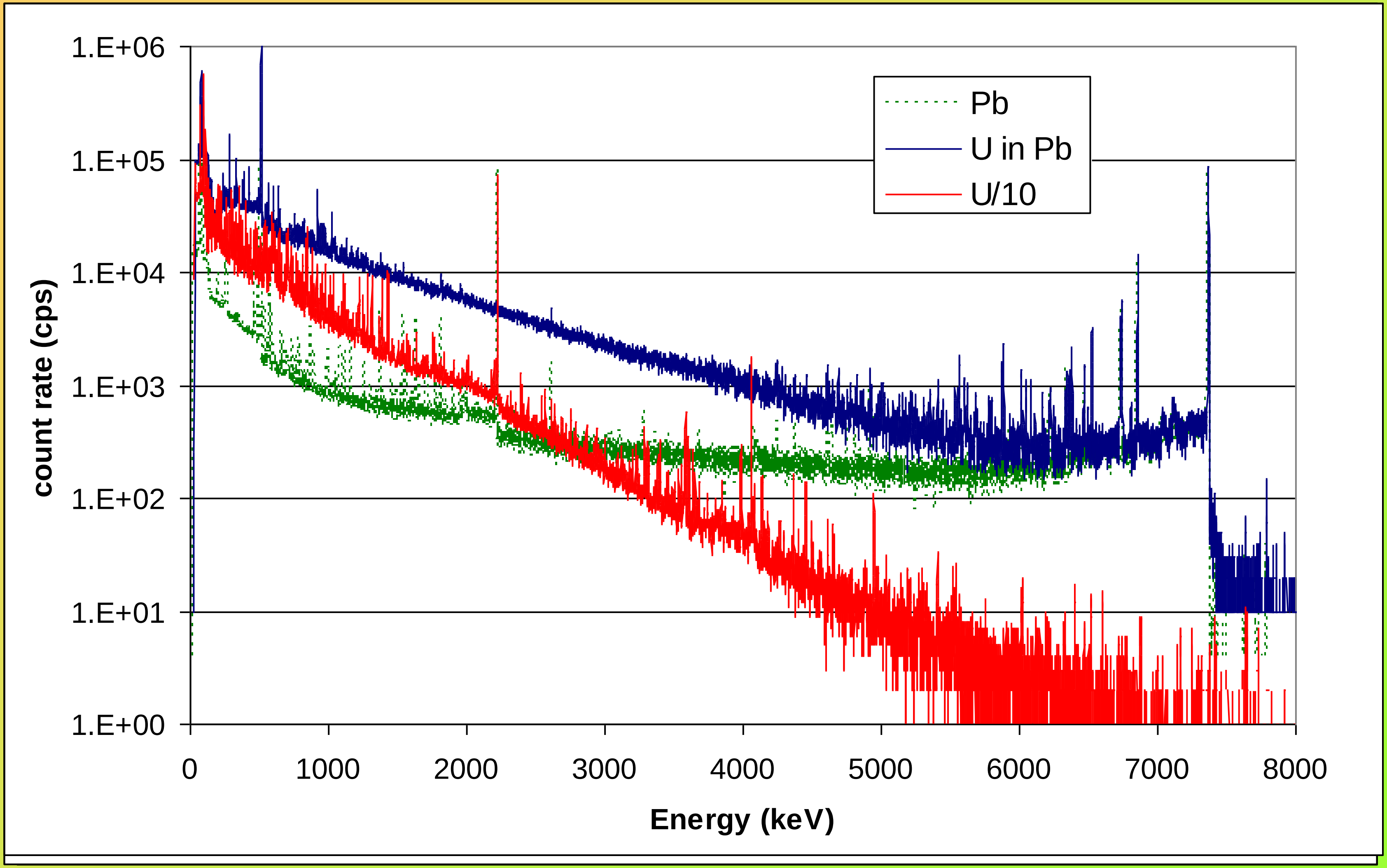
- neutrons and gammas penetrate through the walls of the container.



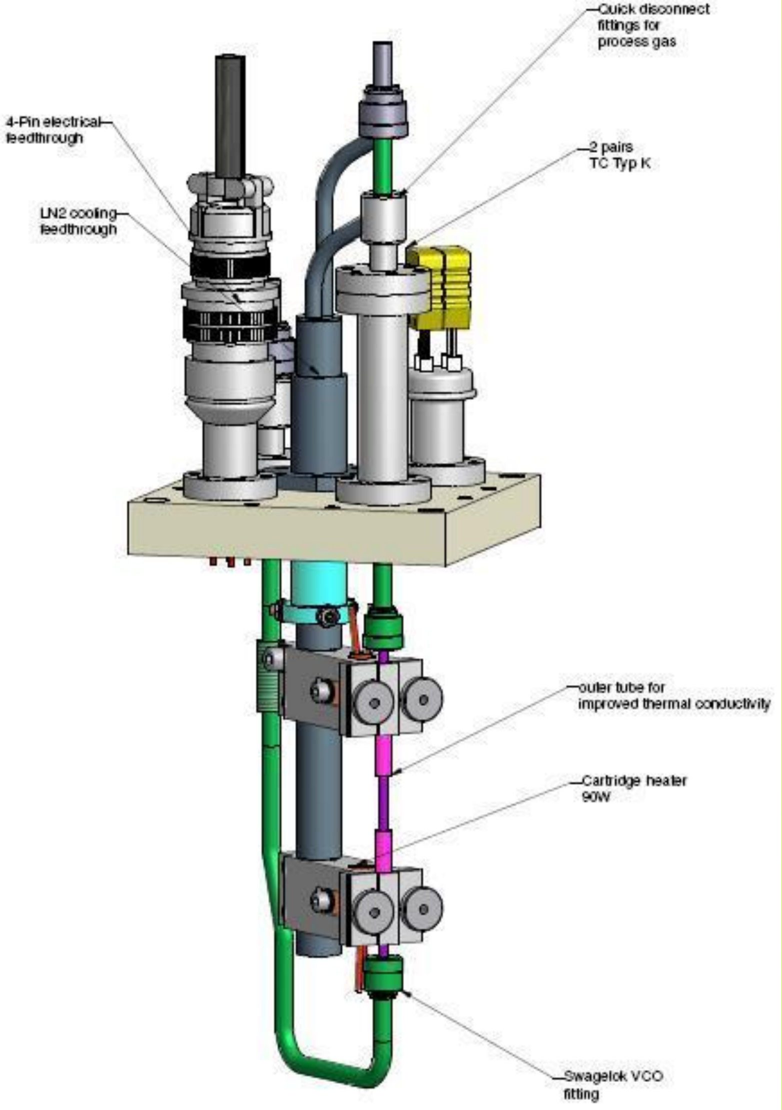
Efficiency for samples in lead containers (^{152}Eu, ^{226}Ra, Cl)

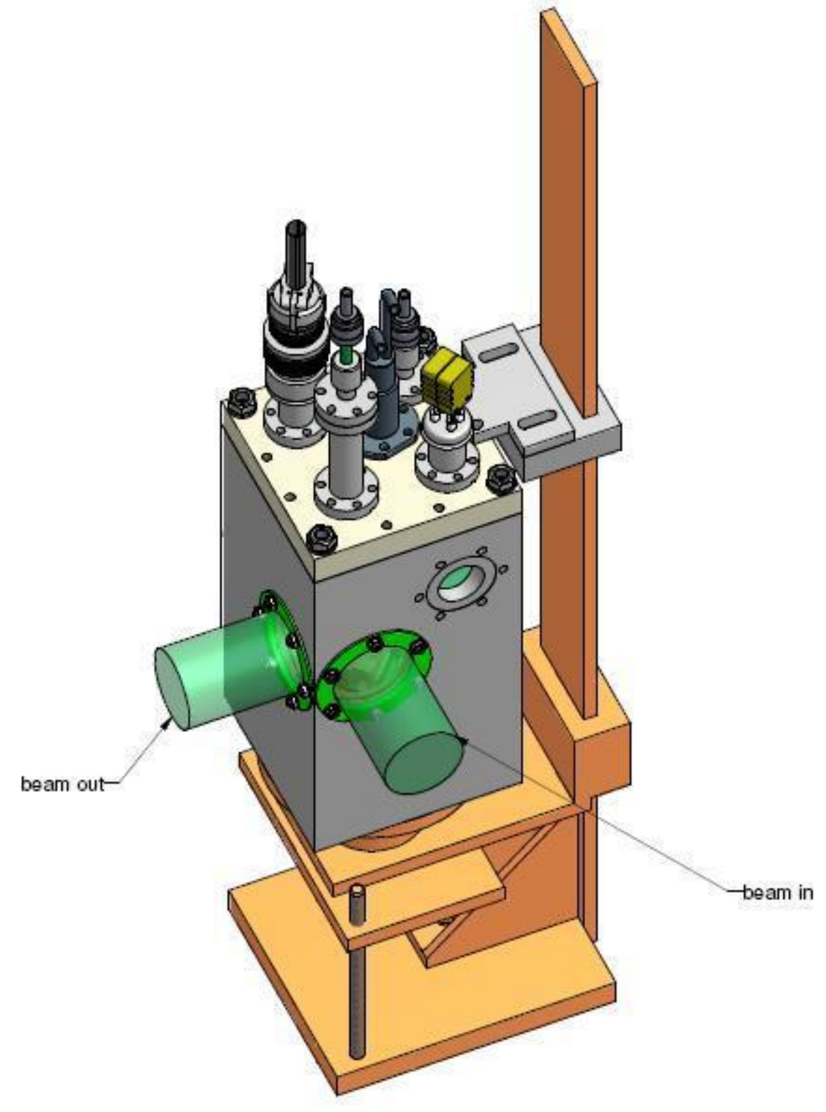


PGAA spectra of uranium+ Pb container



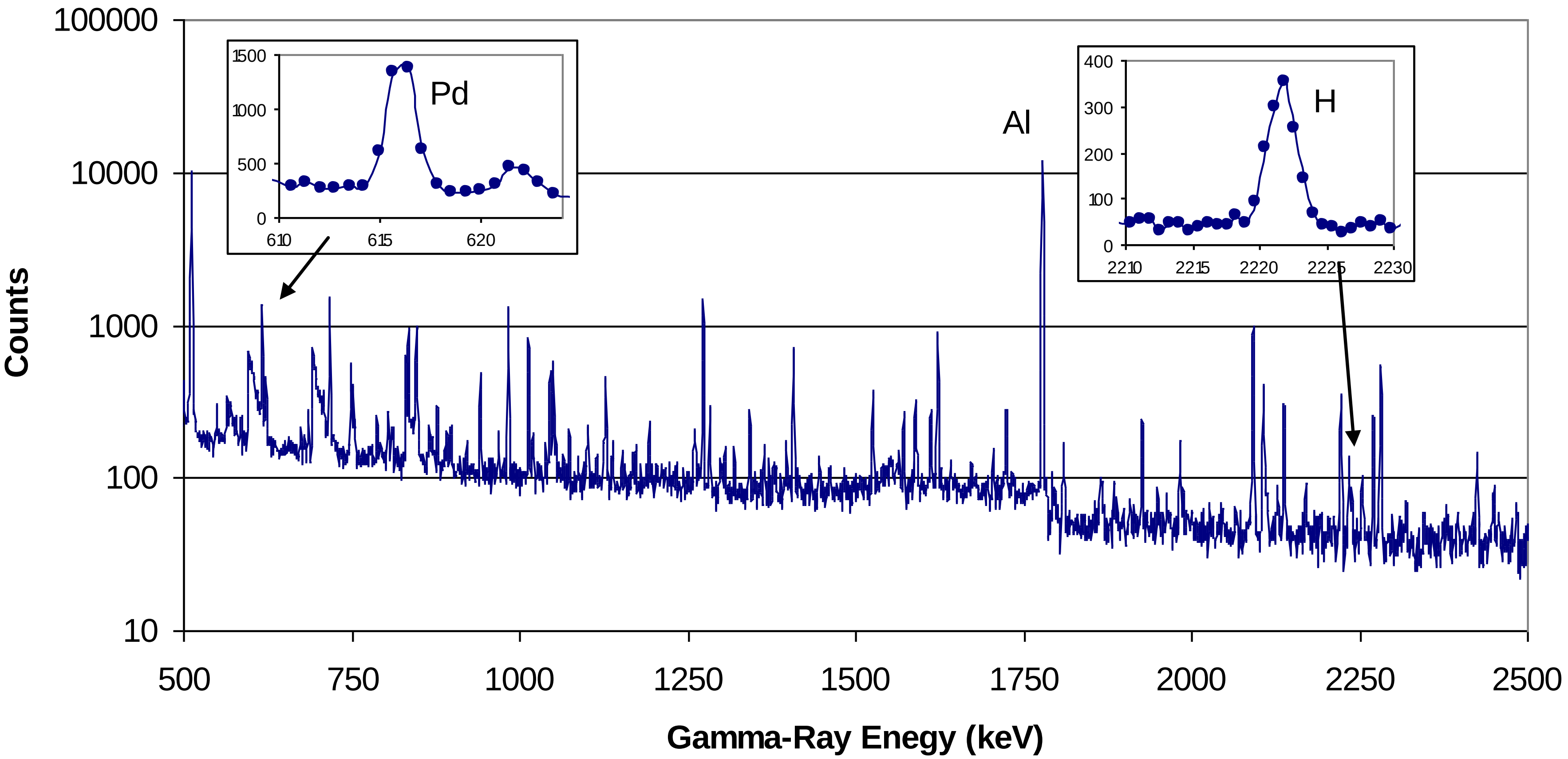
4. In situ PGAA





D. Teschner

PGAA spectrum of the catalytic reactor –monitoring H content

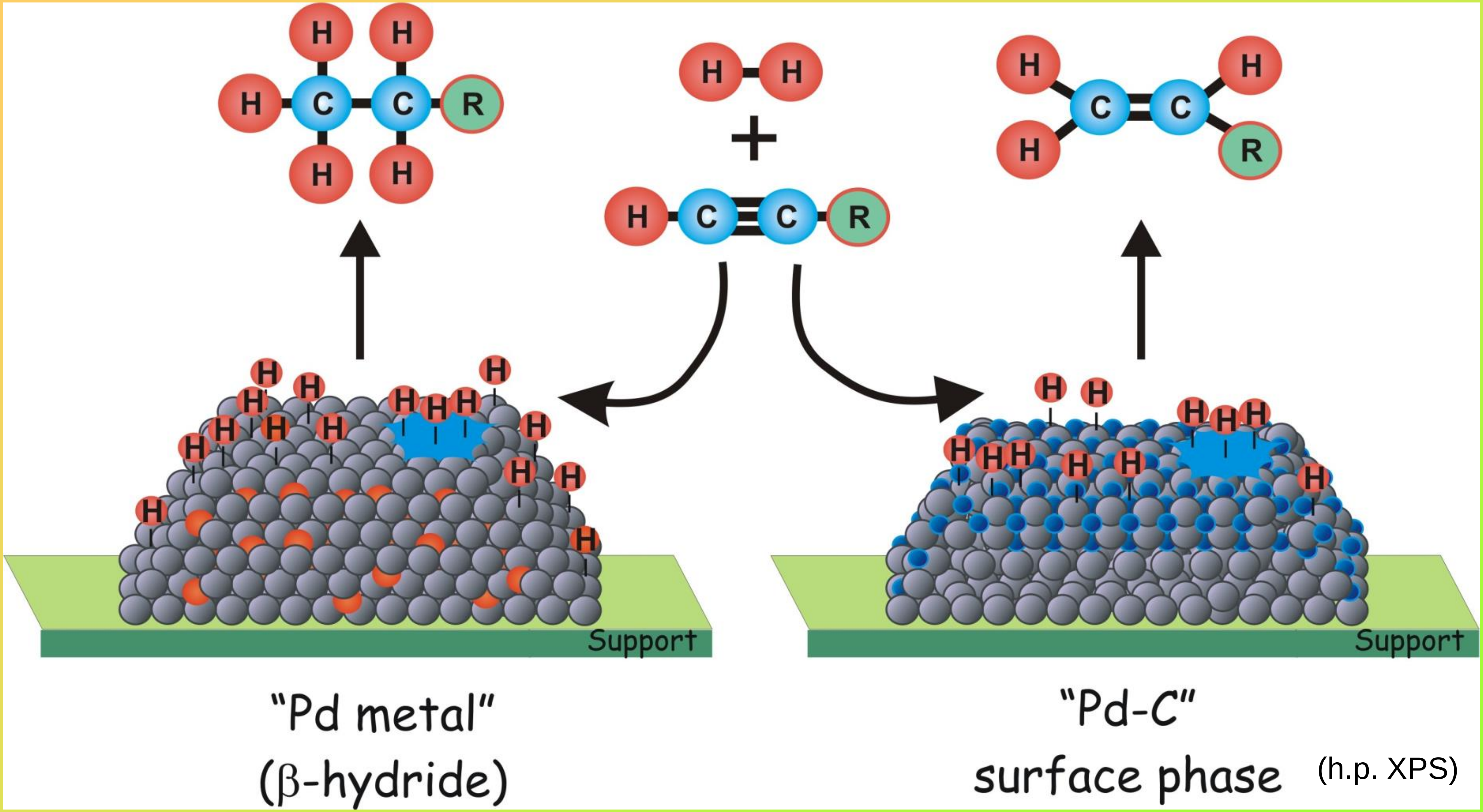


Measurements and Results

- Catalytic experiment
  - 2 g tube reactor
  - 100mg SiC + 7 mg Pd
  - 5—50 µg H
- The mechanism of the reaction could be clarified

H detection limit: 5 µg!!

Model: 1-pentyne hydrogenation



H saturated bulk und subsurface

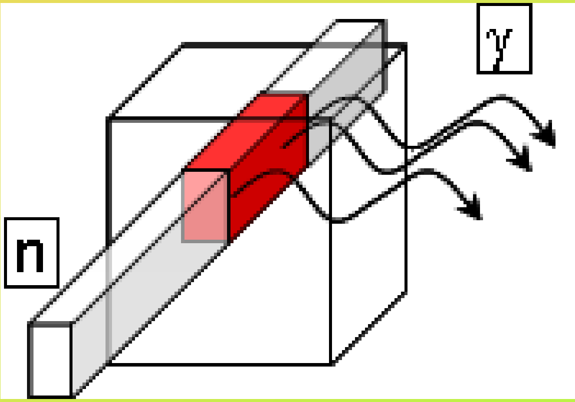
Bulk plays no role:
Decoupled from surface

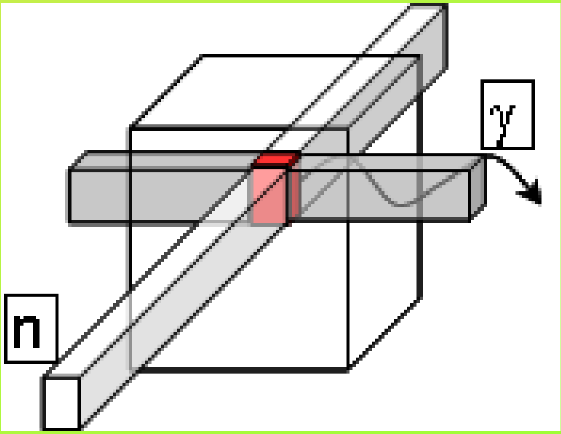
D. Teschner

5. Neutron Radiography driven PGAA

1. Full beam: regular radiography image(s)

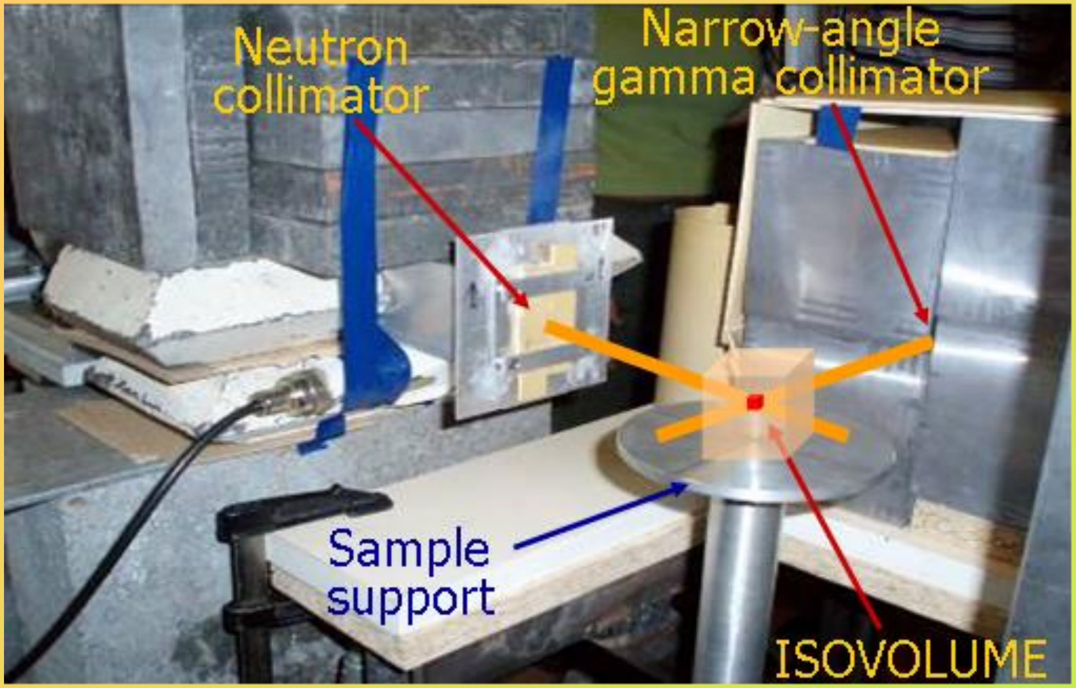
2. Sharp collimation of neutron beam
   Sharp collimation of gamma detection (for analysis)





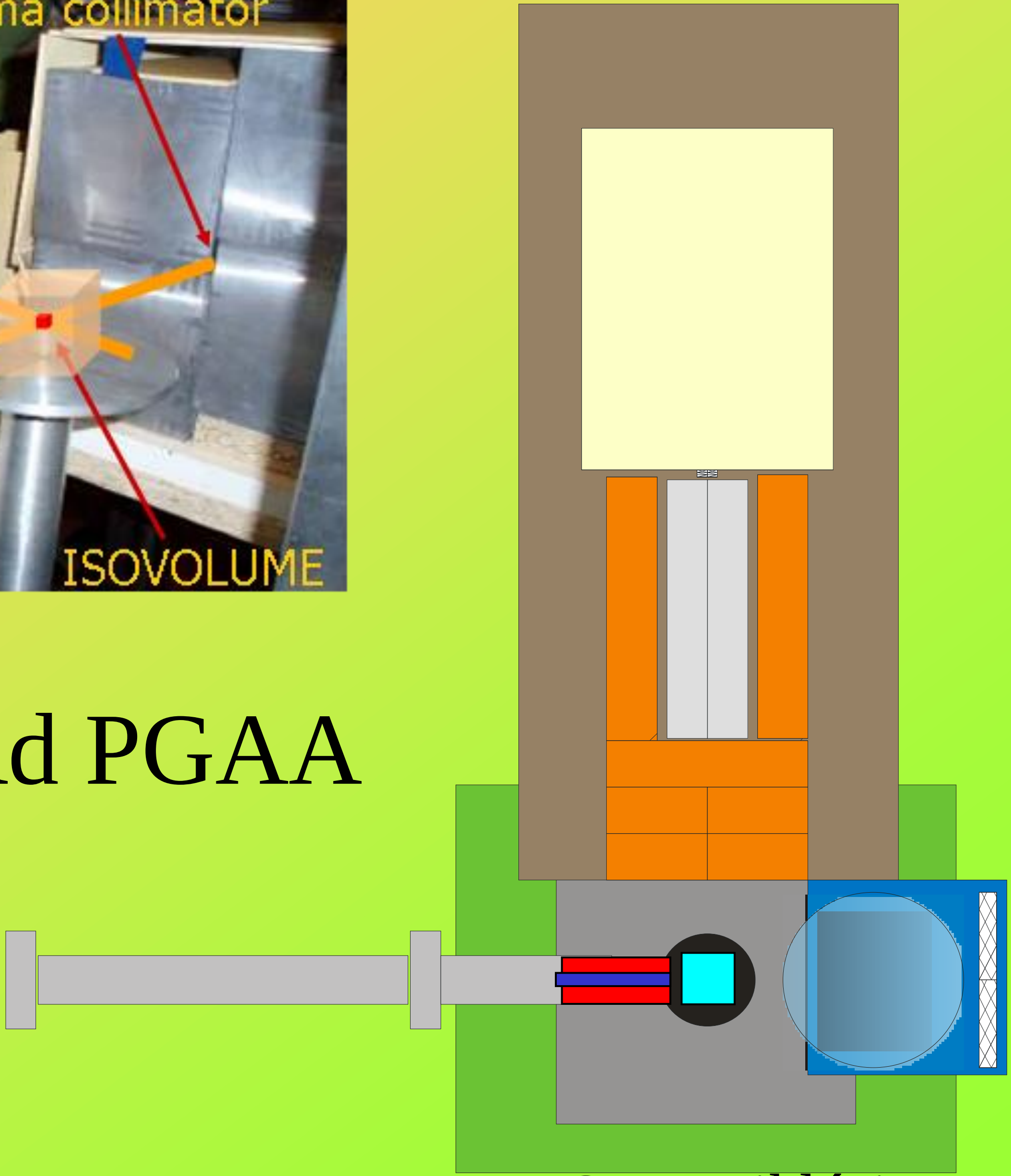
L. Szentmiklósi

NRd PGAA



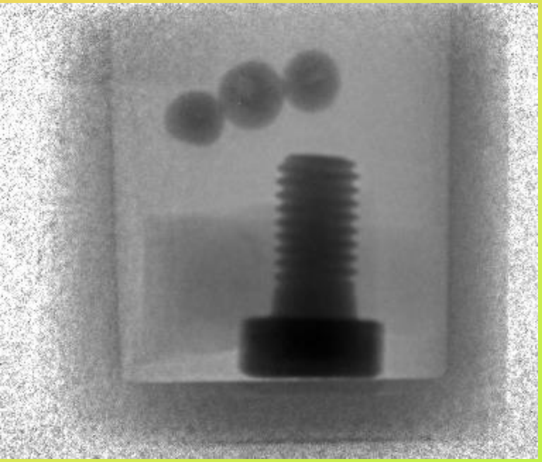
1) Full beam: neutron radiography and/or tomography

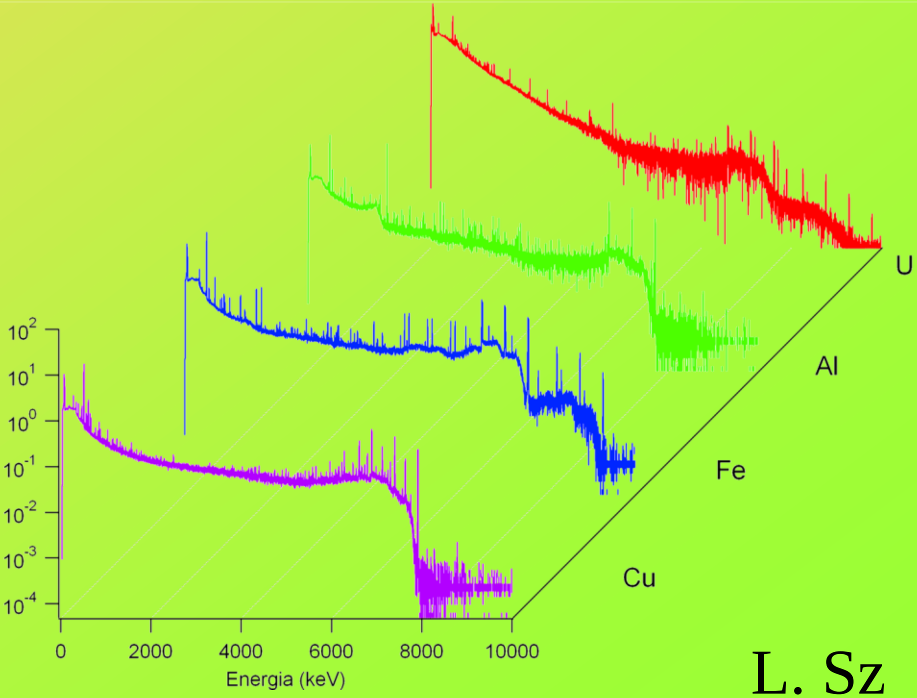
2) Sharp collimation of neutrons and gammas



L. Szentmiklósi

Test sample (U, Fe, Cu, Al)

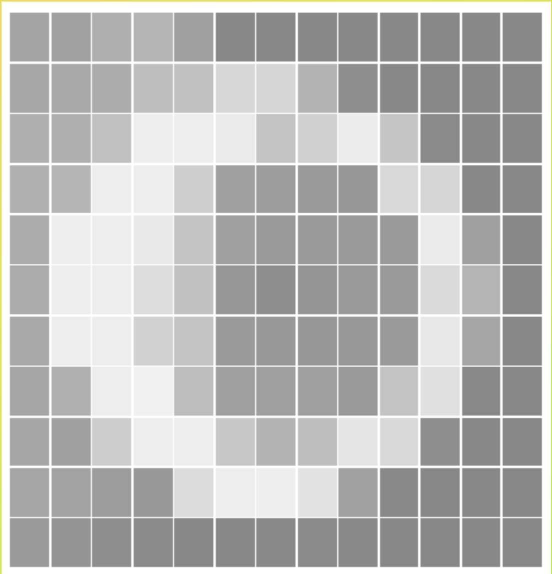




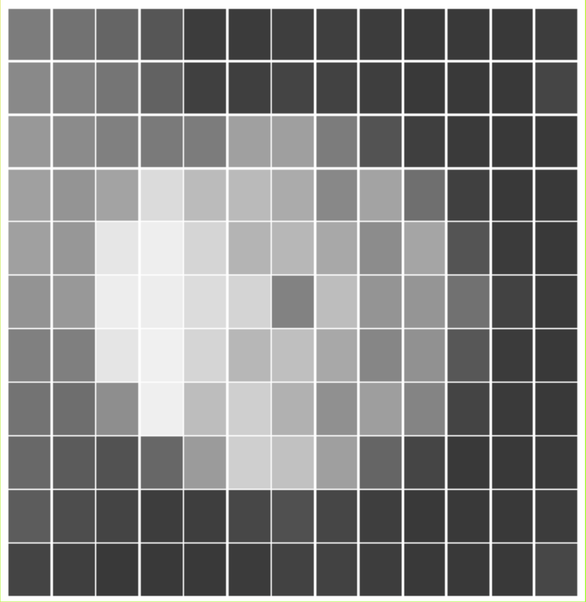
L. Sz

Elemental mapping (on the replica of Frankish fibula, 6th century, Hungary)

n radiogram



Fe map



Cu map

Under publication

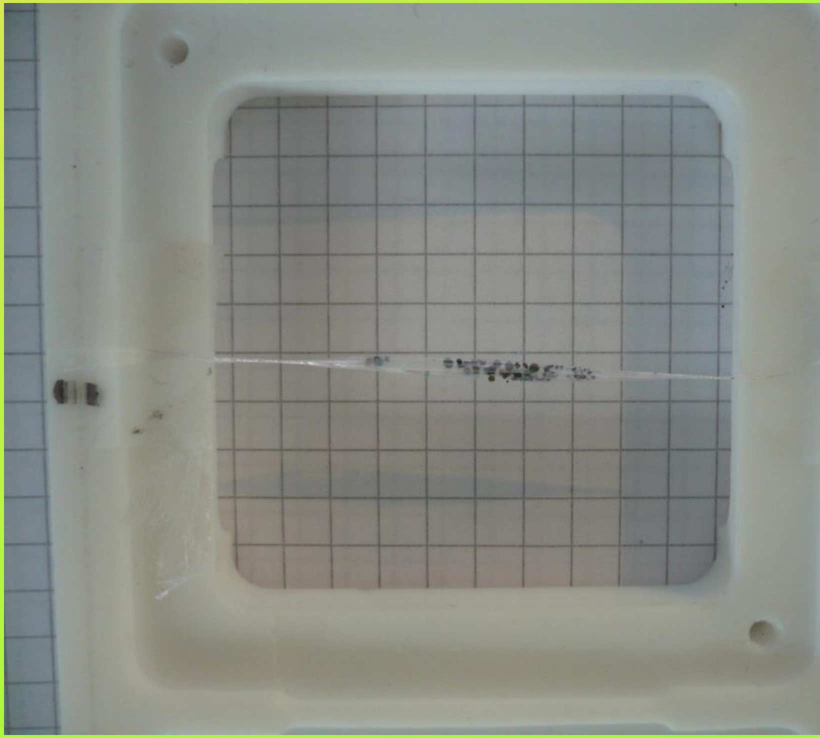
L. Sz.

Applications

1. Micro-meteorites (high flux FRM II)

- Mass ~0.3—2mg
- In 0.5μm Mylar (PET) foil
- No Teflon string

Z	El	M	m meas	*unc %*	m Bkg	*unc %*	m net	ox. st.	m ox	*unc %*
1	**H**	1.008	5.47E-6	*0.8*	1.36E-6	*1.5*	**4.11E-6**	**1**	**3.67E-5**	*1.2*
5	**B**	10.81	6.74E-7	*0.3*	1.15E-8	*1.0*	**6.63E-7**	**3**	**2.13E-6**	*0.3*
13	**Al**	26.98	4.51E-5	*2.2*	1.96E-5	*2.5*	**2.55E-5**	**3**	**4.82E-5**	*4.*
14	**Si**	28.09	9.22E-5	*2.8*	1.96E-5	*3.7*	**7.26E-5**	**4**	**1.55E-4**	*3.7*
16	**S**	32.07	4.67E-6	*14.*		*0.0*	**4.67E-6**	**6**	**1.17E-5**	*14.*
17	**Cl**	35.45	1.09E-6	*18.*	1.15E-7	*22.*	**9.71E-7**	**-1**	**9.71E-7**	*20.*
20	**Ca**	40.08	2.10E-5	*19.*		*0.0*	**2.10E-5**	**2**	**2.94E-5**	*19.*
22	**Ti**	47.87	2.45E-4	*2.6*	1.40E-7	*22.*	**2.45E-4**	**4**	**4.09E-4**	*2.6*
24	**Cr**	52	4.03E-6	*14.*		*0.0*	**4.03E-6**	**3**	**5.89E-6**	*14.*
25	**Mn**	54.94	8.75E-6	*2.0*		*0.0*	**8.75E-6**	**3**	**1.26E-5**	*2.0*
26	**Fe**	55.85	2.31E-4	*2.4*	1.16E-6	*10.*	**2.30E-4**	**3**	**3.28E-4**	*2.4*
27	**Co**	58.93	3.06E-6	*3.1*		*0.0*	**3.06E-6**	**2**	**3.89E-6**	*3.1*
60	**Nd**	144.2	8.89E-7	*13.*		*0.0*	**8.89E-7**	**3**	**1.04E-6**	*13.*
62	**Sm**	150.4	5.32E-8	*6.*		*0.0*	**5.32E-8**	**3**	**6.16E-8**	*6.*
64	**Gd**	157.3	9.89E-8	*7.*		*0.0*	**9.89E-8**	**3**	**1.14E-7**	*7.*



1 mg

R.B. Firestone

2. Air filters (high flux, FRM II)

- ~1mg PC filters, <1mg dust
- In 0.5μm Mylar (PET) foil

- Detection limit for certain trace elements (B, Gd, Sm) <1ng !!

Nuno Canha, Marina Almeida

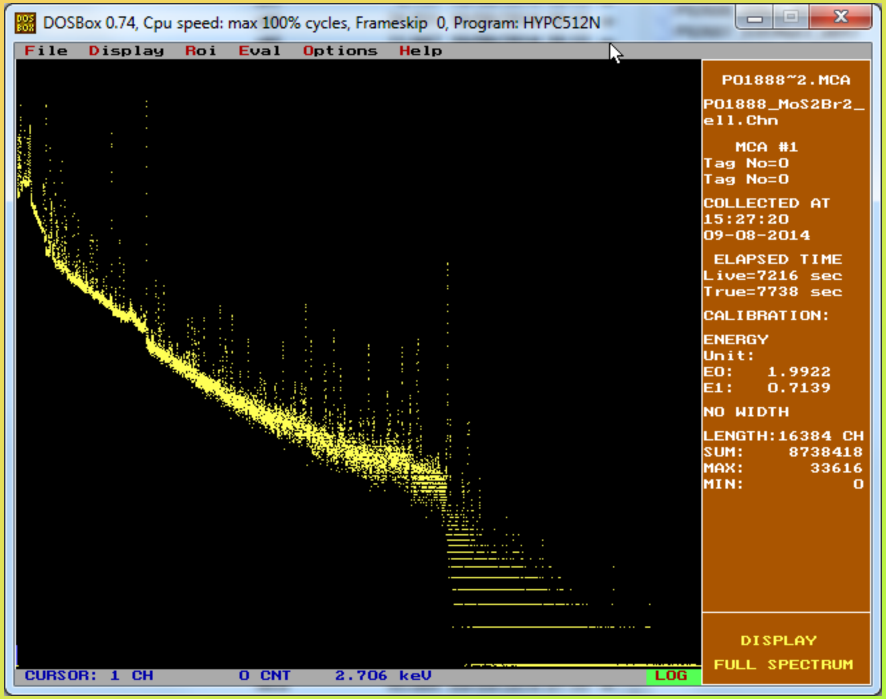
Air filter typical composition

Z	El	M	m meas	*unc %*	m Bkg	*unc %*	m net	ox. st.	m ox	*unc %*
5	**B**	10.81	8.16E-8	*0.5*	5.13E-8	*0.7*	**3.03E-8**	**3**	**9.75E-8**	*1.8*
11	**Na**	22.99	3.65E-5	*3.8*	4.80E-6	*11.*	**3.17E-5**	**1**	**4.27E-5**	*5.*
13	**Al**	26.98	4.33E-5	*3.3*	1.67E-5	*6.*	**2.66E-5**	**3**	**5.03E-5**	*7.*
14	**Si**	28.09	8.56E-5	*3.2*	2.34E-5	*5.*	**6.22E-5**	**4**	**1.33E-4**	*5.*
16	**S**	32.07	1.11E-5	*8.*		*0.0*	**1.11E-5**	**6**	**2.77E-5**	*8.*
17	**Cl**	35.45	3.55E-5	*1.4*	3.00E-7	*16.*	**3.52E-5**	**-1**	**3.52E-5**	*1.4*
19	**K**	39.1	6.95E-6	*7.*		*0.0*	**6.95E-6**	**1**	**8.37E-6**	*7.*
20	**Ca**	40.08	2.34E-5	*6.*	3.26E-6	*9.*	**2.02E-5**	**2**	**2.82E-5**	*7.*
22	**Ti**	47.87	1.89E-6	*5.*		*0.0*	**1.89E-6**	**4**	**3.15E-6**	*5.*
26	**Fe**	55.85	1.73E-5	*4.*	1.30E-6	*11.*	**1.60E-5**	**3**	**2.29E-5**	*4.*
27	**Co**	58.93	1.15E-6	*9.*	4.27E-7	*26.*	**7.27E-7**	**2**	**9.24E-7**	*21.*
29	**Cu**	63.55	2.93E-6	*14.*		*0.0*	**2.93E-6**	**2**	**3.67E-6**	*14.*
62	**Sm**	150.4	2.91E-9	*9.*		*0.0*	**2.91E-9**	**3**	**3.37E-9**	*9.*
64	**Gd**	157.3	2.38E-9	*13.*		*0.0*	**2.38E-9**	**3**	**2.75E-9**	*13.*
82	**Pb**	207.2	2.10E-4	*9.*	1.26E-4	*8.*	**8.45E-5**	**2**	**9.10E-5**	*25.*

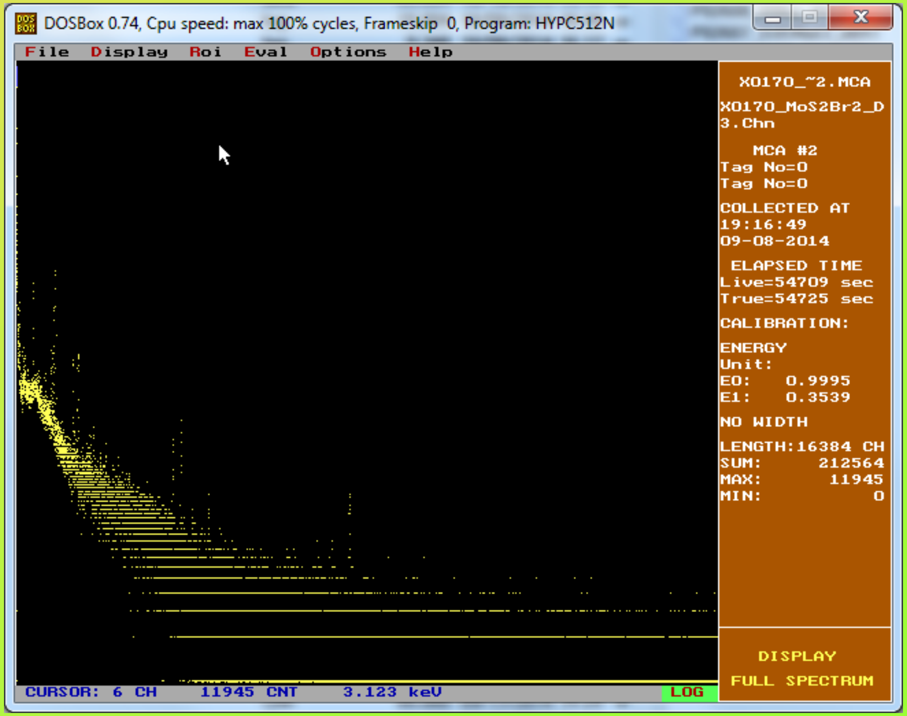
Mass = 0.45 mg

3. Pollutants of MoS_2 (PGAA+NAA, FRM II)

- From prompt spectrum:
  - B 0.067--0.87--240 ppm Cl 0.4 ppm Mo 59 ppm
- From decay spectra:
  - La 300 ppm Br 500 ppm Ir 0.29%
    In 1.7 ppm



```
P01888~2.MCA
P01888_MoS2Br2_
ell.Chn
  MCA #1
Tag No=0
Tag No=0
COLLECTED AT
15:27:20
09-08-2014
 ELAPSED TIME
Live=7216 sec
True=7738 sec
CALIBRATION:
ENERGY
Unit:
E0:    1.9922
E1:    0.7139
NO WIDTH
LENGTH:16384 CH
SUM:     8738418
MAX:       33616
MIN:           0
CURSOR: 1 CH          0 CNT     2.706 keV
```



```
X0170_~2.MCA
X0170_MoS2Br2_D
3.Chn
  MCA #2
Tag No=0
Tag No=0
COLLECTED AT
19:16:49
09-08-2014
 ELAPSED TIME
Live=54709 sec
True=54725 sec
CALIBRATION:
ENERGY
Unit:
E0:    0.9995
E1:    0.3539
NO WIDTH
LENGTH:16384 CH
SUM:      212564
MAX:       11945
MIN:           0
CURSOR: 6 CH      11945 CNT     3.123 keV
```

Bálint Náfrádi

4. Pollutants in MgO (PGAA+NAA, FRM II)

Z	El	M	m meas	*unc %*	w% el/ox	*unc %*
12	**Mg**	24.31	0.252	*5.*	**56**	***2.2***
		0				
1	**H**	1.008	3.82E-3	*0.4*	**0.843**	***2.8***
5	**B**	10.81	2.59E-6	*0.3*	**5.69 ppm**	***2.8***
17	**Cl**	35.45	3.72E-6	*13.*	**8 ppm**	***14.***
19	**K**	39.1	2.60E-5	*5.*	**57 ppm**	***6.***
20	**Ca**	40.08	9.45E-4	*30.*	**0.2**	***30.***
25	**Mn**	54.94	4.90E-7	*11.*	**1.1 ppm**	***11.***
47	**Ag**	107.9	1.10E-4	*4.0*	**240 ppm**	***5.***
49	**In**	114.8	1.40E-7	*3.0*	**0.31 ppm**	***4.***
57	**La**	138.9	9.23E-5	*7.*	**200 ppm**	***8.***
64	**Gd**	157.3	1.25E-8	*8.*	**0.028ppm**	***8.***
		0				
		0				
		0				
		0				

- Smallest masses

  10^{-7}—10^{-8} g
- Detection limits
- Down to 10^{-10} g

Maik Eichelbaum

5. Irradiation radioactive nuclides (high flux, FRM II)

Induced activity > natural radioactivity

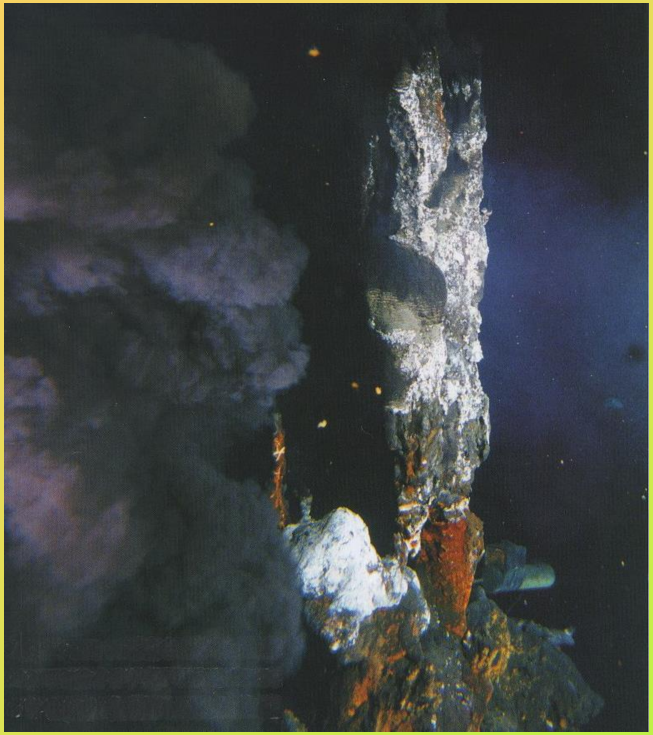
- MBq activities
- Half-life >100a
- Mass > 0.1mg
- Cross-sec. >100b

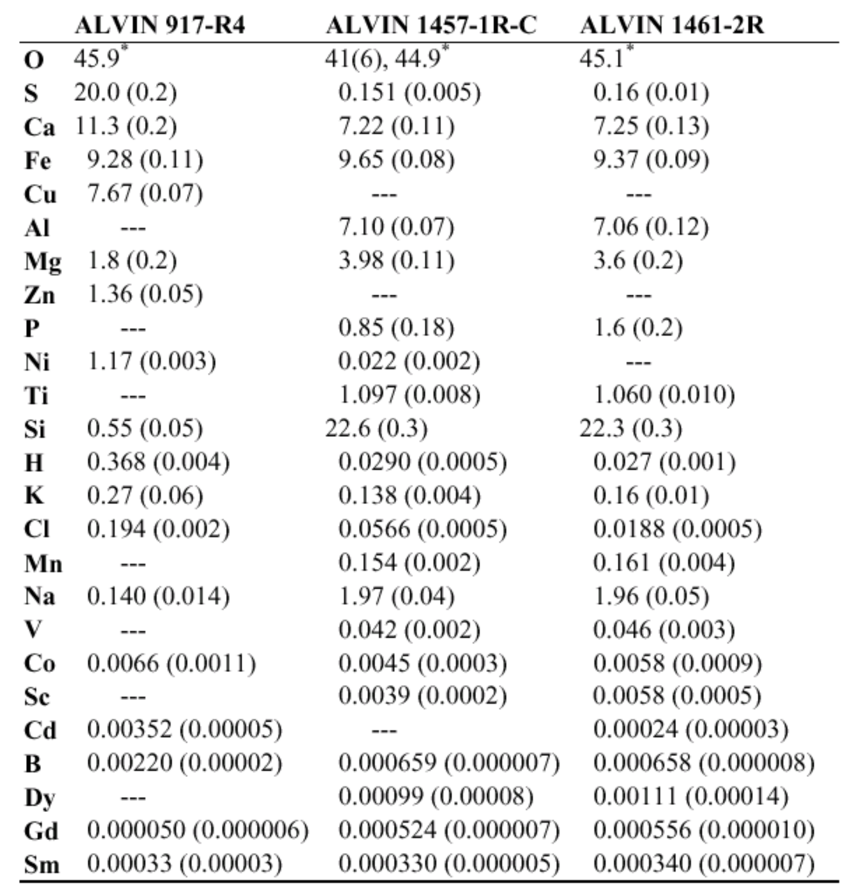
Radioactive samples irradiated at FRM2:

- 30μg (!!) ^{241}Am
- ~100 μg ^{237}Np, ^{242}Pu

Determination of cross section

6. Analysis of Deep Sea Vents (medium flux, Budapest)





	ALVIN 917-R4	ALVIN 1457-1R-C	ALVIN 1461-2R
O	45.9^*	41(6), 44.9^*	45.1^*
S	20.0 (0.2)	0.151 (0.005)	0.16 (0.01)
Ca	11.3 (0.2)	7.22 (0.11)	7.25 (0.13)
Fe	9.28 (0.11)	9.65 (0.08)	9.37 (0.09)
Cu	7.67 (0.07)	---	---
Al	---	7.10 (0.07)	7.06 (0.12)
Mg	1.8 (0.2)	3.98 (0.11)	3.6 (0.2)
Zn	1.36 (0.05)	---	---
P	---	0.85 (0.18)	1.6 (0.2)
Ni	1.17 (0.003)	0.022 (0.002)	---
Ti	---	1.097 (0.008)	1.060 (0.010)
Si	0.55 (0.05)	22.6 (0.3)	22.3 (0.3)
H	0.368 (0.004)	0.0290 (0.0005)	0.027 (0.001)
K	0.27 (0.06)	0.138 (0.004)	0.16 (0.01)
Cl	0.194 (0.002)	0.0566 (0.0005)	0.0188 (0.0005)
Mn	---	0.154 (0.002)	0.161 (0.004)
Na	0.140 (0.014)	1.97 (0.04)	1.96 (0.05)
V	---	0.042 (0.002)	0.046 (0.003)
Co	0.0066 (0.0011)	0.0045 (0.0003)	0.0058 (0.0009)
Sc	---	0.0039 (0.0002)	0.0058 (0.0005)
Cd	0.00352 (0.00005)	---	0.00024 (0.00003)
B	0.00220 (0.00002)	0.000659 (0.000007)	0.000658 (0.000008)
Dy	---	0.00099 (0.00008)	0.00111 (0.00014)
Gd	0.000050 (0.000006)	0.000524 (0.000007)	0.000556 (0.000010)
Sm	0.00033 (0.00003)	0.000330 (0.000005)	0.000340 (0.000007)

7. PRE-COLUMBIAN POTTERY FROM VENEZUELA (BUD)

(Simón Bolívar University, Caracas)

- Fragments of pottery figurines from 12nd-15th Century
- **Provenance**: Valencia Lake Basin and the
  Los Roques Islands
- **Question**: Did the occupants use the same raw material?
- **Analytic**: Major and trace components
  (H, Na, Mg, Al, Si, K, Ca, Ti, Mn, Fe
  B, S, Cl, Sc, V, Cr, Ba, Sm, Eu, Gd, Dy)

Zsolt Kasztovszky

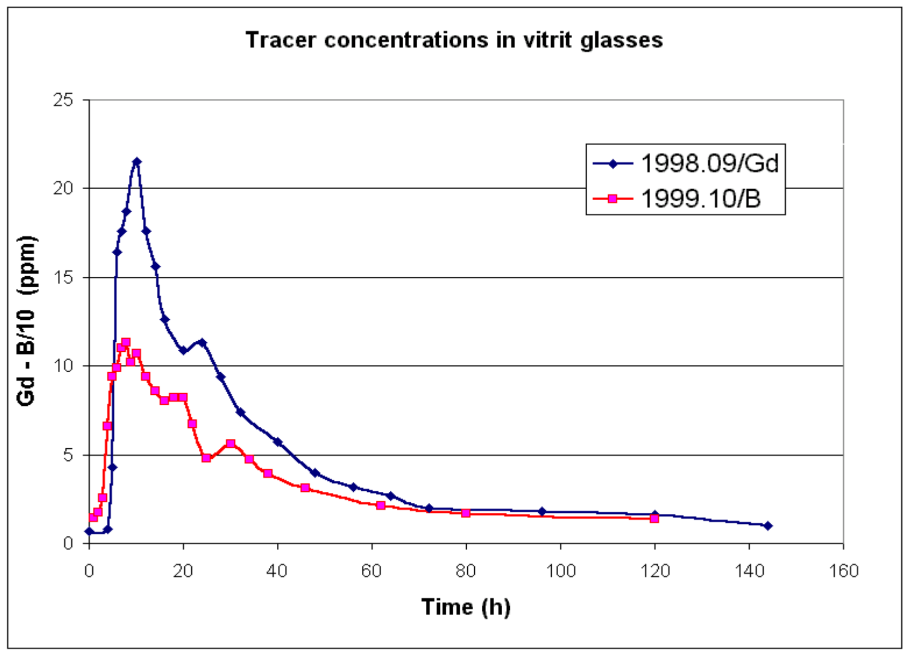
PROVENANCE OF VENEZUELAN POTTERY

Zs.K.

8. INACTIVE TRACING OF A GLASS FURNACE

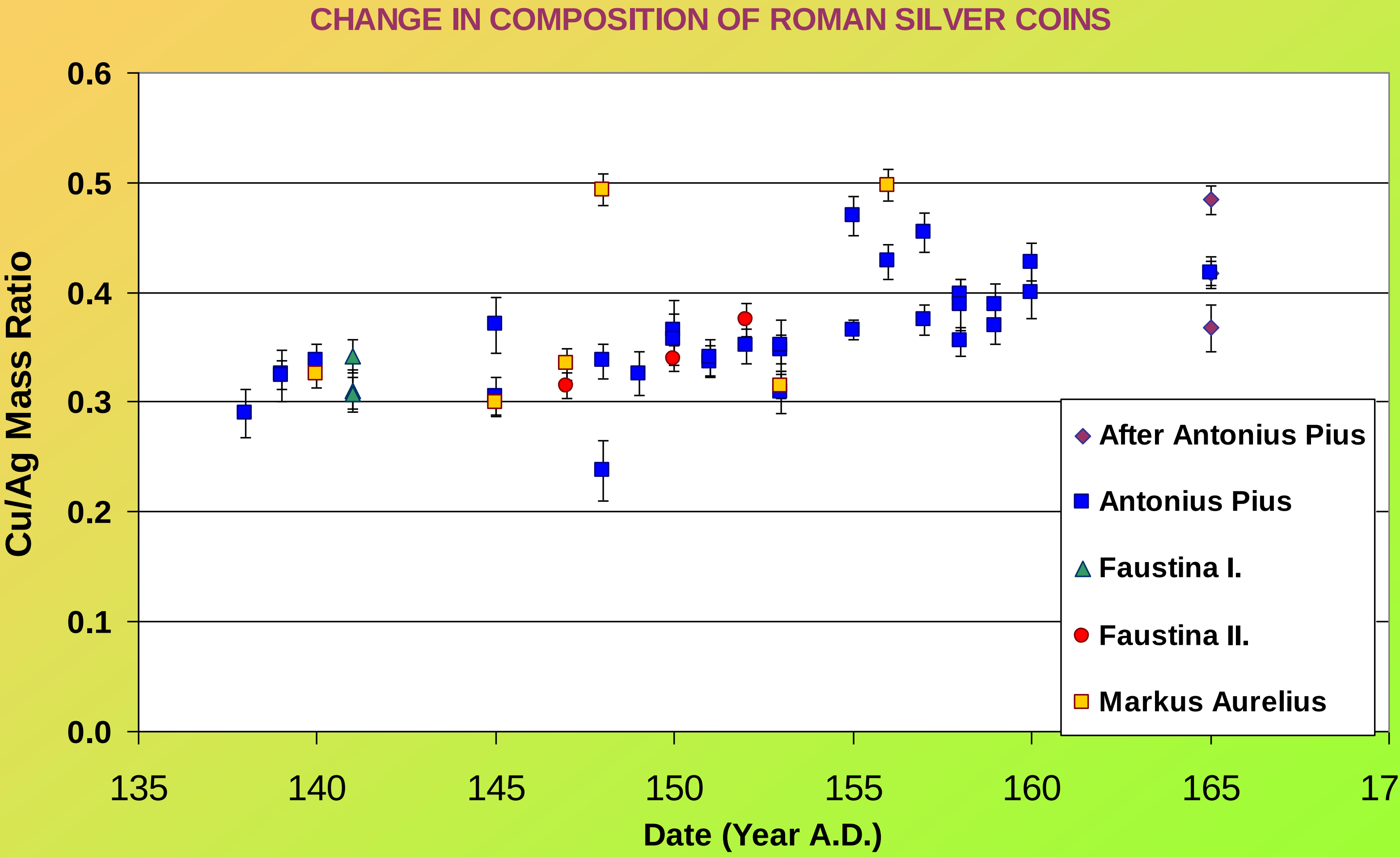
(medium fllux, Budapest)

- Homogenization and flow properties of an industrial melting furnace were investigated
- To avoid high level radioactivity, inactive tracers of Gd_2O_3 and H_3BO_3 were added in 10 ppm concentration
- Samples were taken regularly at the outlet and measured with PGAA
- Properties were found to be close to ideal case



9. ROMAN SILVER COINS

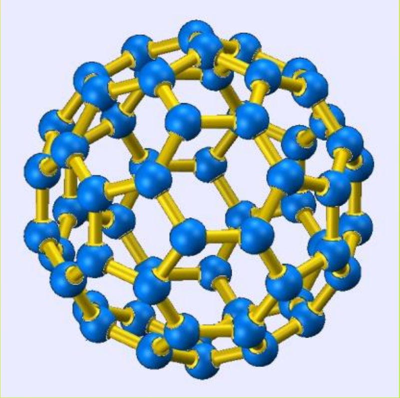
(medium flux, Budapest)

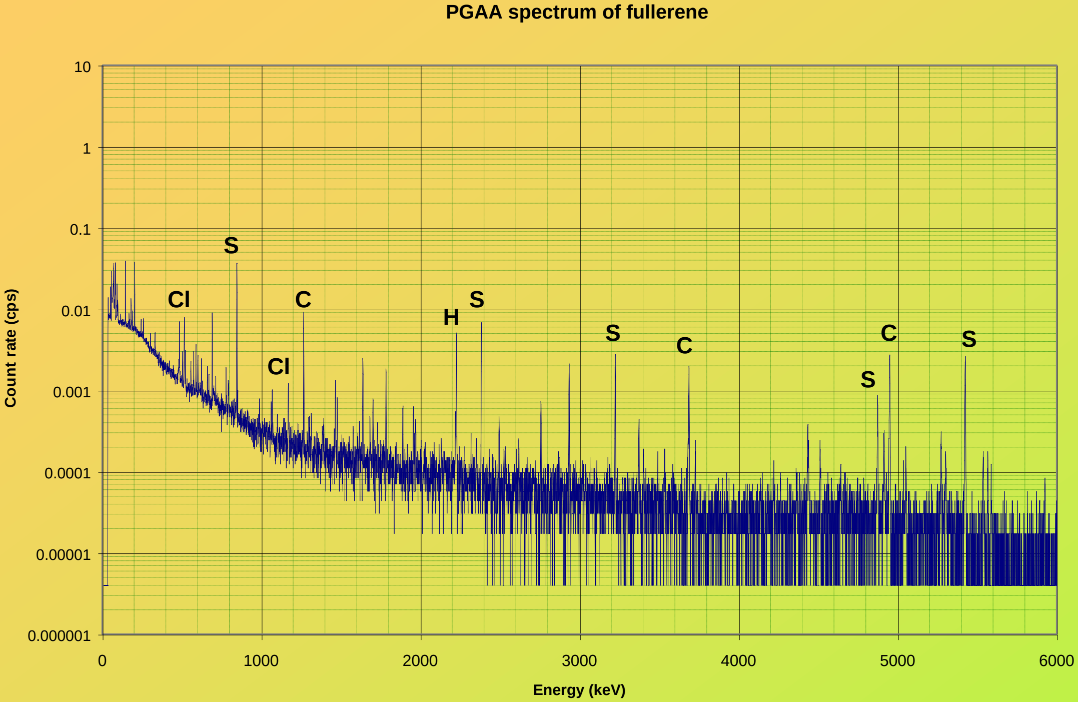


Zs. Kasztovszky, E. Panczik

10. SULFUR IN FULLERENE

(Dept. of Inorganic Chemistry, Eötvös University)





Element	Concentration (%)	Rel. unc (%)	Composition
H	0.012	10	0.08
C	97.1	4.5	60
S	2.88	1.3	0.67
Cl	0.003	20	0.0006

- Sulfur and other impurities were determined with PGAA
- C is an ideal matrix
- S attributed to $C_{60}S_{16}$ (clathrate) during the purification process

Zs. R., T. Braun