

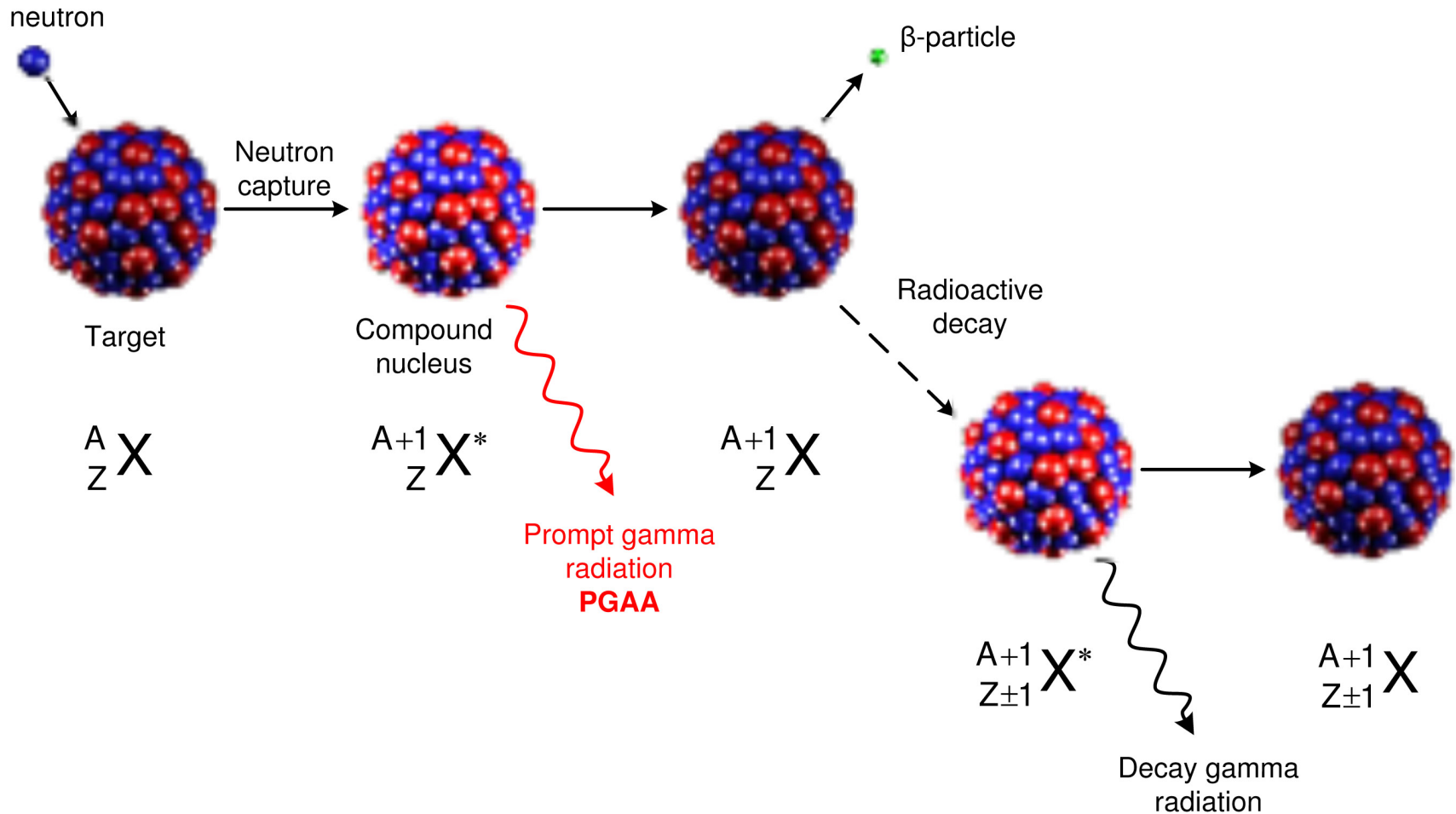


Wir schaffen Wissen – heute für morgen

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R. Dressler, D. Schumann, M. Ayrarov, A. Türler

**Plan to measure the neutron capture cross section of ^{60}Fe
with cold neutrons at the PGAA facility at FRM II in Munich**



$$E_{\gamma, cascade} = E_{kin, n} + E_{bind, n} + E_{recoil}$$

Discovery of neutron 1932

First detection of prompt gamma radiation in 1934 in Hydrogen

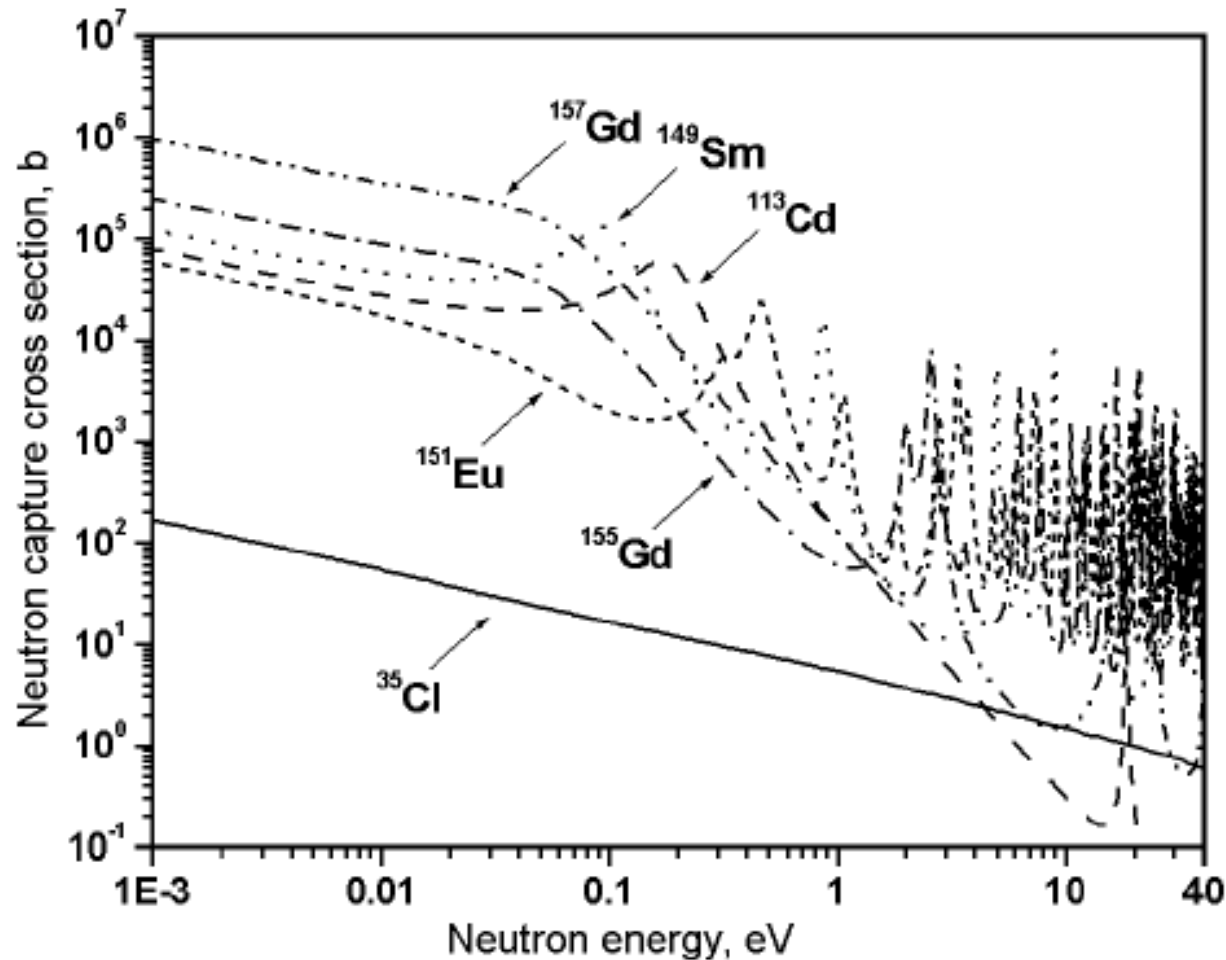
First PGAA results with thermal neutrons at MTAA-3 from
Saclay center for nuclear research in 1968

Few experiments till 1990 at ILL, Kyoto University, Jülich

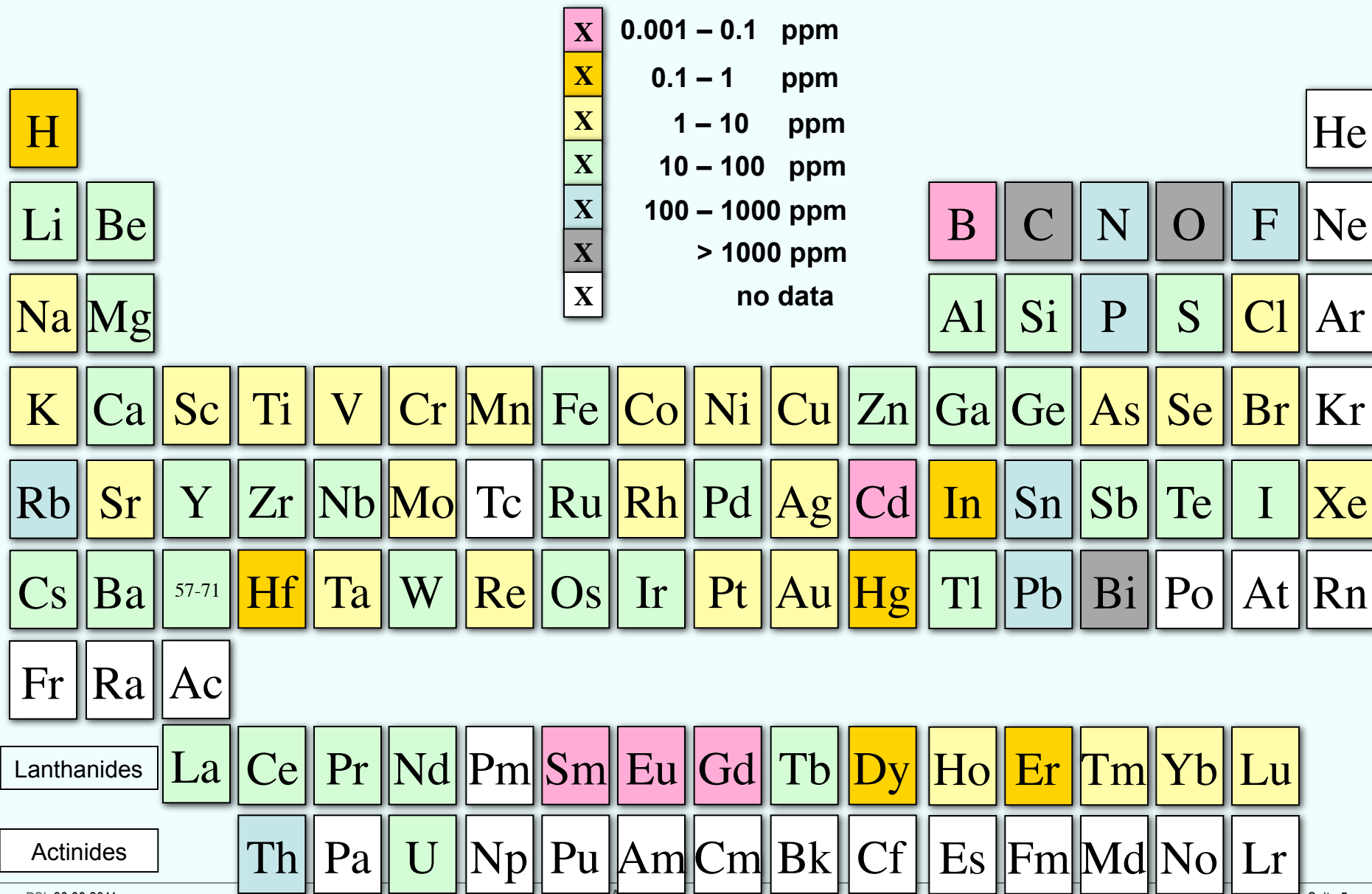
When neutron guides became available in 90s more experiments

PGAA at PSI from October 1997 till January 2002 ($10^8 \text{ n s}^{-1} \text{ cm}^{-2}$ (cold))

In Munich, first experiments in 2008 (up to $10^{10} \text{ n s}^{-1} \text{ cm}^{-2}$ (cold))



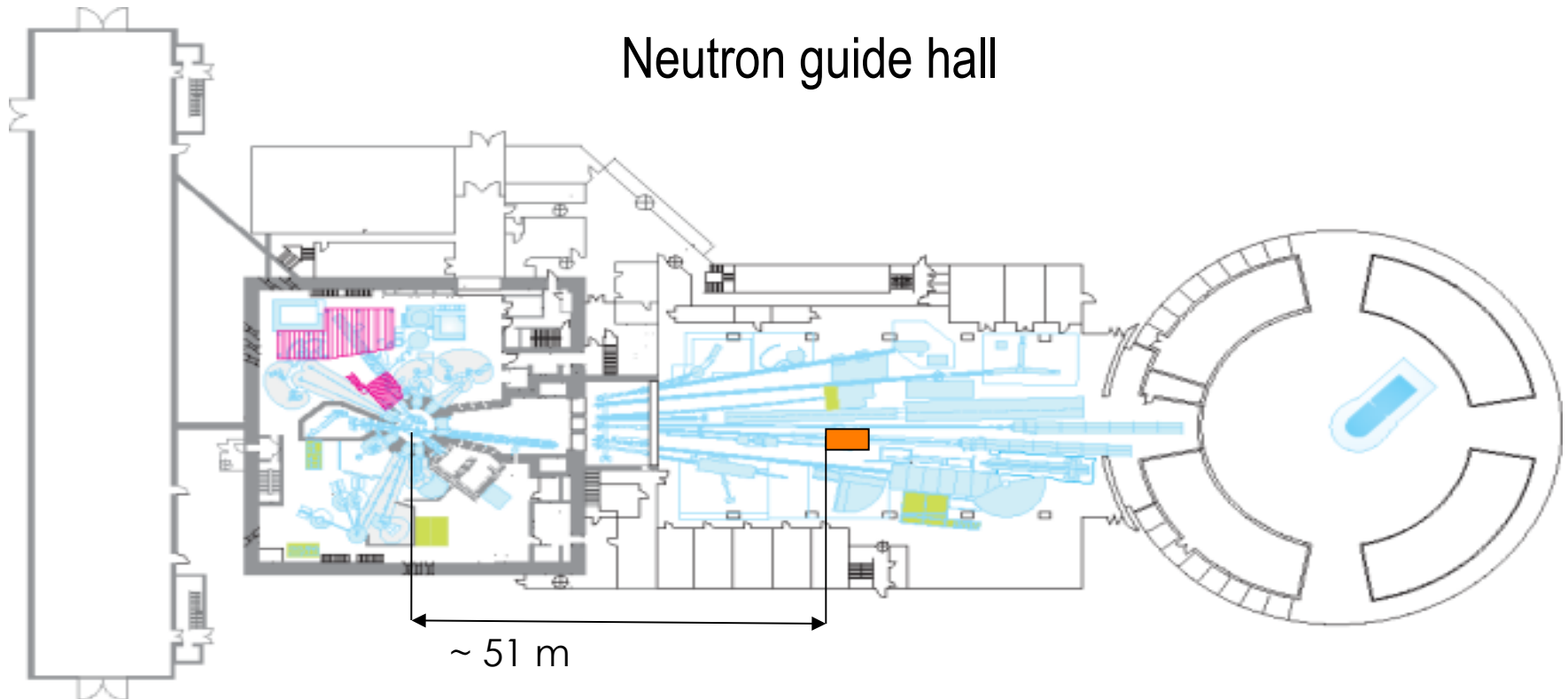
Taken from: S. BYUN, G. SUN, and H. CHOI, "Development of a prompt gamma activation analysis facility using diffracted polychromatic neutron beam," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 487, no. 3, pp. 521–529, Jul. 2002.





www.frm2.tum.de

Neutron guide hall



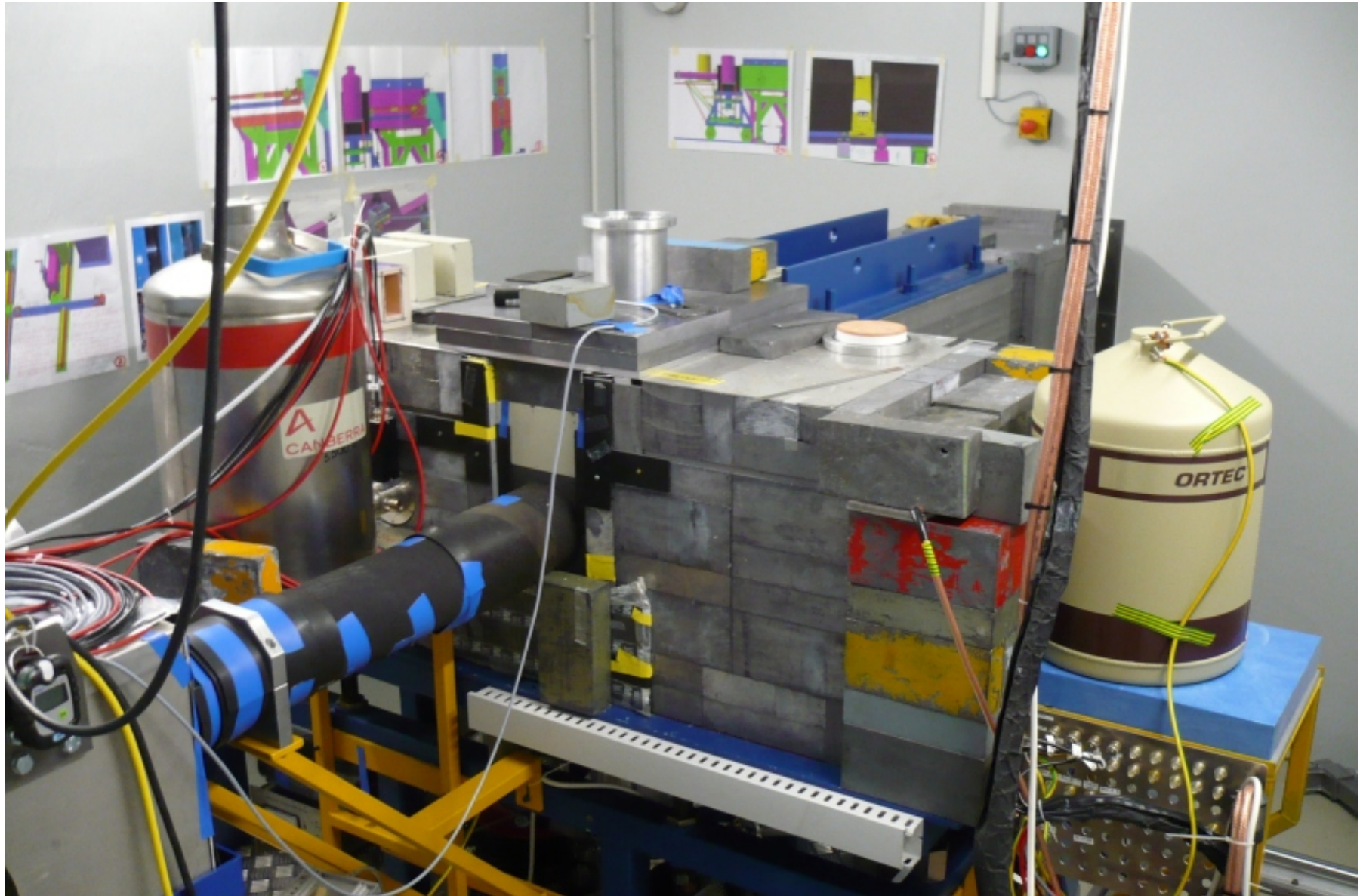
Elliptical neutron guide

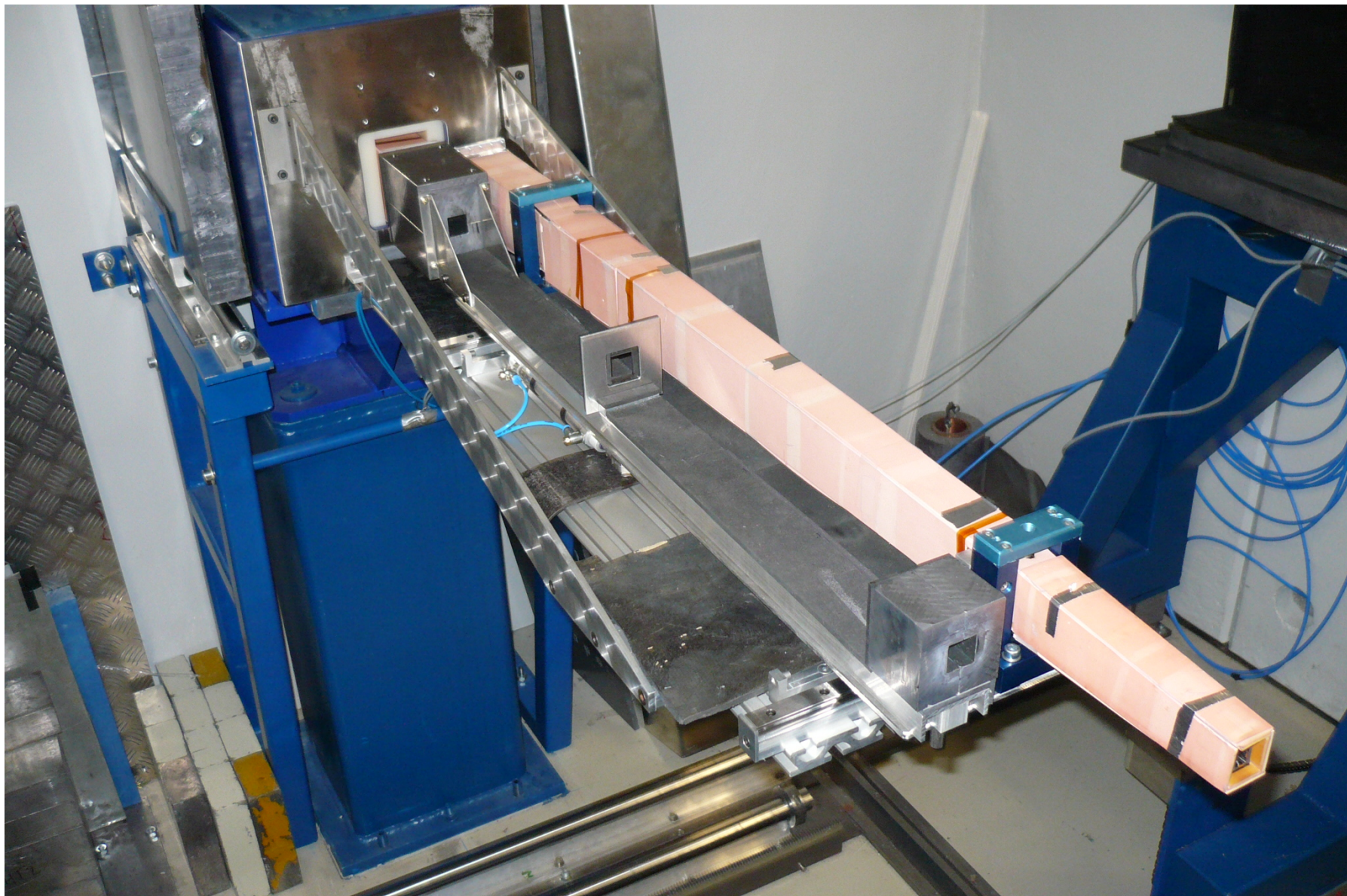


(optional) elliptical “Nose,,

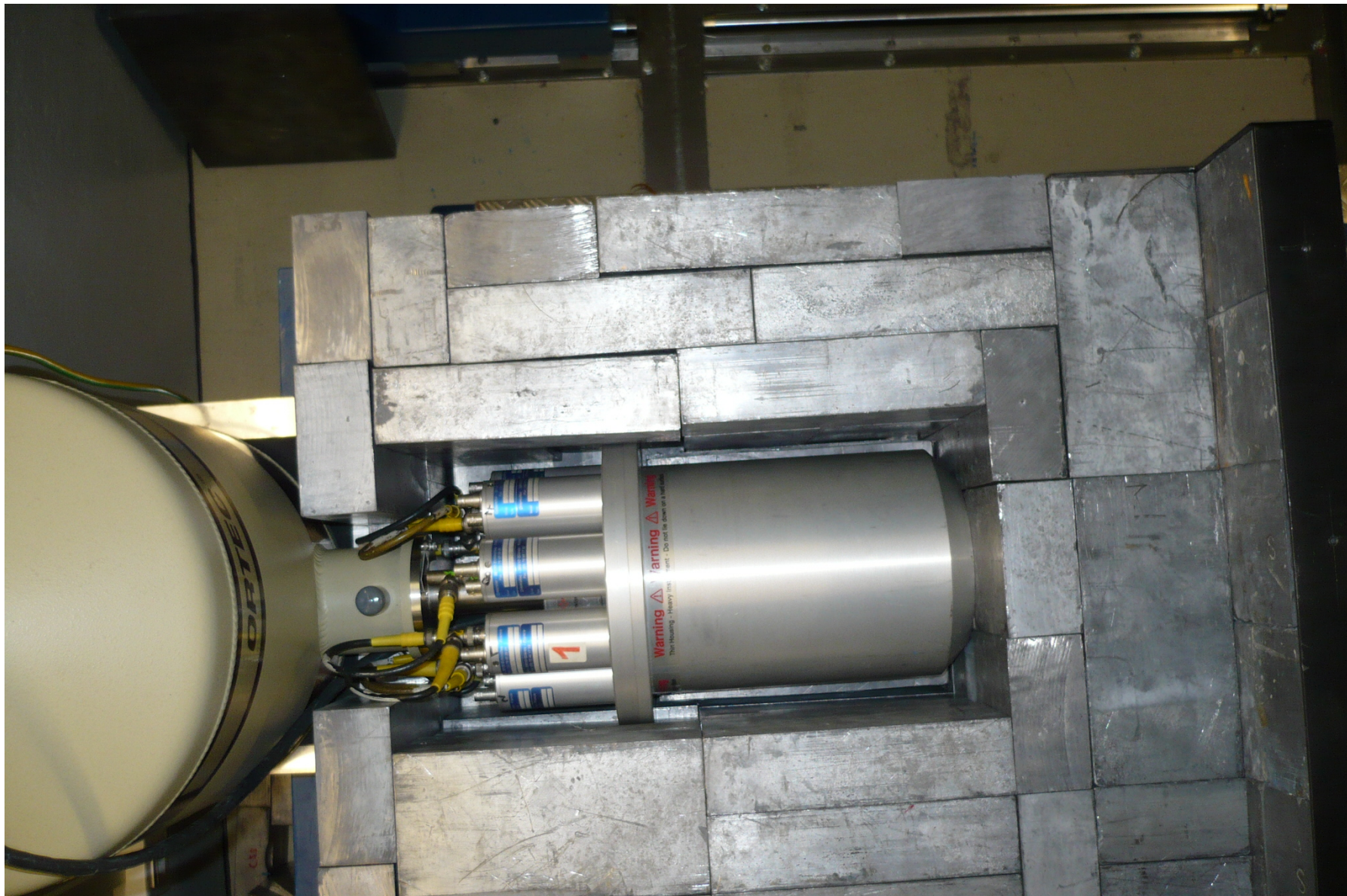


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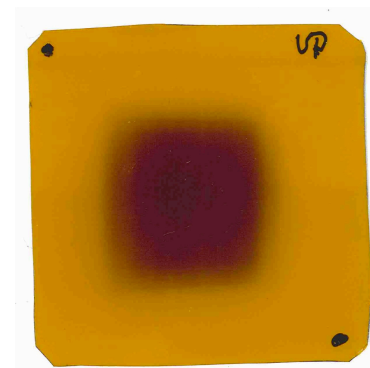






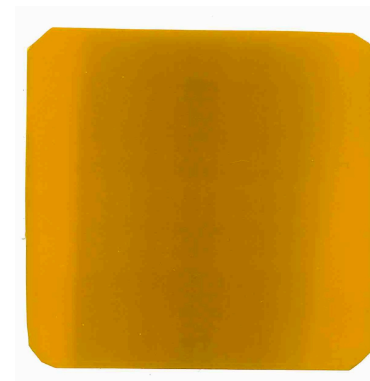
With elliptical focused Beam:

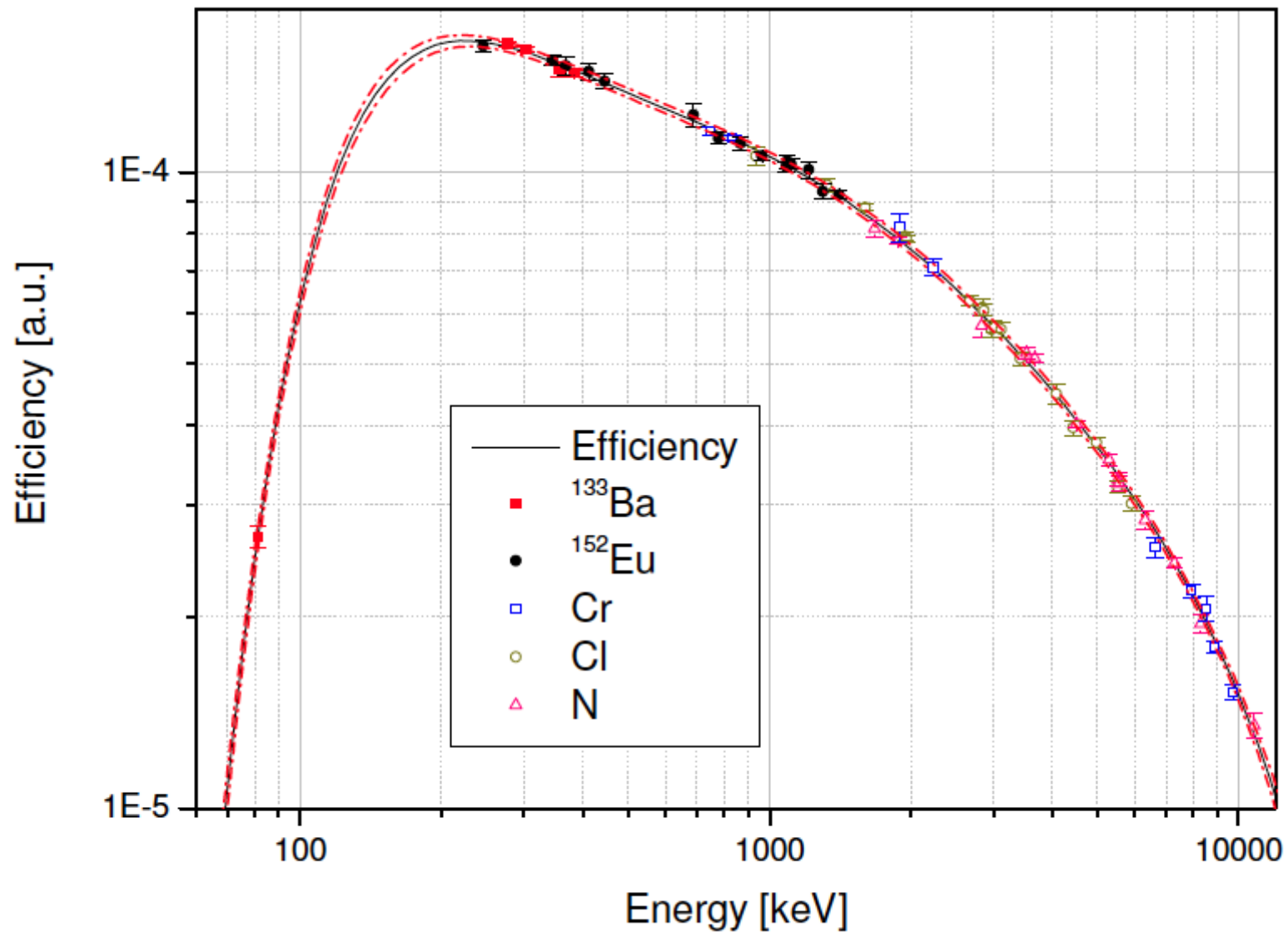
- $1.64 \times 10^{10} \text{ n cm}^{-2} \text{ s}^{-1}$ (cold $E=1.83 \text{ meV}$)
- $6.06 \times 10^{10} \text{ n cm}^{-2} \text{ s}^{-1}$ (thermal equivalent)
- Beam Field: 25 mm x 25 mm



With “normal” Beam:

- $6.54 \times 10^9 \text{ n cm}^{-2} \text{ s}^{-1}$ (cold $E=1.83 \text{ meV}$)
- $2.42 \times 10^{10} \text{ n cm}^{-2} \text{ s}^{-1}$ (thermal equivalent)
- Beam Field: 34 mm x 50 mm





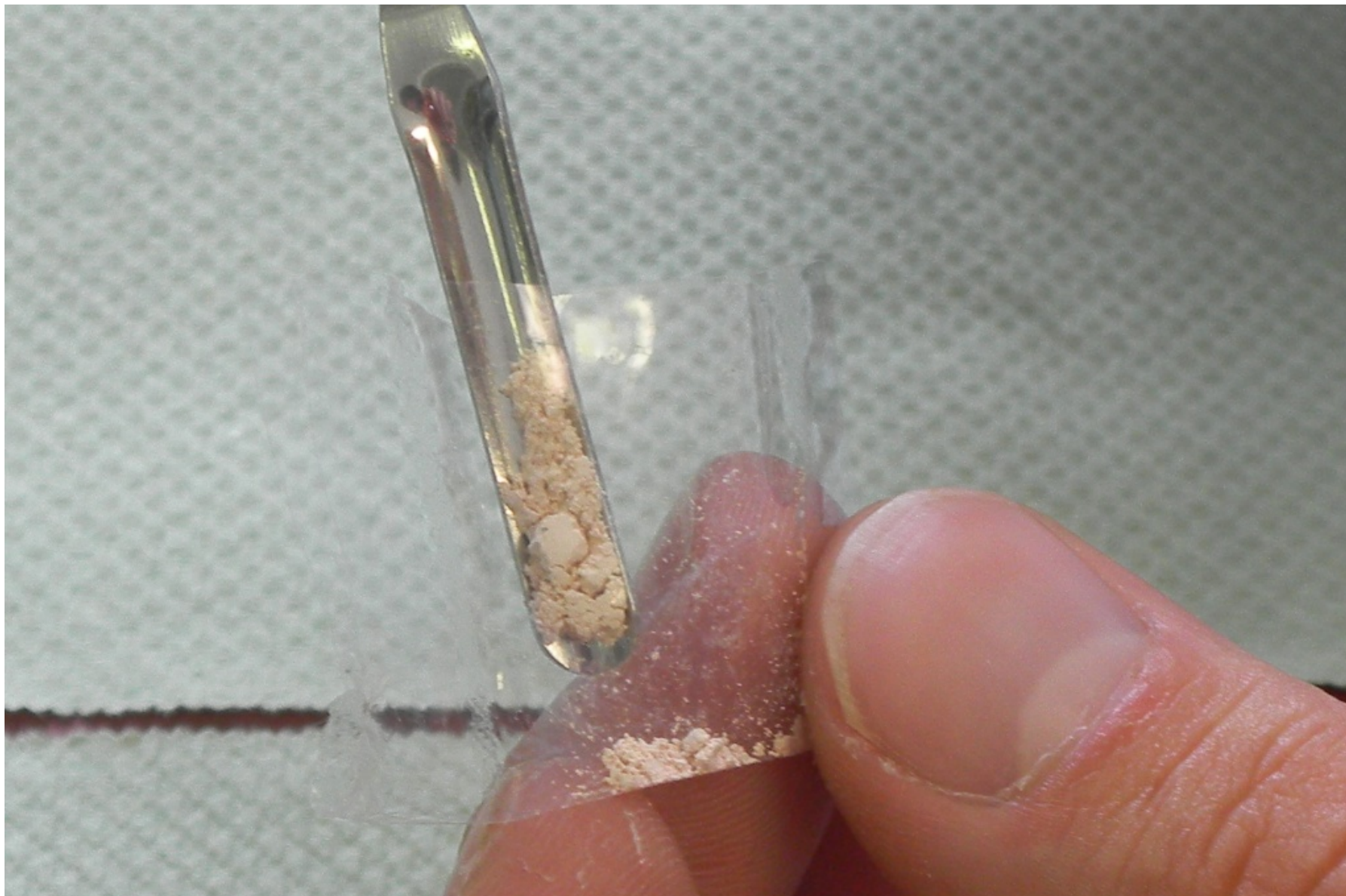
- Measurements can be performed “online”
- Samples can be activated and the activation can be measured
- Measurements in Air and Vacuum (approx. 1mbar)
- Almost any sample shape and condition possible
- Due to low neutron temperature usually no resonances





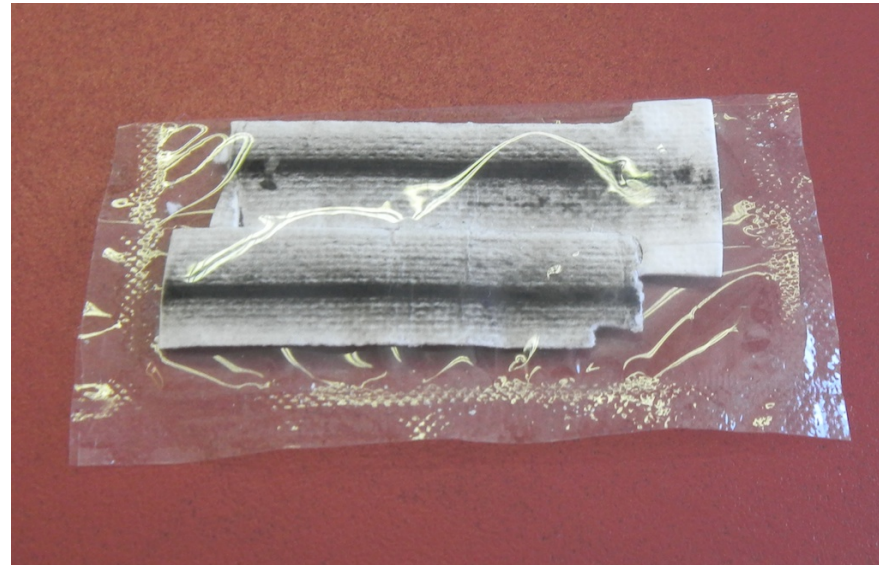


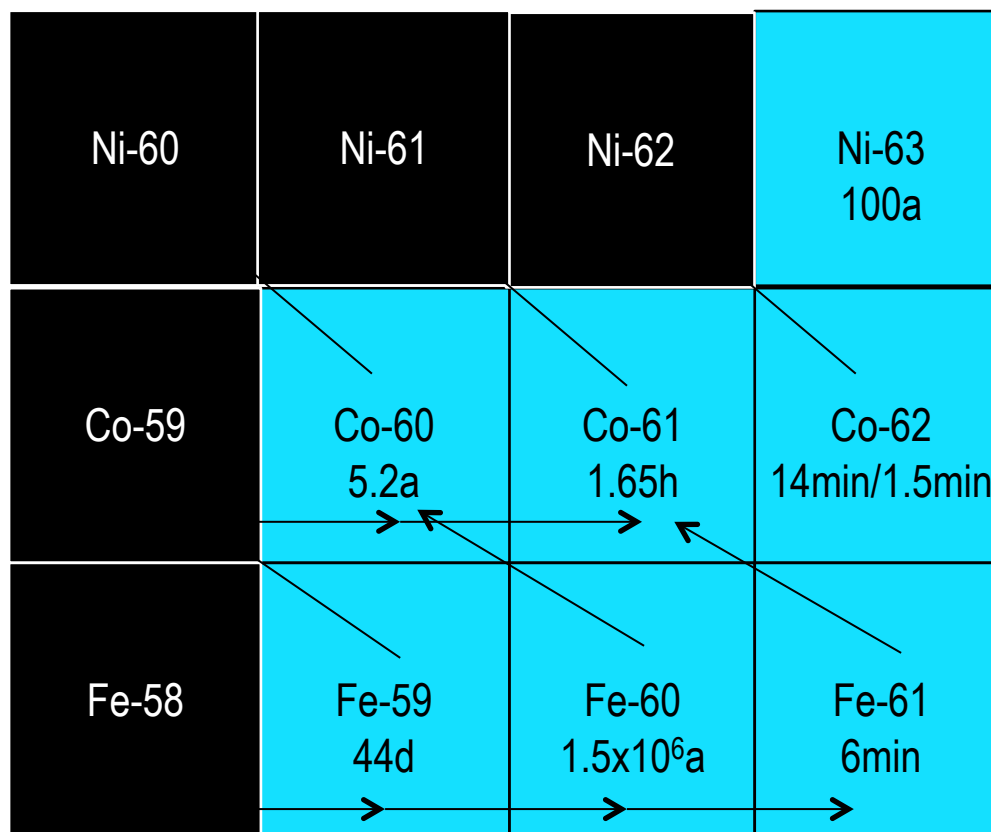






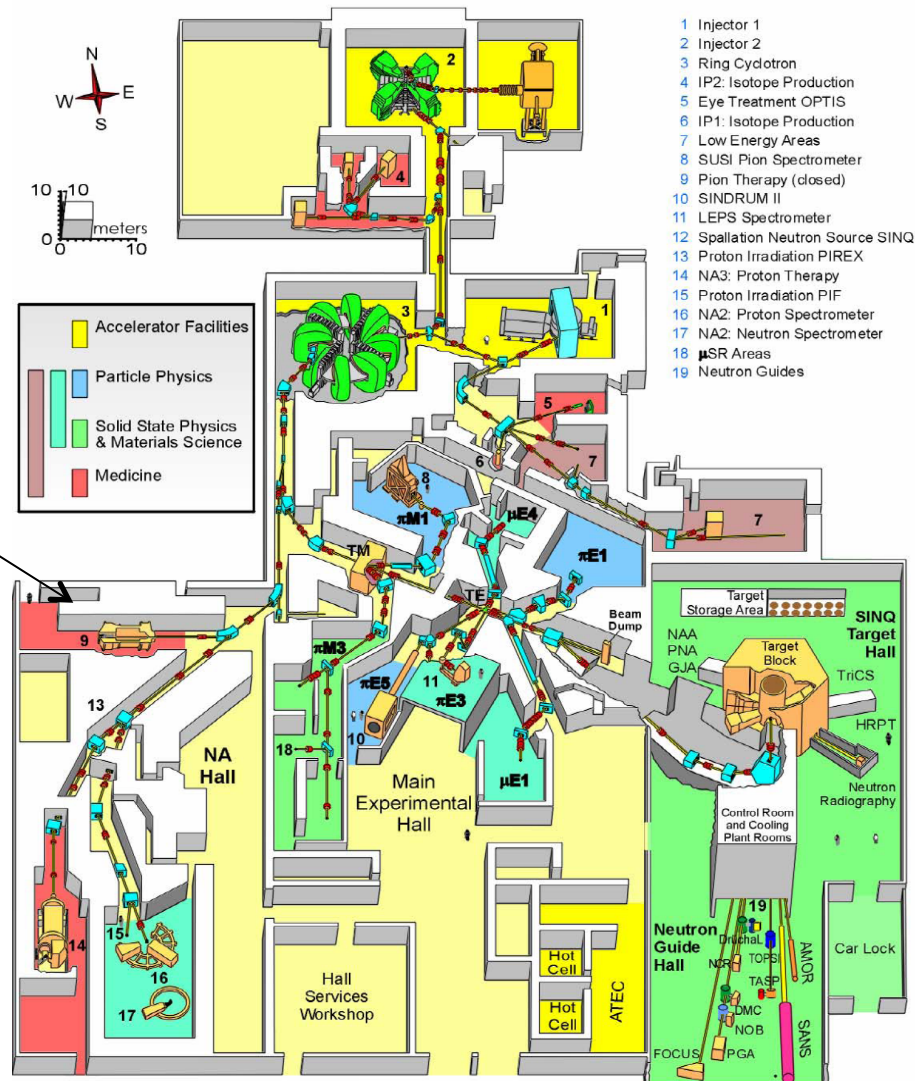




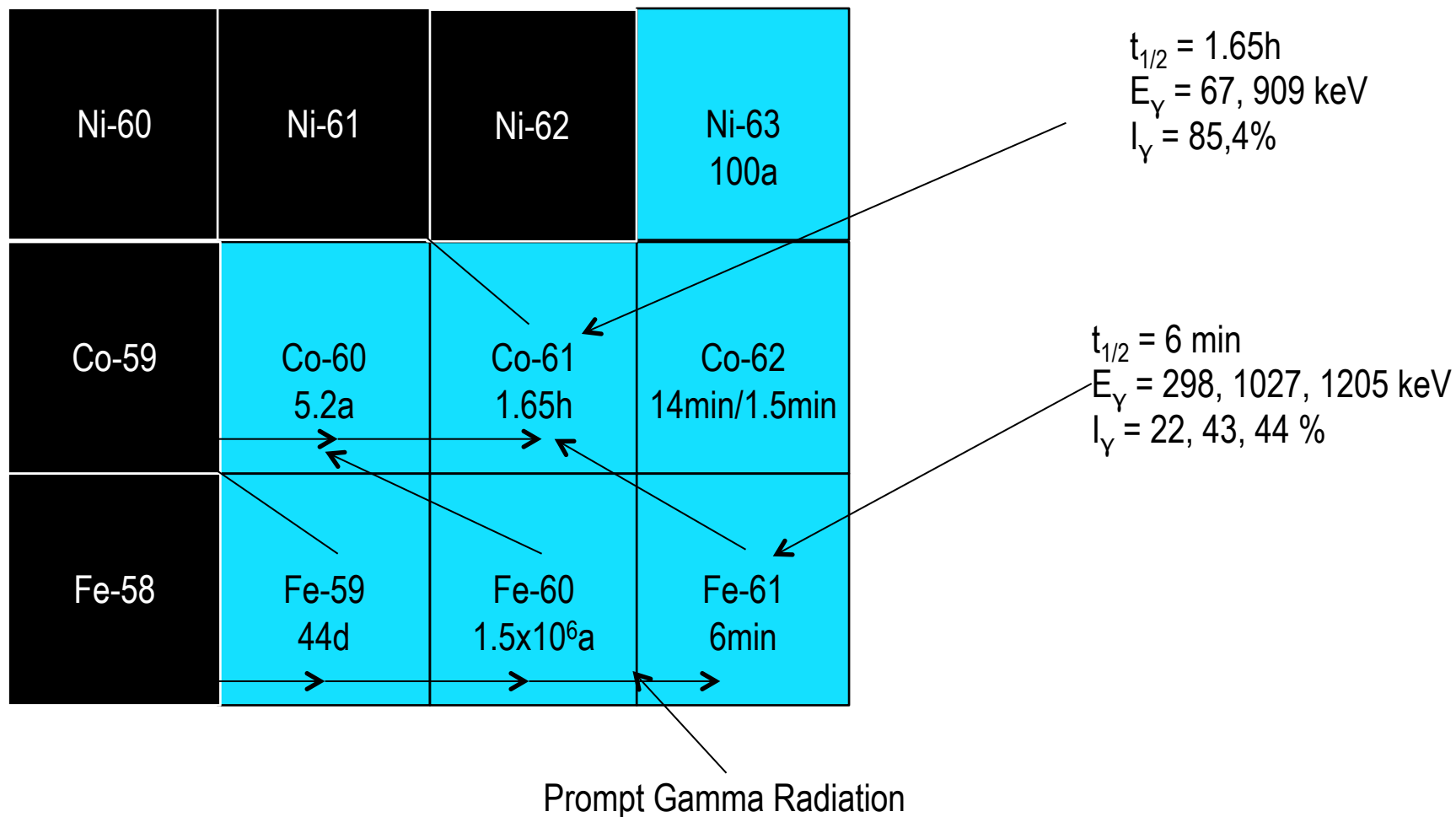


D. Schumann et al., “Preparation of a ^{60}Fe target for nuclear astrophysics experiments,” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 613, no. 3, pp. 347–350, Feb. 2010.

^{60}Fe – Where does it come from?



D. Schumann et al., “Preparation of a ^{60}Fe target for nuclear astrophysics experiments,” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 613, no. 3, pp. 347–350, Feb. 2010.



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N_γ	= No. of γ - photons
n	= number of atoms
σ_γ	= partial γ -ray production cross section
Φ	= Thermal equ. n-flux
A_γ	= Net peak area
$\epsilon(E_\gamma)$	= Efficiency at E_γ
t	= Measurement time

$$N_\gamma = n \sigma_\gamma \Phi$$

$$N_\gamma = \frac{A_\gamma}{\epsilon(E_\gamma) t}$$

Zs Révay and G. L. Molnar, “Standardisation of the prompt gamma activation analysis method,” Radiochimica Acta, vol. 91, no. 6, pp. 361–369, 2003.

σ_γ = partial γ -ray production cross section

σ_0 = isotopic, th. capture cross section

I_γ = Emission probability

θ = Isotopic abundance

N_γ = No. of γ - photons

n = No. of atoms

Φ = Thermal eq. n-flux

A_γ = Net peak area

$\epsilon(E_\gamma)$ = Efficiency at E_γ

t = Measurement time

$$\sigma_\gamma = \theta \sigma_0 I_\gamma$$

$$\sigma_\gamma = \frac{N_\gamma}{n\Phi}$$

$$\sigma_\gamma = \frac{A_\gamma}{\epsilon(E_\gamma) t n \Phi}$$

With the use of a comparator:

- The sample should be a stoichiometric compound
- The mass or number of atoms within the sample should be known
- Good as comparator are isotopes with a well known cross section
e.g: H, Cl, N

$$\frac{\sigma_{\gamma,s}}{\sigma_{\gamma,c}} = \frac{n_s}{n_c} \frac{\frac{A_{\gamma,s}}{\epsilon(E_{\gamma,s})}}{\frac{A_{\gamma,c}}{\epsilon(E_{\gamma,c})}} = \frac{n_s A_{\gamma,s} \epsilon(E_{\gamma,c})}{n_c A_{\gamma,c} \epsilon(E_{\gamma,s})}$$

- Irradiated with 25keV neutrons in Karlsruhe [1]
Because of short half-life 47 repeated irradiations in Karlsruhe
=> Presentation about results on Thursday and Friday
- Another experiment with thermal neutrons is performed in Vienna

[1] E. Überseder, R. Reifarh, D. Schumann, I. Dillmann, C. D. Pardo, others, “Measurement of the Fe-60 (n, gamma) Fe-61 Cross Section at Stellar Temperatures,” Physical Review Letters, vol. 102, p. 151101, 2009.

Purification and conversion to FeCl_3 or $\text{Fe}(\text{NO}_3)_3$?

Sample packed in a Teflon bag:

Sample on Graphite backing as mentioned in paper [1, 2]

Alternative sample preparation e.g. small paper sheet (tissue)

Sample should not contain elements of the background in its compound
(H, B, Na, F, Al, Si, Pb)

Ideal sample contains as less of the decay products (Co, Ni) as possible, as well as other Fe isotopes

Well known isotopic composition

[1] E. Uberseder, R. Reifarh, D. Schumann, I. Dillmann, C. D. Pardo, others, "Measurement of the Fe-60 (n, gamma) Fe-61 Cross Section at Stellar Temperatures," Physical Review Letters, vol. 102, p. 151101, 2009.

[2] D. Schumann et al., "Preparation of a ^{60}Fe target for nuclear astrophysics experiments," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 613, no. 3, pp. 347–350, Feb. 2010.

Direct flux monitor of irradiation: Cl

=> Dead time problem in PGAA beam due to high count rate

Absolute flux monitor: Au

=> Decay measurement (solves dead time problem)

All Fe atoms assumed as FeCl_3

$$\begin{array}{l} \rightarrow n, \sigma_\gamma \rightarrow \Phi \\ \rightarrow \sigma_\gamma = \Theta \sigma_0 I_\gamma \end{array}$$

For natural abundance of Fe:

$$\Theta_{54,n} + \Theta_{56,n} + \Theta_{57,n} + \Theta_{58,n} = 1$$

Assumption that

$$\Theta_{54,s} + \Theta_{55,s} + \Theta_{56,s} + \Theta_{57,s} + \Theta_{58,s} + \Theta_{60,s} = 1$$

And the radioactive nuclei can be estimated by their daughter products

=> Thus the isotopic ratio of stable isotopes may be calculated from known prompt gamma lines according to

$$\frac{\sigma_{\gamma 54,r}}{\sigma_{\gamma 54,n}} = \frac{\Theta_{54,r}}{\Theta_{54,n}}$$

Measured neutron capture cross section for stellar neutrons at 25keV
5.84 mbarn [1] with new half life 2.62Myr [2]

For neutron capture cross section at 1.83 meV IF $1/v$ law holds

$$\sigma_{\gamma,1.8\text{meV}} = \frac{\sigma_{\gamma,25\text{keV}} \sqrt{25\text{keV}}}{\sqrt{1.8\text{meV}}}$$

$$\sigma_{\gamma,1.8\text{meV}} \approx 21.6\text{barn}$$

[1] E. Uberseder, R. Reifarth, D. Schumann, I. Dillmann, C. D. Pardo, others, "Measurement of the Fe-60 (n, gamma) Fe-61 Cross Section at Stellar Temperatures," Physical Review Letters, vol. 102, p. 151101, 2009.

[2] G. Rugel et al., "New Measurement of the Fe60 Half-Life," Physical Review Letters, vol. 103, no. 7, p. 72502, Aug. 2009.

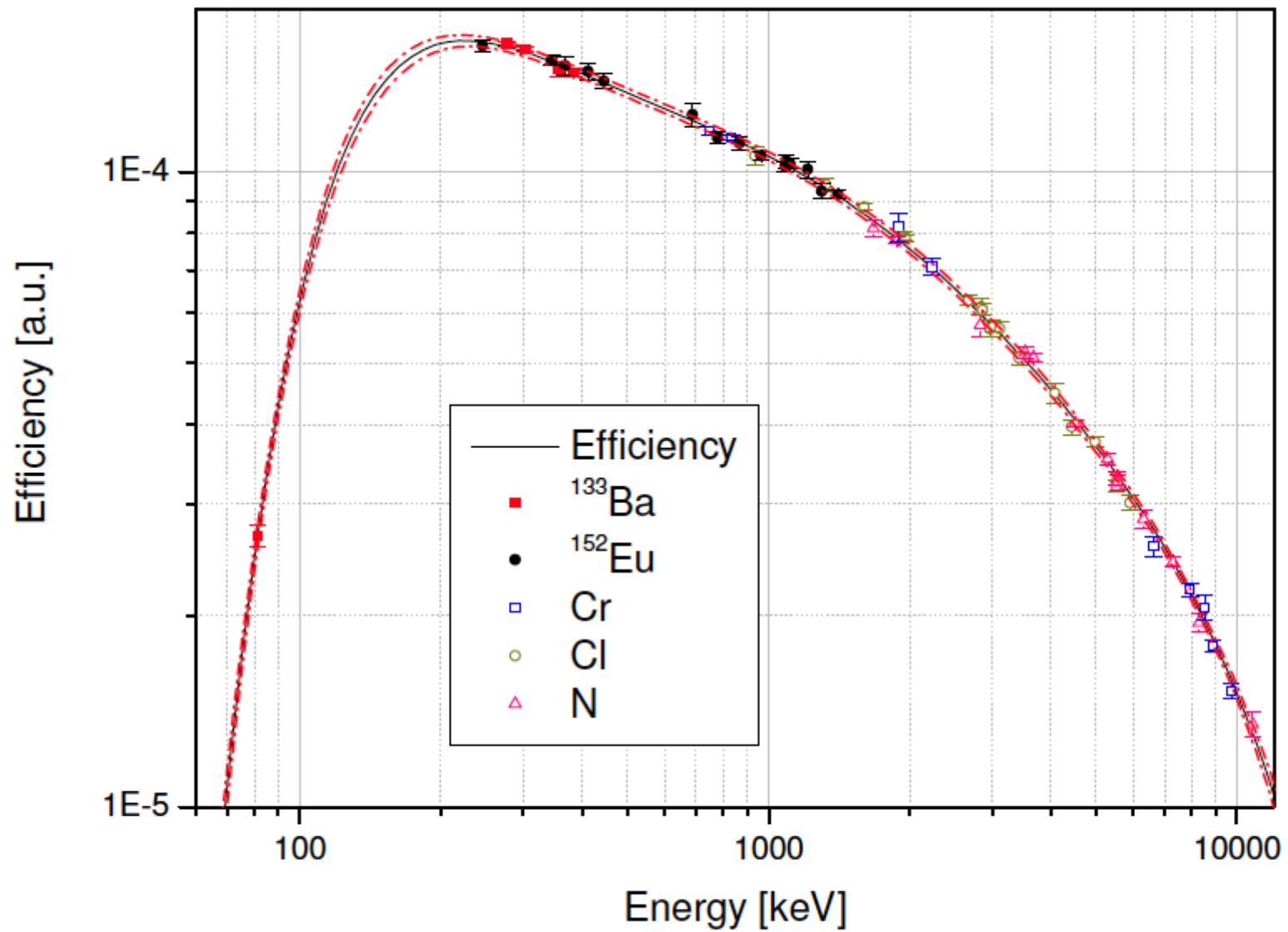
^{61}Fe Energies from decay reaction $^{64}\text{Ni}(n,\alpha)^{61}\text{Fe}$:
Range from 120 keV to 3300 keV [1]

^{61}Fe Energies from $^{61}\text{Mn} \xrightarrow{\beta^-} ^{61}\text{Fe}$ reaction
Range from 200keV to 2200 keV[2]

BUT: For neutron capture reaction even higher energies of excitation
=> Emission probabilities vary from listed values
=> They exist for stable Fe-Isotopes

[1] J. Bron and H. Jongsma, "Phys. Rev. C 11, 966 (1975): Decay of ^{61}Fe to levels in ^{61}Co ," Physical Review C, 1975.

[2] M. Bhat, "ScienceDirect - Nuclear Data Sheets : Nuclear Data Sheets for A = 61*1," Nuclear Data Sheets, 1999.



Count rate equation for a ideally thin sample with a monochromatic, parallel, neutron beam for ^{60}Fe

$$\frac{A_\gamma}{\epsilon(E_\gamma)t} = n\sigma_\gamma\Phi$$

with

$$n = 8 \times 10^{15} \text{ atoms}$$

$$\sigma_\gamma = 21.6 \text{ barn}$$

$$\Phi = 6 \times 10^{10} \text{ n cm}^{-2} \text{ s}^{-1}$$

$$\epsilon \approx 10^{-4} \text{ at approx. 1 MeV}$$

$$\frac{A_\gamma}{\epsilon(E_\gamma)t} \approx 20 \text{ kBq}$$

$$\frac{A_\gamma}{t} \approx 2 \text{ cps}$$

The highest cold neutron flux currently available world wide

- up to $1.64 \times 10^{10} \text{ n cm}^{-2} \text{ s}^{-1}$
- At an energy of 1.83 meV

A Compton suppressed gamma spectroscopy setup

In-beam gamma spectroscopy with different neutron fluxes

An experiment like:

Irradiation for 36 minutes ($6 \times t_{1/2}$ of ^{61}Fe) and decay measurements

How accurate is the isotopic composition of the material?

How will our new background look like?

How was the measurement with thermal neutrons?

What have you experienced during your measurements so far?

What ideas/applications came into your mind during the presentation?

