Activation Experiments for Nuclear Astrophysics

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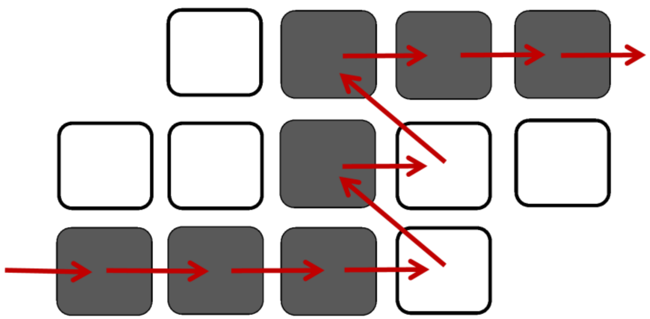
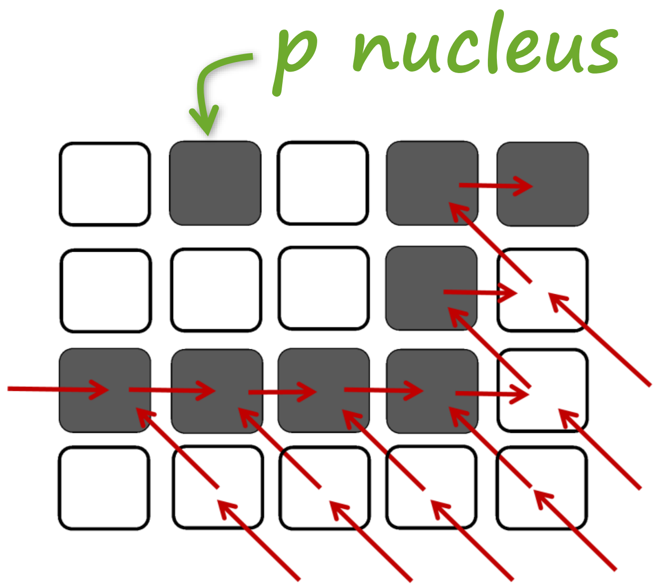
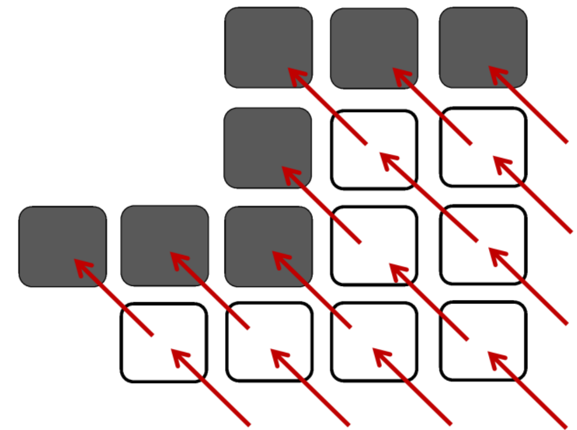
What is the γ process?

Nucleosynthesis beyond the iron peak region



s process

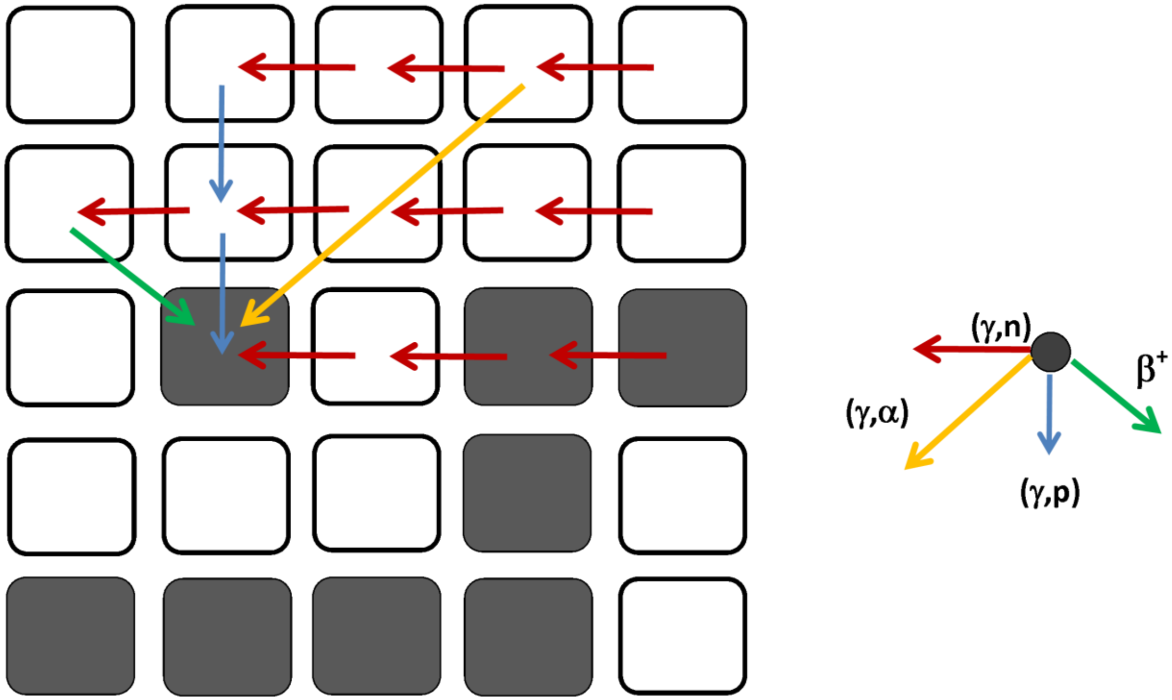




r process

Neutron deficient nuclei
bypassed by *s*- and *r*-process nucleosynthesis

What is the γ process?



- Photodisintegration reactions on s- and r-process seeds
- Huge network of reactions on many mainly unstable nuclei
- Theoretical calculations of reaction rates required

Theoretical Predictions of Cross Sections

- Network calculations rely almost completely on theoretical predictions (Hauser-Feshbach Statistical Model)
- Model is well understood
- Some uncertainties stem from nuclear physics input:
  - Nuclear-level densities
  - γ-strength functions
  - optical-model potentials

- Need for experimental data to improve our theoretical models!

Experimental Studies of Cross Sections

\# Produced Nuclei

$$\sigma = \frac{\text{number of interactions}}{\text{number of incident particles} \cdot \text{number of target nuclei}} = \frac{N_R}{N_P \cdot N_T}$$

Beam Current
Charge Collection

Rutherford
Backscattering
Spectrometry

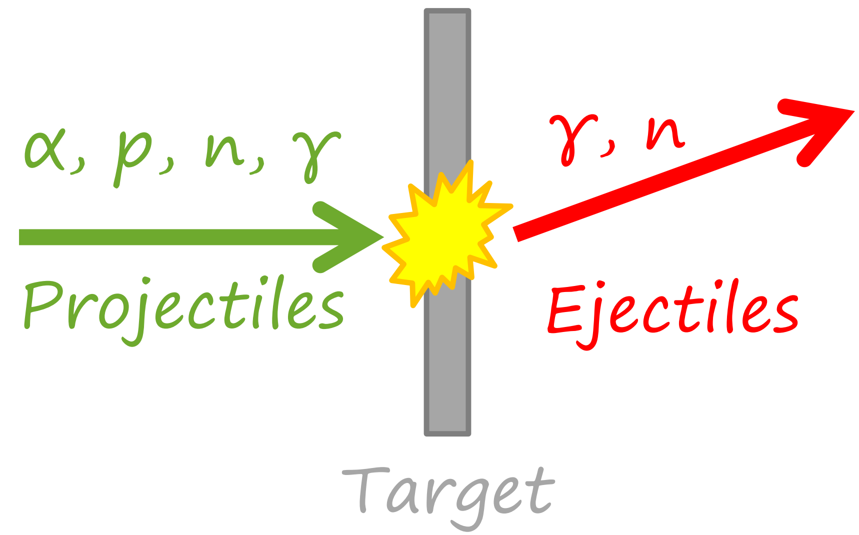
- In-Beam
  - γ-ray Spectroscopy
  - 4π-Summing
- Activation
  - γ-ray Spectroscopy
  - AMS

Thursday, 17:50
A. Spyrou: "p-process overview and status of experimental efforts"

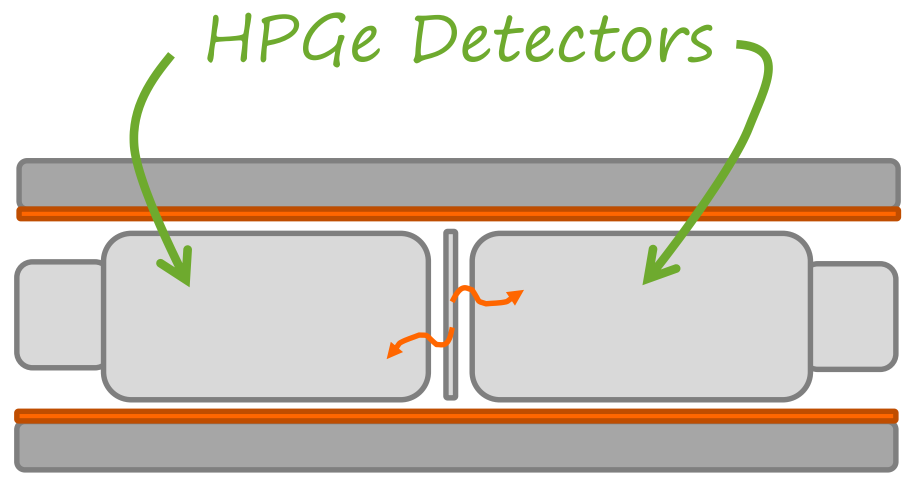
Thursday, 18:35
M. Baldenhofer: "Reaction studies for the astrophysical p-process using in-beam γ-ray spectroscopy"

Activation Method in a Nutshell

1. In-Beam Activation:



2. Off-Beam Counting:



Activation Method in a Nutshell

Separation of creation and detection:

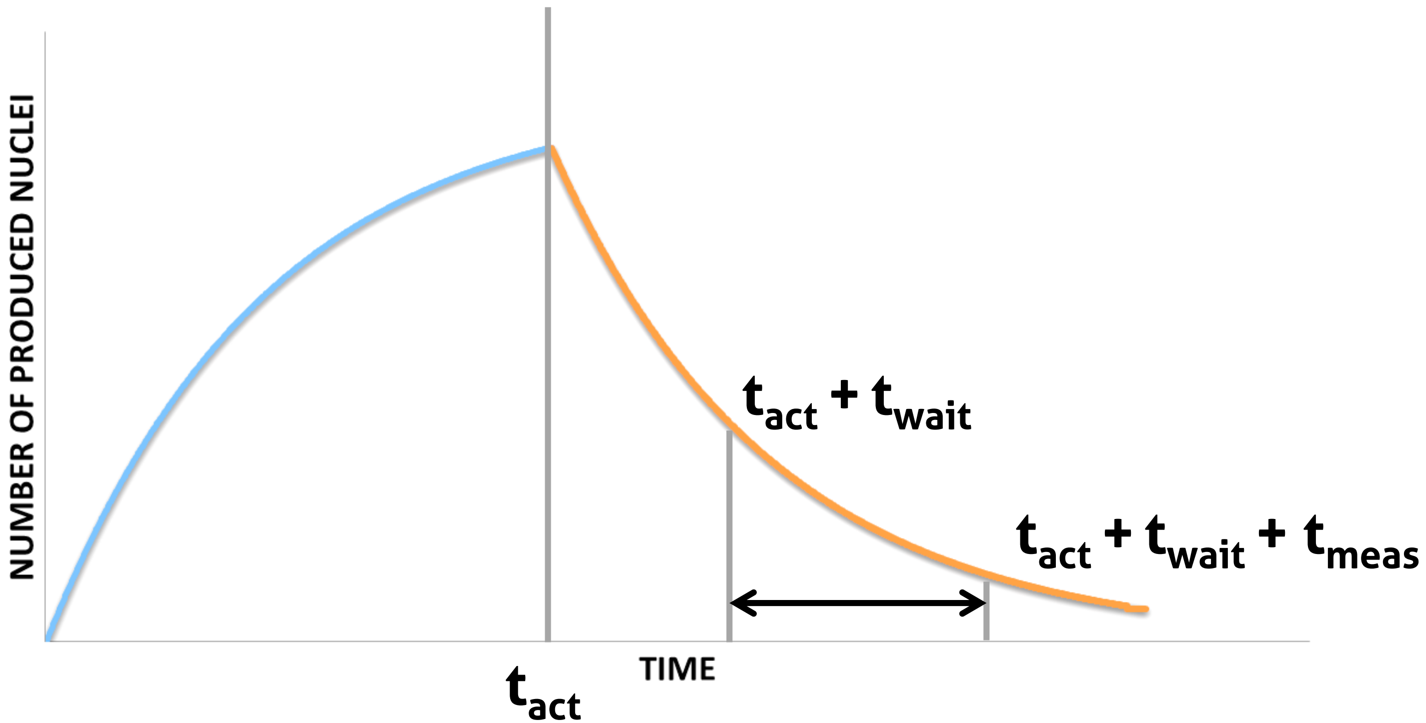
- \+ No direct beam-induced background
- \+ Beam current not limited by detection system
- \- Unstable reaction products required (γ-rays)
- \- Background from activated byproducts

- \+ Detection systems with high efficiency
- \+ Passive & active shielding
- \- Need for feasible half-lifes (not too short, not too long)
- \- No additional results (partial cross sections)

Activation Method in a Nutshell

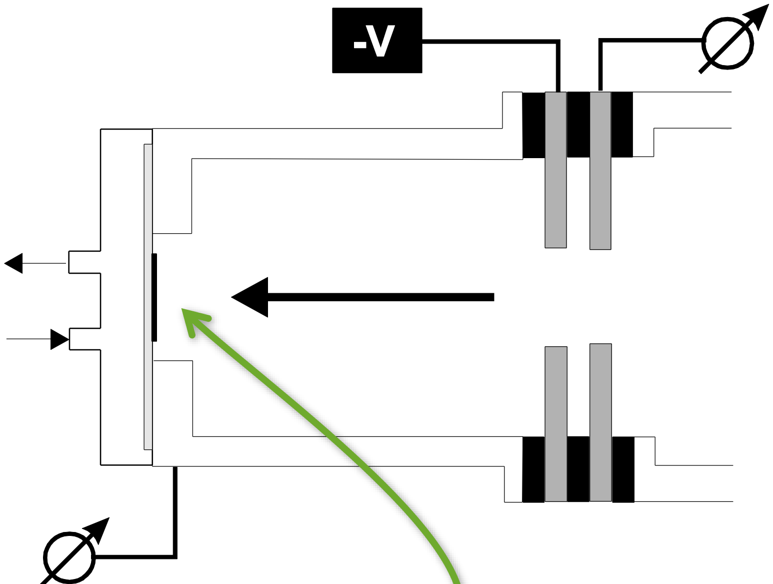
Counting numbers of emitted γ-rays for a certain time to reconstruct N_R

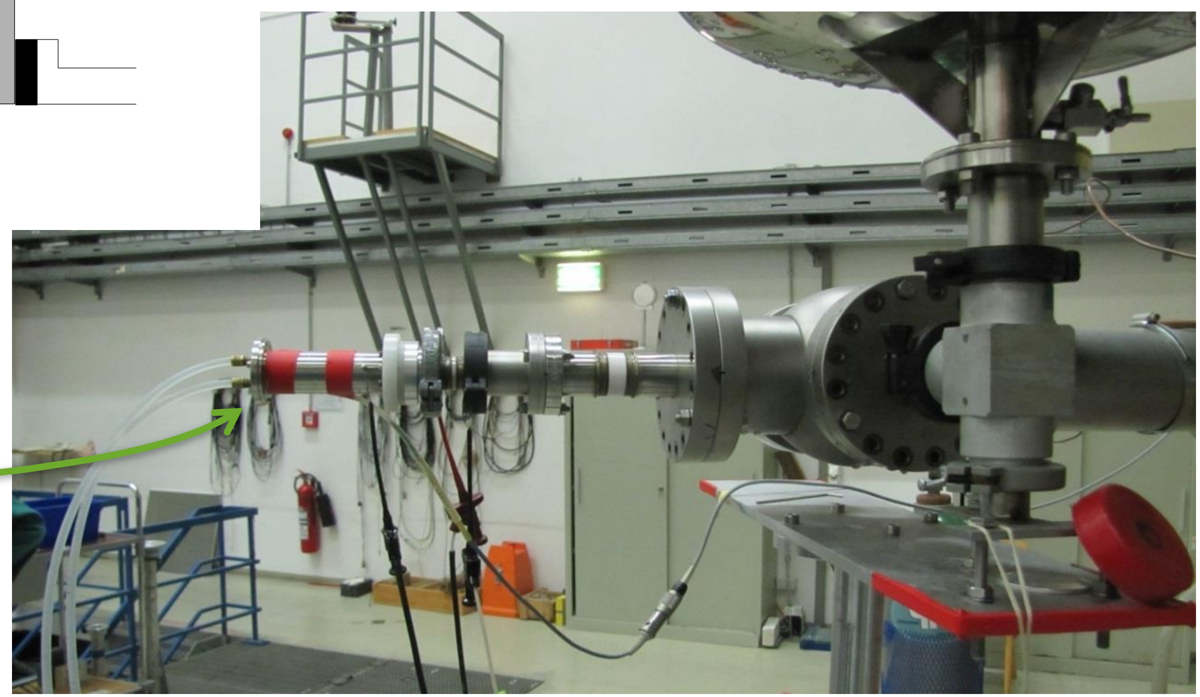
$$\sigma = \frac{N_R}{N_P \cdot N_T} = \frac{Y_\gamma}{I_\gamma \cdot \varepsilon_\gamma \cdot f_{\mathrm{act}} \cdot f_{\mathrm{wait}} \cdot f_{\mathrm{meas}} \cdot N_T \cdot N_P}$$



Activation @ PTB Braunschweig

- Cyclotron @ PTB Braunschweig
- µA α-beam currents
- water cooled target

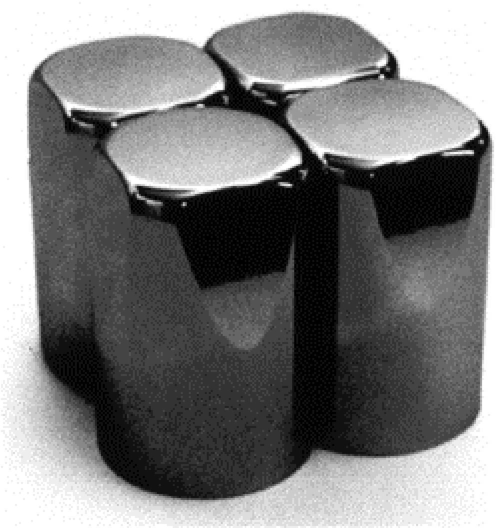




Target

Cologne Clover Counting Setup

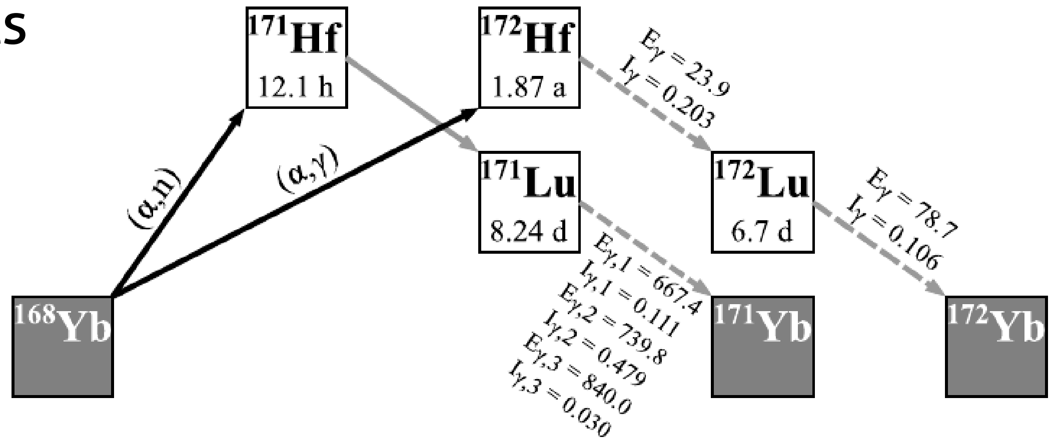
- Two HPGe clover detectors
- face-to-face geometry
  - ≈4π solid angle coverage
  - $\gamma\gamma$ coincidences
- ca. 8% full energy peak efficiency @ 1332 keV
- Shielding with lead and copper

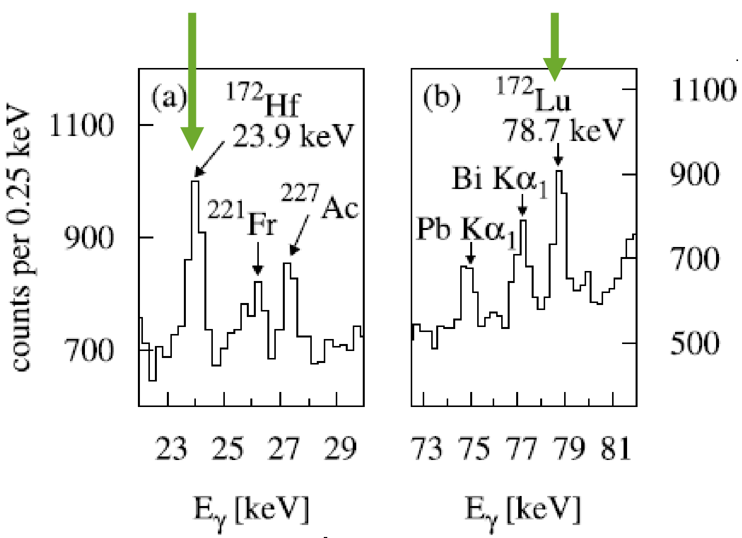


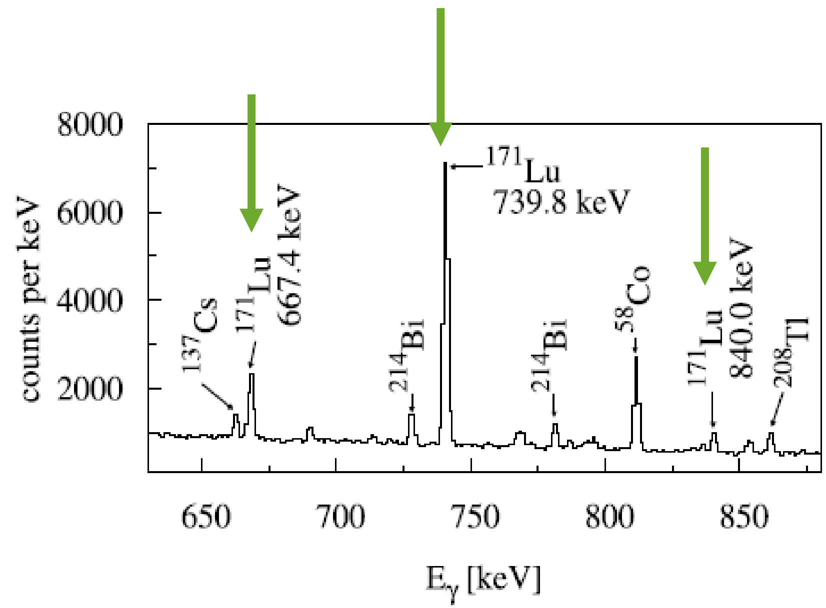
G. Duchêne *et al.*, Nucl. Instr. and Meth. A **432** 90 (1999)

^{168}Yb(α,γ) and ^{168}Yb(α,n)

- Six enriched Yb targets
- Eα = 12.9 - 15.1 MeV
- counting at the Cologne Clover Counting Setup & ATOMKI (Debrecen)

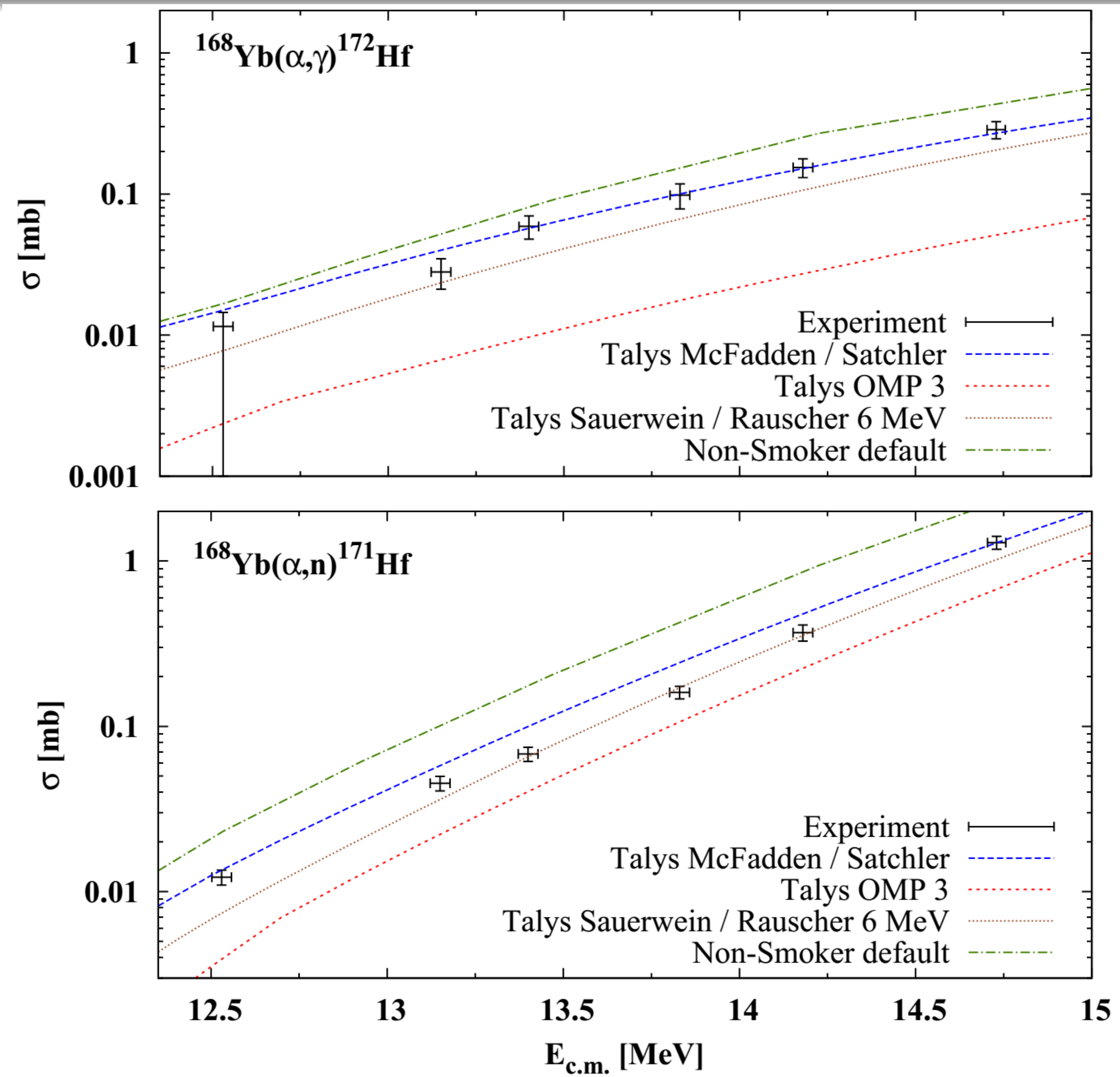






L. Netterdon *et al.*, Nuclear Physics A **916** 149-167 (2013)

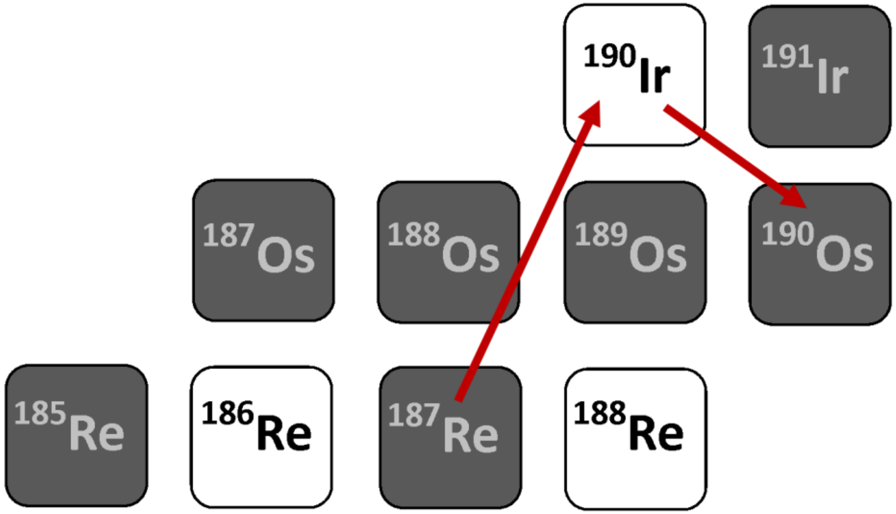
$^{168}Yb(\alpha,\gamma)$ and $^{168}Yb(\alpha,n)$

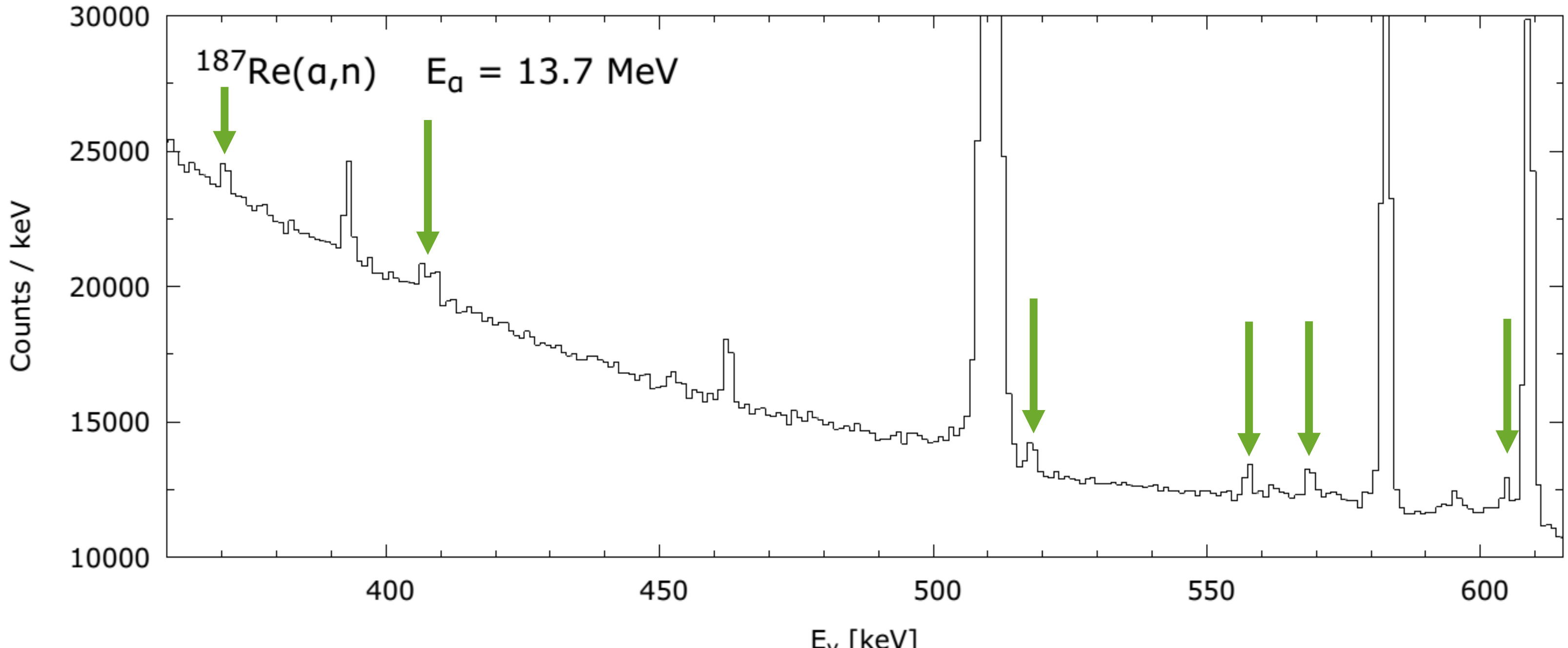


L. Netterdon *et al.*, Nuclear Physics A **916** 149-167 (2013)

$^{187}Re(\alpha,n)$

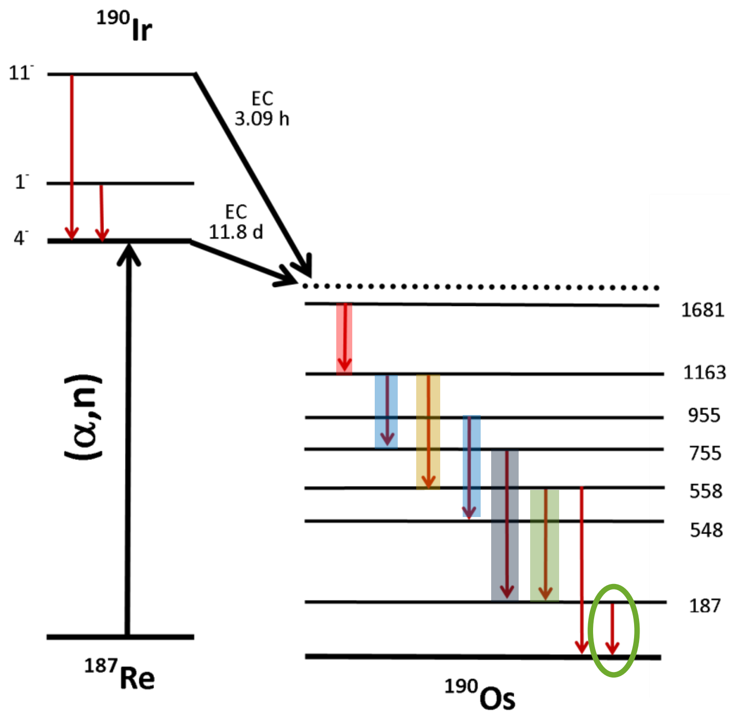
- Five natural rhenium targets
- E_α = 12.4 - 14.1 MeV
- Counting at the Cologne Clover Counting Setup

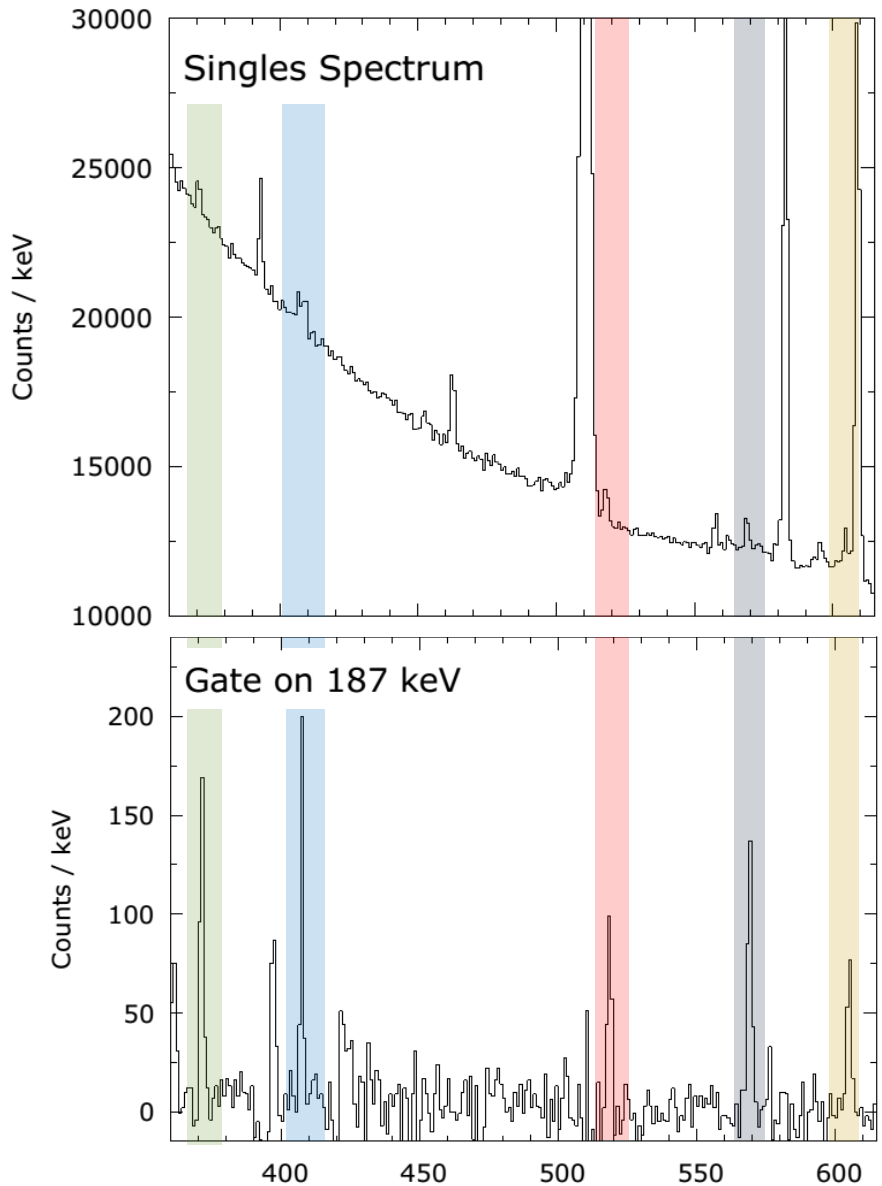




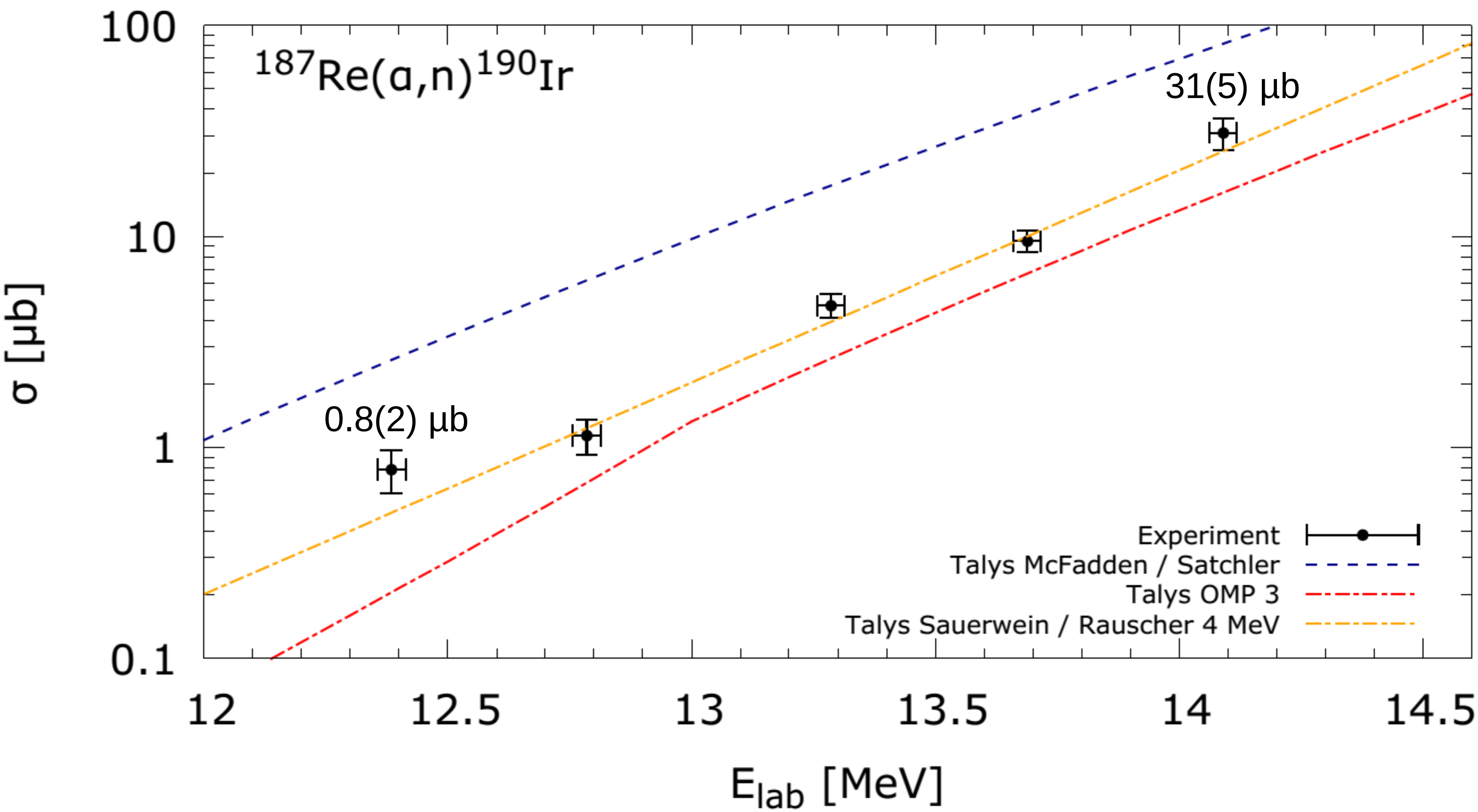
$^{187}Re(\alpha,n)$

- Using $\gamma\gamma$ coincidences to determine cross sections
- Improvement of peak-to-background ratio





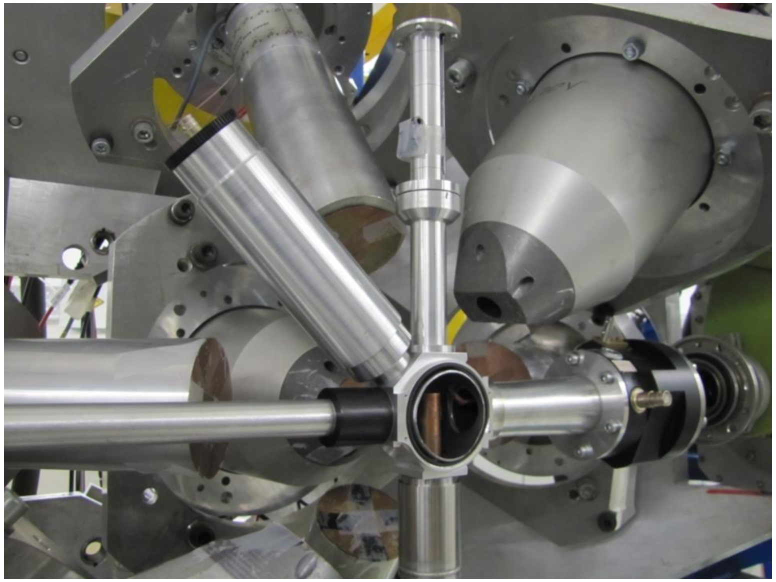
$^{187}Re(\alpha,n)$

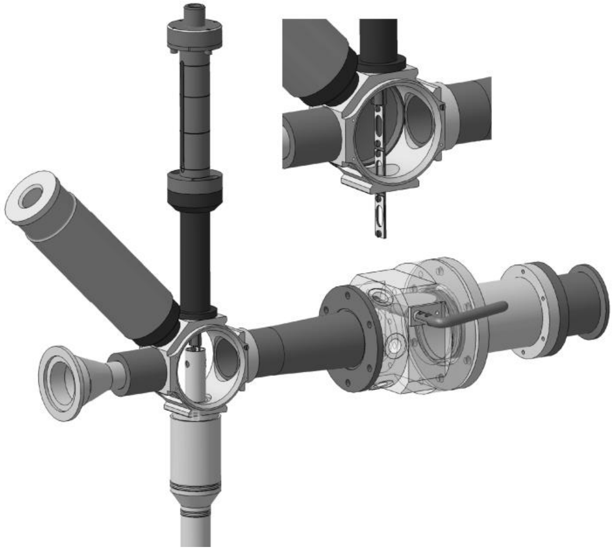


P. Scholz *et al.*, to be published

Activation & In-Beam Measurements @ IKP Köln

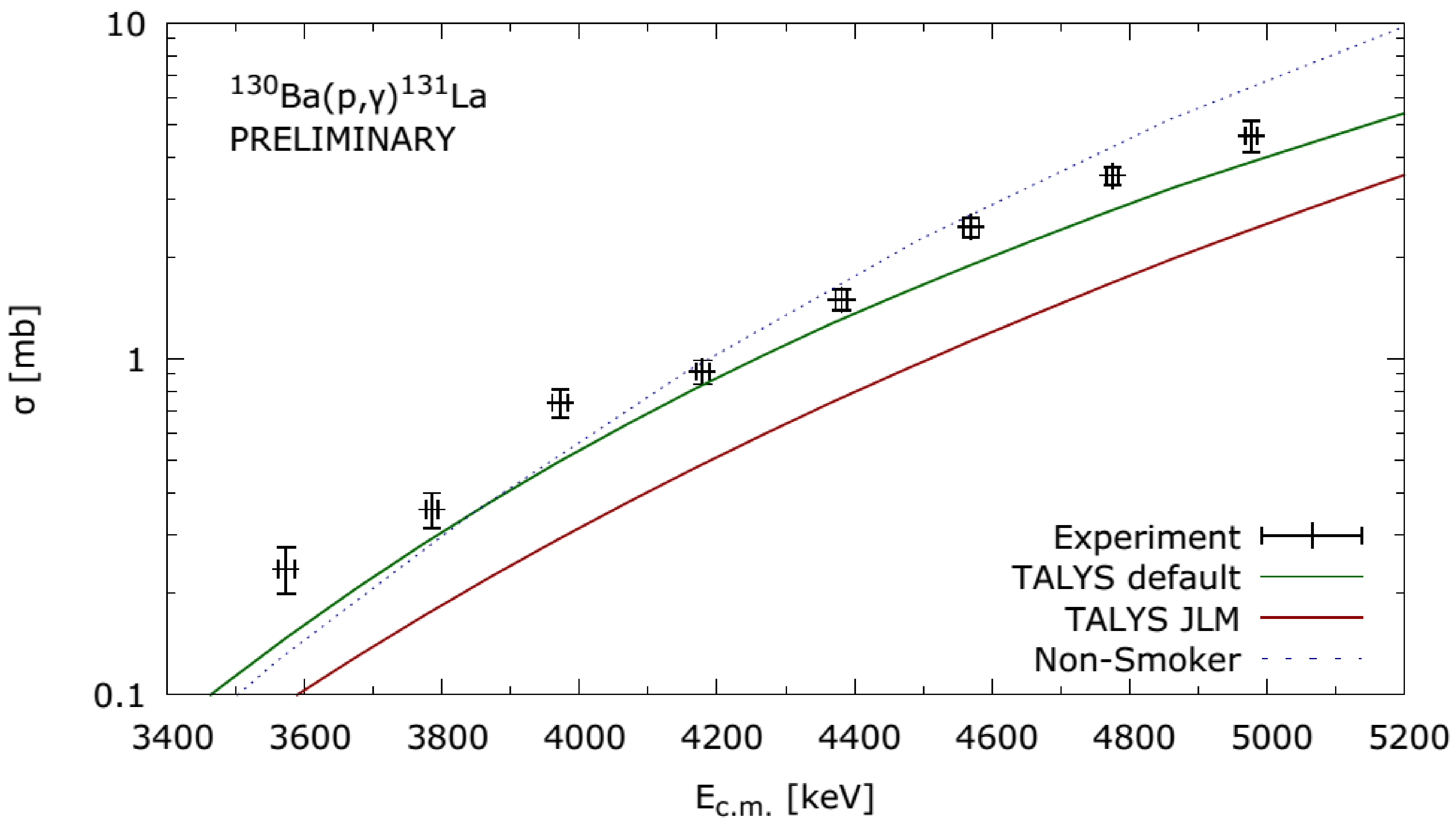
- 10 MV FN-Tandem ion accelerator
- Proton and α-beams
- 14 HPGe Detectors
- Target chamber for In-Beam and Activation Measurements



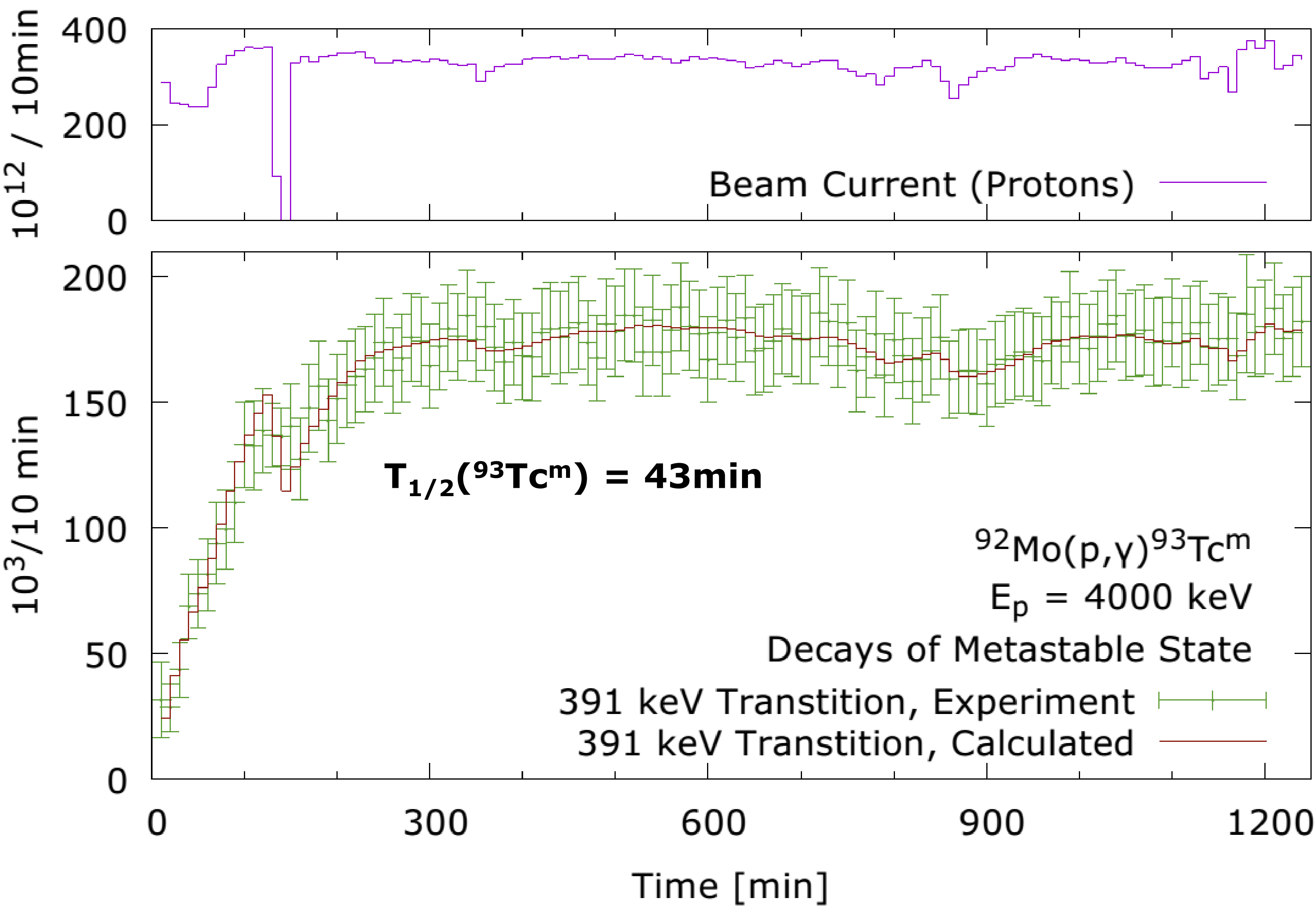


$^{130}Ba(p,\gamma)$

- activation and counting in Cologne



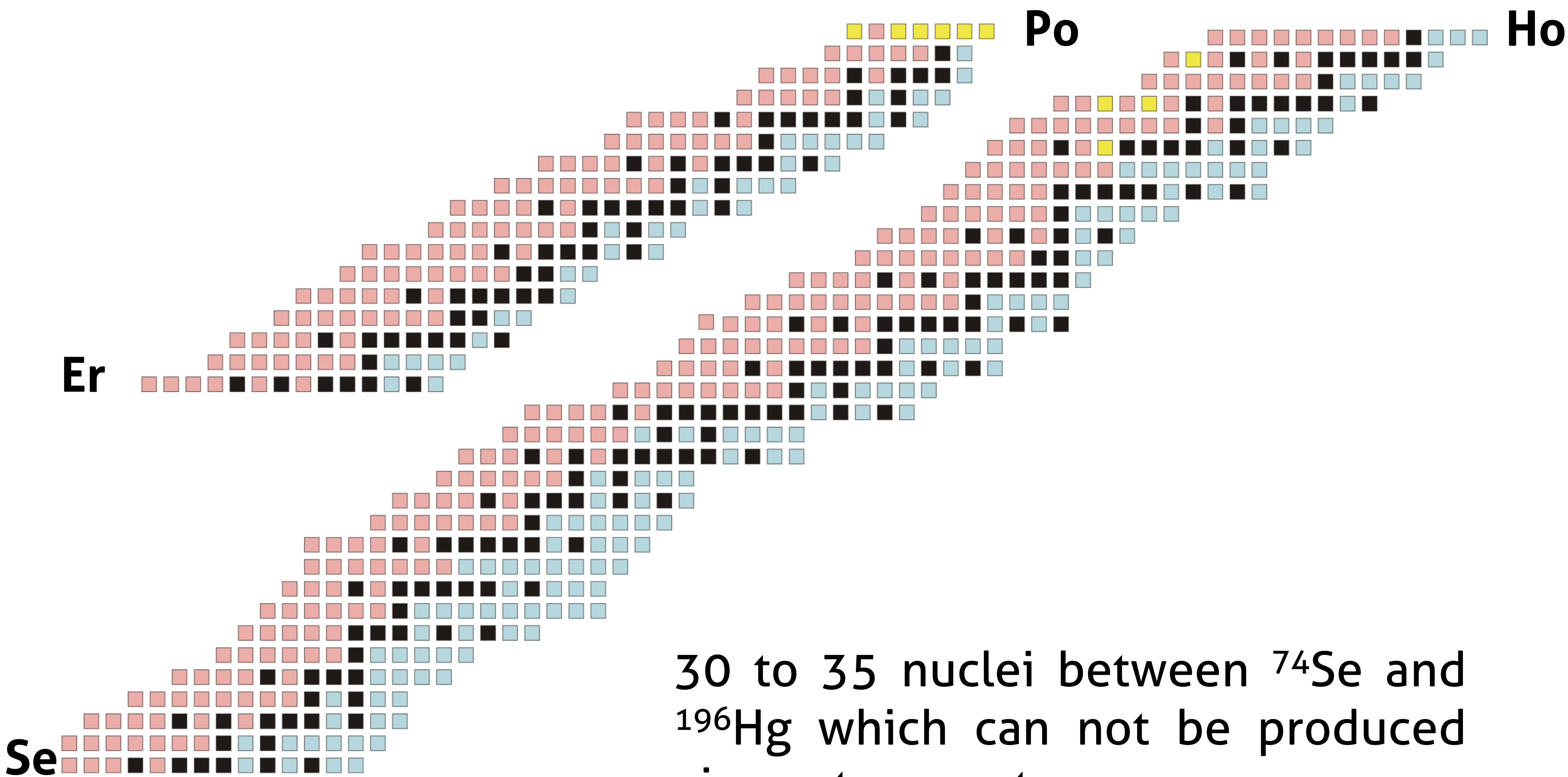
$^{92}Mo(p,\gamma)$ "In-Beam Activation Curve"



Summary

- 2-Step activation method
  - Activation @ PTB Braunschweig & IKP Cologne
  - Decay γ-ray spectroscopy @ IKP Cologne
- Studies with activation method
  - ^{168}Yb(α,γ)/^{168}Yb(α,n) – total cross sections at 6 energies
  - ^{187}Re(α,n) – total cross sections at 5 energies
  - ^{130}Ba(p,γ) – total cross sections at 8 energies
- In-Beam activation curve
  - ^{92}Mo(p,γ)

What is the γ process?



30 to 35 nuclei between ^{74}Se and ^{196}Hg which can not be produced via neutron capture processes

→ ***p* process**

Cross Section in Activation Experiments

$$\sigma = \frac{N_R}{N_P \cdot N_T} = \frac{Y_\gamma}{I_\gamma \cdot \varepsilon_\gamma \cdot f_{\text{act}} \cdot f_{\text{wait}} \cdot f_{\text{meas}} \cdot N_T \cdot N_P}$$

$$N_{\text{act}} = \frac{\xi}{\lambda}\,[1 - \exp(-\lambda \cdot \Delta t_{\text{act}})]$$

$$f_{\text{act}} = \frac{1 - \exp(-\lambda \cdot \Delta t)}{\lambda} \frac{\sum_{k=1}^{M} \xi_k \exp(-\lambda \cdot (M-k) \cdot \Delta t)}{\sum_{k=1}^{M} \xi_k \,\Delta t}$$

$$\begin{aligned} N_{\text{start}} &= N_{\text{act}} \cdot \exp(-\lambda \cdot \Delta t_{\text{wait}}) \\ &= N_{\text{act}} \cdot f_{\text{wait}} \quad , \end{aligned}$$

$$\begin{aligned} \Delta N &= N_{\text{start}} - N_{\text{end}} \\ &= N_{\text{start}} \cdot [1 - \exp(-\lambda \cdot \Delta t_{\text{meas}})] \\ &= N_{\text{start}} \cdot f_{\text{meas}} \quad , \end{aligned}$$

Efficiency and coincidences

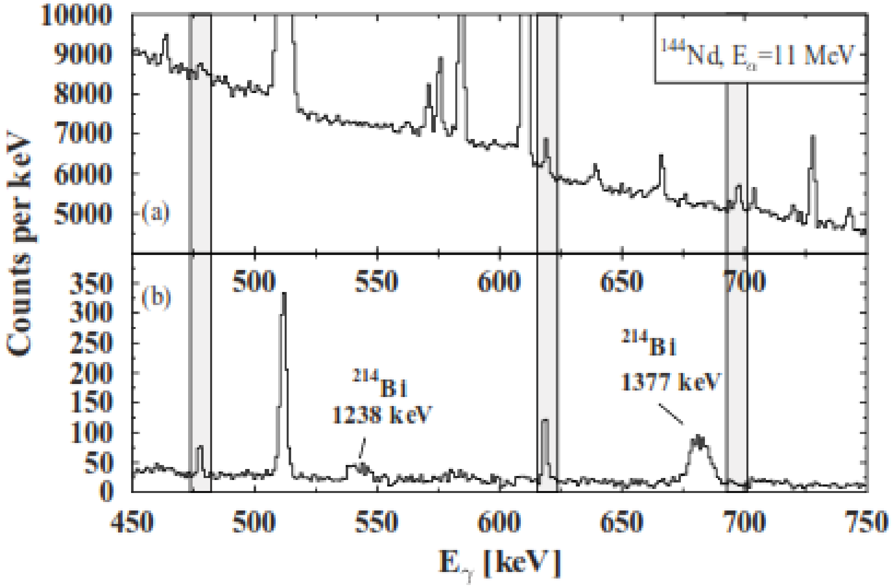


FIG. 7. Sensitivity of the $\gamma\gamma$ coincidence method. In the upper panel (a) the singles spectrum for a target irradiated with 11 MeV α particles is shown, whereas the lower panel (b) shows the corresponding coincidence spectrum for a gate triggered by 696 keV photons.

Efficiency in coincidence spectrum obtained by determining the η-parameter

$$\eta(E_{\text{gate}}, E) = \frac{N_{\text{single}}(E)}{N_{\text{coin}}(E_{\text{gate}}, E)}$$

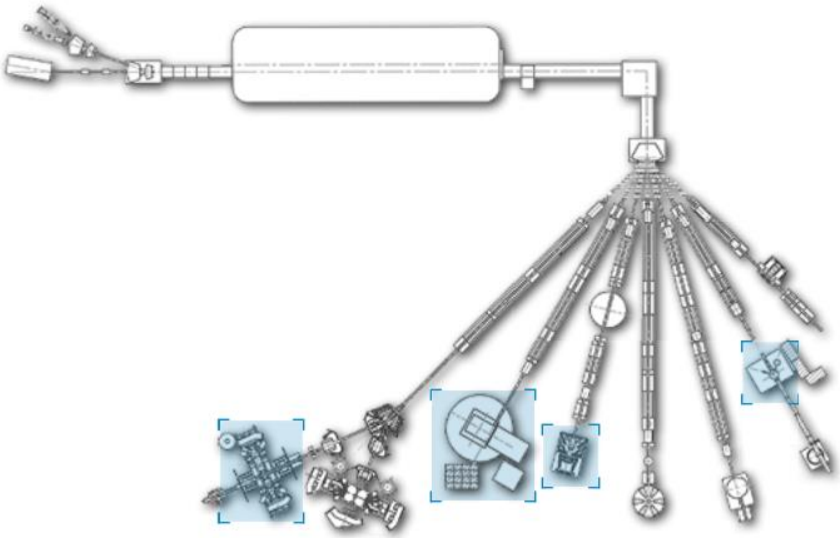
A. Sauerwein et al., Phys. Rev. C **84** 045808 (2011)

Tandem Accelerator in Cologne

- 10 MV FN-Tandem ion accelerator

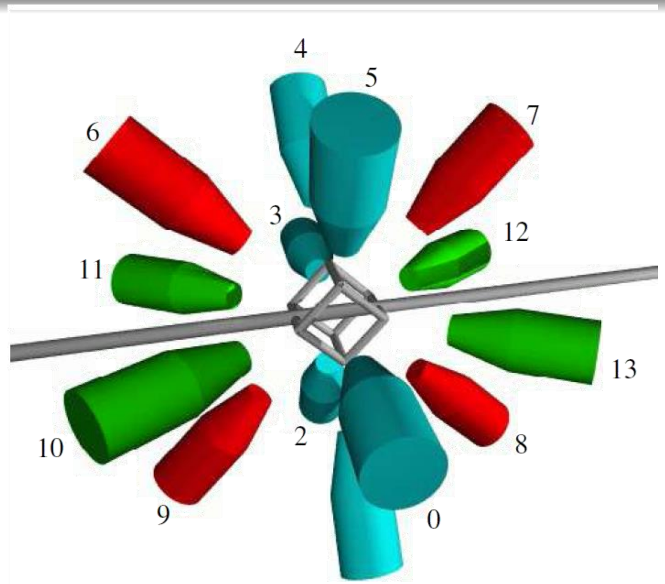
- Ion sources
  - Sputter source (p)
  - Duoplasmatron (α)

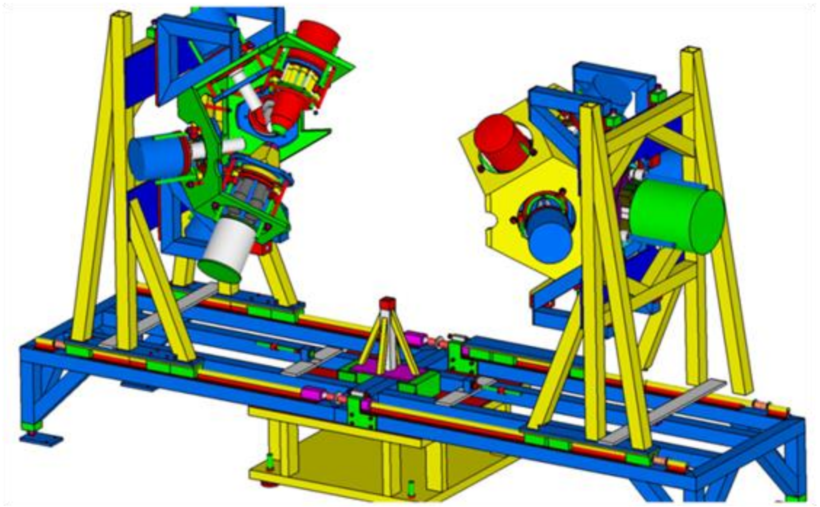
- Multiple Setups
  - Cologne Plunger
  - Orange Spectrometer
  - PIXE
  - HORUS Spectrometer



HORUS γ-ray Spectrometer

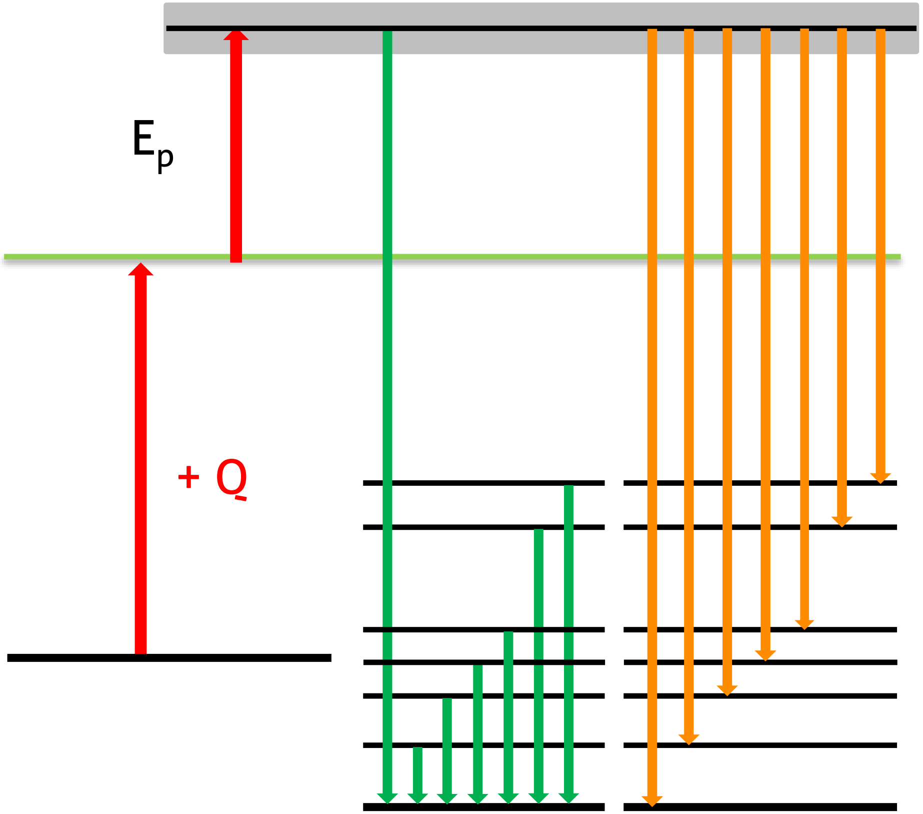
- 14 HPGe detectors
  - High resolution
    ≈ 2 keV @ 1332 keV
  - High total efficiency
    ≈ 2% @ 1332 keV
- 5 different detector angles
  - determination of angular distributions
- BGO shields and lead collimators available



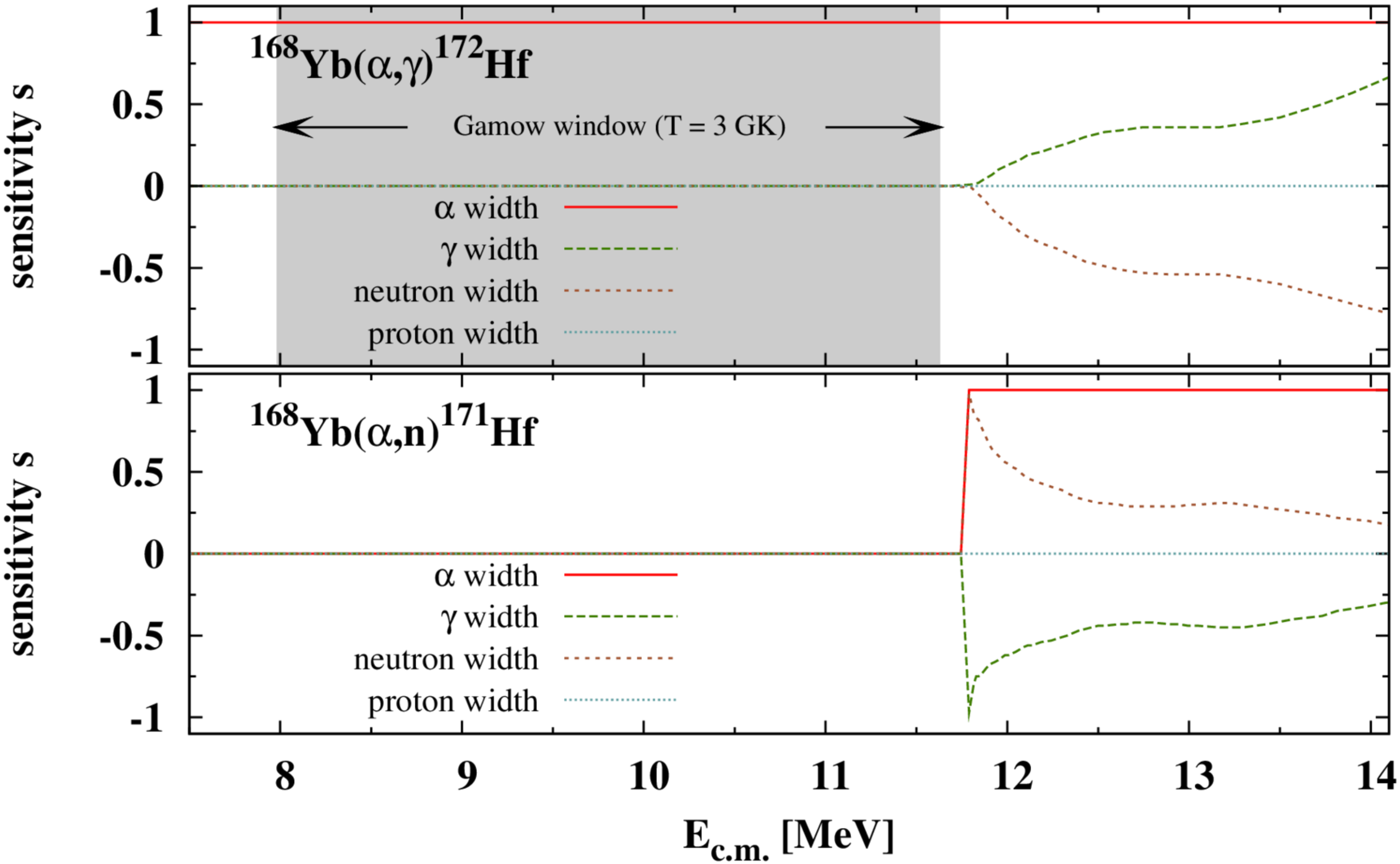


In-Beam γ-ray spectrometry

- transitions to the ground state
  - determination of the total cross section
- de-excitation of the entry state
  - determination of partial cross sections



Sensitivity ^{168}Yb



T. Rauscher, Astrophys. J. Suppl. Ser. **201**, 26 (2011)