In-Beam Experiments for Nuclear Astrophysics at HORUS

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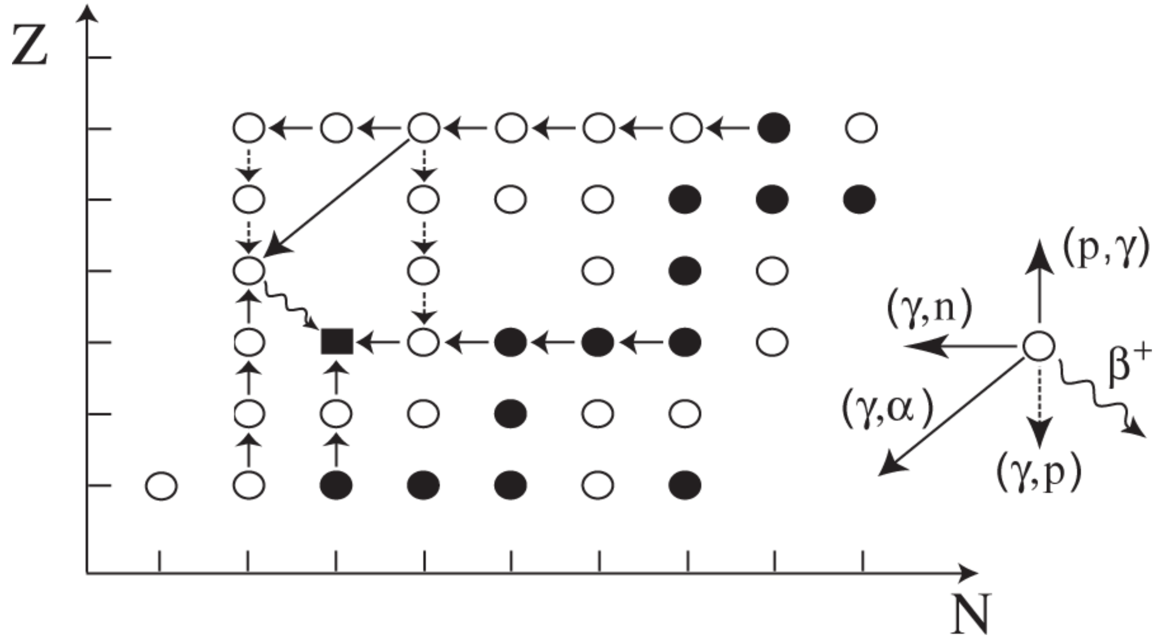
Outline

- Introduction
- Experimental Setup in Cologne
- Data evaluation
- Outlook

Synthesis of Heavy Elements

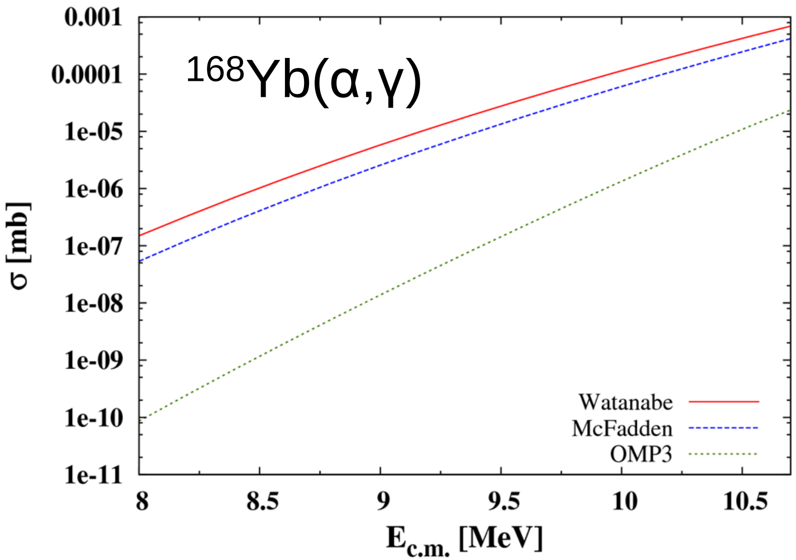
- Different processes in various astrophysical scenarios
- Example: p process
  - large network of reactions
  - thousands of reactions on mainly unstable nuclei



M. Arnould and S. Goriely, Phys. Rep. **384** (2003)

Prediction of reaction rates

- Number of reactions too large to measure all of them (≈ 20000)
- Calculations e.g. with Hauser-Feshbach statistical model necessary



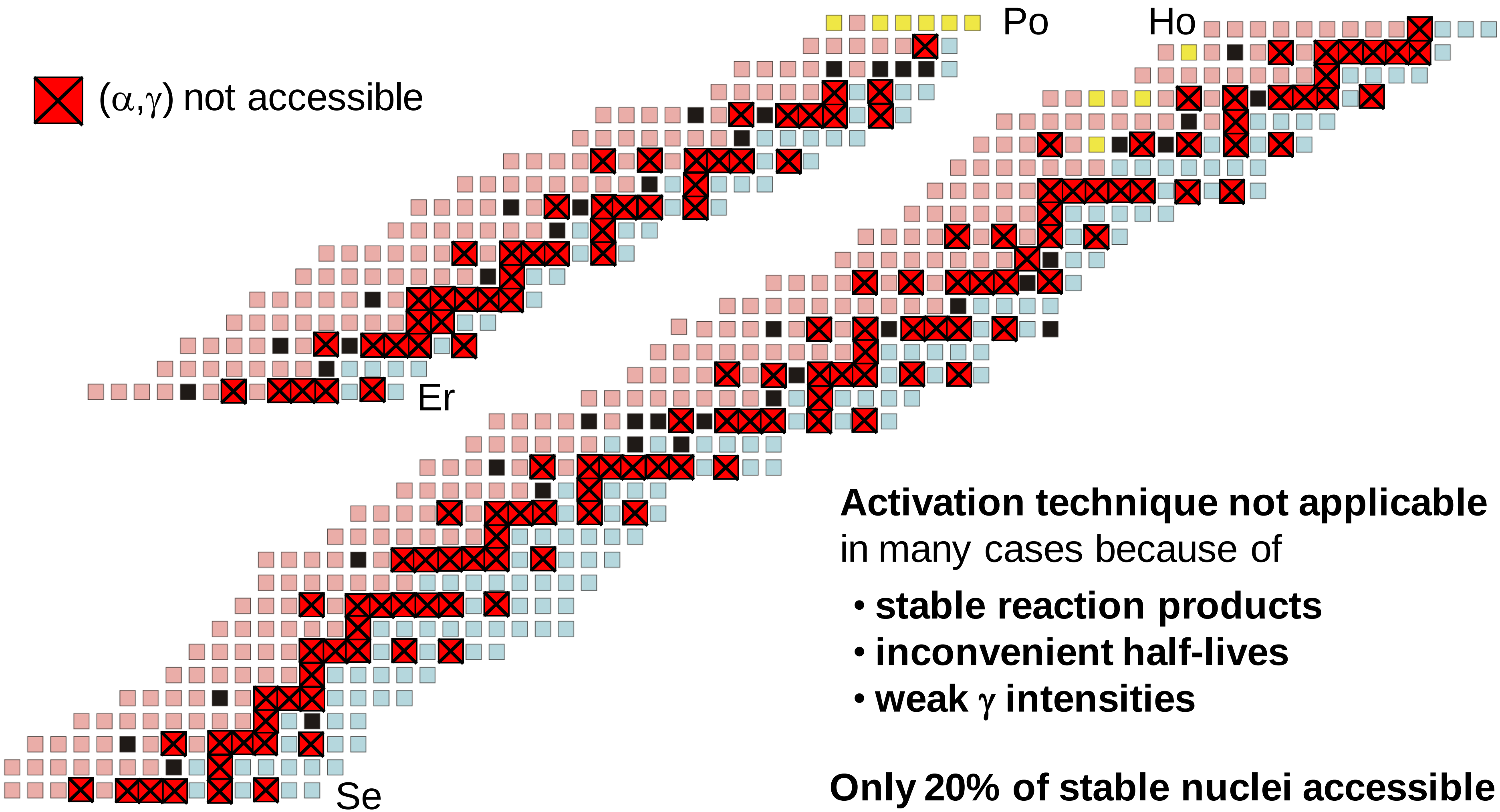
A.J. Koning, S. Hilaire, and M.C. Duijvestijn,
TALYS-1.4

⇨ Experiments required to improve nuclear models!

⇨ Activation / In-Beam / (AMS)

Activation Method on Wednesday
L. Netterdon → ^{168}Yb(α,γ)
P. Scholz → ^{187}Re(α,n)

Limitations of activation technique



Activation technique not applicable in many cases because of

- **stable reaction products**
- **inconvenient half-lives**
- **weak γ intensities**

Only 20% of stable nuclei accessible

⇨ In-Beam technique to overcome limitations

Institute for Nuclear Physics, University of Cologne

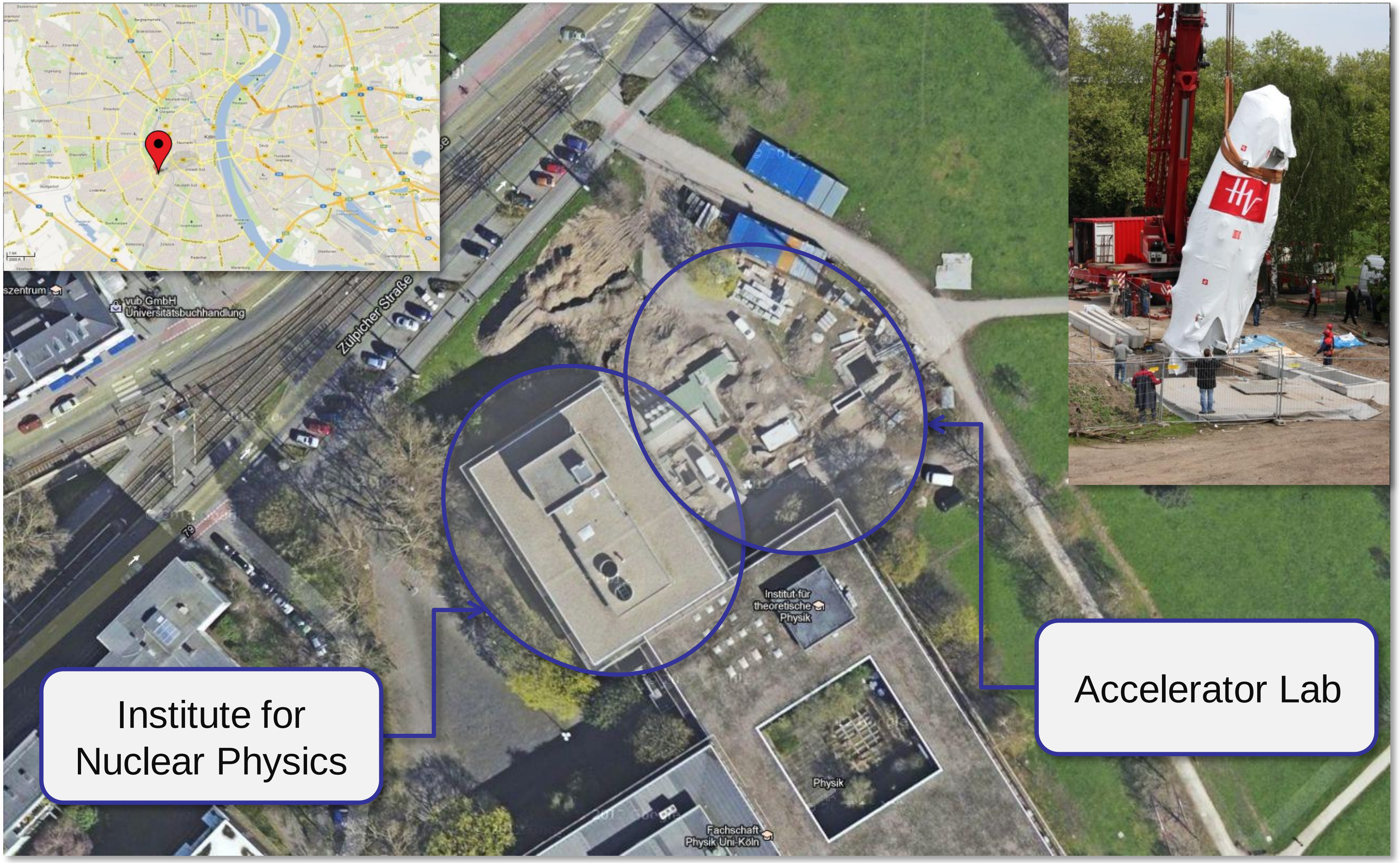


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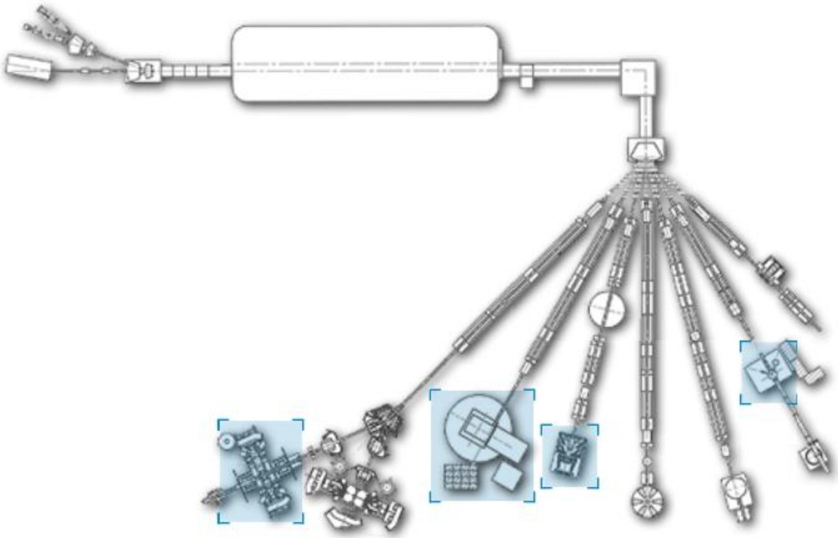
Photo: S. Pickstone

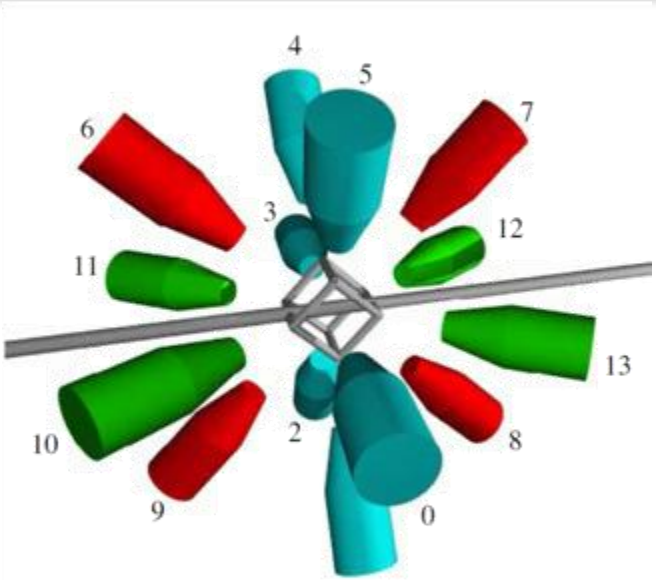
Tandem Accelerator in Cologne

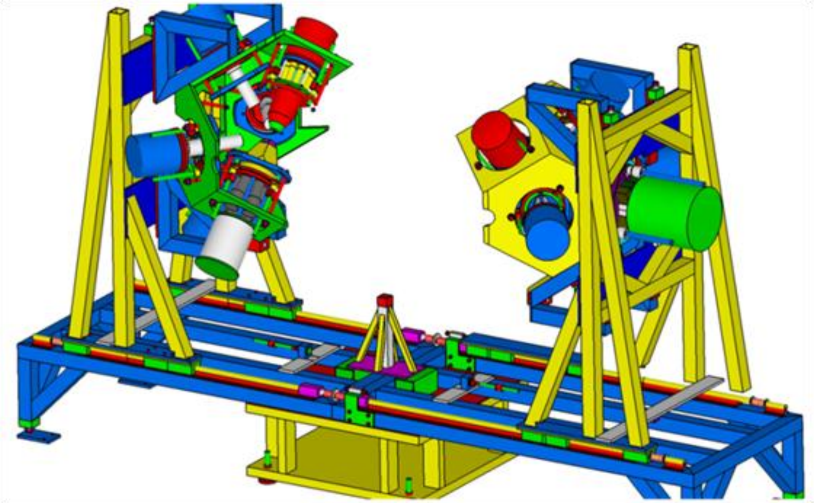
- 10 MV FN-Tandem ion accelerator
- Ion sources
  - Sputter source (p)
  - Duoplasmatron (α)
- Multiple Setups
  - Cologne Plunger
  - Orange Spectrometer
  - PIXE
  - **HORUS Spectrometer**



HORUS γ-ray Spectrometer

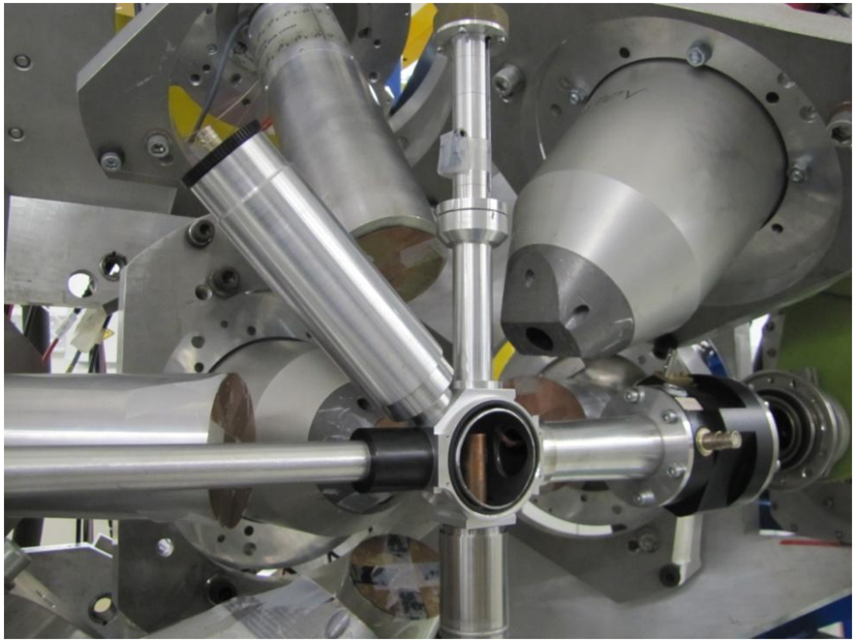
- 14 HPGe detectors
  - High resolution
    ≈ 2 keV @ 1332 keV
  - High total efficiency
    ≈ 2% @ 1332 keV
- 5 different detector angles
  - determination of angular distributions
- BGO shields and lead collimators available
- Digital signal processing
  - MCA and listmode data
  - γγ coincidences



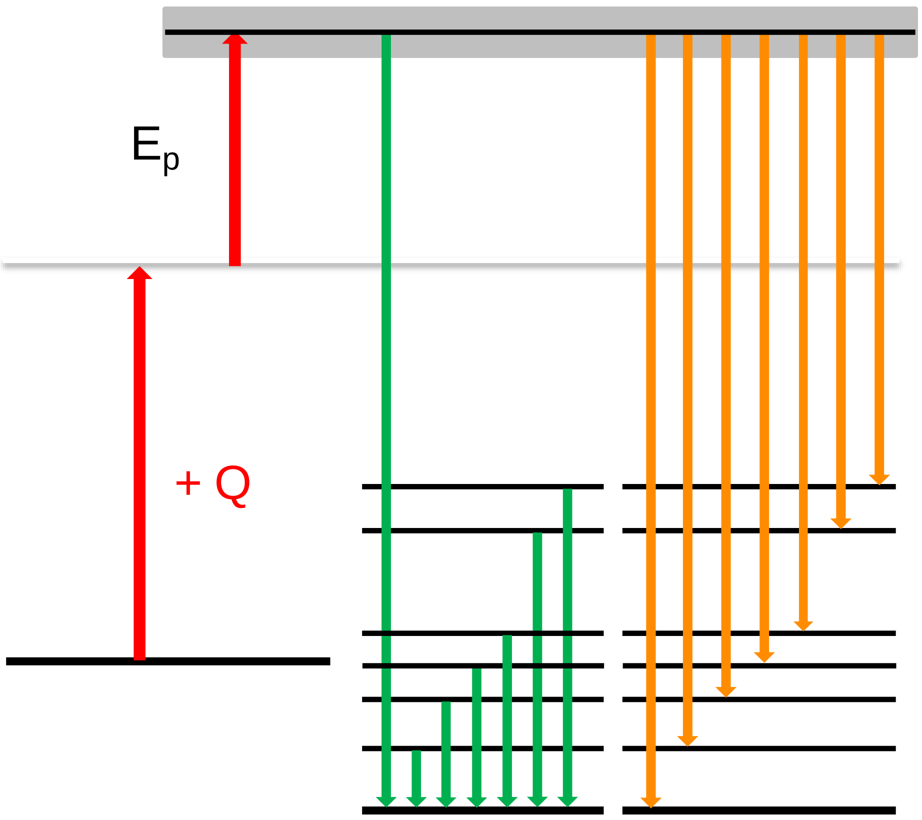


Target Chamber Built for Nuclear Astrophysics

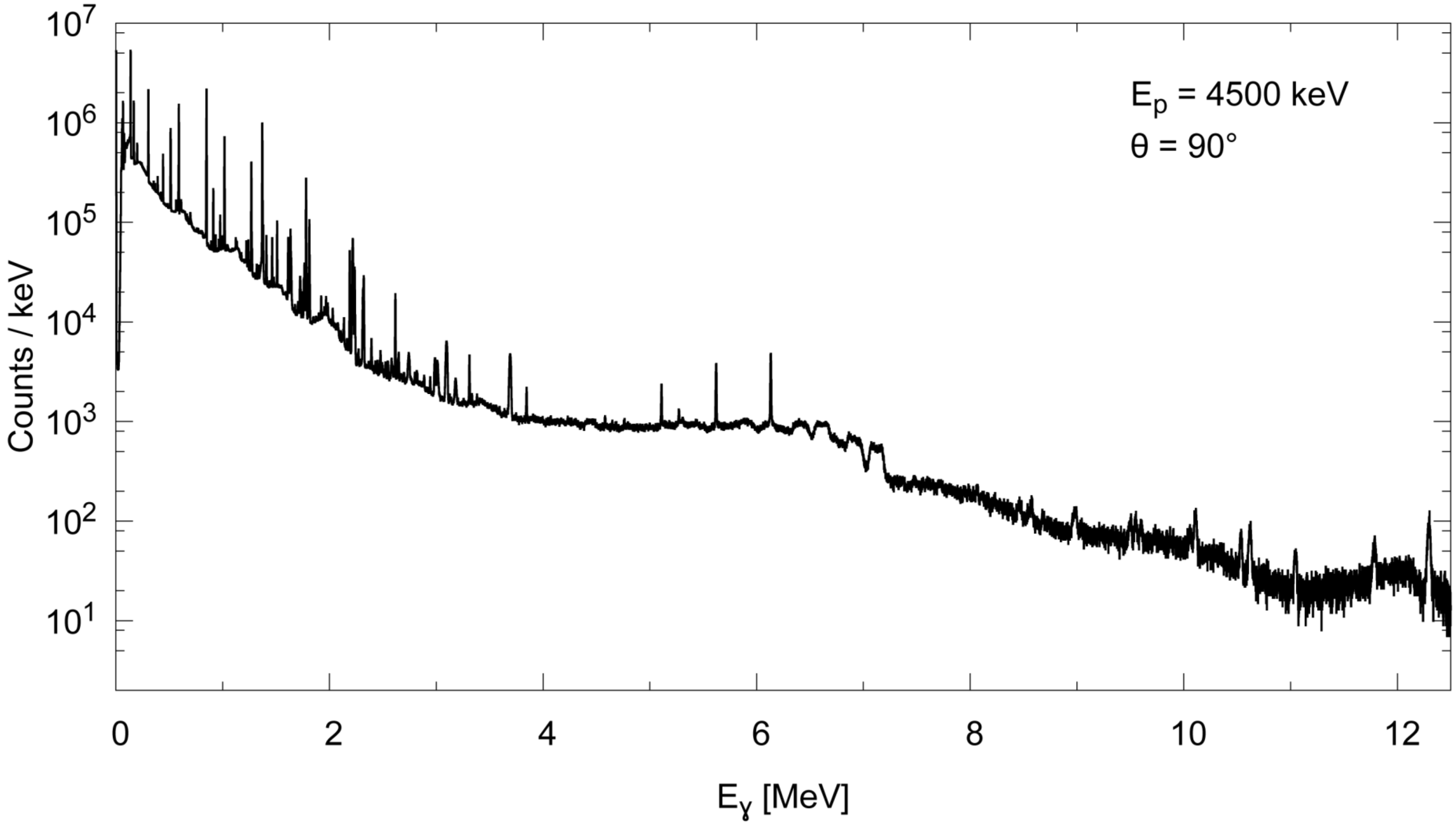
- Built-in detector for Rutherford backscattering spectrometry (RBS)
- Cooling trap
- Tantalum coating
- Current readouts
  - Target, Chamber, Cup
- δ-electron suppression
- Flexible Cup



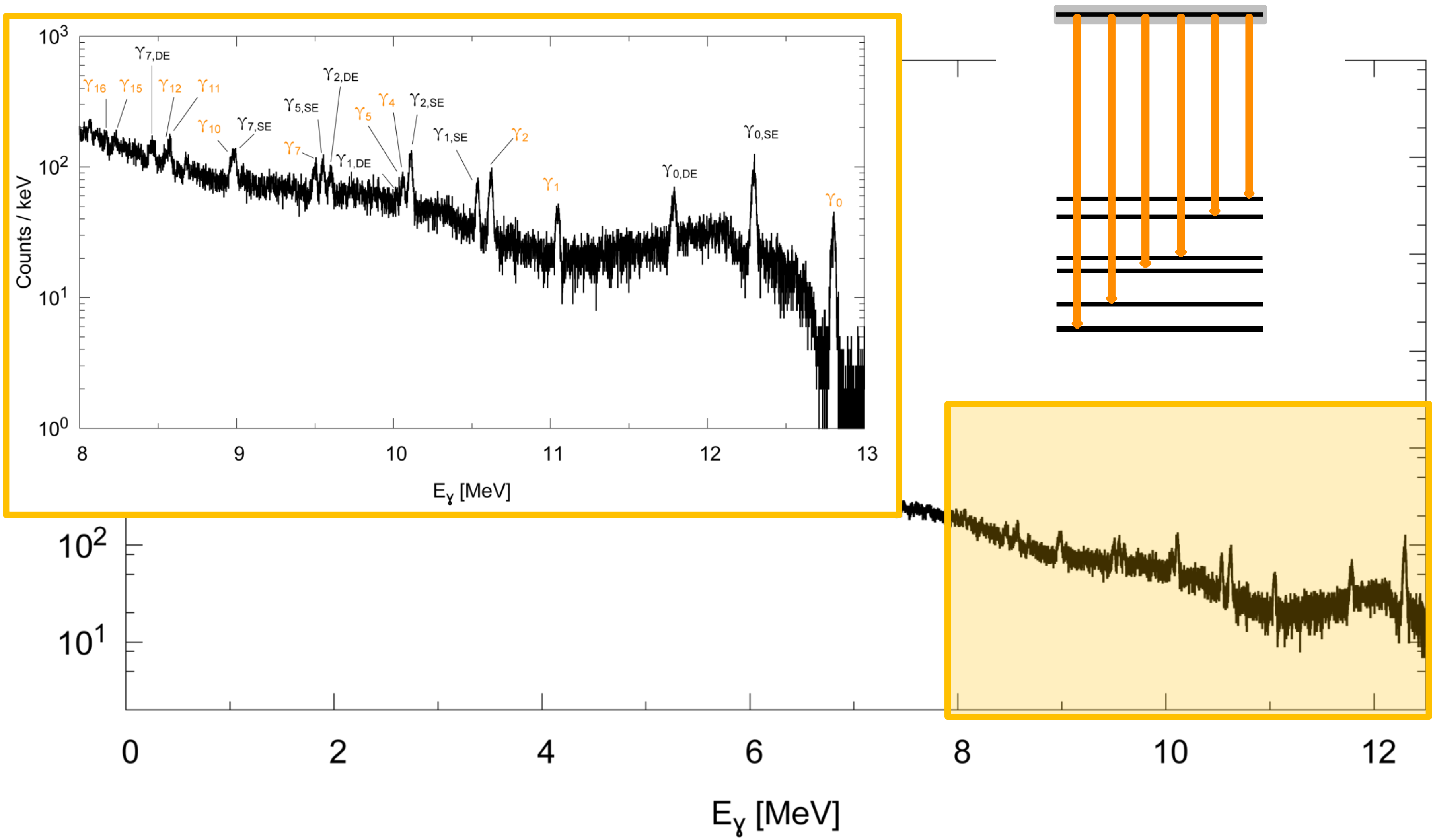
- de-excitation of the entry state
  - determination of partial cross sections
- transitions to the ground state
  - determination of the total cross section
- transitions to excited states
  - production of excited states



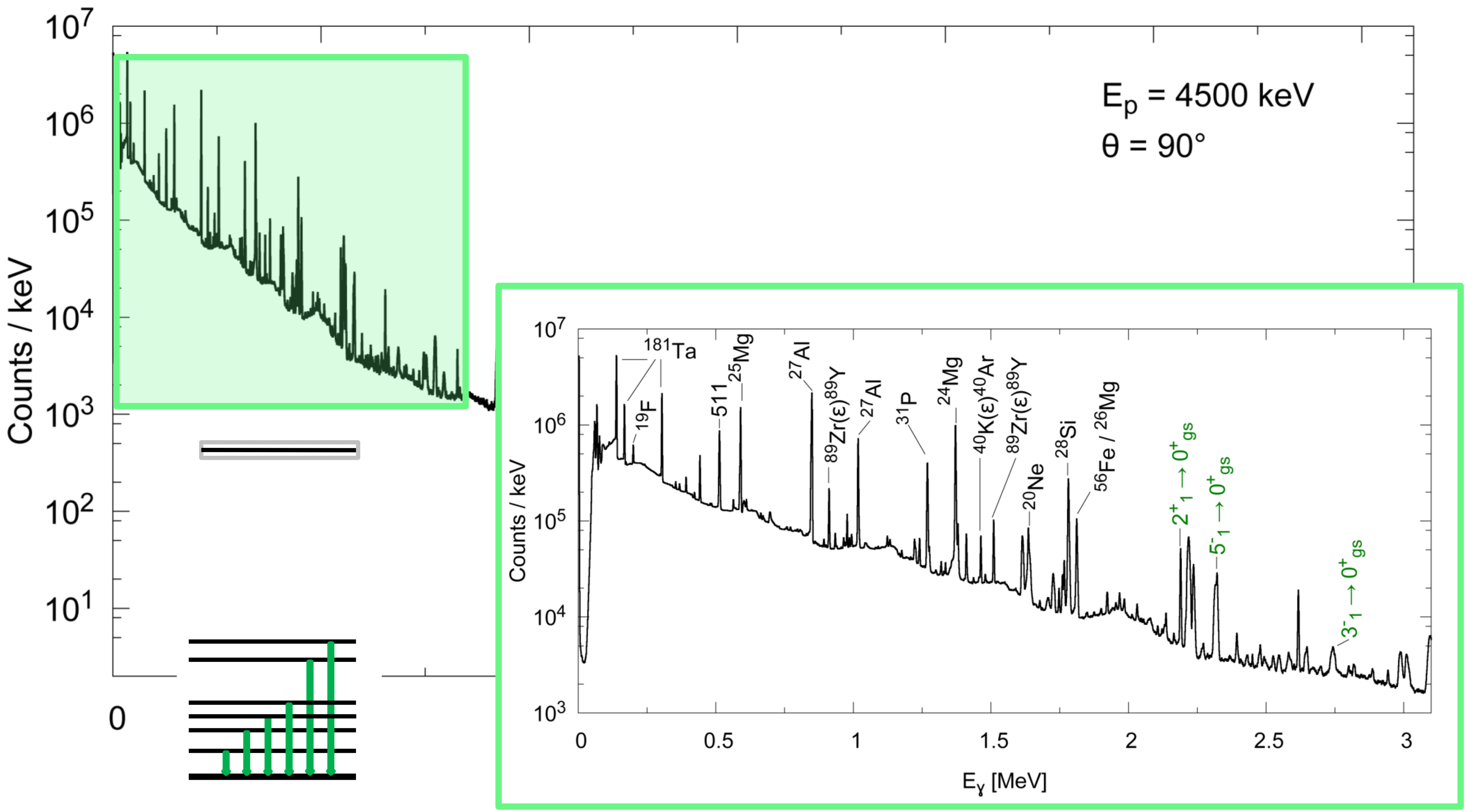
$^{89}Y(p,\gamma)$ – In-Beam Spectrum



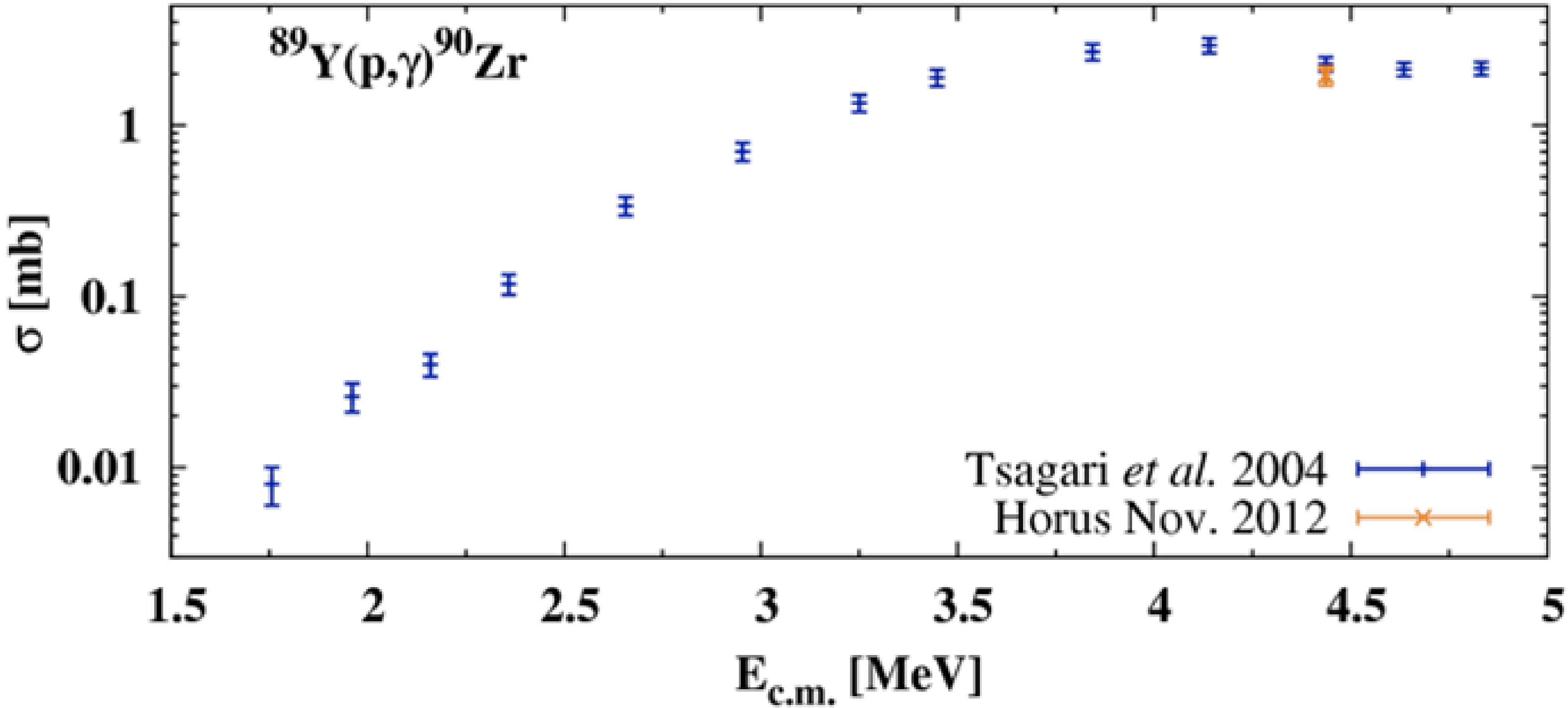
$^{89}Y(p,\gamma)$ – Data Analysis



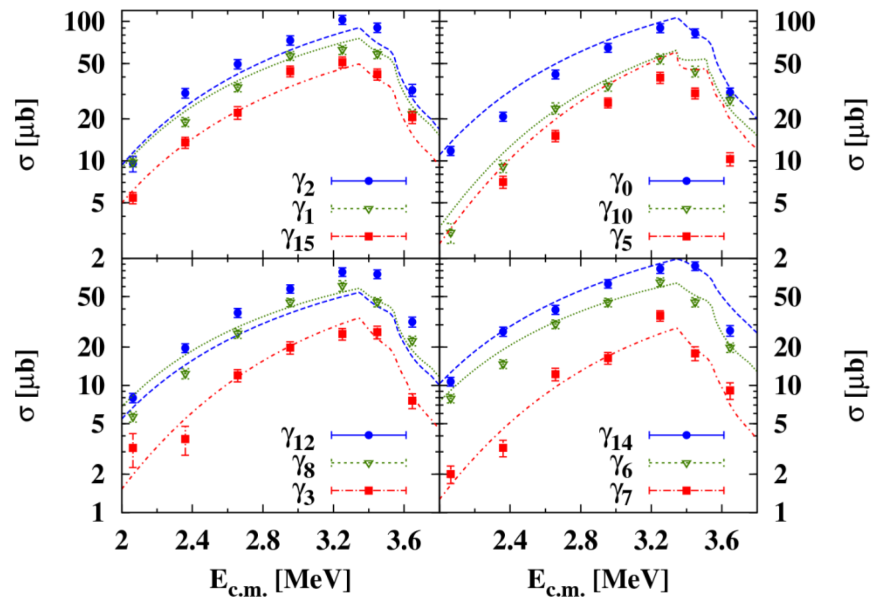
$^{89}Y(p,\gamma)$ – Data Analysis

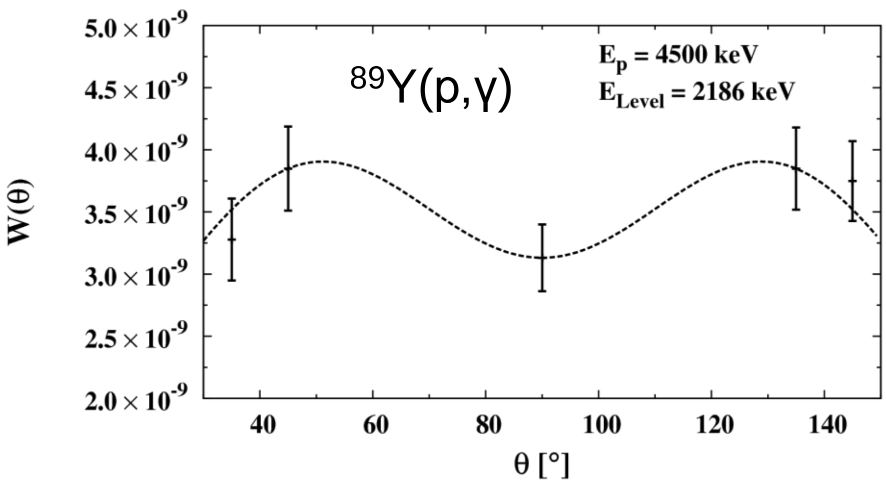


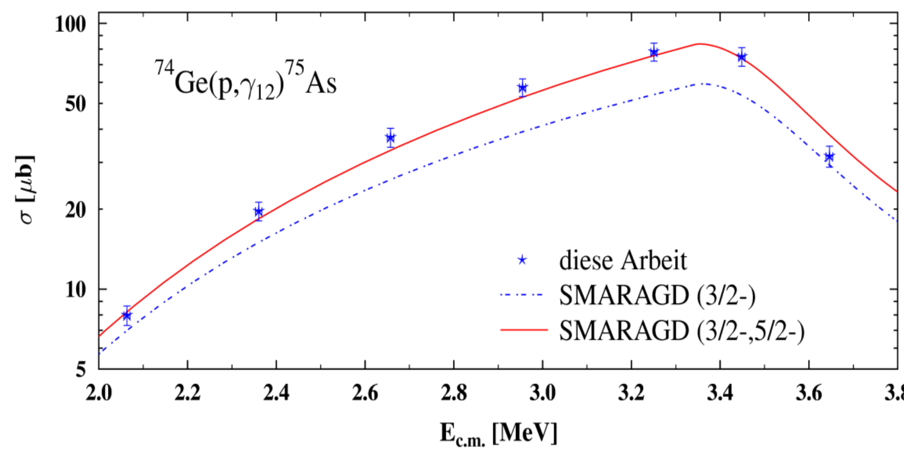
$^{89}Y(p,\gamma)$ - Results



- Partial cross sections
- Angular distributions
- Spin Assignments





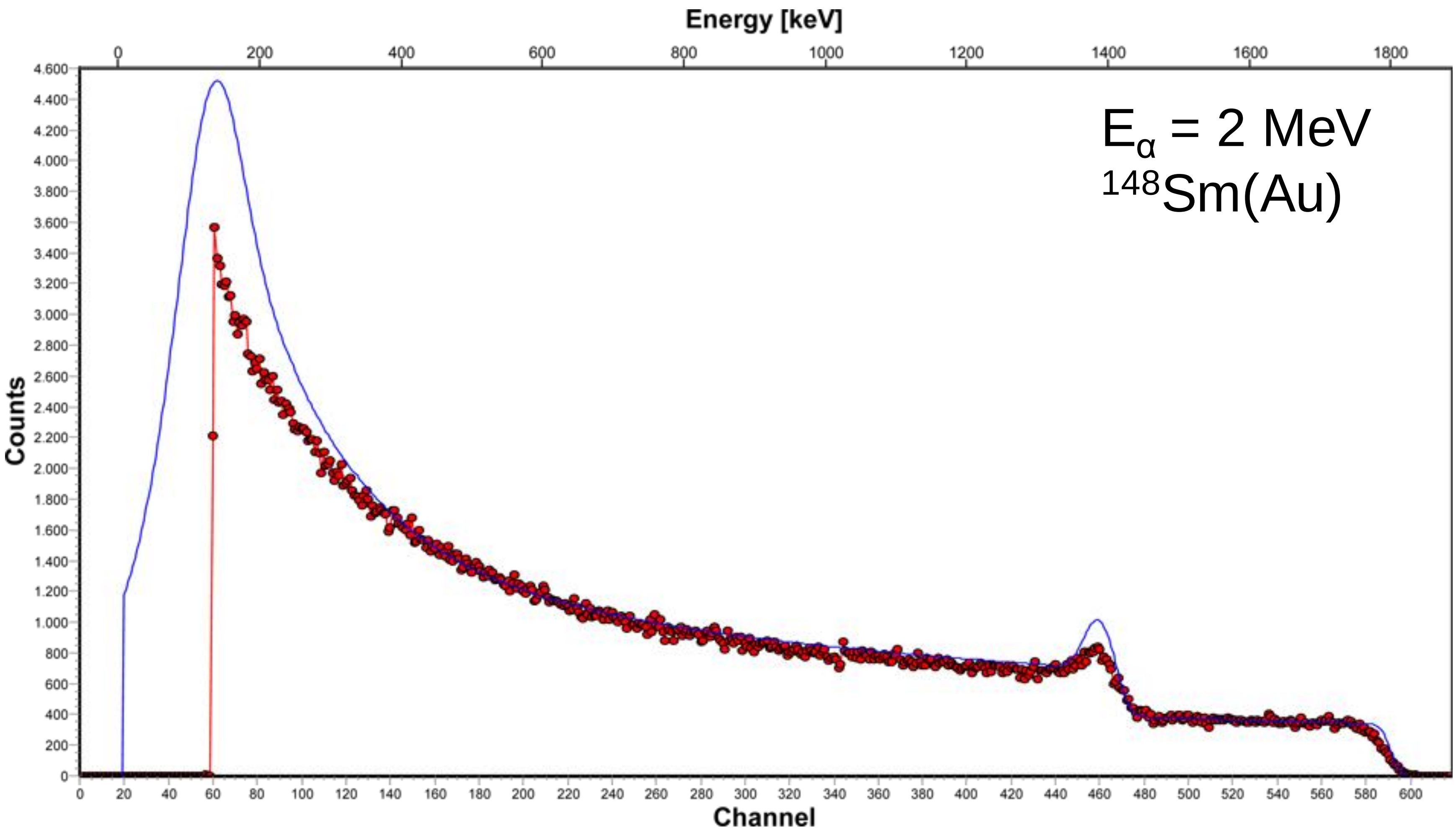


A. Sauerwein *et al.*, Phys. Rev. C **86** (2012) 035801

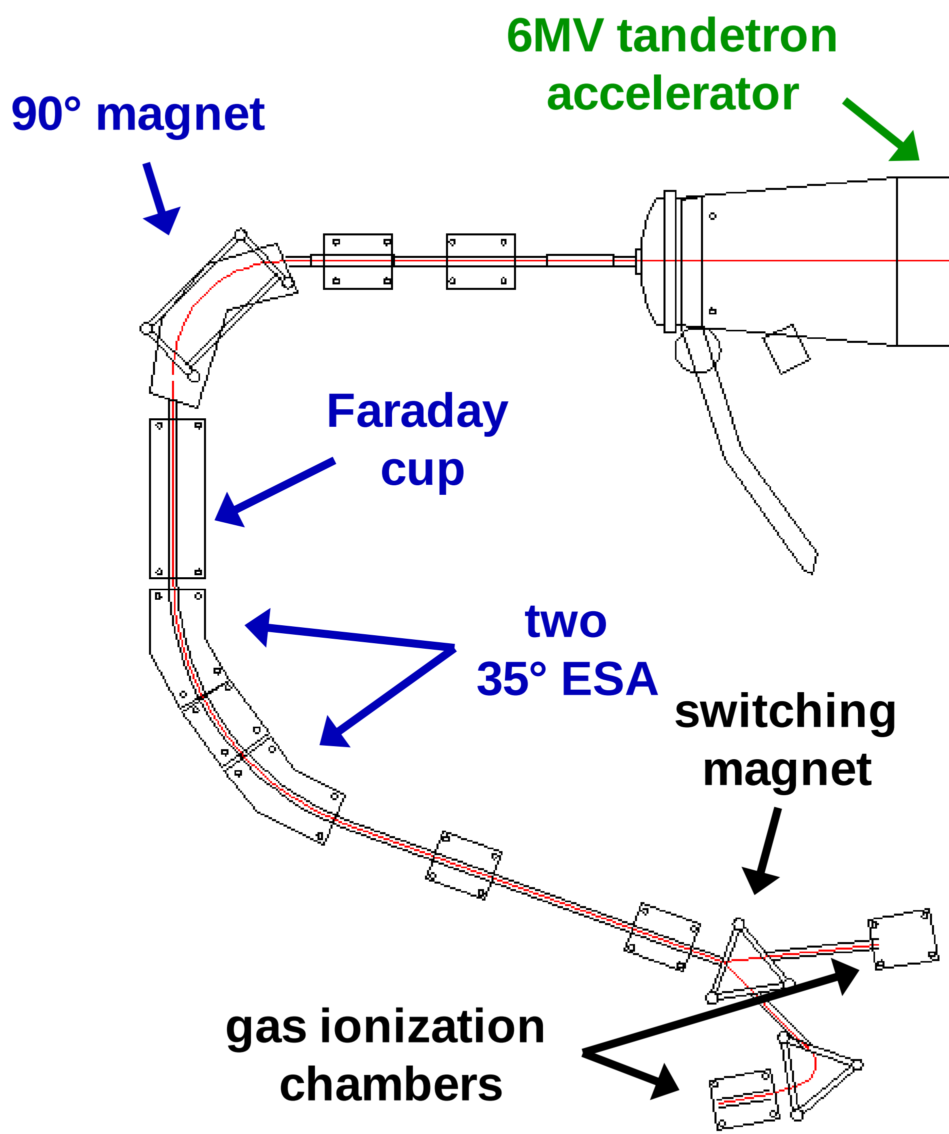
Outlook

- α-particle induced reactions
  - First test experiments with an α-particle beam performed
- Further improvements
  - Shield more detectors with BGOs or lead collimators
  - Reduce beam induced background
- Planned In-Beam experiments
  - (α,γ) and (α,n) reactions on the Samarium isotopic chain
  - (α,γ) and/or (α,n) reactions on ^{104}Pd, ^{176}Hf, ^{198}Pt
  - (p,γ) reactions on ^{110}Cd, ^{142}Nd, ^{182}W

Rutherford Backscattering Spectrometry



Cross section measurements with AMS



Low energy mass spectrometer

6MV Tandetron accelerator

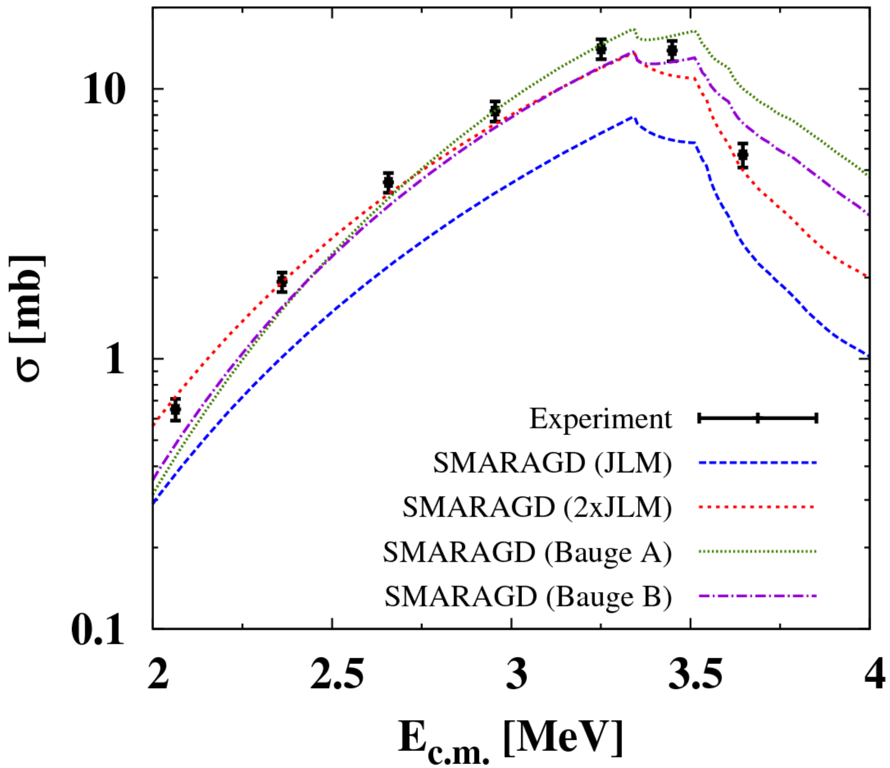
High energy mass spectrometer

Ion detection

Isotope ratios down to 10^{-15}

^{74}Ge(p,γ) - Results

Total cross sections



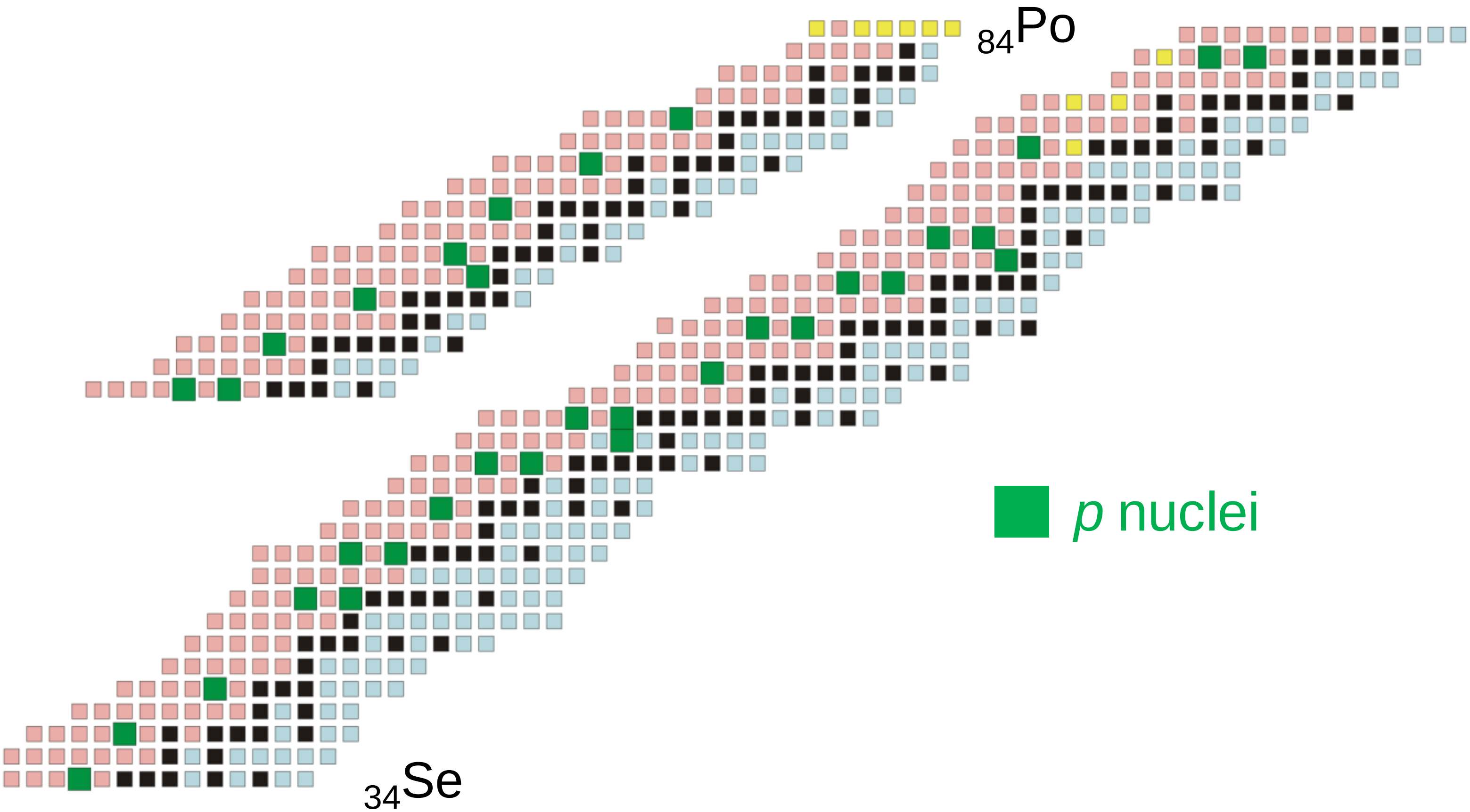
- cross section dominantly sensitive to proton width
- renormalization factor of 2 of proton width yields good reproduction
- reaction rate higher by 28 % compared to non-smoker prediction

A. Sauerwein *et al*., Phys. Rev. C **86** (2012) 035802

T. Rauscher, code SMARAGD, version 0.8.4s, 2012

What are the *p* nuclei?

- 30 to 35 neutron-deficient nuclei between Se and Hg
- not produced by neutron-capture processes
- low isotopic abundances of 0.1 – 1 %



Motivation

- Measurement of ion-induced reactions
- experimental difficulties due to:
  measurement at energies below the Coulomb barrier for heavy nuclei ($E_{Gamow} \approx 6 – 14$ MeV @ 3 GK)
- e.g. for ^{168}Yb(a,g): $E_{Gamow} \approx 7 – 11$ MeV << $E_{coul} \approx 24$ MeV

⇨ $\sigma \approx 0.1 – 100$ µb

⇨ very sensitive determination of small cross sections needed

Experimental difficulties

- number of reactions too large to measure all of them (≈ 20.000)
- many reactions on radioactive nuclei not easily accessible
- measurement inside Gamow window often below Coulomb barrier
  ⇒ small cross sections
- e.g. for ^{168}Yb(α,γ): $E_{Gamow} \approx 8 - 11$ MeV << $E_{coul} \approx 24$ MeV

calculations with Hauser-Feshbach statistical model necessary

- to calculate reaction rates, if no experimental data is available

- to extrapolate the data towards smaller energies, if experimental data is available above the Gamow window

improvement of nuclear models to calculate reaction rates

- nuclear masses
- properties of excited states
- nuclear level densities
- γ-strength functions
- optical model potentials (OMP)