Experimental studies of charged-particle induced reactions for the nucleosynthesis of *p* nuclei

L. Netterdon, J. Endres, J. Mayer*,
A. Sauerwein*, P. Scholz*, and A. Zilges

Institut für Kernphysik, Universität zu Köln

10th Russbach School on Nuclear Astrophysics

Russbach, March 13th, 2013

Supported by the DFG under contract DFG (ZI 510/5-1, INST 216/544-1)
*Supported by the Bonn-Cologne Graduate School of Physics and Astronomy

Outline

- Experimental difficulties
- Motivation: α-induced reactions on ^{168}Yb
- Activation method
- Experimental results:
  - ^{168}Yb(α,n) - Cologne clover setup
  - ^{168}Yb(α,γ) – LEPS @ ATOMKI
- Summary

Experimental difficulties for *p*-process studies

- 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 ⇨ $\sigma \approx \mu b$
- e.g. for $^{168}Yb(\alpha,\gamma)$: $E_{Gamow} \approx 8 – 11$ MeV << $E_{coul} \approx 24$ MeV

Experimental difficulties for *p*-process studies

- 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 ⇨ $\sigma \approx \mu b$
- e.g. for $^{168}Yb(\alpha,\gamma)$: $E_{Gamow} \approx 8 - 11$ 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

Experimental difficulties for *p*-process studies

- 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 ⇨ $\sigma \approx \mu b$
- e.g. for $^{168}Yb(\alpha,\gamma)$: $E_{Gamow} \approx 8 - 11$ MeV << $E_{coul} \approx 24$ MeV

calculations with Hauser-Feshbach statistical model necessary

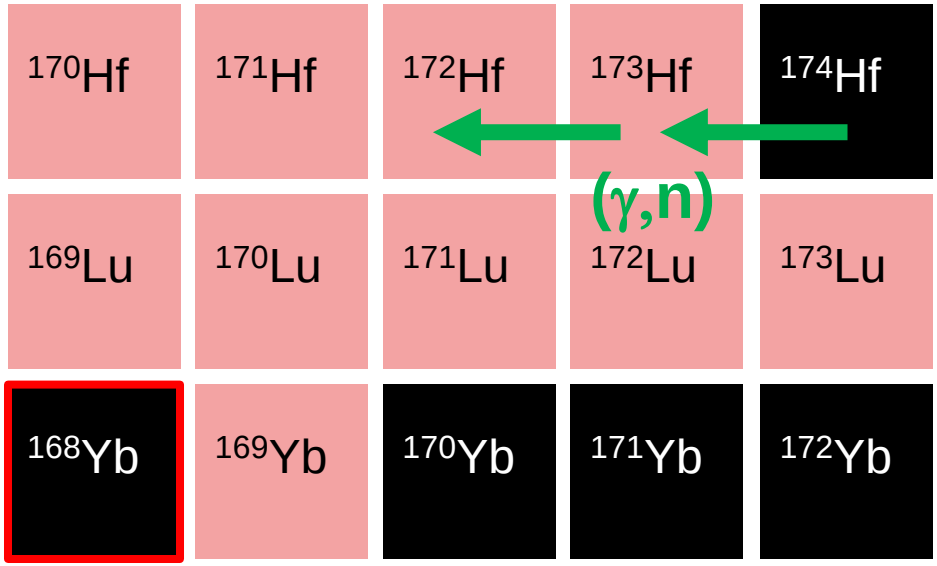
- to calculate reaction rates, if no experimental data is available
- to extrapolate the data towards smaller energies, if experimental data is available above the Gamow window

improvement of nuclear models to calculate reaction rates

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

α-induced reactions on ^{168}Yb

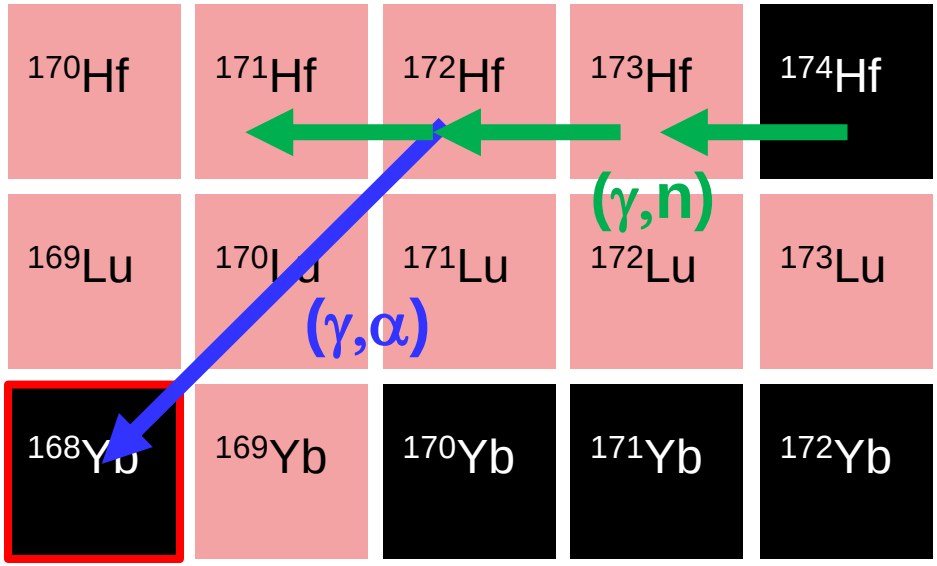
- Motivation: branching point in γ-process reaction flow predicted at ^{172}Hf



T. Rauscher, Phys. Rev. C 73 (2006) 015804

α-induced reactions on ^{168}Yb

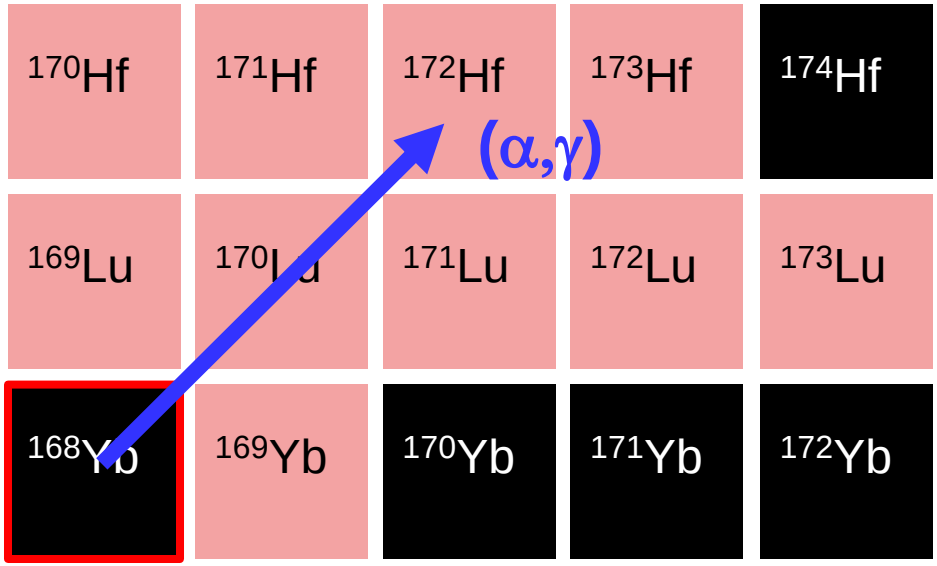
- Motivation: branching point in γ-process reaction flow predicted at ^{172}Hf



T. Rauscher, Phys. Rev. C 73 (2006) 015804

α-induced reactions on ^{168}Yb

- Motivation: branching point in γ-process reaction flow predicted at ^{172}Hf

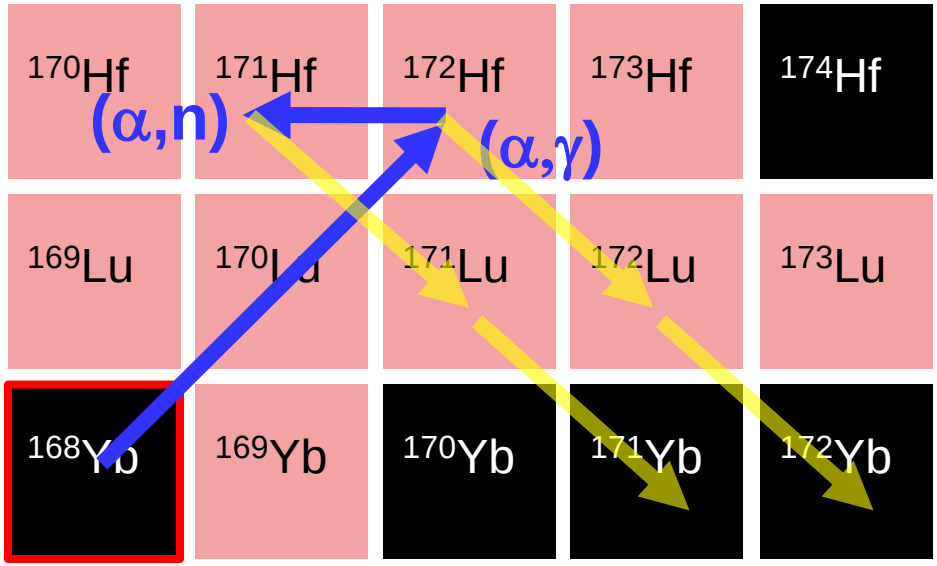


- stellar effects smaller for inverse reaction
- weak & low-energy γ-ray transitions for (α,γ) reaction

T. Rauscher, Phys. Rev. C 73 (2006) 015804

α-induced reactions on ^{168}Yb

- Motivation: branching point in γ-process reaction flow predicted at ^{172}Hf

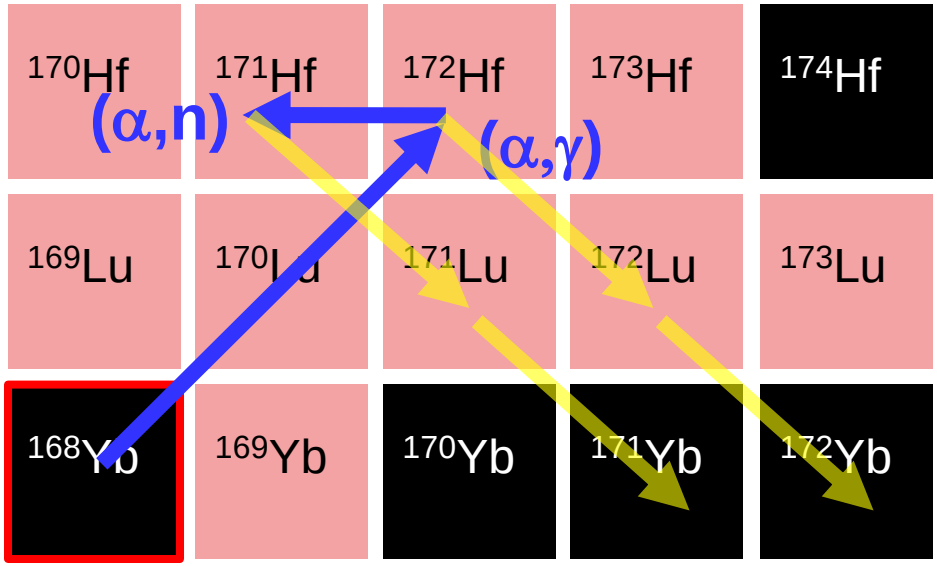


- stellar effects smaller for inverse reaction
- weak & low-energy γ-ray transitions for (α,γ) reaction

T. Rauscher, Phys. Rev. C 73 (2006) 015804

α-induced reactions on ^{168}Yb

- Motivation: branching point in γ-process reaction flow predicted at ^{172}Hf



T. Rauscher, Phys. Rev. C 73 (2006) 015804

Idea:

measure cross section for (α,n) and (α,γ) reaction

⇩

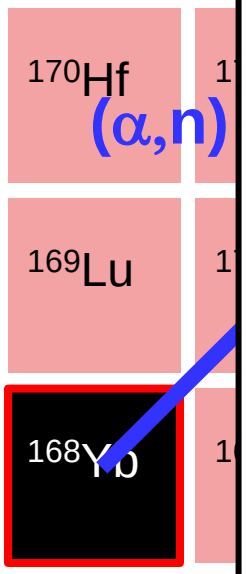
improve nuclear models for HF calculations

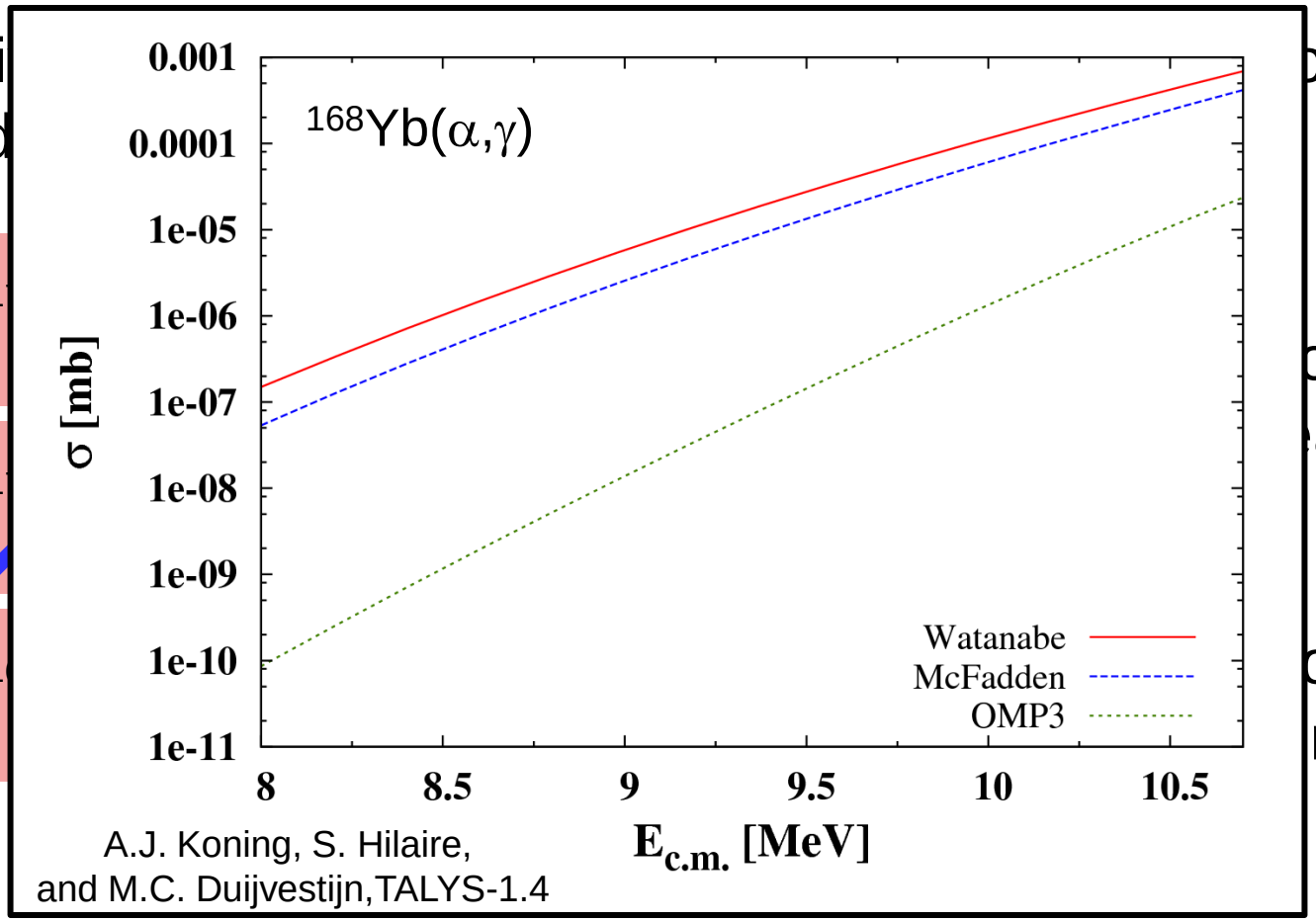
⇩

improve ^{172}Hf(γ,α)^{168}Yb stellar reaction rate

α-induced reactions on ^{168}Yb

- Moti … ow
  pred …





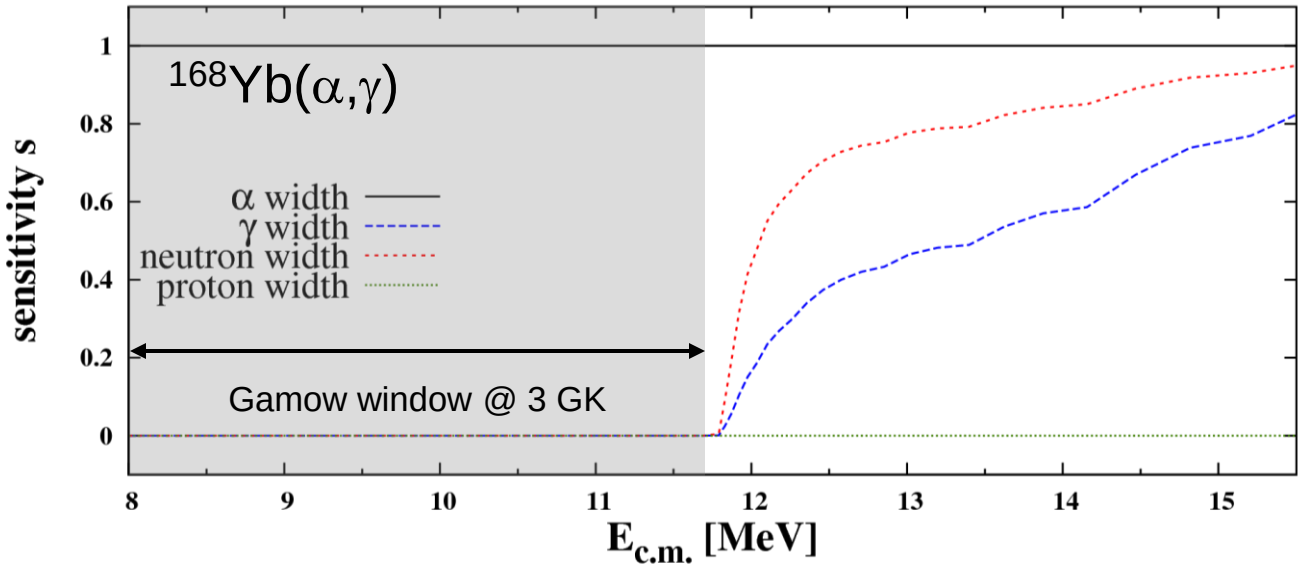
… ction for
… eaction

… odels for
… ns

improve ^{172}Hf(γ,α)^{168}Yb
stellar reaction rate

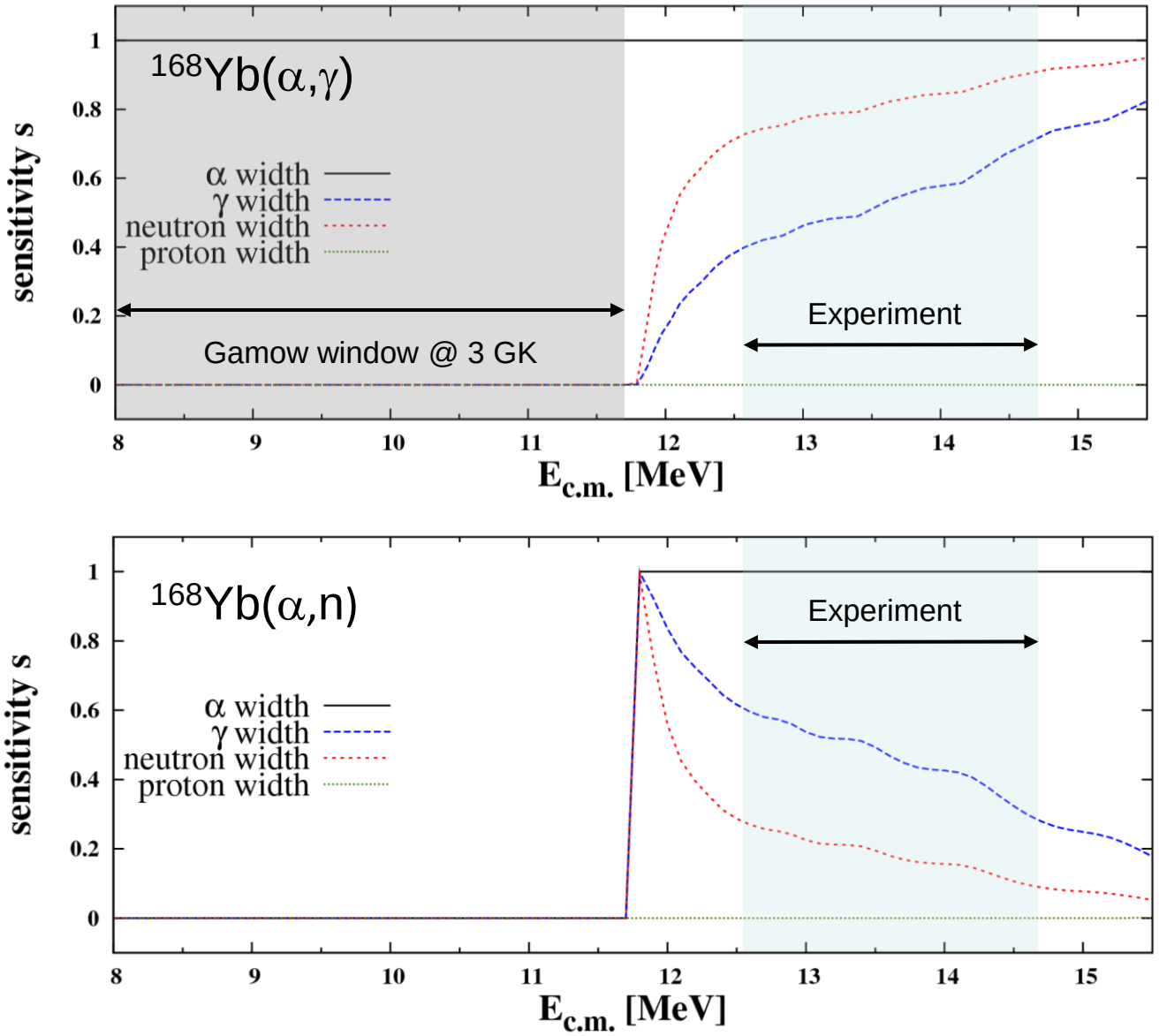
T. Rauscher, Phys. Rev. C 73 (2006) 015804

^{168}Yb(α,x) – Sensitivity studies



T. Rauscher, Ap. J. Suppl. **201** (2012) 26

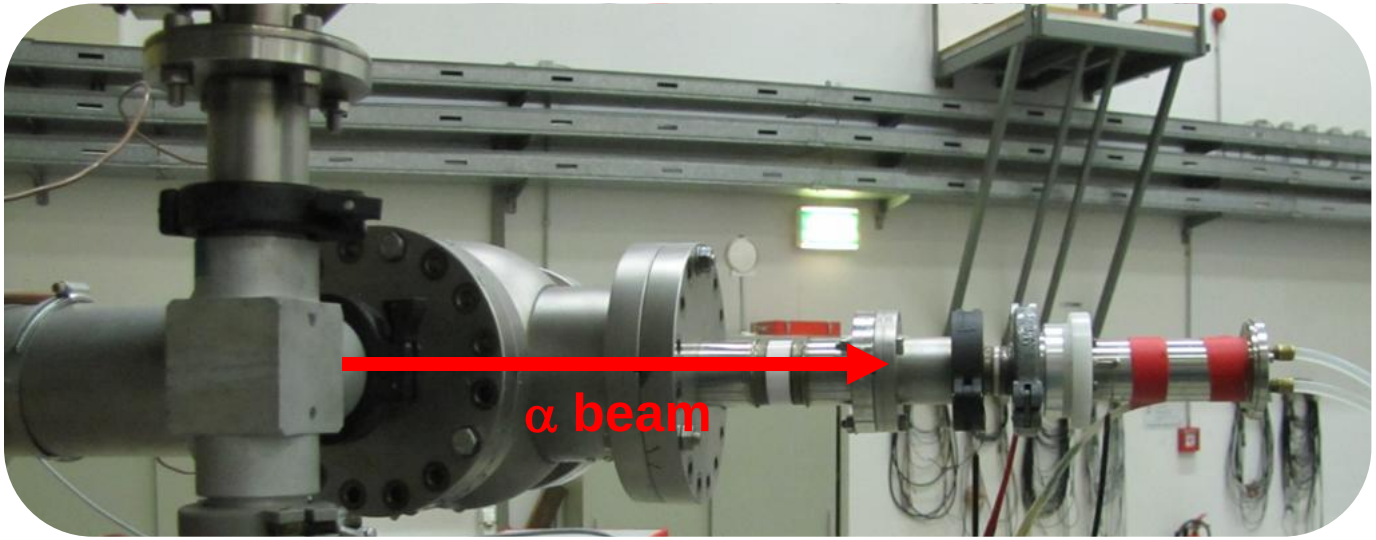
^{168}Yb(α,x) – Sensitivity studies



T. Rauscher, Ap. J. Suppl. **201** (2012) 26

Activation method

1. irradiation of stable targets at accelerator facility

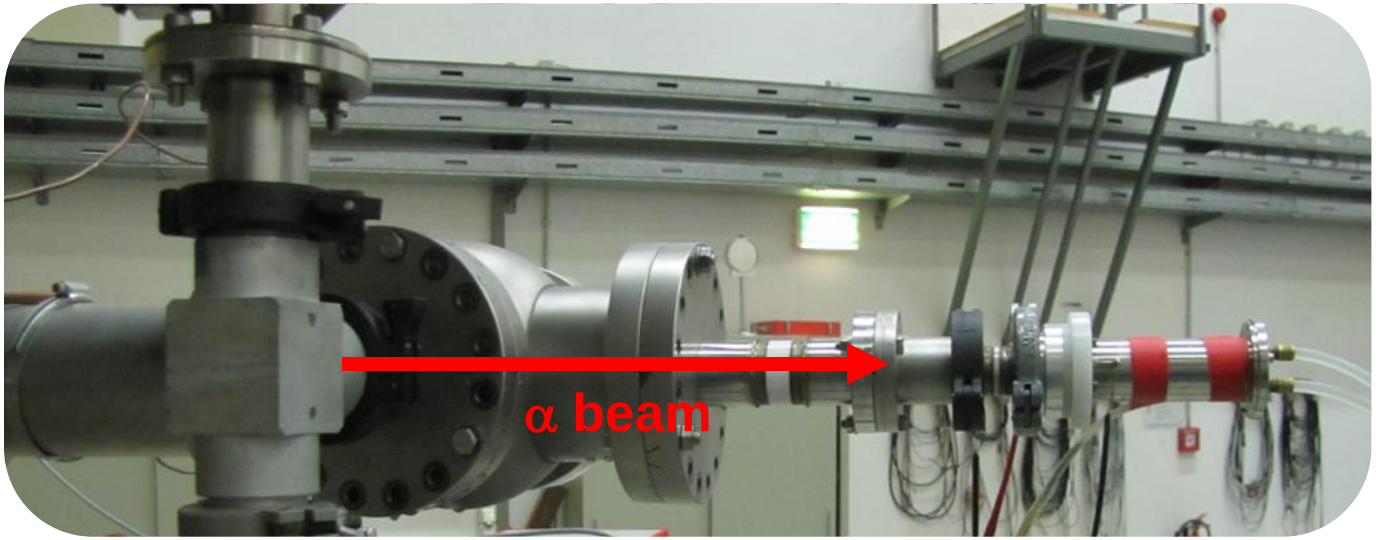


PTB Braunschweig

Beam current:
600 nA for ^{168}Yb

Activation method

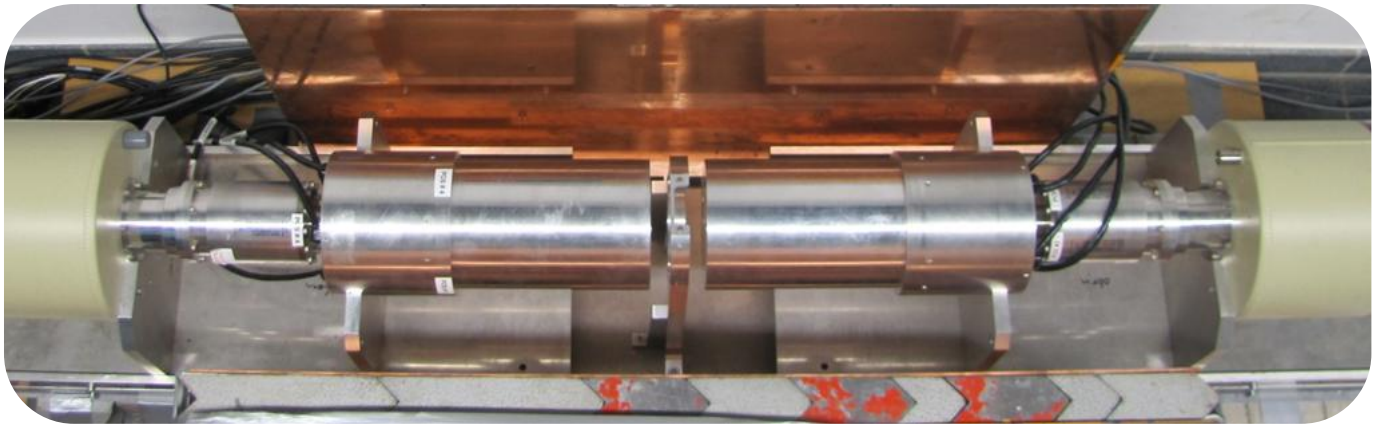
1. irradiation of stable targets at accelerator facility



PTB Braunschweig

Beam current:
600 nA for ^{168}Yb

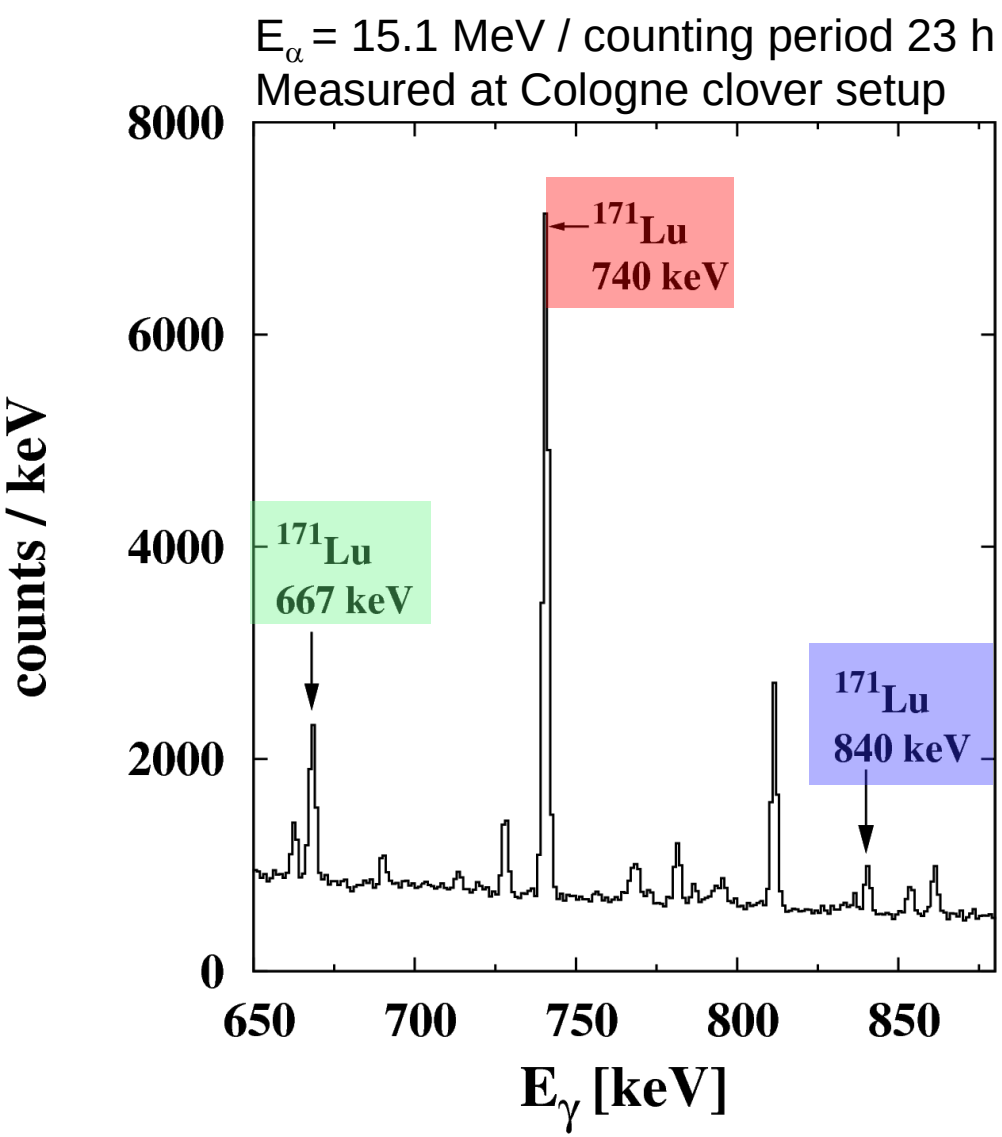
2. spectroscopy of radioactive decay of produced nuclei

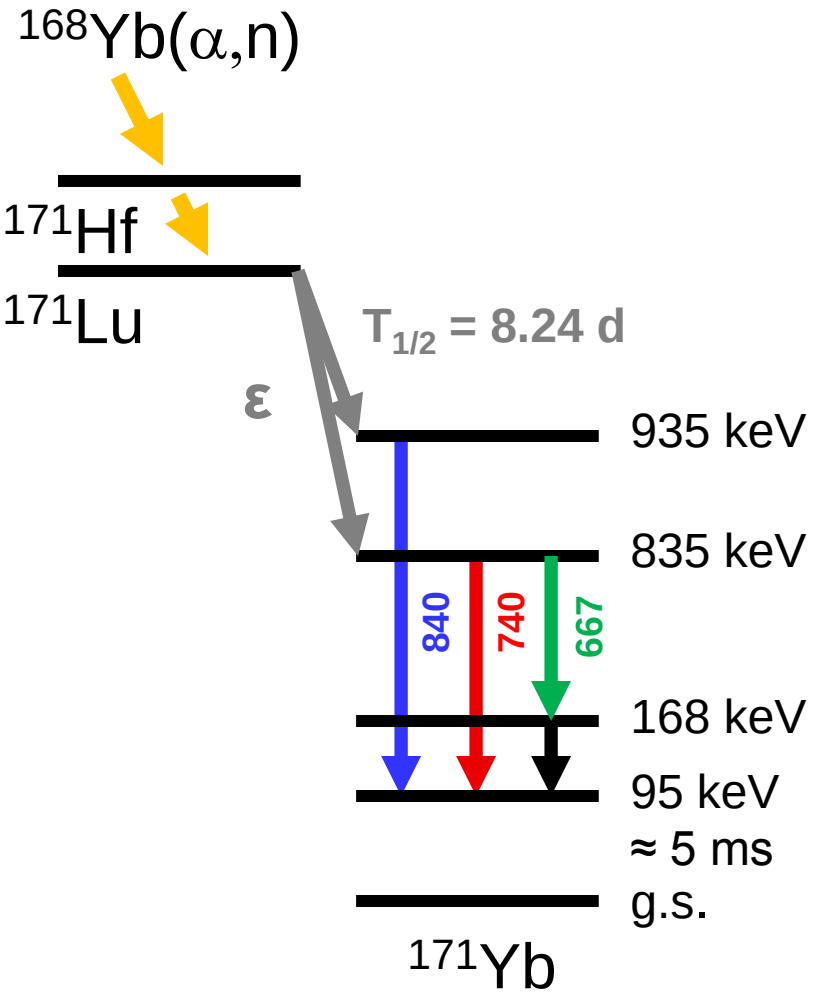


Cologne clover setup

Talk by P. Scholz

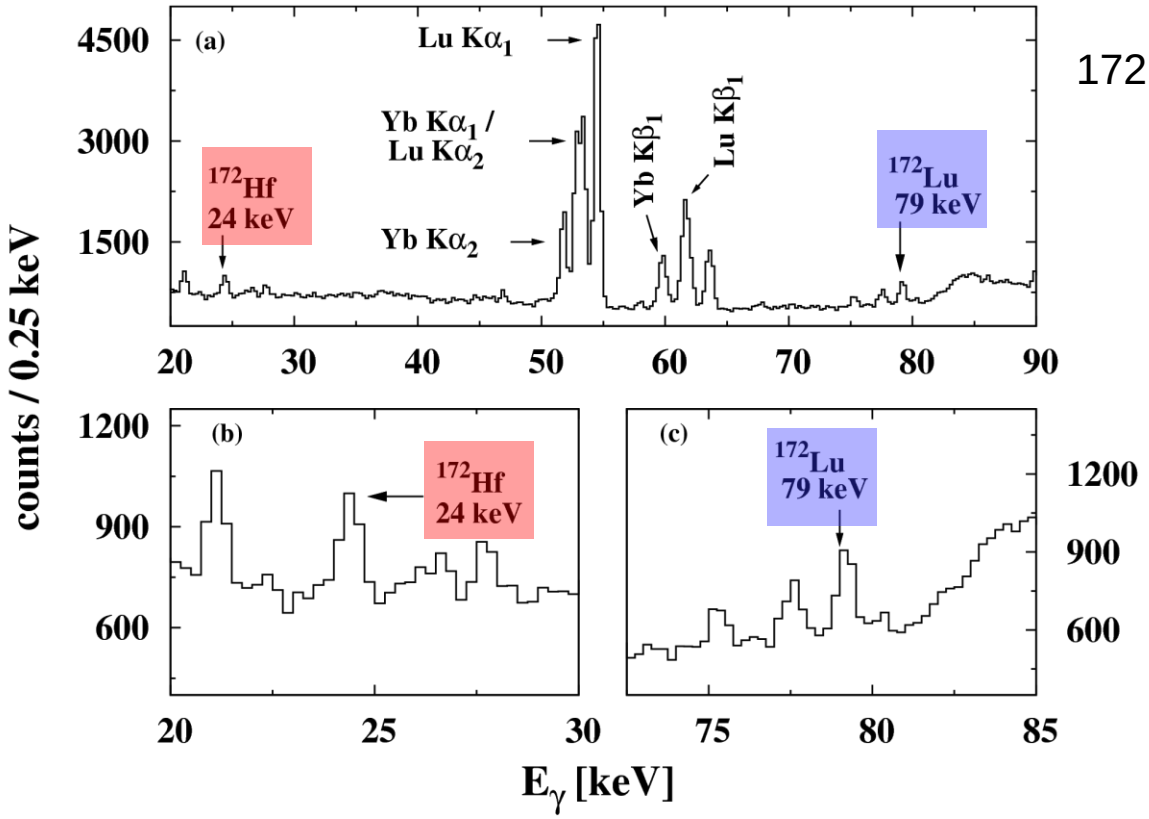
Activation measurement of ^{168}Yb(α,n)

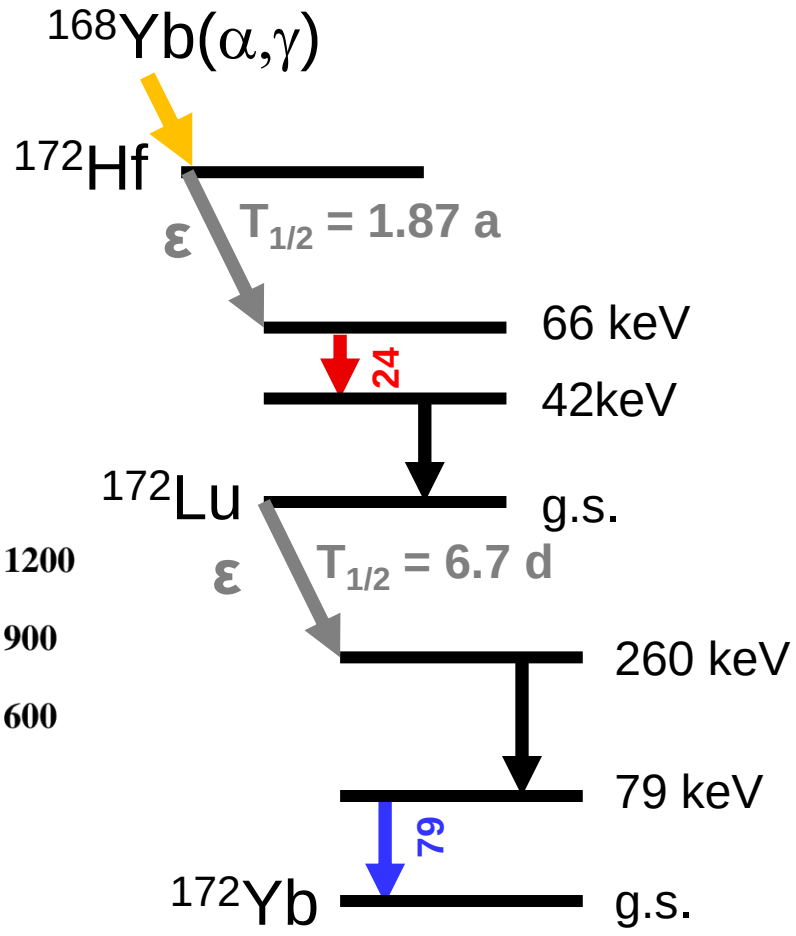




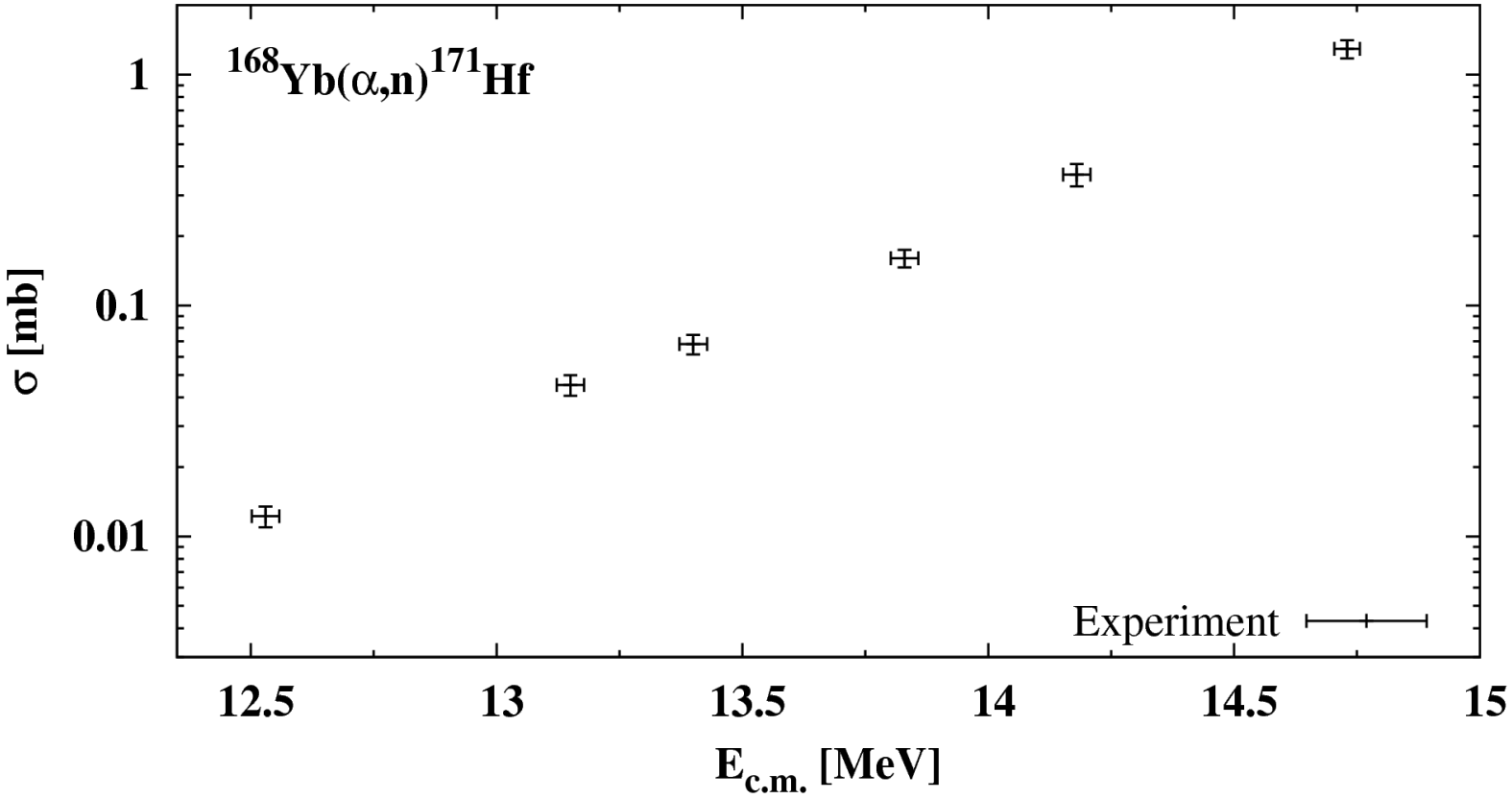
Activation measurement of ^{168}Yb(α,γ)

E_α = 15.1 MeV / counting period 14 d
measured with LEPS @ ATOMKI



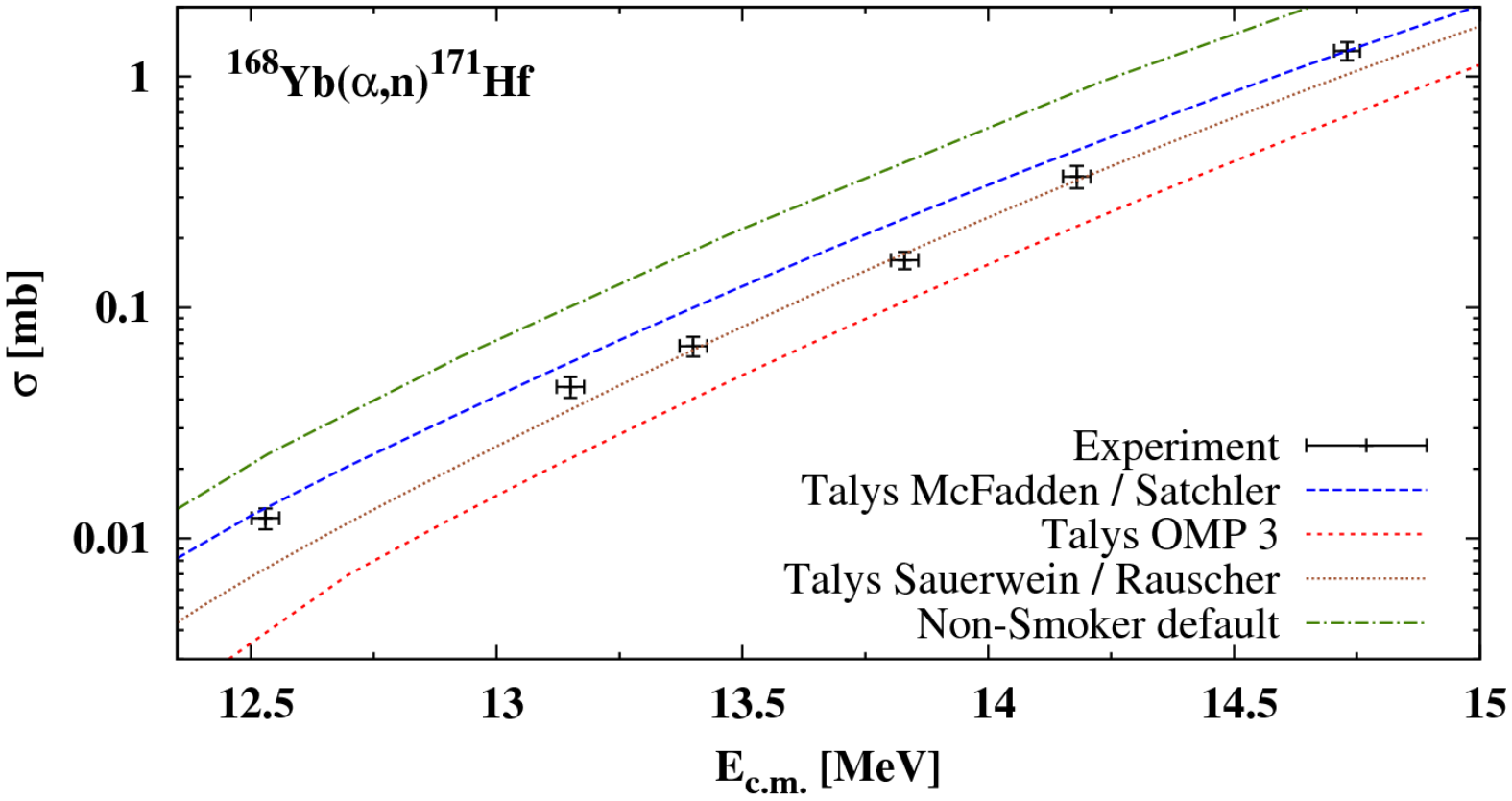


^{168}Yb(α,n) - Results



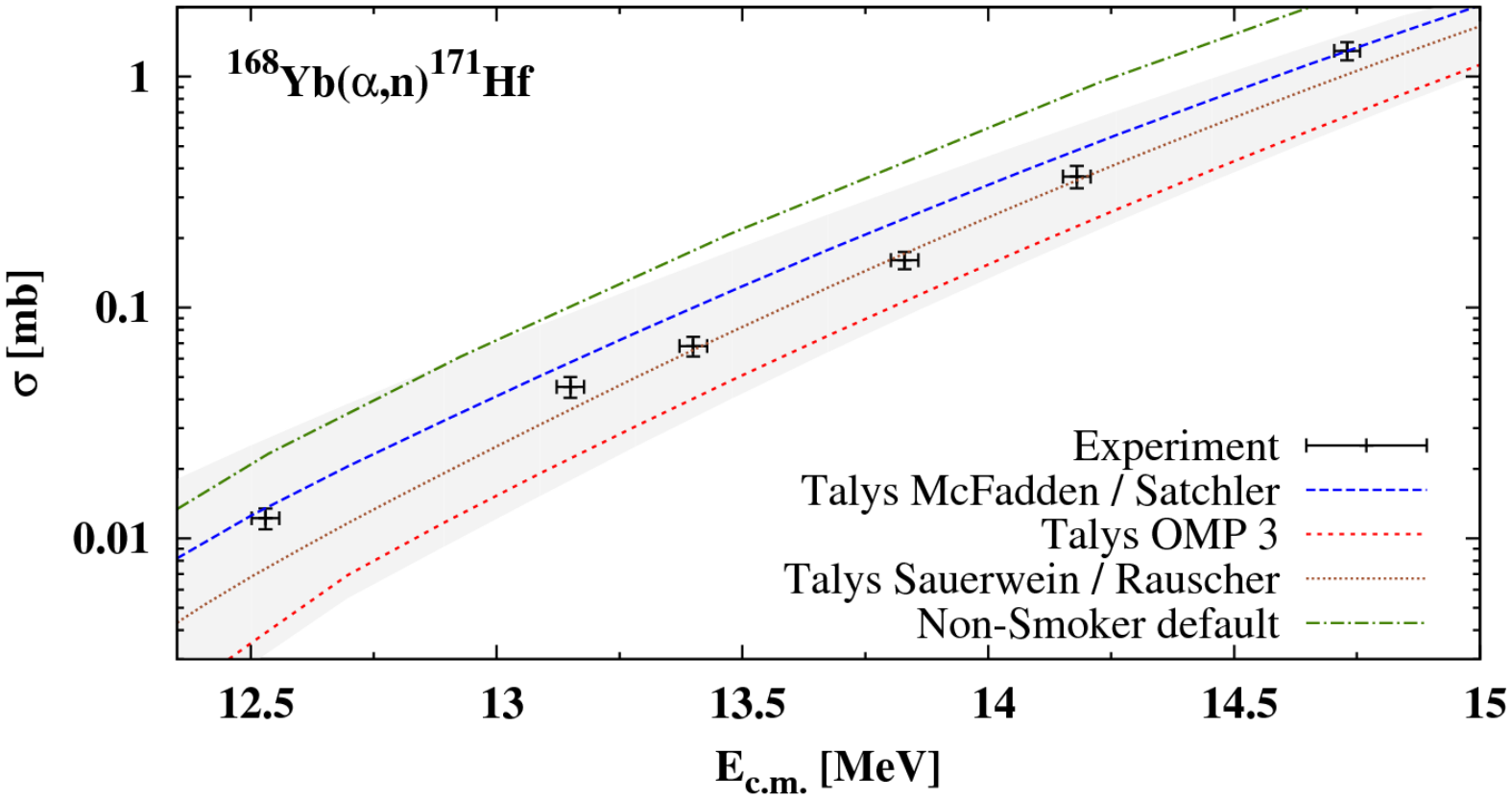
L. Netterdon *et al*., submitted to Nucl. Phys. A (2013)

^{168}Yb(α,n) - Results



L. Netterdon *et al*., submitted to Nucl. Phys. A (2013)
A. Sauerwein *et al*., Phys. Rev. C **84** (2011) 045808

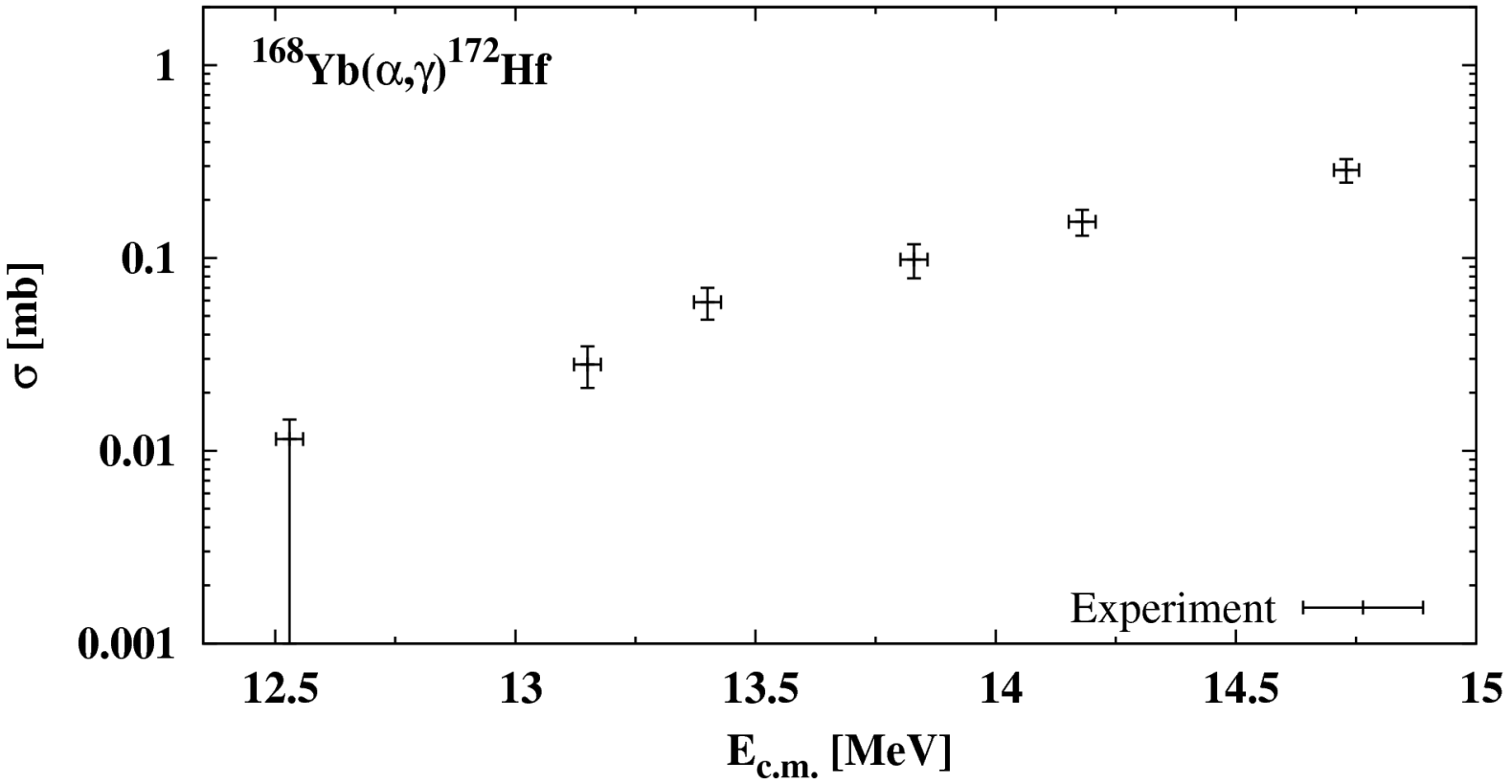
^{168}Yb(α,n) - Results



L. Netterdon *et al*., submitted to Nucl. Phys. A (2013)

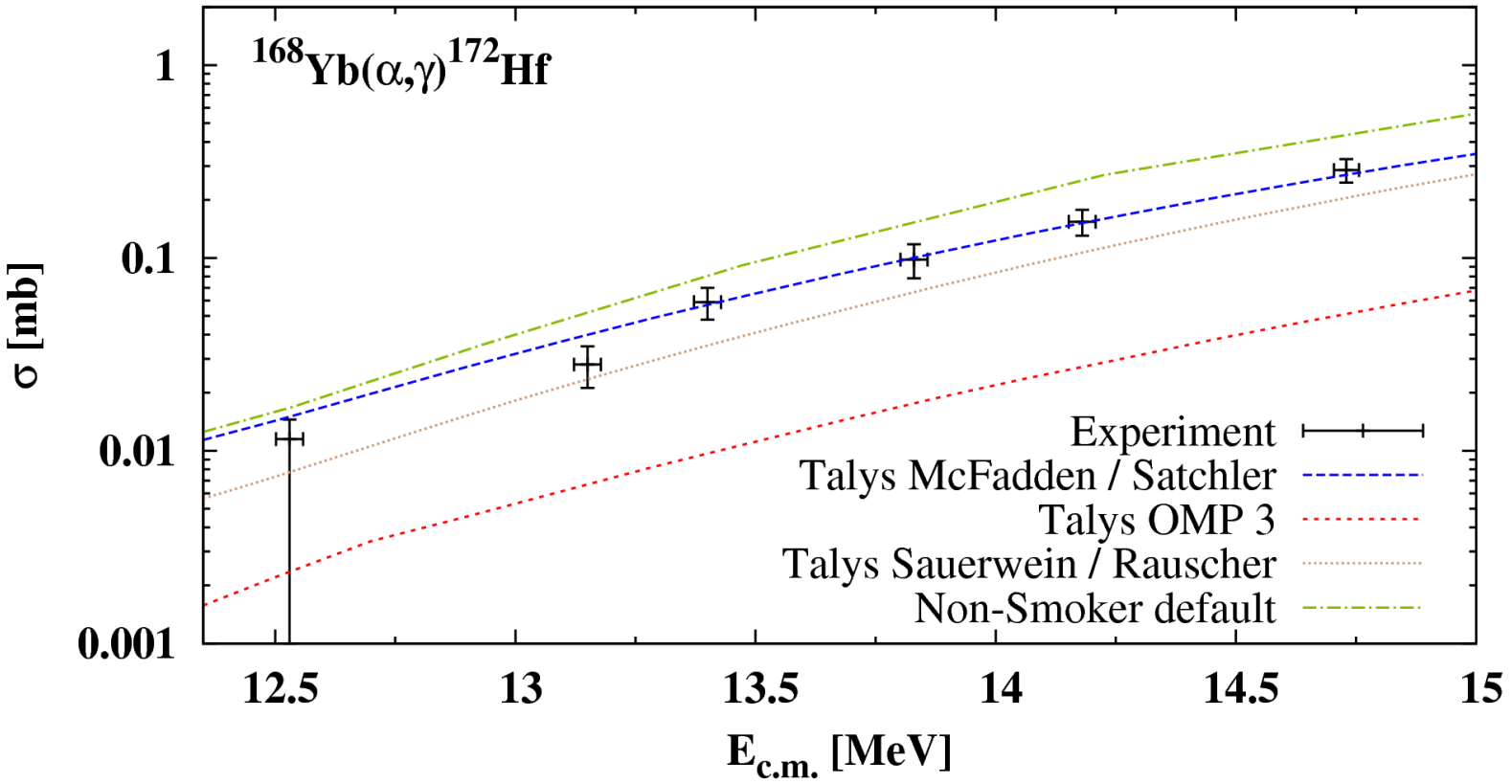
A. Sauerwein *et al*., Phys. Rev. C **84** (2011) 045808

^{168}Yb(α,γ) - Results



L. Netterdon *et al*., submitted to Nucl. Phys. A (2013)

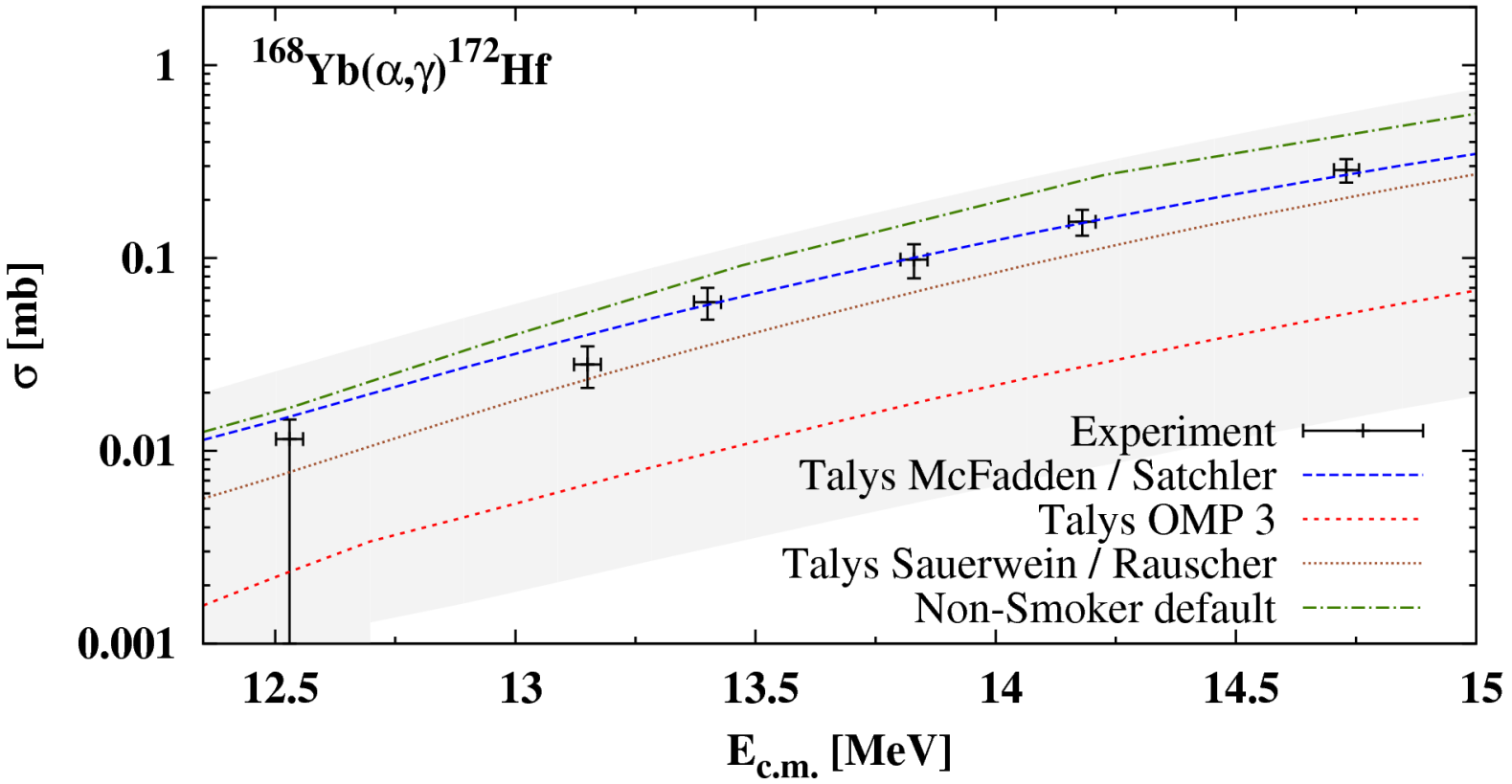
^{168}Yb(α,γ) - Results



L. Netterdon *et al*., submitted to Nucl. Phys. A (2013)

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

^{168}Yb(α,γ) - Results



L. Netterdon *et al*., submitted to Nucl. Phys. A (2013)

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

Summary

- measured cross sections of α-induced reactions on ^{168}Yb
  - ^{168}Yb(α,n) - Cologne clover setup
  - ^{168}Yb(α,γ) - LEPS @ ATOMKI

- good agreement with theoretical calculations using modified Sauerwein / Rauscher α-OMP

- measurement below neutron emission threshold to draw unambiguous conclusions

Charged-particle induced reactions for the nucleosynthesis of *p* nuclei

V. Derya, J. Endres, A. Hennig, J. Mayer, S. Pascu, S. G. Pickstone, P. Scholz, A. Sauerwein, F. Schlüter, M. Spieker, T.-M. Streit, K. O. Zell, and A. Zilges

H.W. Becker and D. Rogalla

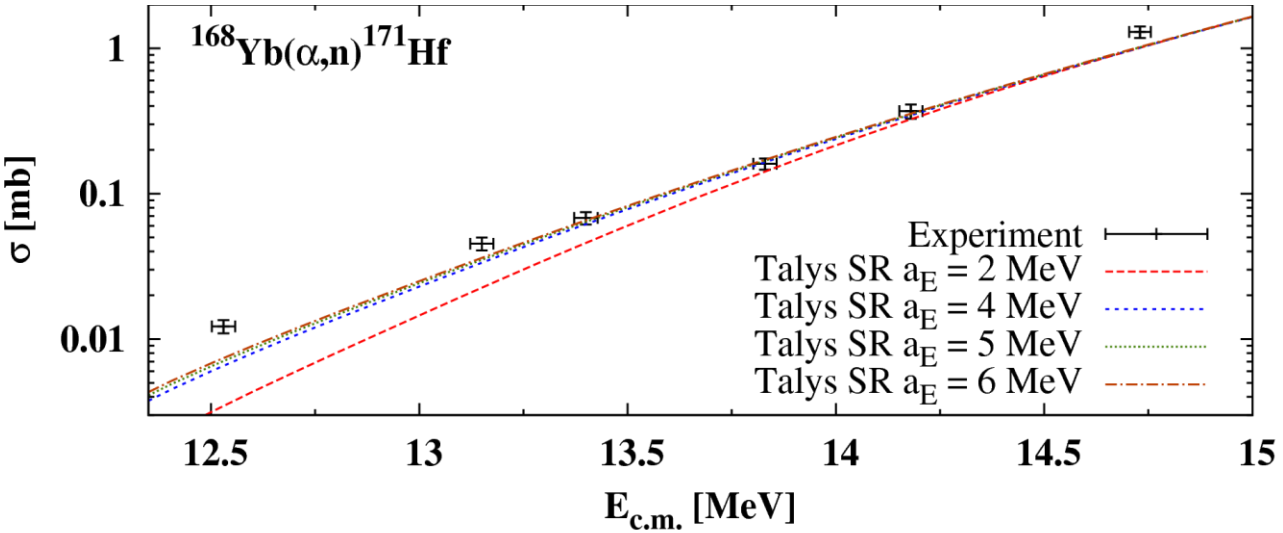
U. Giesen

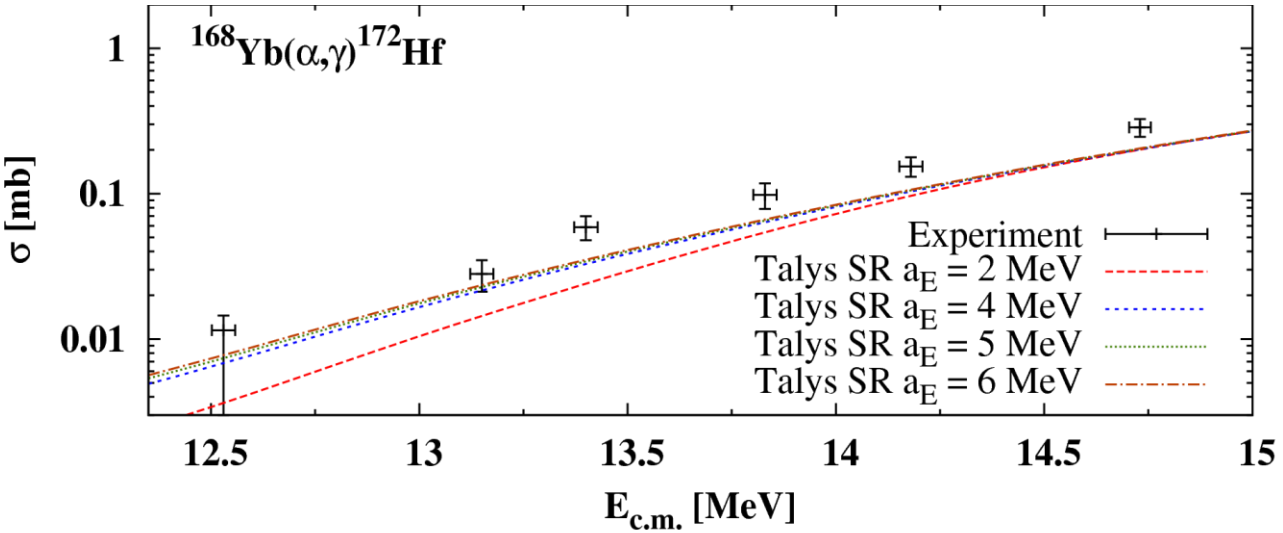
G. G. Kiss and T. Szücs

P. Demetriou

^{168}Yb(α,x) – Modification of SR α-OMP

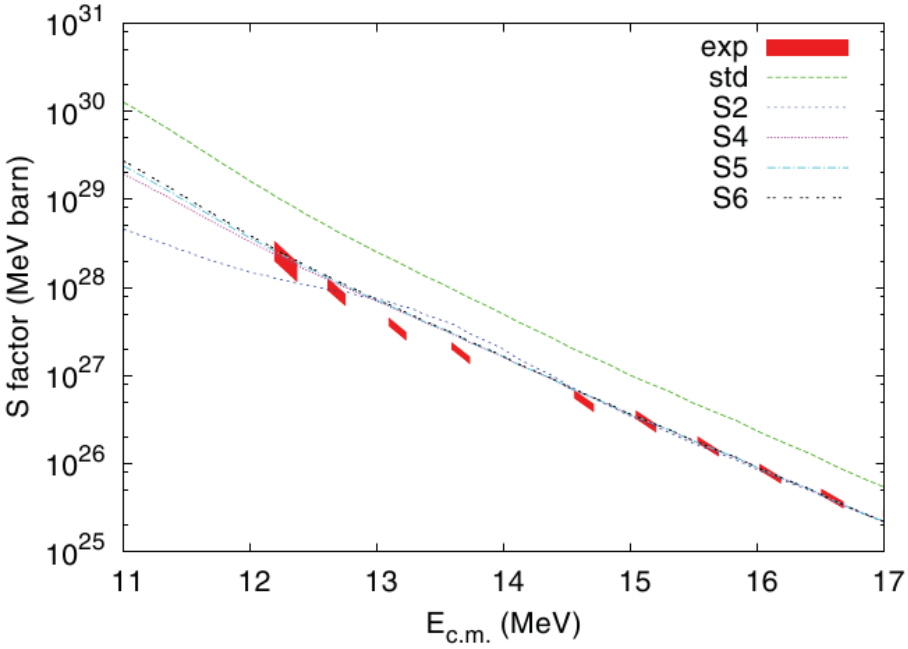
$$W = \frac{25\,\mathrm{MeV}}{1 + e^{(0.9\,E_C - E_{c.m.})/a_E}}$$



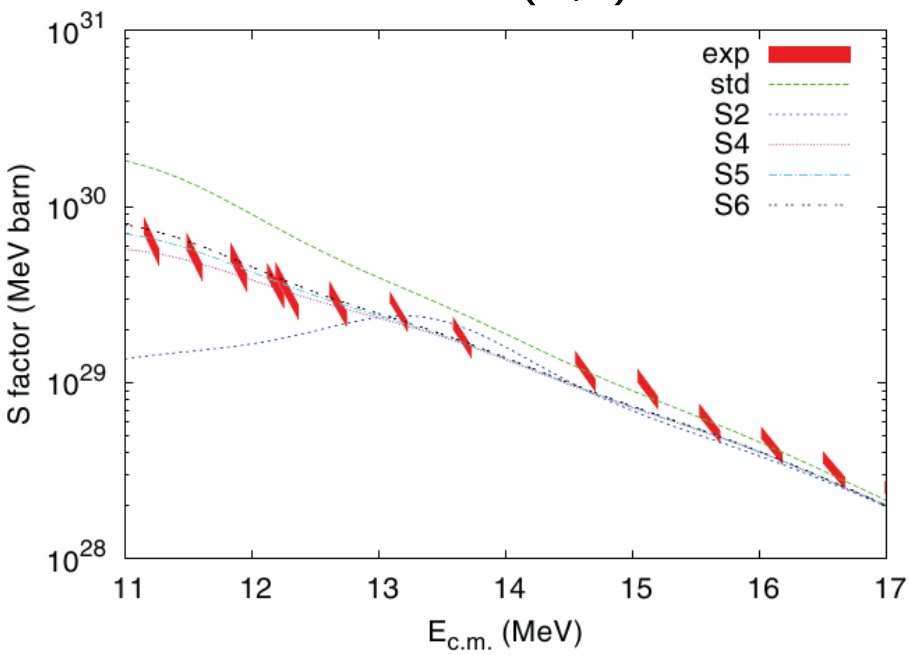


^{169}Tm(α,x) – Modification of SR α-OMP

^{169}Tm(α,γ)

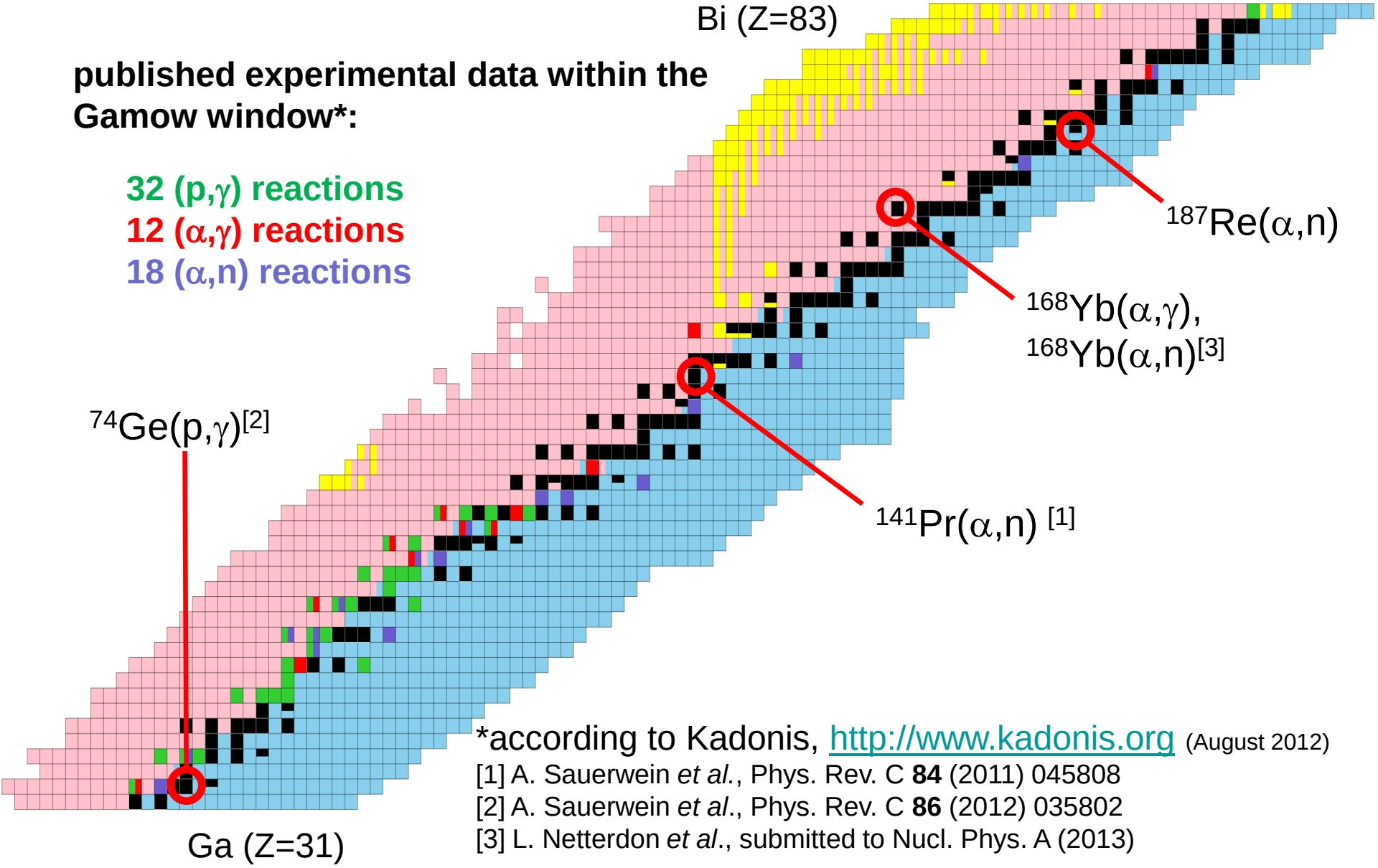


^{169}Tm(α,n)



T. Rauscher *et al.*, Phys. Rev. C **86** (2012) 015804

Experimental situation



*according to Kadonis, http://www.kadonis.org (August 2012)

[1] A. Sauerwein *et al.*, Phys. Rev. C **84** (2011) 045808
[2] A. Sauerwein *et al.*, Phys. Rev. C **86** (2012) 035802
[3] L. Netterdon *et al.*, submitted to Nucl. Phys. A (2013)