Radiative capture and photodisintegration reactions for the synthesis of the *p* nuclei

Philipp Scholz
for the group of Prof. Dr. Andreas Zilges
Institute for Nuclear Physics, University of Cologne

Workshop on New Vistas in Low-Energy Precision Physics (LEPP)
April 4th-7th, 2016

Supported by the ULDETIS project within the UoC Excellence Initiative institutional strategy and by DFG (ZI 510/8-1, INST 216/544-1).
* Partly supported by the Bonn-Cologne Graduate School of Physics and Astronomy.

Outline

Introduction

- Nucleosynthesis of heavy elements and the *p* nuclei
- the γ-process reaction network

Experimental measurements of cross-sections

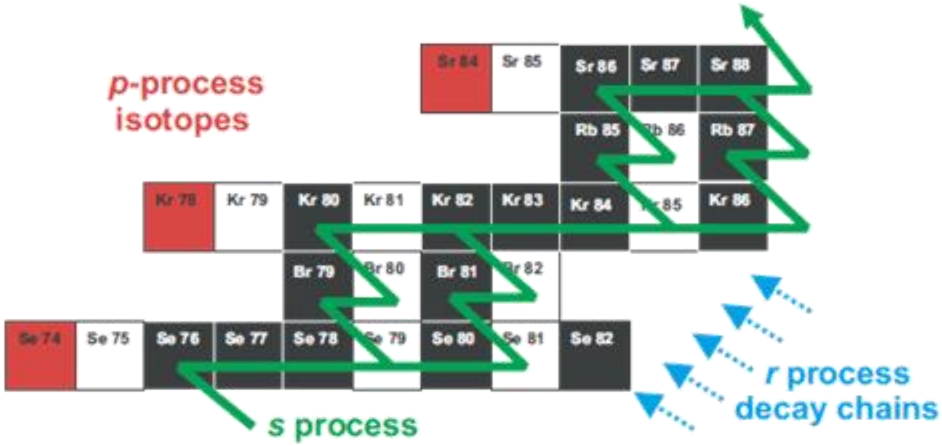
- photo-induced reaction measurements
- charged-particle induced reaction studies

Experimental results

- testing the E1-strength in ^{90}Zr via ^{89}Y(p,γ)
- total and partial cross sections for ^{92}Mo(p,γ)

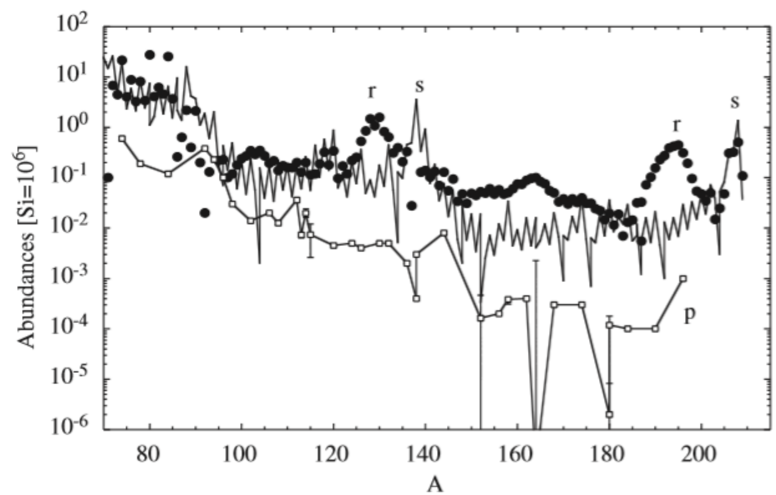
T. Rauscher *et al.*, Rep. Prog. Phys. **76** (2013) 066201

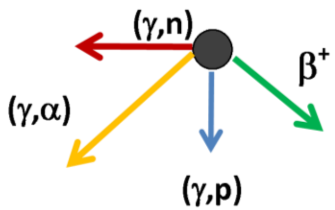
p nuclei

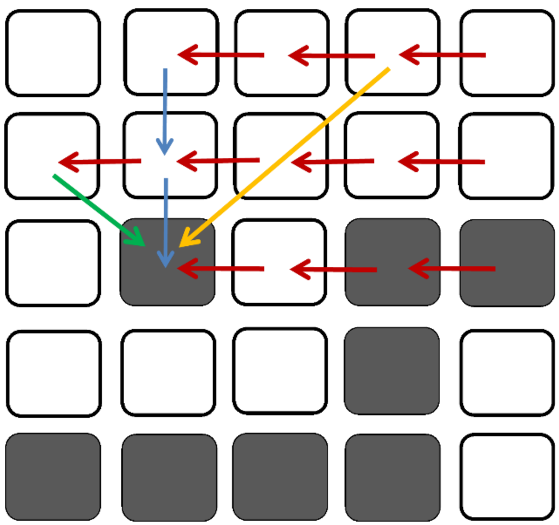


- 30-35 neutron deficient isotopes
- cannot be produced by neutron-capture reactions
- relatively low isotopic abundances in comparison to *s*- and *r*-isotopes
- originally thought to be produced via proton-capture
- temperatures would lead to immediate photodisintegration

M. Arnould *et al.*, Phys. Rep. **450** (2007) 97



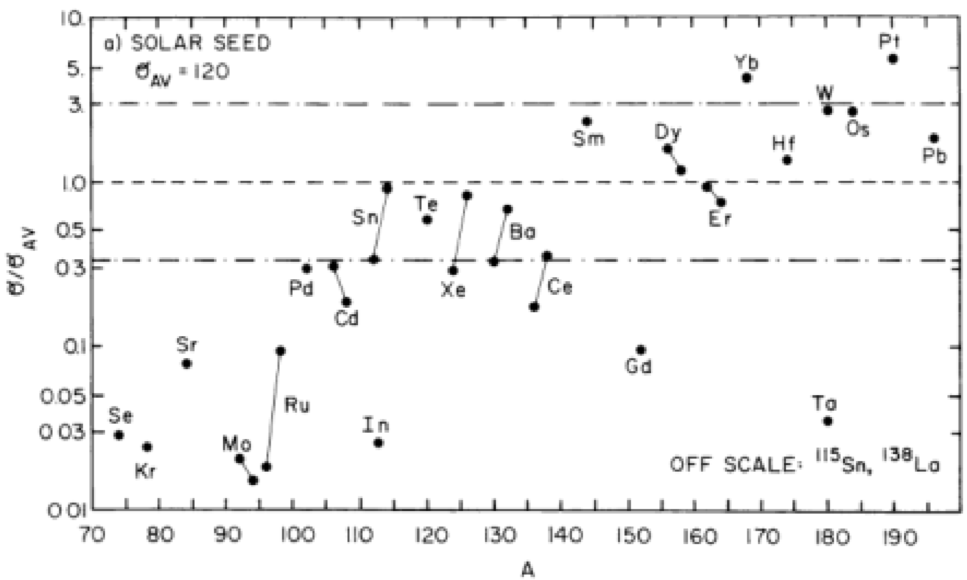




γ process reaction-network

- huge photodisintegration reaction-network
- at temperatures between 1.5 GK and 3 GK in ccSN or type Ia SN
- starting from stable seed nuclei formed in the *s*- or *r*-process
- γ-process path proceeds first via (γ,n) reactions
- branching for A < 130 mainly via (γ,p)
- above A > 130 (γ,α) get more important

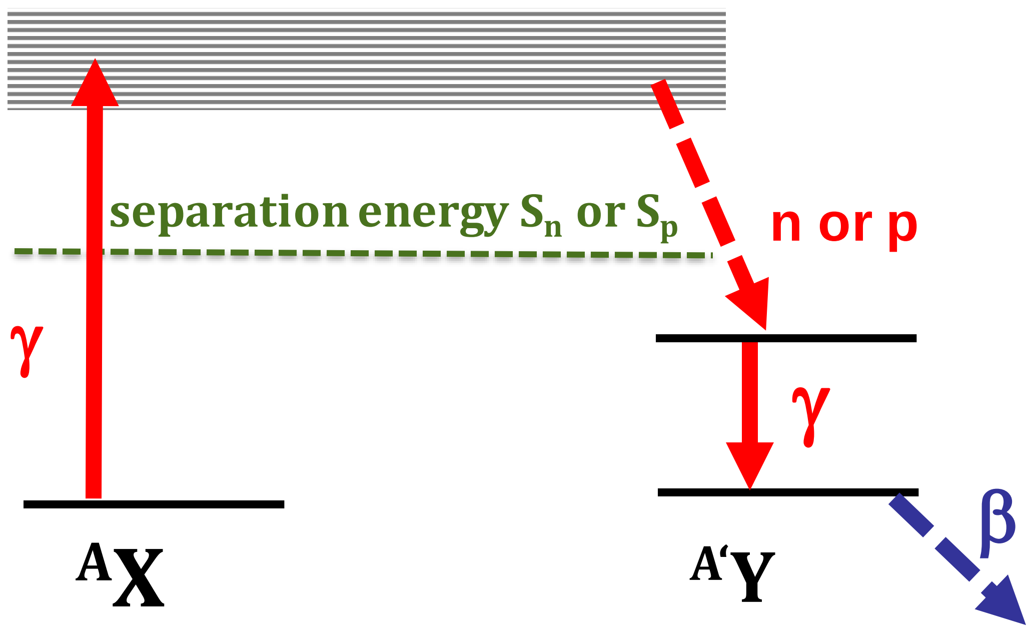
reaction-network calculations



- γ-process network calculations cannot reproduce solar system abundance
- other contributions from *rp*-, α- or other processes?
- problems with photoinduced reaction cross sections?

S.E. Woosley and W. M. Howard, ApJSS **36** (1978) 285

Photodisintegration

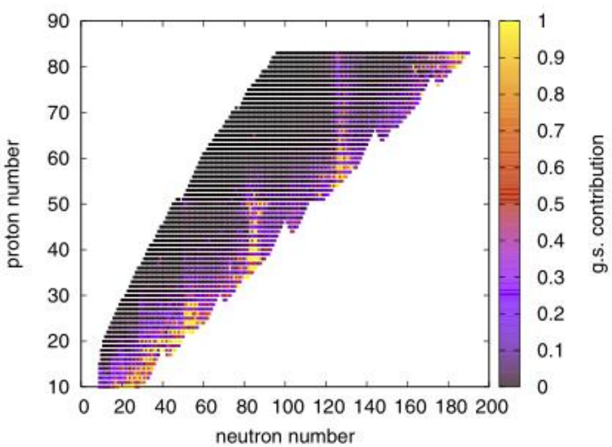


- measuring cross sections via direct detection of ejectiles or via photoactivation
- using either monochromatic γ-ray beams or Bremsstrahlung

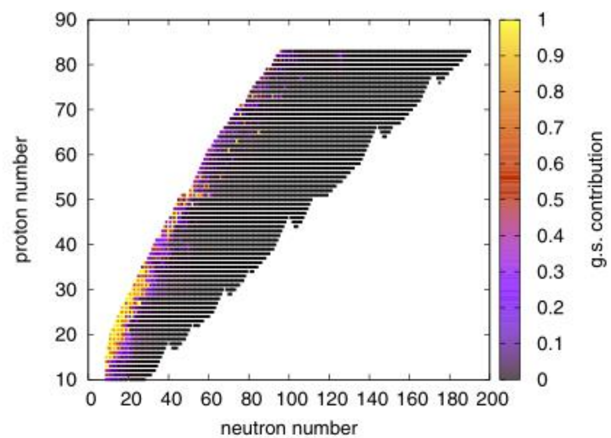
Experimental measurements of cross sections

Ground-state contributions

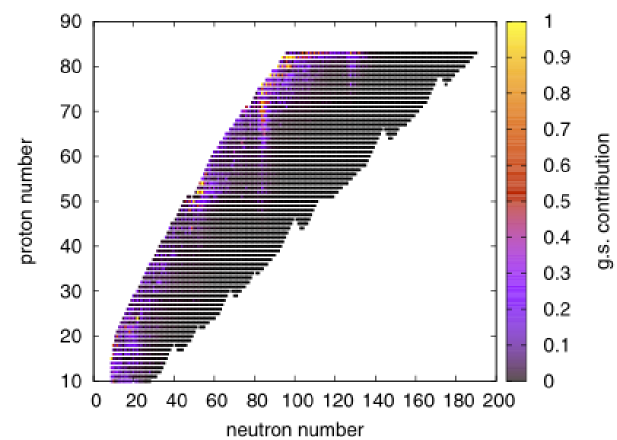
- measured cross sections cannot directly used for astrophysics
- for γ-induced reaction the ground-state contribution is almost zero
- larger contribution from excited states in the stellar plasma ($T_9 > 1.5$)
- reaction rates are obtained from the inverse reactions via reciprocity theorem



(γ,n)



(γ,p)



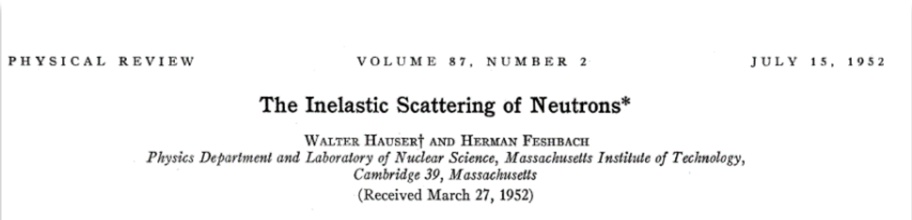
(γ,α)

T. Rauscher, ApJSS **201** (2012) 26

Experimental measurements of cross sections

Statistical model

- cross sections in the Gamow window are small (< μb)
- most of the reactions are not accessible in the laboratory
- reaction rates are calculated mostly in the scope of the statistical model
- cross-section measurements to improve nuclear physics input-parameters:
  - γ-strength function (also via (γ,γ'))
  - particle + nucleus optical model potentials

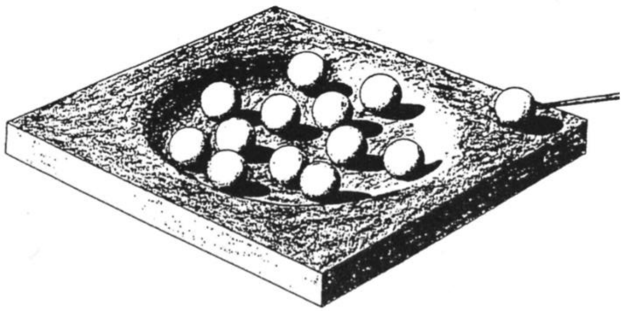

PHYSICAL REVIEW VOLUME 87, NUMBER 2 JULY 15, 1952

The Inelastic Scattering of Neutrons*

Walter Hauser† and Herman Feshbach

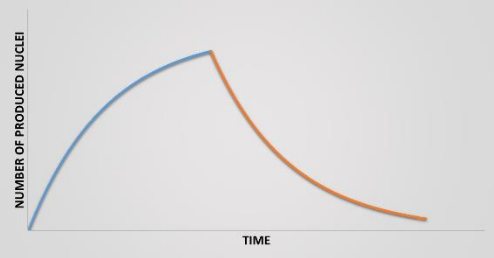
Physics Department and Laboratory of Nuclear Science, Massachusetts Institute of Technology, Cambridge 39, Massachusetts

(Received March 27, 1952)



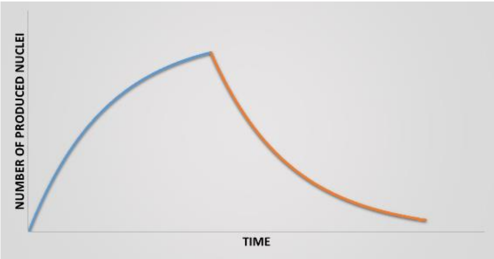
$$\sigma_{jk}^{\mu}(E) = \pi\lambda_j^2 \frac{1}{(2J_I^{\mu}+1)(2J_j+1)} \sum_{J^{\mu}} (2J+1) \frac{T_j^{\mu}(J^{\pi})T_k(J^{\pi})}{T_{tot}(J^{\pi})}$$

Activation technique



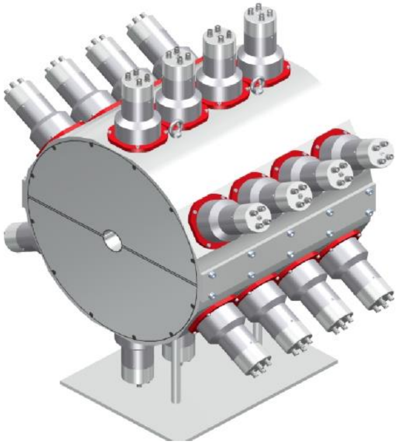
- widely used technique for measureing cross-sections
- temporal and spatial separation of irradiation and spectroscopy
- no access to reactions involving stable reaction products
- feasible half-lives neccessary

Activation technique



- widely used technique for measureing cross-sections
- temporal and spatial separation of irradiation and spectroscopy
- no access to reactions involving stable reaction products
- feasible half-lives neccessary

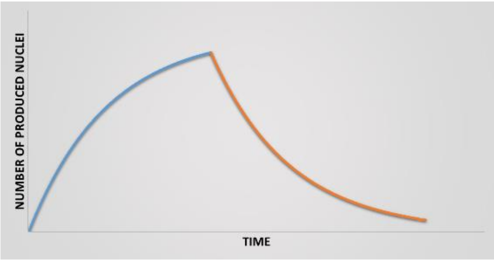
4π summing crystal method



- complete deexcitation is summed up in one peak
- access to stable reaction products
- need for very different Q-values for competing reactions
- no access to partial cross-sections

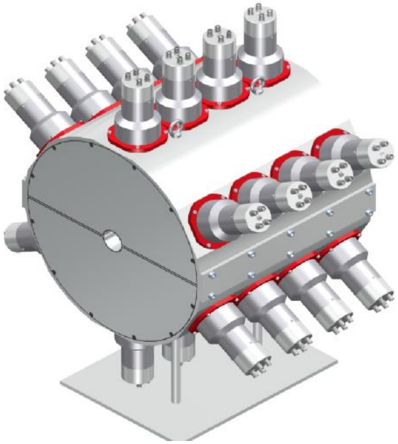
Charged-particle induced reaction cross sections

Activation technique



- widely used technique for measureing cross-sections
- temporal and spatial separation of irradiation and spectroscopy
- no access to reactions involving stable reaction products
- feasible half-lives neccessary

4π summing crystal method

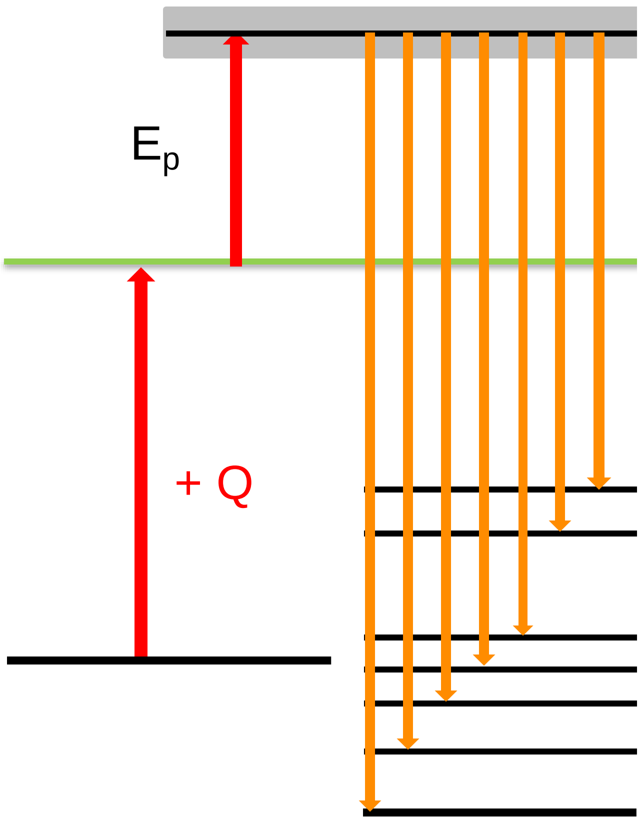


- complete deexcitation is summed up in one peak
- access to stable reaction products
- need for very different Q-values for competing reactions
- no access to partial cross-sections

In-beam method with HPGe detectors

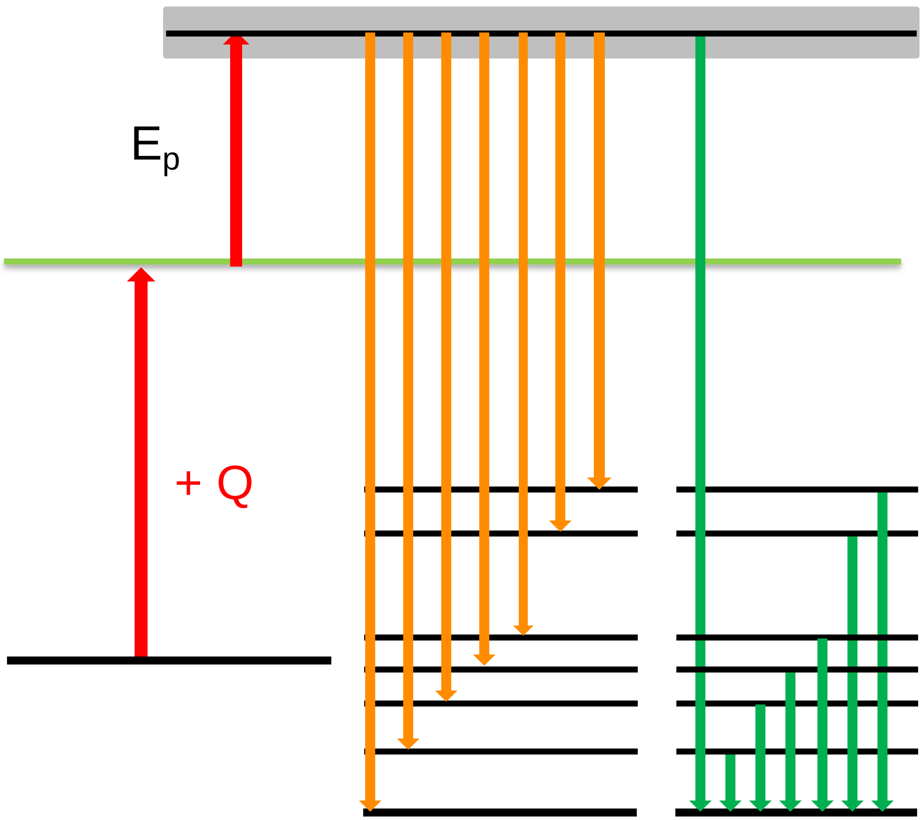
In-beam technique with HPGe detectors

- **de-excitation of the entry state**
  - determination of partial cross sections
  - very sensitive on the γ-ray strength function



In-beam technique with HPGe detectors

- **de-excitation of the entry state**
  - determination of partial cross sections
  - very sensitive on the γ-ray strength function
- **transitions to the ground state**
  - determination of the total cross section

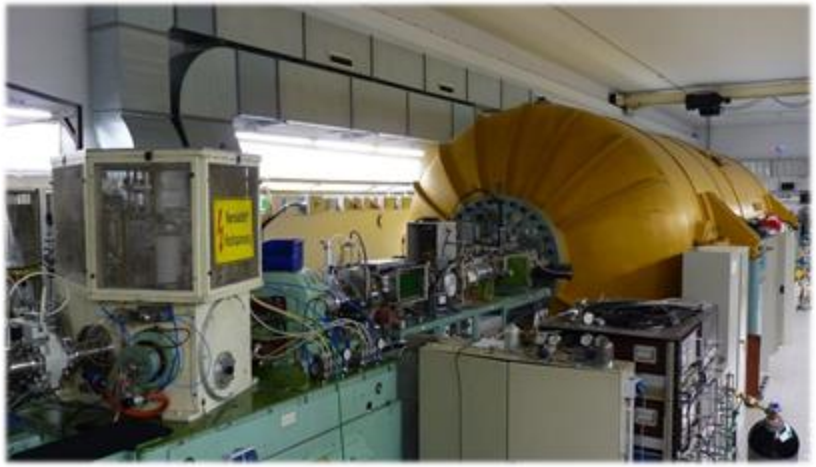


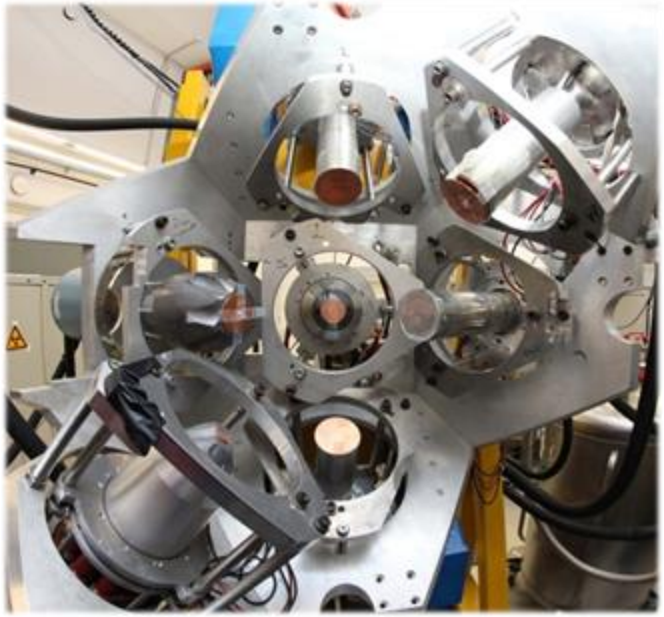
In-beam technique with HPGe detectors

- 10 MV FN-Tandem ion accelerator

HORUS γ-ray spectrometer

- 14 HPGe detectors
  - High resolution
    ≈ 2 keV @ 1332 keV
  - High total efficiency
    ≈ 2% @ 1332 keV
- 5 different angles with respect to beam axis
  - determination of angular distributions
- BGO shields

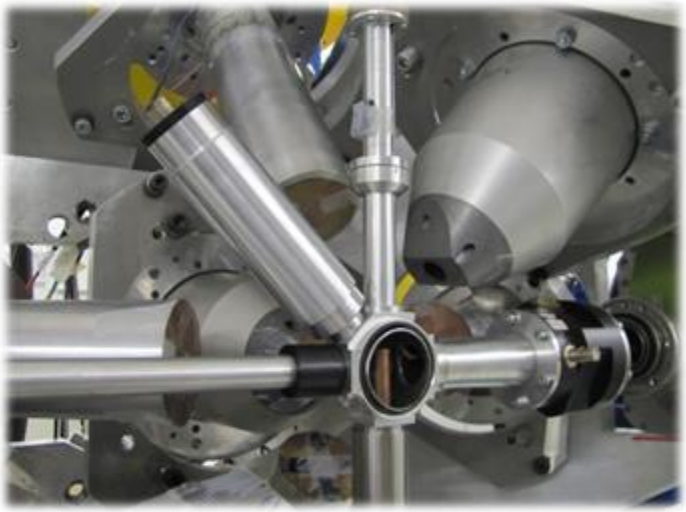


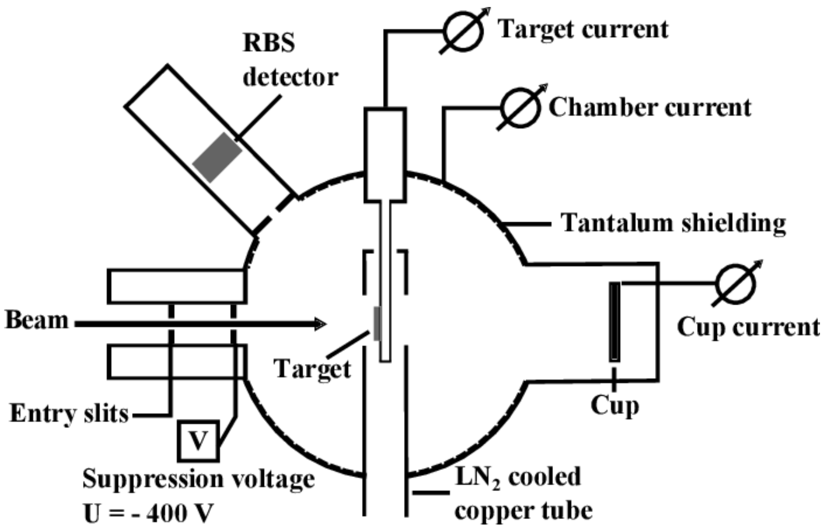


L. Netterdon *et al.*, NIM A **754** (2014) 94-100

Target chamber

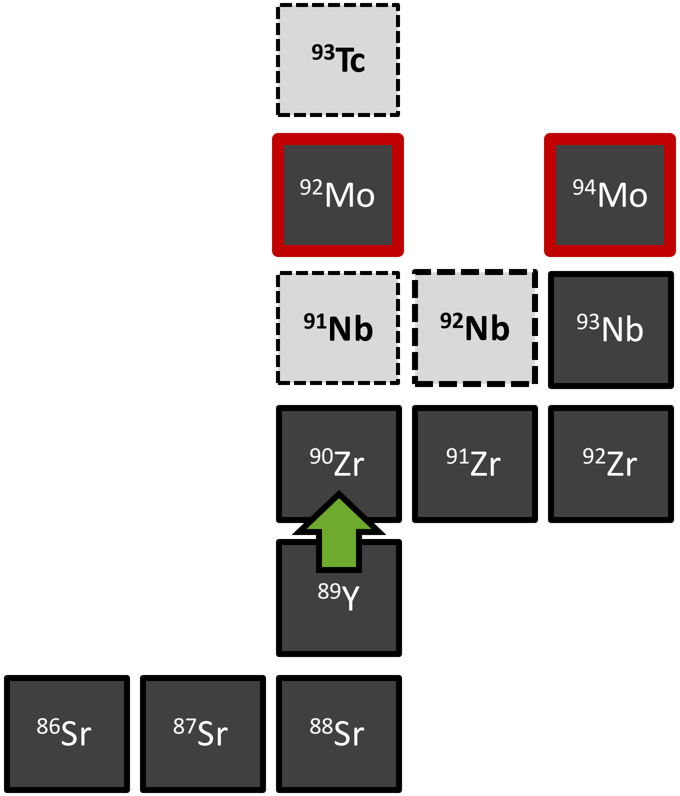
- cooling trap
- tantalum coating
- independent current readouts
- δ-electron suppression
- built-in detector for Rutherford Backscattering Spectrometry (RBS)





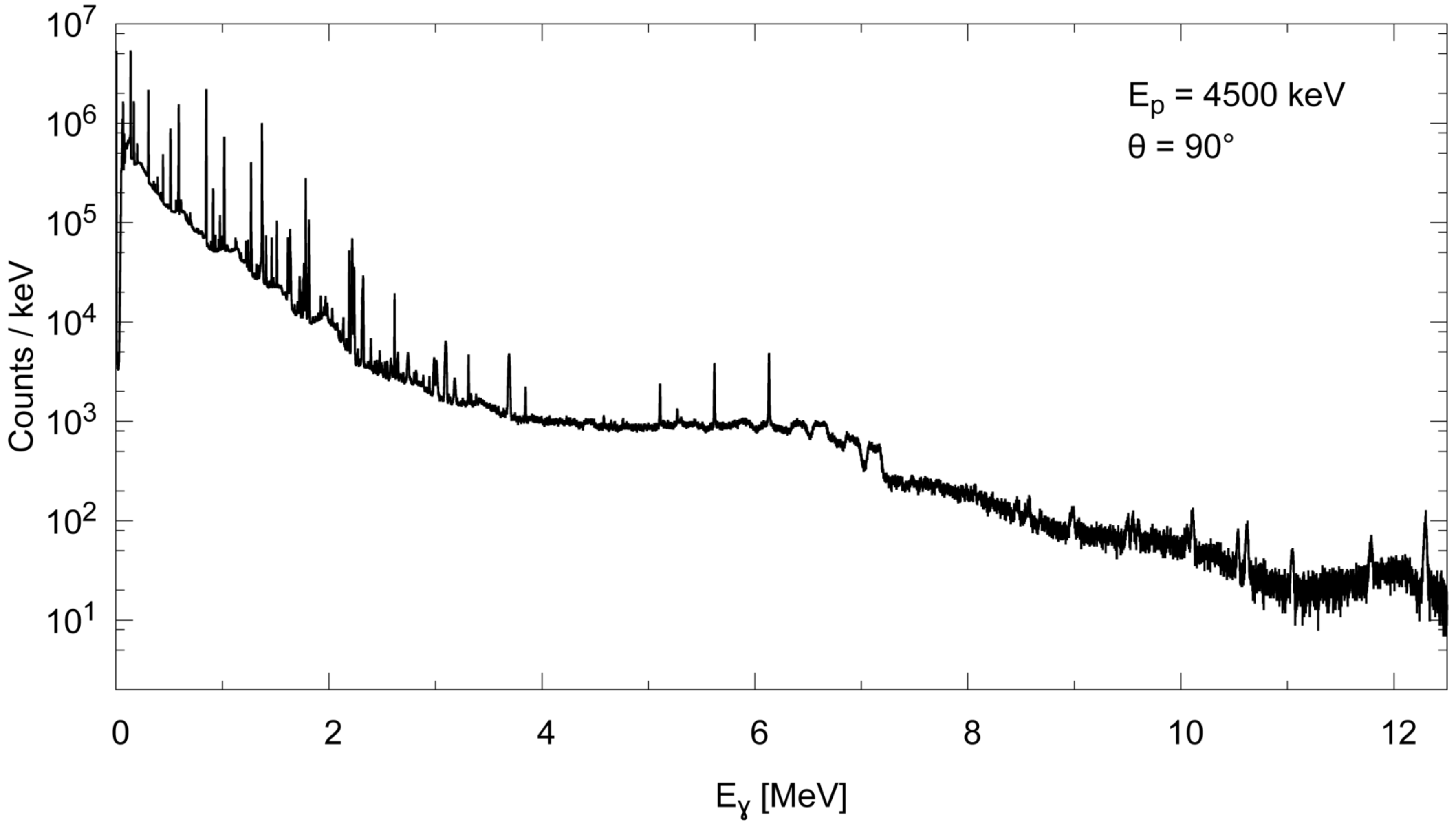
L. Netterdon *et al.*, NIM A **754** (2014) 94-100

In-beam measurement of the $^{89}Y(p,\gamma)$

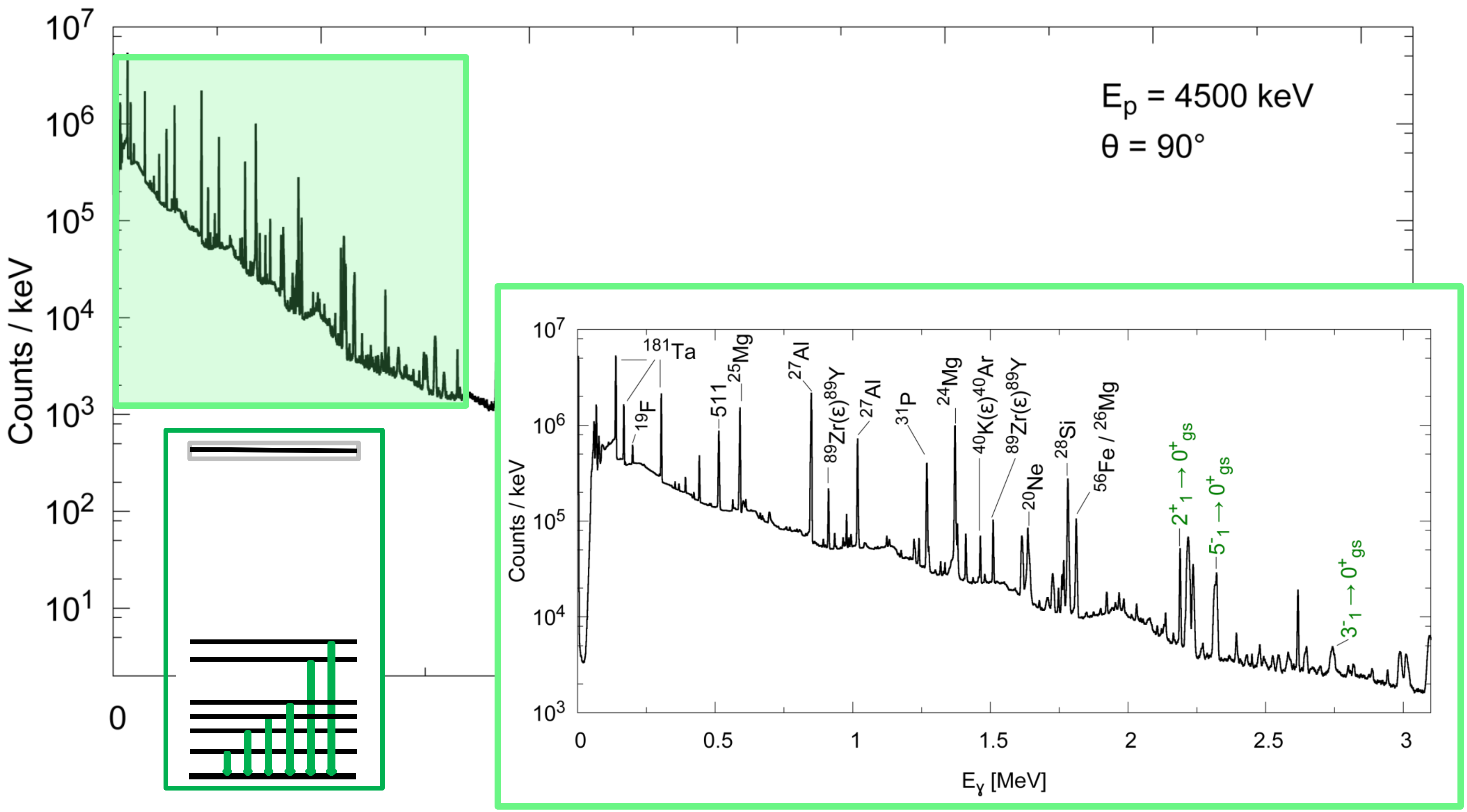


- reaction in a region which is normally underproduced in reaction network calculations
- total cross section was measured twice before
- γ-ray strength function in ^{90}Zr was measured before
- natural yttrium target ($583\mu g/cm^2$)
- beam currents between 1nA and 60nA
- five different proton energies between 3.65 MeV and 4.70 MeV, i.e. γ-ray energies between 7.71 MeV and 12.98 MeV (Q-Value: 8353.4 keV)

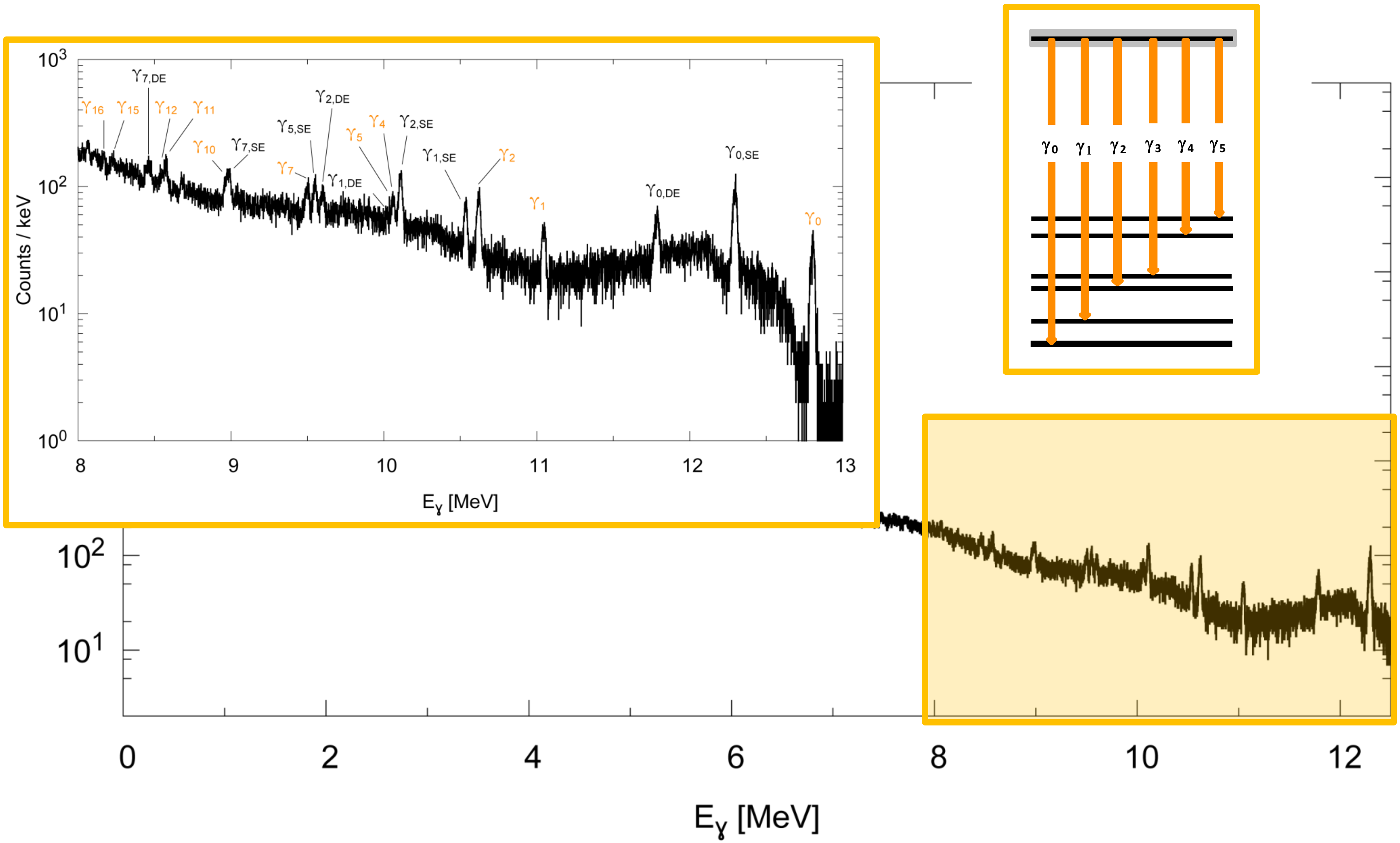
In-beam measurement of the $^{89}Y(p,\gamma)$



In-beam measurement of the $^{89}Y(p,\gamma)$



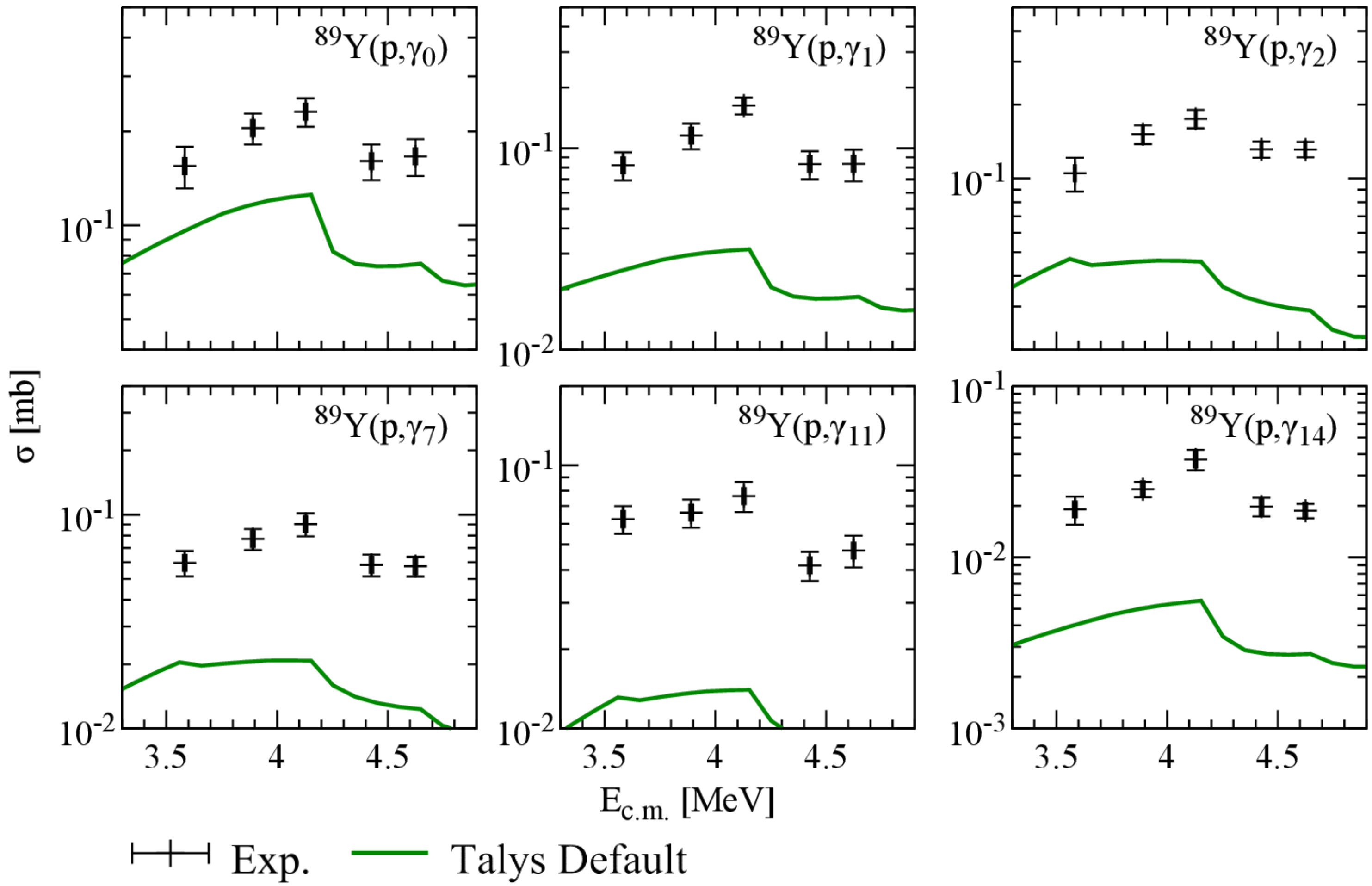
In-beam measurement of the $^{89}Y(p,\gamma)$



L. Netterdon *et al.*, PLB **744** (2015) 358

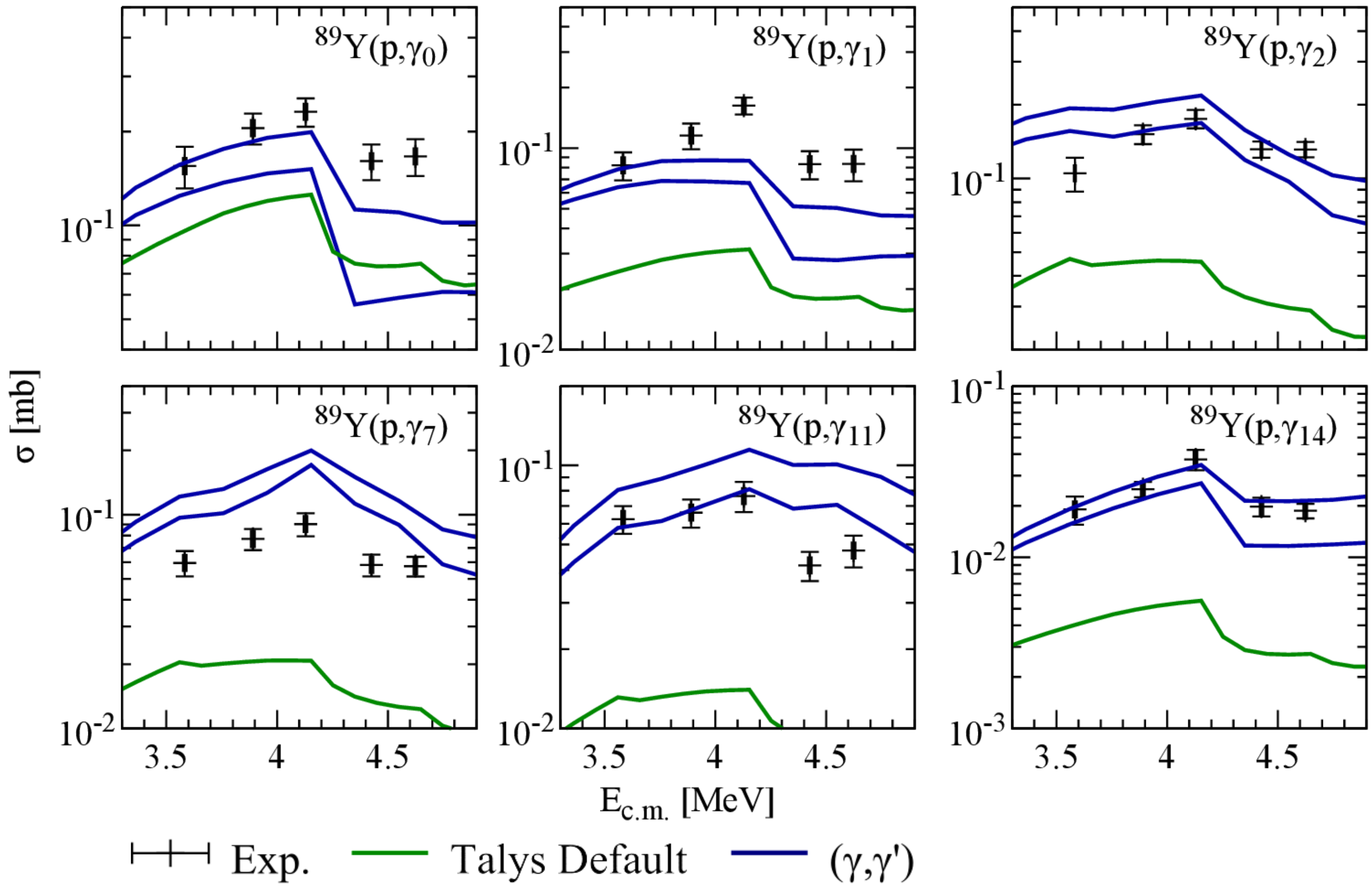
In-beam measurement of the $^{89}Y(p,\gamma)$

- $^{89}Y(p,\gamma)$ partial cross sections: huge deviations



In-beam measurement of the $^{89}Y(p,\gamma)$

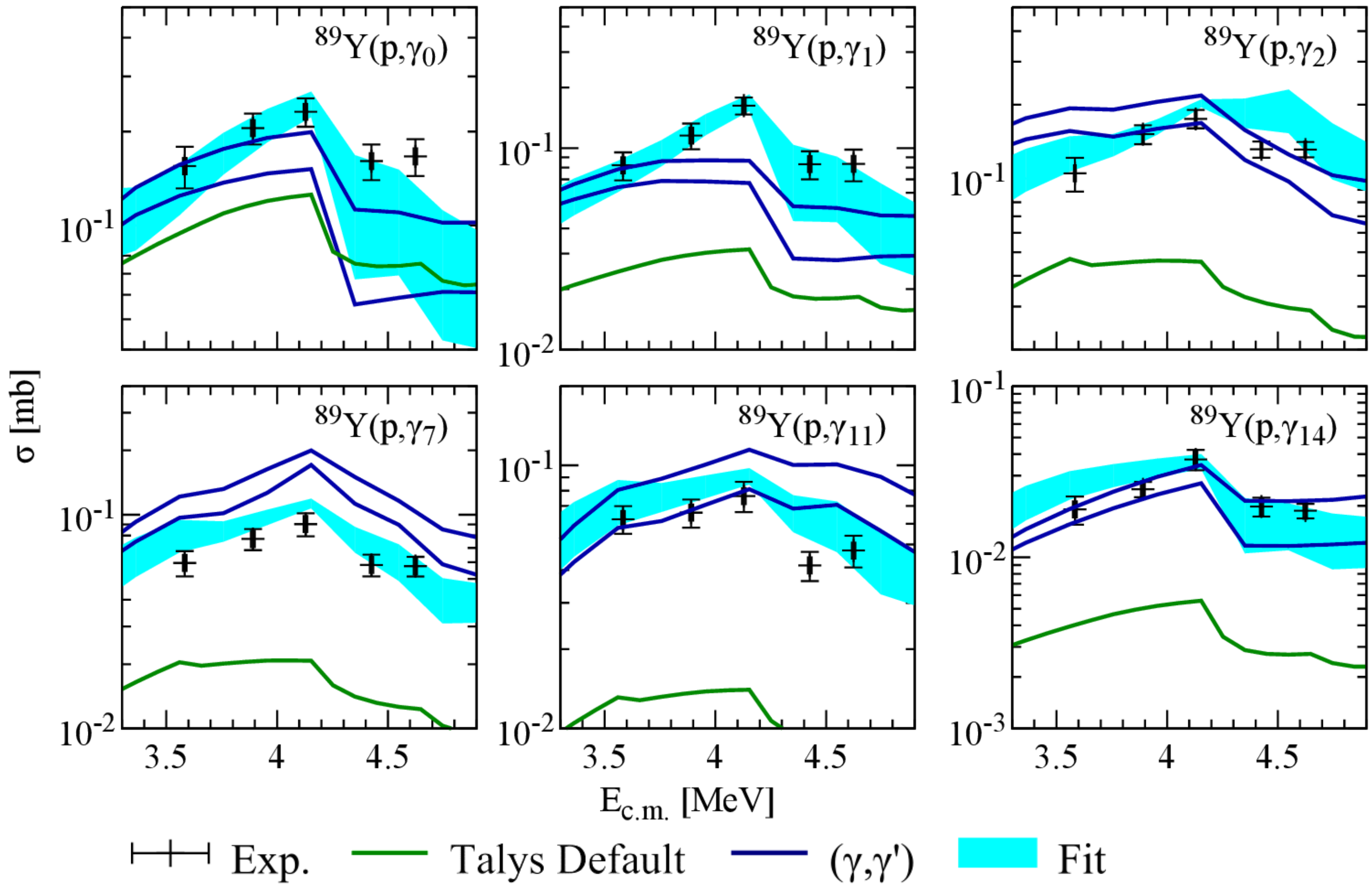
- using γ-strength function from (γ,γ’) measurement:



R. Schwengner *et al.*, PRC **78** (2008) 064314

In-beam measurement of the ^{89}Y(p,γ)

- adjusting γ-strength to measured data

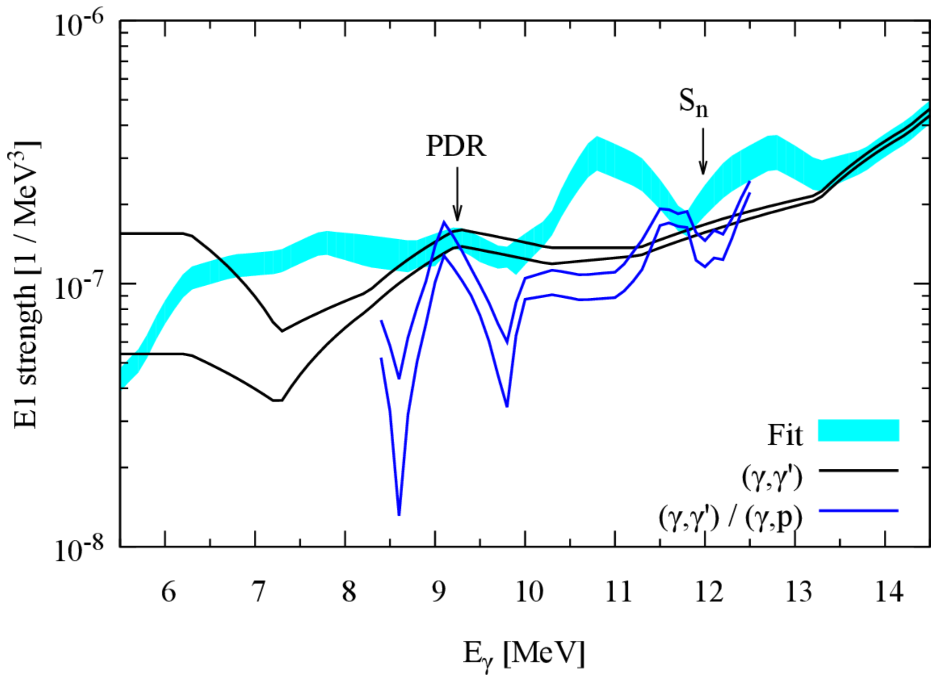


L. Netterdon *et al.*, PLB **744** (2015) 358

R. Schwengner *et al.*, PRC **78** (2008) 064314

Impact on $^{90}Zr(\gamma,p)^{89}Y$

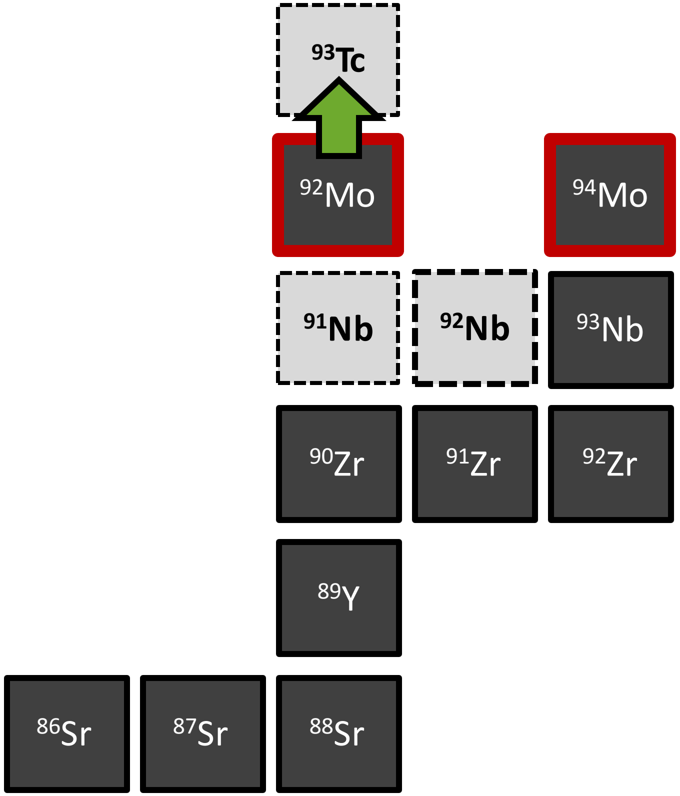
- 15 % larger reaction rate than based on E1-strength from (γ,γ')
- twice as large as BRUSLIB reaction rate (QRPA strength)
- three times smaller than NONSMOKER rates (Lorentzian-type E1-strength)



R. Schwengner *et al.*, PRC **78** (2008) 064314

L. Netterdon *et al.*, PLB **744** (2015) 358

In-beam measurement of the ^{92}Mo(p,γ)



- ^{92}Mo is the most abundant *p* nuclei and its origin is highly debated
- total cross-section were measured before with different techniques at energies below 3.5 MeV
- isotopically enriched ^{92}Mo target (94 %)
- beam currents between 50 nA and 350 nA
- proton energies between 3.7 MeV and 5.4 MeV
  - extending measurement towards higher energies
  - sensitive to higher energy γ-ray transitions

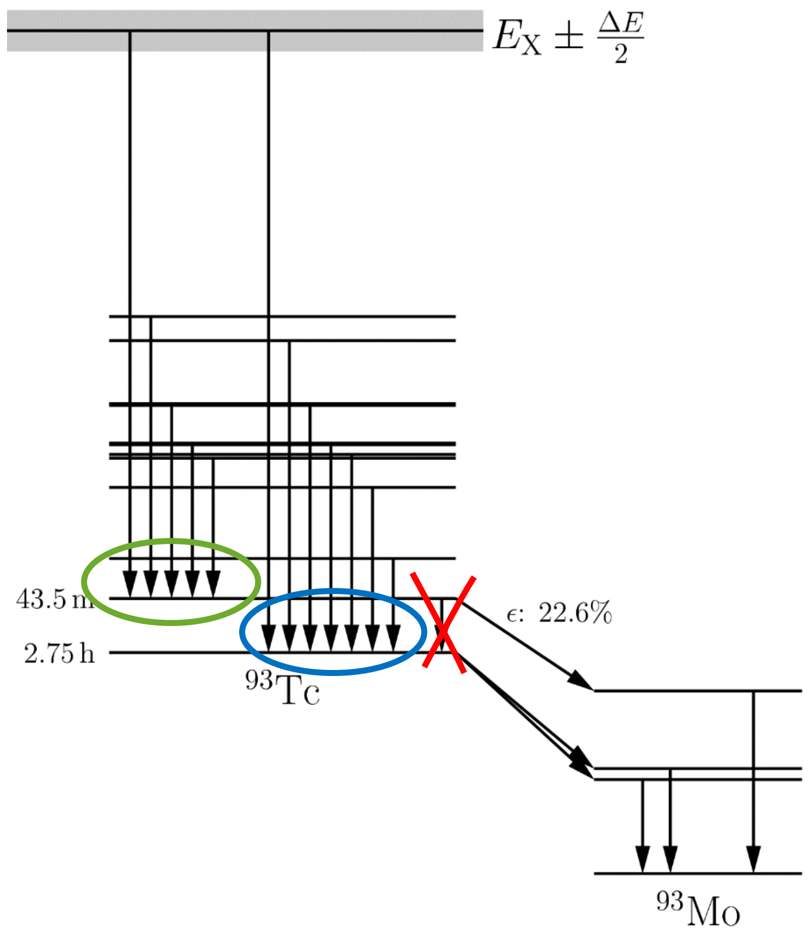
In-beam measurement of the ^{92}Mo(p,γ)

Problem: metastable state @ 391 keV

- Significant half-life
- Electron capture branching to ^{93}Mo

Solution:

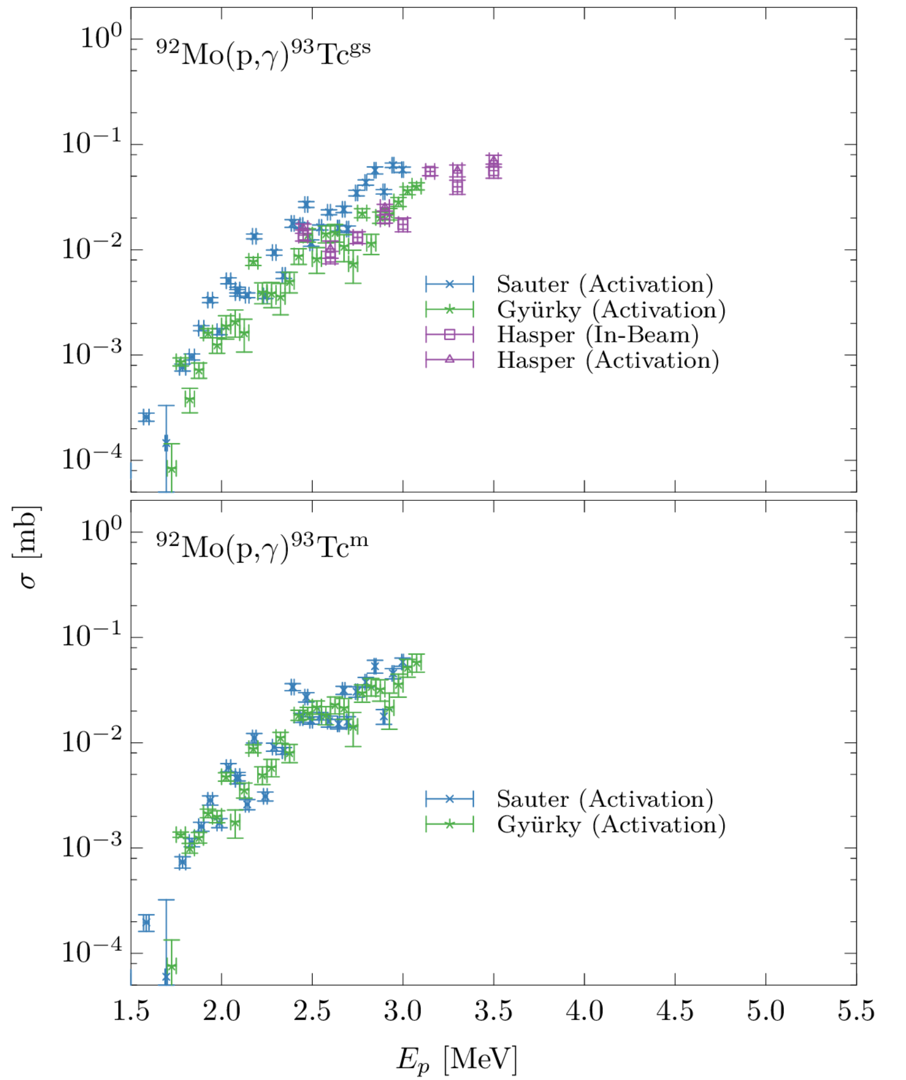
- Determine σ_{gs}
- Determine σ_{m}



In-beam measurement of the ^{92}Mo(p,γ)

Total cross sections

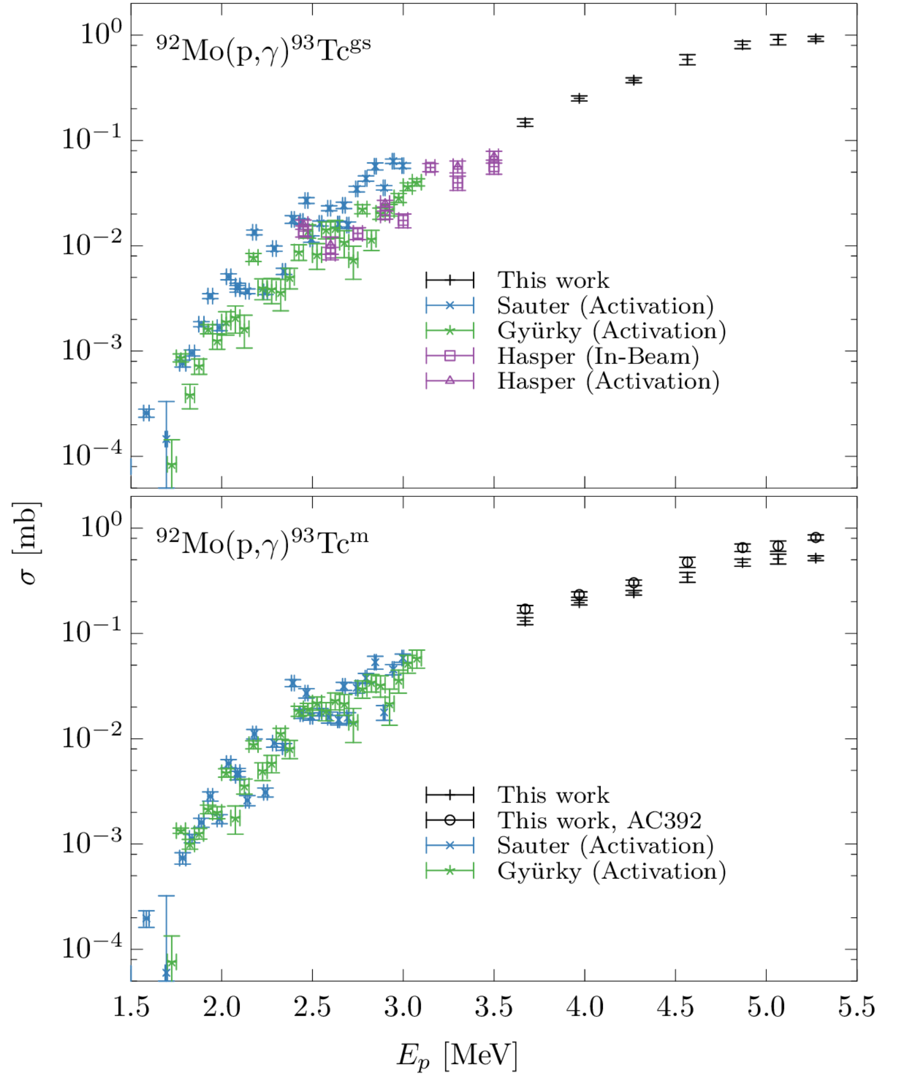
- Previously measured cross sections show fluctuating behavior
- TALYS calculations
  - Unsatisfactory reproduction with default settings
  - modified γ-strengths
    - M1 shell model
    - Gogny-HFB + QRPA
    - Skyrme-HFB + QRPA



T. Sauter and F. Käppeler, PRC **55**, 3127 (1997)
Gy. Gyürky *et al.*, NPA **922**, 112–125 (2014)
J. Mayer *et al.*, PRC, accepted

Total cross sections

- Previously measured cross sections show fluctuating behavior
- TALYS calculations
  - Unsatisfactory reproduction with default settings
  - modified γ-strengths
    - M1 shell model
    - Gogny-HFB + QRPA
    - Skyrme-HFB + QRPA

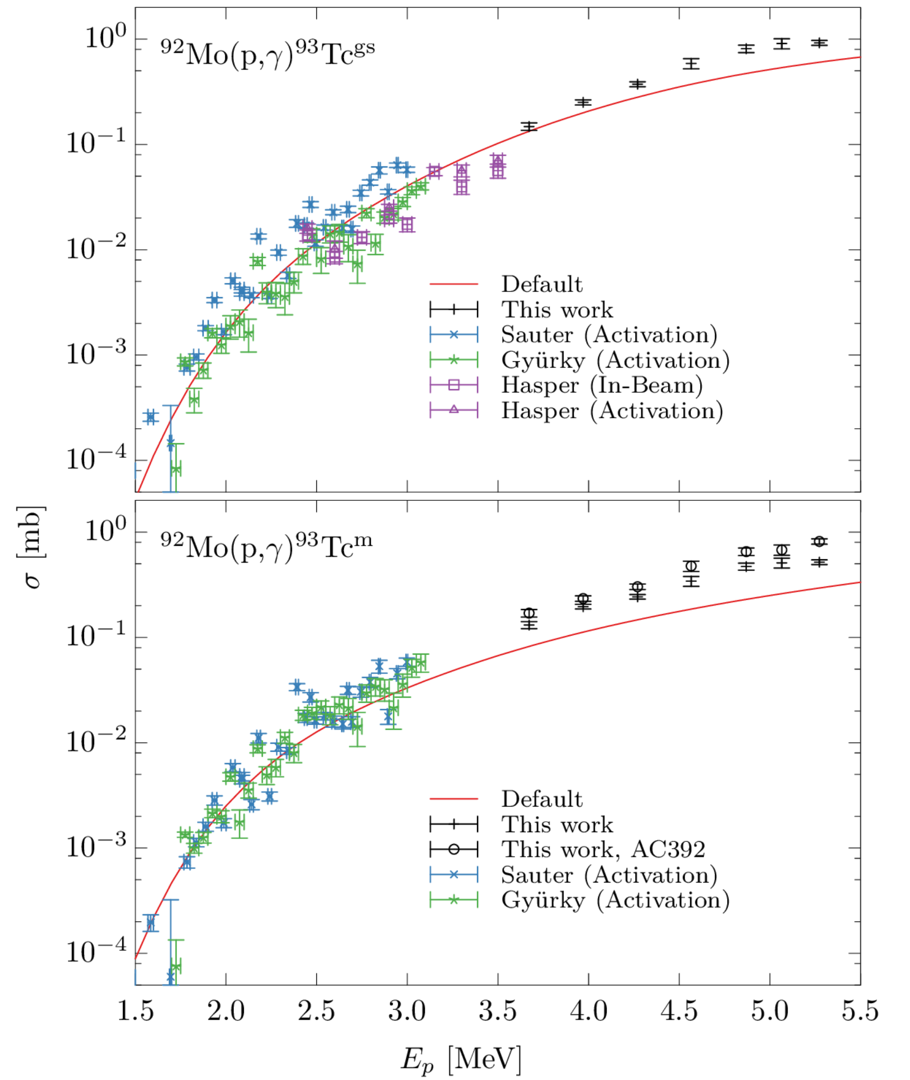


T. Sauter and F. Käppeler, PRC **55**, 3127 (1997)
Gy. Gyürky *et al.*, NPA **922**, 112–125 (2014)
J. Mayer *et al.*, PRC, accepted

In-beam measurement of the ^{92}Mo(p,γ)

Total cross sections

- Previously measured cross sections show fluctuating behavior
- TALYS calculations
  - Unsatisfactory reproduction with default settings
  - modified γ-strengths
    - M1 shell model
    - Gogny-HFB + QRPA
    - Skyrme-HFB + QRPA

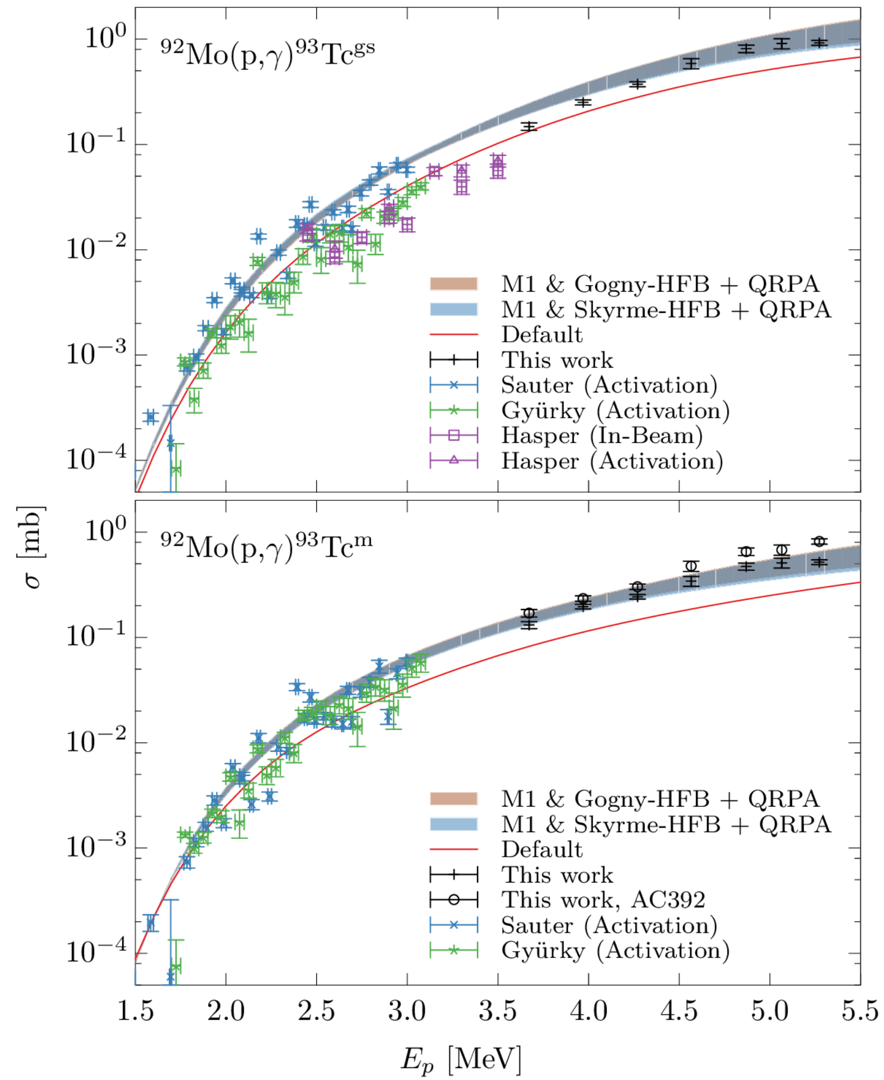


T. Sauter and F. Käppeler, PRC **55**, 3127 (1997)
Gy. Gyürky *et al.*, NPA **922**, 112–125 (2014)
J. Mayer *et al.*, PRC, accepted

In-beam measurement of the $^{92}Mo(p,\gamma)$

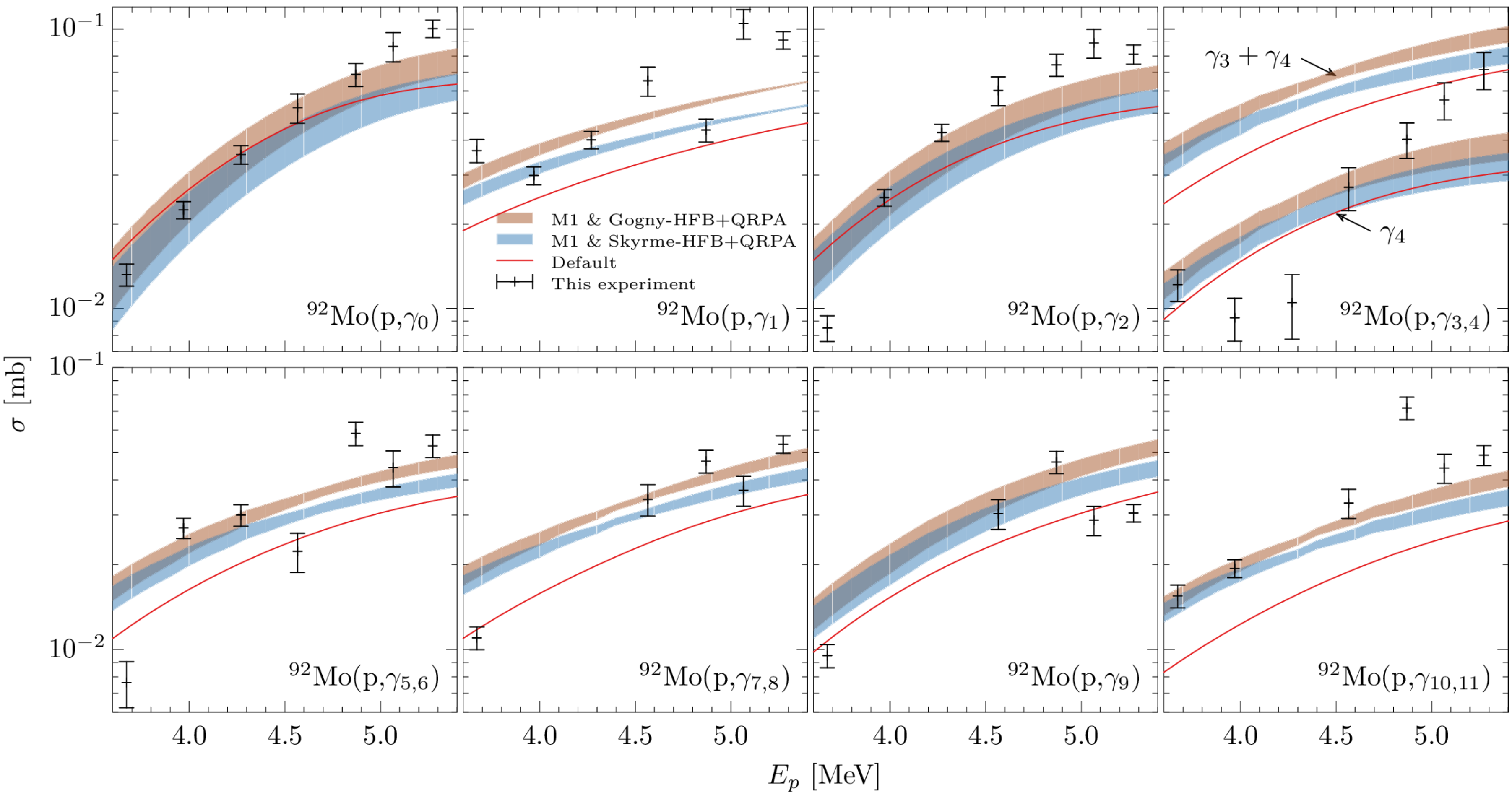
Total cross sections

- Previously measured cross sections show fluctuating behavior
- TALYS calculations
  - Unsatisfactory reproduction with default settings
  - modified γ-strengths
    - M1 shell model
    - Gogny-HFB + QRPA
    - Skyrme-HFB + QRPA



T. Sauter and F. Käppeler, PRC **55**, 3127 (1997)
Gy. Gyürky *et al.*, NPA **922**, 112–125 (2014)
J. Mayer *et al.*, PRC, accepted

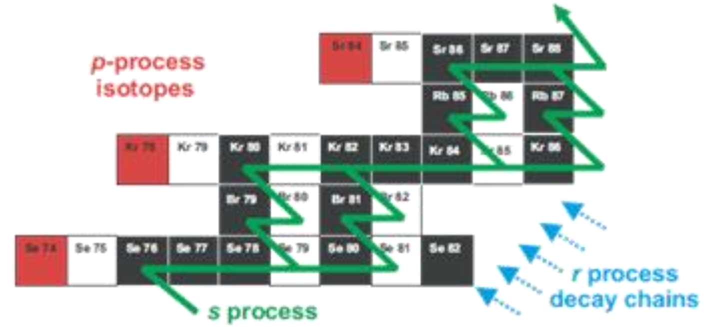
Partial cross sections

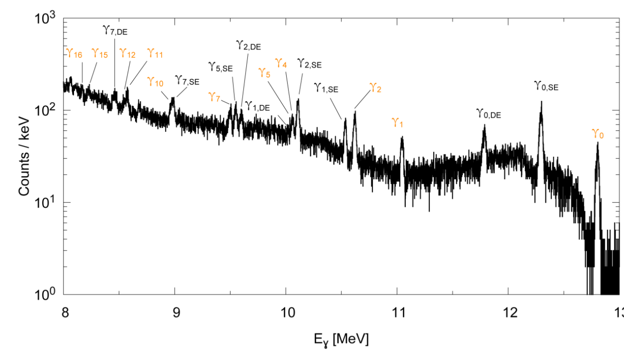


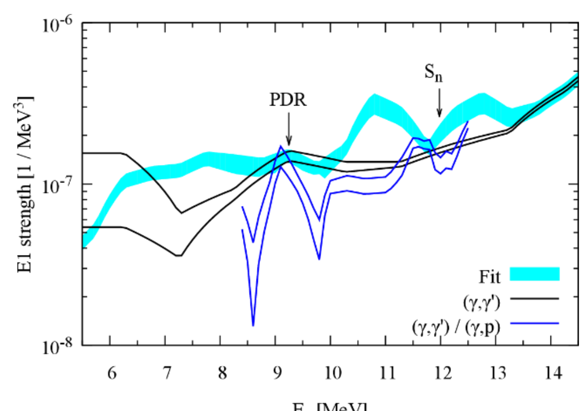
J. Mayer *et al.*, PRC, accepted

Summary

- the origin of the *p* nuclei is still unclear due to astrophysical and nuclear physics uncertainties
- direct measurements of (γ,x) reaction rates can in most cases not directly applied to reaction network calculations
- reaction rates are usually calculated within the statistical model and via reciprocity theorem from the inverse reactions
- charged-particle induced reaction studies can be used for the improvement of models for statistical properties of nuclei
  - γ-ray strength functions
  - particle+nucleus optical model potentials

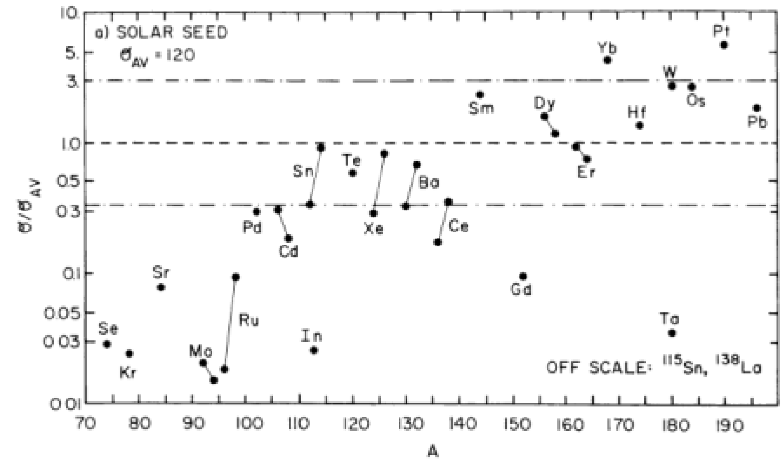


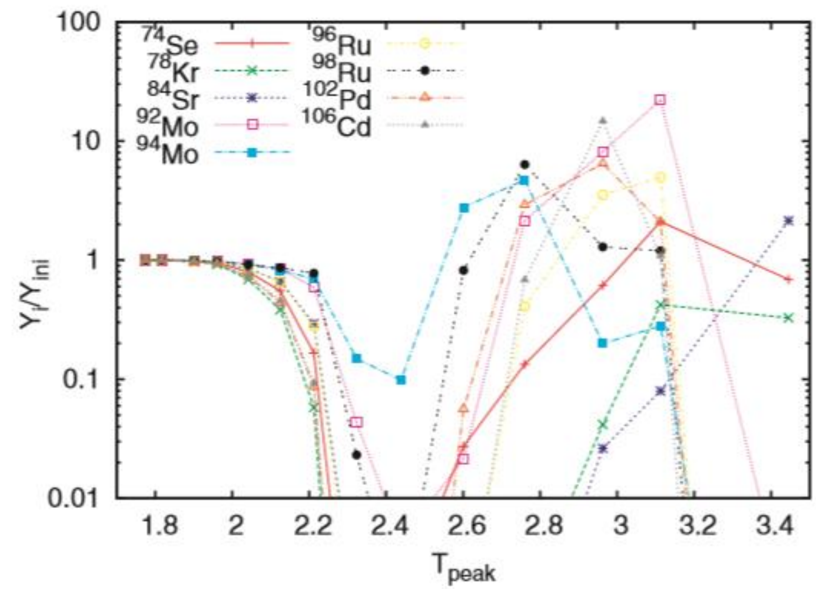




Astrophysical uncertainties

- seed abundances from *s*- or *r*-process or chemical evolution
- temperature and density profiles
- contribution from, for instance, α-process in neutrino-driven wind scenarios or *rp* process in Type Ia X-ray bursts?





S.E. Woosley and W. M. Howard, ApJSS **36** (1978) 285
T. Rauscher *et al.*, Rep. Prog. Phys. **76** (2013) 066201

Uncertainties for γ process nucleosynthesis

Nuclear physics uncertainties

- sensitivity study of the γ process in ccSN
- all *p* isotope abundances are sensitive to (γ,n) reaction rates
- only the lighter *p* nuclei are sensitive to (γ,p)
- (γ,a) especially important for the production factors of the heavier *p* isotopes

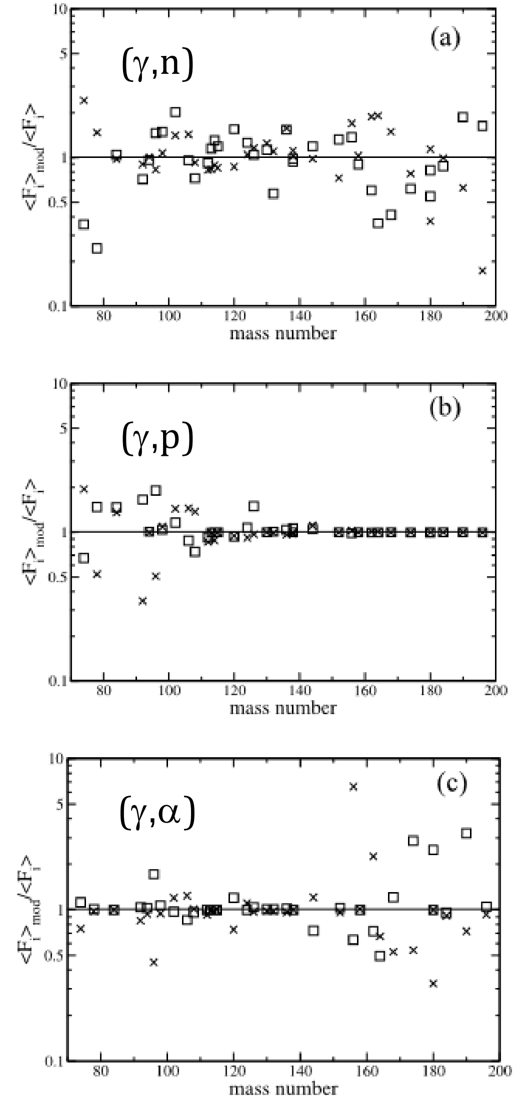


FIG. 10.—Ratio of *p*-abundances calculated with modified rates and the currently accepted HF rates for all (*a*) *n*-induced, (*b*) *p*-induced, and (*c*) α-induced reactions and their inverse processes. Squares and crosses denote results obtained with rates 3 times smaller and larger, respectively.

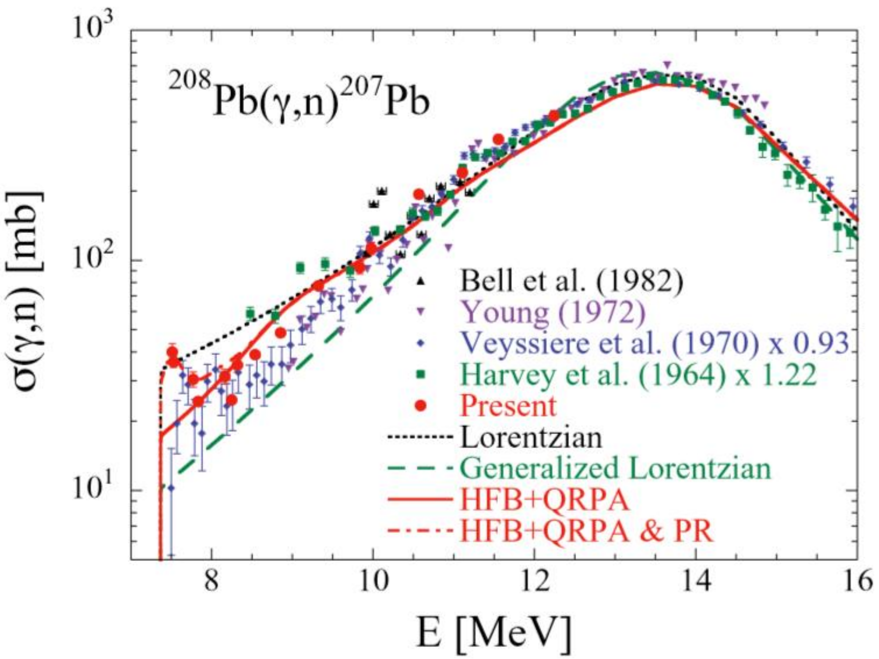
W. Rapp *et al.*, ApJ **653** (2006) 474

Experimental measurements of cross sections

Monochromatic γ-ray beams

Example: HIγS @ Duke, TERAS @ Tsukuba

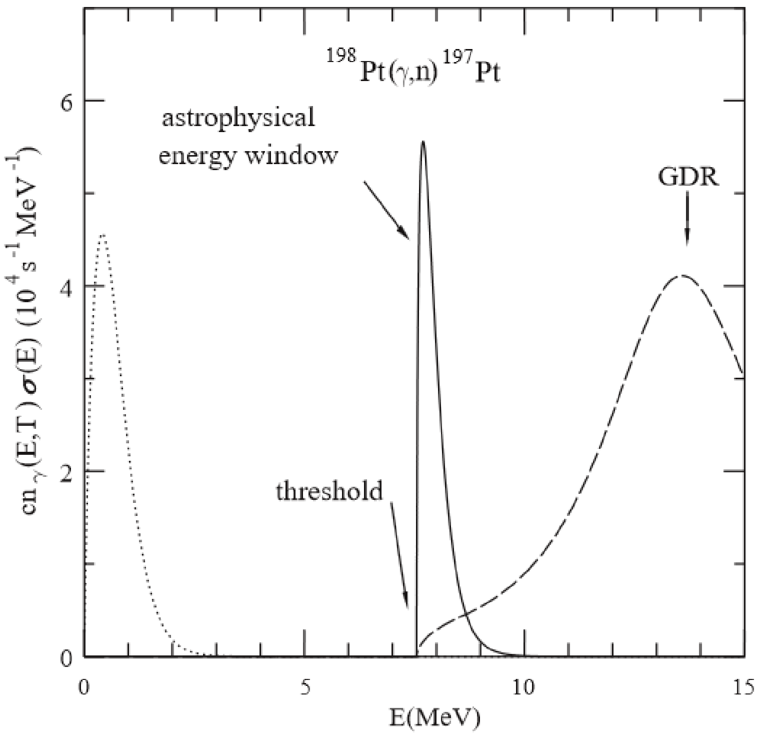
- using Laser Compton-Backscattering to produce (quasi-) monochromatic γ-rays
- measuring (γ,n) cross sections point-by-point until the neutron treshold

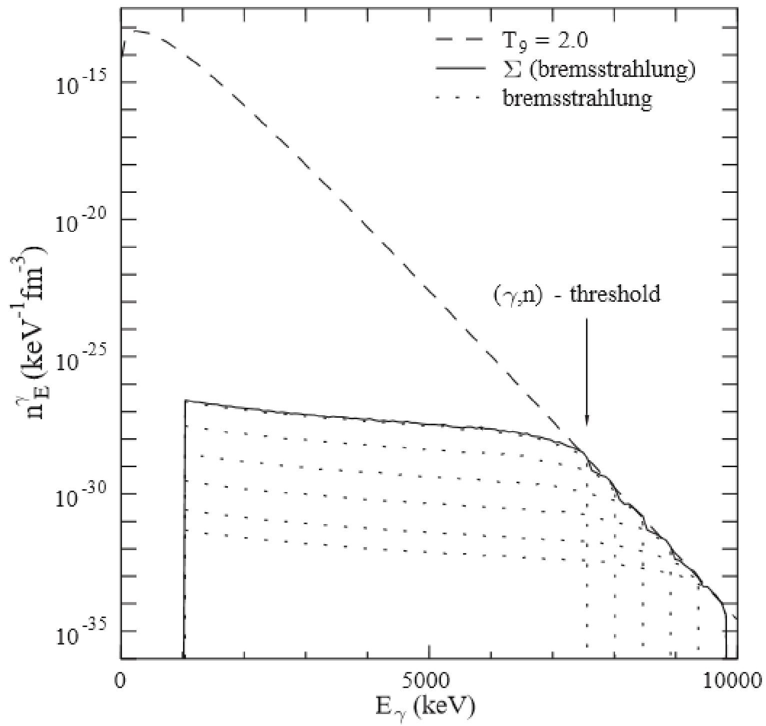


T. Kondo *et al.*, Phys. Rev. C 86 (2012) 014316

Bremstrahlung

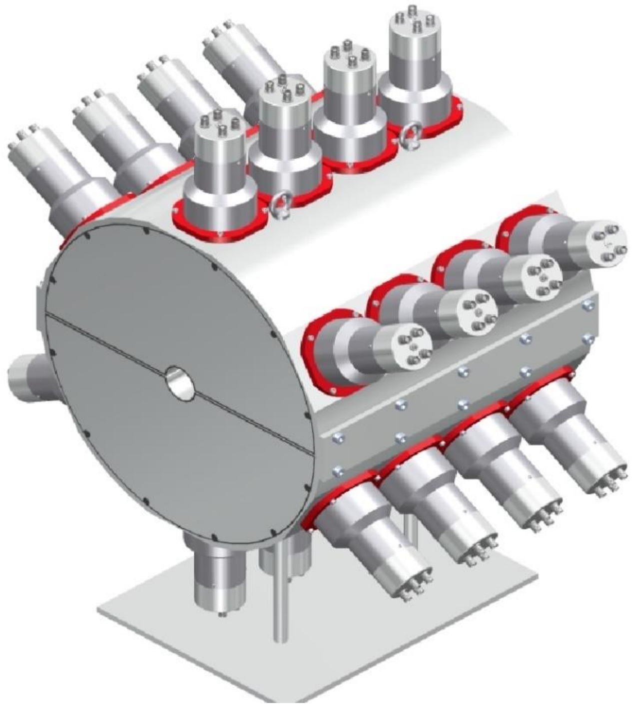
- simulating a planck distribution with many Bremsstrahlung spectra using different endpoint energies
- direct measurement of (γ,n) reaction rate at a specific temperature





P. Mohr *et al.*, PLB 488 (2000) 127

4π-summing crystal



SuN – NaI 4π summing detector [NSCL]

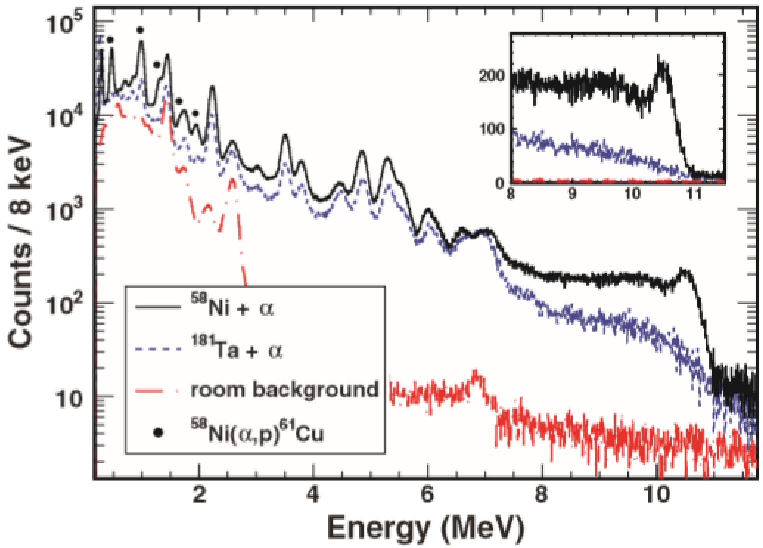
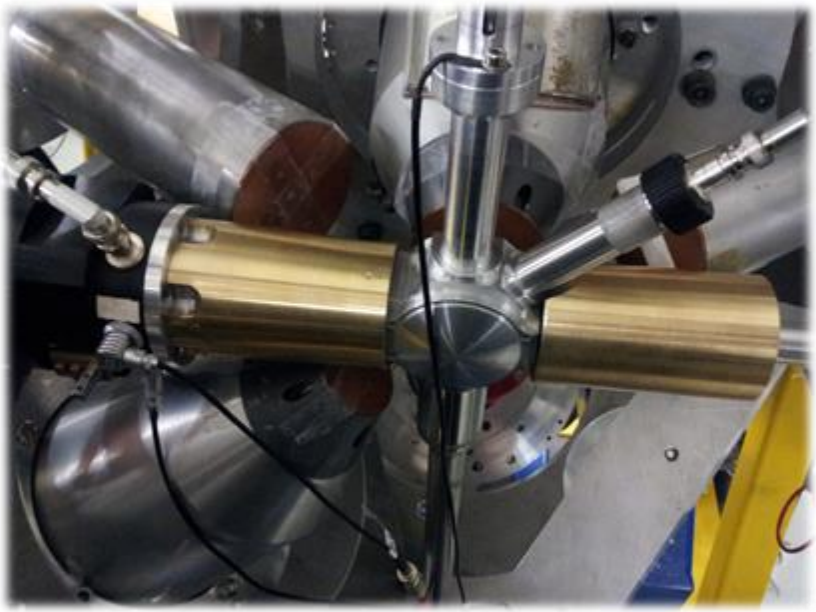


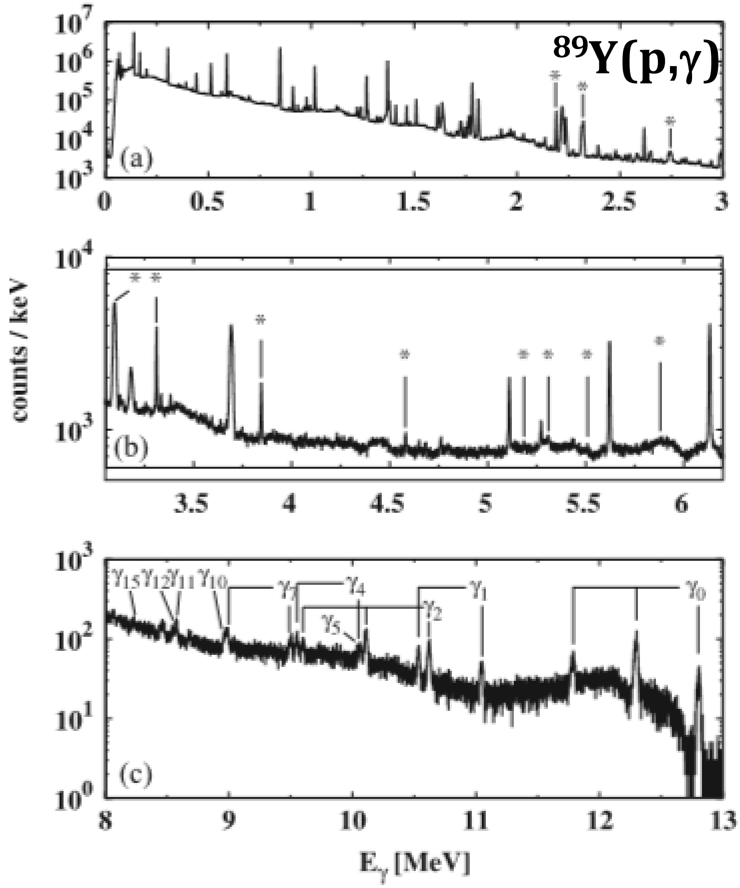
FIG. 1. (Color online) Experimental spectra from the SuN detector for measurements at $E_\alpha = 7.7$ MeV. The spectra correspond to the ^{58}Ni target (solid black), thick tantalum backing (dotted blue), and normalized room background (dotted-dashed red). The inset shows a zoom around the sum-peak region of the ^{58}Ni$(\alpha,\gamma)^{62}$Zn reaction.

S. Quinn *et al.,* Phys. Rev. C **89** (2014) 054611

In-beam method with HPGe detectors



Nuclear astrophysics @ HORUS

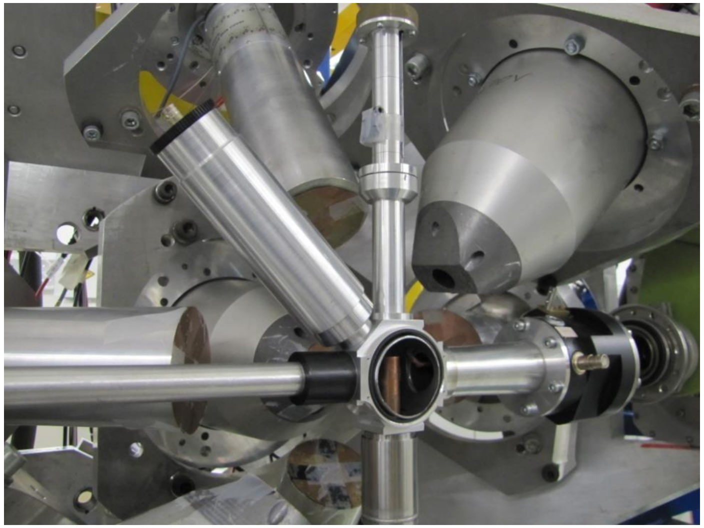


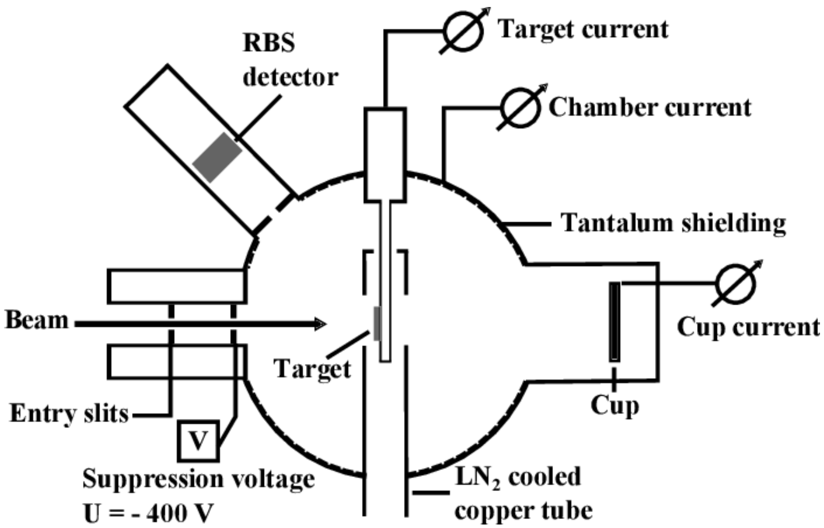
L. Netterdon *et al.*, NIM A **754** (2014) 94

In-beam technique with HPGe detectors

Target chamber

- cooling trap
- tantalum coating
- independent current readouts
- δ-electron suppression
- built-in detector for Rutherford Backscattering Spectrometry (RBS)





L. Netterdon *et al.*, NIM A **754** (2014) 94-100

Target chamber