p-process experiments in Cologne

P. Scholz, F. Heim, J. Mayer, M. Spieker, and A. Zilges

Institute for Nuclear Physics, University of Cologne

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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

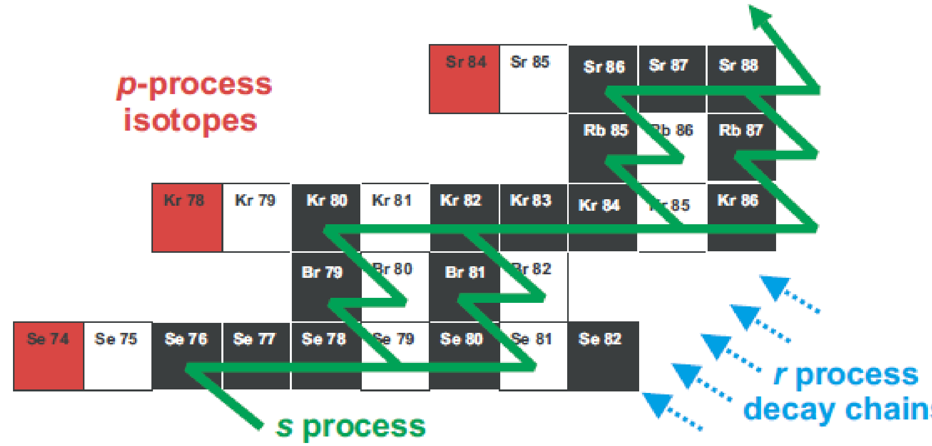
- $^{112}Sn(\alpha,\gamma)^{116}Te$
- $^{108}Cd(\alpha,\gamma)^{112}Sn$

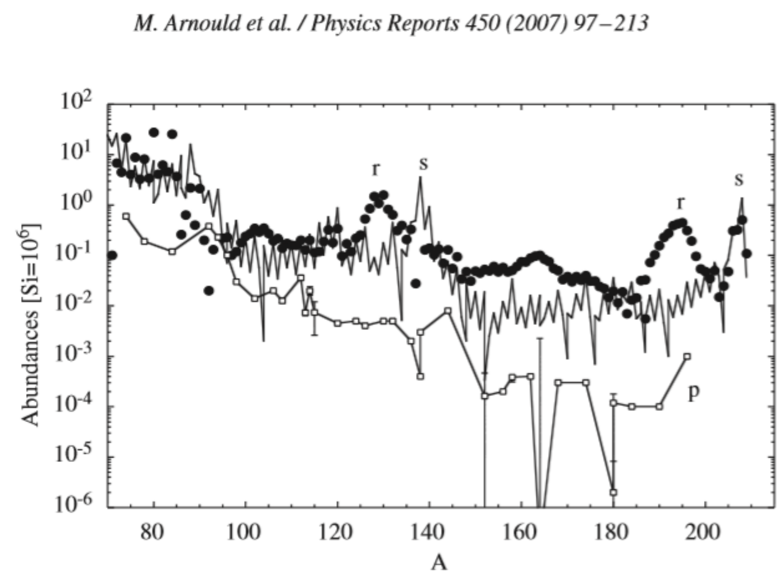
The $^{144}Sm/^{146}Sm$ chronometer

p nuclei

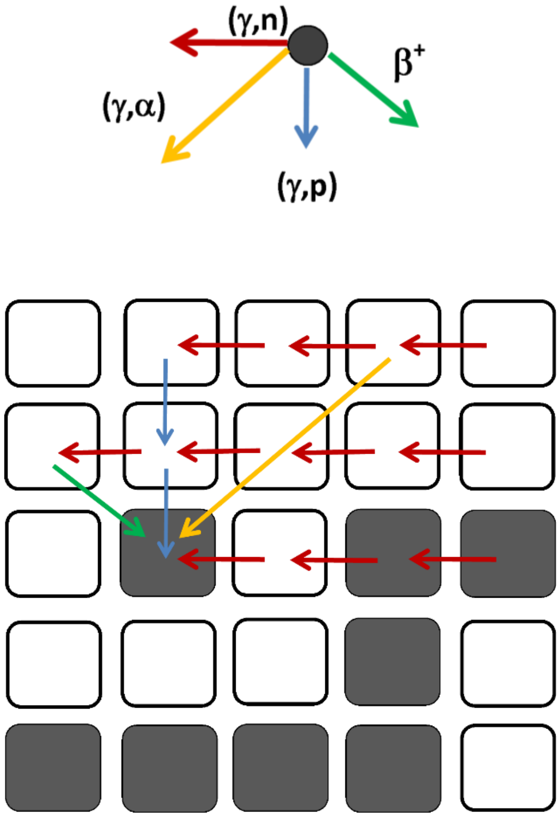
- about 30 stable neutron deficient isotopes which cannot be produced by neutron capture reactions
- relatively low isotopic abundances in comparison to *s*- and *r*-isotopes
- originally thought to be produced via proton-capture
- temperatures would lead to immediate photodisintegration

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





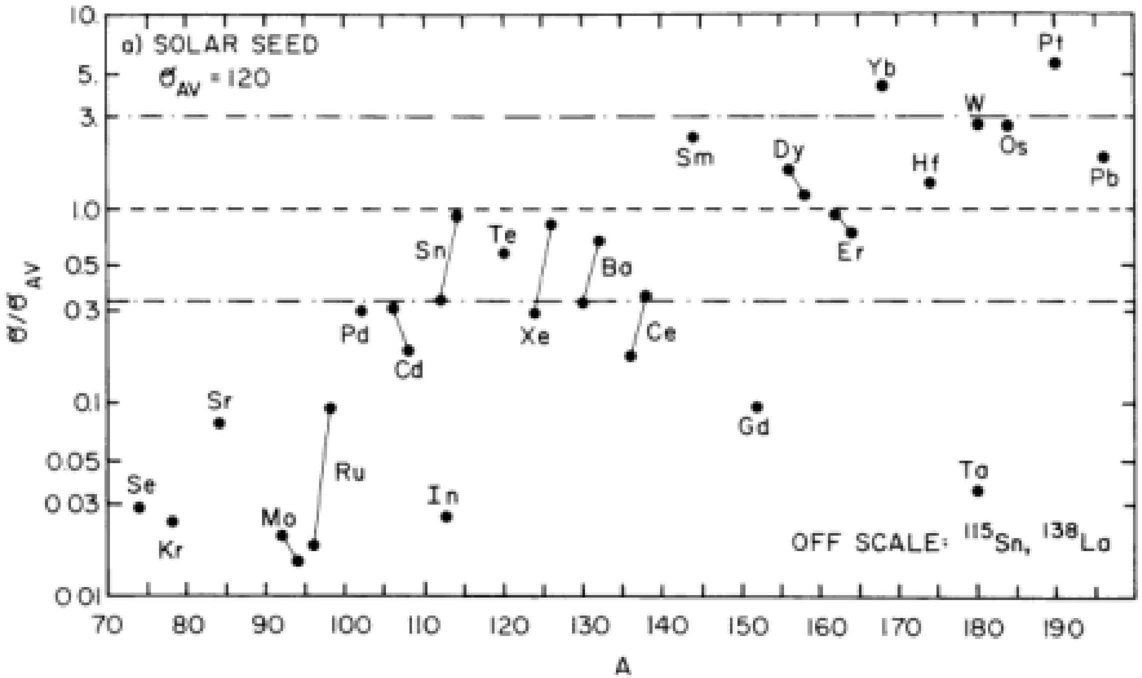
M. Arnould *et al.*, Phys. Rep. **450** (2007) 97



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

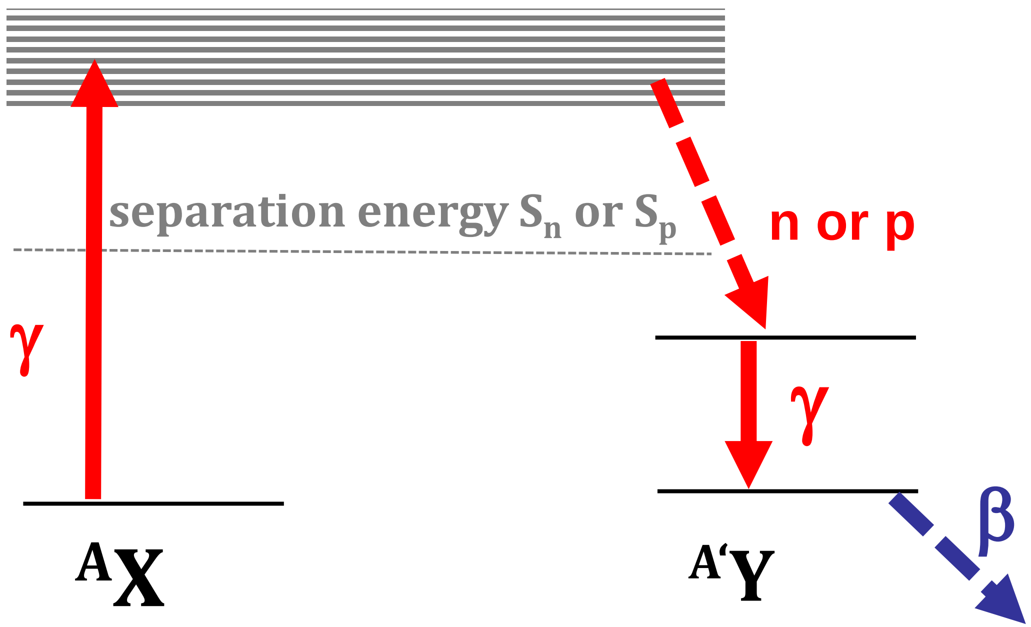
γ-process reaction-network calculations



- γ-process network calculations cannot reproduce solar system abundance
- other contributions from *rp*-, *α*- , νp- other processes?
- problems with reaction rates?

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

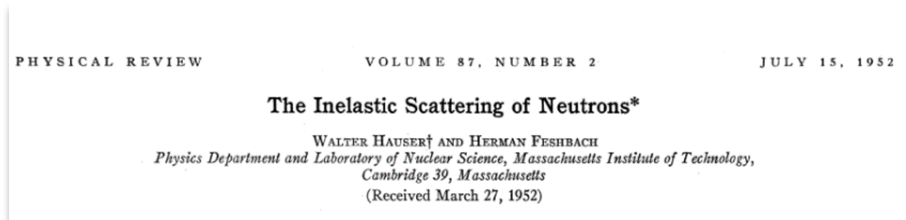
Photodisintegration



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

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
    - particle + nucleus optical model potentials
    - Nuclear Level Densities



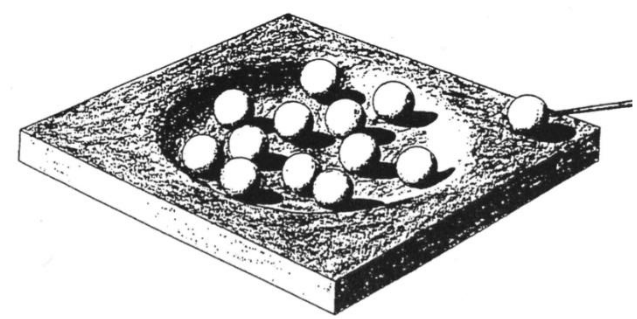
PHYSICAL REVIEW VOLUME 87, NUMBER 2 JULY 15, 1952

The Inelastic Scattering of Neutrons*

WALTER HAUSER† AND HERMAN FESHBACH

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

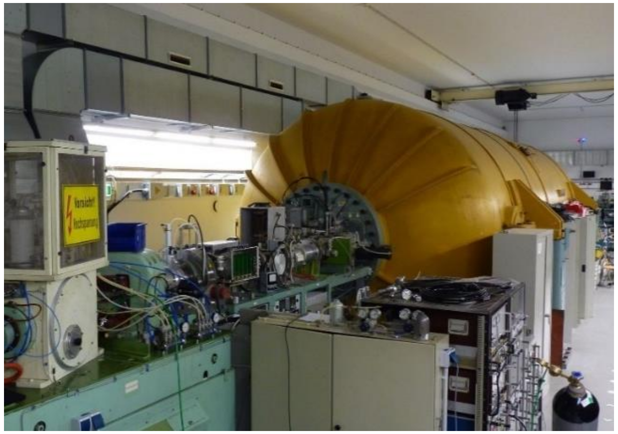
(Received March 27, 1952)

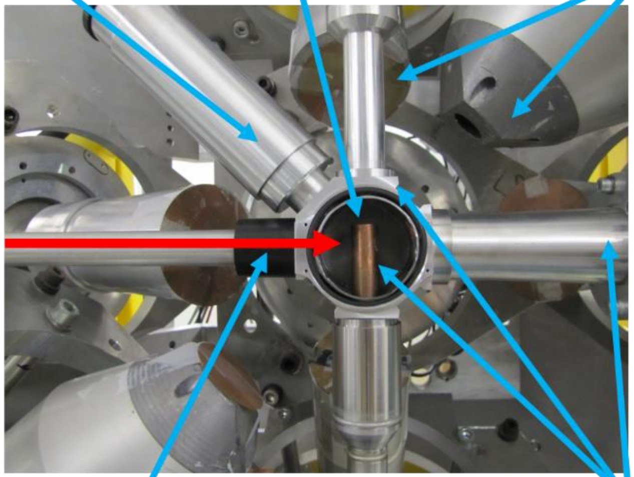


$$\sigma^{\mu}_{jk}(E) = \pi \lambda_j^2 \frac{1}{(2J_I^{\mu}+1)(2J_j+1)} \sum_{J^{\mu}} (2J+1) \frac{T_j^{\mu}(J^{\pi}) T_k(J^{\pi})}{T_{tot}(J^{\pi})}$$

In-Beam γ-ray spectroscopy at HORUS

- **10 MV FN-Tandem accelerator** at the IKP Cologne
- **HORUS γ-ray spectrometer** consists of 13 HPGe detectors (+ RBS)
  - Resolution ≈ 2 keV @ 1332 keV
  - Total efficiency ≈ 2% @ 1332 keV
- **Five different angles** with respect to the beam axis
  - Determination of angular distributions
- BGO shields for five detectors
- γγ-coincidence measurements



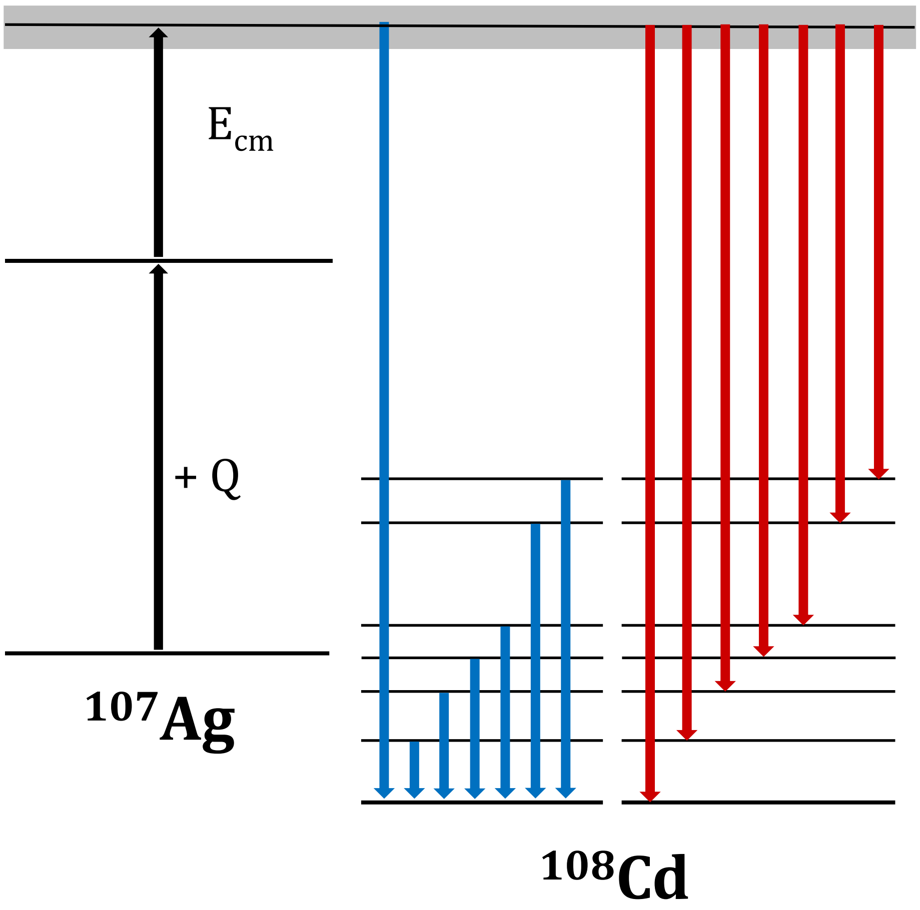


L. Netterdon *et al.*, Nucl. Inst. Meth. A **754** (2014) 94

In-Beam γ-ray spectroscopy

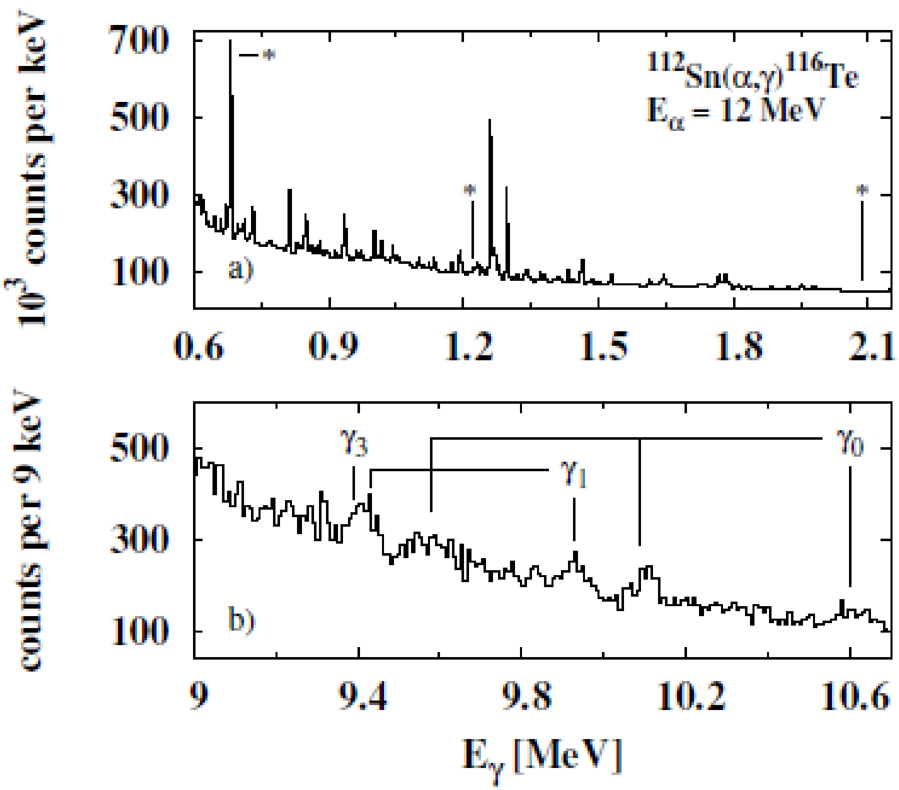
- De-excitation of the entry state
  - Determination of partial cross sections
  - Sensitive to γ-ray strength function

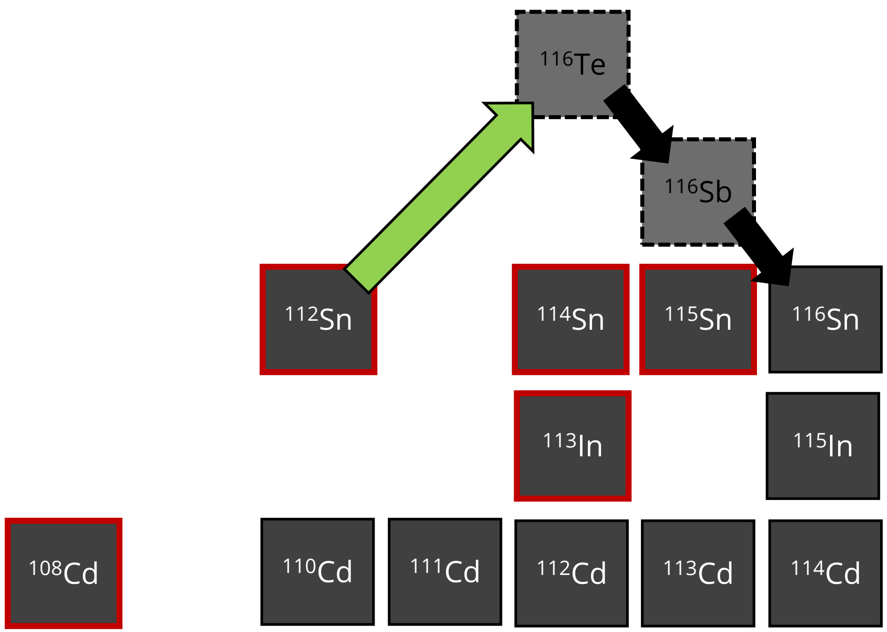
- Transitions to the ground state
  - Determination of the total cross section



The in-beam measurement of $^{112}Sn(\alpha,\gamma)^{116}Te$

- First in-beam measurement of a radiative α-capture reaction on a heavy nucleus @ HORUS
- Measurement of total and partial cross sections at four different α-energies between 10.5 MeV and 12 MeV



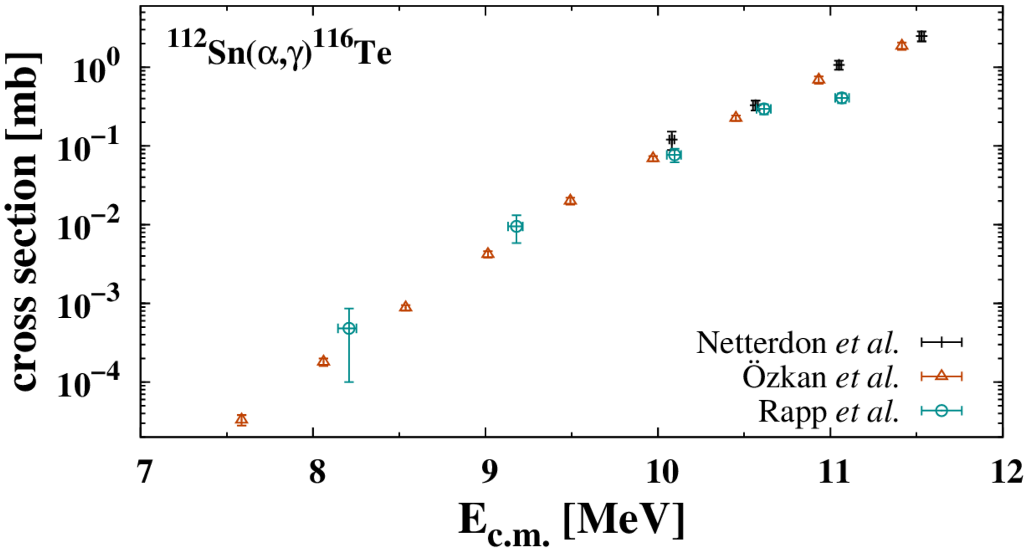


L. Netterdon *et al.*, Phys. Rev. C **91** (2015) 035801

The in-beam measurement of $^{112}Sn(\alpha,\gamma)^{116}Te$

- Measurement confirmed the results of Özkan *et al.*
- None of the widely used α-OMPs led to a good reproduction of the measured cross sections

- Local modifications of the α-OMP could also be used to describe other experimental data of the Cd/Sn- region



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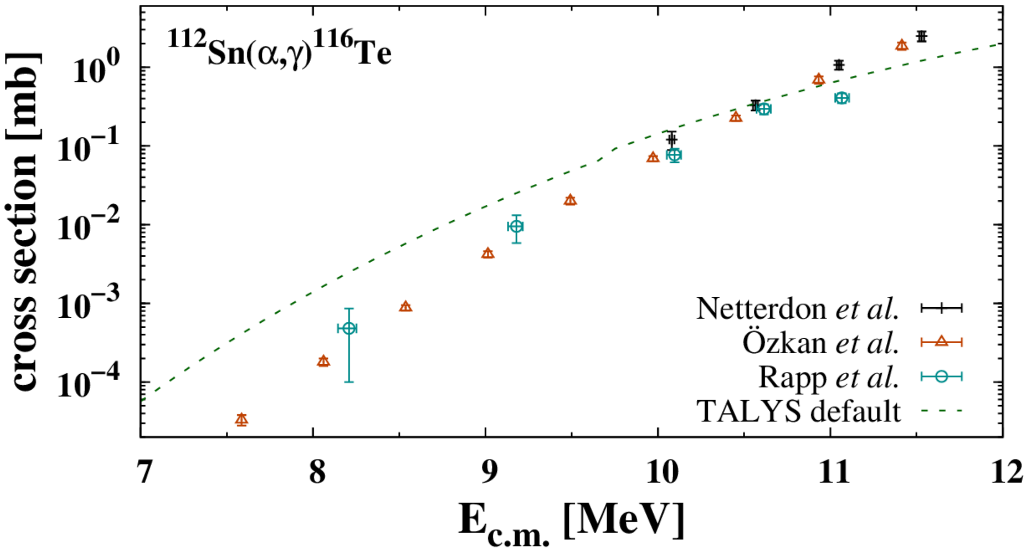

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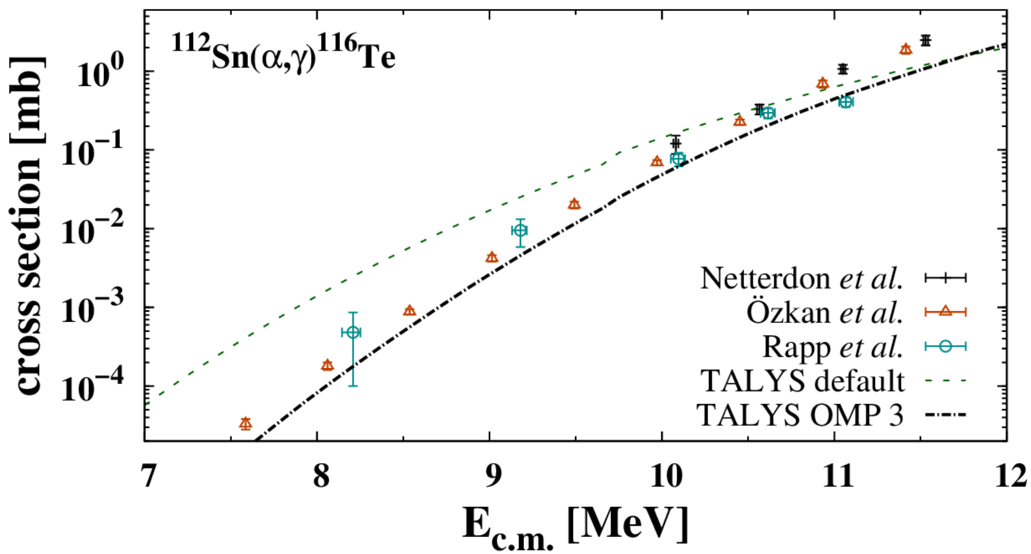

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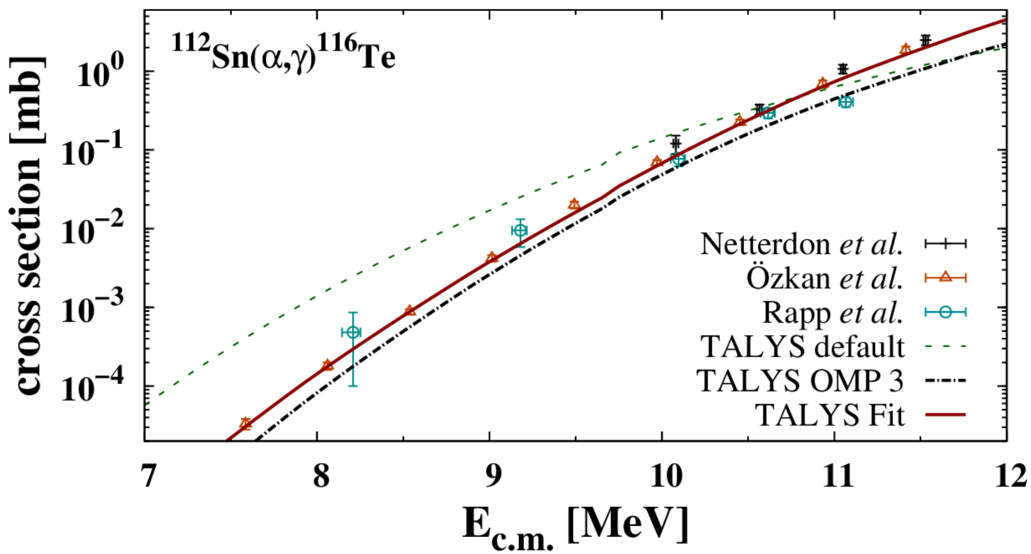

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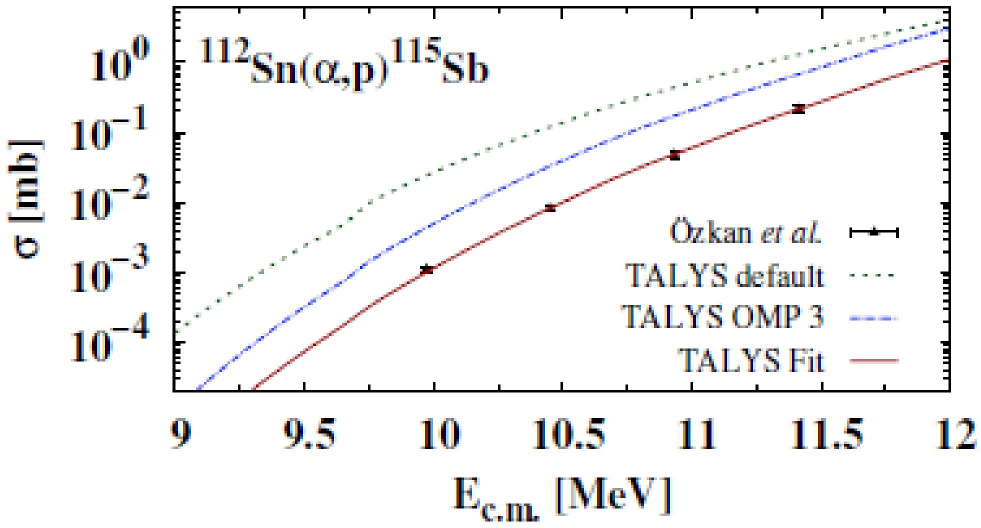
  - $^{112}Sn(\alpha,p)^{115}Sb$



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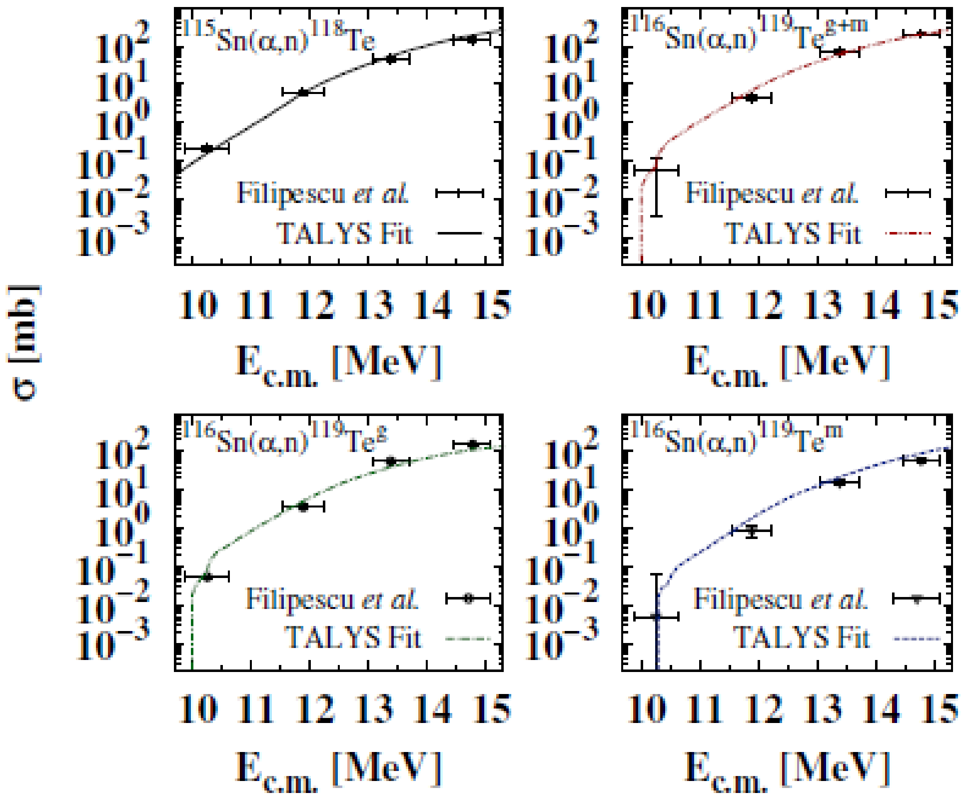
  - $^{115}Sn(\alpha,n)$, $^{116}Sn(\alpha,n)$



L. Netterdon *et al.*, Phys. Rev. C **91** (2015) 035801

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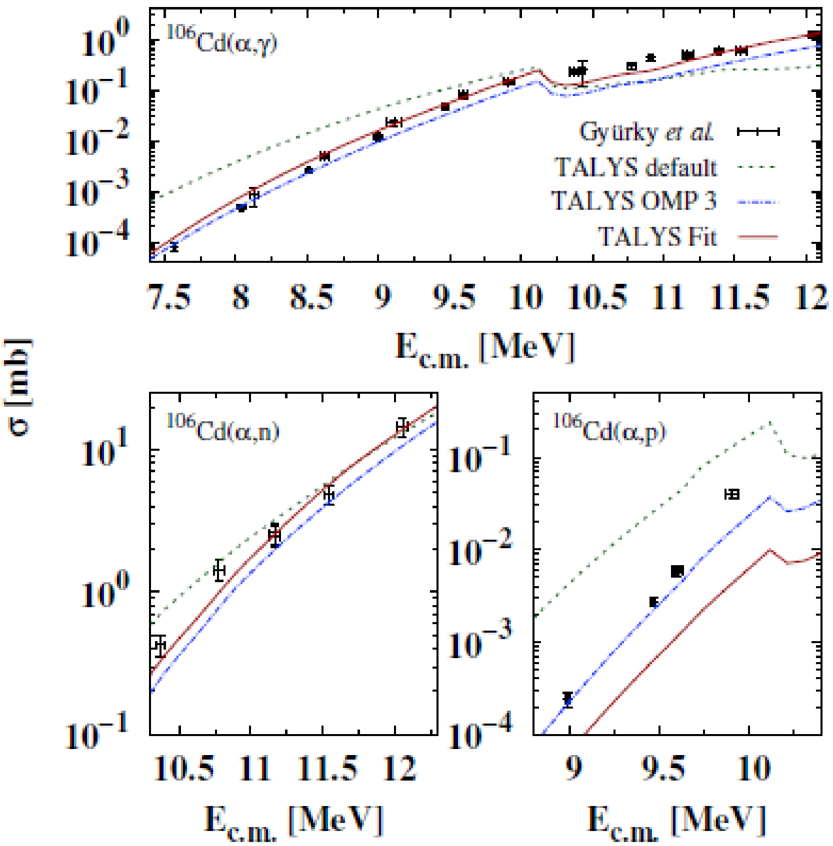

- Local modifications of the α-OMP could also be used to describe other experimental data of the Cd/Sn- region
  - $^{112}Sn(\alpha,p)^{115}Sb$
  - $^{115}Sn(\alpha,n)$, $^{116}Sn(\alpha,n)$
  - $^{106}Cd(\alpha,n)$, $^{106}Cd(\alpha,\gamma)$

L. Netterdon *et al.*, Phys. Rev. C **91** (2015) 035801

The in-beam measurement of ^{112}Sn(α,γ)^{116}Te

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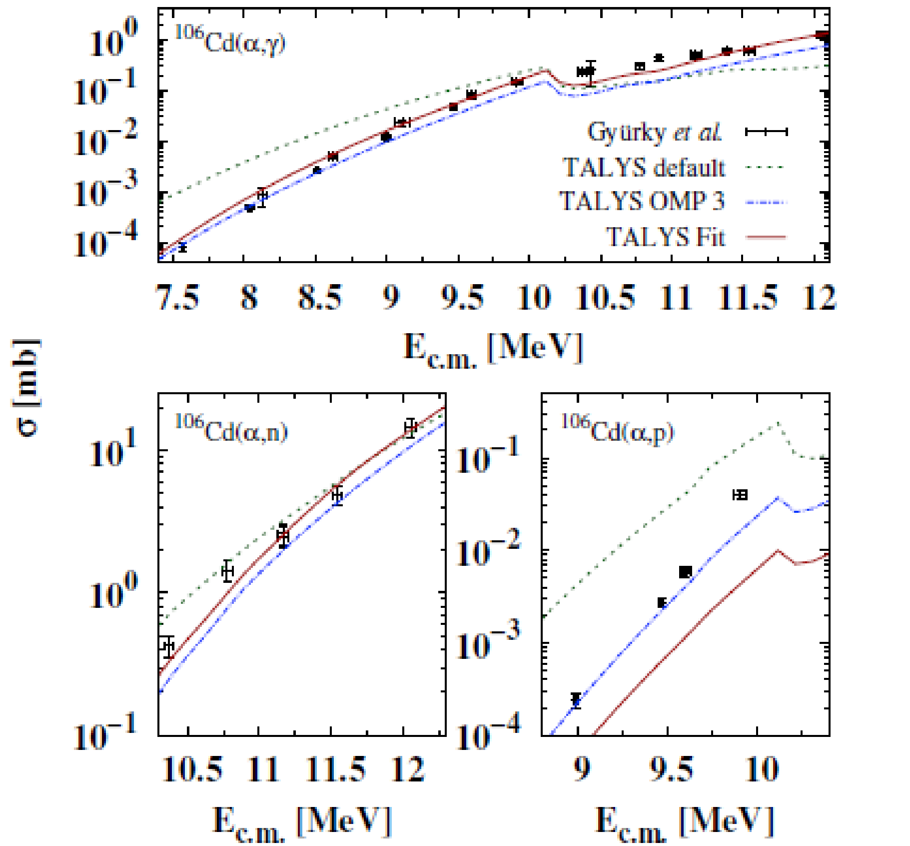
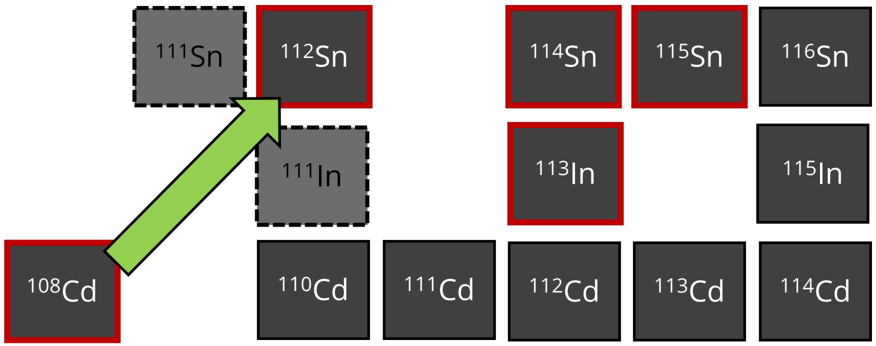
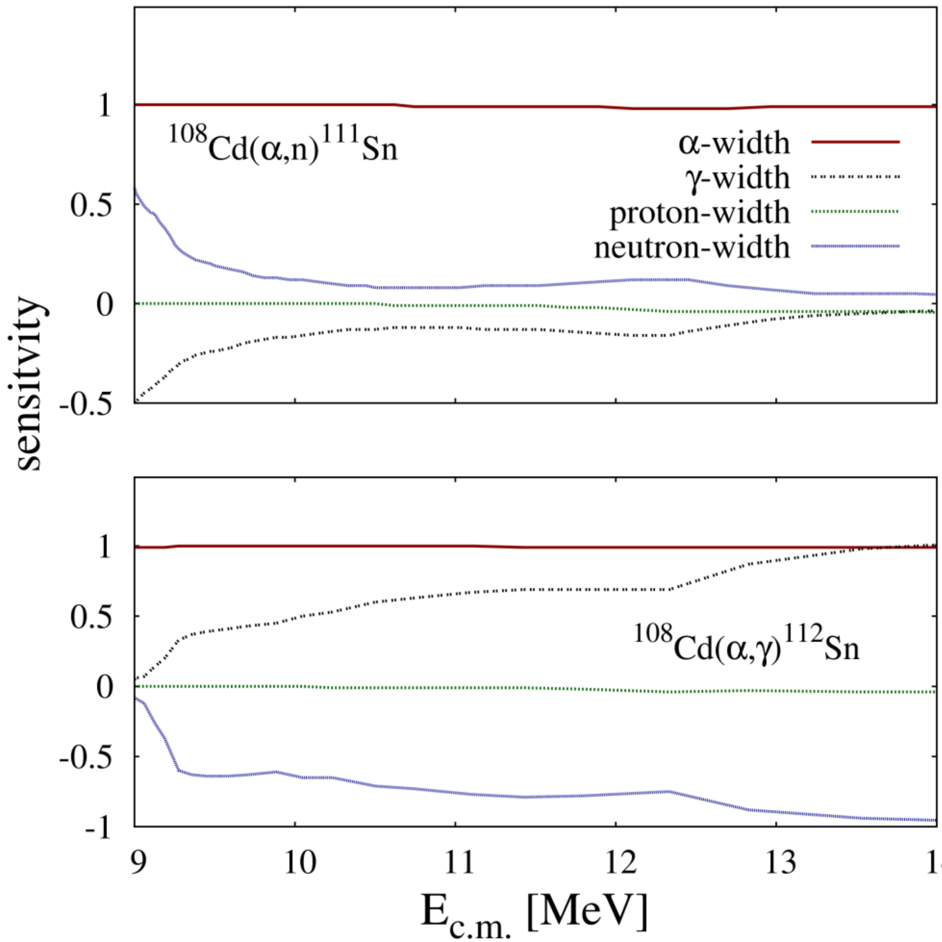


L. Netterdon *et al.*, Phys. Rev. C **91** (2015) 035801

➢ **Measurement of ^{108}Cd(α,γ) and ^{108}Cd(α,n)**

The measurement of ^{108}Cd(α,γ) and ^{108}Cd(α,n)

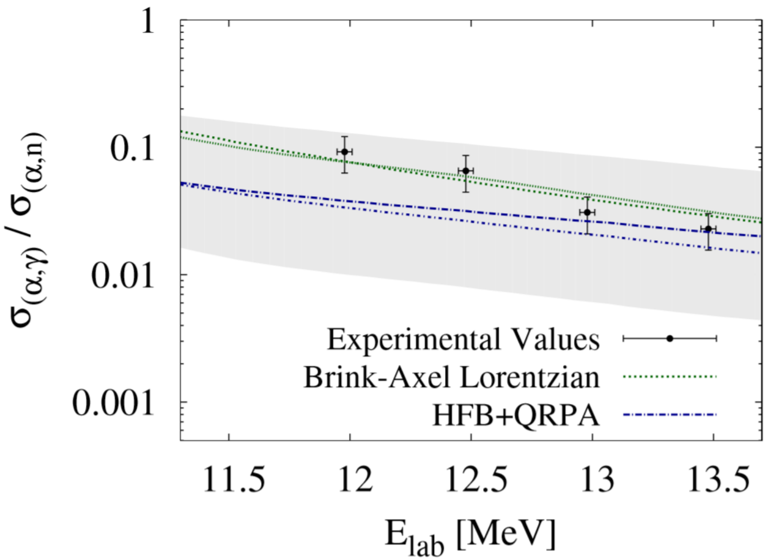




- ^{108}Cd(α,γ) very sensitive to other input-parameters
- In-beam Measurement of ^{108}Cd(α,γ)
- Activation measurement of ^{108}Cd(α,n)
- E_α between 10.2 MeV and 13.5 MeV
- Target thickness via ICP-MS

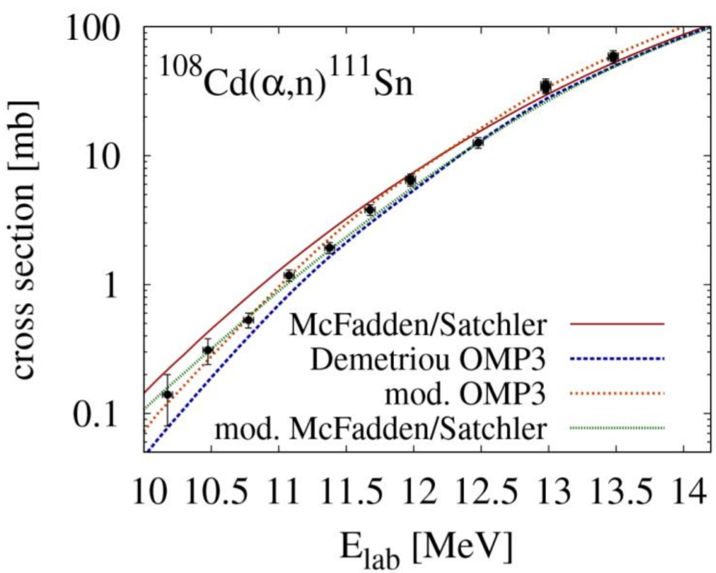
T. Rauscher, *The Astrophysical Journal Supplement Series* **201**, 26 (2012)

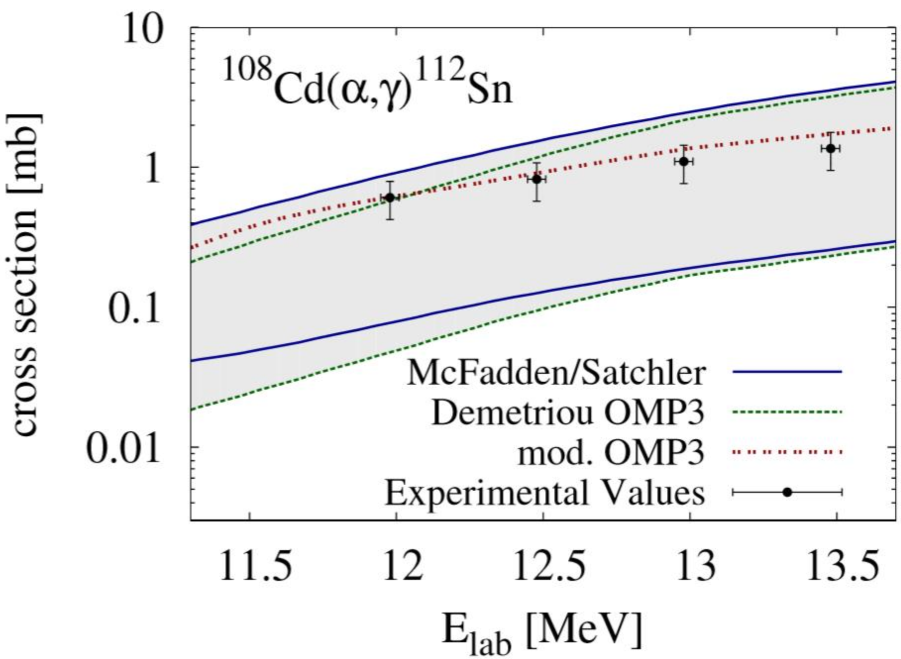
The measurement of ^{108}Cd(α,γ) and ^{108}Cd(α,n)



$$\frac{\sigma(\alpha,\gamma)}{\sigma(\alpha,n)} \approx \frac{T_\alpha T_\gamma}{\sum T_i} \times \frac{\sum T_i}{T_\alpha T_n} = \frac{T_\gamma}{T_n}$$

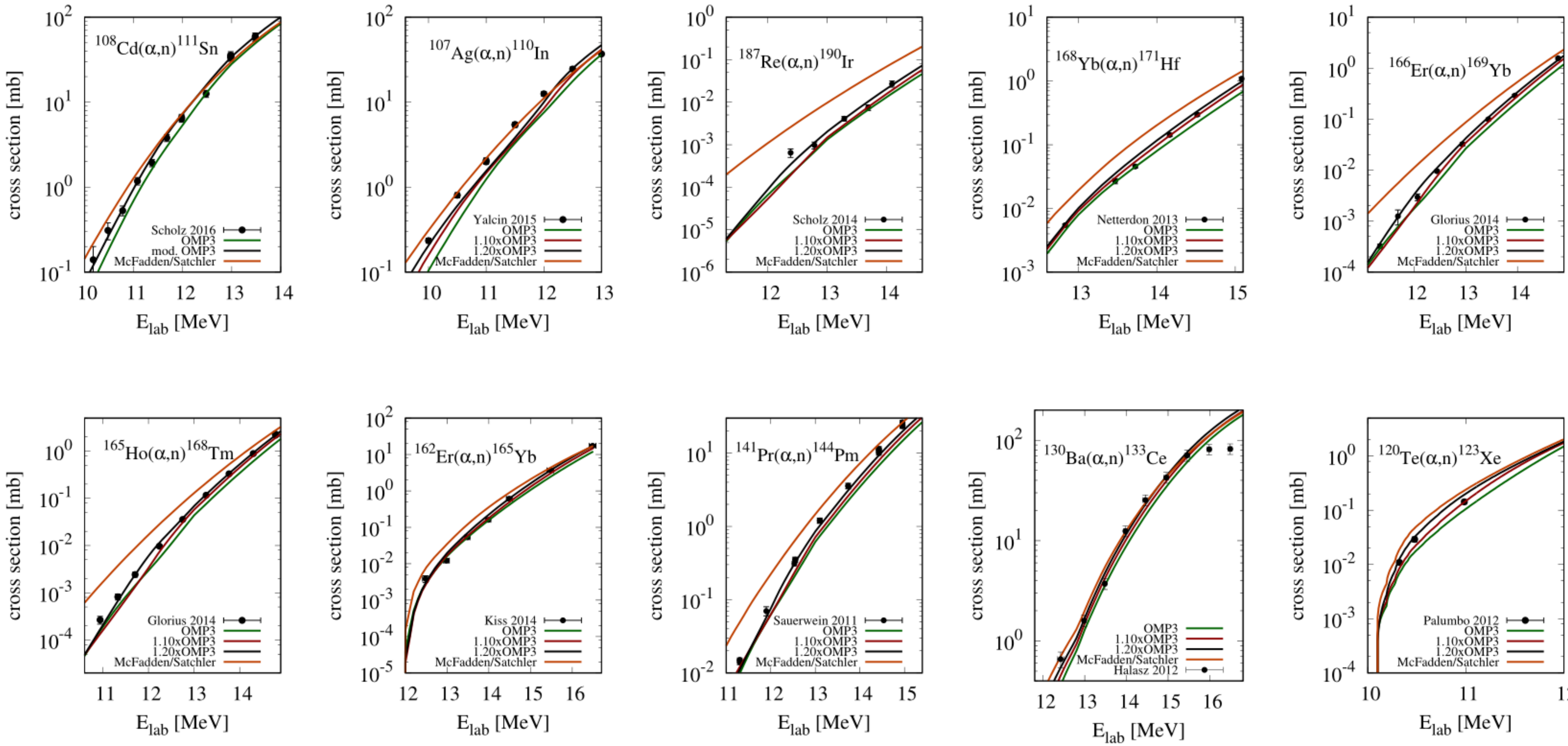
- Too small values at higher energies
- Wrong energy trend for McFadden
- Best reproduction: modified OMP3





P. Scholz, F. Heim *et al.,* Phys. Lett. B **761** (2016) 247

α-optical model potential

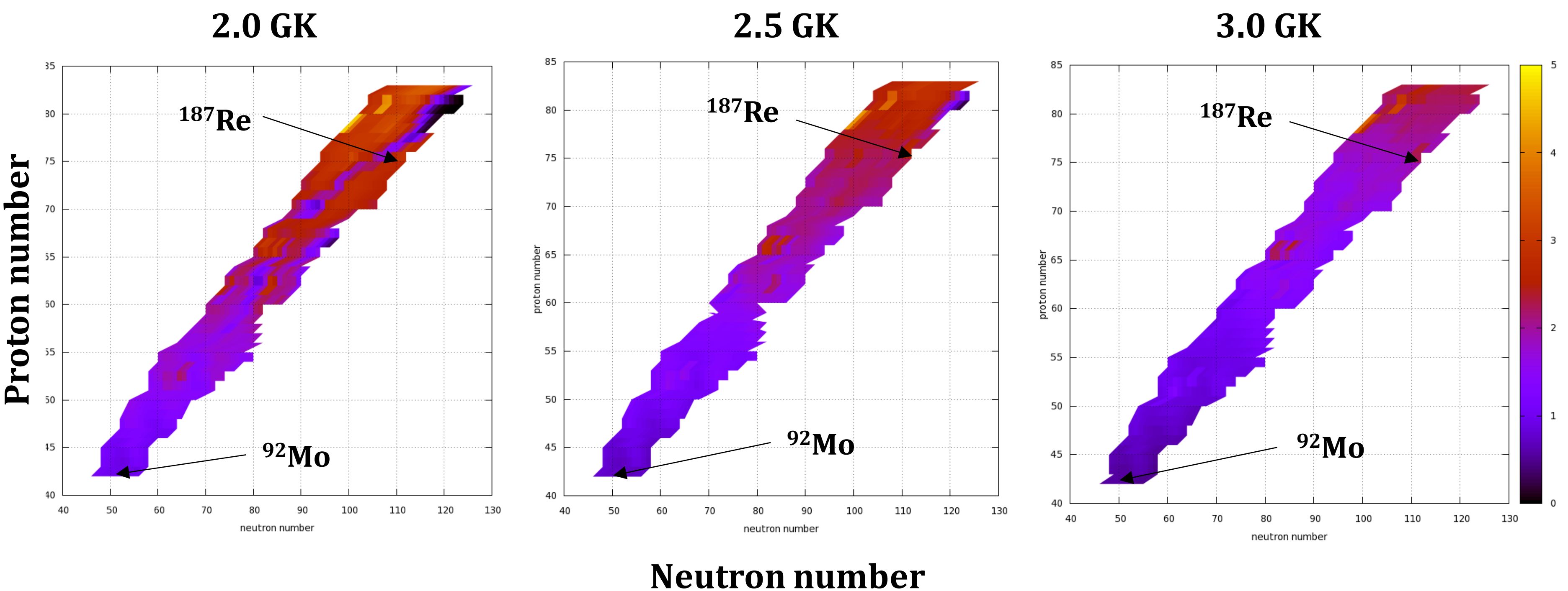


Good reproduction of all experimental (α,n) data at sub-Coulomb energies

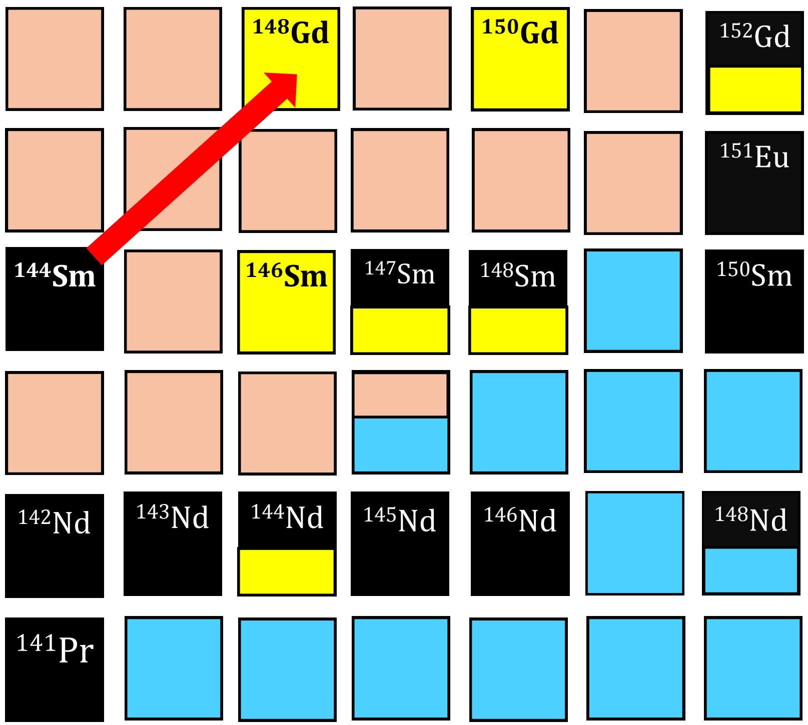
P. Scholz, F. Heim *et al.,* Phys. Lett. B **761** (2016) 247

Comparison of (γ,α) reaction rates using McFadden/Satchler and Demetriou OMP3

- Factor 10 to 100 difference between A =100 and A =140
- 2 to 3 magnitudes difference for A > 140



^{144}Sm/^{146}Sm chronometer

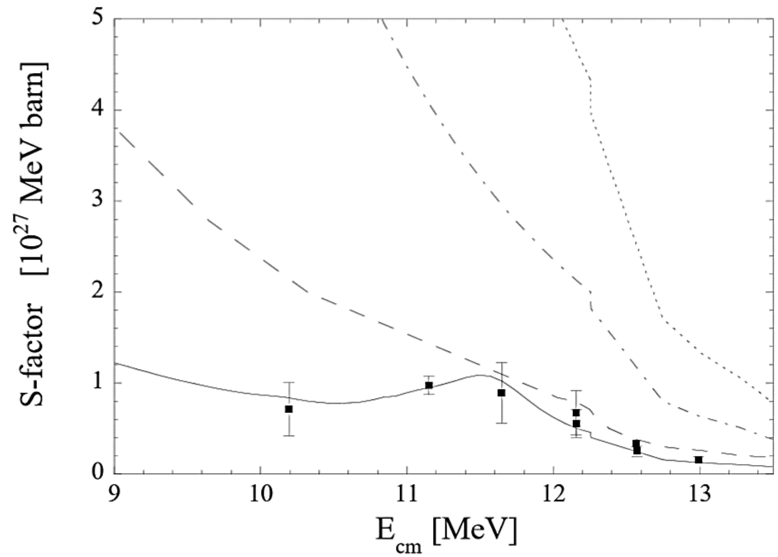


- previous measurement by means of **the activation method and α-counting** was strongly debated due to methodical reasons

➢ new measurement via Accelerator Mass Spectrometry (AMS) & counting in Dresden

- **extinct *p* nucleus ^{146}Sm** serves via its α-decay to ^{142}Nd as a clock for the evolution of our solar system and its planetary processes

- the precise determination of the **initial isotopic abundance ratio** (^{146}Sm/^{144}Sm)$_0$ is of utmost importance



E. Somorjai et al., Astron. Astrophys. **333** (1998) 1112

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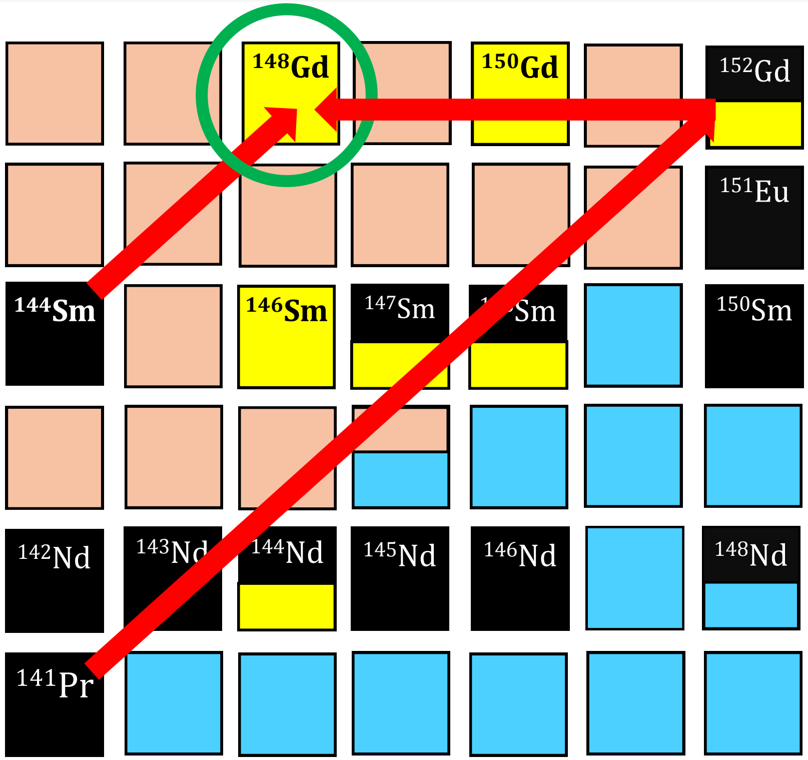

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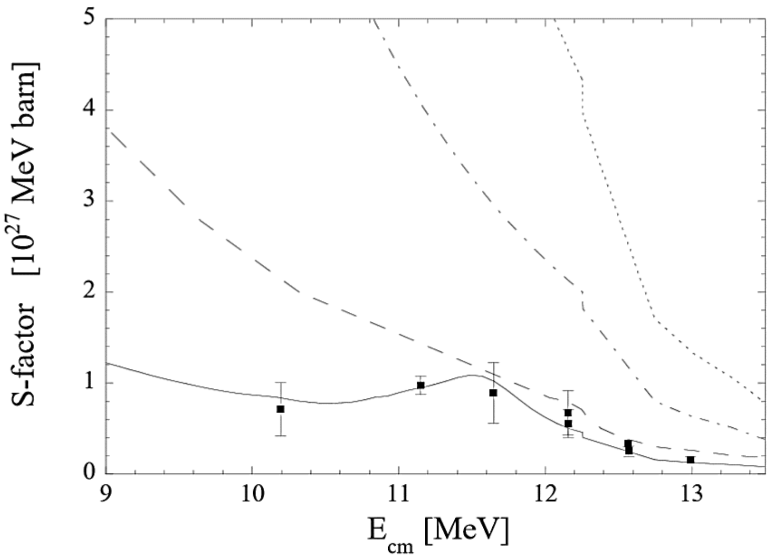

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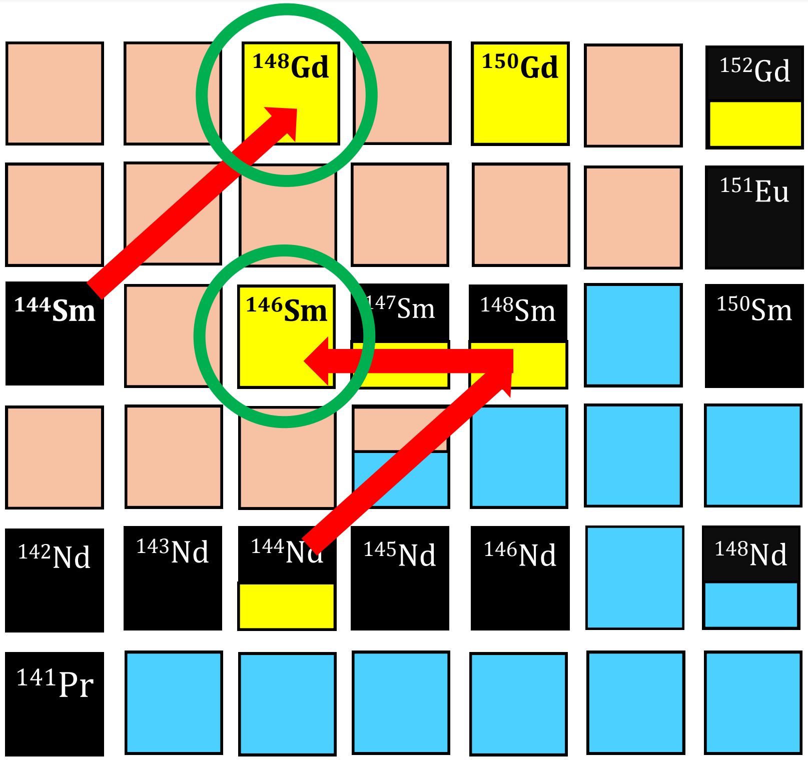

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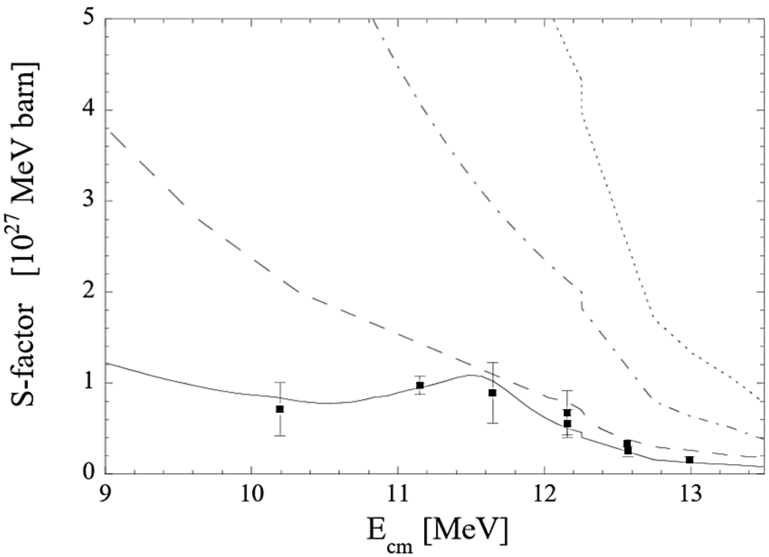

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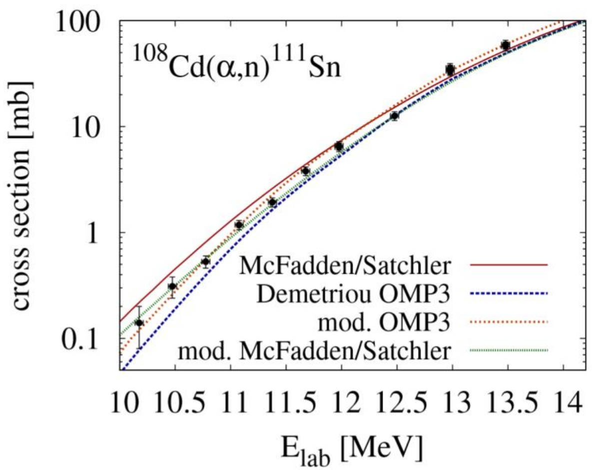
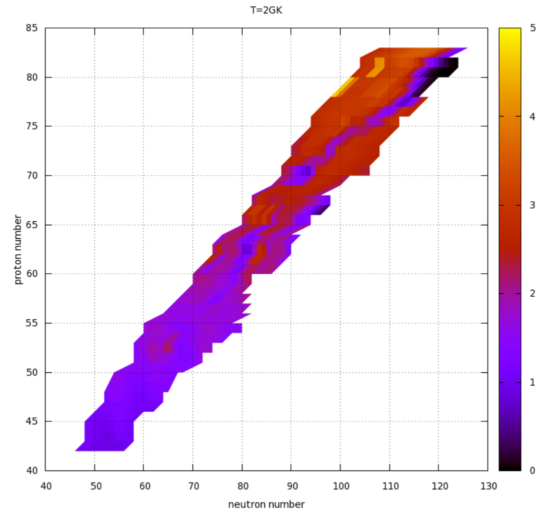
Summary

- Need for robust models for **nuclear physics input** for a reliable description of nucleosynthesis processes
- α optical-model potential can be used in a wide mass range
- Impact on γ-process has to be studied
- What is about other input-parameters?
- AMS measurements will begin soon in Cologne





Thank you for your attention!

R. Altenkirch, V. Derya, A. Dewald, T. Dunai, J. Endres, A. Endres, C. Fransen, F. Heim, S. Heinze, A. Hennig, J. Mayer, C. Müller-Gatermann, C. Münker, L. Netterdon, S.G. Pickstone, S. Prill, M. Schiffer, M. Spieker, P. Sprung, D. Vieß, K.-O. Zell and A. Zilges

J. Meijer and J. Vogt

Messen ▪ Forschen ▪ Wissen

U. Giesen

H.-W. Becker and D. Rogalla

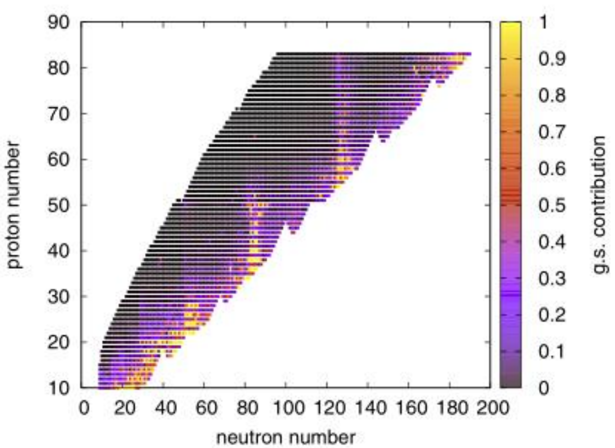
Zentrale Einrichtung für Ionenstrahlen und Radionuklide

H. Wilsenach and K. Zuber

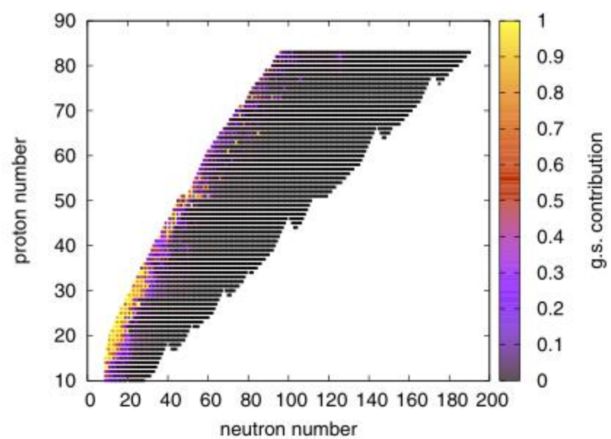
Backup

Ground-state contributions

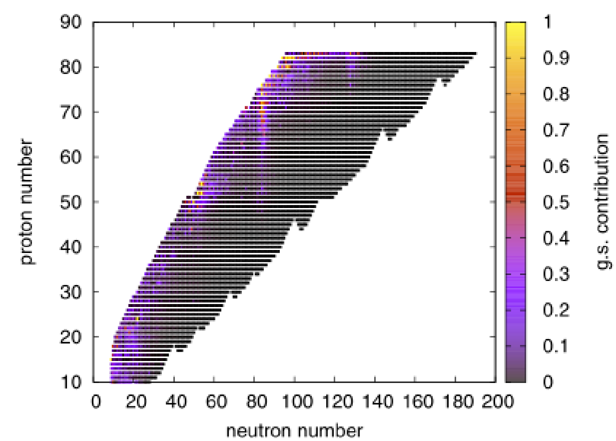
- measured cross sections cannot directly used for astrophysics
- for γ-induced reaction the ground-state contribution is almost zero
- larger contribution from excited states in the stellar plasma (T_9 > 1.5)
- reaction rates are obtained from the inverse reactions via reciprocity theorem



(γ,n)



(γ,p)



(γ,α)

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

Summary

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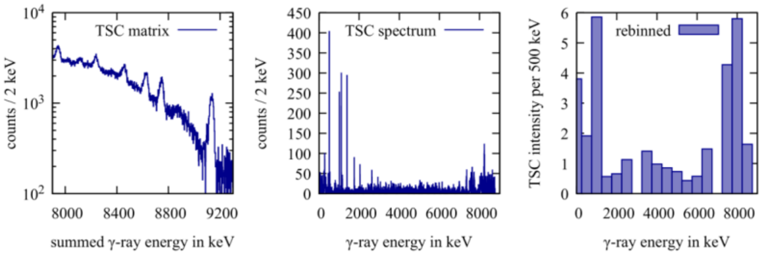
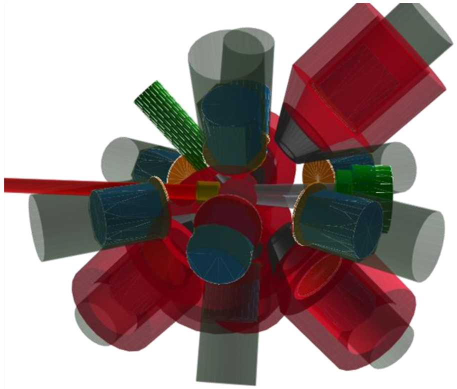
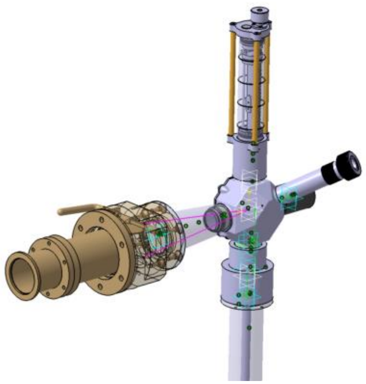


- **Proton-captures** can be used to obtain information about the γ-strength function of even unstable nuclei

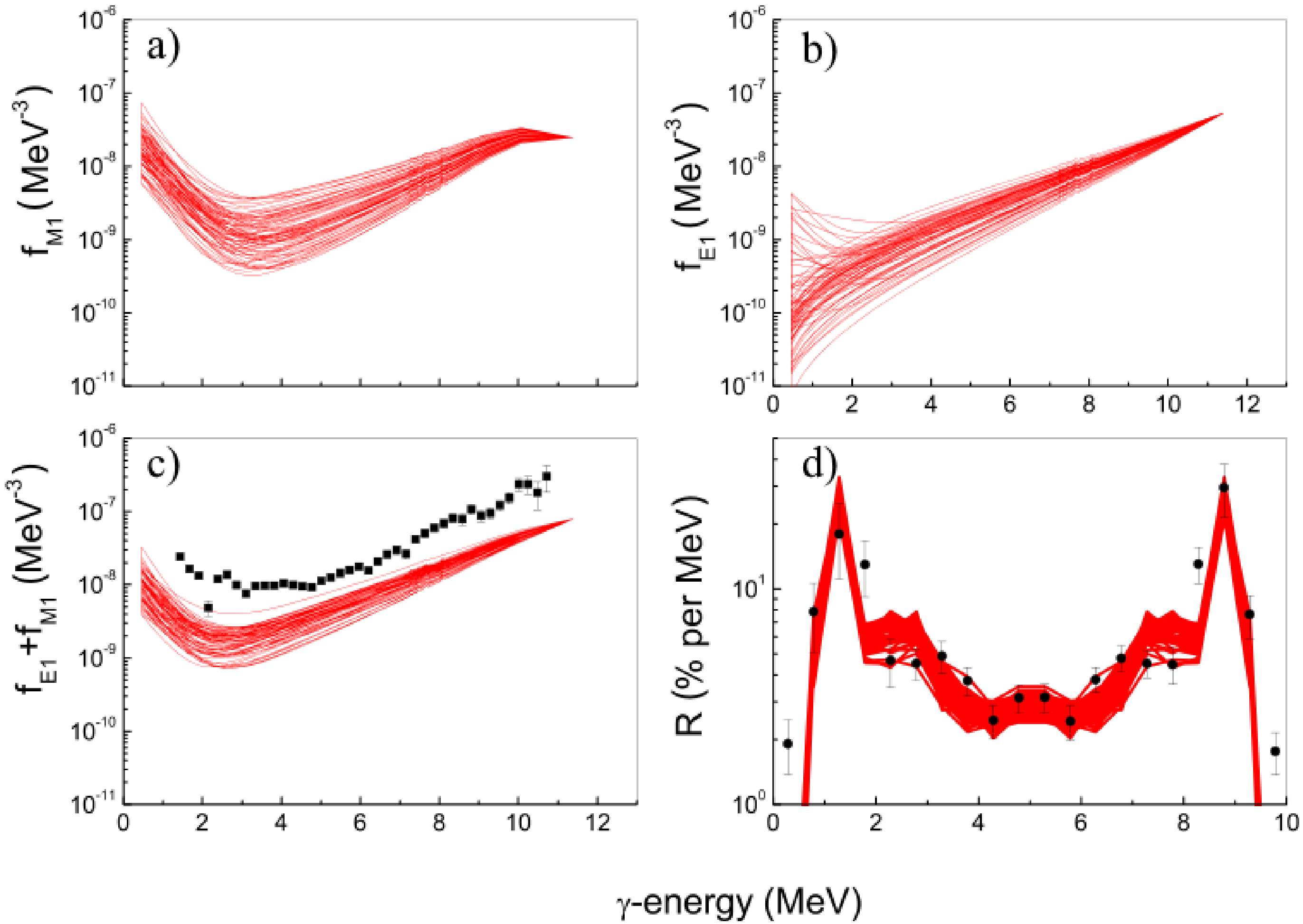


- The method of **Two-Step Cascades** can be used to study γ-strength functions and nuclear level densities



Two Step Cascades

TSC-analysis for $^{59}Co(p,\gamma\gamma)\,^{60}Fe$



A. Voinov *et al.*, PRC **81** (2010) 024319

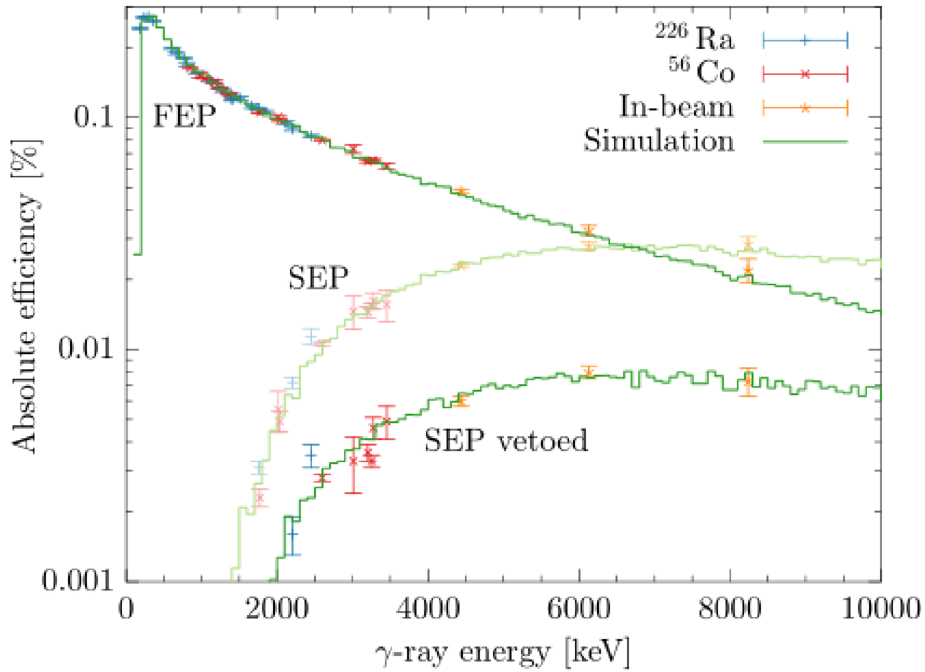
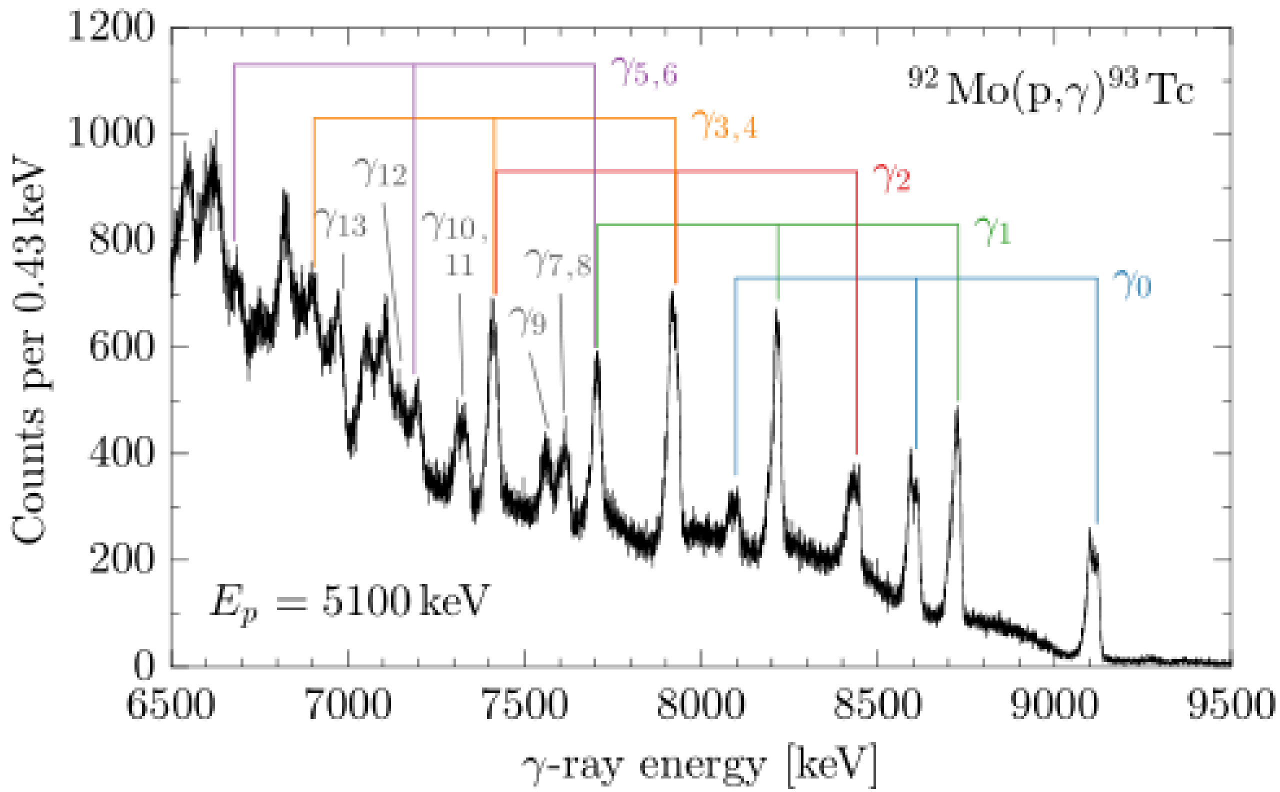


FIG. 2. Full energy peak (FEP) and single escape-peak (SEP) efficiency for one HORUS HPGe detector. Experimental data have been obtained from standard sources and in-beam reactions [^{27}Al(p,γ)^{28}Si, ^{12}C($p,p'\gamma$), ^{19}F(p,α)^{16}O], with the last two scaled to the FEP efficiency. The simulations were carried out by using GEANT4 [25]. It was not necessary to scale the simulated data to match the experimental results. The detector is equipped with a BGO anti-Compton shield whose active veto signal can be used on an event-by-event basis to suppress escape peaks (SEP vetoed).

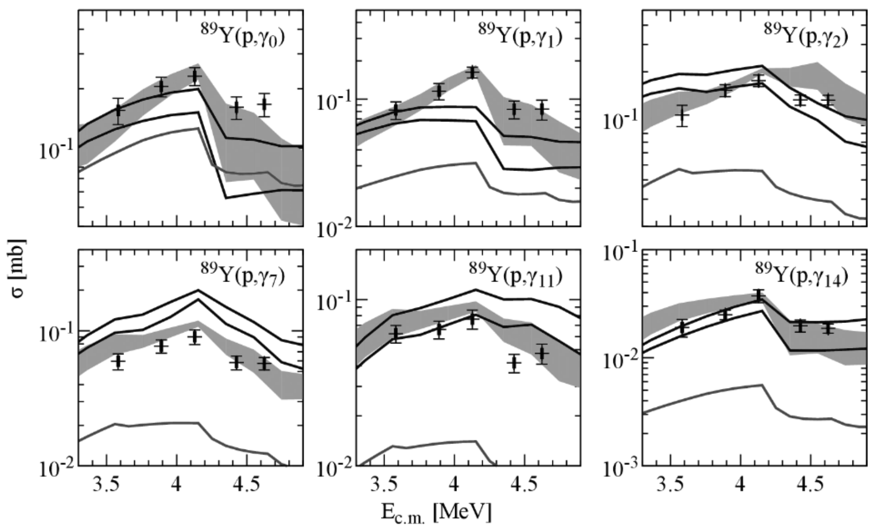


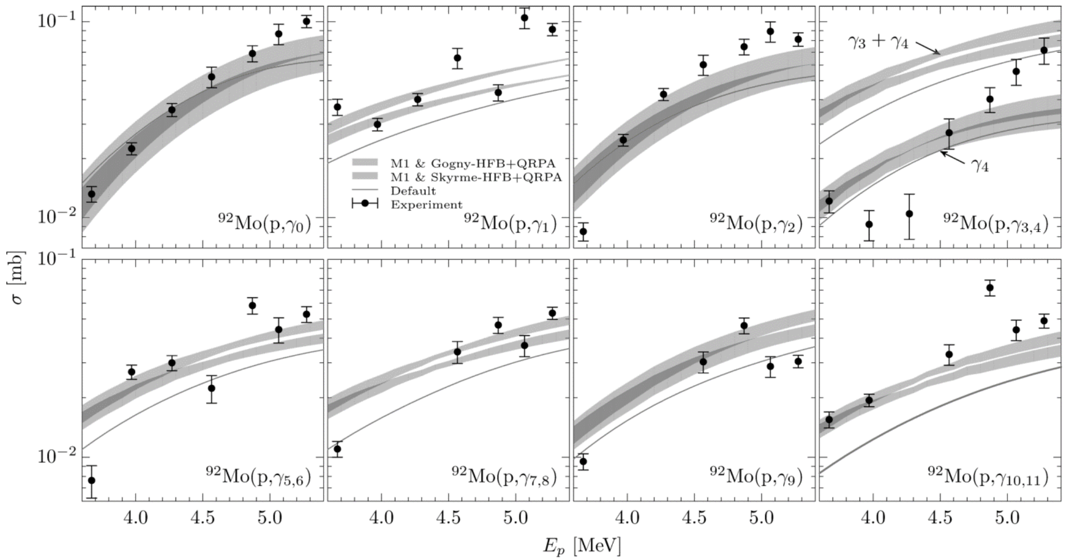
^{92}Mo(p,γ)^{93}Tc
$E_p = 5100$ keV
Counts per 0.43 keV
γ-ray energy [keV]
γ5,6
γ3,4
γ2
γ1
γ0
γ12
γ13
γ10, 11
γ7,8
γ9
0
200
400
600
800
1000
1200
6500
7000
7500
8000
8500
9000
9500

In-beam measurement of cross sections

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

- Measurement of the $^{89}Y(p,\gamma)^{90}Zr$ reaction at 5 different proton energies
- Excitation energies up to 13 MeV
- Comparision to (γ,γ‘) data possible





J. Mayer *et al.*, PRC **93** (2016) 045809

- testing the γ–ray strength function in ^{93}Tc via $^{92}Mo(p,\gamma)$
- partial cross sections at 7 different proton energies between 3.5 MeV and 5.5 MeV
- M1/E2-strength not negligble
  - ➢ shell model calculations by R. Schwengner for ^{93}Tc

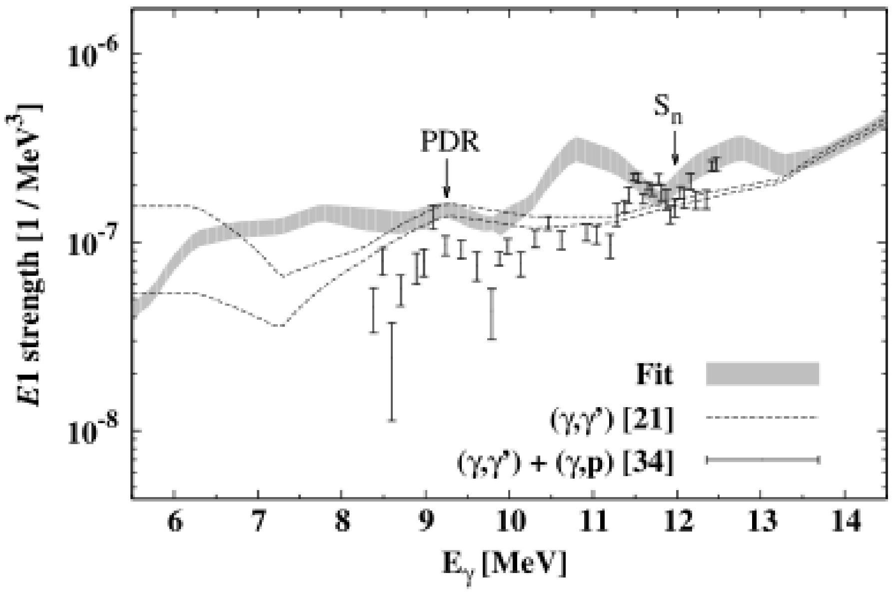


Fig. 5. $E1$-strength distribution as a function of γ-ray energy in ^{90}Zr extracted from the measurement of partial cross sections of the ^{89}Y(p, γ)^{90}Zr reaction. The gray shaded area depicts the adjusted γ-ray strength function used to reproduce the experimental partial cross sections by Hauser–Feshbach calculations. Additionally shown is the γ-ray strength function obtained from a (γ, γ') measurement of Ref. [21] and of Ref. [34]. The dashed lines correspond to the experimental uncertainty of the (γ, γ') data. The strength around the PDR energy of about 9 MeV as found in Refs. [11,21] is well reproduced by the present measurement, but a significant enhancement is observed around the neutron-separation energy S_n.

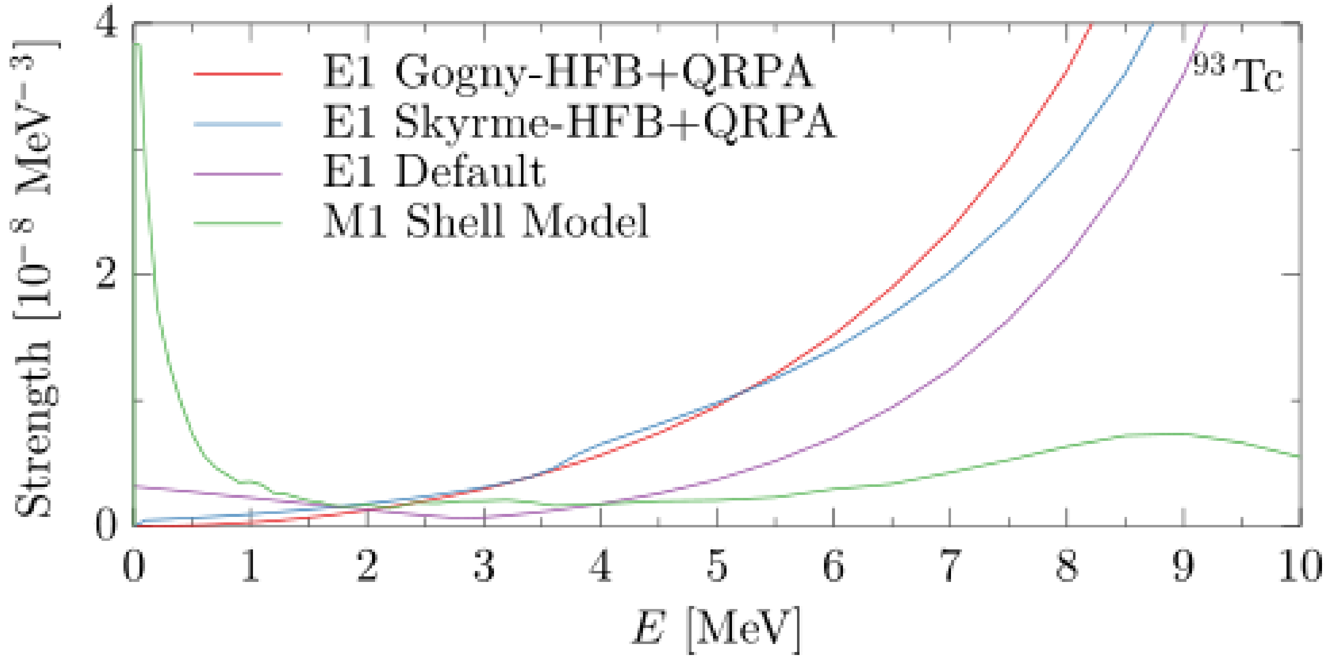
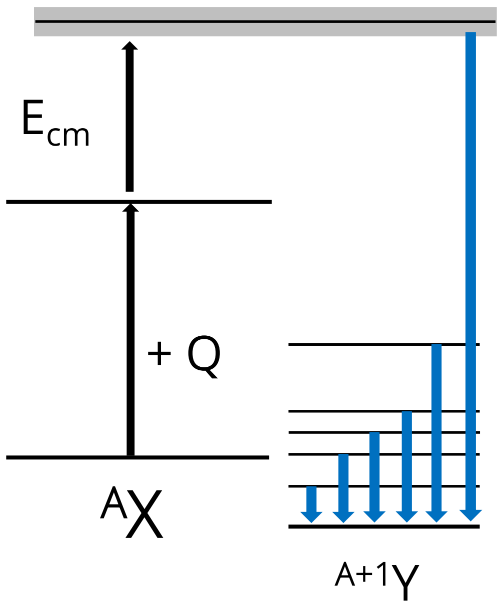
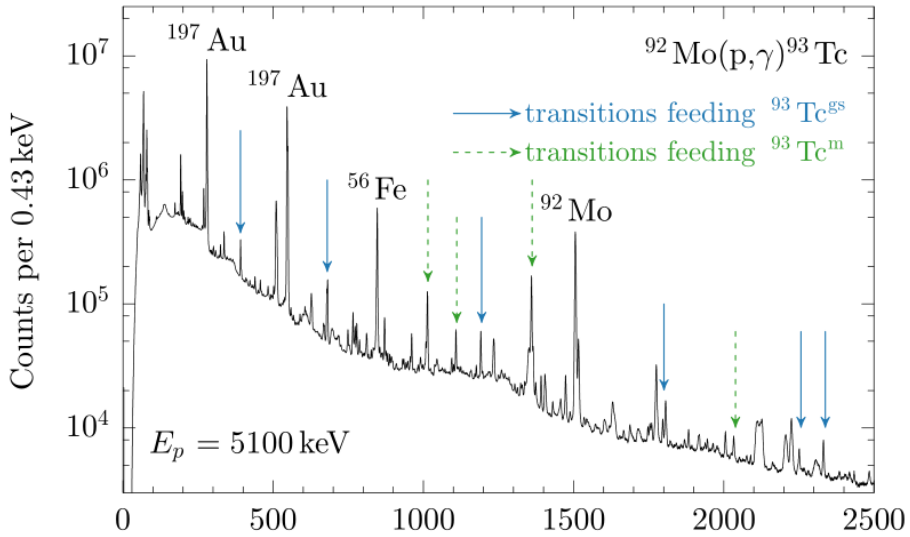


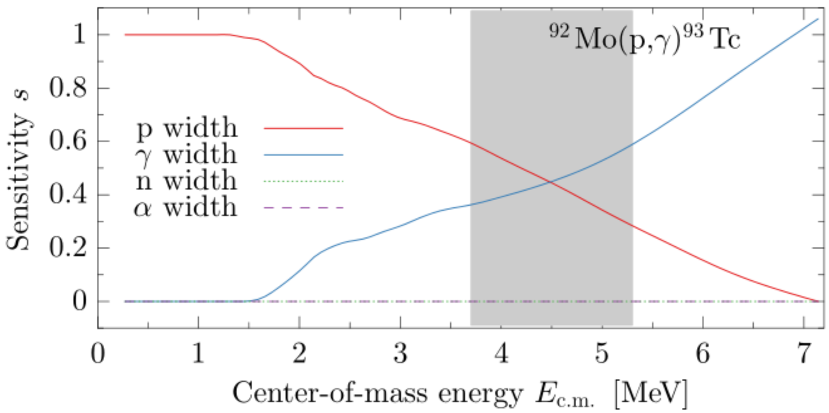
FIG. 10. $E1$ and $M1$ γ strength in ^{93}Tc obtained by Gogny- or Skyrme-HFB + QRPA in the case of $E1$ and shell-model calculations for the case of $M1$ strength. The low-energy $M1$ strength was combined with a Lorentzian for the spin flip. See text for details.

Total cross sections of $^{92}Mo(p,\gamma)^{93}Tc$

- Measurement of $^{92}Mo(p,\gamma)^{93}Tc$ at four energies between 3.6 MeV and 5.3 MeV, thus, above the (p,n) threshold
- Q-Value: 4.1 MeV
- Excitation energies up to 9.2 MeV
- Determination of total yield from angular distribution of γ-rays

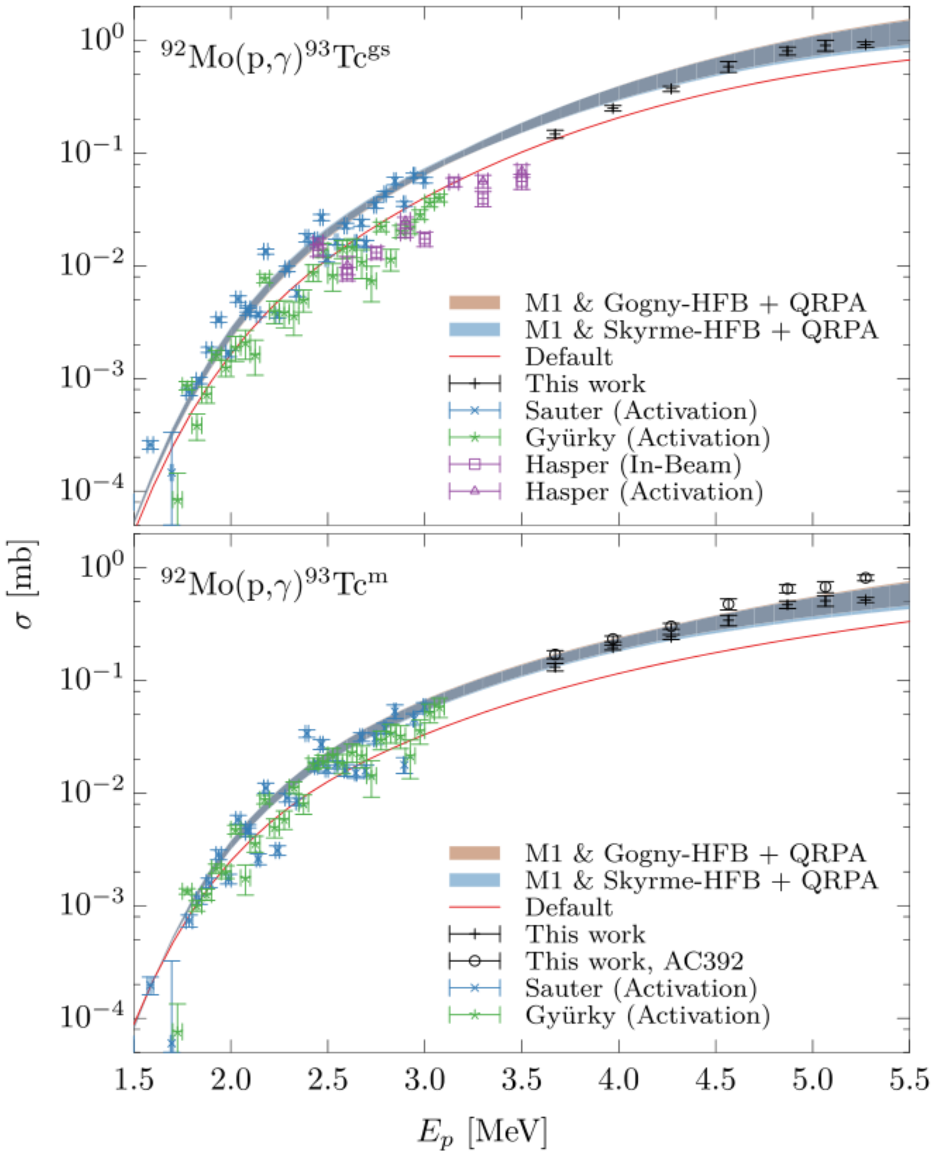






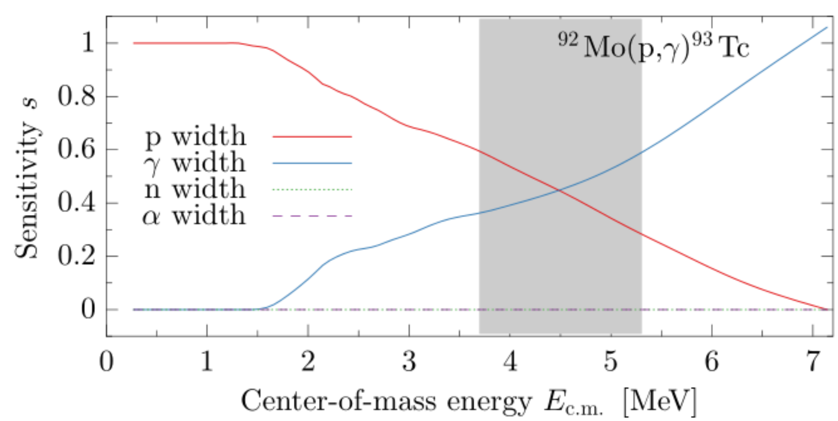
J. Mayer *et al.*, PRC **93** (2016) 045809

Total cross sections of $^{92}Mo(p,\gamma)^{93}Tc$



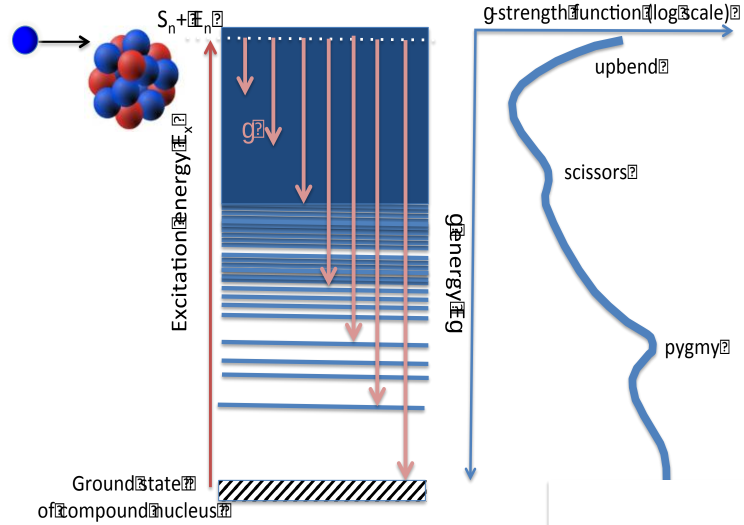
Comparison to statistical model calculations with Talys 1.8

- Measured many times before
- Using different models for γ-strength, NLD, and proton optical model
- Fluctuations at lower energies makes it difficult to draw any conclusions
- Total cross-sections are not enough to find differences in the outcome of various γ-strength models



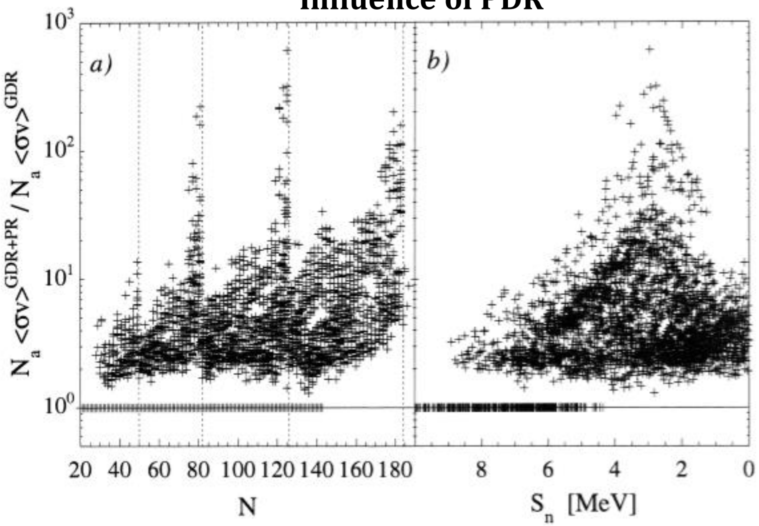
J. Mayer *et al.*, PRC **93** (2016) 045809

- **γ-strength** plays a crucial role in the determination of reaction rates
- the lower the **particle separation energies** the more important the **low energy tail of the γ-strength**
- **Proton-capture** can be used to obtain information about the **γ-strength function** of even unstable nuclei



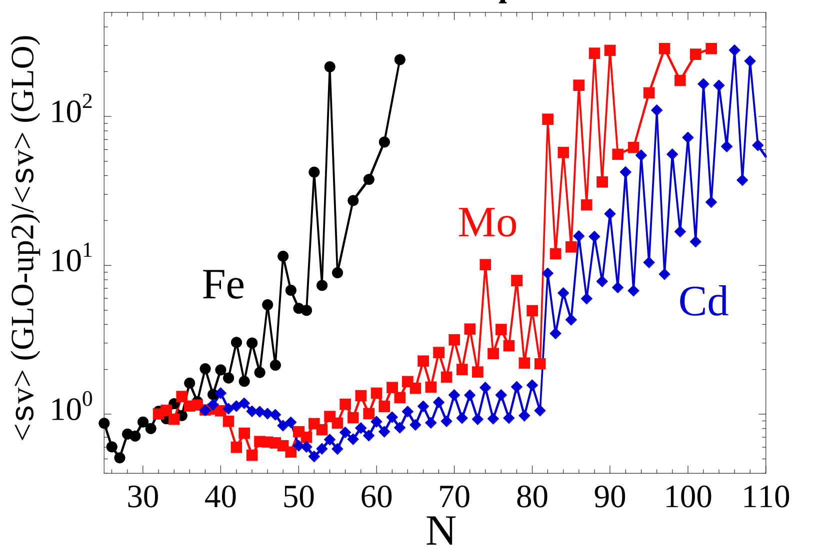
Picture credit: M. Guttormsen

Influence of PDR



S. Goriely, Phys. Lett. B **436** (1998) 10

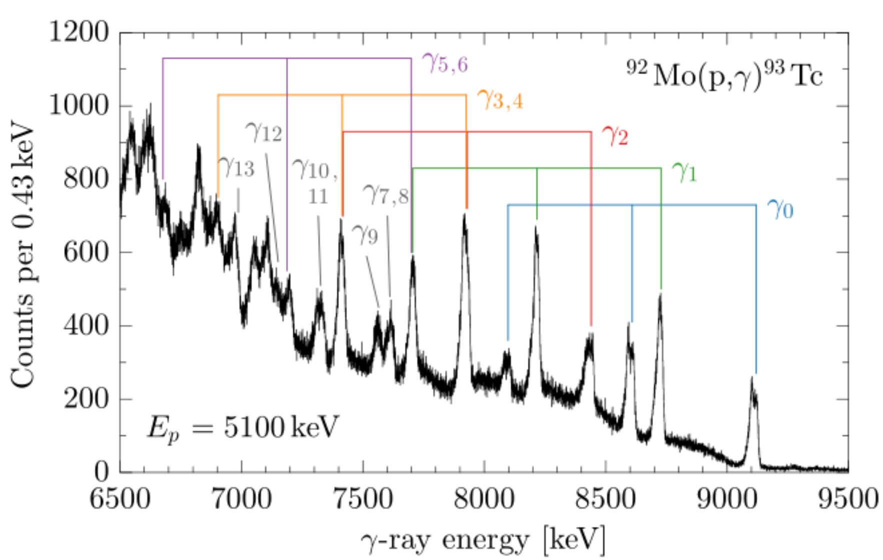
Influence of upbend

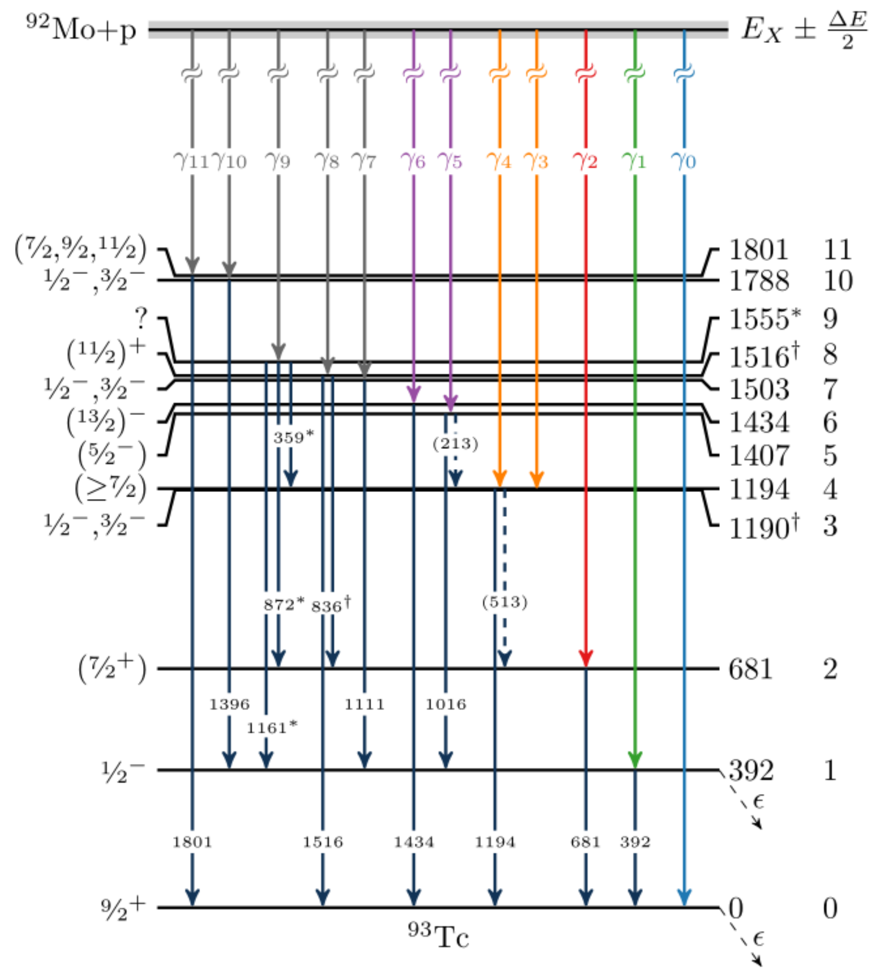


A.C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)

Prompt deexcitation and partial cross sections

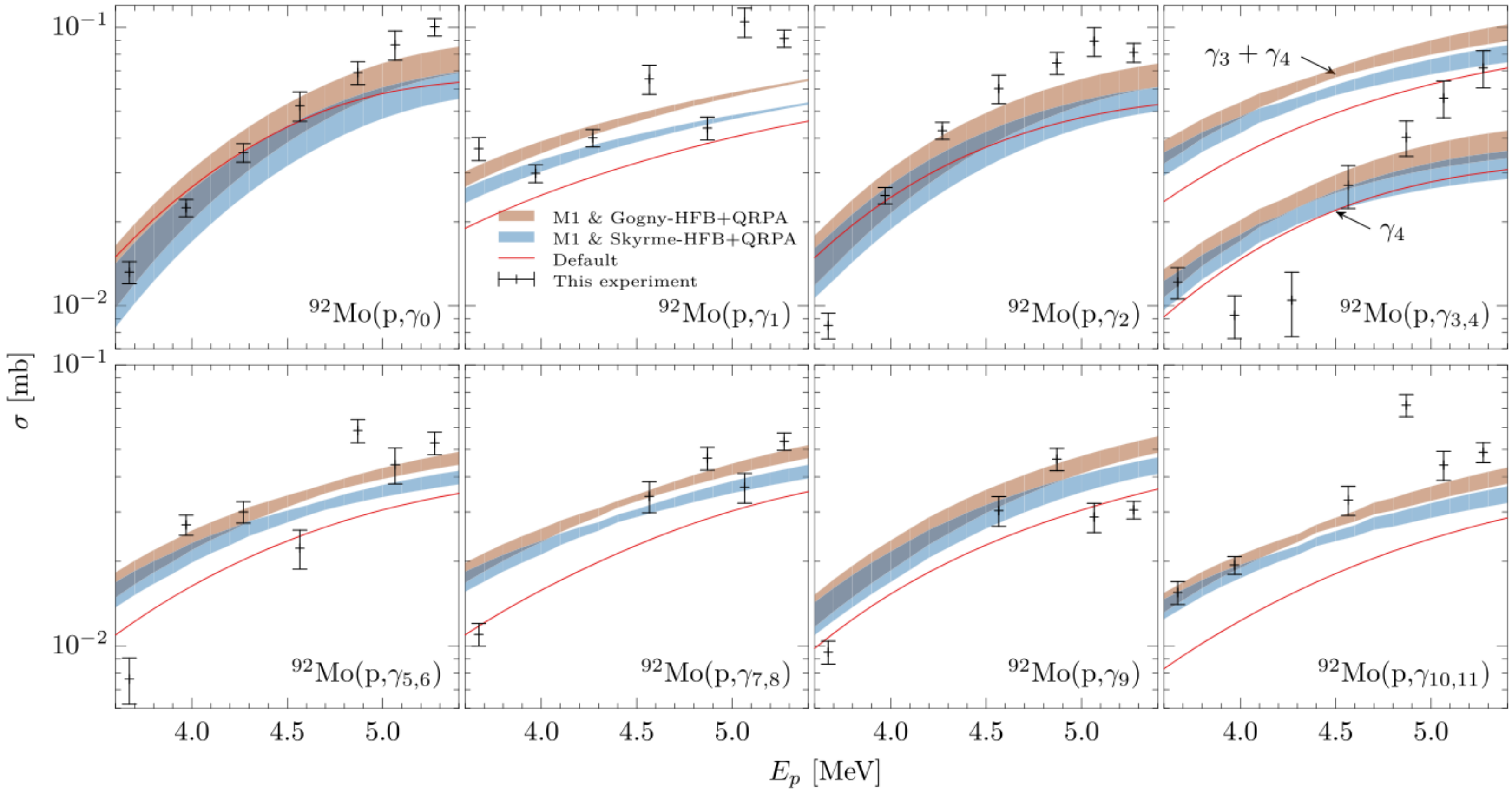
- Detecting the highly energetic prompt γ-rays to excited levels in the reaction product
- Ratios between **partial cross-sections** give information about the energy dependence of the **γ-strength function**
- **Adjust** γ-strength on partial cross-sections
- **Constrain or exclude** existing models





J. Mayer *et al.*, PRC **93** (2016) 045809

In-beam measurement of cross sections



- testing the γ–ray strength function in ^{93}Tc via ^{92}Mo(p,γ)
- partial cross sections at 7 different proton energies between 3.5 MeV and 5.5 MeV
- M1/E2-strength not negligible
  - ➢ shell model calculations by R. Schwengner for ^{93}Tc

J. Mayer *et al.*, PRC **93** (2016) 045809

Two Step Cascades

PHYSICAL REVIEW C VOLUME 46, NUMBER 4 OCTOBER 1992

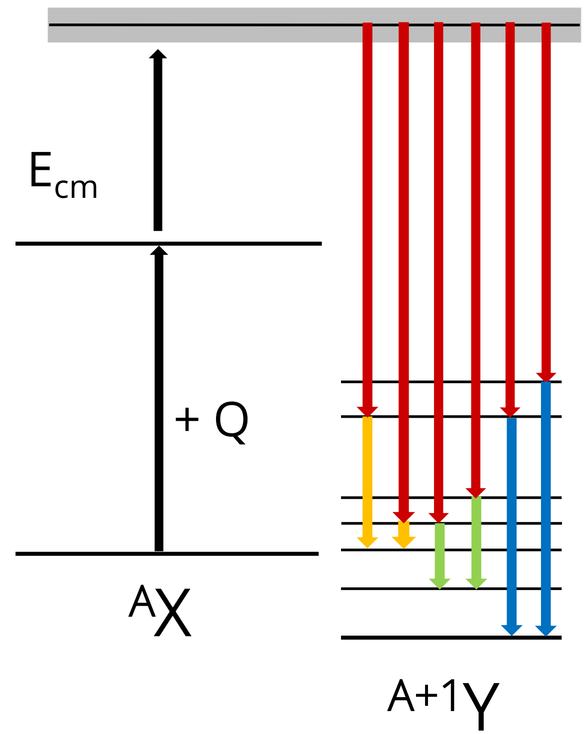
Test of photon strength functions by a method of two-step cascades

F. Bečvář and P. Cejnar
Charles University, Faculty of Mathematics and Physics, Prague 8, CS-18000, Czechoslovakia

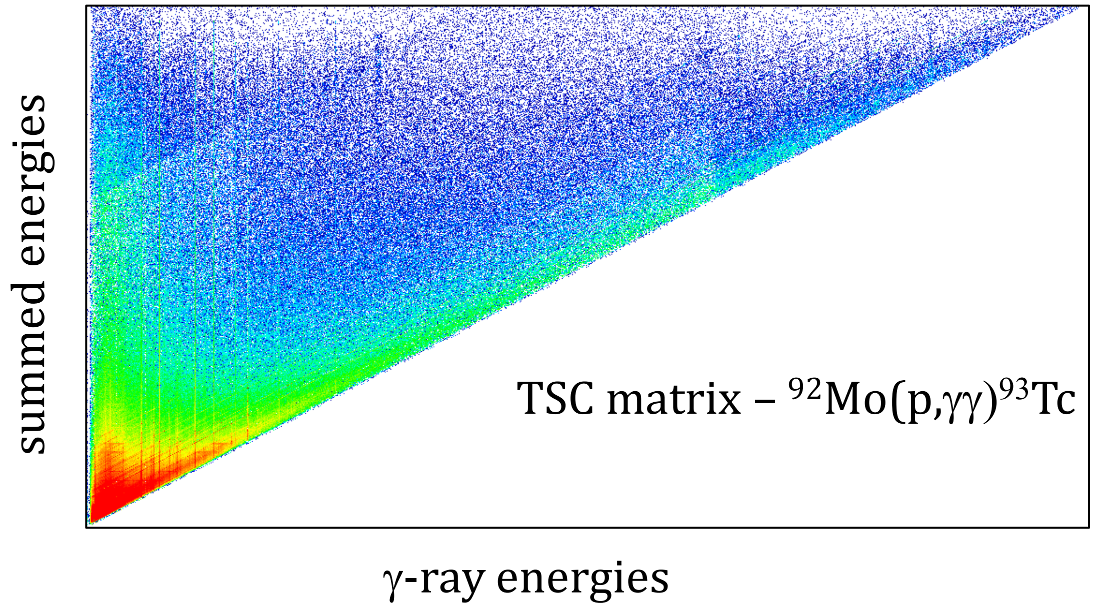
R. E. Chrien
Brookhaven National Laboratory, Upton, New York 11973

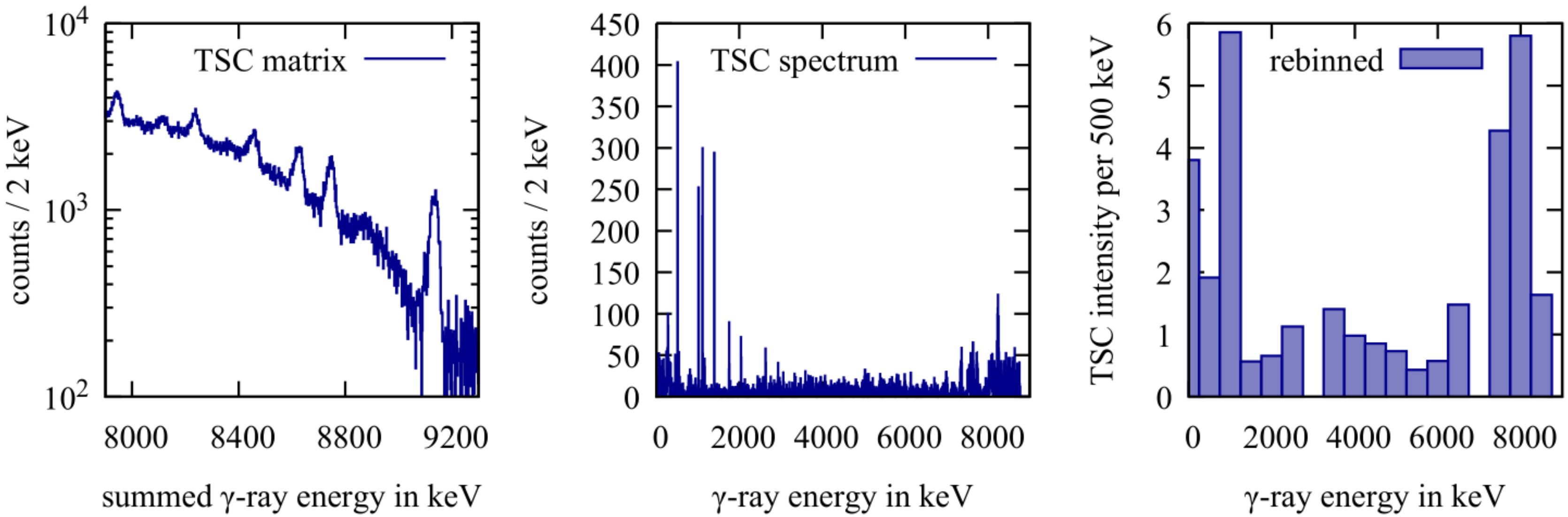
J. Kopecký
Nederlands Energy Research Foundation ECN, P.O.Box 1, 1755 ZG Petten, The Netherlands
(Received 5 February 1992)

- Detecting **two step γ-ray cascades** populating states in the reaction product
- TSC spectrum obtained via gate on sum energy of coincident γ-rays
- TSC spectrum can be simulated in the statistical model regarding contribution of E1 or M1 strength
- Different models for nuclear level densities and γ-strength can be tested

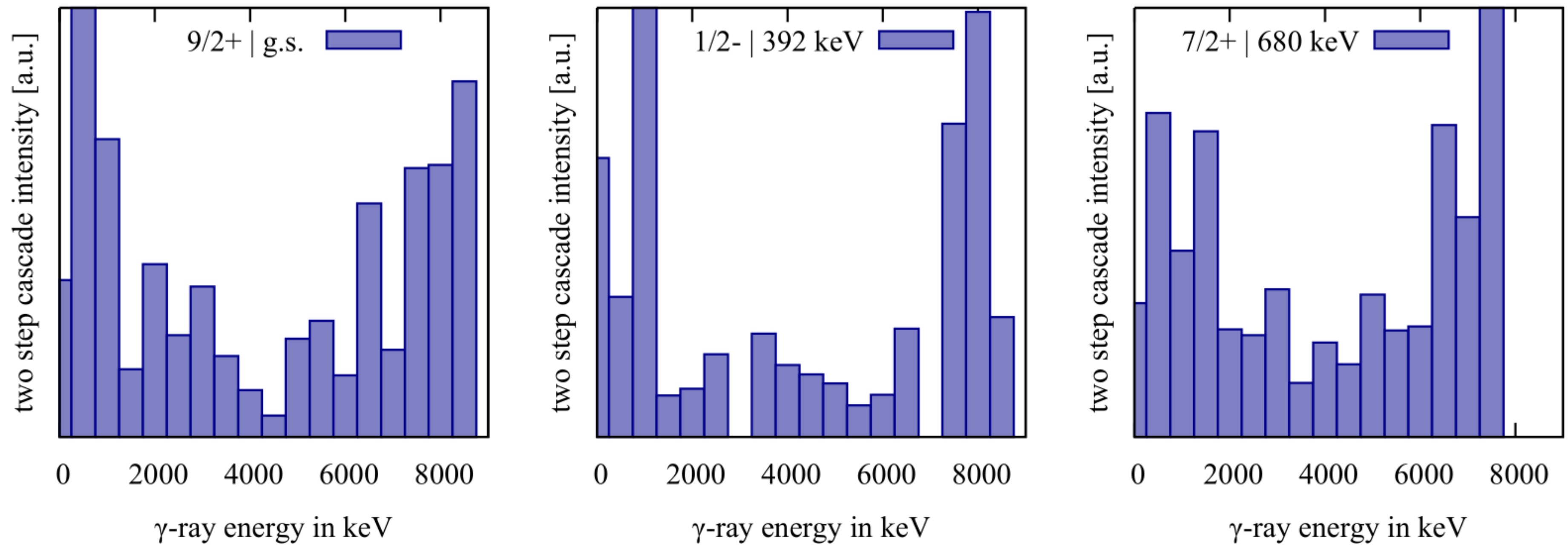


Two Step Cascades for ^{92}Mo(p,γγ)^{93}Tc





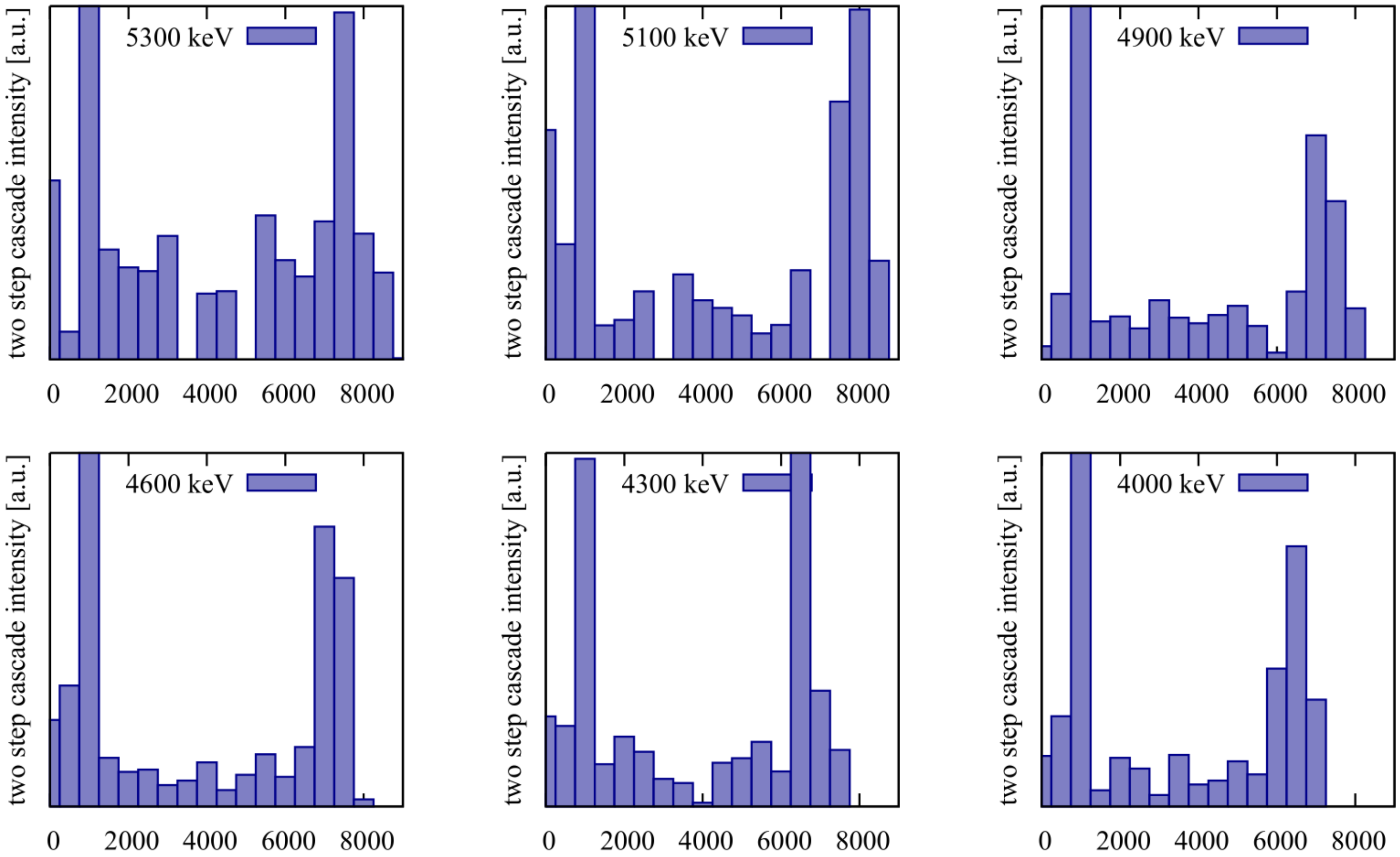
Two Step Cascades for $^{92}Mo(p,\gamma\gamma)^{93}Tc$



$$I_{if}(E_1,E_2) = \sum_{XL,XL',J_m^\pi} \frac{\Gamma_{im}^{XL}(E_1)}{\Gamma_i}\rho(E_m,J_m^\pi)\frac{\Gamma_{mf}^{XL'}(E_2)}{\Gamma_m} + \sum_{XL,XL',J_{m'}^\pi} \frac{\Gamma_{im'}^{XL}(E_2)}{\Gamma_i}\rho(E'_m,J_{m'}^\pi)\frac{\Gamma_{m'f}^{XL'}(E_1)}{\Gamma_{m'}}$$

Two step cascade intensities to different levels

Two Step Cascades for $^{92}Mo(p,\gamma\gamma)^{93}Tc$

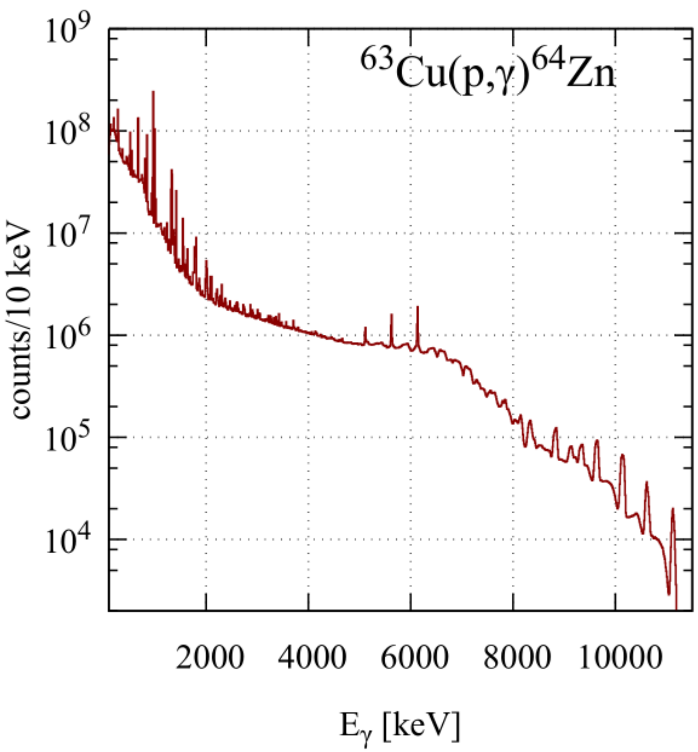


Two step cascade intensities for different excitation energies

Two Step Cascades

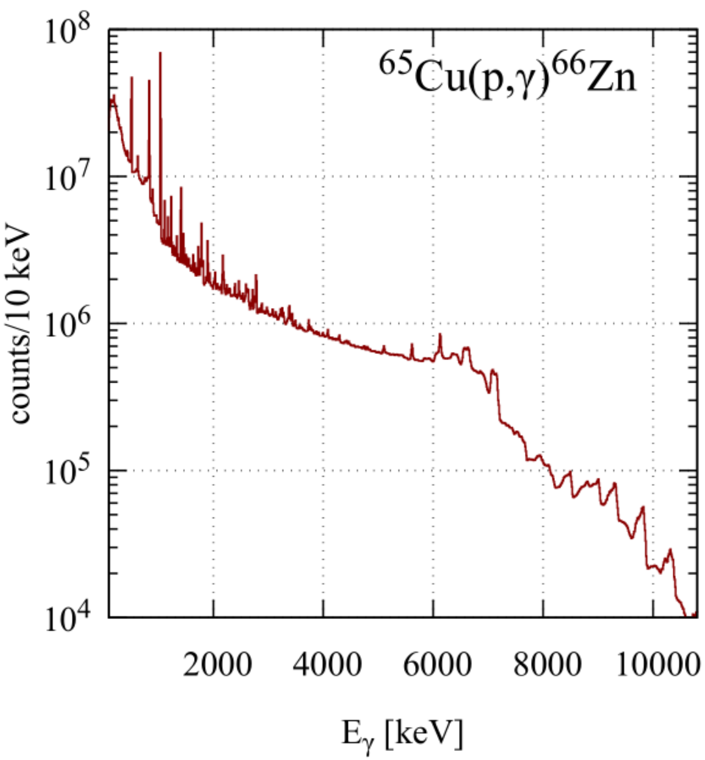
$^{63}Cu(p,\gamma\gamma)\,^{64}Zn$

- 4 days with ~400nA
- Target: ~1mg/cm^2
- Proton energy: 3.5 MeV
- Excitation energies: 11.2 MeV



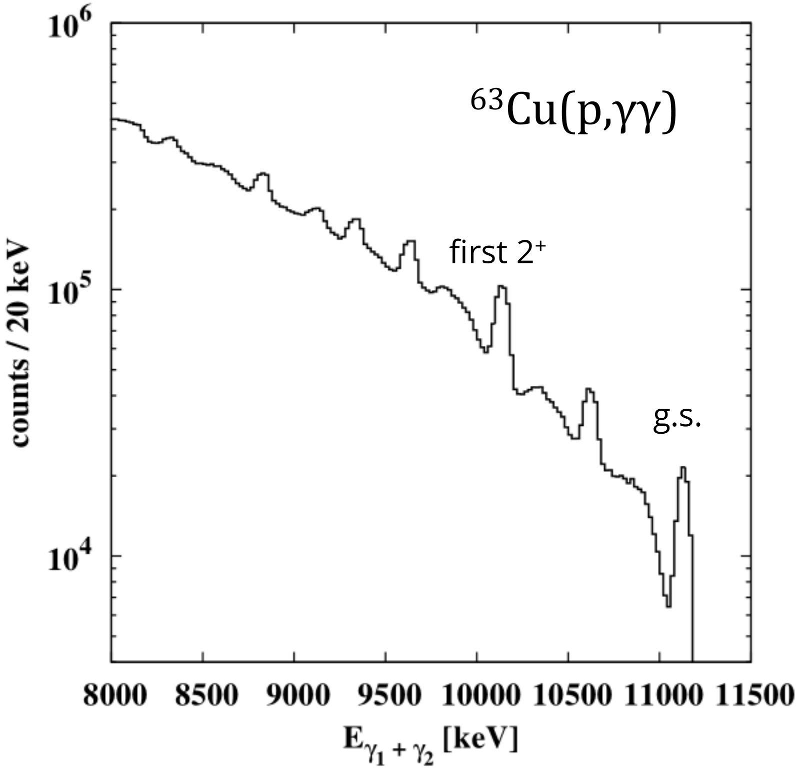
$^{65}Cu(p,\gamma\gamma)\,^{66}Zn$

- 5 days with ~500nA
- Target: ~1mg/cm^2
- Proton energy: 2.0 MeV
- Excitation energies: 10.9 MeV

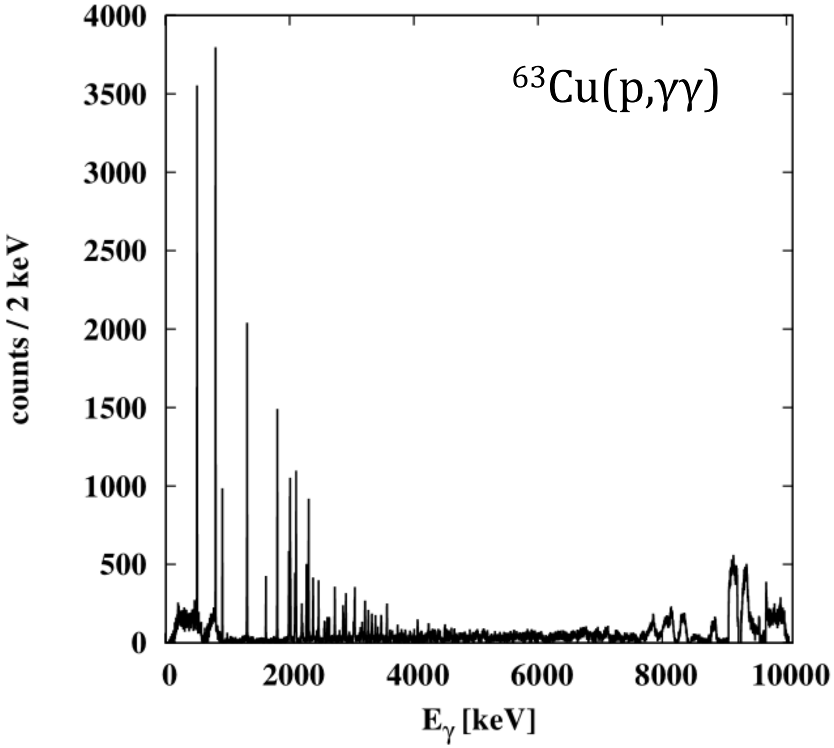


Two Step Cascades

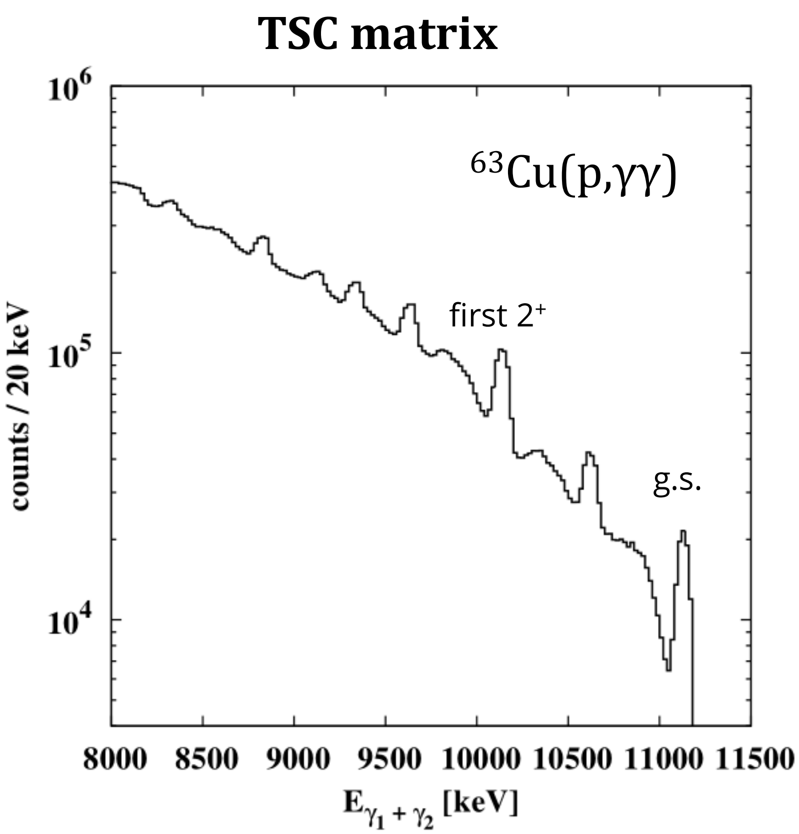
TSC matrix

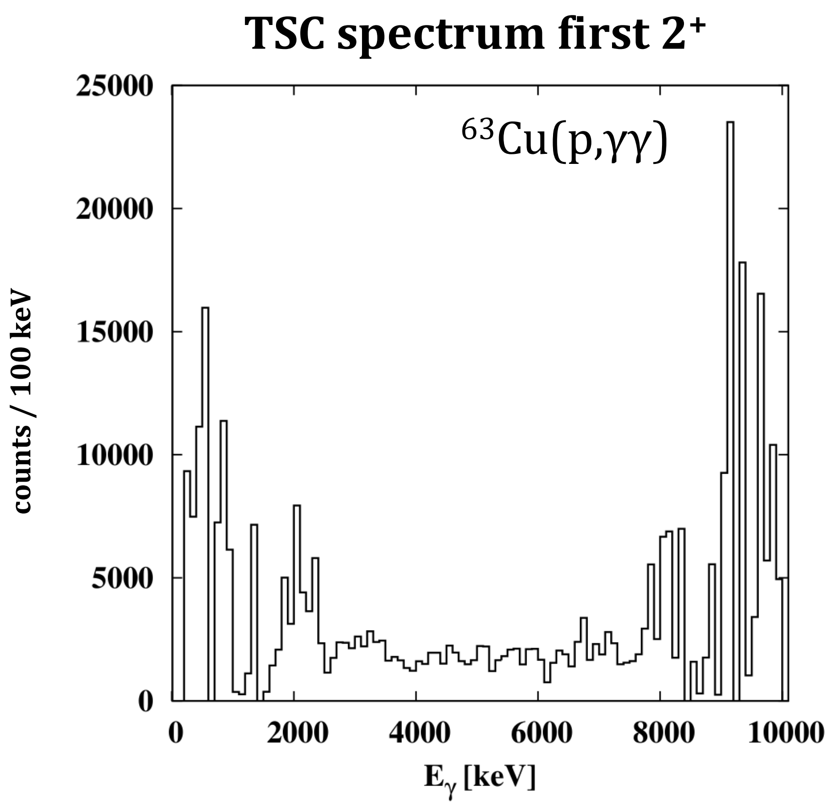


TSC spectrum first 2⁺



Two Step Cascades

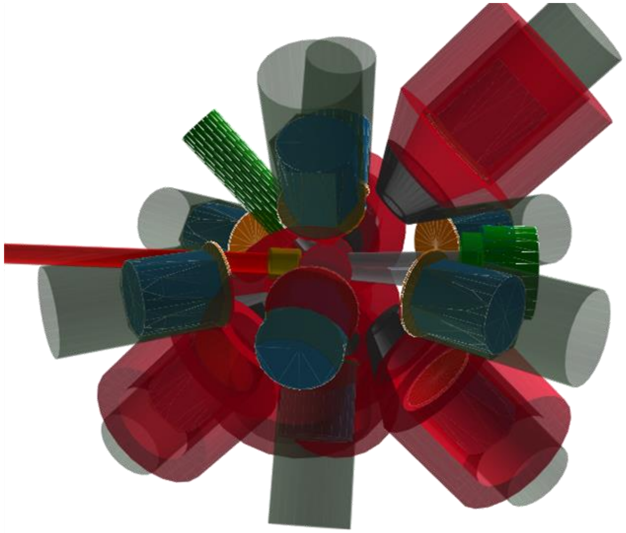




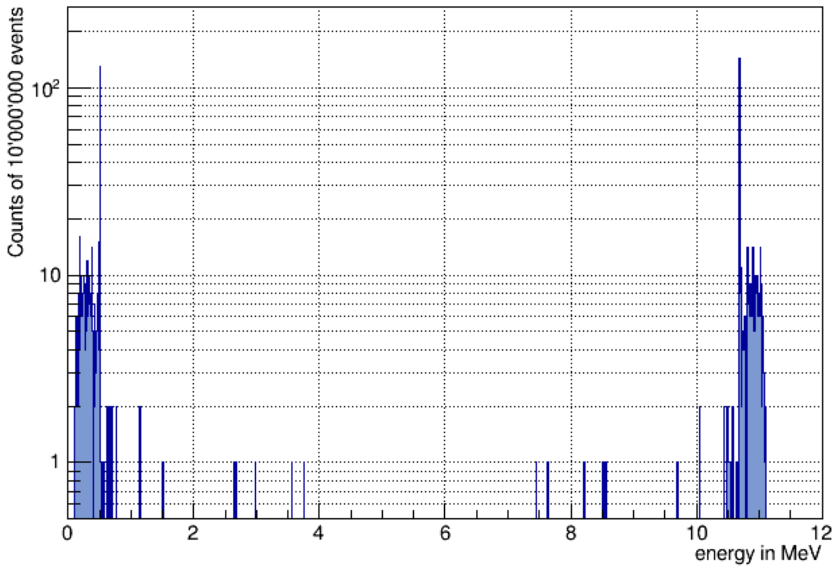
Two Step Cascades

GEANT4 Simulation of the setup

- Efficiency with ^{226}Ra, ^{56}Co, and ^{27}Al(p,γ)^{28}Si @ 3.6 MeV
- Understanding the response of the detector setup
- Understanding the background in the TSC spectrum



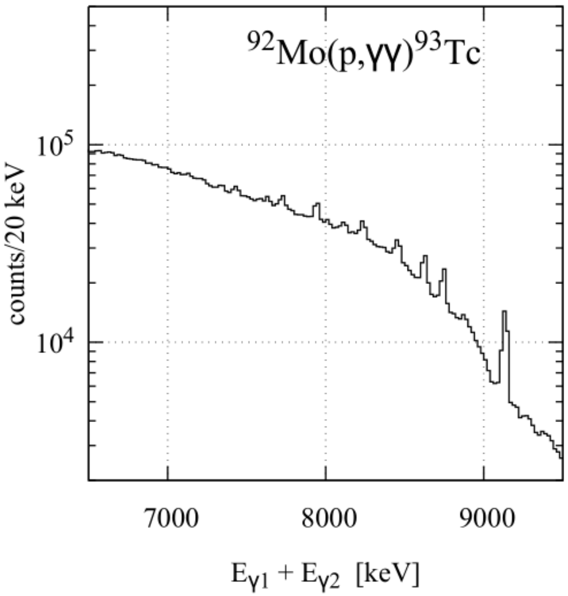
Simulated TSC spectrum of single 11.2 MeV γ-ray



Outlook

Application of TSC analysis on old data

- Coincidence data available for (p,γγ) reactions on ^{89}Y, ^{92}Mo, and ^{107}Ag
- Data available for different beam/excitation energies



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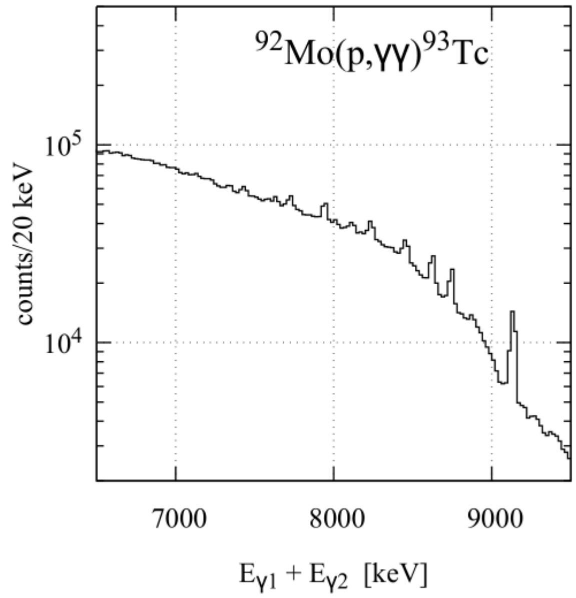

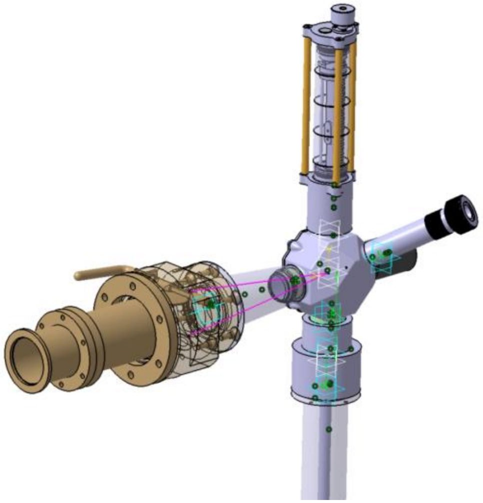

Future experiments

- New target chamber
- Total and partial cross sections on ^{109}Ag(p,γ)^{110}Cd, Zn, and Ge isotopes
- Other two-step cascade experiments
- Studying of (α,γ) reactions