Investigation of radiative proton-capture reactions using high-resolution γ-ray spectroscopy

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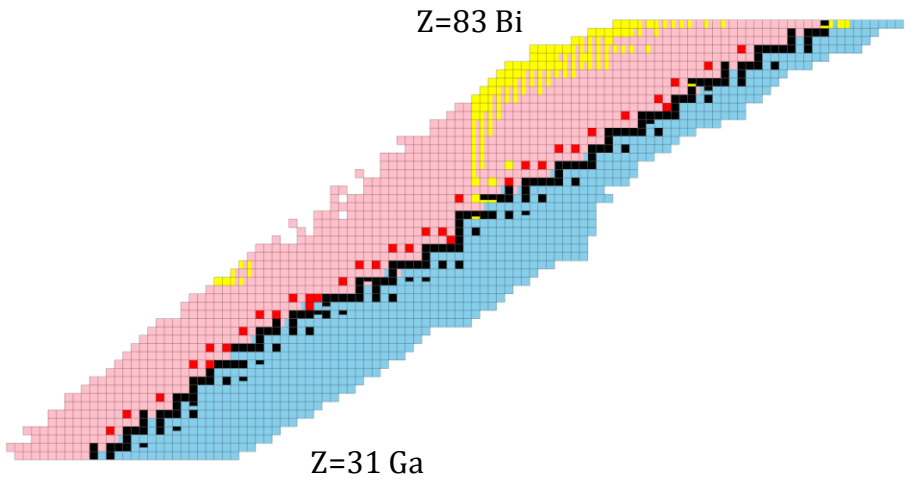
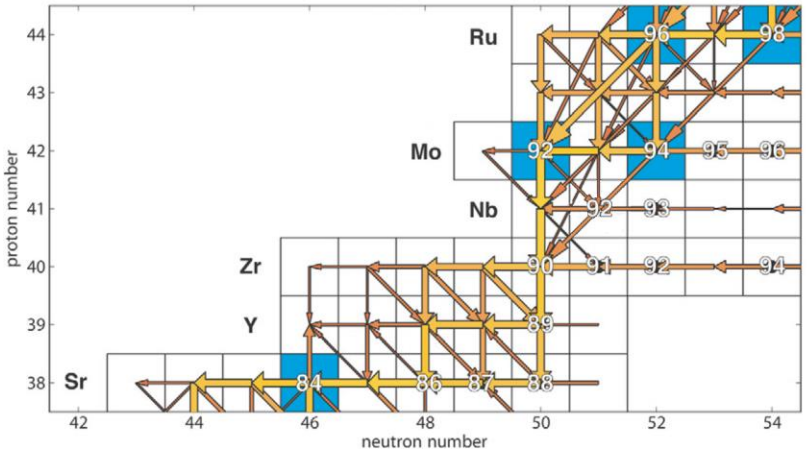
Astrophysical Motivation

- Determination of (p,γ) cross sections is needed for describing the **nucleosynthesis of the *p* nuclei**
- thousands of reactions in the **γ process**

- Theoretical calculations of reaction rates are needed which depend on
  - Nuclear Level Densities
  - Optical model potentials
  - γ-ray strength functions

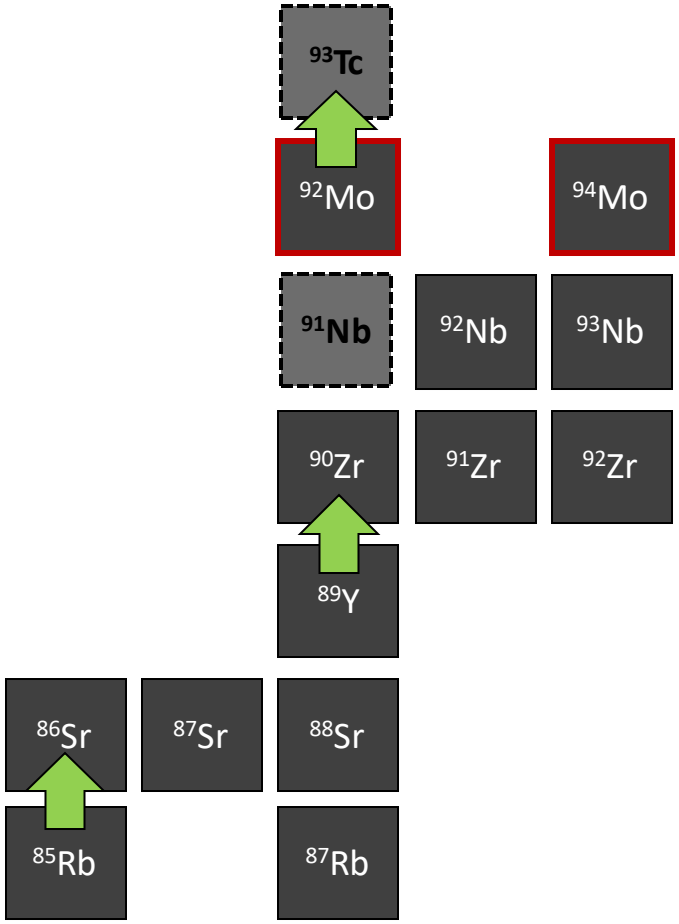
- **Uncertainties in nuclear physics input** can change the outcome of reaction-network calculations tremendously



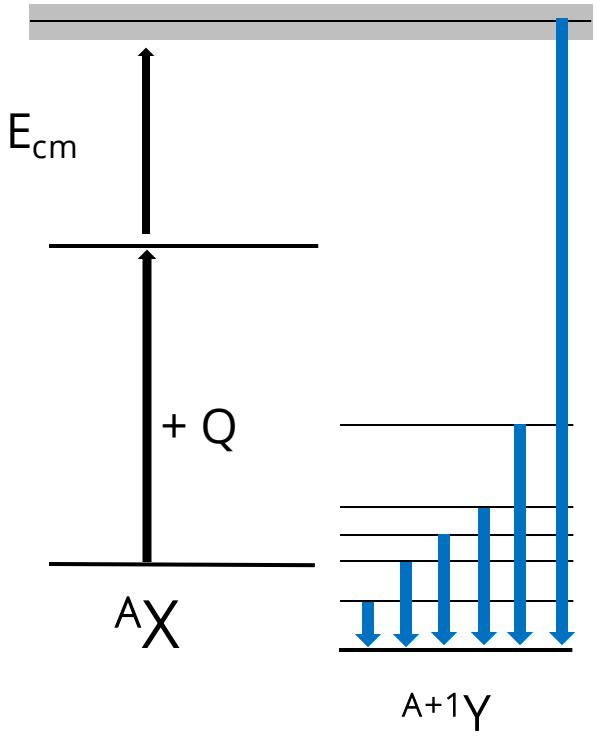


T. Rauscher *et al.*, Rep. Prog. Phys. **76** (2013) 066201

Radiative proton-capture reactions



Detection of ground-state transitions



J. Mayer *et al.*, Phys. Rev. C **93** (2016) 045809

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

In-Beam γ-ray spectroscopy at HORUS

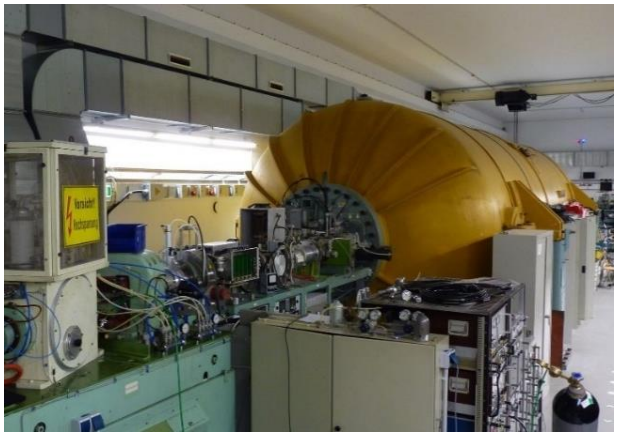
- **10 MV FN-Tandem accelerator** at the IKP Cologne

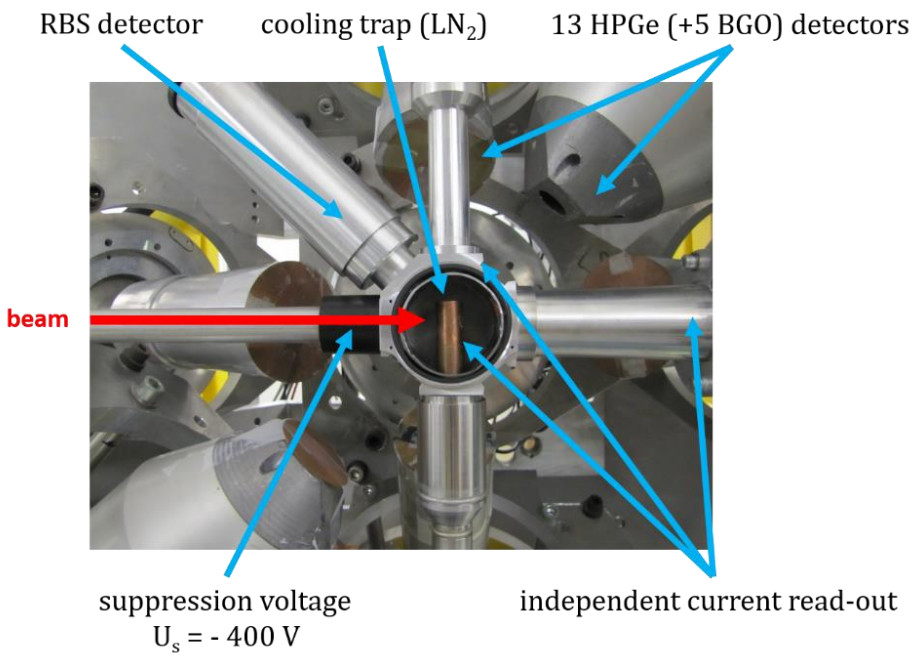
- **HORUS γ-ray spectrometer** consists of 13 HPGe detectors (+ RBS)
  - Resolution ≈ 2 keV @ 1332 keV
  - Total efficiency ≈ 2% @ 1332 keV

- **Five different angles** with respect to the beam axis
  - Determination of angular distributions

- BGO shields for five detectors

- γγ-coincidence measurements

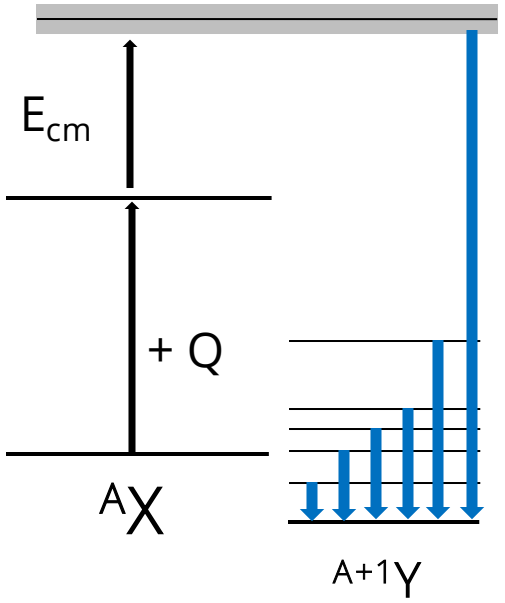


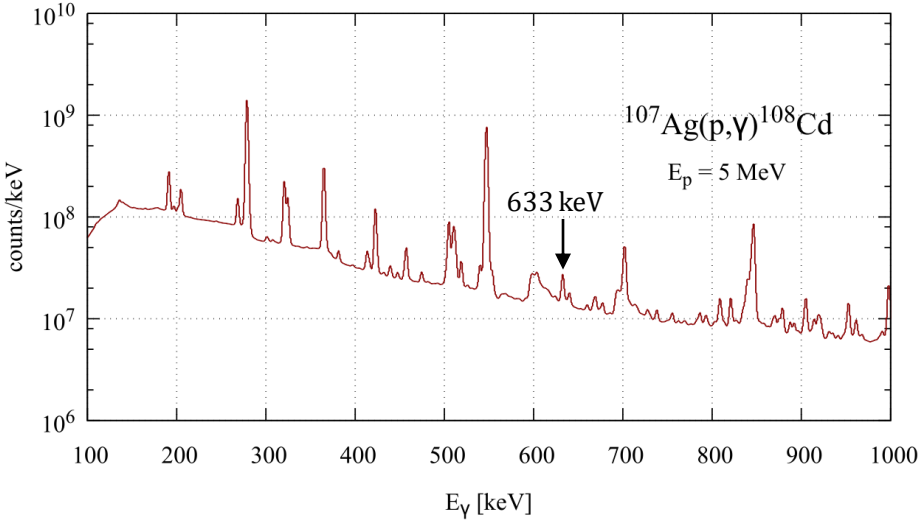


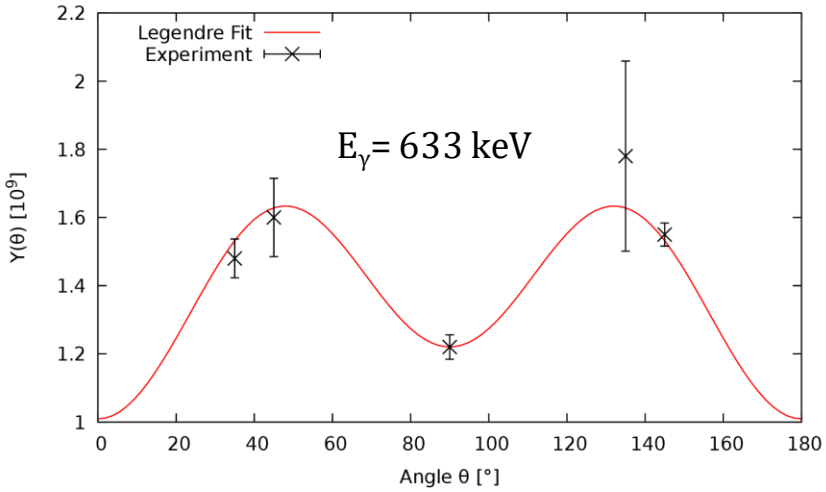
L. Netterdon *et al.*, Nucl. Inst. Meth. A **754** (2014) 94

Total cross sections of $^{107}Ag(p,\gamma)^{108}Cd$

- Measurement of $^{107}Ag(p,\gamma)^{108}Cd$ at four energies between 3.5 MeV and 5.0 MeV, thus, above the (p,n) threshold
- Q-Value: 8.1 MeV
- Excitation energies between 11.6 MeV and 13.1 MeV
- (p,n) reaction produces a lot of background
- Determination of total yield from angular distribution of γ-rays

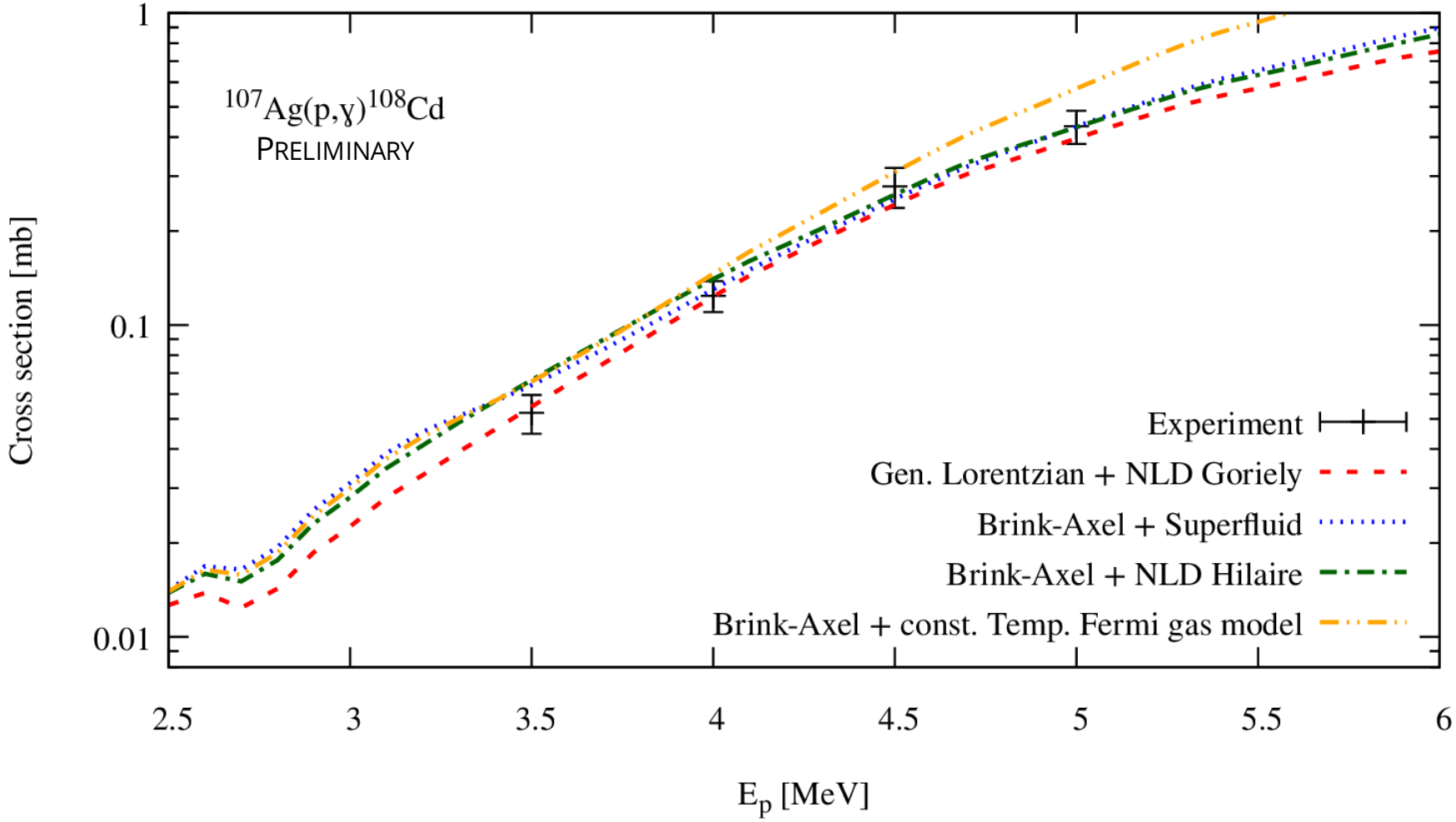






Total cross sections of $^{107}Ag(p,\gamma)^{108}Cd$

Comparison to statistical model calculations with Talys 1.8



F. Heim, Master's thesis

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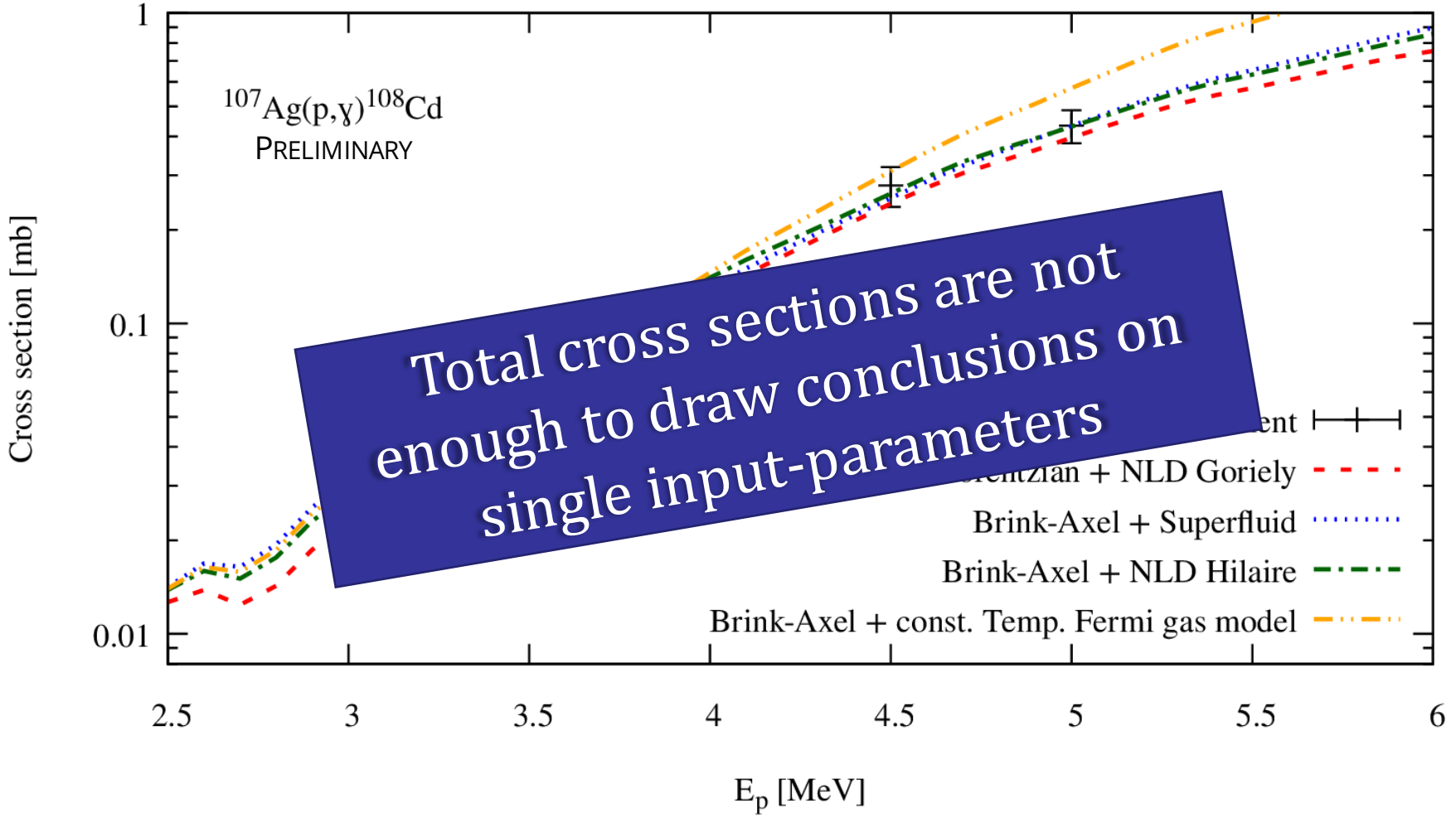
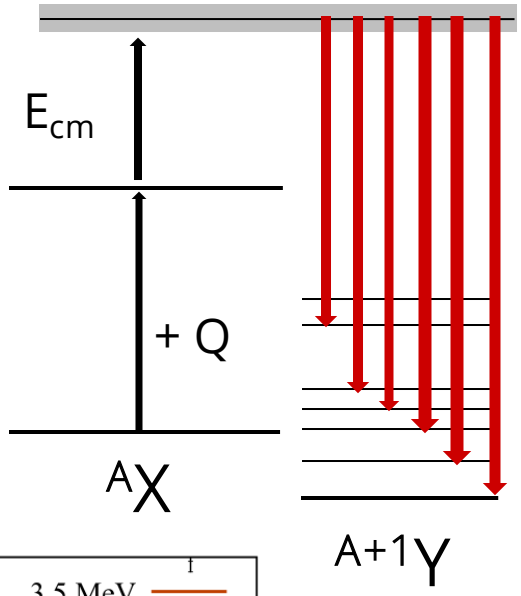
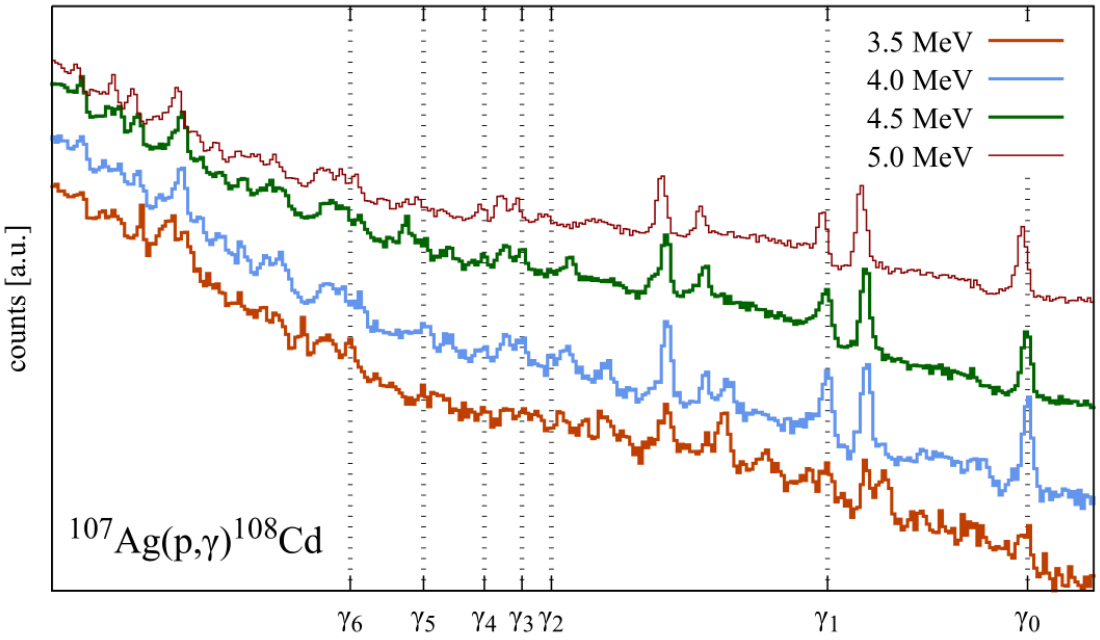


F. Heim, Master's thesis

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

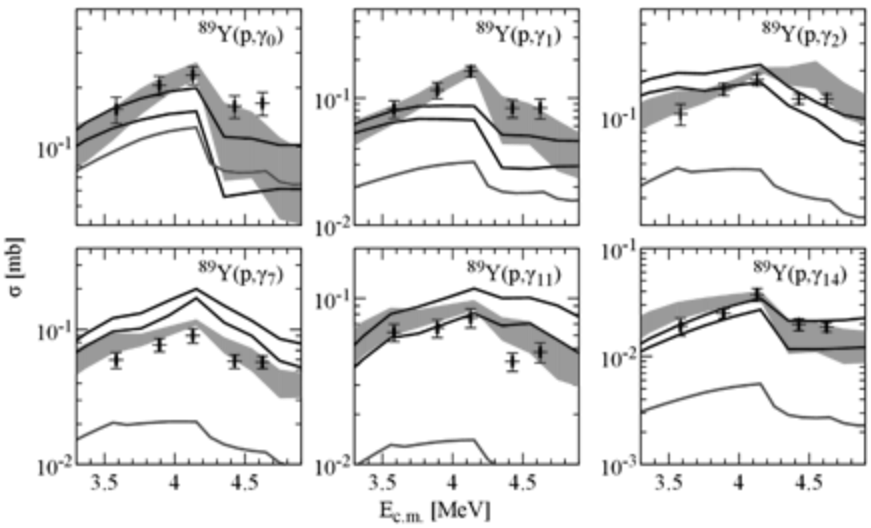


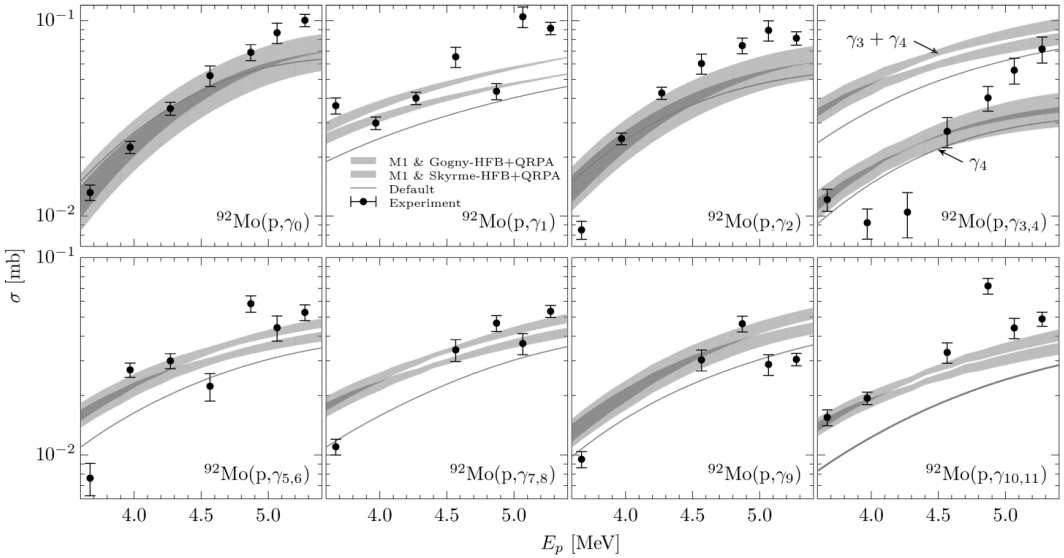


In-beam measurement of cross sections

- 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

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





- 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

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
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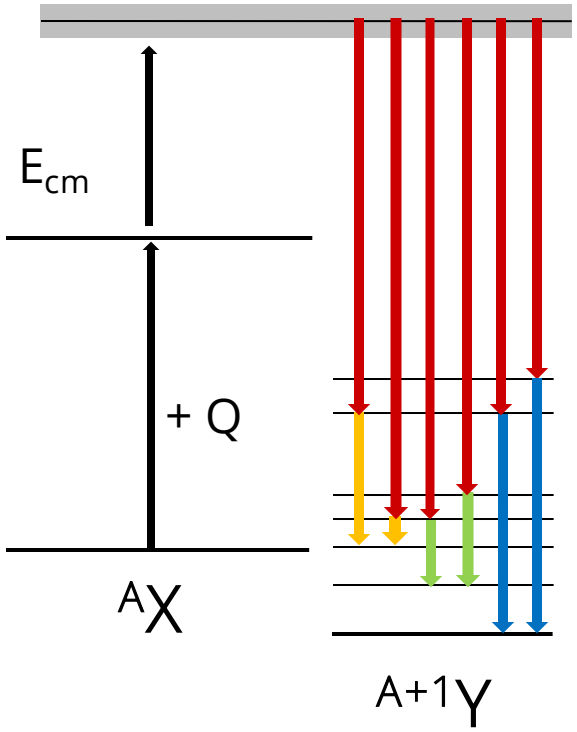
(Received 5 February 1992)

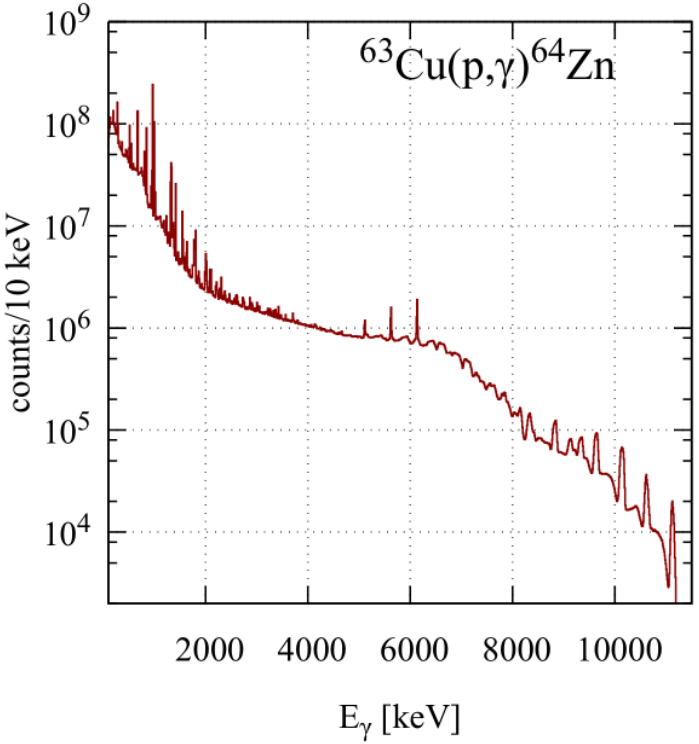
- Detecting **two step γ-ray cascades** populating states in the reaction product
- TSC spectrum obtained via gate on sum energy of coincident γ-rays
- TSC spectrum can be simulated in the statistical model regarding contribution of E1 or M1 strength
- Different models for nuclear level densities and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



Two Step Cascades

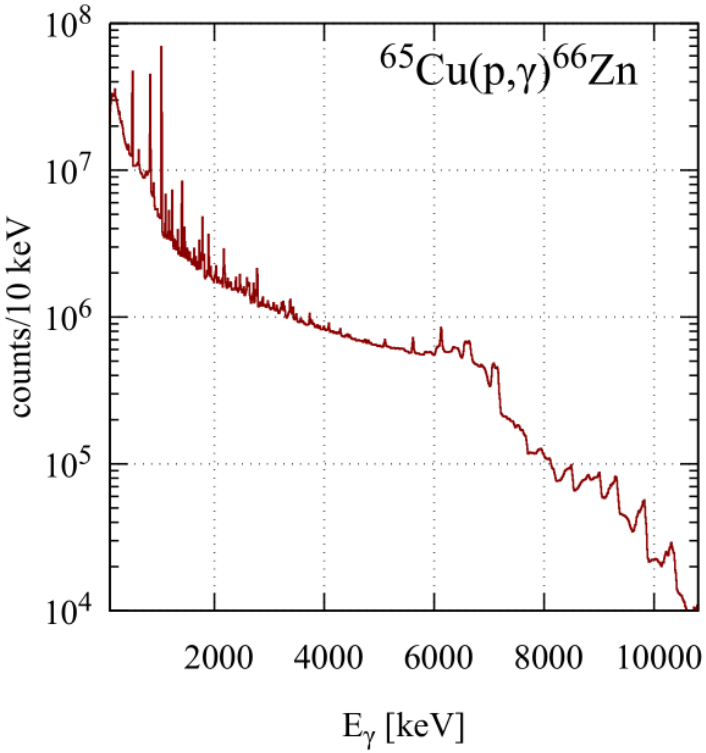
$^{63}Cu(p,\gamma\gamma)^{64}Zn$

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



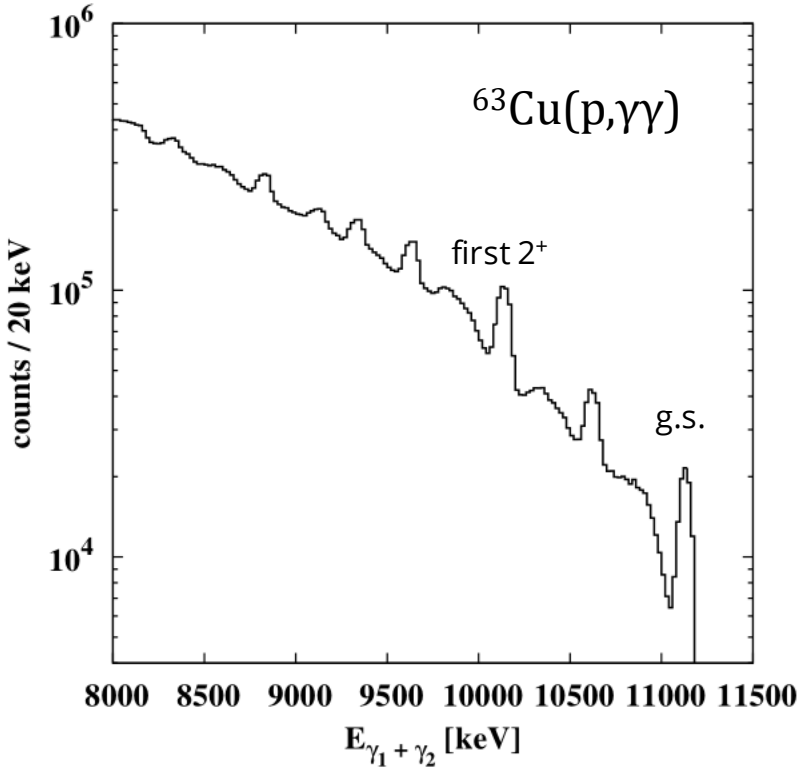
$^{65}Cu(p,\gamma\gamma)^{66}Zn$

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

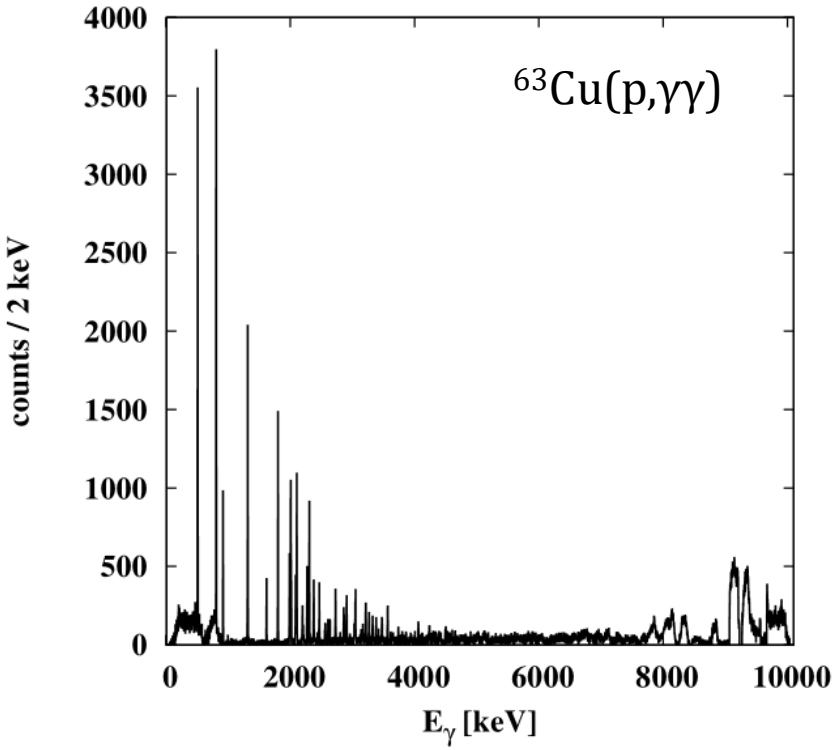


Two Step Cascades

TSC matrix



TSC spectrum first 2$^+$



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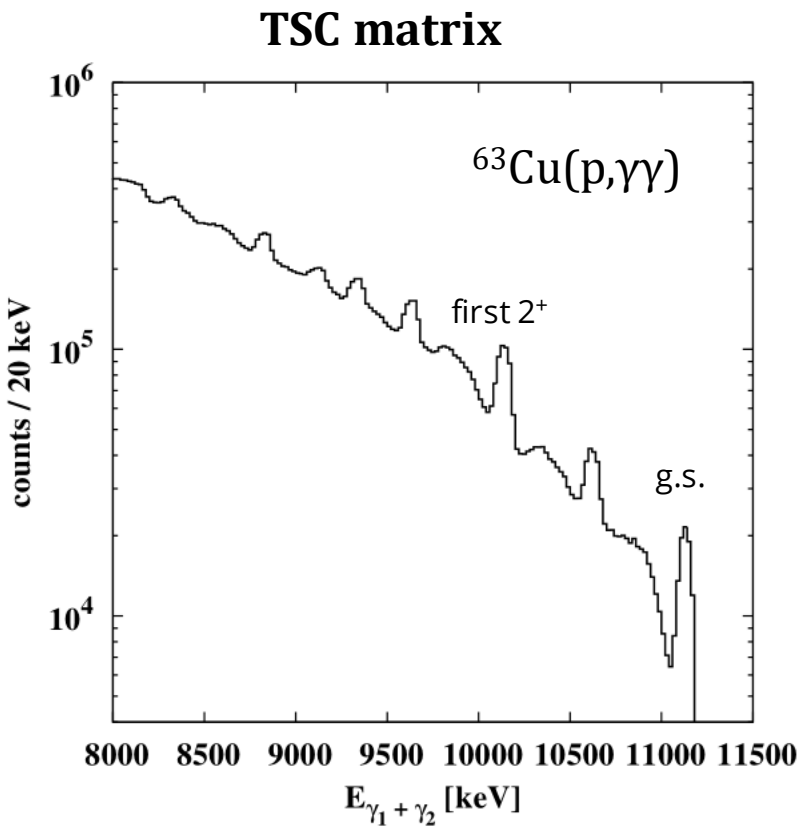
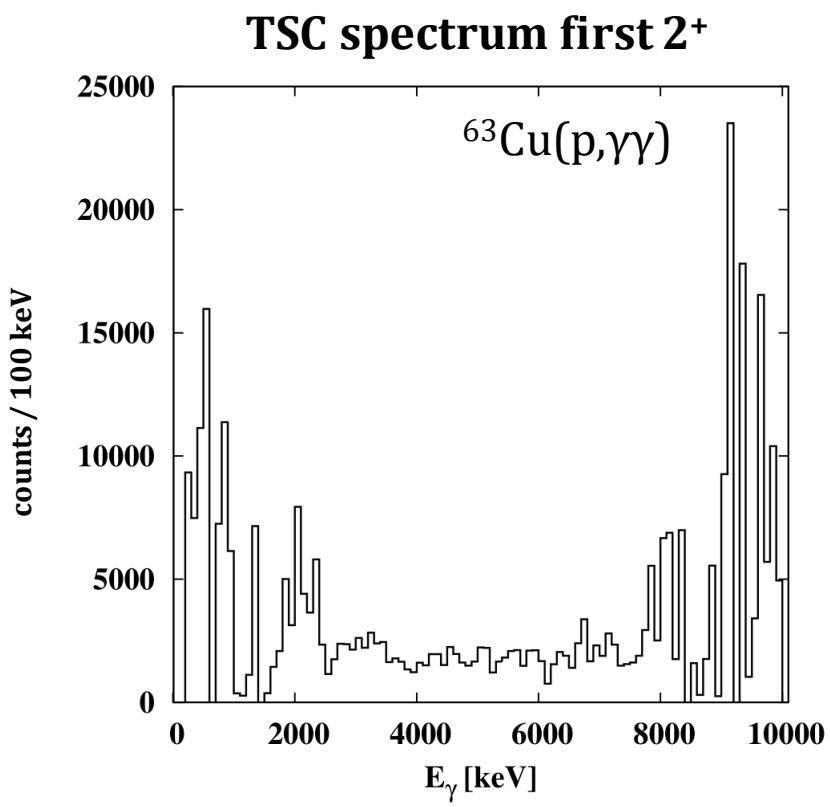
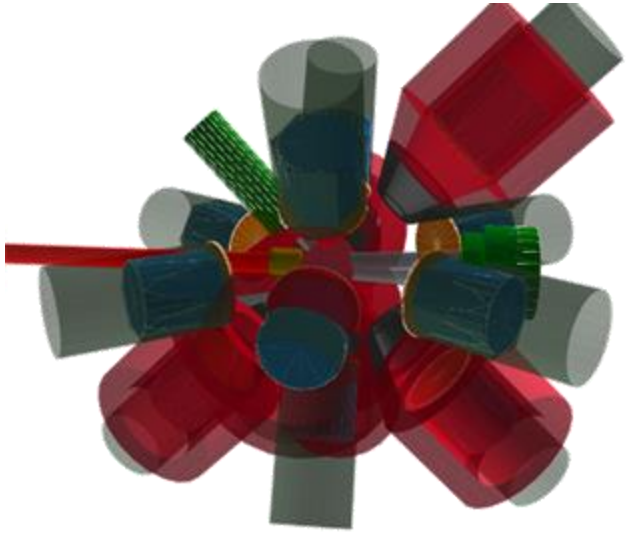




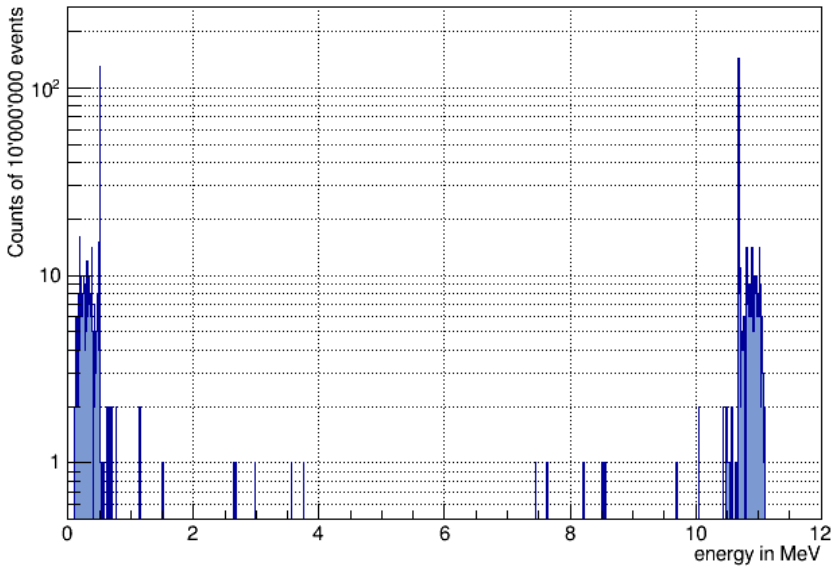
Two Step Cascades

GEANT4 Simulation of the setup



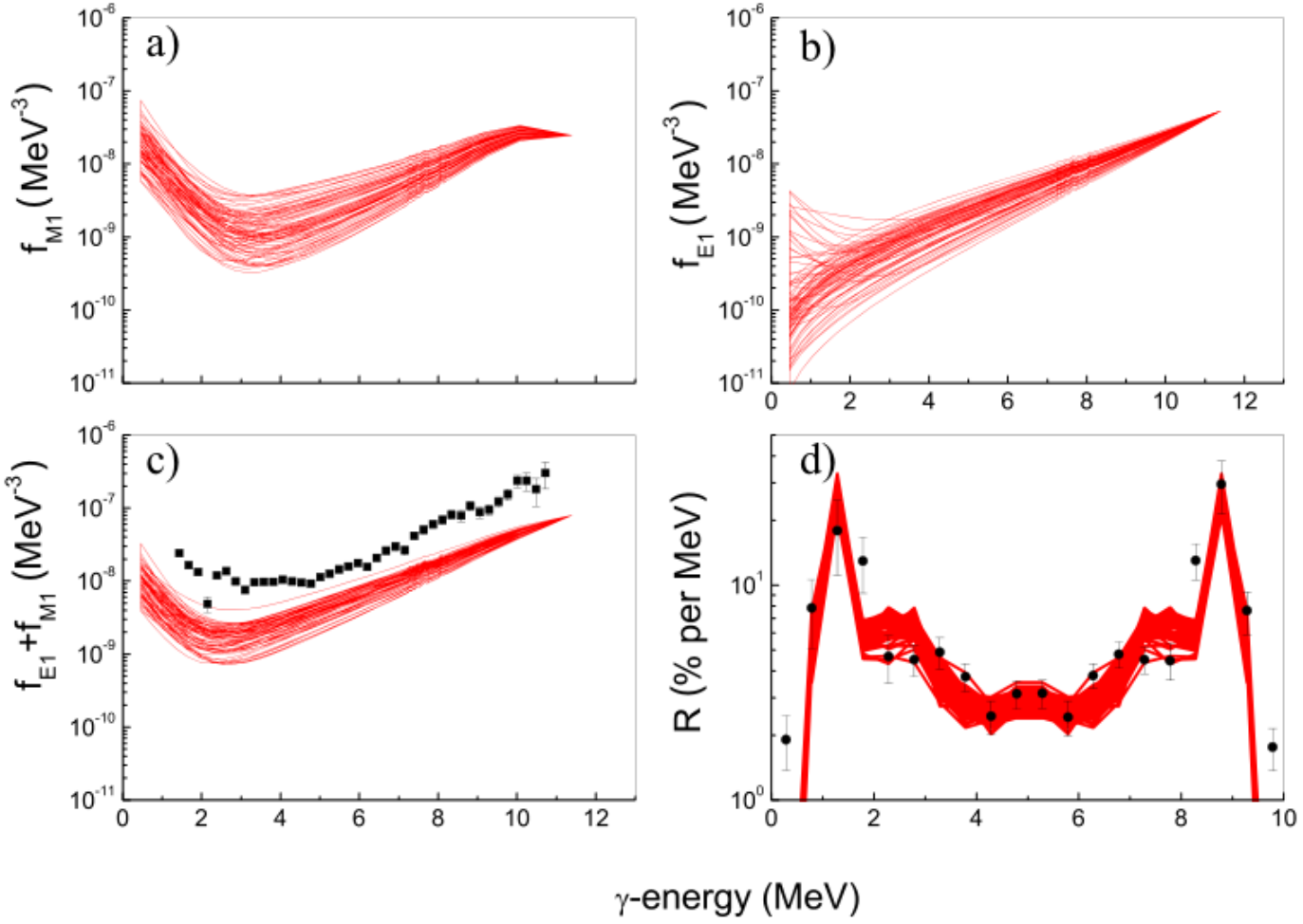
- Efficiency with ^{226}Ra, ^{56}Co, and ^{27}Al(p,γ)^{28}Si @ 3.6 MeV
- Understanding the response of the detector setup
- Understanding the background in the TSC spectrum

Simulated TSC spectrum of single 11.2 MeV γ-ray



Two Step Cascades

TSC-analysis for ^{59}Co(p,γγ) ^{60}Fe

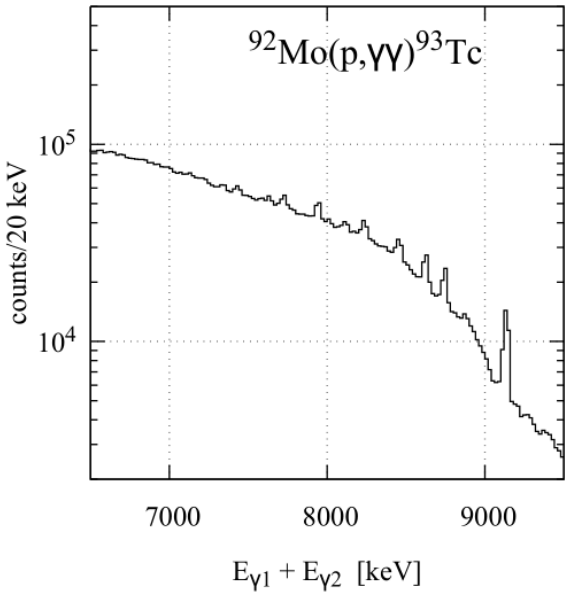


A. Voinov *et al.*, PRC **81** (2010) 024319

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
  - ➢ Energy dependence of TSC population



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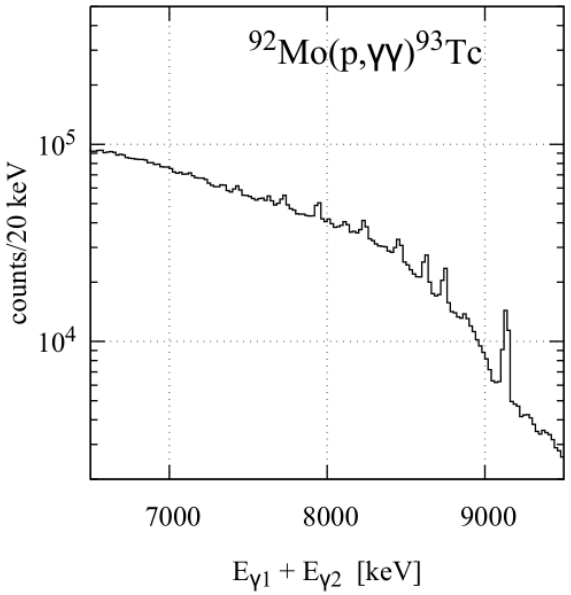
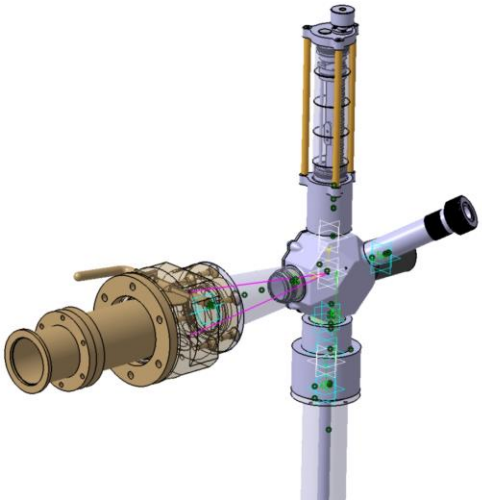


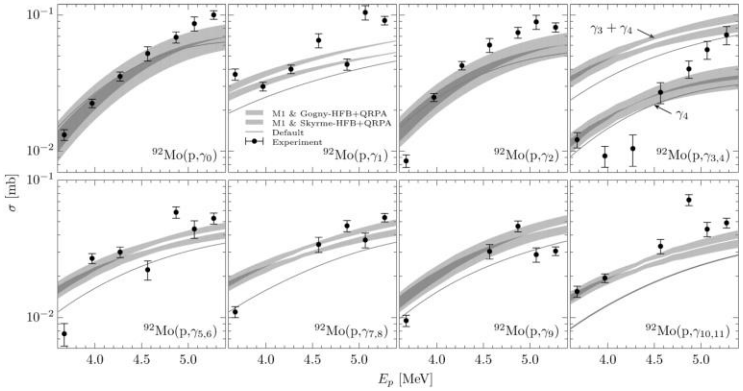


Future experiments

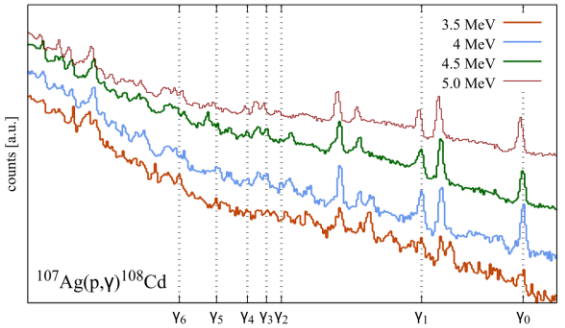
- New target chamber
- Total and partial cross sections on ^{109}Ag(p,γ)^{110}Cd, Zn, and Ge isotopes
- Other two-step cascade experiments

Summary

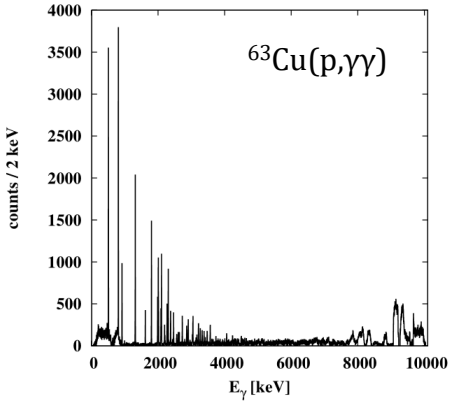
- Uncertainties in **nuclear physics input** can change the outcome of reaction-network calculations tremendously



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



- Applying of TSC method has just begun



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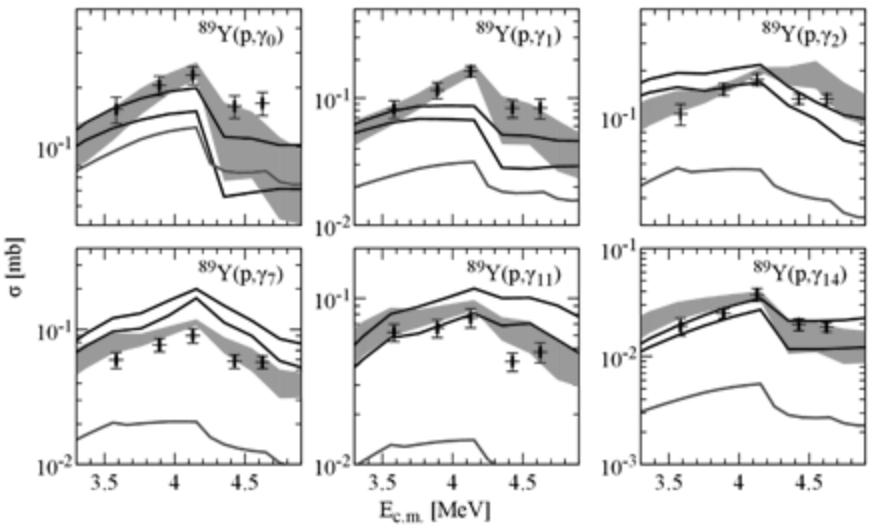

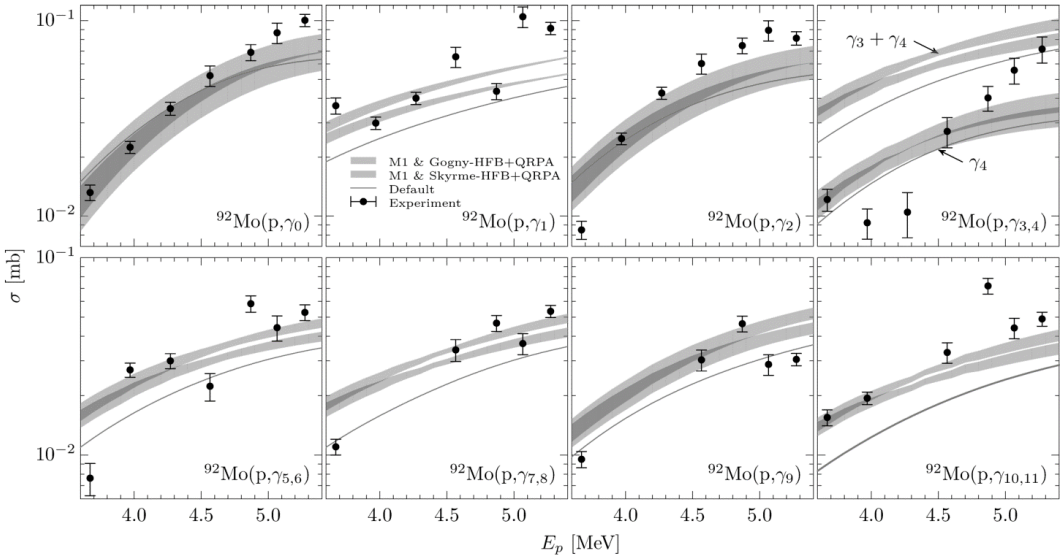

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