The γ-ray strength function in ^{90}Zr constrained by partial cross sections of the ^{89}Y(p,γ)^{90}Zr reaction

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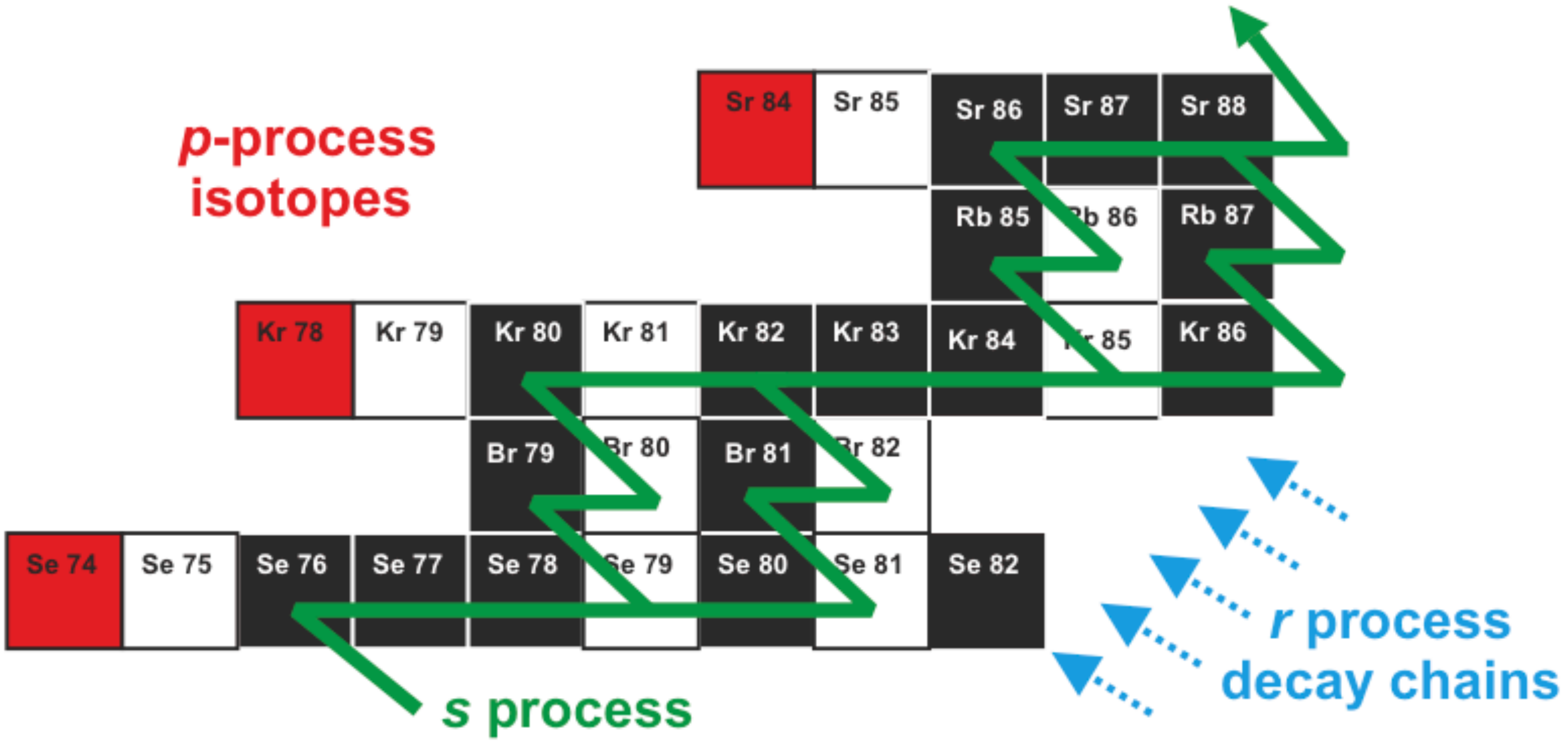
Outline

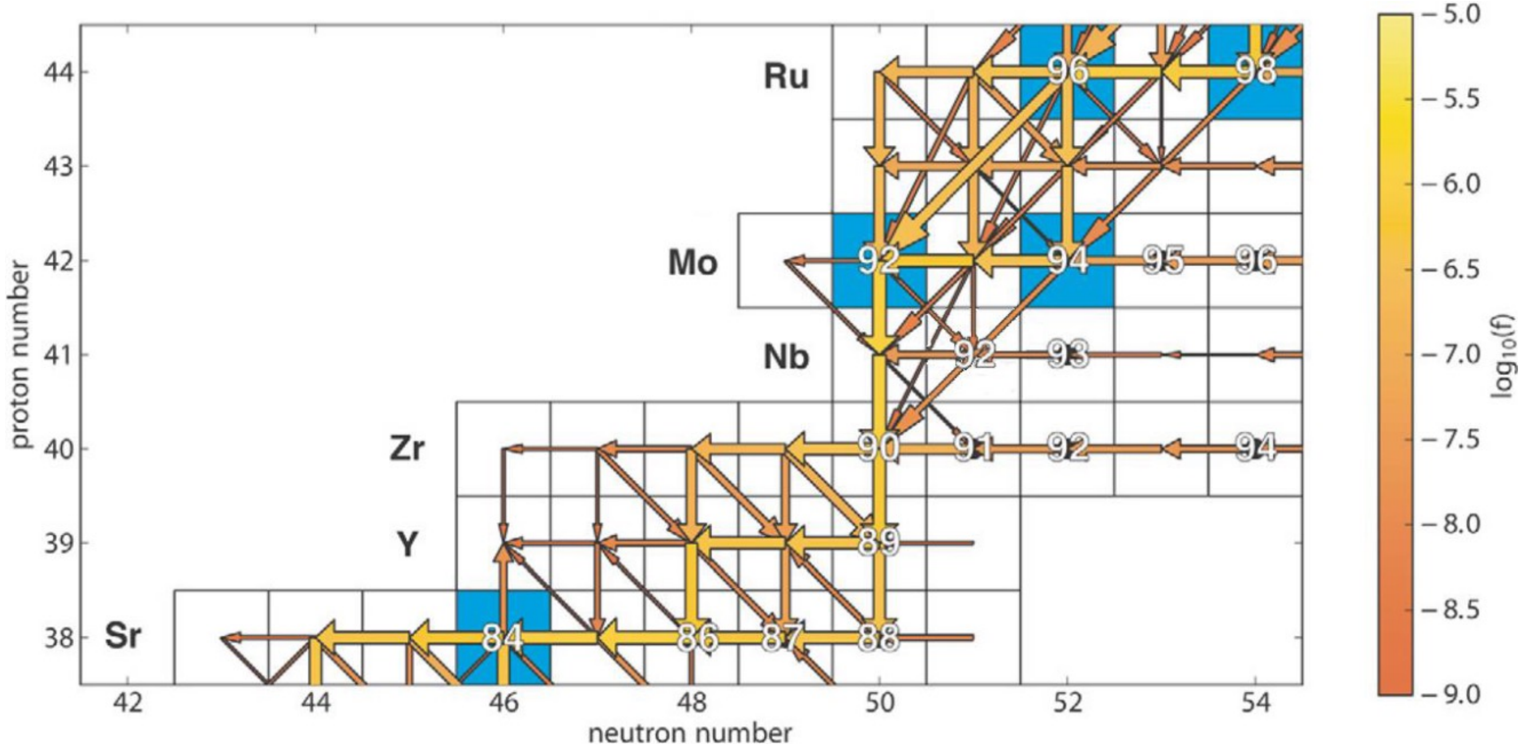
- the γ process: a brief introduction
- γ-ray spectrometer HORUS for nuclear astrophysics
- total and partial cross sections of $^{89}Y(p,\gamma)$ reaction
- constraints on γ-ray strength function in ^{90}Zr
- astrophysical impact on $^{90}Zr(\gamma,n)$ reaction rate

Nucleosynthesis of trans-iron nuclei



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

The γ process



- dominant reaction mechanism for *p* nuclei
- photodisintegration on *s* and *r* seed nuclei
- huge reaction network on mainly unstable nuclei
  - reaction rates based on theory!

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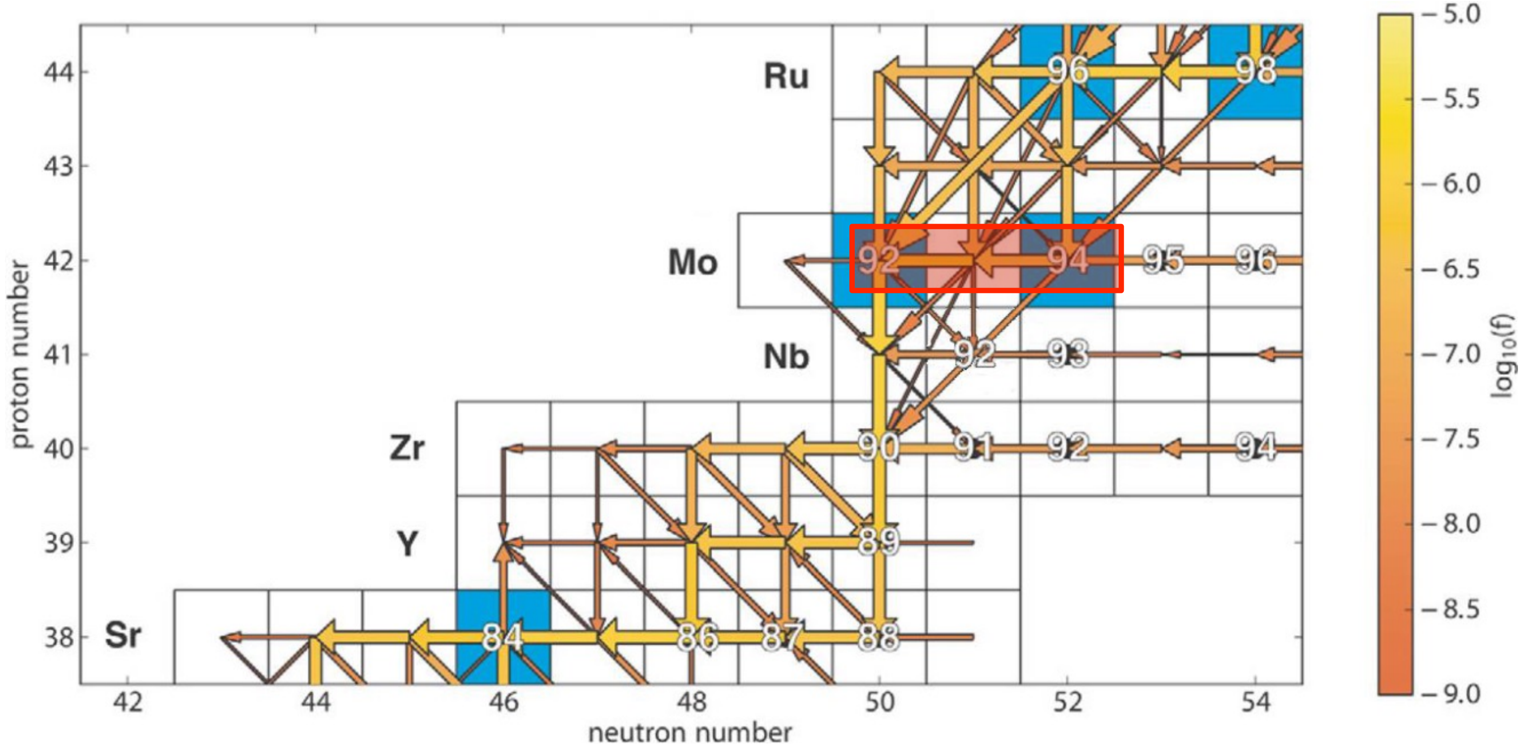
The γ process



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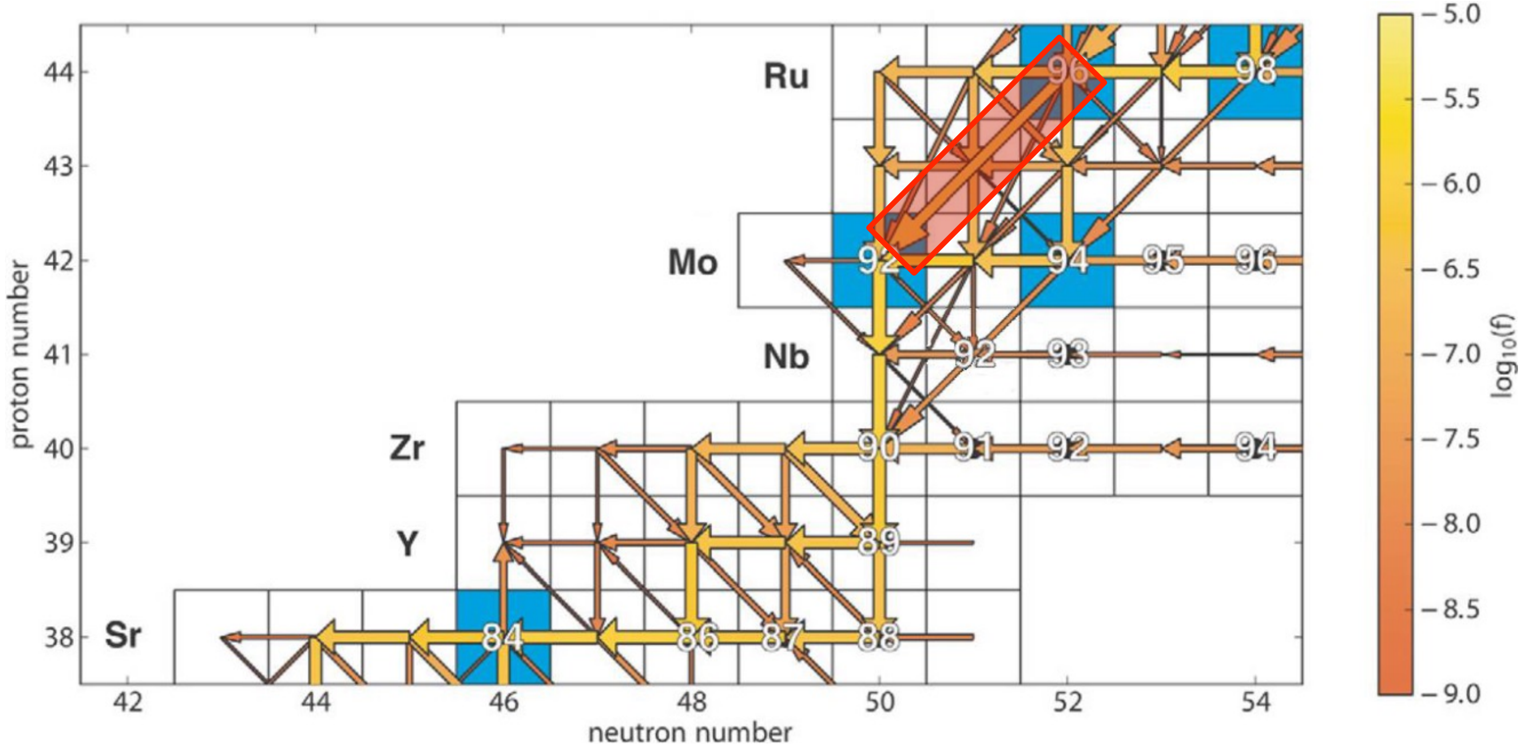
The γ process



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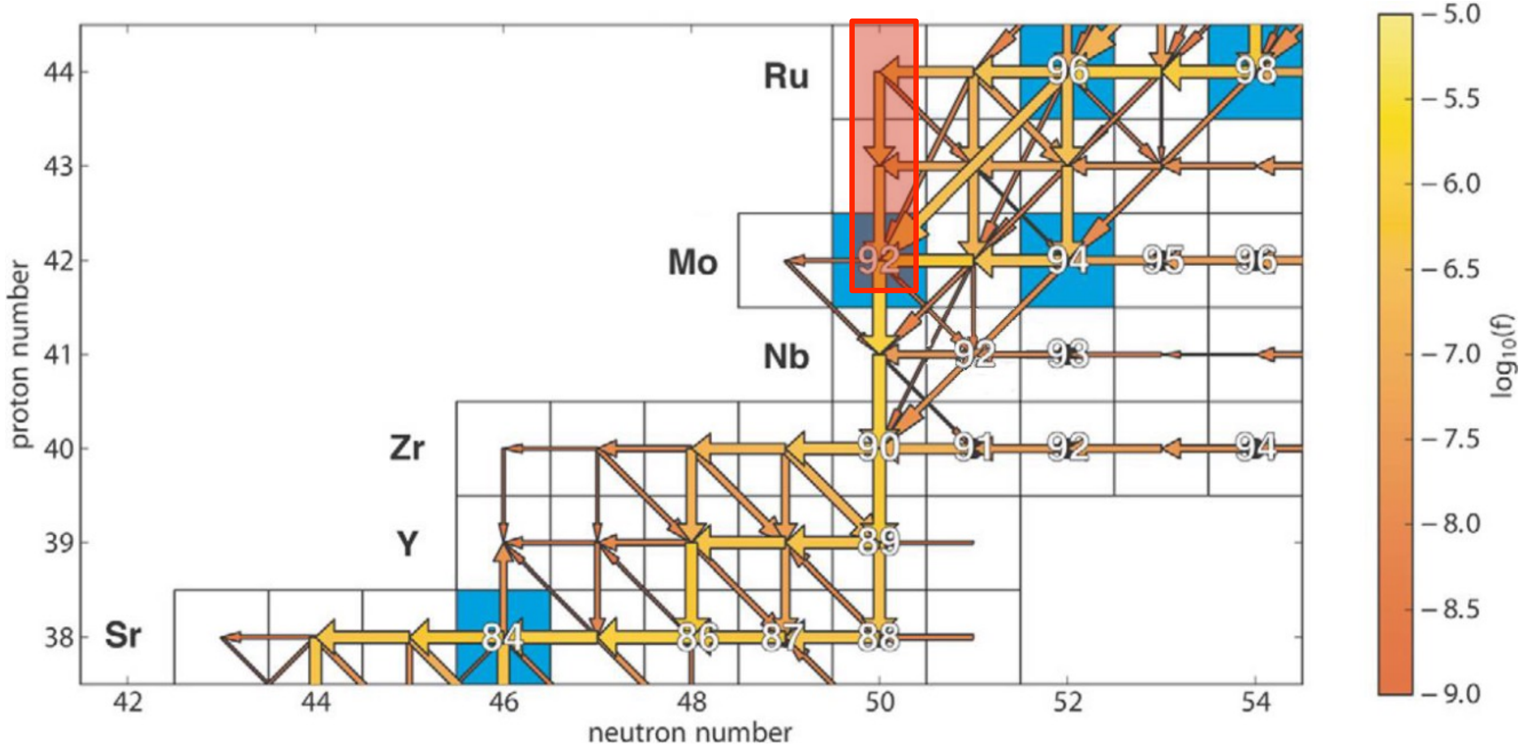

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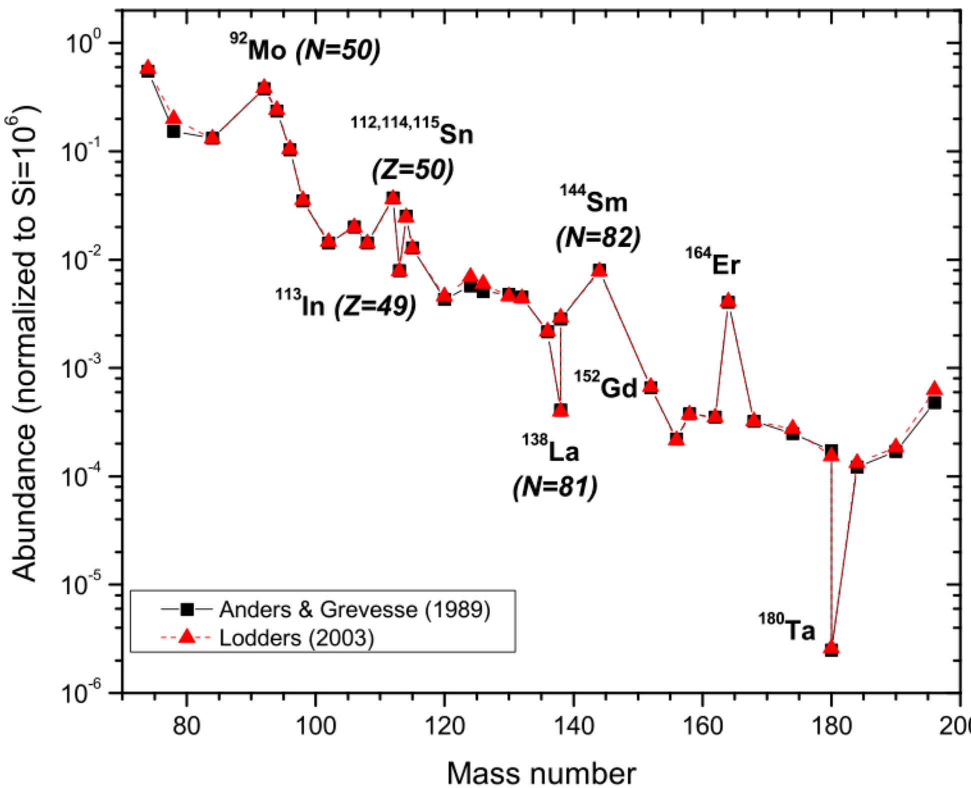
T. Rauscher *et al.*, Rep. Prog. Phys. **76** (2013) 066201

Solar abundance pattern of *p* nuclei

- problems of reproducing solar abundance pattern
- astrophysical uncertainties
  - how many processes?
  - where do these occur?
  - role of neutrinos?
  - supernova models?
- nuclear-physics uncertainties
  - optical-model potentials
  - γ-ray strength functions
  - nuclear level densities
  - nuclear masses



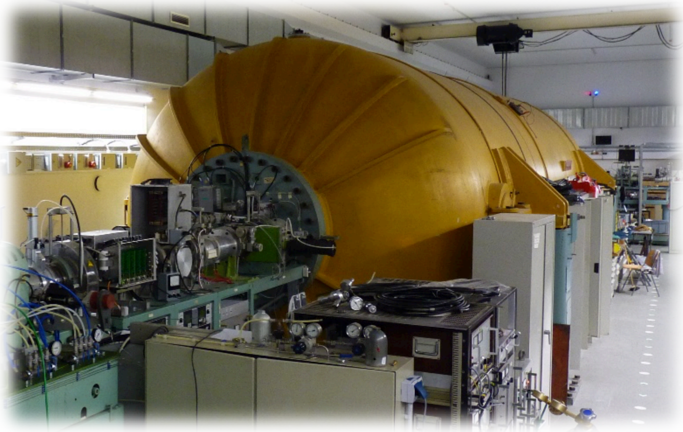
T. Rauscher *et al.*, Rep. Prog. Phys. **76** (2013) 066201

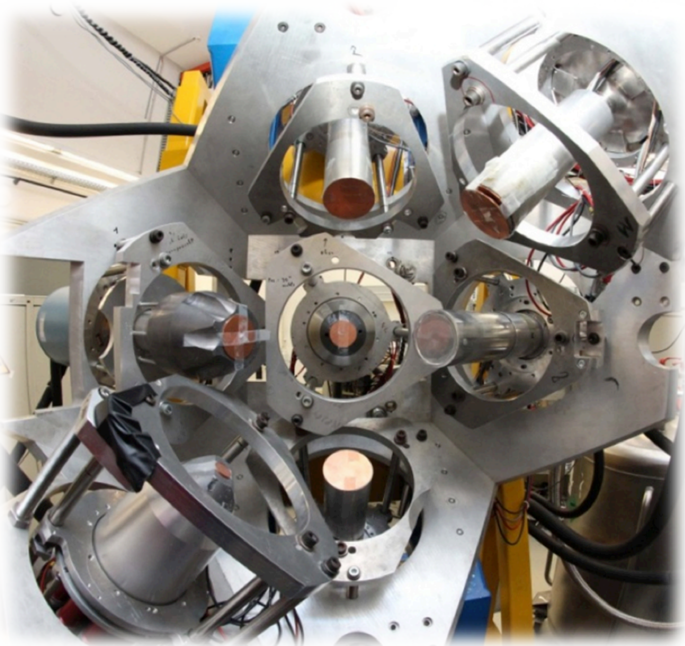
In-beam measurements in Cologne

- 10 MV FN tandem accelerator

<u>**γ-ray spectrometer HORUS:**</u>

- 14 HPGe detectors
  - resolution ≈ 2 keV @ 1332 keV
  - efficiency ≈ 2 % @ 1332 keV
- 5 angles relative to beam axis
  → measure angular distributions
- 6 BGO shields
  → actively suppress Compton-scattered γ rays
- $\gamma\gamma$ coincidences

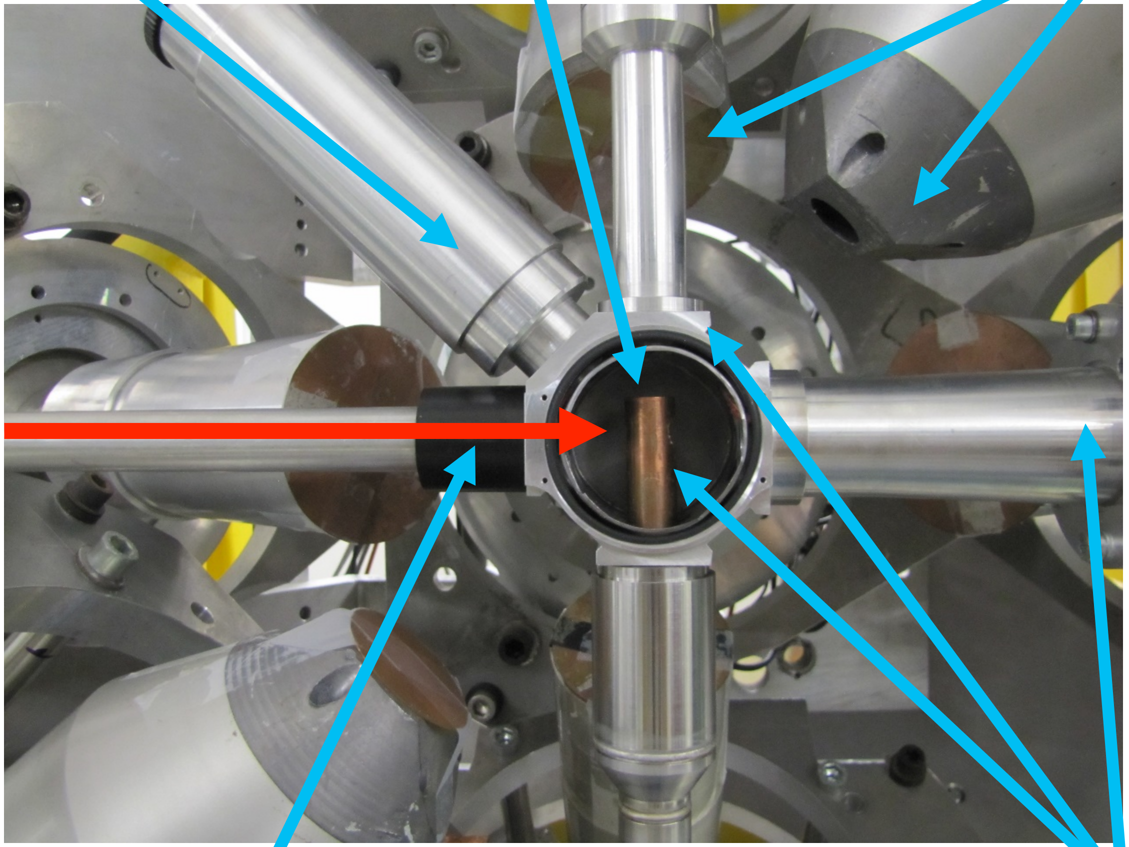




L. Netterdon *et al.*, NIM **A 754** (2014) 94

Experimental setup in Cologne

RBS detector cooling trap (LN_2) HPGe (+BGO) detectors



beam

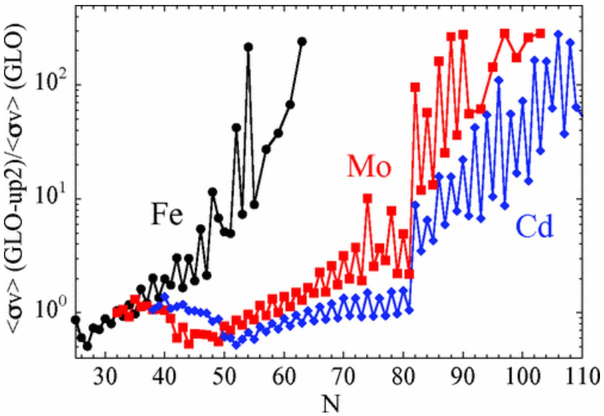
suppression voltage
U_s = - 400 V

independent current read-out

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

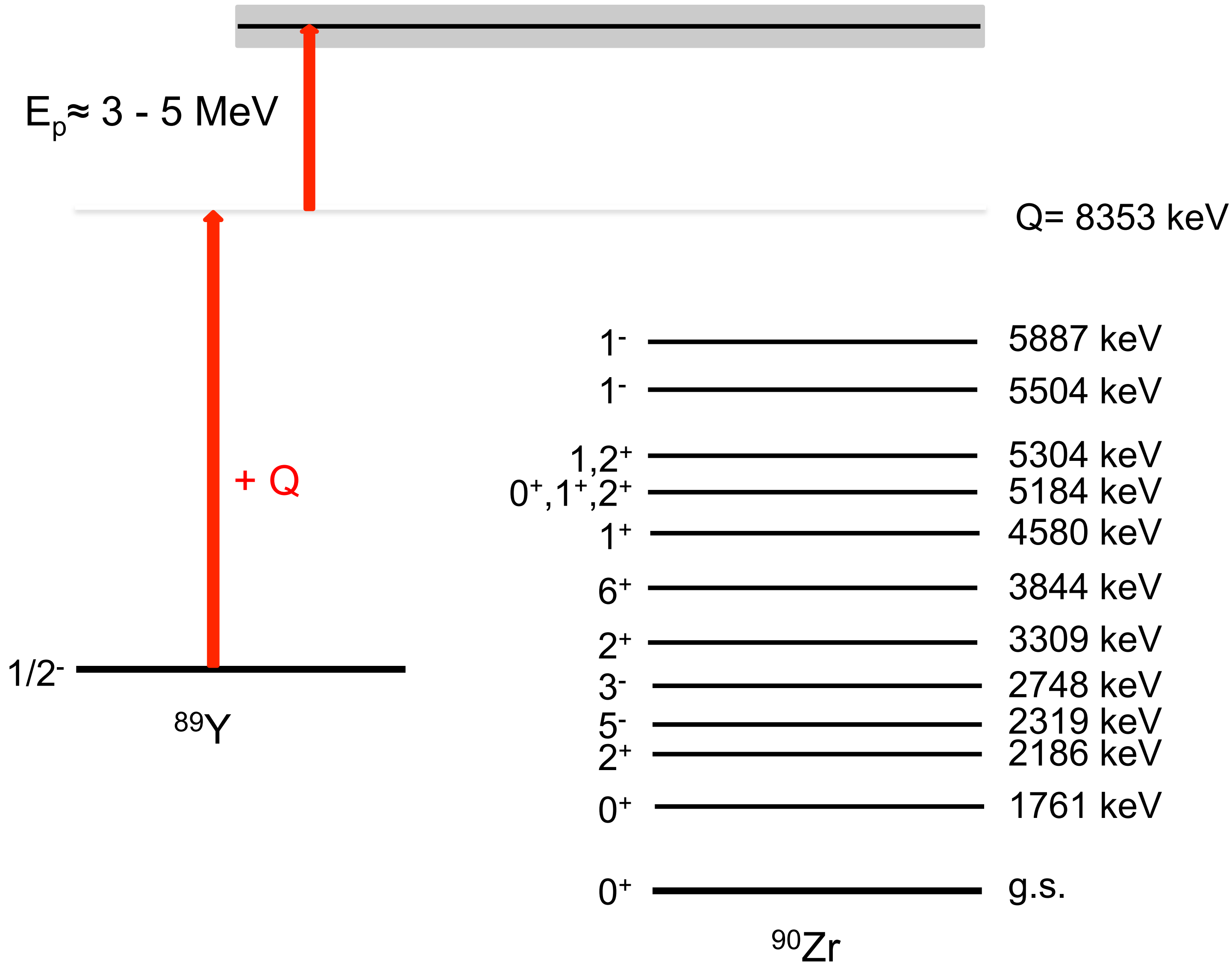
^{89}Y(p,γ) - Motivation

- commissioning experiment for recently developed experimental setup for nuclear astrophysics
- total cross section already measured by in-beam technique with HPGe detectors and 4π summing
- new information: partial cross sections
  - test of γ-ray strength functions
  - access to low-lying dipole strength in ^{90}Zr
- γ-ray strength function important ingredient for astrophysical reaction-rate calculations!

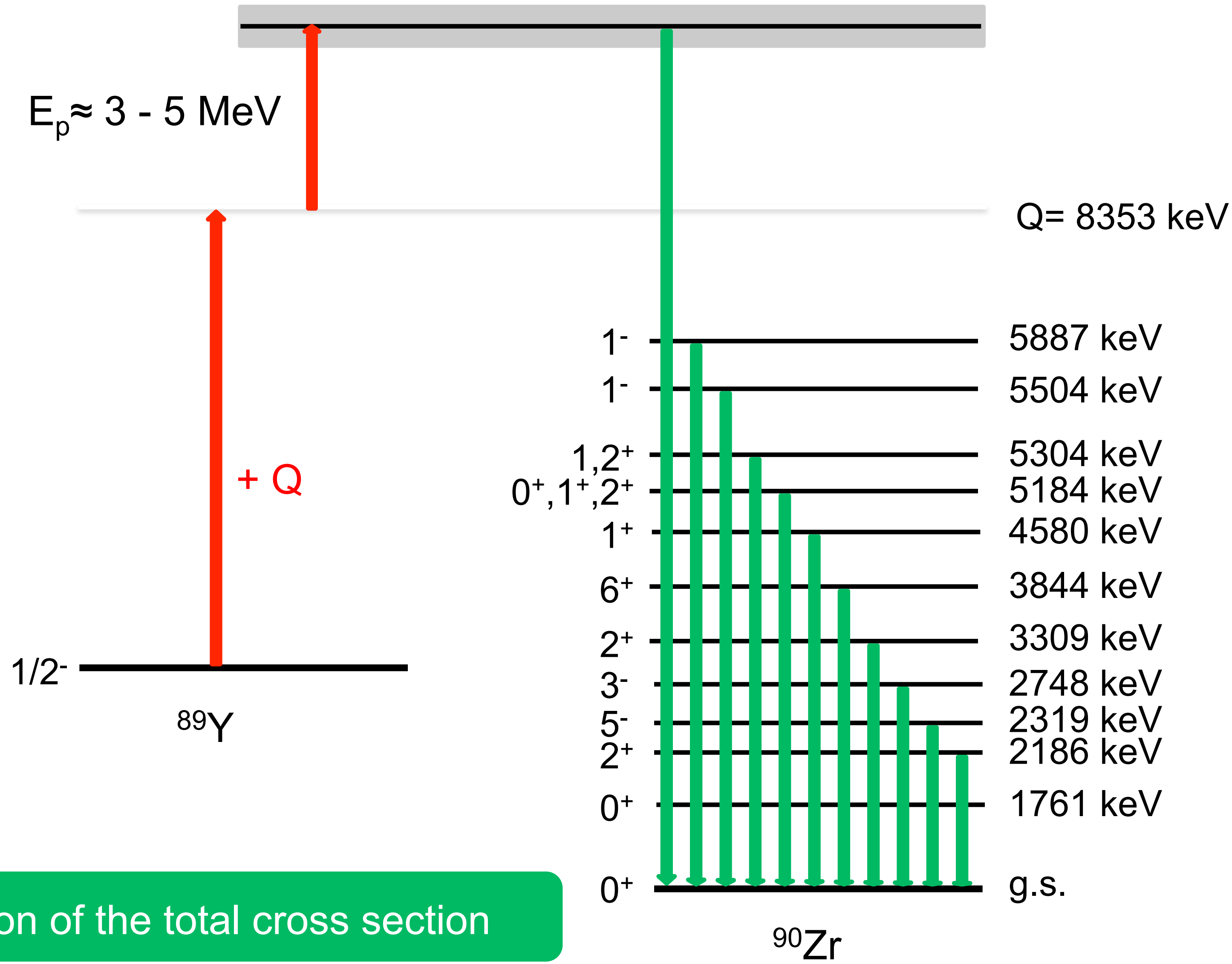


A. C. Larsen and S. Goriely, Phys. Rev. C **82** (2010) 014318

^{89}Y(p,γ) – In-beam method

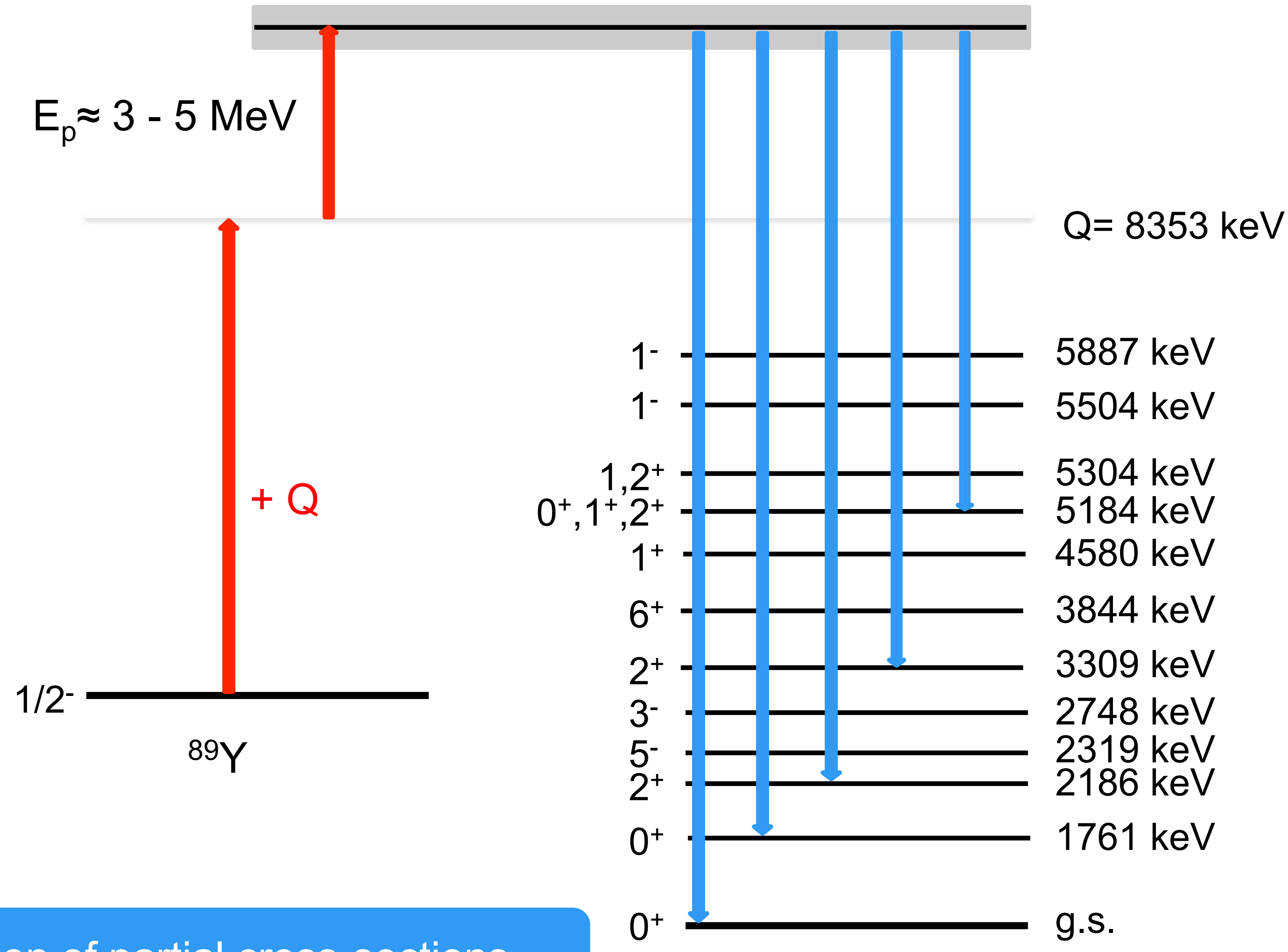


^{89}Y(p,γ) – In-beam method



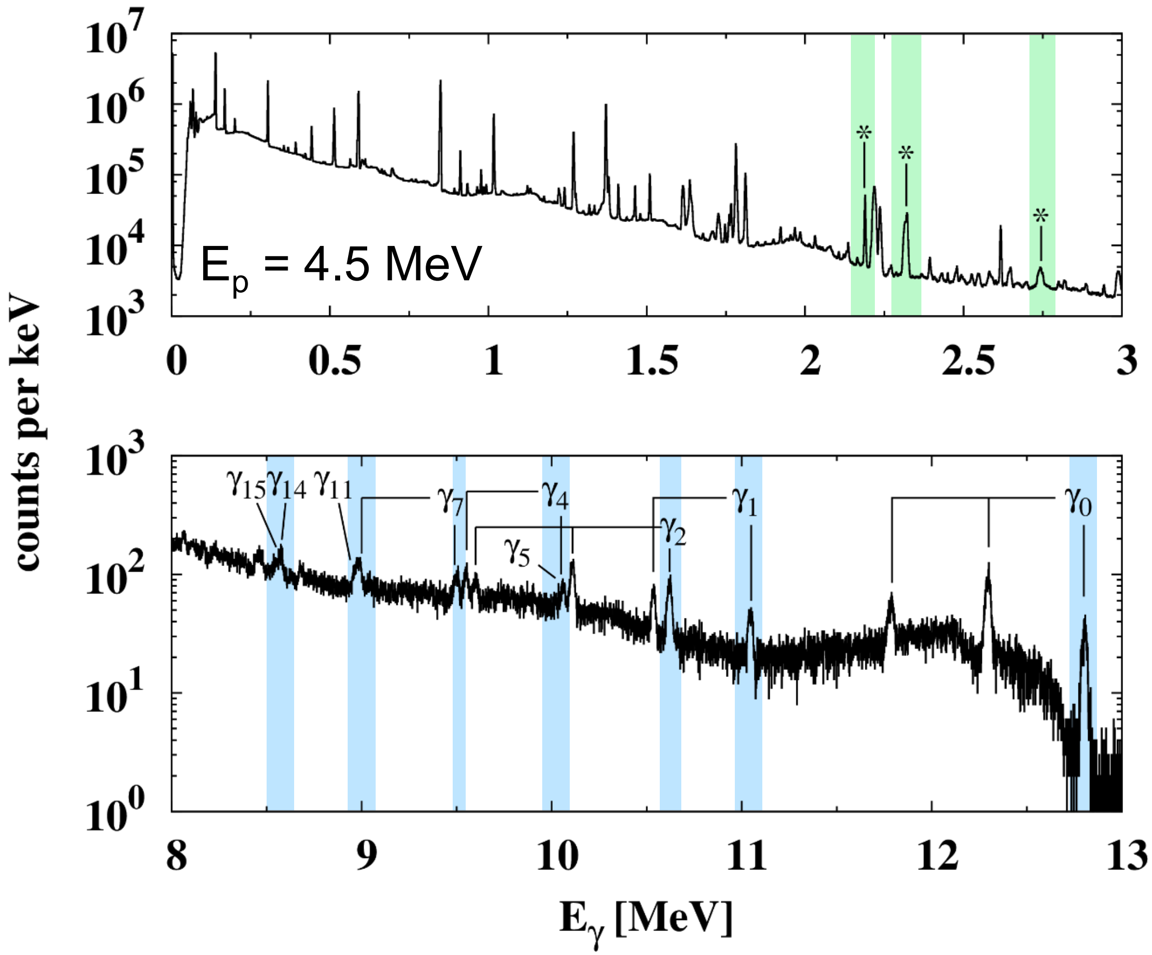
determination of the total cross section

$^{89}Y(p,\gamma)$ – In-beam method



determination of partial cross-sections

$^{89}Y(p,\gamma)$ – In-beam spectrum

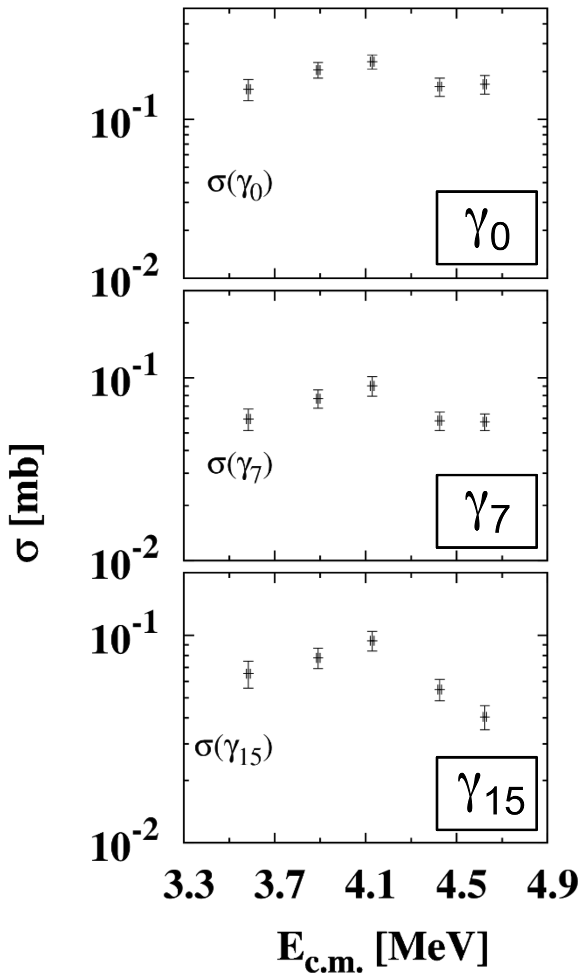


L. Netterdon *et al.*, Phys. Lett. B **744** (2015) 358

- E_p = 3.65 MeV – 4.7 MeV
- beam current ≈ 50 nA
- ^{nat}Y target ≈ 580 μg / cm^2
- five total cross-section values
- partial cross sections for population of seven 0^+ / 2^+ states

→ sensitive to *E*1 strength!

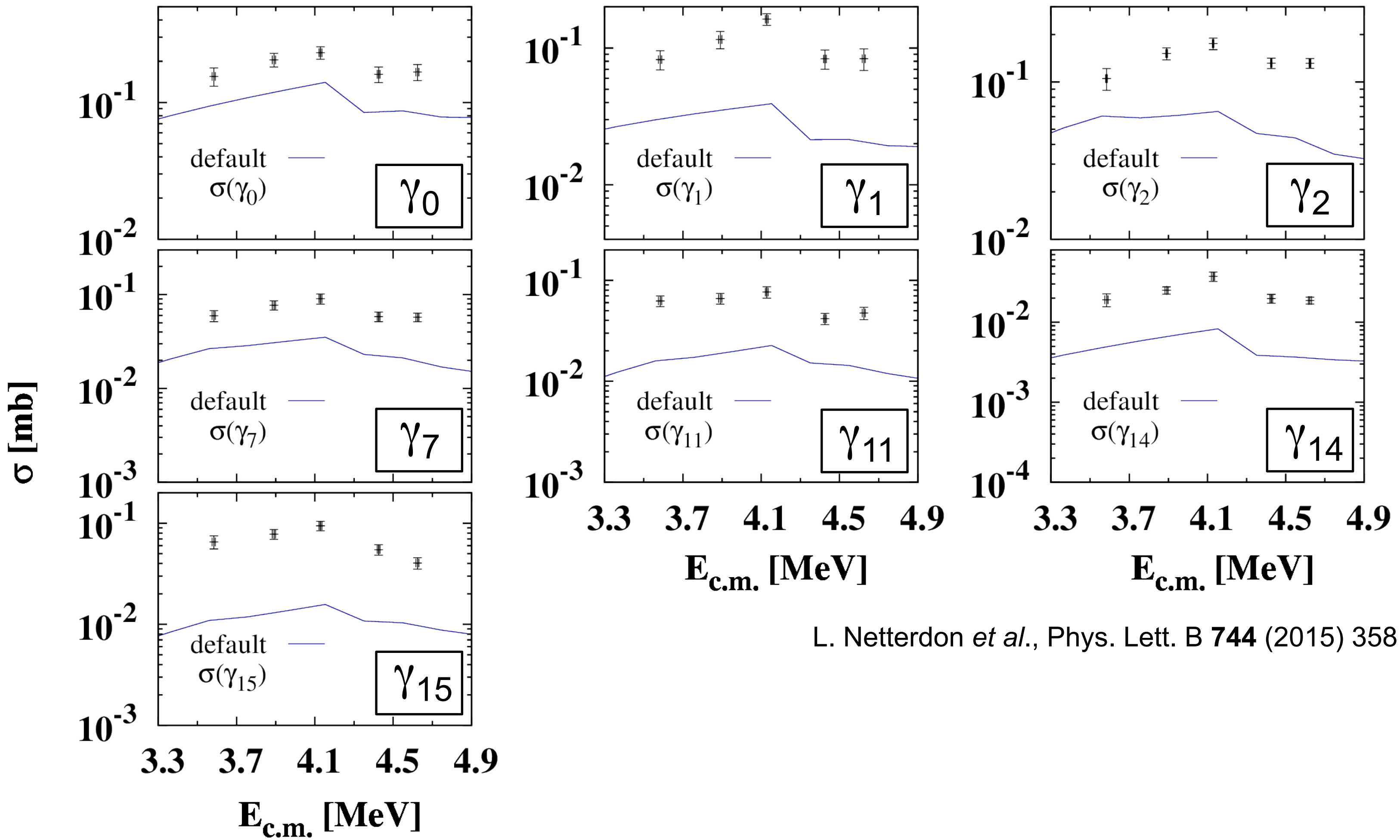
$^{89}Y(p,\gamma)$ – Partial cross-sections



L. Netterdon *et al*., Phys. Lett. B **744** (2015) 358

- goal: describe partial cross sections with appropriate γ-ray strength function in statistical-model calculations

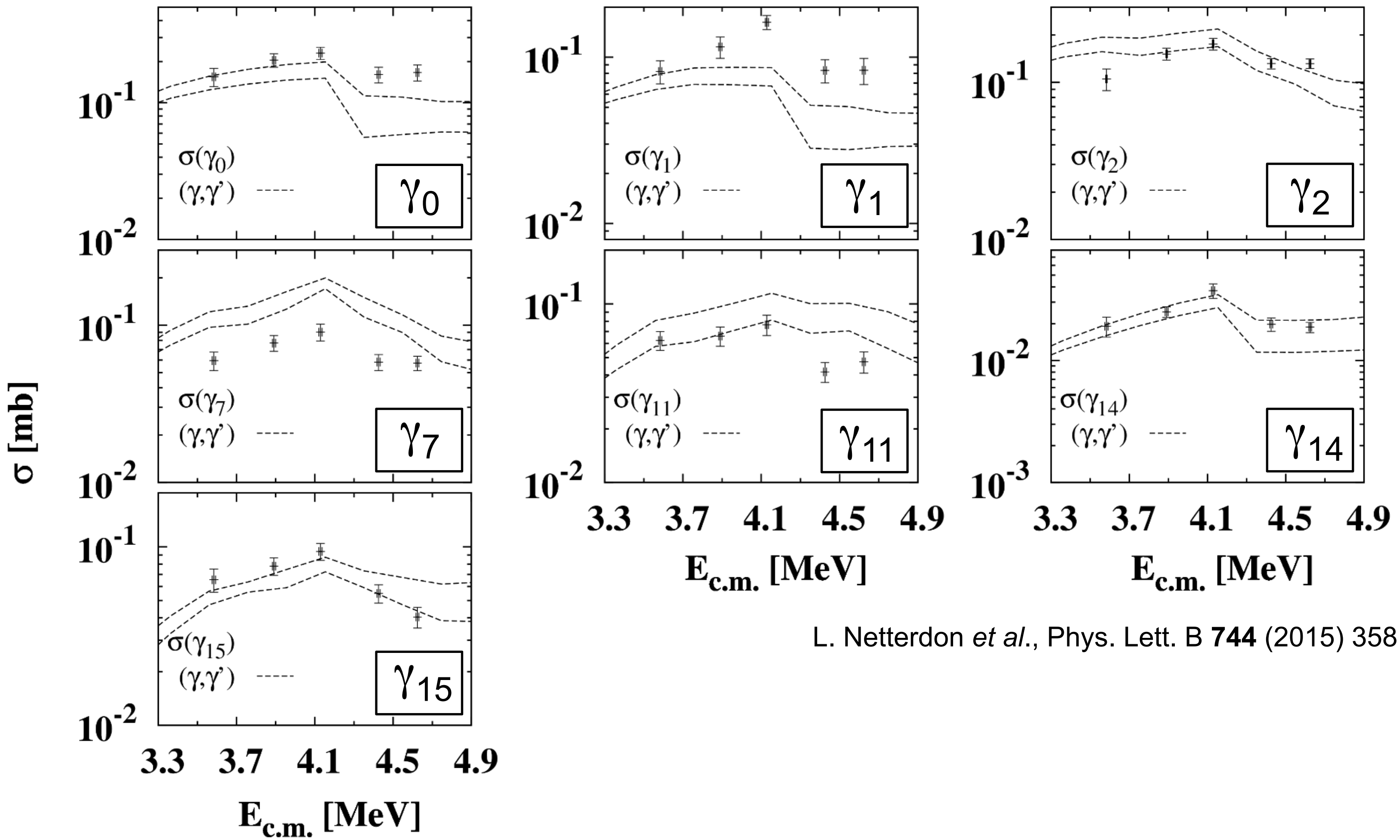
^{89}Y(p,γ) – Partial cross-sections



L. Netterdon *et al.*, Phys. Lett. B **744** (2015) 358

- no "standard" γ-ray strength function is capable of reproducing experimental data

$^{89}Y(p,\gamma)$ – Partial cross-sections

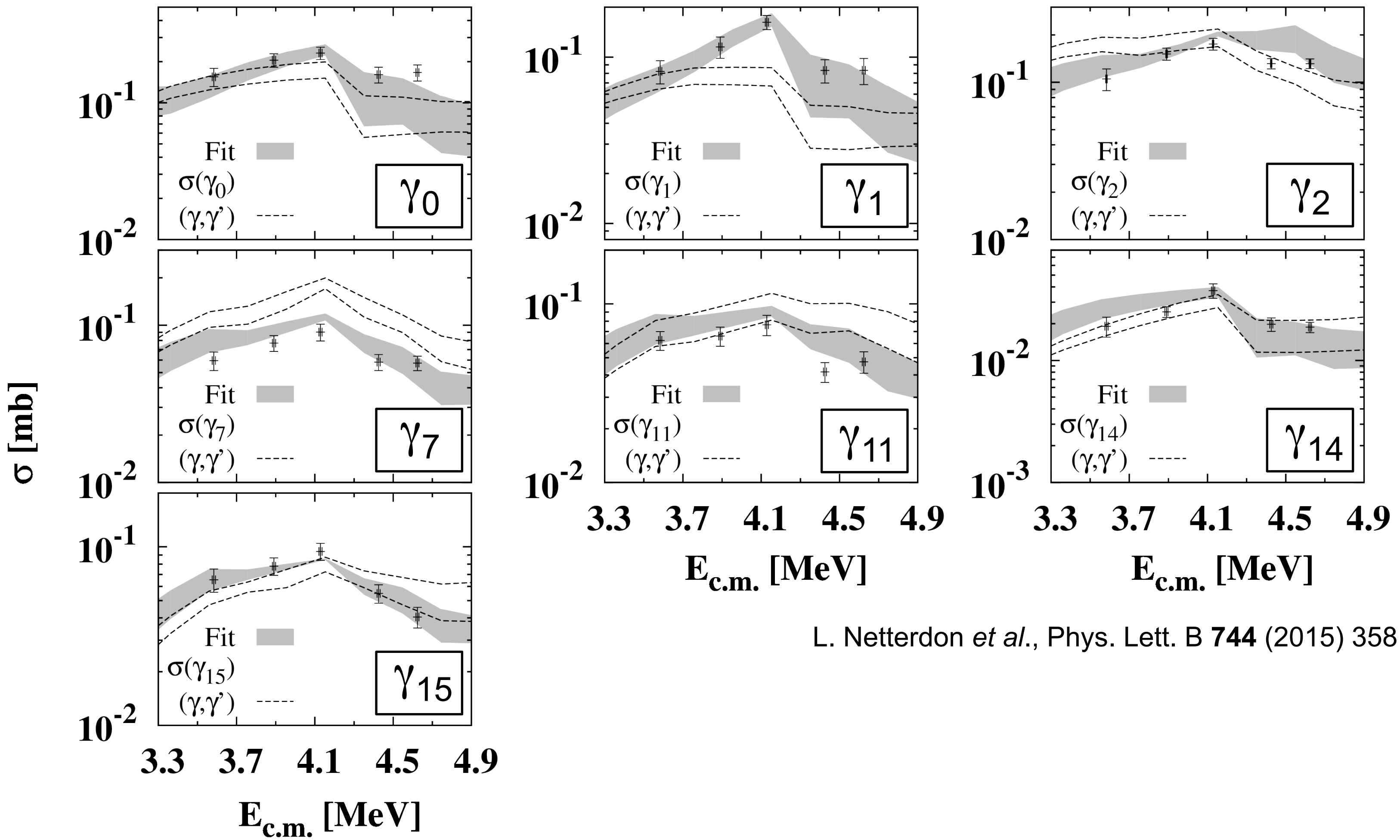


L. Netterdon *et al.*, Phys. Lett. B **744** (2015) 358

- use γ-ray strength deduced from (γ,γ') measurement of Schwengner *et al.*

R. Schwengner *et al.*, Phys. Rev. C **78** (2008) 064314

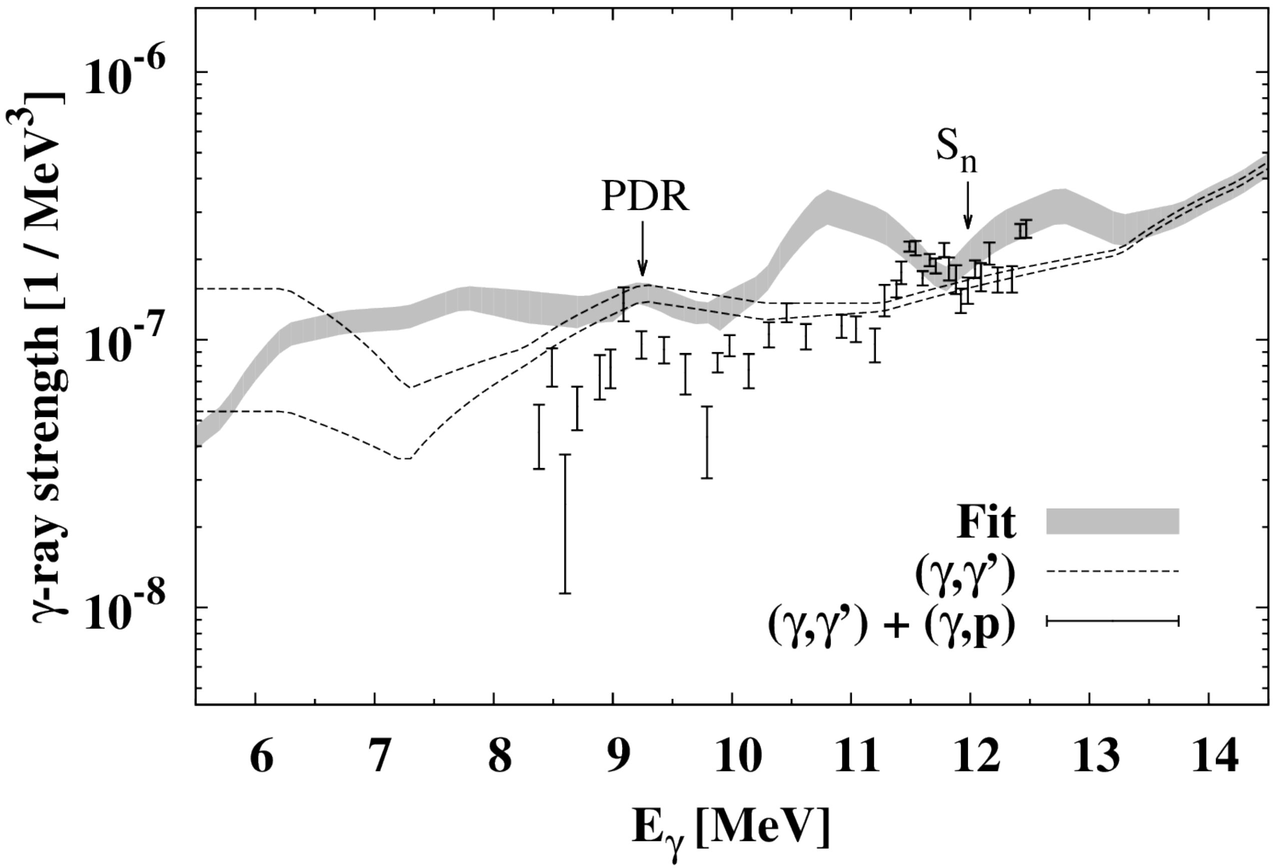
$^{89}Y(p,\gamma)$ – Partial cross-sections



L. Netterdon *et al.*, Phys. Lett. B **744** (2015) 358

- γ-ray strength function fitted to reproduce partial cross sections
  → how does it compare to previous measurements?

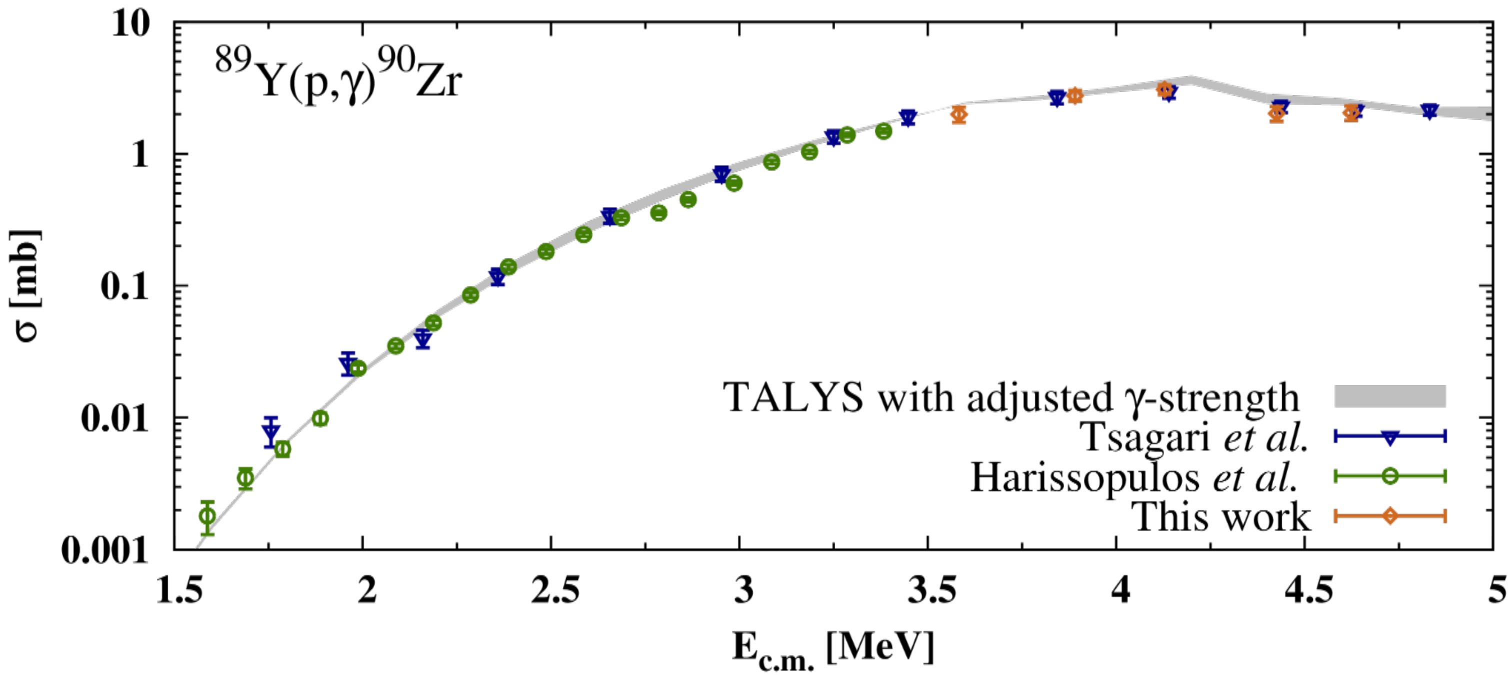
^{90}Zr – γ-ray strength function



- location and strength of PDR is consistent
- where do deviations come from?
  - → γ-branching ratios, dependence on nuclear temperature?

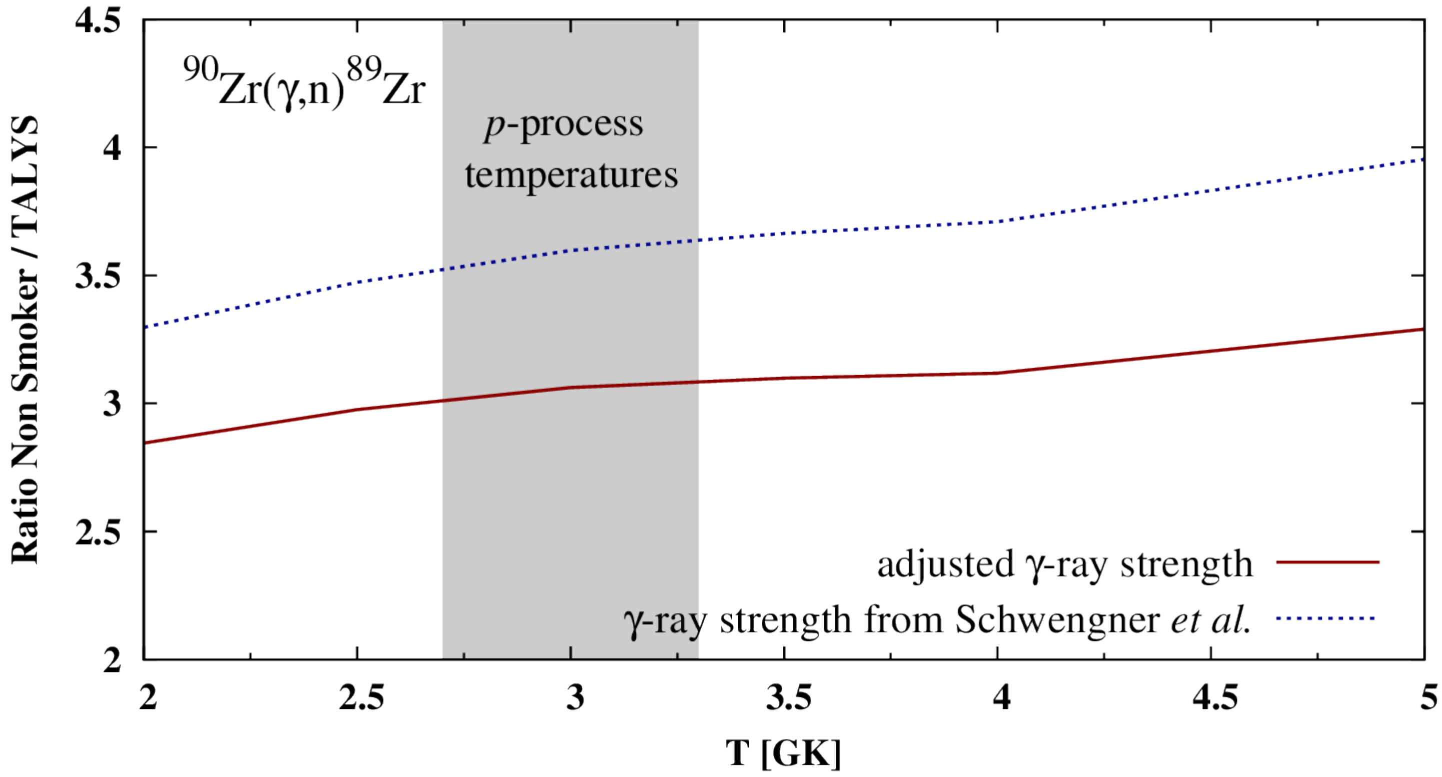
R. Schwengner *et al.*, Phys. Rev. C **78** (2008) 064314
P. Axel *et al.*, Phys. Rev. C **2** (1970) 689
L. Netterdon *et al.*, Phys. Lett. B **744** (2015) 358

$^{89}Y(p,\gamma)$ – Total cross-section



- excellent agreement of experimental data with previous measurements
- using adjusted γ-strength also reproduces total cross section

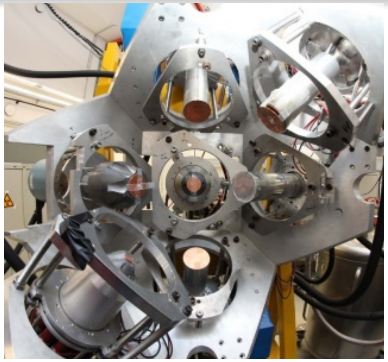
Stellar reaction rate of $^{90}Zr(\gamma,n)$



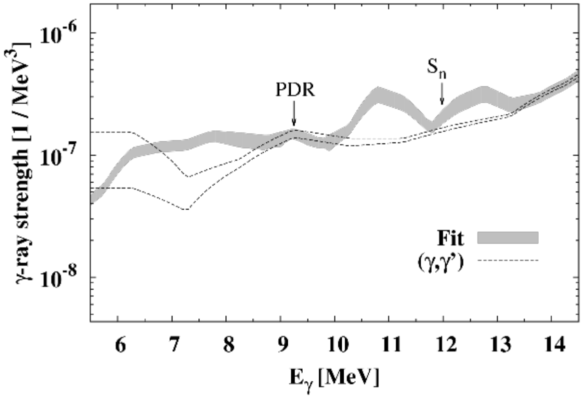
- comparison of stellar reaction rates with widely used Non Smoker code
- reaction rates with experimental γ-ray strength functions lower by about a factor of 3
- impact on solar abundance distribution of *p* nuclei (?)

Summary

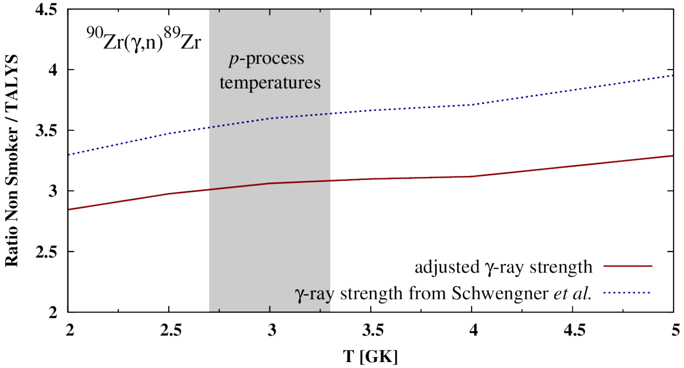
- γ-ray spectrometer HORUS used for in-beam experiments in nuclear astrophysics



- proton-capture reaction on ^{89}Y
  - total cross-section values for five proton energies
  - partial cross sections to seven discrete states
  - extract γ-ray strength function in ^{90}Zr



- significant impact on stellar ^{90}Zr(γ,n) reaction rate



UoC

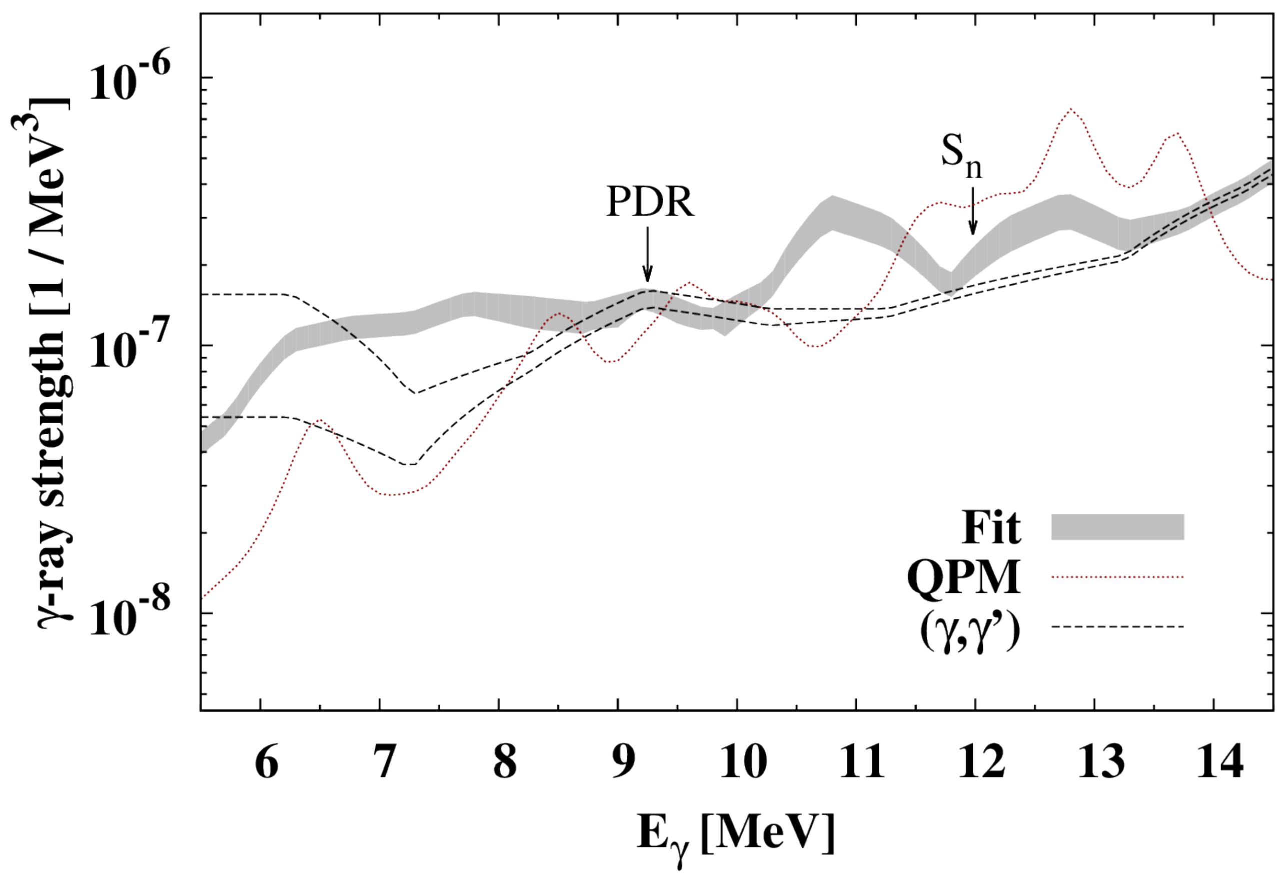
V. Derya, F. Heim, A. Hennig,
T. Lieber, J. Mayer, S. G. Pickstone,
S. Prill, P. Scholz, M. Spieker,
M. Weinert, J. Wilhelmy, K. O. Zell,
and A. Zilges

H.-W. Becker and
D. Rogalla

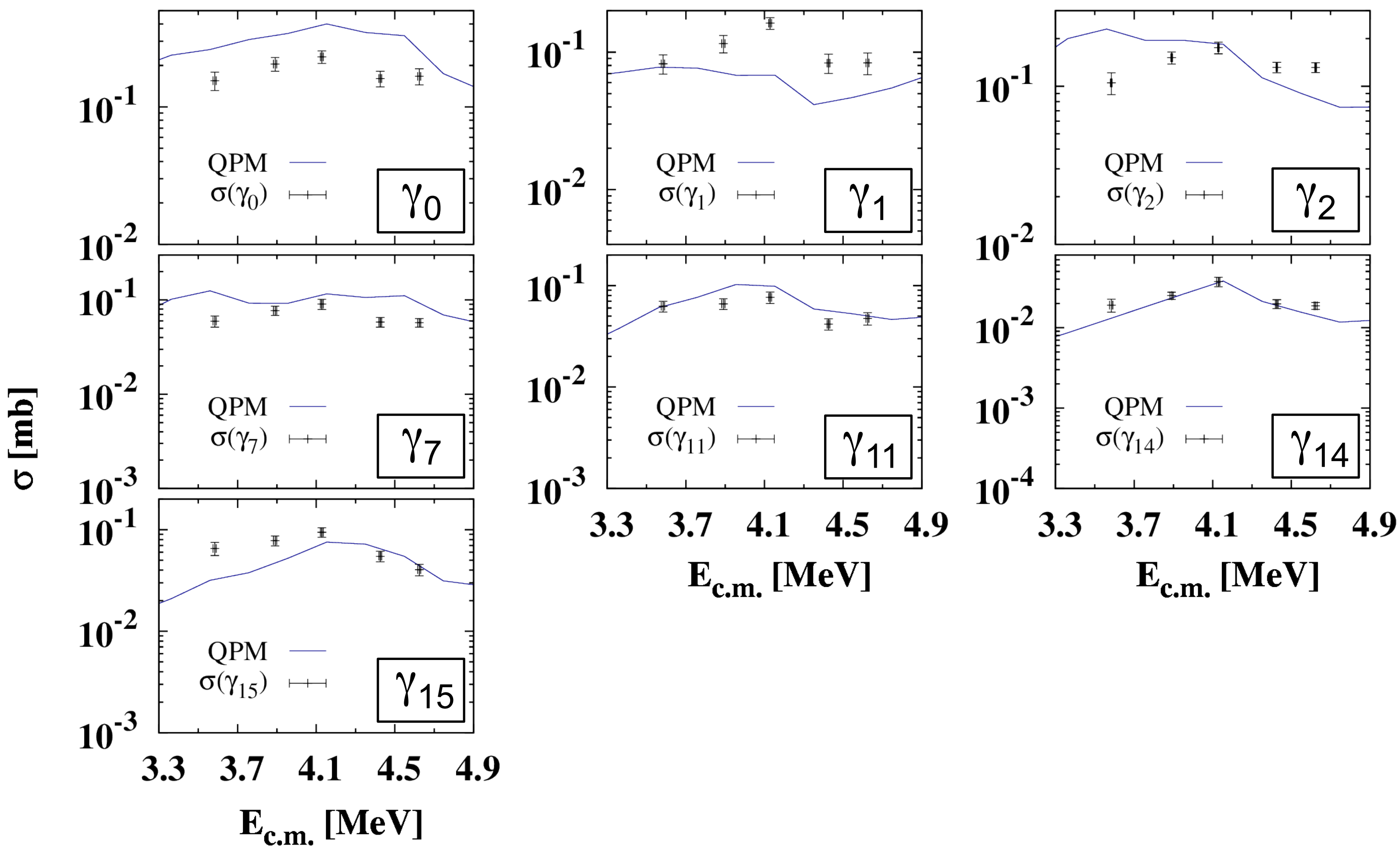
A. Endres

S. Goriely

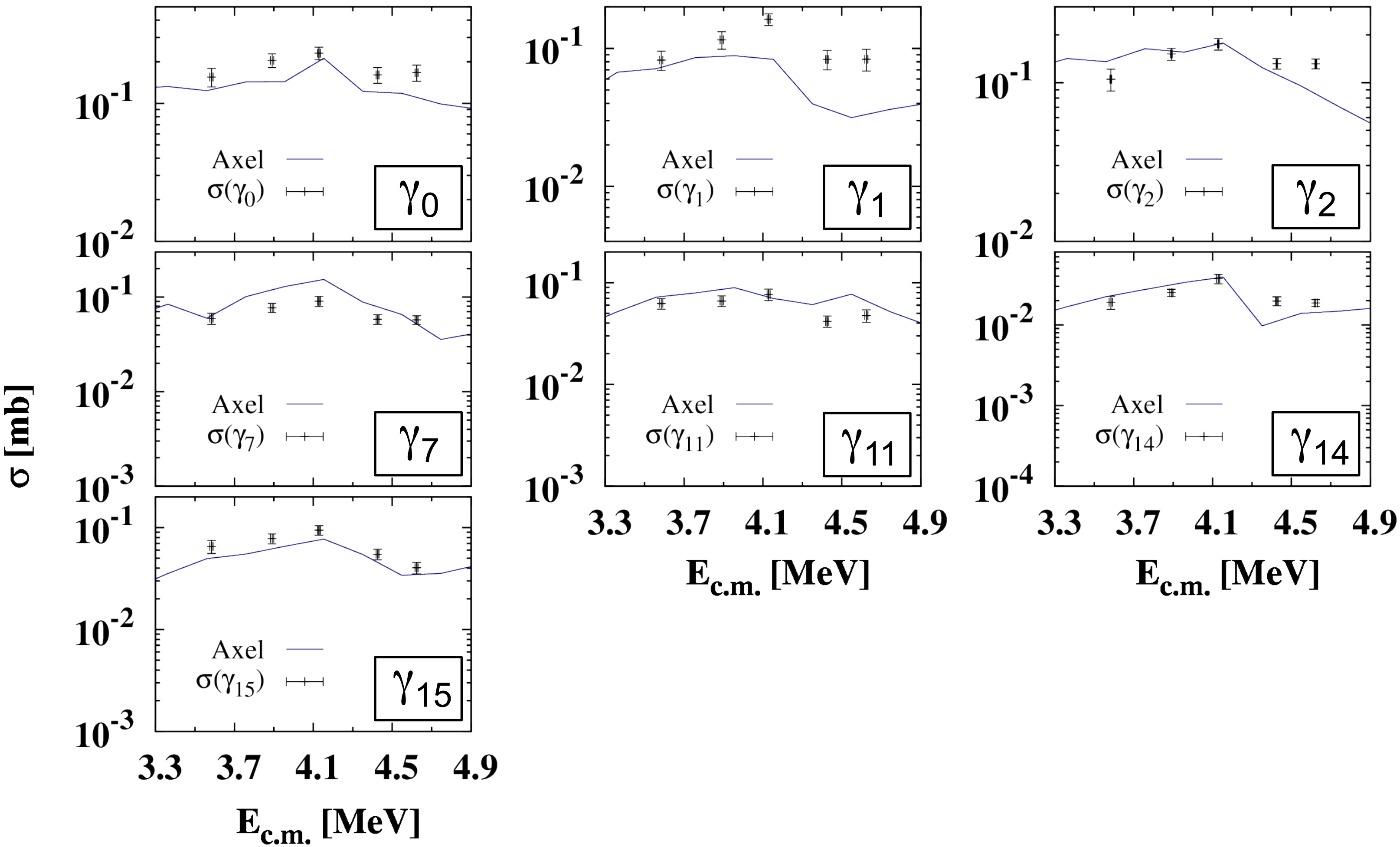
^{90}Zr – γ-ray strength function



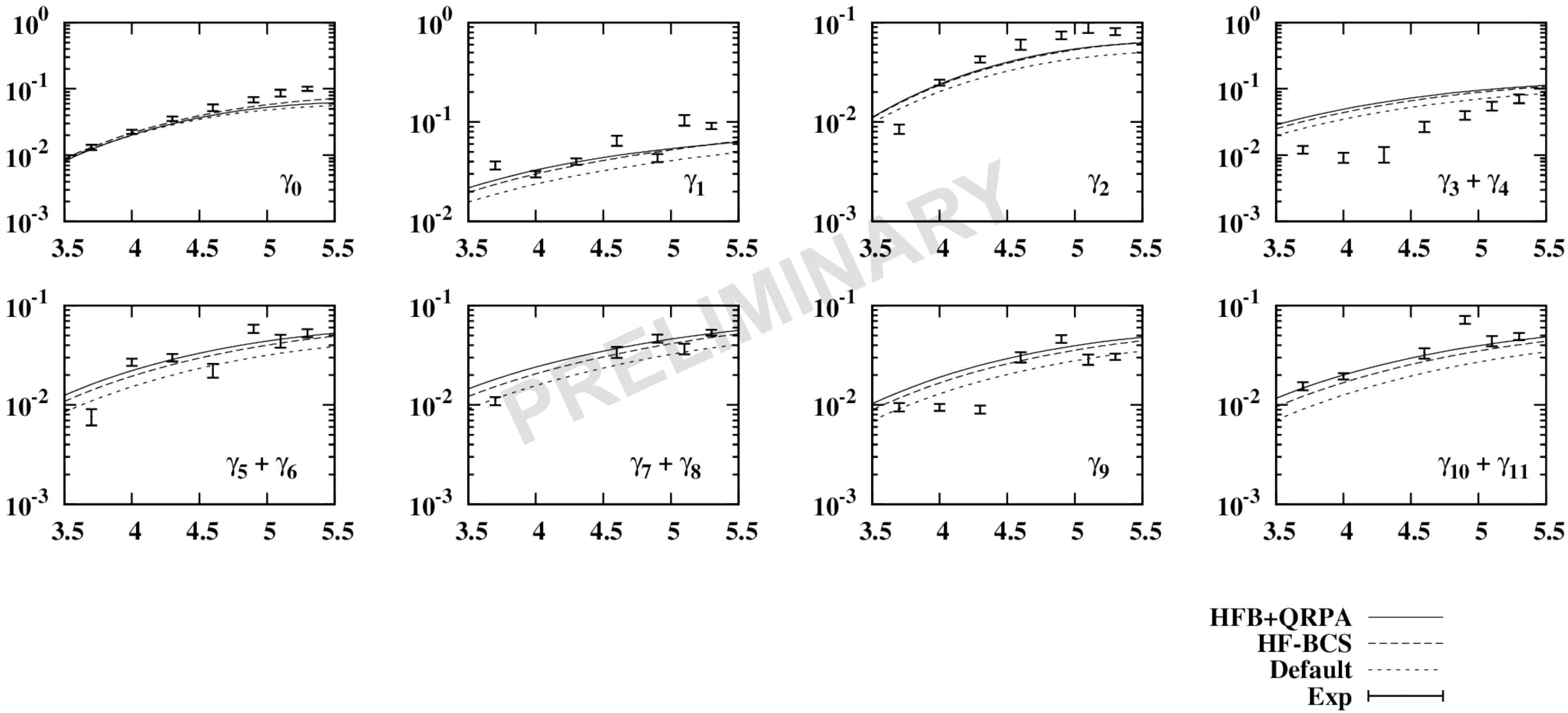
$^{89}Y(p,\gamma)$ – Partial cross-sections QPM



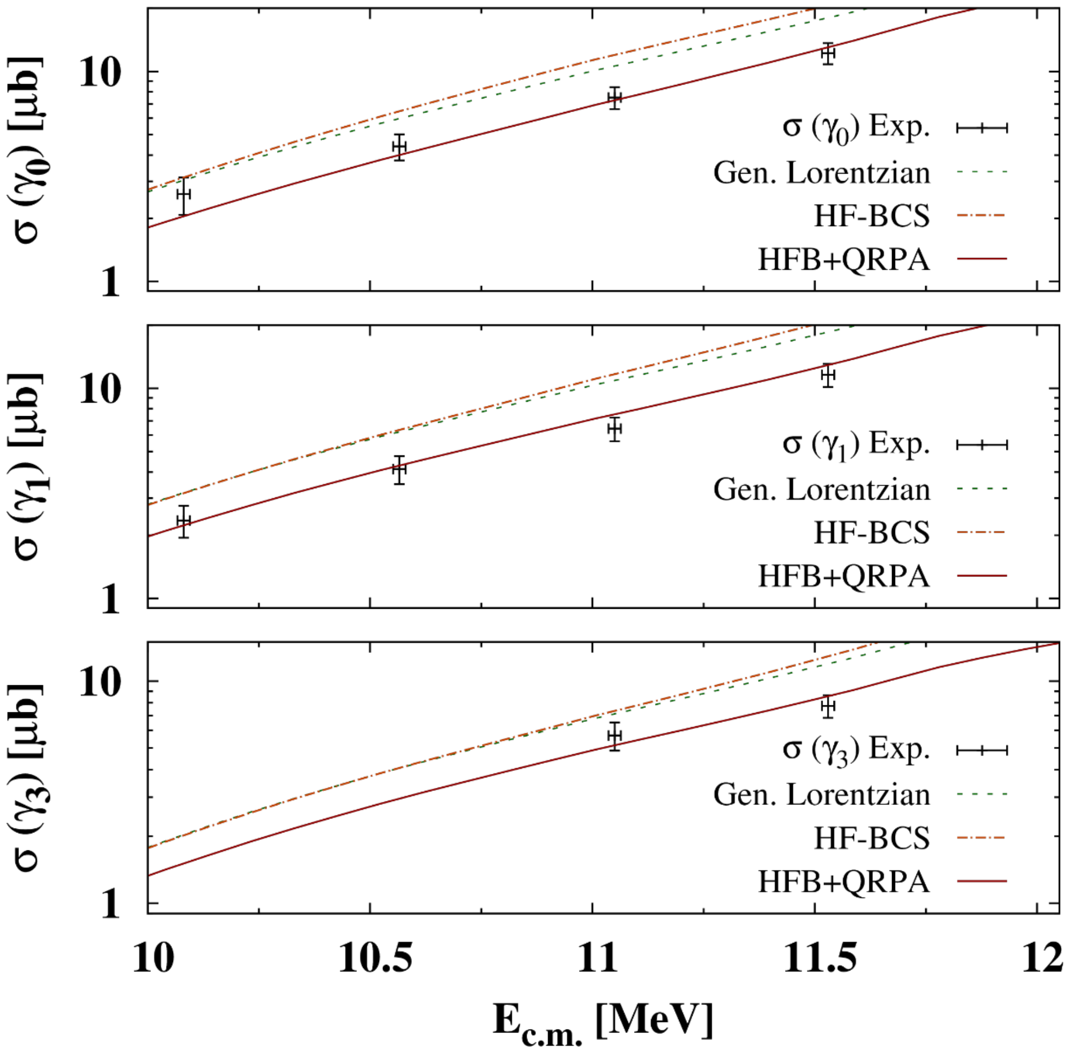
$^{89}Y(p,\gamma)$ – Partial cross-sections Axel *et al.*



$^{92}Mo(p,\gamma)$ – Partial cross-sections



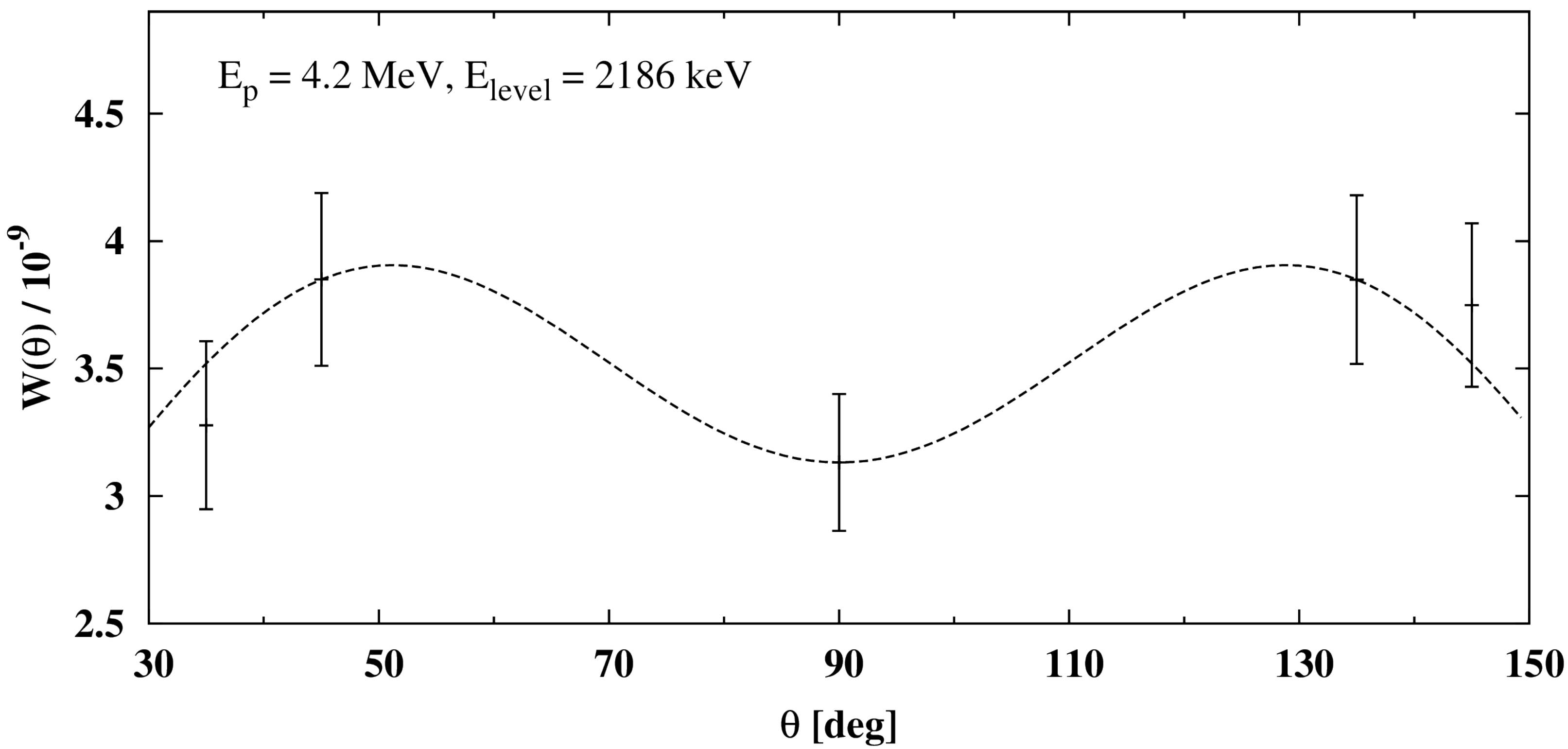
$^{112}Sn(\alpha,\gamma)$ – Partial cross sections



- new experimental information
- allows constraint on γ-ray strength
- first time measured for an α-induced reaction!
- excellent agreement with microscopic model

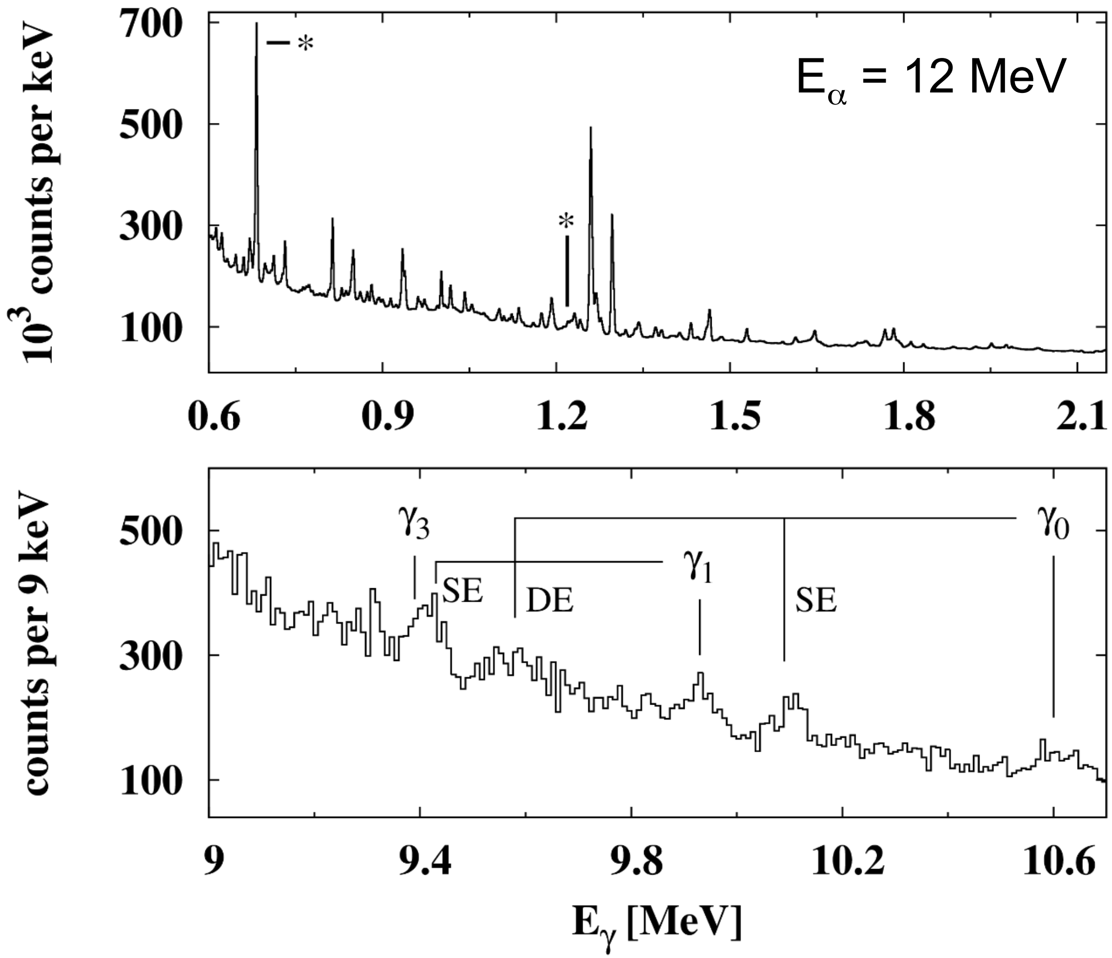
L. Netterdon *et al.*, Phys. Rev. C **91** (2015) 035801

$^{89}Y(p,\gamma)$ – Angular distributions



- measure reaction yield at 5 different angles relative to beam axis
- fit sum of Legendre polynomials
- obtain reaction yield in 4π

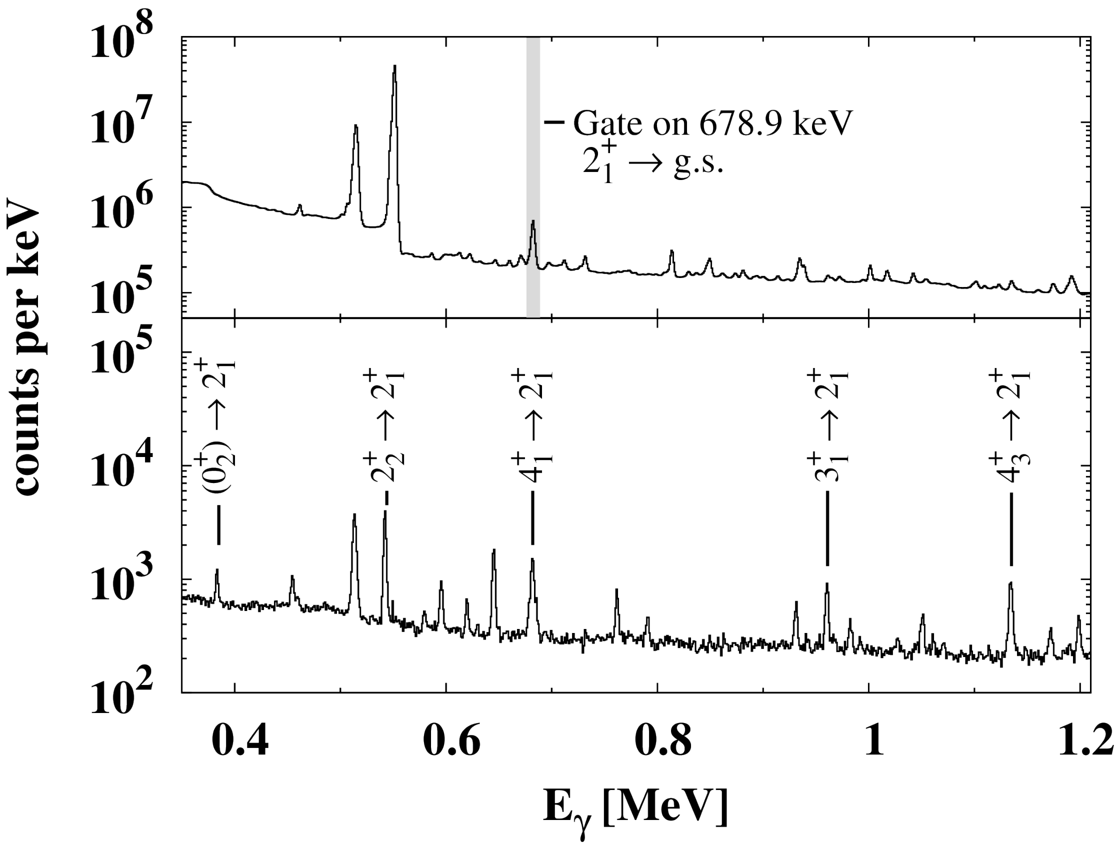
$^{112}Sn(\alpha,\gamma)$ – In-beam spectrum



- E_α = 10.5 MeV – 12 MeV
- beam current ≈ 80 nA – 240 nA
- ^{112}Sn target enriched to ≈ 85 %
- thickness ≈ 360 μg / cm^2
- four total cross-section values
- partial cross-sections for population of three discrete states

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

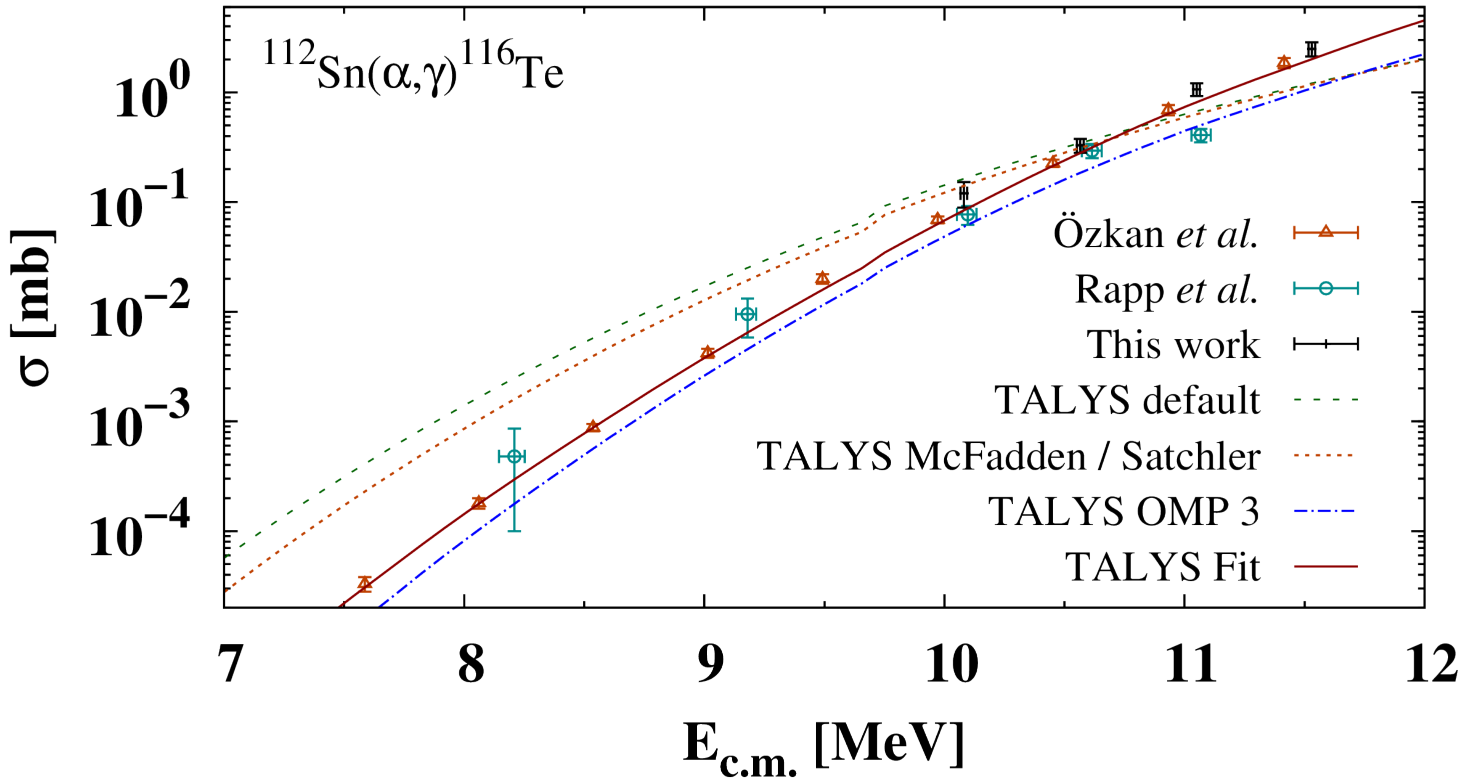
$^{112}Sn(\alpha,\gamma)$ – $\gamma\gamma$-coincidences



- effective background reduction
- only three ground-state transitions available in literature
- reconstruction of experimentally known level scheme up to 16th excited state
- no evidence for further g.s. transitions found

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

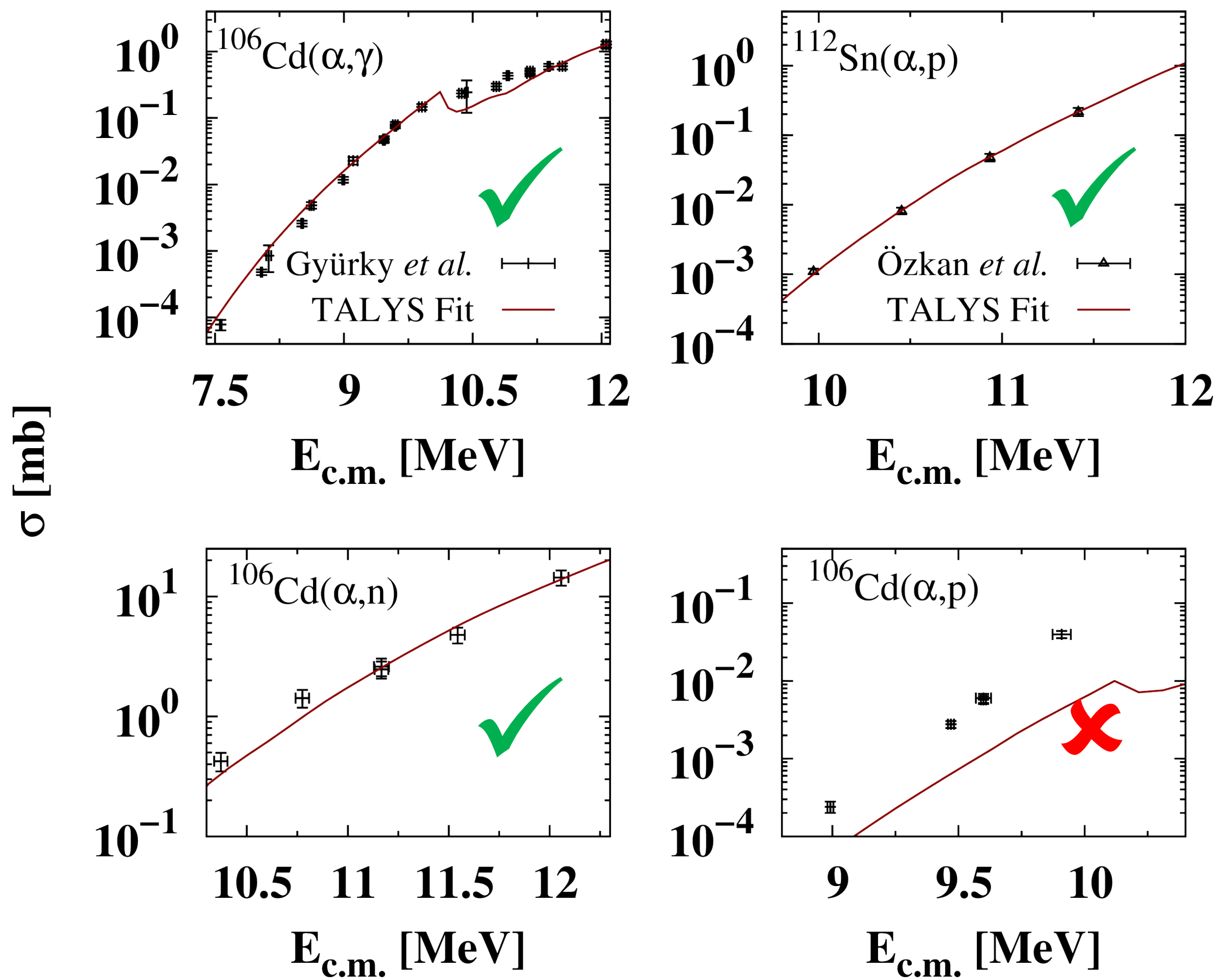
$^{112}Sn(\alpha,\gamma)$ – Total cross-section



- very good agreement with previous activation measurements
  - (α,γ) reactions can be measured in-beam @ HORUS!
- standard α-OMPs fail to reproduce experimental data
- local adjustment necessary → partial cross-sections and other reactions?

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

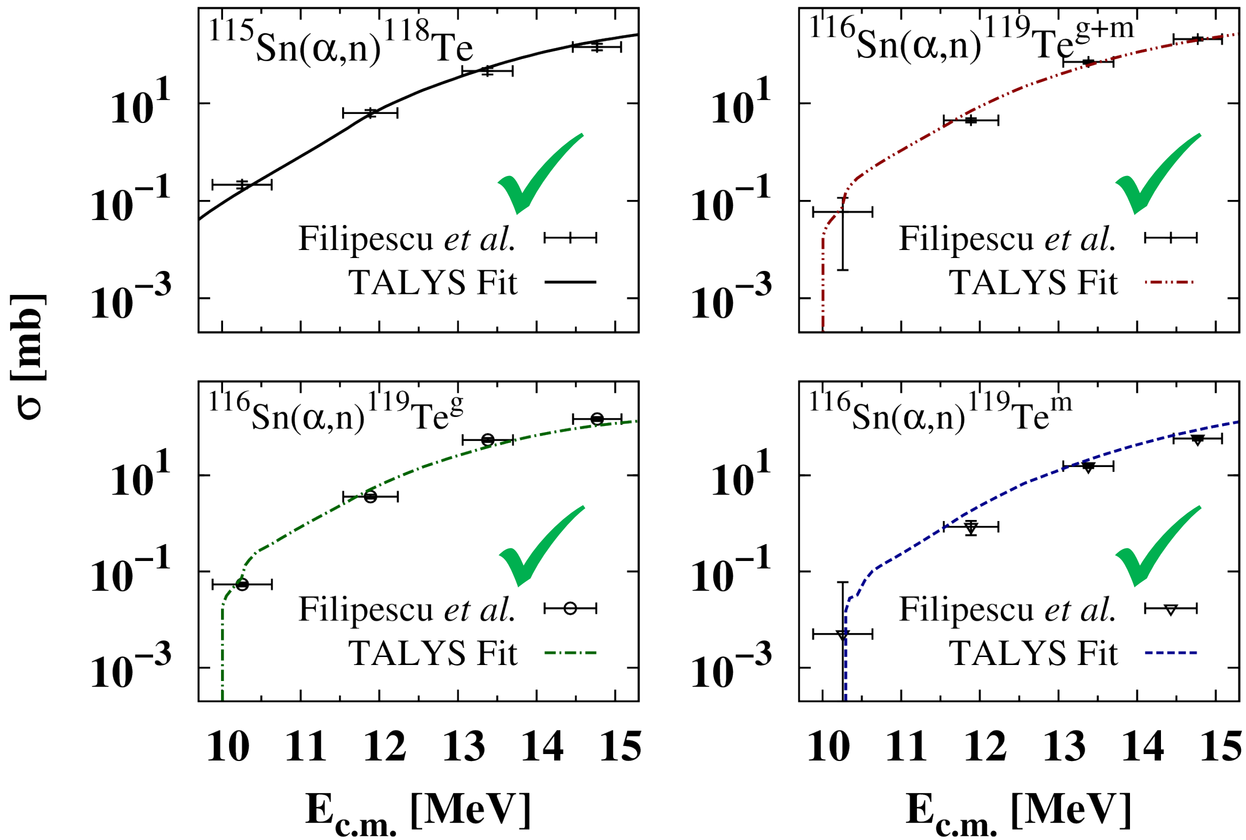
Model applicability in Sn / Cd region



proton-shell closure in Sn?

L. Netterdon *et al*., Phys. Rev. C **91** (2015) 035801
Gy. Gyürky *et al*., Phys. Rev. C **74** (2006) 025805
N. Özkan *et al*., Phys. Rev. C **75** (2007) 025801

Model applicability in Sn / Cd region



- presently found model well-suited for α-induced reactions in Sn / Cd region
- further experimental investigations are needed

L. Netterdon *et al.*, Phys. Rev. C **91** (2015) 035801
D. Filipescu *et al.*, Phys. Rev. C **83** (2011) 064609