Constraining the Astrophysical γ Process: Cross Section Measurement of the $^{82}Kr(p,\gamma)^{83}Rb$ Reaction in Inverse Kinematics

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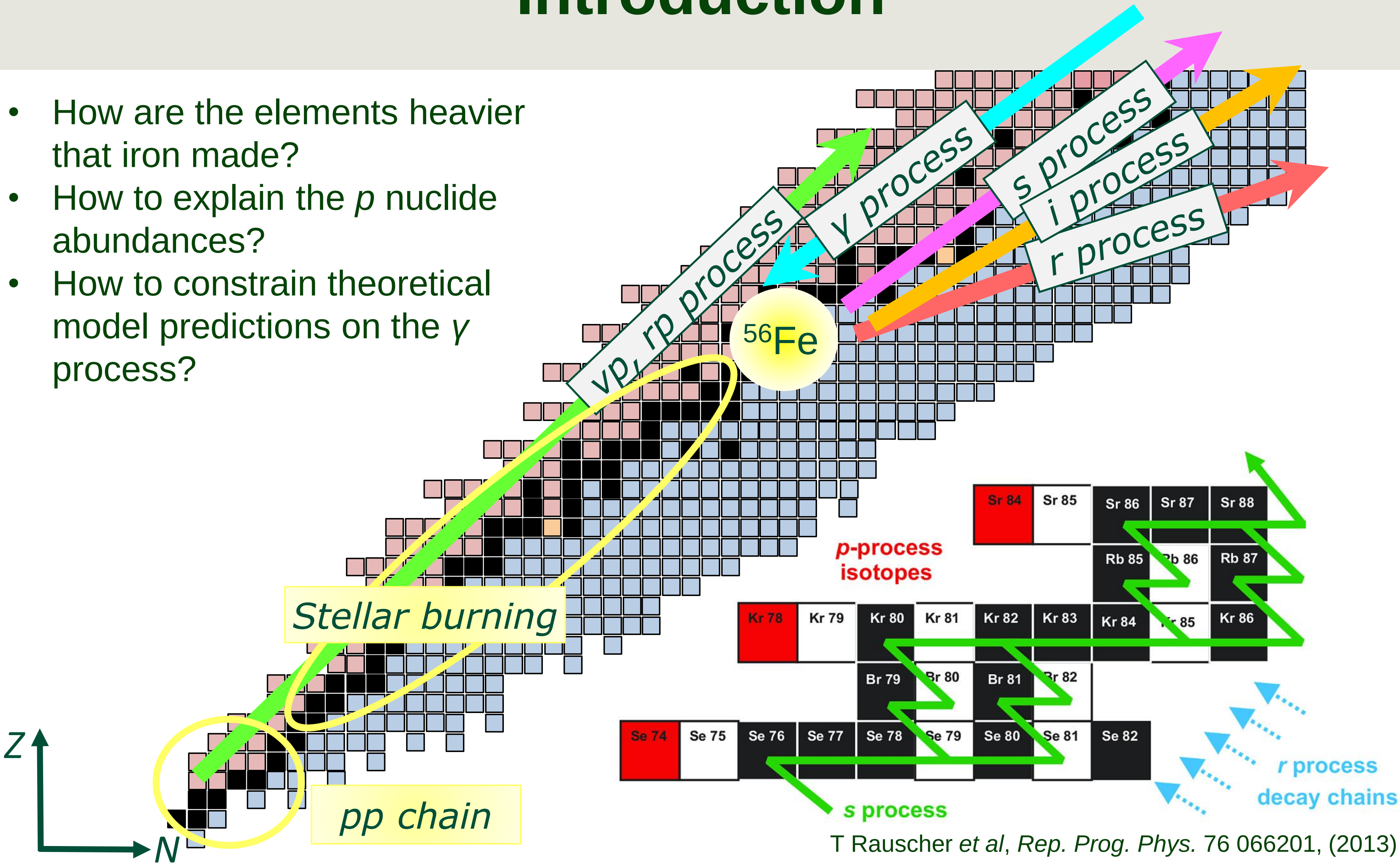
Introduction

- How are the elements heavier that iron made?
- How to explain the *p* nuclide abundances?
- How to constrain theoretical model predictions on the *γ* process?



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

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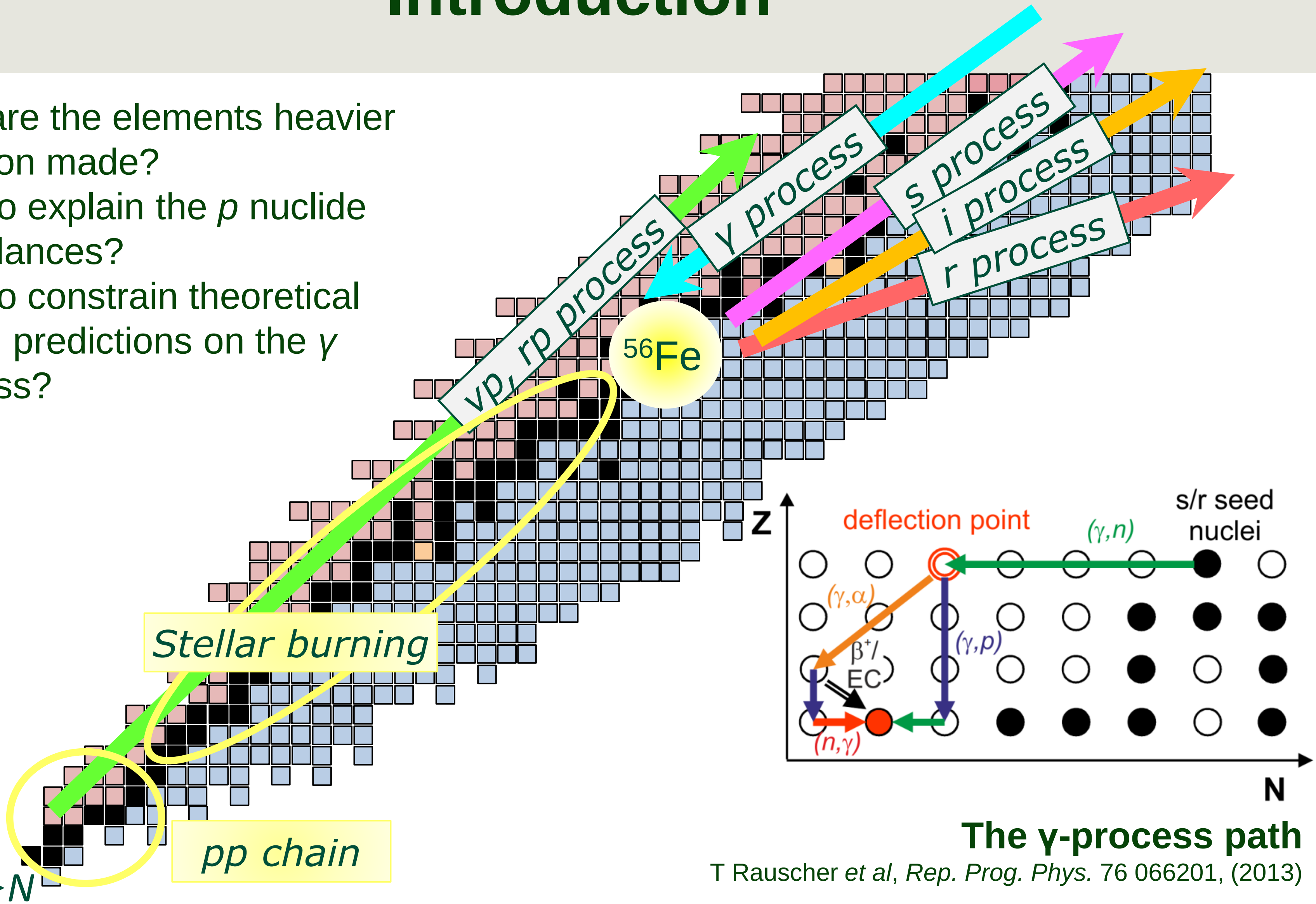

The γ-process path

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

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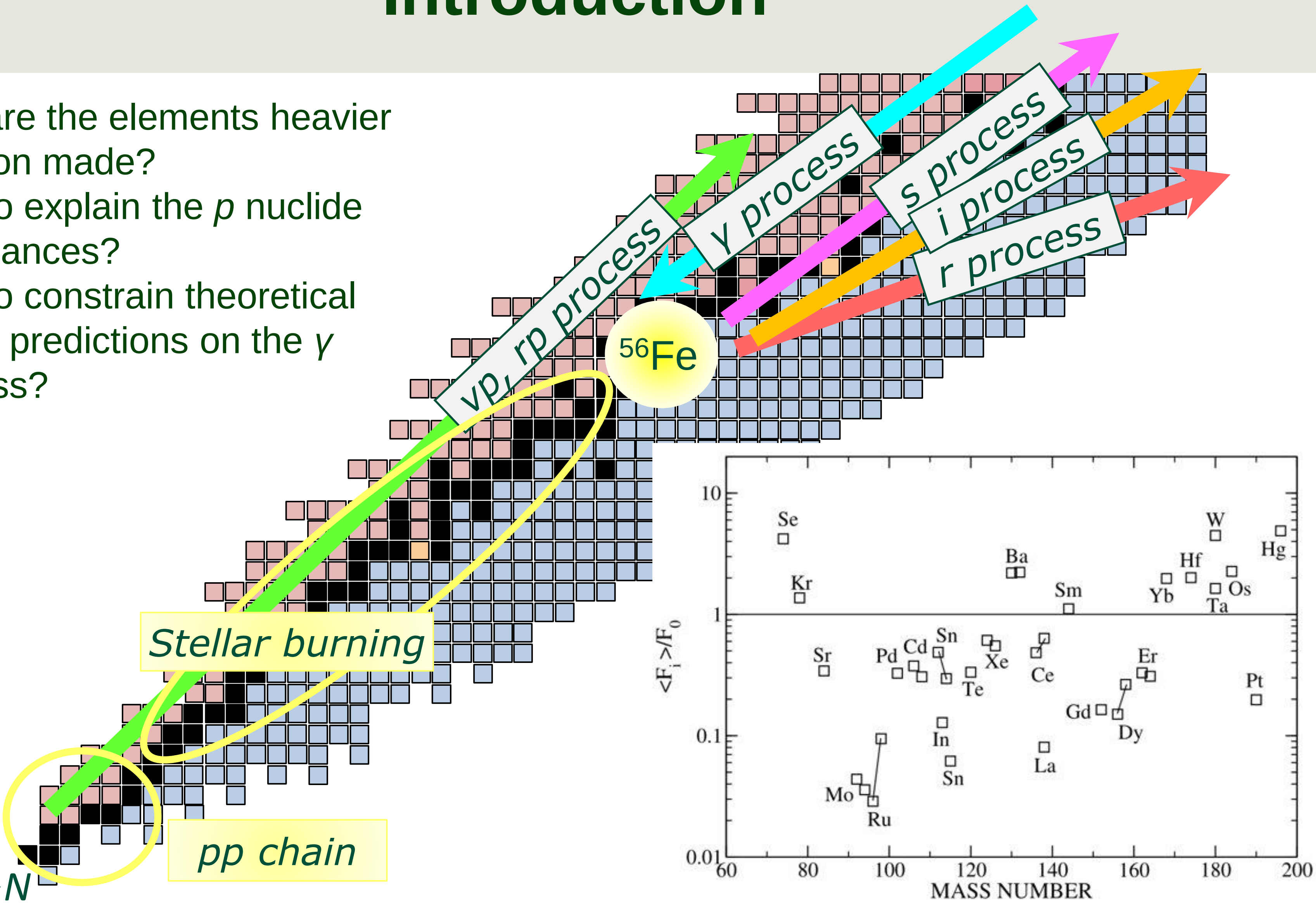
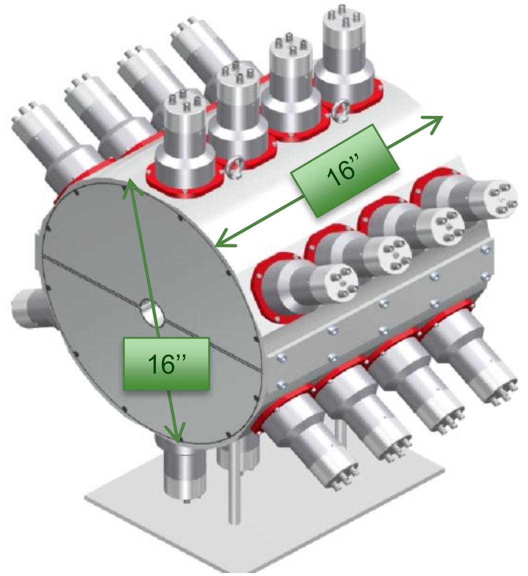
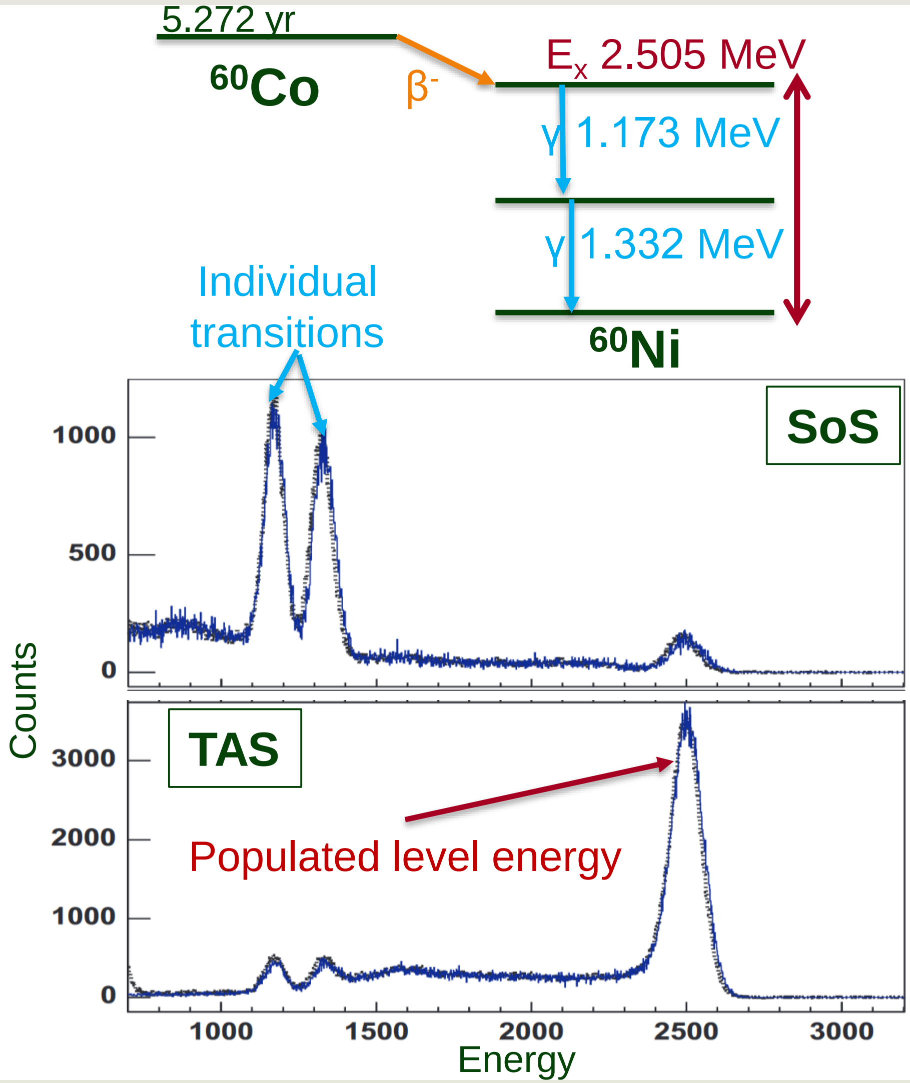


W. Rapp, J. Görres, M. Wiescher, H. Schatz, and F. Käppeler. Astrophys J, 653:474, 2006.

γ-summing technique with SuN

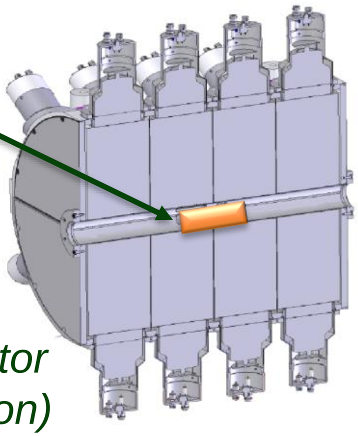




- **Summing NaI(Tl) SuN**: Large size, high efficiency γ-ray detector
- 8 optically isolated segments
- 24 PMTs
- **Sum of Segments (SoS)** → Information about individual γ-rays
- **Total Absorption Spectrum (TAS)** → Information about total excitation energy E_x

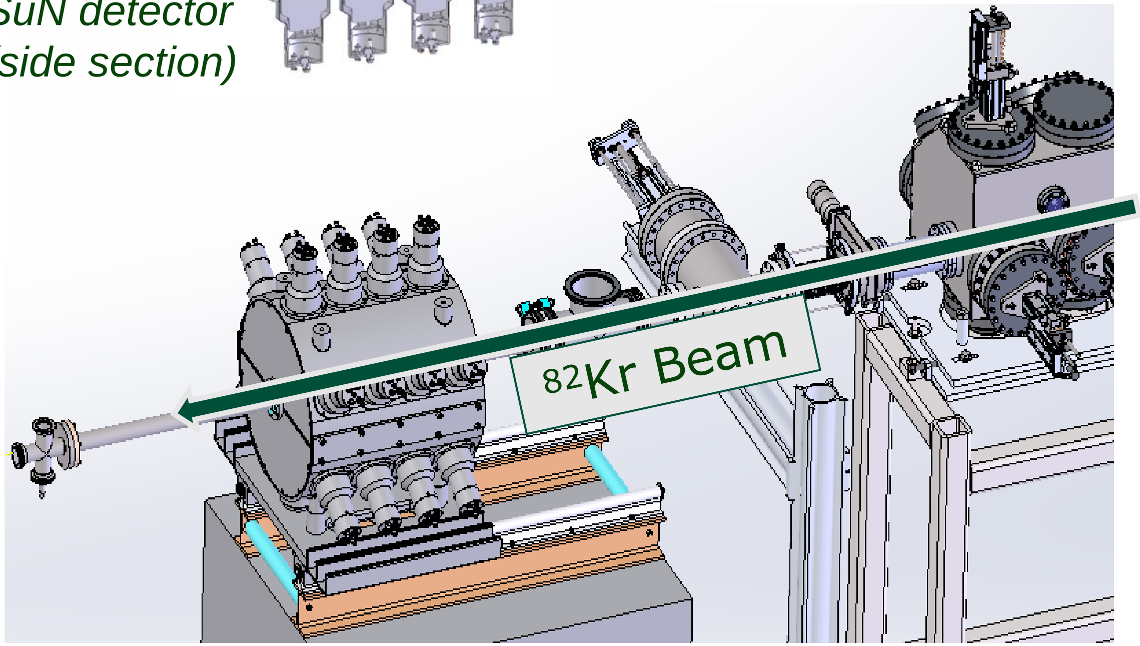
Experiment at ReA NSCL

Gas cell target

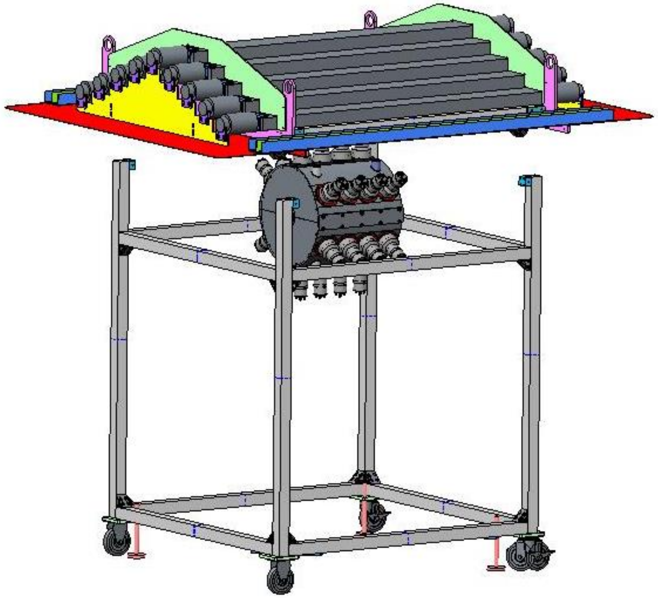


SuN detector (side section)

- Measurement of the ^{82}Kr(p,γ)^{83}Rb reaction cross section in inverse kinematics
- ^{82}Kr pulsed beam at E_{LAB} 3.1, 3.4 and 3.7 MeV
- Hydrogen gas cell target
- SuN for γ-ray detection
- SuNSCREEN as veto detector for cosmic background



Experimental Setup (without SuNSCREEN)



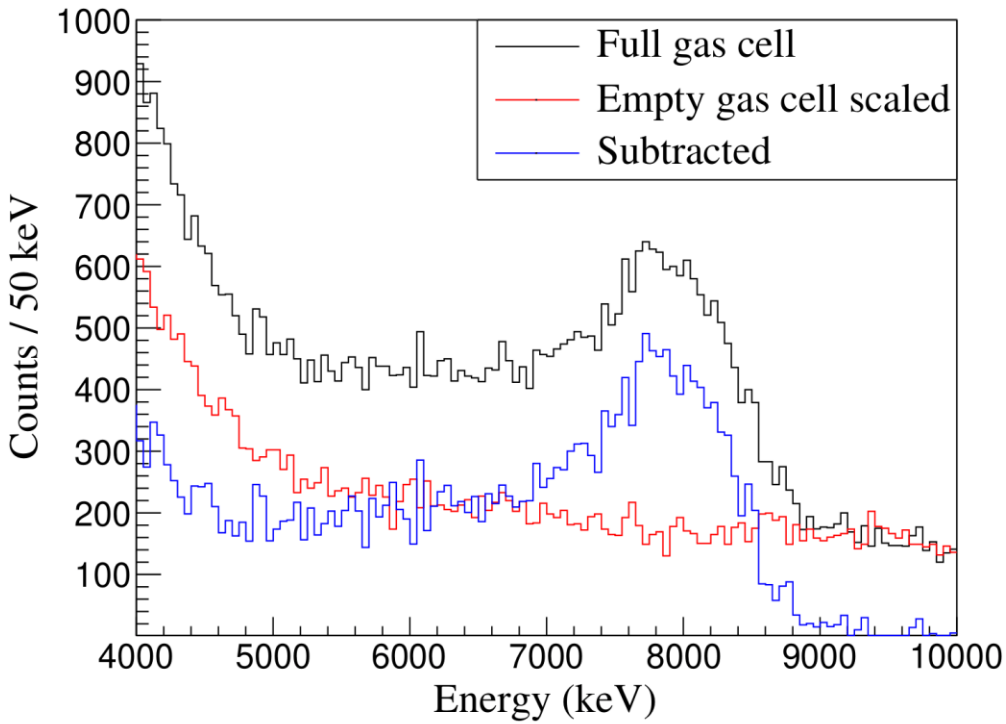
SuNSCREEN and SuN

E. Klopfer *et al*, *Nucl. Instrum. Meth. Phys. Res.* A 788, 5 (2015)

Background Subtraction

Background contributions:

- Cosmic rays → SuNSCREEN veto
- Room Background → Pulsed Beam
- Interaction of the ^{82}Kr beam with the beam line and the gas cell → gas cell full and empty runs



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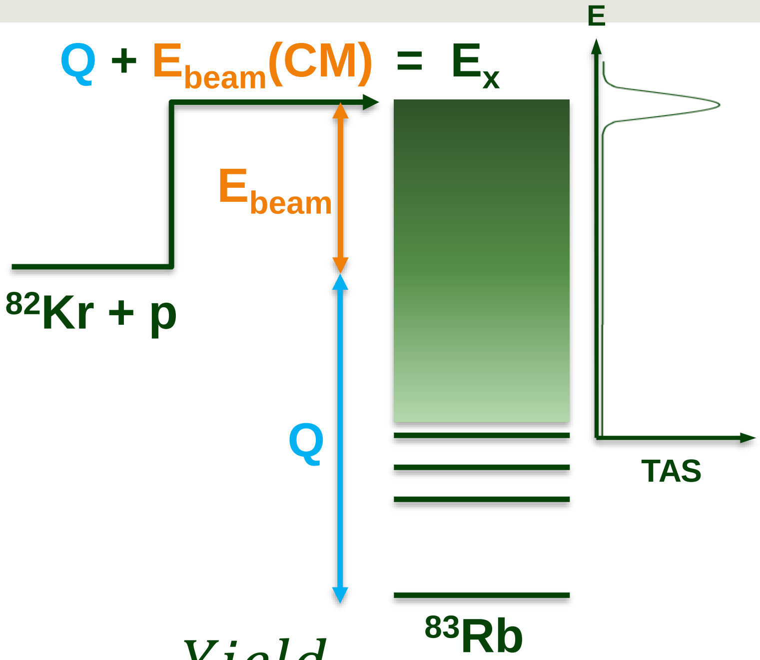
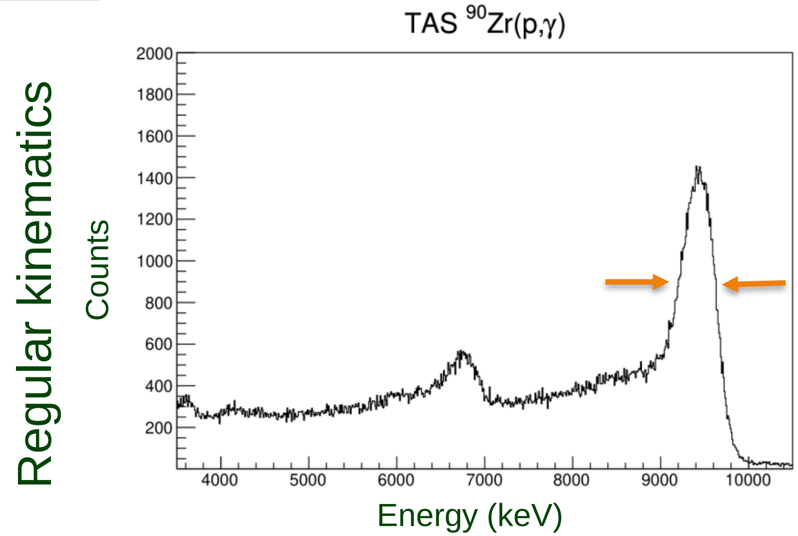
Analysis Overview

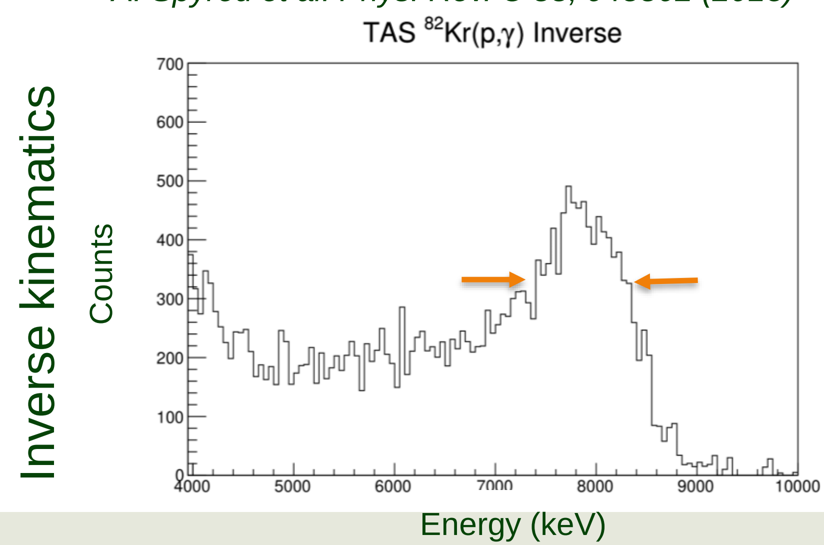


$$\sigma = \frac{Yield}{\Phi \cdot N_t \cdot \varepsilon_{eff}(E)}$$

- σ : Total reaction cross section
- *Yield* : The number of events detected
- $\varepsilon_{eff}(E)$: efficiency of the detector at energy E
- N_t : Number of target nuclei
- Φ : Beam flux



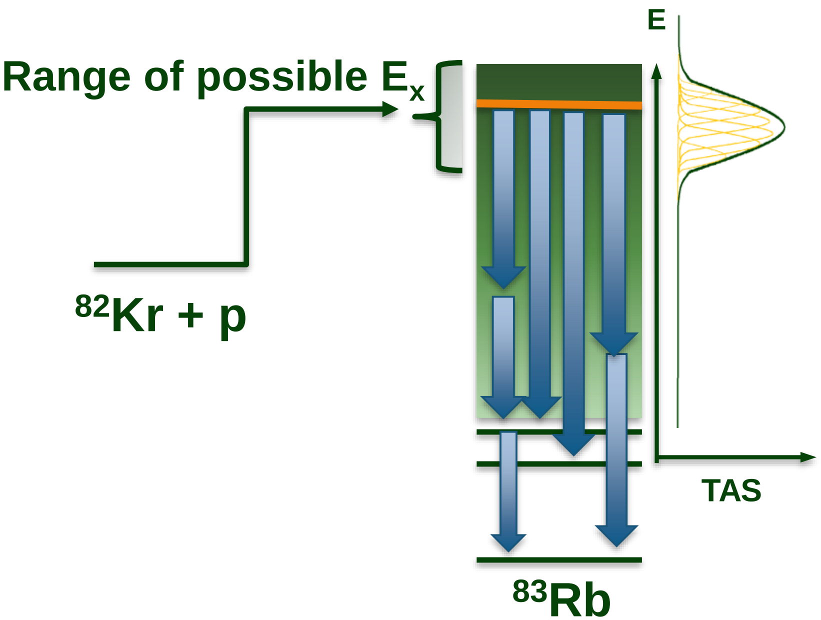
A. Spyrou et al. Phys. Rev. C 88, 045802 (2013)

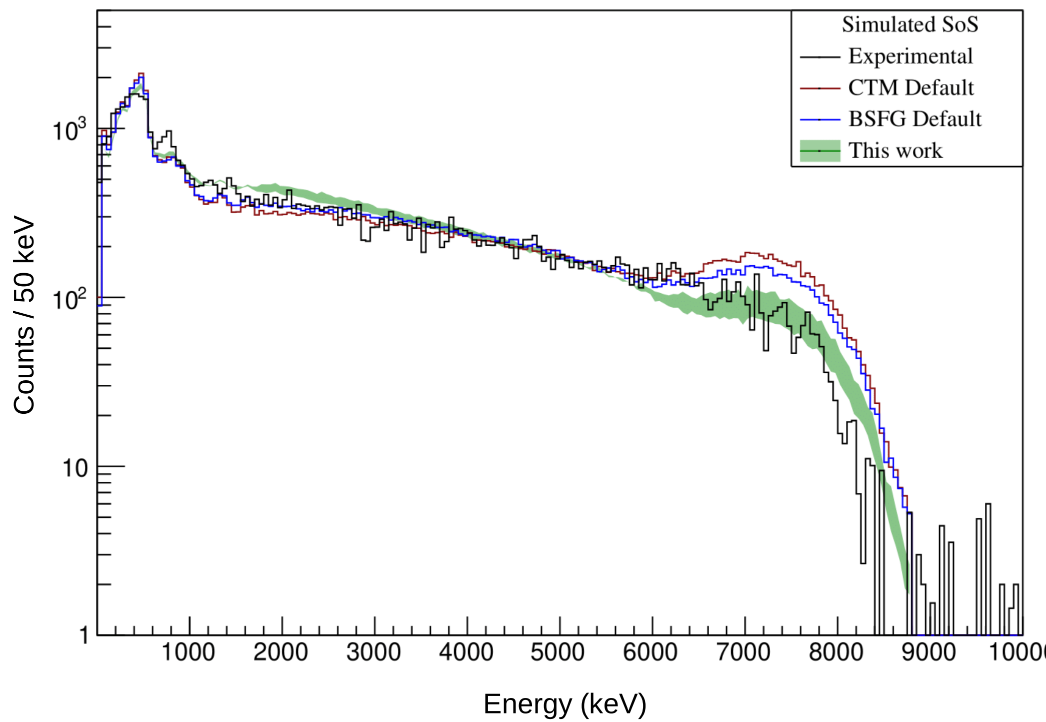


Efficiency and Yield Determination with RAINIER and GEANT4

- RAINIER: Simulates the de-excitation of a compound nucleus through γ cascades
- To describe our compound nucleus we use combinations of nuclear level densities $\rho(E_x - E_\gamma)$ and γ ray strength functions $\gamma SF(E_\gamma)$ that can replicate our SoS
- Simulate the de-excitation of every E_x that can possibly contribute in our TAS peak → obtain all possible γ ray cascades emitted inside SuN

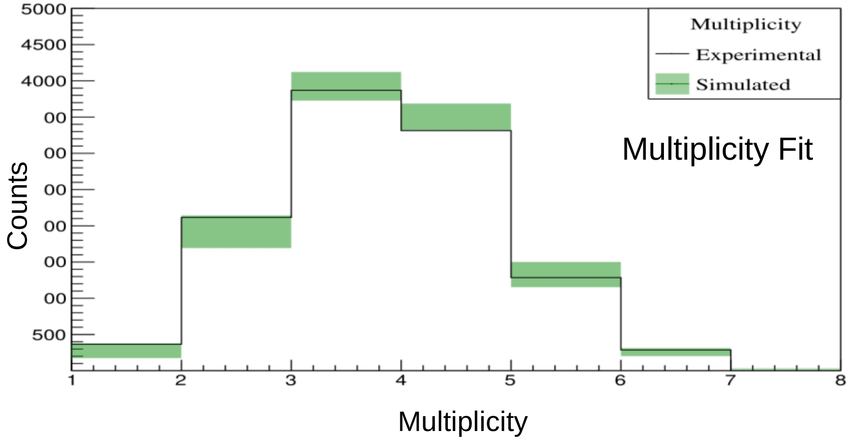
$$P(E_\gamma, \mathrm{E_x}) \propto \rho(E_x - E_\gamma) \cdot \gamma SF(E_\gamma)$$

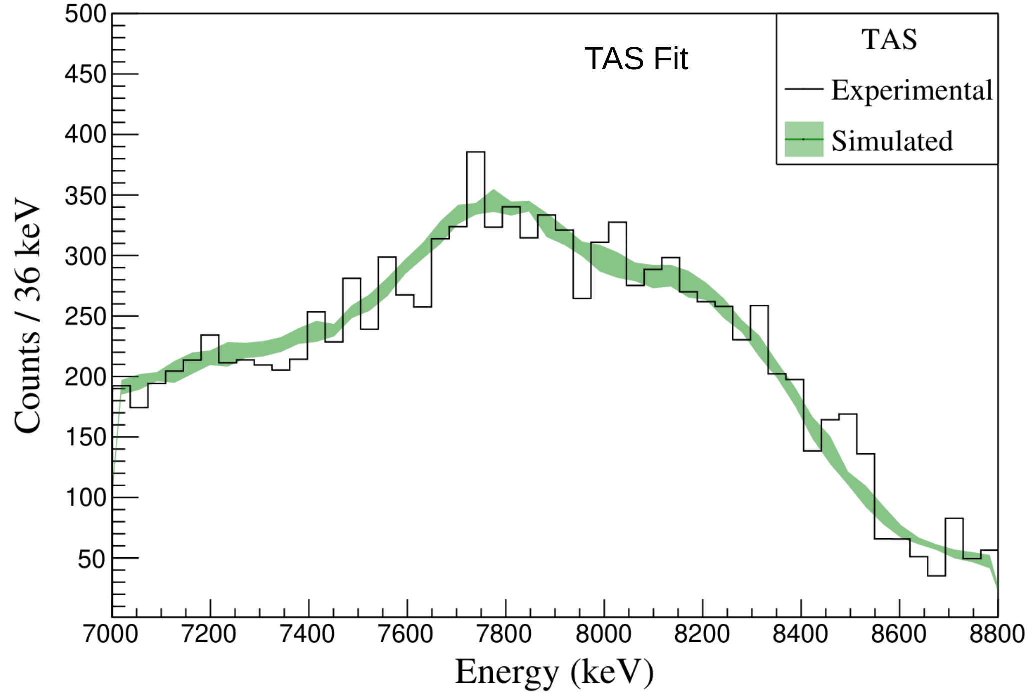


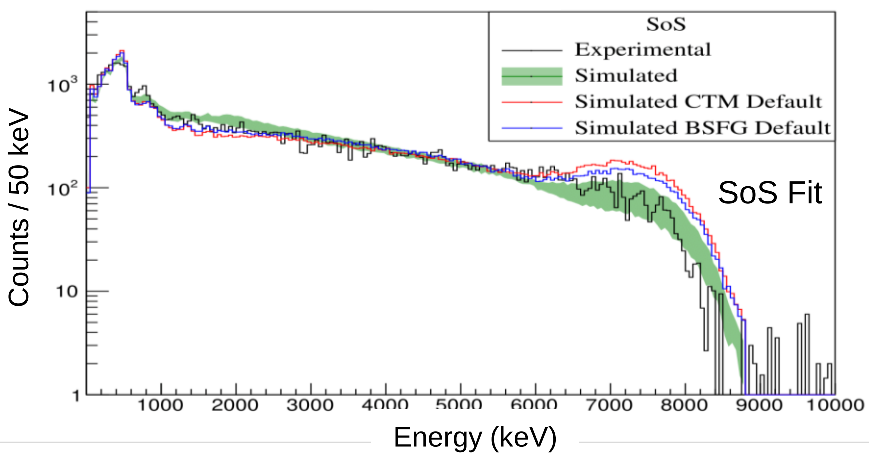


Efficiency and Yield Determination with RAINIER and GEANT4

- GEANT4: account for detector's geometry
- Fit to experimental TAS, SoS and multiplicity using χ^2 minimization code

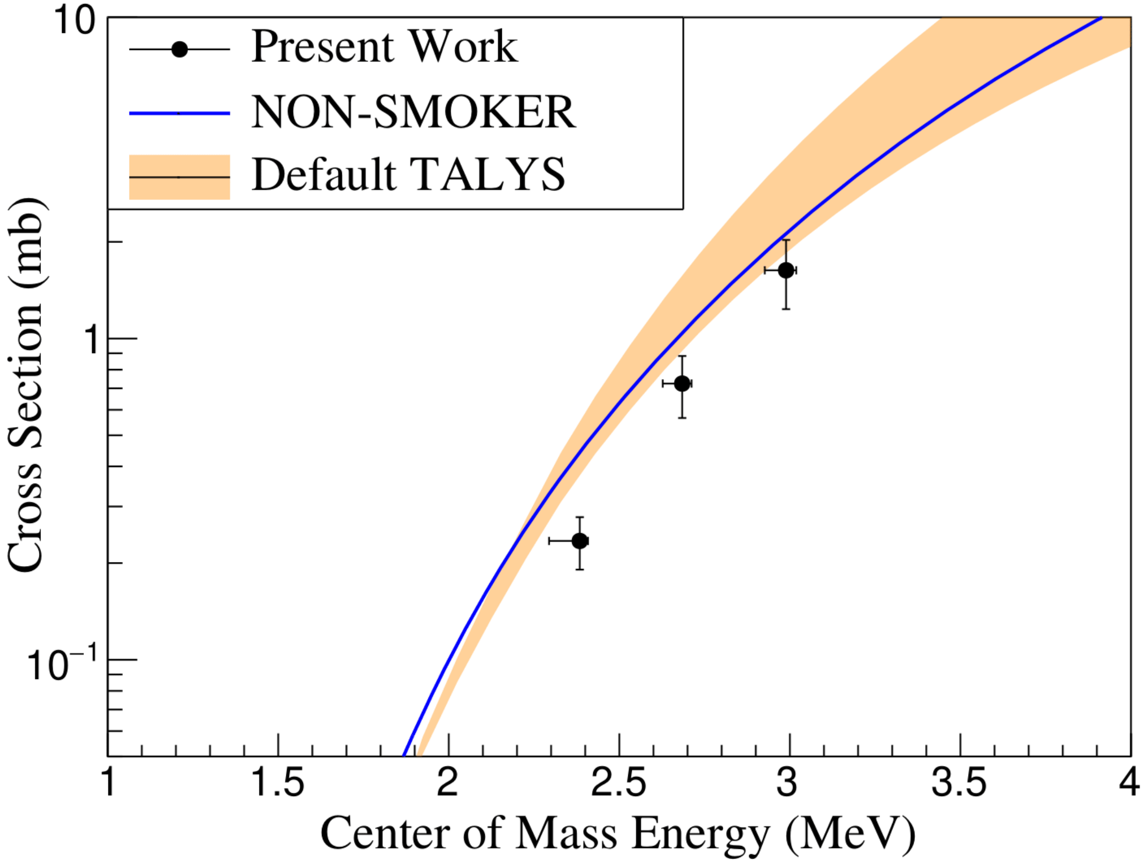






Results

- Standard statistical model calculations tend to overproduce the cross section
- Based on experimental data in neighboring nuclei, theory appears to consistently overestimates reaction rates in this mass region



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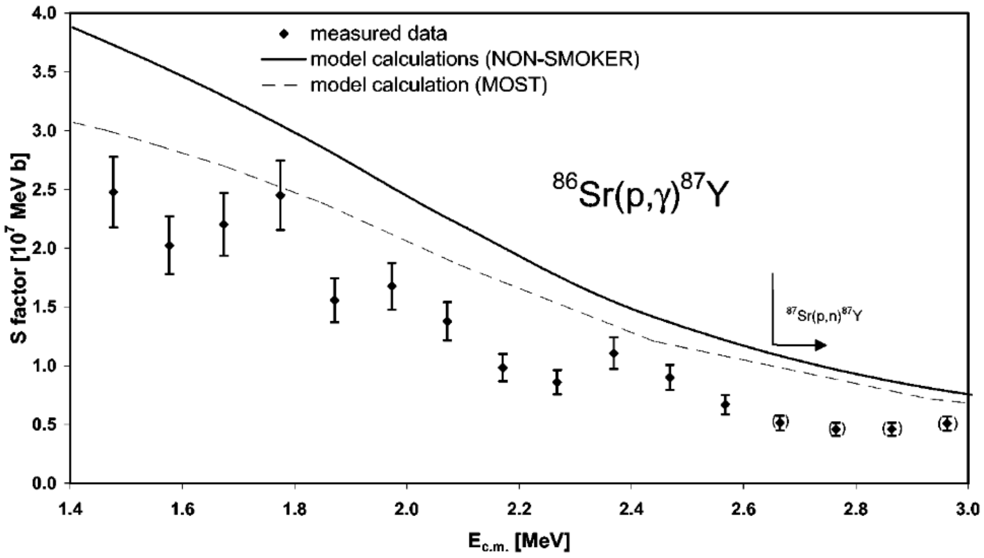
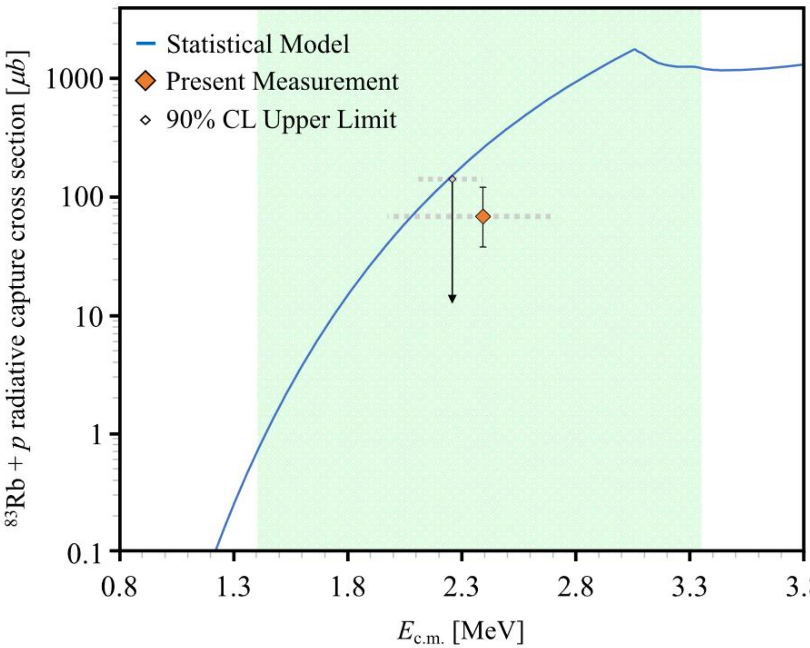


Gyürky et al, PRC 64, 065803 (2001)

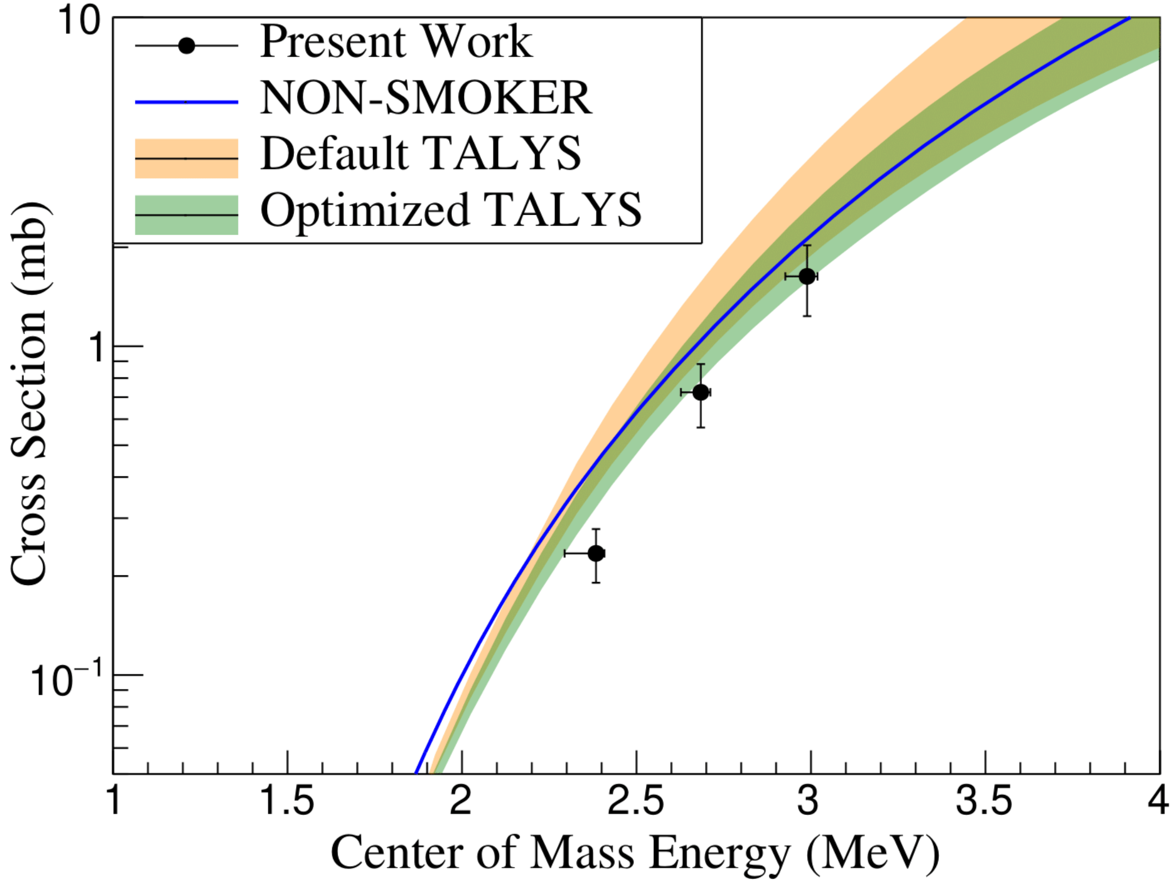


Lotay et al, PRL 127, 112701, (2021)

But we managed to constrain the product of the NLD and γSF, and therefore we should be able to accurately reproduce our extracted cross section with TALYS!

Results

- Standard statistical model calculations (default TALYS) tend to overproduce the cross section
- A better description of the experimental data can be obtained with the suggested combinations of NLD and γSF (Optimized TALYS)
- The cross section at lower energies is dependent on the choice of OMP and width fluctuation correction



Acknowledgments

A. Palmisano,[1, 2, 3] A. Spyrou,[1, 2, 3] P. Mohr,[4] H. C. Berg,[1, 2, 3] P. A. DeYoung,[5] A. C. Dombos,[1, 2, 3] P. Gastis,[6, 3] O. Gomez,[7] E. C. Good,[2, 3] C. Harris, [1,2,3] S. Liddick,[8, 2, 3] S. M. Lyons,[1, 2, 3] G.Owens-Fryar,[1, 2, 3] J. Pereira,[1, 2, 3] A. L. Richard,[1, 2, 3] A. Simon,[7, 3] M. K. Smith,[1, 2] and R. Zegers[1, 2, 3]

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[3] Joint Institute for Nuclear Astrophysics - Center for the Evolution of the Elements,
[4] Institute for Nuclear Research (Atomki), H-4001 Debrecen, Hungary,
[5] Physics Department, Hope College,
[6] Department of Physics, Central Michigan University,
[7] Department of Physics, University of Notre Dame,
[8] Department of Chemistry, Michigan State University

Summary and Conclusion

- Systematic study of (p,γ) reactions allows for constrains on theoretical models used in astrophysical applications
- The ^{82}Kr(p,γ)^{83}Rb reaction cross section was measured for the first time in inverse kinematics
- A better description of the experimental data can be obtained with the suggested combinations of NLD and γSF
- The cross section at lower energies is dependent on the choice of OMP and width fluctuation correction
- A. Tsantiri, A. Palmisano-Kyle, A. Spyrou, P. Mohr, et al. [accepted, in press] *Cross Section Measurement of the ^{82}Kr(p,γ)^{83}Rb Reaction in Inverse Kinematics*, Phys. Rev. C**.**
- Next step: ^{73}As(p,γ)^{74}Se FRIB experiment e22505 scheduled for the summer [PI: A. Palmisano-Kyle]

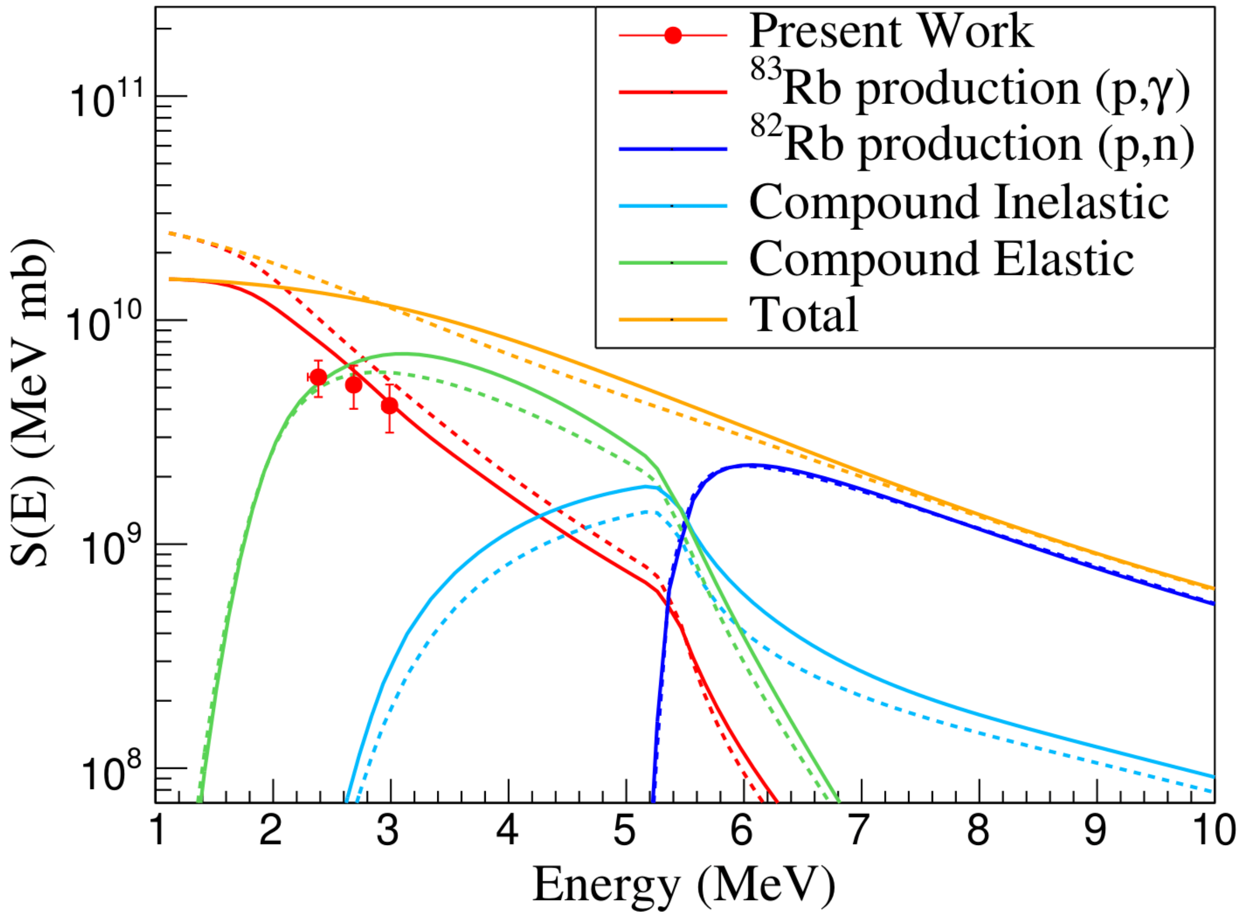
Thank you for your attention!

Backup: Theoretical Investigation

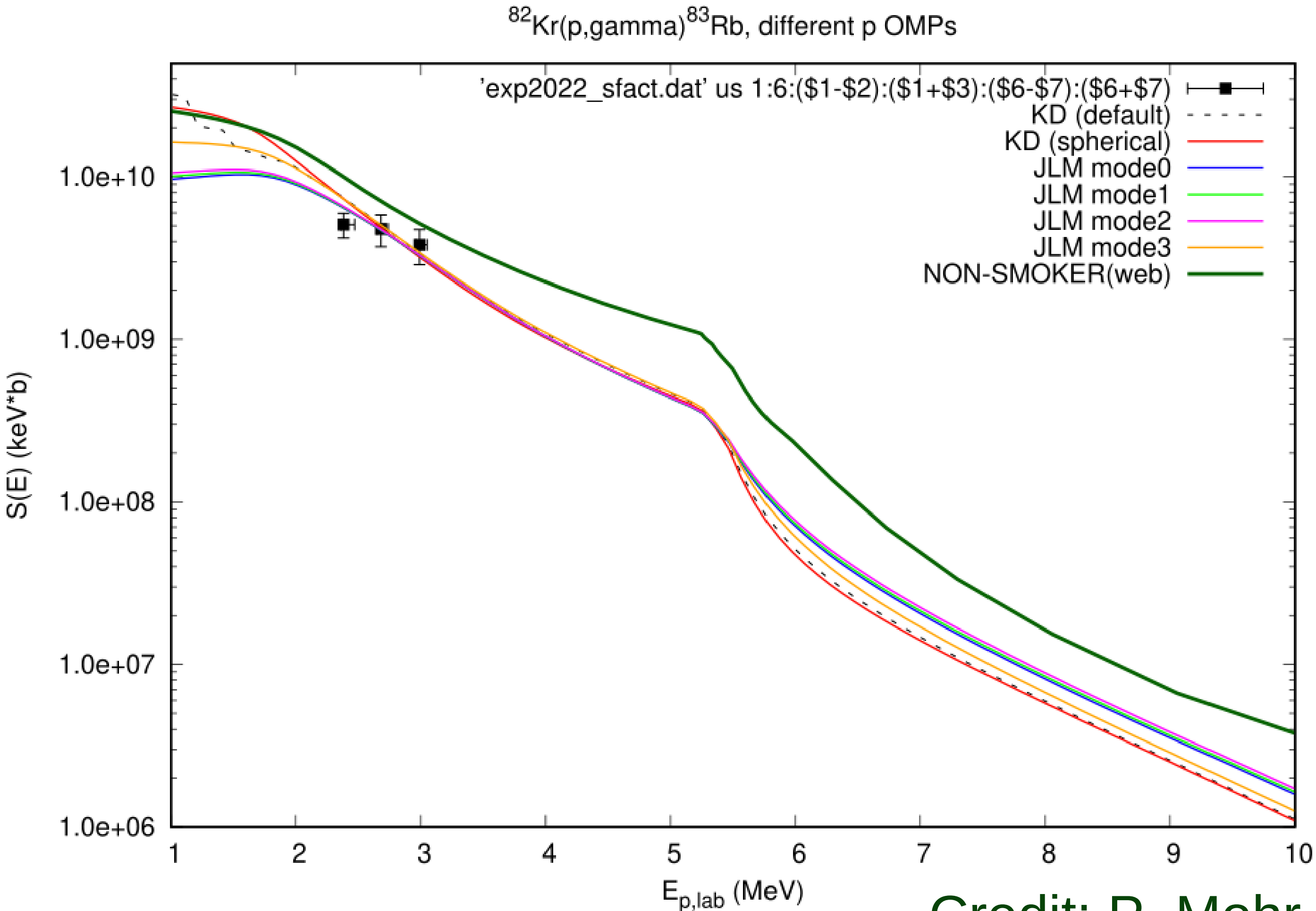
S-factor decomposition plot with our choice of NLD and γSF:

- Dotted lines: default OMP, no w_{12}
- Solid lines: Jeukenne – Lejeune – Mahaux (JLM) OMP, with w_{12}

$$\sigma_{12}(\mathrm{E}) \propto \sum_{\mathrm{J},\pi} \mathrm{w}_{12} \frac{\mathrm{T}_{1,\mathrm{J},\pi} \cdot \mathrm{T}_{2,J,\pi}}{\mathrm{T}_{J,\pi}}$$



Backup: What about OMP?



Credit: P. Mohr

Backup: A little bit of Hauser-Feshbach

$$\langle \sigma_{12}(E) \rangle = \frac{\lambda^2}{2\pi} \sum_{J,\pi} W_{12} \omega_J \frac{T_{1,J,\pi} T_{2,J,\pi}}{T_{J,\pi}}$$

- λ : de Broglie wavelength
- ω : function of angular momenta J_1, J_2 and J_r
- T : transmission coefficients (function of energy width Γ and level density ρ)
- W_{12} : width fluctuation correction (set to 1 through independence hypothesis)

$$T_\gamma(E,J,\pi) = \underbrace{\sum_0^{\nu_r} T_\gamma^\nu(E,J,\pi,E_r^\nu,J_r^\nu,\pi_r^\nu)}_{\text{Experimentally known discrete levels}} + \underbrace{\int_{E_r^{\nu_r}}^{E} \sum_{J_r,\pi_r} T_\gamma^\nu(E,J,\pi,E_r^\nu,J_r^\nu,\pi_r^\nu) \cdot \rho(E_r,J_r,\pi_r)\, dE_r}_{\text{Continuum of states}}$$

$$T_\gamma(E_\gamma, J, \Pi) = 2\pi \underbrace{f(E_\gamma)}_{\gamma\mathrm{SF}} E_\gamma^{2\lambda+1}$$

Backup: NLD models

Constant Temperature Model

(Gilbert, Cameron and Ericson)

Parameters: T, E_0

$$\rho_{\mathrm{CT}}(E_x) = \frac{1}{T} \exp\left(\frac{E_x - E_0}{T}\right)$$

Bach Shifted Fermi Gas Model

(Bethe)

Parameters: α, E_1

$$\rho_{\mathrm{BSFG}}(E_x) = \frac{1}{12\sqrt{2}\sigma\alpha^{1/4}} \frac{\exp\left[2\sqrt{\alpha(E_x - E_1)}\right]}{(E_x - E_1)^{5/4}}$$

Backup: NLD and γSF parameters chosen

LD Model	LD Model Details		Upbend in γSF	
CT default	T = 0.824	E_0 = -1.16 [1]	No	
BSFG default	α = 10.17	E_1 = -0.54 [1]	No	
CT	T = 0.824	E_0 = -2.2	No	
CT	T = 0.861	E_0 = -3.34 [2]	No	
BSFG	α = 10.17	E_1 = -1.6	No	
BSFG	α = 10.17	E_1 = -0.54	a = 1.5	c = 8.7E-8 [3]
BSFG	α = 10.17	E_1 = -0.54	a = 1.0	c = 1.0E-7

γSF chosen: Generalized Lorentzian of the form of Kopecky-Uhl [4]
Upbend added of the form: $f_{upbend} = c \cdot \exp(-a \cdot E_\gamma)$

[1] T. von Egidy and D. Bucurescu, Phys. Rev. C 80, 054310 (2009)
[2] R. Hoffman, F. Dietrich, R. Bauer, K. Kelley, and M. Mustafa 10.2172/15014588 (2004)
[3] M. Guttormsen, R. Chankova, U. Agvaanluvsan, and et. al., Phys. Rev. C 71, 044307 (2005).
[4] J. Kopecky and M. Uhl, Phys. Rev. C 41, 1941 (1990)