Constraining the astrophysical γ process: Cross section measurements of (p,γ) reactions in inverse kinematics

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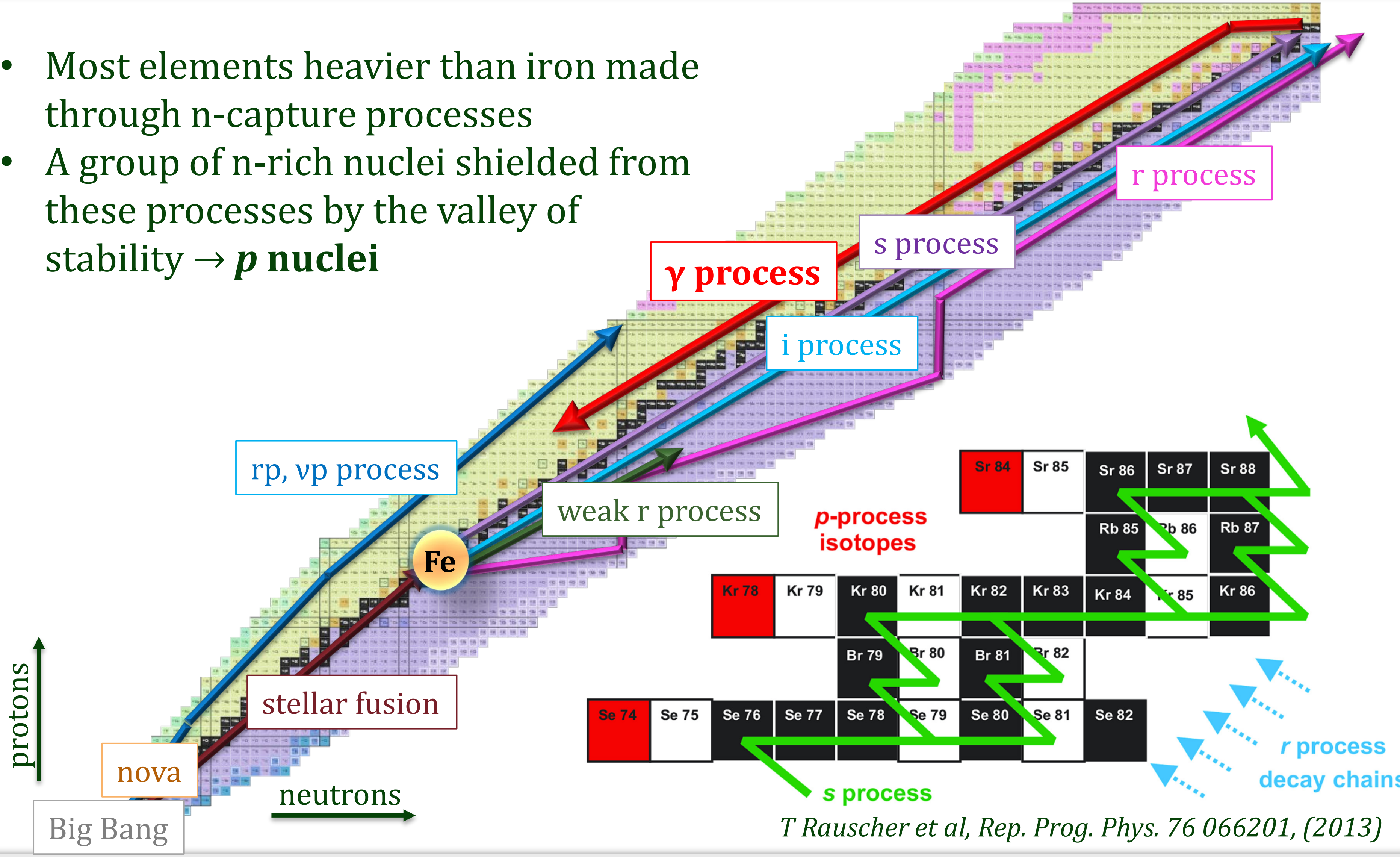
Introduction

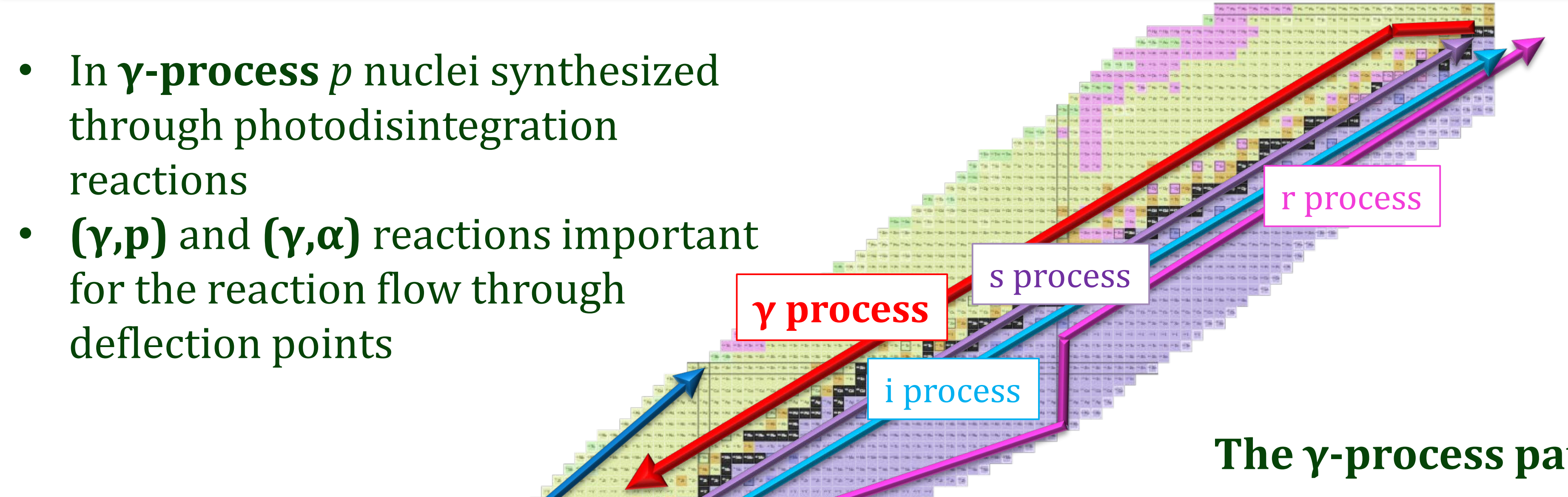
- Most elements heavier than iron made through n-capture processes
- A group of n-rich nuclei shielded from these processes by the valley of stability → ***p* nuclei**



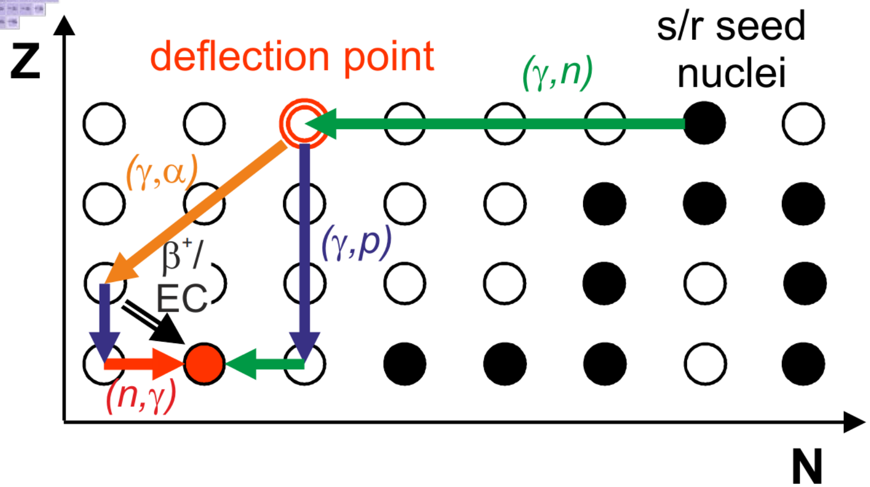
T Rauscher et al, Rep. Prog. Phys. 76 066201, (2013)

Introduction

- In **γ-process** *p* nuclei synthesized through photodisintegration reactions
- **(γ,p)** and **(γ,α)** reactions important for the reaction flow through deflection points



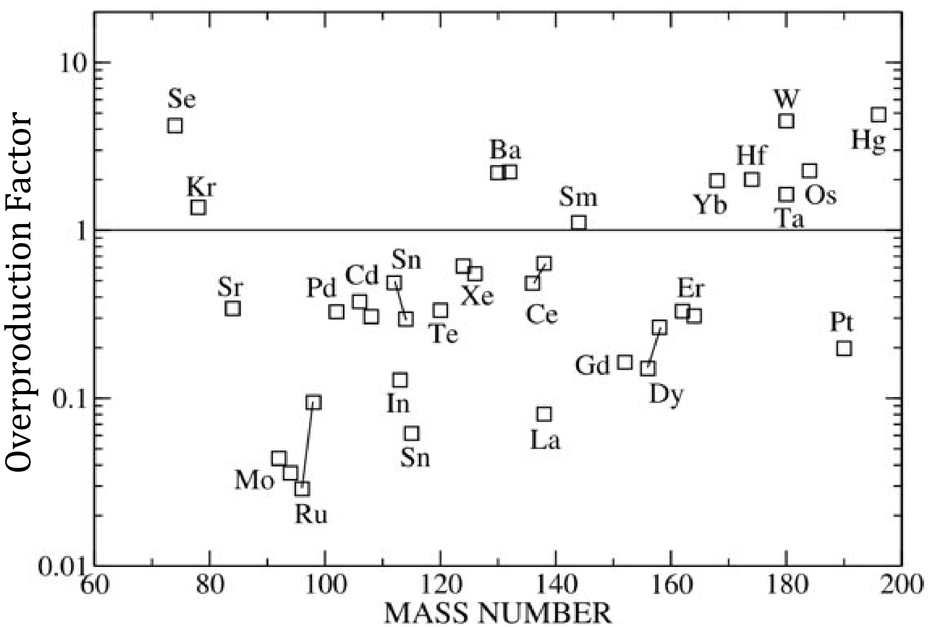
The γ-process path



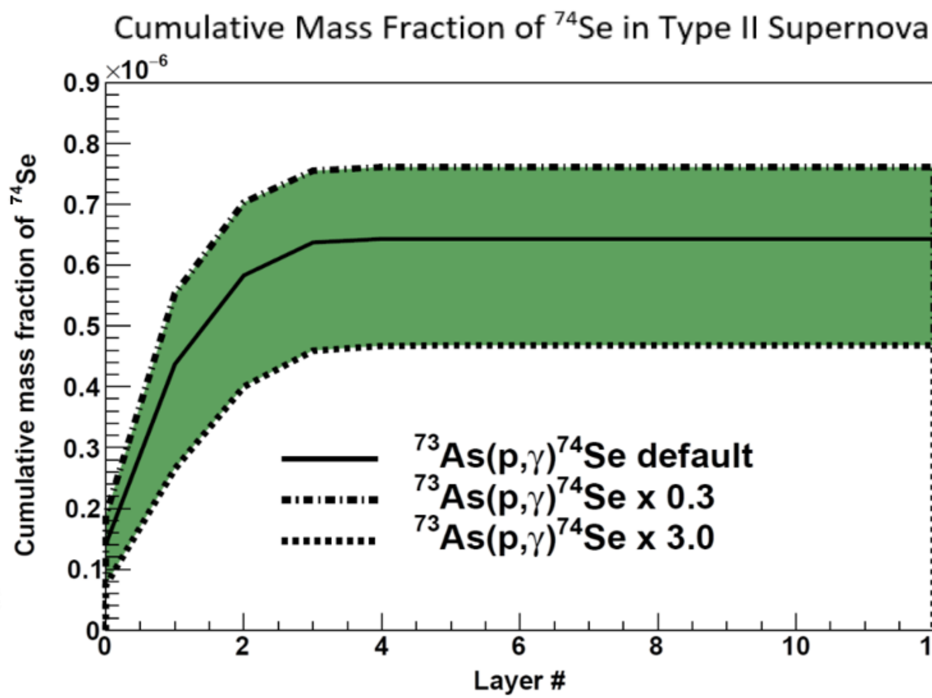
T Rauscher et al, Rep. Prog. Phys. 76 066201, (2013)

Introduction

- Network calculations of γ process do not accurately reproduce solar abundances
- Nuclear input carries large uncertainties, especially for radioactive isotopes
- ^{74}**Se(γ,p)**^{73}**As** reaction rate important for final abundance of p-nucleus ^{74}Se

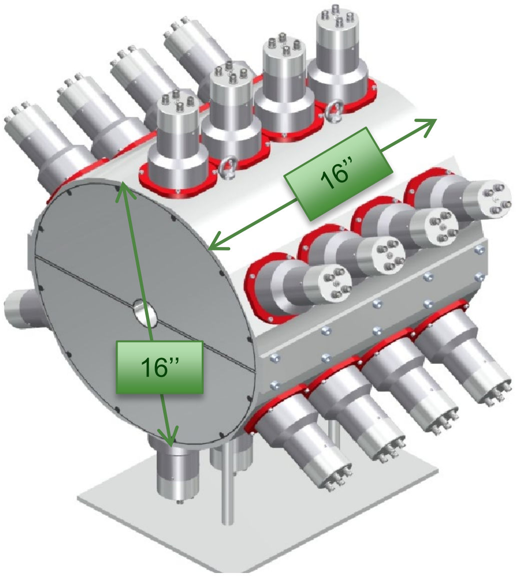


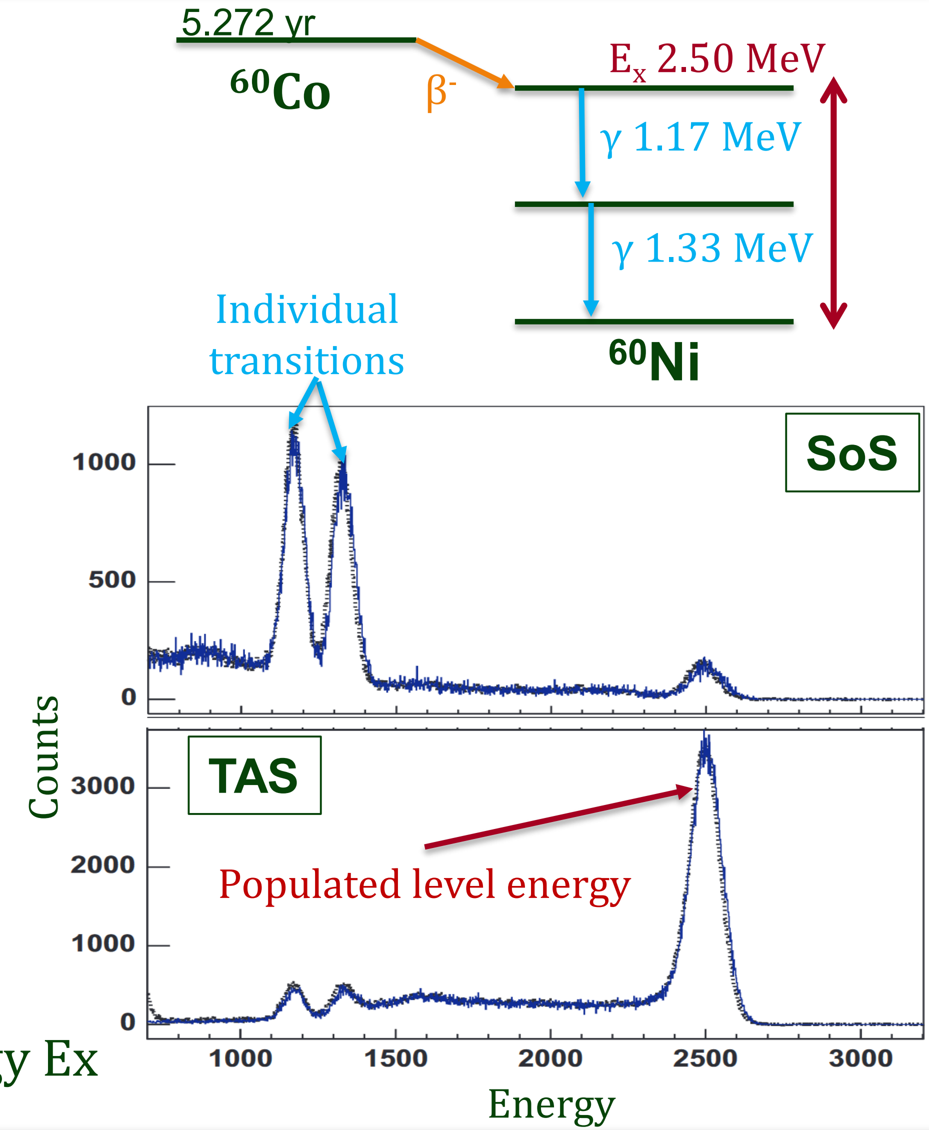
W. Rapp, J. Görres, M. Wiescher, H. Schatz, and F. Käppeler. Astrophys J, 653:474, 2006.



A. Simon using NucNet Tools

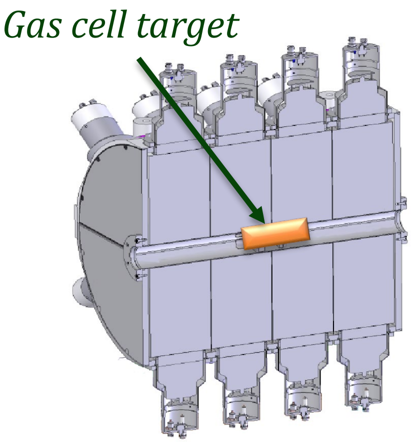
γ-summing technique with SuN





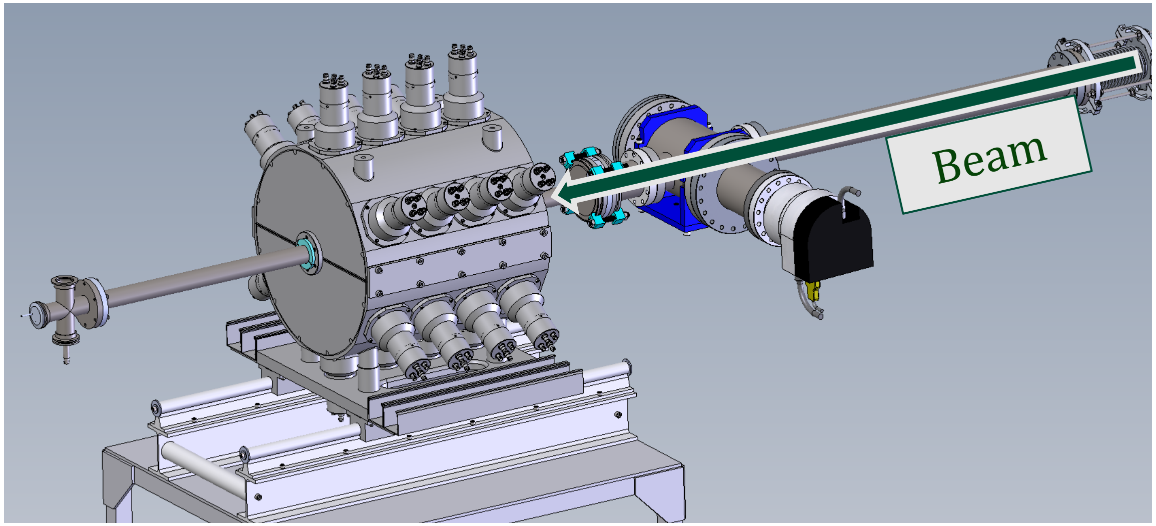
- **Summing NaI(Tl) SuN**: Large size, high efficiency γ-ray detector
- 8 optically isolated segments
- 24 PMTs
- **Sum of Segments (SoS)** → Information about individual γ-rays
- **Total Absorption Spectrum (TAS)** → Information about total excitation energy Ex

Experiments at ReA NSCL/FRIB

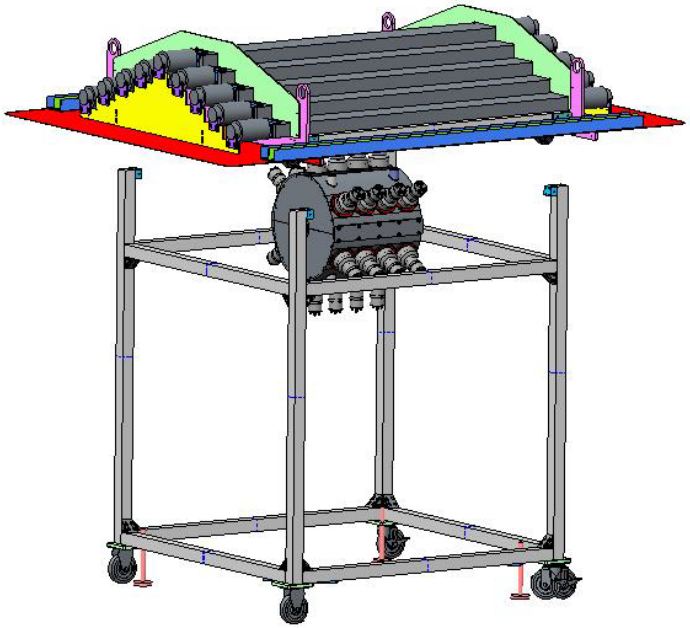


SuN detector (side section)

- Cross section measurements in inverse kinematics
  - Proof-of-principle stable beam 2017: ^{82}**Kr(p,γ)**^{83}**Rb**
  - Radioactive beam 2023: ^{73}**As(p,γ)**^{74}**Se**
- Hydrogen gas cell target
- SuN + SuNSCREEN detectors



Experimental Setup (without SuNSCREEN)



SuNSCREEN and SuN

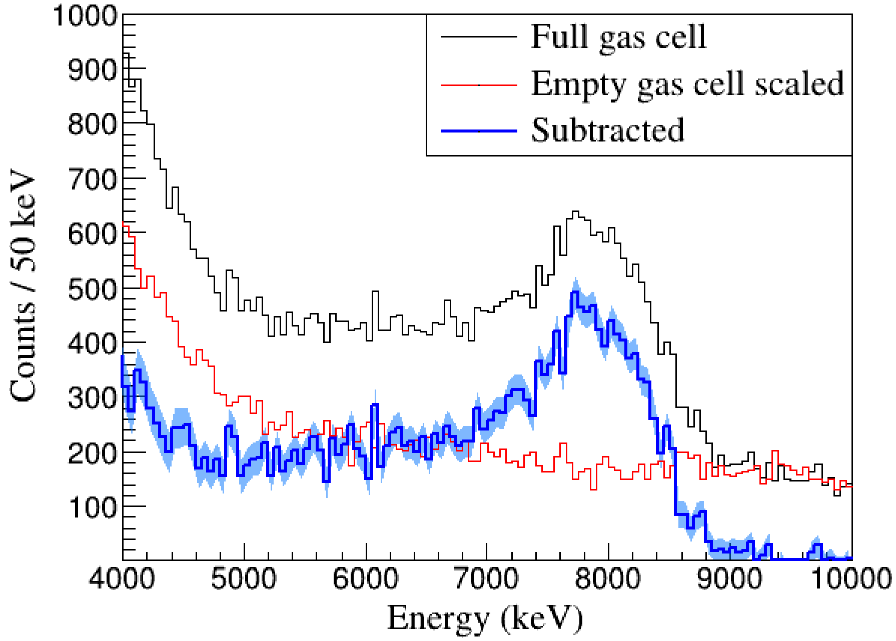
E. Klopfer *et al*, *Nucl. Instrum. Meth. Phys. Res.* A 788, 5 (2015)

Background Subtractions

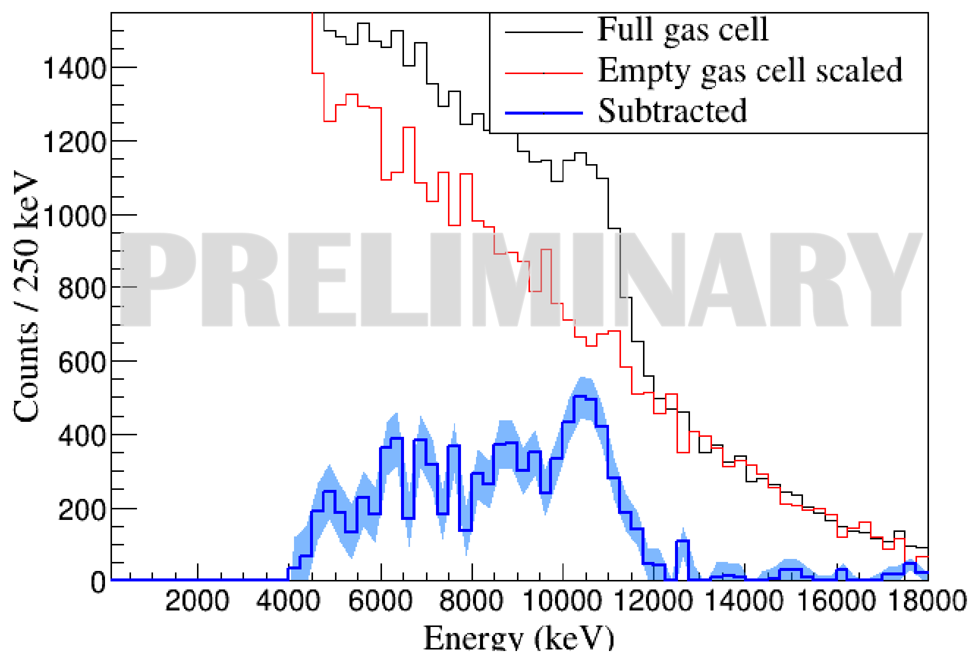
Background contributions:

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

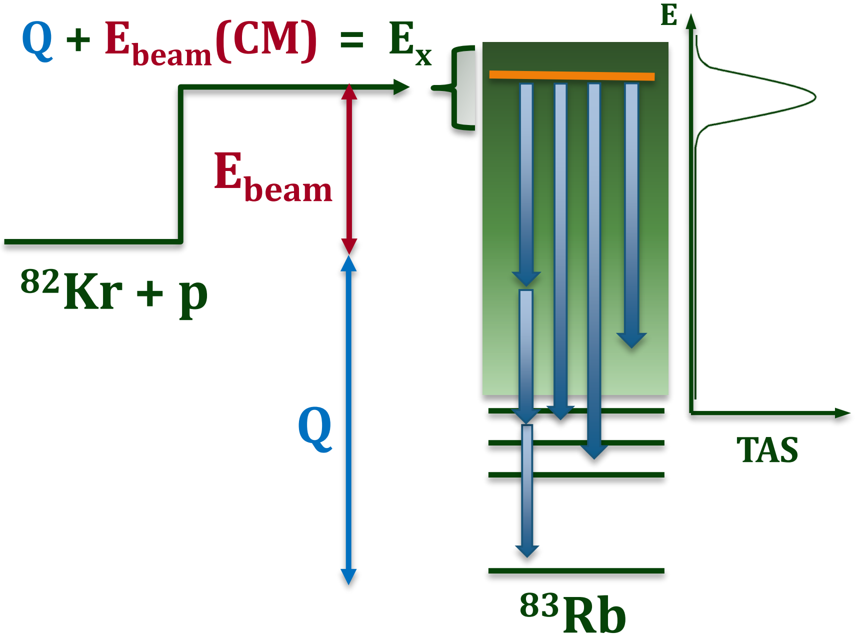
$^{82}Kr(p,\gamma)^{83}Rb$



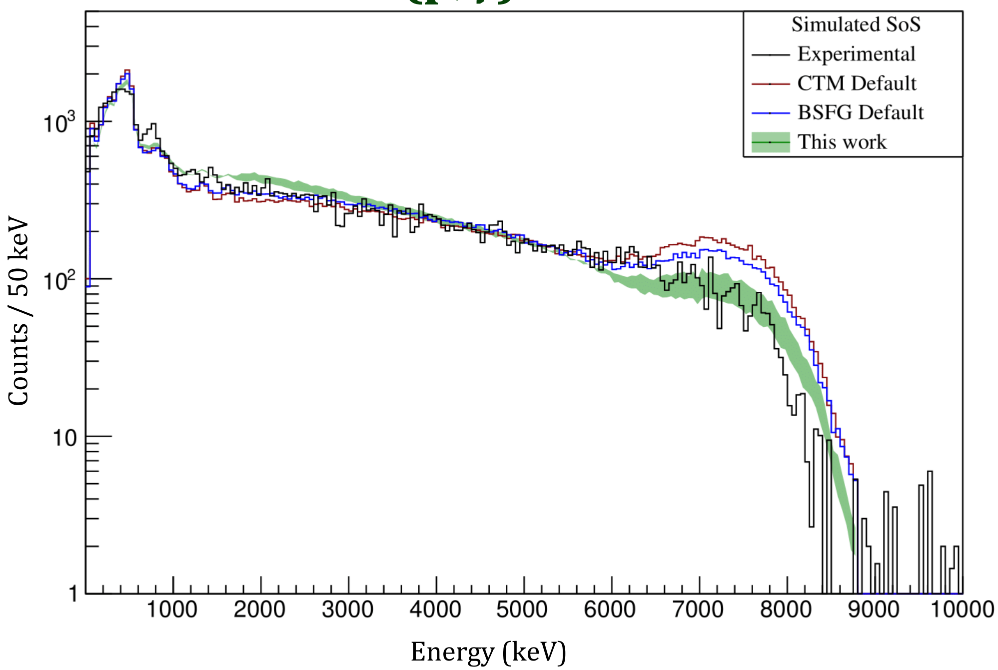
$^{73}As(p,\gamma)^{74}Se$



Analysis Overview



^{82}Kr(p,γ) SOS Fits

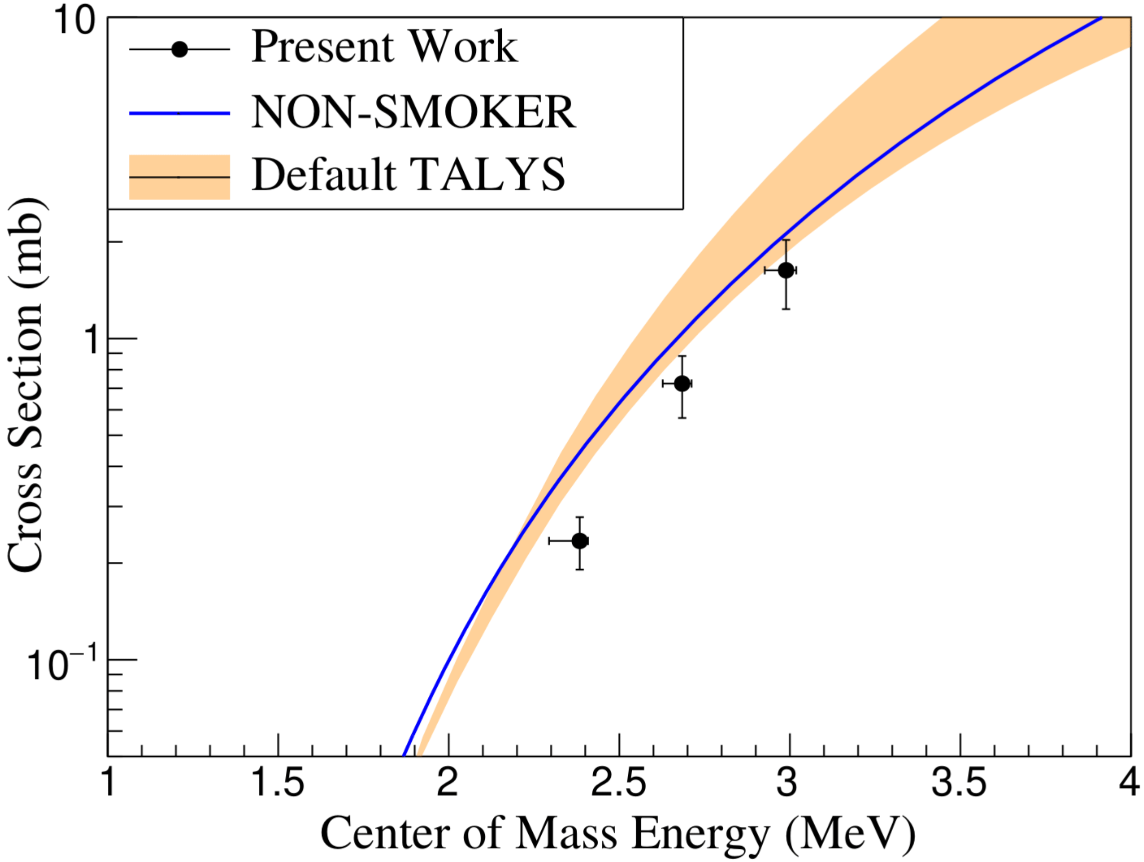


$$\sigma = \frac{Yield}{\Phi \cdot N_t \cdot \varepsilon_{eff}(E)}$$

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

$^{82}Kr(p,\gamma)^{83}Rb$ 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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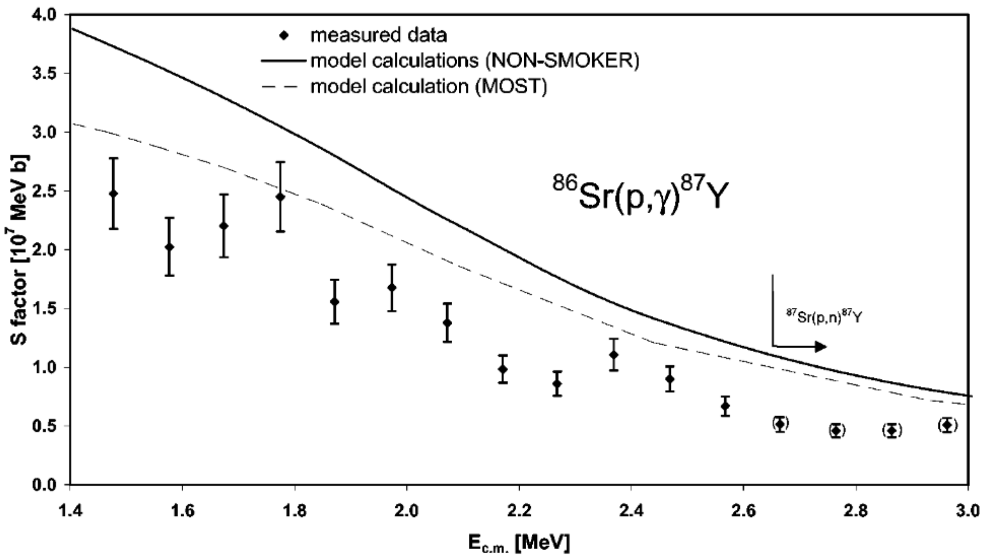
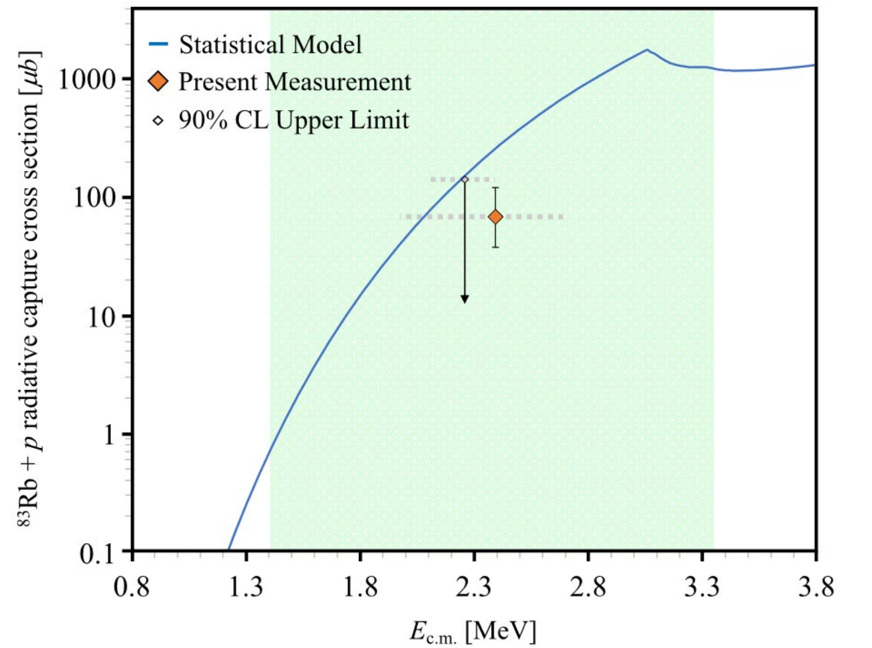


Gyürky et al, PRC 64, 065803 (2001)

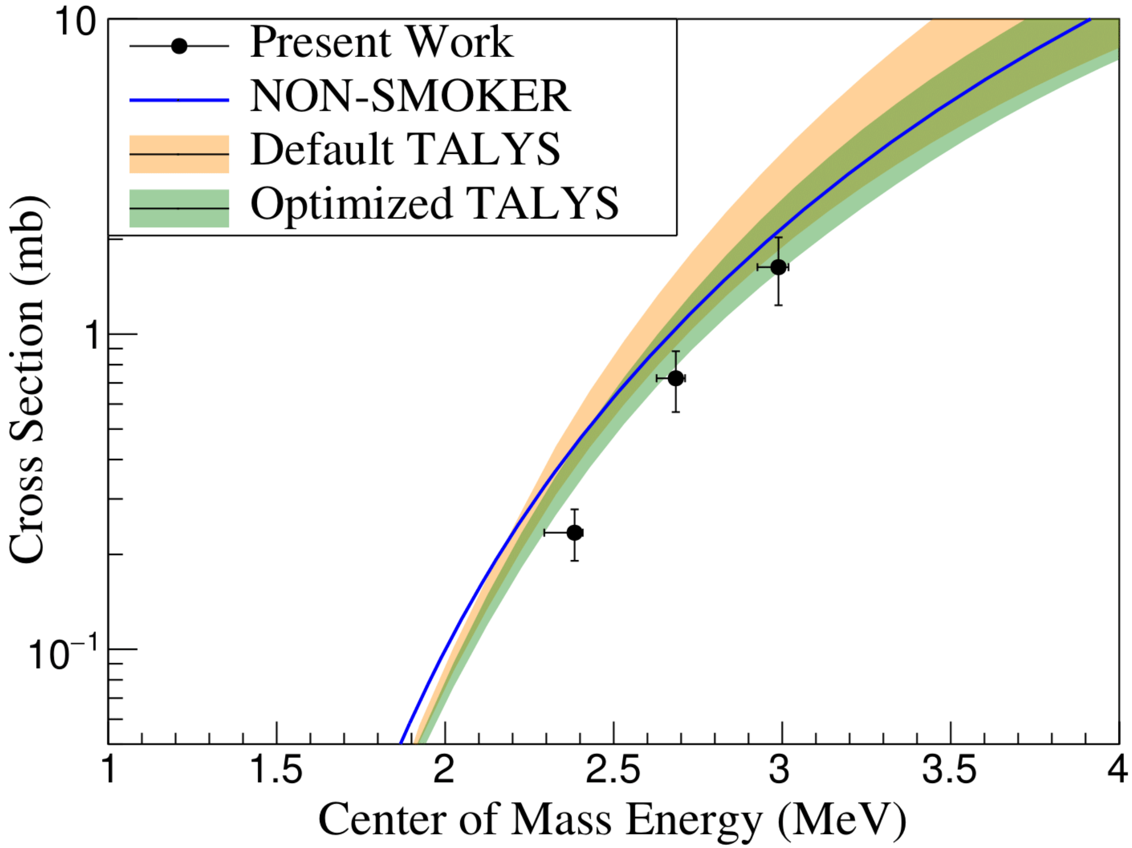


Lotay et al, PRL 127, 112701, (2021)

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!

$^{82}Kr(p,\gamma)^{83}Rb$ Results

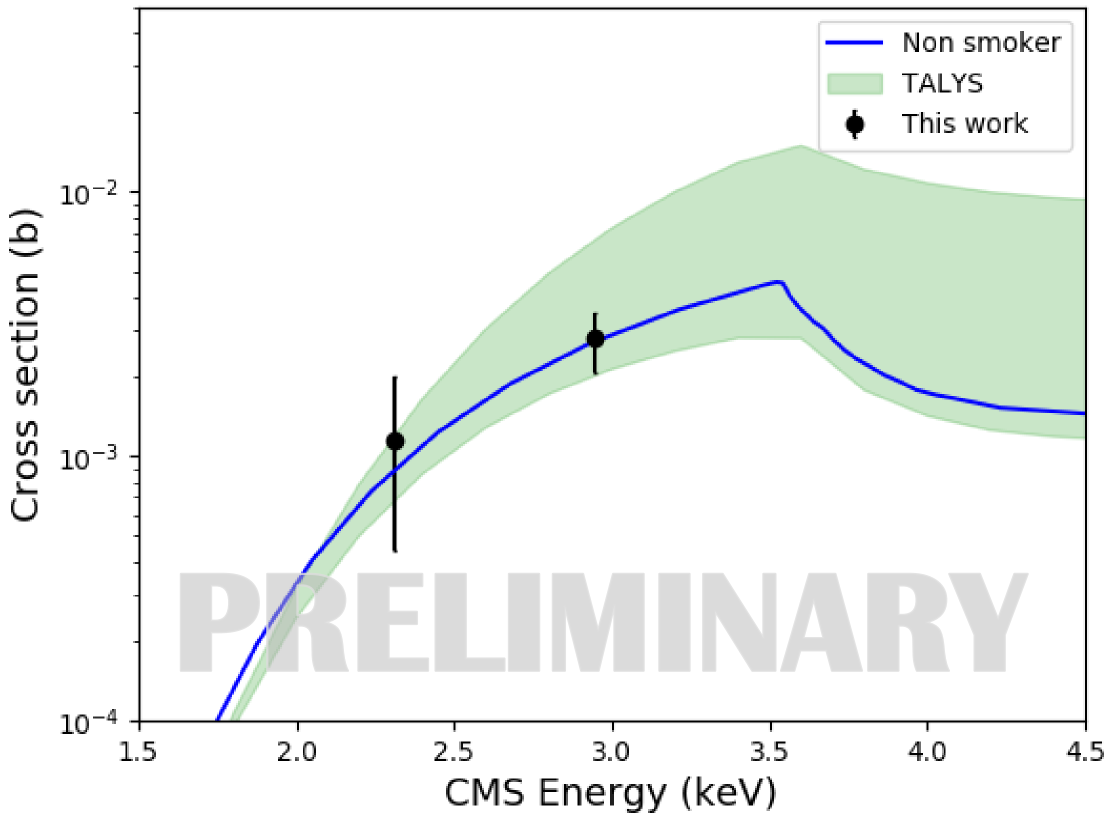
A better description of the experimental data can be obtained with the suggested combinations of NLD and γSF → constrain cross section on broader energy range

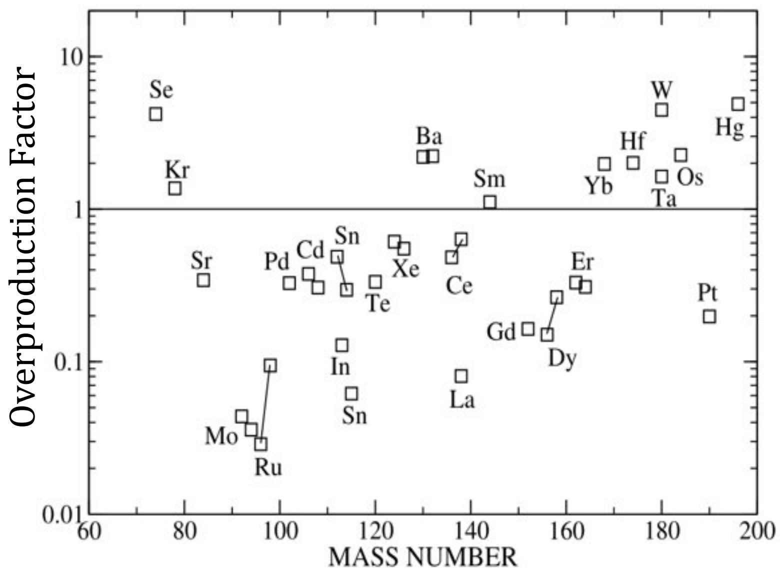


Tsantiri et al, Phys. Rev. C. 107, 035808 (2023)

$^{73}As(p,\gamma)^{74}Se$ Results

$^{73}As(p,\gamma)^{74}Se$ Cross Section

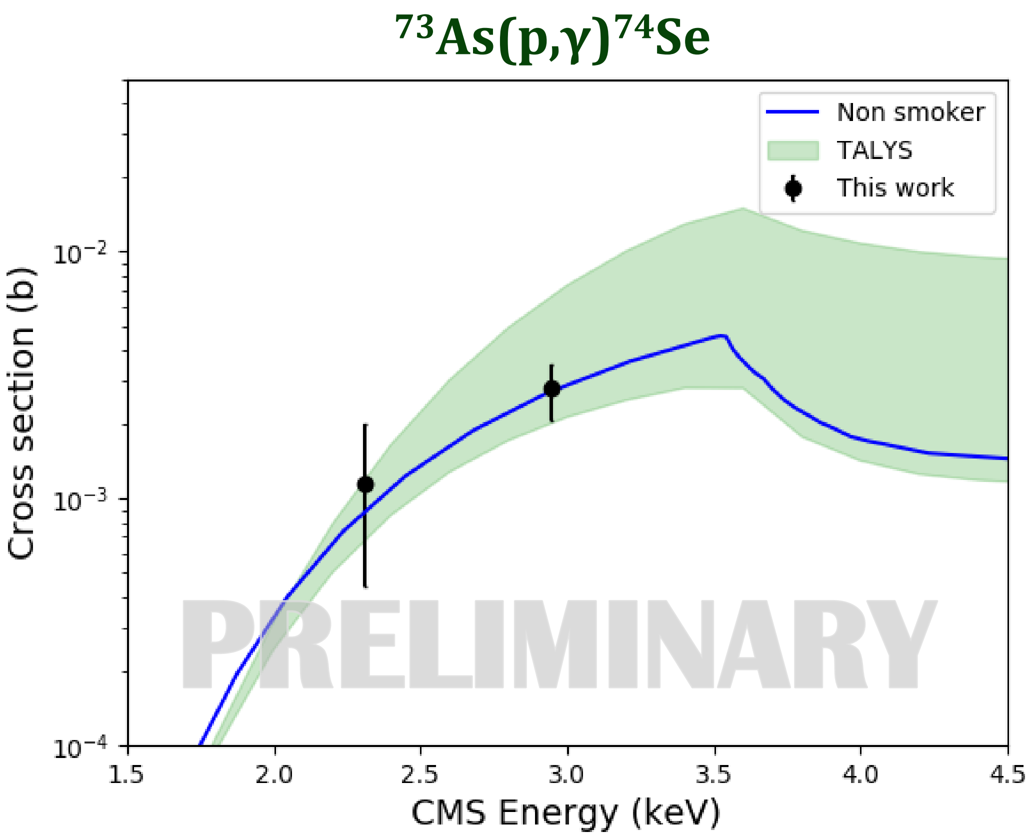




W. Rapp, J. Görres, M. Wiescher, H. Schatz, and F. Käppeler. Astrophys J, 653:474, 2006.

Summary & Outlook

- Systematic study of (p,γ) reactions allows for constrains on theoretical models used in astrophysical applications
- The ^{73}As(p,γ)^{74}Se and ^{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



Future Work:

- Finalize analysis of the ^{73}As(p,γ)^{74}Se data
- Provide broader cross section constraint from statistical properties
- Study the effect of the extracted ^{73}As(p,γ)^{74}Se cross section on the ^{74}Se final abundance for a SNII scenario

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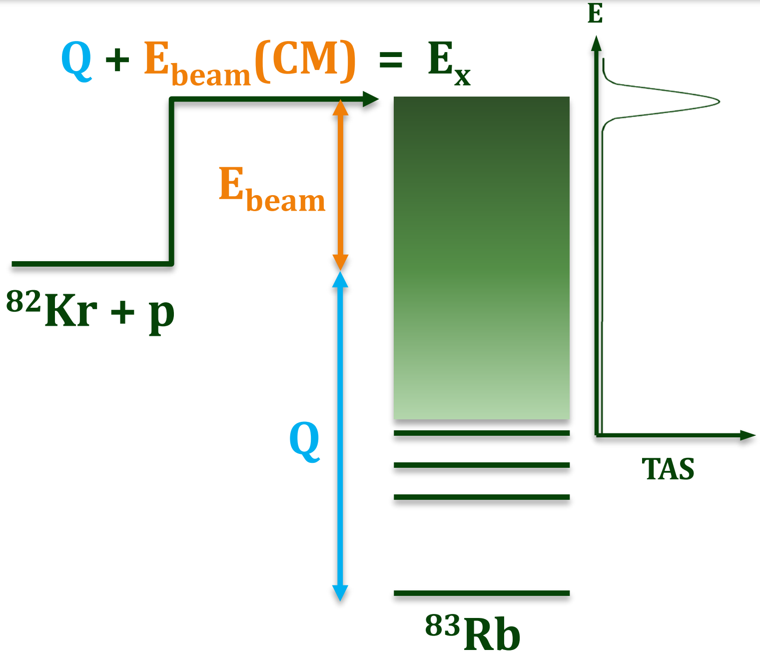
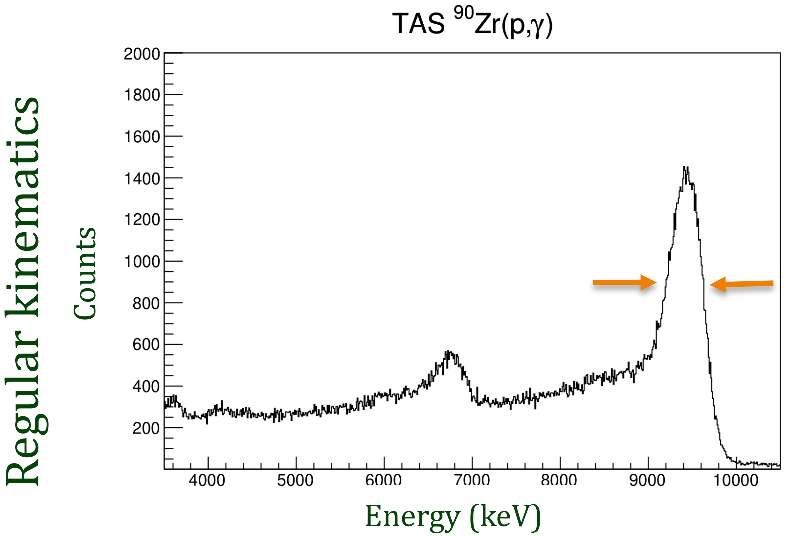
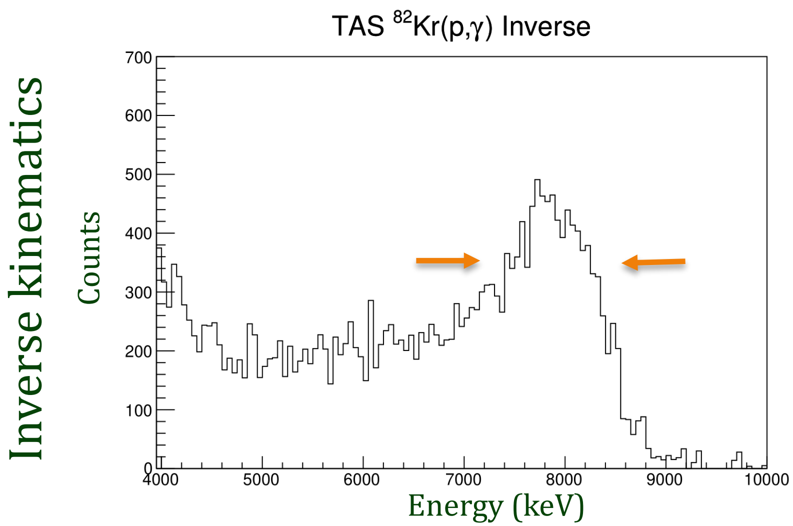
Backup slides

Backup: Broadening of TAS peak



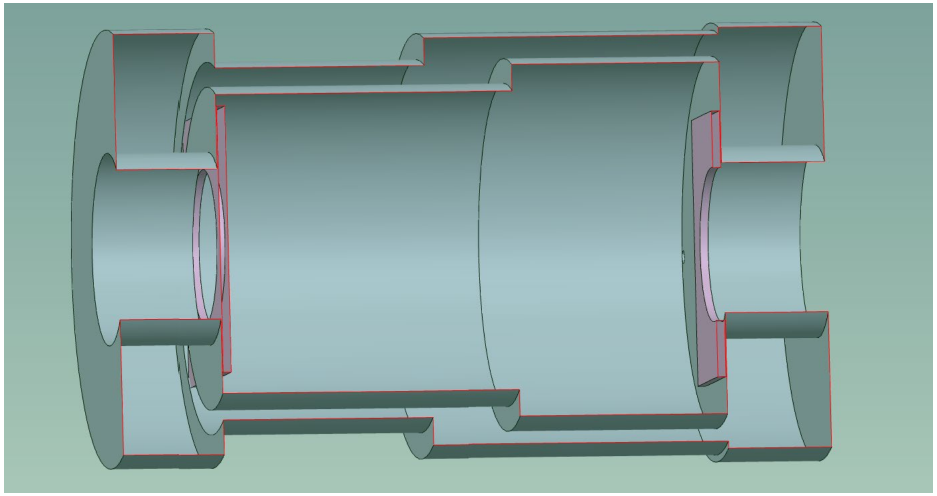


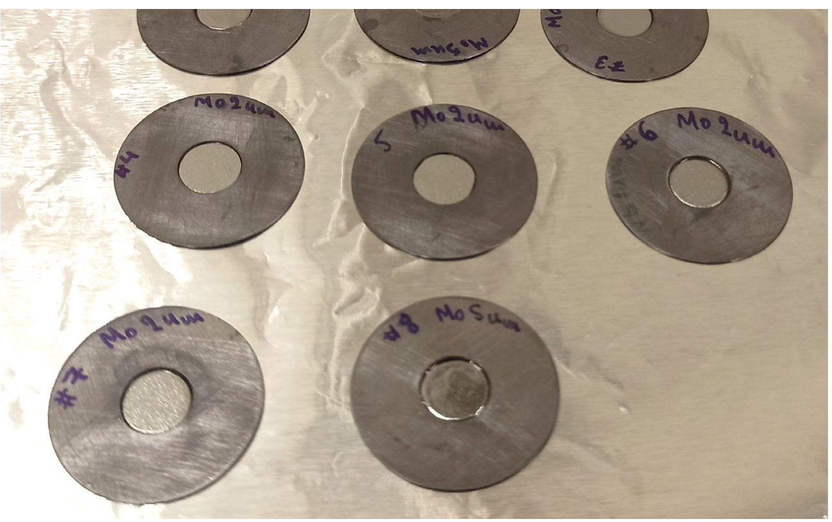
A. Spyrou et al. Phys. Rev. C 88, 045802 (2013)



- 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

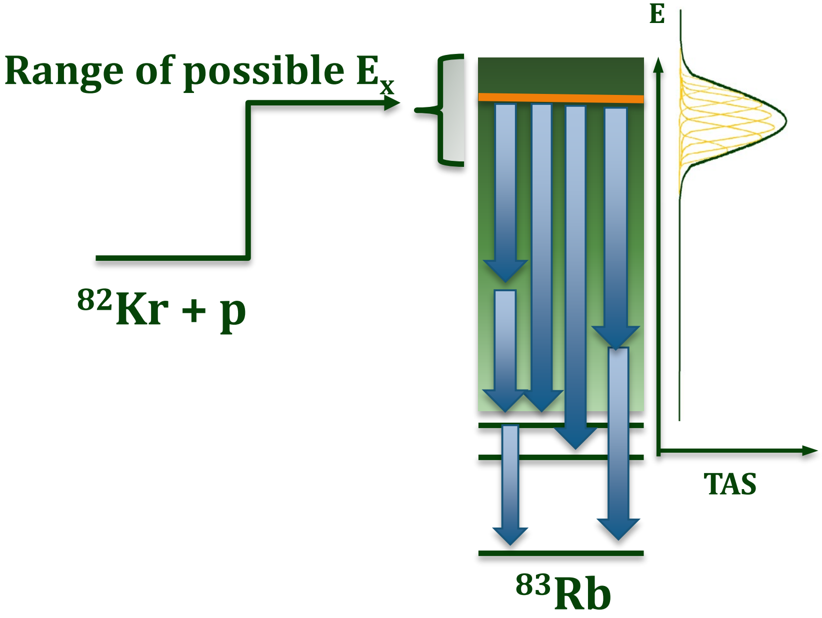
Backup: Gas Cell

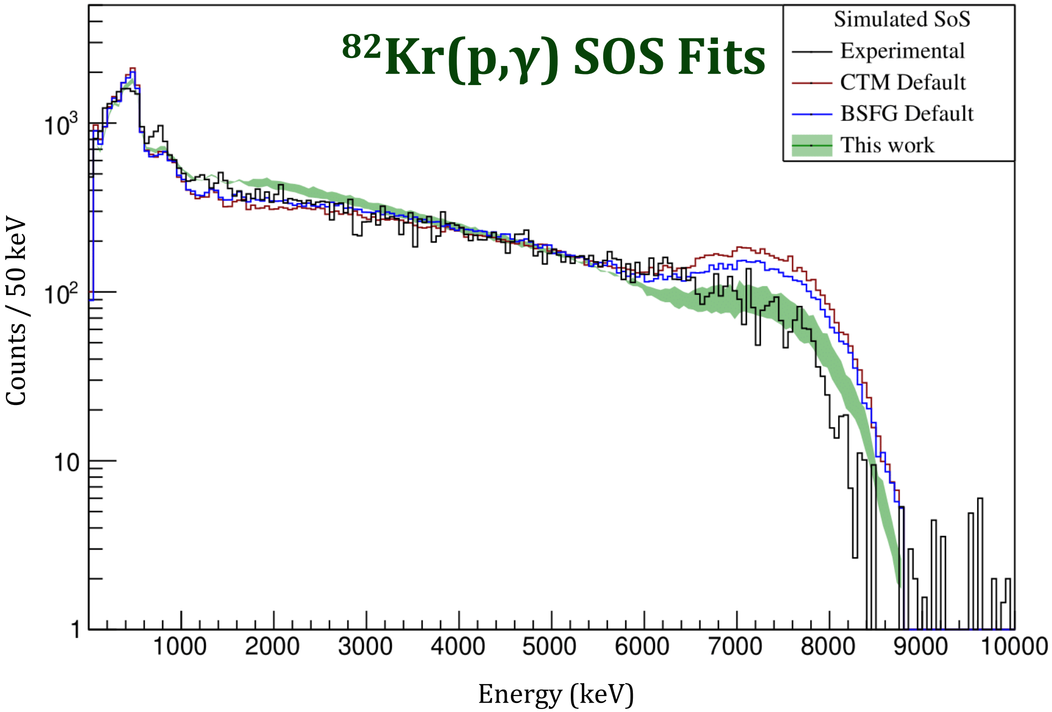




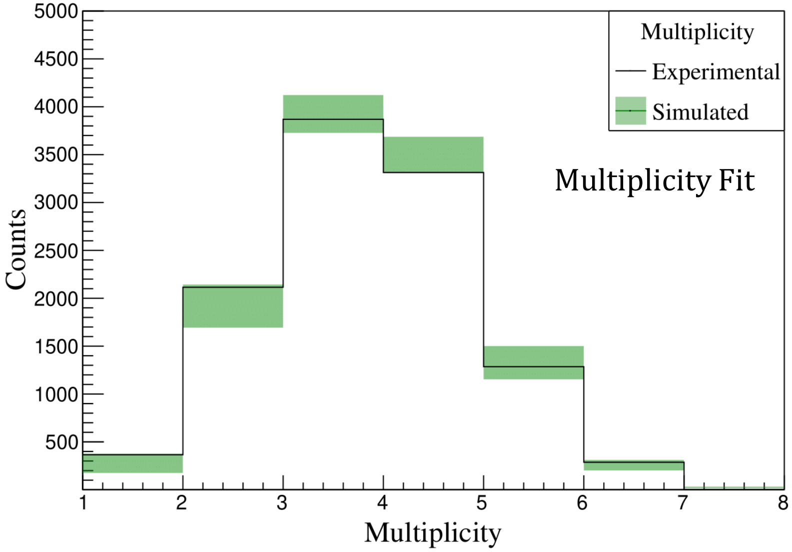
Backup: Efficiency and Yield determination

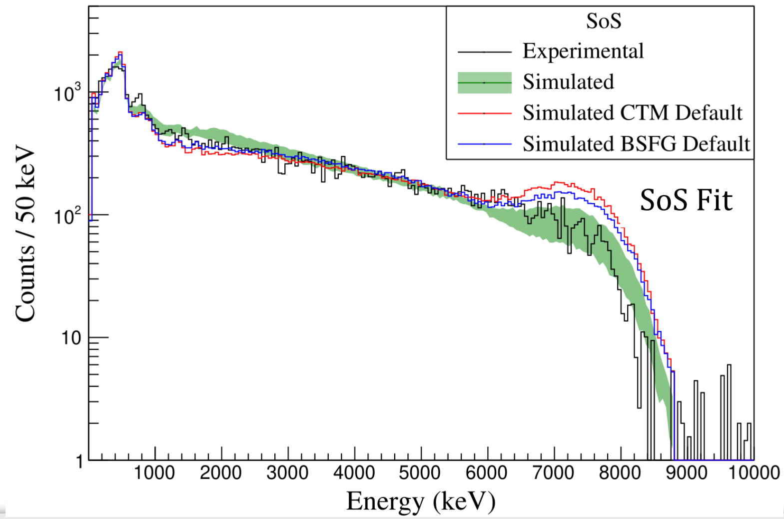
- Calculate efficiency as a function of all the E_x that contribute in our TAS peak
- Simulate all possible γ ray cascades emitted inside SuN with RAINIER
- GEANT4 for detector's resolution
- To describe our compound nucleus we use combinations of nuclear level densities $\rho(E_x - E_\gamma)$ and γ ray strength functions $\gamma SF(E_\gamma)$ that can replicate our SoS

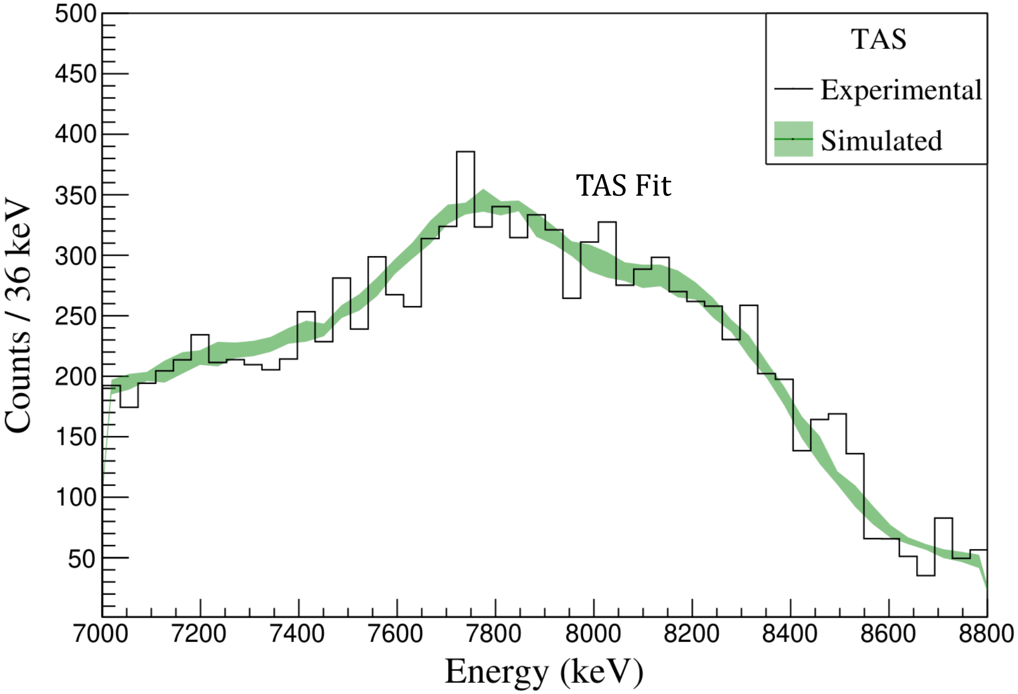




Backup: Efficiency and Yield Determination with RAINIER and GEANT4





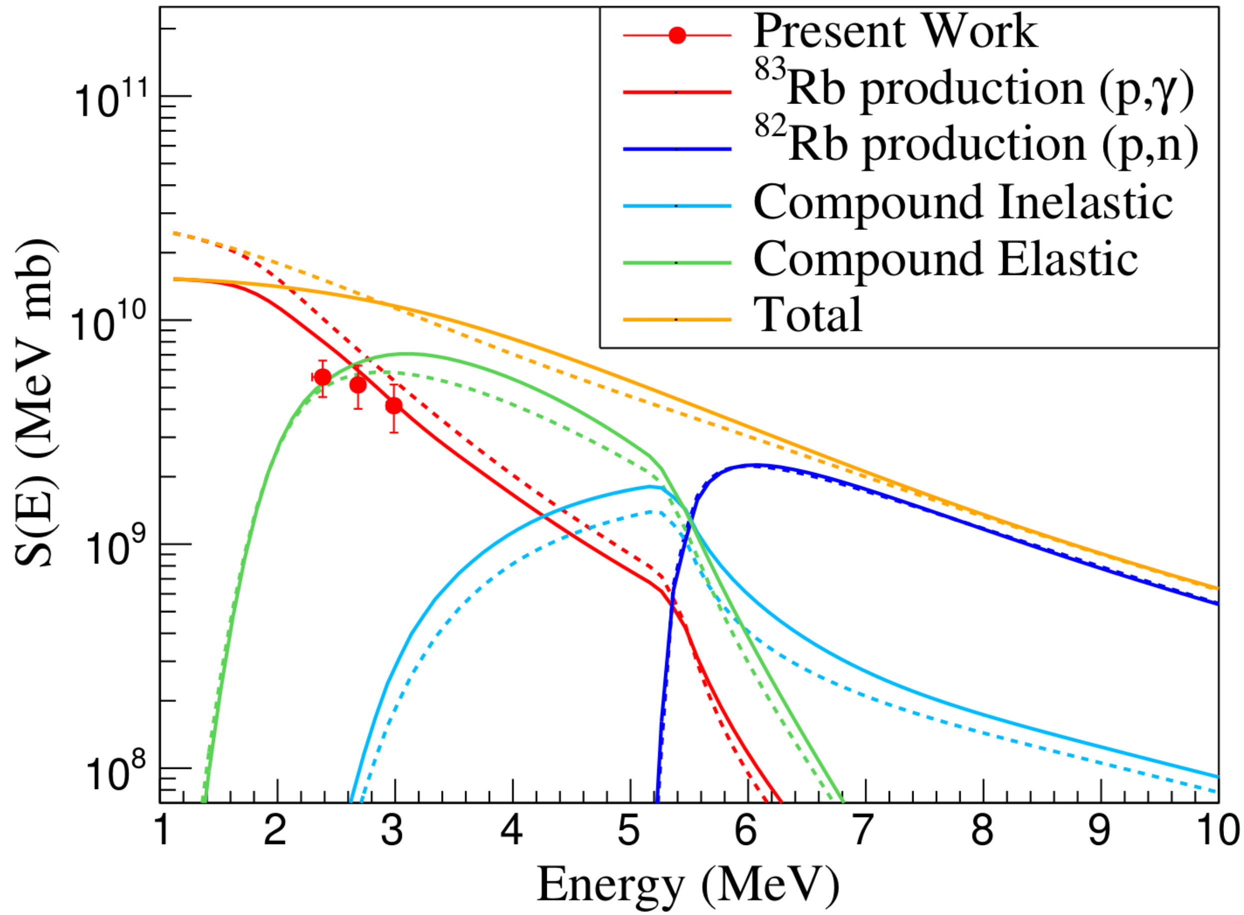


Backup: Theoretical Investigation

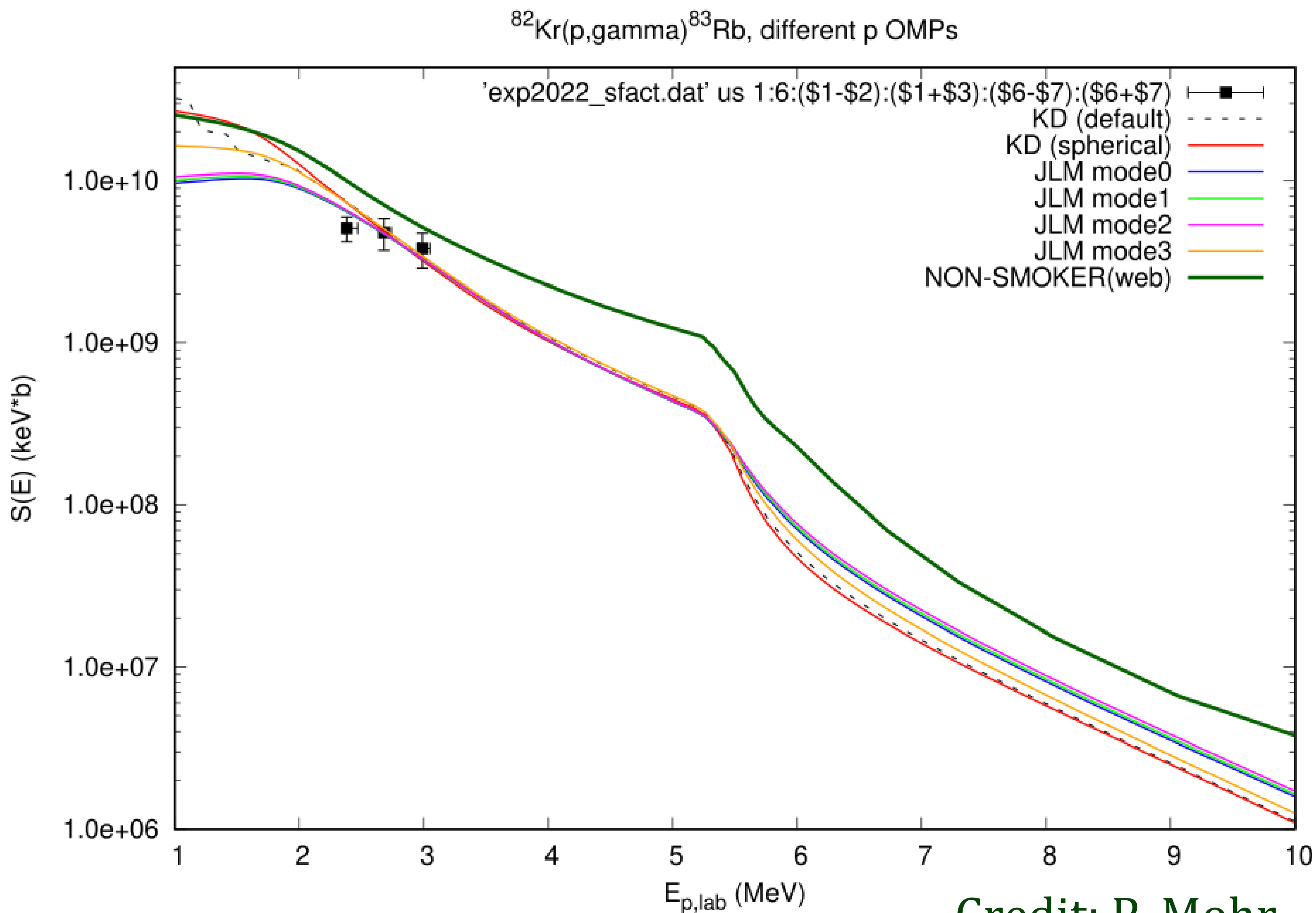
S-factor decomposition plot with our choice of NLD and γSF:

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

$$\sigma_{12}(E) \propto \sum_{J,\pi} w_{12} \frac{T_{1,J,\pi} \cdot T_{2,J,\pi}}{T_{J,\pi}}$$



Backup: What about OMP? Why JLM?



Credit: P. Mohr

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)