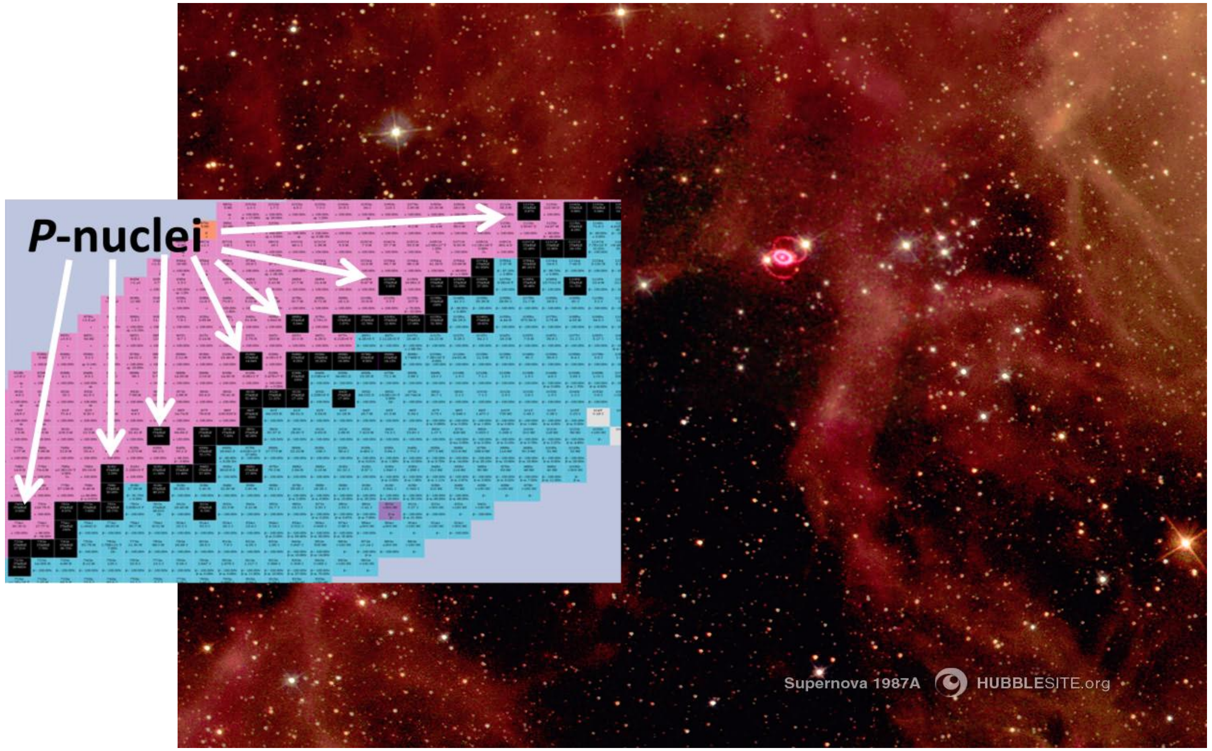
Constraining experimentally photon strength functions using real photons at the HIγS/TUNL facility

Adriana Banu

Department of Physics and Astronomy, James Madison University, Harrisonburg, Virginia, USA



JAMES MADISON UNIVERSITY

The 7th International Workshop on Compound-Nuclear Reactions and Related Topics

July 8-12, 2024, International Atomic Energy Agency, Vienna, Austria

Collaborators:

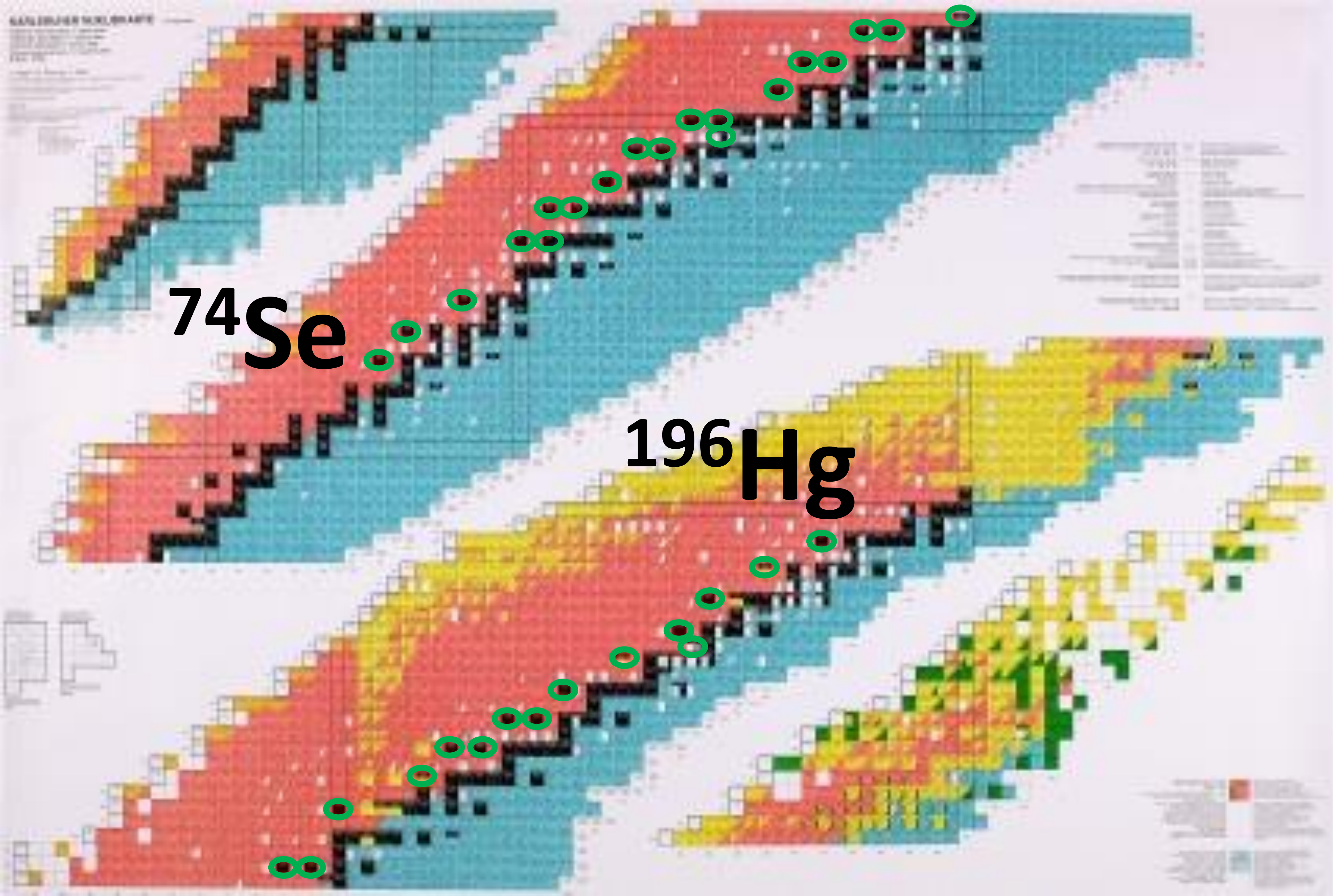
A. M. Balbuena, R. L. Geissler, A. S. Kirk, E. G. Meekins,
B. E. A. Witczak (undergraduate students)
James Madison University, Department of Physics and Astronomy

U. Friman-Gayer(*), S. W. Finch, R. V. F. Janssens, C. R. Howel,
H. J. Karwowski *et al.*
Triangle Universities Nuclear Laboratory (TUNL)
Duke University, University of North Carolina at Chapel Hill
(*) currently at Vysus Group Sweden AB, Malmö, Sweden

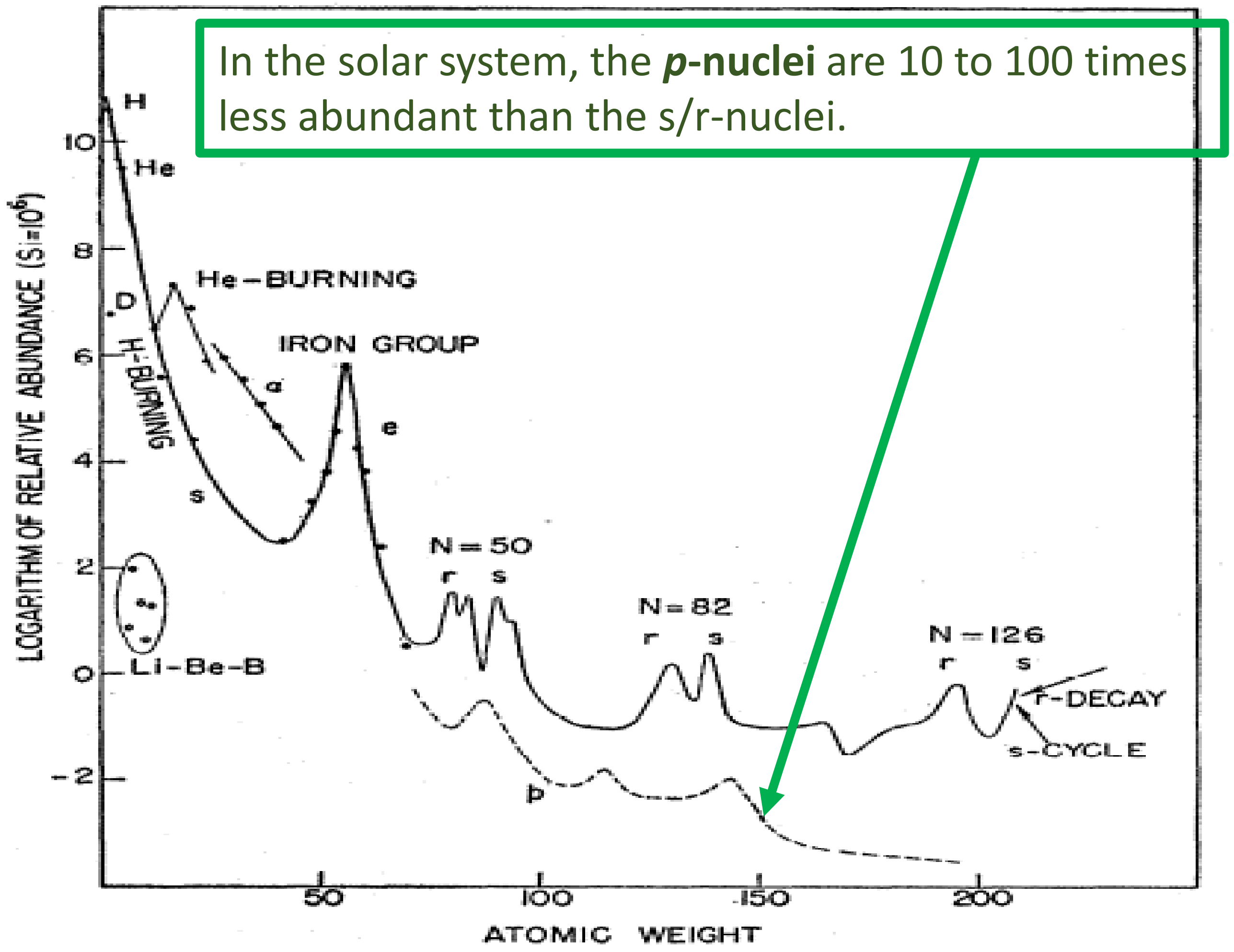
J.A. Silano
Nuclear and Chemical Sciences Division
Lawrence Livermore National Laboratory

S. Goriely
Institut d'Astronomie et d'Astrophysique (IAA)
Université Libre de Bruxelles

The *p-process* is responsible for the nucleosynthesis beyond iron of 35 stable neutron-deficient nuclei

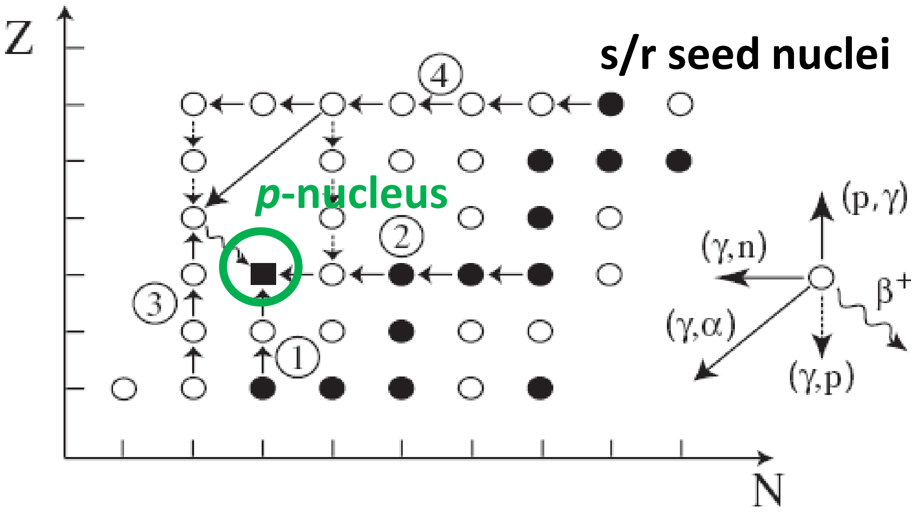


The *p*-Nuclei - 'nuclear astrophysics *p*-nuts'



In the solar system, the ***p*-nuclei** are 10 to 100 times less abundant than the s/r-nuclei.

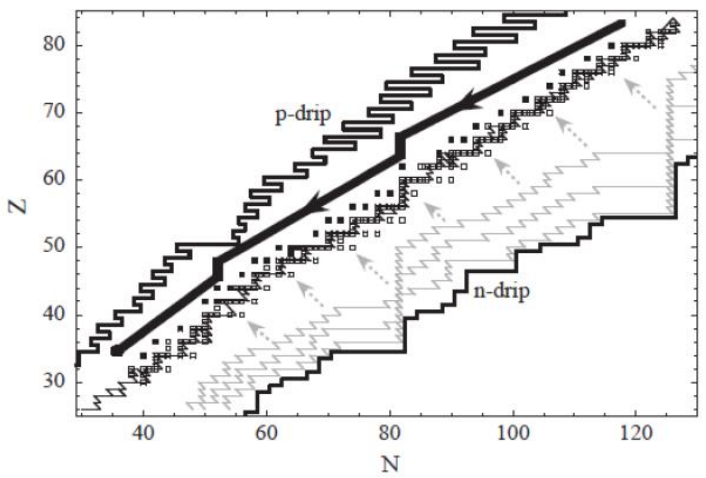
B²FH, Rev. Mod. Phys. 29, 547 (1957)



M. Arnould & S. Goriely, Phys. Rep. 384, 1 (2003)

***p*-Process Nucleosynthesis:**
an extended network of some 20000 reactions
linking about **2000 nuclei** in the A ≤ 210 mass range

- Photodisintegrations (γ,n), (γ,p), (γ,α)
- n-, p-, α-capture reactions
- β^+-decays



M. Arnould & S. Goriely, Phys. Rep. 384, 1 (2003)

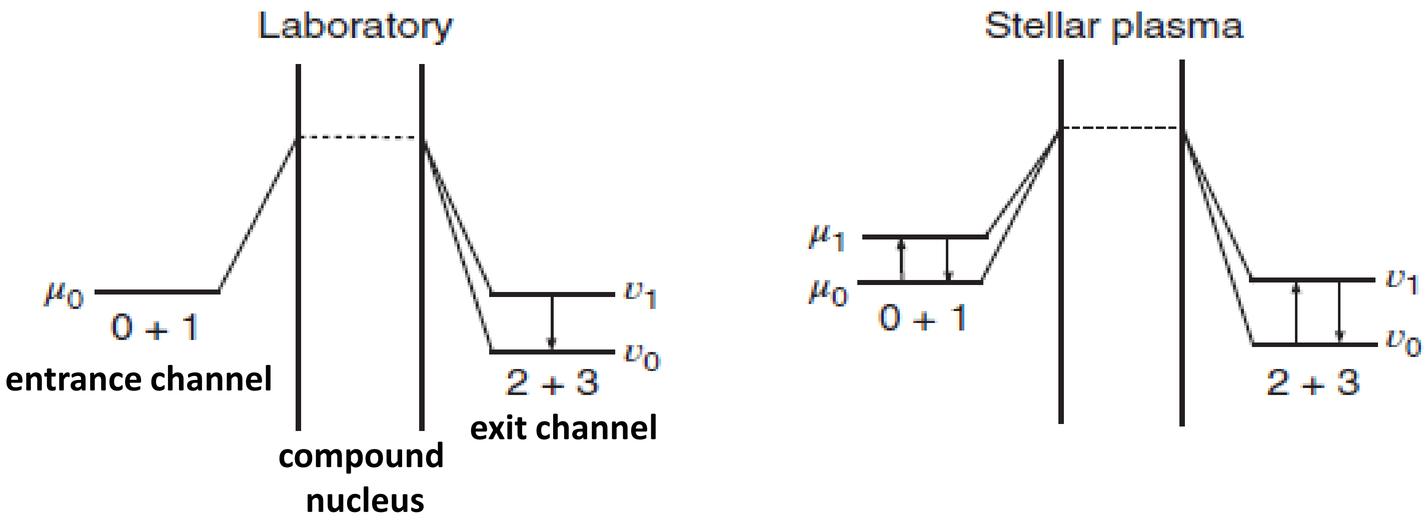


Image from C. Iliadis, Nuclear Physics of Stars (2007)

The **gs contribution** to the ***stellar rate*** for photodisintegration reactions concerning *p*-nuclei typically is only a few tenths per mille.

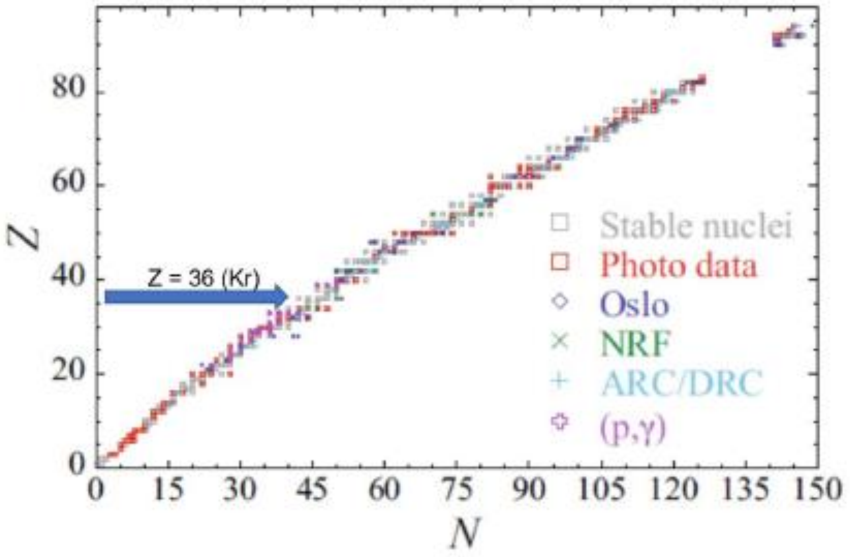
T. Rauscher, Ap. J. Suppl. 201, 26 (2012)

Photodisintegration experiments can only be used to derive information on certain nuclear properties required for the calculation of the stellar rates and, thus, to test and support the theory (statistical Hauser-Feshbach models)!!

- **Gamma-ray strength function**
- Nuclear level density
- Nucleon-nucleus optical potential

Nuclear Resonance Fluorescence (NRF) Measurements on ^{78,80}Kr to determine the γSF for *p*-process nucleosynthesis calculations

No γSF data available for ^{78,80}Kr!!



S. Goriely et al, Eur. Phys. J. A 55, 172 (2019)

PHYSICAL REVIEW C **73**, 015804 (2006)

Branchings in the γ process path revisited

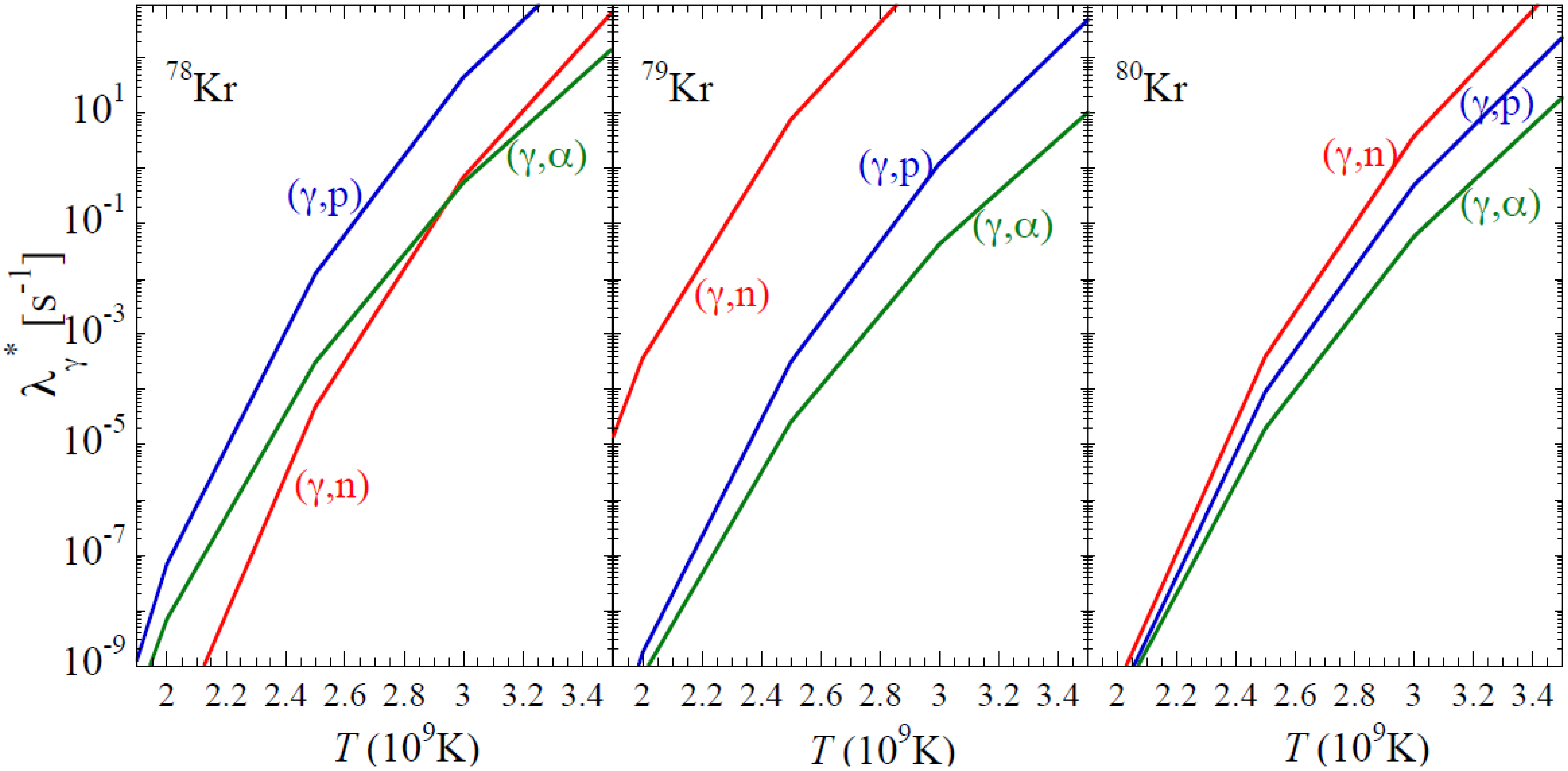
Thomas Rauscher*
Departement für Physik und Astronomie, Universität Basel, CH-4056 Basel, Switzerland

TABLE II. Nuclei with large rate uncertainties (derived from rate set **A** [10], see text); subscripts at each neutron number indicate which rate ($\lambda_{\gamma p}$ or $\lambda_{\gamma\alpha}$) is close to the $\lambda_{\gamma n}$ rate within factors of 3 and 10, respectively.

Z	Neutron number N at given temperature T_9		
	2.0	2.5	3.0
34	42_{α}		
35	46	46	
36	$44_{p,\alpha}$	44_p	
37		48_p	45_p, 48_p
38	43_p	43_p, 46_p	46_p
39	49_p	49_p	49_p
40	47_p	50_p	50_p

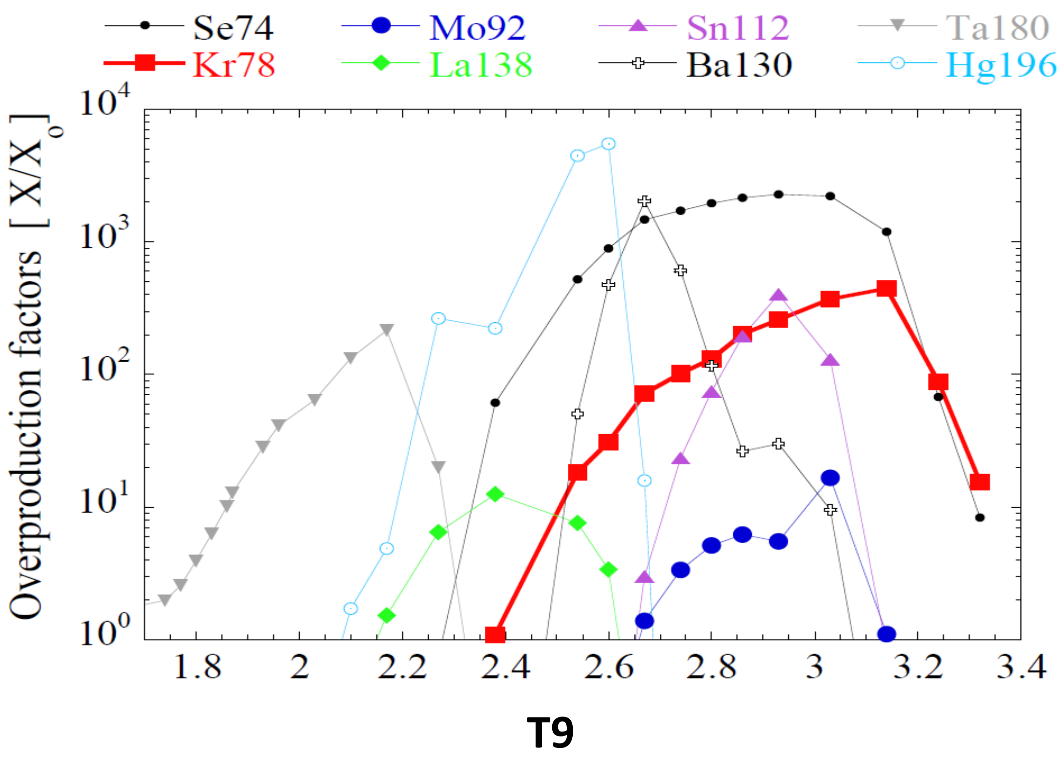
^{80}Kr was identified as *a key branching point*, for which the (γ,p) and (γ,α) reaction rates were found to be larger than the (γ,n) rate – NON-SMOKER calculations with GLO model for γSF & a shifted Fermi-gas model for NLD.

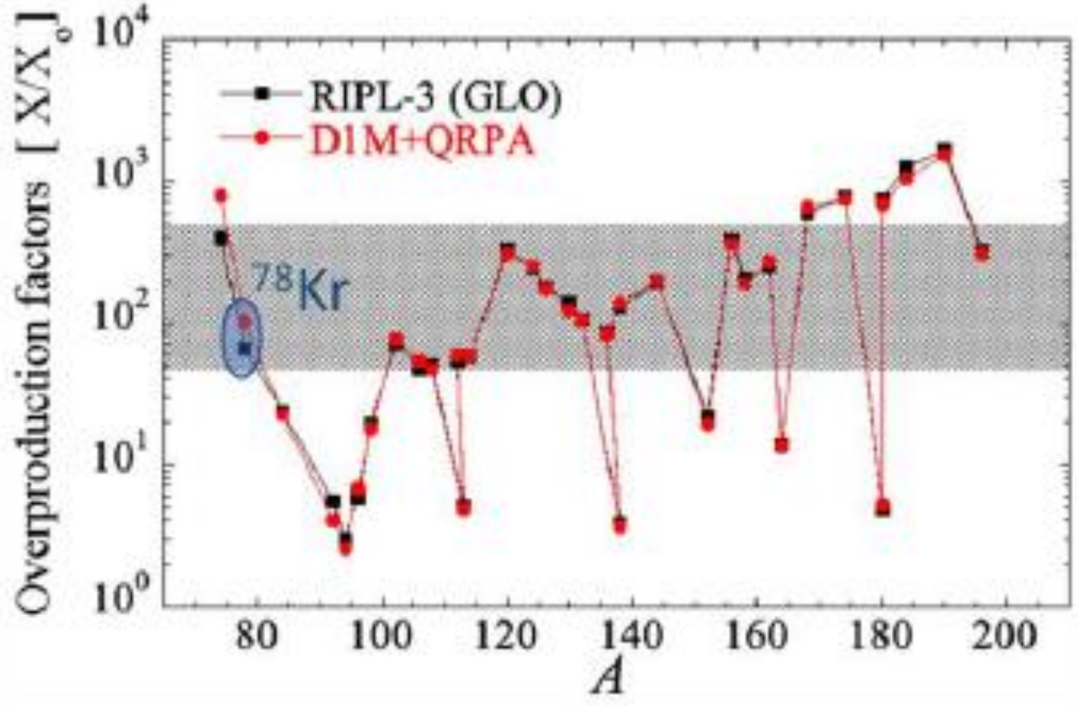
TALYS calculations with the **D1M+QRPA γSF model** and HFB plus combinatorial NLD model



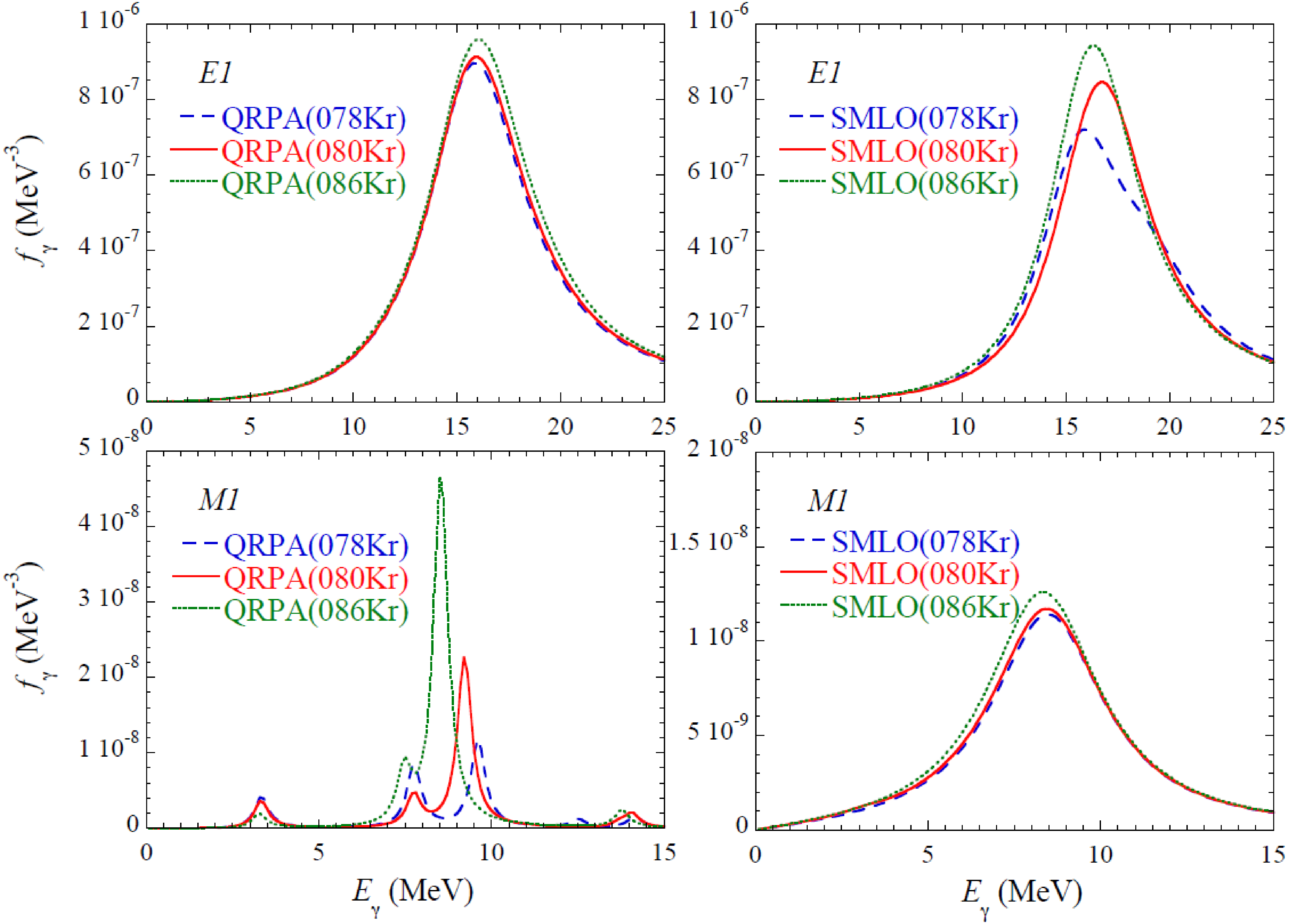
Contrary to NON-SMOKER calculations, TALYS calculations indicate the dominance of the ^{80}Kr(γ,n) channel over the ^{80}Kr(γ,p) and ^{80}Kr(γ,α) channels => **^{78}Kr production follows the path ^{80}Kr(γ,n)^{79}Kr(γ,n)^{78}Kr**

Sensitivity of the astrophysics predictions to the nuclear input





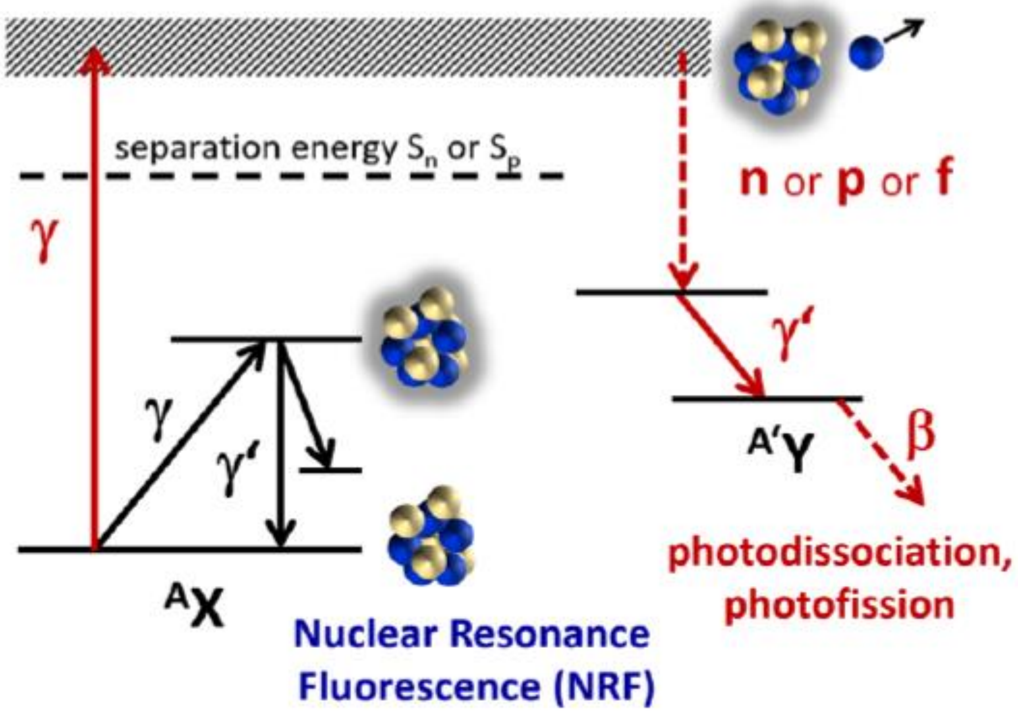
The production of the ^{78}Kr via the path ^{80}Kr(γ,n)^{79}Kr(γ,n)^{78}Kr is increased by 54%, while the (γ,n) destruction of ^{80}Kr is increased by a factor of 2.6 at *T* = 3 GK **when using the D1M+QRPA γSf model comparative to the GLO γSF model**.

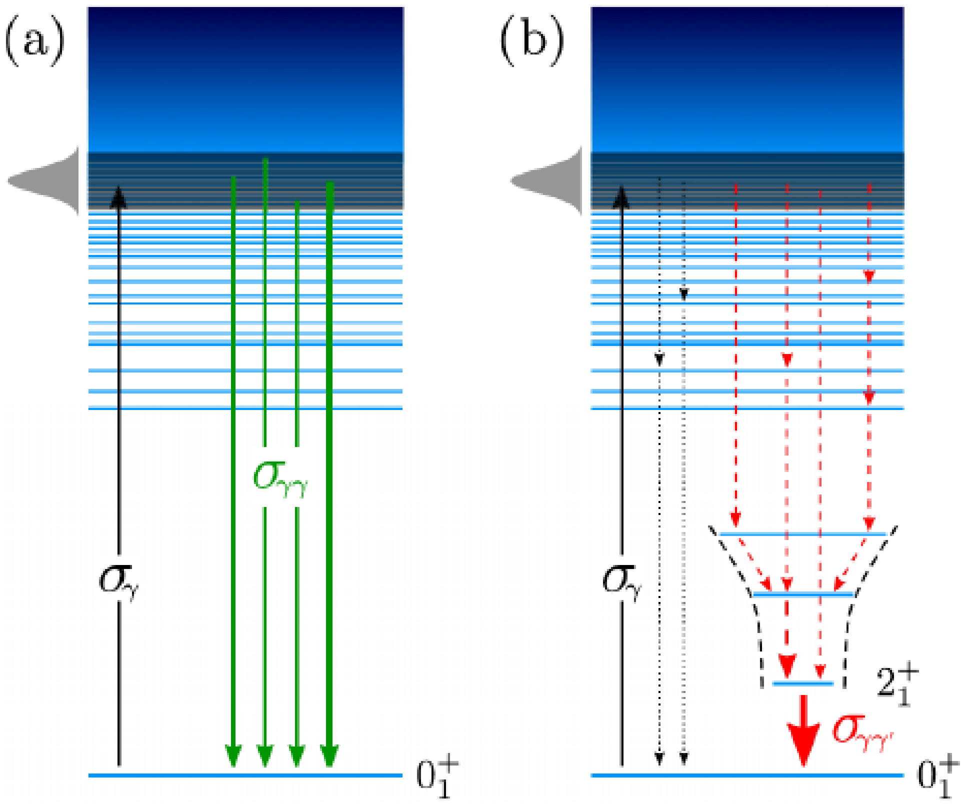


E1
QRPA(078Kr)
QRPA(080Kr)
QRPA(086Kr)
SMLO(078Kr)
SMLO(080Kr)
SMLO(086Kr)
M1
QRPA(078Kr)
QRPA(080Kr)
QRPA(086Kr)
SMLO(078Kr)
SMLO(080Kr)
SMLO(086Kr)
f_γ (MeV^{-3})
E_γ (MeV)

PHOTONUCLEAR REACTIONS

$$\sigma_\gamma = \sigma_{\gamma\gamma} + \sigma_{\gamma\gamma'} \longrightarrow f(E_\gamma) = \frac{1}{3(\pi\hbar c)^2} \cdot \frac{\sigma_\gamma}{E_\gamma}$$





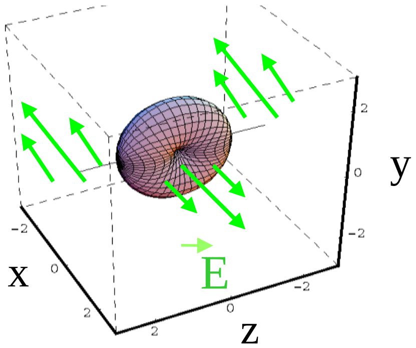
A. Zilges, D.L. Balabanski, J. Isaak, N. Pietralla, Prog. Part. Nucl. Phys. **122** (2022) 103903.

Parity and Spin Measurements with a Linearly Polarized Photon Beam

Dipole

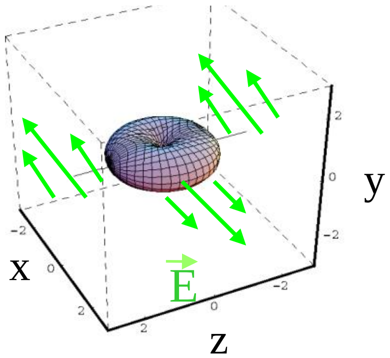
E1

$0^+ \rightarrow 1^- \rightarrow 0^+$



M1

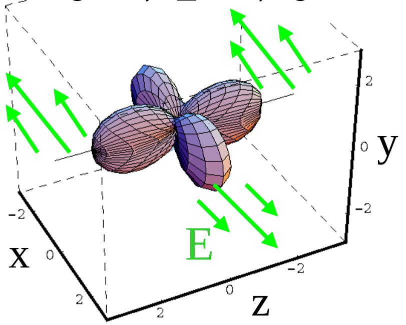
$0^+ \rightarrow 1^+ \rightarrow 0^+$



Quadruple

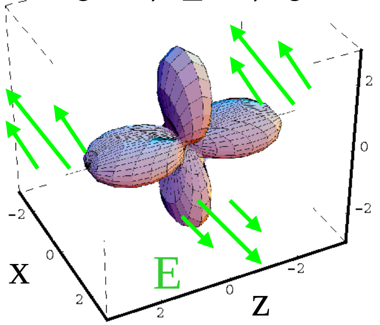
E2

$0^+ \rightarrow 2^+ \rightarrow 0^+$

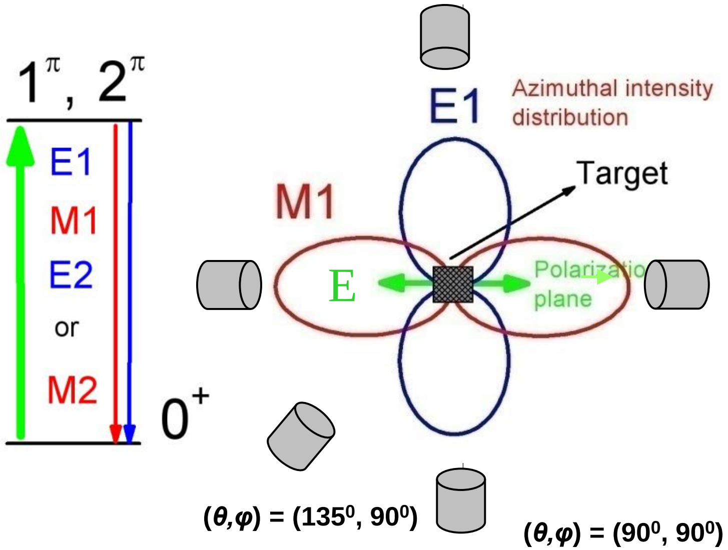


M2

$0^+ \rightarrow 2^- \rightarrow 0^+$



Azimuthal distribution



$$\Sigma = \frac{W(90^o,0^o) - W(90^o,90^o)}{W(90^o,0^o) + W(90^o,90^o)}$$

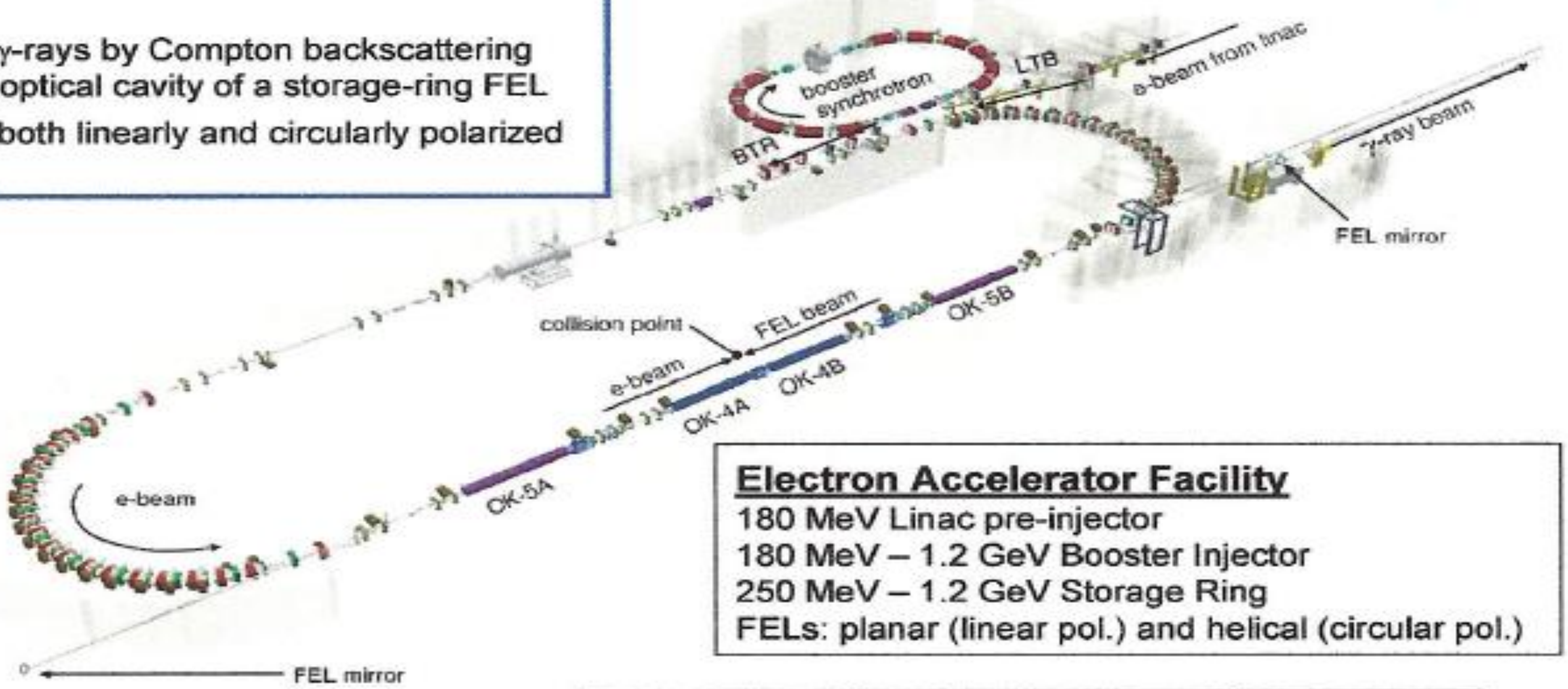
$$= \pi = \begin{cases} +1 & \text{for } J^\pi = 1^+, 2^+ \\ -1 & J^\pi = 1^-, 2^- \end{cases}$$

Experimental Asymmetry = 0.96

N. Pietralla, at al. PRL **88** (2002) 012502; A. Tonchev, NIM **B 241** (2005) 51474

High Intensity Gamma-ray Source (HIGS) at TUNL

- Highest intensity (γ-rays/s/keV) γ-ray beam in the world
- Produces γ-rays by Compton backscattering inside the optical cavity of a storage-ring FEL
- Produces both linearly and circularly polarized beams



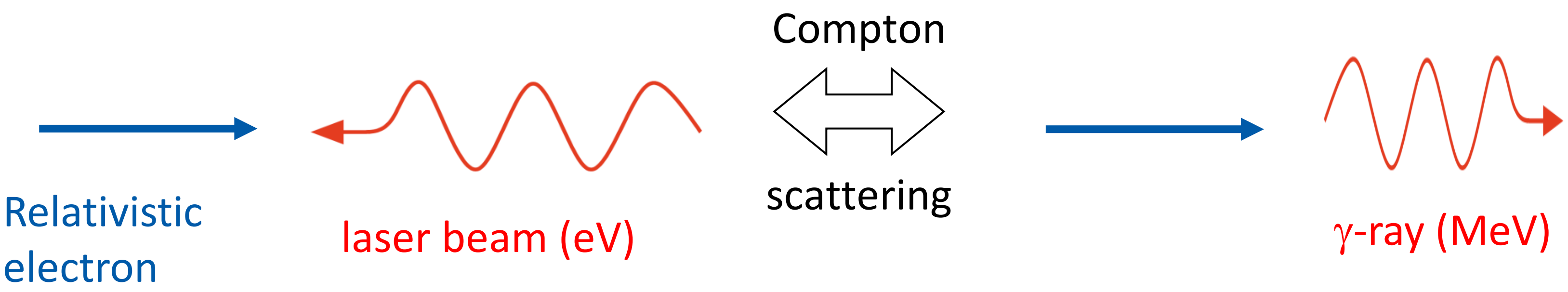
Electron Accelerator Facility

180 MeV Linac pre-injector
180 MeV – 1.2 GeV Booster Injector
250 MeV – 1.2 GeV Storage Ring
FELs: planar (linear pol.) and helical (circular pol.)

γ-ray beam parameters	Values
Energy	1 – 100 MeV
Linear & circular polarization	> 95%
Intensity with 5% $\Delta E_\gamma/E_\gamma$	> 10^7 γ/s

For more details see:
http://www.tunl.duke.edu/higs/

How HIγS Works: Laser Compton Backscattering (LCB)



$$E_\gamma = \frac{\hbar\omega \cdot (1 - \beta \cdot \cos\theta_i)}{1 - \beta \cdot \cos\theta_f + \frac{\hbar\omega}{E_{electron}}(1 - \cos\theta_{photon})} \approx 4\gamma^2 \cdot E_{laser}$$

$\gamma = E_e/mc^2$ (Lorentz factor)

Example:

$E_{laser} = 3.3$ eV

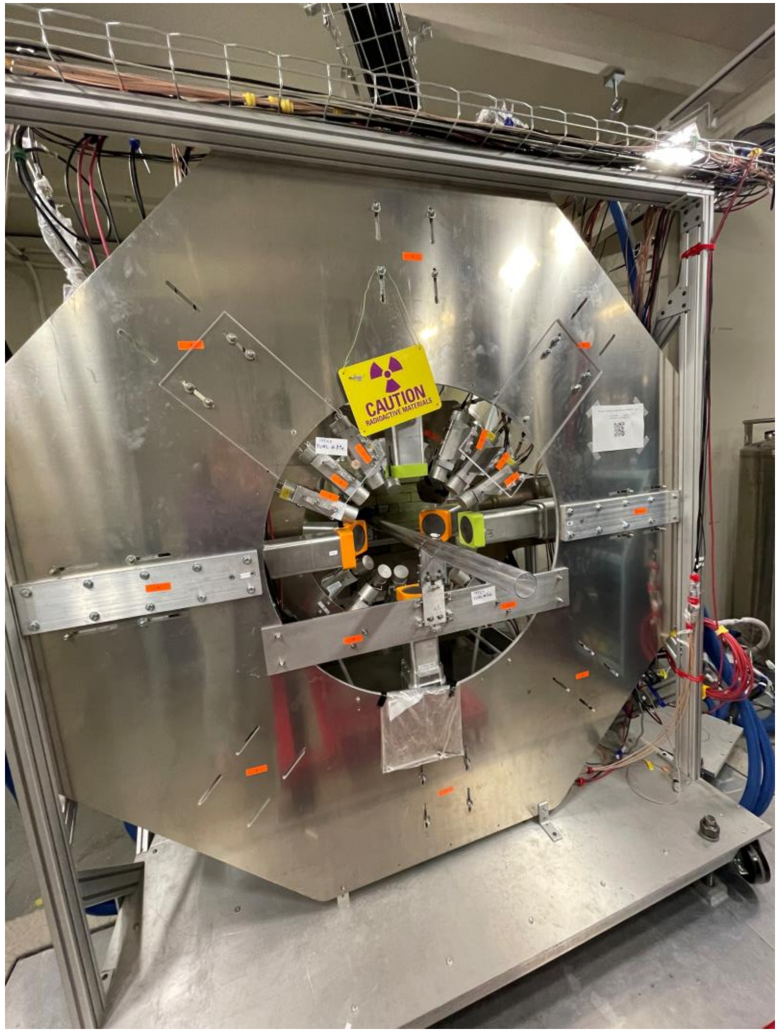
$E_{electron} = 450$ MeV ($\gamma = 882$)

$E_\gamma = 10$ MeV

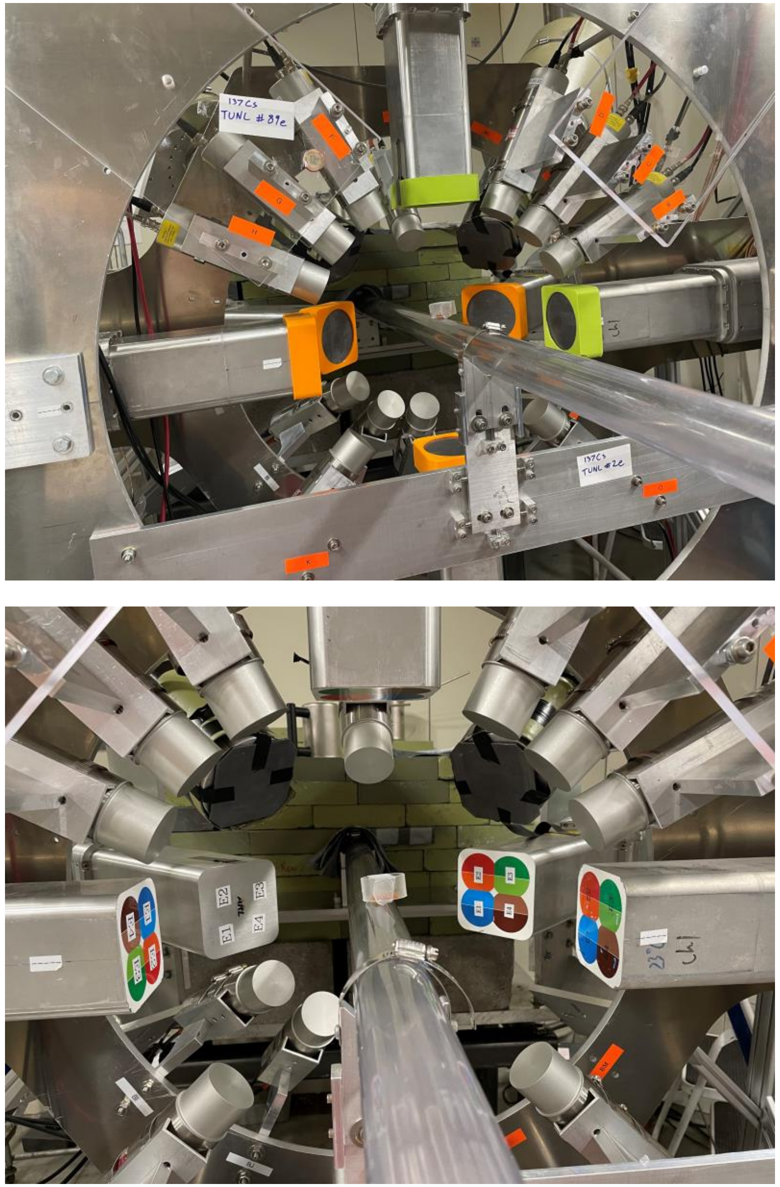
LCB facilities in the world:

- HIγS @ TUNL/Duke University (USA)
- ~~NewSUBARU~~ (Japan); BL01 γ- ray beam usage ended on March 31, 2021
- VEGA @ ELI-NP (Romania); under implementation (*estimated to become available in 2026*)

NRF Experimental Setup at HγGS



Clover array



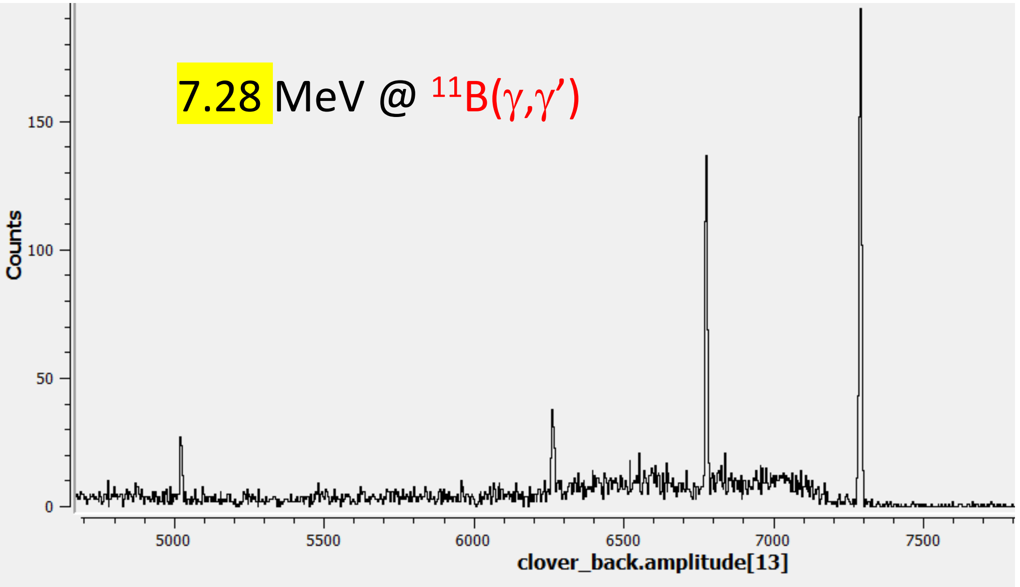
Target gas cell and target holder

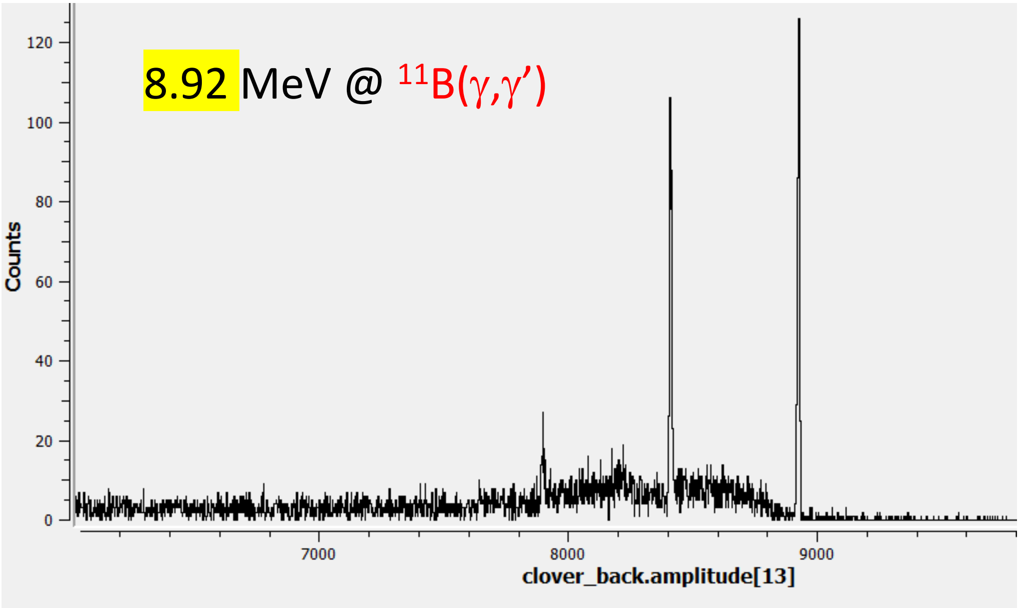
Photon Beam Energies (MeV) for our NRF measurements:

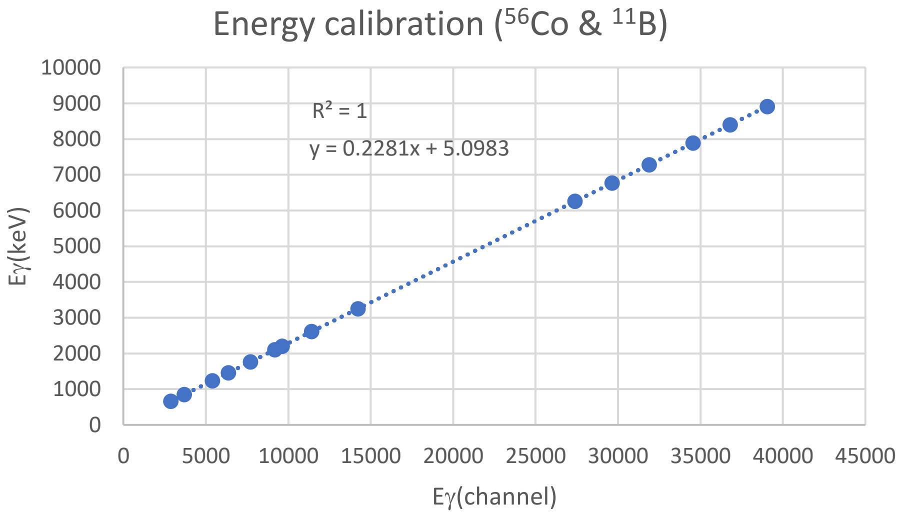
6.40, 6.65, 6.95, 7.20, 7.28, 7.50, 7.80, 8.15, 8.45, **8.80**, 8.92, 9.15, **9.55**, 9.95, **10.35, 10.75, 11.20**

$S_n(^{78}Kr)$ = 12.1 MeV

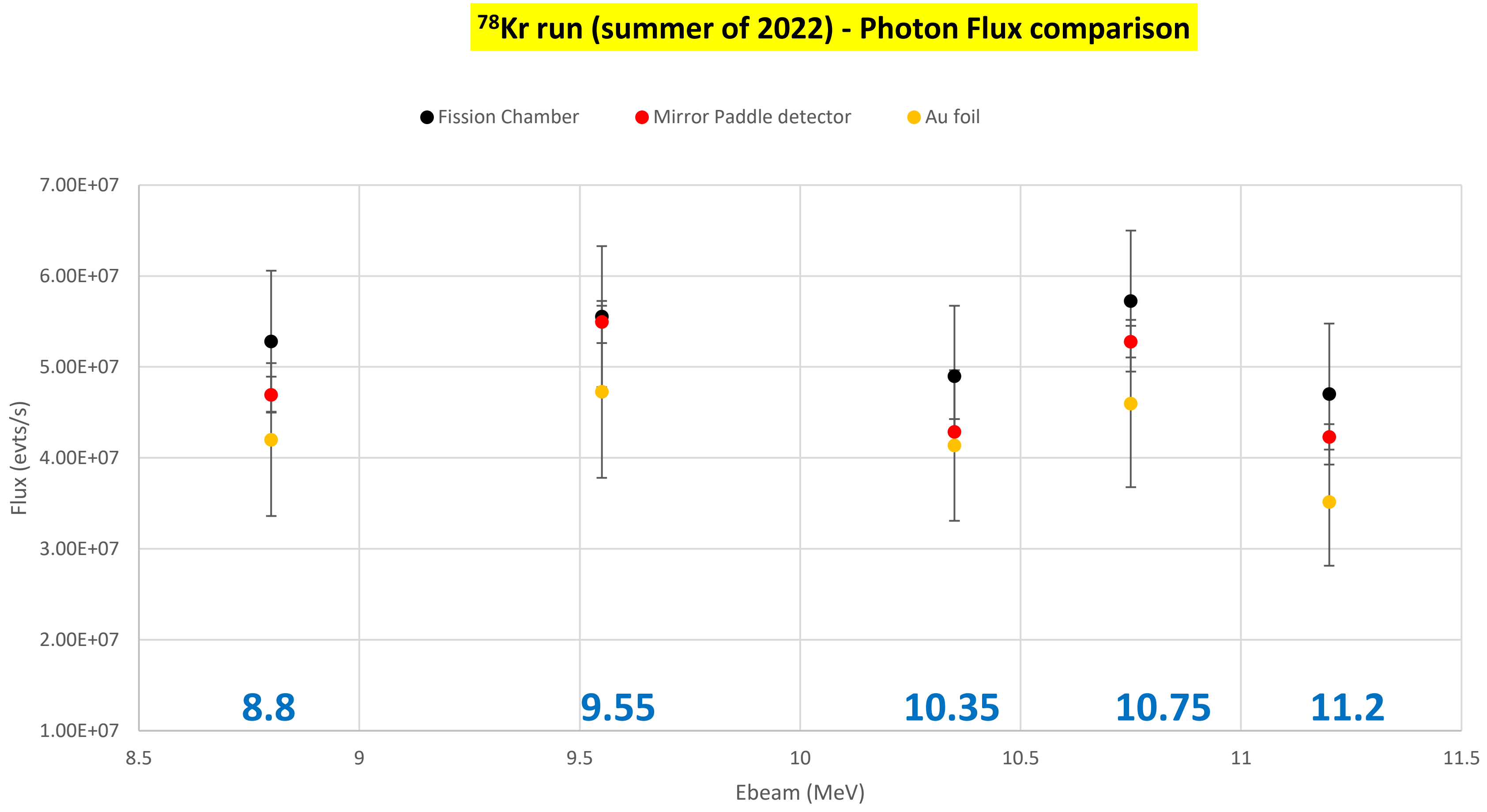
$S_n(^{80}Kr)$ = 11.5 MeV







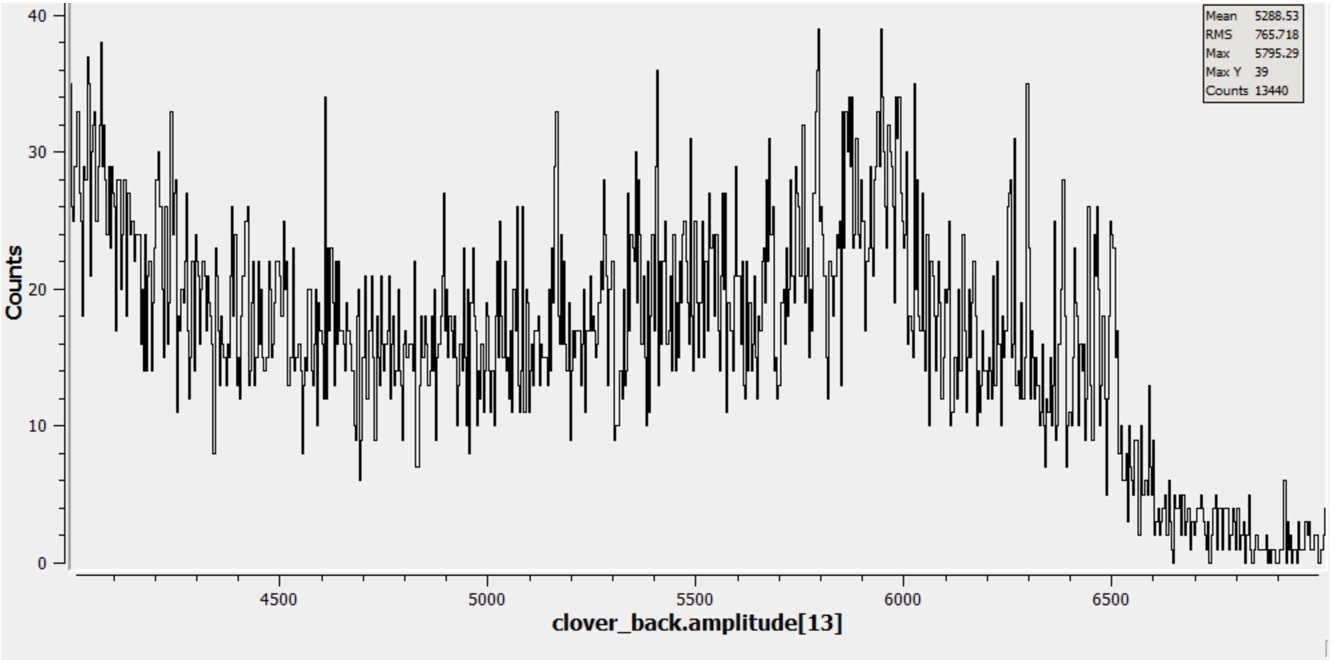
Photon beam flux measurement



^{80}Kr NRF measurements (July 2023)

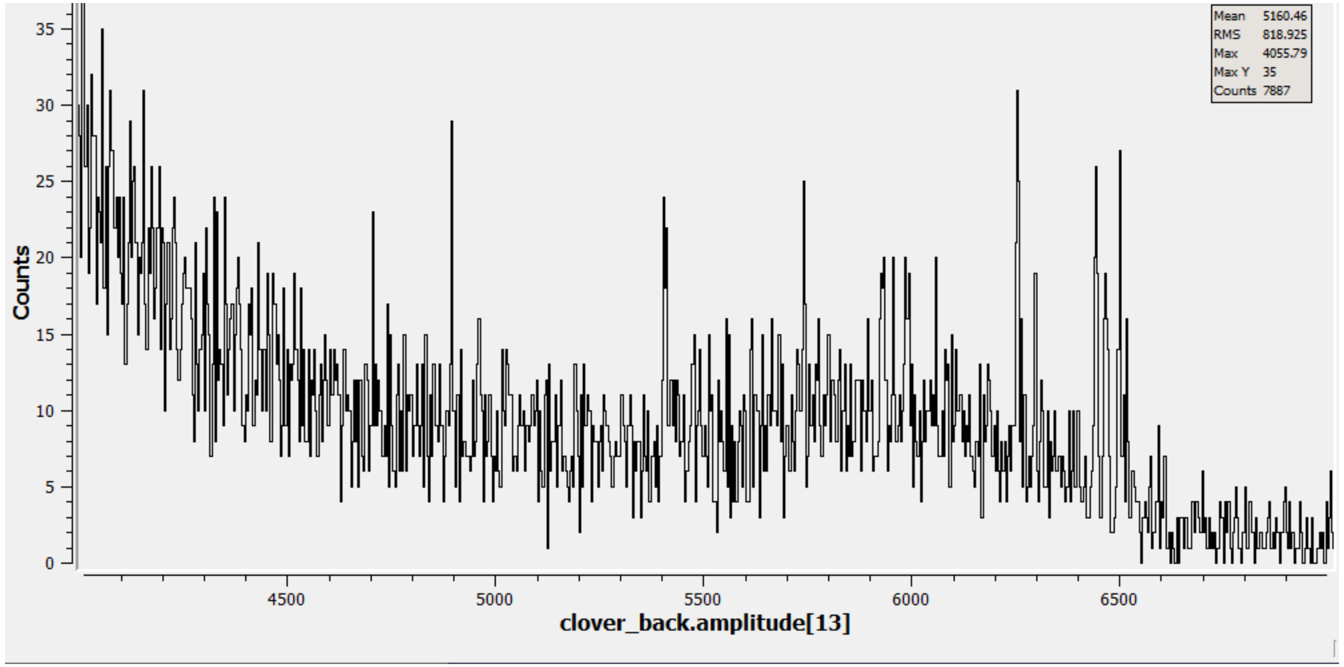
6.4 MeV @ ^{56,54}Fe(γ,γ’) & ^{80}Kr(γ,γ’)

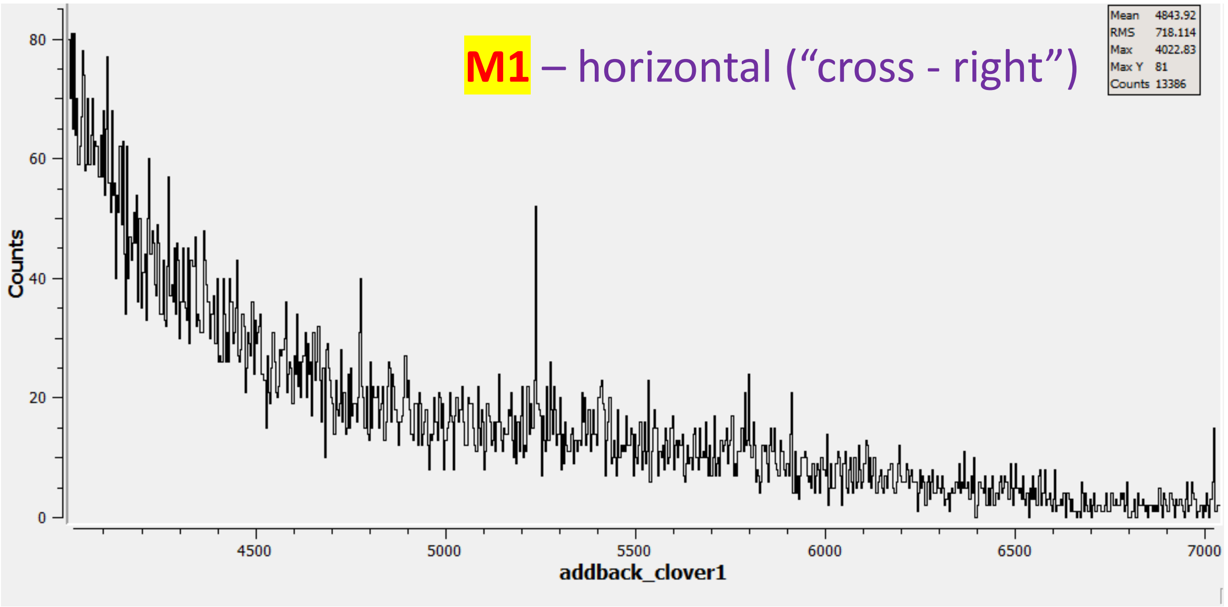
target: stainless-steel cell with **^{80}Kr**

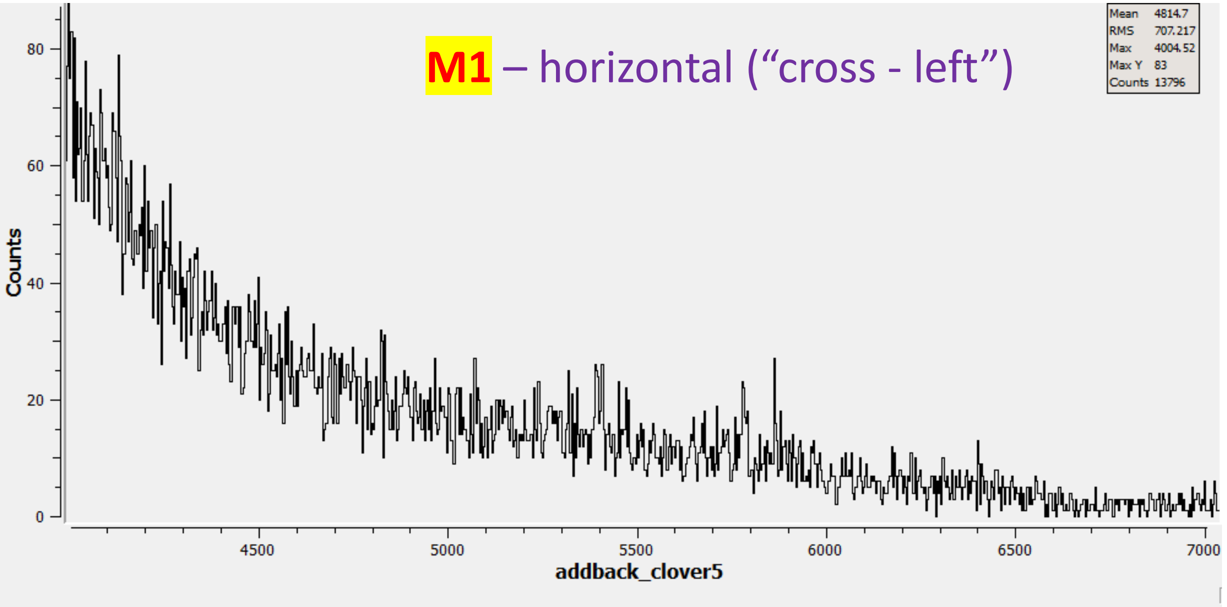


6.4 MeV @ ^{56,54}Fe(γ,γ’)

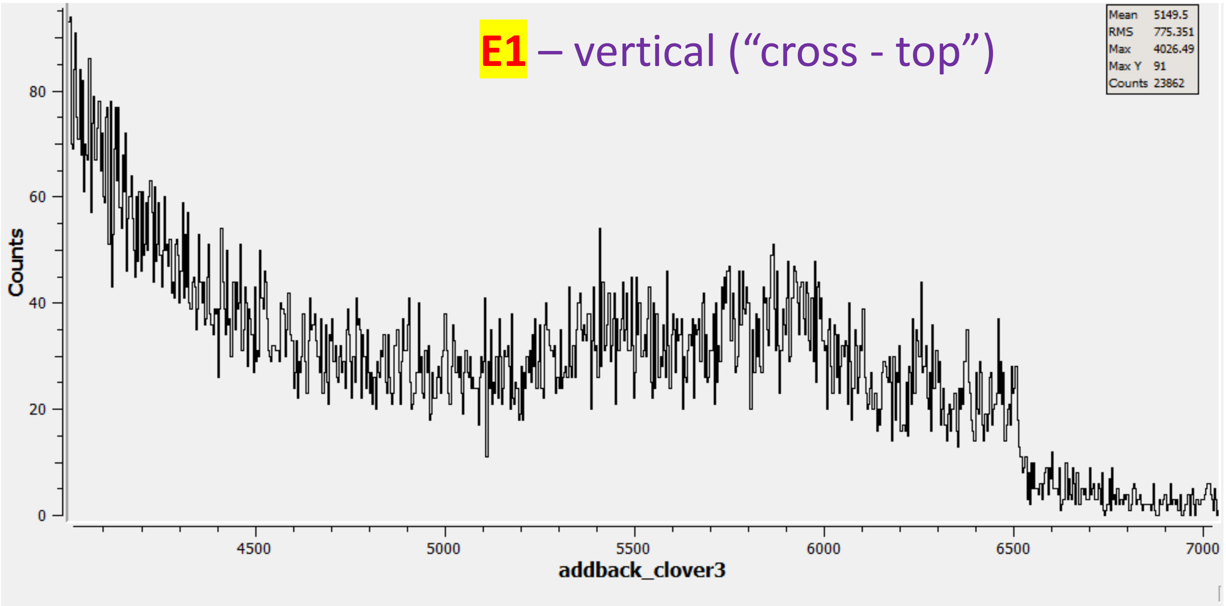
target: stainless-steel **empty cell**

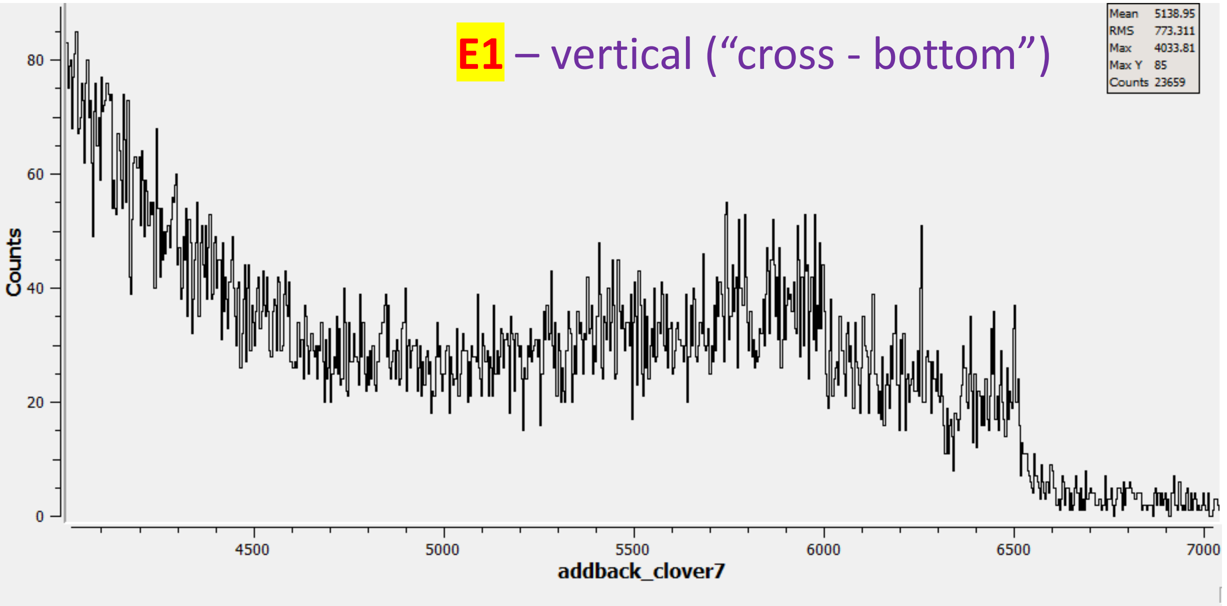






6.4 MeV @ ^{56,54}Fe(γ,γ') & ^{80}Kr(γ,γ')

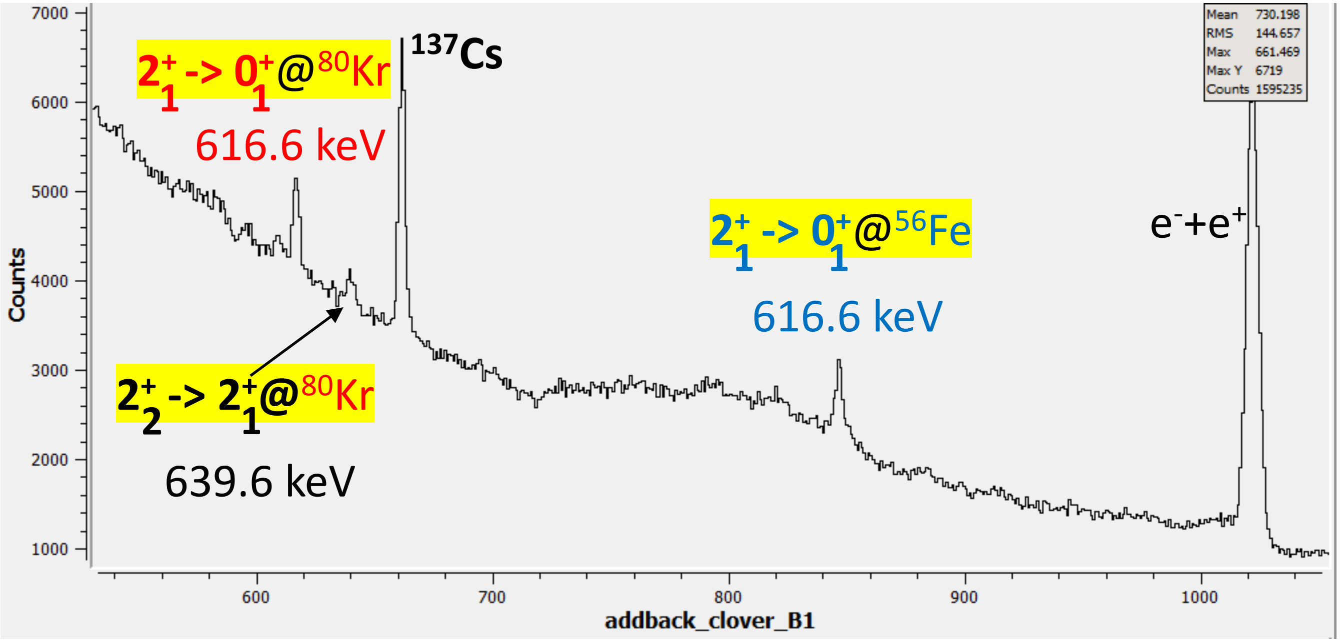




^{80}Kr NRF measurements (July 2023)

11.2 MeV @ ^{56,54}Fe(γ,γ') & **^{80}Kr(γ,γ')**

target: stainless-steel cell with **^{80}Kr**



Data analysis in progress: **stay tuned**

PHYSICAL REVIEW C **99**, 025802 (2019)

Photoneutron reaction cross section measurements on ^{94}Mo and ^{90}Zr relevant to the *p*-process nucleosynthesis

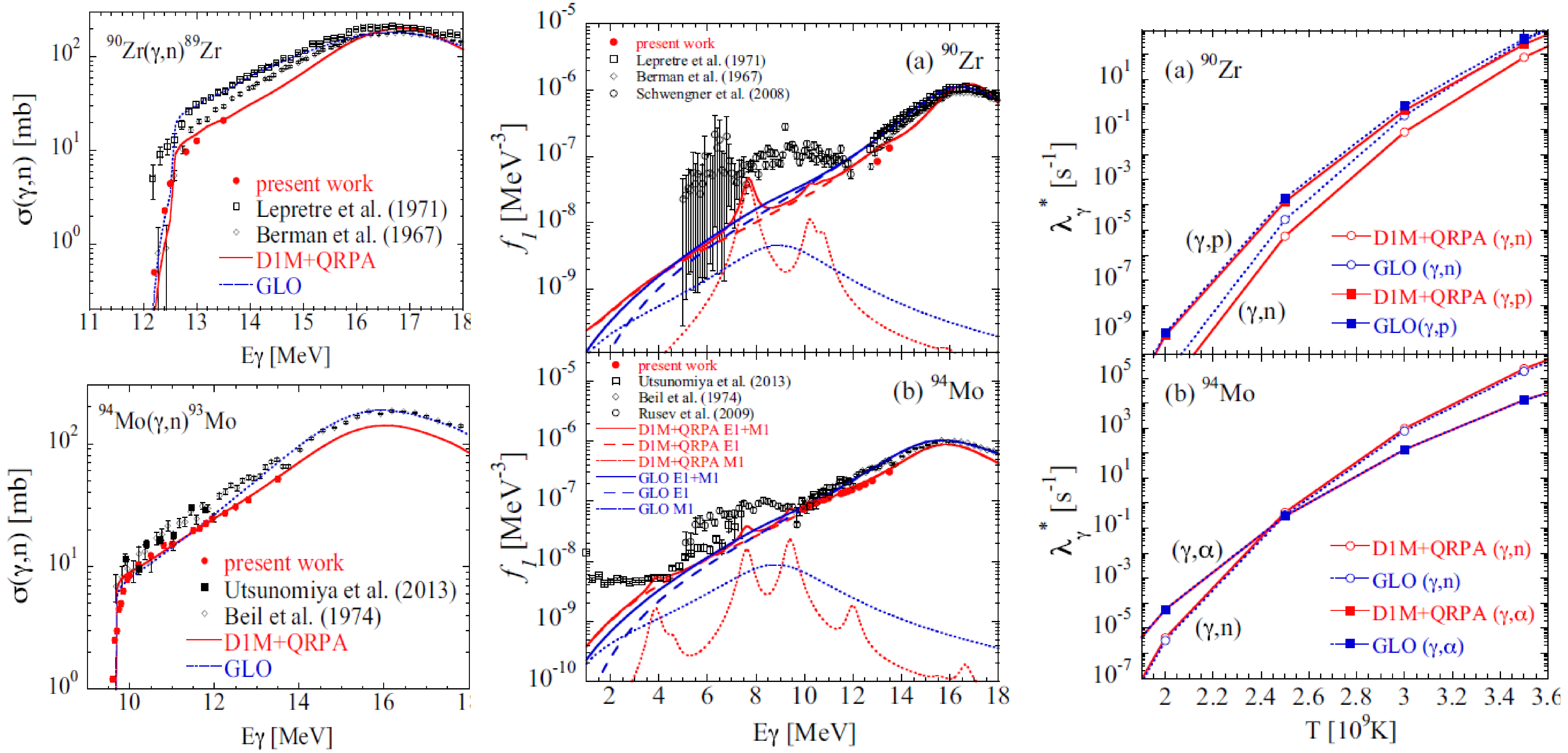
A. Banu[*] and E. G. Meekins[†]
Department of Physics and Astronomy, James Madison University, Harrisonburg, Virginia 22807, USA

J. A. Silano[‡] and H. J. Karwowski
Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA
and University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27516, USA

S. Goriely
Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus de la Plaine, CP-226, 1050 Brussels, Belgium

(Received 10 June 2018; revised manuscript received 19 December 2018; published 11 February 2019)

The photodisintegration cross sections for the ^{94}Mo(γ, n) and ^{90}Zr(γ, n) reactions have been experimentally investigated with quasi-monochromatic photon beams at the High Intensity γ-ray Source (HIγS) facility of the Triangle Universities Nuclear Laboratory (TUNL). The energy dependence of the photoneutron reaction cross sections was measured with high precision from the respective neutron emission thresholds up to 13.5 MeV. These measurements contribute to a broader investigation of nuclear reactions relevant to the understanding of the *p*-process nucleosynthesis. The results are compared with the predictions of Hauser-Feshbach statistical model calculations using two different models for the dipole γ-ray strength function. The resulting ^{94}Mo(γ, n) and ^{90}Zr(γ, n) photoneutron stellar reaction rates as a function of temperature in the typical range of interest for the *p*-process nucleosynthesis show how sensitive the photoneutron stellar reaction rate can be to the experimental data in the vicinity of the neutron threshold.



$$f(E_\gamma) = \frac{1}{3\pi^2\hbar^2c^2}\frac{\sigma_\gamma(E_\gamma)}{E_\gamma}$$

A. Banu *et al.*, Phys. Rev. C 99, 025802 (2019)

Acknowledgments

Research work for the ^{78,80}Kr(γ,γ') measurements is supported by the award no. DE-SC0021199

Research work for the ^{94}Mo(γ,n) and ^{90}Zr(γ,n) measurements was partially supported by the award no. 22662

The theoretical work for the ^{94}Mo(γ,n) and ^{90}Zr(γ,n) measurements was performed within the IAEA CRP on "Updating the Photonuclear Data Library and Generating a Reference Database for Photon Strength Functions" (F41032)

S. Goriely *et al.*, **Eur. Phys. J. A55, 172 (2019):** ***Reference Database for Photon Strength Functions***
T. Kawano *et al.*, **Nucl. Data Sheets 163, 109 (2020):** ***IAEA Photonuclear Data Library 2019***

Thank you for your attention!