Photo-neutron Reaction Cross Section Measurements on ^{94}Mo and ^{90}Zr Relevant to the *p*-Process Nucleosynthesis

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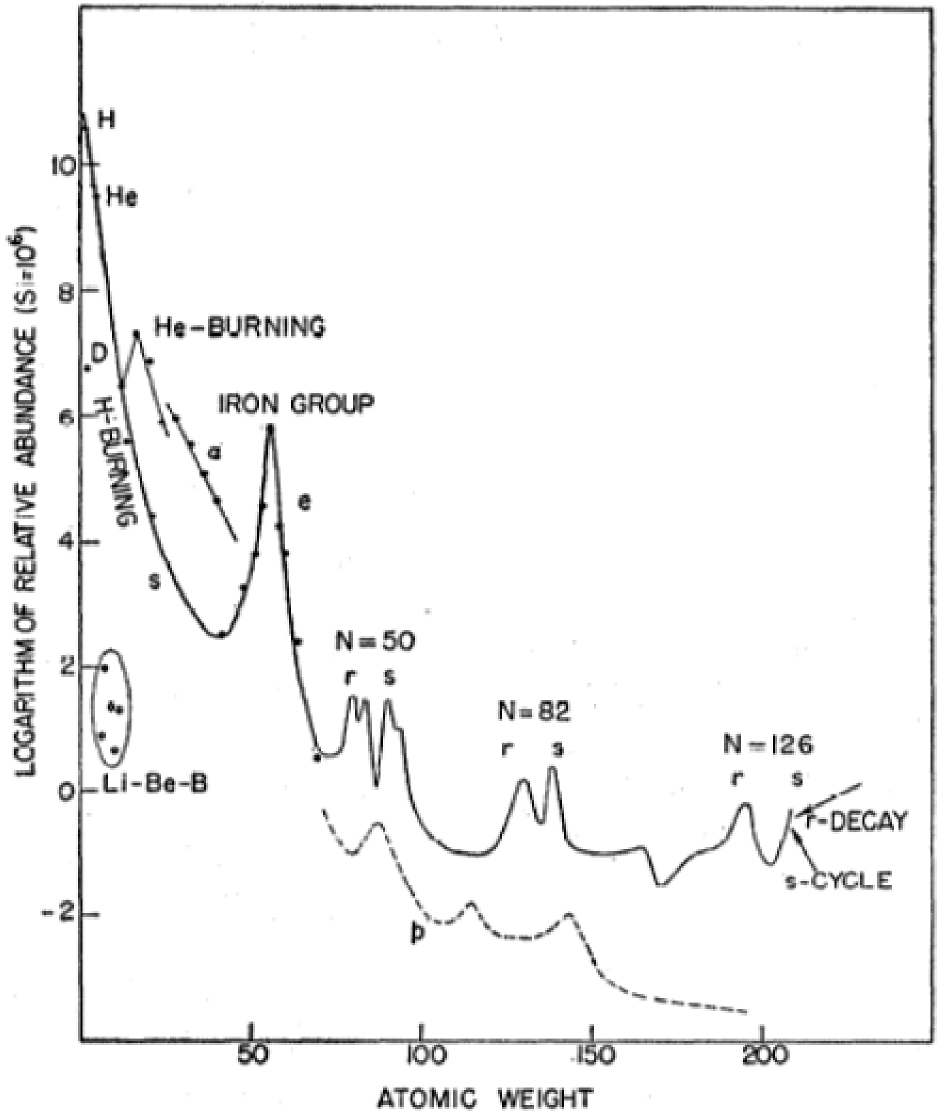
African Nuclear Physics Conference

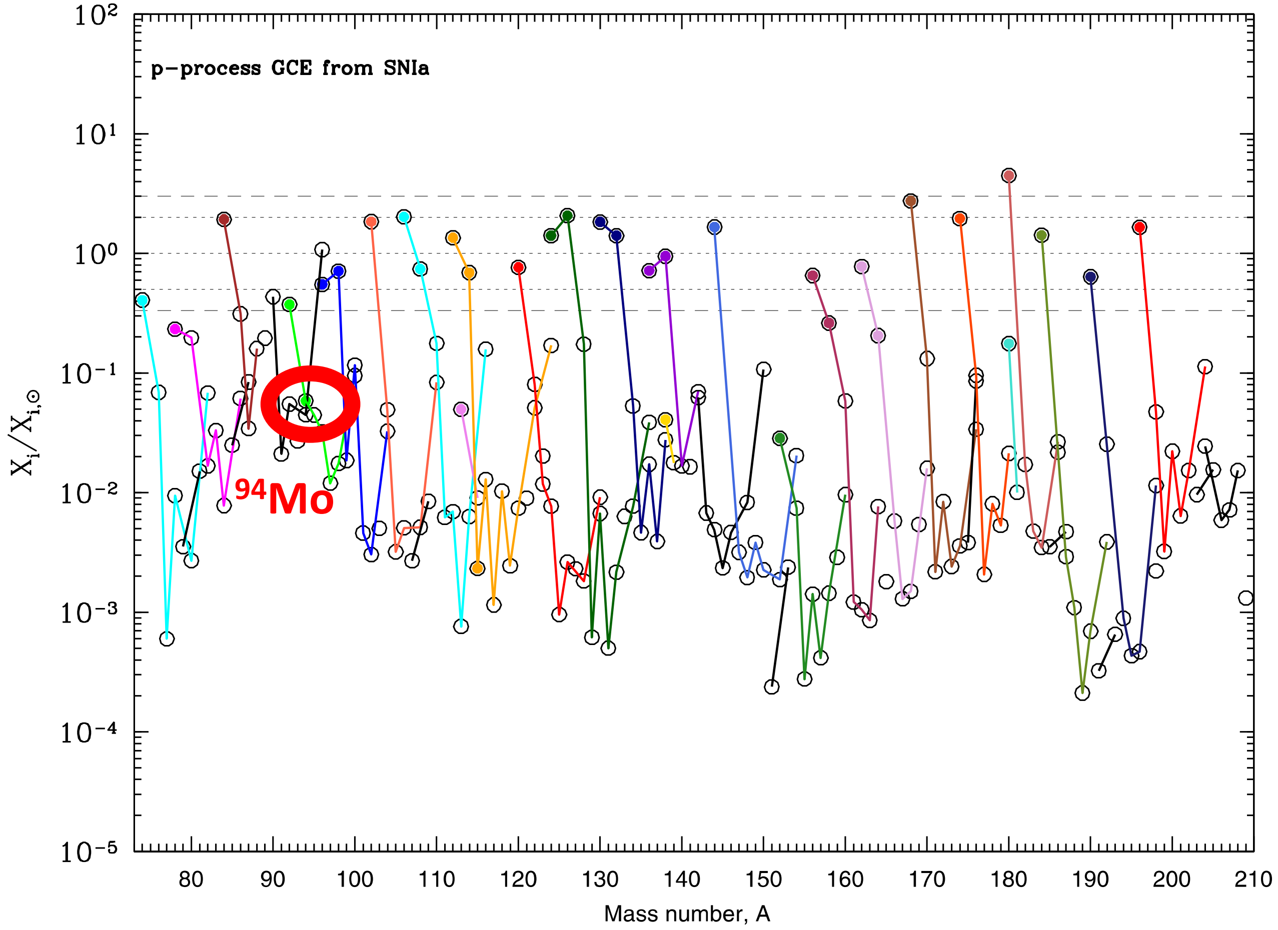
July 1 - 5, 2019

Kruger National Park, South Africa

Seminal curve of atomic abundances

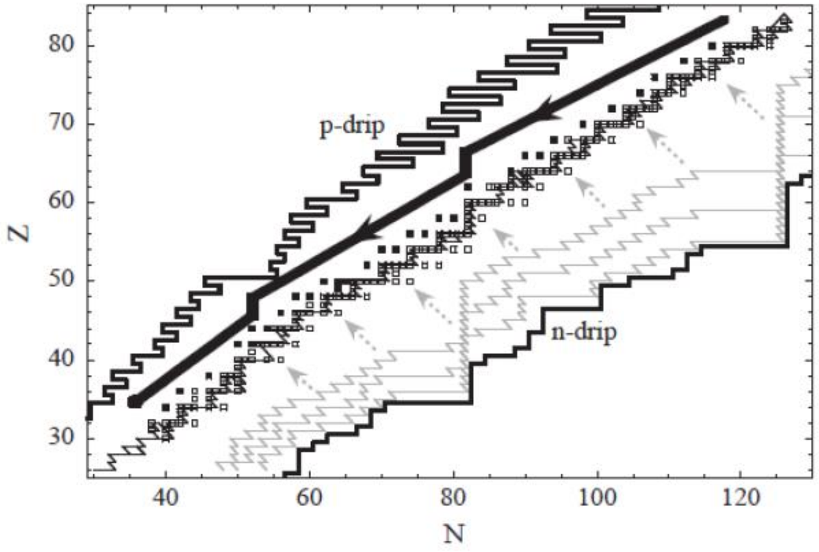


B²FH, Rev. Mod. Phys. 29, 547 (1957)



C. Travaglio et al., ApJ 739, 93 (2011)

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



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

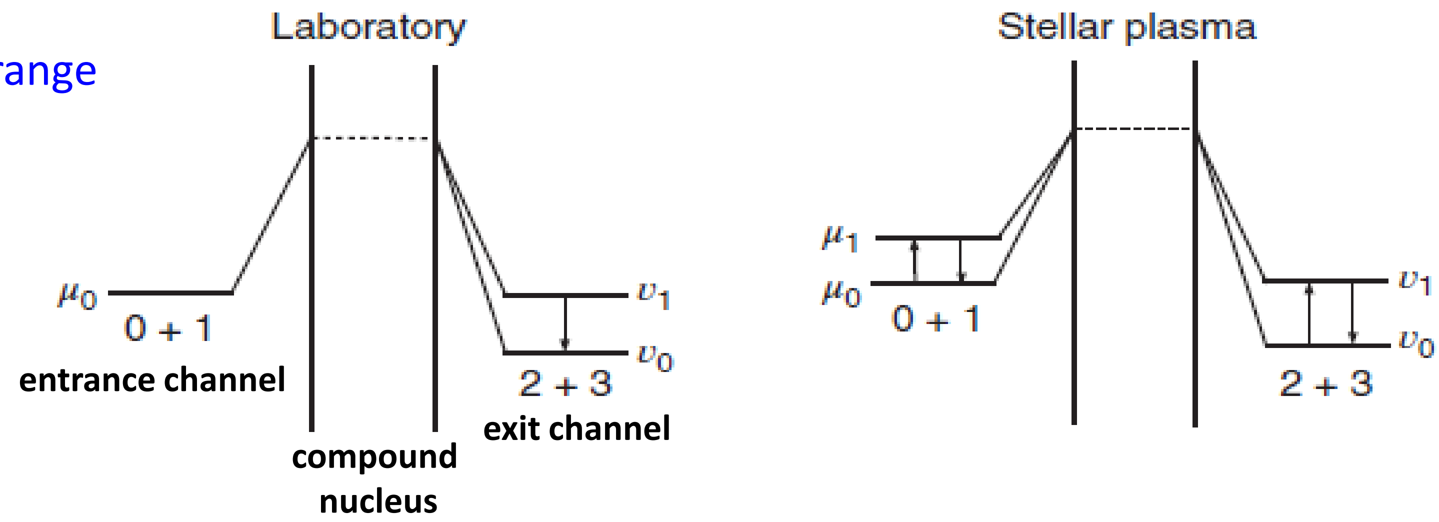


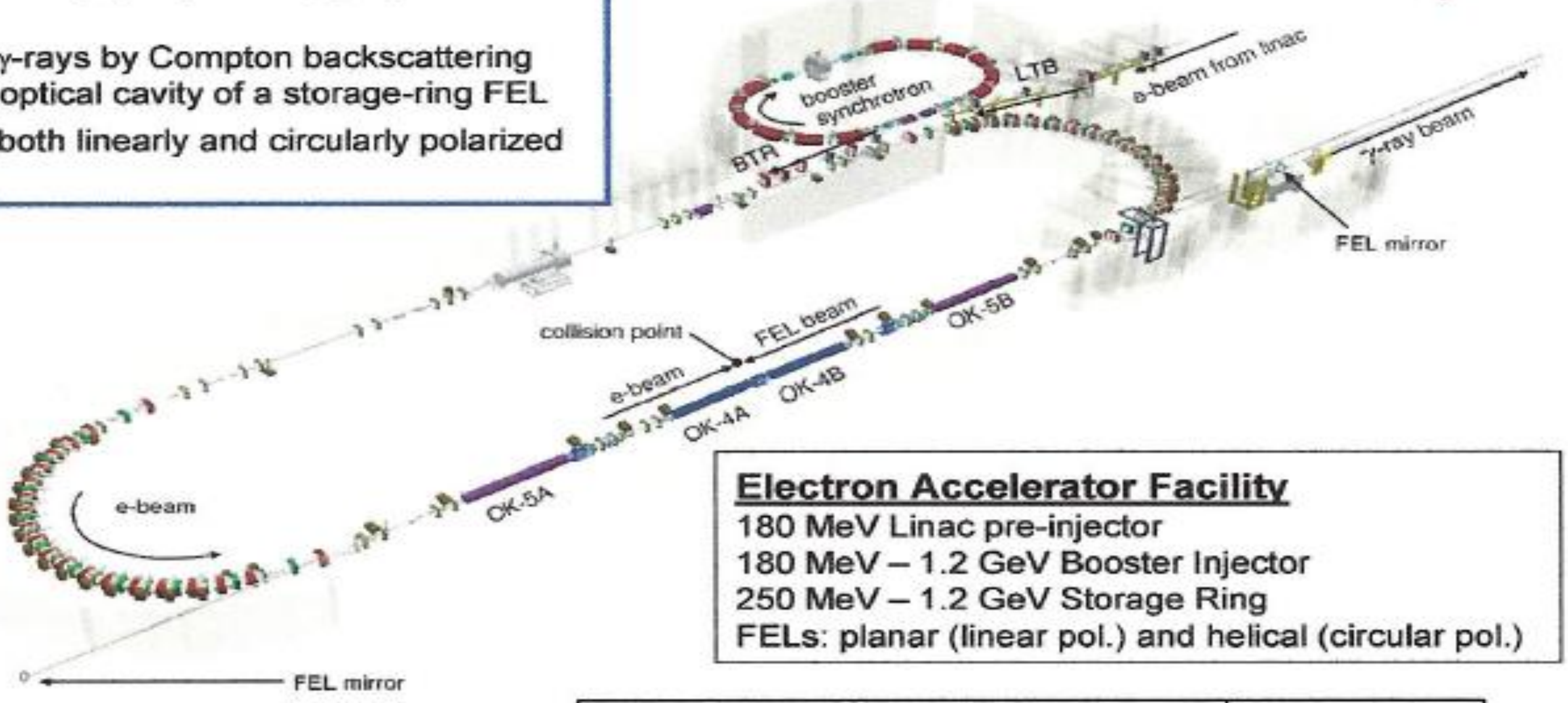
Image from C. Iliadis, Nuclear Physics of Stars (2007)

Essential to improving the accuracy of **stellar reaction rate theoretical predictions** within Hauser-Feshbach statistical models:

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

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

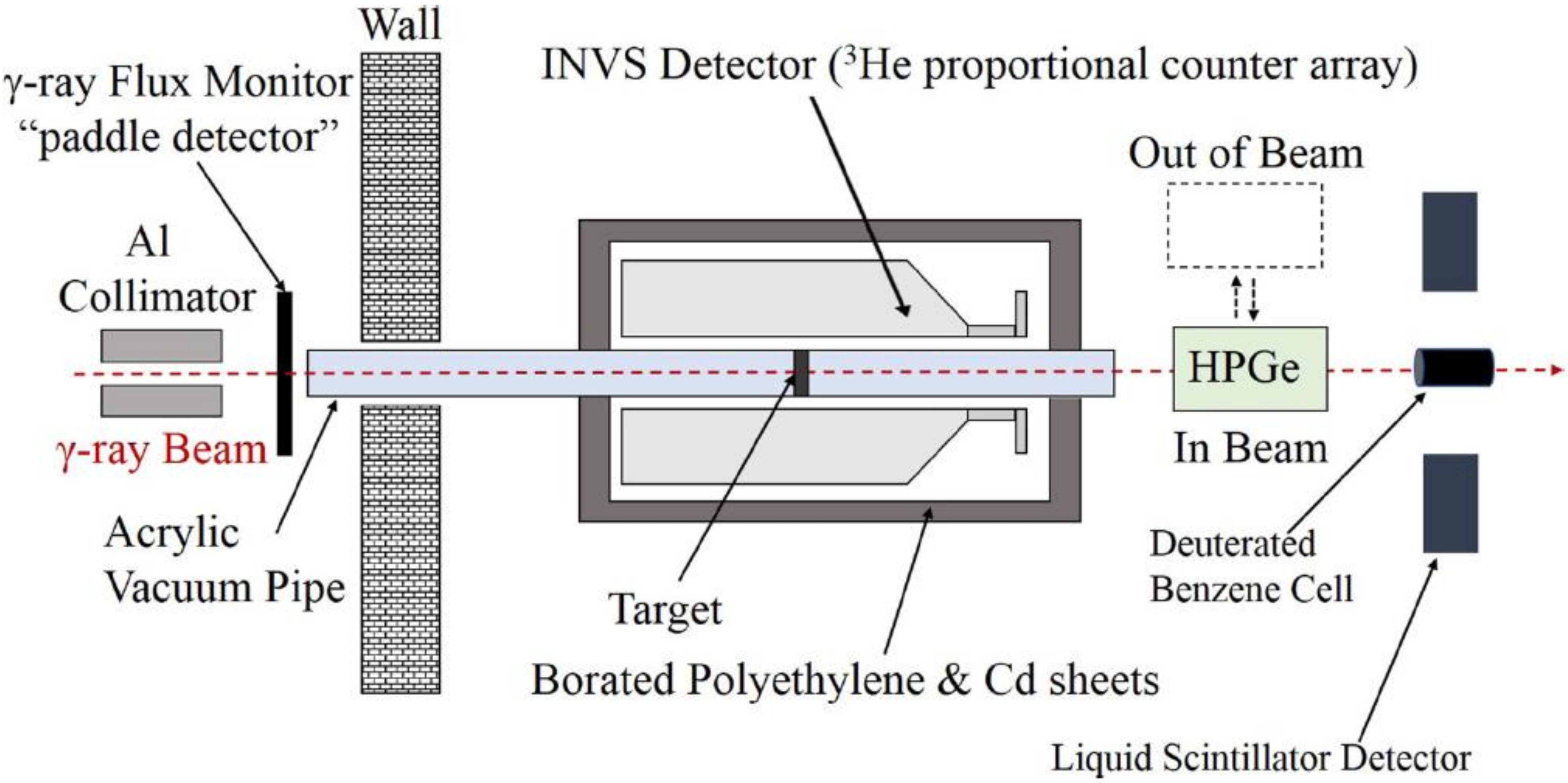


Electron Accelerator Facility

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/

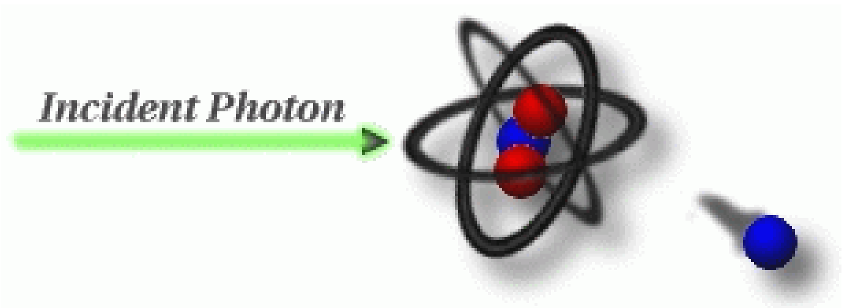


~ $10^7 - 10^8$ γ/s

✧ ^{94}Mo: ~ 600 mg/cm^2 , 98.97%

✧ ^{90}Zr: ~ 1 g/cm^2, 97.7%

$\Delta E_\gamma / E_\gamma \sim 4\% - 5\%$ (FWHM)



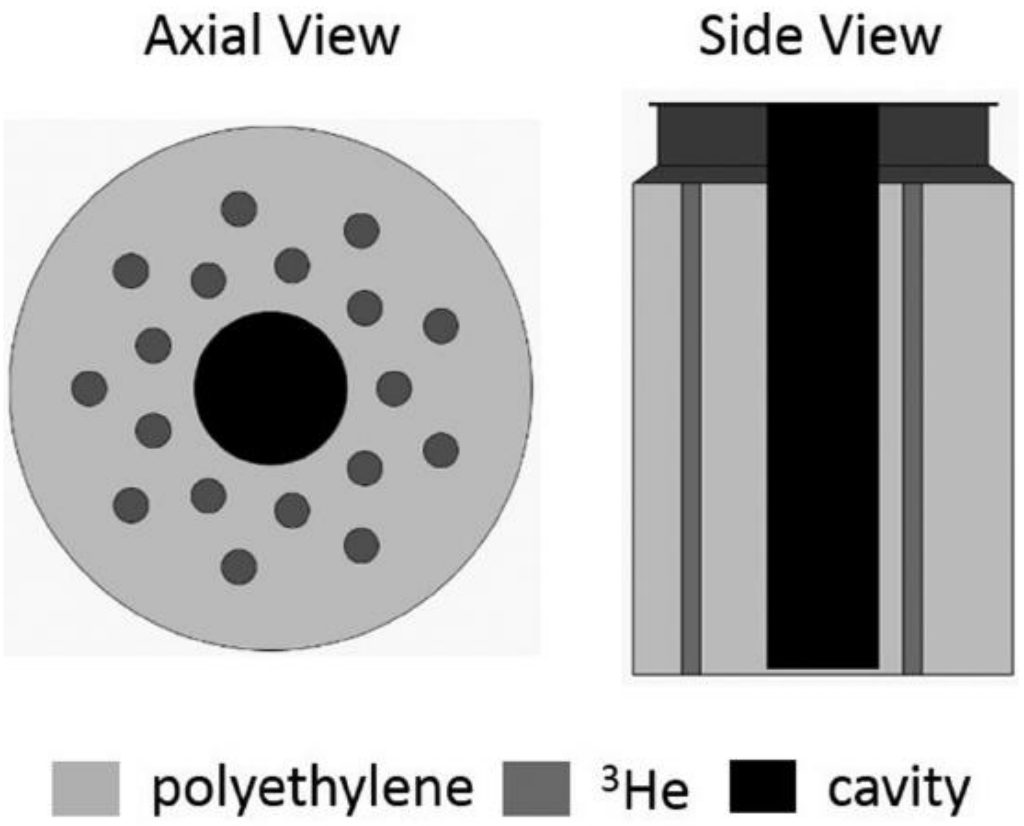
$$\sigma(E_\gamma) = \frac{N_n}{N_\gamma N_t \varepsilon_n(E_\gamma)}$$

N_n – number of neutrons detected using ^{3}He counters

N_γ - number of incident photons

N_t – number of target atoms per unit area (enriched target)

ε_n – neutron detection efficiency

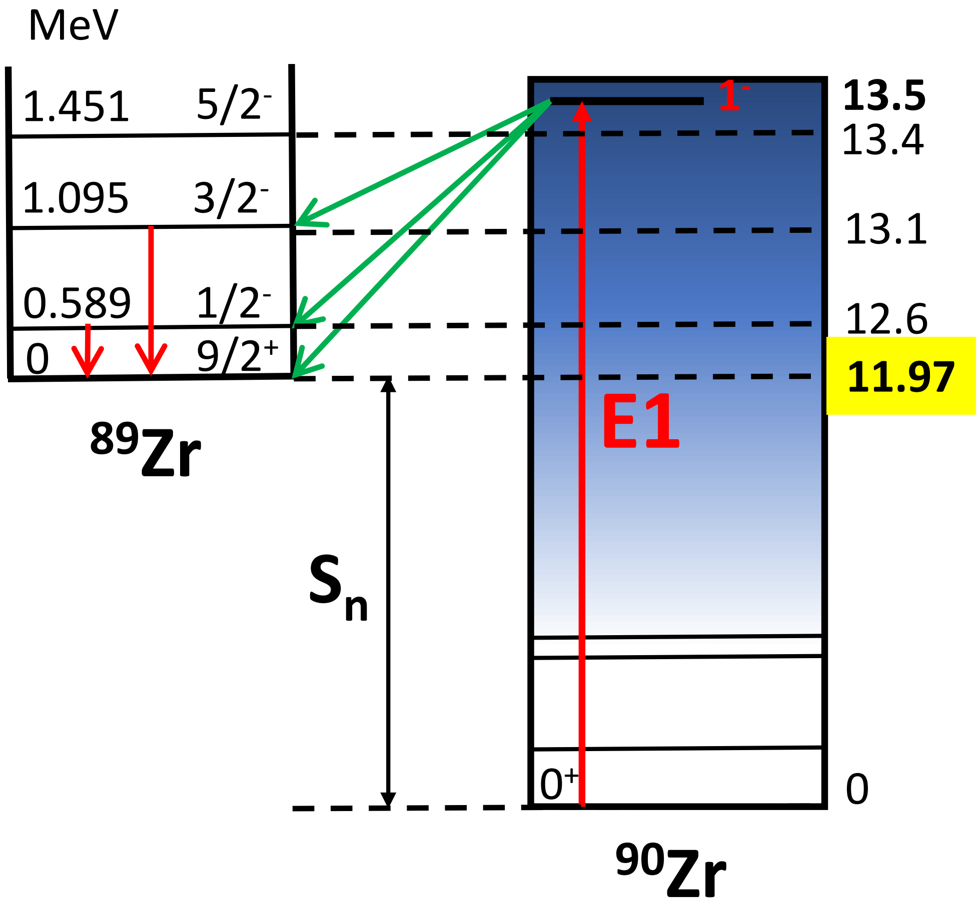


~55% @ 20 keV - ~25% @ 4 MeV

$$E_{n0} = \left(\frac{A-1}{A}\right)(E_\gamma - S_n)$$

$$E_{ni} = \left(\frac{A-1}{A}\right)(E_\gamma - S_n - E_i)$$

$^{90}Zr(\gamma,n)^{89}Zr$



$$E_{ni} = \left(\frac{89}{90}\right)(E_\gamma - S_n - E_i)$$

$\varepsilon_{ni}(E_{ni})$ – neutron efficiency from Geant4 simulations

b_i – neutron branching from TALYS calculations

$$\epsilon_n^{\text{eff}} = \sum_i b_i \epsilon_{n_i}(E_{n_i})$$

γ-ray Beam Energies (MeV): 11.75, 12, 12.1, 12.2, 12.4, 12.5, 12.8, 13, 13.5

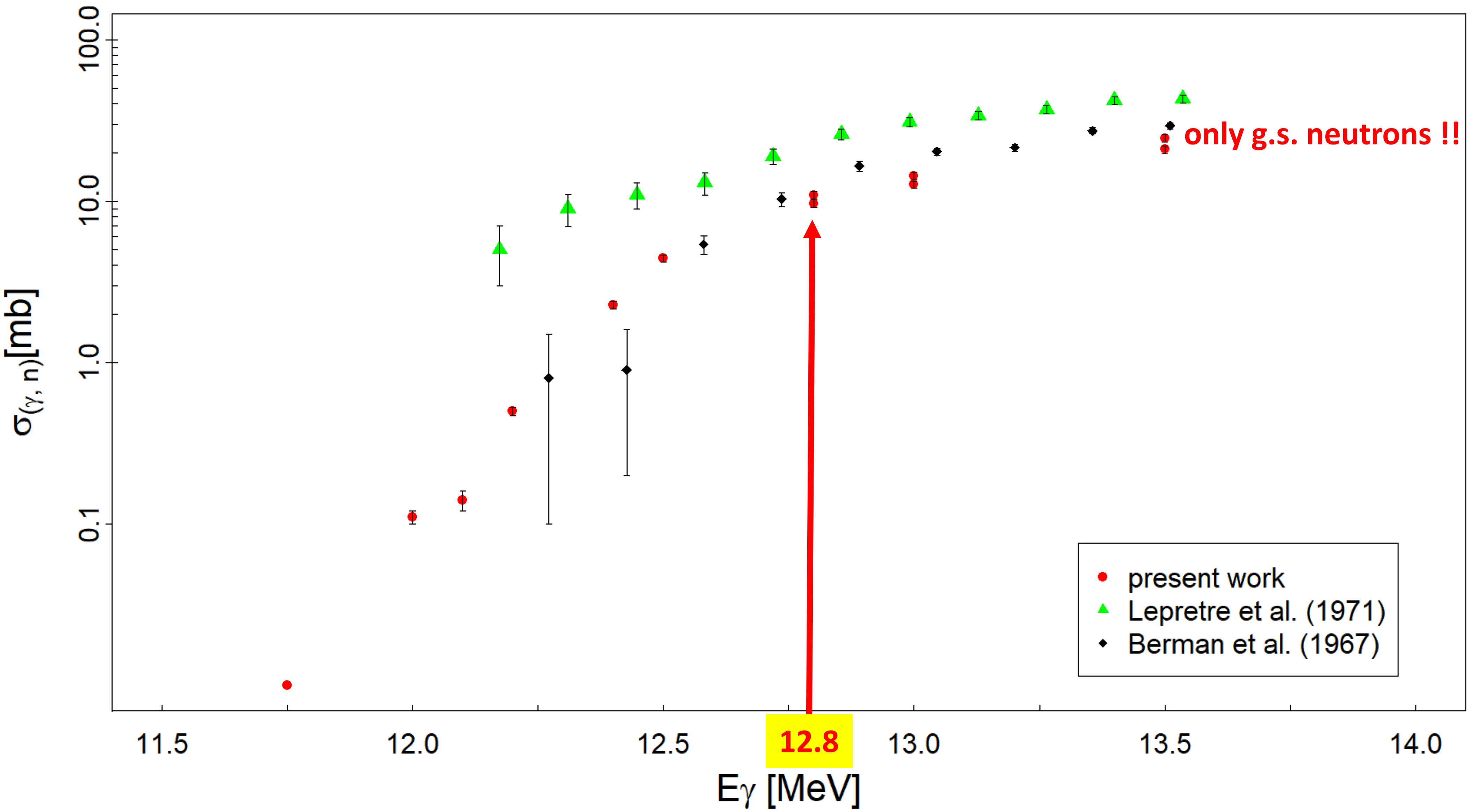
$^{90}Zr(\gamma,n)^{89}Zr$

E_γ (MeV)	E_i (MeV)	$J_i^{\pi_i}$	E_{n_i} (MeV)	l_i	ϵ_{n_i} (%)	b_i	ϵ_n^{eff} (%)
12	0	$9/2^+$	0.03	3 (f wave)	52.89	1	**52.89**
12.1	0	$9/2^+$	0.13	3 (f wave)	52.15	1	**52.15**
12.2	0	$9/2^+$	0.23	3 (f wave)	51.53	1	**51.53**
12.4	0	$9/2^+$	0.43	3 (f wave)	49.21	1	**49.21**
12.5	0	$9/2^+$	0.53	3 (f wave)	47.69	1	**47.69**
12.8	0	$9/2^+$	0.82	3 (f wave)	44.18	0.17	**49.94**
	0.5878	$1/2^-$	0.24	0 (s wave)	51.12	0.83	
13	0	$9/2^+$	1.02	3 (f wave)	41.33	0.23	**46.94**
	0.5878	$1/2^-$	0.44	0 (s wave)	48.61	0.77	
13.5	0	$9/2^+$	1.51	3 (f wave)	36.71	0.26	**42.97**
	0.5878	$1/2^-$	0.93	0 (s wave)	42.68	0.45	
	1.0949	$3/2^-$	0.43	0 (s wave)	49.02	0.29	

$^{90}Zr(\gamma,n)^{89}Zr$

E_γ (MeV)	σ_{E_γ} (MeV)	$\sigma_{(\gamma,n)}$ (mb)	$\eta = \frac{\epsilon_{n0}}{\epsilon_n^{eff}} = \frac{\sigma_{(\gamma,n)}}{\sigma_{(\gamma,n_0)}}$	
11.75	0.21	0.01 ± 0.01	1	
12	0.23	0.11 ± 0.01	1	
12.1	0.21	0.14 ± 0.02	1	
12.2	0.22	0.50 ± 0.03	1	
12.4	0.22	2.28 ± 0.12	1	
12.5	0.23	4.42 ± 0.24	1	
12.8	0.23	9.67 ± 0.52	0.88	1 excited state
13	0.22	12.66 ± 0.68	0.88	1 excited state
13.5	0.24	20.94 ± 1.13	0.85	2 excited states

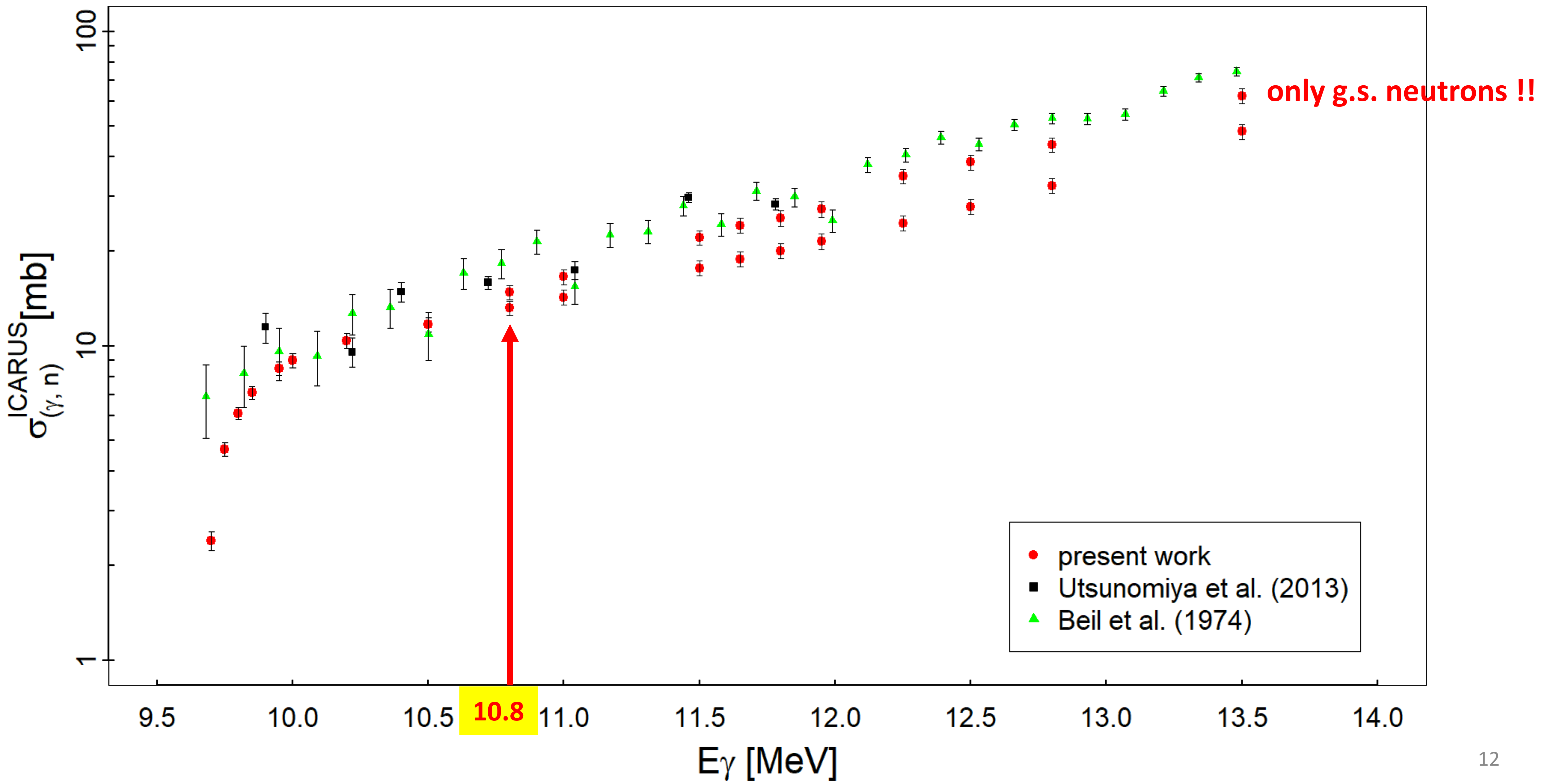
$^{90}Zr(\gamma,n)^{89}Zr$

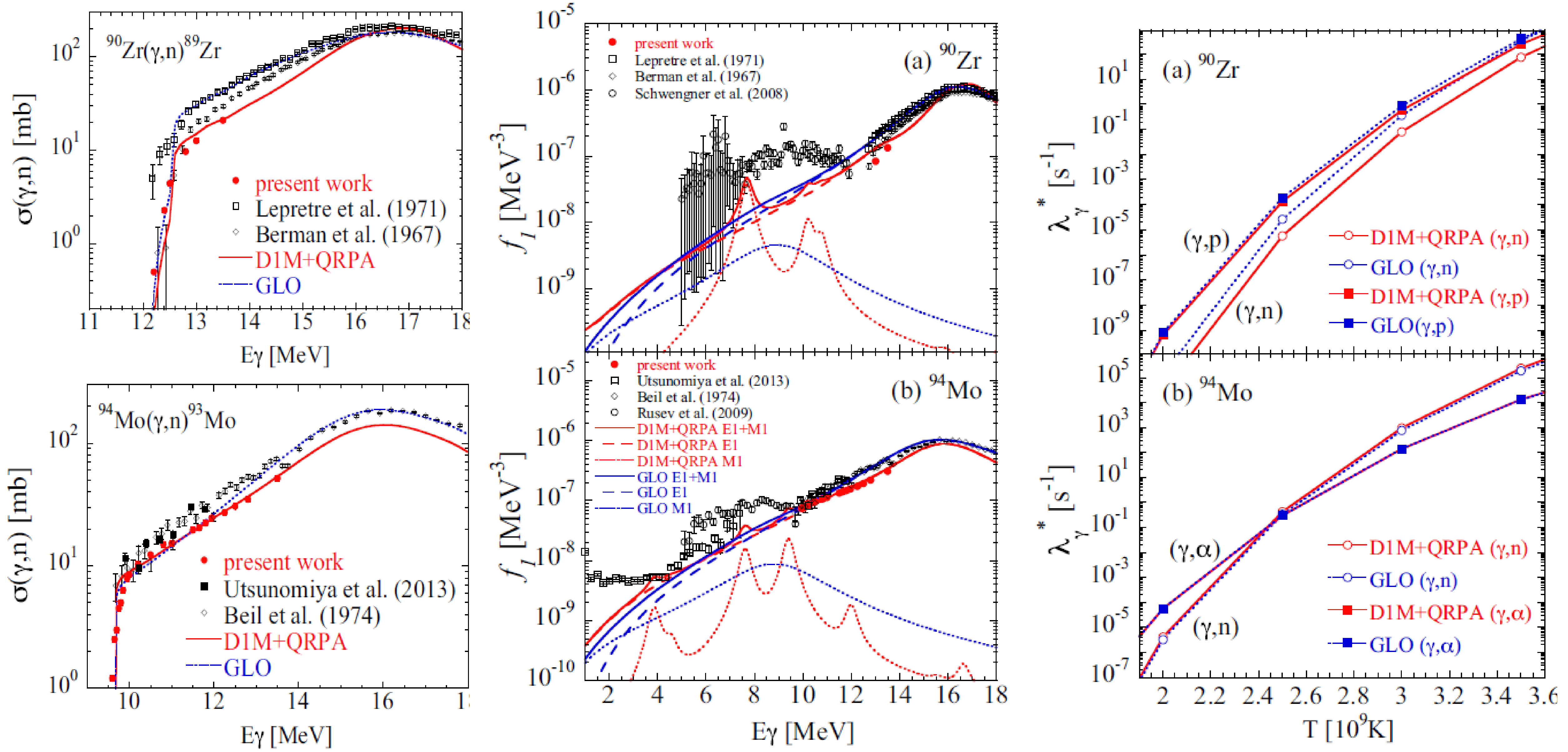


$^{94}Mo(\gamma,n)^{93}Mo$

E_γ (MeV)	σ_{E_γ} (MeV)	$\sigma_{(\gamma,n)}$ (mb)	$\eta = \frac{\epsilon_{n0}}{\epsilon_n^{eff}} = \frac{\sigma_{(\gamma,n)}}{\sigma_{(\gamma,n_0)}}$	
9.5	0.18	0.28 ± 0.02	1	
9.6	0.17	1.21 ± 0.07	1	
9.65	0.17	2.51 ± 0.14	1	
9.7	0.17	2.97 ± 0.16	1	
9.75	0.17	4.50 ± 0.24	1	
9.8	0.17	4.93 ± 0.27	1	
9.85	0.17	6.28 ± 0.34	1	
9.95	0.16	7.83 ± 0.42	1	
10	0.19	8.44 ± 0.46	1	
10.2	0.17	10.11 ± 0.55	1	
10.5	0.17	11.77 ± 0.63	1	
10.8	0.17	13.06 ± 0.70	0.89	1 excited state
11	0.17	14.53 ± 0.78	0.86	1 excited state
11.5	0.24	17.47 ± 0.94	0.80	3 excited states
11.65	0.25	18.73 ± 1.01	0.78	3 excited states
11.8	0.22	20.63 ± 1.11	0.79	3 excited states
11.95	0.23	22.61 ± 1.22	0.79	6 excited states
12.25	0.22	24.20 ± 1.30	0.71	8 excited states
12.5	0.23	27.86 ± 1.50	0.72	11 excited states
12.8	0.23	32.39 ± 1.74	0.74	14 excited states
13.5	0.24	48.64 ± 2.62	0.77	22 excited states

$^{94}Mo(\gamma,n)^{93}Mo$





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

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

Messages to take away

- Laboratory measurements of photodisintegration cross sections **cannot constrain** the actual stellar reaction rates!

- **Accurate measurements of cross sections** of photoneutron reactions help constrain the *E1* γ-ray strength function

- **Neutrons emitted from excited states** in the residual nucleus must be appropriately accounted for when extracting the photoneutron reaction cross sections

- If only **neutrons emitted from directly populated ground state** in the residual nucleus are considered, the photoneutron reaction cross sections can be overestimated!

Acknowledgments

This research is funded by the Research Corporation for Science Advancement – The Cottrell College Science Award

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The theoretical work was performed within the IAEA CRP on "Updating the Photonuclear Data Library and Generating a Reference Database for Photon Strength Functions" (F41032)