

Neutron induced cross-sections on Zr isotopes in the energy range 16-18 MeV

V. Michalopoulou¹, Z. Bari¹, I. Salonidis¹, V. Vlastou¹,
M. Kokkoris¹, M. Diakaki¹, A. Axiotis², A. Lagoyiannis²

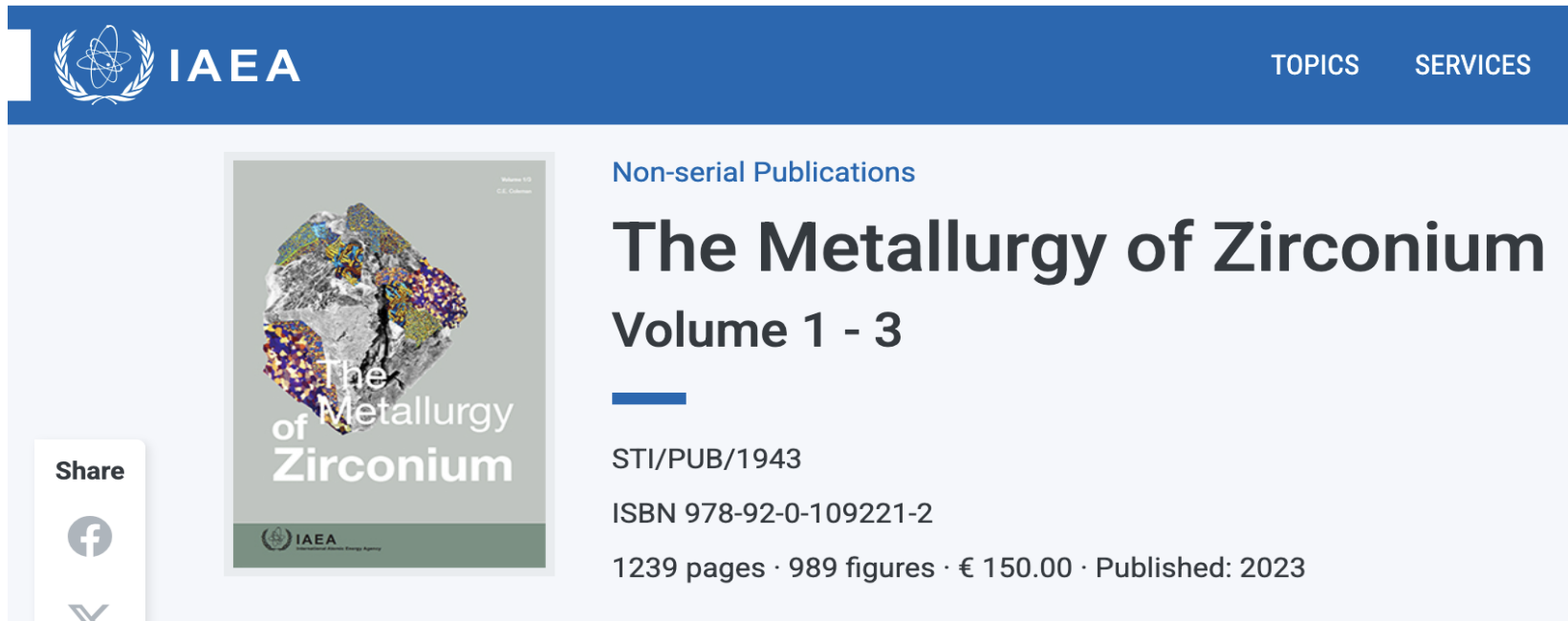
¹National Technical University of Athens, Athens Greece

*²Institute of Nuclear and Particle Physics, NCSR “Demokritos”,
Aghia Paraskevi, Greece*



Introduction

- Zr is a **highly ductile metal** with extreme **resistant to corrosion and heat**
- Has a **very low absorption rate of the neutrons** released by nuclear fission reactions
- Zr is necessary in the **production of nuclear energy**, especially as a cladding for fuel rods inside nuclear reactors
- ~90% of Zr produced in the world is used for nuclear power

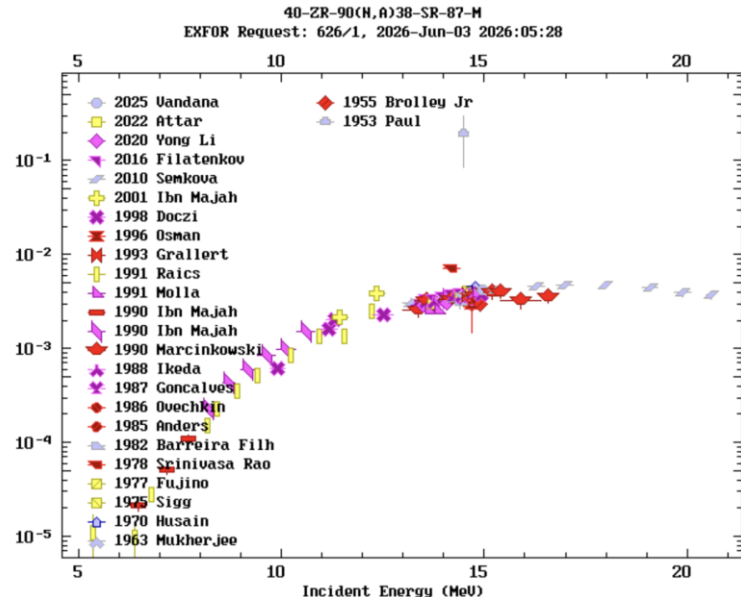
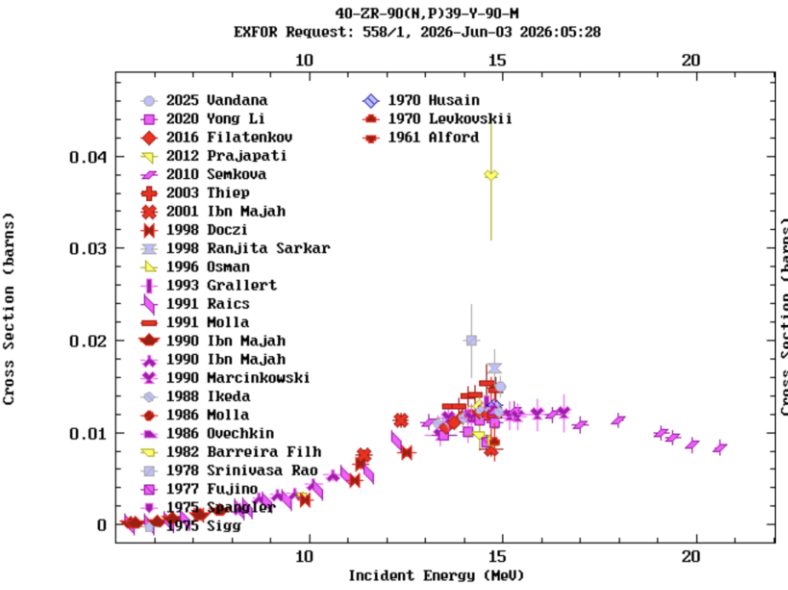


The screenshot shows the IAEA website interface. At the top left is the IAEA logo and the text 'IAEA'. To the right are the links 'TOPICS' and 'SERVICES'. Below this is a section for 'Non-serial Publications' featuring the book 'The Metallurgy of Zirconium Volume 1 - 3'. The book cover is displayed on the left, showing a 3D model of a zirconium crystal structure. To the right of the cover, the book title is prominently displayed. Below the title, the IAEA logo is visible. Further down, the book's identification numbers and details are listed: 'STI/PUB/1943', 'ISBN 978-92-0-109221-2', and '1239 pages · 989 figures · € 150.00 · Published: 2023'. On the far left of the screenshot, there is a 'Share' button with social media icons for Facebook and YouTube.



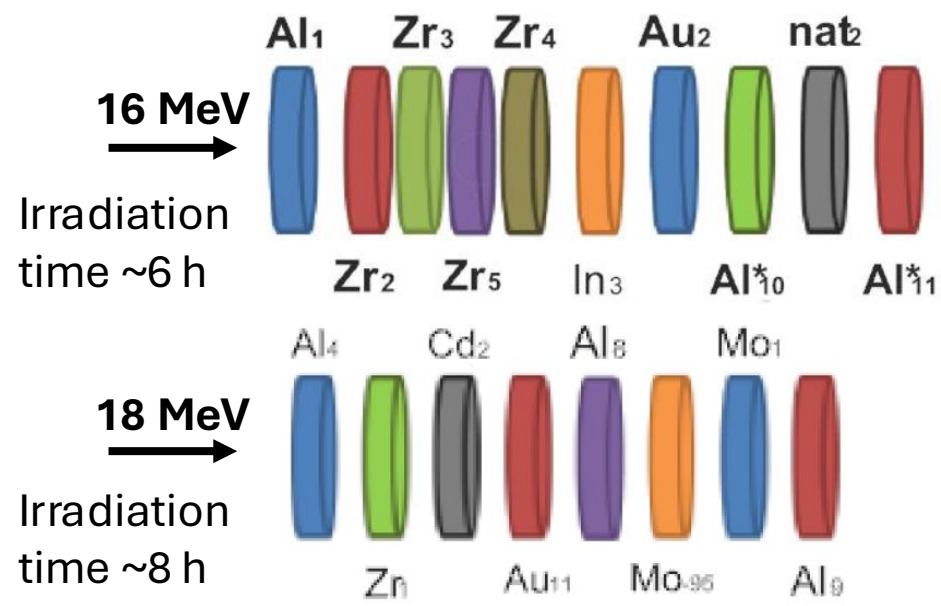
Motivation

- Neutron **cross-section data** on all isotopes of Zr must be known with **high accuracy** in a wide energy range
- **Few experimental data** exist above ~15 MeV, especially for the (n,charged) reactions
- Experimental data must be **coupled with theoretical models** to estimate nuclear data, where no experimental data exist
- Zr stable isotopes: ^{90}Zr (51.5%), ^{91}Zr (11.2%), ^{92}Zr (17.1%), ^{94}Zr (17.4%), ^{96}Zr (2.8%)



Experimental details

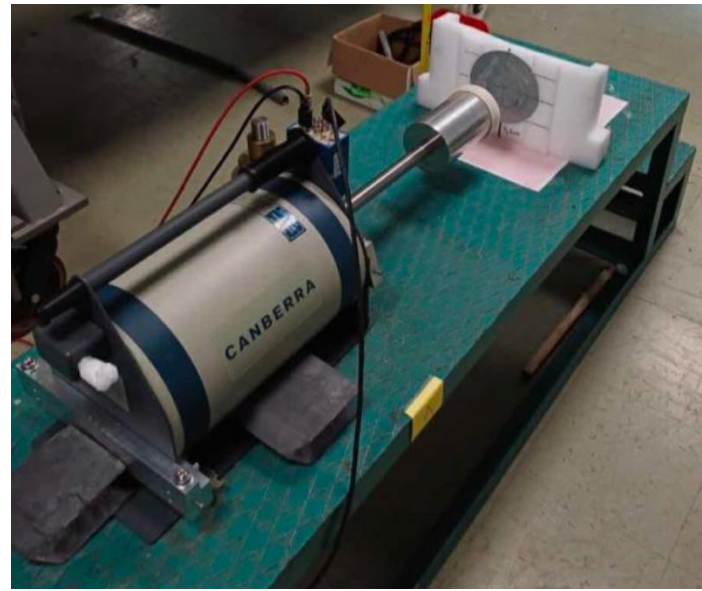
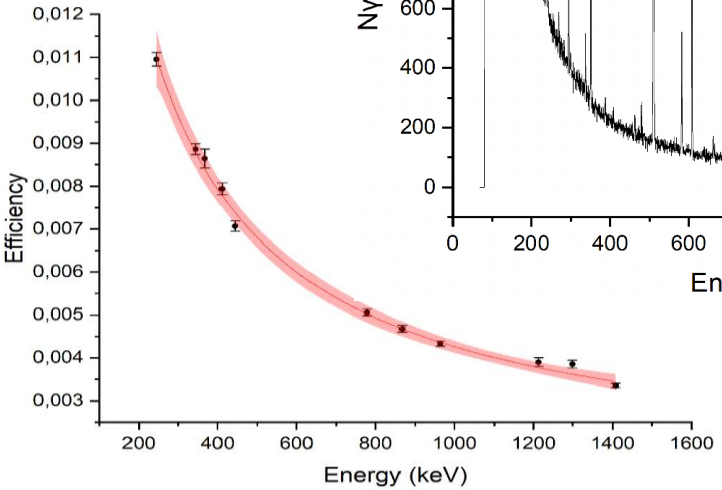
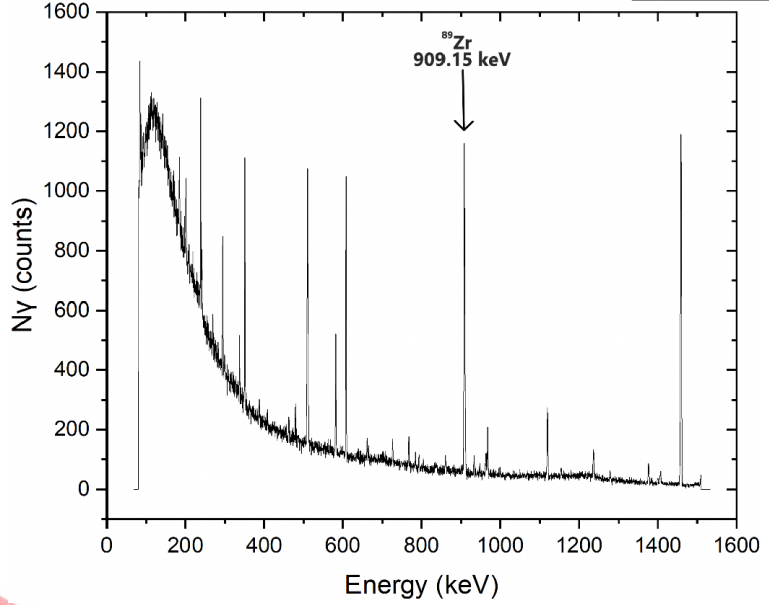
- The experiment was performed at the the **Van de Graaff Tandem accelerator of NCSR “Demokritos”**
- The $^3\text{H}(d,n)^4\text{He}$ reaction (Q-value = 17.59 MeV) was used to produce the quasi-monoenergetic neutron beams (**16-18 MeV**)
- The $^{27}\text{Al}(n,\alpha)^{24}\text{Na}$ and $^{197}\text{Au}(n,2n)^{196}\text{Au}$ reactions were used as references
- BF3 detector to monitor the variations of the neutron beam during the irradiations



Measurement of the irradiated samples

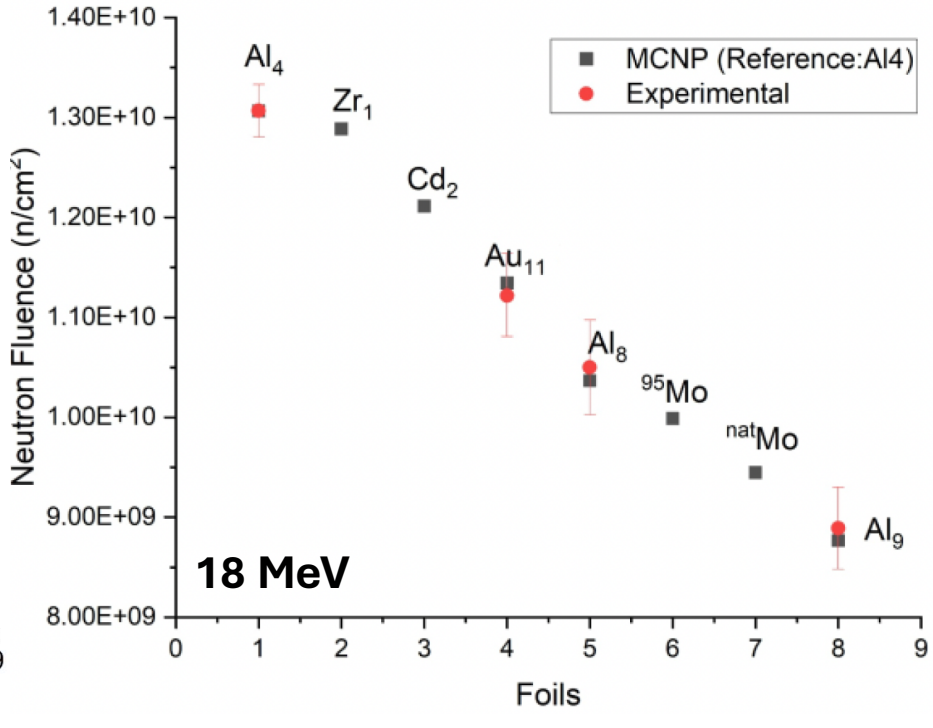
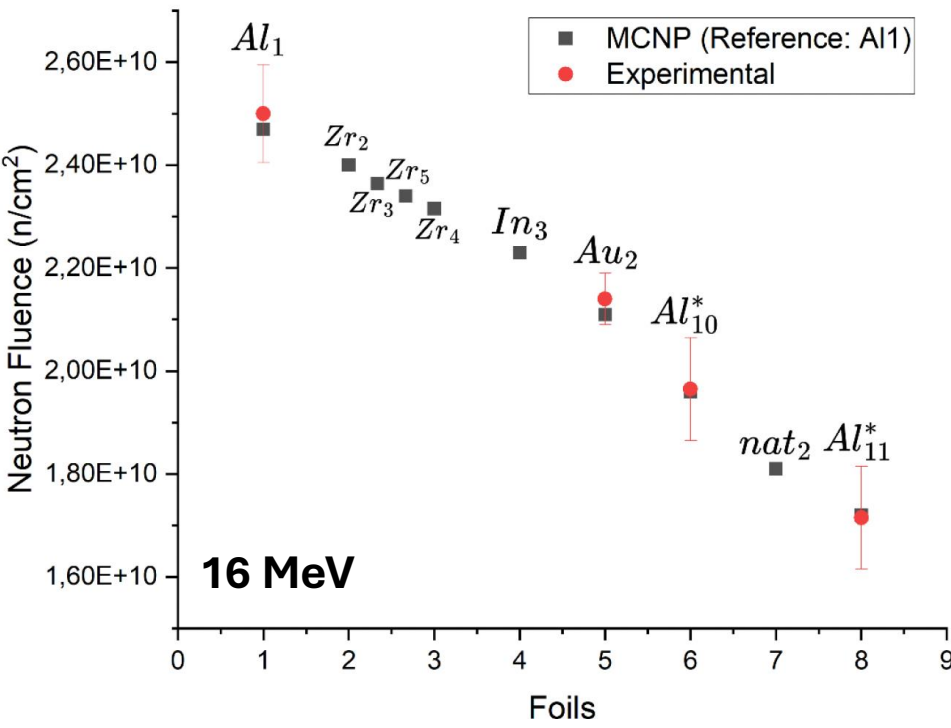
- The irradiated samples were measured at **HPGe detectors** (80% and 50%) at 12 cm
- The HPGe **efficiency** (^{152}Eu) and **background** of each detector was estimated

Reaction	$T_{1/2}$ (h)	E_{γ} (keV)	I_{γ} (%)
$^{90}\text{Zr}(n,2n)^{89}\text{Zr}$	78.41	909.15	99.04
$^{90}\text{Zr}(n,p)^{90\text{m}}\text{Y}$	3.19	202.53	3.89
		479.51	90.74
$^{90}\text{Zr}(n,\alpha)^{87\text{m}}\text{Sr}$	2.815	388.53	2.47



Neutron fluence

- **MCNP simulations** of the experimental setup with the NeuSDesc code used for the description of the neutron source
- Estimation of the **neutron fluence in each reference foil**
- **Normalization** of the simulation to the reference foils
- **Estimation** of the neutron fluence in the rest of the foils



Cross-section calculation

$$\sigma = \frac{N_{\gamma}}{\varepsilon \cdot F \cdot I_{\gamma} \cdot D \cdot f_c} \cdot \frac{1}{N_t} \cdot \frac{1}{\Phi}$$

- N_{γ} : recorded counts in each photopeak
- ε : HPGe photopeak efficiency for the specific γ -ray
- F : correction for self-absorption of γ -rays in the target (MCNP)
- I_{γ} : emission probability of the γ -ray
- D : correction factor for the decay of the produced nuclei between the end of the irradiation and the beginning of the measurements
- f_c : correction factor for the nuclei which decay during the irradiation (BF3 data)
- N_t : number of nuclei in the target
- Φ : neutron fluence (from reference targets)

$$N_t = \frac{m \cdot N_A \cdot \alpha}{A}$$

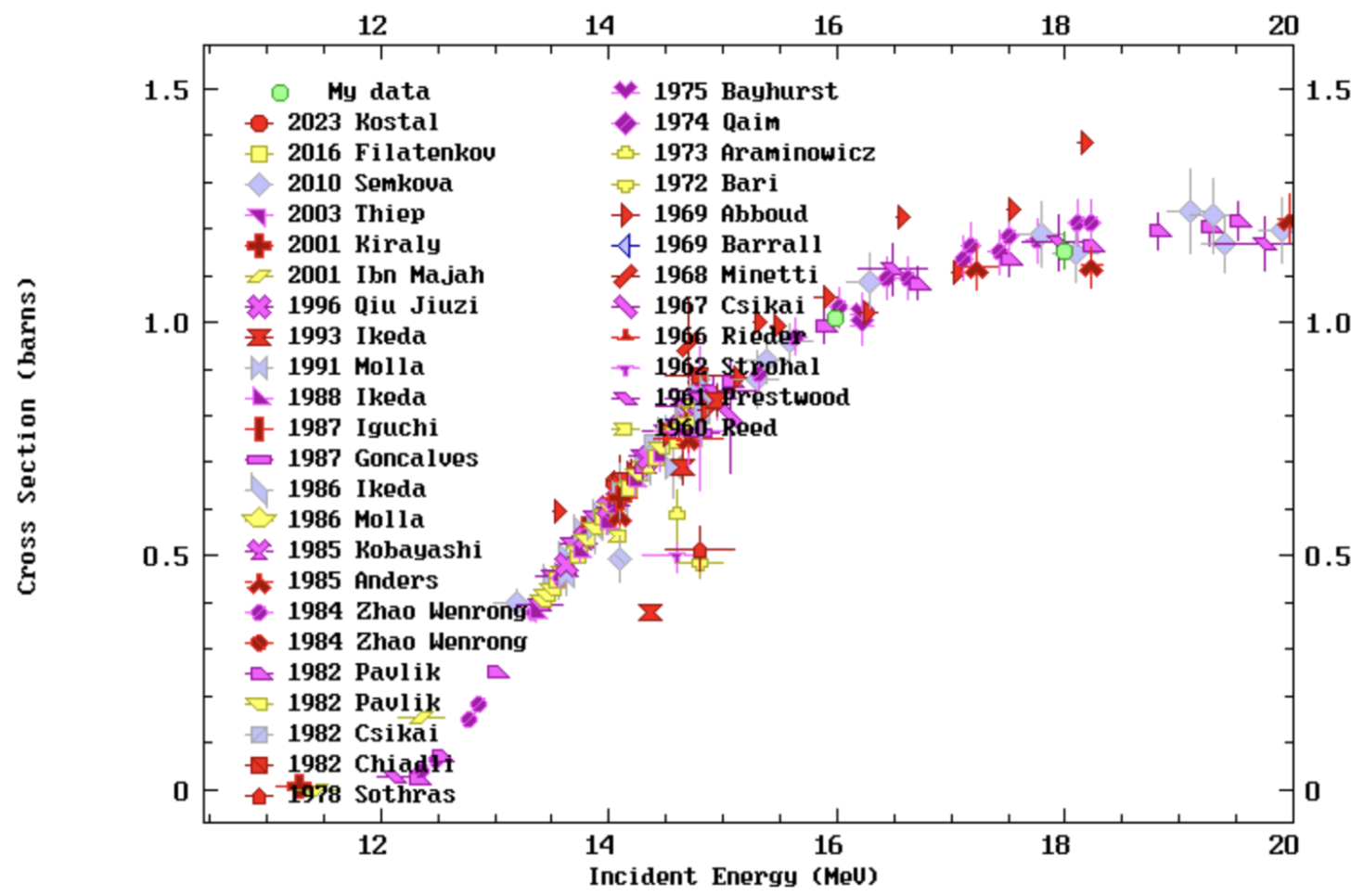
$$D = e^{-\lambda \cdot t_w} - e^{-\lambda \cdot (t_w + t_{RT})}$$

$$f_c = \frac{\int_0^{t_B} e^{\lambda \cdot t} \cdot f(t) dt}{\int_0^{t_B} f(t) dt} \cdot e^{-\lambda \cdot t_B}$$



Cross-section results – $^{90}\text{Zr}(n,2n)^{89}\text{Zr}$

40-ZR-90(N,2N)40-ZR-89
 EXFOR Request: 643/1, 2026-Jun-03 2026:05:28



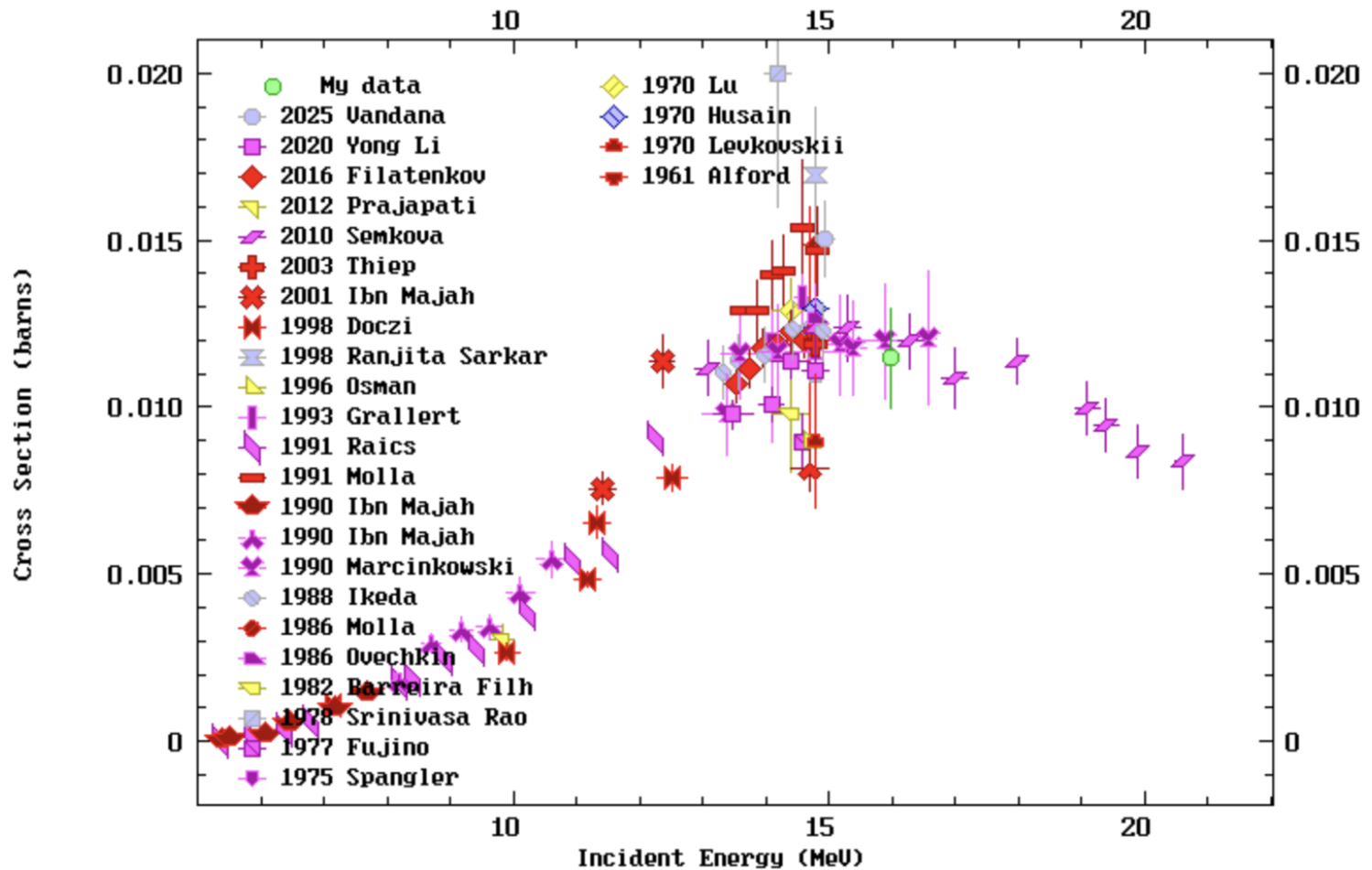
Very good agreement with previous experimental data

Few available datasets after ~18 MeV



Cross-section results – $^{90}\text{Zr}(n,p)^{90m}\text{Y}$

40-ZR-90(N,P)39-Y-90-M
 EXFOR Request: 558/1, 2026-Jun-03 2026:05:28



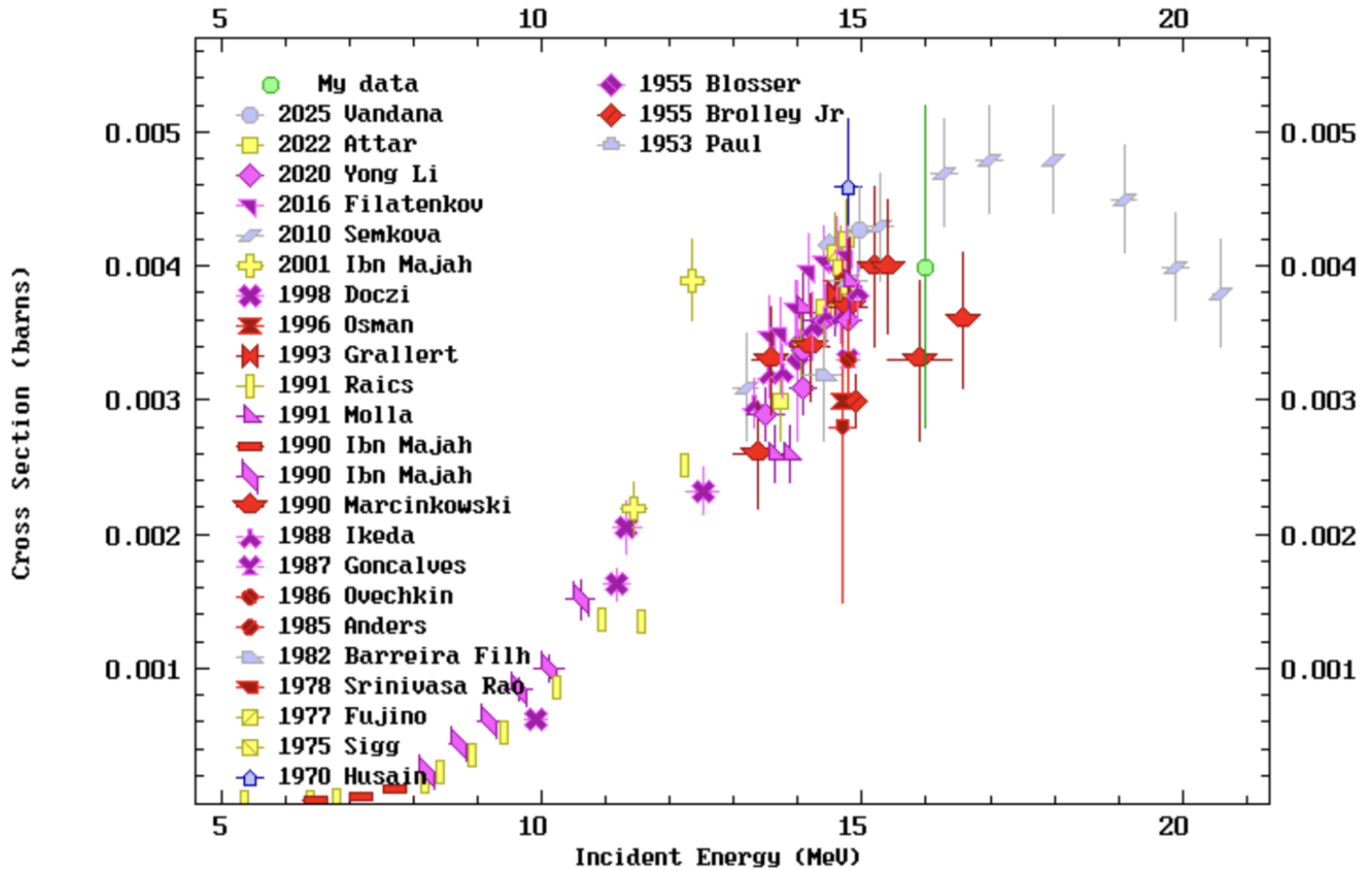
Very good agreement with previous experimental data

Only one dataset available after ~17 MeV



Cross-section results – $^{90}\text{Zr}(n,\alpha)^{87\text{m}}\text{Sr}$

40-ZR-90(N,A)38-SR-87-M
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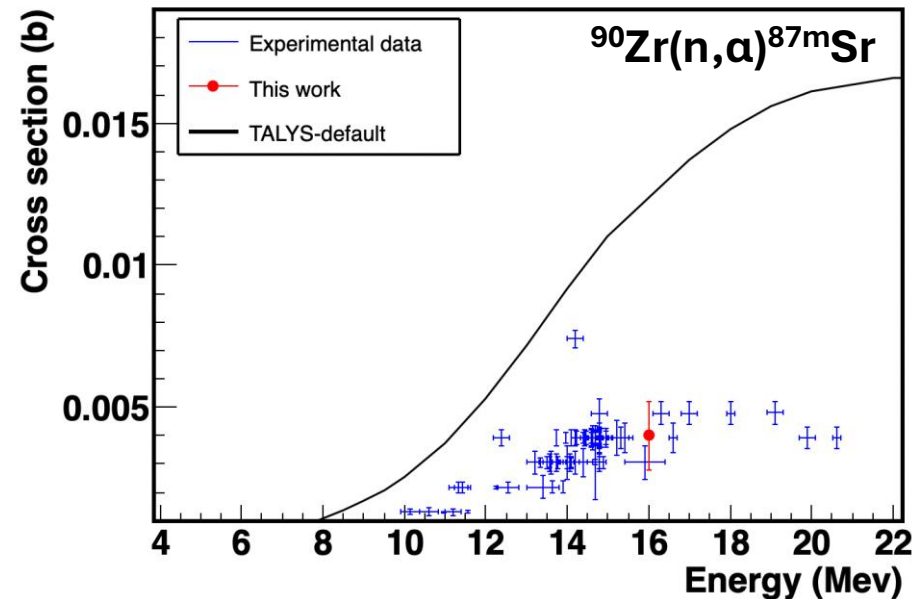
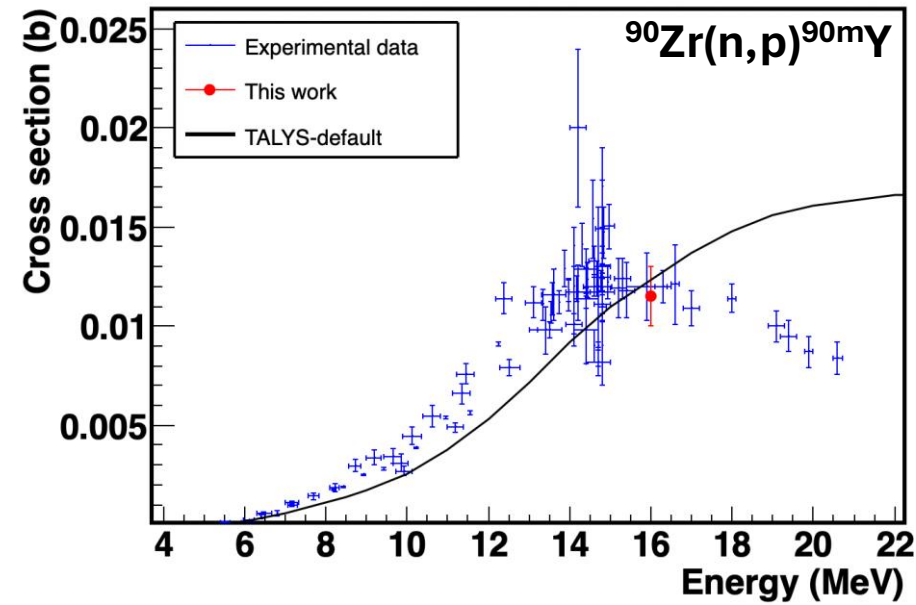
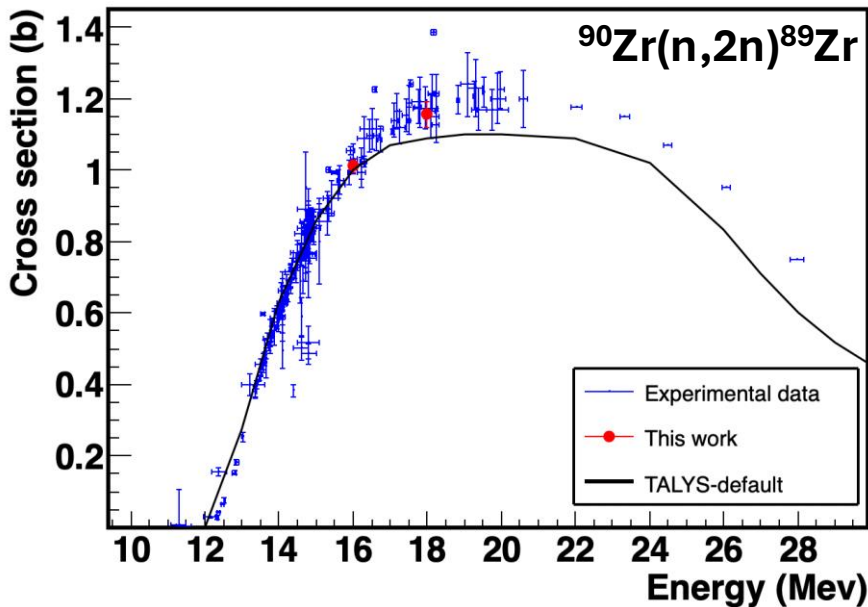


Good agreement with previous experimental data (large error)

Only one dataset available after ~17 MeV (discrepancies before)



TALYS theoretical calculations - default

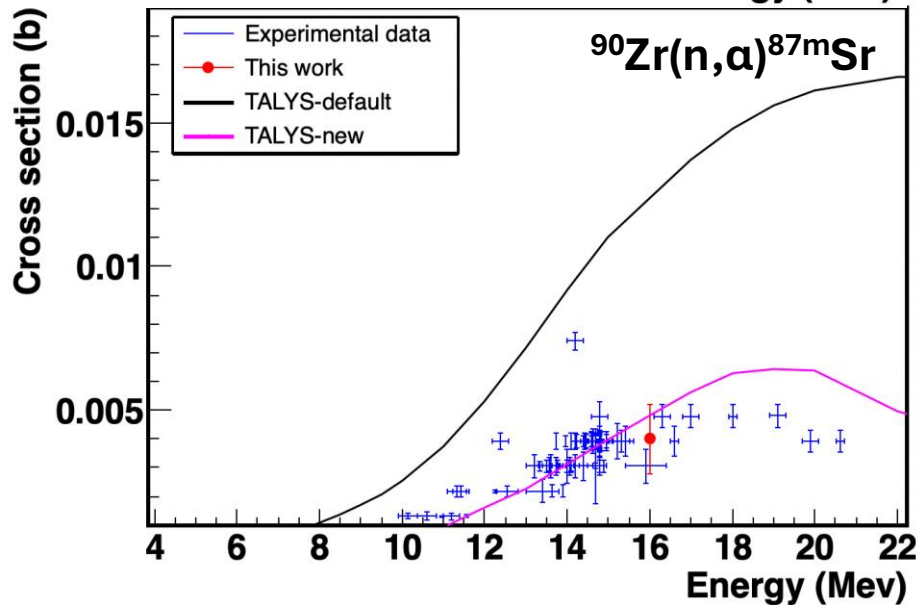
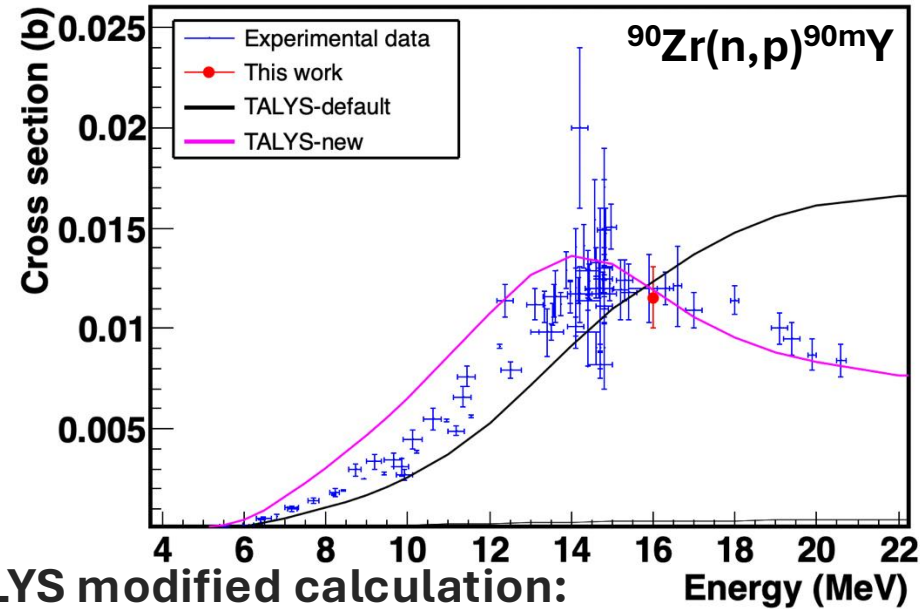
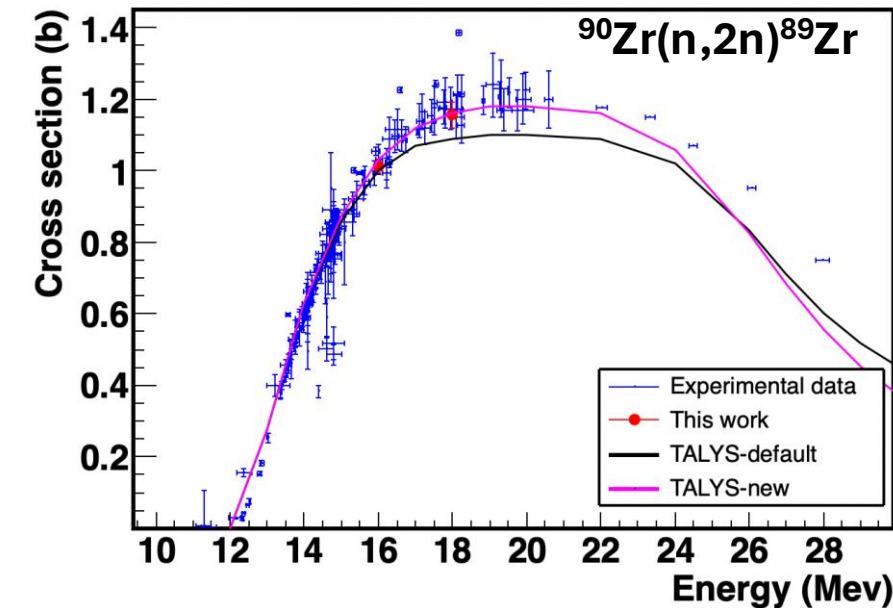


TALYS default calculation:

- Optical model potential of *A.J. Koning and J.P. Delaroche* (nucleus-specific optical model)
- Model for level densities *Constant Temperature + Fermi gas model (CTM)* (phenomenological)
- Preequilibrium model *Exciton model: Numerical transition rates with energy-dependent matrix element.*



TALYS theoretical calculations - modified

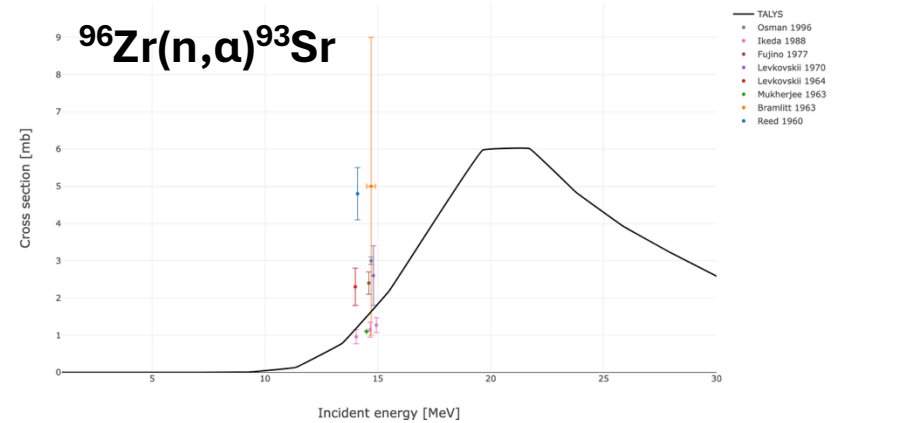
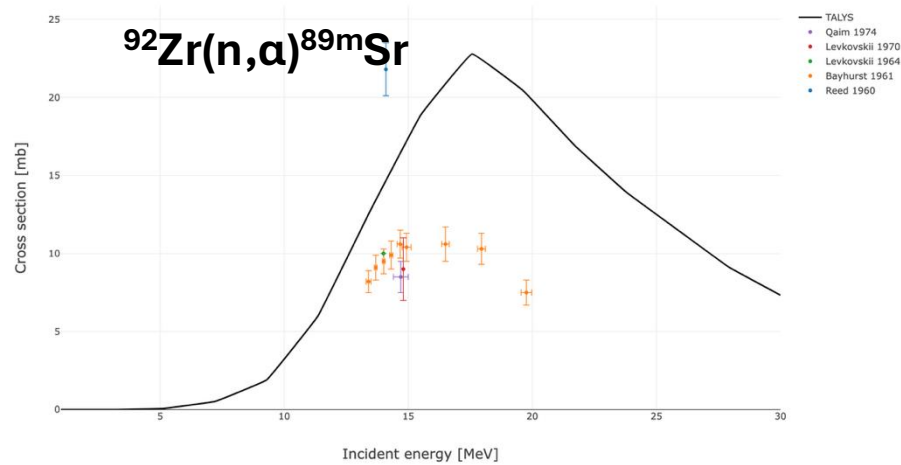
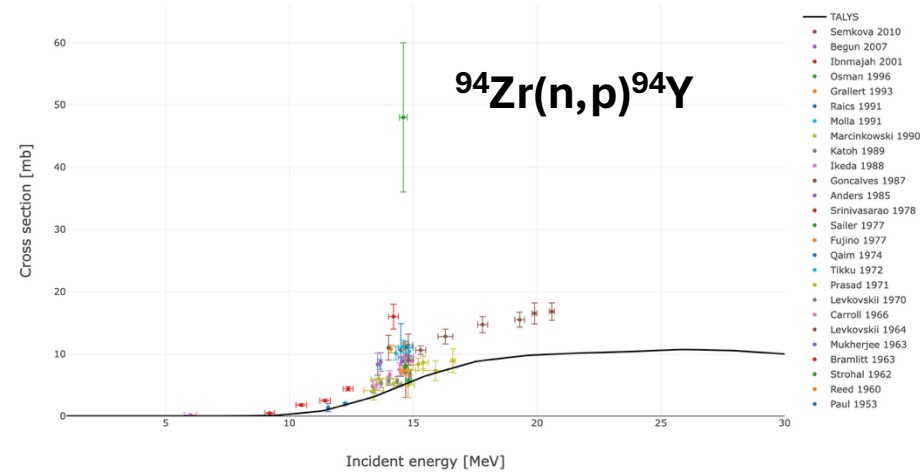
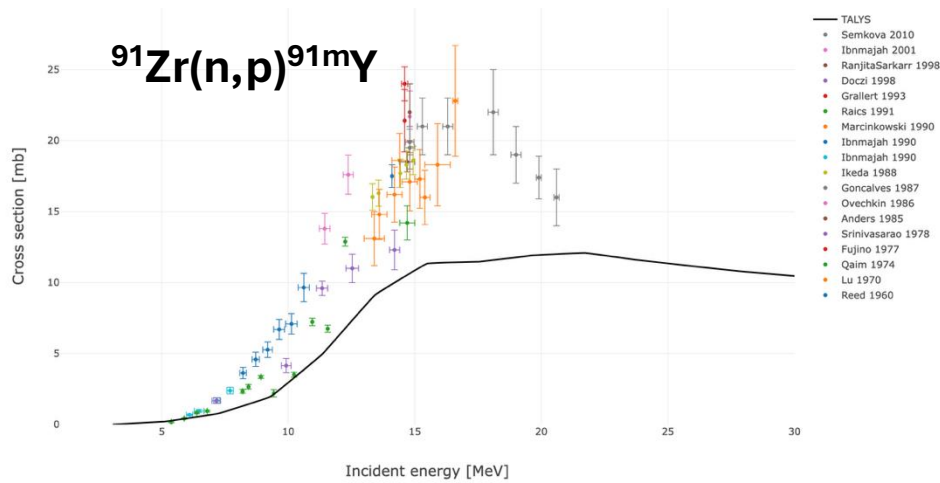


TALYS modified calculation:

- Optical model potential of *A.J. Koning and J.P. Delaroche*
- Model for **level densities** *Back-shifted Fermi gas Model (BFM)* (phenomenological)
- **Preequilibrium model** *Exciton model: Numerical transition rates with optical model for collision probability*
- **Optical model volume radius** *adjusted for protons*



TALYS theoretical calculations – other isotopes



Same parameters as ^{90}Zr used in TALYS calculation
In general, the cross-section is not described very well



Conclusions - future perspectives

- Measurement of natural Zr targets with the activation technique at 16 and 18 MeV
- Additional energies on Zr reactions (in analysis phase)
- Monoisotopic targets to measure (if available!)
- More extensive theoretical calculations to reproduce the other isotopes
- Experimental data are needed to improve theoretical models

Thank you for your attention!

