Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

Istituto Nazionale
di Fisica Nucleare
Sezione di Bologna

Summary of the results of a new measurement of natural erbium Xs(n,γ) between 1-100 eV

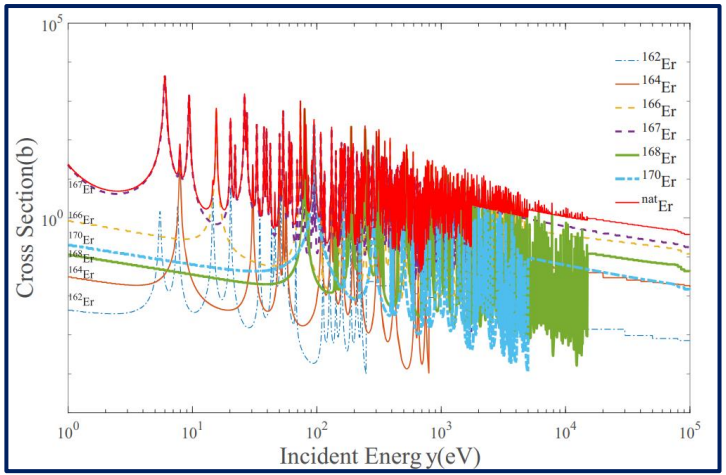
N_TOF Italian national meeting, Pavia 30/11/2021

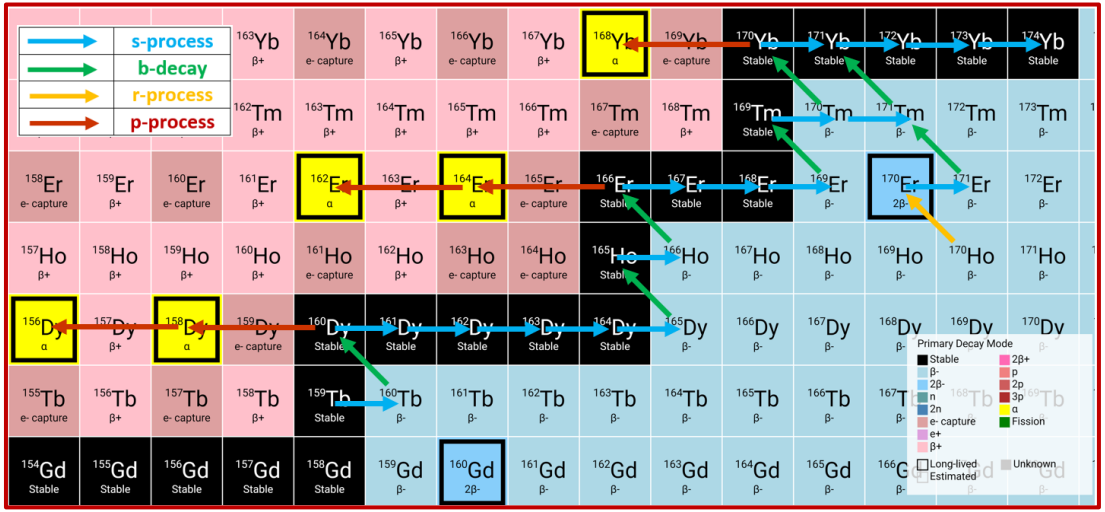
X.X. Li et alt., ***New experimental measurements of natural erbium Xs(n,γ) between 1-100 eV, 2021***

Erbium – astrophysics importance

- Natural Erbium has **six stable isotopes**:

- Er-166, Er-167, Er-168, **s process**;
- Er-170, **r process**;
- Er-162, Er-164, **p-process** (**p-nuclei**).





- Er-166, Er-167, Er-168, Er-170 Xs(n,γ) are of great significance for understanding the pathways taken during the *s process;*
- Er-162, Er-164 Xs(n,g) measurements can help to better understand the results of relevant photonuclear reaction experiments.

Isotopes	Er-162	Er-164	Er-166	Er-167	Er-168	Er-170
%at	0.139	1.606	33.503	22.869	26.940	14.910

X.X. Li et alt results – *New exp. measurements of nat. erbium(n,γ) cross sections between 1-100 eV, 2020*

Erbium – experimental setup

- Experimental facility: China spallation neutron source (CSNS), mainly used for exp. study of neutron scattering;
- Detection system: four C_6D_6 scintillator installed 76 m away from the spallation target;
- Neutron flux: measured using a silicon monitor based on the $^{6}Li(n,\alpha)^{3}H$ reaction, energy range 0.5 eV÷200 MeV;
- Experimental time: a total of 105 h, natural erbium target @ 72h in beam power 50.5-51.5 kW;
- Experimental targets: ^{nat}Er, ^{nat}C, ^{197}Au.

TABLE I. Information of experimental targets.

Material	Formula	Diameter	Thickness	Mass
^{nat}Er	Er > 99.742% Gd = 0.018% Tm <0.005% Fe <0.050% Mg <0.050% Ni <0.050% Si = 0.012% C <0.010% W = 0.035% Ca = 0.023% Tb <0.005% Eu <0.010% Dy <0.020% Sm = 0.010% Yb = 0.010%	50.000(±0.001) mm	1.000(±0.001) mm	4.565(±0.001) *g*
^{nat}C	C >99.900%	50.000(±0.001) mm	1.000(±0.001) mm	4.583(±0.001) g
^{197}Au	Au >99.900%	30.000(±0.001) mm	1.000(±0.001) mm	13.768(±0.001) g

Erbium – experimental error

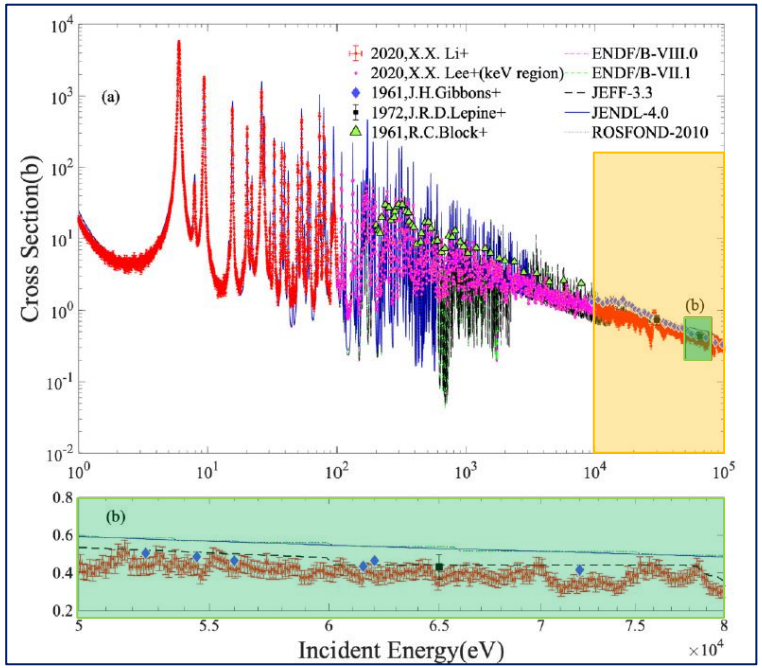
- Experimental error: exp. conditions uncertainty, data analysis method uncertainty, exp. statistical error;

TABLE III. The statistical error and systematic error of the experiment

σ	Meaning	Value
	Experimental conditions	
σ (Beam power)	Uncertainty from beam power	<1.98%
$\sigma(I_1)$	Uncertainty from energy spectra above 0.15 MeV	<4.50%
$\sigma(I_2)$	Uncertainty from energy spectra below 0.15 MeV	<8.00%
	Data analysis	
σ (PHWT)	Uncertainty from PHWT method	<3.00%
σ (Normalized)	Uncertainty from normalized	<1.00%
σ (In beam)	Uncertainty from counts of in-beam BKG	<6.51%
$\sigma(T)$	Uncertainty from target parameters	<0.10%
	Statistical error	
σ (Statistic)	Uncertainty from mathematical statistics	<0.18%

Erbium – results (10-100 keV) @ 2021

- The results were compared with those existing experimental data in 10-100 keV region:

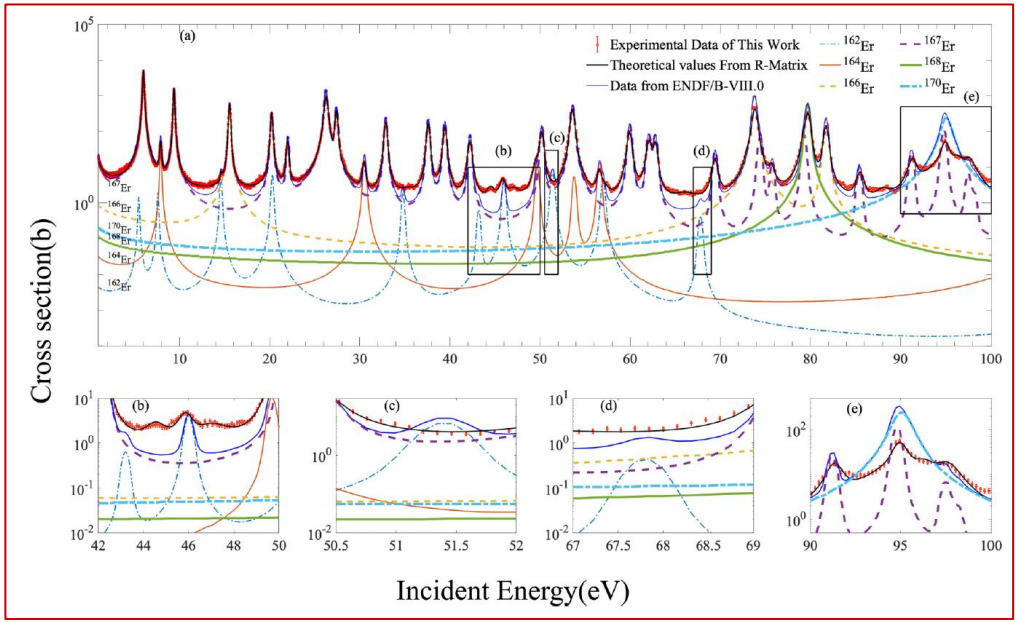


- **10 ÷ 100 keV:**
  - New data shows good agreement with some evaluated and experimental data;
  - The experimental data results could be greatly improved with a more accurate response function of the beam-line.

- **50 ÷ 80 keV:**
  - Three set of experimental data are basically the same and all lower the evaluation database, good agreement with JEFF-3.3.

Erbium – results (1-100 eV) @ 2021

- The only experimental data (EXFOR) for erbium natural element in the 1-100 eV energy region are:
  - Haddan et al. (0.1-1.2 eV), TOF, liquid scintillator, **1963;**
  - X.X. Li (1-100 eV), TOF, C_6D_6 scintillator, **2021**.



- 42 ÷ 50 eV: R matrix program fitting shows that the two nearby faint bumbs to 45.846 eV (due to Er-162) are not real resonance;
- 50.5 ÷ 69 eV: Er-162 should have weak resonance peaks at 51.4 eV and 67.8 eV (ENDF/B-VII.0), no obvious resonance structure found in experimental data.
- 90 ÷ 100 eV: three narrow resonance of Er-167 and a wide resonance of Er-170. Surprisingly the Er-170 contribute seemed to widely off
- Recommend a separate further measurement of the Xs(n,g) of Er-170

Erbium – considerations (1-100 eV) @ 2021

- The resonance peak of natural erbium in the energy region of 1-100 eV is mostly contributed by Er-167 and Er-162, although their abundance is not the largest;
- Most of the discrepancies in the experiments that did not match expectations were related to Er-162;
- Er-162 is the p nuclei in astrophysics. Its resonance structure is significant for astrophysics, it would be necessary to use the high-purity isotope Er-162 for fine measurements analysis.

TABLE IV. Resonance parameters extracted from the *R*-matrix analysis of experimental data.

										ENDF/B-VIII.0	
$E_{Experiment}$(eV)	$E_{Resonance}$(eV)	Mass	abundance (%)	I	l	J	g	Γ_γ(meV)	Γ_n(meV)	Γ_γ(meV)	Γ_n(meV)
6.00	5.73	162.00	0.139	0.00	0.00	0.50	1.00	103.12	0.36	100.00	0.33
	6.00	167.00	22.869	3.50	0.00	3.00	0.44	95.61	20.32	103.00	20.69
	7.75	162.00	0.139	0.00	0.00	0.50	1.00	99.46	0.58	100.00	0.60
7.95	7.94	167.00	22.869	3.50	0.00	4.00	0.56	89.62	0.12	98.80	0.17
	7.85	164.00	1.606	0.00	0.00	0.50	1.00	84.69	0.59	96.00	0.75
9.29	9.39	167.00	22.869	3.50	0.00	3.00	0.44	67.38	9.30	88.30	9.20
14.63	14.63	162.00	0.139	0.00	0.00	0.50	1.00	111.40	2.80	100.00	4.10
15.55	15.55	166.00	33.503	0.00	0.00	0.50	1.00	88.61	1.93	94.00	2.20
20.22	20.29	162.00	0.139	0.00	0.00	0.50	1.00	100.42	8.28	100.00	8.30
	20.22	167.00	22.869	3.50	0.00	4.00	0.56	100.38	4.52	88.00	4.62
21.98	21.98	167.00	22.869	3.50	0.00	3.00	0.44	123.11	1.40	87.00	1.30
26.27	26.27	167.00	22.869	3.50	0.00	3.00	0.44	102.22	108.60	92.00	94.86
27.41	27.41	167.00	22.869	3.50	0.00	4.00	0.56	116.09	9.96	84.00	10.49
30.42	30.46	164.00	1.606	0.00	0.00	0.50	1.00	104.42	2.25	96.00	4.10
32.88	32.88	167.00	22.869	3.50	0.00	4.00	0.56	108.78	6.77	91.00	6.76
34.82	35.47	162.00	0.139	0.00	0.00	0.50	1.00	105.19	3.13	100.00	5.10
37.5	37.59	167.00	22.869	3.50	0.00	4.00	0.56	124.49	7.31	82.00	7.11
39.44	39.44	167.00	22.869	3.50	0.00	3.00	0.44	138.84	6.95	90.00	8.91
42.22	42.22	167.00	22.869	3.50	0.00	3.00	0.44	151.63	3.16	100.00	3.89
44.51	43.25	162.00	0.139	0.00	0.00	0.50	1.00	101.47	2.12	100.00	2.20
45.85	45.85	162.00	0.139	0.00	0.00	0.50	1.00	105.45	18.68	100.00	19.50
49.61	49.61	164.00	1.606	0.00	0.00	0.50	1.00	105.49	4.35	96.00	4.00
50.18	50.18	167.00	22.869	3.50	0.00	4.00	0.56	135.49	7.30	83.00	6.93
53.60	53.60	167.00	22.869	3.50	0.00	4.00	0.56	126.51	49.16	97.00	48.00
	53.80	164.00	1.606	0.00	0.00	0.50	1.00	95.12	2.42	96.00	2.30
56.57	56.57	164.00	1.606	0.00	0.00	0.50	1.00	103.47	3.42	96.00	6.60
	57.02	162.00	0.139	0.00	0.00	0.50	1.00	101.50	12.95	100.00	32.00
59.92	59.92	167.00	22.869	3.50	0.00	3.00	0.44	143.33	15.00	92.00	14.86
62.12	62.12	167.00	22.869	3.50	0.00	4.00	0.56	118.34	5.38	88.00	5.69
62.79	62.79	167.00	22.869	3.50	0.00	3.00	0.44	112.59	6.68	88.00	7.09
66.05	67.80	162.00	0.139	0.00	0.00	0.50	1.00	100.60	2.55	100.00	3.10
69.40	69.40	167.00	22.869	3.50	0.00	4.00	0.56	122.14	2.32	102.00	2.31
73.79	73.79	166.00	33.503	0.00	0.00	0.50	1.00	111.32	24.96	76.00	65.00
73.84	73.84	167.00	22.869	3.50	0.00	4.00	0.56	96.15	5.40	88.00	5.69
75.69	75.69	167.00	22.869	3.50	0.00	4.00	0.56	93.33	0.96	88.00	1.05
79.28	79.28	167.00	22.869	3.50	0.00	3.00	0.44	102.07	10.49	88.00	11.43
79.74	79.74	168.00	26.940	0.00	0.00	0.50	1.00	100.32	31.18	80.00	41.00
81.73	81.73	166.00	33.503	0.00	0.00	0.50	1.00	128.27	6.14	82.00	9.50
85.50	85.50	167.00	22.869	3.50	0.00	3.00	0.44	90.06	1.33	88.00	1.42
91.33	91.33	167.00	22.869	3.50	0.00	4.00	0.56	100.12	3.12	88.00	3.02
94.45	94.45	167.00	22.869	3.50	0.00	4.00	0.56	82.30	10.41	80.00	17.07
97.38	97.38	167.00	22.869	3.50	0.00	4.00	0.56	88.77	0.94	88.00	0.85
98.02	98.02	167.00	22.869	3.50	0.00	4.00	0.56	87.97	0.22	88.00	0.21

Conclusions

- This work has supplemented and perfected the vacancy in the measurement data of neutron capture cross sections of the natural erbium in the 1-100 eV energy region;
- The results shows that Er-162, Er-164 and Er-167 isotopes have a greater influence on the resonance peak of natural erbium in the 1-100 eV energy region;
- Some experimental measurements of the resonance peak parameters and the ENDF evaluation database are different;
- In particular, there are some possible weak resonance peak difference between the Er-162 isotopes experimental measurements and evaluation database;
- We recommended taking further experimental studies for the neutron capture cross sections of isotopes of erbium, particularly Er-162 isotopes;
- More accurate neutron source energy spectrum and detailed background measurements can significantly improve the neutron capture cross sections and nuclear astrophysics neutron capture rate research.