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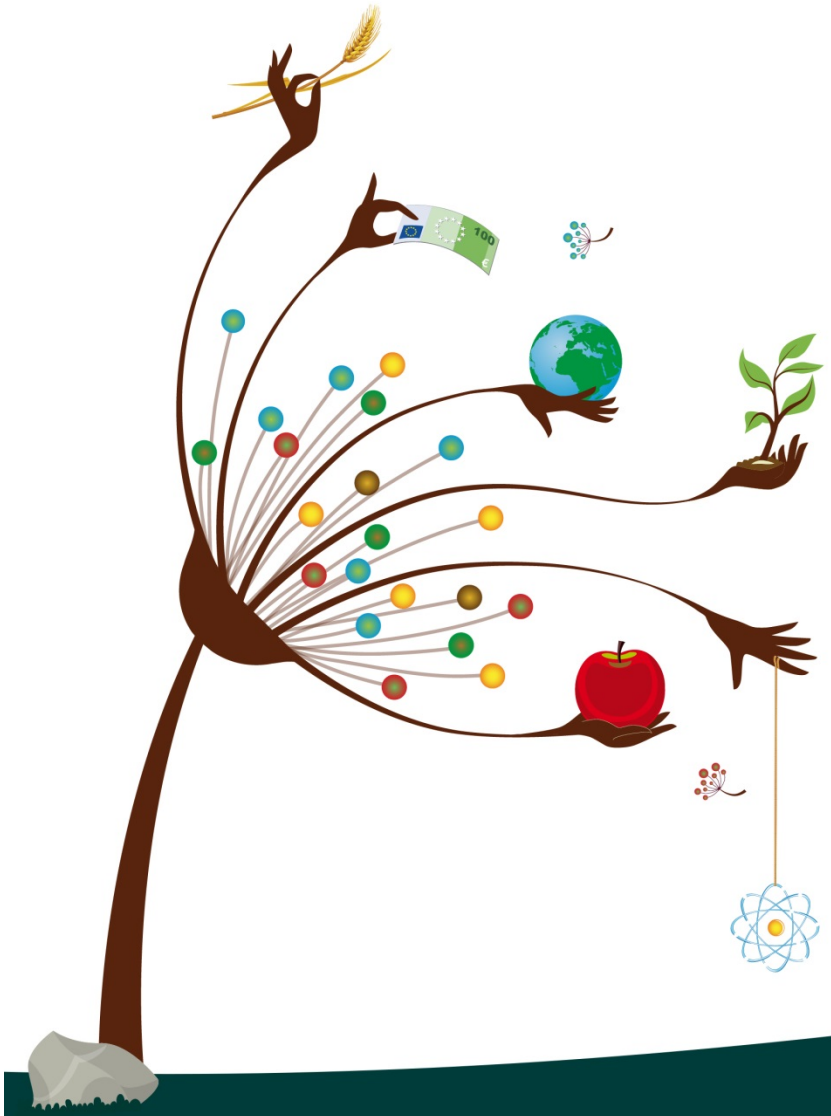

The cross section functions for neutron reactions with Rhenium in the energy range 13.0 -19.5 MeV

N. Jovančević[1], L. Daraban[2], H. Stroh[2], S. Oberstedt[2], M. Hult[2], C. Bonaldi[2], W. Geerts[2], F.-J. Hambsch[2], G. Lutter[2], G. Marissens[2] and M. Vidali[2]

[1]Department of Physics, University of Novi Sad, Novi Sad, Serbia
[2]EC, JRC, IRMM, Geel, Belgium

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Contents

1. Introduction

- Application of different neutron induced nuclear reaction as well as theoretical research request the new measurements of cross section data in a wide energy range.

- **NAXSUN** technique (Neutron Activation X-Section determined using UNfolding) was developed at the JRC-IRMM .

- **Rhenium** (^{185}Re (37.4%) and ^{187}Re (62.6%))
  - high-temperature corrosion resistant material
  - used for cancer treatment/diagnostics
  - the Re/Os cosmos-chronometry
- A lack of existed satisfactory data for the neutron excitation cross-section values for neuron induced reactions on Re.

- **^{187}Re(n, α)^{184}Ta, ^{187}Re(n, 2n)^{186}Re, ^{185}Re(n, 2n)^{184}Re, ^{187}Re(n, p)^{187}W and ^{185}Re(n, 3n)^{183}Re** for **E_n = 13.0 – 19.5MeV**

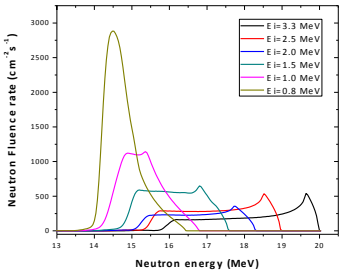
2. The NAXSUN method

$$A_k + \varepsilon_k = \sum_i \Phi_{ki} \cdot \sigma_i, i = 1,2...c, k = 1,2,..m$$

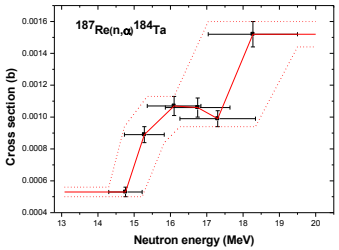
A_k = measured values
e_k = measurement uncertainties
s_i = cross sections
F_{ki} = neutron spectrum

Disk No	A (Br/ atom)
1	
2	
...	

Measured disk activities



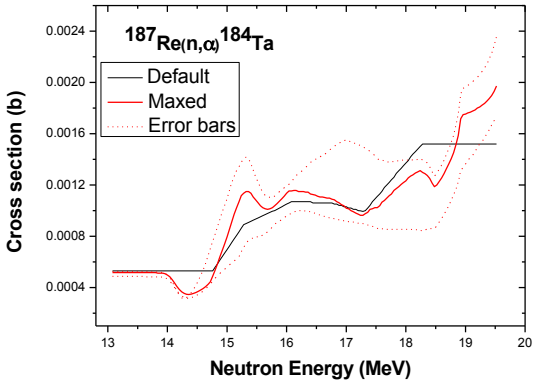
Neutron Fluence data



Default cross section function spectra

Spectrum unfolding

(MAXED, GRAVEL)



Cross-section excitation function

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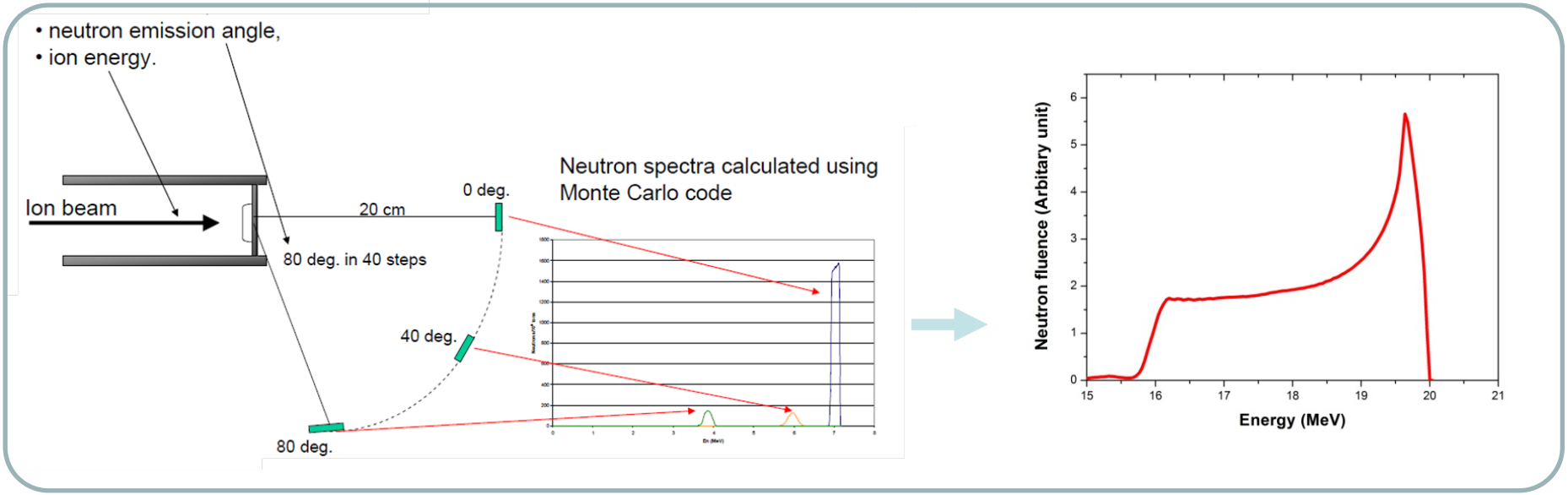
2. The NAXSUN method

- Wide-energy overlapping neutron beams
- By **scanning of the disks over different angles** relative to the ion beam during irradiation, the samples were exposed to a total neutron spectrum over a broad-energy region.

- Neutron produce reaction:
  - $^{7}Li(p,n)^{7}Be$, En: 0 - 5.3 MeV
  - $T(p,n)^{3}He$, En: 0 - 6.2 MeV
  - $D(d,n)^{3}He$, En: 1.8 - 10.1 MeV
  - $T(d,n)^{4}He$, En: 12.1 - 24.1 MeV



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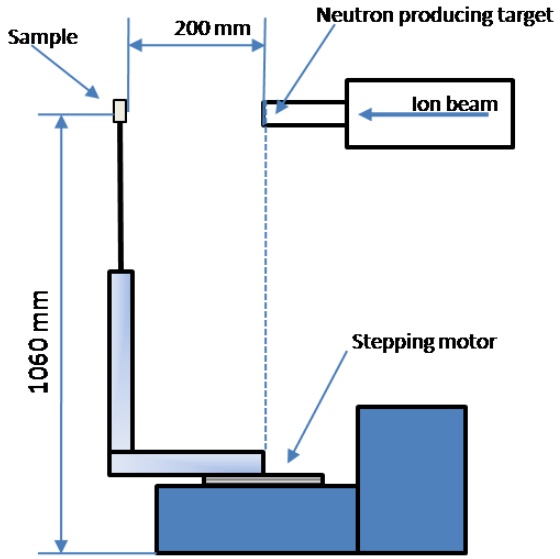
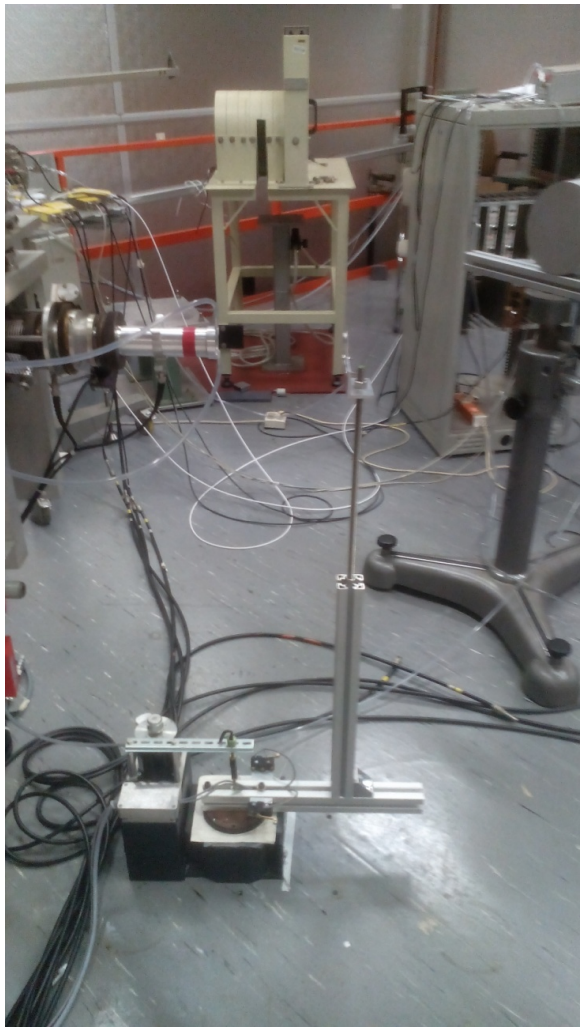
2. The NAXSUN method

- Irradiation set up





3. Measurements of cross section functions of Re induced neutron nuclear reactions

Neutron field and irradiation

- JRC-IRMM **Van de Graff** accelerator (now: JRC Geel MONNET) laboratory.
- Neutron producing reaction: **^{3}H(d,n)^{4}He**
- **6 Re-disks** (^{185}Re (37.4%) and ^{187}Re (62.6%); diameter: 20 mm, 5 mm thick) irradiated at one neutron energy and in an interval from 0º to 80º relative to the beam direction
- 41 different positions in steps of 2º
- **One disk** was irradiated on a fixed position at 0º at an incident neutron energy of **18.1 MeV**

Disk No.	E_i (MeV)	E_n (MeV)	t (s)
1	3.3	19.78(20)	86921(10)
2	2.5	18.71(20)	248402(10)
3	2.0	18.10(28)	157632(10)
4	2.0	18.10(28)	166564(10)
5	1.5	17.16(30)	231958(10)
6	1.0	15.9(8)	243608(10)
7	0.8	15.26(13)	144831(10)

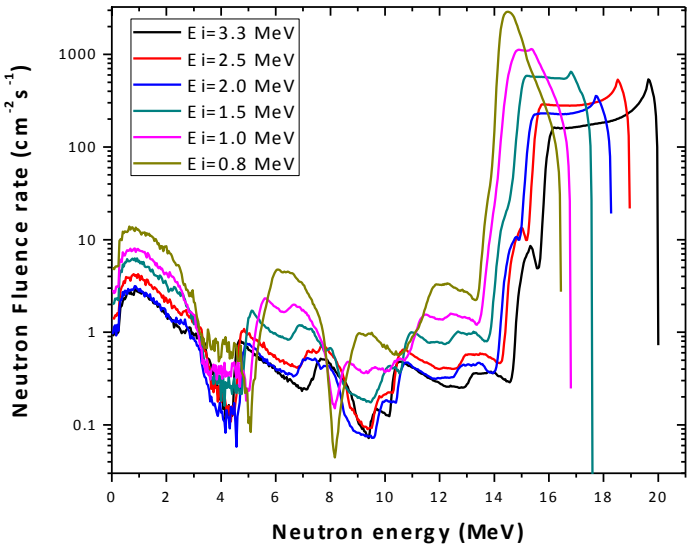
3. Measurements of cross section functions of Re induced neutron nuclear reactions

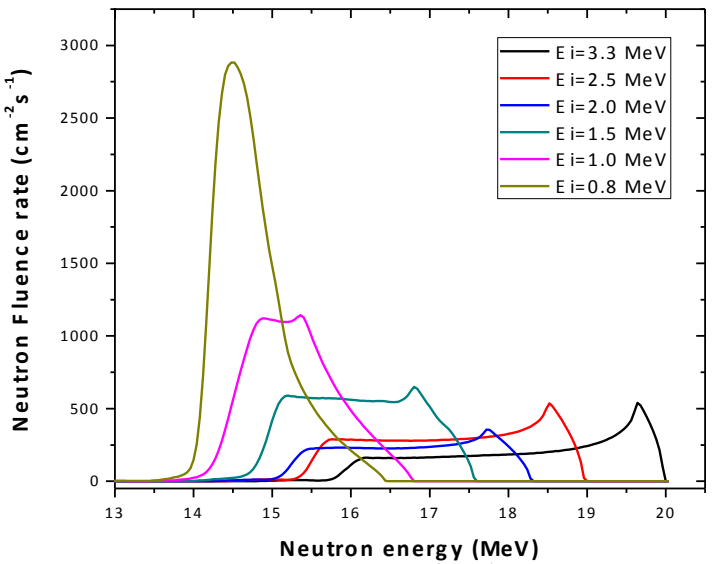
Neutron field and irradiation

The neutron spectra simulated by code TARGET ,Φ_{Tk} , are multiplied by the parameter b_k for experimental variations in the ion-beam current q_i, the irradiation t_{aki} and cooling time t_{cki}

$$\Phi_k = \Phi_{Tk} \cdot b_k$$

$$b_k = \sum_{i=1}^{n} \left(\frac{q_i}{t_{ak_i}} \left(1 - e^{-\lambda t_{ak\,i}}\right) e^{-\lambda t_{ck_i}} \right)$$





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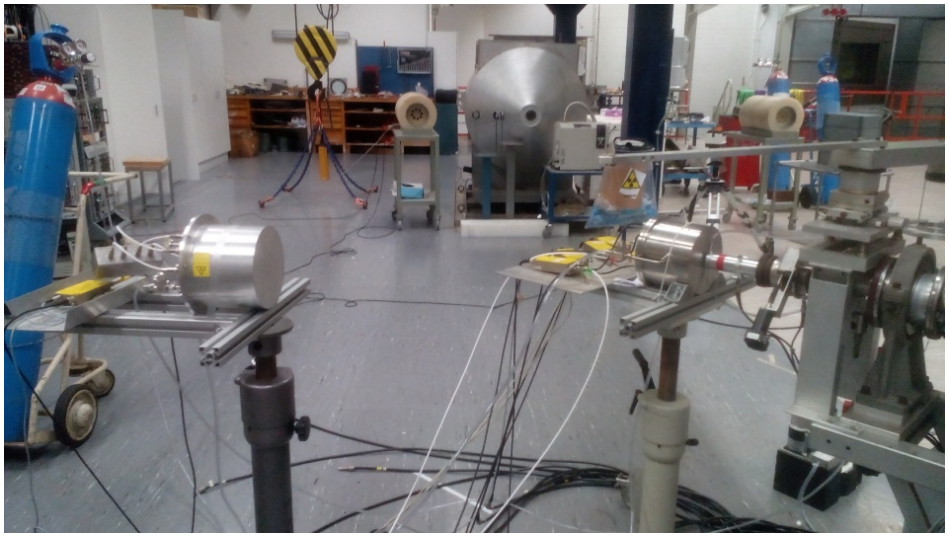
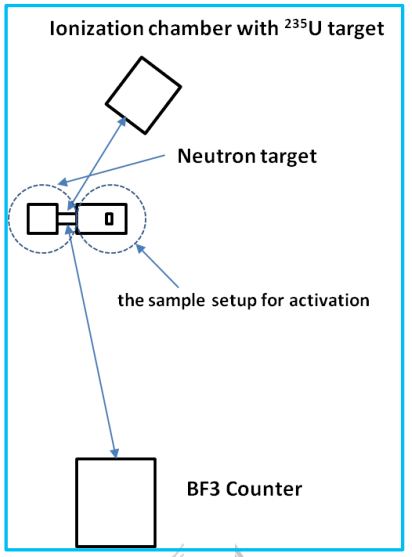
3. Measurements of cross section functions of Re induced neutron nuclear reactions

Neutron flux monitoring and measurements

- Two ionization chambers with **^{238}U and ^{235}U targets**.
- **The number of fission events,** induced by neutrons in the ^{238}U and ^{235}U samples, was counted.
- **The ^{238}U chamber with the ^{238}U target - at the same position as the Re disk**,
- and the measurement was done before each disk irradiation
- **The ^{235}U chamber** -during the neutron fluence rate measurements
- and disk activations at the same position

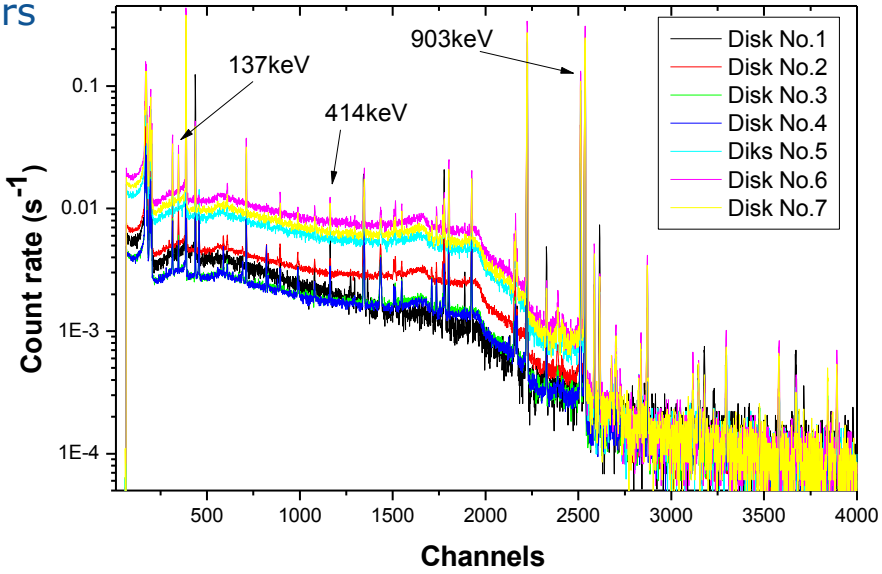




3. Measurements of cross section functions of Re induced neutron nuclear reactions

Gamma spectroscopy measurements

- The first measurement of each sample started around 20 min after irradiation at JRC-IRMM
- Sub-sequent measurements - after 2 days in the ultra-low background underground laboratory **HADES**
- The third measurements – after one month in **HADES**
- Low-background HPGe-detectors



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3. Measurements of cross section functions of Re induced neutron nuclear reactions

Gamma spectroscopy measurements

The specific activity per atom of the activated target isotope, A_k, at the end of the activation:

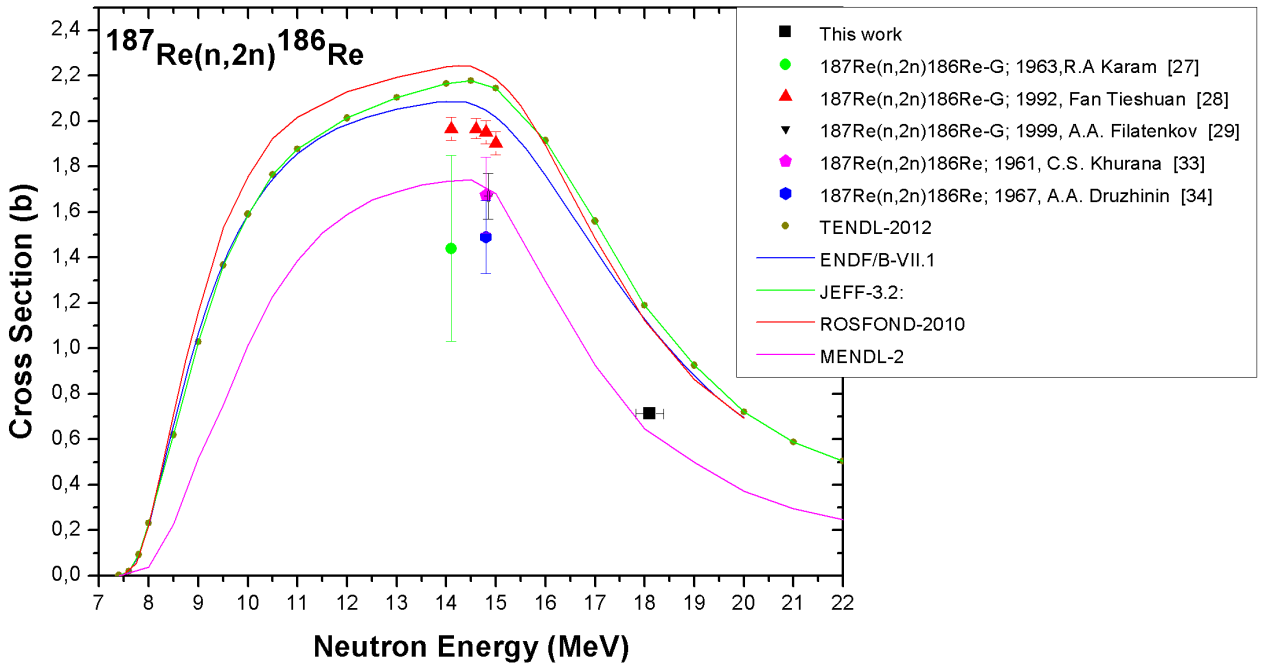
$$A_k = \frac{CM}{N_a m \varepsilon P_\gamma I_A}\left(\frac{\lambda}{1-e^{-\lambda t_m}}\right)e^{\lambda t_c}$$

Reaction	E_γ [keV] ($I_{\gamma,\%}$)	Disk No.1	Disk No.2	Disk No.3	Disk No.4	Disk No.5	Disk No.6	Disk No.7
		$A_k(10^{-24}$Bq/atom)						
^{187}Re(n,2n)^{186}Re	137.2 (9.4)	3430(50)	9850(14)	4490(60)	4790(70)	14680(210)	26800(400)	24700(300)
^{187}Re(n,a)^{184}Ta	414.0 (73.9)	29.10(40)	23.10(30)	16.72(23)	37.30(50)	32.00(40)	32.40(50)	31.20(40)
^{185}Re(n,2n)^{184}Re	903 (37.9)	334.0(50)	1315(19)	676(9)	733(10)	2250(30)	3600(50)	3260(50)
^{185}Re(n,3n)^{183}Re	162.3 (22.3)	165.6(29)	187(3)	119.0(20)	318(6)	237(4)	113.4(20)	67.2(12)
^{187}Re(n,p)^{187}W	618.3 (7.6)	45.5(8)	66.1(11)	50.3(8)	82.4(14)	118.1(20)	93.5(16)	96.8(17)

4. Results

Cross section normalization @ E_n = 18.1 MeV

$$\sigma = \frac{A_k}{\Phi_1} \qquad \Phi_1 = \Phi \cdot \sum_i^n \frac{j}{j_{avg}} \cdot \left(1 - e^{-\lambda t_{a_i}}\right) e^{-\lambda t_{c_i}}$$



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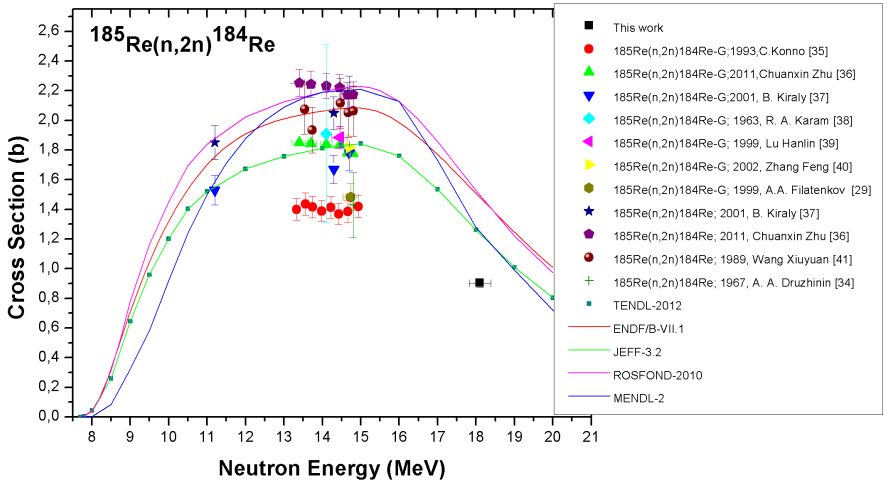

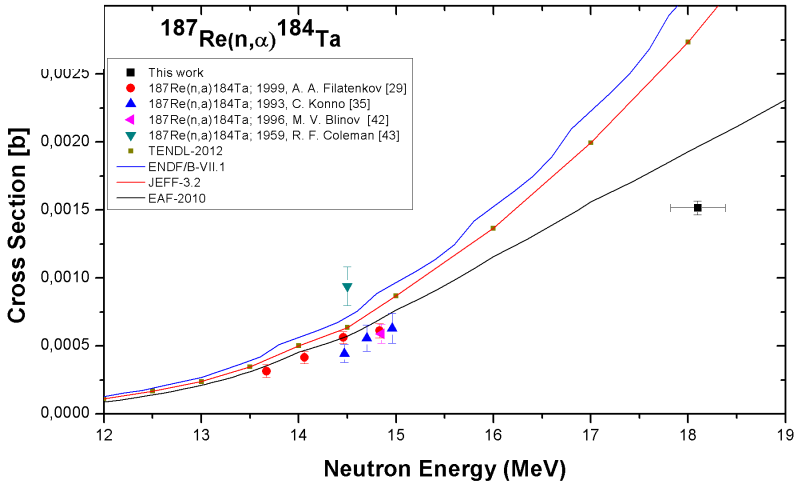

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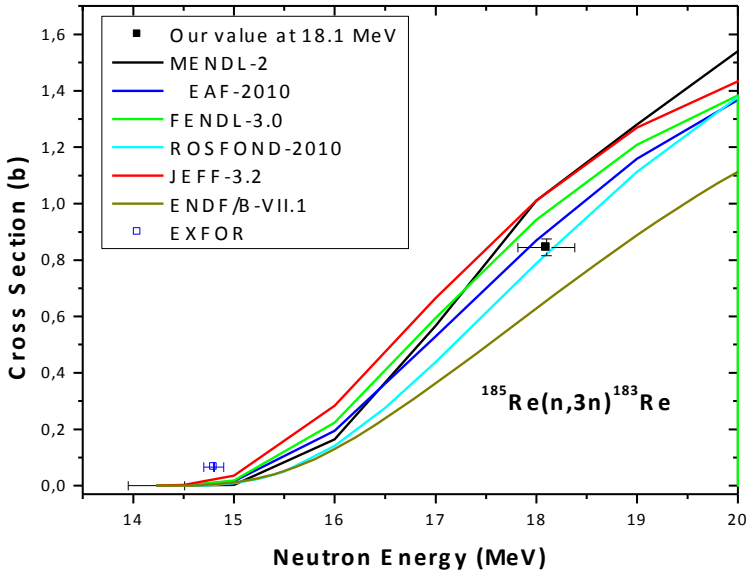

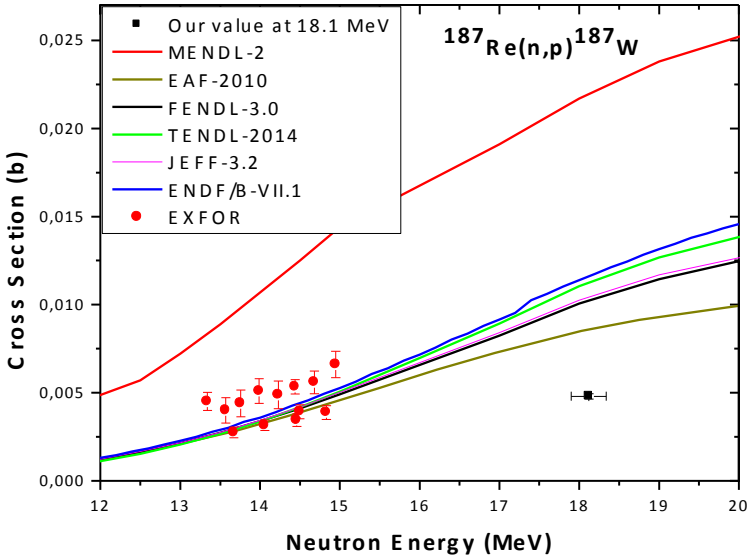

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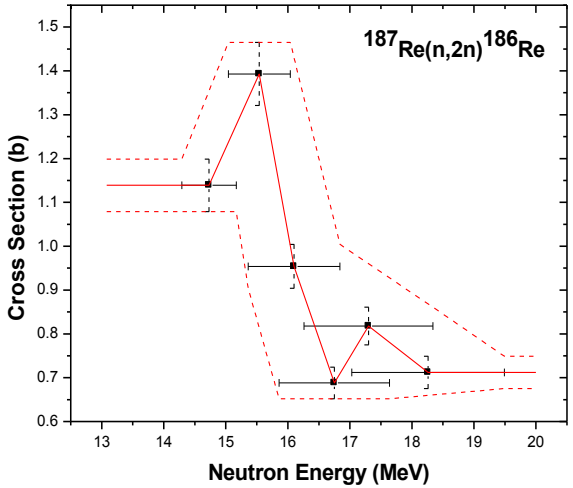
4. Results

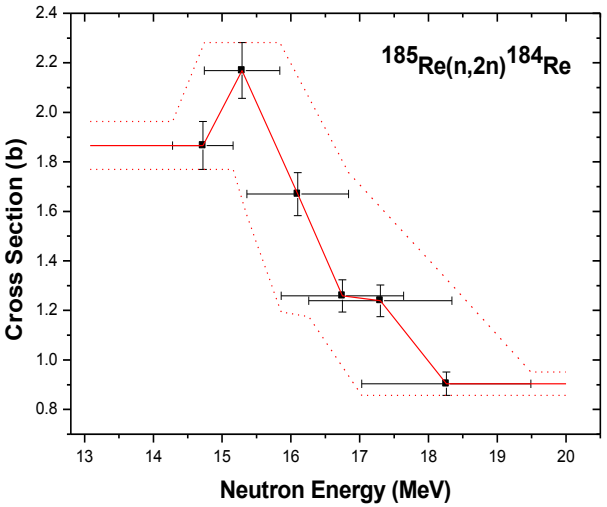
Determination of default functions for the unfolding procedures

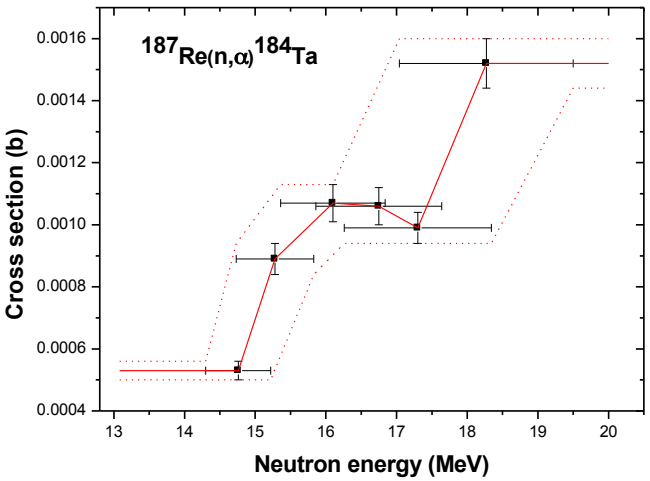
1) The average cross section: $\langle \sigma_k \rangle \approx \frac{A_{sk}}{\sum_i \Phi_{ki}}$

2) The corresponding average neutron energies: $\langle E \rangle_k \approx \frac{\sum_i \Phi_{ki} \cdot E_i}{\sum_i \Phi_{ki}}$

3) **Linear interpolation** of the energy dependence of $\langle \sigma_k \rangle$ on energy $\langle E \rangle_k$







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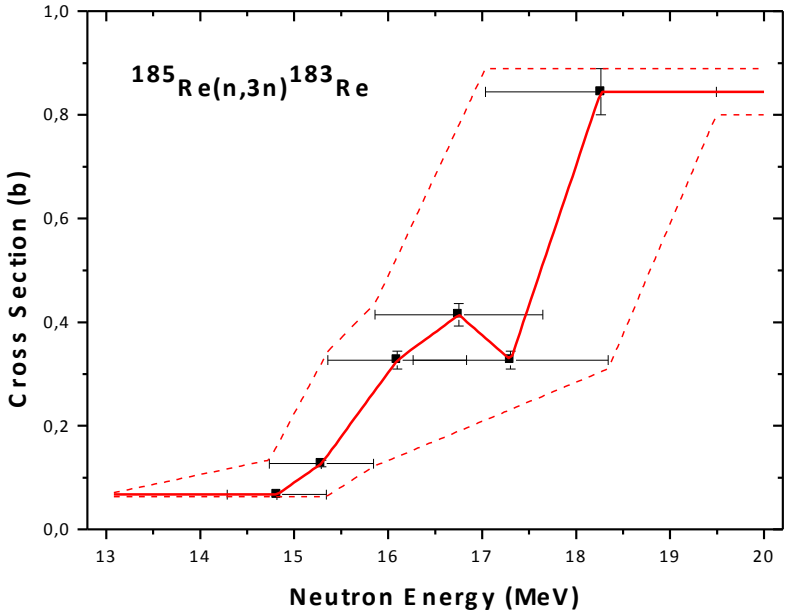

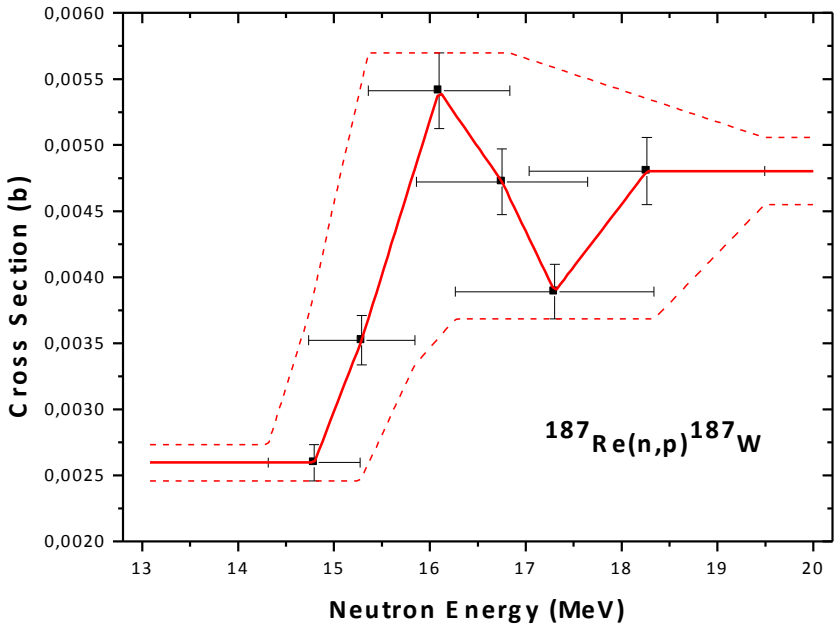

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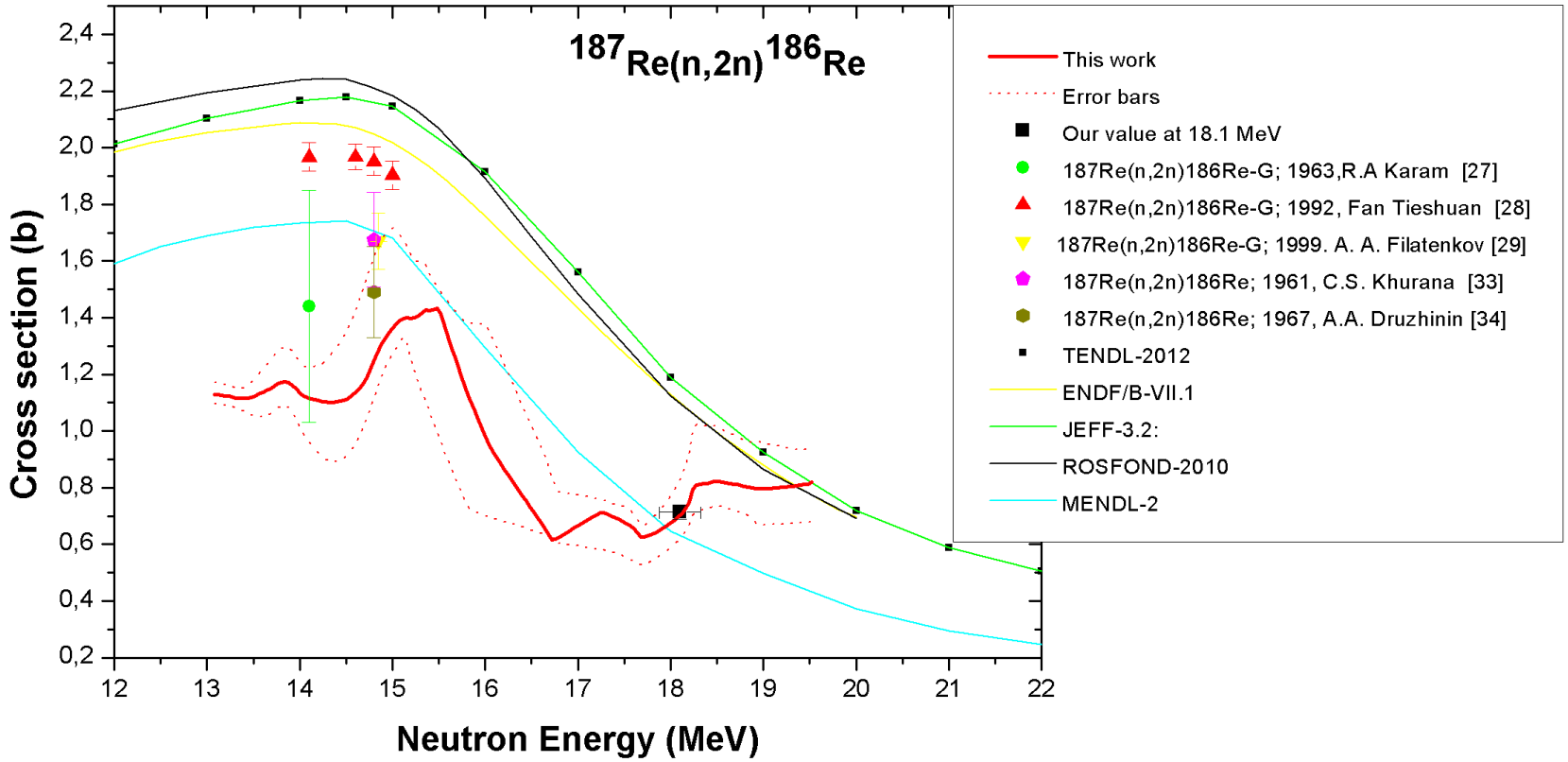
4. Results

Unfolded excitation function

➔ average of the results from MAXED and GRAVEL codes



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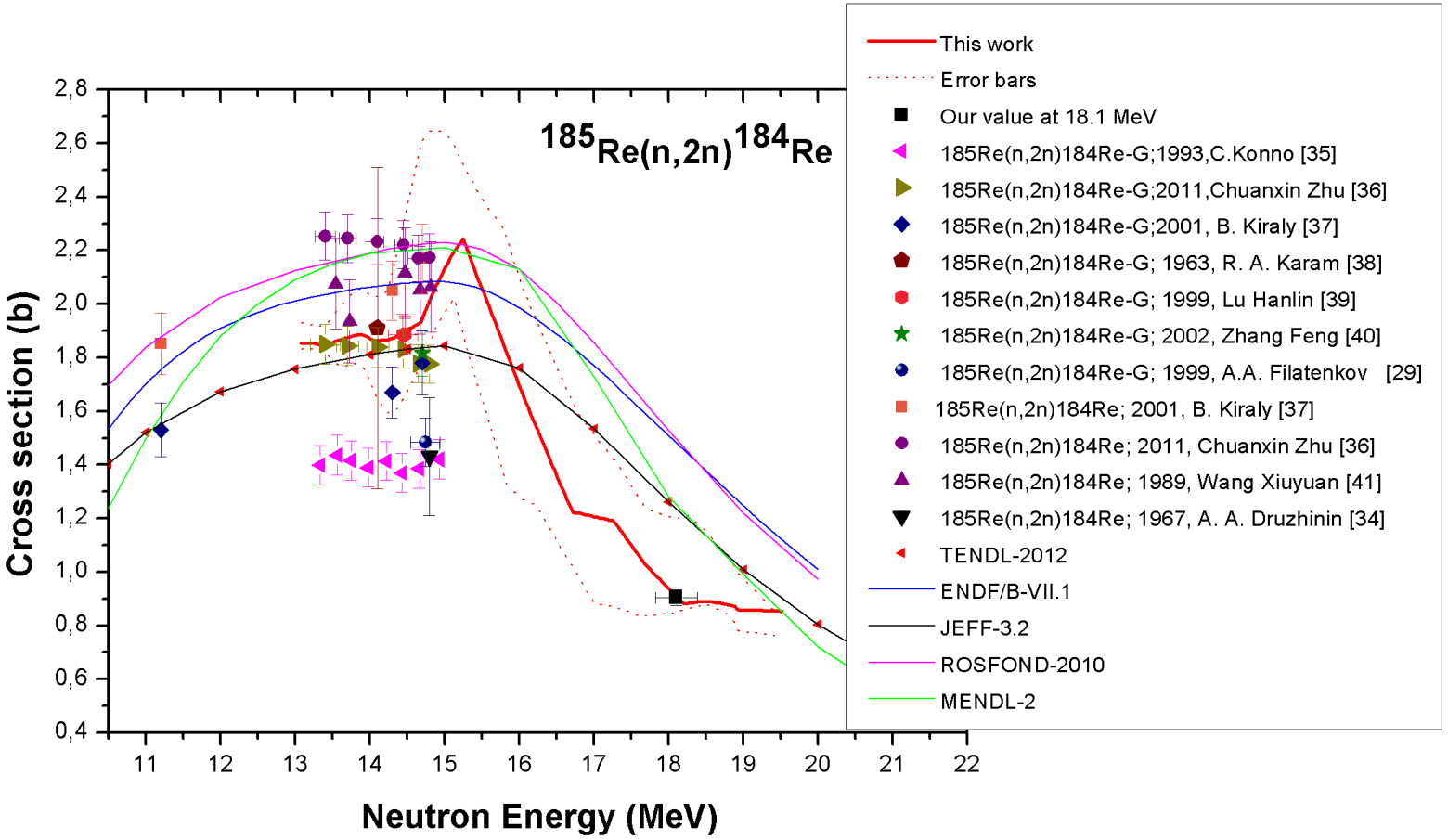

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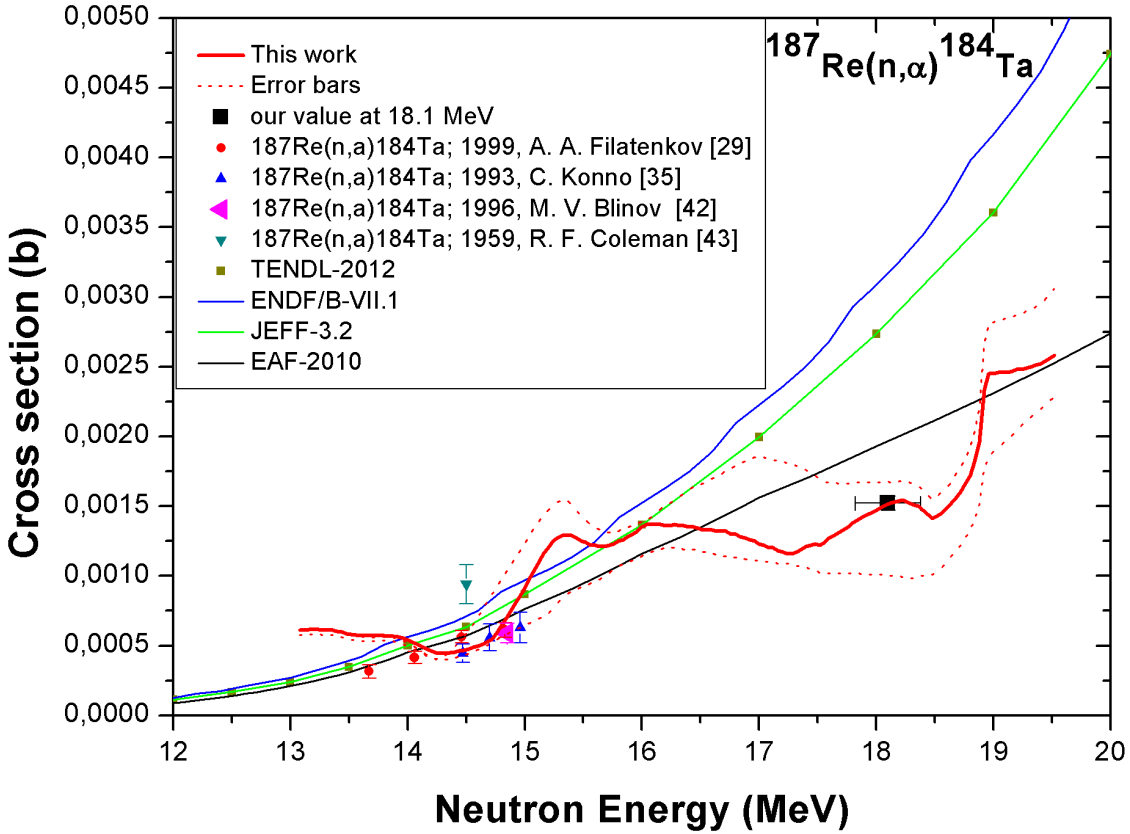

6. Conclusion

- ✓ Measured excitation functions for

  ^{187}Re(n, α)^{184}Ta, ^{187}Re(n, 2n)^{186}Re,

  ^{185}Re(n, 2n)^{184}Re, ^{187}Re(n, p)^{187}W and

  ^{185}Re(n, 3n)^{183}Re

- ✓ Incident neutron energy range from 13.0 to 19.5 MeV by using the NAXSUN technique.
- ✓ First experimental cross-section data for E_n = 15 - 19.5 MeV.
- ✓ The excitation function were obtained by spectrum unfolding and normalized by means of a dedicated cross-section measurement at incident neutron energy of 18.1 MeV.

6. Conclusion

- ✓ Our data show general agreement with some existing data, definitely ruling out other data sets.
- ✓ The new data on neutron excitation functions for several rhenium isotopes may be useful to improve evaluations and nuclear models.
- ✓ From this measurement further excitation functions may be expected
- ✓ $^{187}Re(n, p)^{187}W$ and $^{185}Re(n, 3n)^{183}Re$ analysis in progress.

Thank you to the team

C. Bonaldi, L. Daraban, W. Geerts, F.-J. Hambsch, M. Hult, N. Jovančević, G. Lutter, G. Marissens, S. Oberstedt, H. Stroh, and M. Vidali

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… and I thank you for your kind attention!

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