

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

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**Abstract.** The technique for measuring neutron activation cross-sections using wide energy neutron beams (NAXSUN) was recently developed at JRC-Geel. This method is based on the detection of the gamma activity induced by the activation of the samples in different but overlapping neutron fields and following an unfolding procedure. In the present work, measurements of the cross-section functions by the NAXSUN technique for the (n,α), (n,2n), (n,p) and (n,3n) reactions on rhenium isotopes <sup>185</sup>Re and <sup>187</sup>Re were performed. The results are the first experimental data for the mentioned reaction cross-sections in the energy range 13.0–19.5 MeV. The obtained data are of interest for possible applications of Re in nuclear technology and medicine.

## 1. Introduction

Applications of different neutron induced nuclear reactions, as well as theoretical research are in need of new measurements of cross section data in a wide energy range. Therefore, the NAXSUN technique (Neutron Activation X-Section determined using UNfolding), was developed at the JRC-Geel [1–3].

The NAXSUN method is based on the irradiation of a certain number of metal disks containing the studied isotopes in a series of well known and energy overlapping neutron fields [4]. The induced gamma-activity ( $A_k$ ) can be measured by means of high-resolution gamma-ray spectroscopy systems. Since the induced saturation gamma activity of the disk is proportional to the product of the cross-section ( $\sigma$ ) for a certain reaction and the corresponding neutron flux ( $\Phi_k$ ), this gives us the possibility for the determination of the cross section function:

$$A_k \propto \sigma \cdot \Phi_k \quad (1)$$

For the determination of the cross section values it is necessary to use an unfolding procedure. A detailed description of the NAXSUN technique can be found in Refs. [1–4].

Using the NAXSUN technique measurements of the cross section for the neutron induced reactions on the Rhenium isotopes <sup>185</sup>Re and <sup>187</sup>Re were performed. In this work, we present results for the <sup>187</sup>Re(n, α)<sup>184</sup>Ta, <sup>187</sup>Re(n, 2n)<sup>186</sup>Re, <sup>185</sup>Re(n, 2n)<sup>184</sup>Re, <sup>187</sup>Re(n, p)<sup>187</sup>W and <sup>185</sup>Re(n, 3n)<sup>183</sup>Re reactions in the energy range 13.0–19.5 MeV [4].

These data can be of interest for different applications since Rhenium is a high-temperature corrosion resistant material used, for example, in cancer treatment and diagnostics.

## 2. Measurements

In this work 6 Rhenium disks (<sup>185</sup>Re (37.4%) and <sup>187</sup>Re (62.6%)) with a diameter of 20 mm and 5 mm thickness, were irradiated by scanning of the disks over different angles. One extra disk was irradiated on a fixed position at 0° at an incident neutron energy of 18.1 MeV.

### 2.1. Neutron field and irradiation

Activation of the samples was done at the JRC-Geel Van de Graff accelerator laboratory. We used <sup>3</sup>H(d,n)<sup>4</sup>He as the neutron producing reaction. The disks were irradiated at one neutron energy and in an interval from 0° to 80° relative to the beam direction (41 different positions in steps of 2°). In this way the samples were exposed to a total neutron spectrum over a broad-energy region. In Table 1 we present information about the deuterium beam and neutron energy as well as the irradiation time [4]. The neutron spectra were simulated employing the TARGET code [5]. Simulated fluence rates  $\Phi_{Tk}$  are multiplied by the parameter  $b_k$  for the experimental variations in the ion-beam current  $q_i$ , the irradiation  $t_{aki}$  and cooling time  $t_{cki}$ :

$$\begin{aligned} \Phi_k &= \Phi_{Tk} \cdot b_k \\ b_k &= \sum_{i=1}^n \left( \frac{q_i}{t_{aki}} (1 - e^{-\lambda t_{aki}}) e^{-\lambda t_{cki}} \right) \end{aligned} \quad (2)$$

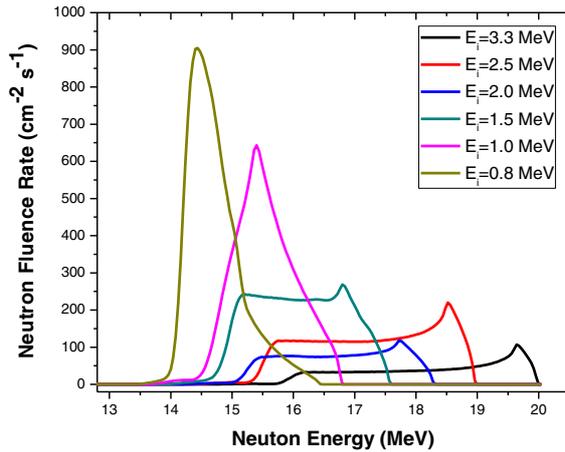
In Fig. 1 we present the obtained neutron fields used for the disk irradiations in the case of the detection of the <sup>186</sup>Re from the <sup>187</sup>Re(n,2n)<sup>186</sup>Re reaction.

During the irradiation the neutron fluence rate was monitored and measured by two ionization chambers with <sup>238</sup>U and <sup>235</sup>U targets [6]. The number of the fission events, induced by neutrons in the <sup>238</sup>U and <sup>235</sup>U samples, was counted. The chamber with the <sup>238</sup>U target was placed at the same position as the Re disk, and the measurement was

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**Table 1.** Information about the deuterium beam and neutron energy as well as the irradiation time.

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	15.97(80)	243608(10)
7	0.8	15.26(131)	144831(10)



**Figure 1.** Neutron fluence spectra simulated by the TARGET code, corrected by the factor  $b_k$  in case of the  $^{187}\text{Re}(n,2n)^{186}\text{Re}$  reaction.

done before each disk irradiation. The chamber with the  $^{235}\text{U}$  target during the neutron fluence rate measurements and disk activations was at the same position about 1 m from the disk irradiation setup.

## 2.2. Gamma spectroscopic measurements

Gamma spectroscopy measurements of the activated disks were performed by low-background HPGe detector systems. The first measurement of each sample started around 20 min after the irradiation at the JRC-Geel. Subsequent measurements were carried out 2 days later in the ultra-low background underground laboratory HADES [8,9]. A third set of measurements was performed one month later in HADES as well. The gamma peaks used in the analysis and the obtained values of the saturated activity are presented in Table 2.

## 3. Results

### 3.1. Cross section values for the $^{187}\text{Re}(n, \alpha)^{184}\text{Ta}$ , $^{187}\text{Re}(n, 2n)^{186}\text{Re}$ , $^{185}\text{Re}(n, 2n)^{184}\text{Re}$ , $^{187}\text{Re}(n, p)^{187}\text{W}$ and $^{185}\text{Re}(n, 3n)^{183}\text{Re}$ reactions at 18.1 MeV neutron energy

The cross section values for the  $^{187}\text{Re}(n, \alpha)^{184}\text{Ta}$ ,  $^{187}\text{Re}(n, 2n)^{186}\text{Re}$ ,  $^{185}\text{Re}(n, 2n)^{184}\text{Re}$ ,  $^{187}\text{Re}(n, p)^{187}\text{W}$  and  $^{185}\text{Re}(n, 3n)^{183}\text{Re}$  reactions at 18.1 MeV neutron energy are determined by measuring the induced activity and the neutron fluence rate [4]. The obtained values for

**Table 2.** Values of the specific activity with gamma peaks energy used in the analysis [7].

	$^{186}\text{Re}$	$^{184}\text{Ta}$	
$E_\gamma$ [keV] ( $I_\gamma$ )	137.2 (9.47(28)%)	414.0 (73.9(5)%)	
$A_k(10^{-24}\text{Bq/atom})$			
Disk No.1	3430(50)	29.10(40)	
Disk No.2	9850(14)	23.10(30)	
Disk No.3	4490(60)	16.72(23)	
Disk No.4	4790(70)	37.30(50)	
Disk No.5	14680(210)	32.00(40)	
Disk No.6	26800(400)	32.40(50)	
Disk No.7	24700(300)	31.20(40)	
	$^{184}\text{Re}$	$^{183}\text{Re}$	$^{187}\text{W}$
$E_\gamma$ [keV] ( $I_\gamma$ )	903 (38(5)%)	162.3 (22(5)%)	618.3 (7.6(9)%)
$A_k(10^{-24}\text{Bq/atom})$			
Disk No.1	334.0(50)	165.6(29)	45.5(8)
Disk No.2	1315(19)	187(3)	66.1(11)
Disk No.3	676(9)	119.0(20)	50.3(8)
Disk No.4	733(10)	318(6)	82.4(14)
Disk No.5	2250(30)	237(4)	118.1(20)
Disk No.6	3600(50)	113.4(20)	93.5(16)
Disk No.7	3260(50)	67.2(12)	96.8(17)

**Table 3.** Average neutron fluence rate and measured cross-section for the three neutron-induced reactions on rhenium. These values were used to normalize the neutron excitation functions.

$^{186}\text{Re}$	$^{184}\text{Ta}$	$^{184}\text{Re}$	$^{183}\text{Re}$	$^{187}\text{W}$
$\Phi_1(\text{cm}^{-2}\text{s}^{-1})$				
6700(200)	24600(700)	811(24)	17200(500)	377(11)
<b>Cross section (b)</b>				
0.713(23)	0.00152(5)	0.904(30)	0.845(29)	0.00480(17)

the average neutron fluence rate and cross sections are summarized in Table 3.

## 3.2. Unfolding results

The unfolding cross section functions for the  $^{187}\text{Re}(n, \alpha)^{184}\text{Ta}$ ,  $^{187}\text{Re}(n, 2n)^{186}\text{Re}$  and  $^{185}\text{Re}(n, 2n)^{184}\text{Re}$ , reactions are given in Figs. 2, 3 and 4, together with the existing experimental and evaluated data [10,11]. The analysis of  $^{187}\text{Re}(n, p)^{187}\text{W}$  and  $^{185}\text{Re}(n, 3n)^{183}\text{Re}$  reactions is still in progress.

In this study, we used the MAXED and GRAVEL algorithms for the unfolding procedures [12,13]. Both of them start with guess default functions which are determined by procedures described in Ref. [2]. As our final results we considered the averaged values from the MAXED and GRAVEL results since those two unfolding codes give slightly different results.

## 4. Conclusion

In this work we measured the excitation functions for  $^{187}\text{Re}(n, \alpha)^{184}\text{Ta}$ ,  $^{187}\text{Re}(n, 2n)^{186}\text{Re}$ ,  $^{185}\text{Re}(n, 2n)^{184}\text{Re}$ ,  $^{187}\text{Re}(n, p)^{187}\text{W}$  and  $^{185}\text{Re}(n, 3n)^{183}\text{Re}$  in the incident neutron energy range from 13.0 to 19.5 MeV by using the NAXSUN technique. The results are the first experimental

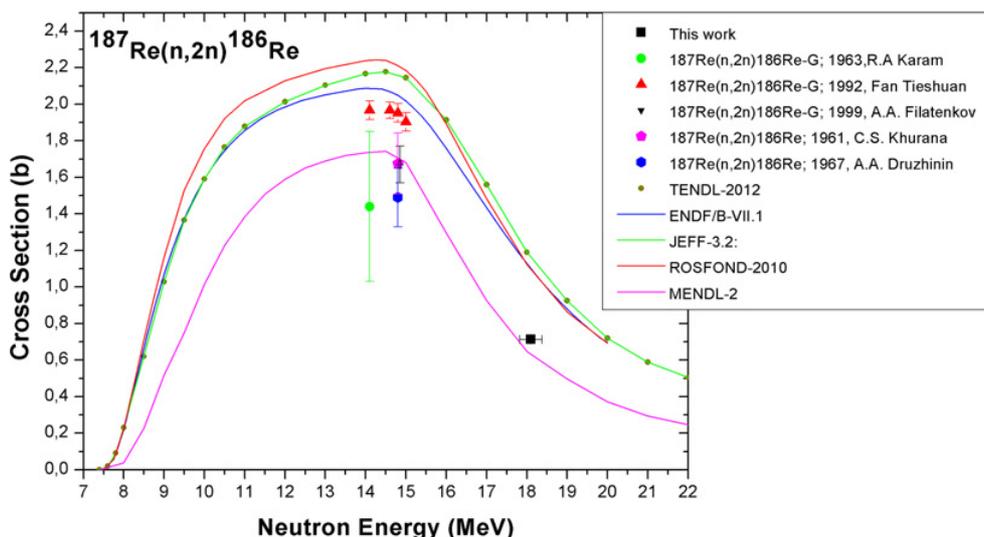


Figure 2. Comparison of the obtained results in this work with ENDF and EXFOR data for  $^{187}\text{Re}(n,2n)^{186}\text{Re}$  reaction [4, 10, 11].

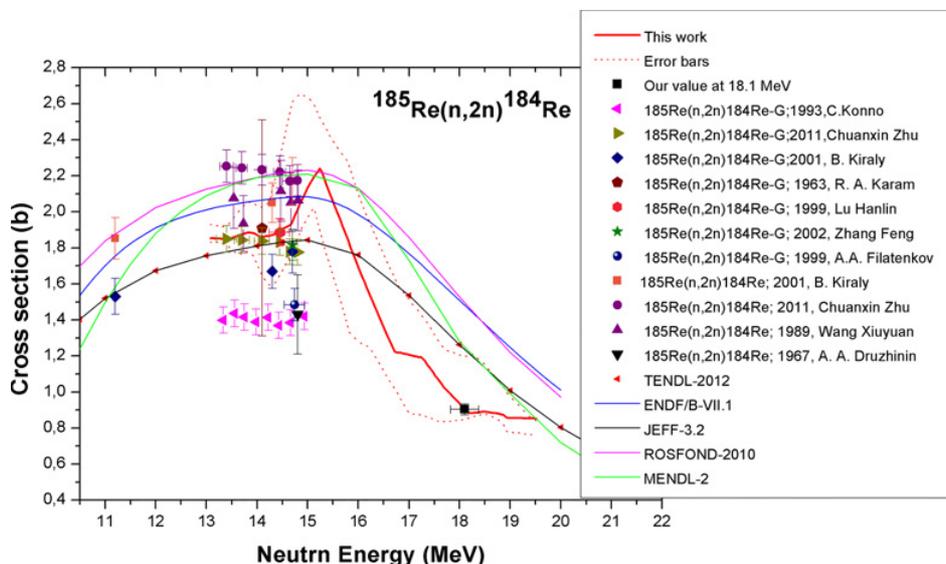


Figure 3. Comparison of the obtained results in this work with ENDF and EXFOR data for  $^{185}\text{Re}(n,2n)^{184}\text{Re}$  reaction [4, 10, 11].

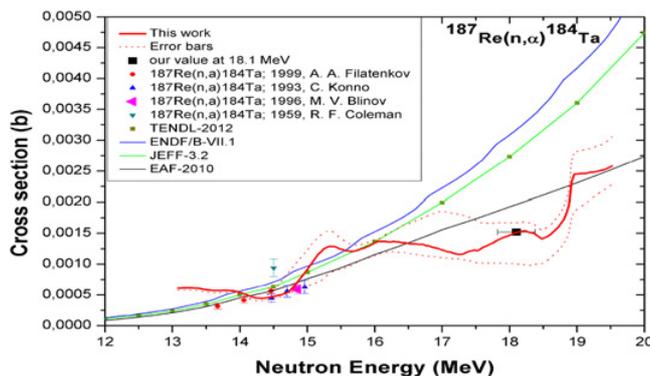


Figure 4. Comparison of the obtained results in this work with ENDF and EXFOR data for  $^{187}\text{Re}(n,\alpha)^{184}\text{Ta}$  reaction [4, 10, 11].

cross-section data for  $E_n = 15 - 19.5$  MeV. The excitation functions were obtained using the spectrum unfolding and normalized by means of a dedicated cross-section measurement at the incident neutron energy of 18.1 MeV. The obtained data show general agreement with some existing data, definitely ruling out other data sets. The

new data on the neutron excitation functions for several rhenium isotopes may be useful to improve evaluations and nuclear models. It should be emphasized that from this measurement further excitation functions may be expected. For example the  $^{187}\text{Re}(n, p)^{187}\text{W}$  and  $^{185}\text{Re}(n, 3n)^{183}\text{Re}$  reaction analysis is already in progress.

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