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ENDF-6 COMPATIBLE EVALUATION OF NEUTRON INDUCED REACTION CROSS SECTIONS FOR ^{182,183,184,186}W

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ABSTRACT

An ENDF-6 compatible evaluation for neutron induced reactions in the resonance region has been completed for ^{182,183,184,186}W. The parameters are the result of an analysis of experimental data available in the literature together with a parameter adjustment on transmission and capture data obtained at the time-of-flight facility GELINA. Complete evaluated data files in ENDF-6 format have been produced by joining the evaluations in the resonance region with corresponding files from the JEFF-32T1 and ENDF/B-VII.1 library. The evaluated files have been processed with the latest updates of NJOY.99 to test their format and application consistency as well as to produce a continuous-energy data library in ACE format for use in Monte Carlo codes. The evaluated files will be implemented in the next release of the JEFF-3 library which is maintained by the Nuclear Energy Agency of the OECD.

1. INTRODUCTION

Accurate nuclear data for tungsten isotopes are required because tungsten is a candidate material for plasma facing components in fusion devices; a target material for for high-current accelerators in accelerator driven systems; and a constituent of structural materials in Generation IV reactors. Neutron induced reaction data on tungsten are also important for neutron dosimetry, in particular the ^{186}W(n,γ) cross section, as well as for producing the two unstable isotopes ^{185}W ($T_{1/2}$ = 75.1 d) and ^{187}W ($T_{1/2}$ = 24.0 h), which besides of being used as radioactive tracers. are also of interest in nuclear astrophysics for determining the abundance in the slow neutron capture process.

Systematic discrepancies between experimental and calculated data were observed in criticality safety benchmarks containing tungsten [1,2], fusion neutronics benchmarks [3-5], and measured constants for neutron activation [6]. The outcome of these studies motivated an evaluation for neutron induced reactions on ^{180,182,183,184,186}W in the continuous region up to 150 MeV produced at the IAEA by Capote et al. [7 - 9]. This evaluation together with the covariance data reported in Ref. [10] has been adopted in ENDF/B-VII.1 [11]. The evaluation is based on a theoretical analysis that utilizes the optical and direct reaction models, pre-equilibrium exciton model and the full featured Hauser- Feshbach model. The evaluated files were tested on selected fusion neutronics benchmarks showing improvements compared to other existing evaluations [9]. The coupled-channel ECIS03 code [12] incorporated into the EMPIRE-2.19 system [13] was used for optical model calculations. Starting values for nuclear model parameters were taken from RIPL database [14]. Since tungsten nuclei are characterized by a stable ground-state deformation, an isospin dependent dispersive coupled-channel optical model potential has been derived for nucleon scattering on tungsten isotopes [7,8]. Direct interaction cross sections to low-lying levels and transmission coefficients for the incident channel on $^{180-186}$W nuclei were obtained from this potential. The same potential was used to calculate direct excitation of the collective levels in the continuum by the DWBA method. Pre-equilibrium emission was considered using one component exciton model PCROSS, which includes nucleon, gamma and cluster emission. Hauser-Feshbach and Hofmann- Richert-Tepel-Weidenmuller versions of the statistical model were used for the compound nucleus cross section calculations. Capote et al. [8] have shown that there is a very good agreement between calculated and experimental cross section data of Ref. [15-17].

Another evaluation for neutron induced reaction cross sections of ^{182,183,184,186}W in the continuous region from 100 keV (45 keV for ^{183}W) up to 150 MeV has been carried out at the Karslruhe Institute of Technology (KIT) by P. Pereslavtsev, A. Konobeyev, and U. Fischer [18]. The main tool used is the GNASH nuclear model code [19] based on statistical Hauser-Feshbach theory including width fluctuations, pre-equilibrium and direct reaction calculations. Particle transmission coefficients are generally introduced into the GNASH calculations from either spherical or coupled-channel optical models. Normally, spin-orbit coupling is ignored, so that the transmission coefficients depend only on the orbital angular momentum quantum number. Spherical optical model transmission coefficients for GNASH calculations are determined with the non-relativistic SCAT code by Bersillon [20]. For calculations with incident neutrons on nuclei that are strongly deformed such as rare earths and actinides, the coupled channel deformed optical model calculations with the ECIS code (ECIS95 for KIT calculations on W) are used to obtain transmission coefficients. The recent measurements of Abfalterer et al. [17] for natural tungsten have been used in the KIT evaluations for the total cross section evaluation. Neutron and charged-particle transmission coefficients have been obtained from the optical potentials. The global optical model potentials of Koning [21] have predominantly been used in coupled-channels calculations for incident neutrons and protons. The ECIS95 code [22] has been utilized for the couple-channels calculations. Spherical optical model calculations have been performed with the SCAT2 [20] code. The information about covariances has been obtained using deterministic and Monte Carlo approaches.

In spite of these attempts to improve the evaluated cross section data for tungsten, the status of the latter is still unsatisfactory. This is especially true for the cross section data in the resonance region . A review of the resonance parameters of tungsten isotopes available in the literature [23 – 45] showed that no significant improvement in quality is possible without new measurements [9, 46, 47].

The important role of tungsten as a fundamental material for various nuclear applications fully justifies an evaluation for neutron induced reactions in the resonance region based on additional high resolution transmission and capture time-of-flight (TOF) measurements. In this report a new evaluation of resonance parameters for ^{182,183,184,186}W based on results of cross section measurements [46, 47] at the GELINA time-of-flight facility [48] is presented. These parameters were used to create two complete nuclear data files using the JEFF-3.2T1 and ENDF/B-VII.1 data library as a basis.

2. EXPERIMENTAL DATA AND EVALUATED DATA LIBRARIES

Resonance parameters for tungsten isotopes in evaluated data libraries are primarily based on a compilation of parameters given by Camarda et al. [39], Ohkubo [40] and Macklin et al. [41]. In the evaluated data libraries no reference is made to e.g. the work of Werner et al. [43], Ohkubo and Kawarasaki [42] and the parameters for ^{180}W derived by Vorona et al. [44]. The latter have been derived from results of TOF transmission measurements on a tungsten sample enriched to 95% in ^{180}W. The work of Camarda et al. [39] is the most comprehensive study of resonance parameters for tungsten isotopes. This study was done at the NEVIS synchrocyclotron of the Columbia University. Transmission and self-indication measurements at 200 m and 40 m, respectively, were carried out using natural W-samples and samples enriched in ^{182,184,186}W. Ohkubo [40] reports resonance parameters for ^{nat}W and ^{182,183}W resulting from transmission and scattering experiments on natural tungsten samples at a 47 m flight path station of the JAERI linear accelerator. Resonance parameters are given for the energies below 1600 eV. Macklin et al. [41] performed capture measurements at a 40.12 m station of ORELA using C_6F_6-detectors for neutron energies between 2.6 keV and 2 MeV and derived characteristics of ^{182,183,184186}W resonances.

There are mainly two different evaluations for tungsten isotopes in the resolved resonance region. These are the evaluations by JENDL-3.3 and JENDL-4.0 [49]. For ^{186}W an independent evaluation based on results of Ref. [39,41] has been produced for the IRDF-2002 library. The JENDL-3.3 evaluation has been adopted in JEFF-3.2T1 and is the basis for ENDF/B-VII.1. In all libraries the resonance parameters for ^{180}W originate from the compilation of Mughabghab [50]. The sources of resonance parameters, upper boundaries of the resolved resonance region (RRR), the average radiation width, and the thermal scattering and capture cross section adopted in the JENDL-3.3 and JENDL-4.0 libraries are given in Table 1. The main differences between JENDL-3.3 and JENDL-4.0 are the upper limits for the RRR and the external levels reflecting the differences in the thermal cross section data. The upper limit of the RRR in JENDL-4.0 has been decreased compared to JENDL-3.3 due to the significant number of missing levels. This was done to avoid the production of parameter file which predominantly consists of a generated ladder of unobserved resonances. In Fig. 1 the total and capture cross sections recommended in ENDF/B-VII.1 and JEFF-3.2T1 are compared. It should be noted that the artefact in the URR capture cross section of ^{182}W from 12 keV to 100 keV (see Fig.1) has recently been corrected by KIT in the JEFF-3.2T1 library.

	Upper boundary RRR eV		$\sigma(n,n)$ barn		$\sigma(n,\gamma)$ barn		$<\Gamma_\gamma>$ meV	
JENDL-	3.3	4.0	3.3	4.0	3.3	4.0	3.3	4.0
^{180}W		110		10.944		37.622		70
^{182}W	12000	5000	8.84	8.8689	20.7	17.872	53	53
^{183}W	2200	770	2.38	2.4088	10.11	10.406	55	55
^{184}W	15000	3500	7.35	7.372	1.70	1.698	57	57
^{186}W	15000	3500	0.93	0.074	39.45	38.100	60	60

Table 1 Upper boundary of the RRR, scattering and capture cross section at thermal energy and the average radiation width ($<\Gamma_\gamma>$) in JENDL-3.3 and JENDL-4.0.

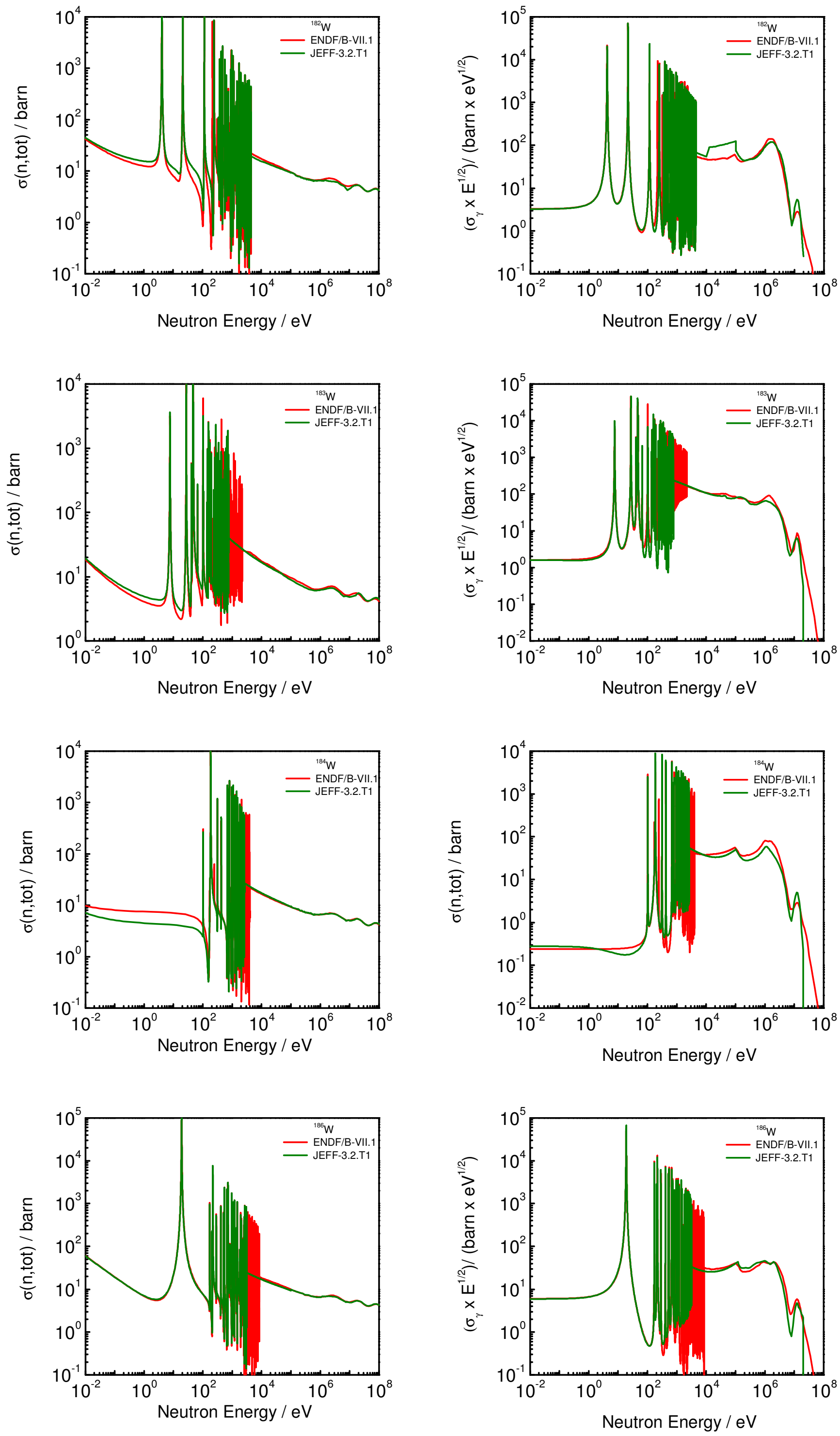


Fig. 1 Comparison of the total and capture cross section recommended in ENDF/B-VII.1 and JEFF-3.2.T1 as a function of neutron energy. The capture cross section is multiplied with the square root of the neutron energy.

Given the limited number of well documented experimental data in the EXFOR library, no attempt has been made to derive resonance parameters from a resonance shape analysis of TOF-data reported in the literature. The limitations are mainly due to the lack of information that is required to perform a resonance shape analysis free of bias effects [51]. To provide data for a new evaluation a set of transmission and capture measurements have been carried at the TOF-facility GELINA following the recommendations given in Ref. [52]. Measurements were performed on natural tungsten samples with different thicknesses and samples enriched in ^{182,183,184,186}W. Experimental details of the measurements are given by Lampoudis et al. [46] and Emiliani et al. [47].

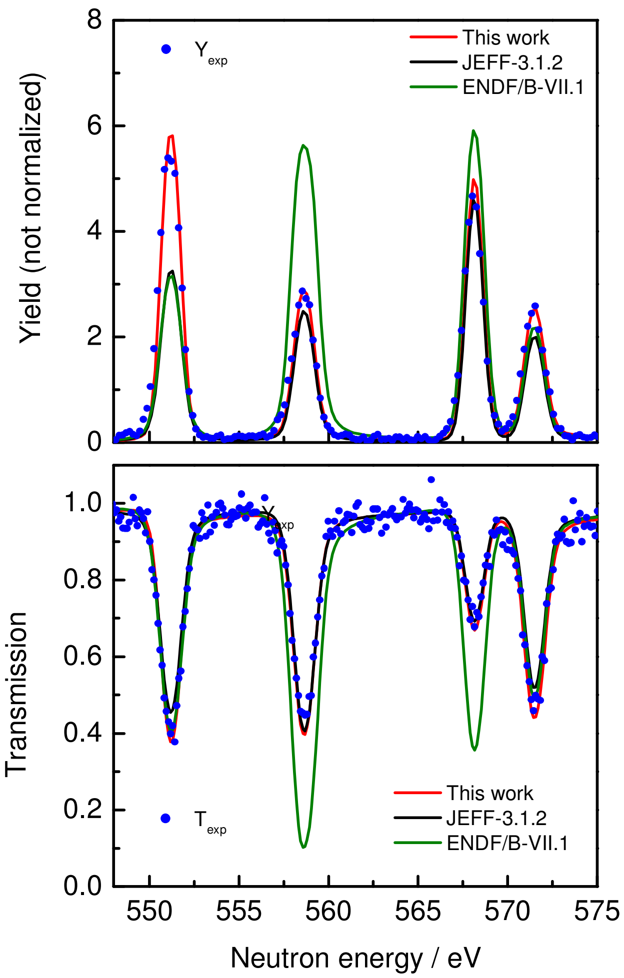
3. ENDF-6 COMPATIBLE FILES FOR TUNGSTEN ISOTOPES

To determine resonance parameters for ^{182,183,184,186}W the same methodology was applied as for cadmium [53]. Starting parameter files were constructed based on resonance characteristics, mostly area data, reported in the literature. Final parameters were obtained from least squares adjustments on the transmission and capture data obtained at GELINA. The resonance shape analysis was carried out with the REFIT code [54] based on the Reich-Moore approximation [56] of the R-matrix theory [55]. In general, from a transmission measurement the parameter $K_t = g_J\Gamma_n$ is deduced and from a capture measurement the capture Kernel $K_\gamma = g_J\Gamma_n\Gamma_\gamma /(\Gamma_n + \Gamma_\gamma)$ is obtained, with Γ_n the neutron width, Γ_γ the radiation width and g_J the statistical spin factor. In case the width of an observed resonance profile is dominated by the total width $\Gamma = \Gamma_n + \Gamma_\gamma$ of the compound state, this width can also be obtained from a RSA of the observed profile. The choice of orbital angular momentum (ℓ = 0 or 1) was based on the Bayes' theorem approach of Bollinger and Thomas [57] and for the spin the most probable spin (largest possible) was chosen. The parameters of the negative resonances were adjusted to reproduce the thermal scattering and capture cross section given in Table 2. The scattering cross sections are consistent with the scattering lengths recommended by Knopf and Waschkowski [58] and the capture cross sections are based on the work of Hurst [59]. The ground state spin and parity I^π, neutron separation energy S_n for the system of target +n, and upper boundaries for the resolved resonance regions are also given in Table 2. In Fig. 2 the results of the evaluation presented in this work is illustrated. In this figure the experimental transmission and yield obtained from measurements with a 1.29 mm thick disc enriched in ^{183}W is compared with the theoretical transmission and yield using the parameters obtained in this work and those in the JEFF-3.1.2 and ENDF/B-VII.1 library. Fig. 2 reveals that there is a much better agreement with the experimental data when using the parameters presented in this work compared to those in the JEFF-3.1.2 library and especially to those in the ENDF/B-VII.1 library.

	I^π	S_n keV	σ(n,n) b	σ(n,γ) b	b_c fm	Upper limit RRR keV
^{182}W	0^+	6190.84	6.340	20.900	7.04	4.5
^{183}W	$1/2^-$	7411.75	5.581	9.500	6.59	2.2
^{184}W	0^+	5753.71	7.278	1.450	7.55	5.2
^{186}W	0^+	5466.55	0.195	33.00	-0.73	8.5

Table 2. Ground state spin and parity I^π, neutron separation energy S_n for ^{A}W +n, scattering and capture cross section at thermal energy, coherent scattering length and upper boundary of the RRR for the tungsten isotopes considered in this work.

The resonance parameter files were joined with the JEFF-3.2T1 and ENDF/B-VII.1 nuclear data libraries to produce complete evaluated data files in ENDF-6 format [60]. The corresponding files are referred to as IRMM-KIT and IRMM-B71, respectively. Some adjustments of the boundaries between the RRR and URR were made. In addition, corrections were introduced to the unresolved resonance region evaluation of ^{183}W in both JEFF-3.2T1 and ENDF/B-VII.1. Namely, the value AMUX = 2 for the sub-threshold competitive width of the d-wave $J^\pi = 1^-$ sequence was corrected to AMUX = 1. The resonance integrals derived from the data files recommended in this work are reported in Table 3. The resonance integrals are calculated for a temperature T = 0 K and with 0.5 eV and 100 keV as a lower and upper integration limit respectively. The evaluated files have been processed with the latest updates of NJOY.99 [61] to test their format and application consistency as well as to produce a continuous-energy data library in ACE format for use in Monte Carlo codes.



Fi.g. 2. Comparison of the experimental transmission and yield with the calculated ones using the resonance parameters presented in this work and those of the JEFF-3.1.2 and ENDF/B-VII.1 library. The experimental data result from measurements at GELINA using a 1.29 mm thick tungsten disc enriched in ^{183}W.

	RI (n,n)		RI (n,γ)	
	IRMM-KIT	IRMM-B71	IRMM-KIT	IRMM-B71
^{182}W	474.50 b	479.21 b	598.15 b	597.43 b
^{183}W	500.66 b	503.61 b	330.64 b	330.70 b
^{184}W	312.42 b	310.89 b	14.95 b	15.02 b
^{186}W	3261.23 b	3263.92 b	443.15 b	443.20 b

Table 3. Resonance integrals derived from the data files recommended in this work for a temperature T = 0 K and with 0.5 eV and 100 keV as a lower and upper integration limit respectively.

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Abstract

An ENDF-6 compatible evaluation for neutron induced reactions in the resonance region has been completed for $^{182,183,184,186}W$. The parameters are the result of an analysis of experimental data available in the literature together with a parameter adjustment on transmission and capture data obtained at the time-of-flight facility GELINA. Complete evaluated data files in ENDF-6 format have been produced by joining the evaluations in the resonance region with corresponding files from the JEFF-32T1 and ENDF/B-VII.1 library. The evaluated files have been processed with the latest updates of NJOY.99 to test their format and application consistency as well as to produce a continuous-energy data library in ACE format for use in Monte Carlo codes. The evaluated files will be implemented in the next release of the JEFF-3 library which is maintained by the Nuclear Energy Agency of the OECD.

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