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JRC SCIENTIFIC AND POLICY REPORTS

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2013

Report EUR 25800 EN

Joint
Research
Centre

European Commission
Joint Research Centre
Institute for Reference Materials and Measurements

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http://www.jrc.ec.europa.eu/

This publication is a Reference Report by the Joint Research Centre of the European Commission.

JRC78696

EUR 25800 EN

ISBN 978-92-79-28421-2 (pdf)

ISSN 1831-9424 (online)

doi:10.2787/72841

Luxembourg: Publications Office of the European Union, 2013

ENDF-6 COMPATIBLE EVALUATION OF NEUTRON INDUCED REACTION CROSS SECTIONS FOR ^{106,108,110,11,112,113,114,116}Cd

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ABSTRACT

An ENDF-6 compatible evaluation for neutron induced reactions in the resonance region has been completed for ^{106,108,110,111,112,113,114,116}Cd. 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-3.1.2 nuclear data library (or with the JEFF-Beta-CAD proposed evaluation in case of ^{113}Cd). These files were produced for use in the JEFF32T2 library. For neutron induced reactions in the unresolved resonance region the JENDL-4.0 evaluation for ^{111}Cd and ^{113}Cd was adopted. 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 ACE files have been utilized to study the effect of the evaluated resonance parameters on results of integral experiments. 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

The interest in cadmium is primarily due to the presence of a very strong resonance at 0.178 eV. A 1-mm thick sheet of ^{nat}Cd can be used to absorb almost all neutrons with an energy below about 0.25 eV, at the same time absorbing only a small fraction of the neutrons with an energy above about 0.5 eV (except in the region of the resonances present in natural cadmium). Therefore, the total cross section for neutron induced reactions in ^{nat}Cd is very important for a correct interpretation and analysis of neutron experiments using cadmium as an absorber. Nevertheless, experimental data covering the resolved resonance region are rather scarce. Resonance parameters for cadmium isotopes recommended in evaluated data files are primarily based on a compilation of parameters listed in Liou et al. [1], Musgrove et al. [2] and Wasson and Allen [3]. The ENDF/B-VII.1 [4] and JENDL-4.0 [5] evaluations include the parameters of Frankle et al. [6] for n+^{113}Cd as well.

A set of capture and transmission measurements have been carried out at the Time-Of-Flight (TOF) facility GELINA [7] of the EC-JRC-IRMM at Geel (B) [8,9], following the measurement and data reduction procedures recommended in Ref. [10]. Volev et al. [10] reported an evaluation for neutron induced reactions in cadmium covering both the thermal and resolved resonance region. This evaluation is based on an extensive study of parameters reported in the literature combined with a simultaneous resonance shape analysis (RSA) of the transmission and capture data obtained at GELINA along with using well documented experimental data from other facilities available in numerical form [6]. The RSA was carried out with the REFIT code [11] based on the Reich-Moore approximation [12] of the R-matrix theory [13].

The evaluations in the resolved resonance region with parameters recommended by Volev et al. [10] have been joined with nuclear data libraries to produce evaluated data files in ENDF-6 format [14]. The JEFF-3.1.2 library [15] was used as a base file. The evaluated files have been processed with the latest updates of NJOY.99 [16] to test the consistency of the files and to study the effect of the evaluated resonance parameters on results of integral experiments.

2. ENDF-6 COMPATIBLE FILES FOR CADMIUM ISOTOPES

The resonance parameter files of Ref. [9] have been joined with the JEFF-3.1.2 nuclear data library (or with the JEFF-Beta-CAD proposed evaluation in case of ^{113}Cd) to produce complete evaluated data files in ENDF-6 format. The ground state spin and parity I^{π}, neutron separation energy S_n for the system ^{A}Cd + n, and boundaries for the resolved and unresolved resonance regions are given in Table 1.

For ^{111}Cd and ^{113}Cd the unresolved resonance region (URR) evaluations recommended in the JENDL-4.0 library were adopted. Thus, the self-shielding calculations related to ^{111}Cd and ^{113}Cd can be performed up to the upper URR boundary of 200 keV (see Fig. 1 and Fig. 2). The capture cross section skip of 128 mb (46%) for ^{111}Cd at the boundary of 200 keV between the unresolved and the continuous region is a result of the JEFF-3.1.2 evaluation sticking to the data derived by Musgrove et al. [2]. It is worth noting that the JEFF-3.1.2 capture cross section of ^{111}Cd in the region from 9 keV up to several hundred keV is based on the capture data by Musgrove et al. [2], while the JENDL-4.0 capture and total cross sections for ^{111}Cd in the URR and above are predominantly influenced by the data determined later in the work of Wisshak et al. [17]. Therefore, an update of the continuous region of JEFF for ^{111}Cd above 200 keV can also be recommended in order to avoid the above mentioned skip.

The upper limit of the RRR (or lower limit of URR) for ^{113}Cd was set at 4 keV. Hence, the approach to account for missing levels by adding a generated ladder of unobserved resonances was avoided after treating the region above 4 keV as unresolved. Additional file corrections were:
to the JEFF-3.1.2 file:
- the Q-value for ^{113}Cd MF3/MT107 of 5310.3 keV was updated to 4948.43 keV;

to the CAD file for ^{113}Cd (in accordance with JEFF-3.1.2):
- the Q-value for MF3/MT102 of 9.0410 MeV was set to 9.04298 MeV;
- the MF5/MT16 fractional probability of 0.1 was set to 1.0.

Isotope	I^{π}	S_n / keV	URR limits / keV	
			Lower	Upper
^{106}Cd	0^+	7931.0	6.0	100
^{108}Cd	0^+	7323.1	6.0	100
^{110}Cd	0^+	6975.72	7.2	100
^{111}Cd	$½^+$	9394.32	2.3	200
^{112}Cd	0^+	6540.00	7.0	100
^{113}Cd	$½^+$	9042.98	4.0	200
^{114}Cd	0^+	6140.9	8.0	100
^{116}Cd	0^+	5777.2	9.0	100

Table 1. Ground state spin and parity I^{π}, neutron separation energy S_n for ^{A}Cd + n, and boundaries of the URR for the cadmium isotopes considered in this work.

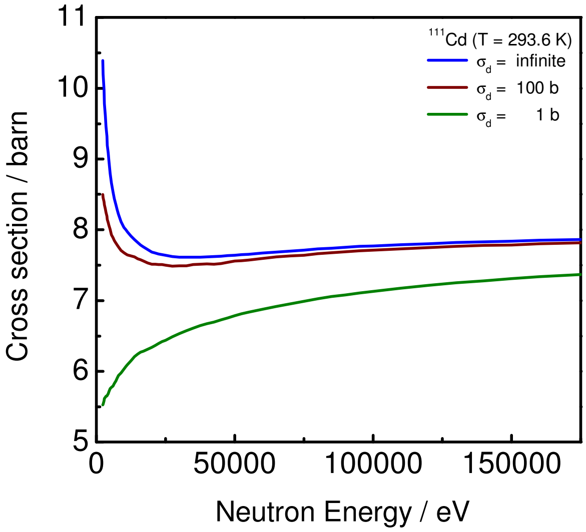

Fig. 1. Average self-shielded total cross sections for ^{111}Cd as a function of neutron energy at a temperature T = 293.6 K for different dilution cross sections $\sigma_d = \infty$, 100 and 1 b.

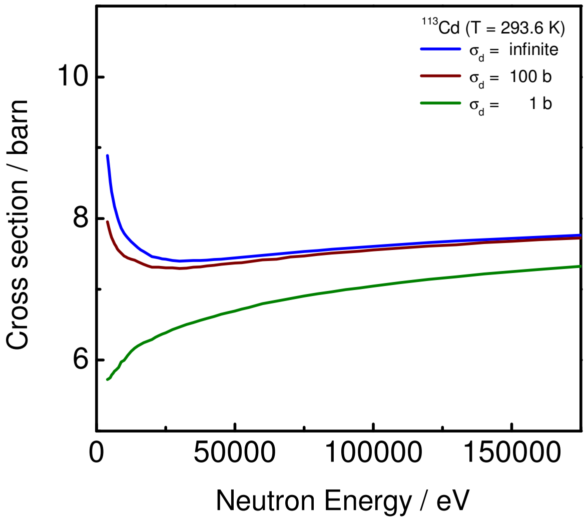

Fig. 2. Average self-shielded total cross sections for ^{113}Cd as a function of neutron energy at a temperature T = 293.6 K for different dilution cross sections $\sigma_d = \infty$, 100 and 1 b.

The total, elastic scattering and capture cross section at thermal energy together with the resonance integral derived from the data files recommend in this work are reported in Table 2. The data are for a temperature T = 0 K. The resonance integral is calculated with 0.5 eV and 100 keV as a lower and upper integration limit respectively.

Isotope	(n,tot)		(n,n)		(n,γ)	
	σ_{tot} / barn	RI_{tot} / barn	σ_n / barn	RI_n / barn	σ_γ / barn	RI_γ / barn
^{106}Cd	5.527	82.217	4.5414	76.446	0.986	5.771
^{108}Cd	4.236	117.639	3.331	101.279	0.906	16.360
^{110}Cd	15.233	157.837	4.235	124.799	10.999	33.038
^{111}Cd	12.457	126.989	5.587	77.121	6.870	49.866
^{112}Cd	7.273	93.725	5.075	80.765	2.198	12.960
^{113}Cd	20185.203	495.631	21.533	95.688	20163.670	399.940
^{114}Cd	5.991	134.692	5.685	122.346	0.305	12.346
^{116}Cd	5.019	71.176	4.943	69.402	0.076	1.774

Table 2. Total σ_{tot}, elastic scattering σ_n and capture σ_γ cross section at thermal energy and resonance integral RI derived from the evaluated data files recommended in this work. The data are for a temperature T = 0 K. The resonance integral is derived with a lower limit of 0.5 eV and an upper limit of 100 keV.

3. COMPARISON WITH EXPERIMENTAL DATA

3.1 Microscopic cross section data

In Fig. 3 the total cross section for neutron induced reactions in natural Cd at thermal energy and at a temperature T = 300 K derived from evaluated data files are compared with experimental data. In Fig. 4 the results of transmission and capture measurements reported in Ref. [10] are compared with the theoretical values derived from the resonance parameters reported in this work as well as with those resulting from the JEFF-3.1.2, ENDF/B-VII.1 and JENDL-4.0 libraries. The comparisons in Fig. 3 and Fig. 4 reveal that the present evaluation reflects the status of experimental data reported in the literature, including the data of Volev et al. [10].

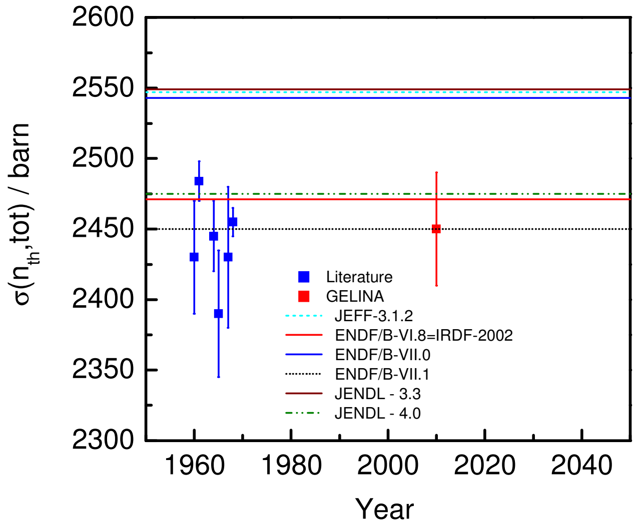

Fig. 3. Comparison of the experimental data for the total cross section of n+^{nat}Cd at 2200 m/s with the values derived from evaluated data files for a temperature T = 300 K. The value resulting from the evaluation reported in this work is σ(n,tot) = 2487 b.

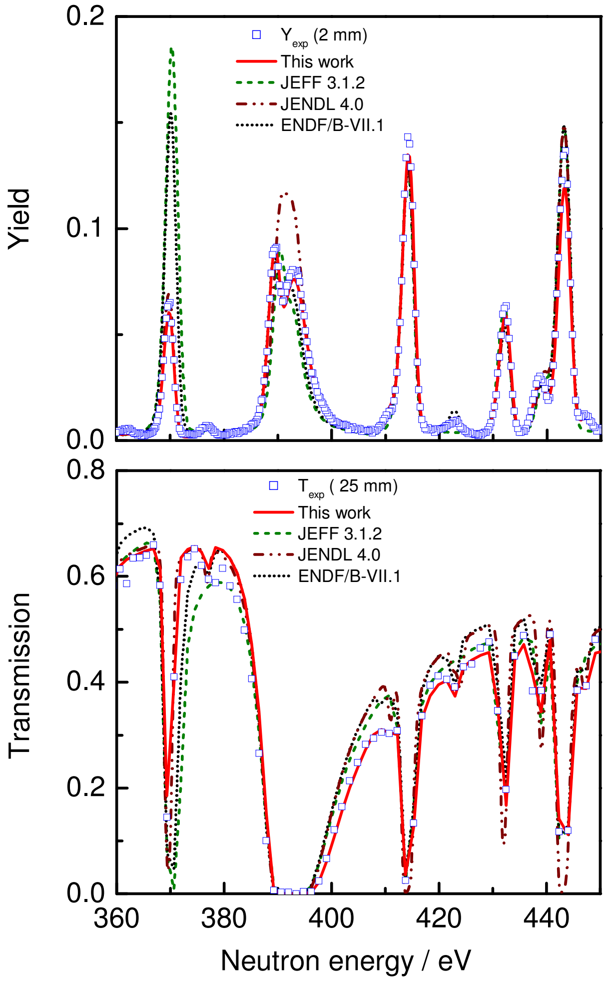

Fig. 4. Result of a RSA of transmission and capture data measured with a natural Cd-sample at GELINA. The experimental transmssion T^{exp} and yield Y_{exp} result from measurements with a 25 mm and 2 mm metal disc of ^{nat}Cd, respectively. The theoretical transmission and yield based on this work, JEFF-3.1.2, ENDF/B-VII.1 and JENDL-4.0 are also shown.

3.2 Integral experiments

To study the effect of the resonance parameters obtained in this work on the interpretation of the integral experiments reported by Lloyd et al. [18], the exercise performed by Kopecky et al. [8] was repeated. The results are given in Table 3. Details of the integral experiments can be found in the handbook of evaluated criticality safety benchmark experiments with reference HEU-SOL-THERM-049 [19]. The experiments consisted of a cylindrical stainless-steel vessel surrounded by an effectively infinite reflector of water around and beneath it. The vessel contained a high enriched uranium solution, with or without cadmium nitrate in the solution. In some cases additional soluble cadmium absorbers were added to the reflector. In Table 3 results of calculations using seven resonance parameter files are compared. The files considered are:
(1) the reference library of Ref. [19]
(2) JEFF-3.1
(3) JEFF-3.1 with the 0.178 eV parameters of Kopecky et al. [8]
(4) ENDF/B-VII.0
(5) ENDF/B-VII.0 with the 0.178 eV parameters of Mosteller et al. [20]
(6) ENDF/B-VII.0 with the 0.178 eV parameters of Kopecky et al. [8]
(7) ENDF/B-VII.0 and the Cd parameter files recommended in this work.
Comparing the results in Table 3 the same conclusion as in the work of Kopecky et al. [8] can be drawn. The changes in the parameters, in particular the neutron width of the resonance at 0.178 eV, have an impact on the results and improve the agreement between calculations and experiment. However, the changes are not enough to bring the calculations in agreement with the results of the experiment. It should be noted that for case 21 in Table 3., which according to Mosteller et al. [20] was the most sensitive to the thermal neutron absorption in cadmium, the result based on the file produced in this work is in better agreement compared with the one obtained by Mosteller et al. [20]. Based on different differential neutron scattering tables, i.e S(α,β) tables, we

verified that the results of the experiments of Lloyd et al. [18] are more sensitive to the scattering treatment than to the resonance parameters of Cd. Therefore, this integral experiment cannot be used to validate the parameters of the 0.178 eV resonance, as in the work of Mosteller et al. [20].

Case	U density (mg/g)	Cd density In-vessel (mg/g)	Cd density in reflector (mg/g)	k_{eff} calculated using different data libraries						
				(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	293.85	0.0	0.0	0.9881	0.9984		0.9983	0.9992	0.9983	
2	294.17	0.0	14.848	0.9897	0.9893	0.9897	0.9885	0.9954	0.9906	0.9908
3	292.98	1.208	0.0	0.9940	0.9937	0.9937	0.9967	0.9960	0.9950	0.9949
4	291.34	2.393	0.0	0.9927	0.9928	0.9935	0.9947	0.9953	0.9958	0.9954
5	290.58	3.897	0.0	0.9922	0.9923	0.9940	0.9961	0.9961	0.9977	0.9971
6	306.43	4.067	0.0	0.9962	0.9954	0.9971	0.9990	1.0000	1.0011	1.0011
7	306.79	4.196	0.0	0.9961	0.9960	0.9979	1.0006	1.0002	1.0015	1.0009
8	306.93	4.279	0.0	0.9952	0.9937	0.9962	0.9980	0.9987	0.9994	0.9999
9	298.38	0.0	0.0	0.9978	0.9967		0.9982	0.9976	0.9982	
10	298.76	0.0	10.596	0.9907	0.9900	0.9902	0.9906	0.9891	0.9902	0.9901
11	301.17	1.240	10.60	0.9901	0.9898	0.9884	0.9907	0.9908	0.9888	0.9883
12	303.48	2.250	10.60	0.9910	0.9909	0.9896	0.9920	0.9924	0.9911	0.9909
13	302.03	3.362	10.60	0.9895	0.9890	0.9905	0.9931	0.9919	0.9921	0.9919
14	301.84	4.189	10.60	0.9887	0.9884	0.9889	0.9906	0.9923	0.9921	0.9911
15	300.94	4.577	10.60	0.9909	0.9909	0.9917	0.9940	0.9941	0.9947	0.9943
16	300.75	4.897	10.60	0.9896	0.9893	0.9908	0.9925	0.9921	0.9931	0.9921
17	301.14	5.049	9.519	0.9885	0.9878	0.9891	0.9910	0.9915	0.9919	0.9910
19	301.55	5.032	0.0	0.9899	0.9900	0.9918	0.9931	0.9936	0.9954	0.9951
20	300.83	5.937	0.0	0.9904	0.9898	0.9914	0.9910	0.9939	0.9963	0.9958
21	303.06	6.262	0.0	0.9879	0.9878	0.9898	0.9911	0.9918	0.9948	0.9939

Table 3. Results of calculated k_{eff} for the integral experiment of Lloyd et al. [18], with reference HEU-SOL-THERM-049 in Ref. [19], using different nuclear data libraries. The indexes of the libraries are explained in the text. The reference benchmark is 1.0012 with uncertainties ranging from ± 0.0019 to ± 0.0029.

Acknowledgments

We are grateful to the Nuclear Data Section of the IAEA and the Nuclear Energy Agency of the OECD for their interest in this work. One of the authors (I.S.) acknowledges the financial support of NEA/OECD. This work was supported by the European Commission within the Seventh Framework Program through the projects EUFRAT (FP7-211499) and ERINDA (FP7-269499).

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European Commission
EUR 25800 – Joint Research Centre – Institute for Reference Materials and Measurements

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Luxembourg: Publications Office of the European Union

2013 – 8 pp. – 21.0 x 29.7 cm

EUR – Scientific and Technical Research series – ISSN 1831-9424 (online)

ISBN 978-92-79-28421-2 (pdf)

doi:10.2787/72841

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LA-NA-25800-EN-N

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ISBN 978-92-79-28421-2