Evaluation of cross sections for neutron interactions with $^{238}\text{U}$ in the energy region between 5 keV and 150 keV

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Abstract. Cross sections for neutron interactions with $^{238}\text{U}$ in the energy region from 5 keV to 150 keV have been evaluated. Average total and capture cross sections have been derived from a least squares analysis using experimental data reported in the literature. The resulting cross sections have been parameterised in terms of average resonance parameters maintaining full consistency with results of optical model calculations by using a dispersive coupled channel optical model potential. The average compound partial cross sections have been expressed in terms of transmission coefficients by applying the Hauser-Feshbach statistical reaction theory including width-fluctuations. A generalized single-level representation compatible with the energy-dependent options of the ENDF-6 format has been applied using standard boundary conditions. The results have been transferred into a full ENDF-6 compatible data file.

1 Introduction

The status of evaluated data files for neutron interactions with $^{238}\text{U}$ in the energy region is discussed in detail by Kopecky et al. [1]. Most of the evaluated data libraries refer for the unresolved resonance region (URR) to the work of Fröhner [2,3]. Fröhner’s evaluation was obtained from an analysis of only energy dependent experimental cross section data without any adjustment to integral benchmark data. Nevertheless, in the energy region below 150 keV differences of more than 5% are observed [1] between the average capture cross sections in the main data libraries, i.e. ENDF/B-VII.1, JEFF-3.2 and JENDL-4, and the one recommended by Carlson et al. [4]. The latter was produced as part of the neutron standards project and results from a combined least squares analysis of experimental data available in the literature, including ratio measurements of different reactions. In addition, results of high resolution time-of-flight (TOF) total cross section measurements carried out by Harvey et al. [5] have not been included in previous evaluations for the URR, e.g. in the evaluation performed by Fröhner [2,3], Maslov et al. [6] and Courcelle et al. [7]. The data of Harvey et al. [5] were analysed by Derrien et al. [8] to derive average total cross sections between 10 keV and 100 keV. This shows the need of a new evaluation based on well documented experimental data. The present evaluation includes the results of Derrien et al. [8], as well as the capture data obtained from TOF experiments at the LANSE [9], GELINA [10] and n_TOF [11,12] facilities, which were not available for previous evaluation projects.

The results of the present work have been included in the evaluated data file for neutron induced reactions on $^{238}\text{U}$ reported by Capote et al. [13]. The file was developed at the IAEA as part of the CIELO (Collaborative International Evaluated Library Organization) project [14,15]. The objective of CIELO is to produce general purpose nuclear data files that are world-wide recognised with a focus on six high-priority nuclides, i.e. $^1\text{H}$, $^{16}\text{O}$, $^{56}\text{Fe}$, $^{235}\text{U}$, $^{238}\text{U}$ and $^{239}\text{Pu}$. The evaluation procedures for CIELO should as much as possible be based on an analysis of
Table 1. Experimental total cross section data used to derive an average total cross section \( \sigma_{\text{tot}} \) for neutron induced reactions on \(^{238}\text{U} \) in the energy region between 5 keV and 150 keV. The fully correlated uncertainty \( u_c \) utilised in the analysis is given together with the energy region of the data employed in the analysis.

| Ref.               | \( u_c \) | Method     | Energy region       | EXFOR entry |
|--------------------|-----------|------------|---------------------|-------------|
| Whalen et al. (1971) | \( 0.1b \) | TOF       | 100 keV–150 keV     | 10009       |
| Konovov et al. (1973) | \( 0.1b \leq u_c \leq 0.6b \) | TOF       | 5 keV–82 keV        | 40328       |
| Poenitz et al. (1981, 1983) | \( 0.08b \leq u_c \leq 0.18b \) | TOF       | 48 keV–140 keV      | 10935       |
| Tsubone et al. (1984)  | \( u_c = 0.05b \) | Fe-filtered beam + TOF | 25 keV–140 keV | 21813       |
| Bokhovko et al. (1990) | \( u_c = 0.1b \) | TOF       | 10 keV–110 keV      | 41016       |
| Derrien et al. (2004)  | \( u_c = 0.03b \) | TOF       | 10 keV–90 keV       |             |

Experimental microscopic cross section data such that the recommended cross sections are not biased by results of integral benchmark experiments.

2 Least squares analysis of average total and capture cross section data

Average total \( \sigma_{\text{tot}} \) and capture \( \sigma_c \) cross sections between 5 keV and 150 keV were derived from a least squares adjustment to experimental data reported in the literature. The generalised least squares code GMA developed by Poenitz [16] was used. This code, which is named after Gauss, Markov and Aitken, is available at the IAEA [17].

2.1 Average total cross section

The average total cross section \( \sigma_{\text{tot}} \) obtained in this work is based on an analysis of the data in table 1. All these data were obtained from TOF experiments [8, 18–23]. Tsubone et al. [22] reduced the background by performing TOF experiments using a Fe-filtered neutron beam. For all these data sets a correction for self-shielding is specified in the papers or reports that describe the experiments and analysis procedures. Only data sets for which at least the total uncertainties are given were included in the analysis. An ideal GMA analysis relies on data for which the individual uncertainty components, in particular correlated and uncorrelated components, are given. When this information could not be retrieved from the papers or the EXFOR data library [24], the covariance matrix was constructed based on one correlated component, due to a normalisation uncertainty, combined with an uncorrelated uncertainty maintaining as much as possible the reported total uncertainty. If only the uncorrelated component is reported then a normalisation uncertainty was added. No correlation between results of different experiments was assumed.

The resulting average total cross section \( \sigma_{\text{tot}} \) is listed in table 2. This \( \sigma_{\text{tot}} \) is compared in fig. 1 with the experimental data that were used in the analysis and the cross section derived from the JEF-2.2 library. The latter is based on the analysis of Moxon et al. [25] in the resolved resonance region (RRR) and the work of Fröhner [2, 3] in the URR. There is a very good agreement between the results of the GMA analysis and the total cross section recommended in JEF-2.2.

2.2 Average capture cross section

The average capture cross section \( \sigma_c \) was derived by combining the capture data used by Carlson et al. [4] with those of Ullmann et al. [9], Kim et al. [10], Mingrone et al. [11] and Wright et al. [12].

The data used by Carlson et al. [4], which are also listed in ref. [26], include: 11 absolute \(^{238}\text{U}(n,\gamma)\), 2 shape \(^{238}\text{U}(n,\gamma)\), 2 absolute \(^{238}\text{U}(n,\gamma)/^{235}\text{U}(n,\alpha)\) ratio, 5 absolute \(^{238}\text{U}(n,\gamma)/^{198}\text{Au}(n,\alpha)\) ratio, 4 shape \(^{238}\text{U}(n,\gamma)/^{198}\text{Au}(n,\alpha)\) ratio, 9 absolute \(^{238}\text{U}(n,\gamma)/^{197}\text{Au}(n,\gamma)\) ratio, 1 shape \(^{238}\text{U}(n,\gamma)/^{197}\text{Au}(n,\gamma)\) ratio, 5 absolute \(^{238}\text{U}(n,\gamma)/^{235}\text{U}(n,f)\) ratio, 6 shape \(^{238}\text{U}(n,\gamma)/^{235}\text{U}(n,f)\) ratio and 1 shape \(^{238}\text{U}(n,\gamma)/^{239}\text{Pu}(n,f)\) ratio measurements. The \(^{238}\text{U}(n,\gamma)\) cross section data of Ullmann et al. [9] and Wright et al. [12] result from measurements with a total absorption detector. Kim et al. [10] and Mingrone et al. [11] applied the total energy detection principle using a set of CsI(Tl) liquid scintillators in combination with the pulse height weighting technique.

The resulting average capture cross section \( \sigma_c \) is reported in table 3. Figure 2 compares this cross section with the one of Carlson et al. [4], the data of refs. [9–12] and the cross section derived from the JEF-2.2 library. The present results are very close to the cross section derived from the JEF-2.2 library. Below 10 keV the cross section obtained in this work shows a similar structure as the experimental data of refs. [9–12] and the cross section in JEF-2.2. The absence of such a structure in the cross section recommended by Carlson et al. [4] is due to the limited number of high-energy resolution data combined with a sparse energy grid involved in the work of Carlson et al. [4]. Above 10 keV the main difference with the cross section of Carlson et al. [4] is a reduction in the uncertainty by about 40%. Similar conclusions were already drawn by Kim et al. [10] from a GMA analysis combining the data used by Carlson et al. [4] with only their data. In fact the results obtained by Kim et al. [10] are very close to those obtained in this work. Differences with the previous evaluation of Carlson et al. [4] are predominantly due
to the GELINA data of Kim et al. [10], which have a substantial lower uncertainty compared to those of Ullman et al. [9], Mingrone et al. [11] and Wright et al. [12].

Above 100 keV the data of Ullman et al. [9] and Mingrone et al. [11] deviate from both the results of Carlson et al. [4] and the present GMA analysis that includes these data. Ullman et al. [9] remark that their data suffer from bias effects in the region of the strong Al resonances at 36 keV, 88 keV and 104 keV. The differences with the results of Carlson et al. [4] around 100 keV are not discussed by Mingrone et al. [11]. It should be noticed, however, that similar deviations can be observed (see ref. [27]) between the $^{197}\text{Au}(n, \gamma)$ cross section data obtained from measurements at the n$_3$TOF facility in ref. [28] and the $^{197}\text{Au}(n, \gamma)$ cross section recommended by Carlson et al. [4], which was confirmed by the GELINA data of Massimi et al. [27].

### 3 Parameterisation of the cross sections in the URR by average resonance parameters

In the URR average compound cross sections can be parameterised in terms of transmission coefficients by means of the Hauser-Feshbach statistical reaction theory with width fluctuations, following various schemes for the fluctuation correction factor [29–32]. The width fluctuation correction factor approach used in this work has been the ENDF statistical integration with a Gauss quadrature scheme [33], which is both equivalent to an accurately calculated Dresner integral and compatible with the ENDF-6 format/model. More details can be found in refs. [34,27].

The average total and capture cross sections are expressed as a function of the scattering radius $R(E)$, neutron strength functions $S_l(E)$ and capture transmission coefficients $T_{\gamma}^{J^p}(E)$, with $f$ the angular momentum and $J^\pi$ the spin and parity of the compound nucleus. In most cases the scattering radius and neutron strength functions depend only weakly on the energy of the incoming neutron.

#### Table 2. Average total cross section $\sigma_{\text{tot}}$, its uncertainty, and correlation coefficient $\rho(\sigma_{\text{tot},i}, \sigma_{\text{tot},j})$ derived from a least squares analysis using the data of refs. [8,18–23].

| $E$/keV | $\sigma_{\text{tot}}$/$b$ | $\rho(\sigma_{\text{tot},i}, \sigma_{\text{tot},j}) \times 100$ |
|---------|-------------------------|---------------------------------|
| 5.5     | 19.43 ± 2.25            | 100 43 9 6 1 1 1 1 1 1 1 1 0 0 0 0 |
| 6.5     | 18.72 ± 2.11            | 100 50 11 1 1 1 1 1 1 1 1 1 0 0 0 0 |
| 7.5     | 16.49 ± 2.19            | 100 54 1 1 0 0 0 1 0 0 0 1 0 0 0 0 |
| 8.5     | 16.06 ± 1.79            | 100 3 0 0 0 1 1 0 1 1 1 0 0 0 0 0 |
| 9.5     | 14.646 ± 0.078          | 100 7 7 6 9 12 8 10 11 11 9 7 2 1 1 |
| 15      | 15.129 ± 0.053          | 100 10 9 13 18 13 16 16 17 13 10 2 2 |
| 20      | 14.674 ± 0.051          | 100 12 13 17 13 16 16 17 13 10 3 2 |
| 24      | 13.943 ± 0.030          | 100 15 16 11 18 16 16 17 13 10 9 10 10 |
| 30      | 13.780 ± 0.034          | 100 22 16 21 21 21 17 13 3 3 |
| 45      | 13.062 ± 0.025          | 100 31 27 27 29 22 17 4 4 |
| 55      | 12.994 ± 0.034          | 100 31 18 21 16 12 3 3 |
| 65      | 12.480 ± 0.019          | 100 43 28 20 15 5 4 |
| 75      | 12.249 ± 0.023          | 100 51 26 16 6 6 |
| 85      | 12.178 ± 0.024          | 100 42 27 7 7 |
| 95      | 12.026 ± 0.032          | 100 29 5 4 |
| 100     | 11.785 ± 0.039          | 100 8 6 |
| 120     | 11.611 ± 0.047          | 100 32 |
| 150     | 11.310 ± 0.048          | 100 |

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Fig. 1. Average total cross section $\sigma_{\text{tot}}$ for neutron interactions with $^{238}\text{U}$ as a function of neutron energy. The experimental data of Whalen et al. [18], Kononov et al. [19], Poenitz et al. [20,21], Tsubone et al. [22], Bokhovko et al. [23] and Derrien et al. [8] are compared with the results of a GMA analysis of these data and the one of JEF-2.2. The latter is based on the evaluation of Moxon [25] in the RRR and the evaluation performed by Fröhner [2,3] in the URR.
Table 3. Average capture cross section $\sigma_{\gamma}$, its uncertainty, and correlation coefficient $\rho(\sigma_{\gamma,i}, \sigma_{\gamma,j})$ derived from a least squares analysis using the capture data recommended by Carlson et al. [4] and the data of refs. [9–12].

| $E$/keV | $\sigma_{\gamma}$/b | $\rho(\sigma_{\gamma,i}, \sigma_{\gamma,j}) \times 100$ |
|---------|------------------|-------------------------------------------------|
| 5.5     | 0.8904 ± 0.0085  | 100 33 23 28 30 34 30 34 32 37 30 31 29 25 18 15 16 16 |
| 6.5     | 0.8427 ± 0.0090  | 100 41 31 30 33 29 33 32 36 30 31 29 24 18 15 16 15 |
| 7.5     | 0.7474 ± 0.0073  | 100 46 30 33 27 32 30 34 28 29 27 23 17 14 15 14 |
| 8.5     | 0.6442 ± 0.0055  | 100 34 36 27 34 32 35 28 29 28 24 17 15 15 15 |
| 9.5     | 0.6844 ± 0.0066  | 100 38 33 38 36 41 34 35 33 28 21 17 18 17 |
| 15      | 0.5910 ± 0.0044  | 100 38 46 44 49 40 41 39 33 24 21 22 21 |
| 20      | 0.5299 ± 0.0051  | 100 43 38 44 36 37 36 30 32 19 21 21 |
| 24      | 0.4718 ± 0.0035  | 100 51 52 43 44 41 36 29 25 26 27 |
| 30      | 0.4345 ± 0.0034  | 100 52 43 44 42 37 31 26 28 28 |
| 45      | 0.3574 ± 0.0028  | 100 51 48 46 40 31 27 28 27 |
| 55      | 0.2895 ± 0.0026  | 100 50 37 35 27 23 25 25 |
| 65      | 0.2449 ± 0.0022  | 100 52 33 28 24 26 24 |
| 75      | 0.2114 ± 0.0020  | 100 49 27 21 25 23 |
| 85      | 0.1879 ± 0.0020  | 100 49 36 23 23 |
| 95      | 0.1815 ± 0.0023  | 100 67 29 24 |
| 100     | 0.1788 ± 0.0025  | 100 39 25 |
| 120     | 0.1637 ± 0.0021  | 100 35 |
| 150     | 0.1411 ± 0.0016  | 100 |

Fig. 2. Average capture cross section $\sigma_{\gamma}$ for $^{238}$U(n, $\gamma$) as a function of neutron energy. The experimental data of Ullmann et al. [9], Kim et al. [10], Mingrone et al. [11] and Wright et al. [12] are compared with the results of a GMA analysis of these data combined with the data used by Carlson et al. [4]. The result of the GMA analysis is compared with the one of Carlson et al. [4] and JEF-2.2. The latter is based on the evaluation of Moxon [25] in the RRR and the evaluation performed by Fröhner [2,3] in the URR.

This dependence can be derived from results of optical model calculations [34,35]. The energy dependence of the transmission coefficient for the capture channel $T_{\gamma}^{J^\pi}(E)$ can be parameterised by [34]

$$T_{\gamma}^{J^\pi}(E) = T_{\gamma,0}^{J^\pi} W_{T_{\gamma}}^{J^\pi}(E),$$  \hspace{1cm} (1)$$

where $T_{\gamma,0}^{J^\pi} = T_{\gamma}^{J^\pi}(E = 0)$ is the capture transmission coefficient at zero neutron energy. The energy dependent term $W_{T_{\gamma}}^{J^\pi}(E)$ is determined from the definition of $T_{\gamma}^{J^\pi}(E)$ as a sum of single-channel photon transmission coefficients $T_{\gamma L}(\epsilon_{\gamma})$. The summation (integration) is over the transition types $X$, multiplicities $L$ and photon energies $\epsilon_{\gamma}$ of the primary $\gamma$-rays that excite the compound nucleus to lower-lying states.

Two models have been tried in the analysis. The first one assumed that the transmission coefficient $T_{\gamma 11}(\epsilon_{\gamma})$ of the predominating electric dipole transition is represented in a Lorentzian approximation of the photo-absorption cross section by a Giant Dipole Resonance (GDR) as proceeded in refs. [34,27]. The alternative model tried (employed for instance in the JENDL-4.0 evaluation) was the energy independent option for the average radiation width $T_{\gamma}$ rather than its energy dependence by the GDR model. The constant radiation width has performed significantly better with the Gilbert-Cameron level density in optimising capture transmission coefficients on the capture data up to 150keV and has ultimately been chosen in the analysis. The $J$-dependence of $T_{\gamma}^{J^\pi}$ can be determined from the known $J$-dependence of the level density with the common assumption that the effective radiation widths only depend on the parity [34]. Thus, independent parameters for the capture channel might be any two $T_{\gamma,0}^{J^\pi}$-values that belong to different parities (even and odd $\ell$), e.g. $T_{\gamma,0}^{(l+1/2)^+}$ and $T_{\gamma,0}^{(l+1/2)^-}$, where $J$ is the spin of the target nucleus.

Hence, independent parameters to determine the average total and capture cross section in the URR are the scattering radius, neutron strength functions and the
the average capture cross section ($\sigma$), parameter $\theta$ and the neutron strength functions $S_0$, $S_1$ and $S_2$ and the capture transmission coefficients. These quantities at zero energy are denoted as constants by $R'$, $S_{\ell=0,1,2}$, $T_{1/2}^+$ and $T_{1/2}^-$. The sensitivities of the average total and capture cross section to the scattering radius $R'$, strength functions $S_{\ell=0,1,2}$ and to the capture transmission coefficients $T_{1/2}^+$ and $T_{1/2}^-$ are shown in fig. 3 as a function of neutron energy. The dependences in fig. 3 reveal that the total cross section is mainly sensitive to the capture transmission coefficients and $\gamma$-ray transmission coefficients $T_{1/2}^+$ and $T_{1/2}^-$. The decreasing sensitivity to $D_0$ (keeping $T_{1/2}^+$ and $T_{1/2}^-$ intact) ranges from $-0.04\%$ at $5\text{ keV}$ to $-1.6\%$ at $150\text{ keV}$, and therefore is practically negligible. Hence, the average level spacing $D_0$ can not reliably be determined from its optimisation to average capture cross section data in the URR and has to be adopted or deduced in another way, as discussed in sect. 4.

The transmission coefficient for an inelastic scattering channel $T_{c\ell}$ is approximated by the transmission coefficient for an elastic neutron channel $T_{c\ell}$, provided that $c$ has the same orbital momentum and the same kinetic channel energy as $c'$. Since only the first inelastic level is considered in the URR, one has

$$T_{c\ell}(E) = T_{c\ell}(E - E_0),$$

with $E_0$ being the inelastic threshold energy, and $\ell$ and $\ell'$ the orbital momentum of $c$ and $c'$, respectively.

The average total and capture cross sections resulting from the GMA analysis were parameterised in terms of average resonance parameters maintaining consistency with the results of optical model (OM) calculations re-

Fig. 3. Sensitivity of the average total ($\delta \bar{\sigma}/\bar{\sigma}_{\text{tot}}$) and the average capture cross section ($\delta \bar{\sigma}_{\gamma}/\bar{\sigma}_{\gamma}$) to the parameter $\theta$ as a function of neutron energy. The parameter $\theta$ represents the scattering radius, the neutron strength functions $S_{\ell=0,1,2}$ and $\gamma$-ray transmission coefficients $T_{1/2}^+$ and $T_{1/2}^-$. The relative contribution of the partial waves to the average total and capture cross sections, shown in fig. 4. The transmission coefficient for an inelastic scattering channel $T_{c\ell}$ is approximated by the transmission coefficient for an elastic neutron channel $T_{c\ell}$, provided that $c$ has the same orbital momentum and the same kinetic channel energy as $c'$. Since only the first inelastic level is considered in the URR, one has

$$T_{c\ell}(E) = T_{c\ell}(E - E_0),$$

with $E_0$ being the inelastic threshold energy, and $\ell$ and $\ell'$ the orbital momentum of $c$ and $c'$, respectively.

The average total and capture cross sections resulting from the GMA analysis were parameterised in terms of average resonance parameters maintaining consistency with the results of optical model (OM) calculations re-
Table 4. The scattering radius, neutron strength functions $S_{T=0,1}$ and capture transmission coefficients, $\Gamma_{\gamma,0}^{1/2}$ and $\Gamma_{\gamma,0}^{1/2}$, at zero energy derived from the average cross section data in table 2 and table 3. The uncertainties and correlation matrix are also given. The neutron strength function $S_2 = 1.376 \times 10^{-4}$ was adopted from the DCCOM.

| $\theta$ | $\rho(\theta, \theta') \times 100$ |
|---------|---------------------------------|
| $R'$/fm | 9.483 ± 0.020                   |
| $S_{0}/10^{-4}$ | 1.064 ± 0.015                   |
| $S_{1}/10^{-4}$ | 1.641 ± 0.033                   |
| $\Gamma_{\gamma,0}^{1/2}/10^{-3}$ | 6.60 ± 0.14                     |
| $\Gamma_{\gamma,0}^{1/2}/10^{-3}$ | 6.37 ± 0.07                     |

Fig. 5. Average total cross section $\sigma_{\text{tot}}$ for neutron interactions with $^{238}\text{U}$ as a function of neutron energy. The result of a GMA analysis and the cross section derived from the average parameters in table 4 are compared with the total cross sections recommended in other data libraries, i.e. ENDF/B-VII.1, JENDL-4.0, JEF-2.2, JEFF-3.2 and JEFF-3.3T4.

4 An ENDF-6 compatible data file for energies between 20 keV and 150 keV

The results obtained in this work were used to produce an evaluated data file for neutron interactions with $^{238}\text{U}$ in the URR, from 20 keV to 149 keV. The boundary between the RRR and URR was kept at 20 keV, as in the file produced by Derrien et al. [43]. It should be noted that no substantial difference was found in the interpretation of integral benchmark experiments by reducing the upper

ported by Capote et al. [36]. The procedure that was applied to evaluate the cross section data in the URR for $^{232}\text{Th}$ [34] and $^{197}\text{Au}$ [27,35] has been followed. The DCCOM potential of refs. [37,38] was used for the optical model calculations with the coupled-channel OPTMAN code [39,40] incorporated into the EMPIRE system [41]. Neutron strength functions $S_0(E), S_1(E)$, and $S_2(E)$ that correspond to the OM data have been obtained so as to reproduce the compound formation cross sections of the DCCOM with the optical model parameters from RIPL 2412 [42]. The energy dependence of the direct inelastic scattering cross section was adopted from the same DCCOM calculations [36], while the energy dependence of the hard-sphere potential scattering radius $R(E)$, which corresponds to the OM calculations, was derived from the shape elastic cross section of the DCCOM. More details about an ENDF URR model, which is equivalent to the OM with respect to the non-fluctuating cross sections (i.e., the total, shape elastic and compound formation one), can be found in refs. [34,35].

The smooth and weak energy dependences obtained from the DCCOM for the scattering radius $R(E)$ and neutron strength functions $S_i(E)$ were parameterized by second order polynomials. The resulting scattering radius $R'$ and neutron strength functions $S_{T=0,1,2}$ at zero energy were used as initial fit parameters. The data sensitivity to $S_2$ was not sufficient for a reliable optimisation. Therefore, the strength function for $d$-wave neutrons was fixed to $S_2 = 1.376 \times 10^{-4}$ as derived from the DCCOM.

The final parameters together with their uncertainty and correlation matrix are listed in table 4. The covariance matrix was obtained by conventional uncertainty propagation of the covariance data in table 2 and table 3. The scattering radius at zero energy derived from the DCCOM ($R' = 9.6028 \text{ fm}$) required a small adjustment. The adjusted radius $R' = (9.483 \pm 0.020) \text{ fm}$ is fully consistent with the scattering radius $R' = 9.48 \text{ fm}$ that was used for a resonance shape analysis in the RRR by Kim et al. [10]. The initial strength functions $S_0$ and $S_1$ at zero energy derived from the DCCOM were practically not changed. The final values $S_0' = (1.064 \pm 0.015) \times 10^{-4}$ and $S_1 = (1.641 \pm 0.033) \times 10^{-4}$ are within the uncertainties in very good agreement with the strengths functions derived from a statistical analysis of resolved resonance parameters: $S_0 = (1.025 \pm 0.047) \times 10^{-4}$ and $S_1 = (1.652 \pm 0.046) \times 10^{-4}$ reported by Derrien et al. [43] and $S_0 = (1.03 \pm 0.05) \times 10^{-4}$ and $S_1 = (1.70 \pm 0.20) \times 10^{-4}$ by Courcelle et al. [7]. Derrien et al. [43] and Courcelle et al. [7] used the same resonance parameter file for their analysis. They are also consistent with the strength functions recommended in the RIPL library [42], i.e. $S_0 = (1.03 \pm 0.08) \times 10^{-4}$ and $S_1 = (1.6 \pm 0.2) \times 10^{-4}$. The total and capture cross sections calculated with the parameters in table 4 are shown in fig. 5 and fig. 6, respectively.
limit of the RRR to 10 keV. More details on the effect of the upper boundary for the RRR can be found in ref. [1].

The average total and capture cross section resulting from the GMA analysis were adopted in file 3 with the LSSF=1 option as infinitely dilute total and capture cross sections, respectively. The inelastic neutron scattering cross section data of Capote et al. [36], which include compound-direct interference effects as discussed by Kawano et al. [44], were also adopted in file 3 by modifying the calculated infinitely dilute inelastic cross section based on both resonance parameters (ENDF-6 single orbital representation of the inelastic neutron widths) and the direct inelastic cross section from the DCCOM. The approximated impact of the compound-direct interference effect is illustrated in fig. 7. In this figure the experimental data of Kegel et al. [45], Tsang and Brugger [46], Winters et al. [47], Litvinsky et al. [48] and Moxon et al. [49] are compared with the cross section calculated with and without accounting for the interference between the contributions of the direct- and of the compound reaction model. More information on the interference effect can be found in ref. [44].

The average parameters listed in table 4 were used to produce an ENDF-6 compatible file 2, which is required for accurate self-shielding calculations. Conversion into the ENDF-6 format requires that the transmission coefficients $T_c^{J_{\gamma}}$ are translated into effective partial widths $T_c^{J_{\gamma}}$ by means of the following relation:

$$T_c^{J_{\gamma}} = 2\pi \frac{T_\pi^{J_{\gamma}}}{D_J},$$

where $c$ may be any entrance or exit, single or lumped, channel and $D_J$ is the level spacing. The level spacing is related to the level density $\rho_J$ by $D_J = 1/\rho_J$. For the capture channels eq. (3) becomes

$$T_c^{J_{\gamma}} = 2\pi \frac{T_\pi^{J_{\gamma}}}{D_J}. $$

Two file versions have been tested in order to assign low-energy values for the s-wave level spacing, $D_0 = D_{1/2}(E = 0)$, and the s-wave radiation width, $T_\gamma^{J_{\gamma}} = T_\gamma^{J_{\gamma}}(E = 0)$, taking into account their relation with the optimised parameter

$$T_{1/2}^{J_{\gamma}} = 2\pi \frac{T_\pi^{J_{\gamma}}}{D_0}. $$

In addition, as mentioned in sect. 3, energy independent radiation widths $T_\gamma^{J_{\gamma}} = T_\gamma^{J_{\gamma}}(E = 0)$ were chosen rather than their GDR energy dependence for the better $\chi^2$-optimization.

In a first version the value of $T_\gamma^{J_{\gamma}}(E = 1) = 22.5$ meV resulting from a resonance shape analysis of transmission and capture data below 1.2 keV by Kim et al. [10] was
Table 5. Spectrum averaged total cross section based on the data reported in this work compared with experimental results reported by Livinsky et al. [48] and Pham et al. [58].

| Ref.          | Most probable energy | Spectrum averaged cross section |
|--------------|-----------------------|-------------------------------|
|              |                       | Exp. data                     | This work                     |
| Litvinsky et al. [48] | 54 keV               | (13.343 ± 0.051) b            | (13.27 ± 0.05) b              |
| (EXFOR Entry = 40924) | 144 keV              | (11.551 ± 0.022) b            | (11.70 ± 0.05) b              |
| Pham et al. [58]     | 54 keV               | (13.31 ± 0.11) b              | (13.10 ± 0.05) b              |
| (EXFOR Entry = 31457) | 144 keV              | (11.52 ± 0.11) b              | (11.43 ± 0.05) b              |

adopted. Using the parameters of table 4 together with eq. (5) this corresponds to $D_0 = 21.4$ eV and $\Gamma_{\gamma}(\ell = 1) = 21.7$ meV. In a second version an effective energy independent radiation width $\Gamma_{\gamma}(\ell = 0)$ for the energy region between 20 keV and 150 keV was obtained after projecting the value of 22.5 meV from zero energy to a mid-energy point of 75 keV assuming a GDR energy dependence and obtaining $\Gamma_{\gamma}(\ell = 0) = 23.3$ meV. This value is in agreement with the one recommended in RIPL 2412 [42], i.e. $\Gamma_{\gamma}(\ell = 0) = (23.6 ± 0.8)$ meV. The GDR parameters for the compound nucleus of $^{238}$U + n was adopted from Holmes et al. [53]. A pairing energy of 0.69 MeV in the effective excitation was considered for the level density of $^{239}$U. Using the transmission coefficients in table 4 together with eq. (5), results in $D_0 = 22.2$ eV and $\Gamma_{\gamma}(\ell = 1) = 22.5$ meV. The level spacing derived for the two cases are within the uncertainties consistent with the value $D_0 = (21.19 ± 0.55)$ eV that was derived from a statistical analysis of resolved resonance parameters by Derrien et al. [43] and Courcelle et al. [7]. Both versions have shown almost the same cross sections and very similar behaviour in the interpretation of benchmark experiments, since they retain the fitted capture transmission coefficients practically intact. The second version has ultimately been chosen for the final evaluation.

The file produced in this work is taken over in the CIELO file that is produced at the IAEA [13], referred to as CIELO(IAEA), and adopted in ENDF/B-VIII.0 [54]. However, it was not considered for the latest version of the JEFF project, which is referred to as JEFF-3.3T4 [55].

The cross sections obtained in this work are shown in fig. 5 and fig. 6 and compared with those recommended in ENDF/B-VIII.1, JENDL-4, JEFF-2.2, JEFF-3.2 and JEFF-3.3T4. These figures show that there is a substantial difference between the capture cross section obtained in this work and the one recommended in JEFF-3.3T4. The capture cross section in JEFF-3.3T4 is in the region between 10 keV and 150 keV on average lower by ~5%. There is also a difference between the cross sections recommended in the previous versions of the JEFF-library (i.e., JEFF-2.2 and JEFF-3.2) and the one in JEFF-3.3T4. Most probable these differences are due to adjustments of nuclear data to results of integral benchmark experiments.

A systematic analysis of the CIELO(IAEA) and JEFF-3.3T4 files was performed based on the results of the BigTen benchmark experiment. This experiment, which is fully documented in the ICSBEP Handbook [56] with reference IMF-007, shows a high sensitivity to the $^{238}$U(n, $\gamma$)
cross section in the URR. In case of the BigTen experiment, a decrease of the capture cross section for $^{238}\text{U}(n,\gamma)$ in the URR by $\sim 5\%$ results in an increase of $k_{\text{eff}}$ of $\sim 500$ pcm. The reduced capture cross section for $^{238}\text{U}(n,\gamma)$ in the JEFF-3.3T4 evaluation is mainly compensated by an increasing cross section for $^{235}\text{U}(n,\gamma)$. A more detailed discussion on the difference with the $^{238}\text{U}(n,\gamma)$ cross section in JEFF-3.3T4 and the compensating effects is being prepared [57].

5 Validation of the ENDF-6 file

The file recommended in this work has been validated by a comparison with results of both spectrum averaged cross section measurements and energy dependent self-shielding factor (Bondarenko) experiments for the capture reaction. The total cross section in table 2 is consistent with results of measurements at filtered neutron beams with neutron energies of $\sim 54$ keV and $144$ keV reported in refs. [48,58]. Calculated spectrum averaged cross sections were derived by combining the data in table 2 with the cross section taken from the CIELO project for energies below 20 keV and above 150 keV [13]. The neutron energy distributions were obtained from calculations that were validated by results of experiments with a hydrogen proportional counter [59]. The calculated values, reported in table 5, are within the uncertainties in full agreement with those measured by Pham et al. [58]. The calculated average total cross section for the 144 keV beam is not in full agreement with the value determined by Litvinsky et al. [48]. This can be due to the spectrum used in the calculations or to an underestimation of the uncertainty quoted by Litvinsky et al. [48].

The average capture cross section $\langle \sigma \rangle$, recommended in this work can be compared with the spectrum averaged cross section reported by Wallner et al. [60]. The latter was obtained from a combination of activation measurements and atom counting of the reaction products using accelerator mass spectrometry. For a neutron beam with a distribution that is very similar to a Maxwell-Boltzmann distribution of $kT \sim 25.3$ keV they derived a spectrum averaged $^{238}\text{U}(n,\gamma)$ cross section of $(391 \pm 17)$ mb [60]. This value is within the uncertainties in agreement with the average value of $(400 \pm 5)$ mb derived from the data in table 3 complemented by the CIELO file for energies below 5 keV and above 150 keV. For the calculations the spectrum reported in the EXFOR library was used.

The compensating effect in JEFF-3.3T4 mentioned in sect. 4 can be confirmed by comparing the experimental capture cross section ratio $R = ^{238}\text{U}(n,\gamma)/^{235}\text{U}(n,\gamma)$ obtained by Wallner et al. [60] for an average energy of $\sim 25.3$ keV with the one derived from the CIELO/IAEA and JEFF-3.3T4 files. Using the energy distribution reported in the EXFOR data library, a ratio of $R_{\text{CIELO}} = 0.57$ is obtained from the CIELO/IAEA file [13,15]. This ratio is within the uncertainty in agreement with the experimental value of $R_{\text{exp}} = 0.60 \pm 0.03$ [60]. The ratio of $R_{\text{JEFF-3.3T4}} = 0.49$ derived from the JEFF-3.3T4 file is smaller by almost 20%, while the experimental uncertainty is less than 5%. This underestimation is due to the combined decrease of the $^{238}\text{U}(n,\gamma)$ cross section and increase of the $^{235}\text{U}(n,\gamma)$ cross section in JEFF-3.3T4. The same ratios are obtained using a Maxwellian energy distribution with $kT = 25.3$ keV for the calculation of the spectrum averaged cross sections. The ratio is also independent of any reference to a standard reaction cross section.

Experimental self-shielding factors $f_s$ for the $^{238}\text{U}(n,\gamma)$ reaction have been deduced from a series of transmission and self-indication measurements by Oigawa et al. [61]. Figure 8 shows the good agreement between the experimental data of Oigawa et al. [61] and the self-shielding factors calculated with NJOY using the file presented in this work. Note that the calculated values below 20 keV are based on the CIELO file in the resolved resonance region [13,15]. This file was constructed by replacing the parameters derived by Derrien et al. [43] below 1200 eV with those of Kim et al. [10].

A test of the $^{238}\text{U}$ evaluated data file based on results of integral benchmark experiments is reported by Capote et al. [13] and Chadwick et al. [15].

6 Summary

An ENDF-6 compatible evaluation of average resonance parameters and dilute average cross sections for neutron interactions with $^{238}\text{U}$ in the energy region from 5 keV to 150 keV has been carried out using only energy dependent microscopic cross section data. Average total and capture cross sections have been derived from a least squares analysis to experimental cross section data. They have been parameterised in terms of average resonance parameters maintaining consistency with results of optical model calculations based on a dispersive coupled channel optical model potential. The average parameters derived from a least squares adjustment to the average total and capture cross sections are within the uncertainties fully consistent with the parameters derived from a statistical analysis of resolved resonance parameters. The average cross sections and average resonance parameters have been used to produce an ENDF-6 compatible evaluated file for neutron interactions with $^{238}\text{U}$ in the unresolved resonance region. The evaluation has been validated by results of both spectrum averaged cross section measurements and self-shielding factor experiments.

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