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Simultaneous Evaluation of Fission Cross Sections for Cm Isotopes

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Abstract. Fission Cross Sections for a complete set of Cm-isotopes, $^{240-250}$Cm, have been calculated in the incident energy range from above resonance region to 20 MeV. This work aims at providing the fission cross sections with consistent set of model parameters for Cm isotopes, as a part of a complete evaluation including covariance files for several minor actinides which play a great role in the Advanced Fuel Cycle (AFC) design and applications as well as the design of new generation of nuclear reactors (GEN-IV). This was accomplished by means of computational analyses carried out with the nuclear model code EMPIRE-2.19 which is the modular system of nuclear reaction codes. A Fission model of this work took into account transmission derived in the WKB approximation within an optical model through a double-humped fission barrier.

1 Introduction

Neutron-induced cross sections with high accuracy including covariances for Minor Actinides (MA) play an increasingly prominent role for an Advanced Fuel Cycle (AFC) design and safeguard applications as well as the design of new generation of nuclear reactors (GEN-IV). Evaluations for many of minor actinides in existing libraries such as ENDF/B-VII.0, JENDL-3.3 and JEFF-3.1 were performed several tens years ago, and have been partially revised for some reactions. Moreover, most of evaluated files do not have covariances or give quality assurance even if they have ones. Accordingly, new evaluations of neutron cross sections with high quality covariances were increasingly recognized.

In response to this situation, we identified priority nuclides that needed the improved nuclear data with covariances for AFC design, and selected plutonium, neptunium and curium elements. This work aims to provide the fission cross sections for a complete set of curium isotopes with half-lives over than 1-day. Although the ultimate object for evaluations of curium isotopes is to provide the neutron cross sections with covariances, we focused here on producing the neutron cross sections with consistent sets of model parameters which would be employed to obtain the sensitivity matrices together with the available measurements. The previous fission cross section evaluations for Cm isotopes in existing libraries were mainly performed by a combination of empirical fitting to the available measurements and model calculations for regions divided by incident energy range. These kinds of evaluations can reproduce well the reactions where the experimental data exit, while they may predict wrong cross sections for reactions where no experimental data are available. It is inconvenient or even impossible for us to generate the covariance files with high fidelity because our uncertainties based on variation of model parameters can be ensured by using model parameters with a consistent set.

This situation can be rectified by a simultaneous evaluation for all Cm isotopic family because their mass dependency do not differ too much among individual members of isotopic family. All evaluations in the fast neutron region were performed with the EMPIRE code [1] that has been used to provide a number of consistent and complete evaluations to the evaluated nuclear data library. This code implemented the fission model describing by the transmission expressed in the first-order WKB approximation within and optical model through a double-humped fission barrier [2].

2 Evaluation Methodology

2.1 Status of Evaluations and experimental data

Our evaluations are always compared with the up-to-date version of the existing libraries such as ENDF/B-VII.0, JENDL-3.3 and JEFF-3.3 and with the measurements. The JENDL-3.3 evaluation is a latest one for the evaluations of Cm isotopes, though most of evaluations had been completed in 1995. While the ENDF/B-VII.0 evaluations were completed in 1978 for ^{241,242,248}Cm and were taken from the JENDL-3.3 ones for $^{243-246,249,250}$Cm. Fission cross sections for ^{248}Cm were recently evaluated in incident energy range 30 keV to 20 MeV. JEFF-3.1 evaluations adopted the evaluations of the previous U.S. library, ENDF/B-VI.8 which adopted the JENDL-3.2 evaluation, for ^{241,242,244}Cm, and those of JENDL-3.3 for $^{240,243,245-250}$Cm.

The most important consideration in the model calculations of fast neutron region is whether experimental data are available or not, because the measured data constrain the model parameters and inversely the results of the model calculations employing those model parameters are able to reproduce the experimental data well. Thus, we

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Table 1. Status of experimental data for $^{240-250}$Cm. The isotopic half-lives ($T_{1/2}$) and upper boundaries of the respective unresolved resonance regions (URR) are also listed

Isotopes	Experimental Data	$T_{1/2}$	URR Upper Limit (keV)
^{240}Cm	-	27 d 1	30.0
^{241}Cm	-	32.8 d 2	30.0
^{242}Cm	f	162.8 d 2	30.9
^{243}Cm	f	29.1 y 1	42.2
^{244}Cm	tot, el, inl, γ, f	18.1 y 1	40.0
^{245}Cm	f	8500 y 100	54.9
^{246}Cm	f	4760 y 40	43.0
^{247}Cm	f	1.56×10^7 y 5	30.0
^{248}Cm	f	3.48×10^5 y 5	30.0
^{249}Cm	-	54.15 m 3	25.0
^{250}Cm	-	8.3×10^3 y	65.0

searched the available experimental data from literatures and the EXFOR library as the first step of evaluation. Table 1 shows the status of experimental data available for $^{240-250}$Cm. The isotopic half-lives ($T_{1/2}$) and upper boundaries of the respective unresolved resonance regions (URR) are also listed. The status of the very limited experimental data shown in Table 1 implies that we have hundreds of degree of freedom in selecting the model parameters for most of Cm isotopes. In the other words, it is difficult to determine the model parameters within reasonable acceptance for isotopes with almost no measurements available. However, ^{244}Cm has the experimental data which can constrain the model parameter to a certain extent.

2.2 Simultaneous Evaluation

In case of these insufficient experimental data available, the simultaneous evaluation of a complete isotopic chain is an important aspect of our evaluation procedure as described in Ref. [3]. We take advantage of the fact that certain critical model parameters, such as optical potential and asymptotic value of the level density parameter, vary smoothly as function of mass number. Accordingly, they do not differ too much among individual members of the isotopic family. Taking into account known mass dependencies or trends for certain model parameters we were able to use experimental data for the neighboring isotopes to constrain model parameters for individual isotopes even if no measurements on a given isotope/reaction are available. When doing this, we accounted for the prominent and well understood differences between various isotopes such as binding energies, deformations, and discrete level schemes. Especially, the model parameters of fission barriers were determined by using the dependence of even or odd nuclides. Adequate consideration of these factors is critical for the reliable implementation of the procedure. Fortunately, most of these quantities are known with a reasonable level of confidence. This justifies ascribing some residual discrepancies between calculations and experiments to the less known but slowly varying parameters that can

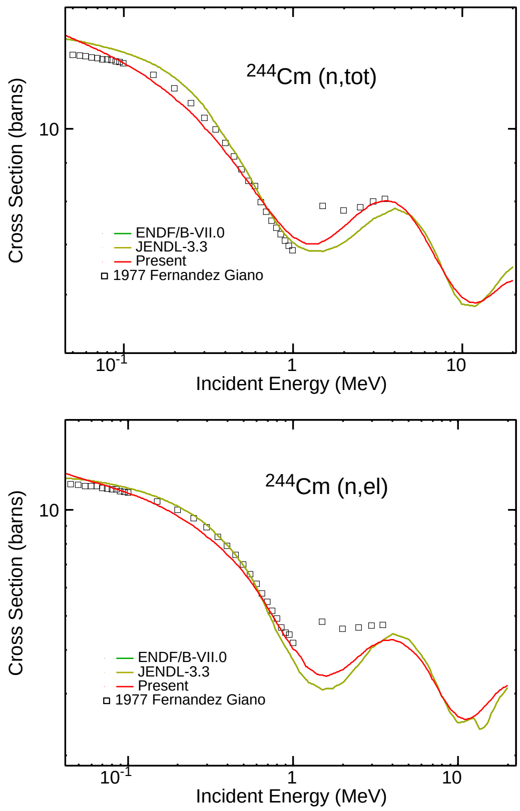

Fig. 1. Total and elastic cross sections for ^{244}Cm compared to the measurements [6].

be adjusted by tuning the related systematics. Implementation of such consistent set in reaction calculations ensures that the differences among evaluations can be understood in terms of the physical differences among the isotopes.

Table 1 shows that the experimental data are not sufficient to determine the optical model potential parameters (OMP), which play a great important role in calculation the amount of each reaction. So, instead of generating new OMP parameters, we searched the existing ones from RIPL-2 and employed the transmission coefficients using an isospin-dependent coupled-channels optical model potential containing a dispersive term (DCCOMP) for neutrons and protons suggested by Capote *et al.* [4] which is considered as the most reasonable parameters for actinides. The total and elastic cross sections using DCCOMP are compared to the measurements and the existing libraries in Figure 1. Although Figure shows some discrepancies with experimental data, we will keep the present result as preliminary one, because the experimental data is the evaluated data rather than real measured ones. The Empire-specific level densities were employed and their parameters adjusted by the cumulative fitting to known nuclear discrete levels and available experimental data. The gamma strength function developed by Plujko *et al.* [5] was employed.

In order to calculate fission cross section, we took into accounts transmission derived in the WKB approximation within an optical model through a double-humped fission

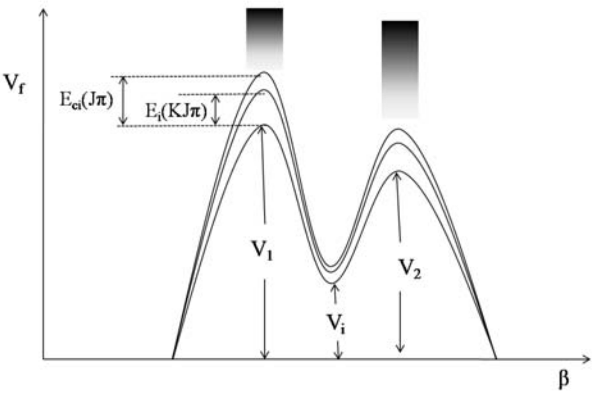

Fig. 2. A double humped fission barrier.

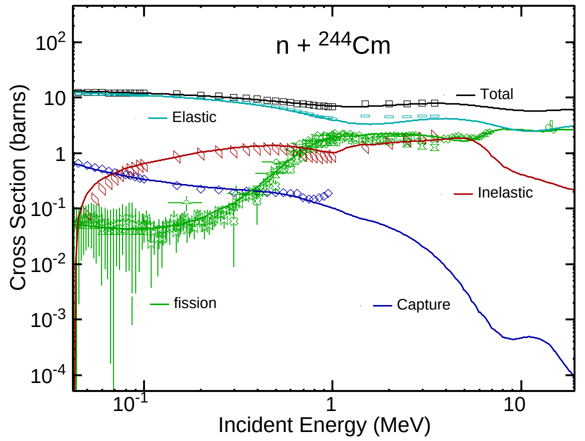

Fig. 3. Total, elastic, fission, capture, and inelastic cross sections for ^{244}Cm compared to the measurements [6–11].

Table 2. The preliminary parameters for fission barriers of $^{240-250}$Cm

Isotope	V_1	V_2	$\hbar\omega_1$	$\hbar\omega_2$	V_i	$\hbar\omega_i$
^{240}Cm	5.35	4.52	0.5	0.45	1.6	1.0
^{241}Cm	6.2	5.52	0.4	0.52	1.6	1.0
^{242}Cm	5.2	4.6	0.54	0.6	1.27	1.0
^{243}Cm	5.8	5.2	0.7	0.62	1.6	1.0
^{244}Cm	5.35	4.6	0.55	0.6	1.67	1.0
^{245}Cm	5.72	5.18	0.7	0.62	1.9	1.0
^{246}Cm	5.62	4.6	0.61	0.52	1.9	1.0
^{247}Cm	5.65	5.0	0.7	0.6	1.9	1.0
^{248}Cm	5.21	4.6	0.65	0.5	1.8	1.0
^{249}Cm	5.52	4.2	0.62	0.46	1.9	1.0
^{250}Cm	5.35	4.5	0.6	0.5	1.9	1.0

barrier. All parameters including fission level densities ones were considered as free parameters. Table 2 shows the preliminary results of the parameters depicted as following:.

$$V_i(\beta) = E_{fi} - \frac{1}{2}\mu\hbar^2\omega_i^2(\beta-\beta_i)^2 \quad i = 1, N \qquad (1)$$

where N is the number of barriers or wells. The energies E_{fi} represent the maxima (minima) of the barrier (well) and the β_i are the corresponding deformations. The harmonic oscillator frequencies ω_i define the curvature of each parabola and μ is the inertial mass parameter, assumed to be independent of β and approximated by the semi-empirical expression $\mu \approx 0.054A^{5/3}$ MeV^{-1}, where A is the mass number.

3 Results

^{244}Cm have the experimental data for total, elastic, capture, and fission cross sections. Thus, the evaluations of ^{244}Cm induced by neutron was selected by first isotope of Cm family. Figure 3 shows the preliminary cross sections of each channel for ^{244}Cm compared to the measurements [6–11]. Each channel is in good agreement with the available experimental data.

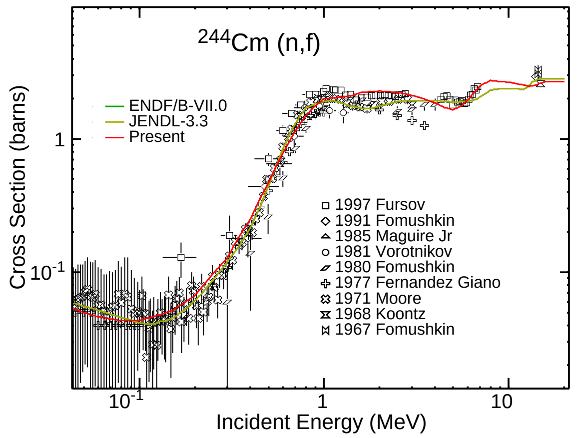

Fig. 4. Fission cross sections for ^{244}Cm compared to the JENDL-3.3 and ENDF/B-VII.0 and the measurements [7–11].

Figure 4 shows the fission cross sections compared to the measurements and the JENDL-3.3 evaluation which was adopted by ENDF/B-VII.0. Our fission cross sections below 1 MeV show in reasonable good agreement with both the measurements and the JENDL-3.3 evaluation. For above 1 MeV, the measurements data of Ref. [6] go down dramatically, while other measurements [7–11] and JENDL-3.3 evaluation show almost flat. The decrease of the first chance fission in this region is compensated by the increase of the second chance one. The shortcoming of our preliminary result is a little broad bump from 1 MeV to about 5 MeV. This bump came from what our fission model did not consider the transition states for discrete fission levels yet. The fission model and it parameters of ^{244}Cm became the reference of the remaining Cm isotopes.

We used the models described in Sec. 2.2 for the evaluations of the remaining curium isotopes. The model parameters of each isotope had the difference by the mass dependence of each model, except for the fission model parameters which were determined in order to reproduce the available experimental data. Table 2 shows the model param-

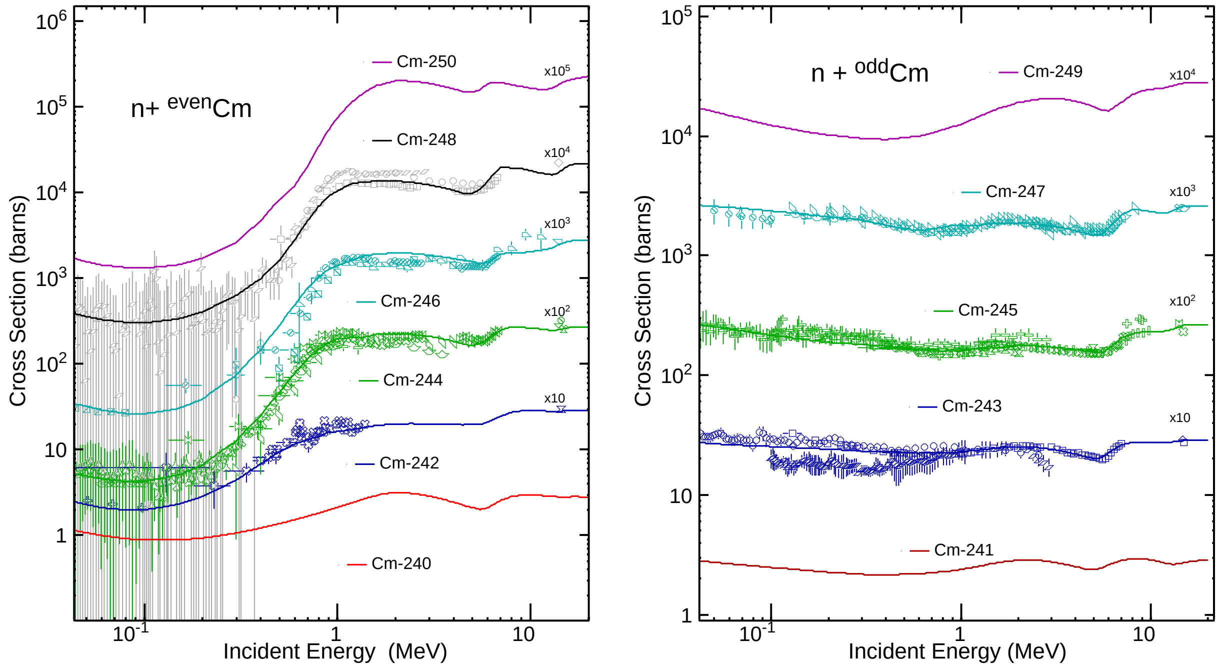

Fig. 5. Fission cross sections for $^{240-250}$Cm compared to the measurements [7–18].

eters employing in this work. Figure 5 shows the fission cross sections of even curium isotopes in left plot and odd in right. Both plots show that the measurements for each isotope are reproduced well by the fission model calculations using the model parameters of Table 2. The fission cross sections for the isotope with no measurements available such as ^{240,241,249,250}Cm were predicted by the model calculation considering the trends of the model parameters for even- or odd- isotope.

4 Conclusion

We calculated the neutron cross sections for curium isotopes using the up-to-date nuclear reaction model code, Empire-2.19. As the results, we produced the preliminary fission cross sections with a consistent sets of model parameters for $^{240-250}$Cm. Although the present results have a shortcoming such as no transition states of discrete fission levels, which produces slight higher cross sections than the measurements between 1 MeV to about 5 MeV, it is worthy of notice that the cross sections as a whole are in reasonable agreements with available measurements. The simultaneous evaluation performed this work ensures the quality assurance of our results, and the suggested consistent set of model parameters will be made practical application for generating covariances with the high-fidelity because our covariance will be generated on basis of the sensitivity matrices produced by the variations of model parameters.

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