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ADJUSTMENT OF EVALUATED FISSION CROSS SECTIONS BY INTEGRAL DATA

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Abstract: Fission cross sections for ^{232}Th, ^{233}U, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{237}Np and ^{239}Pu, evaluated from differential experiments and compiled in JENDL-3T, have been adjusted by using integral fission cross-section ratios measured for $^{232}Th/^{235}U$, $^{237}Np/^{235}U$, $^{238}U/^{235}U$, $^{237}Np/^{238}U$, $^{232}Th/^{237}Np$, $^{236}U/^{235}U$, $^{239}Pu/^{235}U$, $^{233}U/^{235}U$, $^{234}U/^{235}U$, $^{234}U/^{236}U$ and $^{236}U/^{238}U$ in the continuum neutron spectrum produced by bombardment of a thick Be-metal target with 7 MeV deuterons. It has been demonstrated that the fission cross-section curves can be adjusted in the energy range between 1 and 10 MeV. The ratios of the calculated to experimental values for the integral fission cross-section ratios have been revised within ± 1.005 except for ^{232}Th whose result is 1.02. The original values are between 0.995 and 1.067 in JENDL-3T. The adjustment method developed in the present work is valuable to evaluate accurate and consistent cross-sections in the MeV neutron energy region. Differential and integral data are complementary in a cross-section evaluation. The former are useful to determine shapes of the cross-section curves and the latter serve to adjust their absolute values.

(Adjustment, Evaluation, Integral data, Averaged cross-section, Fission cross-section, Heavy nuclides, Simultaneous evaluation)

Introduction

Fission cross sections are among the most important quantities in nuclear data: they should be accurate and consistent in an evaluated file. Simultaneous evaluations /1,2/ have been performed as a method to meet these requirements. What the simultaneous evaluation intends to accomplish is that the measurements correlated to each other should be used to evaluate the cross sections, taking account of their covariances which can be estimated from partial errors associated with the experimental conditions.

Briefly, the method is equivalent to taking weighted averages of the measured values: strongly correlated data have small weight. Weak correlation is expected among different kinds of experiments, for example, with different types of neutron sources, detectors and standards.

Differential fission cross sections, measured with monoenergetic neutron sources or white neutron sources associated with a time-of-flight technique, are entirely heterogeneous to integral data, i.e., averaged cross-sections measured with spectral neutron sources. Cross section evaluations are usually based on the differential data. The integral data have been frequently applied only to examine the values resulting from the differential data, and are rarely utilized to feed back quantitatively to reevaluate them. A reason is that there was not a method available to simultaneously take account of both the differential and integral data. In the previous work /3/, however, it was predicted that some activation cross-sections used in neutron dosimetry evaluated from differential measurements could be successfully adjusted by the integral data measured in fission neutron fields. The same method is applied in this work to adjust the fission cross-sections evaluated from differential data by using integral data measured in the continuum spectrum produced by bombardment of a thick Be-metal target.

The fission cross sections of almost all the heavy nuclides have a plateau in a neutron energy region near a few MeV. It approximately coincides with the predominant yield of a broad neutron spectrum produced by 7.0 MeV deuterons incident on a thick Be-metal target. This coincidence suggests that adjustments of evaluated fission cross-sections by the integral measurements in the d-Be neutron spectrum are effective to achieve highly accurate absolute values in the evaluation. In this procedure, there are two preconditions:the d-Be neutron spectrum and the covariances of the evaluated fission cross sections should be well known. These are satisfied as discussing later.

In the present work, the fission cross-section curves of ^{232}Th, ^{233}U, ^{234}U, ^{236}U, ^{235}U, ^{238}U, and ^{239}Pu in JENDL-3T /4/ are adjusted by the integral fission cross-section ratios measured for the eleven pairs of these nuclides at Argonne National Laboratory /5/.

Formulae

The equations for adjustment of the evaluated cross sections are similar to those in the previous work /3/. The adjusted cross section vector θ and its covariance matrix M are given as

$$\theta = \theta_0 + M_0\Phi^t(\Phi M_0\Phi^t + V)^{-1}(y - \Phi\theta_0) , \quad (1)$$

and

$$M = M_0 + M_0\Phi^t(\Phi M_0 \Phi^t + V)^{-1}\Phi M_0 , \qquad (2)$$

respectively. The experimental data vector y is approximately given as

$$y = \Phi\theta , \qquad (3)$$

where Φ is a design matrix whose components are expressed by B-spline functions. The components of the vector y are logarithms of the integral data. The matrix V is the covariance matrix for y. The components of vector θ_0 and matrix M_0 are the evaluated cross-sections and their covariances, respectively.

Evaluated Data

The evaluated fission cross-sections to be adjusted are taken from JENDL-3T. The values for ^{235}U, ^{238}U, and ^{239}Pu are the results of the simultaneous evaluation /1/, which is conducted to obtain the fission cross-sections of ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu and the capture cross-sections of ^{197}Au and ^{238}U, based on the absolute measurements and the ratio measurements, $\sigma_f(^{238}U)/\sigma_f(^{235}U)$, $\sigma_f(^{239}Pu)/\sigma_f(^{235}U)$, $\sigma_f(^{240}Pu)/\sigma_f(^{235}U)$, $\sigma_f(^{241}Pu)/\sigma_f(^{235}U)$, $\sigma_c(^{238}U)/\sigma_f(^{235}U)$, $\sigma_c(^{238}U)/\sigma_f(^{197}Au)$, $\sigma_c(^{197}Au)/\sigma_f(^{235}U)$.

The values for ^{237}Np are taken from the work for JENDL-3T /6/. They are evaluated from the absolute measurements, the ratio measurements, $\sigma_f(^{237}Np)/\sigma_f(^{235}U)$, $\sigma_f(^{237}Np)/\sigma_f(^{239}Pu)$ and the results of $\sigma_f(^{235}U)$ and $\sigma_f(^{239}Pu)$ in the simultaneous evaluation described above. The components of M_0 for ^{237}Np measurements are estimated from the experimental errors and those for $\sigma_f(^{235}U)$ and $\sigma_f(^{239}Pu)$ are, similarly, the results in the simultaneous evaluation. In consequence, the evaluated data for $\sigma_f(^{237}Np)$ are equivalent to the results of a new simultaneous evaluation, including $\sigma_f(^{237}Np)$ and the seven reactions in the previous simultaneous evaluation. In this procedure, the values of $\sigma_f(^{235}U)$ and $\sigma_f(^{239}Pu)$, and others in the previous evaluation, are possibly changed, but the adjustments are negligibly small as a result.

The evaluated cross-sections for $\sigma_f(^{232}Th)$, $\sigma_f(^{233}U)$, and $\sigma_f(^{234}U)$, $\sigma_f(^{236}U)$ are the data in JENDL-3T. They are given by individual evaluations, in which $\sigma_f(^{235}U)$ data, as the standard, are the result of the previous simultaneous evaluation.

These are the partial components of θ_0 in eqs. (1) and (2).

The evaluated covariances of the fission cross sections for ^{235}U, ^{238}U, ^{237}Np, and ^{239}Pu have been computed in the simultaneous evaluations, although they are not compiled in JENDL-3T.

Otherwise, the covariances for the evaluated fission cross sections of ^{232}Th, ^{233}U, ^{234}U and ^{236}U are not available. It is assumed that the correlation matrices of $\sigma_f(^{232}Th)$ and $\sigma_f(^{236}U)$ are equal to that of $\sigma_f(^{238}U)$, $\sigma_f(^{233}U)$ to $\sigma_f(^{235}U)$, and $\sigma_f(^{234})$ to $\sigma_f(^{240}Pu)$. This is based on qualitative investigations, and comparisons of the evaluated fission cross-section curves and distribution of the experimental data around the curves. According to similar considerations, the errors of the evaluated cross-sections for these four nuclides are assumed to be 7 %. It is taken into account, also, that there are 1-7 % deviations of the integral data between the experiments and the calculations from JENDL-3T. The evaluated covariances for ^{232}Th, ^{233}U, ^{234}U, and ^{236}U can be estimated from these assumptions.

These are the partial matrices of M_0 in eqs. (1) and (2).

Experimental Data

The experimental data used to adjust the evaluations are the averaged neutron-fission cross-section ratios measured for ^{232}Th/^{235}U, ^{237}Np/^{235}U, ^{238}U/^{235}U, ^{237}Np/^{238}U, ^{232}Th/^{237}Np, ^{236}U/^{235}U, ^{239}Pu/^{235}U, ^{233}U/^{235}U, ^{234}U/^{235}U, ^{234}U/^{238}U and ^{236}U/^{238}U in the continuum neutron spectrum produced by bombardment of a thick Be-metal target with 7.0 MeV deutrons at Argonne National Laboratory /5/. They are the components of y in eqs. (1) and (3). The neutron spectrum was measured with time-of-flight technique /7/. It is shown in Fig.1. Since this neutron source has good experimental reproducibility, it can be assumed that the neutron source spectrum is the same for all the integral data. This is very important condition in the present study. The uncertainties and error correlations for the measured fission cross-section ratios can be estimated from the experimental conditions. The experimental covariance matrix V is prepared from this information.

Results and Discussion

The eight fission cross-sections in JENDL-3T are adjusted by applying the eleven experimental spectrum averaged fission cross-section ratios. In Figs. 2, 3 and 4, the cross-section curves for ^{232}Th, ^{234}U and ^{236}U, repspectively, are shown comparing the original and adjusted ones. The adjustments to the cross sections for the other nuclides are very small: they are 0.1 % for ^{233}U, 10^{-1} % for ^{235}U, 10^{-3} % for ^{238}U, 0.1 % for ^{237}Np, and 10^{-5} % for ^{239}Pu in order of magnitude.

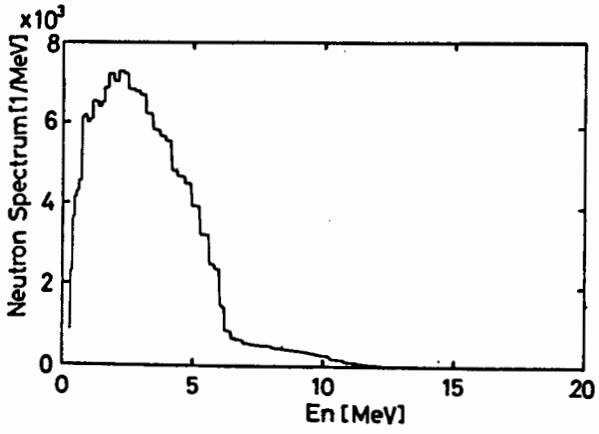

Fig.1 The neutron spectrum produced by 7-MeV deutrons incident on a thick Be-metal target.

The spectrum-averaged fission cross-sections and their ratios to ^{235}U are listed in Table 1, comparing the JENDL-3T with the adjusted values. Also listed are the ratios of the calculated to the experimental data C/E values. They are plotted in Fig. 5 together with those of ENDF/B-V /8/ and JENDL-2 /9/.

The C/E values of JENDL-3T for ^{233}U, ^{238}U, ^{237}Np and ^{239}Pu are within about 1 %. The fission cross-sections of ^{235}U, ^{238}U, ^{237}Np, and ^{239}Pu are simultaneously evaluated, so that they seem to be reasonably accurate and consistent. The observation of extremely small adjusted-amounts for them are also understood from the facts described above. Another reason for the results is that the errors of the evaluated cross-sections obtained in the simultaneous evaluation are so small that the adjustment are severely restricted. However, it is more reasonable to consider that the fission cross-sections of ^{235}U, ^{238}U and ^{239}Pu, simultaneously evaluated from differential data, are consistent with the ANL integral data. The C/E values are within ± 1.005 except for ^{232}Th.

The raw data of the adjusted C/E values for ^{232}Th is 1.011, but negative cross-sections are obtained below 1 MeV. The adopted value is 1.021, which is obtained by limiting the cross-sections to possitive values. A similar effect is found for ^{236}U, but it is negligibly small.

It is demonstrated in the present work that evaluated cross-section curves can be effectively adjusted by integral measurements with a single neutron spectrum. In the case of ^{234}U shown in Fig.3, the cross-section curve near the 10 MeV energy region is adjusted approximately 1 %, although the fraction of the neutron yield there in the source spectrum is small, as found in Fig. 1. This shows that the whole region of the neutron-source spectrum serves significantly to adjust, differentially, the cross-section curve, so that the present study makes it valid to apply integral data directly to evaluation of a differential quantity. Since integral experiments have possibly-better statistical errors than in differential measurements, the former are suitable to evaluate accurate values of the cross-section, while the latter are indispensable to determine correct shapes of the cross-section curves. Both the data are complementary, and should display their own characteristics in a cross-section evaluation.

One of the reasons of success in the present work is the presence of high quality covariances for both the evaluated and integral data. The resulting values from the adjustment depend on the covariances. It is not clear whether the assumptions on the covariances for ^{232}Th, ^{233}U, ^{234}U and ^{236}U are valid or not. However,

Table 1. The spectrum-averaged fission cross sections and their ratios to ^{235}U calculated from the JENDL-3T and adjusted cross sections.

Isotope	$\langle\sigma_f\rangle$ JENDL-3T	$\langle\sigma_f\rangle$ Adjusted	Ratio to ^{235}U JENDL-3T	Ratio to ^{235}U Adjusted
^{232}Th	0.128	0.122	0.101 (1.038)	0.0996 (1.021)
^{233}U	1.876	1.871	1.535 (1.007)	1.531 (1.004)
^{234}U	1.426	1.342	1.167 (1.067)	1.098 (1.004)
^{235}U	1.222	1.222	---	---
^{236}U	0.809	0.765	0.662 (1.062)	0.626 (0.996)
^{238}U	0.465	0.465	0.381 (1.005)	0.381 (1.005)
^{237}Np	1.549	1.541	1.268 (1.012)	1.265 (1.006)
^{239}Pu	1.843	1.844	1.508 (0.995)	1.509 (0.995)

The values in parenthese are C/E.

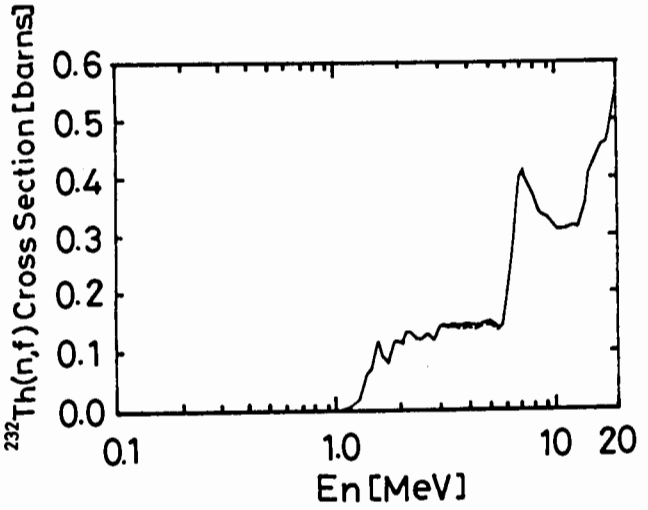

Fig.2 The fission cross-sections for ^{232}Th. The solid curve is JENDL-3T evaluated from differential data and the dashed curve is the result adjusted by the integral data.

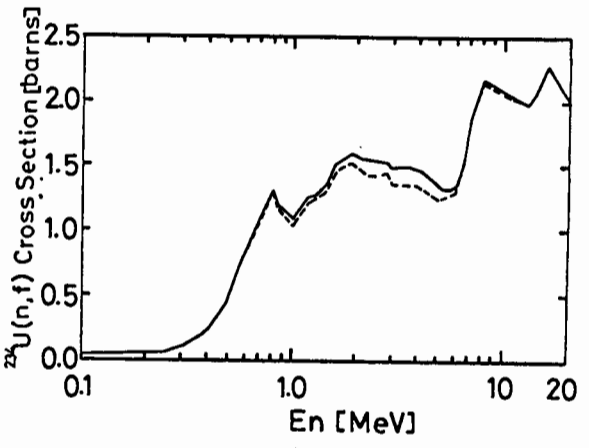

Fig.3 The fission cross-sections for ^{234}U. See the caption of Fig.2.

their evaluated data are plausibly adjusted about the curves and spectrum averages of the cross-sections. As seen in Fig.5, the C/E values for ^{234}U and ^{236}U are 7 % larger than the ANL data consistently in the three evaluated files. They are revised within ±0.5 % of the ANL data. It is understood from the fact that, for ^{234}U and ^{236}U, the experimental errors of the integral measurements are small, 1.3 % and 1.5 %, respectively, the errors given for the evaluated values are large, 7 % together, and the correlation matrices assumed for both the evaluations have strong components.

On the basis of these discussions, it is proposed that the similar integral measurements should be conducted in the higher neutron energy regions with different deuteron energies. Spectrum averaged fission cross-sections have been also measured in the fission neutron spectra of the neutron-induced fission of ^{235}U and the spontaneous fission of ^{252}Cf. These neutron-spectra are fixed. In contrast, the neutron spectrum produced by deutrons incident on a thick Be-metal target can be changed by the deutron acceleration energy. This will be a valuable tool for making accurate and consistent fission cross-section measurements, in conjunction with the evaluation-adjustment method developed in the present work.

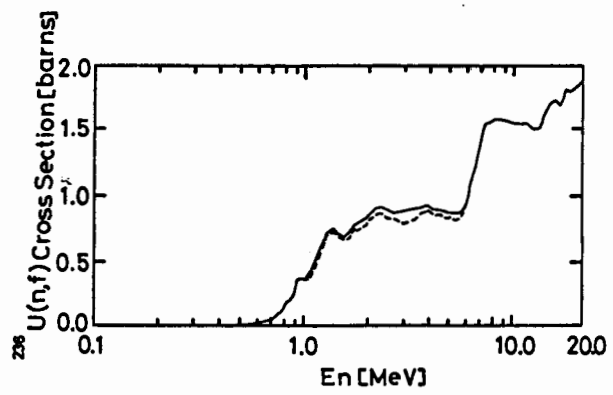

Fig.4 The fission cross-sections for ^{236}U. See the caption of Fig.2.

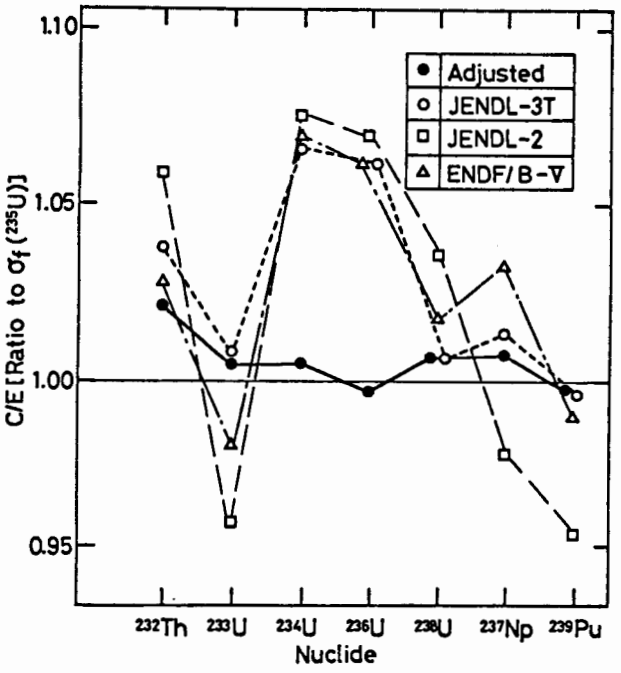

Fig.5 The ratios of the calculated to experimental (C/E) integral fission cross-sections for the nuclides in the d-Be neutron spectrum to that for ^{235}U. The calculations are performed for the adjusted, JENDL-3T, JENDL-2 and ENDF/B-V data.

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