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EVALUATION OF FISSION CROSS SECTIONS AND  
COVARIANCES FOR  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ , AND  $^{241}\text{Pu}$

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## Evaluation of Fission Cross Sections and Covariances for $^{233}\text{U}$ , $^{235}\text{U}$ , $^{238}\text{U}$ , $^{239}\text{Pu}$ , $^{240}\text{Pu}$ , and $^{241}\text{Pu}$

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A simultaneous evaluation code SOK (Simultaneous evaluation on KALMAN) has been developed, which is a least-squares fitting program to absolute and relative measurements. The SOK code was employed to evaluate the fission cross sections of  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$  and  $^{241}\text{Pu}$  for the evaluated nuclear data library JENDL-3.3. Procedures of the simultaneous evaluation and the experimental database of the fission cross sections are described. The fission cross sections obtained were compared with evaluated values given in JENDL-3.2 and ENDF/B-VI.

Keywords : Fission Cross Section, Simultaneous Evaluation, Covariance,  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Pu}$

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# $^{233}\text{U}$ , $^{235}\text{U}$ , $^{238}\text{U}$ , $^{239}\text{Pu}$ , $^{240}\text{Pu}$ , $^{241}\text{Pu}$ に対する 核分裂断面積と共分散の評価

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絶対測定・相対測定に対して最小自乗フィッティングを行う同時評価コード SOK(Simultaneous evaluation on KALMAN)を開発し、JENDL-3.3 のための  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ ,  $^{241}\text{Pu}$  の核分裂断面積評価にこれを用いた。その評価手順、及び核分裂反応断面積の実験データベースについて述べ、得られた核分裂断面積を JENDL-3.2 と ENDF/B-VI の評価値と比較した。

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## 1 INTRODUCTION

Difficulties in evaluating fission cross sections of actinides come from complicated structure of the cross section shape, and variety of experimental data — some of them are absolute measurements, but the others are relative measurements. The complicated structure of the fission cross sections makes it difficult to employ a model calculation for the evaluation, and we have to fit a more flexible function such as a spline function to the experimental data. The experimental data available are absolute and relative measurements. Then the fitting should be done in a way that evaluated cross sections are consistent with both of them. A simultaneous evaluation[1, 2] was adopted to evaluate the fission cross sections of  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ , and  $^{241}\text{Pu}$  and the capture cross sections of  $^{197}\text{Au}$  and  $^{238}\text{U}$  for JENDL-3[3]. The obtained capture cross sections were not adopted in JENDL-3. The results were slightly modified and compiled into JENDL-3.2[4].

The simultaneous evaluation was also adopted by Poenitz and Aumeier[5] for the ENDF/B-VI evaluation, but the experimental database used was largely different from that of the JENDL-3 evaluation. In their evaluation, cross sections of  $^6\text{Li}$ ,  $^{10}\text{B}$ , and thermal constants<sup>\*)</sup> were included as well as the fission cross sections of  $^{235}\text{U}$ ,  $^{238}\text{U}$ , and  $^{239}\text{Pu}$ , and the capture cross sections of  $^{238}\text{U}$  and  $^{197}\text{Au}$ .

After the release of JENDL-3.2, some new measurements of the fission cross sections of these nuclides have been published. These experimental data should be added to the database of the simultaneous evaluation in order to update the evaluated cross sections in JENDL-3.2. In addition, some modifications were made for the results of the simultaneous evaluation[3] in JENDL-3.2. It means that a consistency among the evaluated fission cross sections of those nuclides was lost, and its covariance data are no longer appropriate.

Release of the next revision of JENDL — JENDL-3.3 — is scheduled for fiscal year 2000. A working group on evaluation of nuclear data of heavy nuclides has been organized to update the evaluated nuclear data in JENDL-3.2. The working group investigated new experimental data which were not included in the previous evaluation, and developed a new simultaneous evaluation code SOK — Simultaneous evaluation On KALMAN — which was based on the model parameter estimation code KALMAN[6]. New results of the simultaneous evaluation of the fission cross sections of  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ , and  $^{241}\text{Pu}$  are reported in this paper. In Chap. II, basic formulae of the simultaneous evaluation are presented. Parameters and experimental data required for the calculation are described in Chap. III. The results of the calculations are given in Chap. IV. The SOK code is described in Appendix B.

<sup>\*)</sup>  $\sigma_{n,f}$ ,  $\sigma_{n,\gamma}$ ,  $\sigma_{n,n}$ ,  $g_f$ ,  $g_a$ , and  $\bar{\nu}$  of  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$ ,  $^{252}\text{Cf}$

## 2 FORMULAE OF SIMULTANEOUS EVALUATION

### 2.1 Least-squares Fitting to Absolute Measurements

To evaluate a neutron-induced reaction cross section on the basis of experimental data, one needs an appropriate fitting function which describes the excitation function of the reaction. Nuclear model calculations are often used for this purpose if an adequate model is available. The model calculation is possible for the fission cross sections of heavy nuclei. The fission mode is, however, insufficient for an accurate evaluation since it does not give a precise behavior of the cross sections. Instead of the model calculation, a spline function can be used[7] for the evaluation of the cross sections which have a complicated structure, because of its flexibility.

The least-squares fitting is mainly done for uncorrelated data. The data to be fitted are independent of each other, and their uncertainties are used as weight of each data point. This procedure can be extended to the generalized least-squares technique in which the data are correlated, and the weight is expressed by inverse of a covariance matrix of the data,  $V^{-1}$ .

We denote experimental data by an  $n$ -dimensional vector  $\mathbf{y} = (\sigma(\epsilon_1), \sigma(\epsilon_2), \dots, \sigma(\epsilon_n))^t$ , where  $n$  is the number of measured points (energy points, usually), while the evaluated cross sections are expressed by a parameter vector  $\mathbf{x} = (\sigma(E_1), \sigma(E_2), \dots, \sigma(E_m))^t$  where  $m$  is the number of points where the evaluated cross sections are to be given. The symbol  $t$  stands for the transpose of a matrix. In order to determine the least-squares solution uniquely,  $n$  must be larger than  $m$ . The relation of these vectors is, in a linear regression model,

$$\mathbf{y} = \begin{pmatrix} \sigma(\epsilon_1) \\ \vdots \\ \sigma(\epsilon_n) \end{pmatrix} = \begin{pmatrix} c_{11} & \cdots & c_{1m} \\ \vdots & & \vdots \\ c_{n1} & \cdots & c_{nm} \end{pmatrix} \begin{pmatrix} \sigma(E_1) \\ \vdots \\ \sigma(E_m) \end{pmatrix} + \begin{pmatrix} e_1 \\ \vdots \\ e_n \end{pmatrix} = \mathbf{Cx} + \mathbf{e}, \quad (1)$$

where  $\mathbf{e} = (e_1, e_2, \dots, e_n)^t$  is a vector of uncertainties, and  $\mathbf{C}$  is the design matrix which is defined as  $\{c_{ij}|c_{ij} = \partial y_i / \partial x_j\}$ , and gives appropriate spline-interpolation of the evaluated cross sections  $\sigma(E_j)$  in our procedure.

If a first order spline function is used for the evaluation, this corresponds to a simple linear interpolation, and the elements of the design matrix  $\mathbf{C}$  can be written by

$$c_{ij} = \begin{cases} (\epsilon_i - E_{j-1})/(E_j - E_{j-1}) & E_{j-1} \leq \epsilon_i < E_j \\ (\epsilon_i - E_{j+1})/(E_j - E_{j+1}) & E_j \leq \epsilon_i < E_{j+1} \\ 0 & \text{Otherwise} \end{cases} \quad (2)$$

The least-squares solution  $\hat{\mathbf{x}}$  is given by

$$\hat{\mathbf{x}} = \mathbf{X}\mathbf{C}^t\mathbf{V}^{-1}\mathbf{y}, \quad (3)$$

and

$$\mathbf{X} = (\mathbf{C}^t\mathbf{V}^{-1}\mathbf{C})^{-1}, \quad (4)$$

where  $V$  is the covariance of the experimental data, and  $X$  is the covariance of the evaluated cross sections. The covariance  $X$  obtained must be multiplied by a  $\chi^2$  per degree-of-freedom,

$$\chi^2 = \frac{(\mathbf{y} - \mathbf{C}\hat{\mathbf{x}})^t V^{-1} (\mathbf{y} - \mathbf{C}\hat{\mathbf{x}})}{n - m}. \quad (5)$$

## 2.2 Fitting to Relative Measurements

When the fitting function is a linear function like Eq. (1), the least-squares solution can be calculated analytically as in Eq. (3). However, to fit the function to relative measurements such as a ratio of the  $^{238}\text{U}(n, f)$  cross section ( $\sigma_1$ ) to the  $^{235}\text{U}(n, f)$  cross section ( $\sigma_2$ ) expressed by

$$r = \sigma_1/\sigma_2, \quad (6)$$

the fitting function becomes non-linear.

This equation can be linearized if one takes logarithm of Eq. (6),

$$\ln r = \ln \sigma_1 - \ln \sigma_2. \quad (7)$$

Two sets of the cross sections are to be evaluated from the relative measurements, the first one is denoted by  $\mathbf{x}_1$  and the second one by  $\mathbf{x}_2$ . These two vectors contain logarithmic values of the cross sections. These two vectors are combined and expressed by

$$\mathbf{x} = \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{pmatrix} = \begin{pmatrix} \ln \sigma_1(E_1) \\ \ln \sigma_1(E_2) \\ \vdots \\ \ln \sigma_1(E_{m_1}) \\ \ln \sigma_2(E'_1) \\ \ln \sigma_2(E'_2) \\ \vdots \\ \ln \sigma_2(E'_{m_2}) \end{pmatrix}, \quad (8)$$

and therefore the linearized fitting function is given by

$$\mathbf{r} = \begin{pmatrix} \ln r(\epsilon_1) \\ \ln r(\epsilon_2) \\ \vdots \\ \ln r(\epsilon_n) \end{pmatrix} \approx \left( \begin{array}{c|c} \mathbf{C}_1 & -\mathbf{C}_2 \end{array} \right) \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \end{pmatrix} = \mathbf{C}\mathbf{x}, \quad (9)$$

where  $\mathbf{r}$  is a vector of the experimental data, matrices  $\mathbf{C}_1$  and  $\mathbf{C}_2$  are the design matrices given by Eq. (2). Once the fitting function is expressed by a linear function, the least-squares solution can be calculated in the same manner as in Eq. (3).

## 2.3 Data Update Technique

The total number of experimental data often becomes very large, and sometimes it exceeds a computational capability when one solves the least-squares equation in Eq. (3) by taking

account of all the experimental data at once. To avoid this difficulty, we re-formulate Eq. (3) by setting a prior parameter  $\mathbf{x}_0$ . When a set of experimental data  $\mathbf{y}_1$  is provided, the prior parameter is updated as follows:

$$\begin{aligned}\mathbf{x}_1 &= \mathbf{x}_0 + \mathbf{P} \mathbf{C}^t \mathbf{V}^{-1} (\mathbf{y}_1 - \mathbf{C} \mathbf{x}_0) \\ &= \mathbf{x}_0 + \mathbf{X} \mathbf{C}^t (\mathbf{C} \mathbf{X} \mathbf{C}^t + \mathbf{V})^{-1} (\mathbf{y}_1 - \mathbf{C} \mathbf{x}_0),\end{aligned}\quad (10)$$

$$\begin{aligned}\mathbf{P} &= (\mathbf{X}^{-1} + \mathbf{C}^t \mathbf{V}^{-1} \mathbf{C})^{-1} \\ &= \mathbf{X} - \mathbf{X} \mathbf{C}^t (\mathbf{C} \mathbf{X} \mathbf{C}^t + \mathbf{V})^{-1} \mathbf{C} \mathbf{X},\end{aligned}\quad (11)$$

where  $\mathbf{x}_1$  is the posterior parameter, and  $\mathbf{P}$  the posterior covariance. The parameter  $\mathbf{x}_1$  is updated according to the other experimental data  $\mathbf{y}_2$  with the same equations. This step-by-step updating sequence is repeated for all experimental data sets.

### 3 INPUT PREPARATION

#### 3.1 Experimental Database

The experimental data used in the simultaneous evaluation were taken from the database EXFOR maintained by the 4 center network. The absolute and relative measurements of  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ , and  $^{241}\text{Pu}$  fission cross sections were carefully selected and compiled into the database for the evaluation. In the evaluation of JENDL-3[3], capture cross sections of  $^{238}\text{U}$  and  $^{197}\text{Au}$  were incorporated into the database. These reactions were, however, omitted in the present evaluation, because the data of the  $^{238}\text{U}$  capture cross section to be adopted in JENDL-3.3 are independent[8] of the present simultaneous evaluation, and there will be no data for  $^{197}\text{Au}$  in JENDL-3.3. Our experimental database used in the present simultaneous evaluation is listed in Appendix A.

A covariance of the experimental data is a very important quantity for the least-squares method, because it is used as weight of the data. However, information on the covariance is not well documented in many cases. In the present evaluation, the uncertainty information on all experimental data was investigated to make an experimental database, and categorized as follows:

- (1) The covariance matrix is given.
- (2) The covariance matrix is not given, but sources of the errors are fully documented.
- (3) The sources of the errors are not given, but systematic and statistical errors are separated.
- (4) Only the errors are given.
- (5) No errors.

The case (1) is straightforward. We can use the reported covariance, but this case is seldom. Most of the data were classified into the cases (2) and (3). In the cases (2) and (3), we constructed the covariances for these experimental data from the documented information. In the case (4), we assumed various sources of the uncertainties such as a detector efficiency, sample weight, a neutron flux, and so on, to generate the covariance. The experimental data categorized into (5) were eliminated in the present evaluation.

Further screening of the experimental database was made in order to eliminate sets which were inconsistent with the others. Finally 13 kinds of reaction data were used. Those were the absolute measurements of fission cross sections for  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ , and  $^{241}\text{Pu}$ , and the relative measurements of fission cross sections for  $^{233}\text{U}/^{235}\text{U}$ ,  $^{238}\text{U}/^{235}\text{U}$ ,  $^{238}\text{U}/^{233}\text{U}$ ,  $^{239}\text{Pu}/^{235}\text{U}$ ,  $^{240}\text{Pu}/^{235}\text{U}$ ,  $^{241}\text{Pu}/^{235}\text{U}$ , and  $^{240}\text{Pu}/^{239}\text{Pu}$ .

### 3.2 Prior Parameters

The parameters in the simultaneous evaluation are the fission cross sections of  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ , and  $^{241}\text{Pu}$ . Prior values of these cross sections were taken from JENDL-3.2.

The prior covariance was prepared on the assumption that the uncertainties are 50% for all, and they are uncorrelated. This relatively large uncertainties of the prior parameters assure that the final result is independent of a choice of the prior parameters.

The simultaneous evaluation was done in the energy range of 30 keV to 20 MeV. For  $^{238}\text{U}$  and  $^{240}\text{Pu}$ , the lower energy limit was risen up to 100 keV. The energy points (spline knots) of the evaluated cross section were selected so as to reproduce tendencies of the excitation functions.

## 4 RESULTS AND DISCUSSION

### 4.1 Evaluated Cross Sections

The number of experimental data points ( $n$ ) used for the simultaneous evaluation was 4661, and the number of the spline knots ( $m$ ) was 211. When the fission cross sections of JENDL-3.2 are substituted into  $\hat{x}$  in Eq. (5), the  $\chi^2$  per degree-of-freedom ( $n - m$ ) becomes 7.85. This value was reduced to 5.02 by the present evaluation. This relatively large  $\chi^2$  value is due to low energy regions of  $^{238}\text{U}$  and  $^{240}\text{Pu}$  where a sub-threshold fission is observed. If one ignores the experimental data of  $^{238}\text{U}$  and  $^{240}\text{Pu}$  below 1 MeV, the  $\chi^2$  per degree-of-freedom becomes 2.97.

Comparisons of the present results with the experimental data are shown in Figs. 1–6, where the cross sections of JENDL-3.2 and ENDF/B-VI are depicted by the dotted lines and the dot-dashed lines, respectively. Figures 7–13 show the comparisons of the present results with the measured fission cross section ratios to the  $^{235}\text{U}$ . Since there are so many data points and they are indistinguishable, all experimental data are represented by the same symbol.

As the fission cross sections of  $^{233}\text{U}$  were not included in the simultaneous evaluation of JENDL-3.2, the difference between JENDL-3.2 and the present result is relatively large above 1 MeV. The differences in the cross sections of  $^{235,238}\text{U}$  and  $^{239,240,241}\text{Pu}$  are less than about  $\pm 3\%$  in the energy range from 2 to 12 MeV, while the differences are large above 15 MeV.

After the simultaneous evaluation for JENDL-3 was carried out, the fission cross sections of  $^{235}\text{U}$  for JENDL-3.2 were modified according to a new measurement by Carlson, *et al.*[9] above 13 MeV. However these experimental data were preliminary. We adopted their final data[10] in the present evaluation instead of the preliminary data[9]. This is the main reason of the changes in the  $^{235}\text{U}$  fission cross sections above 12 MeV. This new data[10] also affect the other fission cross sections, as seen in Figs. 1–6, because many cross sections were measured relatively to the  $^{235}\text{U}$  fission cross sections.

As seen in Fig. 1, the obtained  $^{233}\text{U}$  fission cross sections are larger than the absolute measurement of Poenitz[11] in the energy range of 1–5 MeV. However the simultaneous evaluation relies on the ratio measurements, because there are a large number of ratio data points as shown in Fig. 7. The ratios of  $^{233}\text{U}$  to  $^{235}\text{U}$  fission cross sections are in good agreement with the measurements, and the present result is also consistent with the ENDF/B-VI evaluation – the difference between them is less than 2% in this energy range.

Figure 15 shows ratios of the  $^{235}\text{U}$  fission cross sections of the present evaluation to those in JENDL-3.2 and ENDF/B-VI. The presently evaluated  $^{235}\text{U}$  fission cross sections are systematically larger than the ENDF/B-VI evaluation in the energy range 1–5 MeV, and the differences are about 2%. The cross sections in this energy range are important for nuclear engineering, and we compared them in detail. Figure 20 is a magnified plot of Fig. 2, and some of measurements[10][12]–[18] were selectively plotted in order to distinguish each other. One can see clearly from this figure that the measured cross sections by Kari and Cierjacks[15] are systematically larger than the other ones. The other new measurements are mainly from the National Institute for Science and Technology (the former National Bureau of Standards) in the United States, and the ENDF/B-VI evaluation is consistent with their data[19].

## 4.2 Covariances

The covariance matrices of the evaluated cross sections are given by Eq. (11). The uncertainties of the cross sections are depicted in Figs. 14–19 by the dashed lines. A typical value of the uncertainty is about 1–2%, and the value becomes very small for some cases. For example, the uncertainties of the  $^{235}\text{U}$  fission cross sections near 3 MeV are about 0.4 %, which is much smaller than the discrepancy among the experimental data there, as seen in Fig. 20. Such too small uncertainty is probably due to unknown uncertainties of the measurements, and re-normalization of the experimental errors might be needed.

Correlation matrices are shown in Figs. 21–26. The curves on the bottom of the 3-D

drawings are contours of the correlation matrix. Since relative measurements are used for the simultaneous evaluation, a correlation between the different nuclei appears. Figure 27 shows the correlation between the fission cross sections of  $^{233}\text{U}$  and  $^{235}\text{U}$ . The axis labelled by “ $E_n$ ” is for  $^{235}\text{U}$ , and the other axis is for  $^{233}\text{U}$ . This is a sub-matrix of the whole correlation matrix, and a ratio measurement yields strong correlations near the diagonal elements of this sub-matrix. The other correlations between the different nuclei are shown in Figs. 28–32.

## 5 CONCLUSION

Fission cross sections and their covariance matrices of  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ , and  $^{241}\text{Pu}$  were simultaneously evaluated for JENDL-3.3. The evaluation was carried out in the energy range of 30 keV to 20 MeV for  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ , and  $^{241}\text{Pu}$ , and 100 keV to 20 MeV for  $^{238}\text{U}$  and  $^{240}\text{Pu}$ . The evaluated fission cross sections were compared to those in JENDL-3.2 and ENDF/B-VI libraries. The present results are not so different from those in JENDL-3.2, except for the fission cross sections of  $^{233}\text{U}$  and the cross sections above 15 MeV.

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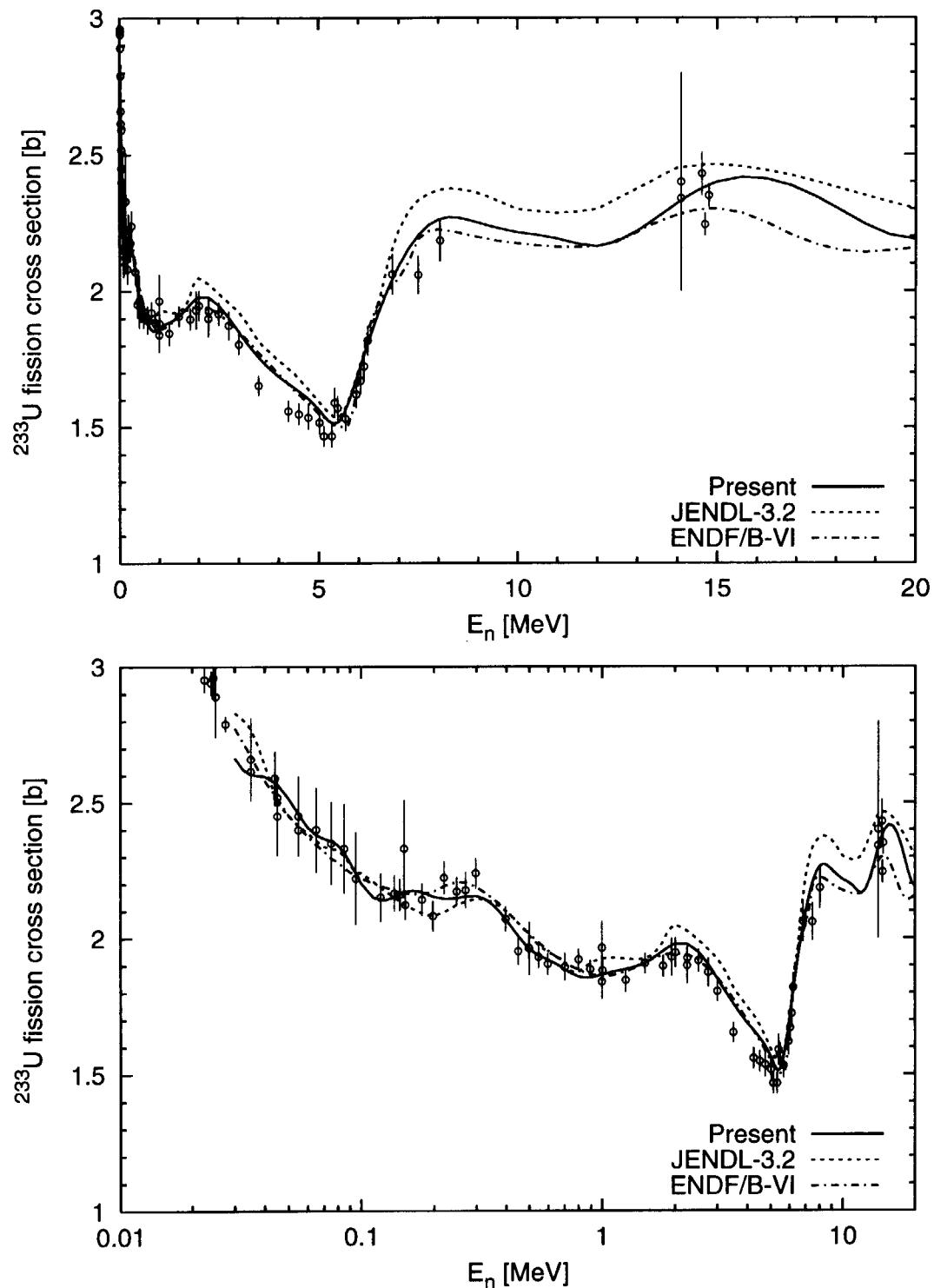


Fig. 1: Comparison of the presently-evaluated fission cross sections of  $^{233}\text{U}$  with the experimental data and the evaluated cross sections of JENDL-3.2 and ENDF/B-VI.

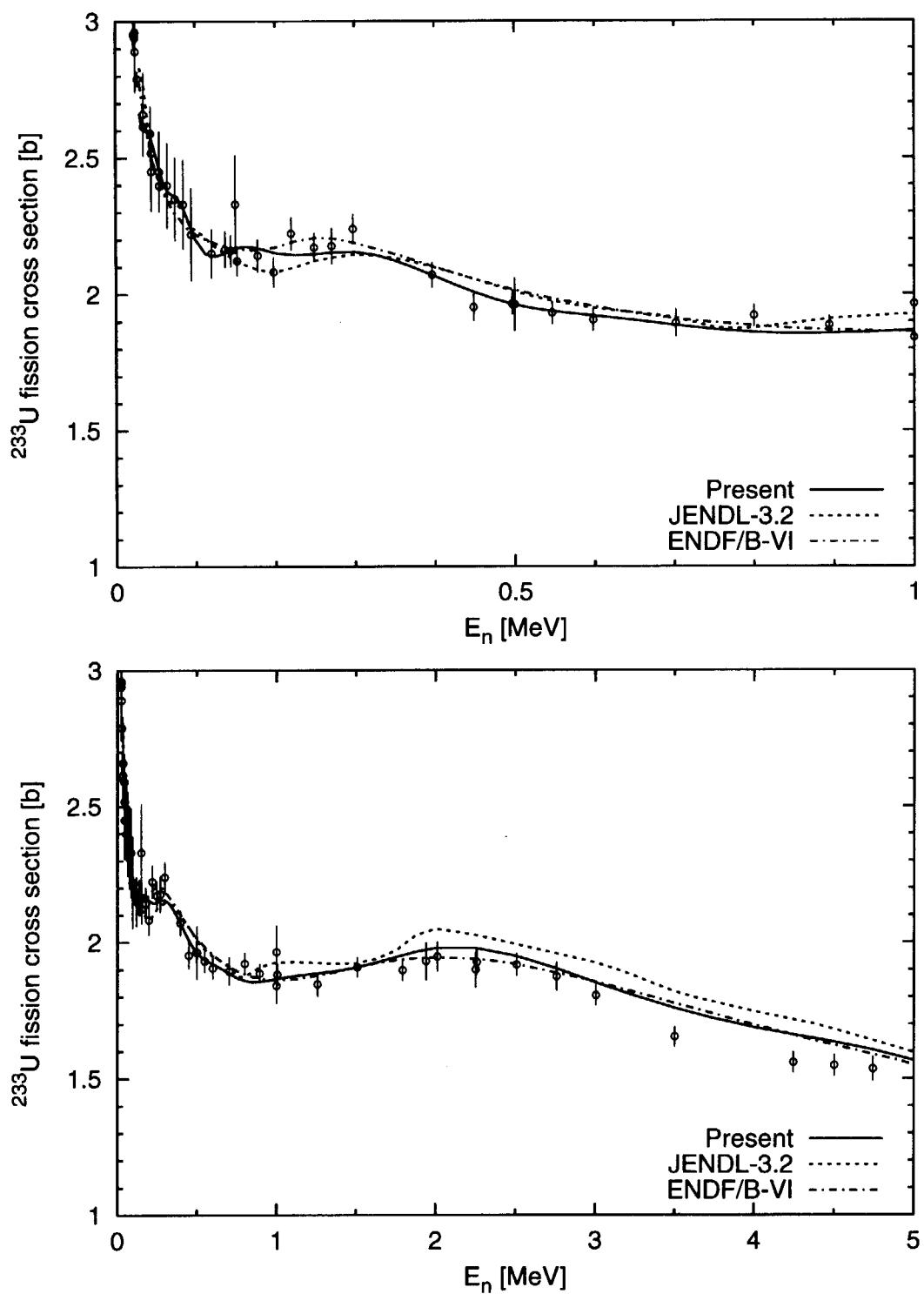


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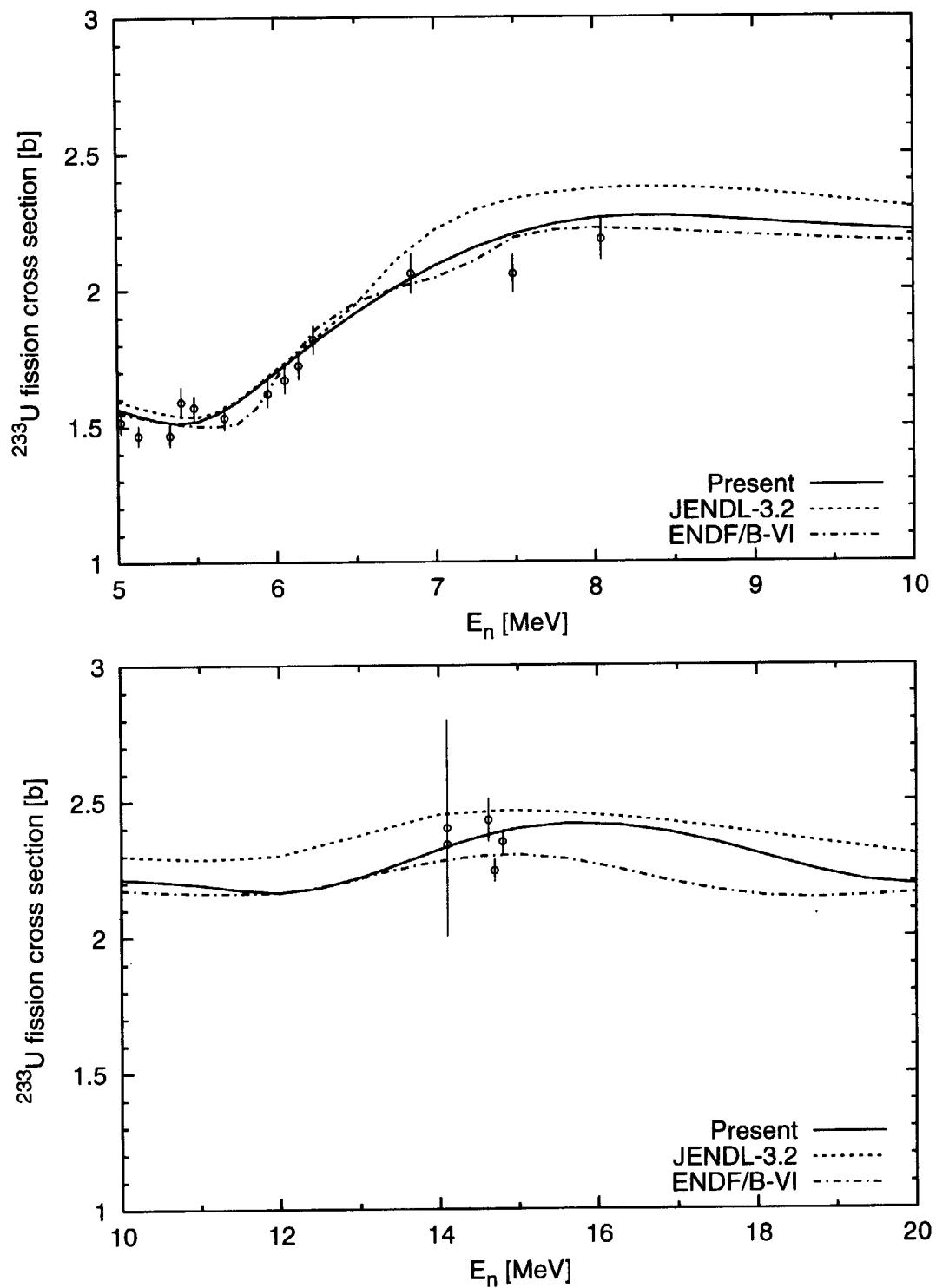


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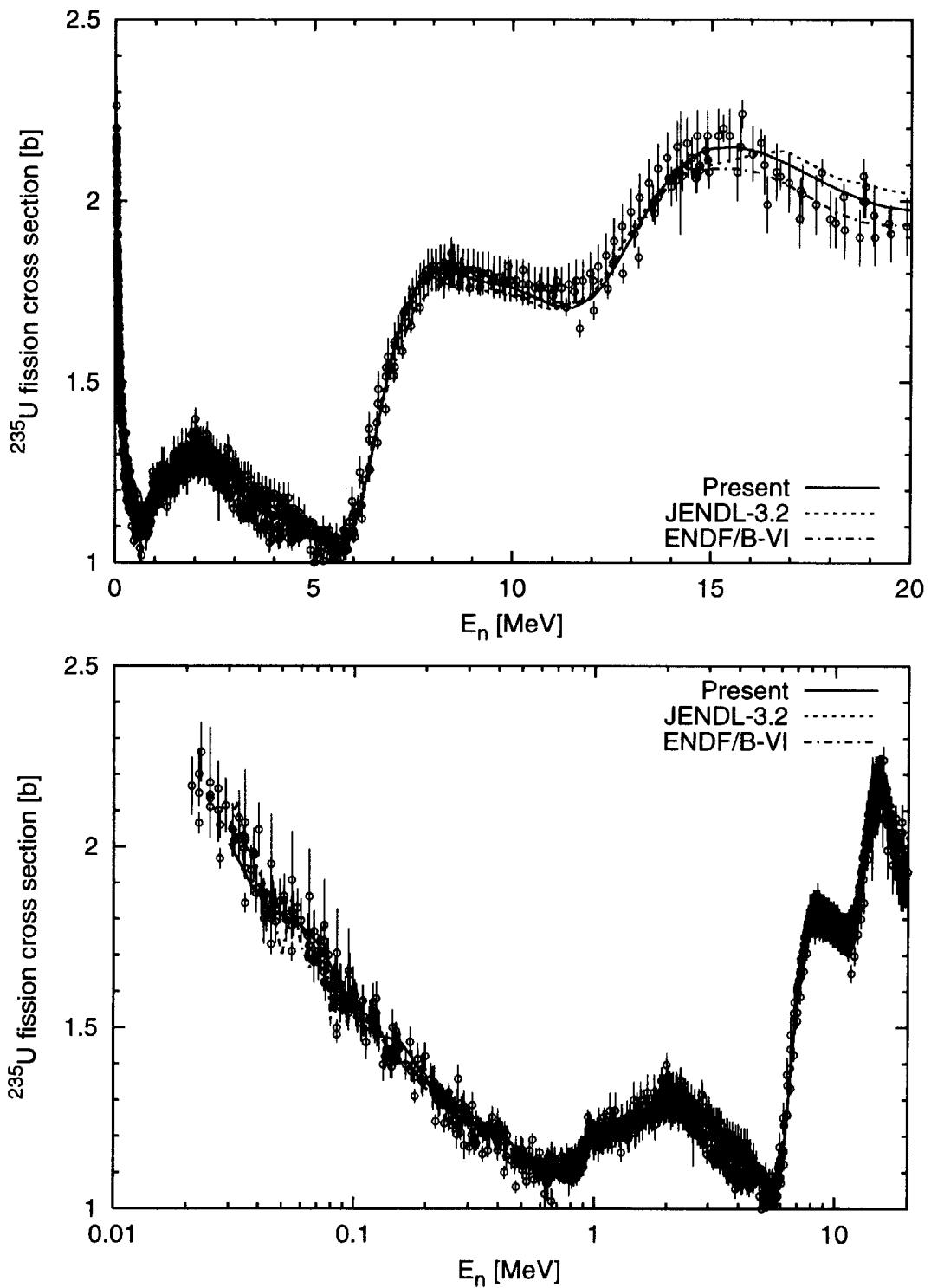


Fig. 2: Comparison of presently-evaluated the fission cross sections of  $^{235}\text{U}$  with the experimental data and the evaluated cross sections of JENDL-3.2 and ENDF/B-VI.

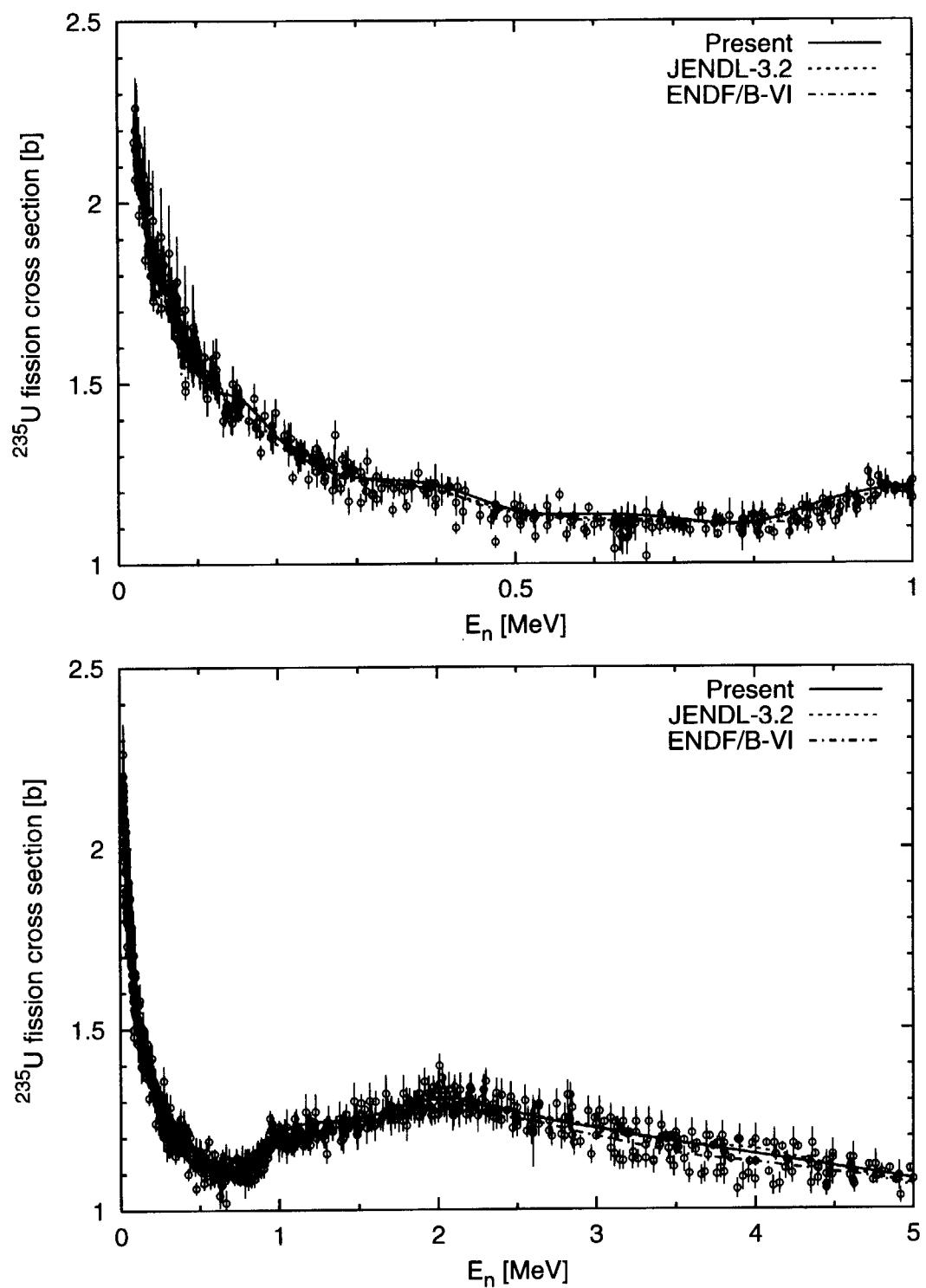


Fig. 2: Continued.

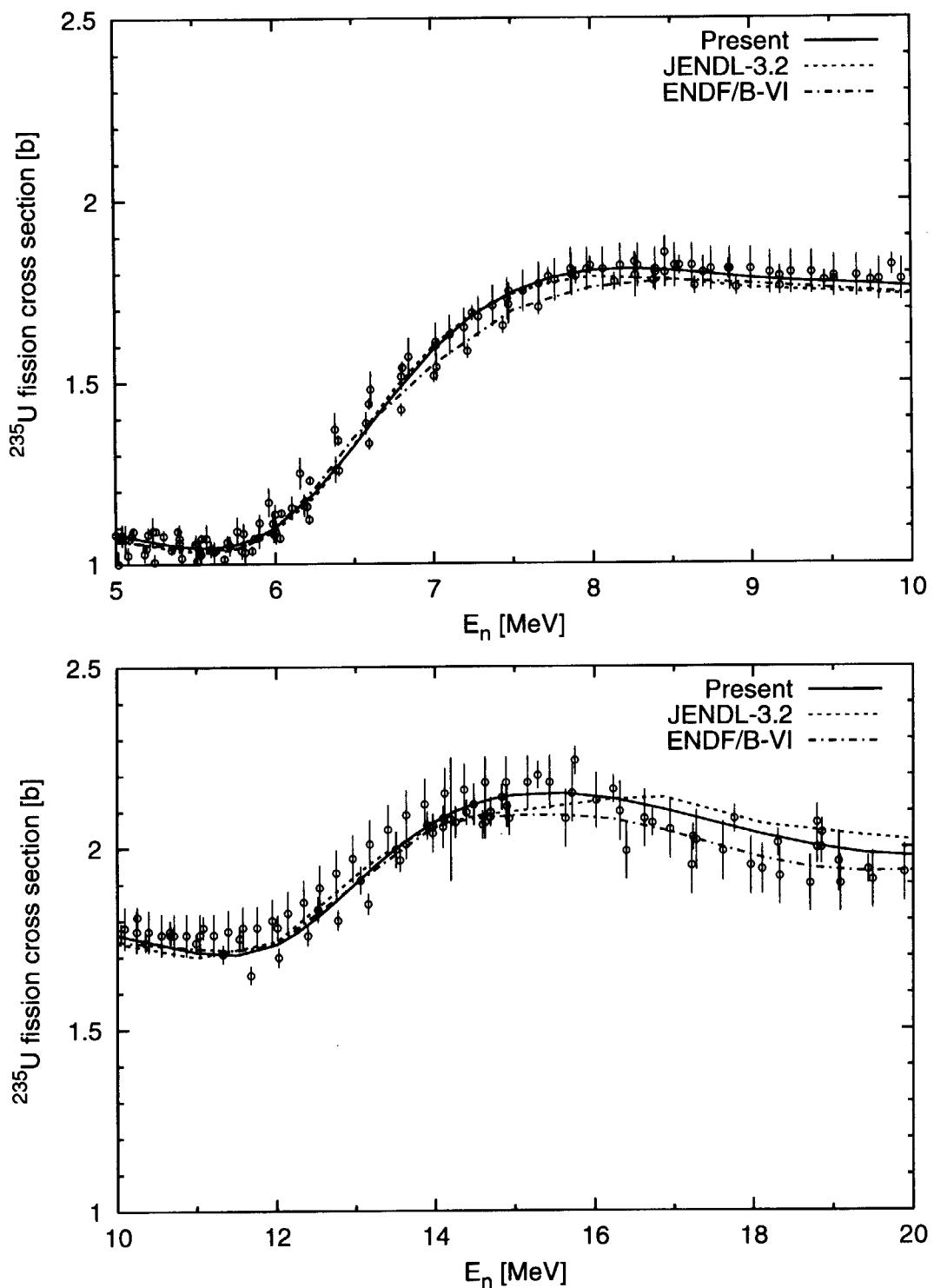


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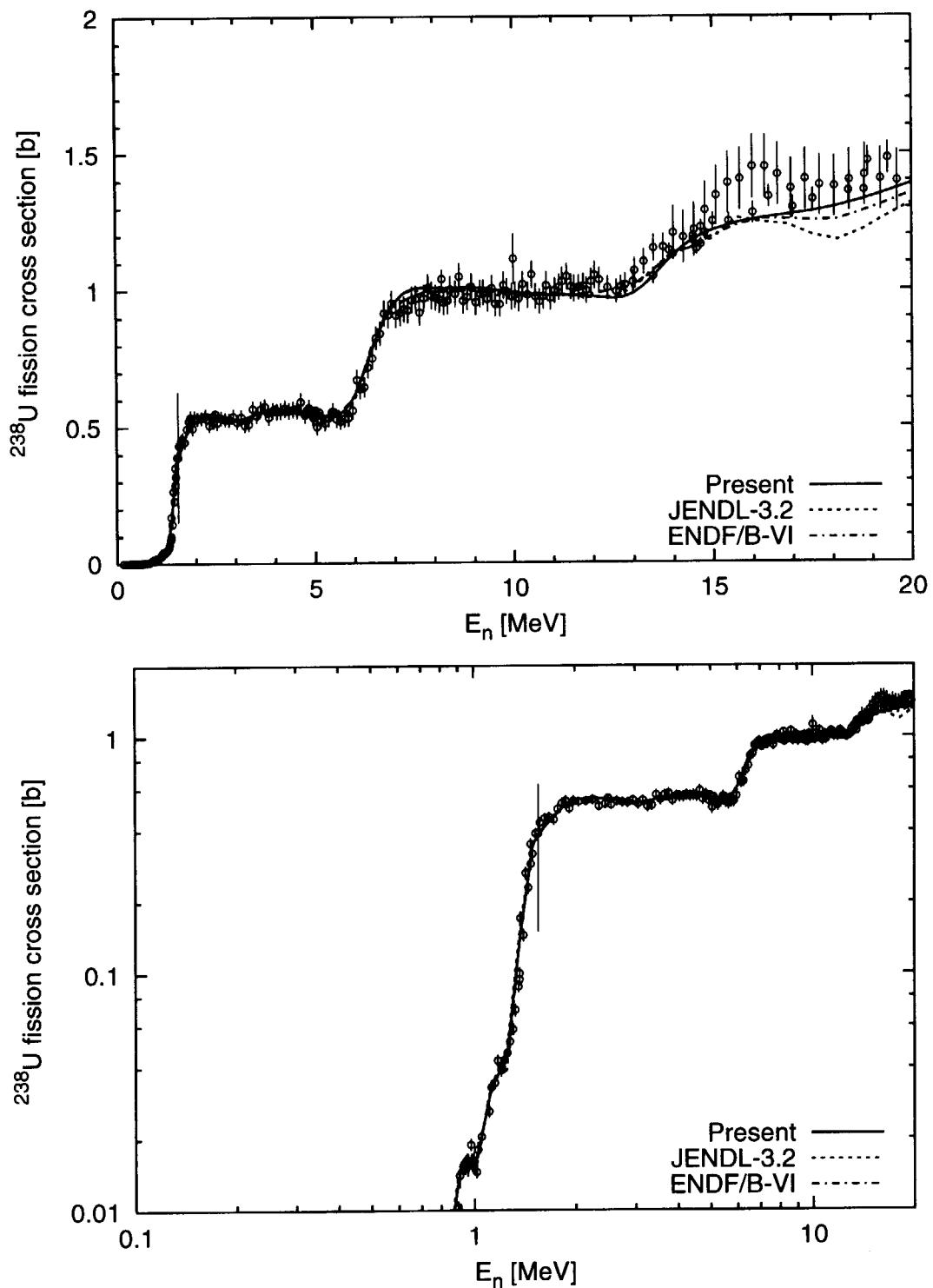


Fig. 3: Comparison of the presently-evaluated fission cross sections of  $^{238}\text{U}$  with the experimental data and the evaluated cross sections of JENDL-3.2 and ENDF/B-VI.

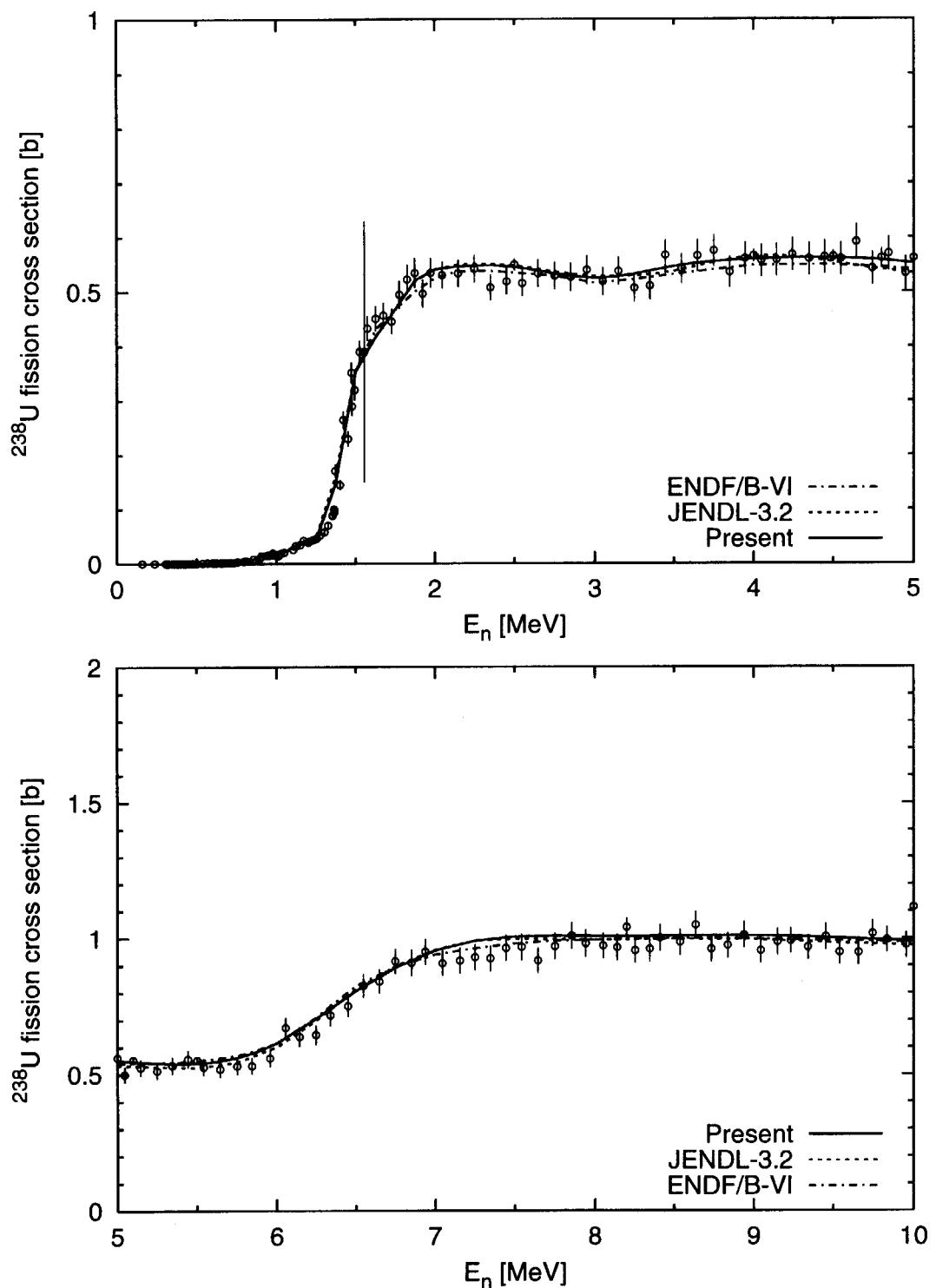


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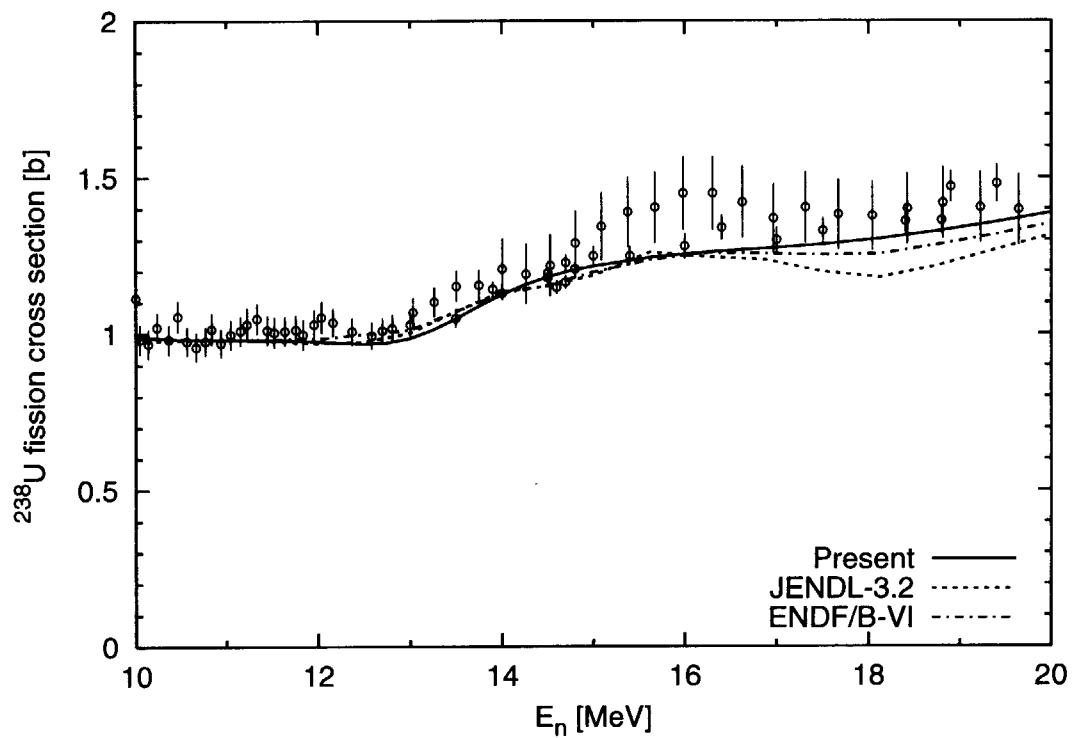


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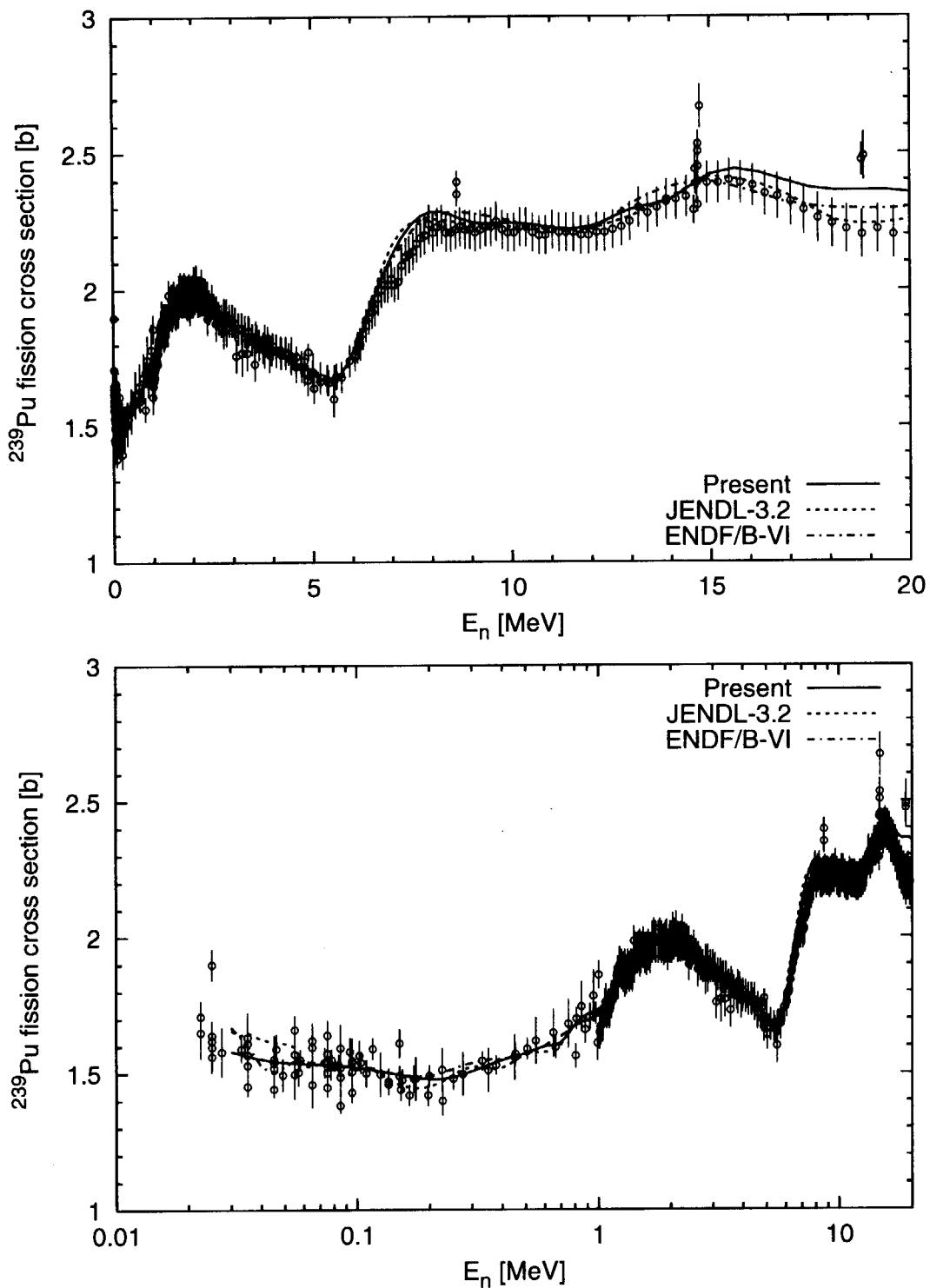


Fig. 4: Comparison of the presently-evaluated fission cross sections of  $^{239}\text{Pu}$  with the experimental data and the evaluated cross sections of JENDL-3.2 and ENDF/B-VI.

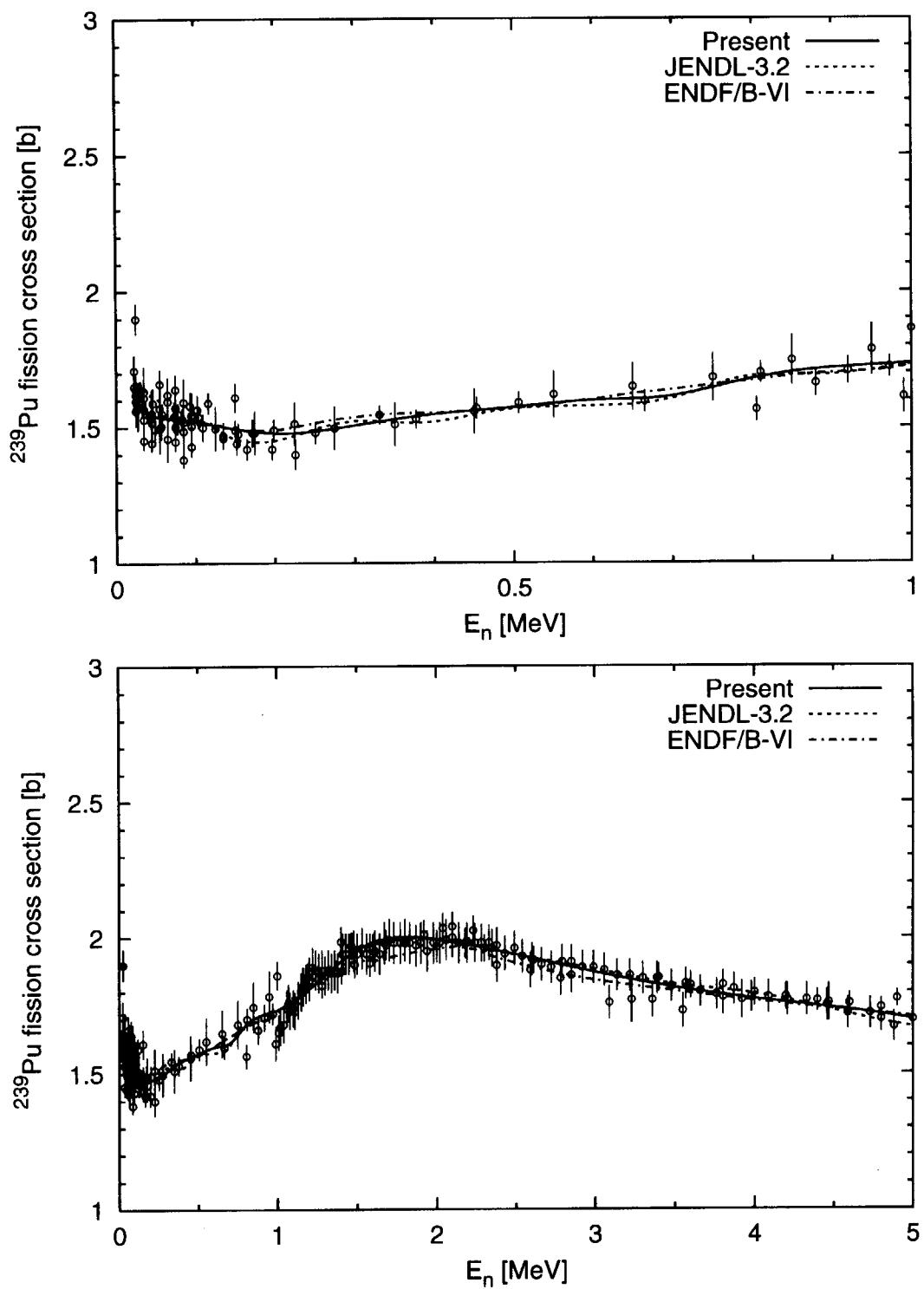


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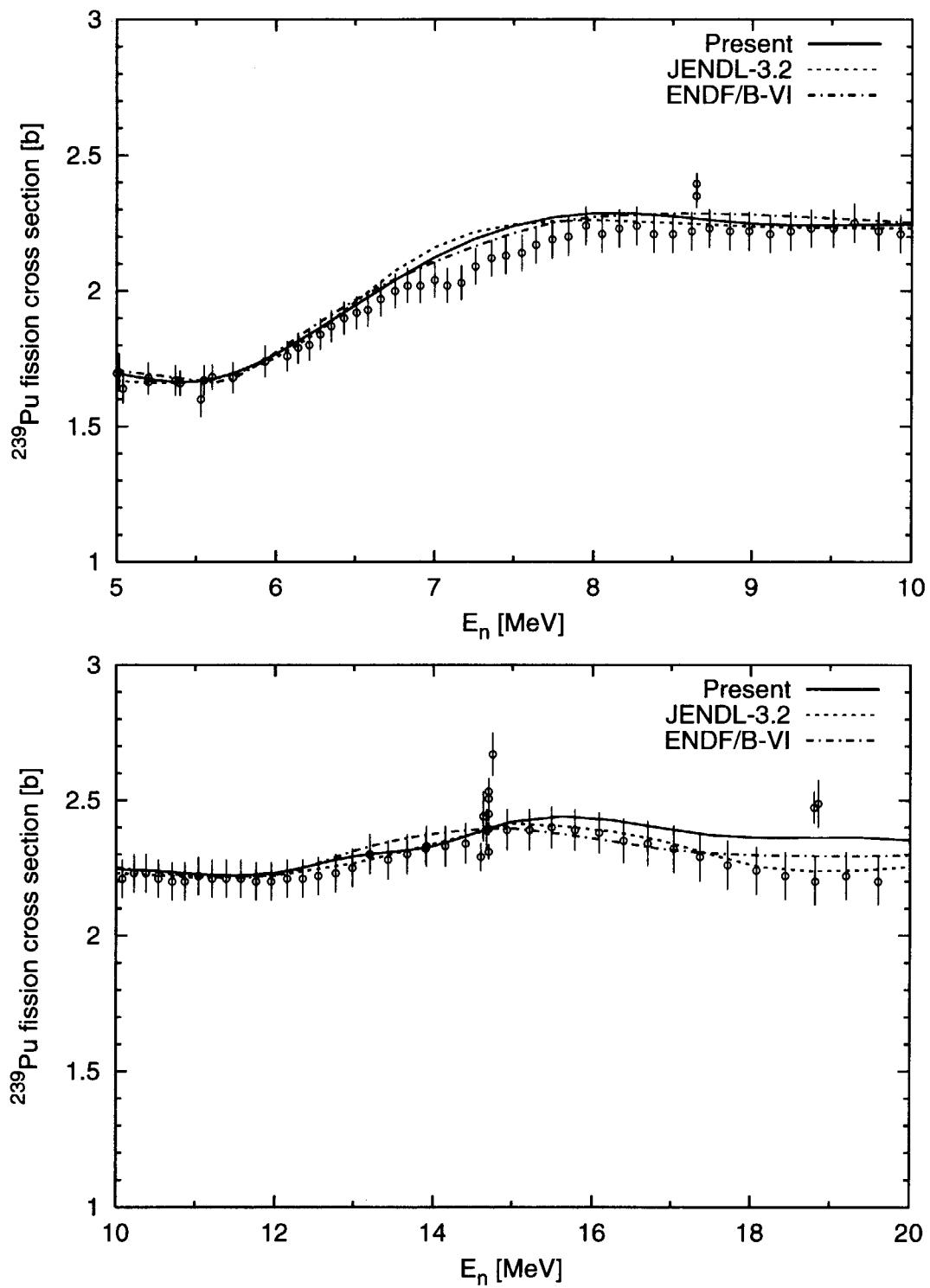


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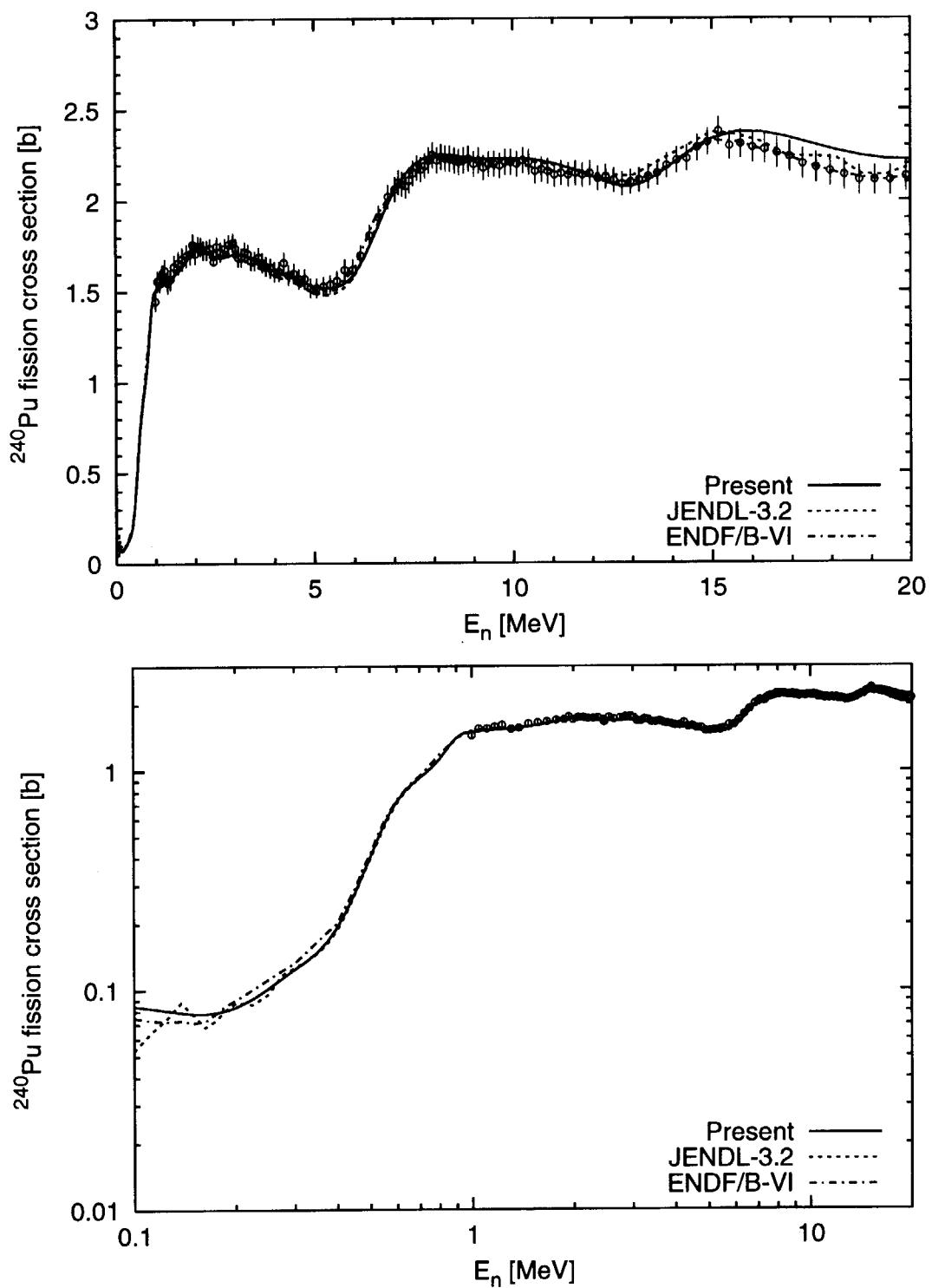


Fig. 5: Comparison of the presently-evaluated fission cross sections of  $^{240}\text{Pu}$  with the experimental data and the evaluated cross sections of JENDL-3.2 and ENDF/B-VI.

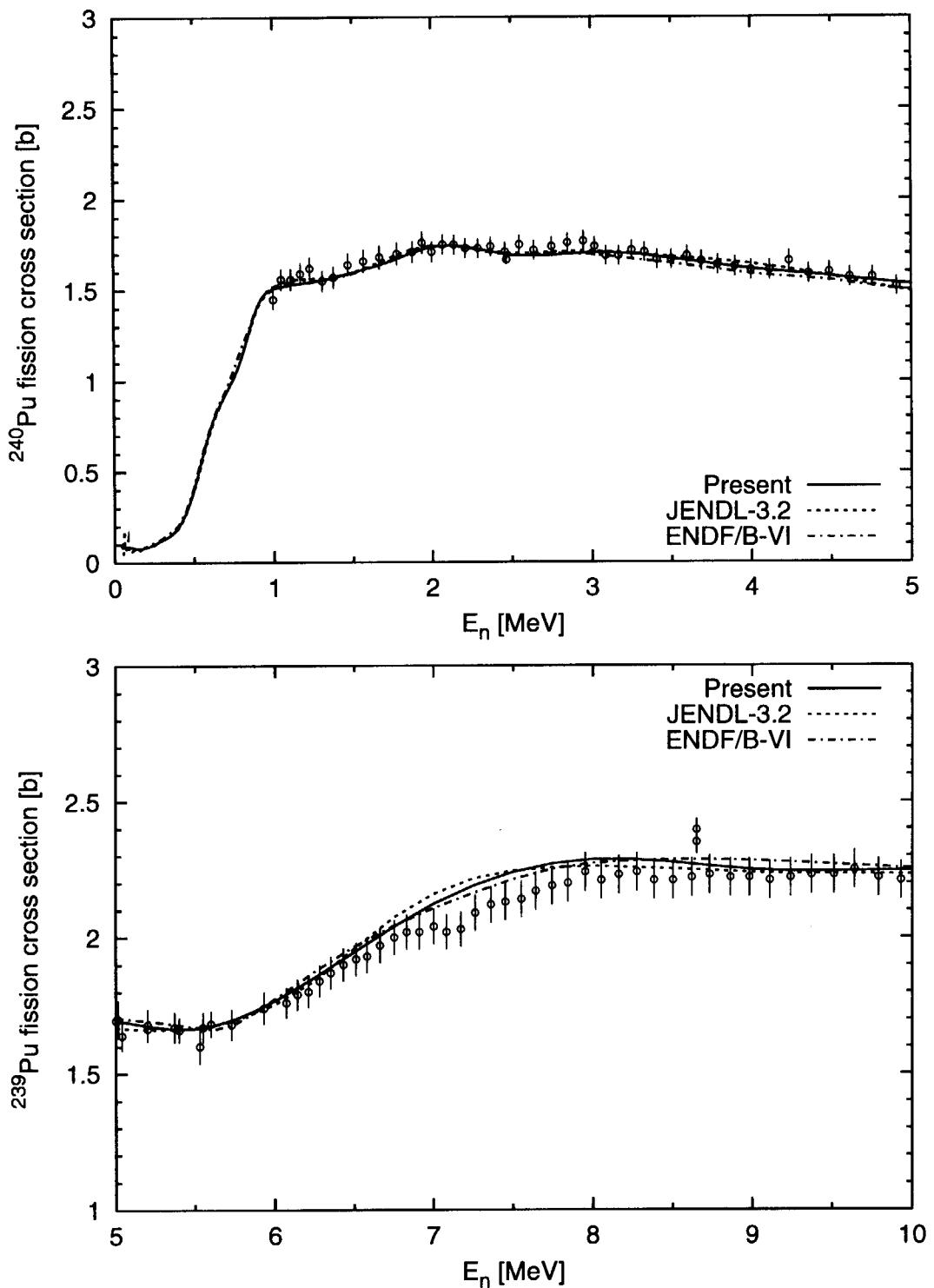


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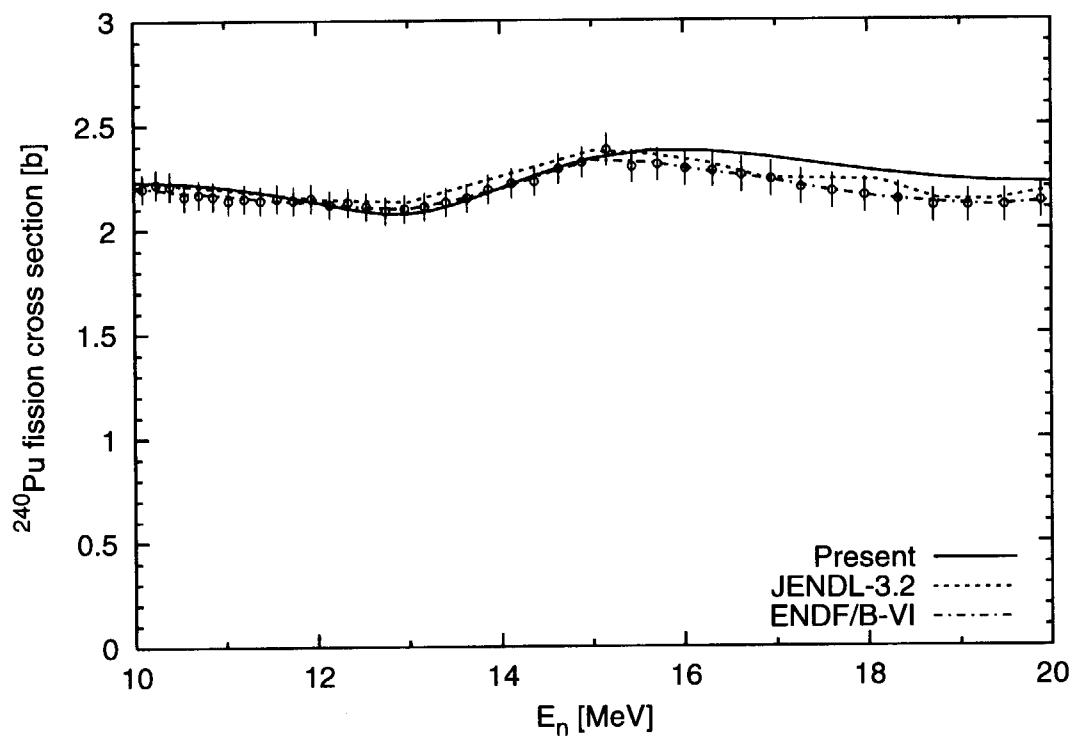


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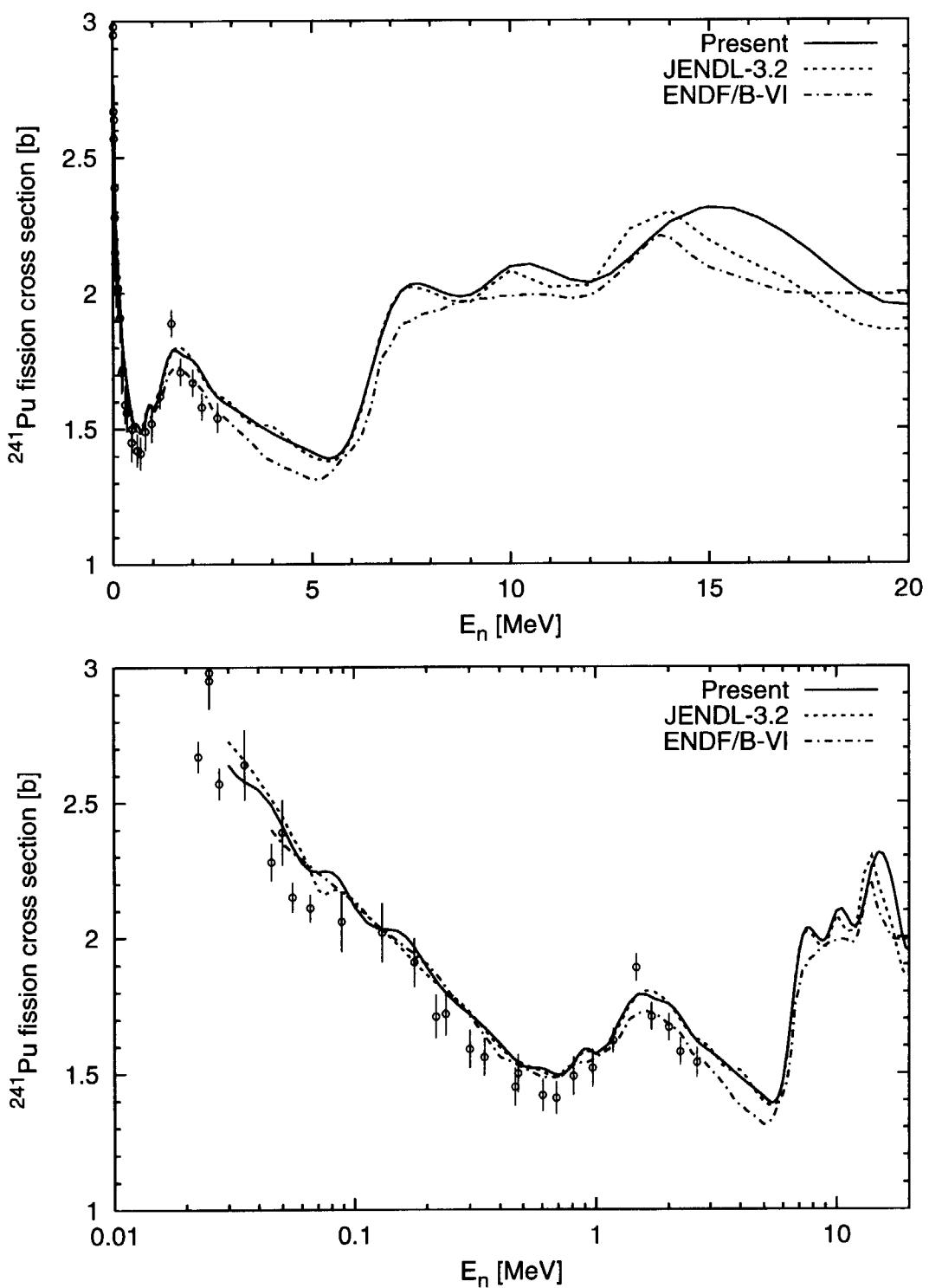


Fig. 6: Comparison of the presently-evaluated fission cross sections of  $^{241}\text{Pu}$  with the experimental data and the evaluated cross sections of JENDL-3.2 and ENDF/B-VI.

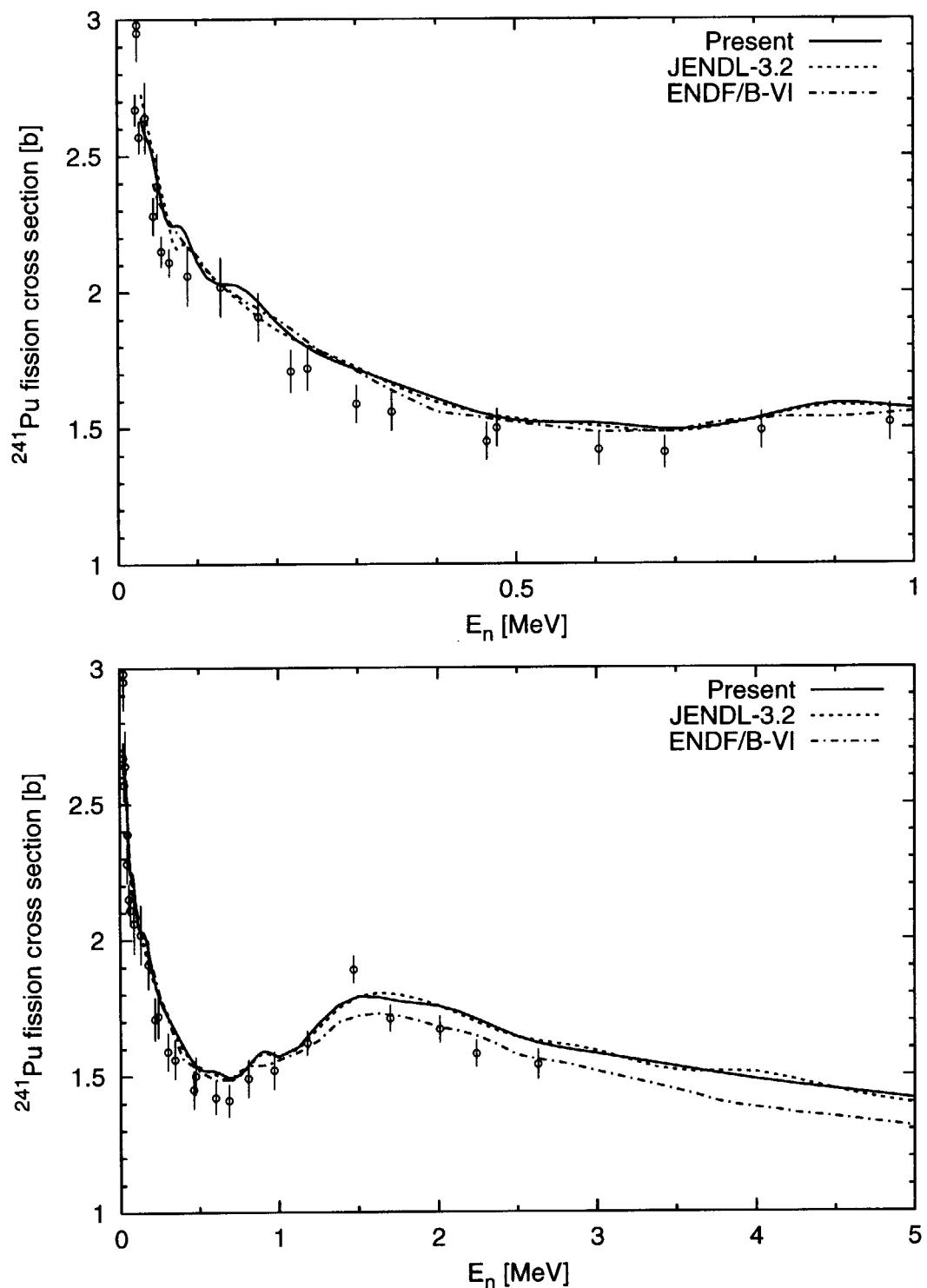


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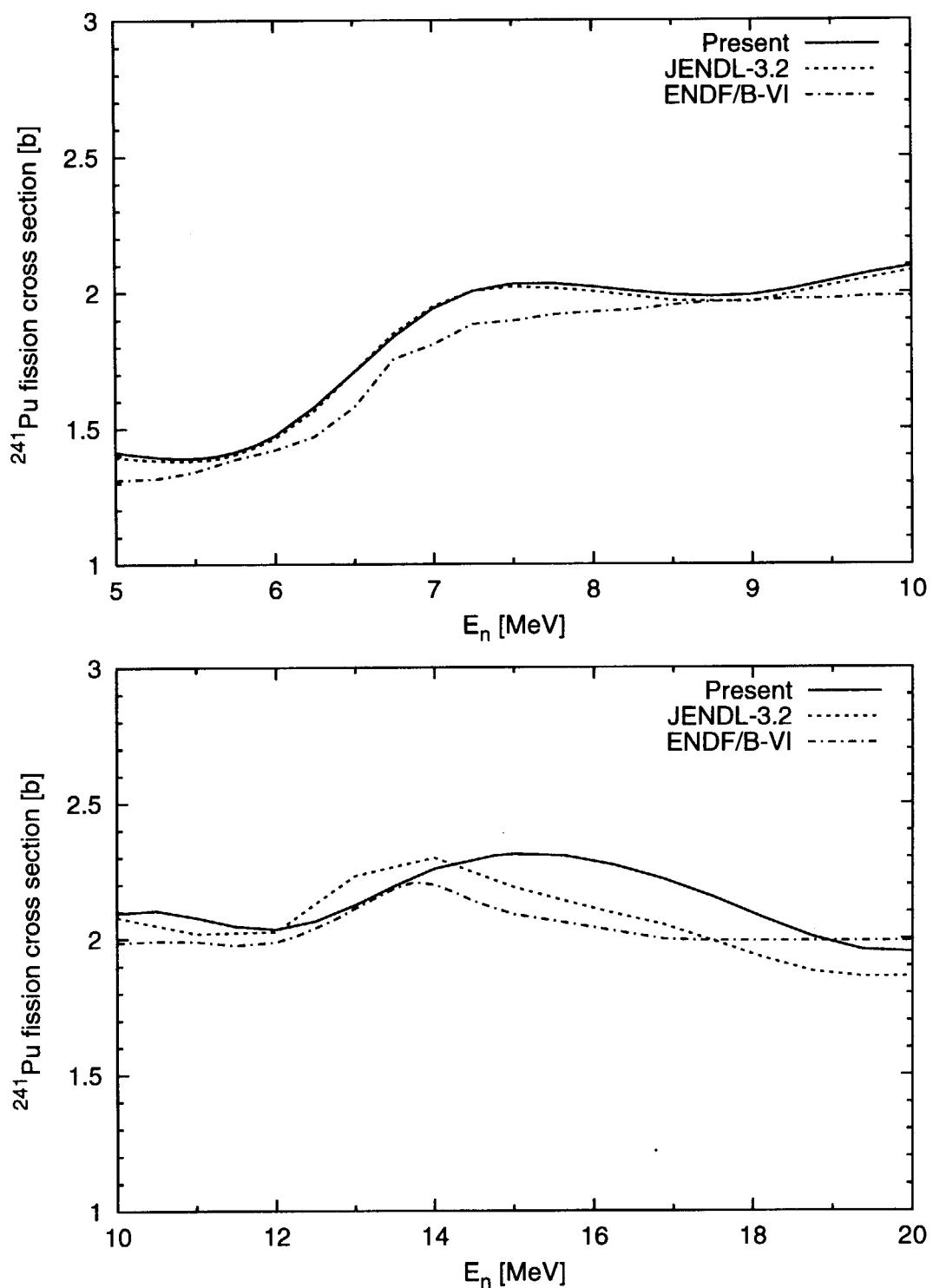


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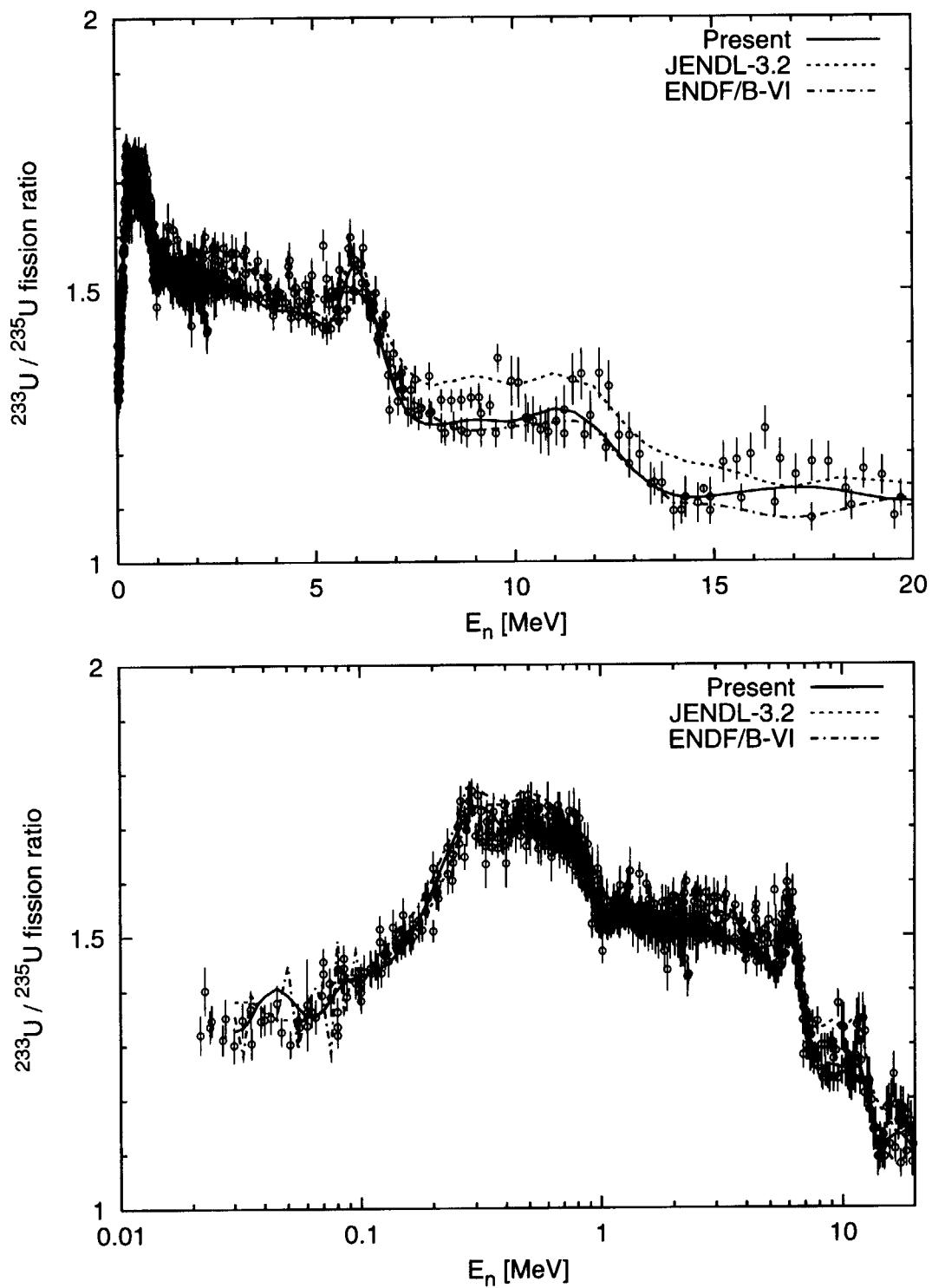


Fig. 7: Comparison of the presently-evaluated fission cross section ratios of  $^{233}\text{U}$  to  $^{235}\text{U}$  with the experimental data, and with the evaluations of JENDL-3.2 and ENDF/B-VI.

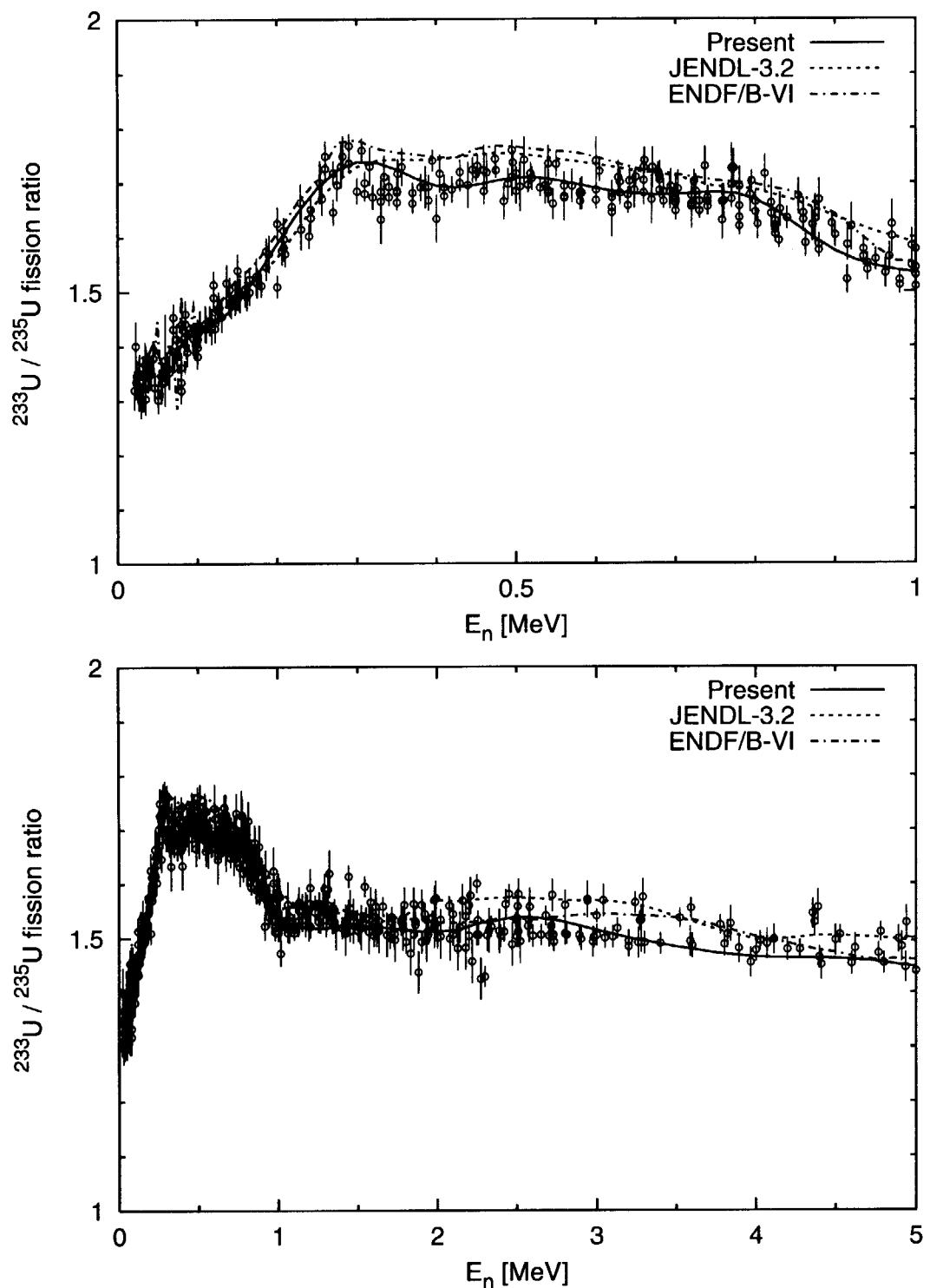


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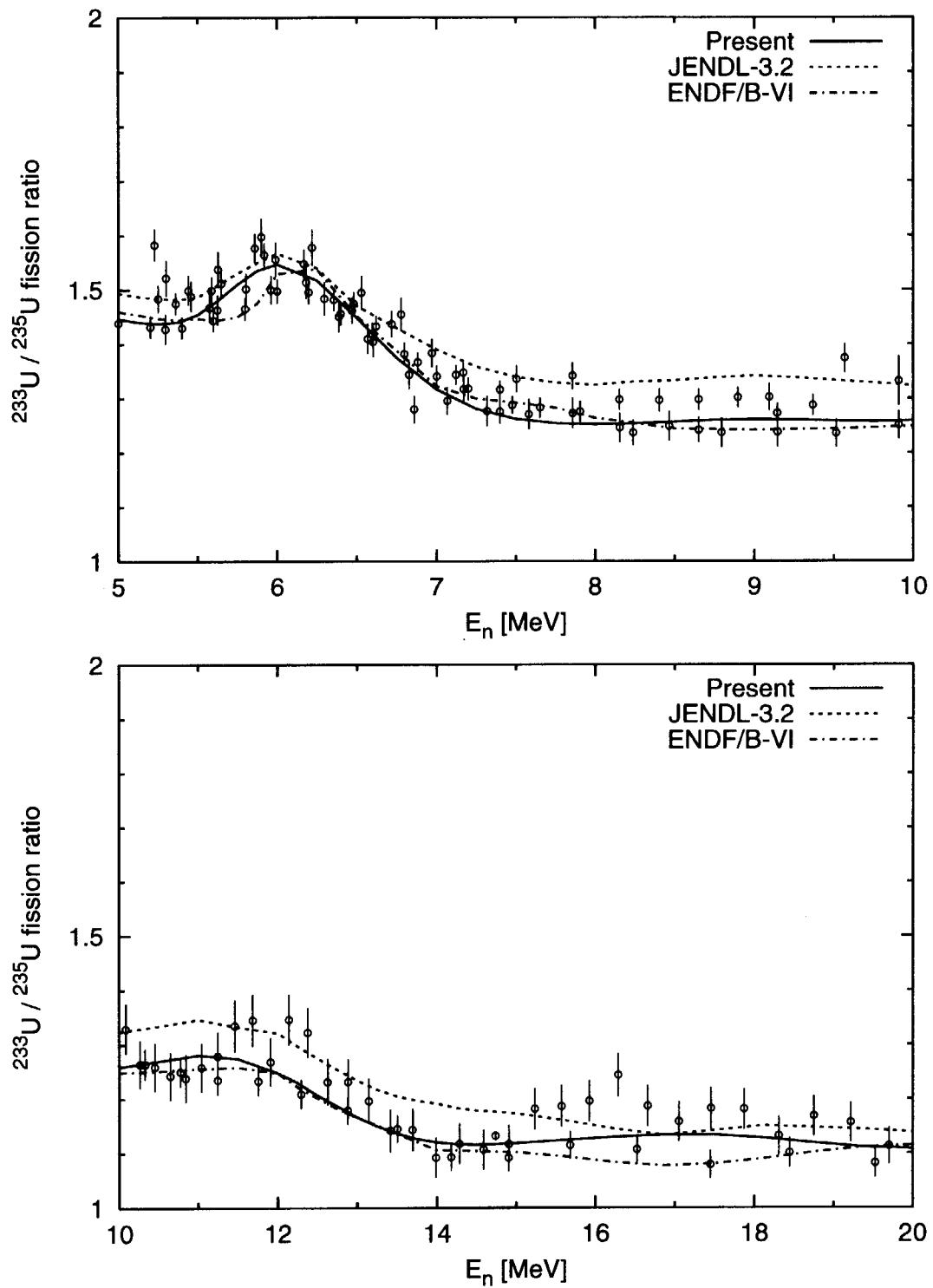


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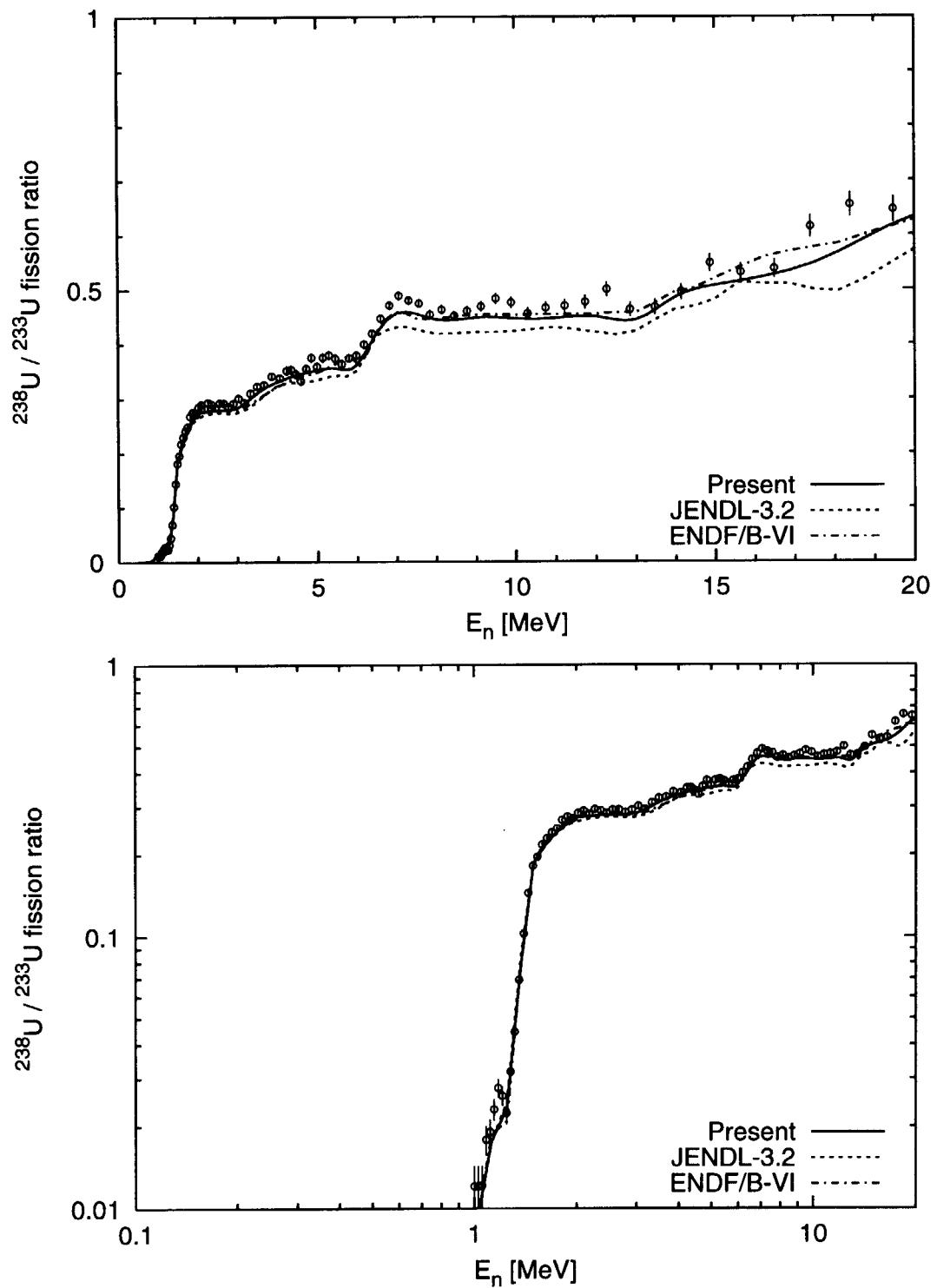


Fig. 8: Comparison of the presently-evaluated fission cross section ratios of  $^{238}\text{U}$  to  $^{233}\text{U}$  with the experimental data, and with the evaluations of JENDL-3.2 and ENDF/B-VI.

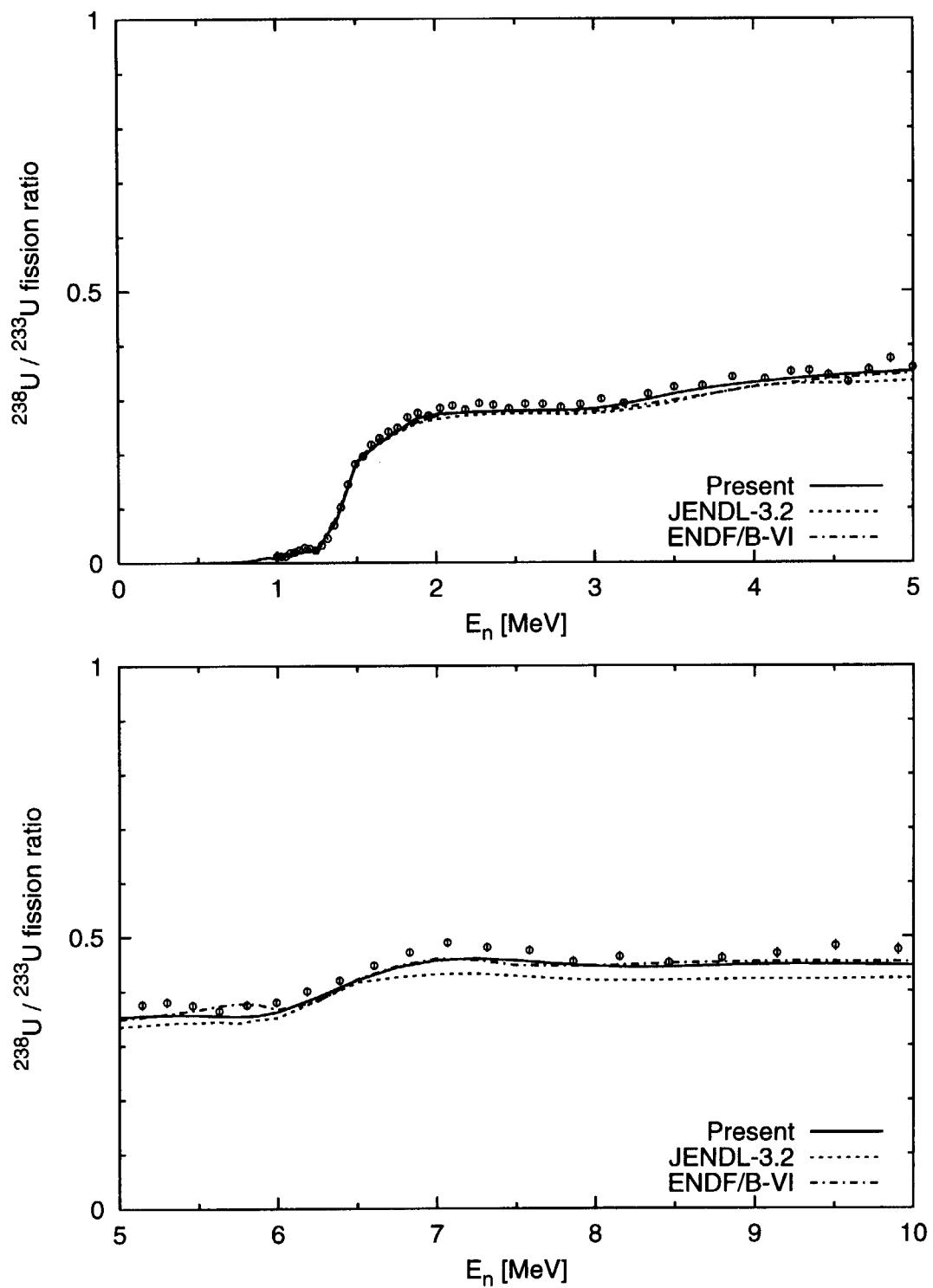


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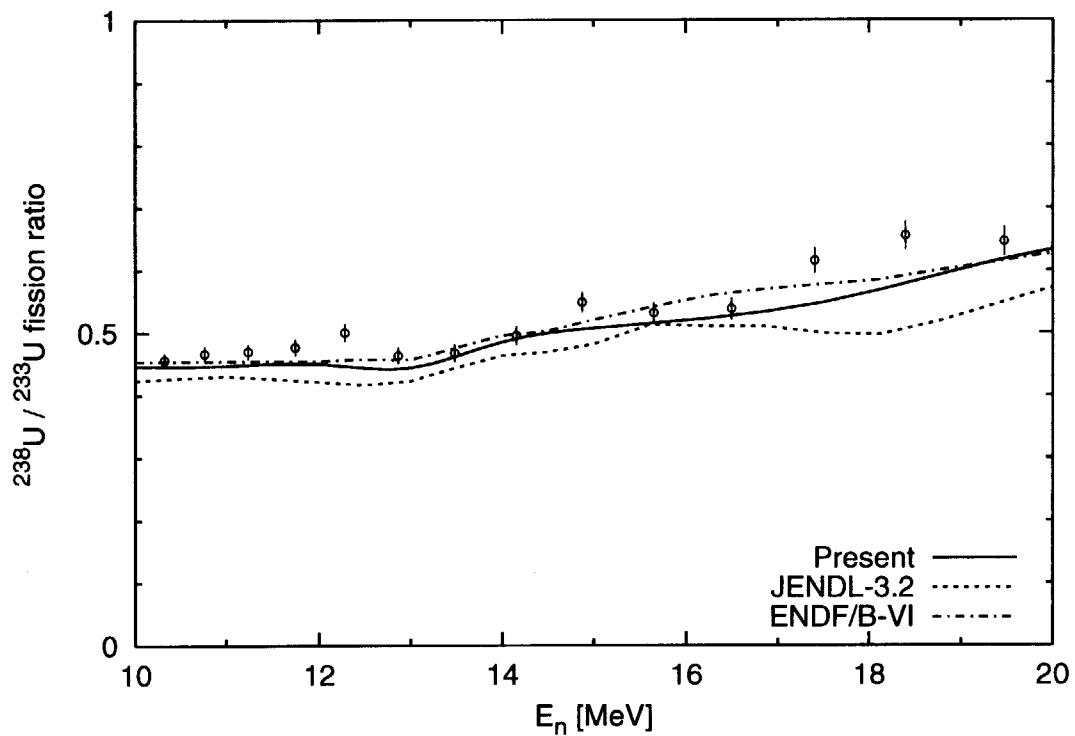


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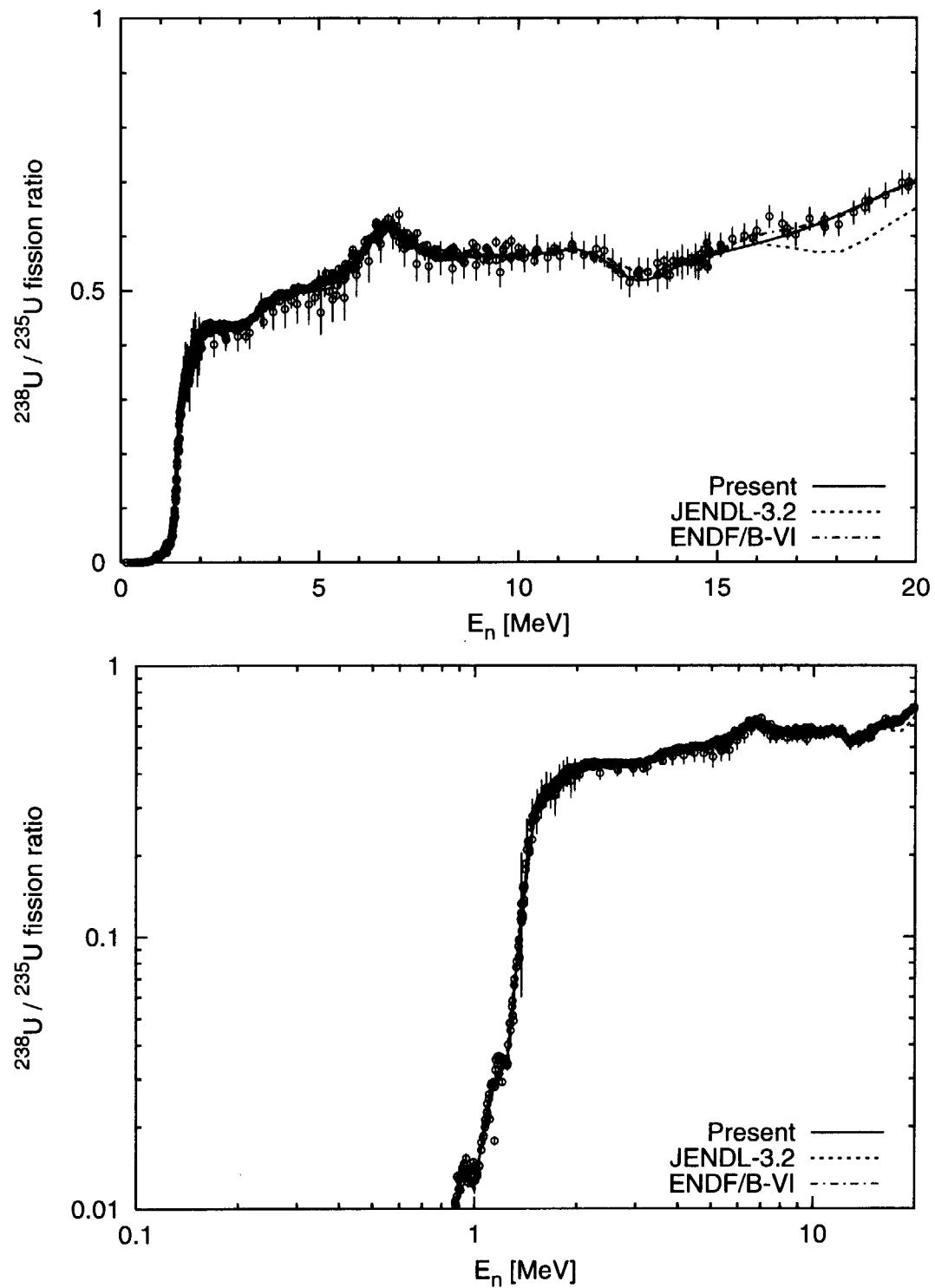


Fig. 9: Comparison of the presently-evaluated fission cross section ratios of  $^{238}\text{U}$  to  $^{235}\text{U}$  with the experimental data, and with the evaluations of JENDL-3.2 and ENDF/B-VI.

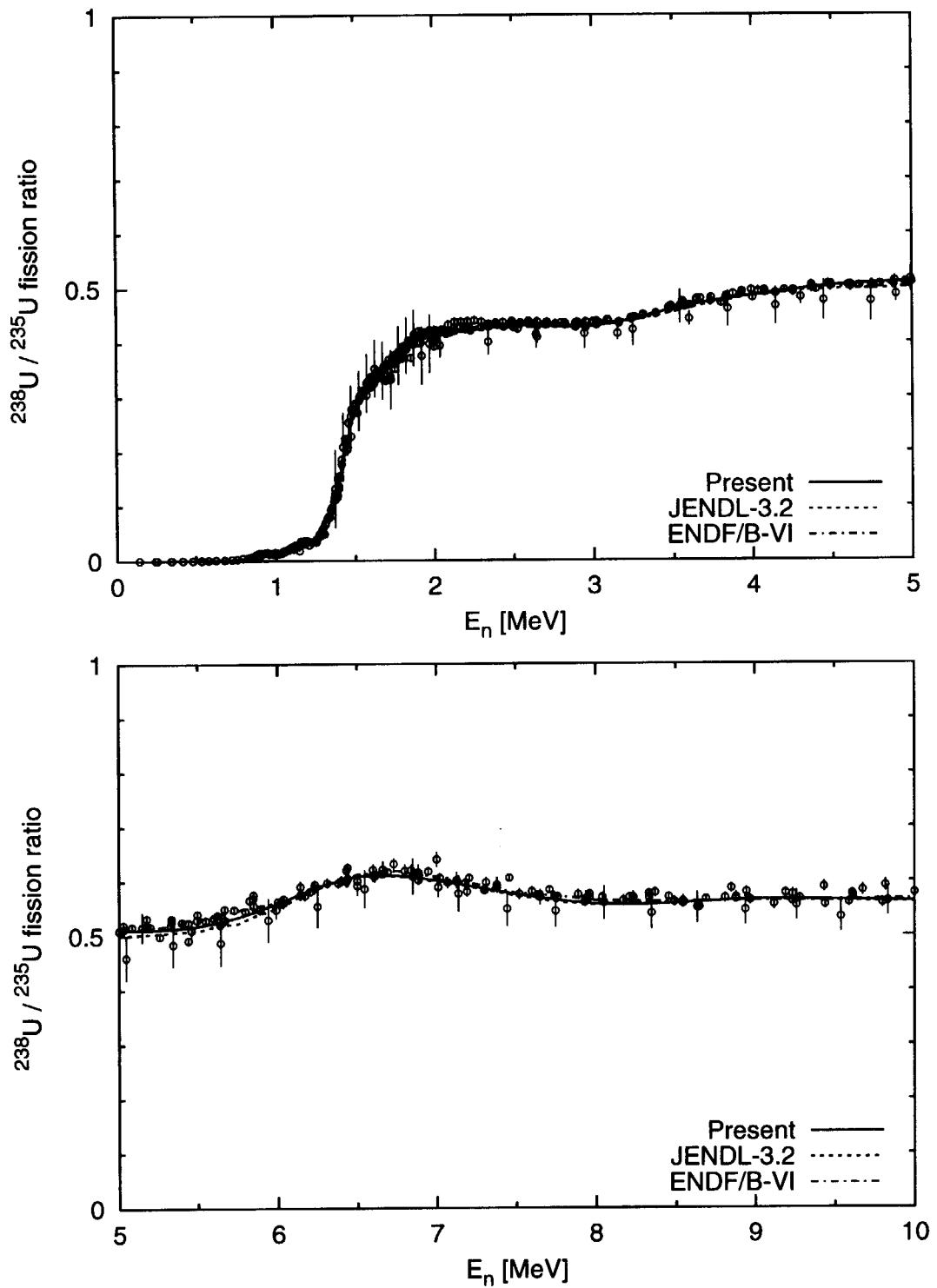


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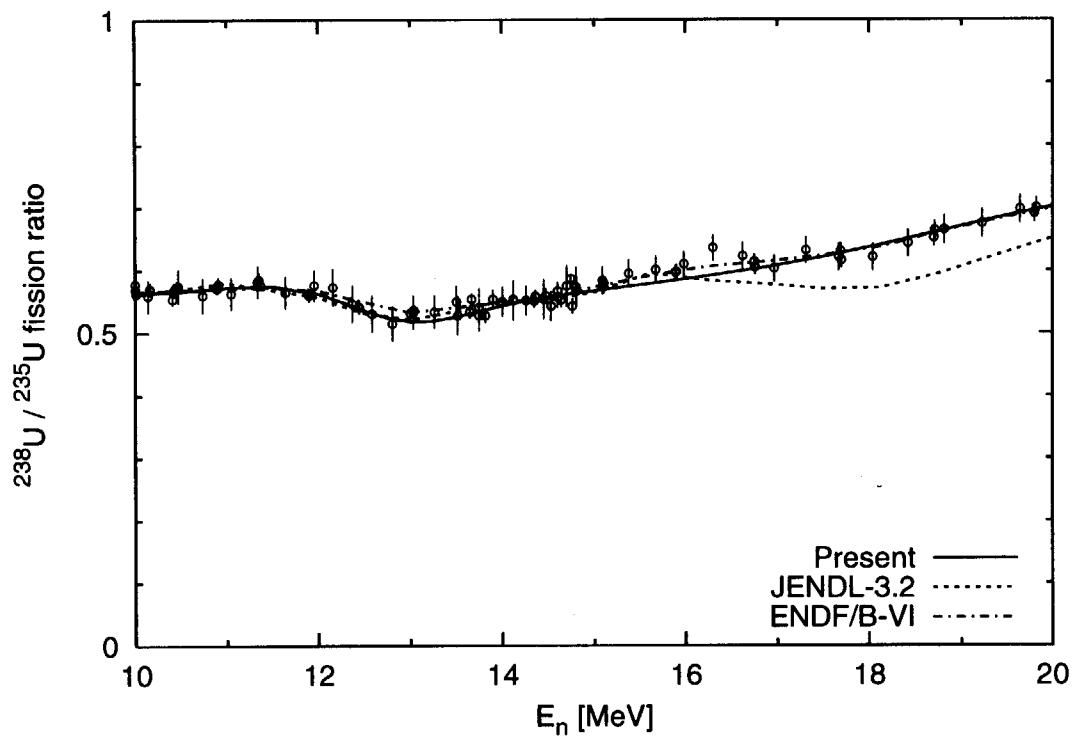


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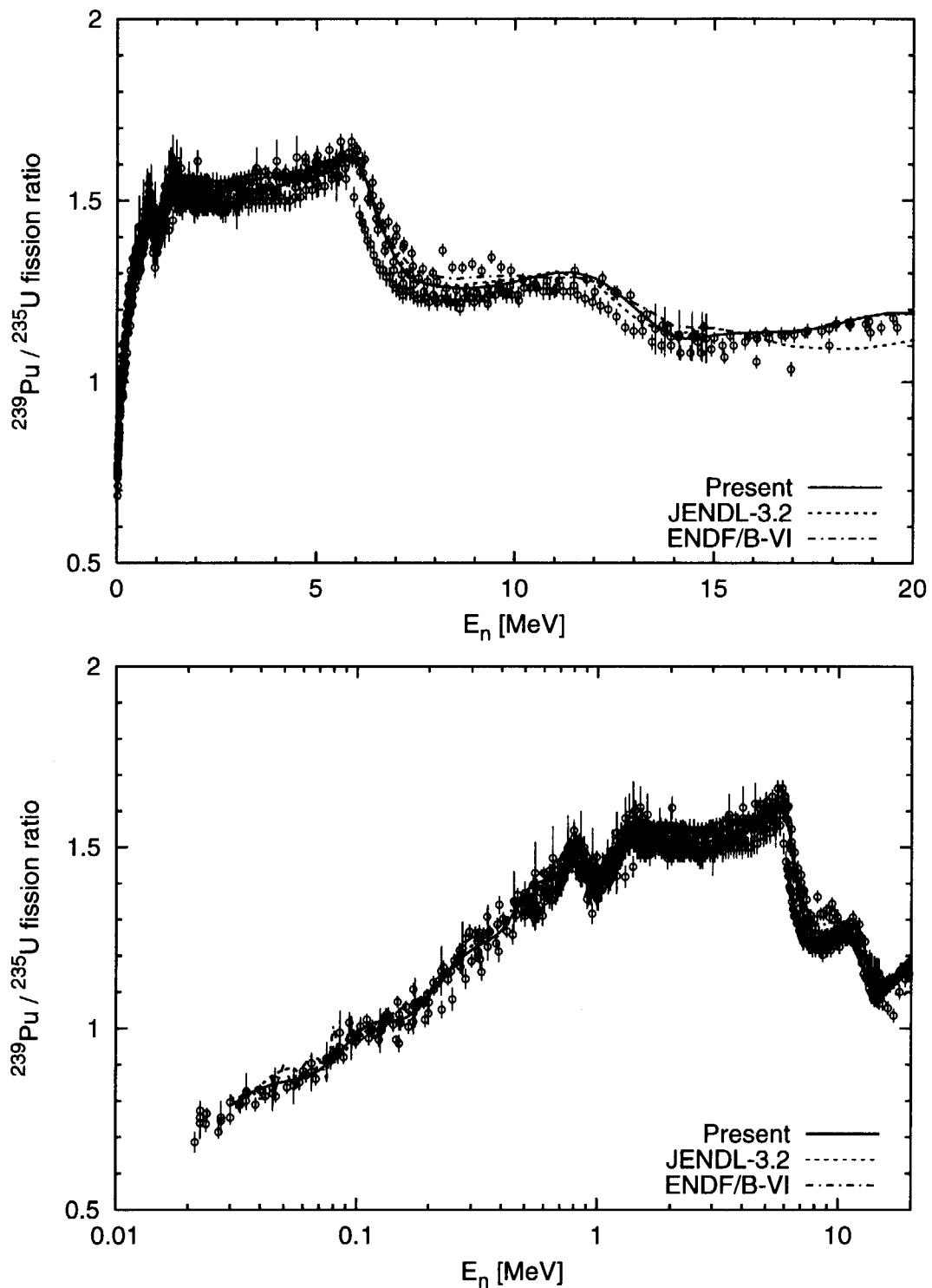


Fig. 10: Comparison of the presently-evaluated fission cross section ratios of  $^{239}\text{Pu}$  to  $^{235}\text{U}$  with the experimental data, and with the evaluations of JENDL-3.2 and ENDF/B-VI.

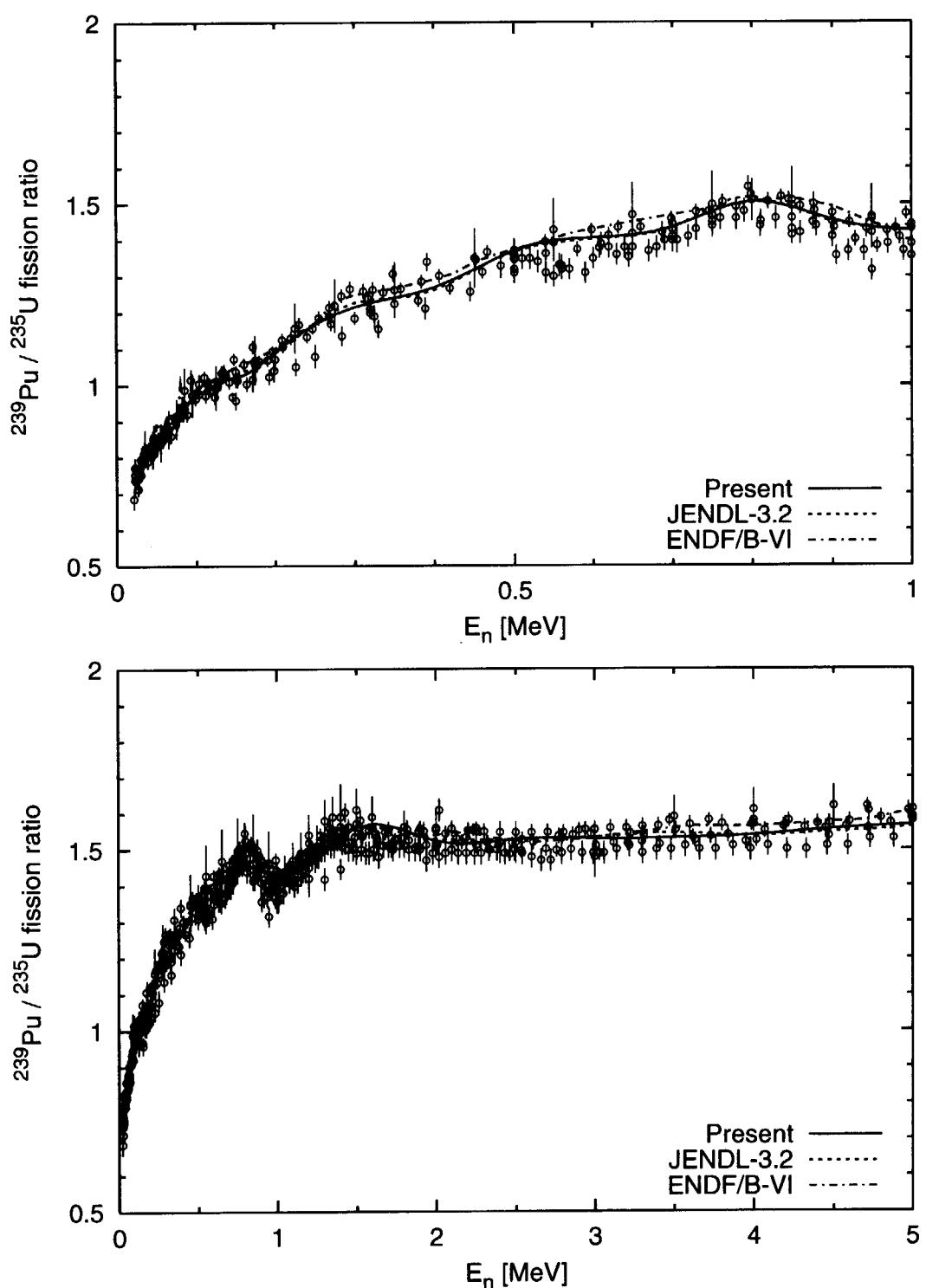


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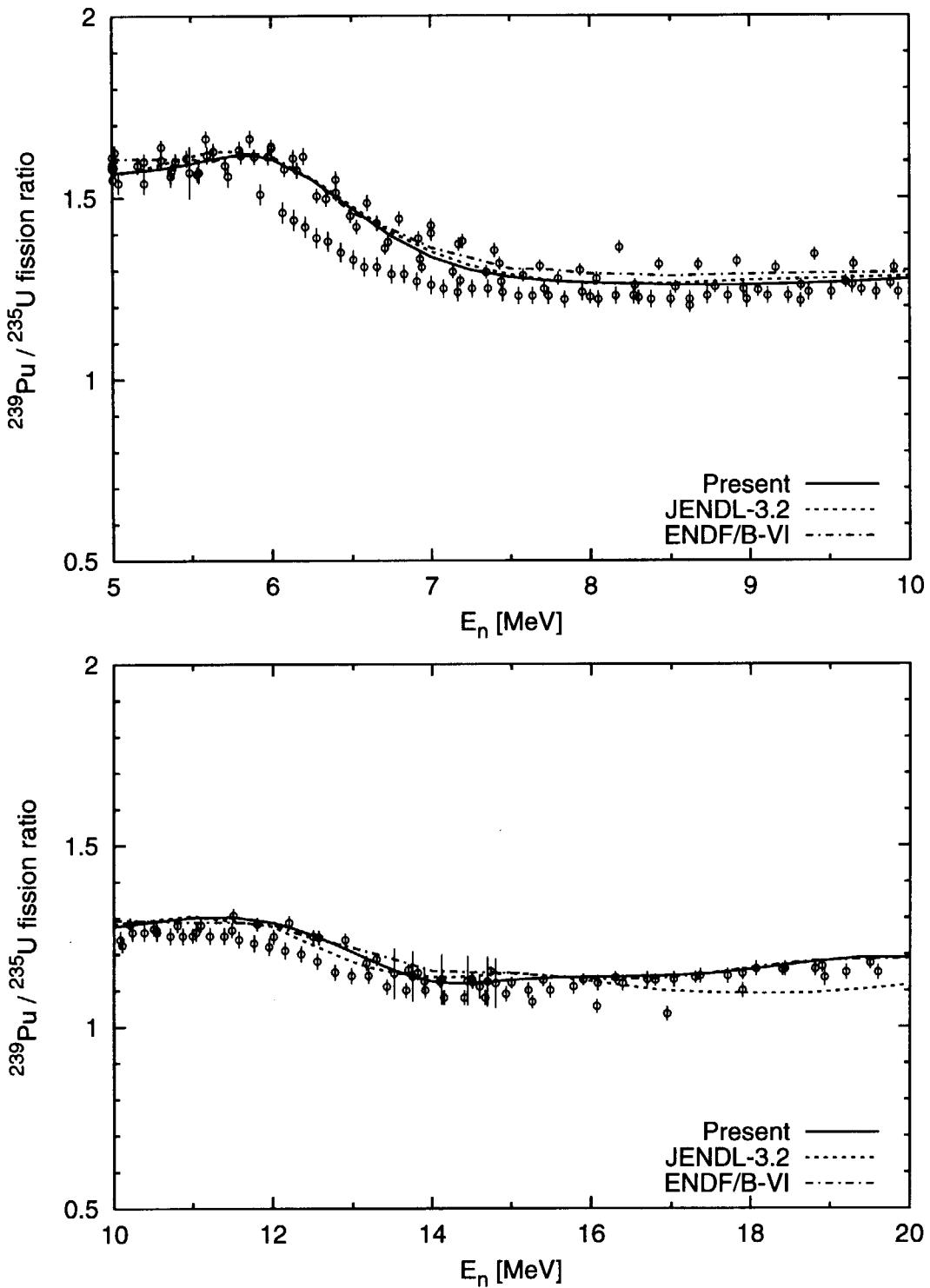


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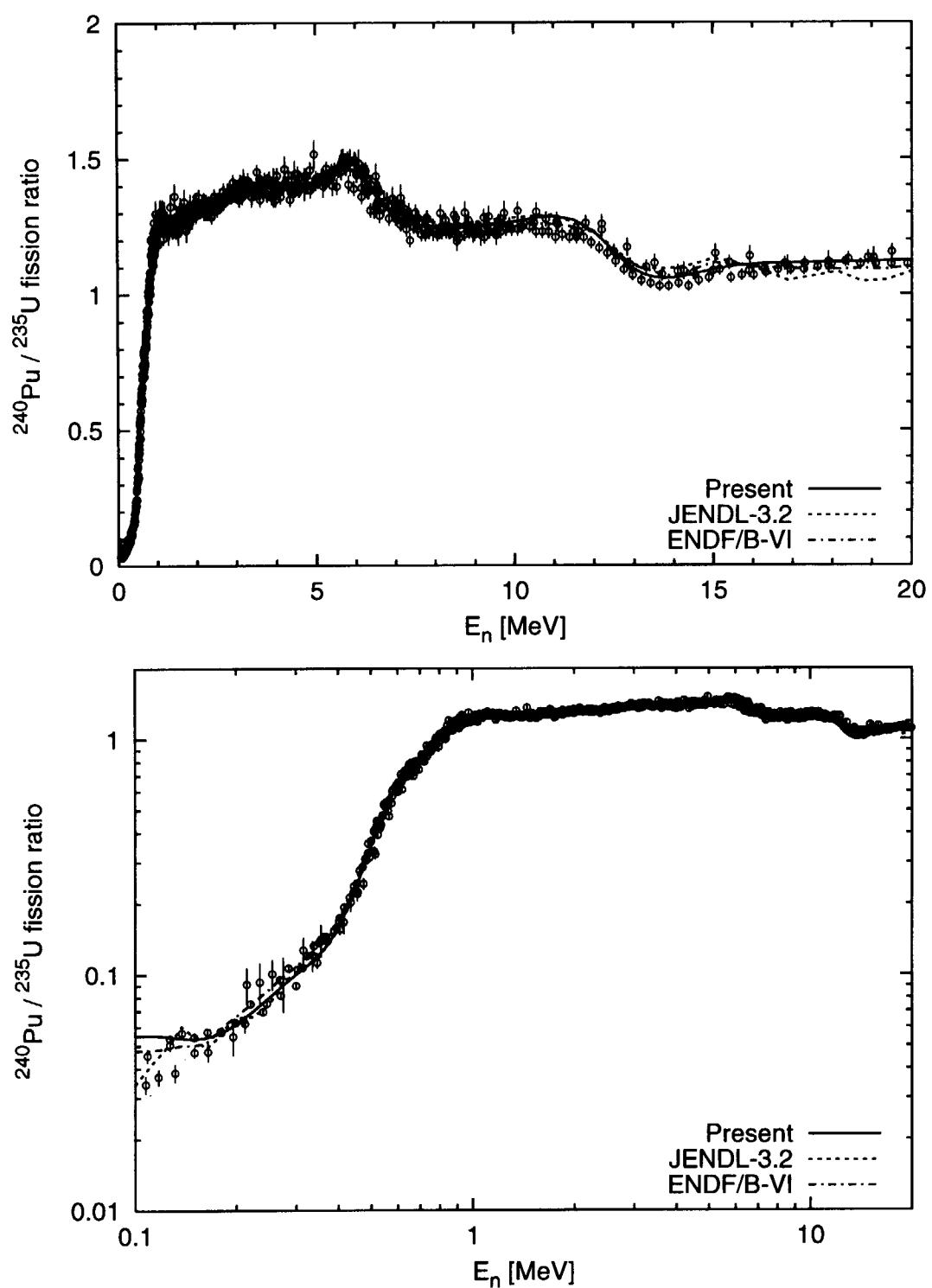


Fig. 11: Comparison of the presently-evaluated fission cross section ratios of  $^{240}\text{Pu}$  to  $^{235}\text{U}$  with the experimental data, and with the evaluations of JENDL-3.2 and ENDF/B-VI.

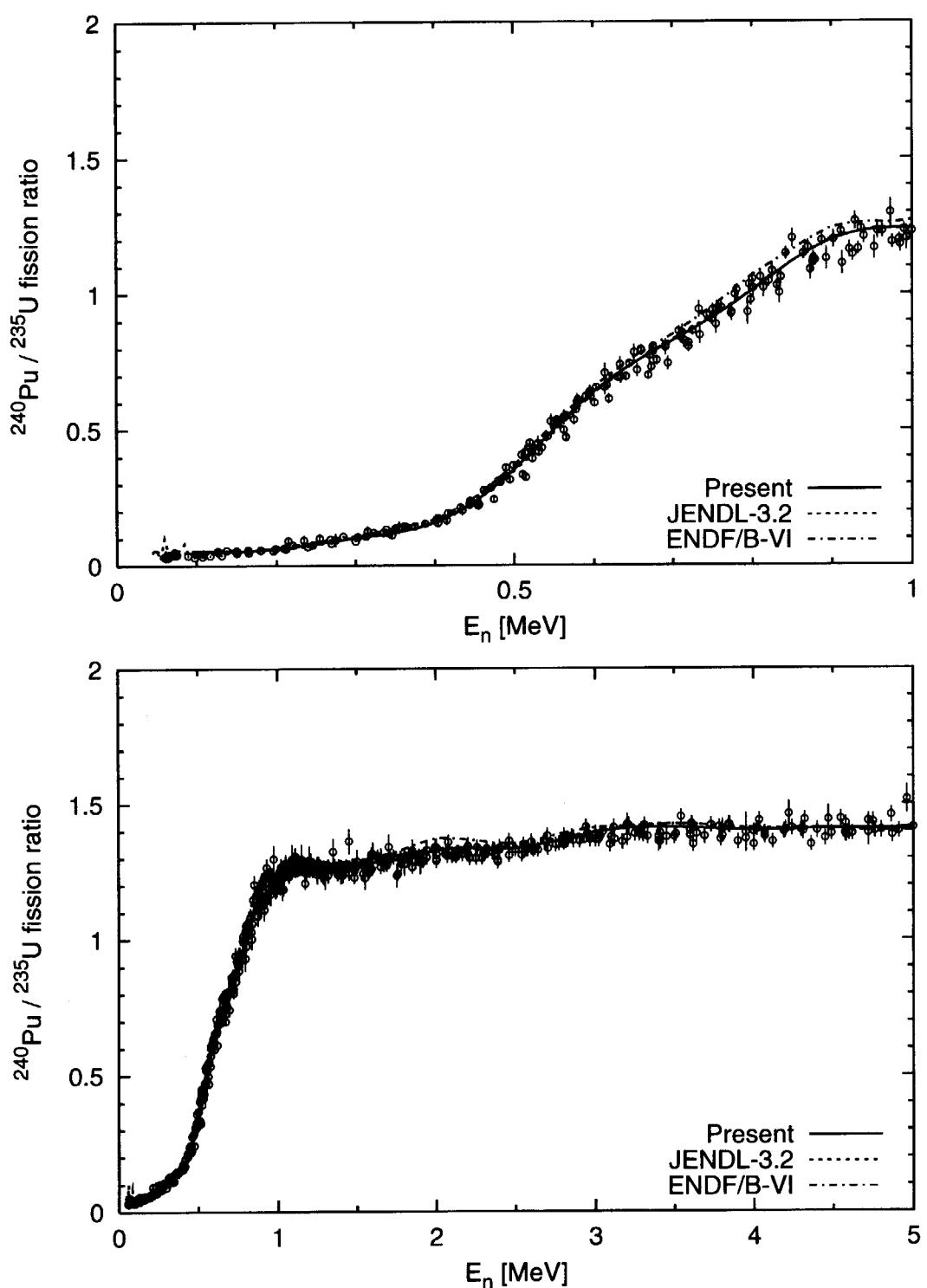


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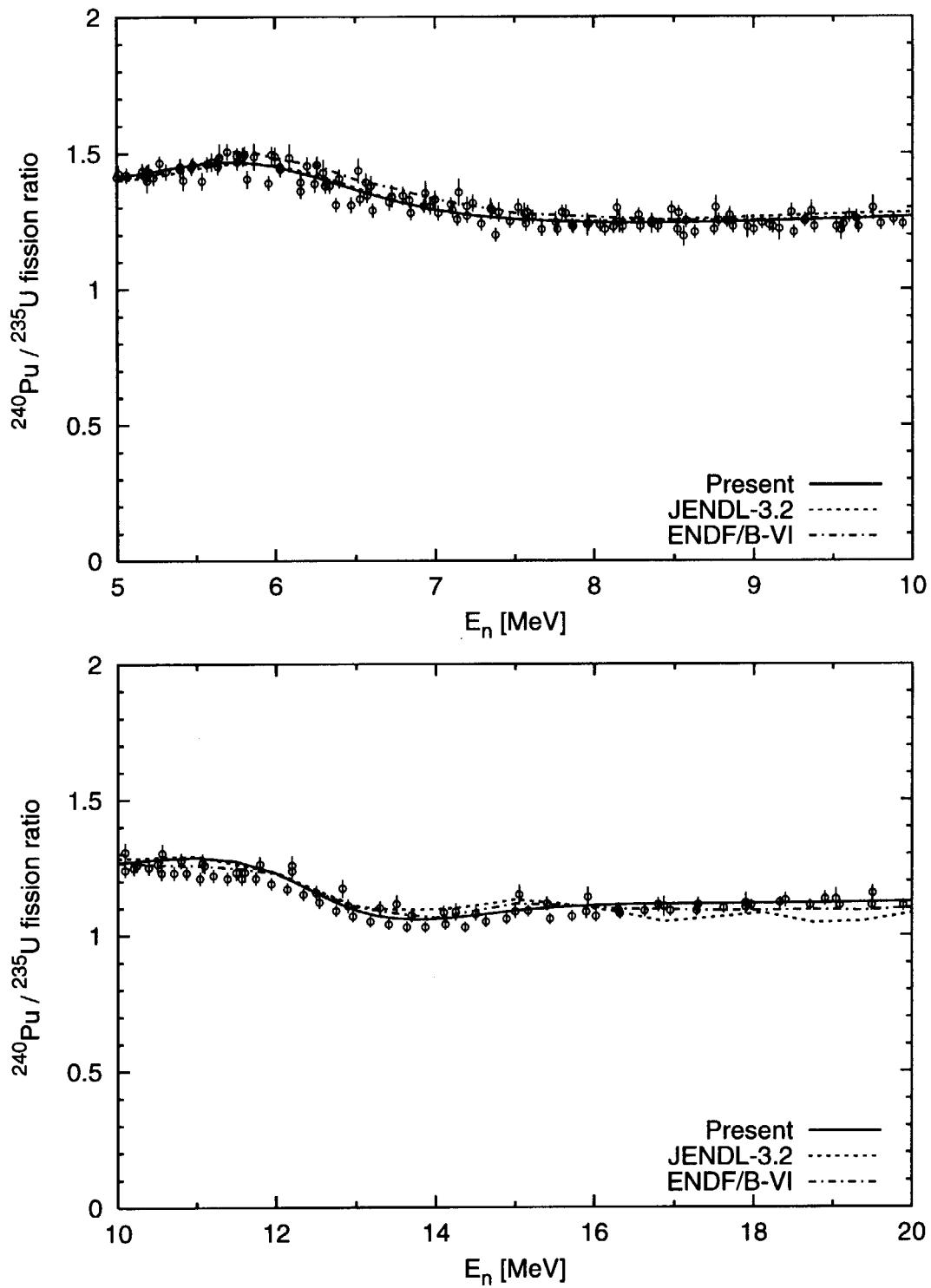


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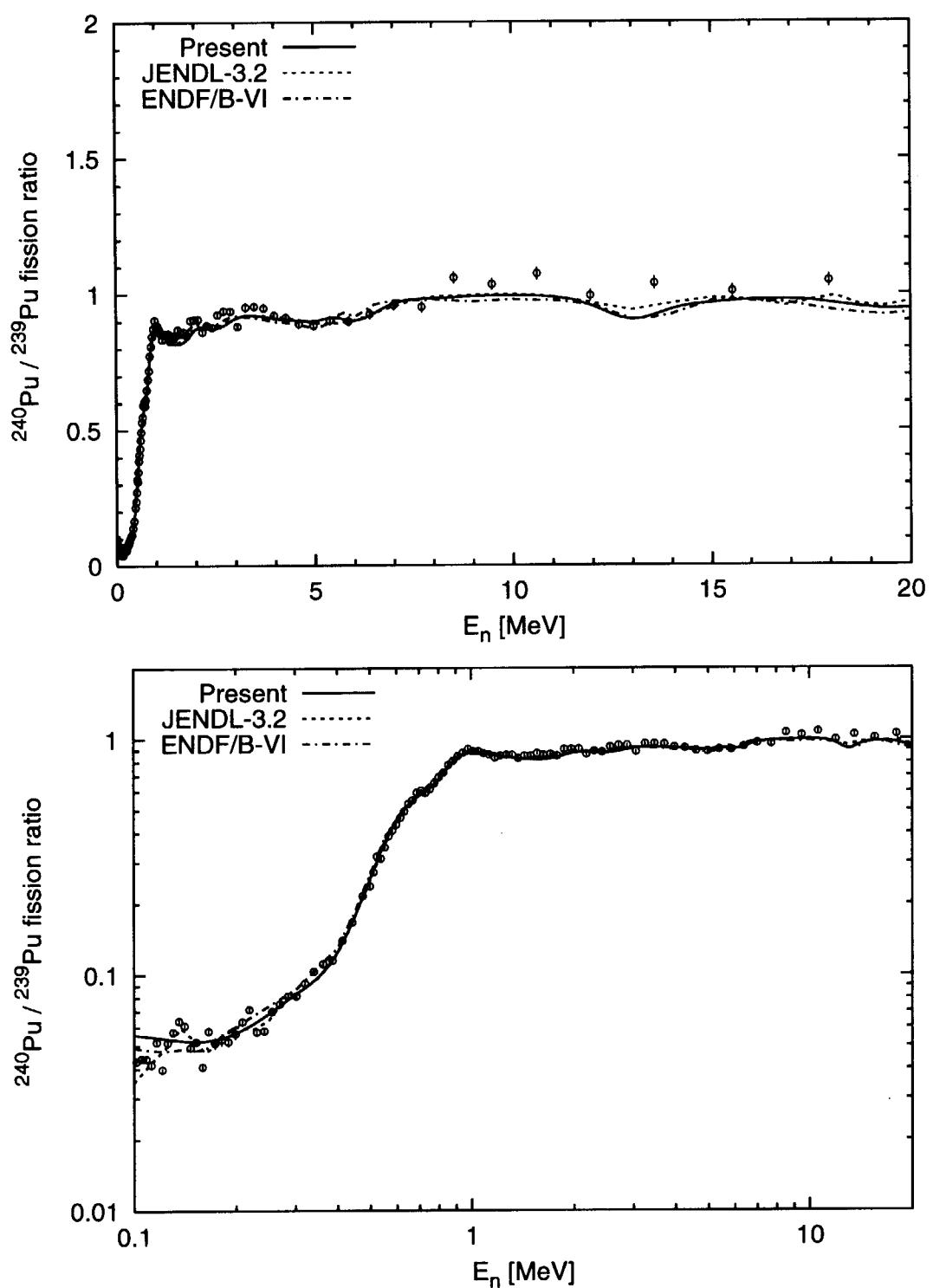


Fig. 12: Comparison of the presently-evaluated fission cross section ratios of  $^{240}\text{Pu}$  to  $^{239}\text{Pu}$  with the experimental data, and with the evaluations of JENDL-3.2 and ENDF/B-VI.

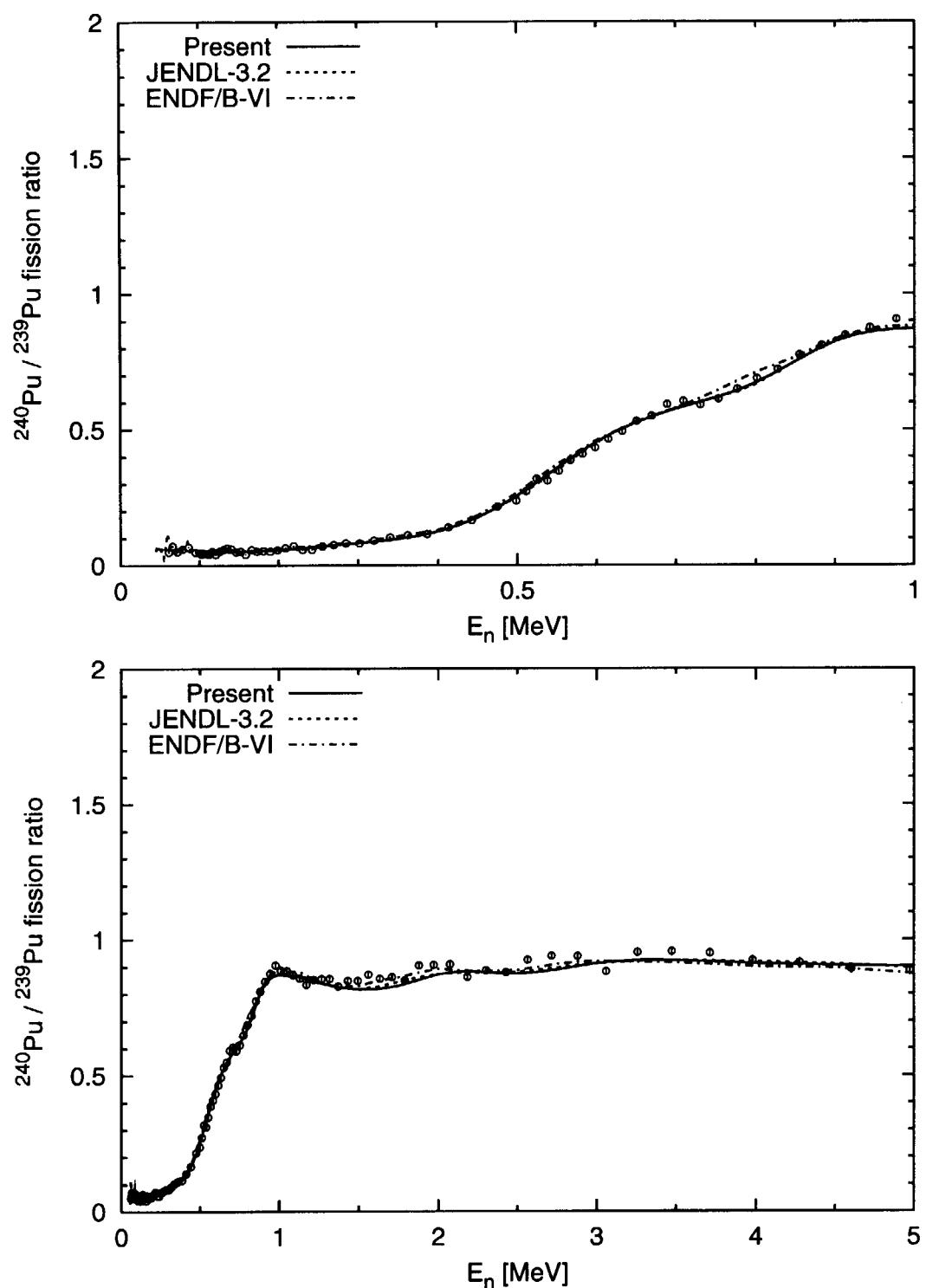


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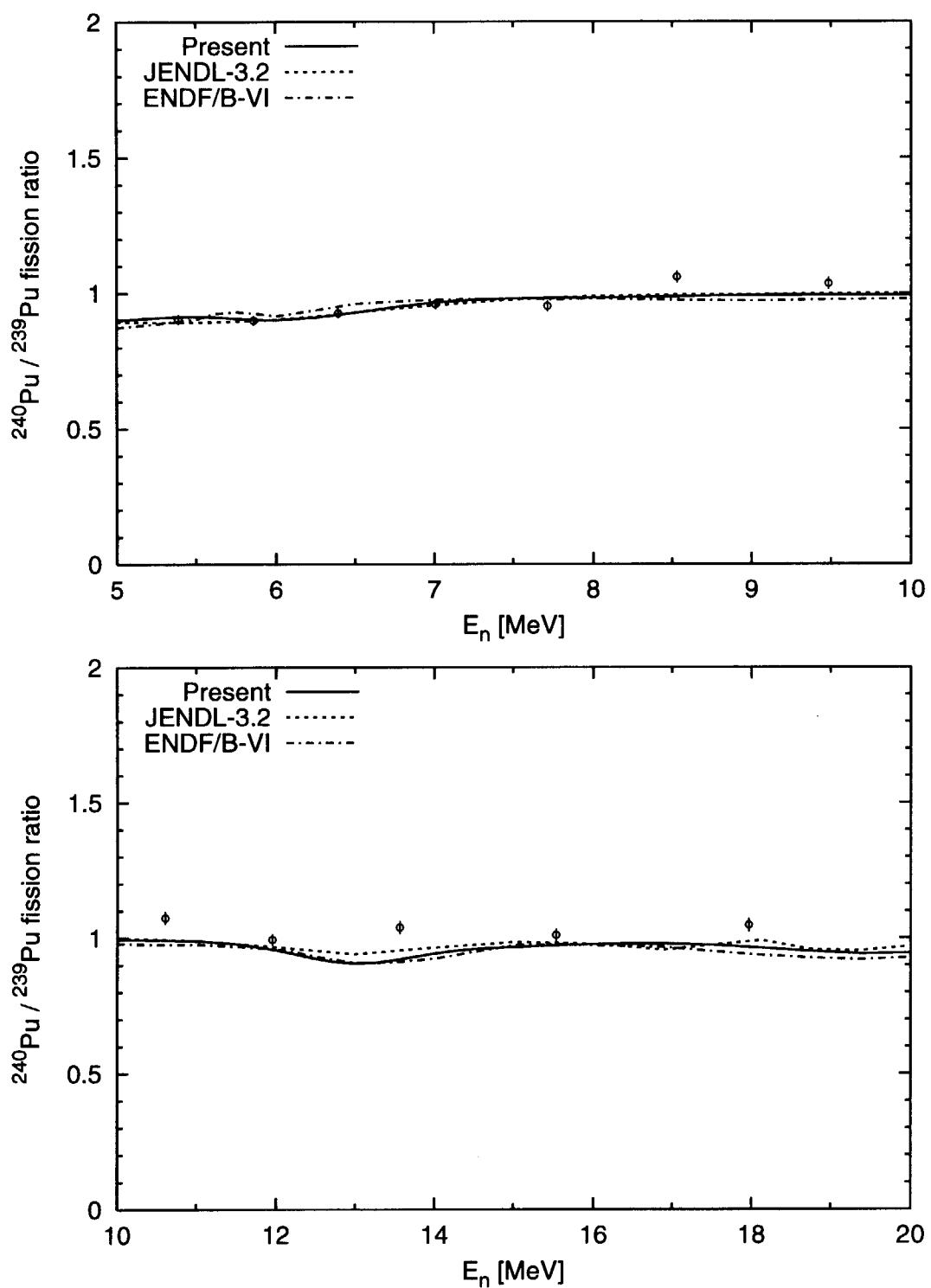


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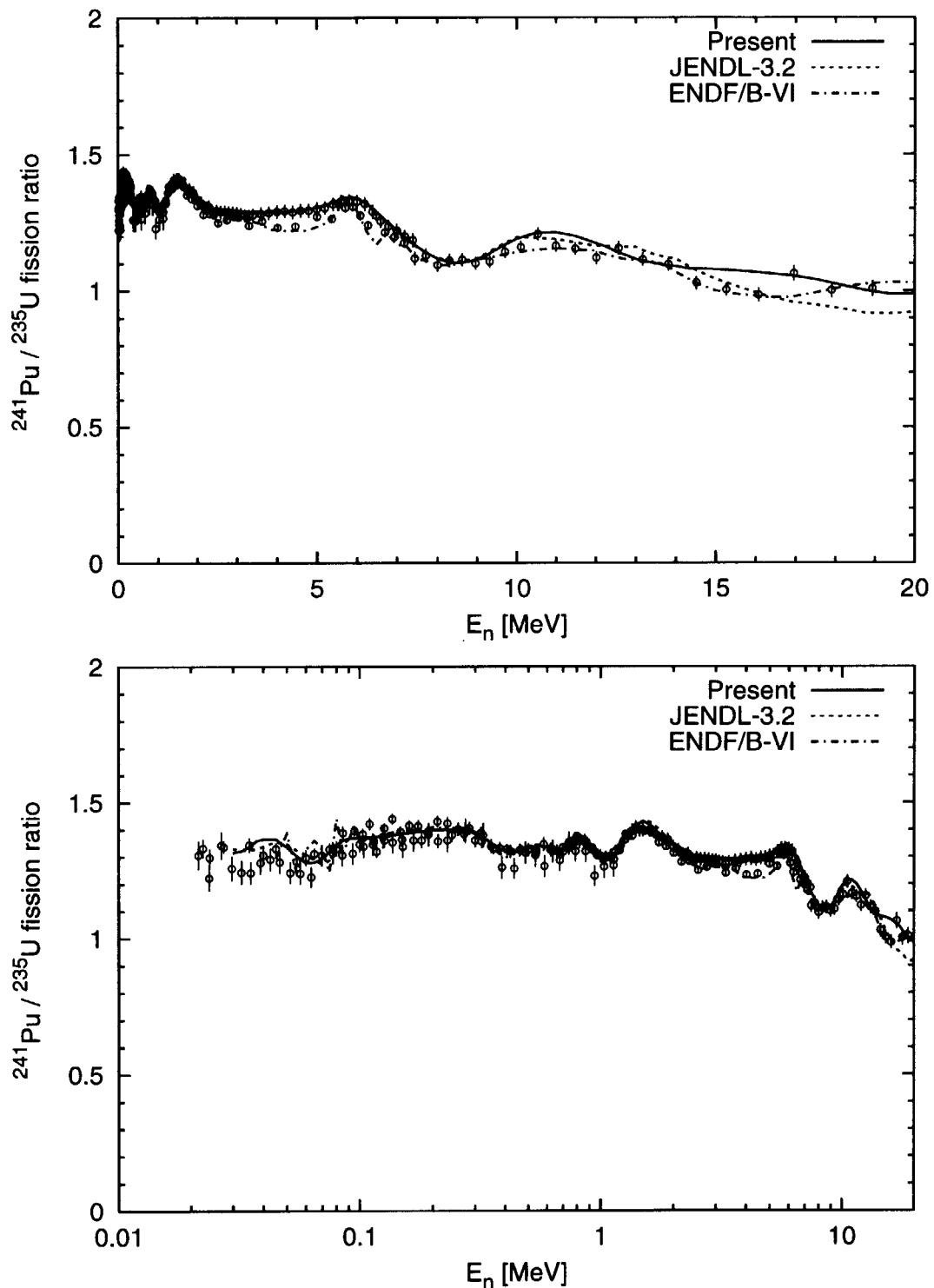


Fig. 13: Comparison of the presently-evaluated fission cross section ratios of  $^{241}\text{Pu}$  to  $^{235}\text{U}$  with the experimental data, and with the evaluations of JENDL-3.2 and ENDF/B-VI.

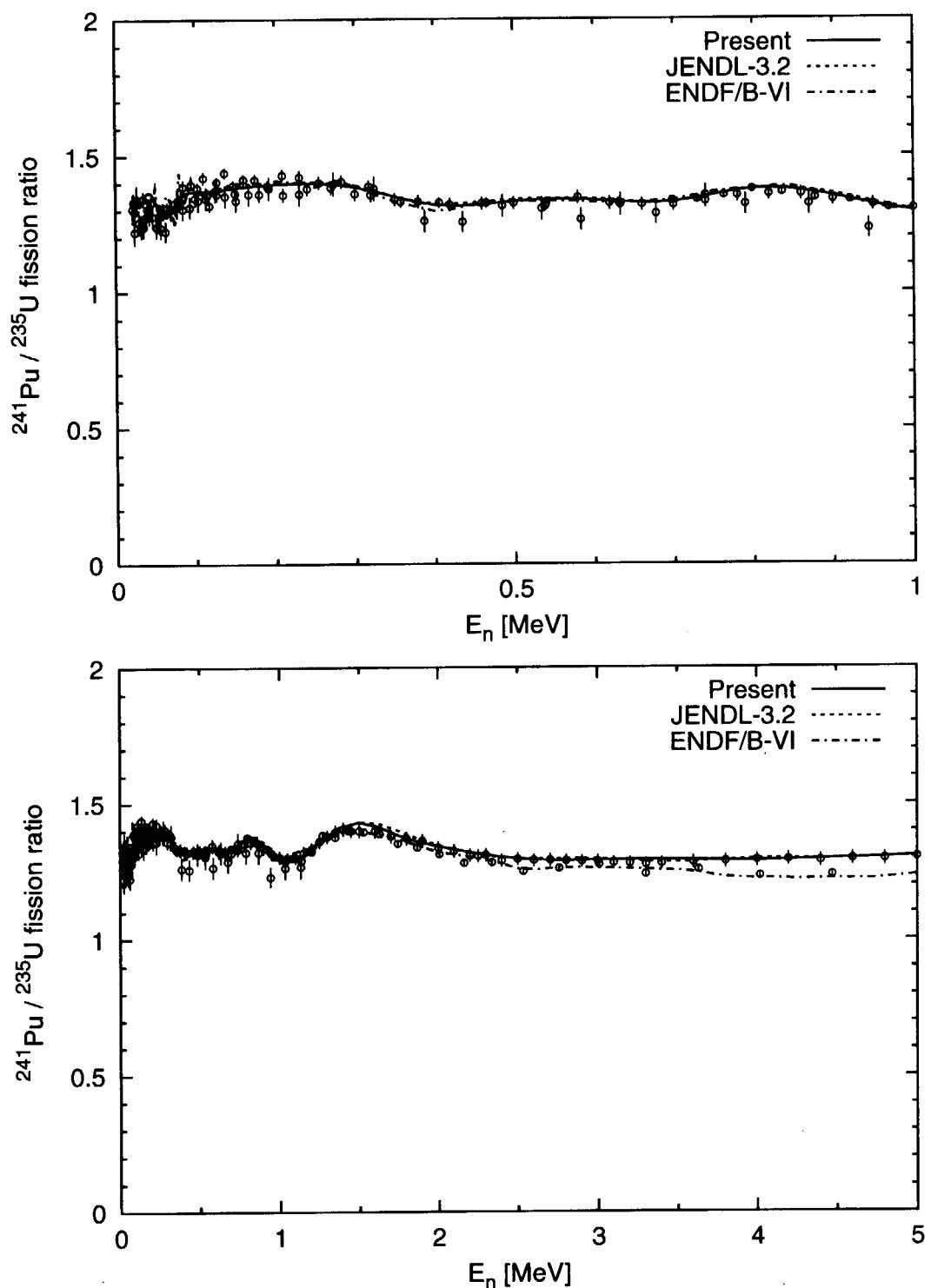


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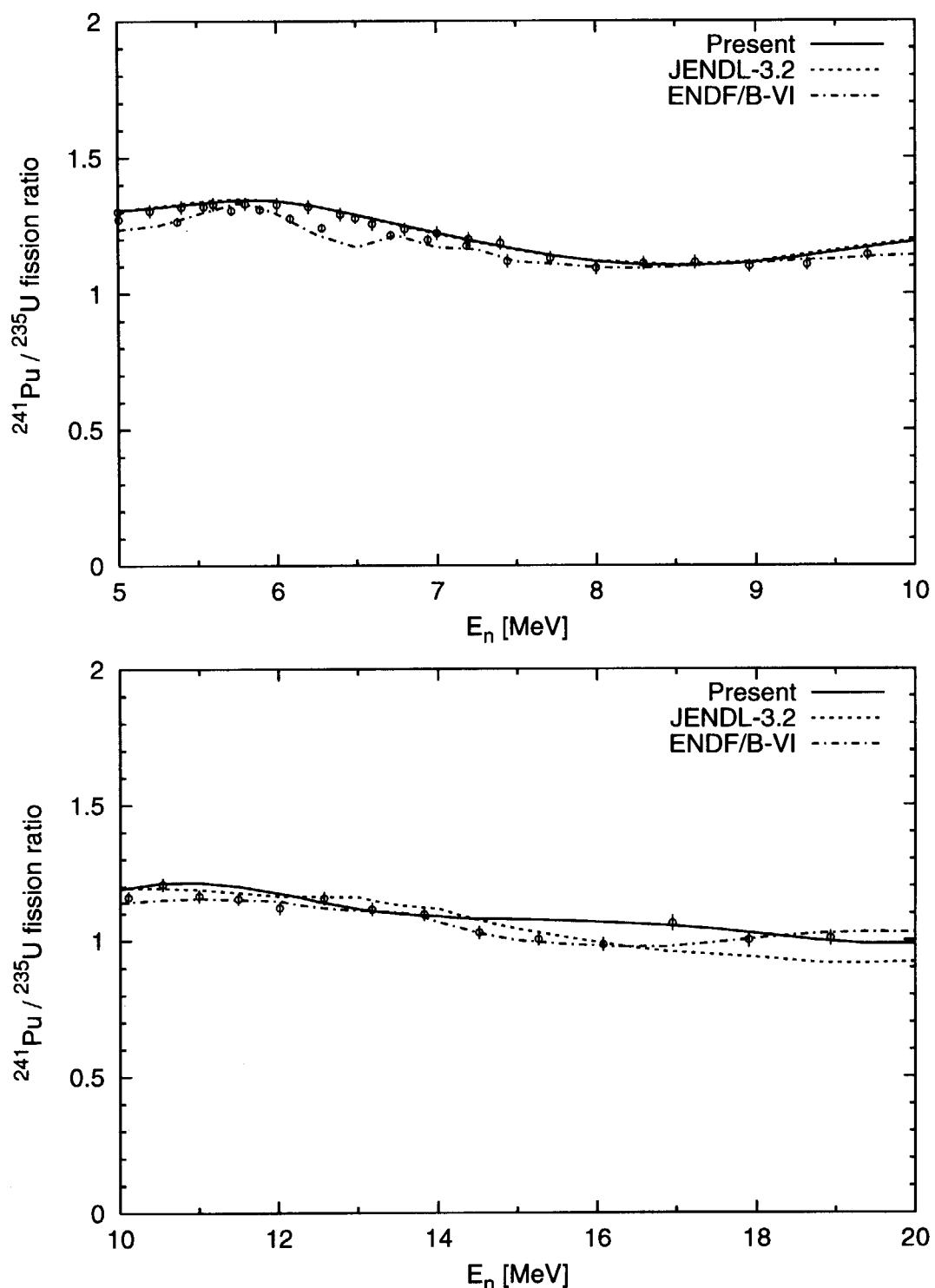


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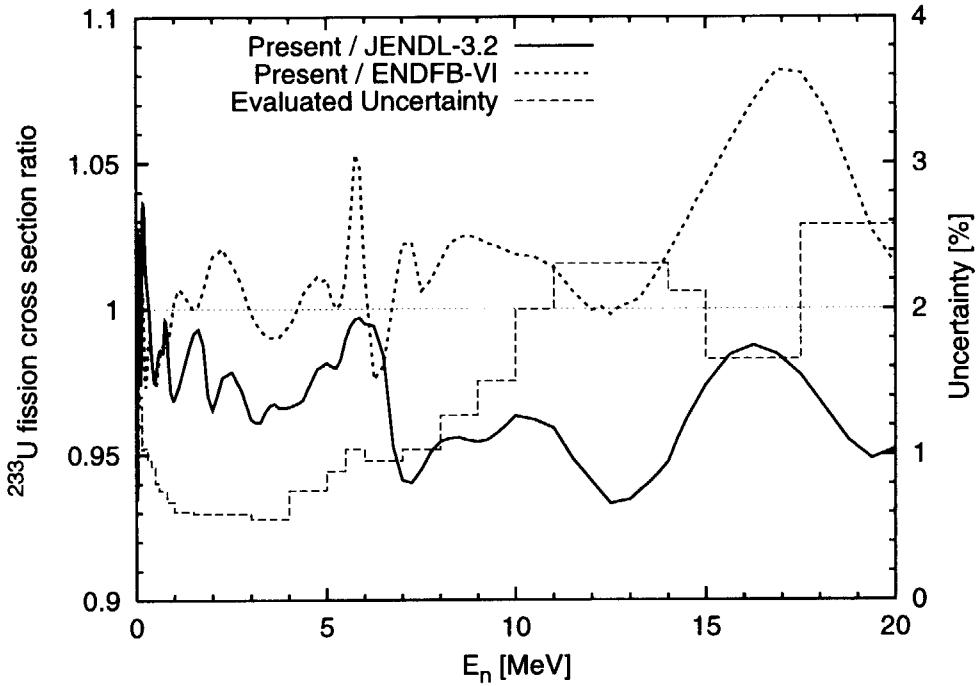


Fig. 14: Ratios of the evaluated  $^{233}\text{U}$  fission cross sections to those of JENDL-3.2 and ENDFB-VI. The dashed line shows the uncertainties of the evaluated cross sections, which is on the right axis.

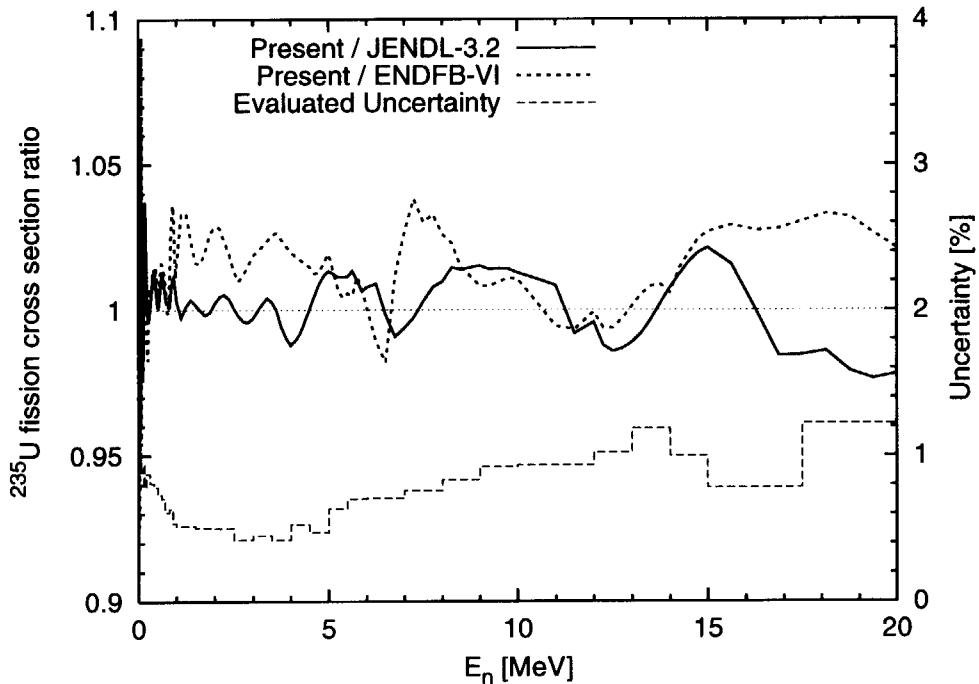


Fig. 15: Ratios of the evaluated  $^{235}\text{U}$  fission cross sections to those of JENDL-3.2 and ENDFB-VI. The dashed line shows the uncertainties of the evaluated cross sections, which is on the right axis.

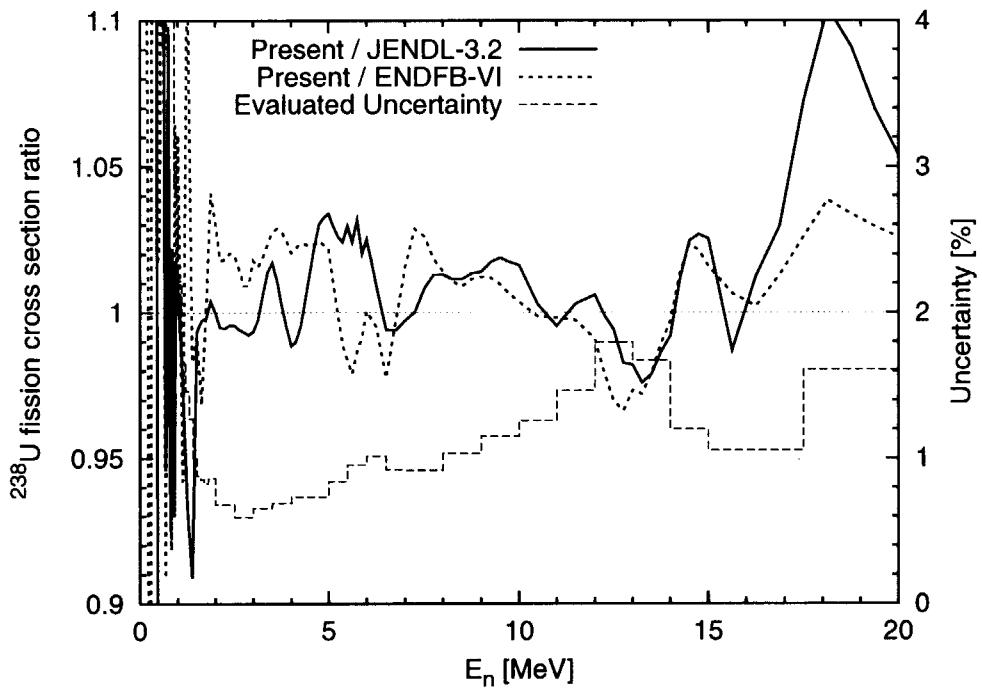


Fig. 16: Ratios of the evaluated  $^{238}\text{U}$  fission cross sections to those of JENDL-3.2 and ENDF/B-VI. The dashed line shows the uncertainties of the evaluated cross sections, which is on the right axis.

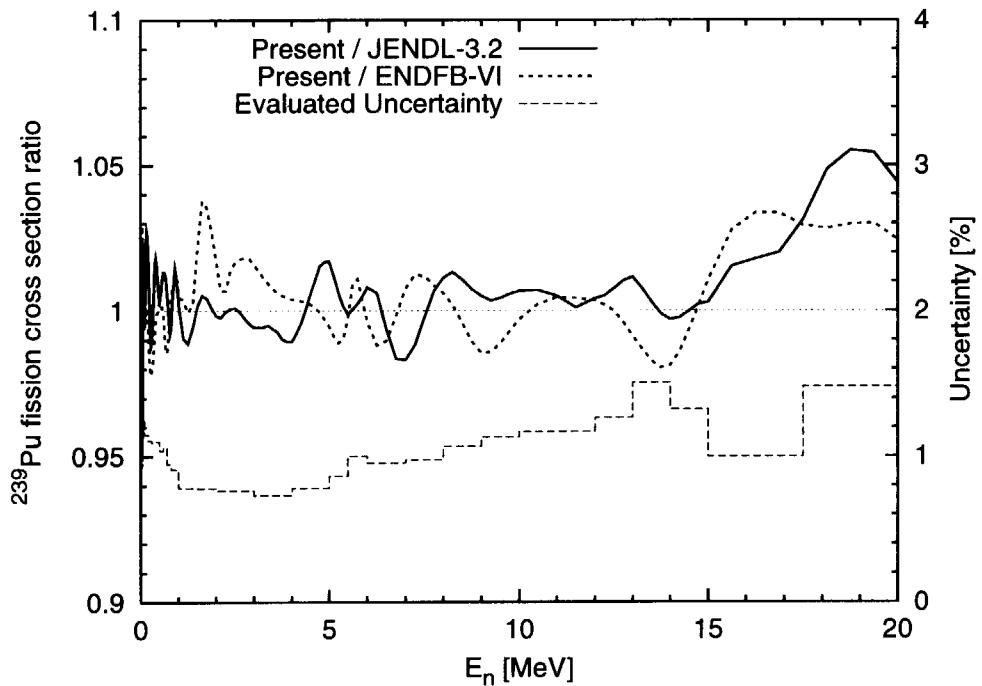


Fig. 17: Ratios of the evaluated  $^{239}\text{Pu}$  fission cross sections to those of JENDL-3.2 and ENDF/B-VI. The dashed line shows the uncertainties of the evaluated cross sections, which is on the right axis.

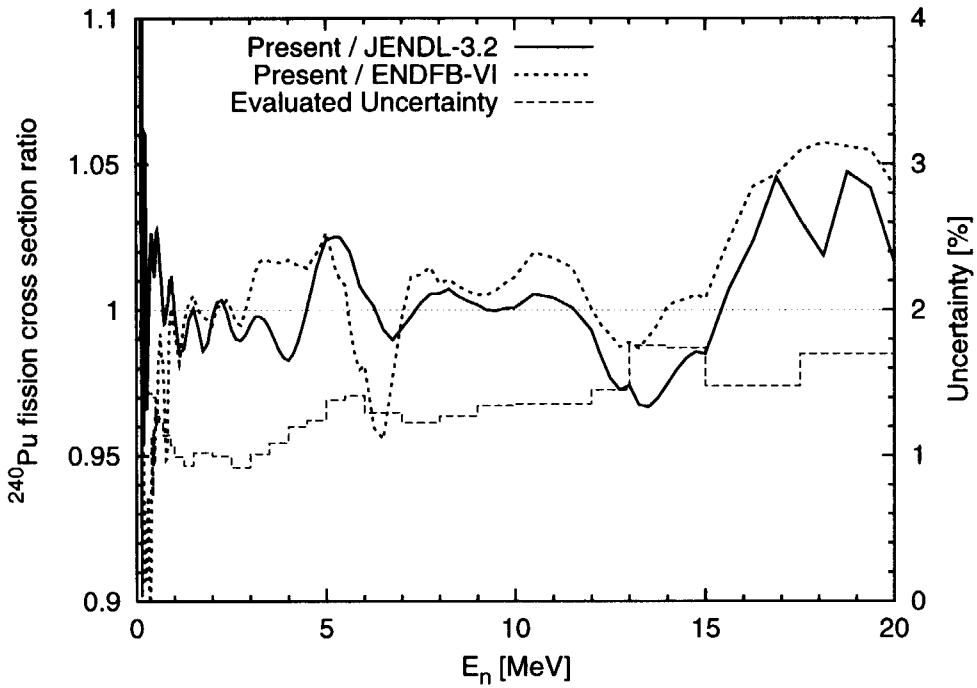


Fig. 18: Ratios of the evaluated  $^{240}\text{Pu}$  fission cross sections to those of JENDL-3.2 and ENDF/B-VI. The dashed line shows the uncertainties of the evaluated cross sections, which is on the right axis.

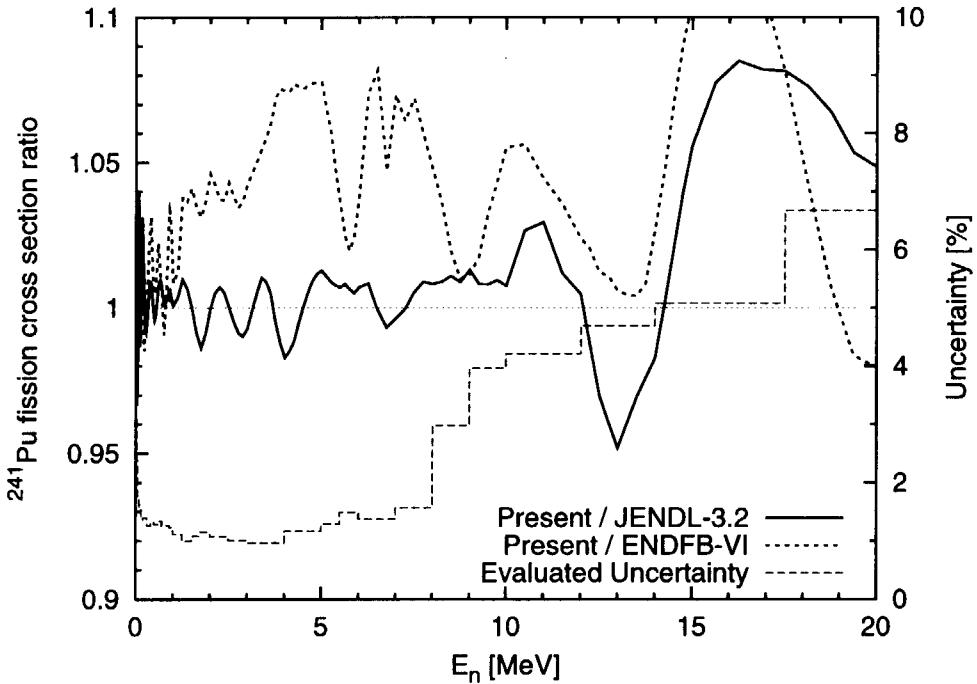


Fig. 19: Ratios of the evaluated  $^{241}\text{Pu}$  fission cross sections to those of JENDL-3.2 and ENDF/B-VI. The dashed line shows the uncertainties of the evaluated cross sections, which is on the right axis.

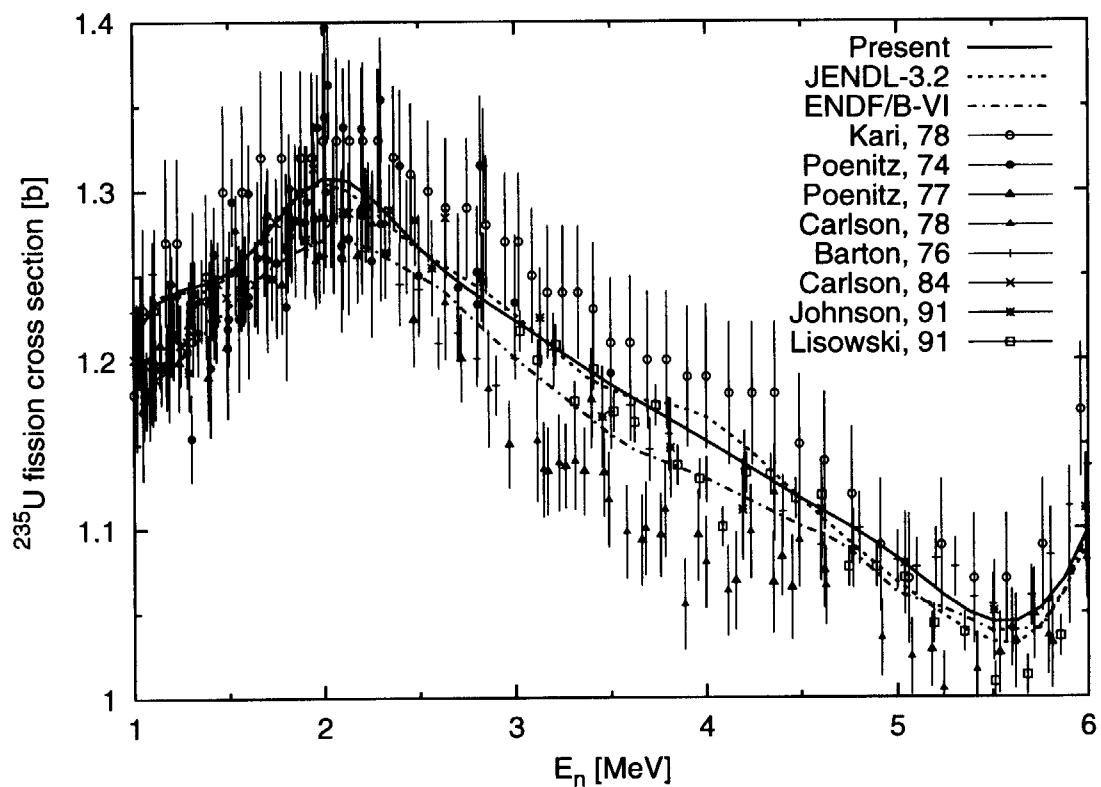


Fig. 20: Comparison of the fission cross sections of  $^{235}\text{U}$  with the experimental data and the evaluated cross sections of JENDL-3.2 and ENDF/B-VI.

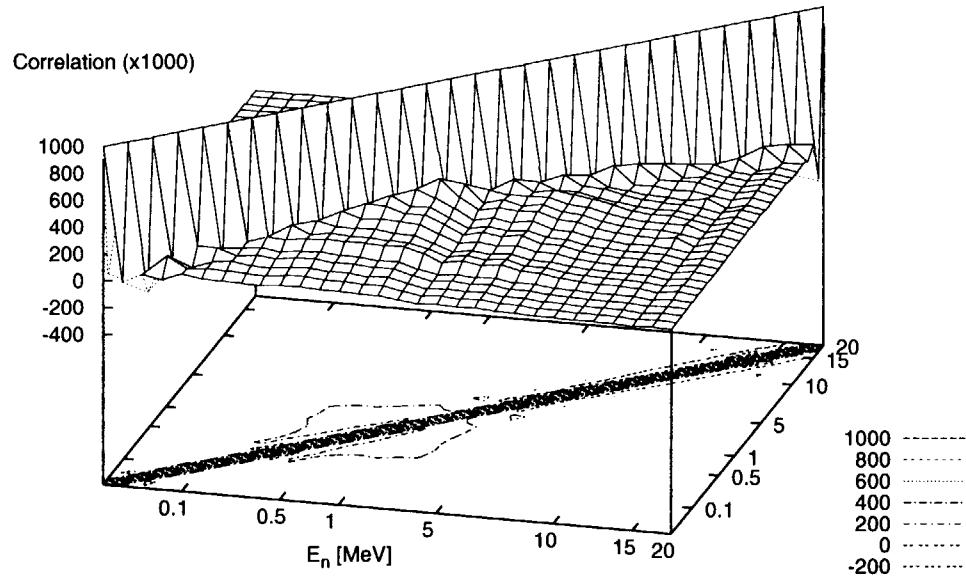


Fig. 21: 3-D plot of the correlation matrix of the evaluated  $^{233}\text{U}$  fission cross sections.

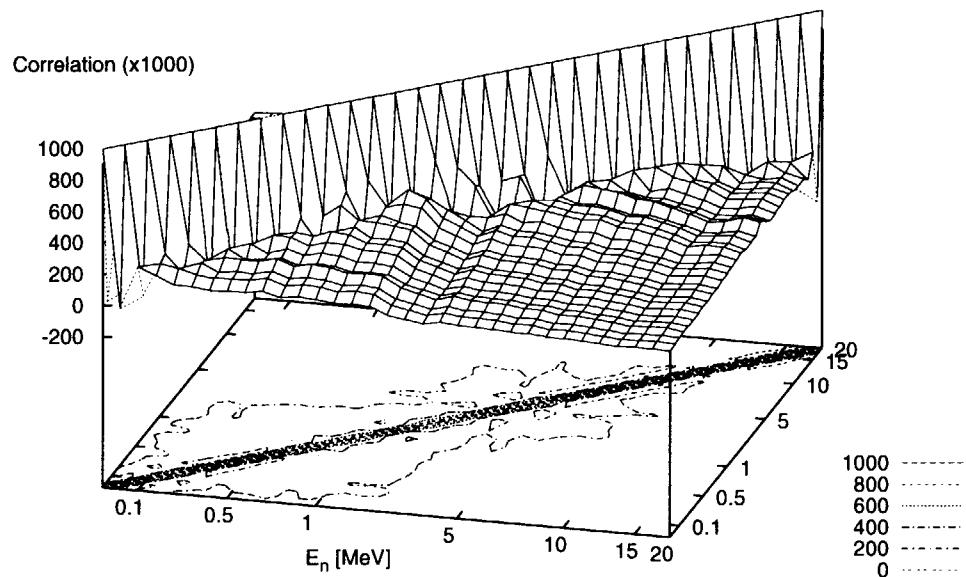


Fig. 22: 3-D plot of the correlation matrix of the evaluated  $^{235}\text{U}$  fission cross sections.

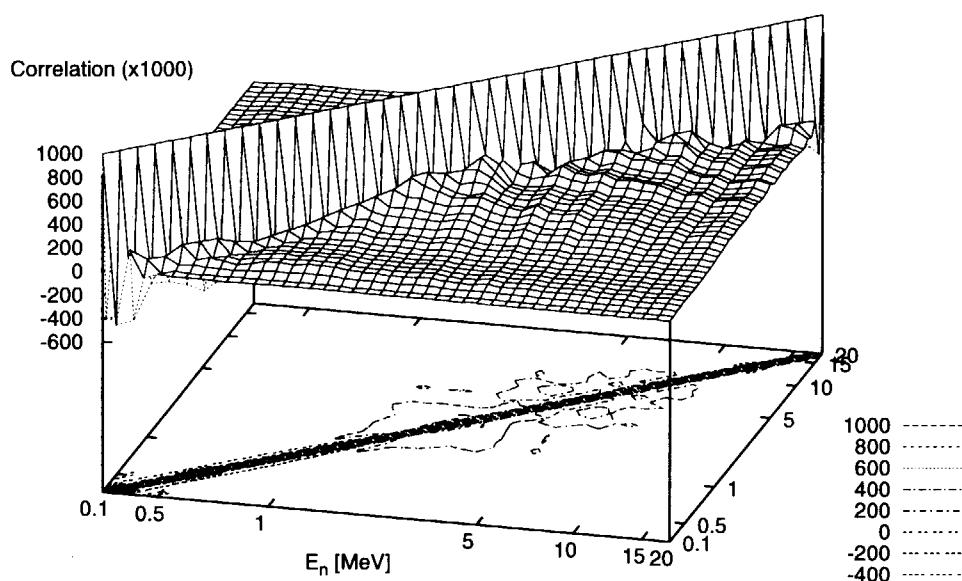


Fig. 23: 3-D plot of the correlation matrix of the evaluated  $^{238}\text{U}$  fission cross sections.

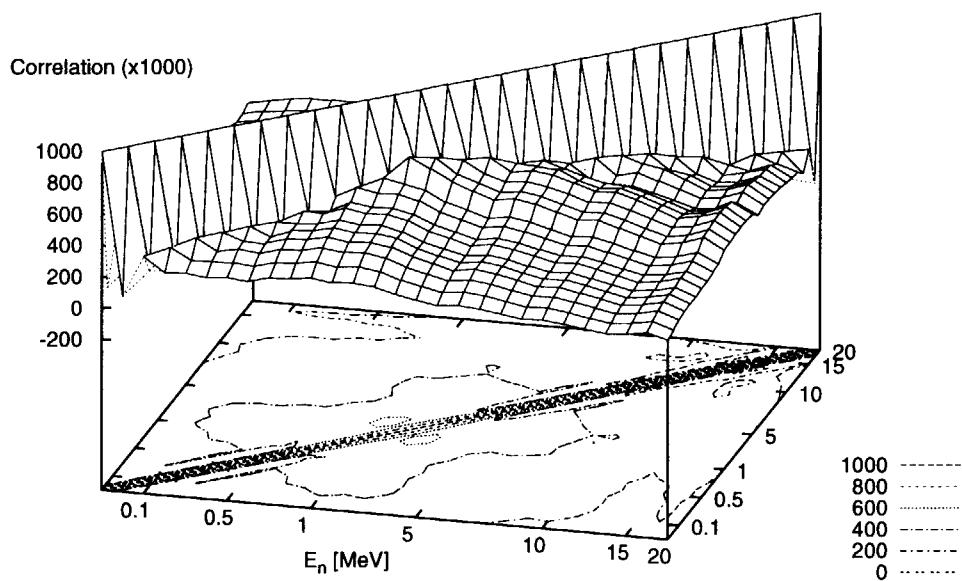


Fig. 24: 3-D plot of the correlation matrix of the evaluated  $^{239}\text{Pu}$  fission cross sections.

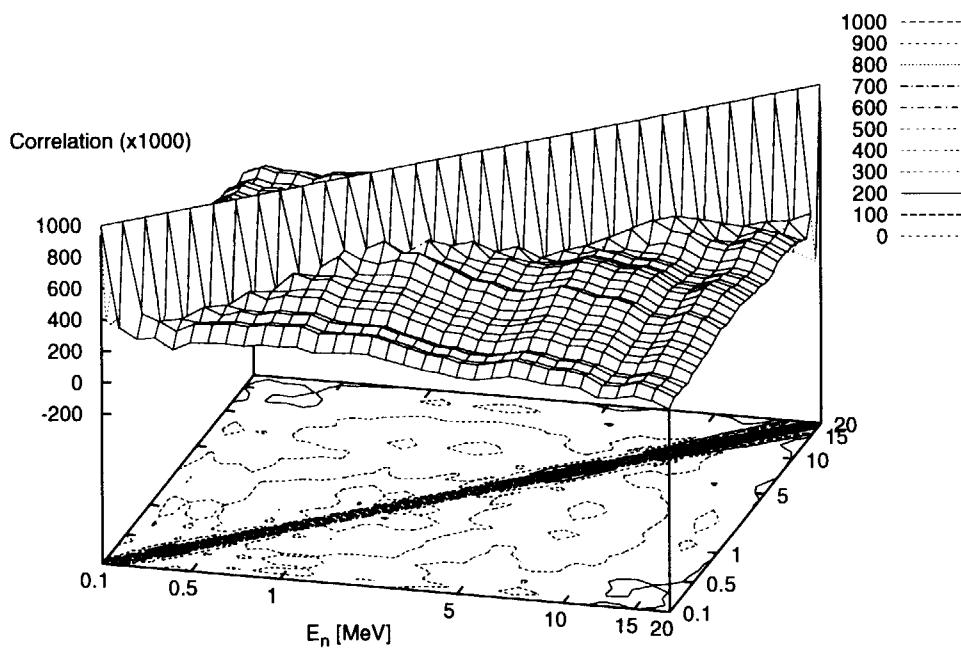


Fig. 25: 3-D plot of the correlation matrix of the evaluated  $^{240}\text{Pu}$  fission cross sections.

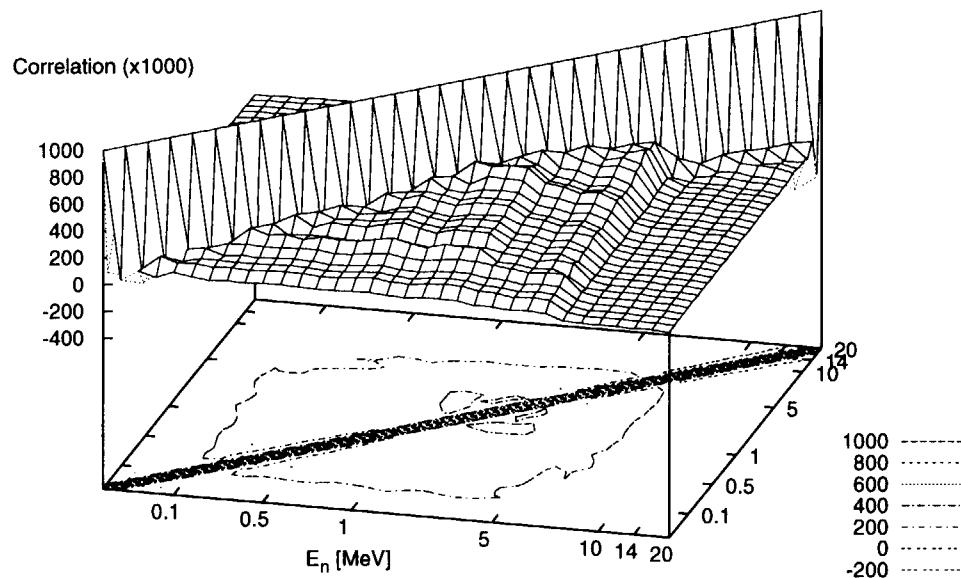


Fig. 26: 3-D plot of the correlation matrix of the evaluated  $^{241}\text{Pu}$  fission cross sections.

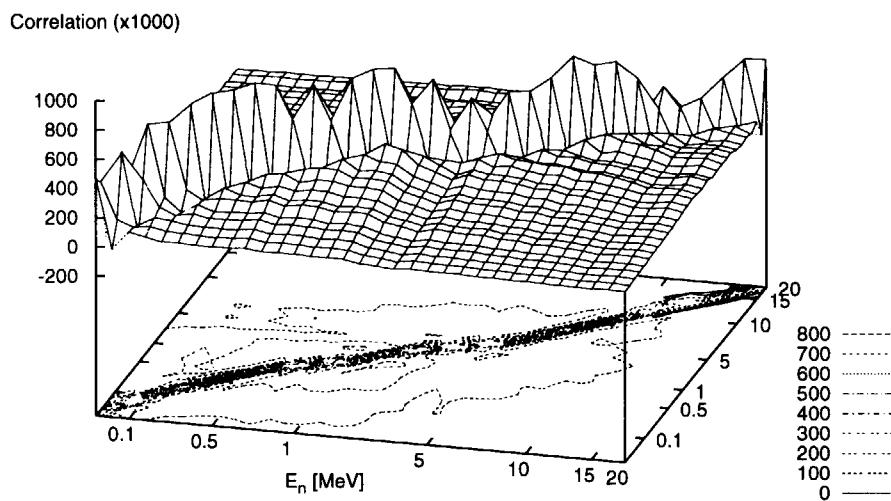


Fig. 27: 3-D plot of the correlation matrix between the evaluated  $^{233}\text{U}$  and  $^{235}\text{U}$  fission cross sections. The energy axis labelled " $E_n$ " is for  $^{235}\text{U}$ , and the other axis is for  $^{233}\text{U}$ .

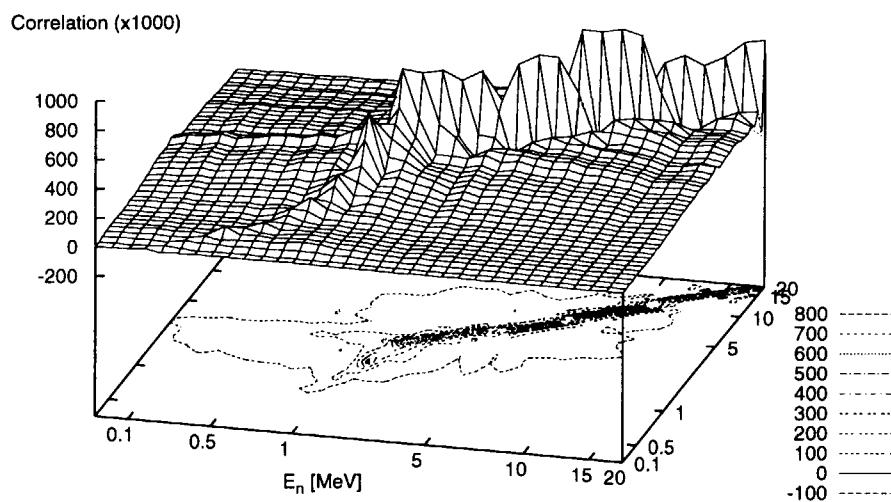


Fig. 28: 3-D plot of the correlation matrix between the evaluated  $^{238}\text{U}$  and  $^{235}\text{U}$  fission cross sections. The energy axis labelled " $E_n$ " is for  $^{235}\text{U}$ , and the other axis is for  $^{238}\text{U}$ .

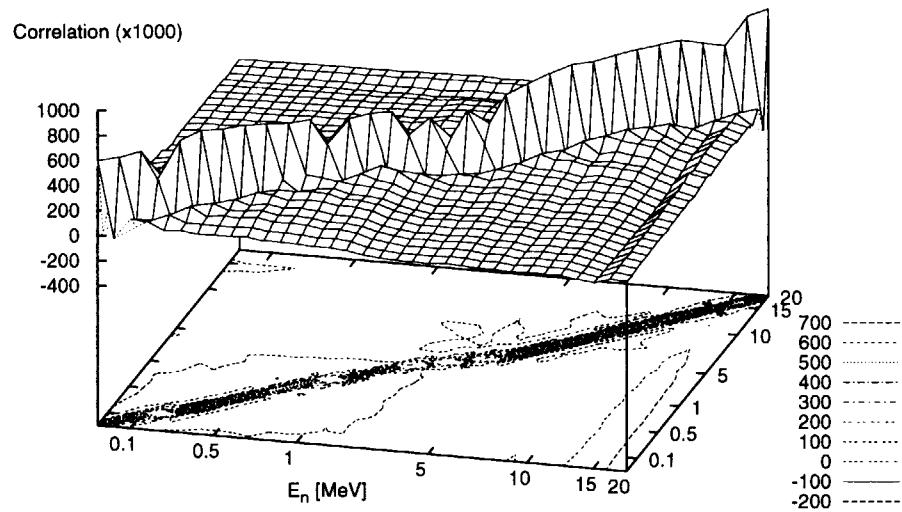


Fig. 29: 3-D plot of the correlation matrix between the evaluated  $^{239}\text{Pu}$  and  $^{235}\text{U}$  fission cross sections. The energy axis labelled " $E_n$ " is for  $^{235}\text{U}$ , and the other axis is for  $^{239}\text{Pu}$ .

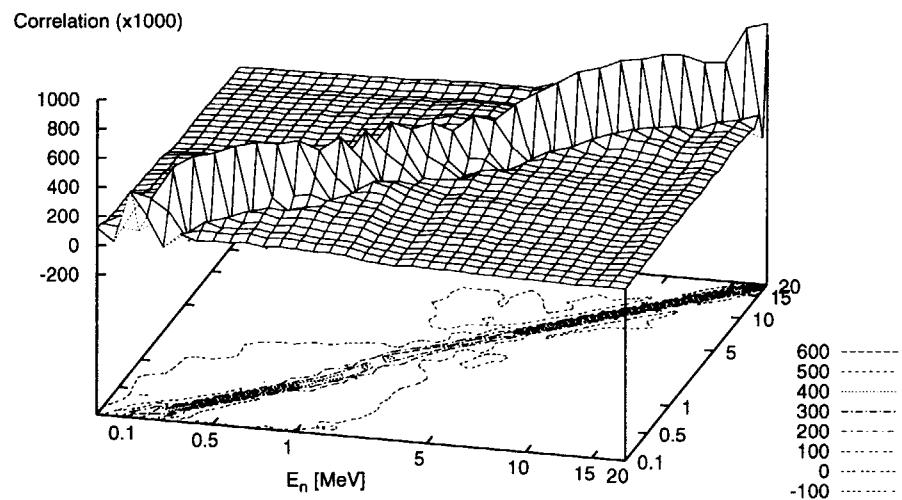


Fig. 30: 3-D plot of the correlation matrix between the evaluated  $^{240}\text{Pu}$  and  $^{235}\text{U}$  fission cross sections. The energy axis labelled " $E_n$ " is for  $^{235}\text{U}$ , and the other axis is for  $^{240}\text{Pu}$ .

Correlation (x1000)

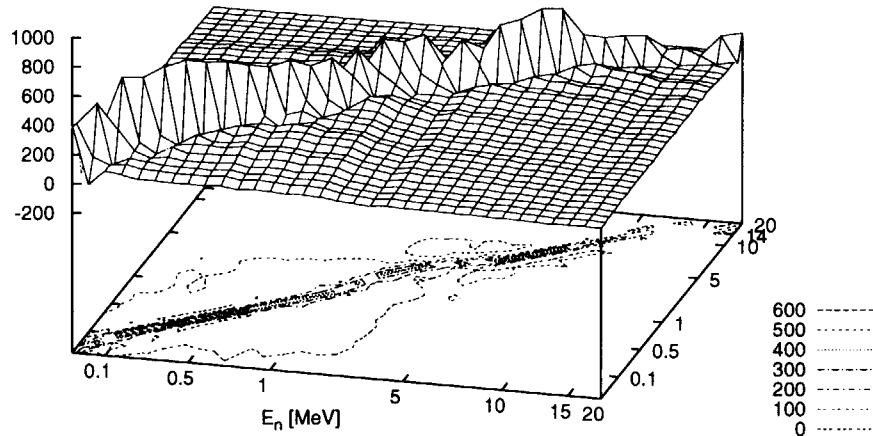


Fig. 31: 3-D plot of the correlation matrix between the evaluated  $^{241}\text{Pu}$  and  $^{235}\text{U}$  fission cross sections. The energy axis labelled “ $E_n$ ” is for  $^{235}\text{U}$ , and the other axis is for  $^{241}\text{Pu}$ .

Correlation (x1000)

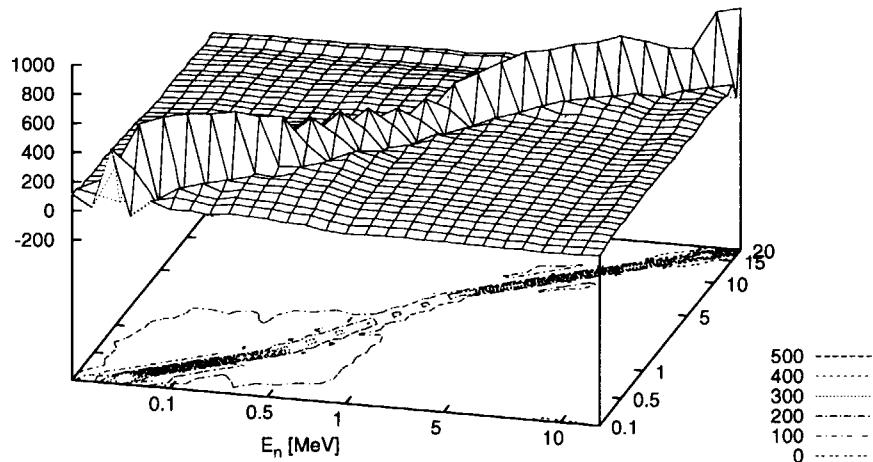


Fig. 32: 3-D plot of the correlation matrix between the evaluated  $^{240}\text{Pu}$  and  $^{239}\text{Pu}$  fission cross sections. The energy axis labelled “ $E_n$ ” is for  $^{239}\text{Pu}$ , and the other axis is for  $^{240}\text{Pu}$ .

## APPENDIX A : EXPERIMENTAL DATABASE

Table A1 :  $^{233}\text{U}$  Absolute cross section data

ENTRY No.	First Author	Institute*)	Year	Ref.
10267 041	R. Gwin	USAORL	1976	[20]
10756 002	W. P. Poenitz	USAANL	1978	[11]
12910 002	K. R. Zasadny	USAMHG	1984	[21]
21195 002	P. H. White	UK ALD	1967	[22]
30035 003	R. H. Iyer	INDTRM	1969	[23]
30475 007	R. Arlt	DDRTUD	1981	[24]
32625 002	Yan Wu-Guang	CPRAEP	1975	[25]
40476 005	K. D. Zhuravlev	CCPNIR	1977	[26]
40547 003	V. M. Adamov	CCPRI	1977	[27]
40587 002	A. V. Murzin	CCPIJI	1980	[28]
40601 005	A. A. Bergman	CCPJIA	1980	[29]
40610 002	E. A. Zhagrov	CCPRI	1980	[30]
40911 003	I. D. Alkhazov	CCPRI	1983	[31]
40927 002	V. I. Shpakov	CCPRI	1986	[32]

Table A2 :  $^{235}\text{U}$  Absolute cross section data

ENTRY No.	First Author	Institute	Year	Ref.
10267 030	R. Gwin	USAORL	1976	[20] a)
10302 002	R. B. Perez	USAORL	1974	[33] a)
10333 002	W. P. Poenitz	USAANL	1974	[12]
10333 003	W. P. Poenitz	USAANL	1974	[12]
10333 006	W. P. Poenitz	USAANL	1974	[12]
10333 007	W. P. Poenitz	USAANL	1974	[12]
10346 002	D. M. Barton	USALAS	1976	[13]
10428 002	J. B. Czirr	USALRL	1975	[34]
10547 002	J. B. Czirr	USALRL	1976	[35]
10558 002	J. B. Czirr	USALRL	1975	[36]
10595 002	O. A. Wasson	USANES	1982	[37]
10711 002	W. P. Poenitz	USAANL	1977	[14]
10950 002	O. A. Wasson	USANES	1982	[37]
10971 002	O. A. Wasson	USANBS	1982	[38]
10987 002	A. D. Carlson	USANBS	1984	[17]
12826 002	M. Mahdavi	USAMHG	1982	[39]
12848 002	A. D. Carlson	USANBS	1978	[16]
12848 003	A. D. Carlson	USANBS	1978	[16]
12877 002	L. W. Weston	USAORL	1984	[40] a)
12924 002	R. G. Johnson	USANIS	1991	[18]

a) Number of data points reduced

\*) Abbreviations of the institutes are the same as CINDA.

Table A2 :  $^{235}\text{U}$  Absolute cross section data (continued)

ENTRY No.	First Author	Institute	Year	Ref.
20567	002 I. Szabo	FR CAD	1976	[41]
20569	002 I. Szabo	FR CAD	1976	[41]
20570	002 I. Szabo	FR CAD	1976	[41]
20618	002 I. Szabo	FR CAD	1976	[41]
20779	002 M. Cancé	FR BRC	1978	[42]
20786	006 K. Kari	GERKFK	1978	[15]
21620	002 M. Cancé	FR BRC	1981	[43]
21777	002 F. Corvi	ZZZGEL	1982	[44]
22091	002 T. Iwasaki	JPNTOH	1988	[45]
22304	002 K. Merla	GERDRE	1991	[46]
22304	006 K. Merla	GERDRE	1991	[46]
30475	002 R. Arlt	DDRTUD	1981	[24]
30558	002 S. S. Kovalenk	DDRTUD	1985	[47]
30559	002 S. S. Kovalenk	DDRTUD	1985	[47]
30634	002 Li Jing-Wen	CPRAEP	1982	[48]
30706	002 S. S. Kovalenk	DDRTUD	1985	[47]
30706	003 S. S. Kovalenk	DDRTUD	1985	[47]
30721	002 Li Jingwen	CPRAEP	1986	[49]
40911	002 I. D. Alkhazov	CCPRI	1983	[31]
40927	003 V. I. Shpakov	CCPRI	1986	[32]
40963	002 V. A. Kalinin	CCPRI	1988	[50]
40969	011 N. N. Buleeva	CCPFEI	1988	[51]
41013	003 I. D. Alkhazov	CCPRI	1988	[52]
41112	002 V. A. Kalinin	CCPRI	1991	[53]
—	— M. Cancé	FR BRC	1983	[54] b)
—	— P. W. Lisowski	USANIS	1991	[10] c)

b) Not published.

c) Data private communication by Lisowski (1997).

Table A3 :  $^{238}\text{U}$  Absolute cross section data

ENTRY No.	First Author	Institute	Year	Ref.
13586	011 J. W. Meadows	USAANL	1996	[55]
20779	003 M. Cancé	FR BRC	1978	[42]
21209	002 B. Adams	UK ALD	1961	[56]
22304	003 K. Merla	GERDRE	1991	[46]
22304	007 K. Merla	GERDRE	1991	[46]
30475	003 R. Arlt	DDRTUD	1981	[24]
30669	002 Wu Jin-Xia	CPRAEP	1983	[57]
40081	002 I. M. Kuks	CCPRI	1991	[58]
40483	003 P.E.Vorotnikov	CCPKUR	1977	[59]
40547	007 V. M. Adamov	CCPRI	1977	[27]
—	— B. Leugers	GERKFK	1976	[60]
—	— G. Winkler	AU IRK	1991	[61]

Table A4 :  $^{239}\text{Pu}$  Absolute cross section data

ENTRY No.	First Author	Institute	Year	Ref.
10267 002	R. Gwin	USAORL	1976	[20]
12826 003	M. Mahdavi	USAMHG	1982	[39]
12877 005	L. W. Weston	USAORL	1984	[40]
20001 002	J. Blons	FR SAC	1973	[62]
20428 003	D. B. Gayther	CPRAEP	1975	[63]
20567 003	I. Szabo	FR CAD	1976	[41]
20569 003	I. Szabo	FR CAD	1976	[41]
20570 003	I. Szabo	FR CAD	1976	[41]
20618 003	I. Szabo	FR CAD	1976	[41]
20779 005	M. Cancé	FR BRC	1978	[42]
20786 004	K. Kari	GERKFK	1978	[15]
21704 003	W. Wagemans	BLGMOL	1980	[64]
22304 005	K. Merla	GERDRE	1991	[46]
22304 009	K. Merla	GERDRE	1991	[46]
30475 005	R. Arlt	DDRTUD	1981	[24]
30634 003	Li Jing-Wen	CPRAEP	1982	[48]
30647 007	I. Garlea	RUMPIT	1983	[65]
30670 002	Zhou Xian-Jian	CPRAEP	1982	[66]
40487 003	Ju. V. Rjabov	CCPJIA	1979	[67]
40547 009	V. M. Adamov	CCPRI	1977	[27]
40911 007	I. D. Alkhazov	CCPRI	1983	[31]
40927 005	V. I. Shpakov	CCPRI	1986	[32]

a) Number of data points reduced.

Table A5 :  $^{240}\text{Pu}$  Absolute cross section data

ENTRY No.	First Author	Institute	Year	Ref.
20786 002	K. Kari	GERKFK	1978	[15]
21821 002	M. Cancé	FR BRC	1982	[68]

Table A6 :  $^{241}\text{Pu}$  Absolute cross section data

ENTRY No.	First Author	Institute	Year	Ref.
10636 002	G. W. Carlson	USALRL	1977	[69]
10768 003	L. W. Weston	USAORL	1978	[70]
20484 002	J. Blons	FR SAC	1971	[62]
20567 004	I. Szabo	FR CAD	1976	[41]
20570 004	I. Szabo	FR CAD	1976	[41]

a) Number of data points reduced.

Table A7 :  $^{233}\text{U}/^{235}\text{U}$  Cross section ratio data

ENTRY No.	First Author	Institute	Year	Ref.
10236 002	J. W. Meadows	USAANL	1974	[71]
13134 004	J. W. Meadows	USAANL	1988	[72]
20363 002	E. Pfletschinger	GERKFK	1970	[73]
21963 003	K. Kanda	JPNTOH	1985	[74]
22014 003	K. Kanda	JONTOH	1986	[75]
40027 004	G. N. Smirenkin	CCPFEI	1967	[76]
40309 003	V. G. Nesterov	CCPFEI	1968	[77]
40361 003	D. L. Shpak	CCPFEI	1975	[78]
40474 002	B. I. Fursov	CCPFEI	1978	[79]
40607 002	D. L. Shpak	CCPFEI	1980	[80]
— —	O. A. Shcherbakov	RUSLIN	1998	[81] d)

d) Preliminary data. Private communication by Shcherbakov (1998).

Table A8 :  $^{238}\text{U}/^{233}\text{U}$  Cross section ratio data

ENTRY No.	First Author	Institute	Year	Ref.
10422 006	J. W. Behrens	USALRL	1976	[82]

Table A9 :  $^{238}\text{U}/^{235}\text{U}$  Cross section ratio data

ENTRY No.	First Author	Institute	Year	Ref.
10232 005	W. P. Poenitz	USAANL	1972	[83]
10232 006	W. P. Poenitz	USAANL	1972	[83]
10237 003	J. W. Meadows	USAANL	1972	[84]
10504 002	J. W. Meadows	USAANL	1975	[85] b)
10506 002	J. W. Meadows	USAANL	1975	[86]
10635 002	F. C. Difilippo	USAORL	1978	[87]
10653 004	J. W. Behrens	USALRL	1977	[88]
13134 007	J. W. Meadows	USAANL	1988	[72]
20409 002	S. Cierjacks	GERKFK	1976	[89]
20779 004	M. Cancé	FR BRC	1978	[42]
20869 002	C. Nordborg	SWDUPP	1976	[90]
20870 002	M. Cancé	FR BRC	1976	[91]
30588 002	M. Varnagy	HUNKOS	1982	[92]
30722 002	Li Jingwen	CPRAEP	1986	[93]
40506 002	B. I. Fursov	CCPFEI	1977	[94]
40831 002	A. A. Goverdovskij	CCPFEI	1983	[95]
40831 003	A. A. Goverdovskij	CCPFEI	1983	[95]
40831 004	A. A. Goverdovskij	CCPFEI	1983	[95]
— —	O. A. Shcherbakov	RUSLIN	1998	[81] d)

b) Not published.

d) Preliminary data. Private communication by Shcherbakov (1998).

Table A10 :  $^{239}\text{Pu}/^{235}\text{U}$  Cross section ratio data

ENTRY No.	First Author	Institute	Year	Ref.
10086 004	W. P. Poenitz	USAANL	1970	[96]
10253 002	W. P. Poenitz	USAANL	1972	[97]
10562 002	G. W. Carlson	USALRL	1978	[98]
13134 009	J. W. Meadows	USAANL	1988	[72]
20363 003	E. Pfletschinger	GERKFK	1970	[73]
20409 002	S. Cierjacks	GERKFK	1976	[89]
20428 004	D. B. Gayther	CPRAEP	1975	[63]
20569 004	I. Szabo	FR CAD	1976	[41]
20779 006	M. Cancé	FR BRC	1978	[42]
30588 005	M. Varnagy	HUNKOS	1982	[92]
40824 002	B. I. Fursov	CCPFEI	1977	[99]
40824 003	B. I. Fursov	CCPFEI	1977	[99]
— —	P. Staples	USALAS	1998	[100]

Table A11 :  $^{240}\text{Pu}/^{235}\text{U}$  Cross section ratio data

ENTRY No.	First Author	Institute	Year	Ref.
10597 004	J. W. Behrens	USALRL	1977	[101]
12714 002	J. W. Meadows	USAANL	1981	[102]
21764 004	C. Budtz-Jørgensen	ZZZGEL	1981	[103]
20766 002	K. Wissak	GERKFK	1979	[104]
20766 003	K. Wissak	GERKFK	1979	[104]
20766 004	K. Wissak	GERKFK	1979	[104]
20766 005	K. Wissak	GERKFK	1979	[104]
22211 002	T. Iwasaki	JPNTOH	1990	[105]
40509 002	V. M. Kuprijanov	CCPFEI	1979	[106]
— —	P. Staples	USALAS	1998	[100]

Table A12 :  $^{240}\text{Pu}/^{239}\text{Pu}$  Cross section ratio data

ENTRY No.	First Author	Institute	Year	Ref.
12766 003	L. W. Weston	USAORL	1983	[107]

Table A13 :  $^{241}\text{Pu}/^{235}\text{U}$  Cross section ratio data

ENTRY No.	First Author	Institute	Year	Ref.
10563 002	G. W. Carlson	USALRL	1978	[108]
20364 002	F. Käppeler	GERKFK	1973	[109]
40474 003	B. I. Fursov	CCPFEI	1978	[79]

## APPENDIX B : PROGRAM SOK INPUT/OUTPUT DESCRIPTION

A computer program SOK (Simultaneous Evaluation on KALMAN) is a modified version of the model parameter estimation code KALMAN[6]. Input data for SOK are similar to those of the KALMAN code. The SOK code requires :

- (1) experimental data (UNIT 10), data error (UNIT 11), and correlation matrices (UNIT 12)
- (2) prior parameters (UNIT 50) and their uncertainties (UNIT 51)
- (3) control data (UNIT 5)

where the UNIT  $N$  is the FORTRAN logical unit number for I/O. The correlation file (UNIT 12) is optional.

In this section, a data file allocated to UNIT  $N$  is called as "fort. $n$ ".

### B.1 Description of Experimental Data

An experimental database is separated into three files — cross section data ( $E_n, \sigma$ ), their uncertainties ( $E_n, \delta\sigma$ ), and their correlation matrix. These three files are allocated to the FORTRAN logical UNITS of 10, 11, and 12, respectively.

One measurement contains several data points. These cross section data and their errors are stored with the following formats:

Cross section Data File – fort.10

```
(A43,I5)  TITLE, ND
(6E11.4) (X(I),Y(I),I=1,ND)
```

Data Error File – fort.11

```
(43X,I5)  ND
(6E11.4) (DUMMY,Z(I),I=1,ND)
```

where TITLE is an arbitrary text, ND is the number of energy points, X, Y, and Z are the energy, cross section, and its uncertainty. The units of energies and cross sections are arbitrary, but the same units must be used for all experimental data. If Z is positive, the uncertainty Z is a relative error. If Z is negative, this value is interpreted as an absolute error. For example, 0.03 is 3%, and Z=-0.1 represents  $\pm 0.1$ .

A correlation matrix of the experimental data is read from UNIT 12.

Correlation File – fort.12

```
(43X,I5)  NC
          DO I=1,NC
(12F6.3)    (V(I*(I-1)/2+J),J=1,I)
```

where V is the correlation ( $-1 \leq V \leq 1$ ), and NC is the number of energy points. Usually NC must be the same as ND, but one can omit the correlation data by setting NC=0.

A set of data describes one measurement of a reaction type. When there are several measurements of various reaction types, those data are stored sequentially in fort.10, 11, and 12. The order of experimental data is arbitrary, but the same order should be used for the data, error, and correlation files. The order of experimental data is defined in the control data given in UNIT 5. When there are six experimental data sets (three measurements of reaction *A*, two of reaction *B*, and one of *C*), the structure of the experimental data files becomes as follows.

Data number 1 of Reaction <i>A</i>
Data number 2 of Reaction <i>A</i>
Data number 3 of Reaction <i>A</i>
Data number 1 of Reaction <i>B</i>
Data number 2 of Reaction <i>B</i>
Data number 1 of Reaction <i>C</i>

The followings are examples of the data files which contain three measurements.

```
-----*----1----*----2----*----3----*----4----*----5----*----6----*----7
1: Data 1
2: 1.4700E+01 6.7300E-01 1.6000E+01 4.5100E-01 1.7000E+01 3.6600E-01
3: 1.8000E+01 2.3400E-01 1.9000E+01 2.7300E-01
4: Data 2
5: 6.4200E+00 6.0000E-02 6.8000E+00 2.7000E-01 6.9600E+00 5.4000E-01
6: 7.0000E+00 4.7000E-01 7.2000E+00 5.1000E-01 7.2500E+00 7.9000E-01
7: 7.4500E+00 8.9000E-01 7.5800E+00 9.8000E-01 7.8200E+00 1.1100E+00
8: 7.8800E+00 1.0700E+00 8.4900E+00 1.2100E+00 8.9600E+00 1.3900E+00
9: 9.4800E+00 1.4600E+00 9.9700E+00 1.4900E+00
10: Data 3
11: 6.8900E+00 2.3300E-01 7.4100E+00 6.0400E-01 7.6700E+00 8.1100E-01
12: 7.9300E+00 8.7900E-01 8.1800E+00 9.9900E-01 8.4400E+00 1.0720E+00
13: 8.6900E+00 1.0290E+00 8.9400E+00 1.1560E+00 9.4400E+00 1.1710E+00
14: 9.9300E+00 1.2320E+00
-----*----1----*----2----*----3----*----4----*----5----*----6----*----7
1: Error 1
2: 1.4700E+01 6.1000E-02 1.6000E+01 1.8000E-01 1.7000E+01 2.0000E-01
3: 1.8000E+01 3.6000E-01 1.9000E+01 3.2000E-01
4: Error 2
5: 6.4200E+00 3.0000E-02 6.8000E+00 2.0000E-02 6.9600E+00 4.0000E-02
6: 7.0000E+00 3.0000E-02 7.2000E+00 4.0000E-02 7.2500E+00 5.0000E-02
7: 7.4500E+00 5.0000E-02 7.5800E+00 5.0000E-02 7.8200E+00 5.0000E-02
8: 7.8800E+00 5.0000E-02 8.4900E+00 5.0000E-02 8.9600E+00 5.0000E-02
9: 9.4800E+00 5.0000E-02 9.9700E+00 5.0000E-02
10: Error 3
11: 6.8900E+00-3.9000E-02 7.4100E+00-5.4000E-02 7.6700E+00-6.2000E-02
12: 7.9300E+00-4.8000E-02 8.1800E+00-4.1000E-02 8.4400E+00-5.2000E-02
13: 8.6900E+00-6.0000E-02 8.9400E+00-4.2000E-02 9.4400E+00-4.6000E-02
14: 9.9300E+00-4.4000E-02
```

```
-----1-----2-----3-----4-----5-----6-----7
1: Correlation 1
2: 1.000
3: 0.111 1.000
4: 0.098 0.033 1.000
5: 0.055 0.019 0.016 1.000
6: 0.062 0.022 0.019 0.010 1.000
7: Correlation 2
8: Correlation 3
9: 1.000
10: 0.060 1.000
11: 0.070 0.132 1.000
12: 0.098 0.184 0.216 1.000
13: 0.131 0.245 0.287 0.402 1.000
14: 0.111 0.208 0.243 0.340 0.452 1.000
15: 0.092 0.173 0.202 0.283 0.376 0.318 1.000
16: 0.148 0.277 0.324 0.454 0.604 0.511 0.425 1.000
17: 0.137 0.256 0.300 0.420 0.558 0.472 0.393 0.631 1.000
18: 0.151 0.282 0.330 0.461 0.614 0.520 0.432 0.694 0.642 1.000
```

## B.2 Description of Prior Parameters

The SOK code reads prior cross sections and their uncertainties from UNIT 50 and 51.

Prior Cross Section File – fort.50

```
(A43,I5)  TITLE, NE
(6E11.4) (E0(I),P0(I),I=1,NE)
```

Prior Cross Section Error File – fort.51

```
(A43,I5)  TITLE, NE
(6E11.4) (DUMMY,PE(I),I=1,NE)
```

where TITLE is an arbitrary text, NE is the number of energy points, E0 and P0 are an energy and a cross section, and PE is a prior uncertainty. The uncertainties are relative errors. The units of energies and cross sections must be the same as those of the experimental data read from UNITs 10 and 11.

Currently there is no way to give a prior covariance of the cross section. The uncertainties of the prior cross sections are regarded as uncorrelated.

The above data describe one type of cross sections. When several cross sections are evaluated simultaneously, these data are concatenated and stored in fort.50 and 51. One can use different energy points for each cross section type. The number of cross sections is calculated automatically, and it is referred to as NKIND in the code. The order of the cross sections in these files is used to specify the reaction type. These numbers (from 1 to NKIND) are an index of each reaction. The maximal number of NKIND is 99.

The following examples present the data files which contain two cross section types (NKIND=2). The prior uncertainties assumed are 50% for all.

```

-----*---1----*---2----*---3----*---4----*---5----*---6----*---7
1: Inelastic 1st level                               24
2: 1.0000E-02 6.5979E+00 1.0000E-01 2.7476E+00 5.0000E-01 1.9889E+00
3: 7.5000E-01 1.6267E+00 1.0000E+00 1.4527E+00 1.2500E+00 1.3435E+00
4: 1.5000E+00 1.2662E+00 1.7500E+00 1.2078E+00 2.0000E+00 1.1615E+00
5: 2.2500E+00 1.0919E+00 2.5000E+00 1.0162E+00 3.0000E+00 8.3853E-01
6: 4.0000E+00 5.9353E-01 5.0000E+00 4.1736E-01 6.0000E+00 3.2365E-01
7: 8.0000E+00 1.7176E-01 1.0000E+01 1.0063E-01 1.2000E+01 3.4596E-02
8: 1.3000E+01 2.4942E-02 1.4000E+01 1.7562E-02 1.5000E+01 1.2131E-02
9: 1.6000E+01 8.2704E-03 1.8000E+01 3.7694E-03 2.0000E+01 1.7137E-03
10: Inelastic 2nd level                             24
11: 1.0000E-02 0.0000E+00 1.0000E-01 0.0000E+00 5.0000E-01 1.3546E-01
12: 7.5000E-01 3.6810E-01 1.0000E+00 4.4806E-01 1.2500E+00 4.8766E-01
13: 1.5000E+00 5.1221E-01 1.7500E+00 5.2979E-01 2.0000E+00 5.4338E-01
14: 2.2500E+00 5.3302E-01 2.5000E+00 5.1264E-01 3.0000E+00 4.5885E-01
15: 4.0000E+00 3.5950E-01 5.0000E+00 2.7149E-01 6.0000E+00 2.2053E-01
16: 8.0000E+00 1.2464E-01 1.0000E+01 7.5152E-02 1.2000E+01 4.3703E-02
17: 1.3000E+01 3.1578E-02 1.4000E+01 2.2305E-02 1.5000E+01 1.5467E-02
18: 1.6000E+01 1.0586E-02 1.8000E+01 4.8735E-03 2.0000E+01 2.2361E-03

-----*---1----*---2----*---3----*---4----*---5----*---6----*---7
1: Inelastic 1st level                               24
2: 1.0000E-02 5.0000E-01 1.0000E-01 5.0000E-01 5.0000E-01 5.0000E-01
3: 7.5000E-01 5.0000E-01 1.0000E+00 5.0000E-01 1.2500E+00 5.0000E-01
4: 1.5000E+00 5.0000E-01 1.7500E+00 5.0000E-01 2.0000E+00 5.0000E-01
5: 2.2500E+00 5.0000E-01 2.5000E+00 5.0000E-01 3.0000E+00 5.0000E-01
6: 4.0000E+00 5.0000E-01 5.0000E+00 5.0000E-01 6.0000E+00 5.0000E-01
7: 8.0000E+00 5.0000E-01 1.0000E+01 5.0000E-01 1.2000E+01 5.0000E-01
8: 1.3000E+01 5.0000E-01 1.4000E+01 5.0000E-01 1.5000E+01 5.0000E-01
9: 1.6000E+01 5.0000E-01 1.8000E+01 5.0000E-01 2.0000E+01 5.0000E-01
10: Inelastic 2nd level                             24
11: 1.0000E-02 5.0000E-01 1.0000E-01 5.0000E-01 5.0000E-01 5.0000E-01
12: 7.5000E-01 5.0000E-01 1.0000E+00 5.0000E-01 1.2500E+00 5.0000E-01
13: 1.5000E+00 5.0000E-01 1.7500E+00 5.0000E-01 2.0000E+00 5.0000E-01
14: 2.2500E+00 5.0000E-01 2.5000E+00 5.0000E-01 3.0000E+00 5.0000E-01
15: 4.0000E+00 5.0000E-01 5.0000E+00 5.0000E-01 6.0000E+00 5.0000E-01
16: 8.0000E+00 5.0000E-01 1.0000E+01 5.0000E-01 1.2000E+01 5.0000E-01
17: 1.3000E+01 5.0000E-01 1.4000E+01 5.0000E-01 1.5000E+01 5.0000E-01
18: 1.6000E+01 5.0000E-01 1.8000E+01 5.0000E-01 2.0000E+01 5.0000E-01

```

### B.3 Description of Input Data

The input data controls the calculational flow and the sequence of the experimental data in fort.10, 11, and 12. Since the experimental database contains several measurements with the different reaction types, the database is divided into several blocks with the same reaction. The sequence of the blocks and the order of the measurements within the block are defined in this input file.

```

(A80)      TITLE
(4I5)      NREAC,KCOVEX,KCTL1,KCTL2
            DO I=1,NREAC
(14I5)      IEXP(I),NMSUR
(7E10.3)    (EW(J),J=1,NMSUR)

```

where **TITLE** is the title of the calculation, **NREAC** is the number of blocks in the experimental database. The index **IEXP** tells a type of reaction and **NMSUR** is the number of measurements in the block.

When the experimental database has the following structure, this database is divided into three blocks — reaction types *A*, *B*, and *C* — then **NREAC**=3. Each block contains four, three, and two measurements, then **NMSUR**=4 for the reaction type *A*, **NMSUR**=3 for *B*, and **NMSUR**=2 for *C*.

Data number 1 of Reaction <i>A</i>
Data number 2 of Reaction <i>A</i>
Data number 3 of Reaction <i>A</i>
Data number 4 of Reaction <i>A</i>
Data number 1 of Reaction <i>B</i>
Data number 2 of Reaction <i>B</i>
Data number 3 of Reaction <i>B</i>
Data number 1 of Reaction <i>C</i>
Data number 2 of Reaction <i>C</i>

An integer number called an index is used to identify the reaction type. The index is the order of the cross sections in fort.50 and 51. The first cross section in those files has the index of “1”, and the second one is “2”, and so on. If the experimental data is a ratio measurement which corresponds to a ratio of the index *a* to *b*, this index is given as  $100 \times a + b$ .

Let us consider an example. In the case of evaluation of  $^{235}\text{U}$  and  $^{238}\text{U}$  fission cross sections, fort.50 and 51 contain their prior values in this order. The index for  $^{235}\text{U}$  is 1, while  $^{238}\text{U}$  is 2, then **NKIND** becomes 2. If the experimental database (fort.10, 11, and 12) contains one measurement which is a fission cross section ratio of  $^{238}\text{U}$  to  $^{235}\text{U}$ , the index of the measurement **IEXP** becomes 201, and the number of reaction block becomes **NREAC**=1.

One can manipulate a weight of each measurement by **EW**. The uncertainties of the corresponding experimental data are multiplied by the value of **EW**. If **EW**=0, the measurement is ignored. Usually **EW** is unity.

**KCOVEX**, **KCTL1**, and **KCTL2** are the flags. If **KCOVEX**=0, the SOK code does not read correlation data, otherwise it reads correlation data from UNIT 12. A  $\chi^2$  test can be done with the flag **KCTL1**. The SOK code calculates the  $\chi^2$  value when **KCTL1**=*N*. The cross sections and their uncertainties are read from UNIT *N* and *N*+1 with the same format as the data in fort.50 and 51. Therefore, if **KCTL1**=50, it gives the  $\chi^2$  value for the prior cross sections. If **KCTL2**=1, smoothly interpolated posterior cross sections are generated by means of the cubic-spline interpolation.

An example of the input data is as follows:

```
-----1-----2-----3-----4-----5-----6-----7
1: SOK INPUT DATA
2:   3   1   0   1
3:   1   4
4: 1.000E+00 1.000E+00 1.000E+00 1.000E+00
5:   2   3
6: 1.000E+00 0.0      1.000E+00
7: 102   2
8: 1.000E+00 1.000E+00
```

The number of measurements is 9 (= 4 + 3 + 2), and there are three blocks (**NREAC**=3). The first block is a type “1”, and there are four measurements. The next block is a type “2”. Three measurements are stored in the file, but the second measurement is ignored. The last block contains two measurements, those are the ratios of the cross sections “1” to “2”.

## B.4 Output

The SOK code prints  $\chi^2$  values and the number of data points for each measurement during execution, and finally it prints the posterior cross sections and their uncertainties. The following is an example of the output.

```
-----1-----2-----3-----4-----5-----6-----7
1: Simultaneous Evaluation for JENDL-3.3
2: NUMBER OF DATA BLOCKS      6
3: NUMBER OF SPLINE KNOTS    211
4:
5: # 21463002 P.H.White          1965   6
6: *** EXP. DATA IGNORED ****
7: CROSS SECTION :U233FIS
8: SQ.NO.:    1  REACT.:    1  POINTS:    0  SUM UP:    0
9: PARTIAL CHI SQ: 0.00000E+00  CUMULATIVE : 0.00000E+00
10:
11: # 21195002 P.H.White         1967   4
12: CROSS SECTION :U233FIS
13: SQ.NO.:    2  REACT.:    2  POINTS:    4  SUM UP:    4
14: PARTIAL CHI SQ: 9.14181E-06  CUMULATIVE : 9.14181E-06
...
812: i0563002      Behrens          107
813: CROSS SECTION :PU241FIS     U235FIS
814: SQ.NO.: 162  REACT.:    3  POINTS:  92  SUM UP: 4661
815: PARTIAL CHI SQ: 1.06892E+02  CUMULATIVE : 1.56656E+04
816:
816: CHI-SQUARE TEST !           CHI - S = 1.56656E+04
817: DEGREE OF FREEDOM = 4450    RATIO   = 3.52035E+00
818:
819:      PARAMETER      INITIAL      FINAL      ERROR
820:
821:      1  2.0000E-02 2.0520E+00 2.2717E+00 1.2846E+00 ( % )
822:      2  3.0000E-02 2.0520E+00 2.0075E+00 8.5634E-01 ( % )
823:      3  6.0000E-02 1.8110E+00 1.7804E+00 7.4145E-01 ( % )
...
1030: 209  1.7500E+01 2.3819E+00 2.3451E+00 2.1581E+00 ( % )
1031: 210  2.0000E+01 2.3000E+00 2.1893E+00 2.7890E+00 ( % )
1032: 211  2.2000E+01 2.3000E+00 2.3086E+00 5.8164E+00 ( % )
```

The printed errors of the parameters are multiplied by the factor  $\sqrt{\chi^2/(n-m)}$ , but this  $\chi^2$  value is approximate. To calculate the exact  $\chi^2$  value, repeat the same calculation but KCTL1=20.

The other information is written on files.

UNIT	contents
14	covariance matrices of the evaluated cross sections
15	evaluated cross sections and their errors
17	cubic-spline interpolated cross sections (if KCTL2=1)
20	evaluated cross sections (the same format as fort.50)
21	evaluated cross section errors (the same format as fort.51)
60+I	experimental data of reaction block "I" (I=1,NREAC)

Note that output data in fort.15, fort.17, fort.60+I can be plotted with GNUPLOT.

# 国際単位系(SI)と換算表

表1 SI基本単位および補助単位

量	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光强度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表3 固有の名称をもつSI組立単位

量	名称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s <sup>-1</sup>
力	ニュートン	N	m·kg/s <sup>2</sup>
圧力、応力	パスカル	Pa	N/m <sup>2</sup>
エネルギー、仕事、熱量	ジュール	J	N·m
功率、放射束	ワット	W	J/s
電気量、電荷	クーロン	C	A·s
電位、電圧、起電力	ボルト	V	W/A
静電容量	ファラード	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V·s
磁束密度	テスラ	T	Wb/m <sup>2</sup>
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	°C	
光束度	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m <sup>2</sup>
放射能	ベクレル	Bq	s <sup>-1</sup>
吸収線量	グレイ	Gy	J/kg
線量等量	シーベルト	Sv	J/kg

表2 SIと併用される単位

名称	記号
分、時、日	min, h, d
度、分、秒	°, ', "
リットル	L, l
トン	t
電子ボルト	eV
原子質量単位	u

1 eV=1.60218×10<sup>-19</sup>J

1 u=1.66054×10<sup>-27</sup>kg

表5 SI接頭語

倍数	接頭語	記号
10 <sup>18</sup>	エクサ	E
10 <sup>15</sup>	ペタ	P
10 <sup>12</sup>	テラ	T
10 <sup>9</sup>	ギガ	G
10 <sup>6</sup>	メガ	M
10 <sup>3</sup>	キロ	k
10 <sup>2</sup>	ヘクト	h
10 <sup>1</sup>	デカ	da
10 <sup>-1</sup>	デシ	d
10 <sup>-2</sup>	センチ	c
10 <sup>-3</sup>	ミリ	m
10 <sup>-6</sup>	マイクロ	μ
10 <sup>-9</sup>	ナノ	n
10 <sup>-12</sup>	ピコ	p
10 <sup>-15</sup>	フェムト	f
10 <sup>-18</sup>	アト	a

(注)

1. 表1~5は「国際単位系」第5版、国際度量衡局1985年刊行による。ただし、1eVおよび1uの値はCODATAの1986年推奨値によった。

2. 表4には海里、ノット、アール、ヘクタールも含まれているが日常の単位なのでここでは省略した。

3. barは、JISでは液体の圧力を表わす場合に限り表2のカテゴリーに分類されている。

4. EC開催理事会指令ではbar、barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

## 換算表

力	N(=10 <sup>3</sup> dyn)	kgf	lbf
1	0.101972	0.224809	
9.80665	1	2.20462	
4.44822	0.453592	1	

粘度 1Pa·s(N·s/m<sup>2</sup>)=10 P(ボアズ)(g/(cm·s))

動粘度 1m<sup>2</sup>/s=10<sup>3</sup>St(ストークス)(cm<sup>2</sup>/s)

力	MPa(=10bar)	kgf/cm <sup>2</sup>	atm	mmHg(Torr)	lbf/in <sup>2</sup> (psi)
	1	10.1972	9.86923	7.50062×10 <sup>3</sup>	145.038
力	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10 <sup>-3</sup>	1.35951×10 <sup>-3</sup>	1.31579×10 <sup>-3</sup>	1	1.93368×10 <sup>-2</sup>
	6.89476×10 <sup>-3</sup>	7.03070×10 <sup>-2</sup>	6.80460×10 <sup>-2</sup>	51.7149	1

エネルギー・仕事・熱量	J(=10 <sup>7</sup> erg)	kgf·m	kW·h	cal(計量法)	Btu	ft·lbf	eV
	1	0.101972	2.77778×10 <sup>-7</sup>	0.238889	9.47813×10 <sup>-4</sup>	0.737562	6.24150×10 <sup>18</sup>
	9.80665	1	2.72407×10 <sup>-6</sup>	2.34270	9.29487×10 <sup>-3</sup>	7.23301	6.12082×10 <sup>18</sup>
	3.6×10 <sup>6</sup>	3.67098×10 <sup>5</sup>	1	8.59999×10 <sup>5</sup>	3412.13	2.65522×10 <sup>6</sup>	2.24694×10 <sup>25</sup>
	4.18605	0.426858	1.16279×10 <sup>-6</sup>	1	3.96759×10 <sup>-3</sup>	3.08747	2.61272×10 <sup>18</sup>
	1055.06	107.586	2.93072×10 <sup>-4</sup>	252.042	1	778.172	6.58515×10 <sup>21</sup>
	1.35582	0.138255	3.76616×10 <sup>-7</sup>	0.323890	1.28506×10 <sup>-3</sup>	1	8.46233×10 <sup>18</sup>
	1.60218×10 <sup>19</sup>	1.63377×10 <sup>20</sup>	4.45050×10 <sup>-26</sup>	3.82743×10 <sup>-30</sup>	1.51857×10 <sup>-22</sup>	1.18171×10 <sup>-19</sup>	1

1 cal= 4.18605J (計量法)  
= 4.184J (熱化学)  
= 4.1855J (15°C)  
= 4.1868J (国際蒸気表)  
仕事率 1 PS(仮馬力)  
= 75 kgf·m/s  
= 735.499W

放射能	Bq	Ci
	1	2.70270×10 <sup>-10</sup>
	3.7×10 <sup>10</sup>	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10 <sup>-1</sup>	1

線量率	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

EVALUATION OF FISSION CROSS SECTIONS AND COVARIANCES FOR  $^{233}\text{U}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{240}\text{Pu}$ , AND  $^{241}\text{Pu}$