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EVALUATION OF COVARIANCES FOR RESOLVED RESONANCE PARAMETERS OF ^{235}U, ^{238}U, AND ^{239}Pu IN JENDL-3.2

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Evaluation of Covariances for Resolved Resonance Parameters of ^{235}U, ^{238}U, and ^{239}Pu in JENDL-3.2

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Evaluation of covariances for resolved resonance parameters of ^{235}U, ^{238}U, and ^{239}Pu was carried out. Although a large number of resolved resonances are observed for major actinides, uncertainties in averaged cross sections are more important than those in resonance parameters in reactor calculations. We developed a simple method which derives a covariance matrix for the resolved resonance parameters from uncertainties in the averaged cross sections. The method was adopted to evaluate the covariance data for some important actinides, and the results were compiled in the JENDL-3.2 covariance file.

Keywords: Covariance, Uncertainty, Resonance Parameter, Reich-Moore R-matrix Theory, JENDL-3.2, ^{235}U, ^{238}U, ^{239}Pu

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JENDL-3.2 に収納されている ^{235}U, ^{238}U, ^{239}Pu の分離共鳴パラメータ共分散の評価

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^{235}U、^{238}U、^{239}Puの分離共鳴パラメータの共分散を評価した。主要アクチニド核種では非常に多くの分離共鳴が観測されているが、原子炉計算では、分離共鳴そのものの誤差よりも、平均断面積の誤差の方が重要である。分離共鳴パラメータの共分散を推定する簡便な手法を開発した。本手法は、平均断面積の誤差に基づいて分離共鳴パラメータの共分散行列を求めるものである。この方法を用いて、JENDL-3.2に格納されている重要なアクチニド核種の分離共鳴パラメータの共分散を求め、その結果をJENDL-3.2共分散ファイルに収納した。

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1 INTRODUCTION

Evaluation of covariances for resonance parameters is required in order to provide complete sets of covariance data for existent evaluated nuclear data libraries. Although covariance data for resonance parameters of heavy nuclei are important for reactor calculations, a reasonable way to evaluate them is still under discussion. Estimation of uncertainties in the resolved resonance parameters is based on a resonance analysis, and there are several nuclei for which the uncertainty information is accessible. For example, Mughabghab *et al.*[1, 2] compiled the resonance parameters with those uncertainties. Nakagawa and Shibata[3] evaluated the uncertainties in ^{239}Pu, ^{240}Pu and ^{238}U resonance parameters, though no correlations among them were given. After that Shibata *et al.*[4] modified the uncertainties in the 1.057 eV resonance for ^{240}Pu and gave a correlation between the neutron and capture widths. The covariances of the ^{241}Pu resonance parameters at −0.1225 and 0.2647 eV were obtained by Derrien[5] with the R-matrix analysis. These covariance evaluations were concentrated mainly on the variances, and the correlations were given for only a few resonances.

On the other hand, the resonance analysis with the SAMMY code[6] provides the complete information on the covariance for resonance parameters. So these data can be adopted for the covariance data files. One difficult point to use the SAMMY results is that some analyses were done a long time ago and the covariances obtained are no longer available[7]. In addition, an analysis with SAMMY is often made for a limited number of resonances. The rest of them are kept fixed during the parameter search, so that no uncertainties are given for those fixed resonance parameters. We would have to repeat the SAMMY calculations for such nuclei. Alternatively, some approximations must be made to generate the covariances in order to prepare the covariance files for the evaluated nuclear data libraries.

In those circumstances we needed to develop a method to evaluate covariances of resolved resonance parameters for JENDL-3.2[8] in a simple way. The KALMAN system[9] was developed to estimate the covariances of evaluated nuclear data. The system generates a covariance of the nuclear model parameters first, and then calculates error propagation from the parameters to the calculated cross sections. The program can be generally used, and it is adaptable to the R-matrix calculation in principle. However, the resolved resonance region has special problems such as Doppler broadening and management of a large number of data points when the calculated cross sections are compared with the measured values. To handle many data points easily we use energy-averaged cross sections instead of the fluctuating cross sections themselves, because uncertainties in the averaged values are usually needed in the reactor calculations, and they can be estimated by experiments. The uncertainties in the resonance parameters are estimated so as to give appropriate uncertainties in the averaged cross sections.

The method developed in this study has an advantage to simplify the computational tasks, although the covariance obtained is just an "estimation" of uncertainties in the resolved resonance parameters. With this technique one can generate covariances not only for the R-matrix representation, but also for other resonance formulae such as the Breit-Wigner type, because what we need is to calculate error propagation from averaged cross sections to model parameters.

The covariances obtained by this method were partly reported in Ref. [10], and this report is the comprehensive results of our covariance evaluations for the resonance parameters of ^{235}U, ^{238}U, and ^{239}Pu. Those results were stored in the JENDL-3.2 covariance file[11], in the ENDF-6 format[12] using MF=32. This file can be processed by the ERRORJ code[13] to generate a covariance of group-constants.

2 Covariance Evaluation Method for Resolved Resonances

Neutron cross sections with an exit channel c' is given by

$$\sigma_{cc'} = \frac{\pi}{k^2} \sum_J g_J \left| \delta_{cc'} - S^J_{cc'} \right|^2 , \tag{1}$$

where $S^J_{cc'}$ is the scattering matrix, J the spin of compound nucleus, k the wave number, and g_J the spin statistical factor. The S-matrix is calculated by the Reich-Moore R-matrix theory[14] as

$$S^J_{cc'}(E) = \exp^{-i(\phi_c+\phi_{c'})} \left\{ 2 \left[\left(\mathrm{I} - \frac{i}{2}\mathrm{R} \right)^{-1} \right]_{cc'} - \delta_{cc'} \right\} , \tag{2}$$

where ϕ_c is the hard-sphere phase shift, E the neutron energy, R the R-matrix, and I, the unit matrix. The element of R-matrix, $R_{cc'}$, is given by

$$R_{cc'}(E) = \sum_k \frac{\sqrt{\Gamma^{(k)}_c}\sqrt{\Gamma^{(k)}_{c'}}}{E^{(k)}_r - E - i\Gamma^{(k)}_\gamma/2}, \tag{3}$$

where $E^{(k)}_r$ is the k-th resonance energy, and $\Gamma^{(k)}_c$ is the width of channel c. In the R-matrix theory, a radiative capture width Γ_γ is eliminated, and Γ_γ appears in the denominator of Eq. (3) as an "eliminated radiation width."

For fissile nuclei, channels taken into account are the neutron, capture, and fission channels. Some nuclei have two fission channels, and those corresponding widths are described by Γ_{f_a} and Γ_{f_b}. The total (σ_t), fission (σ_{f_a} and σ_{f_b}), and elastic scattering (σ_e)

cross sections are calculated from the S-matrix in Eq. (2). The capture cross section (σ_c) is calculated as

$$\sigma_c = \sigma_t - (\sigma_e + \sigma_{f_a} + \sigma_{f_b}). \tag{4}$$

The resonance parameters given in the nuclear data library are the energy E_r and the widths Γ_n, Γ_γ, Γ_{f_a}, and Γ_{f_b}. To construct a covariance of the resonance parameters one has to determine uncertainties in those quantities. In the covariance evaluation technique with the KALMAN system[9], the accuracy of model parameters is determined according to the accuracy of experimental data. The same idea can be used for the evaluation of resonance parameter covariances. If we have knowledge of the accuracy of measurements, the uncertainties in the resonance parameters are determined by means of the error propagation,

$$\begin{aligned} \mathrm{P} &= \left(\mathrm{X}^{-1} + \mathrm{C}^t\mathrm{V}^{-1}\mathrm{C}\right)^{-1} \\ &= \mathrm{X} - \mathrm{X}\mathrm{C}^t\left(\mathrm{C}\mathrm{X}\mathrm{C}^t + \mathrm{V}\right)^{-1}\mathrm{C}\mathrm{X}, \end{aligned} \tag{5}$$

where P is the posterior covariance of the parameters, X the prior one, V the covariance of experimental data, and C the sensitivity matrix. An accuracy of the parameters should be determined by the covariance of experimental data V, and the prior covariance X is unnecessary in principle. In fact, when $\mathrm{X}^{-1} = \emptyset$, Eq. (5) expresses the error propagation from V to P. However, if sensitivity of some parameter is very small, its uncertainty becomes unreasonably large. The matrix X reflects implicit information for the parameters and it gives a certain upper limit of the uncertainties when reasonable values are given. Such control has an advantage to prevent an unreasonably large uncertainty in a parameter.

To calculate Eq. (5), we need the sensitivity matrix C, and covariances X and V. The matrix C can be calculated by means of the numerical derivatives of Eq. (1).

3 Evaluation Procedure and Results

3.1 Covariance of ^{235}U Resonance Parameters

JENDL-3.2 adopted the ^{235}U resolved resonance parameters of Leal, de Saussure, and Perez[15]. The upper limit of resolved energy region is 500 eV, and there are 23 s-wave resonances in the energy range 0–4 eV, 240 in 4–110 eV, 384 in 110–300 eV, and 382 in 300–500 eV. Although estimation of uncertainties for all resonance parameters is possible, we reduced the number of resonances since contributions of small resonances to the calculated cross sections can be ignored. For the sake of simplification and to make an evaluated covariance file smaller, we selected the resonances for which the covariance evaluation is performed.

Usually an R-matrix analysis is carried out within a certain energy range, and several resonances standing outside the energy range are included in order to summarize an effect of distant levels. In the present error analyses, only the resonances inside the energy range were taken into account and those distant levels were ignored, because the effect of the distant levels on the error analysis is only important at energies close to the border between the energy regions.

For fissile nuclei, one resonance contains five resonance parameters: the resonance energy, the neutron width, the radiative capture width, and the two fission widths. The resonance energies were assumed to have no uncertainty because they were regarded as well-determined.

Up to 4 eV, all resonances inside the energy range were chosen except for 0.036575 meV resonance, because the sensitivity of the cross section to this resonance is too small. Above 4 eV, sensitivities of the total cross sections to Γ_n were calculated firstly, and the sensitive resonances were selected. Consequently about 1/4 of the resonances were chosen to construct the covariance data file.

The evaluation of the resonance parameter covariance up to 4 eV was done according to the following procedure. Firstly the total, capture, and fission cross sections were calculated with 0.05 eV energy resolution. Secondly we surveyed the experimental uncertainties in the resonance region, and found that total cross sections were measured within an accuracy of several percent. Figure 1 shows some typical example of experimental errors in the total cross sections. Only two measurements[16, 17] are depicted in this figure, though the experimental database adopted for the JENDL-3.2 evaluation is larger. For fission and capture cross section measurements those data errors are slightly larger than the total cross section errors. Therefore we assumed that the uncertainty for the total cross sections in this energy range was 3%, while those for the capture and fission cross sections were 5%. Since the energy range of interest is narrow, the data in this energy range may be correlated with each other because of systematic errors. We assumed correlations of 50% between the different energy points, while correlations among the different reactions were zero. A calculation at the thermal energy was also included, and the uncertainties in the cross sections were 1% there. This value was roughly estimated by using experimental errors. The prior uncertainties in the resonance parameters were assumed to be 50%.

The uncertainties obtained are shown in Table 1, and the correlation coefficients are shown in Table 2. The averaged standard deviations are 2.2% for Γ_n, 3.3% for Γ_γ, and 11% for Γ_f. Figure 2 shows the calculated uncertainties in the total, capture, and fission cross sections. The averaged uncertainties are depicted by the horizontal lines, and their values are 0.6% for the total, 1.5% for the capture, and 1.1% for the fission cross sections. Since we gave a small error for the thermal cross section, those averaged values are smaller than the assumed 3% and 5% uncertainties in the cross sections. The correlation matrices for those cross sections are shown in Figs. 3, 4, and 5.

In the ENDF-6 format, there is an alternative way to express the covariances in the resolved energy region, which is to give uncertainties for background cross sections. It is, however, difficult to evaluate correlations between the different reactions with this method. An advantage of the present evaluation method is that the correlations between the different reactions can be obtained by calculating CPC^t which represents the error propagation from the posterior covariance P to various cross sections. Figures 6, 7, and 8 show the correlation matrices among the total, capture, and fission cross sections.

The covariance of the cross sections at the thermal energy can be calculated from the covariance of the resonance parameters, and it is shown in Table 3. The strong correlation between the total and fission cross sections is due to the large fraction of the fission cross section in the total one. The uncertainties in the compilation by Mughabghab[2] are 0.17% for the total, 0.81% for the capture, and 0.19% for the fission cross sections. The values in Table 3 are about two times larger than those values but still in the same order.

Above 4 eV, it is difficult to calculate the sensitivities because of the relatively wide energy regions. For instance, to calculate the sensitivities in the 4–110 eV energy range with the resolution of 0.1 eV, the size of sensitivity matrix becomes $1060 \times N$, where N is the number of resonance parameters. Then we replaced the fluctuating cross sections due to resonance by the energy-averaged values. The sensitivity calculation was done for the averaged cross sections within the energy interval of 2 eV. For ^{235}U the average *s*-wave level spacing D_0 is 0.44 eV[2], so the value of 2 eV ensures that there is at least one resonance within the averaging energy span. An example for the cross section averaging is shown in Fig. 9. With this technique, we can reduce the size of sensitivity matrix to 1/20.

In the energy range of 4–110 eV, 110–300, and 300–500 eV, the uncertainties of 3% for the total, and 5% for the capture and fission cross sections were assumed, and correlations among them were zero. The assumed uncertainties were taken from measurements, as one can see in Fig. 1.

Figure 10 (upper portion) shows the calculated uncertainties in the averaged cross sections in the energy range of 4–110 eV. The averaged values in this region are 1.9% for the total, 4.5% for the capture, and 3.9% for the fission cross sections. The uncertainties in the resonance parameters are shown in the lower drawing in Fig. 10. The correlation matrix is not shown here because it has 26,106 elements. The values obtained are scattered in the domain from several percent to 50%. The maximal error 50% is our input value, and it is roughly chosen. Probably another value for the prior variance could be chosen. However, the results would not be so different because the resonance parameter whose posterior uncertainty is large is insensitive to the averaged cross sections. Such an insensitive parameter has a small contribution to the error propagation.

Above 110 eV, the cross section uncertainties obtained are shown in Figs. 11 and 12, as well as the uncertainties for the resonance parameters. The averaged values of the cross section uncertainties in the energy range of 110–300 eV are 1.8% for the total, 4.8% for the capture, and 4.1% for the fission cross sections, while in the energy range of 300–500 eV, those are 1.7%, 4.6%, and 4.0%, respectively. The posterior uncertainties for Γ_n and Γ_γ become much smaller than the prior value (50%), but many Γ_{fa} and Γ_{fb} remain as their initial value. This means that the cross sections are more sensitive to the neutron width than to the fission width, and thus the uncertainties of the calculated cross sections are mainly determined from the uncertainties of the neutron and capture widths.

3.2 Covariance of ^{238}U Resonance Parameters

JENDL-3.2 adopted the ^{238}U resonance parameters of Moxon *et al.*[18] The upper limit of the resolved energy region is 10 keV, and the whole energy range is divided into 10 regions with 1 keV energy interval. Each region contains about 100–150 resonances for *s*- and *p*-waves, and we selected about 30 *s*-wave resonances for which the covariance is given.

The covariance estimation procedure for ^{238}U was similar to that for ^{235}U except for Γ_f, because the fission cross sections of ^{238}U are very small in the resonance region. Only the resonances inside the energy range were taken into account, and those standing outside were assumed to have no uncertainty. We also assumed that the resonance energies were exact. The *p*-wave resonances were not considered because they usually have small contributions to the averaged cross sections. The resonance parameters of interest were the neutron and radiative capture widths for *s*-wave.

The uncertainties of 3% for the total, and 5% for the capture cross sections were assumed for all energy regions except the thermal energy, and the correlations among them were zero. At the thermal energy 1% error was given for the total cross section and 2% for the capture. The prior uncertainties for the resonance parameters were assumed to be 50%. The cross sections were calculated with 0.1 eV energy resolution, and these cross sections were averaged within the 20 eV energy interval. This averaging width was determined from the average level spacing $D_0 = 20.9$ eV[2].

The obtained covariance for the resonance parameters in the 0–1 keV energy region was used to calculate the covariance of the cross sections at the thermal energy, which is shown in Table 4. The uncertainty of capture cross section in Ref. [2] is 0.71%. The uncertainty for the total cross section is not shown in Ref. [2], however, it may be about 1 % because the elastic scattering has an accuracy of 1%. The uncertainties obtained here are in the same magnitude as these values.

Moxon *et al.*[18] evaluated uncertainties for some resonance parameters in low energy region. Table 5 compares the evaluated uncertainties of Moxon *et al.*[18] with our results. Althought such a comparison does not make sense because these are not physically meaningful quantities, the present uncertainties obtained are comparable with those of Moxon *et al.* at several resonance energies even thought we made a crude approximation.

Since the correlation matrices obtained are very large, a sub-matrix of them is shown in Table 6, which is the correlation matrix for the resonances at 6.674, 20.871, 36.682, 66.032, 102.56, and 116.902 eV. Generally the correlation between a resonance and its adjacent one is strong, and it is weak between the distant resonances.

The calculated uncertainties of the averaged cross sections as well as those for the resonance parameters are shown in Figs. 13–22. The horizontal lines in the upper drawings are the averaged values. The average uncertainties for Γ_n and Γ_γ were 14% and 12%, respectively. Nakagawa and Shibata[3] also estimated those values, which were mainly based on the experimental data[19] and the resonance analysis of Moxon *et al.*[18] They assigned the 15% uncertainty for Γ_n, and 1 meV for Γ_γ which corresponds to about 4% error. Our result (14% for Γ_n) is in the same order, while the Γ_γ error is larger. The 4% uncertainty of Γ_γ is probably too small except for those in the low energy region, because our result was obtained so that the uncertainties in the capture cross sections could be about 5%. If one assigns smaller uncertainties for Γ_γ, the calculated capture cross section errors may become smaller than the total cross section errors.

3.3 Covariance of ^{239}Pu Resonance Parameters

The resonance parameters of ^{239}Pu adopted in JENDL-3.2 were obtained by Derrien and co-workers[20, 21] with SAMMY. The upper limit of the resolved energy region is 2.5 keV, and there are 405 *s*-wave resonances in the energy range 0–1 keV, 441 in 1–2 keV, and 224 in 2–2.5 keV. To reduce the number of resonance parameters for which uncertainties are given, some representative resonances were selected. Firstly, sensitivities of the total cross sections to Γ_n were calculated, because Γ_n is the most sensitive to the cross sections. Then, about 1/4 of resonances were chosen.

The procedure of the covariance estimation for ^{239}Pu was the same as that for ^{235}U. Only the resonances inside the energy range were taken into account, and those standing outside were assumed to be no uncertainty, except for 2 negative resonances. The resonance energies were assumed to have no errors either.

For three energy regions (0–1 keV, 1-2 keV, and 2–2.5 keV), the uncertainties of

3% for the total, and 5% for the capture and fission cross sections were assumed, and the correlations among them were zero. At the thermal energy 1% error was given for the total cross section and 2% for the capture and fission cross sections. These values were roughly estimated from the experimental data. The prior uncertainties for the resonance parameters were assumed to be 50%. The cross sections were calculated with 0.1 eV energy resolution, and these cross sections were averaged within the 10 eV energy interval. This averaging width was determined from the average level spacing $D_0 = 2.3$ eV[2].

The obtained covariance for the resonance parameters in the 0–1 keV energy region were used to calculate the covariance of the cross sections at the thermal energy, which is shown in Table 7. The uncertainties obtained are about 2–4 times larger than the compiled values[2], which are 0.28% for the total, 1.0% for the capture, and 0.27% for the fission cross sections.

The calculated uncertainties of the averaged cross sections and the resonance parameters are shown in Figs. 23, 24, and 25, for the energy ranges of 0–1, 1–2, and 2–2.5 keV, respectively. The horizontal lines in the upper drawings are the averaged values of the cross section uncertainties. In the case of ^{239}Pu, both Γ_{fa} and Γ_{fb} are given for $J = 0$ levels, while Γ_{fb} is not given for $J = 1$ levels. Then the uncertainties of Γ_{fb} become zero for $J = 1$ resonances.

Nakagawa and Shibata[3] estimated the average uncertainties of the resonance parameters, which were based on the R-matrix analysis of Derrien *et al.*[20, 21] The averaged uncertainty for the resonance energy was less than 0.01%, which supports our assumption that the resonance energies are well-determined. The averaged uncertainties for the widths were about 10–15%. Those values obtained here are 13% for Γ_n, 28% for Γ_γ, 34% for Γ_{fa}, and 42% for Γ_{fb}. The uncertainties for the neutron width are in the same magnitude as the R-matrix analysis. However, the other widths have larger uncertainties than the R-matrix analysis.

An important resonance of ^{239}Pu is located at 0.2956 eV. The calculated covariance for this resonance is shown in Table 8. In Ref. [2], 4.6% for Γ_n, 7.7% for Γ_γ, and 6.7% for Γ_f are given.

4 Conclusion

We have developed a method to generate covariance matrices for the resolved resonance parameters of the Reich-Moore R-Matrix theory. In this method, uncertainties in the total, capture, and fission cross sections are assumed, then uncertainties in the resonance parameters which reproduce the accuracy of the cross sections are estimated by means of the error propagation. It is possible to give correlations among cross sections, which corresponds to a case for existence of systematical errors in experimental data.

This method was adopted to evaluate the covariances of resonance parameters for ^{235}U, ^{238}U, and ^{239}Pu, and the results were compiled into the covariance data files for JENDL-3.2.

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Table 1: Resonance parameters of ^{235}U selected for the covariance evaluation and calculated uncertainties (0–4 eV).

k	E_r [eV]	Γ_n [μeV]	$\delta\Gamma_n$ [%]	Γ_γ [keV]	$\delta\Gamma_\gamma$ [%]	Γ_{f_a} [meV]	$\delta\Gamma_{f_a}$ [%]	Γ_{f_b} [meV]	$\delta\Gamma_{f_b}$ [%]
1	0.2819	4.4392	2.97	38.571	4.63	106.43	3.48	−4.8450	11.6
2	1.1389	13.806	1.31	38.694	2.65	−0.0047793	49.2	112.60	1.69
3	2.0361	8.9501	1.65	37.76	1.81	−8.0462	5.93	−1.6365	14.4
4	2.7767	1.2736	4.70	37.0	6.20	62.366	7.14	−43.820	11.0
5	3.1566	24.224	1.57	38.0	2.72	−82.492	3.88	17.706	14.7
6	3.6208	41.286	1.05	36.0	1.93	−27.60	3.06	29.516	2.65

Table 2: Correlation of ^{235}U resonance parameters $\Gamma^{(k)}$ in the 0–4 eV energy region, where k is shown in Table 1.

		Correlation (×1000)											
		1	2	3	4	5	6	7	8	9	10	11	12
1	$\Gamma_n^{(1)}$	1000											
2	$\Gamma_\gamma^{(1)}$	−19	1000										
3	$\Gamma_{f_a}^{(1)}$	648	192	1000									
4	$\Gamma_{f_b}^{(1)}$	−159	−64	−51	1000								
5	$\Gamma_n^{(2)}$	267	86	127	64	1000							
6	$\Gamma_\gamma^{(2)}$	91	391	−35	−16	−76	1000						
7	$\Gamma_{f_a}^{(2)}$	51	−12	42	11	21	−11	1000					
8	$\Gamma_{f_b}^{(2)}$	−22	−104	−46	81	365	55	1	1000				
9	$\Gamma_n^{(3)}$	316	305	155	4	325	317	1	43	1000			
10	$\Gamma_\gamma^{(3)}$	97	295	11	−16	79	296	−5	−76	91	1000		
11	$\Gamma_{f_a}^{(3)}$	−16	141	−8	−49	−88	154	16	−92	−82	143	1000	
12	$\Gamma_{f_b}^{(3)}$	−132	2	−144	−27	−74	13	−27	−57	−48	−34	−124	1000
13	$\Gamma_n^{(4)}$	−9	106	−12	−56	−42	113	4	−69	62	69	18	−78
14	$\Gamma_\gamma^{(4)}$	87	268	8	−16	92	294	−10	−53	200	170	87	11
15	$\Gamma_{f_a}^{(4)}$	−110	71	−103	−115	−89	80	13	−68	−24	41	97	−38
16	$\Gamma_{f_b}^{(4)}$	36	50	2	−16	52	59	14	47	60	46	41	14
17	$\Gamma_n^{(5)}$	338	59	208	35	373	66	16	155	274	51	−93	8
18	$\Gamma_\gamma^{(5)}$	68	306	−6	8	68	341	−10	−67	224	217	118	−5
19	$\Gamma_{f_a}^{(5)}$	−142	62	−170	−110	−52	78	−7	−63	3	41	−38	171
20	$\Gamma_{f_b}^{(5)}$	−84	−15	−136	−88	62	−5	−3	14	20	−23	−114	210
21	$\Gamma_n^{(6)}$	368	150	213	−37	369	163	18	109	334	125	−63	20
22	$\Gamma_\gamma^{(6)}$	93	378	−1	−15	85	420	−10	−85	285	279	136	1
23	$\Gamma_{f_a}^{(6)}$	−45	79	−51	4	−54	88	5	−95	47	47	−27	69
24	$\Gamma_{f_b}^{(6)}$	−1	−152	−6	−29	26	−170	13	−6	−55	−125	−165	144
		13	14	15	16	17	18	19	20	21	22	23	24
13	$\Gamma_n^{(4)}$	1000											
14	$\Gamma_\gamma^{(4)}$	−12	1000										
15	$\Gamma_{f_a}^{(4)}$	4	4	1000									
16	$\Gamma_{f_b}^{(4)}$	−384	−156	447	1000								
17	$\Gamma_n^{(5)}$	−321	47	41	235	1000							
18	$\Gamma_\gamma^{(5)}$	16	−8	52	65	−42	1000						
19	$\Gamma_{f_a}^{(5)}$	232	92	334	0	−274	−149	1000					
20	$\Gamma_{f_b}^{(5)}$	29	25	531	164	70	−55	752	1000				
21	$\Gamma_n^{(6)}$	−41	130	−58	82	273	70	108	159	1000			
22	$\Gamma_\gamma^{(6)}$	110	237	46	44	3	176	77	−31	−108	1000		
23	$\Gamma_{f_a}^{(6)}$	98	70	95	−94	185	81	88	252	−39	−16	1000	
24	$\Gamma_{f_b}^{(6)}$	55	−47	121	−148	90	−158	373	549	−100	−77	362	1000

Table 3: Covariance matrix of cross sections for ^{235}U at the thermal energy.

	Error [%]	Correlation ($\times$1000)		
Total	0.343	1000		
Capture	0.425	265	1000	
Fission	0.396	984	93	1000

Table 4: Covariance matrix of cross sections for ^{238}U at the thermal energy.

	Error [%]	Correlation ($\times$1000)	
Total	0.60	1000	
Capture	1.88	463	1000

Table 5: Comparison of uncertainties in resonance parameters of ^{238}U

Energy (eV)	$\delta\Gamma_\gamma(\%)$		$\delta\Gamma_n(\%)$	
	Moxon, *et al.*	This work	Moxon, *et al.*	This work
6.67	0.18	2.4	0.15	2.0
20.9	0.17	20.	0.091	17.
36.7	0.21	4.9	0.067	3.6
66.0	0.52	0.42	0.17	0.46
80.8	2.5	—	1.2	—
102.6	0.83	2.0	0.25	6.1
116.9	1.1	13.	0.36	13.
145.7	45.	—	5.0	—
165.3	11.	—	0.22	—
189.7	1.8	7.0	0.18	4.6
208.5	1.3	4.8	0.39	5.2
237.4	3.3	1.9	0.59	1.9
273.7	4.7	0.94	0.67	1.4
291.0	9.9	—	1.0	—
311.3	16.	—	12.	—

Table 6: The sub-matrix of correlation for ^{238}U resonance parameters $\Gamma^{(k)}$, where the indices k represent the 6.674, 20.871, 36.682, 66.032, 102.56, and 116.902 eV resonances.

		Correlation (×1000)											
		1	2	3	4	5	6	7	8	9	10	11	12
1	$\Gamma_n^{(1)}$	1000											
2	$\Gamma_\gamma^{(1)}$	999	1000										
3	$\Gamma_n^{(2)}$	302	299	1000									
4	$\Gamma_\gamma^{(2)}$	−370	−364	−951	1000								
5	$\Gamma_n^{(3)}$	−276	−274	−994	917	1000							
6	$\Gamma_\gamma^{(3)}$	402	393	684	−874	−613	1000						
7	$\Gamma_n^{(4)}$	−14	−14	−33	36	32	−34	1000					
8	$\Gamma_\gamma^{(4)}$	11	11	31	−32	−31	27	−940	1000				
9	$\Gamma_n^{(5)}$	−49	−49	−20	31	18	−44	75	−76	1000			
10	$\Gamma_\gamma^{(5)}$	34	34	19	−28	−17	37	−61	61	−775	1000		
11	$\Gamma_n^{(6)}$	49	48	17	−29	−15	42	−74	75	−995	724	1000	
12	$\Gamma_\gamma^{(6)}$	−45	−45	−19	30	17	−43	73	−74	964	−911	−943	1000

Table 7: Covariance matrix of cross sections for ^{239}Pu at the thermal energy.

	Error [%]	Correlation (×1000)		
Total	0.84	1000		
Capture	1.91	194	1000	
Fission	1.22	831	−380	1000

Table 8: Covariance matrix of resonance parameters for ^{239}Pu at 0.2956 eV.

	Error [%]	Correlation (×1000)		
Γ_n	5.48	1000		
Γ_γ	5.99	184	1000	
Γ_{f_a}	5.08	949	422	1000

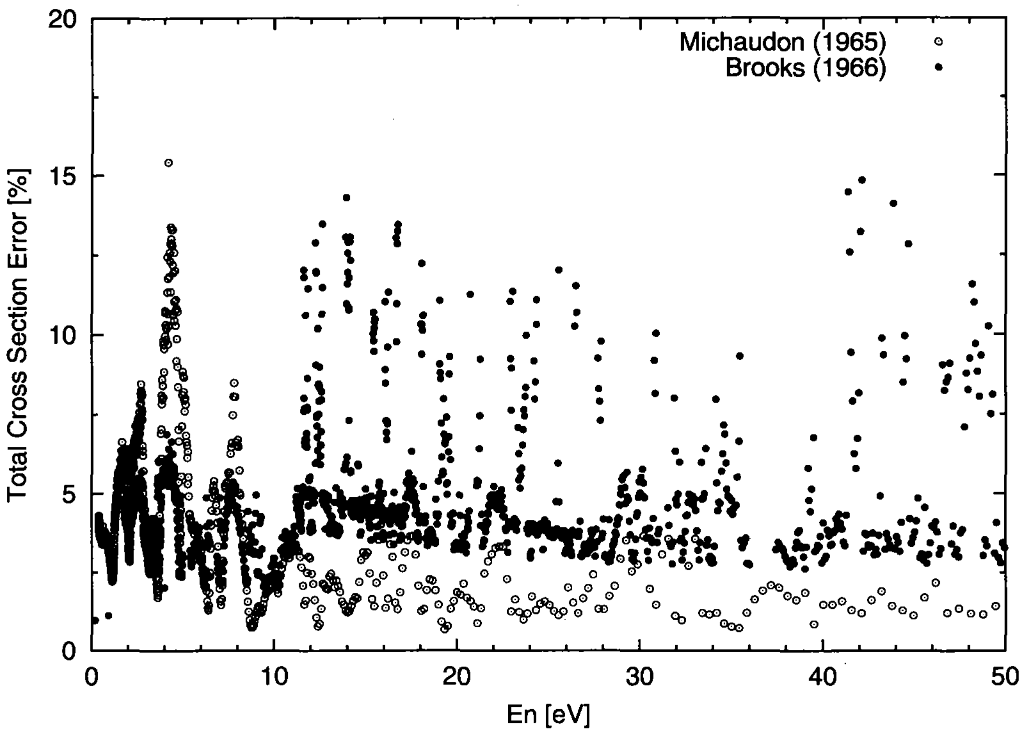


Fig. 1: Typical data errors in the total cross section measurements for ^{235}U at low energies.

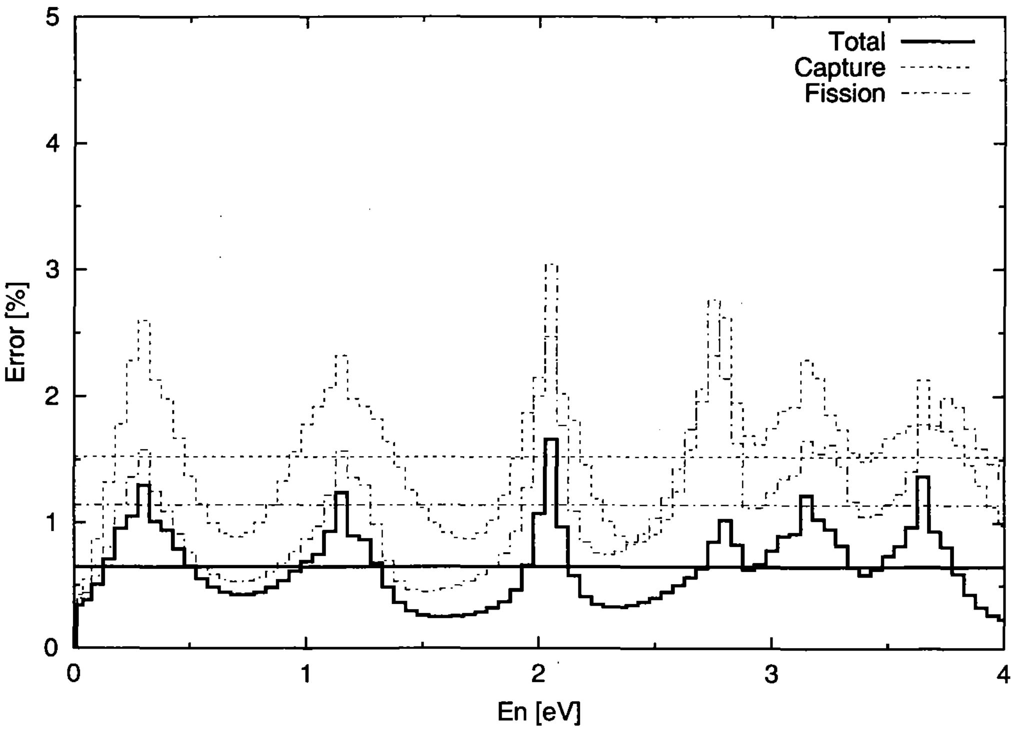


Fig. 2: Calculated uncertainties in total, capture, and fission cross sections of ^{235}U. The horizontal lines are the averaged values.

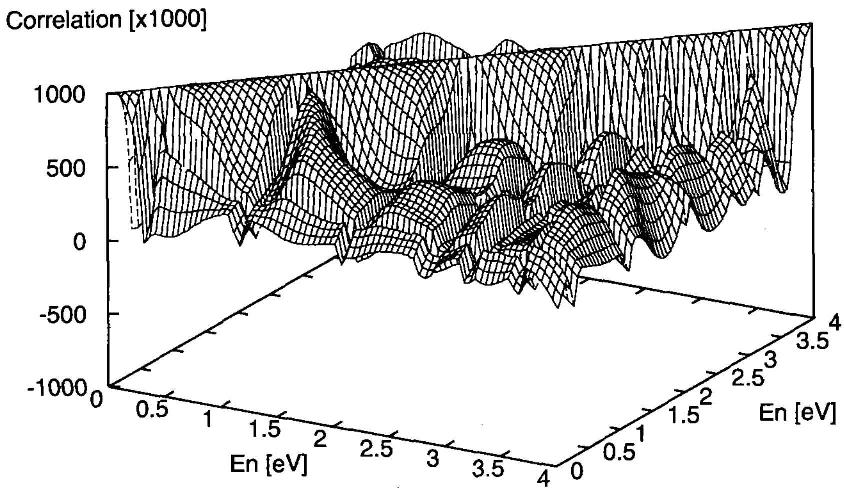


Fig. 3: Correlation matrix of the ^{235}U total cross sections in the energy range 0–4 eV.

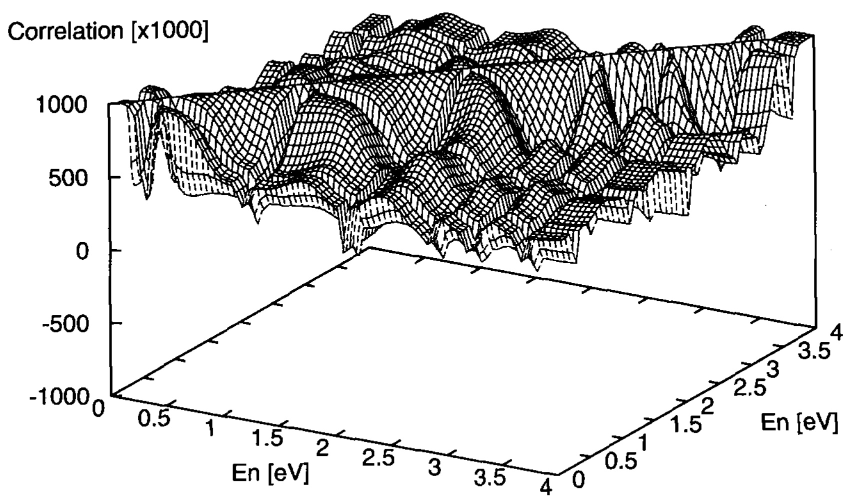


Fig. 4: Correlation matrix of the ^{235}U capture cross sections in the energy range 0–4 eV.

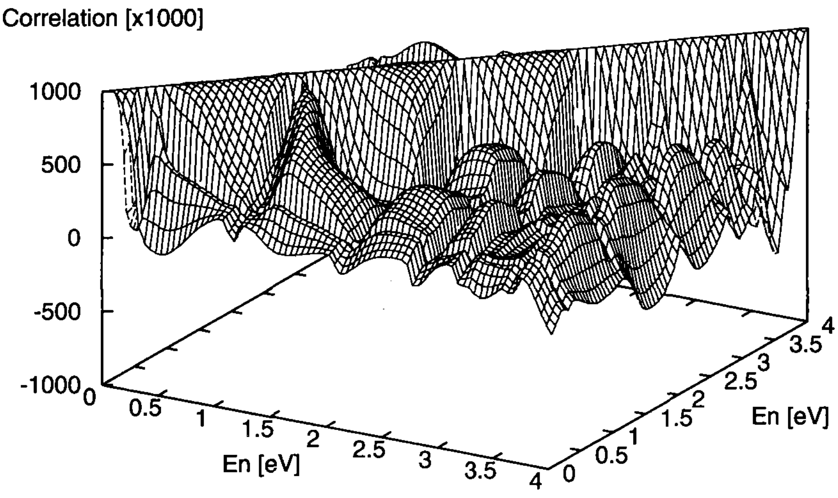


Fig. 5: Correlation matrix of the ^{235}U fission cross sections in the energy range 0–4 eV.

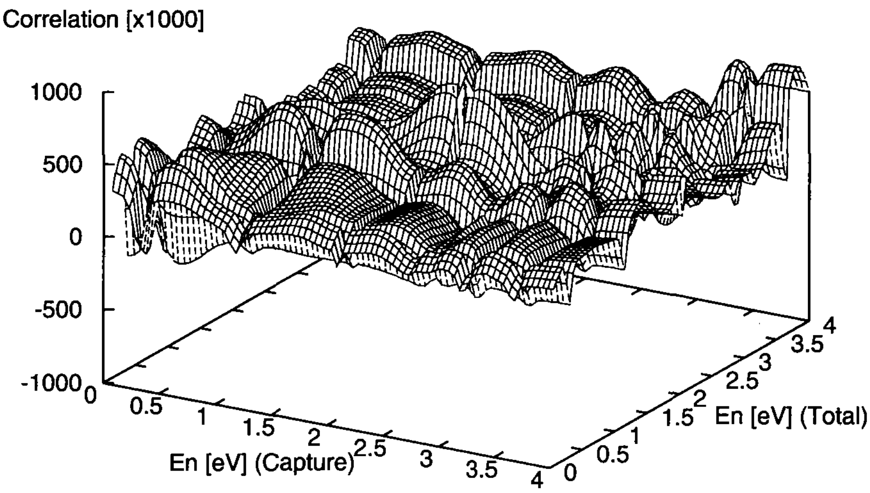


Fig. 6: Correlation matrix between the total and capture cross sections of ^{235}U in the energy range 0–4 eV.

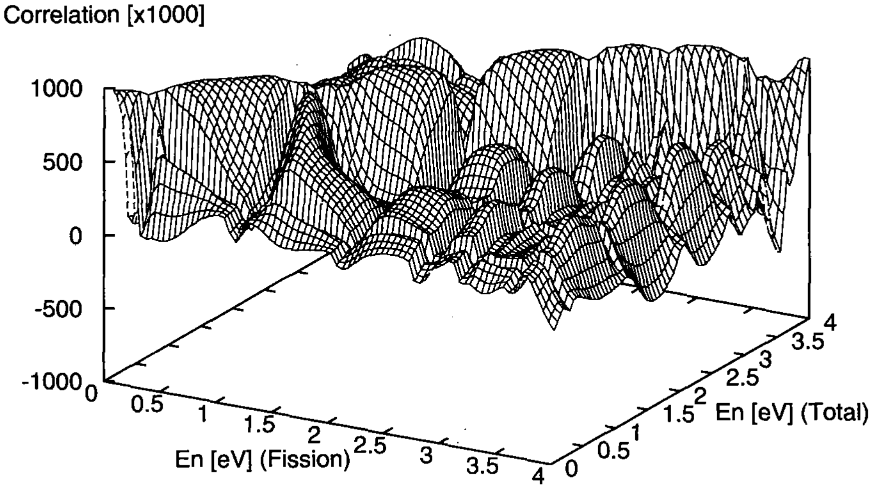


Fig. 7: Correlation matrix between the total and fission cross sections of ^{235}U in the energy range 0–4 eV.

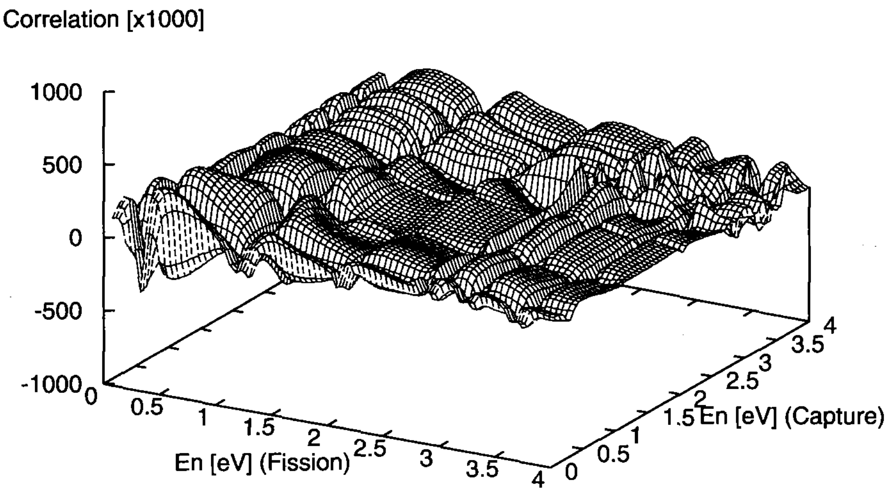


Fig. 8: Correlation matrix between the capture and fission cross sections of ^{235}U in the energy range 0–4 eV.

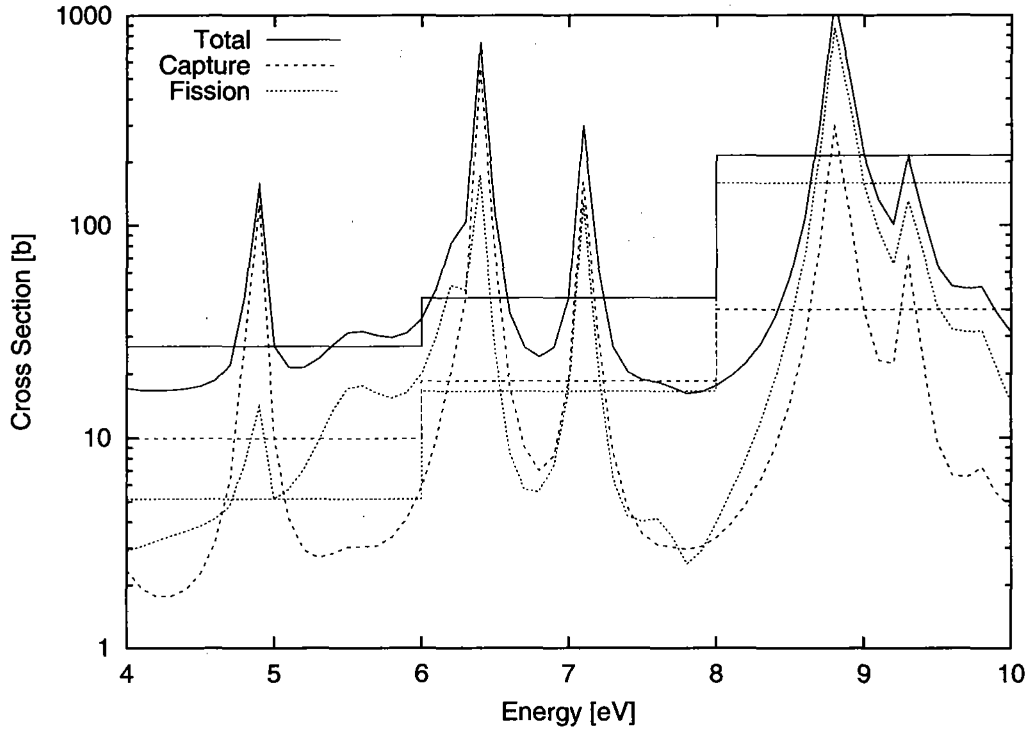


Fig. 9: Comparisons of the total, capture, and fission cross sections of ^{235}U in the energy range of 4–10 eV, with the averaged cross sections within the energy interval of 2 eV as shown by horizontal lines.

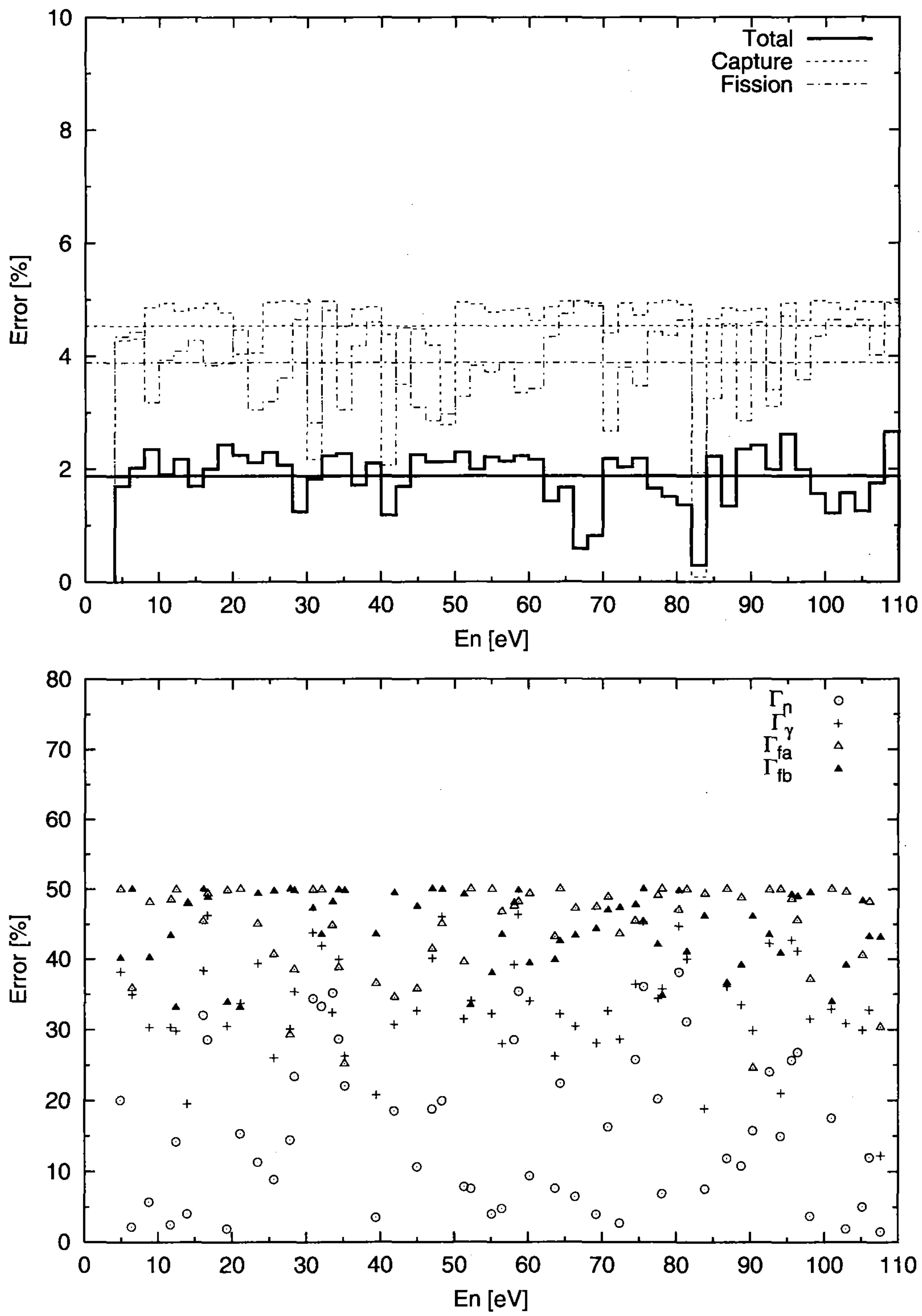


Fig. 10: Calculated uncertainties for ^{235}U in the energy range of 4–110 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n, Γ_γ, Γ_{fa}, and Γ_{fb}.

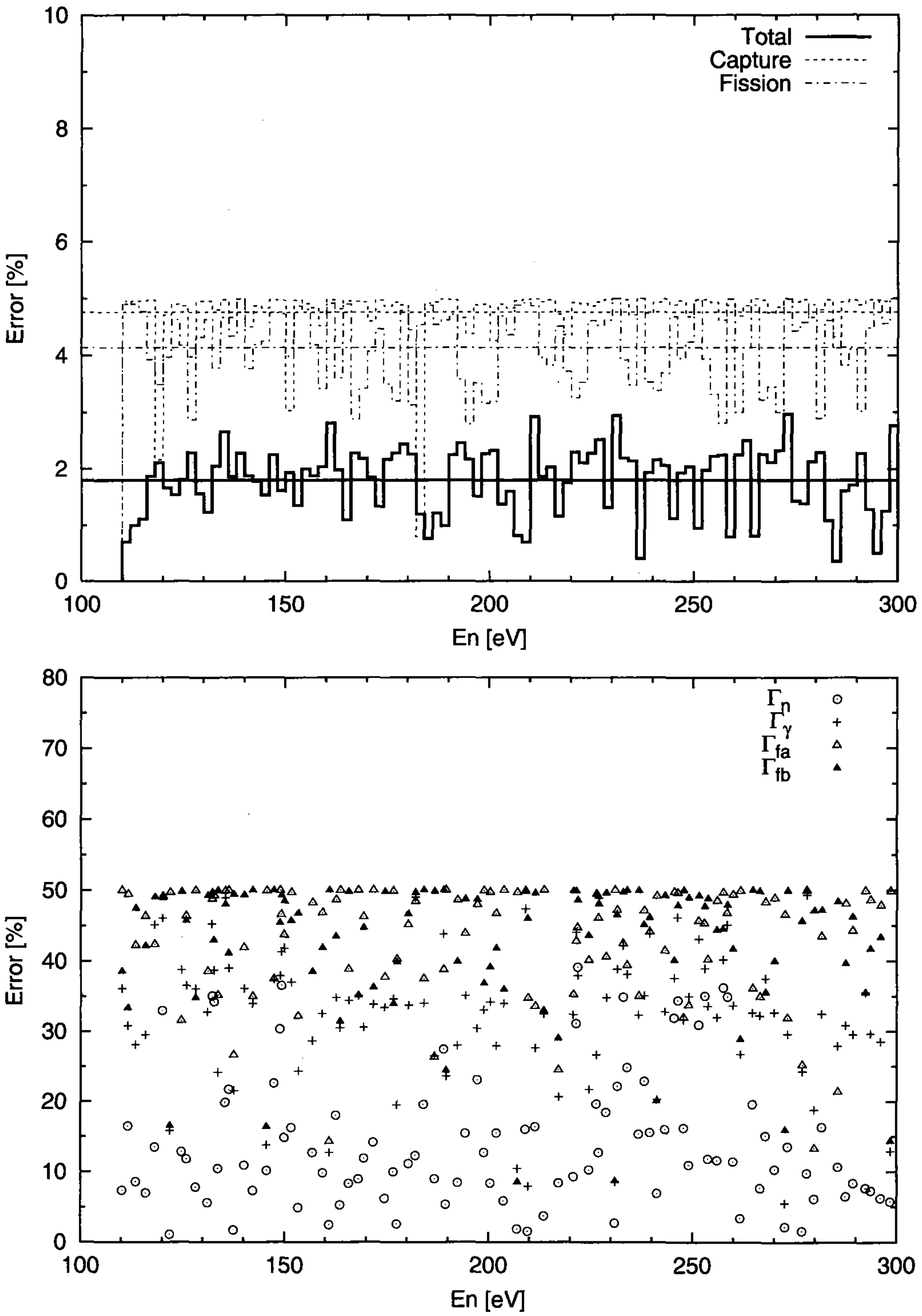
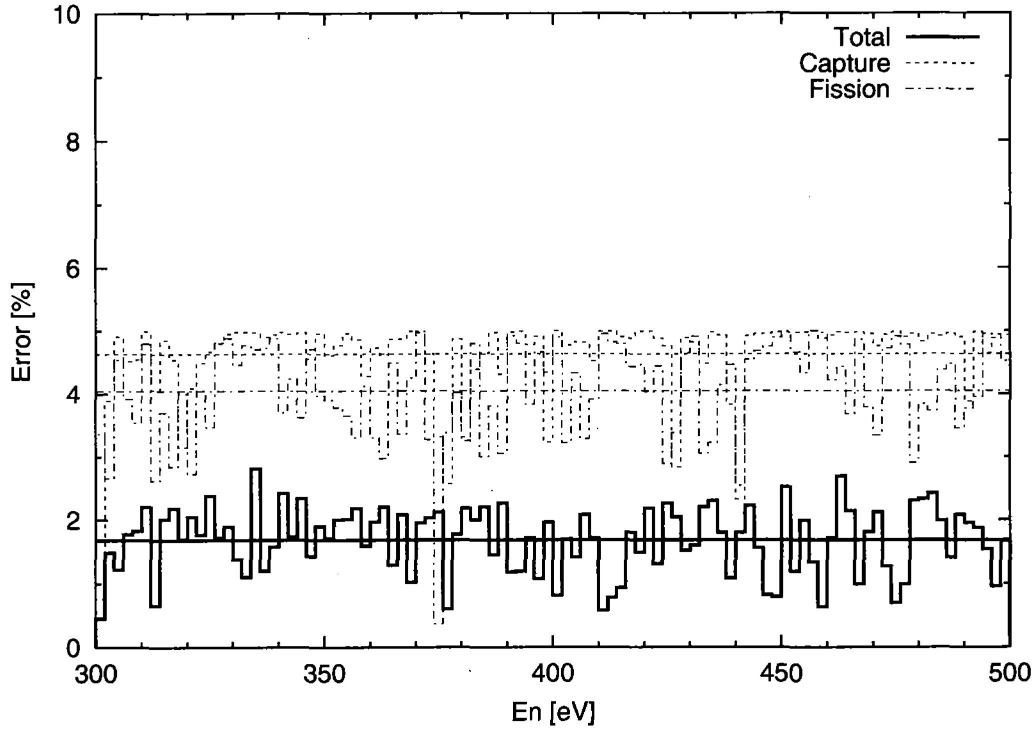


Fig. 11: Calculated uncertainties for ^{235}U in the energy range of 110–300 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n, Γ_γ, Γ_{fa}, and Γ_{fb}.



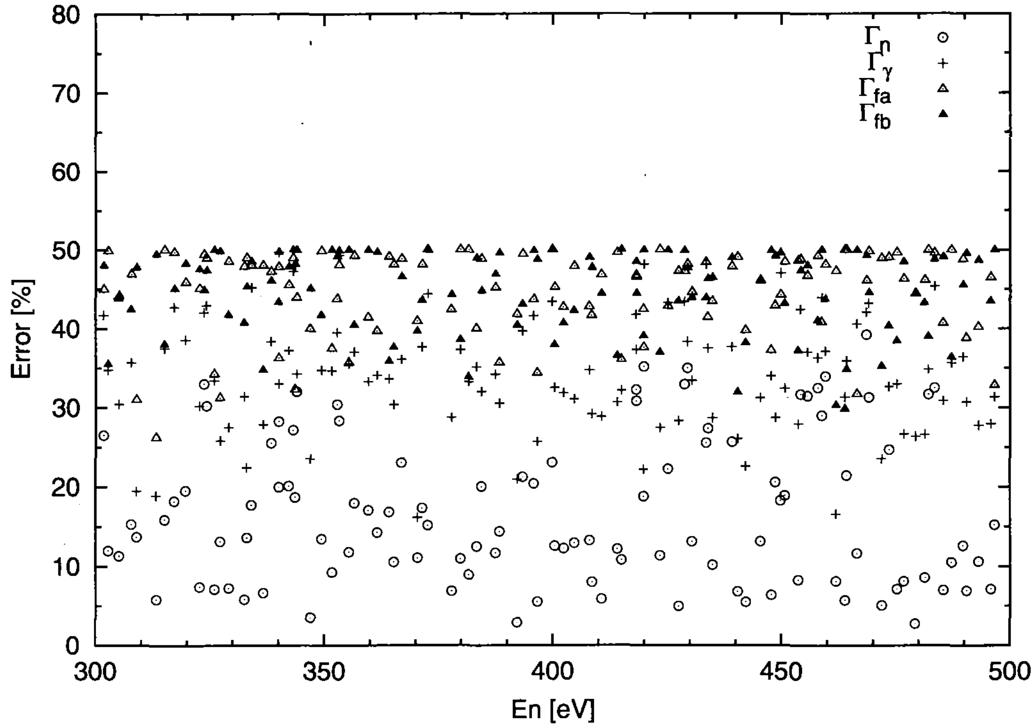
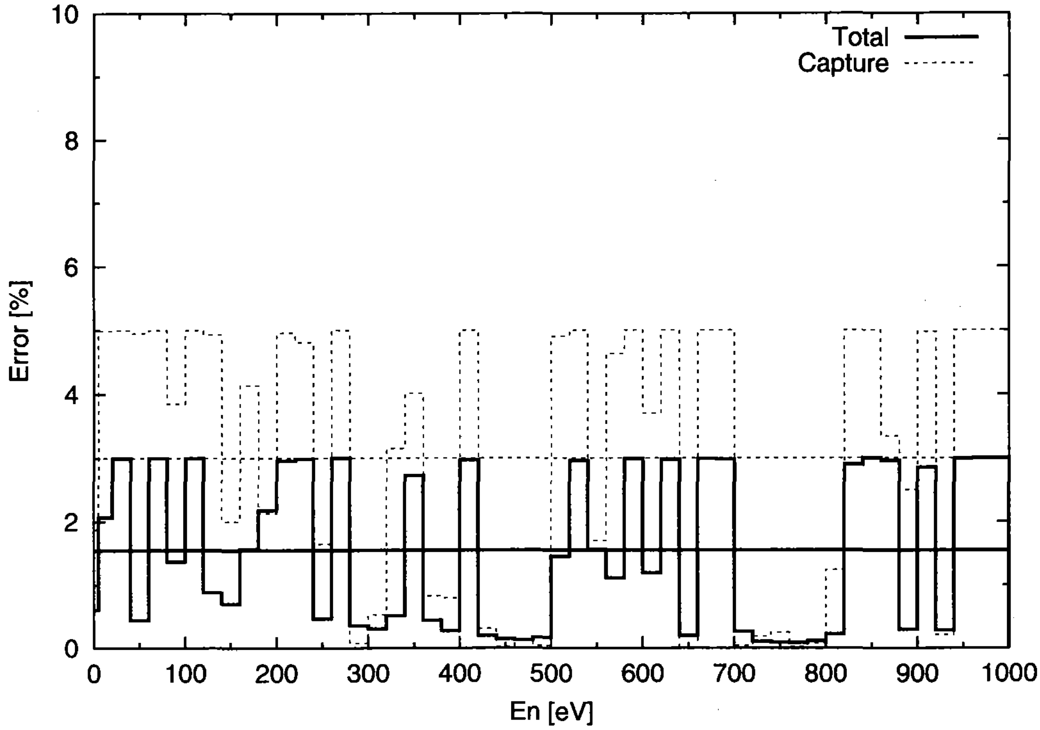


Fig. 12: Calculated uncertainties for ^{235}U in the energy range of 300–500 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n, Γ_γ, Γ_{fa}, and Γ_{fb}.



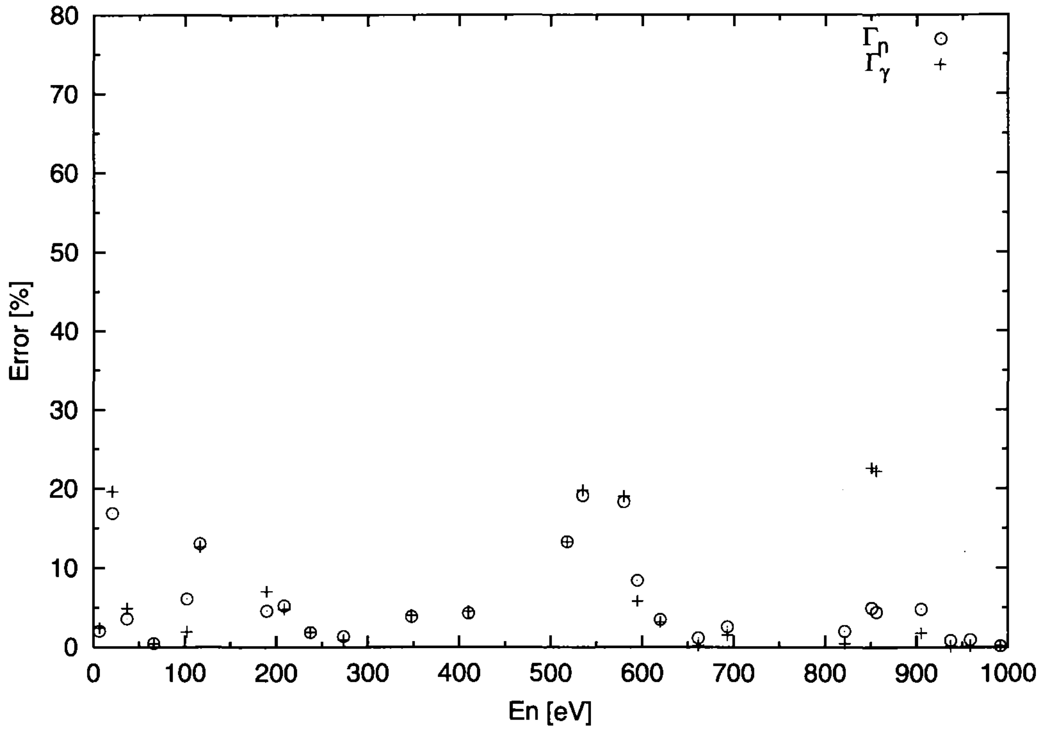


Fig. 13: Calculated uncertainties for ^{238}U in the energy range of 0–1000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.

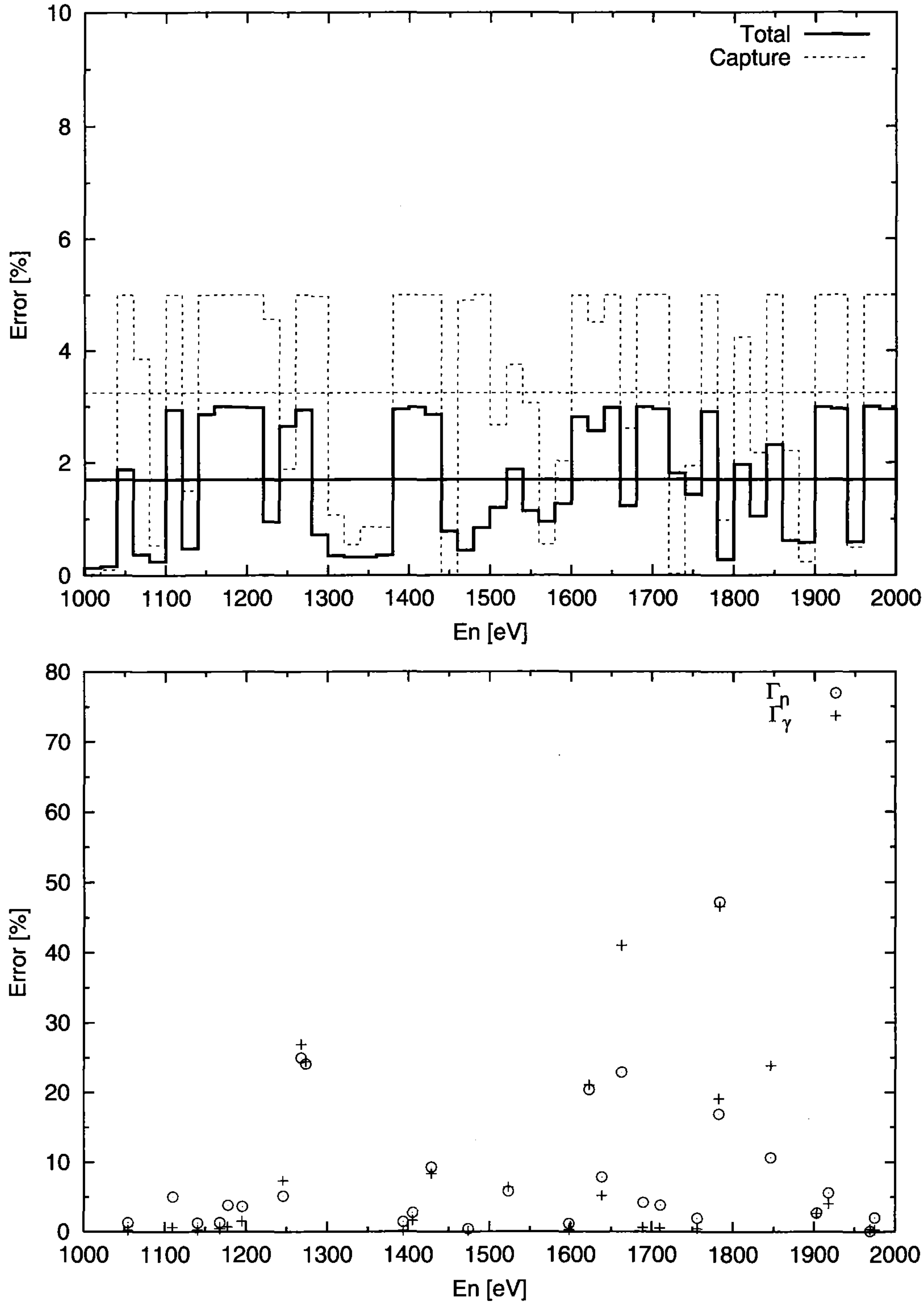


Fig. 14: Calculated uncertainties for ^{238}U in the energy range of 1000–2000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.

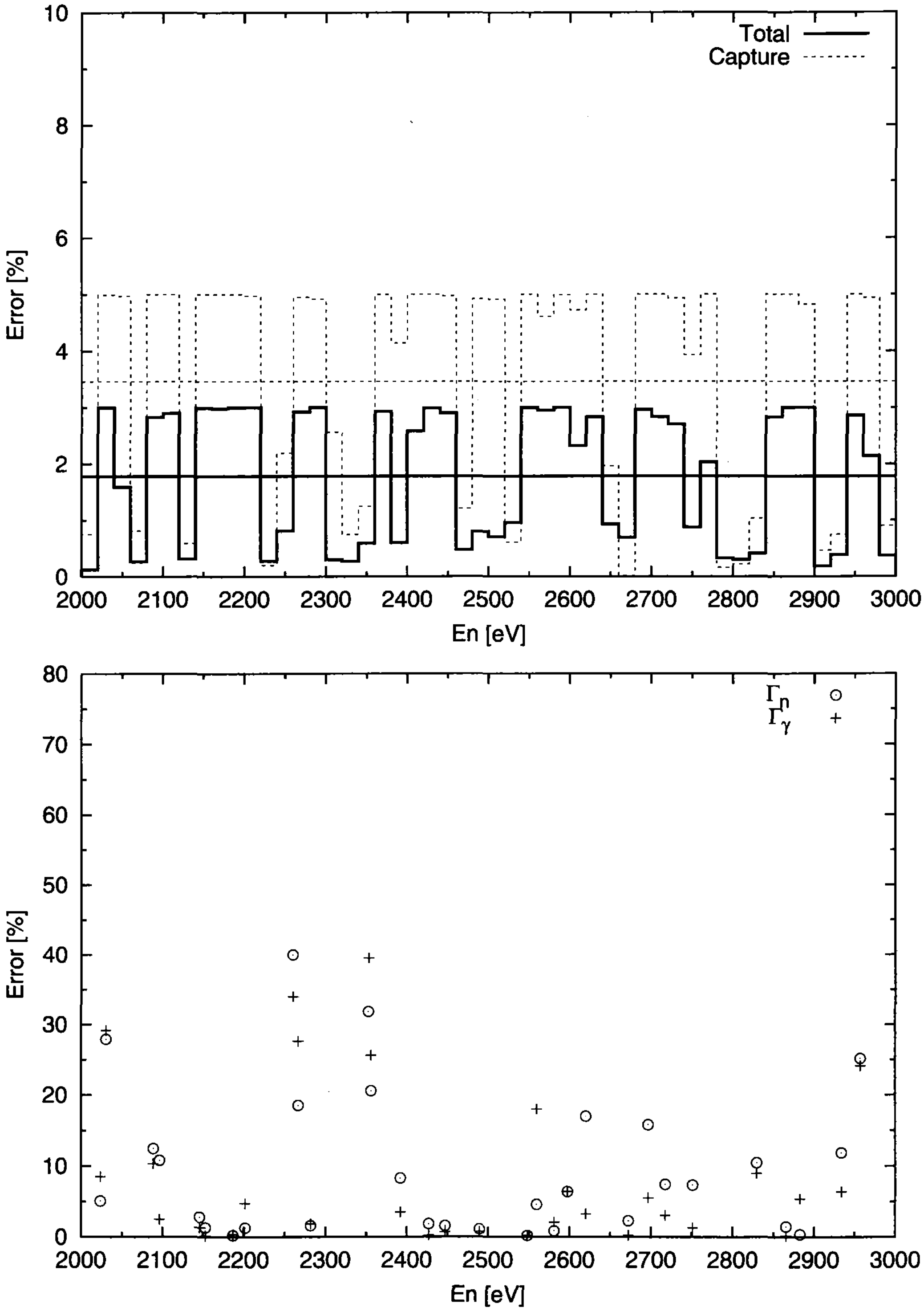
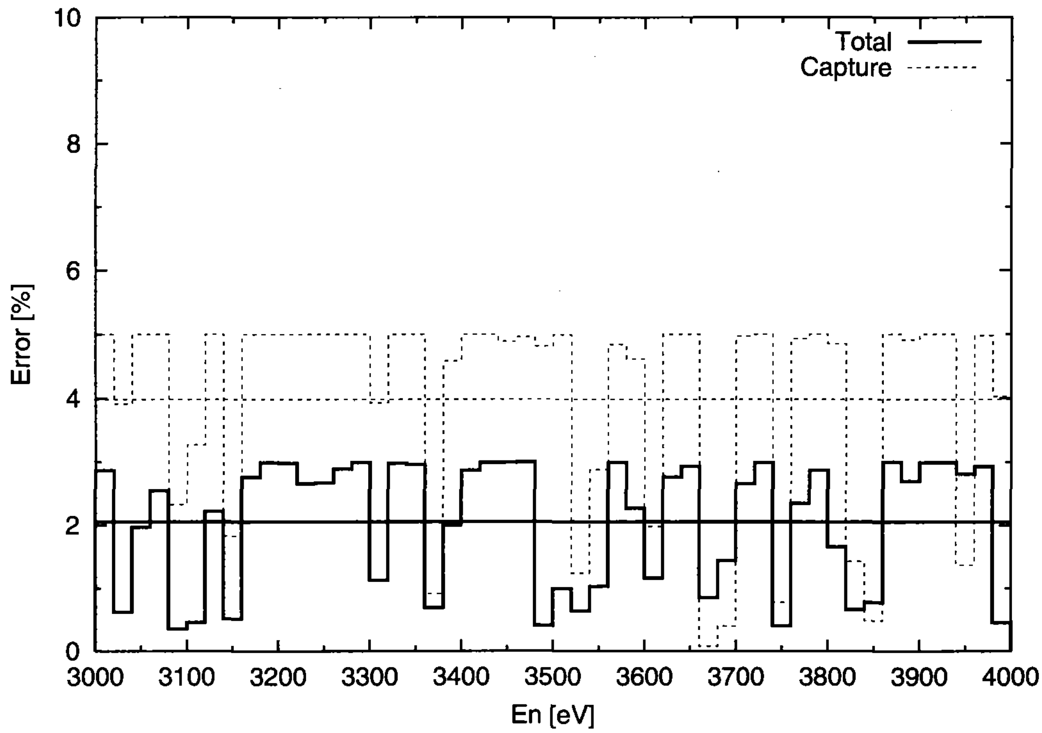


Fig. 15: Calculated uncertainties for ^{238}U in the energy range of 2000–3000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.



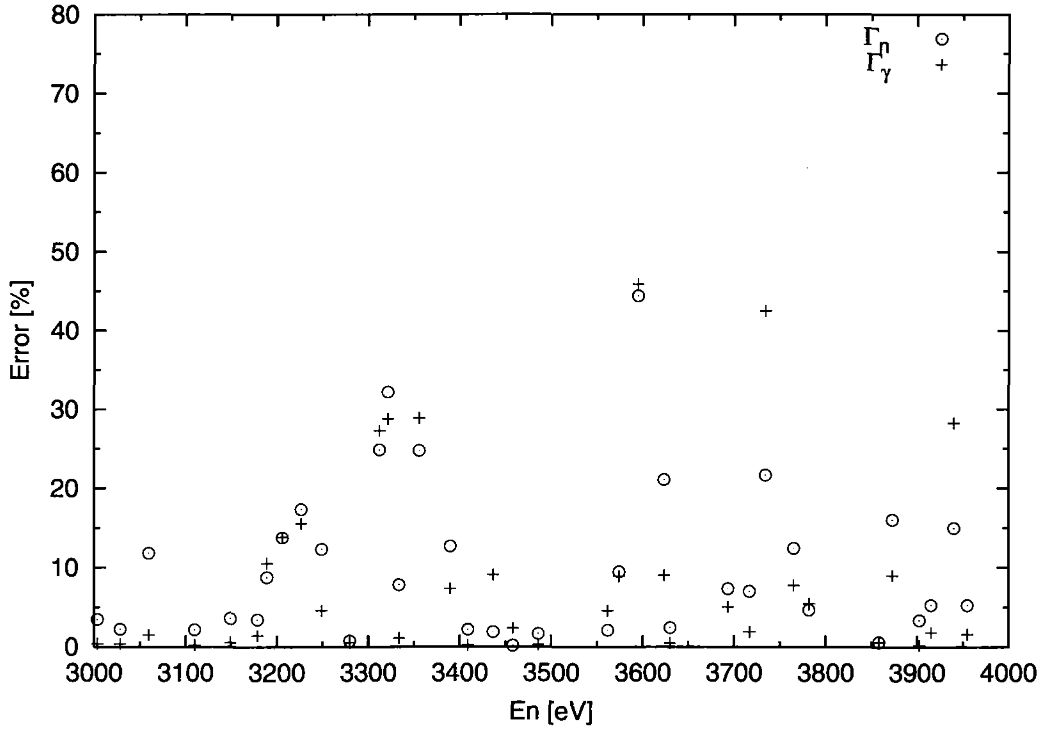


Fig. 16: Calculated uncertainties for ^{238}U in the energy range of 3000–4000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.

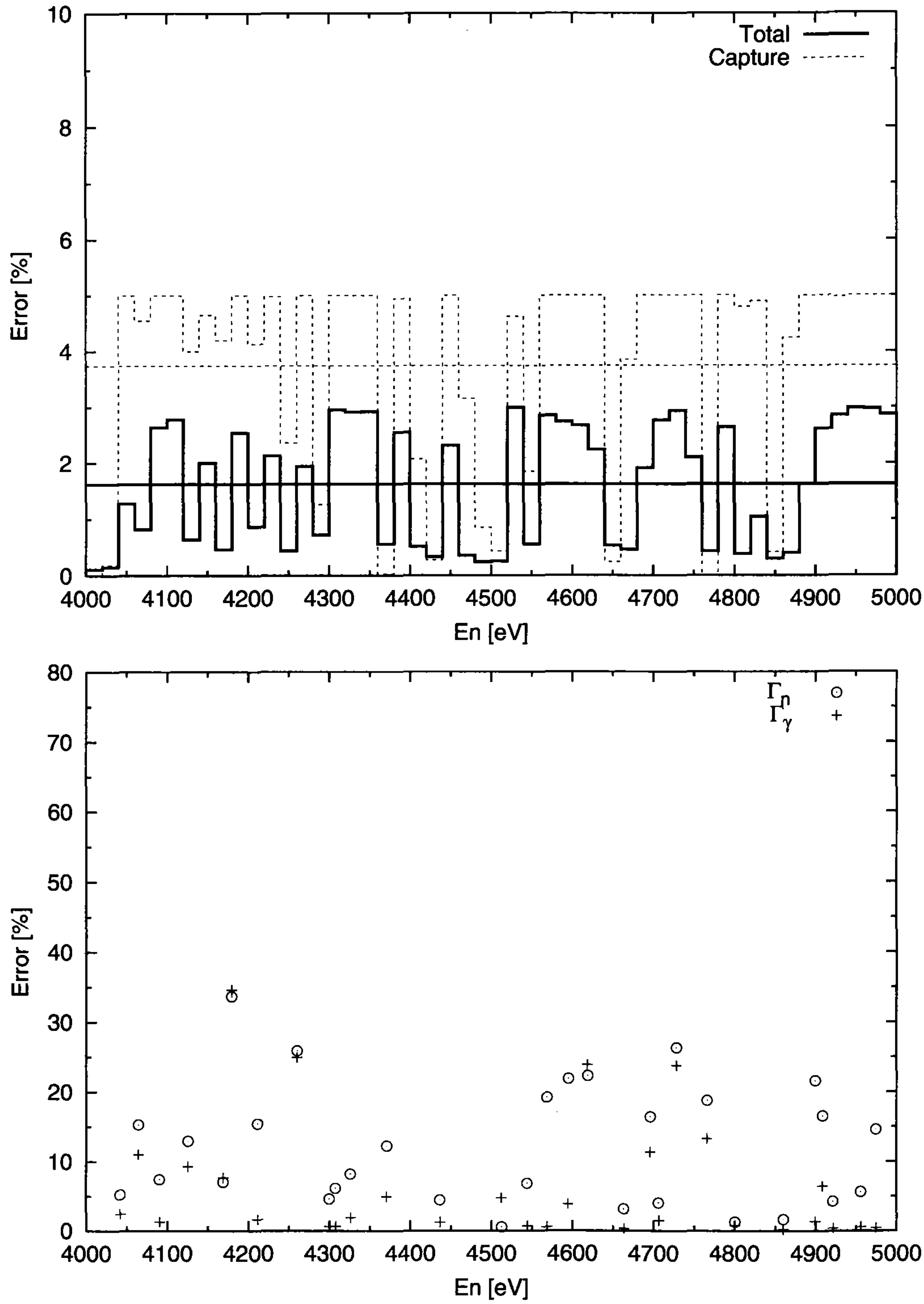
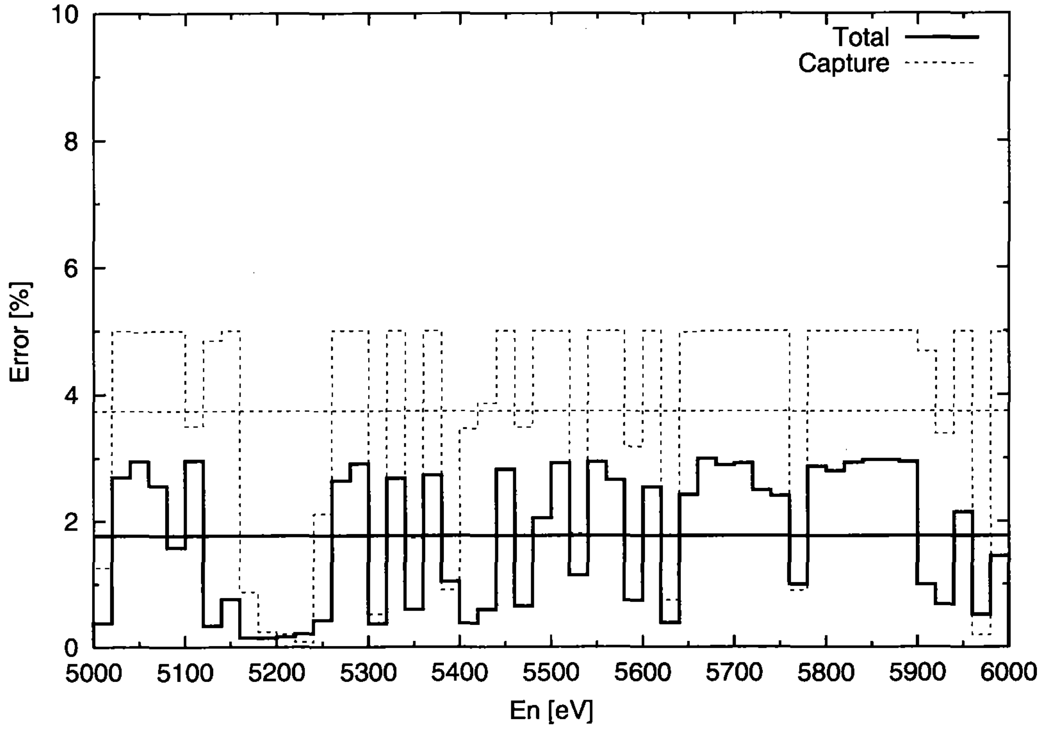


Fig. 17: Calculated uncertainties for ^{238}U in the energy range of 4000–5000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.



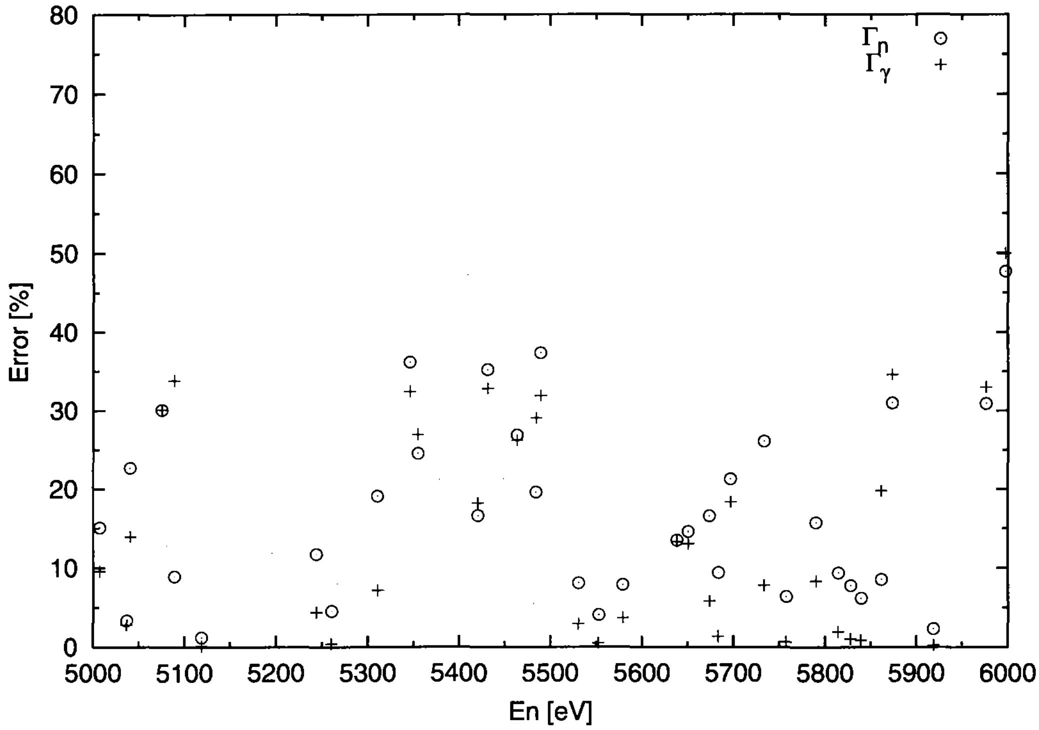


Fig. 18: Calculated uncertainties for ^{238}U in the energy range of 5000–6000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.

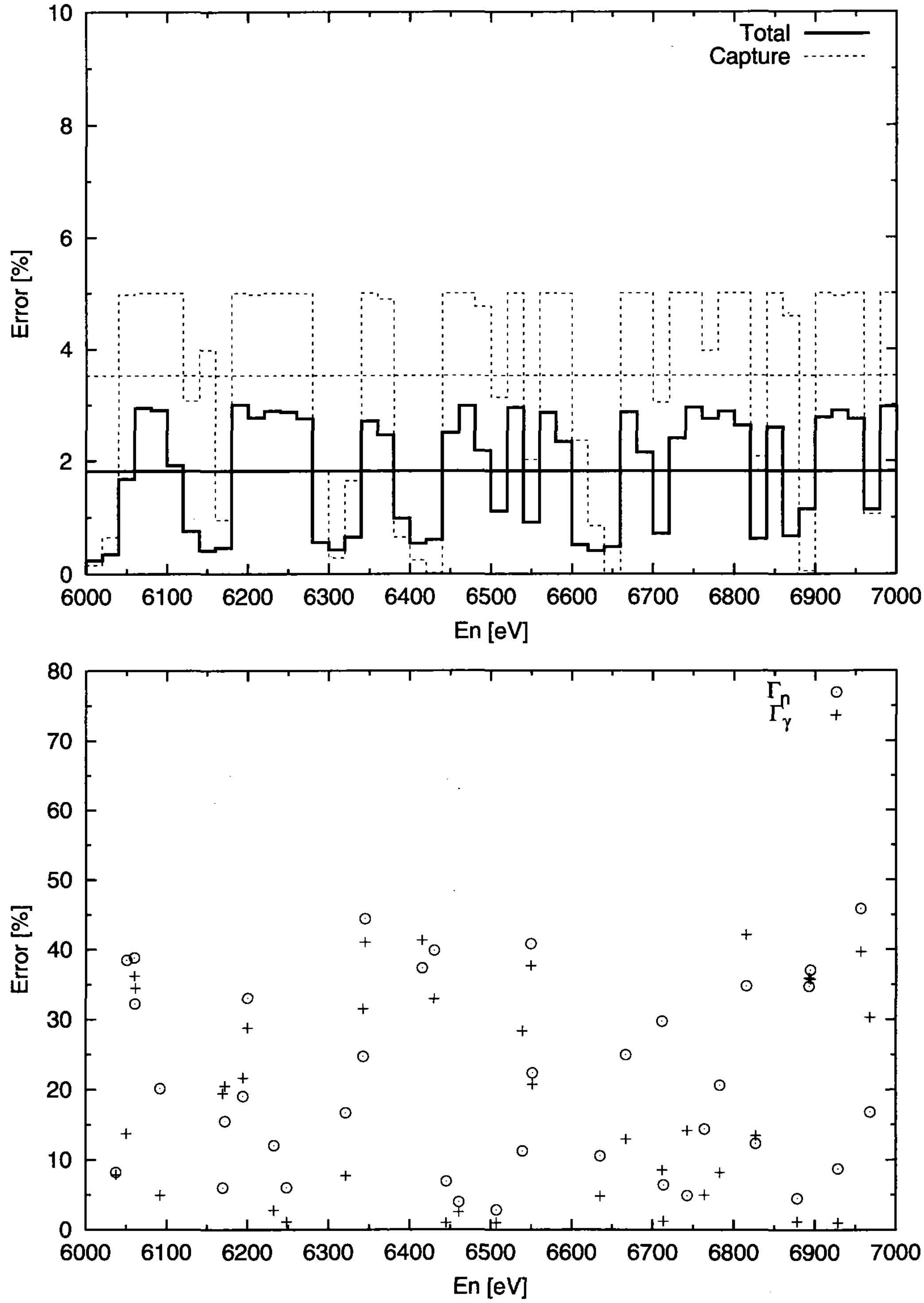


Fig. 19: Calculated uncertainties for ^{238}U in the energy range of 6000–7000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.

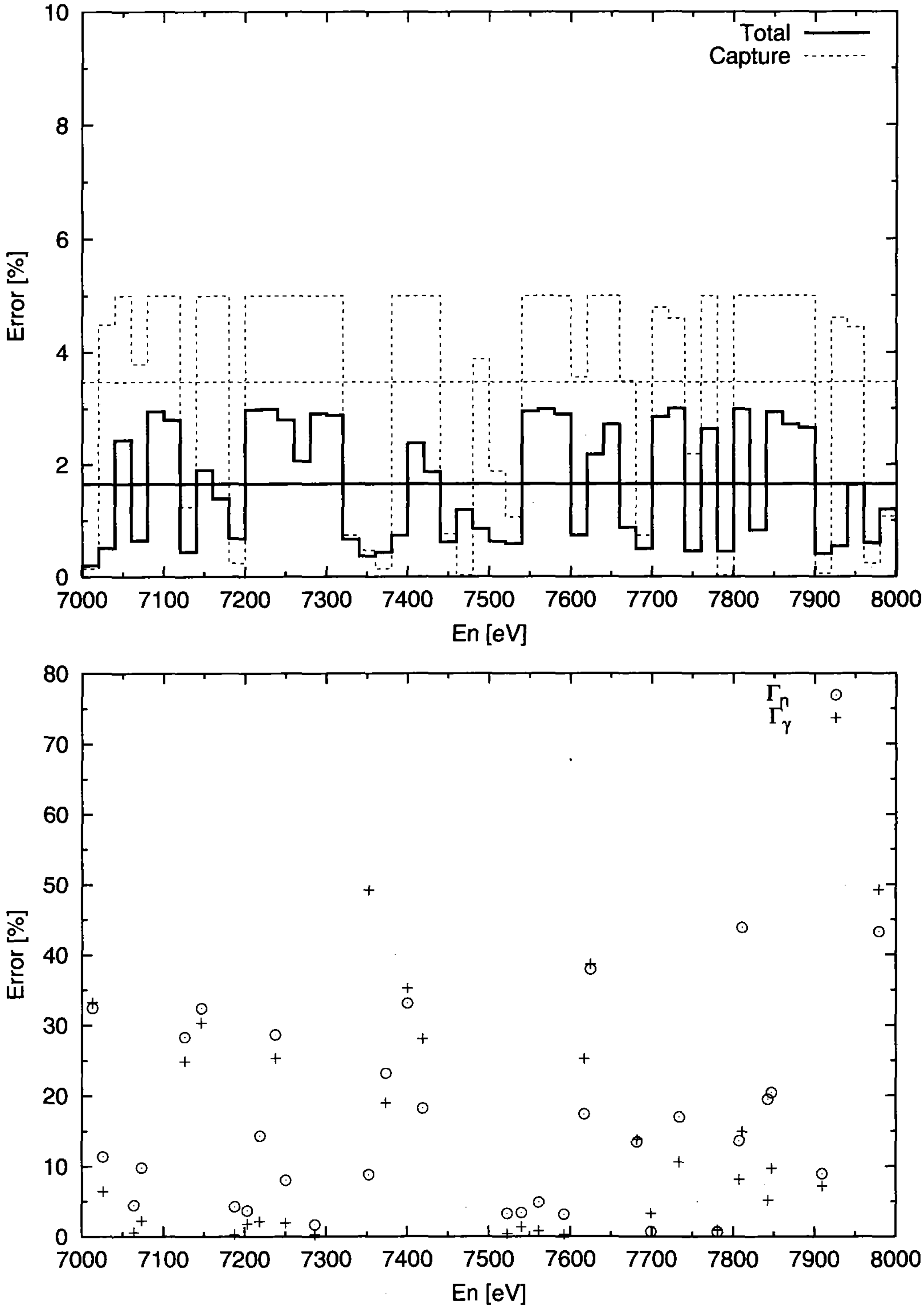


Fig. 20: Calculated uncertainties for ^{238}U in the energy range of 7000–8000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.

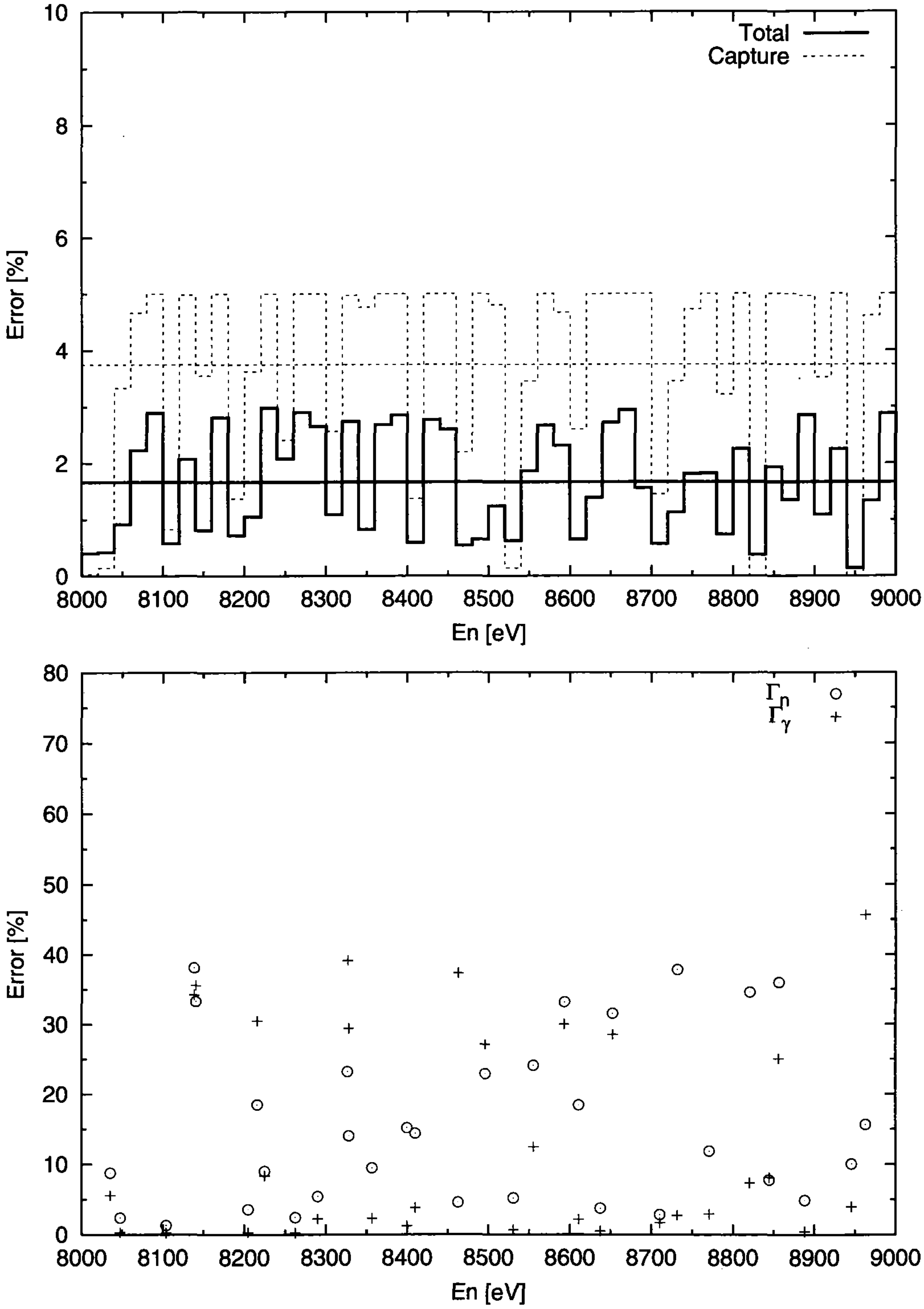


Fig. 21: Calculated uncertainties for ^{238}U in the energy range of 8000–9000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.

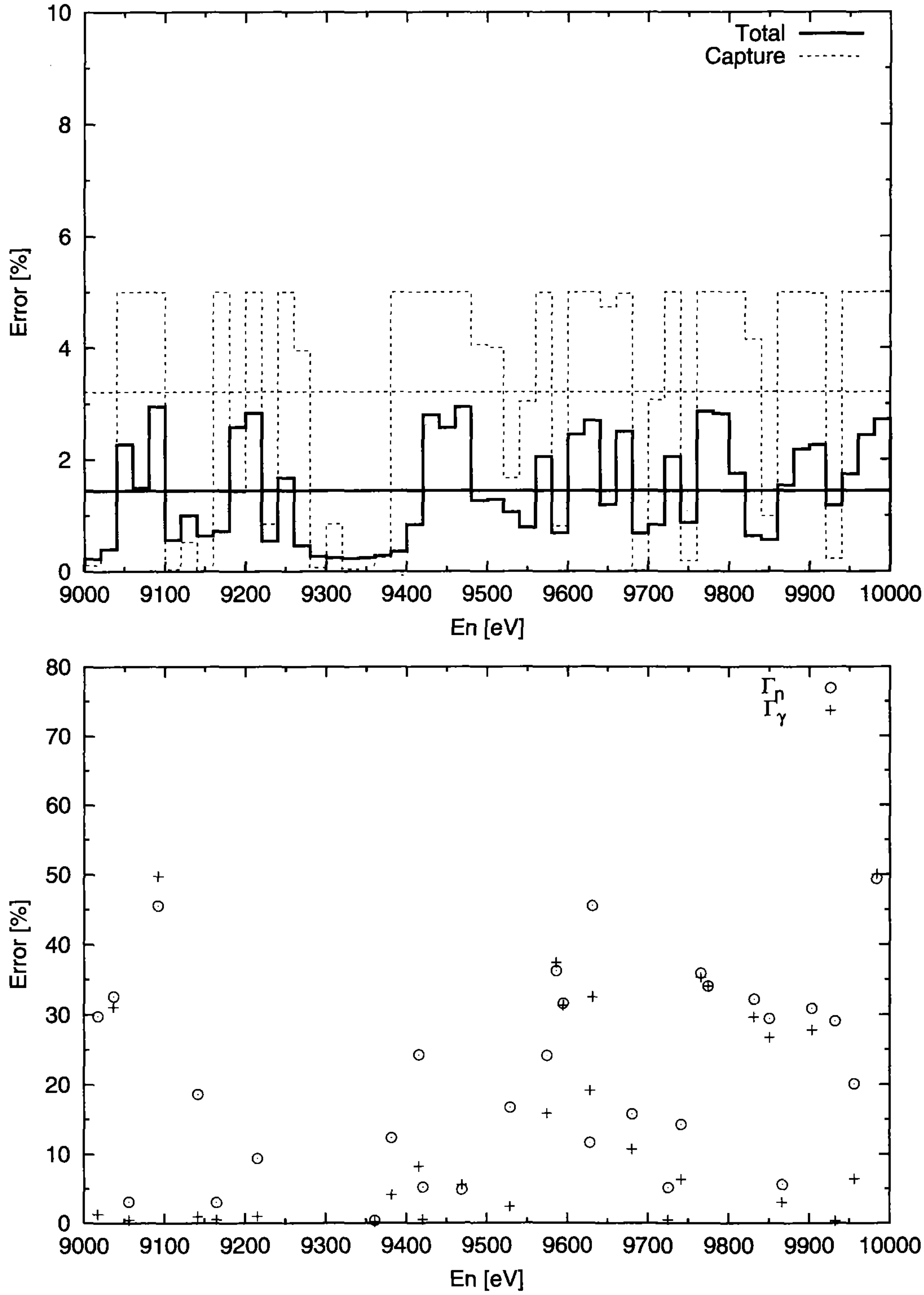
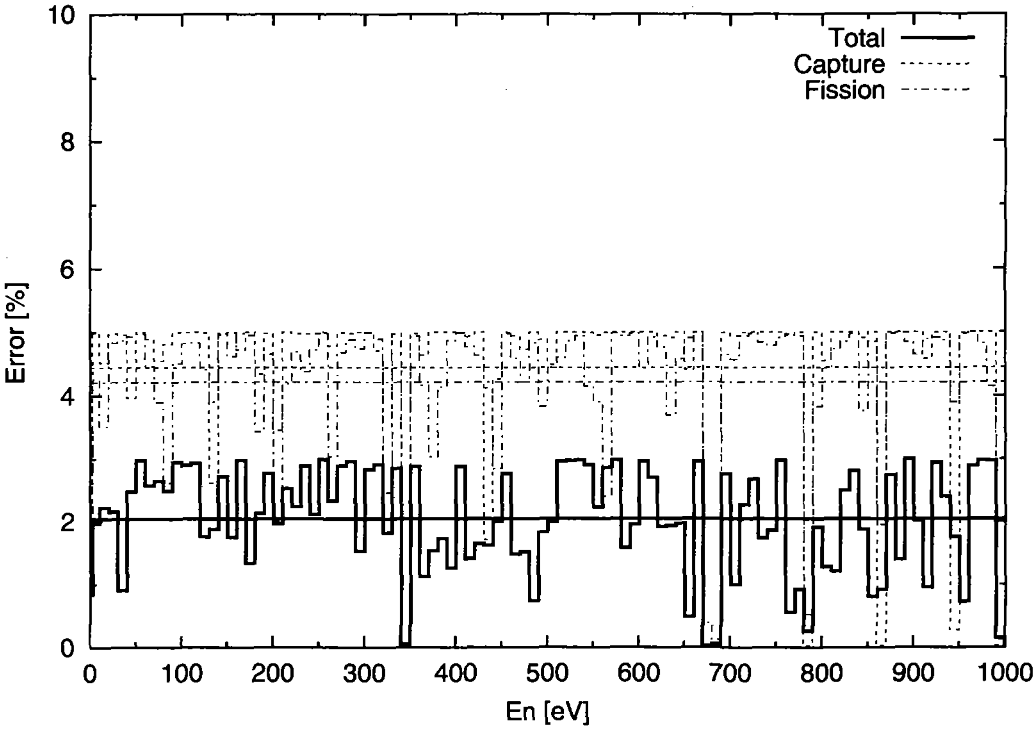


Fig. 22: Calculated uncertainties for ^{238}U in the energy range of 9000–10000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n and Γ_γ.



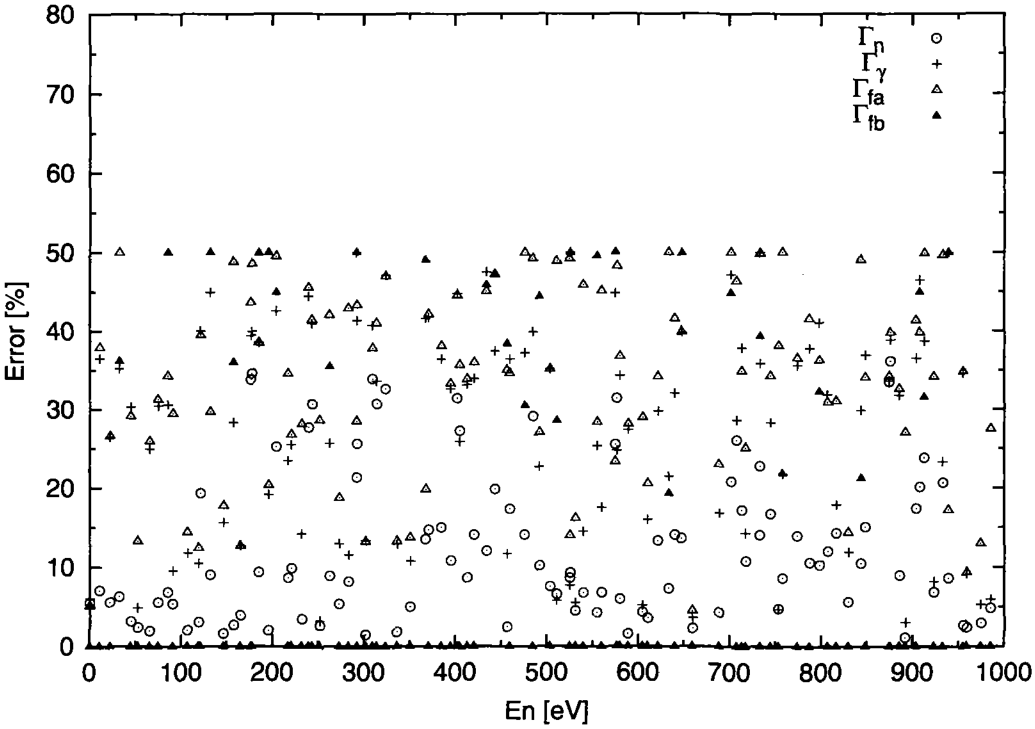
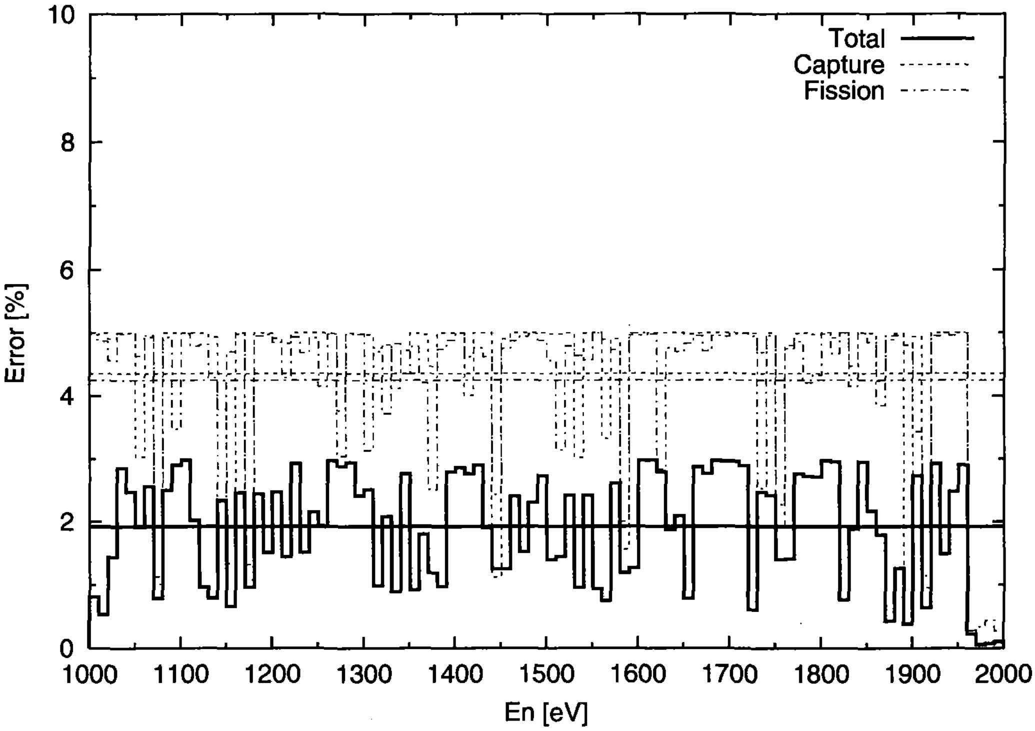


Fig. 23: Calculated uncertainties for ^{239}Pu in the energy range of 0–1000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n, Γ_γ, Γ_{fa}, and Γ_{fb}.



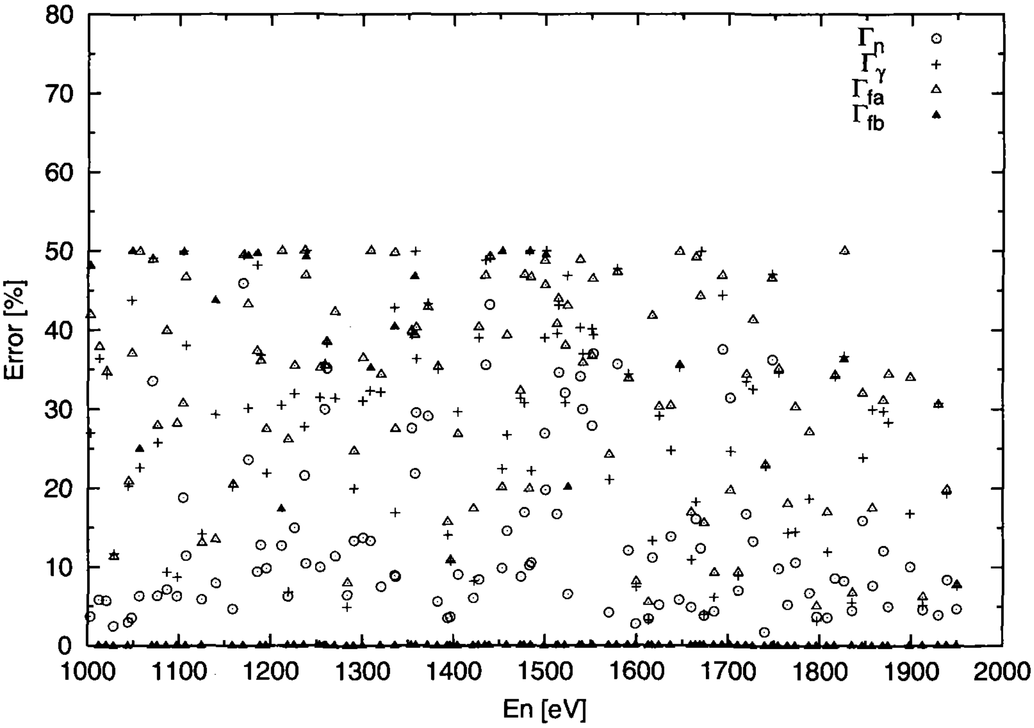
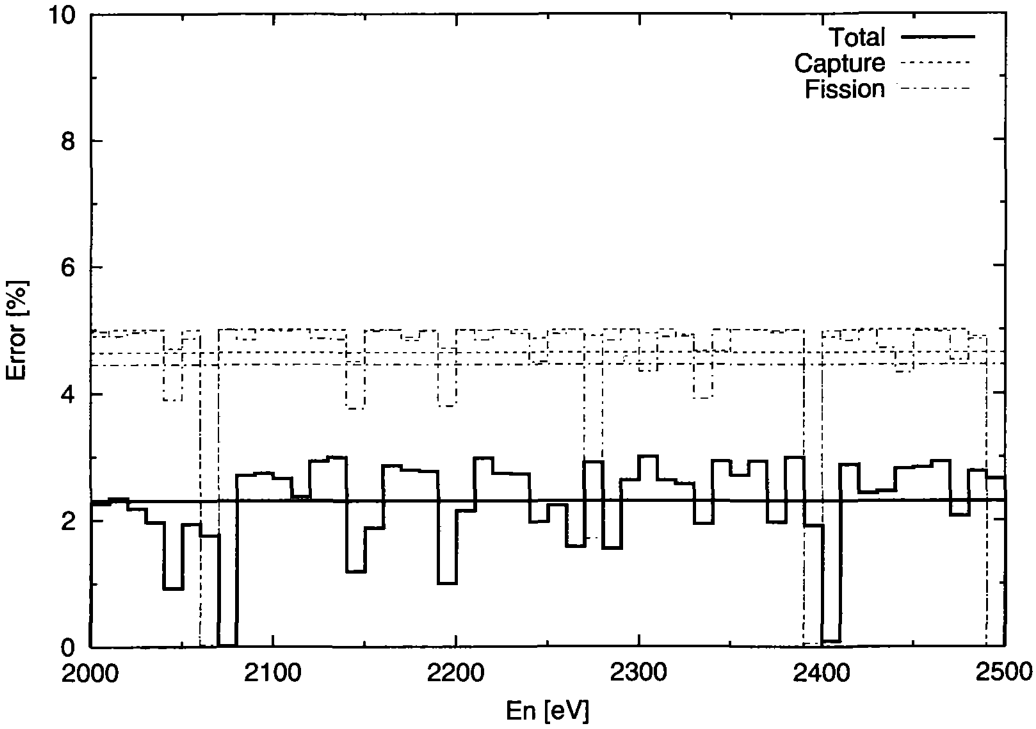


Fig. 24: Calculated uncertainties for ^{239}Pu in the energy range of 1000–2000 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n, Γ_γ, Γ_{fa}, and Γ_{fb}.



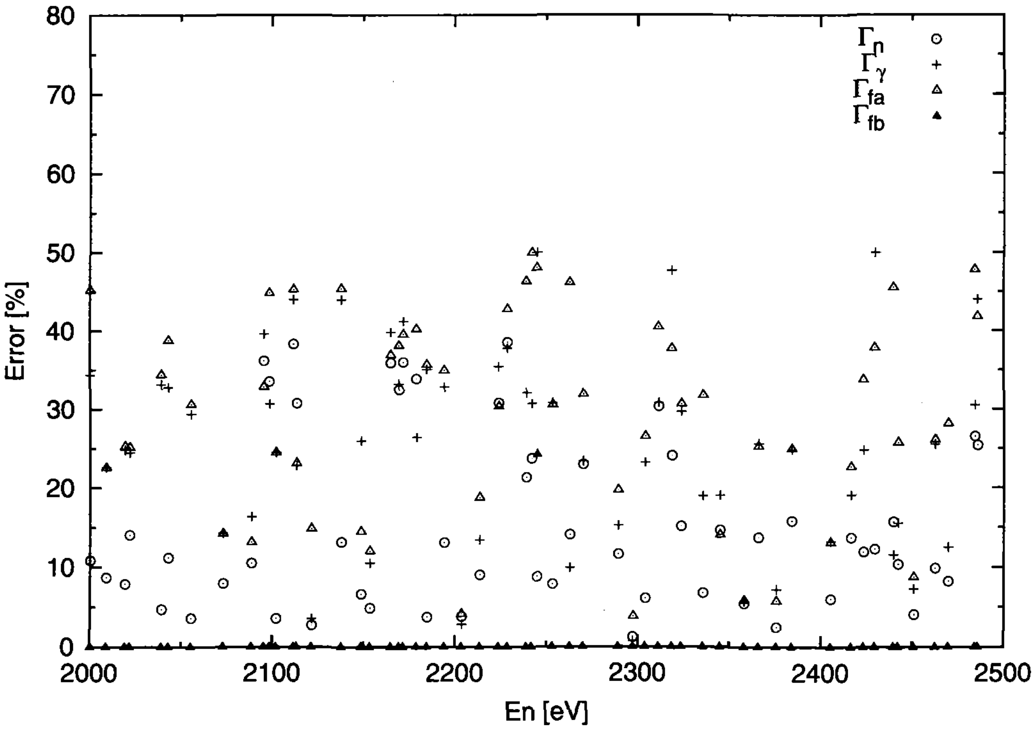


Fig. 25: Calculated uncertainties for ^{239}Pu in the energy range of 2000–2500 eV. The upper drawing is the uncertainties in the total, capture, and fission cross sections, and the lower is for the resonance parameters — Γ_n, Γ_γ, Γ_{fa}, and Γ_{fb}.

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　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

$1\ \mathrm{eV}=1.60218\times10^{-19}\ \mathrm{J}$

$1\ \mathrm{u}=1.66054\times10^{-27}\ \mathrm{kg}$

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^{-1}
力	ニュートン	N	$m\cdot kg/s^2$
圧力，応力	パスカル	Pa	N/m^2
エネルギー，仕事，熱量	ジュール	J	N·m
工率，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^2
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	℃	
光束	ルーメン	lm	cd·sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量当量	シーベルト	Sv	J/kg

表4　SIと共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ \text{Å}=0.1\ \mathrm{nm}=10^{-10}\ \mathrm{m}$

$1\ \mathrm{b}=100\ \mathrm{fm}^2=10^{-28}\ \mathrm{m}^2$

$1\ \mathrm{bar}=0.1\ \mathrm{MPa}=10^5\ \mathrm{Pa}$

$1\ \mathrm{Gal}=1\ \mathrm{cm/s^2}=10^{-2}\ \mathrm{m/s^2}$

$1\ \mathrm{Ci}=3.7\times10^{10}\ \mathrm{Bq}$

$1\ \mathrm{R}=2.58\times10^{-4}\ \mathrm{C/kg}$

$1\ \mathrm{rad}=1\ \mathrm{cGy}=10^{-2}\ \mathrm{Gy}$

$1\ \mathrm{rem}=1\ \mathrm{cSv}=10^{-2}\ \mathrm{Sv}$

表5　SI接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	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，1 eVおよび1 u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では流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閣僚理事会指令では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（$=10^5$dyn）	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa·s（$N\cdot s/m^2$）＝10 P（ポアズ）（g/（cm·s））

動粘度　1 $m^2/s=10^4$St（ストークス）（cm^2/s）

圧力	MPa（=10 bar）	kgf/cm^2	atm	mmHg（Torr）	lbf/in^2（psi）
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

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

1 cal＝4.18605 J（計量法）
　　＝4.184 J　（熱化学）
　　＝4.1855 J　（15 °C）
　　＝4.1868 J（国際蒸気表）

仕事率　1 PS（仏馬力）
　　＝75 kgf·m/s
　　＝735.499 W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

（86年12月26日現在）

Evaluation of Covariances for Resolved Resonance Parameters of ^{235}U, ^{238}U, and ^{239}Pu in JENDL-3.2

古紙配合率100%
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