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NEUTRON NUCLEAR DATA OF ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu ADOPTED IN JENDL-1
—PRELIMINARY RESULTS—

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Neutron Nuclear Data of ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu Adopted in JENDL-1

- Preliminary Results -

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This report reviews the evaluated nuclear data of ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu, adopted in Japanese Evaluated Nuclear Data Library Version 1 (JENDL-1) in April 1976. Part I gives reviews of the smooth cross sections by individual evaluators. Part II explains the compilation of JENDL-1.

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JENDL－1の^{235}U，^{238}U，^{239}Pu，^{240}Pu，^{241}Puの核データ
－中間報告－

日本原子力研究所東海研究所シグマ研究委員会

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1976年4月に，JENDL－1に収納された，^{235}U，^{238}U，^{239}Pu，^{240}Pu，^{241}Puの核データについて概略が述べられている。第1部においては，この5核種の滑らかな断面積に対する評価方法が，各評価者により述べられている。第2部においては，JENDL－1の編集方法が略述されている。

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Introduction

Japanese Evaluated Nuclear Data Library has been developed as the standard domestic evaluated nuclear data library by Nuclear Data Center, JAERI in cooperation with the members* of Japanese Nuclear Data Committee (JNDC). Its first version (JENDL-1) is mainly aimed at providing the data necessary for calculation of fast reactors. Its compilation was started early in 1974 and was tentatively completed in April 1976. A series of benchmark tests are now in progress in order to examine the reliability of JENDL-1.

As for the cross sections of the main fissile or fertile nuclides, i.e., ^{235}U, ^{238}U, ^{239}Pu, ^{240}Pu and ^{241}Pu, intensive works of evaluation have been carried out by the members of JNDC in the last few years. At the time of compilation of JENDL-1, the evaluations in the energy region above 1 keV were already completed** by the authors of this report, i.e., by Matsunobu for ^{235}U, by Kanda for ^{238}U, by Kawai for ^{239}Pu, by Murata for ^{240}Pu and by Kikuchi for ^{241}Pu. On the other hand, only the compilation of the existing experimental data was completed in the evaluations of the resonance parameters.

Under such situations, the compilation group*** of JENDL-1 (JENDL-1 C.G.) mainly adopted the results of the above evaluations for the energy region above a few tens of keV, and adopted the resonance parameters evaluated in other countries according to the recommendation by the JNDC members in charge of evaluations of the parameters. The unresolved resonance parameters were evaluated for all the five nuclides by Kikuchi as his partial charge in the JENDL-1 C.G.. The angular distribution of the secondary neutrons and the average number of neutrons per fission (ν) were evaluated by the above evaluators. On the other hand, the data of ENDF/B-IV were adopted for the energy distribution of the neutrons due to inelastic scattering to continuum levels, the fission yield and fission spectrum.

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* Here the members of JNDC includes the members of the subcommittee and the working group.

** Some parts of the evaluation were made under contract with JAERI.

*** Members of the group are S. Igarasi (Leader), T. Asami, Y. Kikuchi, T. Nakagawa and T. Narita.

This report reviews the data of these five nuclides adopted in JENDL-1 at April 1976. The Part I of this report is devoted to description of the original evaluations above 1 keV. Each section of Part I is written independently by each evaluator and the references are given at the end of each chapter. The Part II gives brief reviews of the compilation of JENDL-1 by JENDL-1 C.G. at April 1976.

It should be noted that the data adopted in JENDL-1 at April 1976 are not final and have the following problems : (1) The evaluation was made independently for each nuclide and the consistencies among the nuclides were not sufficiently taken into consideration. (2) Some evaluations were completed a few years ago and new experimental data have become available since then. (3) The benchmark test in progress suggests some drawbacks of the evaluation particularly on the selection of some experimental data which scatter in a wide range. A simultaneous reevaluation work is now in progress for these nuclides by the authors, and some modification will be made by March 1977 when the final files of JENDL-1 are released. However, it still seems worthwhile to publish the data originally adopted in JENDL-1, since the benchmeark tests have been made on them and the results of the reevaluation will be always compared with the previous ones.

Part I

Evaluation in the Energy Range above 1 keV

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1.1. URANIUM-235

Hiroyuki MATSUNOBU

1.1.1. Introduction

The nuclear data of ^{235}U have been measured in many countries, and a number of available data have been accumulated up to the present day. In this work, many new experimental data published after 1965 were compiled on the basis of the CINDA list.[1] The evaluation work was performed on the basis of the compiled experimental data.

The nuclear data of ^{235}U evaluated in this work are total cross section, α-value (capture to fission cross section ratio), elastic and inelastic scattering cross sections, (n,2n) and (n, 3n) cross sections, and ν_p-value (prompt neutron number per fission). Capture cross section of ^{235}U was derived from the evaluated α-value and fission cross section. These nuclear data were evaluated in the energy range 1 keV to 15 MeV except for α-value which was evaluated below 1 MeV. The angular distribution of elastic scattering cross section was calculated by the ELIESE-3[2] code based on the optical model, and the Legendre coefficients were obtained at each energy point. The detailed description on evaluation of the above quantities is given in the following sections.

1.1.2. Total Cross section

Many experimental data on total cross section of ^{235}U have been published up to the present day. In this work, nine new data published after 1965 were compiled and examined in detail. In particular, the problems of error estimation of each data and discrepancies among the data were checked. As the result of examination, the data measured by Uttley[3] between 1 keV and 1 MeV, by Schwartz[4] et al. between 500 keV and 15 MeV, and by Foster and Glasgow[5] between 2.5 MeV and 15 MeV were finally adopted as an object of evaluation in this work. The discrepancies of these data are satisfactorily small in each overlapping energy range, and their experimental errors are also small compared with those of the other data.

The cross section curve was obtained by applying the least χ^2 fitting method with polynomials in six energy intervals appropriately divided. The boundaries of these energy intervals were chosen at five energy points so as to connect smoothly the fitting functions from both sides. The evaluated total cross section is compared with the experimental data as well as the data of ENDF/B-IV in Fig. 1.1.1. They agree with each other. By the use of the cross section thus evaluated, the optical potential parameters were searched for with the TOTAL code.[6] These parameters will be used for the evaluation of elastic and inelastic scattering cross sections, and are tabulated in Table 1.1.1. The total cross section calculated from these parameters agree with the evaluated one as shown in Fig. 1.1.1. This suggest the applicability of the obtained parameters.

1.1.3. Fission Cross Section

The experimental data on fission cross section of ^{235}U are very abundant. Therefore, many new data published after 1965 were compiled and examined in this work. The measurement of fission cross section is divided into two kinds of method, that is, relative measurement and absolute measurement. Many kinds of standard cross sections are used in relative measurements and it is very difficult to renormalize these data using a kind of standard cross section. Therefore, in this work, the data by relative measurements were used to determine the shape of fission cross section, and the data by absolute measurements were used to determine the absolute value of fission cross section.

Comparing the compiled experimental data in the energy range below 100 keV, it is noticed that some remarkable discrepancies exist among the data as shown in Figs. 1.1.2 and 1.1.3. However, most of the data published after 1965 agree fairly well with each other and show lower values than Davey's evaluated data.[7),8)] In particular, the agreement among the data is good in the energy range from 55 to 80 keV. Hence these new data were adopted in this energy range. Above 100 keV, the scatters among the experimental data are fairly large as shown in Fig. 1.1.4. Extremely low data by 68 Pönitz[9] were omitted in this work. The data by 72 Käppeler[10] between 500 and 700 keV were also abandoned considering the global shape of fission cross section. The agreement among the experimental data is satisfactory near 1 MeV. In the energy range above 6 MeV, the experimental data are comparatively poor except the data near 14 MeV.

The experimental data adopted as an object of evaluation for fission cross section are those of the following authors.

1 ∿10 keV	:	Patrick et al.[11], and Lemley et al.[12]
10 ∿100 keV	:	White[13], Perkin et al.[14], Knoll and Pönitz[15], Szabo et al.[16),17], Patrick et al.[11], Lemley et al.[12], and Pönitz[18]
100 keV ∿1 MeV	:	White[13], Macklin et al.[19], Szabo et al.[16),17], Käppeler[10),20], Lemley et al.[12], Pönitz[18], and Gilliam and Knoll[21]
1 ∿ 20 MeV	:	White[13], Hansen et al.[22),23], Käppeler[20], and Pönitz[18]

The cross section curve based on the adopted experimental data was obtained by using the least χ^2 fitting method with polynomials. The energy range from 1 keV to 20 MeV was divided into ten intervals taking account of the shape of fission cross section, the distribution of data points, and smooth connecting condition of the fitting functions of both sides at each boundary. The order of polynomials was decided according to the shape in each interval, and polynomials of the second, third, and fourth order for neutron energy were used in this work. The result of present evaluation is shown with the experimental data and other evaluated data in Figs. 1.1.2, 1.1.3 , 1.1.4 , and 1.1.5.

1.1.4. α-value and Capture Cross Section

α-value (capture to fission cross section ratio) is an important quantity in order to obtain capture cross section, because the latter has not been measured independently. The data of α-value have been measured in the limited energy range below 1 MeV due to difficulties of the measurement in the high energy range. Accordingly, they are most abundant in the low energy range 15 to 40 keV, and become scarce with increase of neutron energy. The discrepancies and scatters of the experimental data are remarkable in the low energy range, and the experimental errors are large over the whole energy range. Therefore, it is considerably difficult to select the experimental data appropriate as an object of evaluation. As the result of examination on the compiled data, the following data were adopted for each energy range.

1 ∿ 10 keV	:	Uttley[3], Ryabov et al.[24], Czirr and Lindsey[25], Muradjan et al.[26], Kurov et al.[27], Vorotnikov et al.[28], Bandl et al.[29], and Perez et al.[30]
10 ∿ 100 keV	:	Hopkins and Diven[31], Weston and de Saussure[32]

Lottin et al.[33], Ryabov et al.[24], Kononov et al.[34], Czirr and Lindsey[25], Kurov et al.[27], Vorotnikov et al.[28], and Bandl et al.[29]

100 keV ∿ 1 MeV : Hopkins and Diven[31], Weston and de Saussure[32], Lottin et al.[33], Kononov et al.[34], and Vorotnikov et al.[28]

The evaluated curve of α-value was obtained by applying the least χ^2 fitting method with polynomials of the fourth order for neutron energy. The energy range from 1 keV to 1 MeV was divided into four intervals according to the shape, distribution of the adopted data, and smooth connecting condition as mentioned in the previous sections. The result of evaluation is shown in Fig. 1.1.6 with the experimental data.

The evaluated value of capture cross section was derived from the evaluated α-value and fission cross section in the energy range below 1 MeV. Above 1 MeV no experimental data are available. Therefore the data of ENDF/B-III were tentatively adopted, because the data of ENDF/B-III showed a good agreement with the evaluated capture cross section at 1 MeV as seen in Fig. 1.1.7.

1.1.5. Elastic and Inelastic Scattering Cross Sections

The experimental data of elastic and inelastic scattering cross sections are poor compared with those of total and fission cross sections and α-value, and the energy range in which the experimental data exist is limited to a narrow region.

There exist only five sets of the available data between 300 keV and 2.3 MeV for elastic scattering cross section. These five data sets were measured by Allen et al.[35], Cranberg and Levin[36], Smith[37], Smith and Whalen[38], and Knitter et al.[39] The discrepancies among these data sets are small, while some scatters of the data are noticed.

On the other hand, there exist also five sets of the available data between 130 keV and 7.5 MeV for inelastic scattering cross section. However, the number of data points is less than that of elastic scattering cross section. These five data sets were measured by Andreev,[40] Armitage et al.[41], Drake[42], Batchelor and Wyld[43], and Knitter et al.[39]. The discrepancies among these data sets are considerably large between 1 and 3 MeV.

The evaluation of elastic and inelastic scattering cross sections was done by the following procedures. At first, the evaluation in the energy range in which the data were measured was performed on the basis of the experimental data. The cross section curves were obtained by using the least χ^2 fitting method with polynomials between 200 keV and 1.5 MeV for elastic scattering cross section, and between 1.5 and 7.5 MeV for inelastic scattering cross section, respectively. The values of inelastic scattering cross section in the former energy range, and of elastic scattering cross section in the latter energy range were obtained by subtracting other evaluated cross sections from total cross section in order to keep the consistency. For simplicity, this procedure is referred as subtraction method in the following description.

Next, the elastic scattering cross section was obtained in the energy range between 11 and 15 MeV by calculation using the ELIESE-3 code[2] based on the optical model with the parameters in Table 1.1.1. The cross section curve between 7.5 and 11 MeV was determined by eye-quide method. The inelastic scattering cross section in the energy range 7.5 to 15 MeV was obtained by subtraction method as is mentioned above.

In the energy range 1 to 200 keV, the inelastic scattering cross section was determined by drawing a smooth curve from the threshold energy point with eye-quide method. The elastic scattering cross section in this energy range was obtained by subtraction method.

The present procedure is summarized as follows :

Energy Range	σ_{el}	σ_{in}
1∿200 keV	$\sigma_{el}=\sigma_t-\sigma_f-\sigma_c-\sigma_{in}$	Eye-quide Method
200 keV∿1.5 MeV	Least χ^2 Fitting Method	$\sigma_{in}=\sigma_t-\sigma_f-\sigma_c-\sigma_{el}$
1.5 MeV∿7.5 MeV	$\sigma_{el}=\sigma_t-\sigma_f-\sigma_c-\sigma_{n,2n}-\sigma_{in}$	Least χ^2 Fitting Method
7.5 MeV∿11 MeV	Eye-quide Method	$\sigma_{in}=\sigma_t-\sigma_f-\sigma_c-\sigma_{n,2n}-\sigma_{el}$
11 MeV∿15 MeV	Optical Model Calculation	$\sigma_{in}=\sigma_t-\sigma_f-\sigma_c-\sigma_{n,2n}-\sigma_{n,3n}-\sigma_{el}$

The results of evaluation for elastic and inelastic scattering cross sections are shown in Fig. 1.1.8 with the experimental data and the data of ENDF/B-IV.

The angular distribution of elastic scattering cross section was calculated by the ELIESE-3 code,[2] and the Legendre coefficients were obtained at each energy point. For inelastic scattering cross section, the isotropic distribution was assumed on the basis of the experimental data.

1.1.6. (n,2n) and (n,3n) Cross Sections

The experimental data on (n,2n) and (n,3n) cross sections are very poor. There is only one available set of data by Mather et al.[44] Their data are given at 7.1, 8.0, 12.4, and 14.1 MeV for (n,2n) cross section, and at 12.4 and 14.1 MeV for (n,3n) cross section. Accordingly, it is difficult to evaluate these cross sections with high reliability on the basis of the above experimental data whose number is too few to be fitted with polynomials. Therefore, the cross section curves were drawn with eye-guide method smoothly connecting the data points and the threshold energy point. The curves of (n,2n) and (n,3n) cross sections are shown in Fig. 1.1.9 with the experimental data by Mather et al.

1.1.7. ν_p-value

ν_p-value (prompt neutron number per fission) is one of the most important quantities as well as fission cross section and α-value in the field of reactor physics and reactor design. Reflecting this situation, many experimental data have been accumulated up to the present day. In particular, they are abundant in the low energy range below 2 MeV. However, the discrepancies among the data and the scatters of each data are considerably large in the energy range up to 7.5 MeV. On the other hand, the discrepancies and the scatters in the energy range above 8 MeV are small compared with those in the low energy range, while the number of data is rather small. The experimental error of ν_p-value is fairly small over the whole energy range except some data.

The energy dependence or the linearity of ν_p-value will be discussed in three ranges of neutron energy. In the energy range below 2.5 MeV, the linearity is not clear. The existence of the structure has been recently discussed in this energy range, but no definite conclusion has yet been obtained due to the discrepancies and the experimental errors of data. The status of the experimental data is shown in Fig. 1.1.10. Accordingly, the linearity of the energy dependence was assumed in this work for simplicity. The linearity is much clearer in the energy range from 2.5 to 7.5 MeV than in the lower energy range, although the discrepancies and the scatters of data are considerably large. The gradient of ν_p-value for neutron energy is largest in this energy range. The linearity is very clear in the energy range from 7.5 to 15 MeV, and the gradient is somewhat gentle compared with that in the energy range between 2.5 and 7.5 MeV.

On the basis of the facts mentioned above, the evaluation of ν_p-value was performed by applying the least χ^2 fitting method with a linear function in the above three intervals. The experimental data by the following authors were adopted in order to determine the coefficients of three fitting functions.

40 keV $\sim$ 2.5 MeV	:	Colvin and Sowerby[45], Meadows and Whalen[46], Kuznetsov and Smirenkin[47], Prokhorova and Smirenkin[48], Soleilhac et al.[49], Boldman and Walsh[50], Prokhorova et al.[51], and Frehaut et al.[52]
25 MeV $\sim$ 7.5 MeV	:	Colvin and Sowerby[45], Conde and During[53], Prokhorova and Smirenkin[48], and Frehaut et al.[52]
7.5 MeV $\sim$ 15 MeV	:	Conde and Holmberg[54], Conde and During[53], Conde[55], and Frehaut et al.[52]

The linear functions thus obtained are :

$$\begin{aligned} \nu_p &= 0.1099\ E\ (\mathrm{MeV}) + 2.426 && \text{in } 1\ \mathrm{keV} \sim 2.48\ \mathrm{MeV} \\ &= 0.1673\ E\ (\mathrm{MeV}) + 2.283 && \text{in } 2.48 \sim 7.5\ \mathrm{MeV} \\ &= 0.1358\ E\ (\mathrm{MeV}) + 2.522 && \text{in } 7.5 \sim 15\ \mathrm{MeV} \end{aligned}$$

The result of evaluation for ν_p-value is shown in Figs. 1.1.10 and 1.1.11 with the experimental data.

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Table 1.1.1. Optical Potential Parameters for ^{235}U

Real Part

$V = 40.0512 - 0.2301\ E + 0.0109\ E^2$ (MeV)

$r_o = 1.3526$ (fm)

$a = 0.4972$ (fm)

Imaginary Part (Surface type)

$W_s = 8.7702$ (MeV)

$r_s = 1.3466$ (fm)

$a = 0.4169$ (fm)

Spin-orbit Force

$V_{so} = 13.6935$ (MeV)

$r_{so} = 1.0885$ (fm)

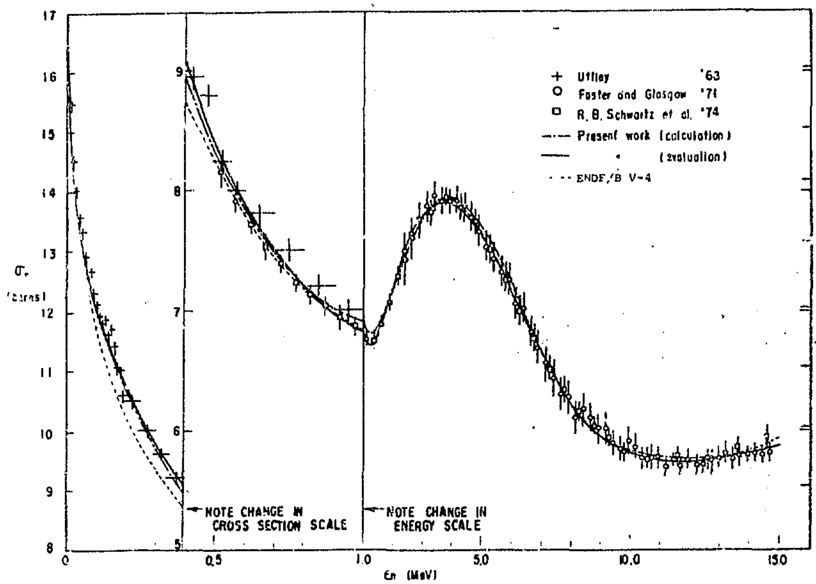
$a = 0.5003$ (fm)

Table 1.1.2. Level Density Parameters for ^{235}U

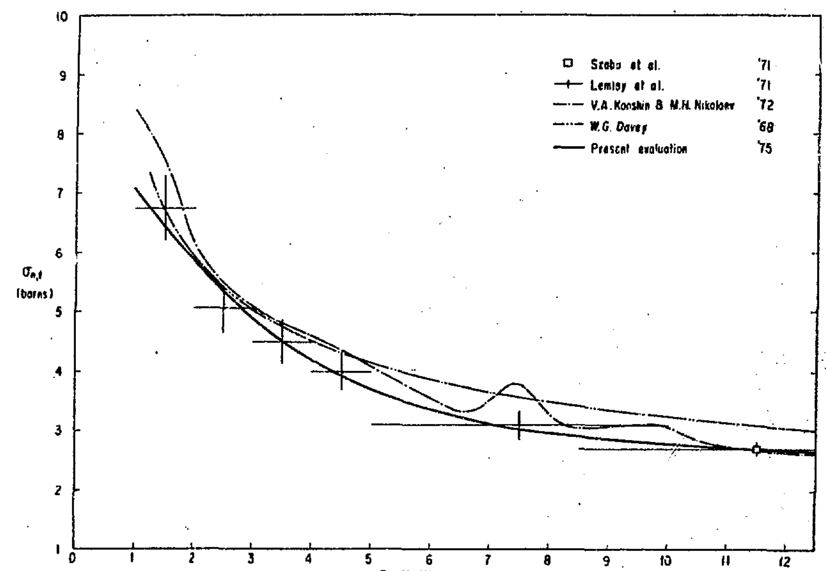
	Target nucleus	Compound nucleus
a (MeV^{-1})	28.1785	28.2118
Δ (MeV)	0.69	1.18
α (MeV$^{-1/2}$)	29.5136	29.7057
E_x (MeV)	3.8283	4.3156
C_o	5947.45	5979.82
S_n (MeV)	5.3057	6.5457

Table 1.1.3 Level Scheme of ^{235}U

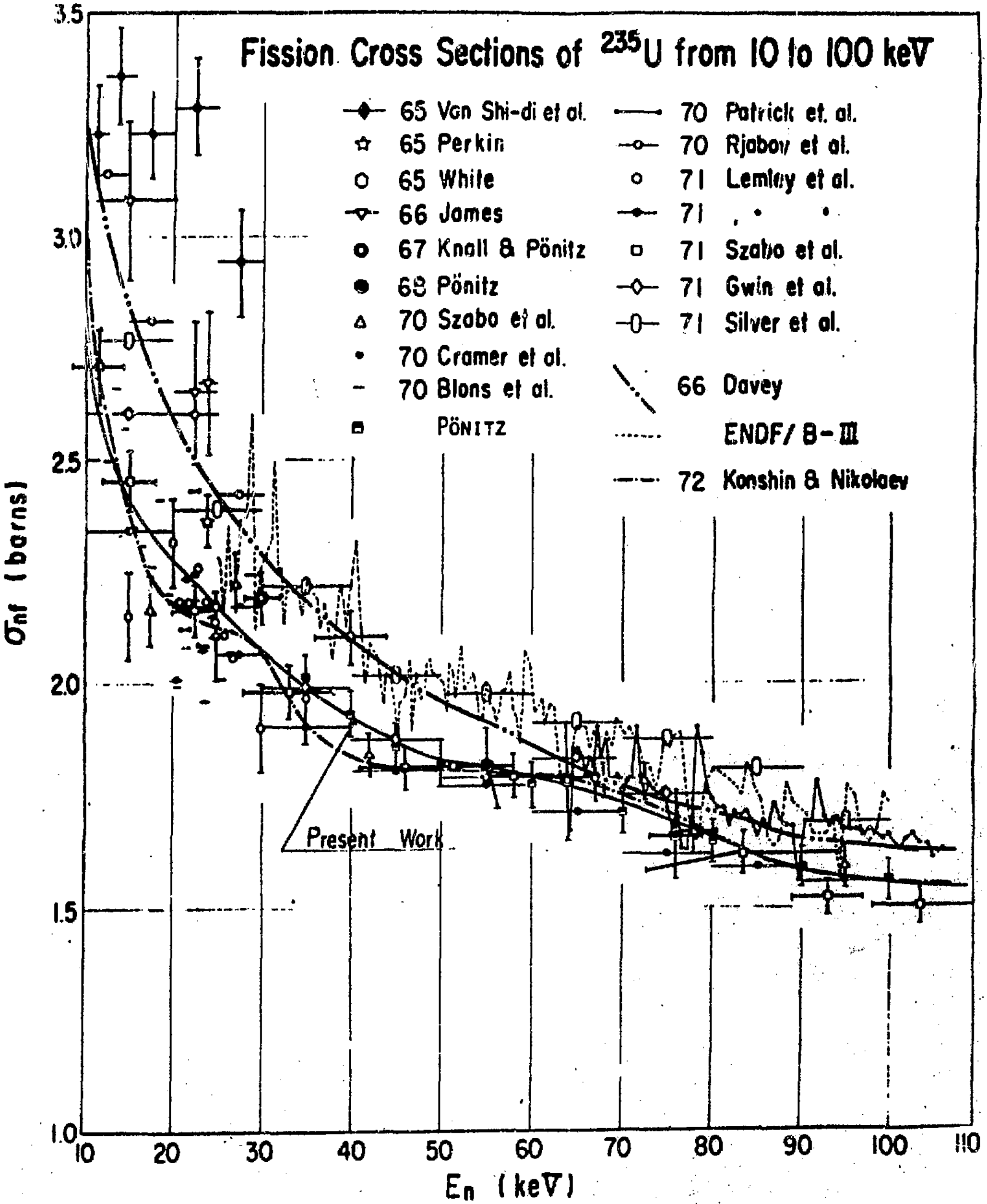
Excitation (keV)	Spin	Parity
0	7/2	-
0.00008	1/2	+
0.0131	3/2	+
0.0462	9/2	-
0.0517	5/2	+
0.0817	7/2	+
0.1030	11/2	-
0.1293	5/2	+
0.1504	9/2	+
0.170	13/2	-
0.1714	7/2	+
0.1970	11/2	+
0.2253	9/2	+
0.248	15/2	-
0.2946	13/2	+
0.3329	5/2	+
0.3673	7/2	+
0.3935	3/2	+
0.4145	9/2	+
0.4268	5/2	+
0.4743	7/2	+
0.5333	9/2	+
0.652	3/2	-
0.658	1/2	+
0.771	1/2	+



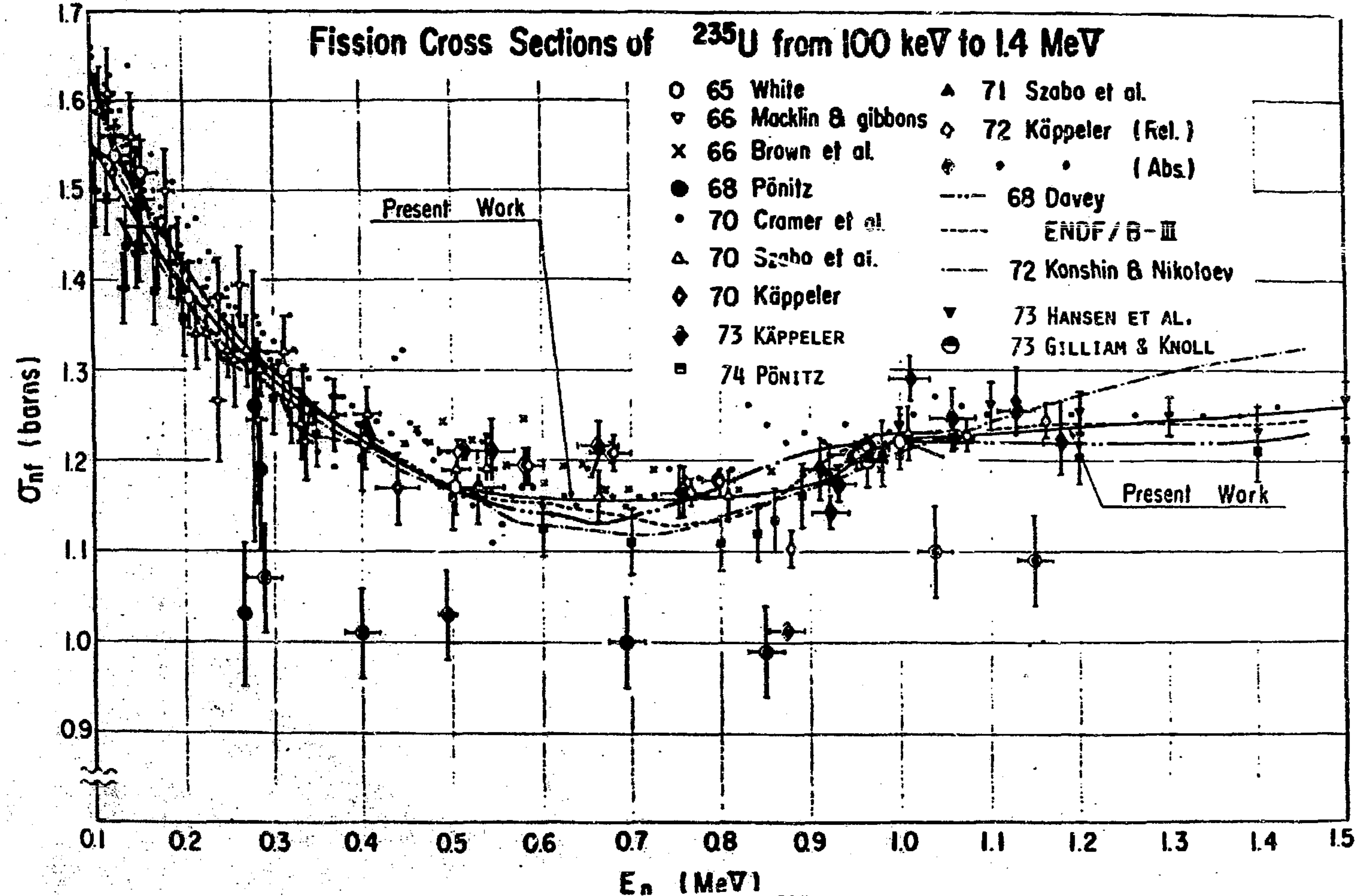
1.1.1. Total cross section of ^{235}U



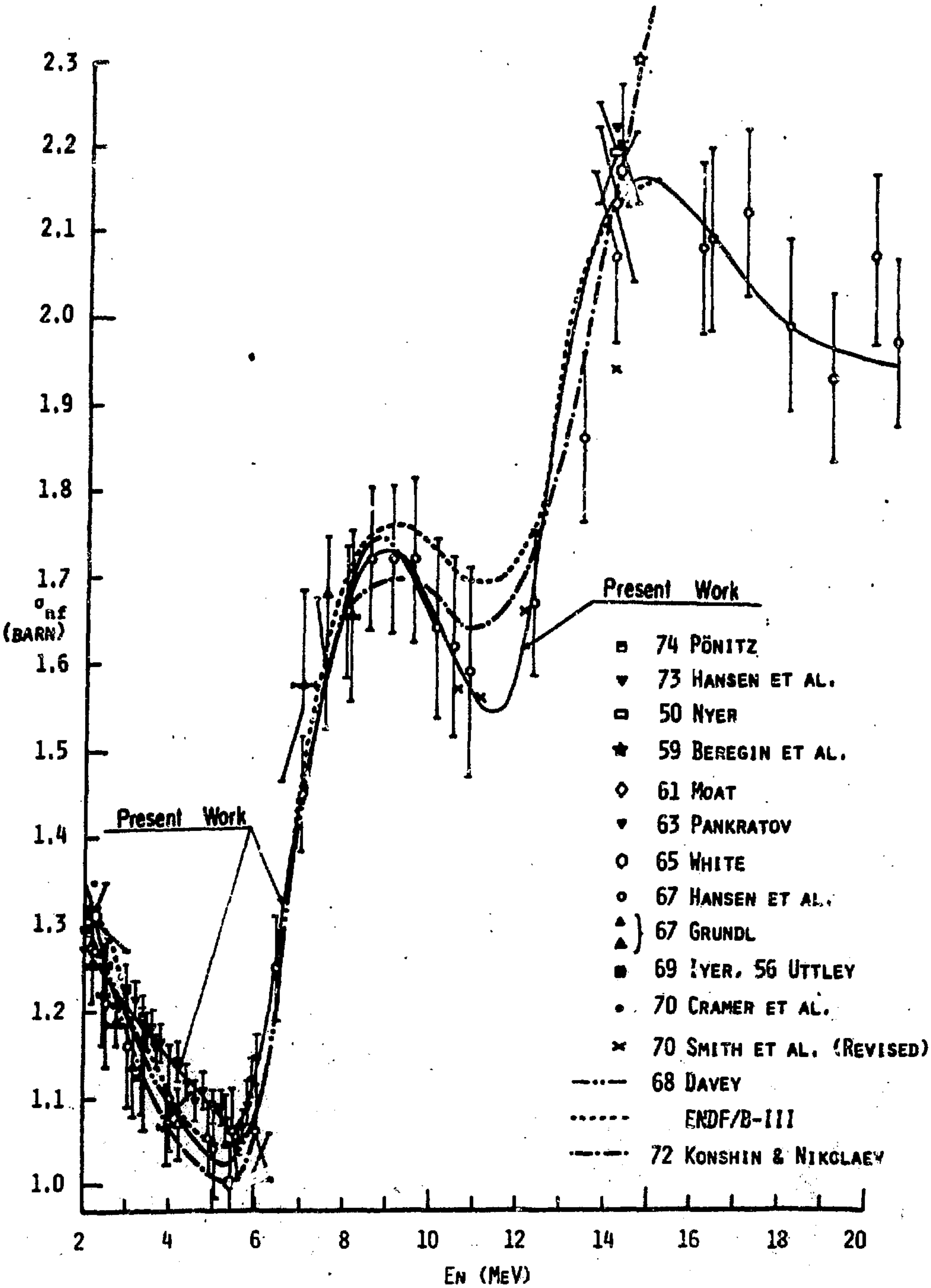
1.1.2. Fission cross section of ^{235}U from 1 to 12 keV



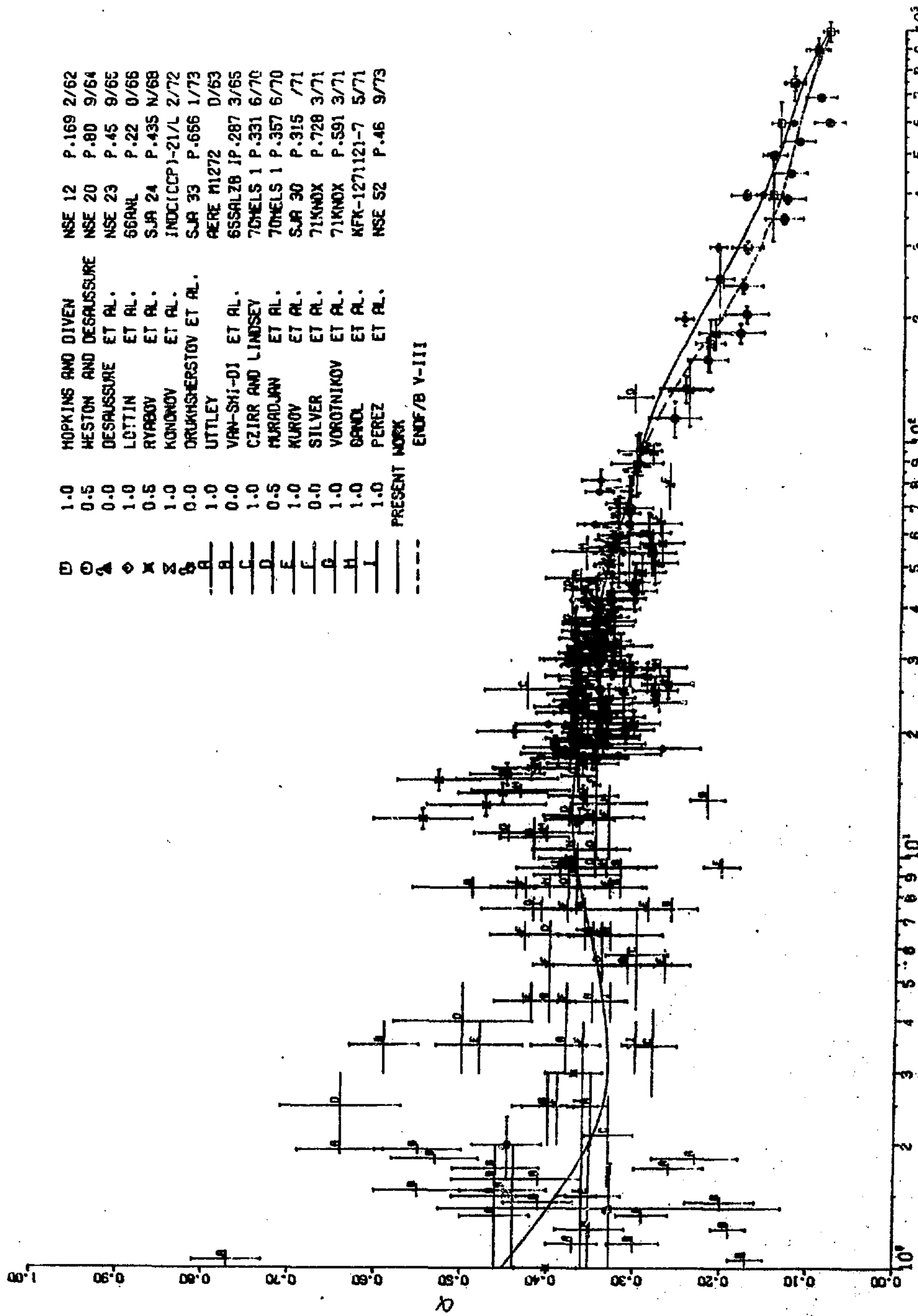
1.1.3. Fission cross section of ^{235}U from 10 to 100 keV



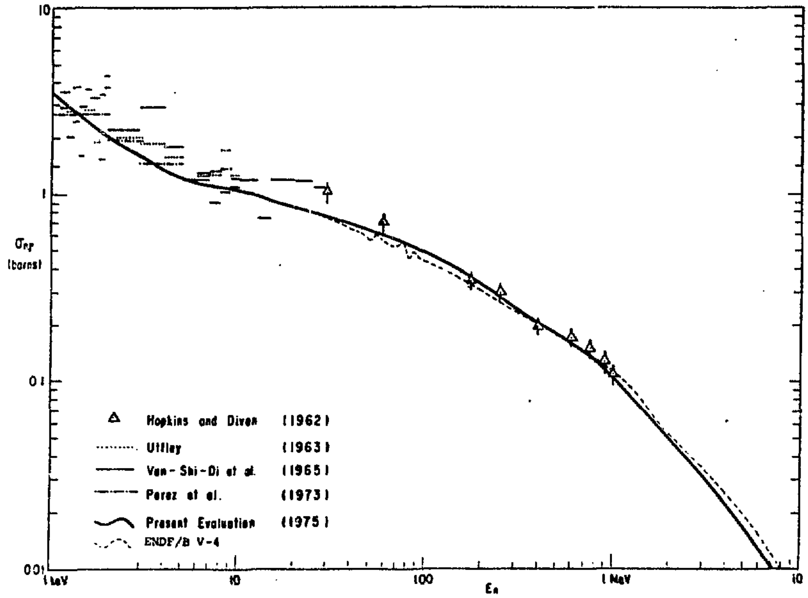
1.1.4. Fission cross section of ^{235}U from 100 keV to 1.4 MeV



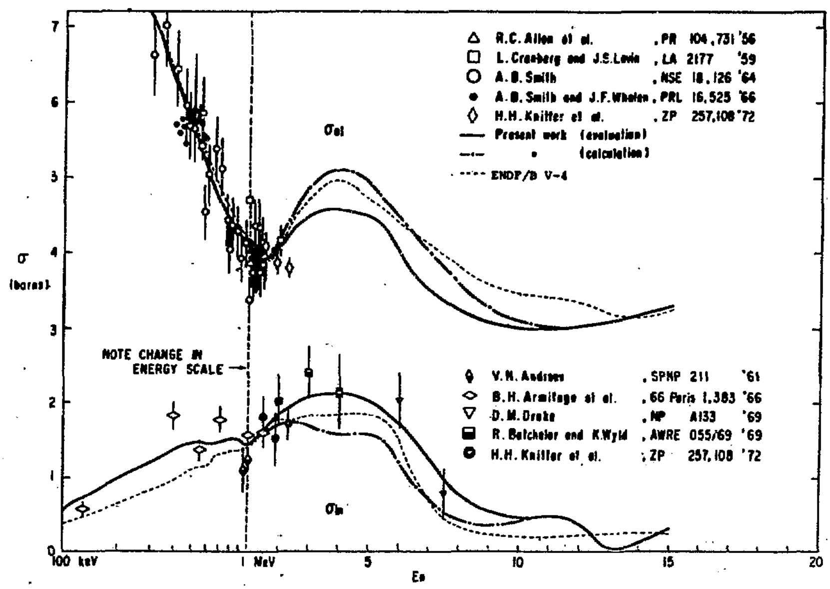
1.1.5. Fission cross section of ^{235}U from 2 to 20 MeV



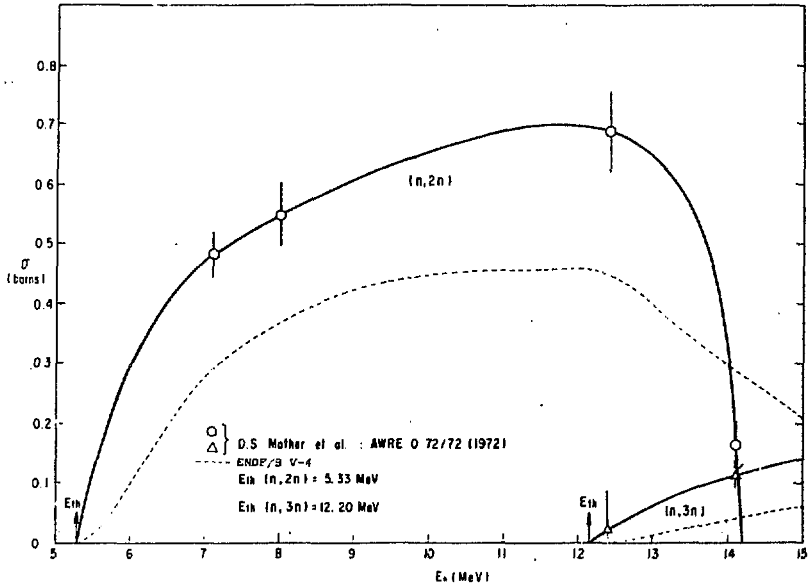
1.1.6. α-value of ^{235}U from 1 keV to 1 MeV



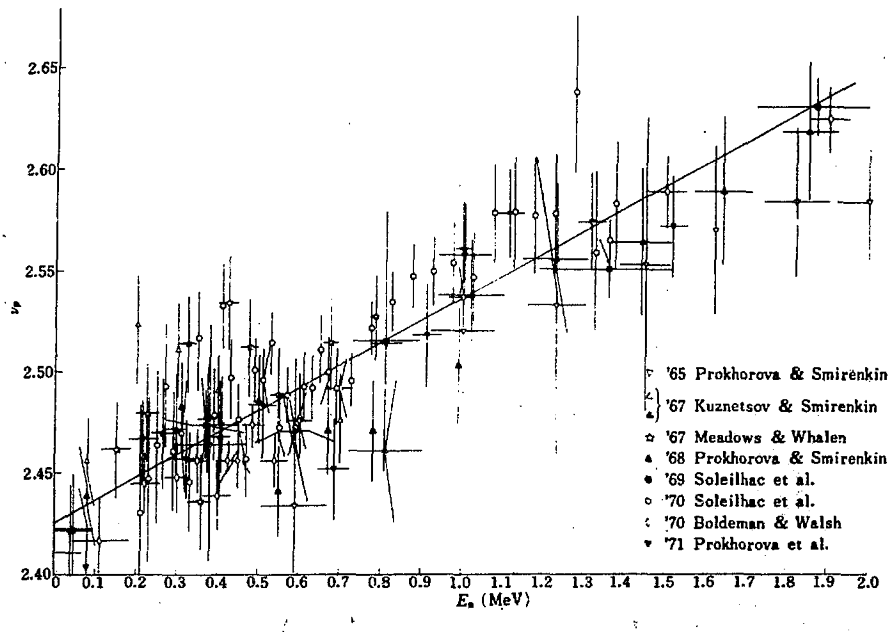
1.1.7. Capture cross section of ^{235}U from 1 keV to 1 MeV



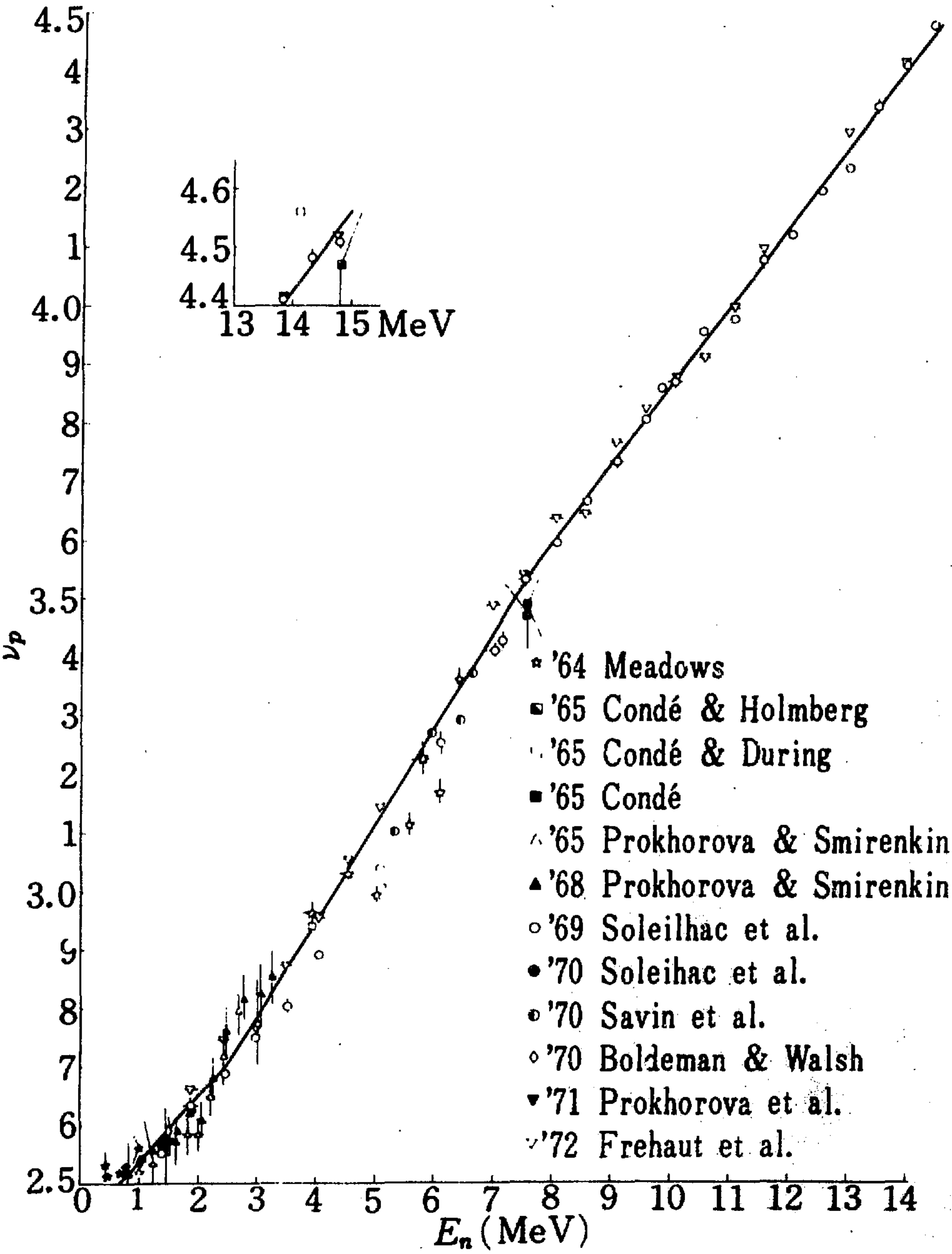
1.1.8. Total, elastic and inelastic scattering cross sections of ^{235}U



1.1.9. (n,2n) and (n,3n) cross sections of ^{235}U



1.1.10 ν_p of ^{235}U below 2 MeV



1.1.11 ν_p of ^{235}U from 1 MeV to 10 MeV

1.2. URANIUM-238

Yukinori KANDA

1.2.1. Introduction

The evaluation was made in 1973 for the energy range between 1 keV and 20 MeV. The main part of this work was already published[1] and therefore a brief review is given here as a document on JENDL-1. The evaluated quantities are the total, capture, fission, (n,2n), (n,3n), elastic and inelastic scattering cross sections. The experimental data reported till 1972 were adopted in this work. The data of relative measurements were renormalized to the common standard cross sections, i.e., the fission cross sections of ^{235}U evaluated by Davey[2], and the scattering cross sections of hydrogen by Horsley[3].

1.2.2. Total Cross Section

A large fraction of the experimental uncertainties in measuring the total cross sections may result from inscattering neutrons. Their amounts depend on the geometrical conditions in the experiments. Briefly speaking, the longer is the flight-path of neutrons between a sample and detector, the smaller becomes the contribution from inscattering neutrons. The data by Kopsch (1970)[4] were adopted in the present work between 0.5 and 4.5 MeV because of the best geometrical condition among the measurements of the total cross sections in this energy range. They agree with the data measured by Utlley (1966)[5], Whalen (1969)[6] and Foster (1971)[7]. The cross sections were evaluated on the basis of the data by Uttley (1966) and Whalen (1969) below 0.5 MeV, and of the data by Foster (1971), Bratenahl (1958)[8] and Peterson (1960)[9] above 4.5 MeV. The evaluated total cross sections are shown in Fig. 1.2.1 with the experimental data.

1.2.3. Capture Cross Section

Below 1 MeV, the data by Moxon (1969)[11] and Fricke (1970)[12] were selected. Differences between the both data are outside the errors given by the authors. Ratios of signals to noises (S/N ratios) for detecting γ-rays may be a measure of the systematic errors in the capture cross section measurements. Comparing the S/N ratios inferred from the experimental conditions described in their reports, it seems that the data by Fricke (1970) are slightly better than those by Moxon (1969).

The data by Fricke (1970) agree well with those by Menlove(1968)[13] and Panitkin (1970)[14] whose experimental methods are diffirent from Fricke's. Hence the data by Fricke (1970) were adopted below 1 MeV. Avobe 1 MeV, the data by Poenitz (1970)[15] and Nagle (1971)[16] were adopted. The results are shown in Fig. 1.2.2 with the experimental data.

1.2.4. Fission Cross Section

The evaluated fission cross sections were obtained on the basis of the experimental data by Lamphere (1956)[20], Stein (1968)[21], Adams (1961)[22], Pankratov (1963)[23], and White (1967)[24]. The original data by Lamphere were decreased by 6 % after the discussion of Davey[2]. The evaluated cross sections by Davey are supported by Stein's data measured after his evaluation. The evaluated cross sections are shown in Fig. 1.2.3.

1.2.5. (n,2n) Cross Section

The (n,2n) cross sections were measured by Knight (1958)[25] and Graves (1958)[26], below 10 MeV and from 13 to 15 MeV, respectively. An excitation function for this reaction was calculated from the semi-empirical method of Pearlstein[27] and was modified so that it might be fitted to the data by Knight (1958) and by Graves (1958). The evaluated cross sections are shown in Fig. 1.2.4 with the experimental data.

1.2.6. (n,3n) Cross Sections

The measurements of the (n,3n) cross sections were reported by Mather (1969)[28] and White (1962)[29]. The data of the latter include large errors. The curve of the cross sections was obtained by means of Pearlstein's method[28] and was modified by referring to the both data. The evaluated cross sections are shown in Fig. 1.2.5.

1.2.7. Elastic and Inelastic Scattering Cross Sections

Below the threshold energy of the inelastic scattering (0.45 MeV), the elastic scattering cross sections σ_n were calculated from the equation,

$$\sigma_n = \sigma_t - \sigma_\gamma$$

Between 0.45 and 1 MeV, the elastic scattering cross sections were estimated from

$$\sigma_n = \sigma_t - (\sigma_\gamma + \sigma_{n'})$$

using the integrated inelastic scattering cross sections $\sigma_{n'}$ measured by Smith (1963)[30]. Since these values of σ_n thus obtained agreed well with the experimental results by Smith (1963) below 1 MeV, the elastic scattering cross sections between 1 and 1.5 MeV were obtained by extrapolating the curve by referring the experimental data. The curve for σ_n is shown with the experimental data by Smith (1963) and Barnard (1966)[31] in Fig. 1.2.6.

Above 1.5 MeV, σ_n and $\sigma_{n'}$ were determined by referring the elastic scattering cross sections measured by Batchelor (1965)[32] and Voigner (1968)[33], so that the summation of the partial cross sections may be equal to the evaluated total cross sections.

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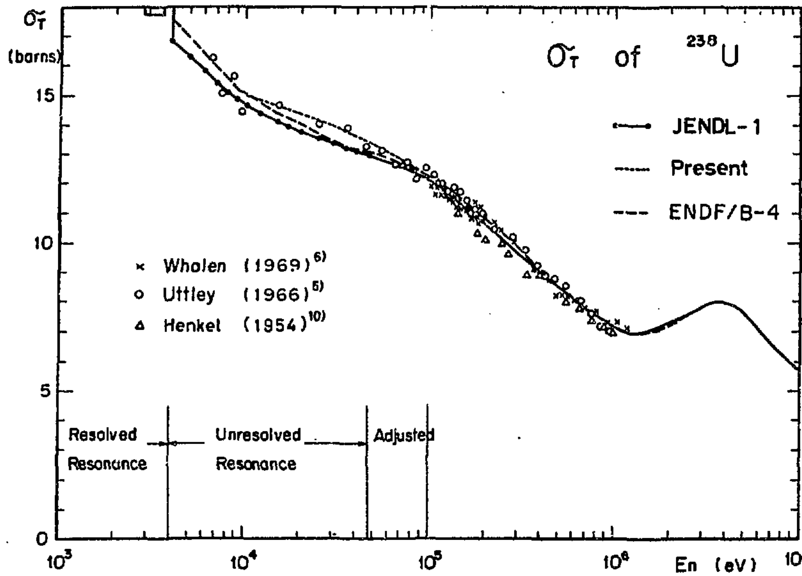
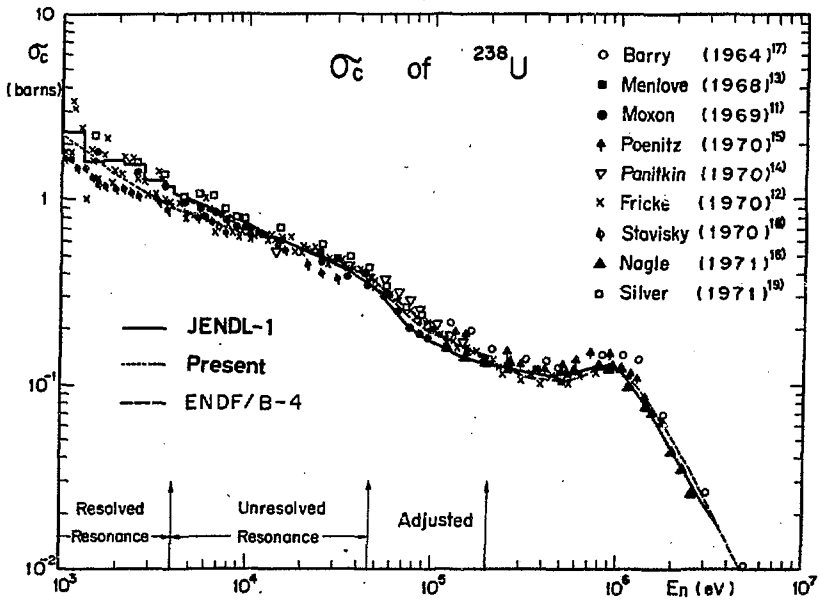
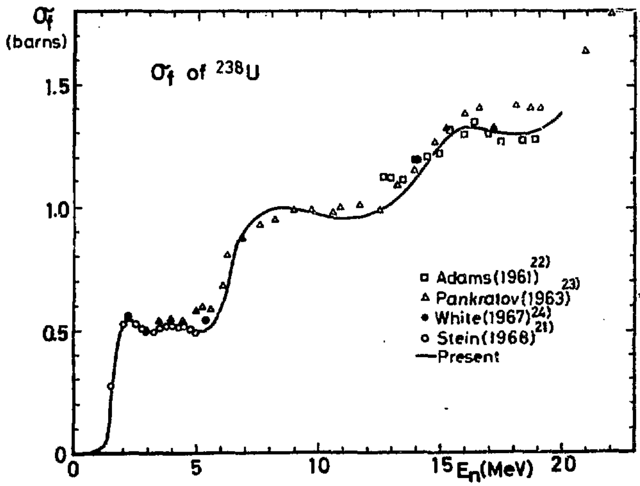


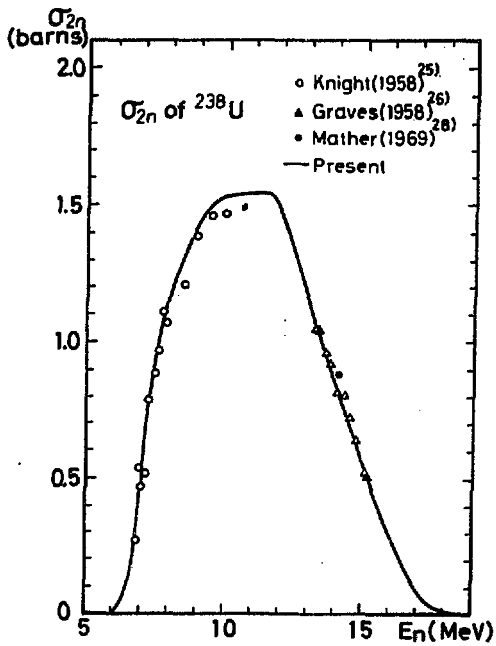
1.2.1 Total cross sections of ^{238}U. The data of Whalen (1968) plotted in this figure are the parts of theirs, which are selected arbitrarily.



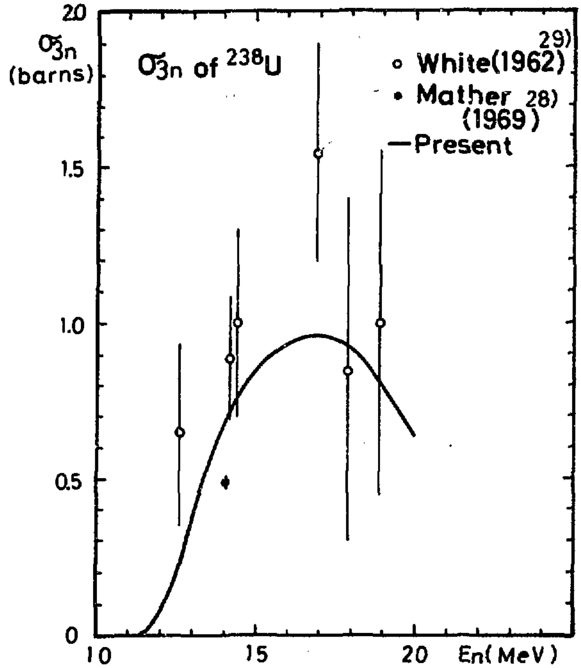
1.2.2 Capture cross sections of ^{238}U.



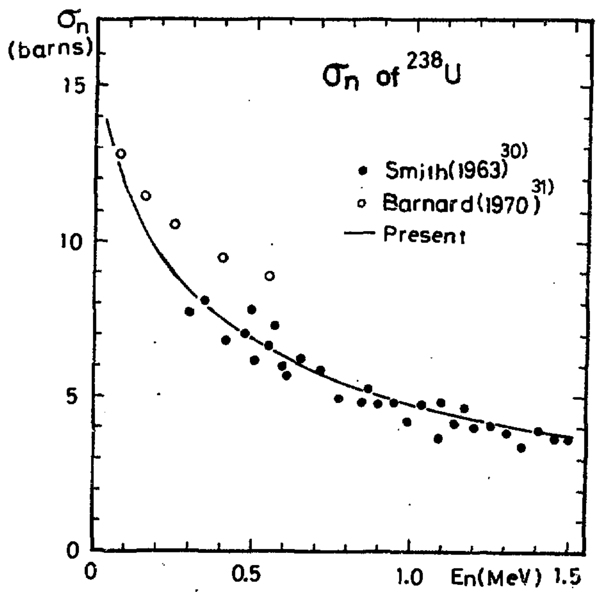
1.2.3 Fission cross sections of ^{238}U.



1.2.4 (n,2n) cross section of ^{238}U.



1.2.5 (n,3n) cross section of ^{238}U.



1.2.6 Elastic scattering cross sections of ^{238}U below 1.5 MeV.

1.3. PLUTONIUM-239

Masayoshi Kawai

1.3.1. Introduction

An evaluation of fast neutron cross sections has been performed in the energy range from 100 eV to 15 MeV. Evaluated quantities are the total, fission, capture, elastic scattering, inelastic scattering, (n,2n) and (n,3n) cross sections, the angular distribution of elastically scattered neutrons and the average number of prompt neutrons per fission. Most of the experimental data reported up to 1973 were obtained from NEUDADA Library of CCDN.

Many measurements have been made for the total and fission cross sections, and for the α-value (the capture to fission ratio) and average number of prompt neutron per fission. Experimental data from these measurements were used for the evaluation of the quantities mentioned above, whereas the theoretical calculation was used for the evaluation of the other quantities because of scarce experimental data. In the following sections, the present evaluation will be described for the individual quantities.

1.3.2. Total Cross Section

Below 50 keV, there are no measurements since 1967 except the experiments by Farrell et al.[1] by means of the nuclear explosion, whose numerical results are not available so far. Consequently, the present evaluation adopted Uttley's[2] experimental data which were also adopted in Schmidt's[3] and Ribon's[4] evaluations.

Above 50 keV, a precise measurement was performed by Schwartz et al.[5] Their result agrees with those of Henkel et al.[6], Foster and Glasgow[7], and Smith et al.[8] within the experimental error, but is higher by 2-4 % than that of Cabe et al.[9] A weighted least squares fit with polynomials was applied to these experimental data including Uttley's[2] data for three energy ranges which slightly overlap with each other. The present evaluation is compared with the experimental data in Fig.1.3.1.

1.3.3. Fission Cross Section

There exist both the absolute measurements and the relative measurements for the fission cross seciton. The data obtained by the relative measurment were converted into the data of the absolute fission cross section, which will be called renormalized data hereafter, by the use of the following standard cross sections; the (n,α) cross section of ^{10}B evaluated by Sowerby et al.[10], the fission cross sections of ^{235}U and ^{238}U evaluated by Matsunobu[11] and Kanda[12], respectively.

The least squares fit with suitable polynomials was applied to the renormalized data in each small energy interval. The recent experimental data were given higher weights in this least squares fit. Below 10 keV, higher weight was assigned to the data of the absolute measurements, since the uncertainty in the fission cross section of ^{235}U seemed to give considerable ambiguity to the renormalized fission cross section of ^{239}Pu.

Table 1.3.1 gives the experimental data[13∿29] mainly used in this evaluation work. From 100 eV to 30 keV, there are many precision measurements[13∿18] with the white neutron source and time-of-flight technique. The evaluation was performed by using the data of these experiments averaged over the small energy intervals in which the evaluated data were given in the histograms. The same methed was used for the capture cross section which will be described in the next section. From 30 keV to 1 MeV, both of the absolute[15,19,20] and renormalized[20∿26] data were simultaneously used in the least squares fit in some small energy intervals. From 1 to 20 MeV, only the ratio data[22,24∿29] were used. The fitted curve was modified so as to reproduce the experimental data at 5.5 and 14.1 MeV, where many experimental data agree with each other.

Fig. 1.3.2 shows the present evaluation with the recent evaluated and experimental data [13,19,20,22,24∿27,30∿33] in the energy range from 1 keV to 10 MeV. There are the discrepancies by 15 % at most among four evaluated curves below 10 keV. Above 10 keV, they agree with each other within the error of 5 % but do not in the details of the structure, for instance from 50 keV to 500 keV and near 2 MeV.

Fig. 1.3.3 shows the present evaluation and that of ENDF/B-IV with the renormalized experimental data[22,24,27∿29,34]. A marked difference in the structure of two evaluation is shown from 8 to 13 MeV where only a few experimental data have been reported.

1.3.4. Capture Cross Section

The present evaluation was made on the α-value by the use of the least squares fit, and the capture cross section was obtained by multiplying the best fitted α-value with the presently evaluated fission cross section. Table 1.3.2 shows the status of α-value measurement[1,14,15,17,18,35∿46].

In the energy range below 30 keV, most experiments were performed by using the white neutron source and time-of-flight technique. In these measurements, the α-values were obtained simultaneously with fission cross sections. The high α-value in the keV energy range was confirmed by the recent experiments as shown in Fig. 2.3.2. However, large discrepancies have been found in the experimental data. In this evaluation, the data by Gwin et al.[14,15], Schomberg et al.[17], Kurov et al.[18], and Crirr and Lindsey[40] were given higher weights, because (1) they agree relatively well with each other, (2) the fission cross sections measured simultaneously are thought to be reliable, and (3) the resonance self-shielding effect in their measurements may be negligible as dicussed previously in JAERI-1228[47].

Above 30 keV, there are η measurements[35,36,38] by using the photo neutron source as well as the direct measurements of α-value by Van de Graaf. Since the α-value derived from η-value by the use of the assumed value of ν may bring some ambiguity, the higher weights were given to the data of the direct α-value measurements by Hopkins and Diven[37], Lottin et al.[39], Kononov et al.[44], Bandl et al[45], and Gwin et al[15] in the least squares fit with polynomials. The data by Lottin et al[39] and Kononov et al[44] were renormalized to the results of the precision measurements mentioned above in the energy range between 15 and 30 keV. The results are shown in Fig. 1.3.4 with the data of ENDF/B-IV and the experimental data in the energy range from 10 keV to 1 MeV.

From 1 MeV to 5.5 MeV, the capture cross section was calculated on the basis of the spherical optical and statistical models with the CASTHY code developed by Igarasi[48]. The optical potential parameters were determined so as to reproduce the evaluated total cross section and the experimental data[2] of the s-wave and p-wave neutron strength functions, and are given in Table 1.3.3. The level density parameters were taken from the values recommended by Gilbert and Cameron[49] and were renormalized so that the mean level spacing[50,51] observed in the resolved resonances may be reproduced for ^{239}Pu and ^{240}Pu. The radiation width was assumed to be 30 meV so as to reproduce the evaluated capture cross section at 100 keV. The level density parameters and the level scheme used in the calculation are given in Table 1.3.4 and 1.3.5, respectively. In the present calculation, we took account of the level-fluctuation effect and the resonance interference effect[52,53] as well as the competition of the fission, (n,2n) and (n,3n) processes. The calculated values agree well with the present evaluated data as shown in Fig. 1.3.5, which also includes the total and elastic scattering cross sections. The values calculated by the CASTHY code above 1 MeV were renormalized to the value evaluated from the experimental data at 1 MeV. Above 5.5 MeV, the data of ENDF/B-IV were adopted, because the present calculation could not treat the direct capture process.

1.3.5. Elastic Scattering Cross Section

Allen et al.[54], Cranberg et al.[55], Knitter and Coppola[56], and Smith et al.[8] made measurements of the elastic scattering cross sections in the energy range from 190 keV to 2 MeV. All data of their experiments included some component of inelastic scattering, since their energy resolution was not sufficient. Consequently, the elastic scatterng cross section was obtained by subtracting the nonelastic scattering cross section calculated with the statistical model from the total cross section as

$$\sigma_{el} = \sigma_{tot} - \sigma_f - \sigma_c - \sigma_{in} - \sigma_{2n} - \sigma_{3n}$$

The elastic scattering cross section agrees with less than 5 % of error with the value calculated with the optical and statistical models, as shown in Fig. 1.3.5. Figure 1.3.6 shows the present evaluation and the experimental data for the elastic scattering cross section from 100 keV to 10 MeV. The solid line donotes the pure elastic scattering. The dashed line includes the contribution from inelastic excitation of low lying levels and should be compared with the experimental data. For instance, one must consider the contributions from the first 3 levels above the ground state to describe the data of Knitter and Coppola[56]. It is obvious that the evaluated data agree stisfactorily well with the experimental data.

The angular distribution of elastically scattered neutrons was calculated with the CASTHY code[48]. The average cosine of scattering angle in laboratory system, $\bar{\mu}_L$, which is used in reactor calculation, agrees with the data of ENDF/B-III in the energy range from 100 keV to 800 keV, and those of ENDF/B-IV above 1 MeV, but differs from both of them below 100 keV.

1.3.6. Inelastic Scattering Cross Section

The inelastic scattering cross section was calculated together with the capture cross section on the basis of the spherical optical model and the statistical model (Hauser-Feshbach theory[54] or Moldauer theory[52,53]) The parameters used in this calculation are described in the section 1.3.4

and are given in Tables 1.3.4 to 1.3.6. Above 875 keV, levels were assumed to be continuum, where the level density was taken from recommendation by Gilbert and Cameron[49].

Fig. 1.3.7 shows the differential inelastic scattering cross section measured by Cavanagh et al.[58] at 90° for some separate levels and for some combinations of two levels. The solid lines were obtained by Moldauer theory[52,53] with the radiation width of 35 meV, whereas the dashed lines by Hauser Feshbach theory[57] with the radiation width of 27.5 meV. It is observed from this figure that the former rigorous thory gives a slightly better excitation curve, especially near the threshold energy, though both lines agree fairly well with each other. For the capture cross section, the same situation is seen in Fig. 1.3.5. Consequently, the results by Moldauer theory[52,53] was adopted in this evaluation.

However, the excitation curve of the combination of second and third levels (57 keV and 76 keV) deviates from the experimental data in the energy range above 400 keV. This deviation may diminish, if the rotational effect[59] is taken into account as reported by Prince et al.[60].

1.3.7. (n,2n) and (n,3n) Cross Sections

The (n,2n) and (n,3n) cross sections were calculated with Pearlstein's procedure[61]. The neutron emission cross section was obtained by subtracting the fission cross section from the compound nucleus formation corss section calculated with the spherical optical model. The parameters used in the calculation were also given in Table 1.3.3. The cross sections thus obtained agree well with the experimental data measured by Mather et al.[62] as shown in Fig. 1.3.8. Much difference is seen between the present evaluation and that of ENDF/B-IV from this figure.

1.3.8. Average number of prompt neutrons per fission

There have been reported many measurements[63~74] of the average number of prompt neutrons per fission, ν_p. The discrepancy among the experimental data of ν_p is 1-2 %. The values evaluated by Davey[75], Hinkelmann et al.[76] and Manero and Konshin[77] were derived by a weighted least squares fit with polynomials. The values measured by Soleilhac et al.[68,69] were used in their works. Recently, Bolodin et al.[73], and Walsh and Boldeman[74] measured ν_p in the energy range up to 2 MeV with the accuracy of 0.4 to 1.0 %. The experimental data by Bolodin et al.[73] scatter slightly above the data by

Soleilhac et al.[68,69] within the experimental error.

In this evaluation, the experimental data were renormalized by the use of the following standards recommended by Hanna et al.[78],

$\nu_p = 3.756$ for spontaneous fission of ^{252}Cf,

$\nu_p = 2.8738$ for thermal fission of ^{239}Pu.

The polynomial of the third order was fitted to the renormalized data. Higher weights were given to the data by Hopkins and Diven[65], Mather et al.[66,70], Conde et al.[67], Soleilhac et al.[68,69], Savin et al.[70], Bolodin et al.[73], and Walsn and Boldeman[74]. The best fitted curves were obtained for two energy regions ,

$$\nu_p = 2.8738 + 0.83192E + 0.081643E^2 - 0.016536E^3 : E\ (\mathrm{MeV}) \leq 1.5\ \mathrm{MeV},$$
$$= 2.8612 + 0.162757E - 9.984\times10^{-4}E^2 - 3.178\times10^{-6}E^3 : E\ (\mathrm{MeV}) \geq 1.5\ \mathrm{MeV}.$$

Fig. 1.3.9 compares the present evaluation with other recent evaluations.[74~77] Present evaluation is in good agreement with the evaluations by Manero and Konshin[77], and Walsh and Boldeman[74] except for the energy near 2 MeV where the differences among the three evaluations amount to about 0.6 %.

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Table 1.3.1. Experimental Data of ^{239}Pu Fission Cross Section Mainly Used in the Prsent Work.

Energy Range	Experimental Data	Ref.
100 eV - 30 keV	Blons (1973), Absolute	13
	Gwin et al. (1971, 1972), Absolute, Pu-239/U-235	14,15
	James (1970), Absolute	16
	Schomberg et al. (1970), Absolute	17
	Kurov et al. (1970), Absolute	18
30 keV - 1 MeV	Gwin et al. (1972), Absolute, Pu-239/U-235	15
	Szabo et al. (1970,1971), Absolute, Pu-239/U-235	19,20
	Poenitz (1970, 1972), Pu-239/U-235	21,22
	Pfletshinger-Käppeler (1970), Pu-239/U-235	23
	Savin et al. (1970), Pu-239/U-235	24
	Nesterov-Smirenkin (1968), Pu-239/U-235	25
	White-Warner (1967), Pu-239/U-235	26
1 MeV - 20 MeV	Poenitz (1972), Pu-239/U-235	22
	Savin et al. (1970), Pu-239/U-235	24
	Nesterov-Smirenkin (1968), Pu-239/U-235	25
	Smith et al. (1957, revised in 1968), Pu-239/U-235 and U-238/Pu-239	27
	White-Warner (1967), Pu-239/U235	26
(near 14 MeV)	Adams et al. (1961), U-238/Pu-239	28
	Barton-Koontz (1967), Pu-239/U-235	29

Table 1.3.2. Present Status of Measurements for α-value (σ_c/σ_f) of ^{239}Pu

	Author	Energy	Neutron source	Quantity	Fission and gamma detector	Ref.
56	Spivak+	30keV- 900keV	Photo n	η	Ionization Chamber, BF_3	35
58	Andeev	24keV- 880keV	Photo n	η	Ionization Chamber	36
62	Hopkins+	30keV- 1MeV	Van de Graaff	α	Large Liq. Scint. (Cd)	37
65	Van'kov+	24keV	Photo n	η,σ_a	Fission Chamber	38
66	Lottin+	20keV- 600keV	Van de Graaff	α	Large Liq. Scint. (Gd)	39
70	Schomberg+	10eV- 30keV	Linac	α,σ_f	Liq. Scint. (P.S.D.)+Moxon Rae	17
70	Czirr+	0.29eV- 30keV	Linac	α,σ_f	Liq. Scint. (P.S.D.)+Moxon Rae	40
70	Belyaev+	Thermal- 10keV	Cyclotron	α,σ_f	Stilbene (P.S.D.)/ZnS+NaI	41
70	Farrell+	10^2eV- 10^6eV	Explosion	$\sigma_f,\sigma_c,\sigma_s,\sigma_T$	Fission Chamber+Moxon Rae	1
70	Kononov+	100eV- 30keV	Pulsed Reactor	α,σ_f	Fission Chamber+Large Liq. Scint.	42
70	Kurov+	100eV- 30keV	Pulsed Reactor	α,σ_f	Large Liq. Scint. (Cd)	18
71	Gwin+	0.02eV- 30keV	Linac	α,σ_f	Large Liq. Scint (High bias)/Fission Chamber	14
71	Bergman+	1.05keV-12.5keV	Pb Spectrometer	α	Fission Chamber+Gas γ Proportional	43
71	Kononov+	10keV- 1MeV	Van de Graaff	α	Large Liq. Scint. (Cd)	44
72	Bandl+	8keV- 60keV	Van de Graaff	α	Liq. Scint., ^{6}Li Glass Scint.	45
72	Gwin+	0.02eV- 200keV	Linac	α,σ_f	Fission Chamber+Large Liq. Scint.	15
72	Weston+	0.02eV- 200keV	Linac	α,σ_f	Fission n detect (P.S.D.)+Modification of Moxon-Rae	46

Table 1.3.3. Optical Potential Parameters for ^{239}Pu

Real Part

$V = 41.15 + 0.45\,E - 0.1825\,E^2$	(MeV)	$E \leq 2$ MeV
$\;\;= 41.92 - 0.32\,E + 0.0097\,E^2$	(MeV)	$E \geq 2$ MeV
$r_o = 1.32$	(fm)	
$a = 0.47$	(fm)	

Imaginary Part (Surface type)

$W_s = 7.82 - 2.71\,E + 0.82\,E^2$	(MeV)	$E \leq 2$ MeV
$\;\;= 4.48 + 0.65\,E - 0.020\,E^2$	(MeV)	$E \geq 2$ MeV
$r_s = 1.38$	(fm)	
$a = 0.47$	(fm)	

Spin-orbit Force

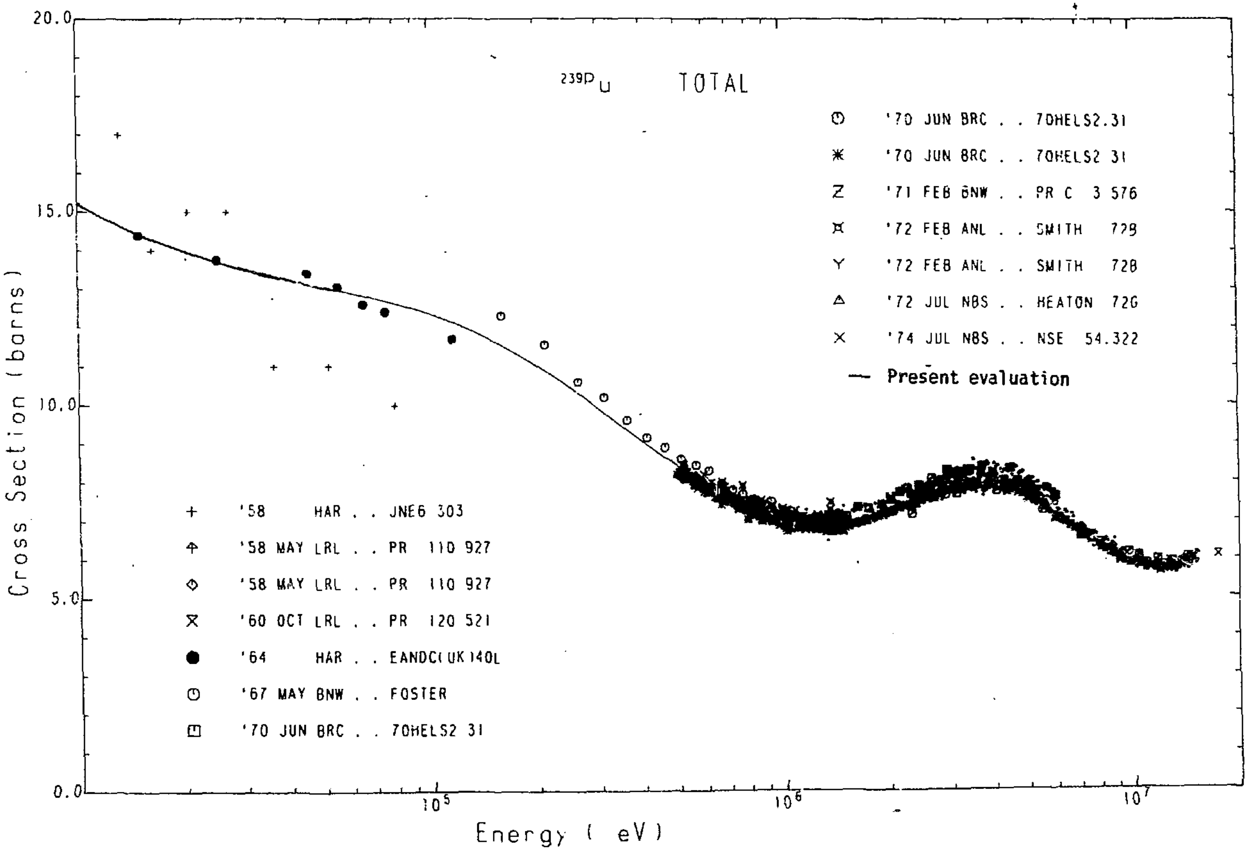
$V_{so} = 7.0$	(MeV)
$r_{so} = 1.32$	(fm)
$a = 0.47$	(fm)

Table 1.3.4. Level Density Parameters for ^{239}Pu

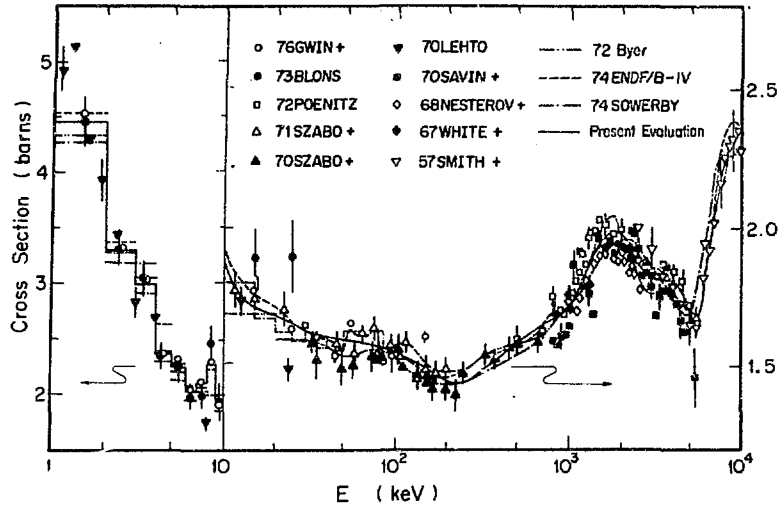
	Target nuclcus	Compound nucleus
a (MeV^{-1})	26.5522	26.9293
Δ (MeV)	0.61	1.04
α $(MeV^{-1/2})$	17.6156	17.7964
E_x (MeV)	3.7376	4.1650
C_o	8292.63	11277.38
S_n (MeV)	5.6557	6.5337

Table 1.3.5. Level Scheme of ^{239}Pu

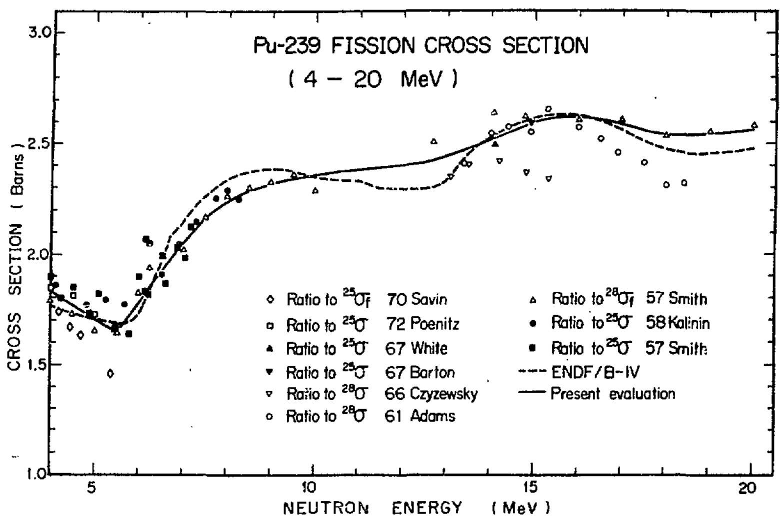
Excitation (keV)	Spin	Parity
0	1/2	+
8	3/2	+
57	5/2	+
76	7/2	+
164	9/2	+
193	11/2	+
286	5/2	+
330	7/2	+
388	9/2	+
392	7/2	-
432	5/2	+
434	9/2	-
463	11/2	+
470	1/2	-
480	7/2	+
486	11/2	-
492	3/2	-
505	5/2	-
512	7/2	+
556	7/2	-
735	3/2	+
759	5/2	+
800	7/2	+
849	9/2	+



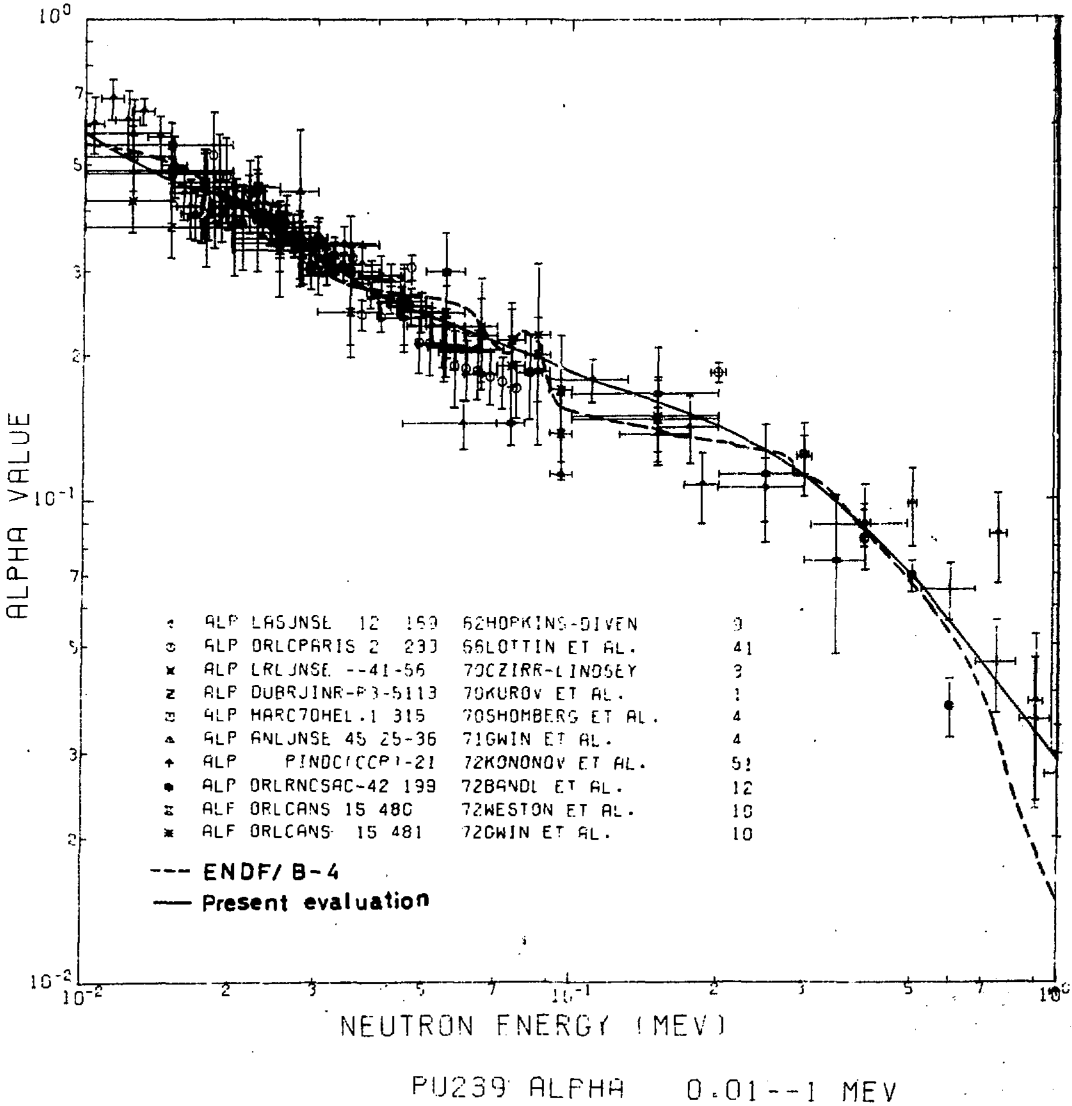
1.3.1. Total cross section of ^{239}Pu



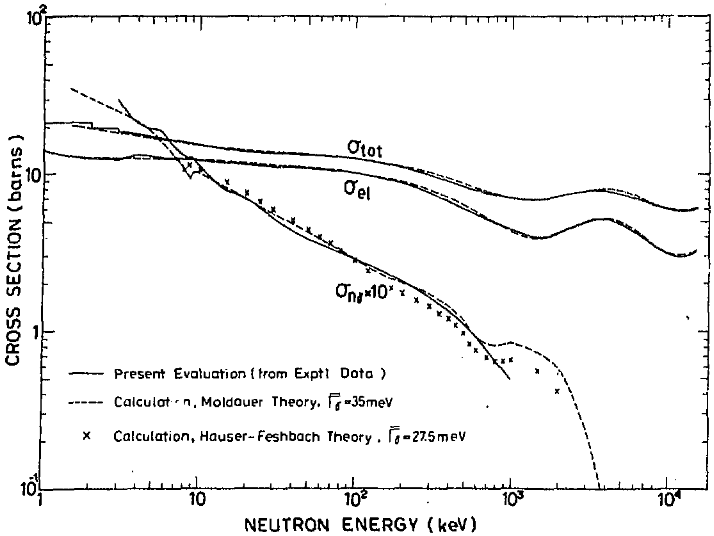
1.3.2. Fission cross section of ^{239}Pu



1.3.3. Fission cross section of ^{239}Pu from 4 MeV to 20 MeV



1.3.4. α-value of ^{239}Pu above 10 keV



1.3.5. Comparison of present evaluation with statistical calculations for total, elastic scattering and capture cross sections of ^{239}Pu

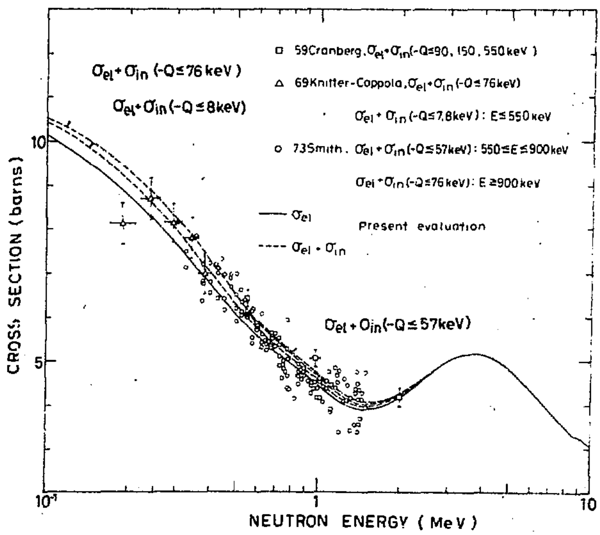
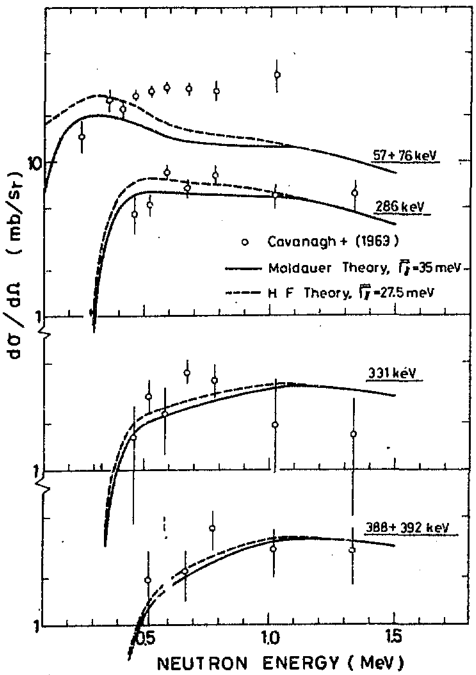
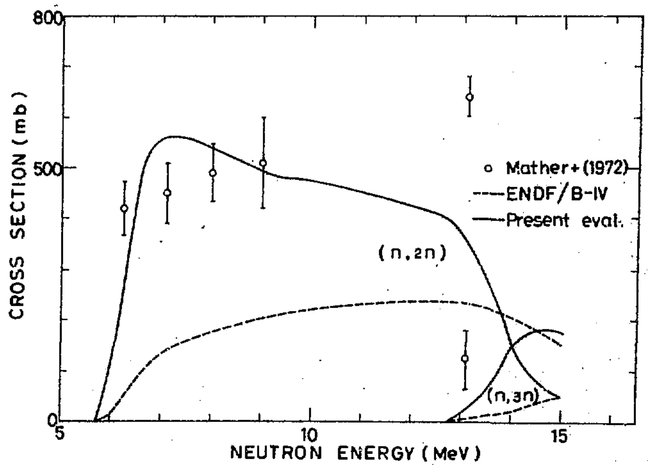


Fig.1.3.6 ELASTIC AND SOME INELASTIC SCATTERING CROSS SECTION OF Pu-239

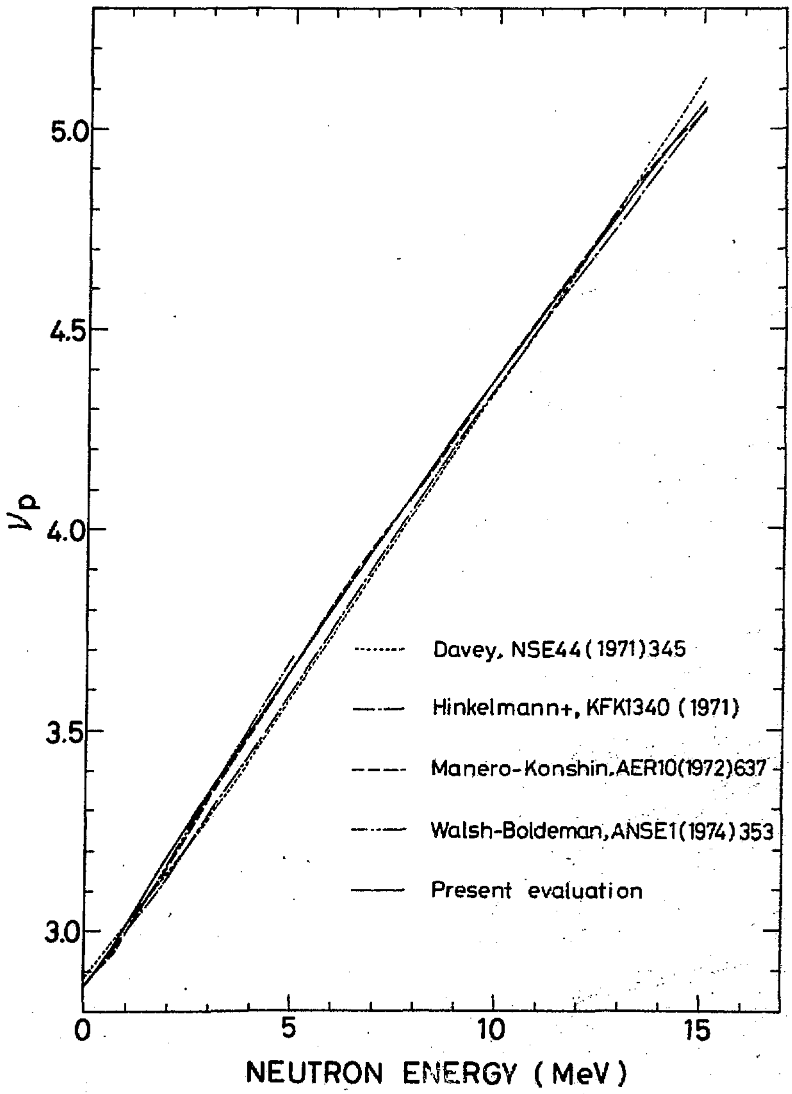
1.3.6. Elastic and some inelastic scattering cross sections of ^{239}Pu



1.3.7. Partial inelastic scattering cross section of ^{239}Pu measured at 90°



1.3.8. (n,2n) and (n,3n) cross sections of ^{239}Pu



1.3.9. ν_p of ^{239}Pu

1.4. PLUTONIUM-240

Toru MURATA

1.4.1. Introduction

Evaluation was made for the following cross sections in the energy range from 1 keV to 15 MeV : total, elastic scattering (including angular distribution), inelastic scattering, fission, radiative capture, (n,2n) and (n,3n) reactions.

For ^{240}Pu, only a few experimental data are available for the fast neutron cross sections except for fission cross section. The fission cross section was evaluated on the basis of the experimental data in the almost all energy region of incident neutrons. The other cross sections were estimated with the aids of theoretical calculations. Then, modifications were made for some cross sections by normalizing the estimated values to the experimental data.

1.4.2. Total Cross Section (σ_t)

Measurements of the total cross section were made by Smith et al.[1] in the energy range of En = 0.1 MeV-1.5 MeV with the experimental error of about 5%. An alloy of 98.7 wt % plutonium and 1.3 wt % aluminum was used as a target sample. Though the data were corrected for the effects of aluminum resonance, there remained some structures in the cross section near En = 0.53 MeV, which could be ascribed to the effects.

For neighbouring nuclei, ^{235}U, ^{238}U and ^{239}Pu, many measurements of fast neutron total cross section show similar tendency[2] with each other, which can be explained by the spherical optical model. It was assumed in the present work that the total cross section of ^{240}Pu has the same tendency as that of ^{238}U and can be estimated from the cross section of ^{238}U with the aid of the optical model calculation.

The potential parameters of the calculation were searched for with the TOTAL code[3] to reproduce the evaluated total cross section of ^{238}U within 5%. The searched parameters are given in Table 1.4.1. Using these parameters, the ratio of total cross section of ^{240}Pu to that of ^{238}U was calculated. The cross section was estimated by

$$\sigma_t = \sigma_t(^{238}U) \times [\frac{\sigma_t(^{240}Pu)}{\sigma_t(^{238}U)}]_{\text{calculated}},$$

where $\sigma_t(^{238}U)$ is the total cross section of ^{238}U evaluated by Kanda.[4]

The cross section thus estimated was decreased by 3 % so as to reproduce the experimental cross sections by Smith et al. The evaluated cross section curve is shown in Fig. 1.4.1 with the experimental data.

1.4.3. Elastic Scattering Cross Section (σ_{el})

The angular distributions of elastically scattered neutrons were measured by Smith et al.[1] at eight angles, in the energy range of En = 0.3 MeV - 1.5 MeV. They obtained the coefficients of Legendre polynomials with which these angular distributions are reproduced.

The elastic scattering could be divided into two processes after the optical model theory ; shape elastic and compound elastic scattering. The shape elastic scattering cross section (σ_{se}) may be very similar to that of ^{238}U, and is assumed to be given by

$$\sigma_{se} = \sigma_{se}(^{238}U) \times [\frac{\sigma_{se}(^{240}Pu)}{\sigma_{se}(^{238}U)}]_{\text{calculated}},$$

where $\sigma_{se}(^{238}U)$ is the shape elastic scattering cross section of ^{238}U which was obtained by multiplying the evaluated elastic scattering cross section of ^{238}U[4] to the ratio of the calculated shape elastic to elastic scattering cross section.

The ratio of the shape elastic scattering cross section of ^{240}Pu to that of ^{238}U was calculated by using the TOTAL code. The ratio of the shape elastic to elastic scattering cross sections of ^{238}U was calculated by using the statistical model code CASTHY[5] with taking account of competition of the other reactions. The same potential parameters were used for the calculations as described in Section 1.4.2. The other parameters for the calculations are given in Table 1.4.2.

Large difference of the fission cross sections between ^{240}Pu and ^{238}U makes it difficult to estimate the compound elastic scattering cross section of ^{240}Pu from that of ^{238}U. The compound elastic scattering cross section was estimated from the cross sections of the other processes with the aid of the CASTHY calculation as

$$\sigma_{ce} = \{\sigma_t - \sigma_{se} - \sigma_f - \sigma\gamma\}[\frac{\sigma_{ce}}{\sigma_{ce} + \sigma_{n'}}]_{\text{calculated}},$$

where σ_f, σ_γ and $\sigma_{n'}$ denote the fission, capture and inelastic scattering cross sections, respectively.

At the final stage of the evaluation, the estimated elastic scattering cross section was so modified slightly that the sum of the partial cross sections was equal to the total cross section. The evaluated curve is shown in Fig. 1.4.2 with the experimental cross sections by Smith et al.(1)

The Legendre polynomial expansion coefficients of the angular distribution were calculated using the optical model code ELIESE-3(6) and modified to reproduce the experimental angular distributions of ^{240}Pu in the energy range of En = 0.4 MeV - 1.2 MeV and those of ^{238}U(7) in the higher energy region.

1.4.4. Fission Cross Section (σ_f)

For the fission cross section, many experimental data(8) are available in the whole energy range considered in the present evaluation. Some of them are the data of the ratio measurement relative to the fission of ^{235}U or ^{239}Pu. To derive the fission cross section from the fission ratios relative to ^{235}U fission, Matsunobu's evaluated fission cross section(9) of ^{235}U was used.

In the low energy region (En $\leq$ 10 keV), several measurements have been made and show the resonance structures of the class I and class II subthreshold fission. Though the evaluated resonance parameters should be given in this energy region, the smooth cross section was obtained to see the connection of the cross section in this energy region with that in the higher energy region. The evaluation was made by averaging the point-wise data by Byers et al. and by Migneco et al. in the energy step of 1 keV.

In the medium energy region (En = 10 keV - 4 MeV), many measurements have been made. The data show slowly varying cross sections in the subthreshold region, the fission threshold at about En = 0.7 MeV and the cross section plateau in the MeV range. In this region, the evaluated cross section was obtained by drawing eyeguide curve with rather strong weight on the data of ratio measurements. There seem to be some small structures in the cross section near the threshold. These structures were ignored in the present evaluation, since no significant structures more than experimental errors were recognized.

In the high energy region (En $\geq$ 4 MeV), a few measurements have been made. The data show the structure which might be due to the (n,n'f) and (n,2nf) reactions. In this energy region, the evaluated cross section was obtained by the statistical model calculation whose parameters were determined so as to reproduce the experimental cross sections. The cross section was divided into three terms and calculated as follows.

The first chance fission :

$$\sigma_{fo} = \sigma_c \times \frac{\Gamma_f}{\Gamma_n + \Gamma_f} ,$$

where σ_c is the compound nucleus formation cross section calculated as $(\sigma_t - \sigma_{se})$ by using the evaluated cross sections. The branching ratio $\Gamma_f/(\Gamma_n + \Gamma_f)$ was calculated by[10]

$$\frac{\Gamma_n}{\Gamma_f} = \frac{4A^{2/3}\, a_f\, E_n\, \exp\{2\sqrt{a_n E_n} - 2\sqrt{a_f(E_n-E_f)}\}}{(\hbar^2/2mr_0^2)\, a_n\, [2\sqrt{a_f(E_n-E_f)} - 1]} ,$$

where E_n is the incident neutron energy, E_f the fission threshold (0.71 MeV[11]), a_n , a_f the level density parameters and the factor $4A^{2/3}/(\hbar^2/2mr_0^2)$ was calculated to be 13.01 MeV^{-1} for A=241 and r_o=1.32 fm.

The fission after (n,n') reaction :

$$\sigma_{n'f} = \langle P_{f1} \rangle\, (\sigma_c - \sigma_{fo}) ,$$

where $\langle P_{f1} \rangle$ is average fission probability of ^{240}Pu excited after the (n,n') reaction and was estimated in this work by using the experimental fission probability[12] and the calculated energy spectrum of the emitted neutrons.

The fission after (n,2n) reaction :

$$\sigma_{2nf} = \frac{\langle P_{f2} \rangle}{1 - \langle P_{f2} \rangle}\, (\sigma_{2n} + \sigma_{3n}) ,$$

where $\langle P_{f2} \rangle$ is the average fission probability of ^{239}Pu excited after the (n,2n) reaction.

The evaluated curve is shown in Fig. 1.4.3 with the experimental cross sections.

1.4.5. Radiative Capture Cross Section ($\sigma\gamma$)

Measurements of the capture cross section were made by Hockenbury et al.[13] and by Weston and Todd,[14] in the energy range of E_n = 20 eV - 30 keV and E_n = 0.1 keV - 350 keV, respectively. Hockenbury et al. gave the average radiative capture width : $\Gamma\gamma$ = 29.5 mV, which agrees well with the revised value of Weigmann and Theobald[15]: $\Gamma\gamma$ = 32 ± 2 mV.

The evaluated capture cross section in the energy range below 2 MeV was obtained by normalizing the estimated values obtained with the CASTHY code to the experimental cross sections. In the high energy region, the collective and direct capture processes increase, and the statistical model does not predict the cross section well. Hence, in this region, the cross section was obtained by normalizing the evaluated capture cross section of ^{238}U to that of ^{240}Pu around E_n = 1 MeV.

The result of the evaluation is shown in Fig. 1.4.4 with the experimental cross sections.

1.4.6. The (n,2n) and (n,3n) Cross Sections (σ_{2n} , σ_{3n})

Since no experimental data were available for these reactions, each cross section was estimated by the calculation using Pearlstein's formula.[16]

At first, the ratio of each reaction cross section to the neutron emission cross section for ^{238}U was obtained from the evaluated cross sections[4] of ^{238}U. Then, the ratios of ^{238}U were converted to that of ^{240}Pu with the formula taking account of the differences in reaction Q-value and so on.

Neglecting the (n,γ) and charged particle emission reactions, the neutron emission cross section σ_{nM} is given by (σ_c - σ_f), and

$$\sigma_{nM} = \frac{(1-\langle P_{f1}\rangle)\cdot(1-\langle P_{f2}\rangle)}{1-\langle P_{f2}\rangle+\langle P_{f2}\rangle(\eta_2 + \eta_3)} (\sigma_c - \sigma_{fo}) \quad ,$$

where P_f is the fission probability described in Section 1.4.4, η_2 the ratio σ_{2n}/σ_{nM} and η_3 the ratio σ_{3n}/σ_{nM}. The (n,2n) reaction cross section is given by $\eta_2\sigma_{nM}$, and the (n,3n) reaction cross section by $\eta_3\sigma_{nM}$.

1.4.7. Inelastic Scattering Cross Section ($\sigma_{n'}$)

Smith et al.[1] measured the partial inelastic scattering cross sections to the levels of ^{240}Pu ; excitation energy of E_x = 42 ± 5, 140 ± 10, 300 ± 20, 600 ± 20 and 900 ± 50 keV, in the energy range of E_n = 0.3 MeV ∿ 1.5 MeV.

The estimation of the inelastic scattering cross section was made at first by

$$\sigma_{n'} = \sigma_t - (\sigma_{el} + \sigma_f + \sigma_\gamma + \sigma_{2n} + \sigma_{3n}) \quad .$$

The partial cross section to the i-th level of ^{240}Pu was calculated by

$$\sigma_{n'}^{(i)} = \sigma_{n'} \times \left[\frac{\sigma_{n'}^{(i)}}{\sigma_{n'}}\right]_{calc} \quad ,$$

where $[\sigma_{n'}^{(i)}/ \sigma_{n'}]_{calc}$ denotes the cross section ratio calculated with the CASTHY code. The level scheme of ^{240}Pu used in the present calculation is given in Table 1.4.2. For some of the excited levels, the calculated partial cross section showed disagreement with the experimental cross sections. For these levels, the calculated results were normalized to the experimental cross sections. The evaluated partial inelastic scattering cross sections for some levels are shown in Fig. 1.4.5 with the experimental data.

Summing up the partial cross sections, the evaluated inelastic scattering cross section was obtained.

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Table 1.4.1. Optical Potential Parameters of ^{240}Pu

Real Part		
	$V = 40.85 - 0.053\ E$	(MeV)
	$r_o = 1.32$	(fm)
	$a = 0.47$	(fm)
Imaginary Part (Surface type)		
	$W_s = 4.88 + 0.659\ E - 0.0387\ E^2$	(MeV)
	$r_s = 1.41$	(fm)
	$b = 0.47$	(fm)
Spin-orbit force		
	$V_{so} = 7.0$	(MeV)
	$r_{so} = 1.32$	(fm)
	$a_{so} = 0.47$	(fm)

Table 1.4.2.

Parameters for the CASTHY calculation

(1) Level scheme of ^{240}Pu and ^{238}U

Pu - 240 E_x (keV)	J^π	U - 238 E_x (keV)	J^π
0	0^+	0	0^+
42.8	2^+	45.0	2^+
141.7	4^+	148.4	4^+
293.9	6^+	307.8	6^+
500	8^+	518.9	8^+
597.4	1^-	680.2	1^-
648.9	3^-	732.0	3^-
742.2	5^-	827	5^-
860.7	0^+	925	0^+
900.3	2^+	930.8	1^-
938.1	2^+	939	2^+
958.9	2^-	950.2	2^-
		965	2^+
		968	2^+
		993	0^+

The levels which excitation energy are greater than 1 MeV are assumed to be continuum. Discrete level schemes adopted here are based on the evaluation of Schomorak(17) for ^{240}Pu and that of Ellis(18) Ellis(18) for ^{238}U

(2) Level density parameters

Fermi gas model for $U \geq Ux$

$$\rho_g(U,J) = \frac{(2J+1)}{C_o U^2} \exp\{2\sqrt{aU} - \frac{J(J+1)}{2\sigma_M}\} ,$$

constant temperature model for $U \leq Ux$

$$\rho_T(U,J) = \rho_g(U_x,J)\exp\{(U-U_x)/T\} ,$$

wher $Ux = E_x - \Delta$.

Parameters of the above formula

Parameter		Pu-240	Pu-241	U-238	U-239
a	(MeV^{-1})	26.93	27.40	28.20	29.2
Δ	(MeV)	1.04	0.61	1.12	0.69
C_o	(MeV^{-1})	1.007×10^4	1.246×10^4	1.884×10^4	1.923×10^4
U_x	(MeV)	5.5	5.5	5.5	5.5

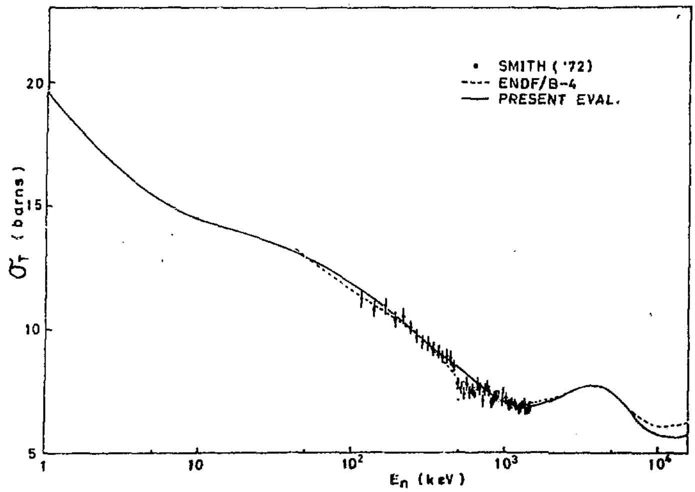


Fig. 1.4.1.
Total cross section of ^{240}Pu

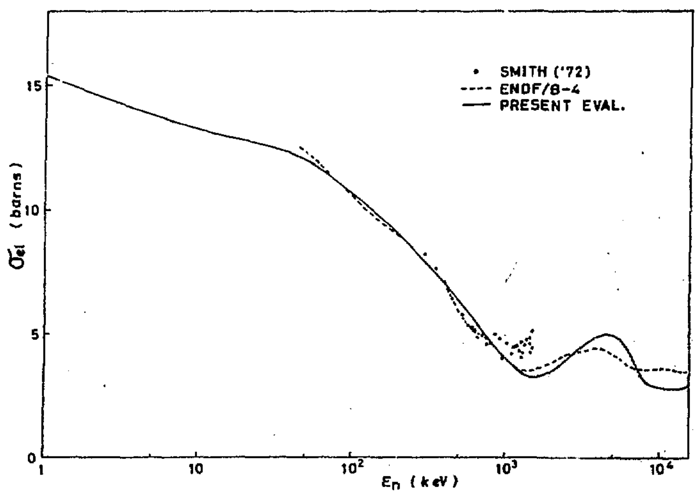
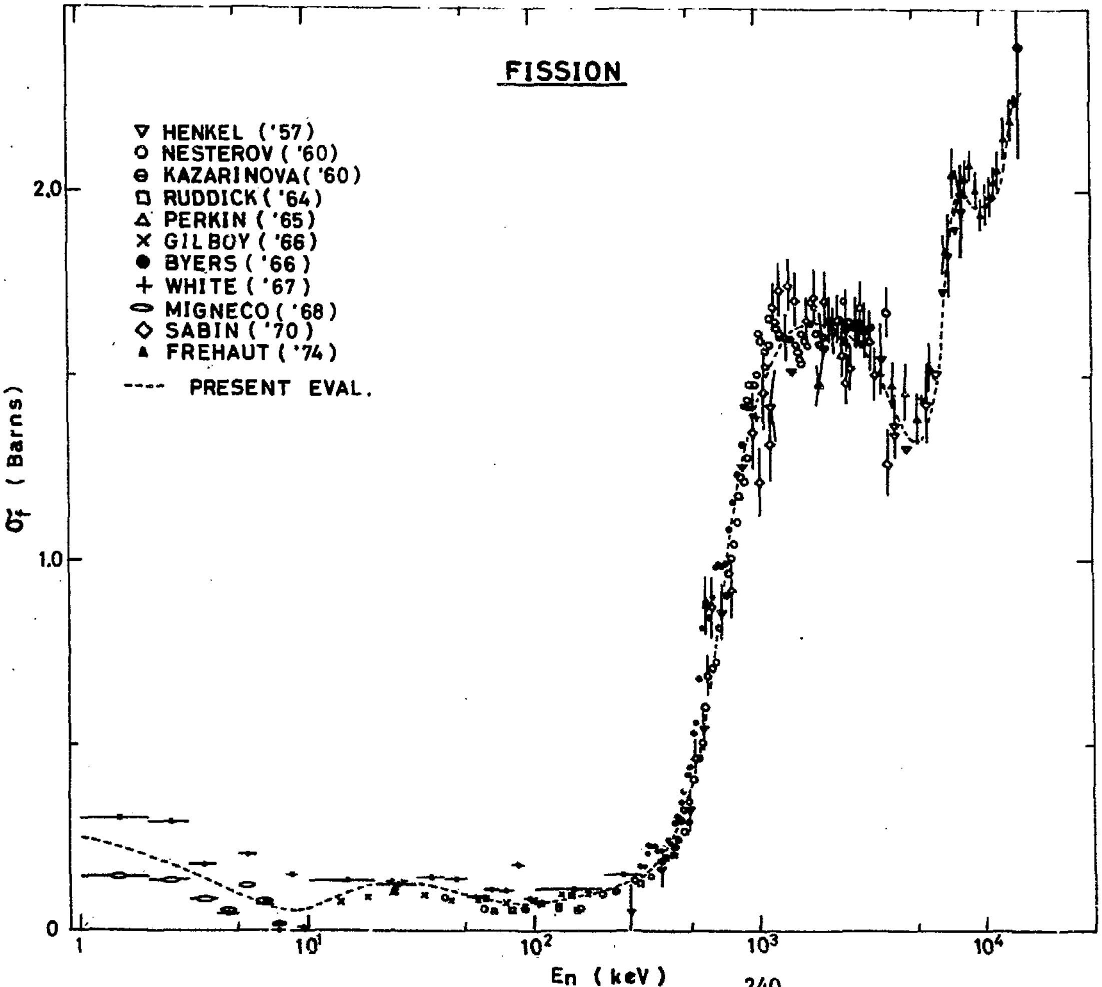
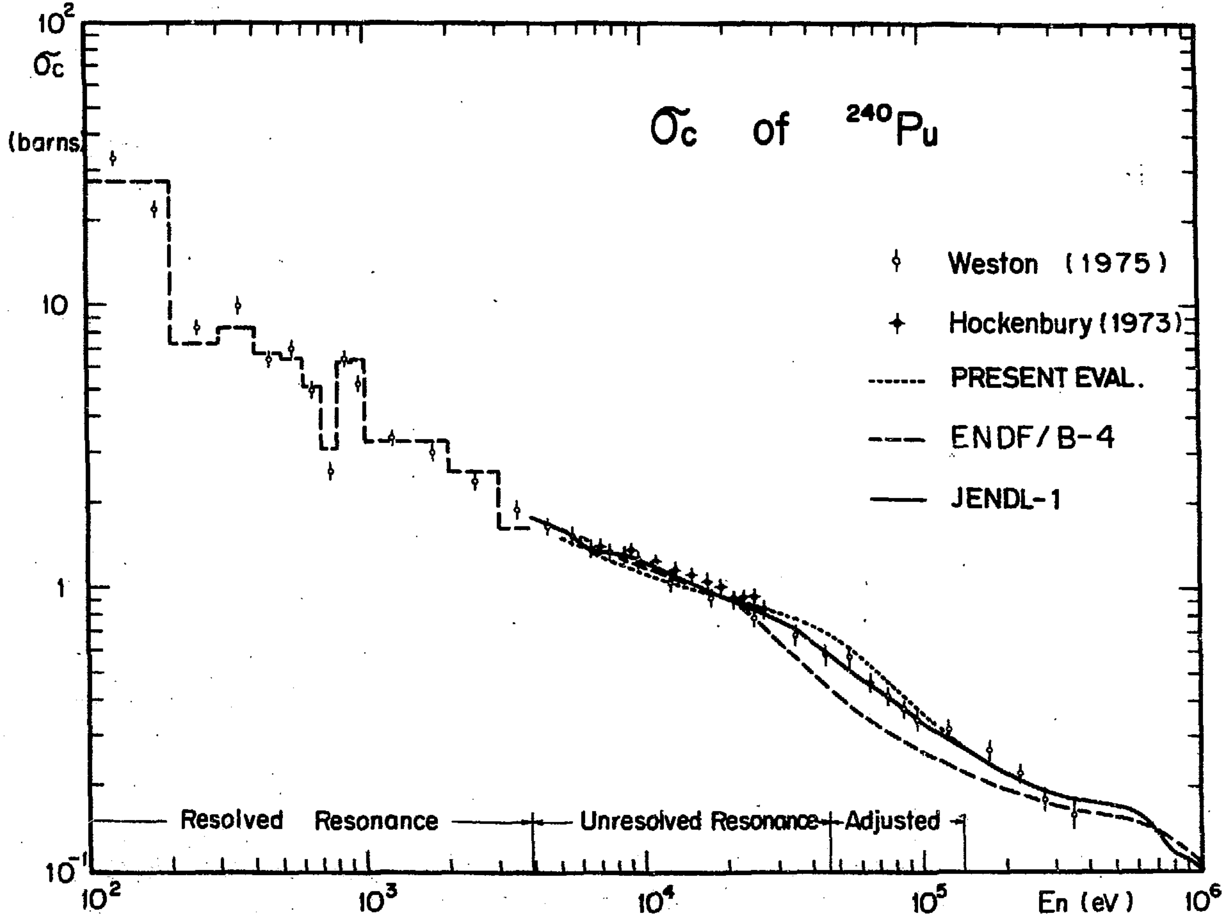


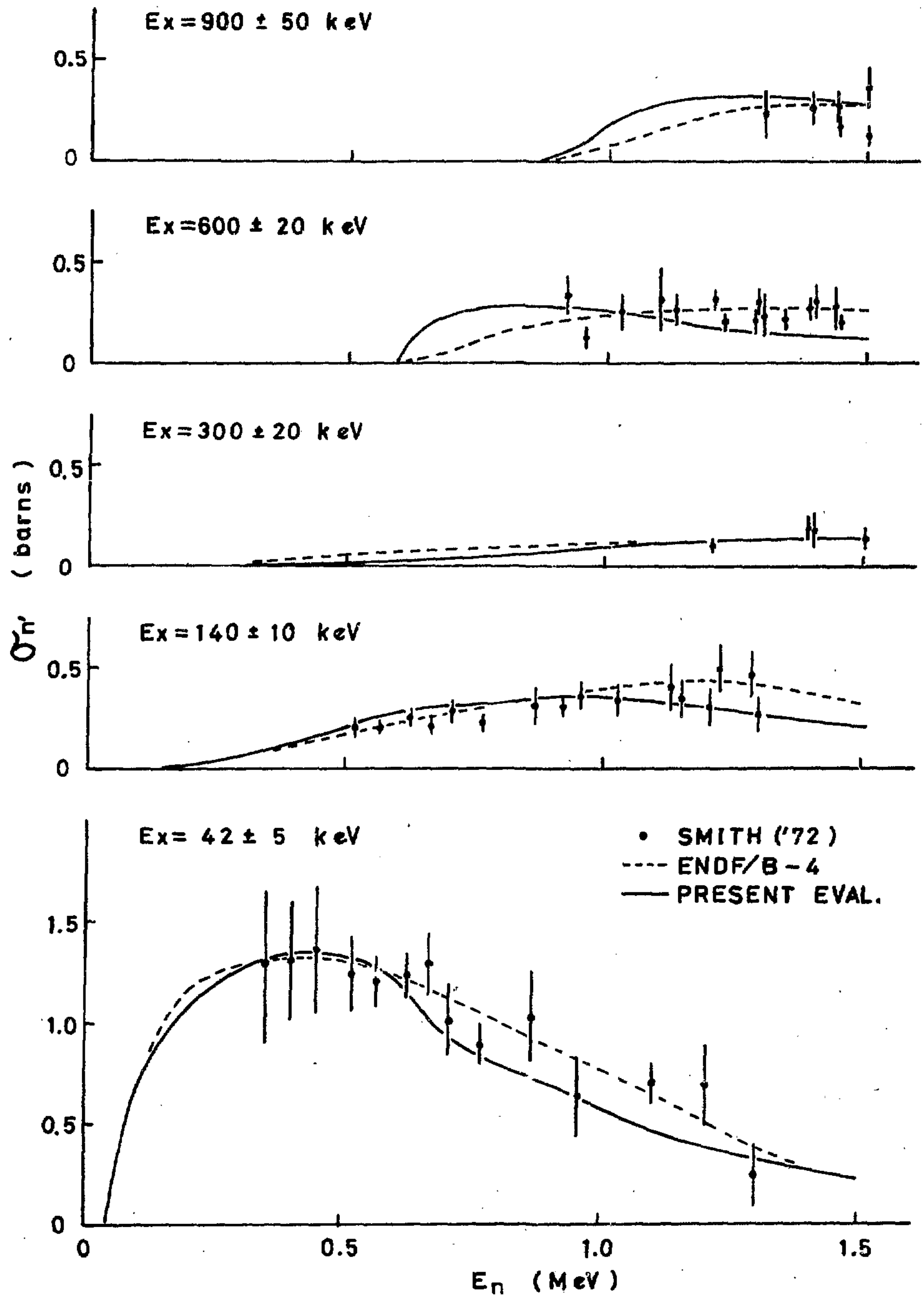
Fig. 1.4.2.
Elastic scattering cross section of ^{240}Pu



1.4.3. Fission cross section of ^{240}Pu



1.4.4. Radiative capture cross section of ^{240}Pu



1.4.5. Partial inelastic scattering cross sections of ^{240}Pu

1.5. PLUTONIUM-241

Yasuyuki KIKUCHI

1.5.1. Introduction

The evaluation was made for the full energy range. The results will be soon published[1] and therefore only a brief review is described here for the smooth cross sections above 21.5 keV. The thermal cross sections and the resonance parameters will be described in chapter 2.5.

The evaluated quantities are the total, fission, capture, elastic and inelastic scattering, (n,2n) and (n,3n) cross sections and the angular distribution of the elastically scattered neutrons. The experimental data are very scarce except for the fission cross section, and therefore the theoretical calculations were often used.

1.5.2. Total Cross Section

The total cross section was calculated with the spherical optical model. As no experimental data were available for the total cross section in MeV region, it was impossible to determine the potential parameters by fitting the calculated total cross section to the experimental one. Then we adopted tentatively the same potential parameters as those used in the evaluation of ^{241}Am by Igarasi.[2] It was found that this potential gave satisfactory results for the compound nucleus formation cross section and for the strength function and therefore this potential was finally adopted. The potential parameters are given in Table 1.5.1. The evaluated curve is shown in Fig. 1.5.1.

1.5.3. Fission Cross Section

Evaluation of fission cross section was performed on the basis of the experimental data, since the experiments cover the full energy range. Most of these experimental data are given as the ratio to the fission cross section of ^{235}U. To obtain the cross section of ^{241}Pu, the results of these relative measurements were normalized by the fission cross section of ^{235}U adopted in JENDL-1, which were evaluated by Matsunobu except in the energy range above 6 MeV where Matsunobu's evaluation was modified by the use of the recent measurements as will be described in chapter 2.1.

Below 100 keV the data by Kaeppeler and Pfletschinger[3] were adopted and normalized. The cross section agrees with the value of absolute measurement by Perkin et al.[4] at 24 keV. The cross section curve was obtained by the eye-guide method. Between 100 keV and 1 MeV, the data by Kaeppeler and Pfletschinger[3] and by Behrens and Carlson[5] were adopted. The cross section obtained from these relative measurements gives higher values than the data by the absolute measurement by Szabo et al.[6] between 200 and 400 keV. This discrepancy might be caused partially by the present normalization based on Matsunobu's data which seem to be a little higher than those of ENDF/B-IV between 150 keV and 500 keV. However, we used the data of ^{235}U adopted in JENDL-1 without modification in order to keep the consistency of JENDL-1. Above 1 MeV the data by Behrens and Carlson[5] were adopted. Between 1 and 3 MeV the data by Behrens and Carlson normalized by Matsunobu's data agree very well with the data from the absolute measurement by Szabo et al.[7]

The evaluated curve thus obtained is shown in Fig. 1.5.2 with the experimental data as well as the data in ENDF/B-IV. The ENDF/B-IV data seem to be based on the data by Smith et al.[8] above 1 MeV and take higher value than the present evaluation.

1.5.4. Capture Cross Section

The capture cross section was evaluated by the use of the α-value by Weston and Todd[9] in the energy range up to 250 keV. Above 250 keV, the capture cross section was calculated by the CASTHY code on the basis of the optical and statistical models simultaneously with the elastic and inelastic scattering cross sections. The level density parameters were taken from the recommendation by Gilbert and Cameron[10] and the level scheme evaluated by Prince[11] was adopted. They are given in Tables 1.5.3 and 1.5.4, respectively. The sum of the fission, (n,2n) and (n,3n) cross sections was given as the cross section of the competing processes. The γ-ray transmission coefficient was renormalized so that the calculated capture cross section was fitted at 250 keV to the value obtained from the experimental data. The calculated results are shown in Fig. 1.5.3 with the experimental values. The calculation gives a satisfactory agreement with the experimental values below 250 keV, taking into account the error* of

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* The error bars in Fig. 1.5.3 are the quoted ones in α measurements and do not include the errors in the fission cross section used for normalization.

the experiments. This suggests the reliability of the present calculation. However, the capture cross section decreases abruptly in the energy range above 1 MeV. The present evaluation may underestimate the capture cross section in this energy range because of the negligence of the direct capture process. This error is not significant, however, for the capture is not important in this energy region.

1.5.5. Elastic Scattering Cross Section

The elastic scattering cross section was also obtained by the CASTHY code with the angular distribution of scattered neutrons. The result is shown in Fig. 1.5.4. The following should be noted. The statistical model calculation was carried out so as to fit the calculated capture cross section to the experimental data at 250 keV. On the other hand, as will be described in chapter 2.5, unresolved resonance parameters were determined so that the calculated fission and capture cross sections may reproduce the experimental data. Nevertheless, the elastic scattering cross section obtained from the resonance parameters is 10.97 barns at 21.5 keV, which coincides very well with the value of 11.06 barns calculated with the statistical model. This suggests the selfconsistency of the present evaluation.

1.5.6. Inelastic Scattering Cross Section

The inelastic scattering cross section was also calculated by the CASTHY code. The calculated curve is compared in Fig.1.5.5 with that of ENDF/B-IV. The present calculation gives considerably lower value than that of ENDF/B-IV evaluated by Prince,[11] though the same level scheme was used. This discrepancy cannot be neglected, as the inelastic scattering is the most important for reactor calculations in this energy range. Prince used the coupled channel optical model, while the present calculation is based on the spherical optical model. However, it is not expected that the difference between two models gives such a large discrepancy of the inelastic scattering cross section as in the present case. On the other hand, the following three points should be remarked : (1) The competition with the fission was not mentioned by Prince.[11] (2) The inelastic scattering cross section of ENDF/B-IV is independent of the structure in the fission cross section, which should be reflected on the inelastic scatterig through competition.

(3) The sum of the fission and inelastic scattering cross sections in the present calculation agrees approximately with the inelastic scattering cross section of ENDF/B-IV. These might suggest that the competition with the fission was not taken into consideration by Prince.

1.5.7. (n,2n) and (n,3n) Cross Sections

The (n,2n) and (n,3n) cross sections are calculated with Pearlstein's method.[12)] The calculated results are shown in Fig. 1.5.5. The (n,3n) cross section may be overestimated in the higher energy region, because (n,4n) and the other competing processes are ignored in the present calculation.

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Table 1.5.1. Optical Potential Parameters for ^{241}Pu

Real Part

V	$= 40.5 + 0.5 \times E$	(MeV)
r_0	$= 1.32$	(fm)
a	$= 0.47$	(fm)

Imaginary Part

W_s	$= 8.2 + 0.5 \times \sqrt{E}$	(MeV)
r_0	$= 1.32$	(fm)
a	$= 0.47$	(fm)

Spin-orbit Force

V_{so}	$= 7.0$	(MeV)
r_0	$= 1.32$	(fm)
a_{so}	$= 0.47$	(fm)

Table 1.5.2 Level Density Parameters for ^{241}Pu

		Target nucleus	Compound nucleus
a	(MeV^{-1})	27.3951	27.7751
Δ	(MeV)	0.61	1.11
α	($MeV^{-1/2}$)	17.9995	18.1740
E_x	(MeV)	3.7324	4.2298
Co		5929.74	6036.93
Sn	(MeV)	5.2397	6.3017

Table 1.5.3. Level Scheme of ^{241}Pu Evaluated by Prince[11)]

Excitation (keV)	Spin	Parity
0	5/2	+
40	7/2	+
95	9/2	+
163	1/2	+
169	3/2	+
174	7/2	+
231	9/2	+
245	7/2	+
300	11/2	+
335	9/2	+
448	5/2	+
753	1/2	+
828	1/2	-
894	3/2	+
918	5/2	+
941	7/2	+

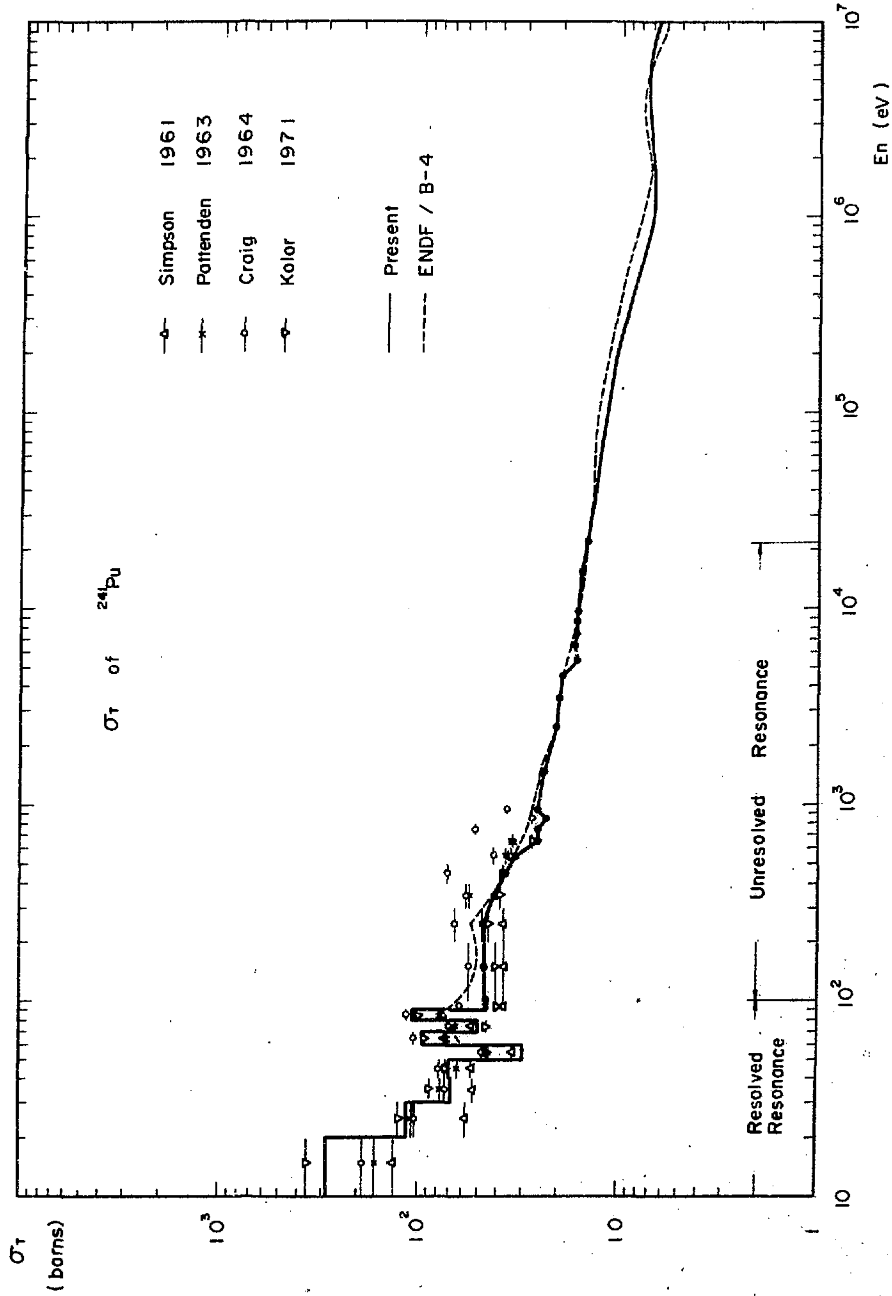
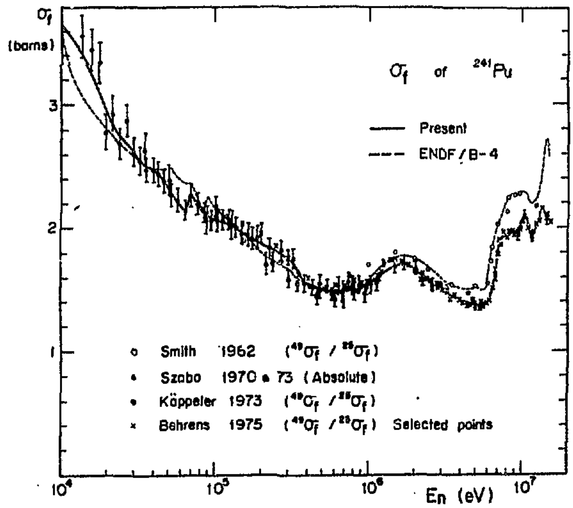
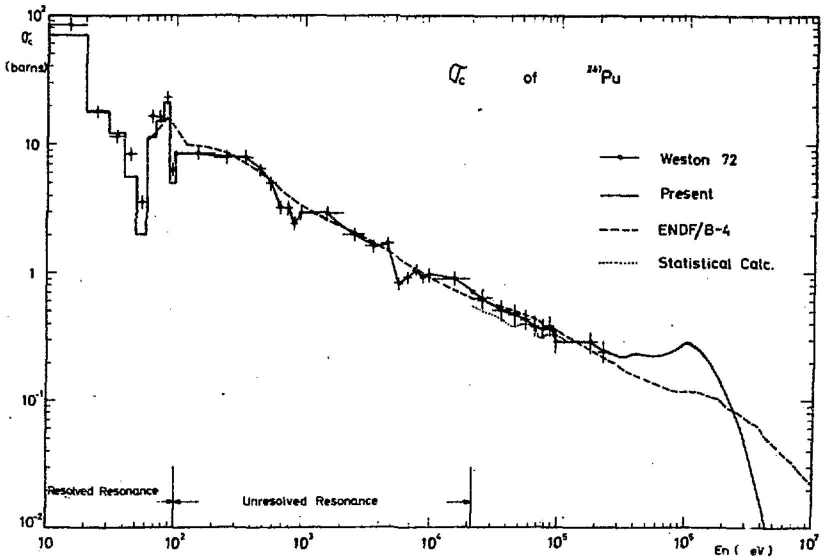


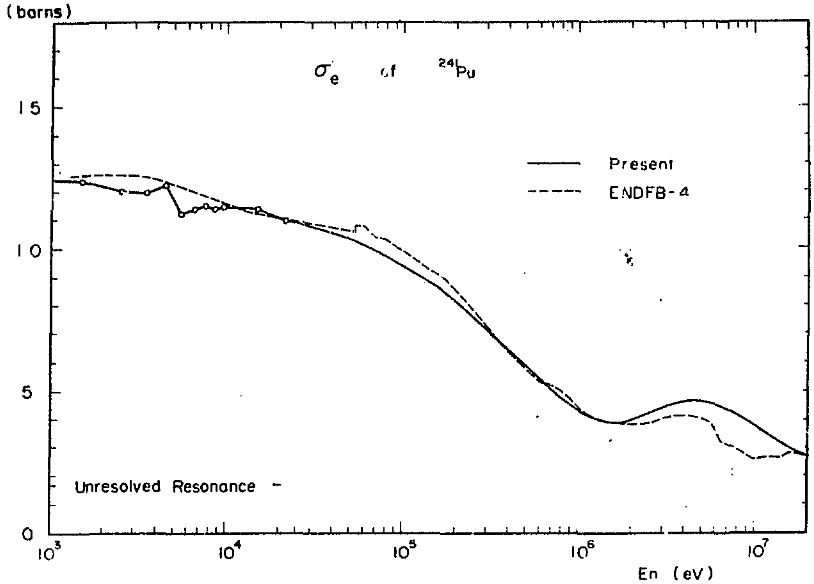
Fig. 1.5.1. Total cross section of ^{241}Pu



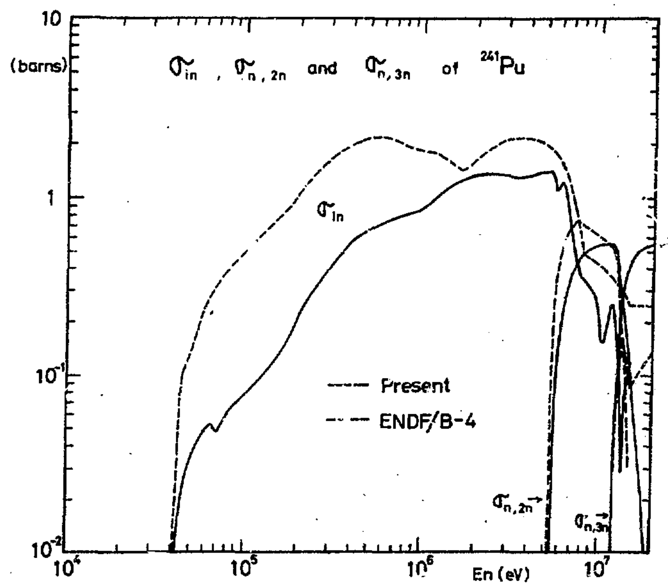
1.5.2. Fission cross section of ^{241}Pu



1.5.3. Capture cross section of ^{241}Pu



1.5.4. Elastic scattering cross section of ^{241}Pu



1.5.5. Inelastic scattering, (n,2n) and (n,3n) cross sections of ^{241}Pu

Part II

Compilation of JENDL-1

Yasuyuki KIKUCHI
Tsuneo NAKAGAWA

2.1. URANIUM-235

2.1.1. Thermal Cross Sections

The cross sections are given as point-wise data below 1 eV. The data of ENDF/B-IV were adopted.

2.1.2. Resonance Parameters

Resolved resonance parameters

The resolved resonance parameters are given in the energy range up to 82 eV. The parameters of ENDF/B-IV were adopted with the background cross sections, according to the recommendation by Asami who has examined the present status of the resonance parameters of ^{235}U.

Unresolved resonance parameters

The unresolved resonance parameters are given between 82 eV and 21.5 keV. The parameters were determined so as to reproduce the evaluated fission and capture cross sections. As for the fission and capture cross sections to be reproduced, the data measured by Perez[1)] were adopted in the present work. These cross sections are shown in Figs.2.1.1 and 2.1.2 with the other experimental data.

The fission widths and the strength functions were searched for. The spin-dependence of the fission width was estimated[2)] by means of the channel theory of the fission, and was fixed. The ratio of the s-wave to p-wave strength functions was determined from the values recommended in BNL-325, 3rd edition[3)]. The resonance parameters thus obtained are given in Table 2.1.2 with the cross sections. The total cross section calculated from these parameters agree very well with the experimental data measured by Uttley[4)]. All the cross sections join smoothly with the smooth cross sections evaluated by Matsunobu at 21.5 keV.

2.1.3. Smooth Cross Sections above 21.5 keV

Total cross section

Matsunobu's evaluated data were adopted, which are shown in Fig. 1.1.1.

Fission cross section

Matsunobu's evaluated data were adopted below 6 MeV, which are shown in Figs.1.1.3 and 1.1.4. Above 6 MeV, there are large discrepancies among existing evaluated data. Recently, a new measurement was reported by Czirr and Sidhu[5)] who paid much attention to obtain the correct shape of cross section. Therefore JENDL-1 adopted their data with normalizing them to Matsunobu's data between 3 and 5.4 MeV. Consequently Czirr's data were reduced by about 2% from the values reported by themselves. The adopted data in JENDL-1 are shown in Fig. 2.1.3 with those in ENDF/B-IV and Sowerby's evaluation.[6] They agree well with each other.

Capture cross section

Matsunobu's evaluation was adopted, which is shown in Fig. 1.1.7.

Elastic scattering cross section

Matsunobu's evaluation was adopted up to 6 MeV. Above 6 MeV, the elastic scattering cross section was obtained as

$$\sigma_{el} = \sigma_t - \sigma_f - \sigma_c - \sigma_{in} - \sigma_{n,2n} - \sigma_{n,3n} ,$$

taking account of the modification of the fission cross section.

Inelastic scattering, (n,2n) and (n,3n) cross sections

Matsunobu's evaluation was adopted, as shown in Figs. 1.1.8 and 1.1.9.

2.1.4. Angular Distribution of Secondary Neutrons

The angular distribution of the elastically scattered neutrons was calculated by Matsunobu with the optical and statistical models and was adopted in JENDL-1. The isotropic scattering was assumed for the inelastically scattered neutrons. μ_L was calculated with the angular diatribution.

2.1.5. ν

ν_p

Matsunobu's evaluated data were adopted as shown in Fig. 1.1.10.

ν_d

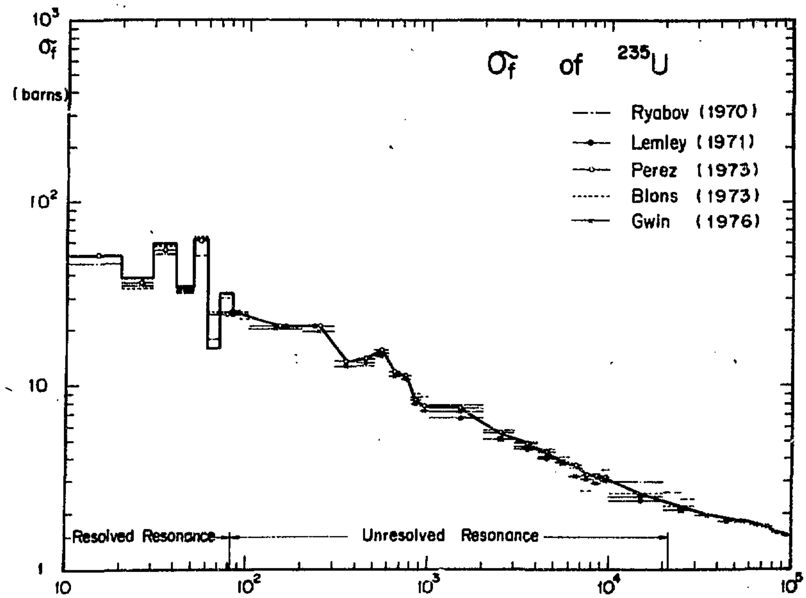
The evaluation by Schatz[7] was adopted :

ν_d	$= 0.0158 \pm 0.005$		0.025 eV
	$= 0.018 \pm 0.002$		below 10 MeV
	$= 0.095 \pm 0.0008$		above 10 MeV

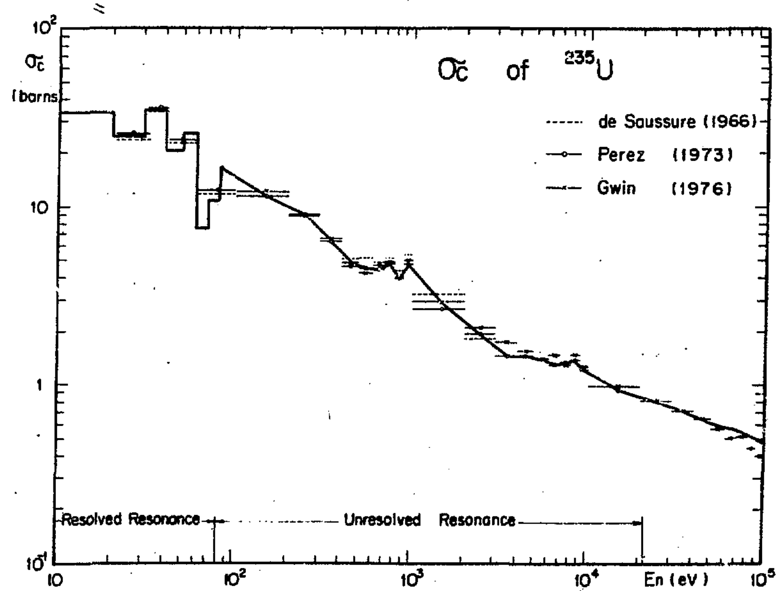
Table 2.1.1. Unresolved resonance parameters and the calculated cross sections of ^{235}U

Fixed Parameters ; Dobs = 0.63 eV $\Gamma\gamma$ = 45 meV R = 9.5663 fm

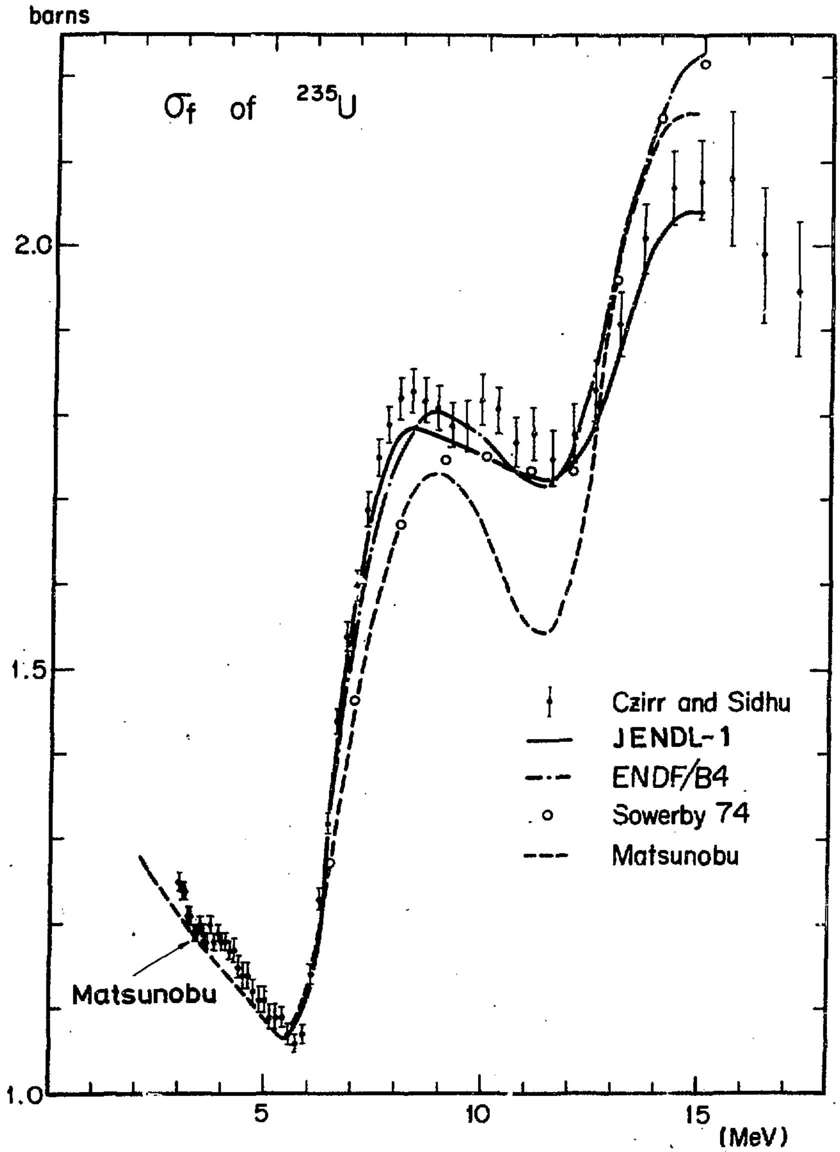
En (keV)	So ($\times 10^{-4}$)	S_1 ($\times 10^{-4}$)	$\Gamma_f^{(3-)}$ (meV)	$\Gamma_f^{(4-)}$ (meV)	$\Gamma_f^{(2+)}$ (meV)	$\Gamma_f^{(3+)}$ (meV)	$\Gamma_f^{(4+)}$ (meV)	$\Gamma_f^{(5+)}$ (meV)	σ_t (b)	σ_f (b)	σ_c (b)
0.082	0.94	1.85	161	89	174	72	161	89	54.49	25.40	16.50
0.15	0.99	1.95	201	111	217	90	201	111	45.04	21.03	11.45
0.25	1.19	2.33	269	149	290	120	269	149	42.69	20.92	9.02
0.35	0.93	1.81	237	131	256	106	237	131	31.99	13.34	6.36
0.45	0.99	1.94	362	200	391	162	361	200	30.91	13.95	4.77
0.55	1.18	2.31	[illegible]	247	483	200	447	247	32.40	15.57	4.49
0.65	1.04	2.04	315	174	339	141	315	174	28.44	11.71	4.44
0.75	1.12	2.19	273	151	295	122	273	151	28.51	11.28	4.75
0.85	0.91	1.78	233	129	251	104	233	129	24.48	8.31	3.98
0.95	0.99	1.94	166	92	179	74	166	92	24.87	7.66	4.75
1.5	1.03	2.01	305	168	329	136	305	168	22.60	7.53	2.90
2.5	0.93	1.82	339	188	366	152	339	188	19.34	5.47	1.94
3.5	0.92	1.80	423	234	456	189	423	234	18.12	4.87	1.46
4.5	0.97	1.89	363	201	392	162	363	201	17.66	4.37	1.47
5.5	0.94	1.84	320	177	345	143	320	177	16.95	3.77	1.40
6.5	0.97	1.90	340	188	366	152	340	188	16.70	3.66	1.30
7.5	0.96	1.87	281	155	303	126	281	155	16.30	3.23	1.33
8.5	1.02	2.00	262	145	282	117	262	145	16.33	3.18	1.38
9.5	1.00	1.96	300	166	324	134	300	166	16.00	3.11	1.22
15.0	0.94	1.83	327	181	353	146	327	181	14.89	2.54	0.95
21.5	0.93	1.82	339	187	366	152	339	187	14.32	2.28	0.84



2.1.1. Fission cross section of ^{235}U in unresolved resonance region



2.1.2. Capture cross section of ^{235}U in unresolved resonance region



2.1.3. Fission cross section of ^{235}U in MeV region

2.2. URANIUM-238

2.2.1. Thermal Cross Sections

The cross sections are given as point-wise data below 1 eV. The data of ENDF/B-IV were adopted.

2.2.2. Resonance Parameters

Resolved resonance parameters

The resolved resonance parameters are given in the energy range up to 4 keV. The parameters of ENDF/B-IV were adopted with the background cross sections, according to the recommendation by Nakagawa who has examined the present status of the resonance parameters of ^{238}U.

Unresolved resonance parameters

The unresolved resonance parameters are given in the energy range between 4 keV and 46.5 keV. The subthreshold fission was neglected and the strength function was determined so as to reproduce the experimental total and capture cross sections. The total cross section was evaluated on the basis of the experimental data by Uttley et al.[8] As for the capture cross section, Kanda's evaluation was based on the data by Fricke et al.[9] However, Moxon's data[10] were adopted here, since the energy dependence of Moxon's data is very similar to that from the calculation.

The ratio of the s-wave to p-wave neutron strength function was assumed to be constant and the value recommended in BNL-325, 3rd edition[3] was adopted. The strength functions thus obtained are given in Table 2.2.1 with the cross sections calculated from these strength functions. The calculated total and fission cross sections are shown in Figs. 1.2.1 and 1.2.2 of Part I with the experimental data.

2.2.3. Smooth Cross Sections above 46.5 keV

Total cross section

Kanda's evaluation was adopted above 100 keV, which is shown in Fig. 1.2.1. Below 100 keV, however, the results of Kanda's evaluation were slightly modified so as to connect smoothly to the cross section calculated from the unresolved resonance parameters.

Fission cross section

Kanda's evaluation was worked out in 1972 on the basis of the experimental data. Ratio measurements of ^{238}U fission to ^{235}U fission were normalized by using the fission cross section of ^{235}U evaluated by Davey[11].

Two ratio measurements were released after Kanda's evaluation over a wide range of energy. One was carried out by Coates et al.[12] in the energy range from 600 keV to 20 MeV. Meadows[13] measured the ratio in the energy range from 1 to 10 MeV. He obtained, in particular, the absolute values of the ratio in the energy region between 2 to 3 MeV. His results agree well with the ratio values by Poenitz et al.[14], Jarvis[15] and White et al.[16] The JENDL-1 adopted the shape of Coates' data[12], whose values were increased by 3% so as to agree with Meadows' data[13] between 2 and 3 MeV. The adopted curve of the ratio data is shown in Fig.2.2.1. The cross section of ^{238}U was obtained by normalizing the ratio data with the fission cross section of ^{235}U adopted in JENDL-1 which were described in chapter 2.1. The fission cross section of JENDL-1 is compared with the other evaluations in Fig. 2.2.2. The data of JENDL-1 are larger than the other evaluated data from 7 to 12 MeV and are smaller from 14 to 18 MeV. The small values near 15 MeV are due to the small value of the fission cross section of ^{235}U adopted in JENDL-1.

Capture cross section

Kanda adopted the data by Fricke et al.[9] below 1 MeV, because the S/N ratios of γ-ray detector is better than in the experiment by Moxon,[10] and because they agree with the data measured by Menlove et al.[17] and Panitkin et al.[18] with different methods. However, JENDL-1 adopted the data by Moxon[10] below 200 keV taking account of the energy dependence of the capture cross section in the unresolved resonance region. Above 200 keV, Kanda's evaluation was adopted. The cross section is shown in Fig. 1.2.2.

Elastic scattering cross section

The elastic scattering cross section was obtained below 3 MeV from the adopted total, capture, fission and inelastic scattering cross sections by

$$\sigma_{el} = \sigma_t - \sigma_c - \sigma_f - \sigma_{in}.$$

Above 3 MeV, Kanda's evaluation was adopted.

Inelastic scattering cross section

The inelastic scattering cross section calculated by Igarasi et al.[19] with the optical and statistical models was adopted up to 3 MeV. The optical potential parameters are given in Table 2.2.2. The level density parameters and the level scheme are given in Tables 2.2.3 and 2.2.4, respectively. Above 3 MeV the evaluation by Kanda was adopted, which was made by

$$\sigma_{in} = \sigma_t - \sum_i \sigma i$$

where i's represent the other partial cross section already evaluated. The evaluated cross section agrees with the experimental data at 14 MeV.

(n,2n) and (n,3n) cross sections

Kanda's evaluated data were adopted, which are shown in Figs. 1.2 4 and 1.2.5 respectively.

2.2.4. Angular Distribution of Secondary Neutron

The angular distribution of elastically scattered neutrons was calculated with the optical and statistical models by using the parameters given in Tables 2.2.1 to 2.2.3. The angular distribution of neutrons due to inelastic scattering to the first and second excited states were evaluated on the basis of the experimental data by Guenther and Smith.[20] The isotropic scattering in the center of mass system was assumed for the inelastic scattering to the other discrete levels.

2.2.5. ν

The data of ENDF/B-IV were adopted.

Table 2.2.1. Unresolved resonance parameters and the calculated cross sections of ^{238}U

Fixed parameters : D_{obs} = 20.8 eV $\Gamma\gamma$ = 2.3 meV R = 9.1840 fm

E_n (keV)	S_o ($\times 10^{-4}$)	S_1 ($\times 10^{-4}$)	σ_t (b)	σ_c (b)	σ_{el} (b)	σ_{in} (b)
4	0.93	1.57	16.80	1.03	15.77	
5	0.95	1.61	16.30	0.94	15.36	
6	0.94	1.60	15.80	0.86	14.94	
7	0.94	1.59	15.40	0.80	14.60	
8	0.93	1.59	15.10	0.76	14.34	
9	0.93	1.59	14.85	0.72	14.13	
10	0.93	1.59	14.65	0.69	13.96	
12	0.95	1.62	14.38	0.65	13.73	
15	0.98	1.66	14.00	0.60	13.50	
17	1.00	1.69	13.96	0.57	13.39	
20	1.01	1.71	13.75	0.53	13.22	
25	1.05	1.79	13.55	0.48	13.07	
30	1.08	1.83	13.35	0.44	12.91	
35	1.10	1.87	13.20	0.41	12.79	
40	1.14	1.94	13.10	0.38	12.72	
46.5	1.17	1.99	12.95	0.35	12.59	0.011

Table 2.2.2. Optical potential parameters for ^{238}U

Real Part

V =	40.5	(MeV)
r_o =	1.32	(fm)
a =	0.47	(fm)

Imaginary Part (Surface type)

W_s =	9.0	(MeV)
r_s =	1.32	(fm)
b =	0.47	(fm)

Spin-orbit Force

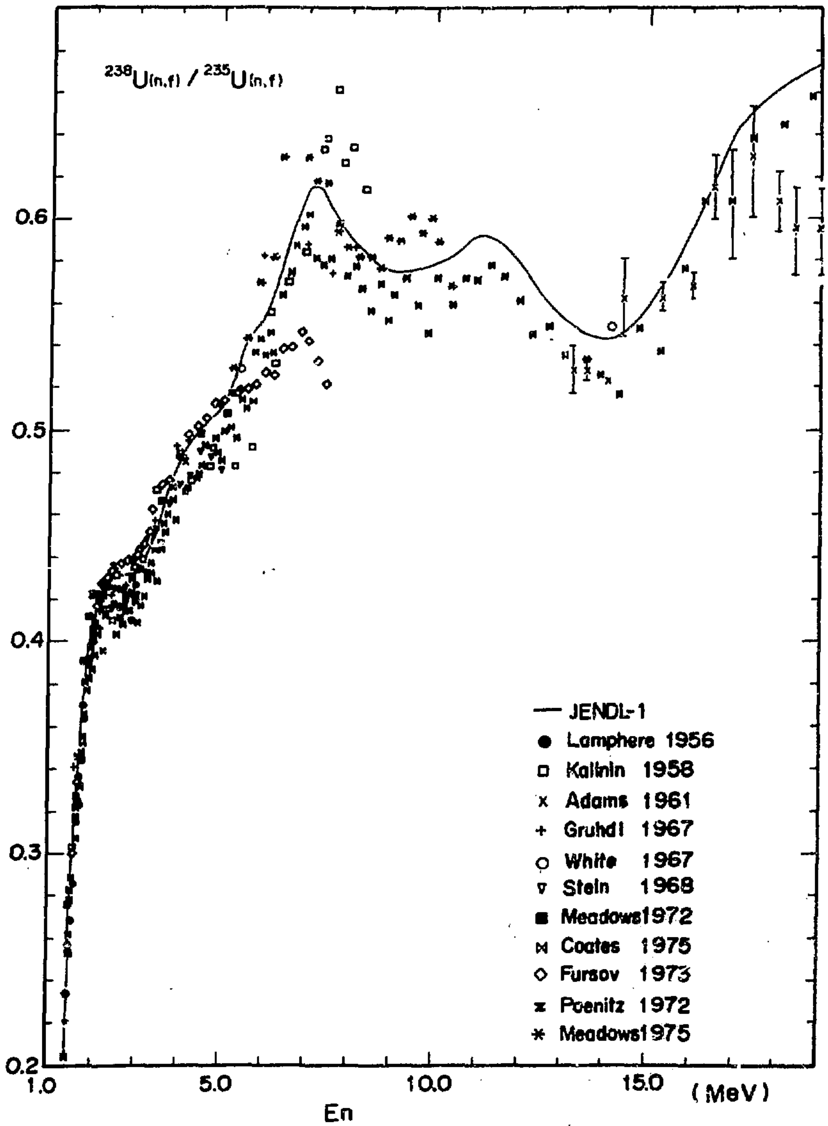
V_{so} =	15.0	(MeV)
r_{so} =	1.32	(fm)
a_{so} =	0.47	(fm)

Table 2.2.3. Level density parameters for ^{238}U

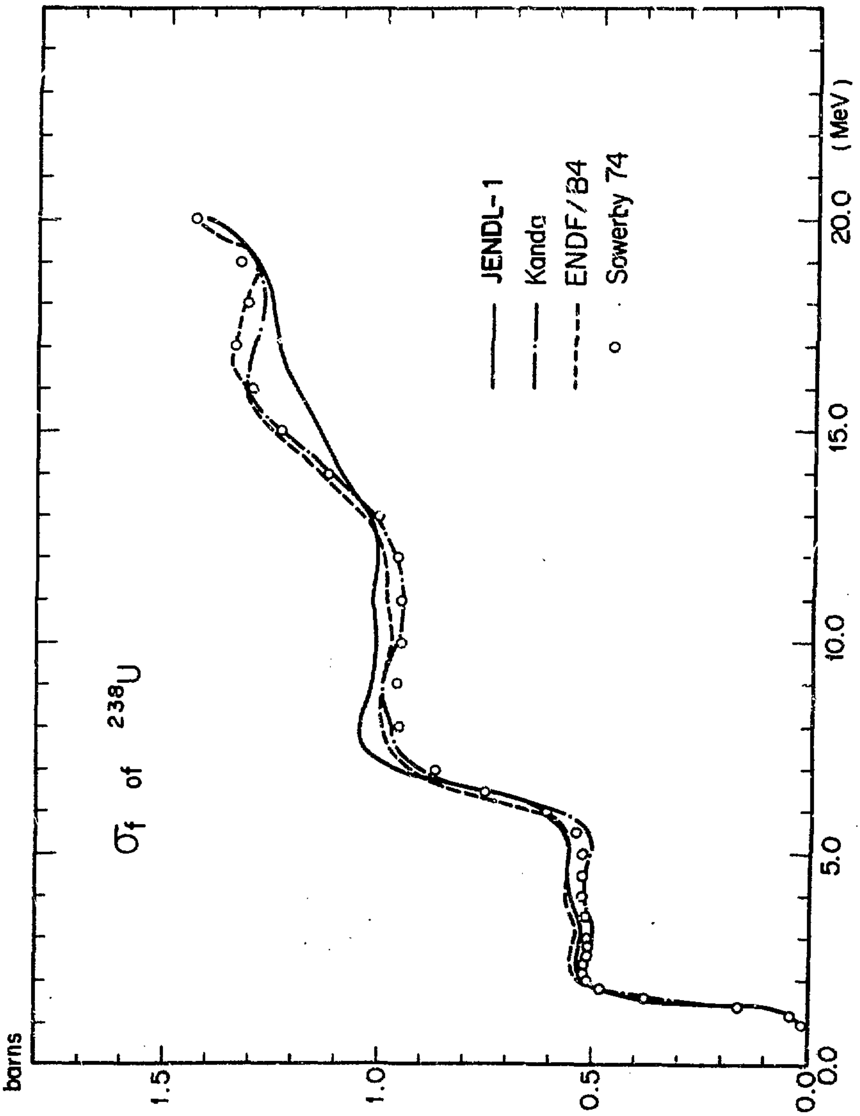
		Target nucleus	Compound nucleus
a	(MeV^{-1})	28.7128	29.1841
Δ	(MeV)	1.12	0.69
α	($MeV^{-1/2}$)	18.2741	18.4750
E_x	(MeV)	4.2503	3.8176
C_o		6137.59	6264.54
S_n	(MeV)	6.1437	4.8027

Table 2.2.4. Level scheme of ^{238}U

Excitation (keV)	Spin	Parity
0.0	0	+
44.7	2	+
148.0	4	+
301.0	6	+
520.0	8	+
680.0	1	-
732.0	3	-
790.0	10	+
838.0	5	-
939.0	2	+
968.0	2	+
1006.0	0	+
1047.0	2	+
1076.0	2	+
1100.0	12	+
1123.0	1	-
1150.0	2	-
1190.0	3	-
1210.0	2	+
1246.0	4	-
1272.0	5	-
1313.0	2	+
1361.0	2	+
1401.0	2	+
1437.0	14	+
1470.0	1	-



2.2.1. Ratio of fission cross section of ^{238}U to that of ^{235}U



2.2.2. Fission cross section of ^{238}U

2.3. PLUTONIUM-239

2.3.1. Thermal Cross Sections

The cross sections are given as point-wise data below 1 eV. The data contained in ENDF/B-IV were adopted except for the capture cross sections which was decreased between 0.5 and 1 eV so as to attain the smooth connection with the cross sections calculated from the resonance parameters.

2.3.2. Resonance Parameters

Resolved resonance parameters

The resolved resonance parameters evaluated by Ribon[21] were adopted in the energy range up to 598 eV according to the recommendation by Yoshida, who had examined[22] the present status of the resonance parameters.

The background cross sections were applied to the elastic scattering and total cross sections so that the cross sections calculated with the single-level Breit-Wigner formula may agree with the results calculated with the multi-level Breit-Wigner formula. Near 1 eV, the background cross sections of 1/v type were applied so that the calculated cross sections may connect smoothly with the cross sections given as point-wise data below 1 eV.

Unresolved resonance parameters

The unresolved resonance parameters are given between 598 eV and 21.5 keV. The parameters were determined so as to reproduce the total, fission and capture cross sections evaluated by Kawai on the basis of the experimental data. His evaluation was described in chapter 1.3. The weight of the capture cross section was lower than the weights of the total and fission cross sections in determining the parameters because of the large uncertainties in the experimental data of the α-value.

The fission width and the strength functions were searched for. The ratio of the s-wave to p-wave strength functions was kept constant and the ratio value was determined from the values recommended in BNL-325,3rd edition[3]. According to the analysis[2] based on the channel theory of fission, the 0^+ state has at least one open fission channel but the 1^+ state has one subthreshold channel. Therefore the intermediate structure is expected[23] for the fission width of the 1^+ state due to the coupling to the excited states on the second minimum point of the fission potential.

In the present analysis, only the fission width of the 1^+ state was changed to reproduce the cross sections, while the fission widths of the other states have been kept constant as the values expected[2] from the channel theory.

The resonance parameters thus obtained are given in Table 2.3.1 with the cross sections calculated with these parameters. The fission cross section and the α-value calculated from these parameters are given in Figs. 2.3.1 and 2.3.2 with the experimental data.

2.3.3. Smooth Cross Section above 21.5 keV

Total cross section

Kawai's evaluation was adopted, which is shown in Fig. 1.3.1.

Fission cross section

Kawai's evaluation was adopted which is based on the experimental data published up to 1973 and is shown in Figs. 1.3.2 and 1.3.3. After Kawai's evaluation, however, a ratio measurement to the fission cross section of ^{235}U was reported by Behrens and Carlson[24]. The present evaluation is compared with these data in Fig. 2.3.3. The present results are considerably lower in the energy ranges between 150 keV and 500 keV and near 800 keV, and are higher above 7 MeV. These discrepancies must be further investigated.

Capture, elastic and inelastic scattering, (n,2n) and (n,3n) cross sections

Kawai's evaluated data were adopted. They are illustrated in Figs. 1.3.5 to 1.3.8.

2.3.4. Angular Distribution of Secondary Neutron

The angular distribution of elastically scattered neutron was calculated with the optical and statistical models by Kawai, and μ_L was calculated from this distribution. The isotropic scattering was assumed for the inelastically scattered neutrons.

2.3.5. ν

ν_p

Kawai's evaluation described in chapter 1.3 was adopted.

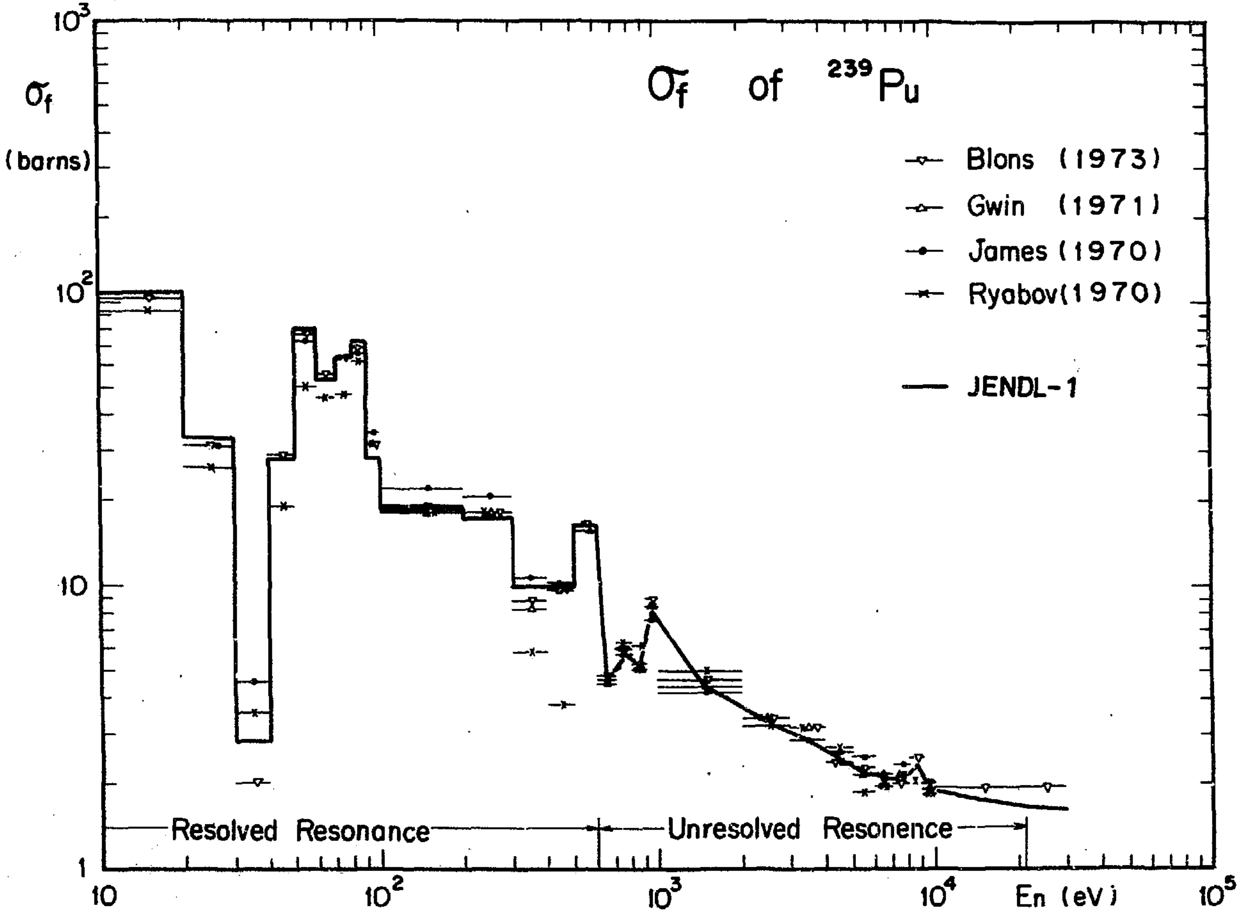
ν_d

The evaluation by Manero and Konshin[25] was adopted.

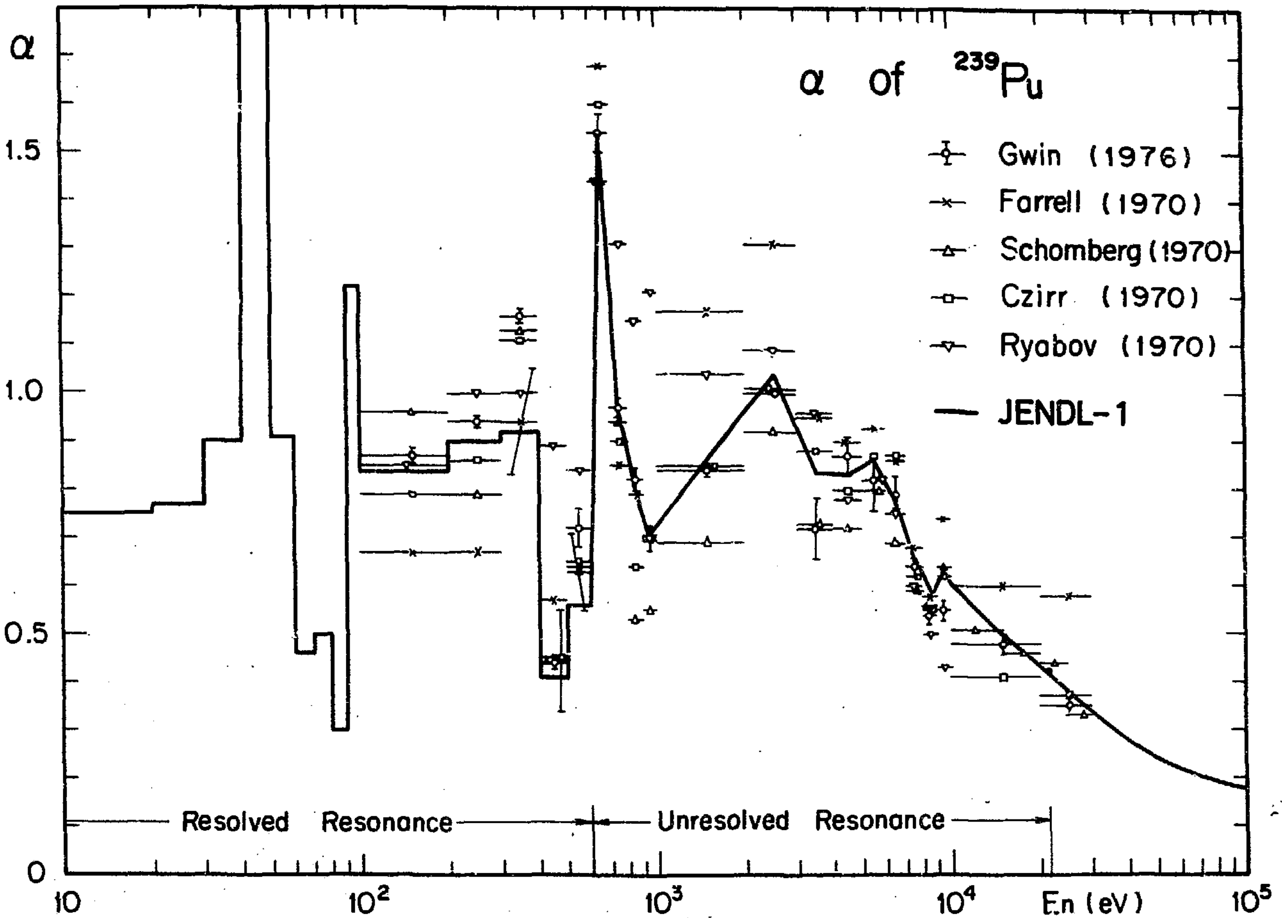
Table 2.3.1. Unresolved resonance parameters and the calculated cross sections of ^{239}Pu

Fixed parameters : D_{obs} = 2.3 eV $\Gamma\gamma$ = 40 meV R = 9.0094 fm
$\Gamma_f^{(0^+)}$ = 2800 meV $\Gamma_f^{(0^-)}$ = 0 meV $\Gamma_f^{(1^-)}$ = 1000 meV, $\Gamma_f^{(2^-)}$ = 600 meV

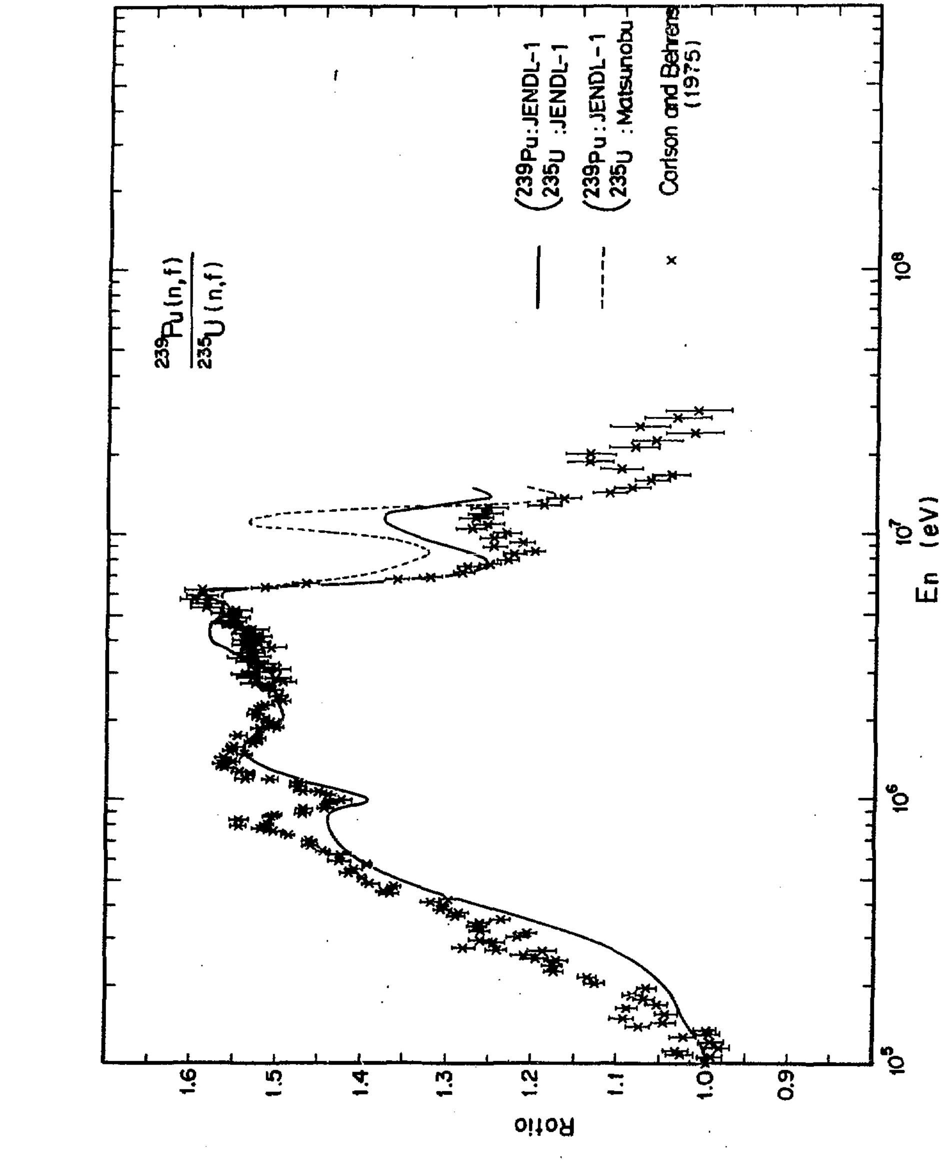
E_n (keV)	S_o ($\times 10^{-4}$)	S_1 ($\times 10^{-4}$)	$\Gamma_f^{(1^+)}$ (meV)	σ_t (b)	σ_c (b)	σ_f (b)	σ_{el} (b)	σ_{in} (b)	α
0.598	1.41	2.49	33.2	34.06	8.50	9.71	14.85		0.88
0.65	0.90	1.59	8.15	24.86	6.99	4.54	13.33		1.54
0.75	0.93	1.64	28.4	24.24	5.56	5.71	12.97		0.97
0.85	0.80	1.41	44.9	21.60	4.21	5.24	12.14		0.80
0.95	1.32	2.34	50.5	28.04	5.60	7.94	14.50		0.70
1.5	1.03	1.82	30.4	21.30	3.86	4.45	12.99		0.87
2.5	1.18	2.08	13.4	20.11	3.38	3.24	13.49		1.04
3.5	1.06	1.87	22.8	17.77	2.39	2.82	12.56		0.84
4.5	1.05	1.86	20.1	16.90	2.06	2.46	12.38		0.84
5.5	1.08	1.92	14.4	16.48	1.91	2.20	12.37		0.87
6.5	1.03	1.82	18.6	15.72	1.62	2.07	12.03		0.78
7.5	1.02	1.80	28.3	15.30	1.40	2.11	11.79		0.66
8.5	1.16	2.05	29.8	15.71	1.31	2.25	11.94	0.221	0.58
9.5	1.08	1.92	19.8	15.09	1.20	1.91	11.70	0.285	0.63
10.0	1.08	1.91	21.2	14.97	1.14	1.90	11.63	0.302	0.60
12.0	1.08	1.92	19.3	14.60	1.01	1.79	11.46	0.346	0.57
15.0	1.09	1.93	20.7	14.21	0.866	1.73	11.25	0.366	0.50
18.0	1.08	1.92	22.9	13.86	0.763	1.69	11.05	0.362	0.45
21.5	1.11	1.97	21.1	13.67	0.697	1.67	10.93	0.375	0.42



2.3.1. Average fission cross section of ^{239}Pu in the resonance region.



2.3.2. α-value of ^{239}Pu below 20 keV



2.3.3. *Ratio of the fission cross section of ^{239}Pu to that of ^{235}U*

2.4. PLUTONIUM-240

2.4.1. Thermal Cross Sections

The cross sections are given as point-wise data below 0.5 eV. The data of ENDF/B-IV were adopted.

2.4.2. Resonance Parameters

<u>Resolved resonance parameters</u>

The resolved resonance parameters are given in the energy range up to 3.91 keV. The parameters of ENDF/B-IV were adopted with the background cross sections, according to the recommendation by Zukeran who has examined the present status of the resonance parameters of ^{240}Pu.

<u>Unresolved resonance parameters</u>

The unresolved resonance parameters are given from 3.91 keV to 46.5 keV. The parameters were determined so as to reproduce the evaluated fission and capture cross sections. The evaluation by Murata was adopted for the fission cross seciton, which is shown in Fig. 1.4.3. On the other hand, the capture cross section evaluated by Murata seems to be lower than the experimental data below 10 keV and considerably higher above 30 keV as seen in Fig. 1.4.4. It was found in the preliminary calculation that the parameters obtained from Murata's evaluated fission and capture cross sections gave a very anomalous shape in the total cross section. Then a new evaluation was made for the capture cross section below 120 keV on the basis of the experimental data by Hockenbury et al.[26] and by Weston and Todd.[27] The present evaluation took the values by Weston and Todd[27] in the energy ranges below 10 keV and above 30 keV, and took the mean values of the two sets of data between 10 and 30 keV. The total cross section evaluated by Murata was ignored, since this cross section seemed too low to be connected smoothly to that calculated from the resolved resonance parameters as seen in Fig. 2.4.1.

The fission widths and the strength functions were searched for. The fission width was assumed to be the same for all the spin states. The ratio of the s-wave to p-wave strength function was kept constant and the value recommended in BNL-325, 3rd edition[3] was adopted. The resonance parameters thus obtained are given in Table 2.4.1 with the cross sections.

As seen in Fig. 2.4.1 the total cross section calculated from these parameters shows a reasonable energy dependence, but is larger than that evaluated by Murata.

2.4.3. Smooth Cross Sections above 46.5 keV

Total cross section

Murata's evaluation was adopted in the energy range above 120 keV. Between 46.5 and 120 keV, however, JENDL-1 adopted a smooth curve drawn with the eye-guide method, since his evaluated cross section is considerably lower than that calculated from the resonance parameters below 46.5 keV.

Fission cross section

Murata's evaluation was adopted, which was based on the experimental data published up to 1975, and is shown in Fig. 1.4.3. After his evaluation, Behrens et al.[24] reported the ratio measurement to the fission cross section of ^{235}U from 20 keV to 30 MeV. The present evaluation is compared with these data in Fig. 2.4.2. The present evaluation gives considerably lower values above 3 MeV. This problem should be further investigated.

Capture cross section

Murata's evaluation was adopted in the energy range above 120 keV. As discussed in section 2.4.2, his evaluated cross section is higher than the experimental data by Weston and Todd.[27] Hence a curve was drawn between 46.5 and 120 keV with the eye-guide method so as to pass the data by Weston and Todd. The adopted curve is shown in Fig. 1.4.4.

Elastic scattering cross section

Murata's evaluation was adopted in the energy range above 120 keV. Below 120 keV, the elastic scattering cross section was modified so that the sum of the partial cross sections may be equal to the total cross section.

Inelastic scattering, (n,2n) and (n,3n) cross sections

Murata's evaluation was adopted.

2.4.4. Angular Distribution of Secondary Neutrons

Murata's evaluation was adopted for elastic scattering. The isotropic scattering in the center of mass system was assumed for inelastic scattering.

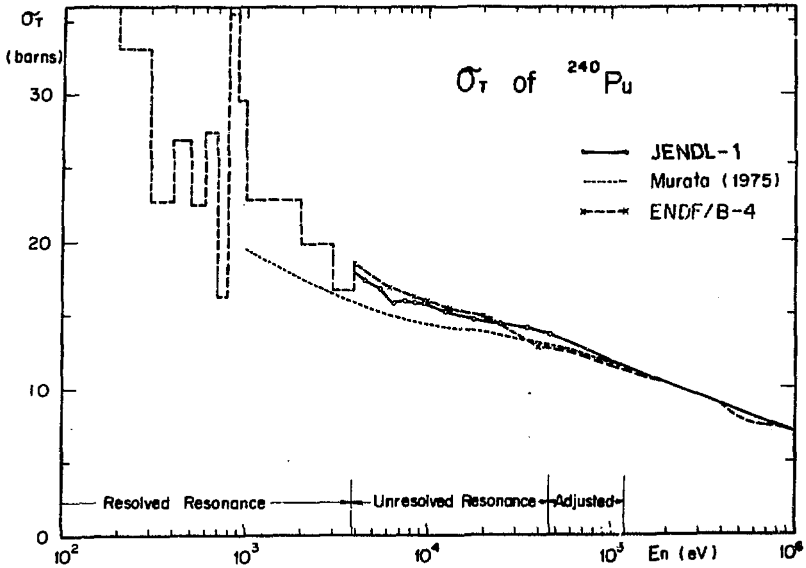
2.4.5. ν

The data of ENDF/B-IV were adopted.

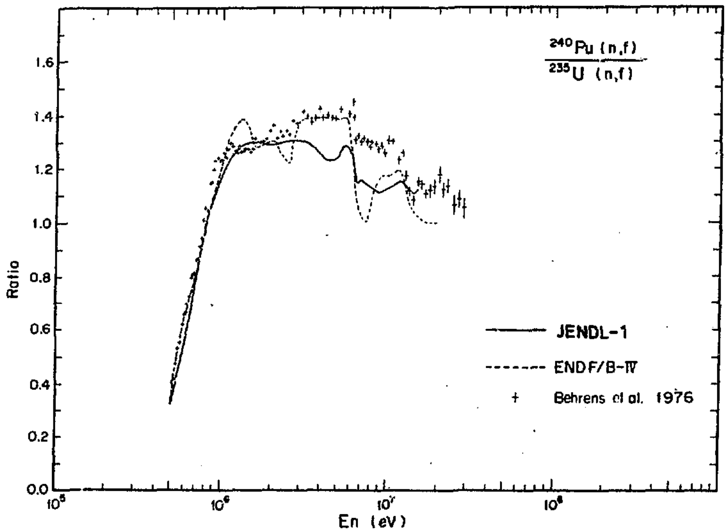
Table 2.4.1. Unresolved resonance parameters and the calculated cross sections of ^{240}Pu

Fixed parameters : D_{obs} = 13.6 eV $\Gamma\gamma$ = 29.5 meV R = 9.18 fm

E_n (keV)	So ($\times10^{-4}$)	S_1 ($\times10^{-4}$)	Γ_f (meV)	σ_t (b)	σ_c (b)	σ_f (b)	σ_{el} (b)	σ_{in} (b)
3.91	1.04	2.66	2.44	17.9	1.72	0.133	16.05	
4.5	1.04	2.64	2.22	17.4	1.61	0.114	15.68	
5.5	1.03	2.62	1.83	16.8	1.48	0.087	15.23	
6.5	0.93	2.37	1.65	15.8	1.32	0.070	14.41	
7.5	1.01	2.56	1.35	15.9	1.30	0.057	14.54	
8.5	1.04	2.64	1.29	15.8	1.26	0.053	14.48	
9.5	1.06	2.71	1.38	15.7	1.23	0.055	14.42	
12.0	1.07	2.72	2.29	15.2	1.09	0.080	14.03	
17.5	1.06	2.69	3.97	14.6	0.936	0.115	13.55	
25.0	1.14	2.89	5.23	14.4	0.819	0.131	13.45	
35.0	1.17	2.99	5.63	14.1	0.703	0.122	13.27	
46.5	1.15	2.91	5.79	13.7	0.589	0.106	12.92	0.039



2.4.1. Total cross section of ^{240}Pu



2.4.2. The ratio of $^{40}\sigma f/^{25}\sigma f$ above 100 keV.

2.5. PLUTONIUM-241*

2.5.1. Thermal Cross Sections

The cross sections are given as point-wise data below 1 eV. As for the total and fission cross sections, the data of ENDF/B-IV were adopted, since these data agree well with the existing experimental data. These cross sections join smoothly at 1 eV to those calculated from the resonance parameters described in the next section as shown in Fig. 2.5.1. Figure 2.5.1 also shows that the adopted cross sections agree with the values of the recent IAEA evaluation by Lemmel[28)] for 2200 m/s neutrons.

No experimental data are available for elastic scattering in this energy region below 1 eV. Then the cross section was calculated from the resolved resonance parameters which will be described in the next section. In the present calculation the scattering radius of 1.0×10^{-12} cm was used so as to reproduce the IAEA evaluated value[28)] for 2200 m/s neutrons. For the capture cross section, no experimental data have been reported except for the 2200 m/s neutrons. Therefore the capture cross section was derived by subtracting the fission and elastic scattering cross sections from the total cross section.

2.5.2. Resonance Parameters

Resolved resonance parameters

The parameters recommended in BNL-325, 3rd edition[3)] were adopted up to 100 eV. For the levels whose parameters are not given completely in BNL-325, the fission width (Γ_f) deduced by Blons[29)] were adopted with the assumption of Γ_γ = 40 meV. The scattering radius was assumed to be 1.0×10^{-12} cm so as to give the correct elastic scattering cross section in the thermal energy region.

In order to examine the propriety of these adopted parameters, the cross sections calculated from these parameters were compared with the available experimental data. It was concluded from the comparison that the present resonance parameters satisfactorily reproduced the fission and total cross sections, but a little underestimated the capture cross section.

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* The detail of the evaluation will be published in J. Nucl. Sci. Technol.

Unresolved Resonance Parameters

The unresolved resonance parameters are given in the energy range between 100 eV and 21.5 keV. The parameters were determined so as to reproduce the fission and capture cross sections evaluated on the basis of experimental data.

As to the fission cross section, the evaluation was made by averaging the data published in 1970's with equal weights below 2 keV. Above 2 keV the newest data by Blons[30] were adopted. The capture cross section was obtained from the only available α - data measured by Weston and Todd[31]. The fission and capture cross sections thus evaluated are shown in Figs. 2.5.2 and 1.5.3.

The s-wave and p-wave neutron strength functions were searched for with fixing their ratio to that recommended in BNL-325, 3rd edition[3]. According to the analysis[2] based on the channel theory of fission, the 3^+ state has one open fission channel and one subthreshold fission channel, while the 2^+ state has two open fission channels. Hence it has been expected[32] that the intermediate structure may be observed in the fission width of the 3^+ state. It was found, however, in the preliminary calculation that the structure of α above 1 keV was too large to be explained by the intermediate structure in the fission width of the 3^+state only. Hence the fission widths of the 2^+ and 3^+ states were searched for with keeping their ratio as expected from the channel theory[2], while the fission widths of the p-wave states were kept constant. The scattering radius was set as 9.3×10^{-13} cm in this energy region. This is based on the shape elastic scattering cross section calculated with the optical model described in chapter 1.5.

The strength functions and fission widths are given in Table 2.5.1 with the cross sections. The total cross section calculated from these parameters are compared with the experimental data in Fig. 1.5.1. The calculated values are a little lower than the experimental data above 500 eV. Considering the large discrepancies among the experimental data, this underestimation can be accepted.

2.5.3. Smooth Cross Section above 21.5 keV

Kikuchi's evaluation described in chapter 1.5 was adopted for all the cross sections.

2.5.4. Angular Distribution of Secondary Neutron

The angnlar distribution of elastically scattered neutrons was calculated by Kikuchi with the optical and statistical models, and μ_L was calculated from this distribution. The isotropic scattering in the center of mass system was assumed for the inelastically scattered neutrons.

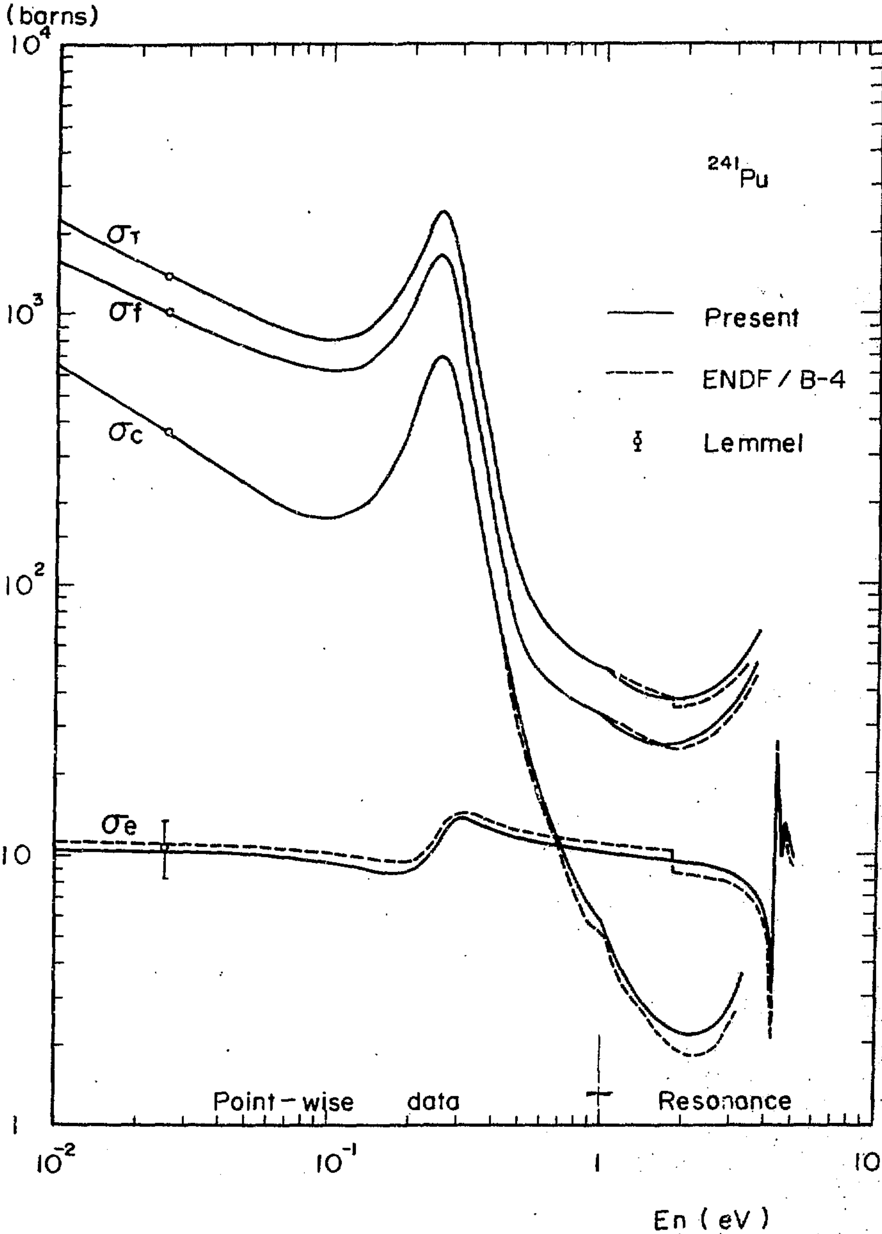
2.5.5. ν

The data of ENDF/B-IV were adopted.

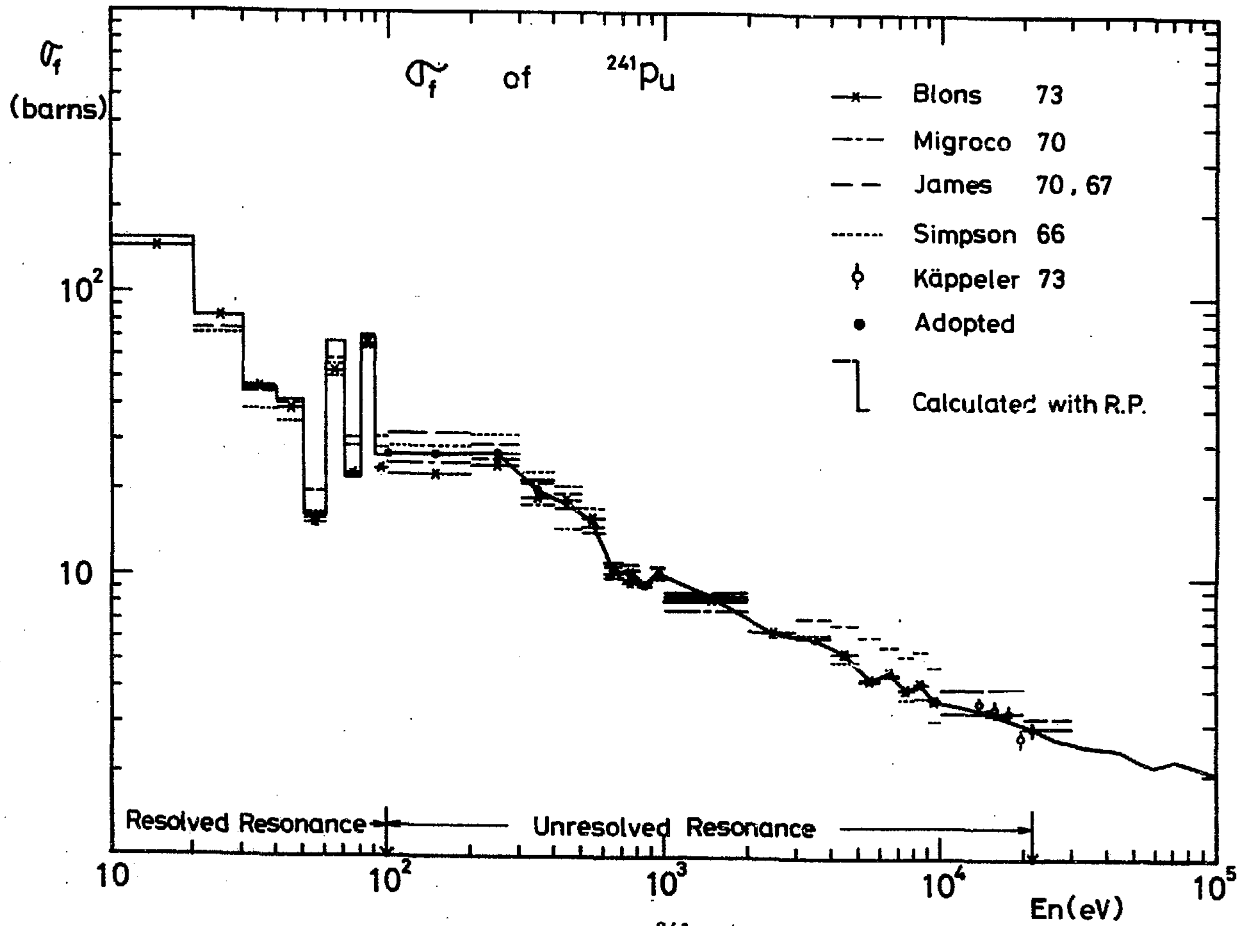
Table 2.5.1. Unresolved resonance parameters and the calculated cross sections of ^{241}Pu

Fixed Parameters : Dobs = 1 eV, Γ_γ = 40 meV, R = 9.33 × 10^{-13} cm
$\Gamma_f^{(1^-)}$ = 420 meV, $\Gamma_f^{(2^-)}$ = 275 meV, $\Gamma_f^{(3^-)}$ = 760 meV,
$\Gamma_f^{(4^-)}$ = 640 meV.

En (keV)	S_0 (×10^{-4})	S_1 (×10^{-4})	$\Gamma_f^{(2^+)}$(meV)	$\Gamma_f^{(3^+)}$(meV)	σ_c(b)	σ_f (b)	σel(b)	σ_t(b)
0.1	0.87	1.52	604	417	8.30	26.70	11.90	46.90
0.15	1.08	1.88	586	405	8.30	26.70	12.37	47.37
0.25	1.41	2.45	621	429	7.79	26.80	13.13	47.72
0.35	1.38	2.40	385	266	7.81	20.20	13.47	41.48
0.45	1.35	2.35	424	293	6.39	17.70	13.20	37.29
0.55	1.24	2.16	513	354	4.90	15.30	12.66	32.86
0.65	0.89	1.55	580	400	3.18	10.50	11.79	25.47
0.75	0.94	1.64	552	381	3.15	10.19	11.89	25.23
0.85	0.87	1.51	755	522	2.38	9.29	11.61	23.28
0.95	1.06	1.85	633	438	2.89	10.37	12.01	25.27
1.5	1.18	2.05	422	292	2.90	8.38	12.38	23.65
2.5	1.10	1.92	471	325	1.98	6.25	12.00	20.23
3.5	1.22	2.13	606	419	1.62	6.13	11.95	19.70
4.5	1.31	2.28	429	296	1.70	5.37	12.18	19.25
5.5	0.94	1.64	1150	795	0.816	4.34	11.21	16.37
6.5	1.11	1.93	980	677	0.916	4.58	11.36	16.85
7.5	1.12	1.95	606	419	1.031	4.01	11.30	16.54
8.5	1.17	2.03	828	572	0.90	4.17	11.37	16.44
9.5	1.16	2.02	577	398	0.965	3.71	11.45	16.12
15	1.28	2.23	495	342	0.899	3.33	11.38	15.61
21.5	1.17	2.03	613	424	0.690	2.85	10.96	14.50



2.5.1. Cross sections of ^{241}Pu below a few eV



2.5.2. Fission cross section of ^{241}Pu in the resonance region

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