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Neutron Nuclear Data Evaluation for Thorium-232

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An evaluation was made on the neutron cross sections, resonance parameters and average neutron yield in fission for ^{232}Th in the energy range from thermal energy to 20 MeV. The fission and capture cross sections were evaluated on the basis of the experimental data by converting the relative ratio data into cross section values by making use of recent evaluations for reference cross sections. The total cross section was determined from experimental data in the region from 24 keV to 15 MeV and then extrapolated to lower and higher energies by using the optical model whose parameters had been adjusted as so to reproduce the measured data. The elastic and inelastic scattering, $(n, 2n)$ and $(n, 3n)$ reaction cross sections were calculated by means of the statistical model combined with the optical model. A set of resonance parameters were recommended in the energy range below 3.5 keV and average resonance parameters were deduced in the unresolved resonance region. A value of 7.40 b was chosen for the capture cross section at 0.025 eV, and the picket-fence negative-energy levels were introduced so as to reproduce the non-$1/v$ behavior of the capture cross section in the epithermal region.

The results were incorporated in the Japanese Evaluated Nuclear Data Library, Version 2 (JENDL-2). Comparison was made between the present and other evaluations such as ENDF/B-V and possible reasons for the discrepancy were discussed.

***KEYWORDS:** thorium 232, nuclear data evaluation, statistical model, total cross sections, elastic scattering, inelastic scattering, radiative capture, fission, resonance parameters, comparative evaluations, 0-20 MeV range*

I. INTRODUCTION

The need for optimum utilization of non-renewable energy sources, such as uranium, along with recent concern about proliferation of plutonium, has led to a renewed interest in the nuclear breeder systems based on the ^{232}Th-^{233}U fuel cycle. Efficient utilization of thorium has been studied in various systems including molten-salt reactors, intermediate and fission-fusion hybrid reactors, as well as in fast breeder and high-temperature gas-cooled reactors. This situation gives rise to increasing requirements for the cross sections of neutron interactions of various types with greater accuracy.

The present work is an attempt to obtain a consistent set of cross sections for ^{232}Th, the result of which has been incorporated into the Japanese Evaluated Nuclear Data Library, Version 2 (JENDL-2). The evaluation has been carried out on the basis of measured data when sufficient body of experimental informations are available. Use has also been made of nuclear reaction theories, such as the Moldauer formalism and the optical model, to calculate the required data where no or only few measurements exist. The results of the present evaluation are compared with the ENDF/B-V and other evaluations.

II. REQUESTS AND PRESENT STATUS OF MEASUREMENTS

WRENDA 79/80[1] summarizes the users' requests on the nuclear quantities together

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with required accuracy, energy region to be covered and the purpose of utilization. Comparison with the requests seen in the earlier version (WRENDA 75[(2)]) reveals some recent trends in the requirements:

(a) For total cross section, data of high accuracy are required especially in the thermal and resonance regions.

(b) There are many requests for the capture cross section in the wide energy region extending from thermal to fast regions. This is a consequence of the great importance of this reaction for breeding.

(c) Newer requests are found for $(n, 2n)$ reaction cross section. This is because this reaction leads to the production of ^{232}U, which is the starting point of a decay chain of nuclides, among which are highly γ-active isotopes, namely ^{212}Bi and ^{208}Tl. A possible application of thorium as a neutron multiplier in the blanket of a hybrid fusion reactor is another motive to the interest in this reaction.

(d) There are notable interests in the fission cross section at higher energies, where the dominant processes are multiple-chance fission, such as $(n, n'f)$ and $(n, 2nf)$ reactions.

(e) A new item on the energy-dependent γ-ray production cross sections has been added in the newer version of WRENDA.

III. Evaluation of Nuclear Data

1. Fast Neutron Cross Sections

(1) Total Cross Section and Optical Potential Parameters

Many measurements[(3)~(14)] have been made on the total cross section of ^{232}Th in the MeV region, although the measured data are rather sparse below 1 MeV. The data are plotted in **Fig. 1** (In referring to previous works, we often use hereafter such an abbreviation as Whalen 78, indicating the first author and the year of publication). In the region of size resonance, Foster 67[(3)] and Fasoli 70[(4)] have given data points that are in good agreement to each other. Thus in our previous evaluation for JENDL-1[(15)], we relied primarily upon these two measurements. The values of Walt 53[(5)] and Leroy 63[(6)] are smaller than the two measurements by 0.2~0.4 b. These data are, however, sparse and scattered so that they have not been adopted in the present evaluation. Measurement by Tsukada 60[(7)] shows different behavior around 4 MeV both in shape and magnitude. The ENDF/B-IV evaluation shows a resonance with narrower width and higher peak. However the data base of the evaluation is not evident.

Recent measurement by Whalen 78[(13)] provides values a little higher than JENDL-1 evaluation in the region 1.5~3.0 MeV, and a little lower in 3.5~5 MeV. The peak position of the size resonance is displaced toward lower energies by 0.4 MeV from JENDL-1 evaluation, but the difference is not very significant; overall behavior of the cross section curve is rather in good agreement with JENDL-1 than with ENDF/B-IV evaluation.

Below 1.5 MeV, fewer measurements have been made. Uttley 61, 66[(10)(11)] and Walt 53[(5)] yielded data higher than Seth[(8)], on which ENDF/B-IV evaluation seems to be based. The JENDL-1 evaluation relied upon the higher group of values.

The new measurement of Whalen 78[(13)] agrees very well with Uttley's data, thus supporting the JENDL-1 evaluation. At 24 keV, Kobayashi 78[(14)] obtained the value 14.993± 0.041 b; this is 16% higher than the value 12.90±0.24 b calculated by using parameters given in ENDF/B-IV, but agrees with the data of Uttley 61, 66[(10)(11)], within errors (Fig. 1).

To summarize, newer measurements do not show marked discrepancy from the JENDL-1

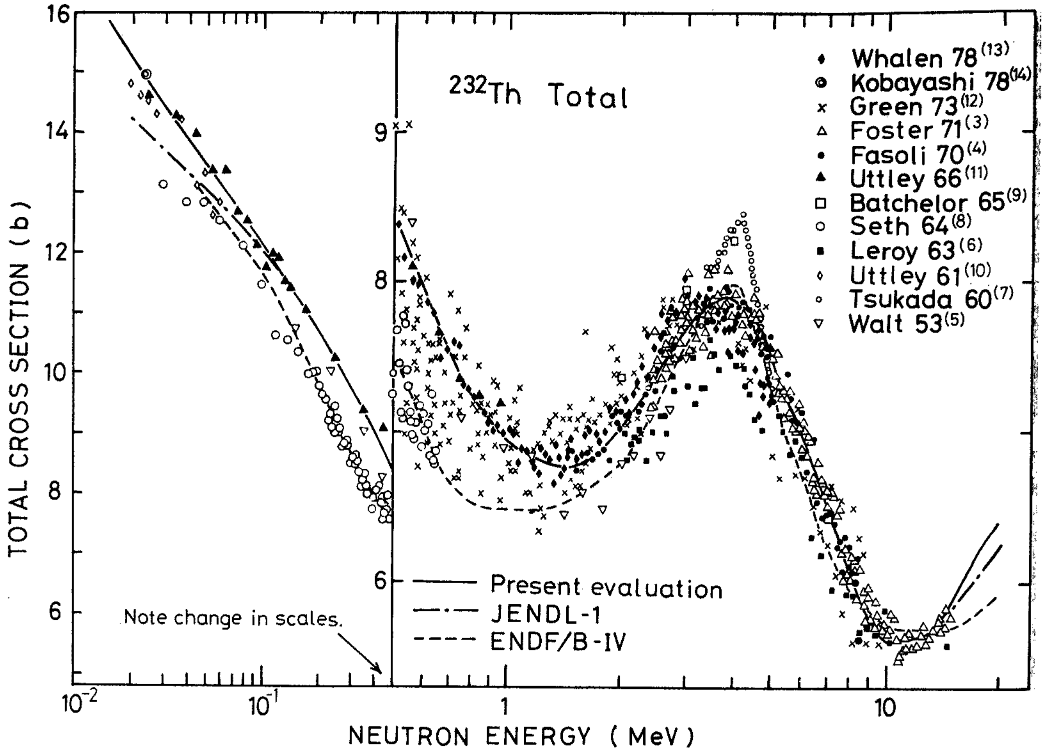


Fig. 1 Total cross section for ^{232}Th

evaluation in the region 150 keV~15 MeV, thus the latter has been employed without revision in the present evaluation. Below 150 keV, new evaluation has been made based on the data of Uttley 61, 66[10][11], Whalen 78[13] and Kobayashi 78[14]. Recent ANL evaluation[16] for ENDF/B-V gives values very close to the present work*.

The optical potential parameters have been chosen so that the calculated total cross section should give the best overall fitting to the evaluated data. The potential employed in this work is of the form

$$V(r)=V_c f(r,\ a,\ r_0)+iW_s g(r,\ b,\ r_s)+V_{so}\left(\frac{\hbar}{m_\pi c}\right)^2\frac{1}{r}\left|\frac{d}{dr}f(r,\ a_{so},\ r_{so})\right|(\boldsymbol{\sigma}\cdot\boldsymbol{l}), \qquad (1)$$

$$f(r,\ a,\ r_0)=[1+\exp\{(r-r_0A^{1/3})/a\}]^{-1}$$

$$g(r,\ b,\ r_s)=4\exp\{(r-r_sA^{1/3})/b\}/[1+\exp\{(r-r_sA^{1/3})/b\}]^2.$$

The parameters obtained are shown in **Table 1** and compared with other sets obtained for thorium, or actinides including thorium. The present parameters have been used to extrapolate the total cross section to the energy ranges below 150 keV and above 15 MeV.

(2) Elastic Scattering Cross Section

Several measurements[9][20]~[25] have been undertaken of the elastic scattering cross section of ^{232}Th, but the results are largely discrepant among them. One of the reasons for the limitted accuracy should lie in the experimental difficulty to separate the inelastic components from the scattered neutrons. We thus resorted to the optical model calculations

* Recent measurement on the total cross section by Baba *et al.*[17] (Tohoku Univ.) provides data that are in good agreement with the present evaluation.

Table 1 Comparison of some optical model parameter sets for ^{232}Th

Author	Real part		Imaginary part			Radius (fm)	V_{so} (MeV)	Energy region considered in fitting (MeV)	Ref.
	V_c (MeV)	a (fm)	W_s (MeV)	Shape	b (fm)				
Present	$41.0-0.05E$	0.47	$6.4+0.15\sqrt{E}$	D.W.S.†	0.47	r_0: 1.31 r_s: 1.38 r_{so}: 1.31	7.0	0.024～15.0	—
Mann & Schenter (1977)††	43.0	0.65	13.0	D.W.S.	0.47	1.28	0.0	——	(18)
Auerbach & Moore (1964)†††	41.3	0.47	7.28	Gauss	1.0	1.32	7.0	0.1～3.0	(19)

† Derivative Woods-Saxon form.
†† Used in evaluation of some actinide cross sections for ENDF/B-V.
††† Obtained for ^{232}Th by fitting to total cross section of *BNL*-325 (2nd ed.) and to elastic scattering cross section of Smith 62[23].

using the above parameters to obtain the evaluated data. It should also be noted that the elastic scattering cross section has been adjusted to assure consistency between the total cross section and the sum of partial cross sections in the region of 50 keV～3 MeV, where some corrections have been made, as will be stated later, to the inelastic scattering cross section. The obtained result is shown and compared with other evaluations in **Fig. 2.** The present evaluation agrees rather well with the measurements, ENDF/B-IV and -V evaluations tending to be a little lower.

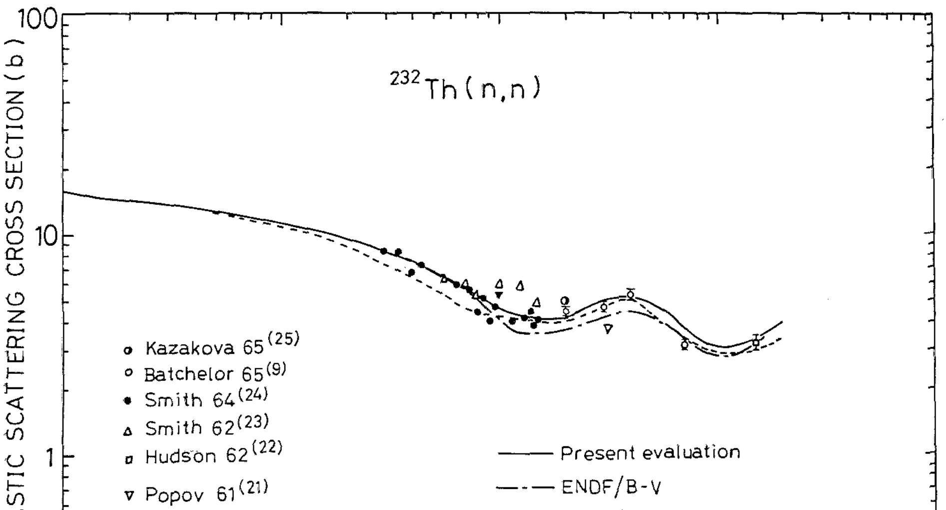
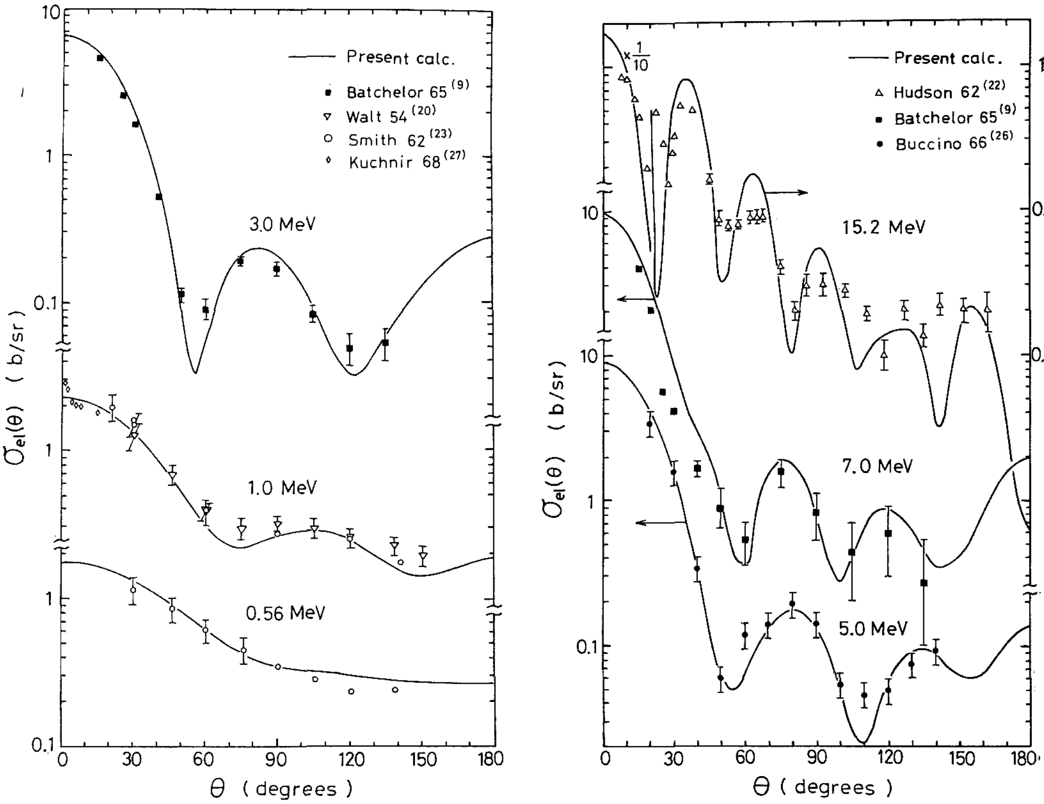


Fig. 2 Elastic scattering cross section for ^{232}Th

Differential elastic scattering cross sections calculated by the optical model using the parameters in Table 1 are shown in **Fig. 3**(a) and (b) together with experimental data[9][20][22][23][26][27]. For $E_n \lesssim 5$ MeV, the calculation reproduces fairly well the behavior of the measured data. At higher energies, some discrepancies are observed; this may be ascribed to increasing direct reaction component in this energy region as well as to insufficient separation of inelastically scattered neutrons from the elastic ones. Coupled-channel calculations would be required for the better analysis of data in this region, but, for convenience sake, use has been made of the spherical optical model in the present evaluation.



(a) E_n=0.56, 1.0, 3 MeV (b) E_n=5.0, 7.0, 15.2 MeV

Fig. 3(a),(b) Differential elastic scattering cross sections

(3) Radiative Capture Cross Section

Mutual agreement of the measured data of neutron radiative capture cross section is rather poor both in magnitude and shape. The values are often discrepant among themselves by more than 50%. Most of the data are obtained from relative measurements, and this introduces a problem regarding the choice of reference cross section. Thus, in order to eliminate the ambiguities relevant to the reference data, we renormalized the measured cross sections by means of unified reference data: Matsunobu's new evaluation(28) was employed for ^{235}U(n, f), and Kanda's(29) for ^{238}U(n, γ). It should, however, be noted that the measurements relative to Au(n, γ), such as those by Poenitz 78(30) and Macklin 77(31), were not renormalized, since these two measurements were based on the same reference data, *i.e.* those from ENDF/B-IV.

The renormalized data are plotted in **Fig. 4.** The marks [M] and [K] indicate that the data of the authors were renormalized by using evaluations of Matsunobu and Kanda, respectively. The scatter of the data points has been somewhat reduced by this procedure, but there remains discrepancy of more than 30%.

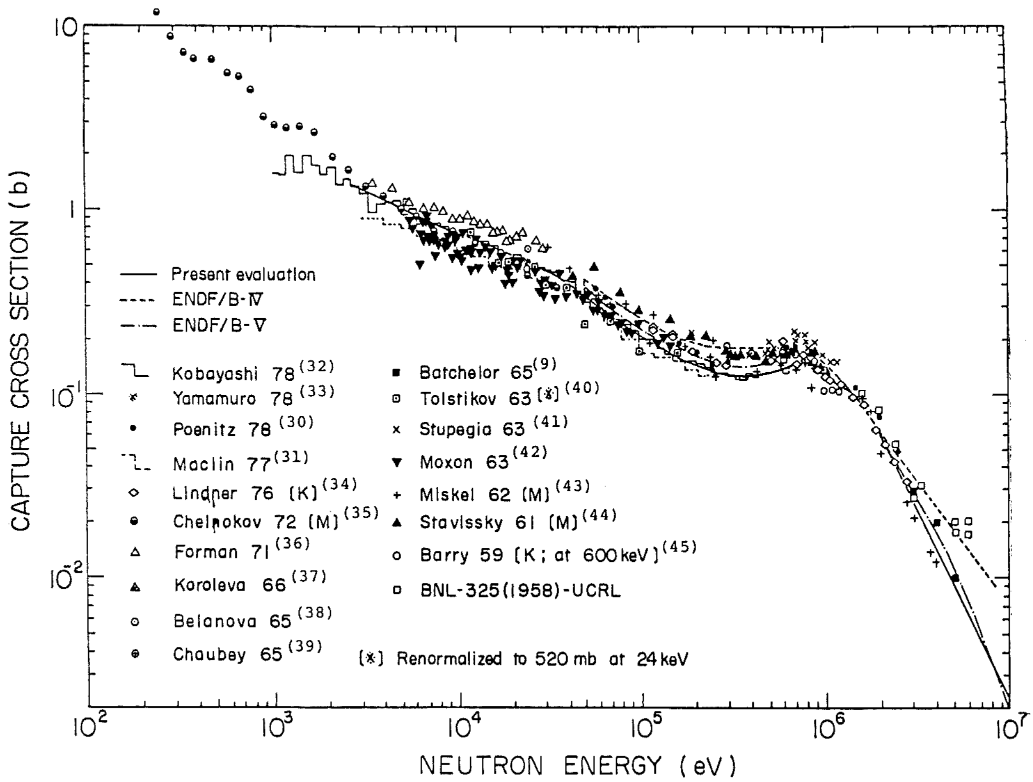


Fig. 4 Radiative capture cross section for ^{232}Th

The data of Forman 71[36] and Moxon 63[42] show large discrepancy of 40~50%, although these are both measurements by means of Moxon-Rae detectors. One of the possible reasons for the discrepancy lies in the difference in the data of ^{7}Li(n, α) and ^{10}B(n, α) reactions used as standards in the two experiments, respectively. Moxon measured ^{238}U(n, γ) and ^{232}Th(n, γ) cross sections in the same experimental condition. Later, renewed measurement has been made and revised data have been published for ^{238}U(n, γ)[42], but not for ^{232}Th(n, γ). In addition, Moxon's data for ^{232}Th(n, γ) have not been well-documented. Hence these data were considered with lesser weight.

A marked aspect in the trend of measurements of radiative capture cross section is that experiments performed after 1976 tend to yield systematically lower values than ENDF/B-IV and JENDL-1 evaluations in the region 0.05~0.8 MeV. Macklin 77[31], among others, gave the lowest values, Kobayashi 78[32] tending to be a little higher than this. Poenitz 78[30] agrees well with Lindner 76[34] below 1 MeV, but is higher than Kobayashi 78[32] by 0~15%. It can thus be seen that, even between the new measurements, there remain discrepancies of 25% at most.

In the present evaluation, we relied primarily on the data of Kobayashi 78[32] in the region 3.5~450 keV due to the facts that (a) this measurement gives intermediate values among the new measurements, and (b) its energy dependent behavior is consistent with theoretical calculation. Above 450 keV, the data of Lindner 76[34] have been adopted, since these give better connection to evaluated values below 450 keV.

Results are compared with other evaluations in Fig. 4. The ENDF/B-V evaluation lies between the data of Macklin 77[31] and Lindner 76[34], and gives values that are 5~15% higher than the present evaluation in the energy range of 50~800 keV.

(4) Fission Cross Section

There have been many measurements[46]~[56] performed on the fission cross section. Several measurements have also been carried out with special attention to the structures observed near the fission threshold. Former evaluations, including ENDF/B-IV, JENDL-1 and Davey[57], have been based on the work of Henkel 57[46] which provided fission cross section data covering a wide range of energies from threshold up to 9 MeV.

Recently, a new extensive measurement has been undertaken by Behrens 77[56] on the ratio of ^{232}Th(n, f)/^{235}U(n, f). Another newer measurement by Nordborg 78[58] on the ratio is in good agreement with this measurement. The evaluated data of ^{235}U(n, f) cross section[28] were used to convert the ratio data into ^{232}Th(n, f) cross section. This resulted in values that are systematically higher than previous evaluations by ~10% at energies below 6 MeV (**Fig. 5**). The result thus obtained is in fairly good agreement with ENDF/B-V evaluation, which presents some weighted average of the three sets of data from ^{232}Th(n, f)/^{238}U(n, f), ^{232}Th(n, f)/^{235}U(n, f) and absolute values of ^{232}Th(n, f) cross section. Fission-spectrum averaged cross section has been calculated in order to make a comparison between the previous evaluation (JENDL-1) and the present result, as well as to check the consistency between the energy-differential and integrated cross sections. The typical spectra used in the calculations are of the form:

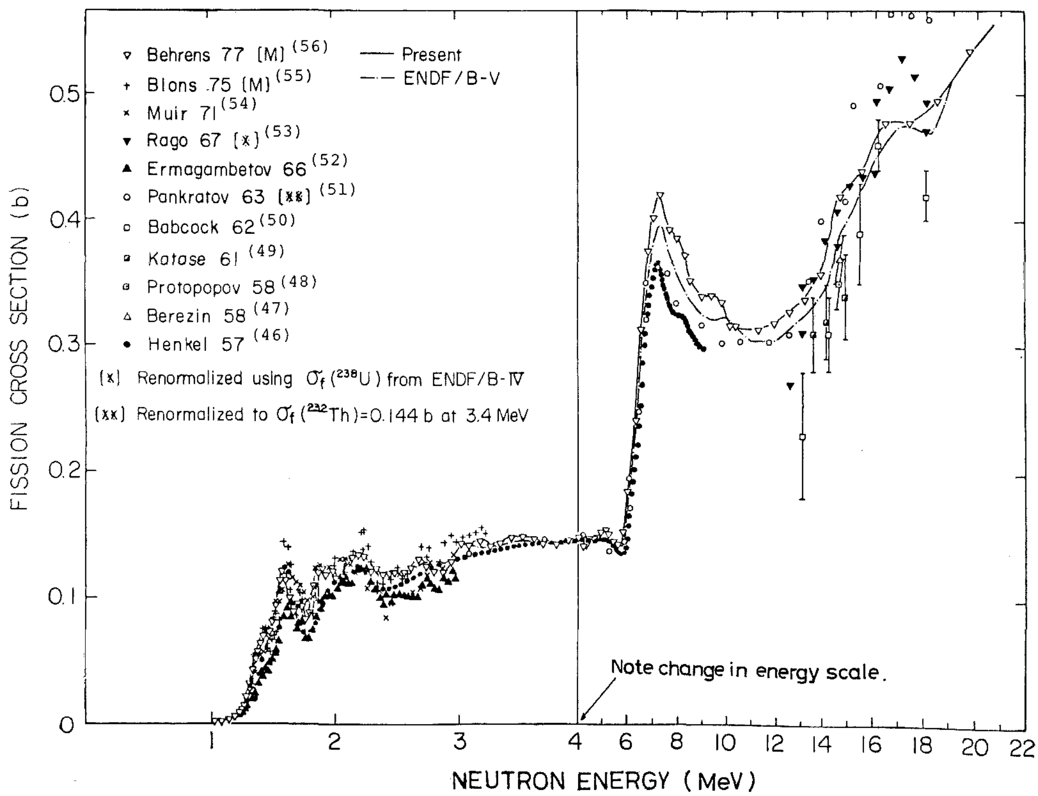


Fig. 5 Fission cross section for ^{232}Th

Watt type[59] : $\chi(E)=0.484\exp(-E)\sinh\sqrt{2E}$, (2)
$\bar{E}=2.000$ MeV,

Cranberg type[60] : $\chi(E)=0.453\exp(-E/0.965)\sinh\sqrt{2.29E}$, (3)
$\bar{E}=1.975$ MeV,

Maxwell type[61] : $\chi(E)=0.770\sqrt{E}\exp(-E/1.29)$, (4)
$\bar{E}=1.935$ MeV,

CSEWG type[62] : $\chi(E)=0.4306\exp(-E/0.998)\sinh\sqrt{2.249E}$, (5)
$\bar{E}=2.057$ MeV.

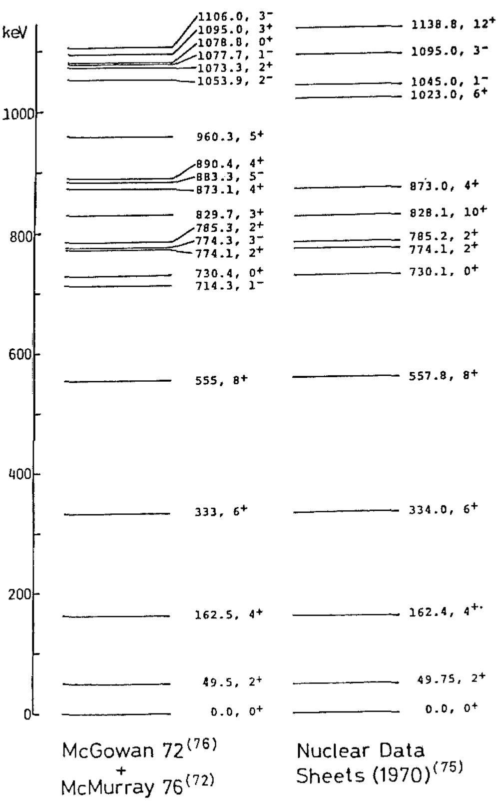
Here, Eq. (5) is the one adopted by the Cross Section Evaluation Working Group (CSEWG) for ENDF/B-V, the functional form of which being the same as Eq. (3) but with different parameters. The calculated and measured spectrum-averaged cross sections are compared in **Table 2.** The present evaluation is seen to give values higher than the previous evaluation by ~10%. This tendency is consistent with the result of fission rate measurement in benchmark experiments[68] which reveal that the fission rates in ^{232}Th are systematically underpredicted by the calculation using ENDF/B-IV. However it should also be noted that there remains some discrepancy between the measured and calculated average cross sections. A possible reason for this lies in the uncertainty in the neutron spectra used in experiments and/or calculations.

Table 2 Fission neutron-spectrum averaged cross section for ^{232}Th (n,f) reaction

Calculation					Experiments	
$\chi(E)$	JENDL-1	Present work (JENDL-2)	ENDF/B-IV	ENDF/B-V		
Watt	68.98 mb	75.06 mb	68.97 mb	72.85 mb	Kobayashi 76[63]	78.6±3.9 mb
Cranberg	68.40	74.42	68.40	72.25	Eder 73[64]	72
Maxwell	65.99	71.91	65.97	69.78	Fabry 72[65]	82±3.5
CSEWG	71.25	77.50	71.24	75.21	McElroy 72[66]	85.2±7.7
					Fabry 70[67]	87.5±3.5

(5) Inelastic Scattering Cross Section

Inelastic scattering of neutrons by ^{232}Th is the prime mechanism establishing the reactor spectrum, hence precise data are required on its cross section. But unlike in the case of total and fission cross sections, the existing measured data for inelastic scattering are not satisfactory both in quantity and quality; the data sets provided from several measurements[9][23][69]~[72] show considerable discrepancies among themselves, thus they do not make it possible to perform evaluation on the basis of the experimental information only. Therefore we resorted to theoretical calculations based on the Hauser-Feshbach statistical model modified according to Moldauer[73] for level width fluctuations and resonance-interference effects. Use has been made of a code CASTHY[74] for the calculation. Information on the level structure of ^{232}Th can be found in Nuclear Data Sheets[75], but newer measurements by McMurray 78[72] and McGowan 72[76] have yielded more detailed level informations. In the present work we combined the latter two sets to obtain a level scheme to be used in the calculations (**Fig. 6**); the use of the former would reduce the calculated inelastic cross section by at most 7% in the range of 0.8~1.3 MeV. Above 1.11 MeV the levels are assumed to be a continuum region which is represented with the level density formula and parameters



Low-lying discrete levels used in the present calculation (left) are compared with an earlier determination (right).

Fig. 6 Level structure of ^{232}Th

tering cross section for the i-th excited state. The sum of the differences between the calculated and evaluated partial cross sections was then added to the total inelastic scattering cross section to obtain the final evaluation:

$$\sigma_{in}=\sigma_{in}(\text{calc})+\Delta\sigma_{in} \qquad (7)$$

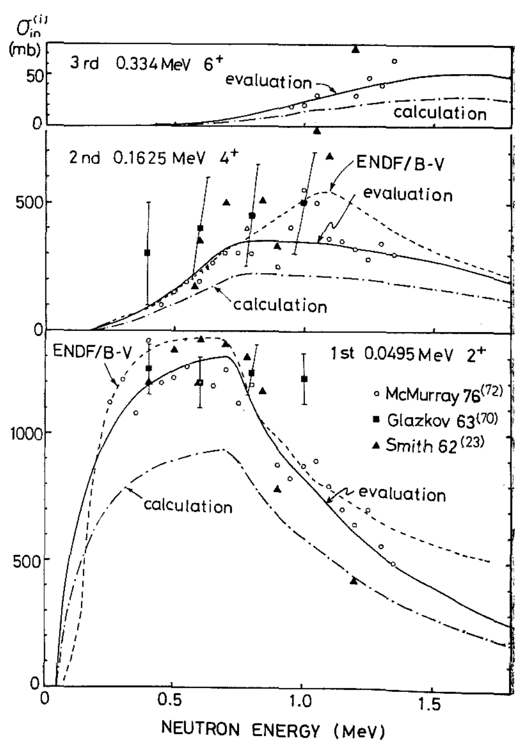
$$\Delta\sigma_{in}=\sum_{i=1}^{3}[\sigma_{in}^{(i)}(\text{eval})-\sigma_{in}^{(i)}(\text{calc})].$$

The results for the total inelastic scattering cross section are shown in **Fig. 8.** The agreement with measurements has been greatly improved. While the present evaluation agrees well with the ANL evaluation[16] for ENDF/B-V below 0.8 MeV, considerable disagreement (at most 30%) can be observed between the two evaluations at energies of Gilbert & Cameron[77].

Calculated excitation functions of inelastic scattering for low-lying levels are shown in **Figs.** 7(a)~(c). It can be seen that the optical model calculation tends to underestimate the excitation functions. This is attributed to the fact that the present calculation does not take into account the direct excitation of the collective modes of the deformed target nucleus. Fortunately, some measured data are available for excitation functions corresponding to the low-lying discrete states of ^{232}Th. Hence a correction was made for the first three excited levels by applying a factor that would give the best fits to the measurements:

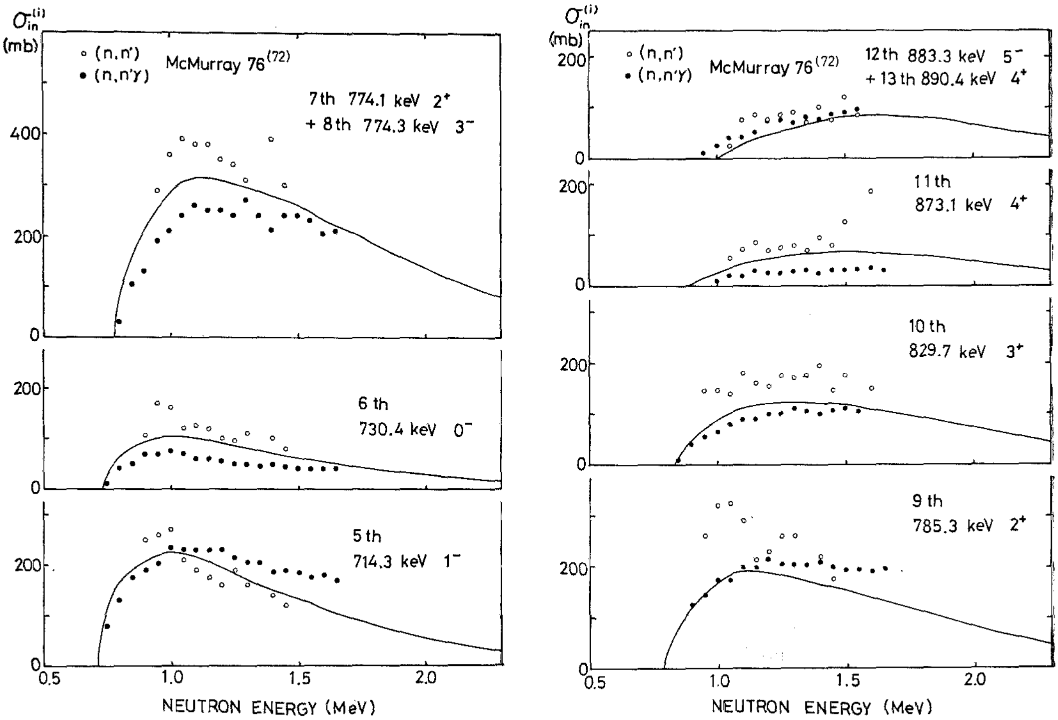
$$\left.\begin{aligned}\sigma_{in}{}^{(1)}(\text{eval})&=1.4\,\sigma_{in}{}^{(1)}(\text{calc})\\ \sigma_{in}{}^{(2)}(\text{eval})&=1.6\,\sigma_{in}{}^{(2)}(\text{calc})\\ \sigma_{in}{}^{(3)}(\text{eval})&=1.8\,\sigma_{in}{}^{(3)}(\text{calc})\end{aligned}\right\}\quad(6),$$

where $\sigma_{in}^{(i)}$ denotes the partial inelastic scat-



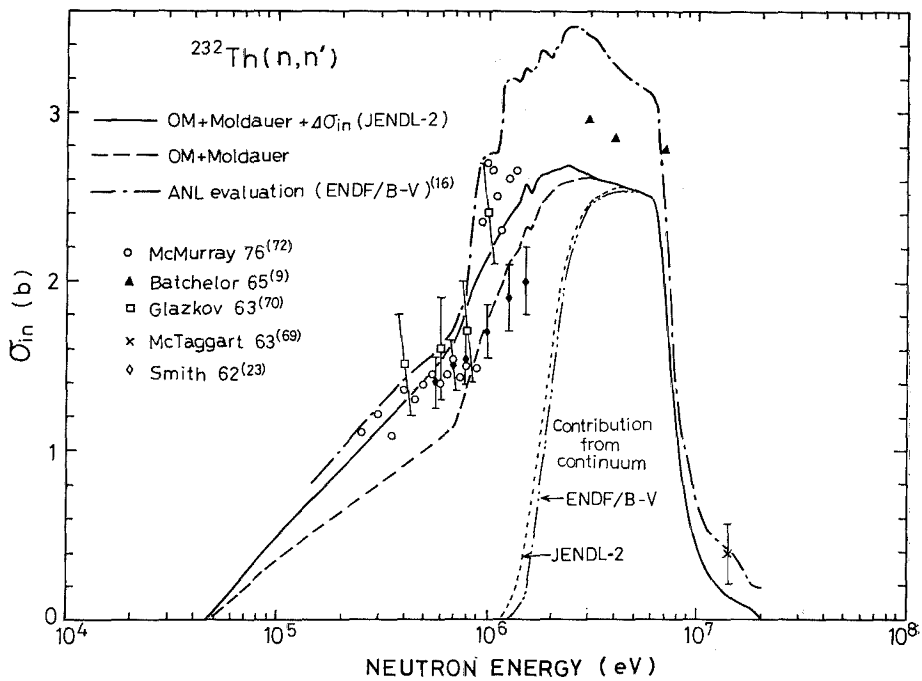
(a) 1st~3rd excited levels

Fig. 7 Partial inelastic scattering cross section



(b) 5th～8th excited levels (c) 9th～12th excited levels

Fig. 7 Partial inelastic scattering cross sections



The results of calculations using the optical model (OM) and Moldauer formalism with and without correction $\Delta\sigma_{in}$ are compared.

Fig. 8 Total inelastic scattering cross section for ^{232}Th above 0.8 MeV. The ANL evaluation was obtained from the coupled-channel calculation for the discrete levels below 1.25 MeV and from statistical-model calculation including the precompound as well as compound components at higher energies. Considering the fact that the contributions from the continuum are nearly equal in the two evaluations, we can conclude that the difference comes from the direct reaction (collective excitation plus pre-equilibrium process) components, the strength of which, however, is not exactly known yet.

The angular distribution of inelastically scattered neutrons was calculated by means of a code ELIESE-3[78] using the parameter set of Eq. (2). Experimental data[23] are available only for the first excited state, for which the calculation agrees with measurement within experimental errors (**Fig. 9**). The distribution is symmetric about 90° and nearly isotropic.

(6) (n, $2n$) and (n, $3n$) Reaction Cross Sections

The (n, $2n$) reaction as a neutron-production reaction is of greater relative importance for ^{232}Th than for ^{238}U, because of its lower fission cross section and higher fission threshold. This reaction is important also because it is the main pathway for production of ^{232}U. It is known, for instance, that this path accounts for over 95% of the ^{232}U produced for residence times greater than 50 days in LMFBR[79].

Nine measurements[80]~[88] have been made on the energy-dependent cross section of (n, $2n$) reaction. The agreement between the experimental data is not good enough to permit evaluation on the basis of these data alone. Especially, large discrepancy is observed on the higher energy side of the cross section curve. We therefore used model calculation to obtain the evaluated values.

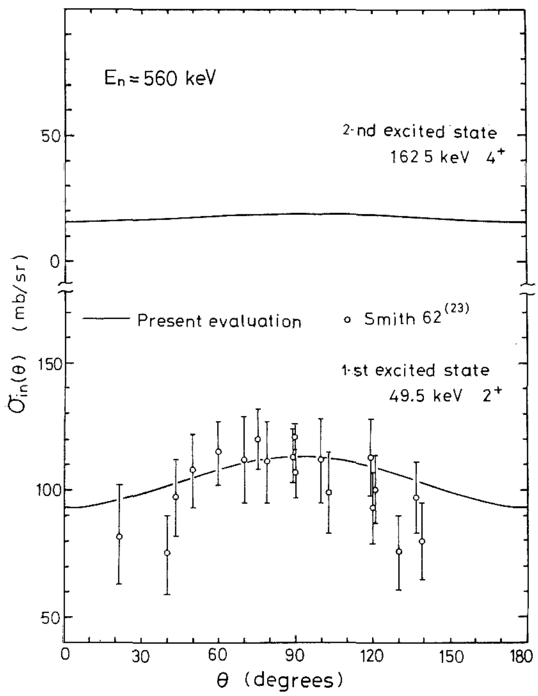


Fig. 9 Angular distribution of inelastically scattered neutrons for 1st and 2nd excited states

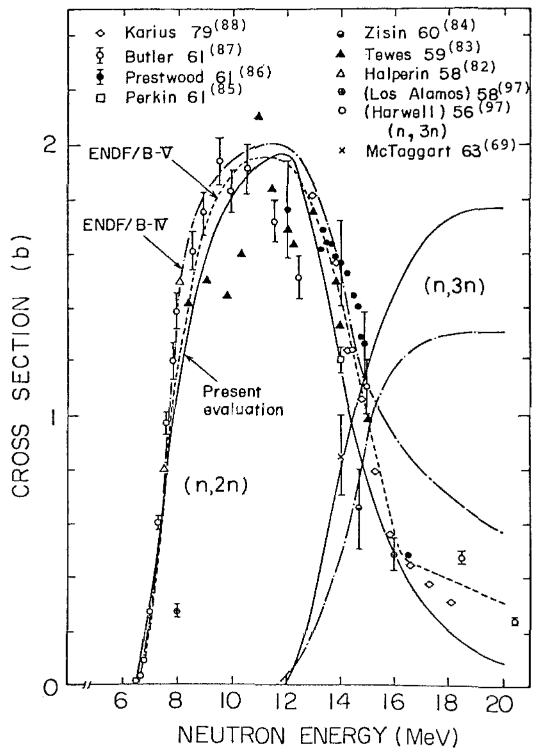


Fig. 10 (n, $2n$) and (n, $3n$) reaction cross sections for ^{232}Th

In the conventional prescription, $(n, 2n)$ cross section σ_{2n} is factorized into three parts:

$$\sigma_{2n}=\sigma_{ne}\times(\sigma_{nM}/\sigma_{ne})\times(\sigma_{2n}/\sigma_{nM}), \qquad (8)$$

where σ_{ne} denotes the nonelastic cross section, and σ_{nM} the neutron-multiplication cross section. Pearlstein's method(89), which makes use of empirical formulas(90)(91) for σ_{ne} and σ_{nM}/σ_{ne}, has been found to fail to reproduce well the behavior of the cross section for heavy nuclei. Hence, we devised the following ameliorations: (a) to use $\sigma_R-\sigma_f$ in place of σ_{ne}, where σ_R is the reaction cross section calculated from the optical model and σ_f the fission cross section, (b) to use more recent version(92) of empirical formula for σ_{nM}/σ_{ne}, and (c) to use the "reduced" cross section $R_2(E)$ of Segev *et al.*(93) for σ_{2n}/σ_{nM}. Thus the cross section formula is

$$\sigma_{2n}(E)=[\sigma_R(E)-\sigma_f(E)](\sigma_{nM}/\sigma_{ne})R_2(E). \qquad (9)$$

The $(n, 3n)$ reaction cross section was calculated in a similar way. The results are shown in **Fig. 10.** The present evaluation is generally a little smaller than the ANL evaluation(16) and ENDF/B-IV. Comparison has been made of the calculated and measured fission-neutron-spectrum averaged cross sections in **Table 3.** It can be seen that the calculations tend to give higher values than experiments. The present evaluation gives result that is relatively in better agreement with measured integral data.

Table 3 Fission-neutron-spectrum averaged cross section for ^{232}Th $(n, 2n)$ reaction

	Calculation				Experiments	
$\chi(E)$	JENDL-1	Present work (JENDL-2)	ENDF/B-IV	ENDF/B-V		
Watt	13.42 mb	13.37 mb	15.26 mb	13.90 mb	Kobayashi 71(94)	12.5±0.48 mb
Cranberg	12.26	12.4	13.98	12.72	Philips 58(95)	12.4±0.6
Maxwell	13.95	13.83	15.76	14.39	Erdtmann 76(96) (evaluation)	14.2±1.1
CSEWG	15.12	15.04	17.16	15.63		

2. Resonance and Thermal Regions

(1) Resonance Parameters and Resonance Integral

Main measurements of resonance parameters performed so far are listed in **Table 4.** Earlier evaluations, such as *BNL*-325, 2nd edition, Supplement 2(97) and ENDF/B-IV, gave recommended values relying upon the data of Ribon 64(100) and Garg 64(99). Later, an extensive measurement from 22 eV up to 4 keV has been carried out at Columbia University(101) with improved precision. Forman 77(36) has measured resonances between 8.35 eV and 1.94 keV using nuclear explosion as a neutron source. Recently, Macklin 77(31) has reported the results of measurement on the resonances in the keV region, and Chrien 79(102) on the 4

Table 4 Measurements of resonance parameters for ^{232}Th

Author	Energy region	Method
Utlley 63 (AERE)(98)	59.3 eV~1.3 keV	Linac, transmission
Garg 64 (Columbia)(99)	113 eV~3.9 keV	Synchrocyclotron, transmission, NaI
Ribon 64 (Saclay)(100)	83 eV~3.0 keV	Linac, transmission, scattering
Forman 71 (LASL)(30)	37 eV~2.0 keV	Nuclear explosion, Moxon-Rae detector
Rahn 72 (Columbia)(101)	22 eV~4.0 keV	Synchrocyclotron, transmission, capture
Macklin 77 (ORNL)(31)	2.6~10.4 keV	Linac, small liquid scintillator
Chrien 79 (BNL)(102)	21.78~69.07 eV	Fast chopper, transmission, self-indication

major resonances between 21.78 and 69.07 eV. In the present evaluation, data have been selected according to the following lines:

(a) Main body of the data have been taken from the work of Rahn 72[101], since this is a consistent measurement covering a wide range of energies with improved accuracy.

(b) The upper limit of the resolved resonance region has been chosen as 3.5 keV, since the cumulative sum of reduced neutron width, $\Sigma\Gamma_n^\circ$, when plotted against neutron energy, shows deviation to lower side from the expected line, indicating that considerable number of resonances have been missed above this energy.

(c) For small resonances not observed by Rahn 72[101], we adopted only those resonances that are identified by more than two independent measurements. The adopted values are those recommended in *BNL*-325, 3rd edition[103].

(d) For resonances of which the γ width is not known, the average value 21.2 meV of Rahn's measurement has been assigned. Thus the total number of 299 reasonances have been employed in the present evaluation.

The energy region above 3.5 keV was considered as the unresolved resonance region. The unresolved resonance parameters were determined[104] so that they should reproduce the evaluated values of total and radiative capture cross sections. Under the assumption that the radiative width in the unresolved region is equal to the average value in the resolved resonance region, *i.e.* $\bar{\Gamma}_\gamma$=21.2 meV, the following values were obtained: D_{obs}= 18.64 eV and R=10.01 fm. The strength functions deduced from fitting to the total cross section ($S_0=0.95\times10^{-4}$ and $S_1=2.0\times10^{-4}$) were then somewhat modified (while the ratio S_0/S_1 was kept unchanged) so as to give best fits to the radiative capture cross section at each energy point. The energy dependent strength functions thus obtained are shown in **Table 5**.

Table 5 Strength functions in the unresolved region

E_n	S_0	S_1
3.5 keV	0.95×10^{-4}	2.00×10^{-4}
4.0	1.00	2.10
5.0	0.96	2.01
6.0	0.95	2.00
7.0	0.96	2.03
8.0	0.93	1.96
9.0	0.92	1.95
10.0	0.93	1.96
20.0	0.94	1.98
30.0	0.99	2.08
40.0	1.01	2.13
50.0	0.89	1.88

The capture resonance integral has been measured by many authors either with activation method or reactivity measurement. Available experimental data are shown in **Table 6.** The original values have been renormalized by using new values[103] for standard data so that the different measurements should be compared on the equal basis. The weighted average of the renormalized data yields 84.8 b, which has been adopted in the present work.

(2) Thermal Cross Sections

The neutron capture cross section at thermal energies for thorium is of primary importance for thorium-fueled thermal reactors. Existing evaluations give values for the thermal (0.025 eV) capture cross section ranging from 7.4 to 7.615 b, *i.e.*, 7.4 b (JENDL-1, Derrien[118], ENDF/B-IV and -V), 7.45 b (Stoughton & Halperin[119]), and 7.615 b (Newman *et al.*[120]). Available experimental data are summarized in **Table 7.** In order to be sure that the measured data are compared on the equal basis, the earlier data have been renormalized by using newer values[103] for standard cross sections. The average (weighted with reciprocal square of the experimental error) of the earlier data not more recent than 1960 yields 7.40 b. Three newer measurements[102][121][122] performed in recent years support this value, ruling

Table 6 Measured resonance integrals for ^{232}Th

Author	Activation method		Reactivity measurement	
	Original (b)	Renormalized (b)	Original (b)	Renormalized (b)
Van der Linden 74[105]	72. 4	72. 9		
Alian 73[106]	85. 3†	85. 9†		
Steinnes 72[107]	88±3	88. 6±3		
Breitenhuber 70[108]	89. 8±4	90. 1±4	93±6	93. 3±6
Carre 66[109]			87±4	
Hardy 65[110]	82. 5±3. 0	83. 55±3. 0		
Foell 65[111]			81. 2±3. 4	80. 2±3. 4
Brose 64[112]	82. 7±1. 8	88. 1±1. 8		
Johnstone 50[113]	85	84. 7		
Tattersal 60[114]			106±10	104. 9±10
Myashshcheva 57[115]	70. 0††	80. 1††		
Klimentov 57[116]			61. 8±12	61. 5±12
Macklin 56[117]	67±5	69. 1±5		
Average		85. 0		83. 9
Adopted value		84. 8		

† Average of three measurements using Cd capsules with different thickness.
†† Average of three measurements in different neutron spectrum.

out an alternate evaluation of 7.615 b suggested by Newman *et al.*[120] We therefore employed the value 7.40 b for the thermal capture cross section.

Table 7 Measured thermal neutron capture cross sections for ^{232}Th

Author	$\sigma_{n\gamma}$ (0. 25 eV)		Relative to	Method
	Original (b)	Renormalized† (b)		
Chrien 79[102]	7. 41±0. 08		$^{197}Au(n, \gamma)$	Activation
Poenitz 78[121]	7. 33±0. 17			Activation
Kobayashi 74[122]	7. 35±0. 21		$^{197}Au(n, \gamma)$	Activation
Tattersal 60[123]	7. 50±0. 30		$^{10}B(n, \alpha)$	Pile oscillator
Hubert 57[124]	7. 60±0. 16			Transmission
Myasishcheva 57[125]	7. 31±0. 10	7. 32±0. 10	$^{197}Au(n, \gamma)$	Activation
Wade 57[126]	7. 55±0. 25	7. 61±0. 25	$^{56}Fe(n, \gamma)$	Reactivity comparison
Samll 55[127]	7. 57±0. 17	7. 51±0. 17	$^{55}Mn(n, \gamma)$	Pile oscillator
Crocker 55[128]	7. 31±0. 12	7. 32±0. 12	$^{197}Au(n, \gamma)$	Activation
Egelstaff 55[129]	7. 2±0. 2			Transmission
Pomerance 52[130]	7. 0±0. 4	7. 28±0. 4	$^{197}Au(n, \gamma)$	Pile oscillator
Grumitt 44[131]	7. 75±0. 3	7. 69±0. 30	$^{55}Mn(n, \gamma)$	Activation
Seren 44[132]	7. 58±0. 76			Activation
Adopted value	7. 40			

† Values renormalized by using newer data[89] for the standard reaction cross section.

A particular feature of the behavior of the capture cross section in the epithermal region is its non-$1/v$ character; it has been observed[133] that the capture cross section decreases more rapidly with energy than inferred from a $1/v$ energy dependence. This is important since it leads to the possibility of making the reactor temperature coefficient positive. Neither the non-$1/v$ behavior nor the absolute value 7.4 b at 0.025 eV can be explained solely by positive energy resonances, which account only for 0.46 b at 0.025 eV. This requires introducing negative energy resonances. Here we employed the "picket fence" model which assumed several equidistant levels with an equal width. We adopted as a basis the parameter set of Steen[134] and adjusted the position of a floating level as well as a background term with $1/v$-dependence so that the single-level Breit-Wigner calculation should reproduce the values of $\sigma_\gamma=7.40$ b at 0.025 eV and $\sigma_T=13.28$ b[135] at 1.44 eV. Thus we obtained the following values: $E(n)=-n\bar{D}$ $(n=1, 2, \cdots, 13)$, $\bar{D}=16.31$ eV, $\Gamma_\gamma=26.31$ eV, $\Gamma_n^\circ=0.0124(\text{eV})^{1/2}$, $g=1$ for 13 equidistant levels; $E_{(0)}=-4.6906$ eV for a floating level; and $0.0144/\sqrt{E}$ for the background term. These parameters have been found to give good fits to the data of Lundgren[133] (**Fig. 11**).

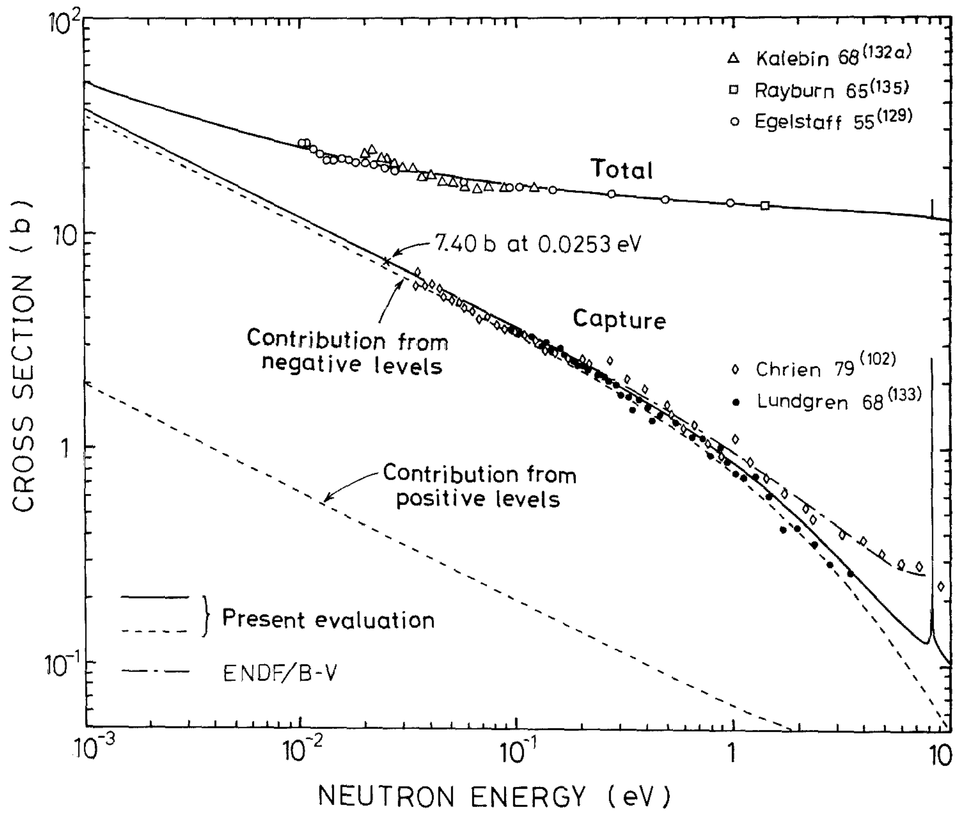


Fig. 11 Total and capture cross sections in thermal region

It should, however, be noted that, after the completion of the present evaluation, a new result of a measurement[102] between 0.03 and 15 eV has been reported which confirms the previous observation of a significant departure from a $1/v$ dependence but the extent of the departure being less than that reported by Lundgren[133]. This result is in good agreement with the ENDF/B-V evaluation.

3. Average Number of Neutrons Emitted per Fission

Several sets of measured data are available for the average number $\bar{\nu}(E)$ of prompt neutrons emitted in fission[136]~[142]. They agree each other within experimental errors in the region between 1.3 and 4.0 MeV. However, at higher energies, data are very scarce and scattered (**Fig. 12**). Two energy dependent formulas for $\bar{\nu}$ have been proposed, *i.e.*, a single linear fit

$$\bar{\nu}(E_n)=1.854+0.154\ E_n \qquad (10)$$

by Condé *et al.* (1965)[139], and two-segment fit

$$\bar{\nu}(E_n)=3.653-1.000\ E_n \qquad E_n<1.57\ \text{MeV}, \qquad (11)$$

$$\bar{\nu}(E_n)=1.847+0.1515\ E_n \qquad 1.57\ \text{MeV}<E_n<15\ \text{MeV}, \qquad (12)$$

by Davey (1971)[143]. While ENDF/B-IV employed the single linear representation Eq. (10), close observation reveals apparent rise in $\bar{\nu}$ (with decreasing energy) at energies below 1.57 MeV. This behavior is considered to be related to the near-threshold structure in fission cross section. In the present evaluation, we thus adopted Eqs. (11) and (12). The ANL evaluation[16] for ENDF/B-V, on the other hand, recommended the values calculated by using a semi-empirical method developed by Howerton[144]. This result gives systematically lower values compared to the other two evaluations.

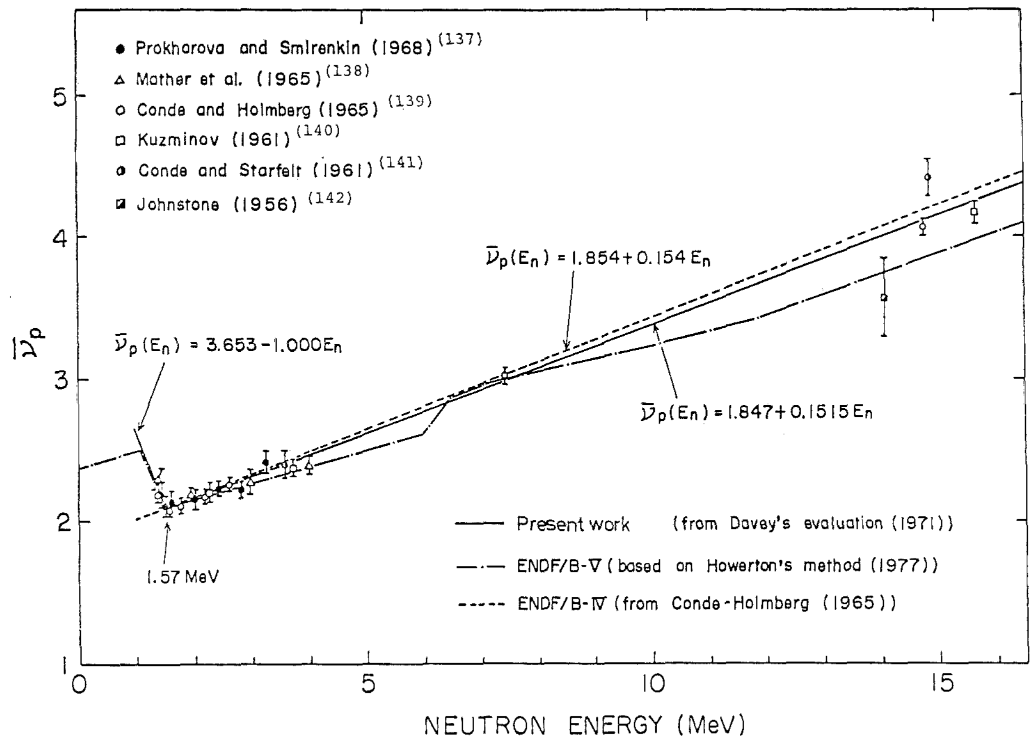


Fig. 12 Average number of prompt neutrons emitted in fission as a function of incident neutron energy

IV. CONCLUDING REMARKS

Consistent set of cross sections for ^{232}Th has been obtained by evaluating the available experimental data and by making use of the optical and statistical models. The evaluation is based on data as available to March 1979; newer data published after then are shown only for the comparison purpose.

The data base for ^{232}Th are insufficient in a number of areas. This is a reason for the uncertainties and discrepancies observed among different evaluations. For instance, considerable discrepancy can be seen for inelastic scattering, $(n, 2n)$ reaction and radiative capture at epithermal energies, in spite of their great importance in reactor physics. Quantitative improvement of the present evaluation requires further precision measurements as well as more detailed study of the calculational models and pertinent parameters.

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