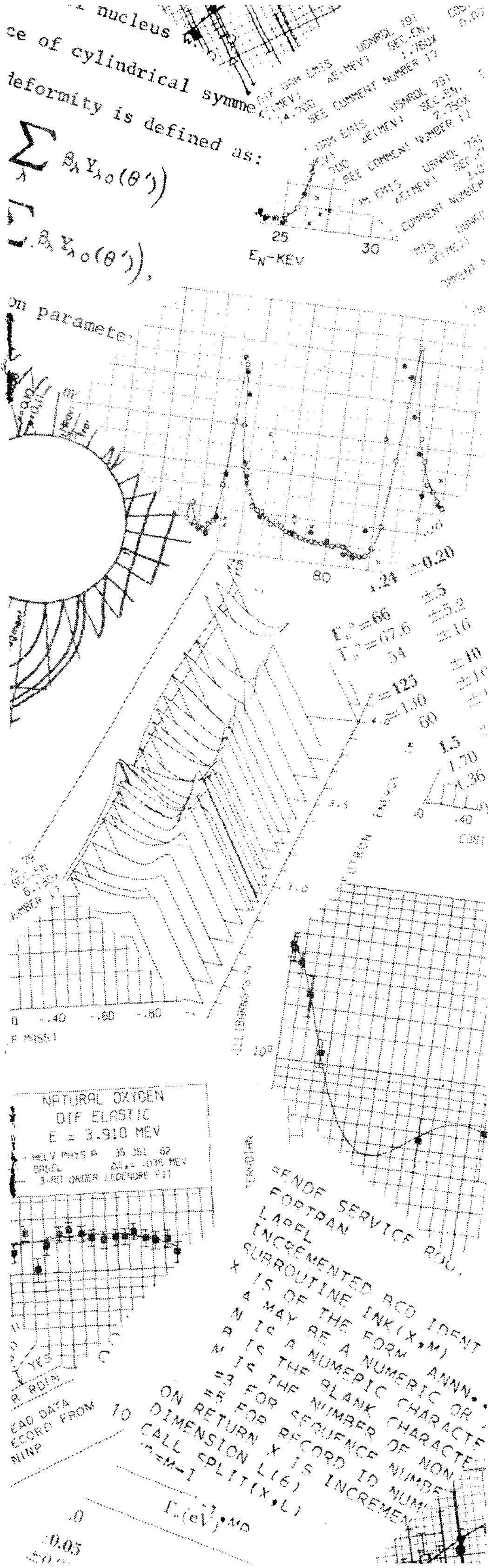

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EVALUATION OF ^{235}U NEUTRON CROSS SECTION AND GAMMA RAY PRODUCTION DATA FOR ENDF/B-V

M.R. BHAT

March 1980

INFORMATION ANALYSIS CENTER REPORT

NATIONAL NUCLEAR DATA CENTER
BROOKHAVEN NATIONAL LABORATORY
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Abstract

This report describes the evaluation of neutron and gamma ray production cross sections of ^{235}U from 10^{-5} eV to 20 MeV and discusses the parts contributed by the author. All available new data have been included in this evaluation and the procedures adopted to assess the experimental data and adopt a set of recommended values are described.

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Evaluation of ^{235}U Neutron Cross Section and Gamma Ray Production Data for ENDF/B-V

1. Introduction

This report describes the evaluation of neutron cross section and gamma ray production data of ^{235}U for ENDF/B-V (MAT=1395). The final evaluated data files on ^{235}U are the result of collaboration by a large number of persons contributing as individuals or as various specialized subcommittees of the Cross Sections Evaluations Working Group (CSEWG). Contributions from Battelle-Northwest, E.G.& G., Los Alamos, Argonne, Oak Ridge and Brookhaven were used in this evaluation. This report does not presume to discuss all these contributions in detail, appropriate references are given to the relevant documentation where they are available. Only those aspects of the evaluation in which the author of this report was involved are discussed in detail here. Within the time that was available for this new evaluation, it was also not possible to reevaluate all sections of the data files. Hence, parts of the ENDF/B-IV evaluation[1] were included in the present data files without any changes. The purpose of this report is to document the new and significant changes in the present evaluation, justify them as far as possible and discuss their relationship to the previous versions. Possible changes or improvements to be included in future evaluations are also indicated.

The neutron and gamma-ray production cross sections given in the present evaluation of ^{235}U (MAT=1395 of ENDF/B-V) over the neutron energy range 1.0E-05eV to 20 MeV may be summarized as follows:

File 1: General description of the evaluation with references. This also has $\bar{\nu}_t$, $\bar{\nu}_d$ and $\bar{\nu}_p$ evaluations conforming with the latest available data. The $\bar{\nu}_d$ evaluation is by Kaiser and Carpenter[2] and the $\bar{\nu}_p$ data and the evaluation are discussed in Section 4.0. The energy released in fission and its partition into the different decay modes is by Sher et. al.[3]

File 2: Resolved resonance region parameters extend from 1 eV to 82.0 eV and were evaluated by Smith and Young[4] for ENDF/B-III, used in version IV (MAT=1261) and taken over unchanged from it. Unresolved resonance parameters are from a new evaluation discussed in Section 2.0.

File 3: This file has smooth cross sections for total, elastic, total inelastic, (n,2n), (n,3n), fission, capture and inelastic cross sections to individual discrete levels. In the current data file, the thermal cross-sections (10^{-5} eV to 1 eV) are based on an evaluation by Leonard et. al[5]. This fit was modified between 0.85 and 1.0 eV to join smoothly with the resonance region. From 25 keV to 100 keV, the fission cross section has the same structure as in ENDF/B-IV and was obtained by multiplying the Version IV evaluation by 0.9781 to give wide bin averages corresponding to the current evaluation (see Section 2.0). Fission cross section from 100 keV to 20 MeV was evaluated by Poenitz[6]. The capture cross section from 25 keV to 20 MeV was obtained by multiplying the capture-to-fission ratio from Version IV with ENDF/B-V fission cross section. Total cross section is the same as in ENDF/B-IV except for the region below 1.0 eV where the Leonard fit was used. The total inelastic, (n,2n), (n,3n) and the inelastic scattering to discrete levels and the continuum are the same as in Version IV. The scattering cross section was modified to conform to changes in capture and fission cross sections.

File 4: Angular distributions from Version IV were taken over essentially unchanged and used in ENDF/B-V.

File 5: Prompt fission neutron spectrum evaluation is described in Section 4.0. Delayed neutron specta were evaluated by Kaiser and Carpenter[2]. Secondary neutron energy distributions for (n,2n), (n,3n) reactions and inelastic scattering into the continuum are the same as in ENDF/B-IV.

File 8: Fission products yield data are from the Fission Products Yields Subcommittee[7] (with T.R. England, Chairman). Radioactive decay data were prepared by Reich[8].

File 12: Photon multiplicities in File 12 for total inelastic scattering, fission and capture were taken over unchanged from ENDF/B-IV.

File 13: Gamma ray production Cross Sections from E_n = 1.09-20 MeV were reevaluated to include some new data (see Section 5.0).

File 15: Energy spectra of secondary gamma rays due to all non-elastic processes from E_n = 1.09-20 MeV were changed to conform to the new data used in the current evaluation. Energy spectra of gamma rays below E_n = 1.09MeV were taken over unchanged from ENDF/B-IV.

File 31 and 33: The evaluation of the variance-covariance matrices for $\bar{\nu}_t$, (n,f) and (n,γ) cross sections is by R.W. Peelle[9].

2.0 Neutron Cross Sections

2.1 Fission Cross Section

a. Fission Cross Section from 1.0E-05 to 1.0 eV

The evaluated cross section was obtained by B.R. Leonard et. al[5] in their analysis and fit of all available thermal data on ^{235}U. A simultaneous fit of the total and partial cross section data of ^{235}U in the thermal region was obtained to give the best-estimate cross sections as well as their uncertainties. Details of this analysis are given in the above reference and will not be discussed here. This fit, however, was modified between 0.85 eV to 1.0 eV so as to join smoothly with the doppler unbroadened cross sections as given by the resolved resonance parameters at 1.0 eV. The 0.0253 eV value of fission cross section obtained by Leonard et. al is equal to 583.54±1.7 b.

b. Fission Cross Section from 1.0 eV to 82.0 eV

This is the energy region of resolved resonance parameters. These were evaluated by Smith et al[4] for ENDF/B-III; used in Version IV and have now been included in Version V. The fit is in terms of single level parameters.

In assembling the ENDF/B-V data files, an attempt was made to include the results of Reich-Moore analysis of the resolved resonance data by Reynolds[10] from 1-60 eV and by Smith[11] from 1-82 eV. The proposal was to convert these Reich-Moore parameters to equivalent Adler-Adler parameters, merge them and obtain a set of Adler-Adler parameters and a smooth background.

However, in carrying out this merger, it was found that the background had pronounced structure and the resulting data files were not considered to be significantly better than the single level resonance parameters from Version IV and it was decided to retain them for Version V. A reanalysis of the resolved resonance region to include more recent data on cross sections and polarization measurements for spin assignments, is indicated for future versions of ENDF/B.

c. Fission Cross Section: Unresolved Resonance Region from 82 eV to 25 keV-Fine Structure

It is well know that the fission cross section of ^{235}U in this energy region has pronounced structure which should be included in an analysis. The problem is to find whether the structure as seen in different experiments can be matched against one another in detail and if possible arrive at a consensus structure which could then be used in a fit. In addition, this structure should be normalized such that broad-bin averages over a few keV should agree with average cross sections determined after renormalization to a suitable set of primary standards. The details of finding the consensus structure and subsequent analysis is given in this section. Discussion about finding the broad-bin average cross sections is given in Section d.

The problem of correlating the energy scales of different time-of-flight measurements has been discussed by a number of authors[12,13,14] and it is found that the uncertainties in the energy scale δE could be expressed in terms of an error δt in the time-of-flight t and an error δL in the flight path L as follows. It is well known that

$$E = \mu^2 \frac{L^2}{t^2} \qquad (1)$$

where E is measured in eV; $\mu = 72.3\ eV^{1/2}\ \frac{\mu\ sec}{m}$; L is measured in meters and t in microseconds. In this case it can be shown that[14] the true energy scale E will be related to the apparent energy scale

$$E^* = E + \delta E \text{ by}$$

$$E = E^* (1 + a + bE^{*\,1/2}) \qquad (2)$$

where $a = 2\delta L/L$ and $b = 2\,\delta t/\mu L$. Therefore, if two experiments of comparable energy resolution are measuring the same structure in the fission cross-section, after correcting for the energy scale as discussed above, it should be possible to establish a one-to-one correspondence in this structure. However, a and b in the above expression are usually unknown. The procedure adopted here was to take one data set (the one measured with the longest flight path and the highest possible resolution) as the standard and calculate the correlation coefficient defined as

$$\rho = \frac{\sum_i (x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_i (x_i-\bar{x})^2 \sum_j (y_j-\bar{y})^2}} \qquad (3)$$

where x_i are the fission cross-sections in the standard data set at energies E_i and y_i are the fission cross-sections in another data set at the same energies calculated as a function of a and b. Then the problem is to vary a and b so as to maximize the correlation coefficient and for small reasonable values of a and b it is hoped that different data sets could be correlated for uncertainties δt and δL and represented on a common basis (i.e with respect to the standard data set) so that the structure in the different data sets could be averaged to give a consensus structure.

To carry out this procedure, a program CROC was written which could handle up to 3000 data points in each time-of-flight cross section data set. The standard data set chosen for this analysis was that of Lemley et al.[15] which was obtained with a flight path of 244m. and a nominal resolution of 1n sec/m. The program reads in the standard data set giving the fission cross section x_i at energies E_i. Another data sets is similarly read in and using input values of a and b and the energies E_j* of the data set, "true" energies E_j are calculated. The cross sections y_j corresponding to the energies E_j are then interpolated on to the same energy grid as the standard data set assuming linear interpolation between successive data points. The correlation coefficient is calculated as given in Equation 3 for different values of a and b till a maximum is reached. Using these values of a and b a corrected optimum energy scale is obtained and the different data sets are averaged to give a structure in the cross section common to them.

The fission cross section data sets used in this analysis were those of Lemley et al.[15], Blons[16], ORNL-RPI[14] and Gwin et al.[17] and the final structure obtained represents an average over these data sets. In Table I are shown the correlation coefficients between the different data sets and the Lemley data for different energy ranges without any energy shift (i.e. $a=b=0.0$) and with a and b corresponding to a maximum in the correlation coefficient. From the Table it is noticed that the changes in ρ can be quite appreciable as in the low energy Gwin data. These changes are shown in Figs. 1 & 2 where these four data sets are shown binned in 10 eV wide bins with $a = b = 0.0$ and corresponding to optimum a and b parameters which give a maximum. The consensus structure obtained by energy shifting and averaging over these four data sets is shown in Figs. 3-9. In these figures the fission cross section has also been normalized to give broad bin averages given in Table VII.

In practice it is not possible to represent the unresolved resonance region to show all the detailed structure seen in Figs. 3-9. In addition, the unresolved resonance region parameters should be given at energy points which are far apart compared to the average level spacing in order that the concept of average cross sections is valid. With this in mind some 137 grid points were chosen such that when they are connected by straight lines, the average cross-section under these over broad bin regions was equal to those given in Table VII. Using these averages and the polarization data,[18] the resonance parameters for the unresolved resonance region were extracted. These are given in Table II and the details of this analysis are given by Moore et al.[18] To obtain the unresolved resonance parameters from the input data of fission and capture cross sections, a code UR written by E. Pennington[19] was used. This program calculates capture, fission and scattering cross sections from unresolved resonance parameters after averaging over the appropriate statistical distributions. There are options to vary either the neutron or the fission widths or both until the iterative process converges and the calculated capture and fission cross sections agree with input cross sections and their ratios within a specified small fractional deviation ϵ. In using this code for the present case, the reduced neutron and fission widths for the J=3 and 4 s-wave resonances were varied to achieve a fit and the rest of the parameters were kept constant. Table III gives the input σ_f and $\sigma_{n\gamma}$ cross-sections used in the fit.

d. <u>Fission Cross Section: 82 eV to 200 keV-Broad-bin-Averages</u>

The fission cross section of ^{235}U has been measured in many cases with respect to $^{1}H(n,n)^{1}H$, $^{6}Li(n,\alpha)$ and $^{10}B(n,\alpha)$ cross sections. Hence, the latest data on these were reviewed and assessed in order to obtain a consistent set of standards for these reactions. It was decided to retain the ENDF/B-IV evaluation of the hydrogen scattering cross section as a standard because of lack of any significant new data and the feeling that this evaluation continues to be the best valid estimate of the cross section. This evaluation is by L. Stewart et al.[20] and includes the analysis by Hopkins and Breit[21]. The $^{6}Li(n,\alpha)$ and $^{10}B(n,\alpha)$ cross sections were evaluated by Hale and Dodder[22] and Hale and Arthur[23] respectively using R-matrix analysis and having as input experimental data pertaining to all the relevant reaction channels. Further details of these analyses will be published soon. In addition, this $^{235}U(n,f)$ evaluation is based on the results of the analysis in the thermal region by Leonard et al.[5,24]. They obtain a fission cross section of 583.54±1.7 b at 0.0253 eV. In the following discussion, all experimental data have been renormalized to the thermal value of Leonard and the $^{1}H(n,n)^{1}H$, $^{6}Li(n,\alpha)$ and $^{10}B(n,\alpha)$ evaluations accepted as ENDF/B-V standards.

It was suggested by Bowman,[25] and others that if the shape of ^{235}U fission cross section is determined over a wide energy range from thermal energies to a few hundred keV using for example a linac, it could be normalized to the accurately known thermal value. Therefore, it was decided to start from the low-energy region with a common thermal normalization and determine average fission cross section in the eV region. This average in the eV region could be used to renormalize higher energy data to give an average in the keV region and so on, so that different data sets could be represented in terms of a common "basis" for comparison. Such data could then be combined with absolute point-wise measurements to arrive at what would be a final evaluation of the data.

Fission cross section data which extend down to thermal energies were normalized to a common 2200 m/sec value of 583.54 b to obtain an average of the fission integral between 7.8 eV-11.0eV which has been suggested by Deruytter[26] as a possible region for cross-normalization of various data sets. The data sets considered are by Deruytter and Wagemans,[26] Czirr,[27] Gwin,[28] de Saussure et al.[14] Bowman[29] and Shore and Sailor.[30] The fission integrals from 7.4-10.0 eV ($I_{7.4}^{10.0}$) and from 7.8-11.0 eV ($I_{7.8}^{11.0}$) obtained from these data sets are given in Table IV. The second column of this Table gives the thermal cross sections of the different data sets as obtained by a reanalysis and fit to these data by Leonard[5] and were used to renormalize the data. The third and fourth columns give the fission integrals as obtained from the CSISRS (Cross Section Information Storage and Retrieval System maintained by the National Nuclear Data Center at Brookhaven) data and column six gives the fission integral from 7.8-11.0 eV normalized to the ENDF/B-V standards. The next column gives the errors assigned to these different data sets in obtaining a weighted average of 241.2±1.6b-eV. The weighting was inversely as the variance of the different data sets. The Shore and Sailor[30] data extend only up to 10 eV; hence, the fission integral $I_{7.8}^{11.0}$ was calculated using the mean value of the ratio $I_{7.8}^{11.0}$ / $I_{7.4}^{10.0}$. However, the value thus obtained was rejected as being too low. It should be noted that the quoted error in this integral is underestimated since the range of values used in this average is about 16 b-eV.

The Fission Integral from 0.1-1.0 keV($I_{0.1}^{1.0}$)

The data used to obtain this integral are those of Gwin,[28] Czirr,[27] de Saussure,[14] Wasson,[31] and Wagemans and Deruytter.[32] The low energy data of Wasson were measured relative to a 0.5mm. ^{6}Li glass scintillator and extended from a few eV to 70 kev and were normalized to $I_{7.8}^{11.0}$ = 238.4-eV. These data were renormalized to a value of 241.2 b-eV for use in the current analysis. These data do not cover the energy region from 300-400 eV due to filters in the beam. Hence, to obtain the fission integral, mean of $I/_{I}'$ (where I is the integral from 0.1-1.0 keV and I' is the same integral leaving out the 300-400 eV band, see Table V) was determined from the data of Gwin, Czirr, de Saussure, Blons[16] and and Lemley et al.[15] and multiplied by I' as obtained by Wasson. The data of Wagemans[32] were measured with respect to $^{10}B(n,\alpha)$ assumed to be a 1/v cross section and

$I_{7.8}^{11.0}$ = 240.0 b-eV. These data were renormalized to $I_{7.8}^{11.0}$ = 241.2 b-eV and the ENDF/B-V $^{10}B(n,\alpha)$ cross section. The results thus obtained are shown in Table V. There is a spread of about 9% in the fission integral from 0.1-1.0 keV though the precision claimed by the individual experiments are much smaller. An unweighted mean of the five data sets listed in Table V is 1.1924×10^4 b-eV. The average cross sections from 100 eV to 1 keV are shown in Fig. 10. The Blons data[16] were normalized to this fission integral. Similarly, the data of Perez et al.[33,34] at higher energies were normalized to the same integral. The average cross sections thus obtained from 1 to 10 keV are shown in Fig. 11. An average of the fission integrals of Gwin, Czirr, Perez, Blons and Wagemans between 10 and 50 keV; $I_{10}^{50} = 8.339 \times 10^4$ b-eV was used to normalize the high energy data of Wasson from 5-800 keV measured with respect to hydrogen. These data have been used in the present evaluation above 5 keV as suggested by Wasson though there are some data by the same author measured with repsect to $^6Li(n,\alpha)$ and extending up to 70 keV. The average fission integral between 10-50 keV was also used to normalize the Gayther[35] data. Lemley[15] data were not used in this evaluation as the raw data were not available to correct for the (n,α) angular distribution in the flux monitor using ENDF/B-V evaluation. It is estimated[36] that this correction amounts to about +3% at 100 keV, though it decreases at lower energies. Thus, from 10-100 keV mean of the data of Gwin, Czirr, Wasson, Perez, Blons, Wagemans and Deruytter and Gayther were obtained as the best estimate of the fission cross section. A comparison of the cross sections of the different data sets in the same energy bins indicates quite a wide variation by as much as 12% in the 80-90 keV region (see Table VI). In the energy range from 100-200 keV there are only the data of Gwin, Wasson and Gayther; they also show a spread of as much as 10% from 110-120 keV. These average values were compared with the Van de Graaff data of Szabo,[37,38,39,40] Poenitz,[41] White[42] and increased by 1% between 10-200 keV to improve their agreement with the measurements at isolated energies. The experimental data for the fission cross sections from 10-100 keV are shown in Fig. 12. The renormalized fission cross sections for individual data sets and the evaluated averages are given in Table VI and the average cross sections from 100 eV to 100 keV are listed in Table VII. In the energy region between 30-100 keV the ENDF/B-V averages are 2-4% lower than the corresponding Version IV values.

Between 25 keV and 100 keV the structure in Version IV was carried over to Version V subject to the condition that broad bin averaged fission cross section from 25 to 100 keV agree with the corresponding value from Table VII; this implied multiplying the ENDF/B-IV cross-sections by 0.9781.

Fission Cross Section from 100 keV-20 MeV

This was evaluated by W.P. Poenitz[6] in conjunction with the Normalization and Standards Subcommittee of CSEWG. The details of this evaluation have been published recently.

2.2 Capture Cross Section

a. Capture Cross Section 1.0E-05 eV to 1.0 eV

The capture cross section in this energy region is from the Leonard evaluation[5] with modifications from 0.85 eV to 1.0 eV in order to join smoothly with the doppler unbroadened capture cross section obtained from the resolved resonance parameters at 1.0 eV. The 0.0253 eV capture cross section is 98.38±0.76 b.

b. Capture Cross Section 1.0 eV to 82.0 eV

The resolved resonance parameters and the background cross section in File 3 together give the capture cross section in this region. The resolved resonance parameters are from the analysis by Smith and Young.[3]

c. Capture Cross Section 82.0 eV to 25 keV

The analysis used here parallels that used for the fission cross section and described in Section 2.1. It consists of first, energy shifting different data sets with respect to one another and then averaging the fine structure to arrive at a consensus structure corresponding to all the data sets and second, renormalizing the different data sets to ENDF/B-V standards to determine broad-bin averages.

The three capture data sets used in this analysis are the data of de Saussure et al.,[14] Gwin et al.[17] and Perez et al.[33] The point-wise capture data of de Saussure are available to about 3.0 keV, Gwin to 200 keV and the Perez data to 200 eV. Though binned data from these experiments are available at higher energies they obviously could not be used in the analysis for calculating correlation coefficients with an energy shift as described in Section 2.1. For shifting the energy scale, the same coefficients a and b which had been used for corresponding fission data were used. (See Table I). Since the available Perez point-wise data extend only up to 200 eV they were not used in the correlation analyses and the fine structure in the capture cross section shown in Figs. 13-19 are based on the ORNL-RPI and the Gwin data. The three sets were used after renormalization to the ENDF/B-V $^{10}B(n,\alpha)$ standard. The bin average cross sections are given in Table VIII. From this Table it is apparent that the different the data sets give widely discrepant bin averages. With such discrepant data it appeared to be futile to attempt any other renormalization or manipulation of these data sets and an average of these was considered to give the best estimate of the capture cross section. These are shown in the last column of Table VIII. In obtaining the unresolved resonance region parameters, cross sections at 137 grid points were determined such that when these points are connected by straight lines, the area under these is equal to broad bin averaged cross sections given in Table VIII. The structure in the capture cross section and the grid points used for the unresolved resonance region analysis are shown in Figs. 13-19. The input used at grid points are given in Table III.

d. Capture Cross Section 25 keV to 20 MeV

This was determined by using the capture to fission ratio for the Version IV evaluation and multiplying it by the fission cross section for Version V.

3.0 Fission Neutron Spectrum

The spectrum of prompt fission neutrons is described either by a Maxiwellian form (1)

$$f(E') \sim E' e^{-E'/\theta(E)} \tag{1}$$

or by a Watt distribution (2)

$$f\ (E') \sim e^{-E'/a(E)}\ \mathrm{Sinh}\ (\sqrt{b(E)\ E'}) \tag{2}$$

where the parameters a(E) and b(E) are in general dependent on the energy of the incident neutron E. For the Watt distribution, the average energy of the fission neutrons is given by

$$\overline{E}' = 1.5a + 0.25\ ba^2 \tag{3}$$

An analysis of the recent careful measurements of fission spectra by Johansson et al.[43] showed that the Watt spectrum gave a somewhat better description of the experimental data than a Maxwellian. Hence, it was decided to use an energy dependent Watt spectrum representation to describe the prompt neutron fission spectrum of ^{235}U. However, it should be noted that experimental data on the variation of the parameters of the Watt spectrum a and b with changes in the incident neutron energy are scant. A recent analysis of the fission spectrum data has been made by Adams[44] who obtains a = 0.9878±0.0108 (MeV) and b =

2.1893±0.1552 (MeV^{-1}) and E'_{U-235} = 2.016±.047. Further the ratio $\bar{E}'_{Pu239}/E'_{U-235}$ was found to be equal to 1.04. Though this ratio between the mean energies of ^{239}Pu and ^{235}U had been obtained from data measured for low incident neutron energies, for want of any experimental information, it was decided to maintain the same ratio for all incident neutron energies. The evaluation of the prompt fission neutron spectrum for ^{239}Pu for ENDF/B-V has been described by Kujawski[45] in terms of an energy dependent Watt spectrum. These parameters are given in Table IX along with $\bar{E}_{Pu-239}$. From this Table, one could calculate the mean energy of the ^{235}U Watt spectrum such that $\bar{E}_{Pu-239}/\bar{E}_{U-235}$ = 1.04 and knowing the mean energy, determine the parameters a and b consistent with it. At low energies, a was set equal to 0.988 a value obtained by Adams and b could be calculated consistent with $\bar{E}'$. As in the case of ^{239}Pu the Watt spectrum parameters are kept constant from 1.0E-05 eV to 1.5 MeV and a small energy dependence, similar to the one in the ^{239}Pu parameters, is built into them at higher energies. Future experimental data will have to decide whether this energy dependenc is correct or not. The parameters given in Table IX for ^{235}U are used to describe the fission spectrum due to first, second and third chance fission. The boil off neutrons for second and third chance fission are described by an evaporation type spectrum

$$f(E') \sim E' e^{-E'/\theta(E)}$$

whose parameter $\theta(E)$ was represented to have the same energy variation as that for the continuum inelastic scattering given in File 5/91. The mean energies corresponding to the first, second and third chance fission were added to give the mean energy of the total fission process after weighting them properly with ratios of first, second and third chance fission cross sections to the total fisson cross section. From this mean energy one could determine the corresponding Watt spectrum parameters a and b for the total fission.

4.0 Evaluation of $\bar{\nu}_p$

Evaluation of $\bar{\nu}$ prompt for ^{235}U was carried out by assuming ^{252}Cf $\bar{\nu}_p$ = 3.757±0.015 and ^{235}U $\bar{\nu}_p$ (thermal) = 2.420±0.012 as recommended by the Standards and Normalization Subcommittee of CSEWG.[46] Data uncertainties in the standard values were folded into the errors in different experimental data sets while making the least squares fit. The data sets[47-62] used in this evaluation are given in Table X. The data of Colvin and Sowerby,[49] Conde,[50] Hopkins and Diven[56] and Mather el al.[57] were corrected for delayed γ-rays and fission neutron specta differences as suggested by Boldeman.[63] Similarly, the Boldeman[53] and Soleilhac[61] data were mulitiplied by 1.0021 as suggested by Boldeman[53] to allow for the current best representation of the fission spectrum as a Watt spectrum. The Soleilhac data[60] were renormalized to the 1.87 MeV value in the Boldeman[53] paper as suggested by Boldeman.[64]

The renormalized data plots are shown in Figs. 20 and 21. The data were fitted with a least-squares program using inverse of the data variances as weights. Straight line fits were initially made between 0-2.0 MeV, 2-6.0 MeV and 6.0-20.0 MeV as there appears to be breaks in the data at 2 and 6 MeV. From the 0-2.0 MeV fit, the zero energy intercept was obtained to be 2.418±.002 which is in quite good agreement with the assumed thermal value of 2.420±.012. Hence, in the data files a constant $\bar{\nu}_p$ = 2.420 is given from 1.0E-05 eV to 25 keV joined to the straight line obtained from the fit up to 2.0 MeV. From 2 to 5.5 MeV the data are represented again by a straight line. There appears to be a break in the data between 5.5 and 6.0 MeV which is represented by a straight line joining the 5.5 MeV point to the 6.0 MeV point and using the 6-20.0 MeV straight line fit at higher energies.

5.0 Evaluation of the Gamma-Ray Production Cross Section above 1.09 MeV

There are some recent data[65,66] on the gamma-ray production cross section in ^{235}U for neutron energies from 1 to 14.2 MeV. These data sets have a low energy cut-off of E_γ = 0.25 MeV for most of the measurements and a cut-off of E_γ = 0.3 MeV for the 14.2 MeV measurements. It has been pointed out that the agreement between the new measurements and Version IV evaluation is good.[66] There are some older data of Nellis and Morgan[67] and Buchanan et al.[68] which have a low-energy cut-off of E_γ = 0.5 MeV. In Fig. 22 are shown these data as well as the new data of Drake et al. integrated over gamma-ray energies from 0.5 MeV and up. The agreement between these two data sets is good.

One of the problems in the evaluation of the total γ-ray production cross section is how to extrapolate the gamma-ray spectrum beyond the measured low energy cut-off. To determine the low energy part of the gamma spectrum, a simple linear extrapolation joining the last two measured data points in the Drake gamma spectra was used and the resulting contributions added to a smooth curve drawn through the data points in Fig. 22 to obtain the total x-ray production cross section. The Drake data and its low energy extrapolation were also used to determine the normalized energy distribution of the x-ray spectra in File 15.

Table III (Cont.)

Input Data for the Unresolved Resonance Region Fit

Energy (eV)	σ_f(b)	$\sigma_{n\gamma}$(b)
1.670+3	7.461	2.505
1.700+3	6.396	1.819
1.750+3	6.252	2.427
1.900+3	7.346	3.167
2.000+3	6.094	3.111
2.150+3	5.222	2.458
2.300+3	5.325	2.066
2.500+3	5.877	1.968
2.650+3	5.102	1.521
2.900+3	5.003	1.508
3.000+3	4.870	1.484
3.150+3	4.644	1.774
3.250+3	5.129	1.679
3.500+3	4.773	1.582
3.700+3	4.382	1.482
3.800+3	5.214	1.661
3.900+3	4.305	1.589
4.000+3	4.667	1.597
4.150+3	4.055	1.480
4.250+3	4.982	1.582
4.350+3	4.331	1.544

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Table III (cont.)

Input Data for the Unresolved Resonance Region Fit

Energy (eV)	σ_f(b)	$\sigma_{n\gamma}$(b)
2.60+2	23.487	10.893
2.65+2	27.214	9.332
3.00+2	11.015	5.220
3.35+2	15.520	8.181
3.90+2	10.419	5.235
4.30+2	14.514	4.598
4.60+2	12.665	4.784
4.90+2	13.790	4.858
5.10+2	18.325	4.841
5.50+2	13.732	5.218
6.00+2	13.142	4.637
6.50+2	8.492	4.814
6.65+2	13.131	5.558
6.80+2	12.728	3.970
7.00+2	10.171	3.482
7.15+2	14.693	6.207
7.30+2	10.965	6.118
7.55+2	9.408	4.630
7.70+2	10.798	4.046
8.00+2	8.998	3.784
8.50+2	7.557	3.831

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Table II

Parameters of the Unresolved Resonance Region for ^{235}U

	S-wave Parameters		P-wave Parameters	
	J=3	0.92×10^{-4}	J=2	1.449×10^{-4}
Strength Function			J=3	1.251×10^{-4}
	J=4	1.11×10^{-4}	J=4	1.251×10^{-4}
			J=5	1.449×10^{-4}
	J=3	$\nu=3$	J=2	0.394 eV $\nu=4$
$<\Gamma_f>$			J=3	0.277 eV $\nu=3$
	J=4	$\nu=2$	J=4	0.258 eV $\nu=4$
			J=5	0.179 eV $\nu=3$
	J=3	0.9526 eV	J=2	1.2383 eV
Spacing			J=3	0.9526 eV
	J=4	0.8093 eV	J=4	0.8093 eV
			J=5	0.7477 eV
Γ_γ		0.035 eV		0.035 eV
R		9.5663 fm		

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Table III (cont.)

Input Data for the Unresolved Resonance Region Fit

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3.35+2	15.520	8.181
3.90+2	10.419	5.235
4.30+2	14.514	4.598
4.60+2	12.665	4.784
4.90+2	13.790	4.858
5.10+2	18.325	4.841
5.50+2	13.732	5.218
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6.50+2	8.492	4.814
6.65+2	13.131	5.558
6.80+2	12.728	3.970
7.00+2	10.171	3.482
7.15+2	14.693	6.207
7.30+2	10.965	6.118
7.55+2	9.408	4.630
7.70+2	10.798	4.046
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15. J.R. Lemley, G.A. Keyworth and B.C. Diven, Nuc. Sci and Eng. 43 281 (1971).

Table III (Cont.)

Input Data for the Unresolved Resonance Region Fit

Energy (eV)	σ_f(b)	$\sigma_{n\gamma}$(b)
1.670+3	7.461	2.505
1.700+3	6.396	1.819
1.750+3	6.252	2.427
1.900+3	7.346	3.167
2.000+3	6.094	3.111
2.150+3	5.222	2.458
2.300+3	5.325	2.066
2.500+3	5.877	1.968
2.650+3	5.102	1.521
2.900+3	5.003	1.508
3.000+3	4.870	1.484
3.150+3	4.644	1.774
3.250+3	5.129	1.679
3.500+3	4.773	1.582
3.700+3	4.382	1.482
3.800+3	5.214	1.661
3.900+3	4.305	1.589
4.000+3	4.667	1.597
4.150+3	4.055	1.480
4.250+3	4.982	1.582
4.350+3	4.331	1.544

5.0 Evaluation of the Gamma-Ray Production Cross Section above 1.09 MeV

There are some recent data[65,66] on the gamma-ray production cross section in ^{235}U for neutron energies from 1 to 14.2 MeV. These data sets have a low energy cut-off of $E_\gamma = 0.25$ MeV for most of the measurements and a cut-off of $E_\gamma = 0.3$ MeV for the 14.2 MeV measurements. It has been pointed out that the agreement between the new measurements and Version IV evaluation is good.[66] There are some older data of Nellis and Morgan[67] and Buchanan et al.[68] which have a low-energy cut-off of $E_\gamma = 0.5$ MeV. In Fig. 22 are shown these data as well as the new data of Drake et al. integrated over gamma-ray energies from 0.5 MeV and up. The agreement between these two data sets is good.

One of the problems in the evaluation of the total γ-ray production cross section is how to extrapolate the gamma-ray spectrum beyond the measured low energy cut-off. To determine the low energy part of the gamma spectrum, a simple linear extrapolation joining the last two measured data points in the Drake gamma spectra was used and the resulting contributions added to a smooth curve drawn through the data points in Fig. 22 to obtain the total x-ray production cross section. The Drake data and its low energy extrapolation were also used to determine the normalized energy distribution of the x-ray spectra in File 15.

Table III (Cont'd)

Input Data for the Unresolved Resonance Region Fit

Energy (eV)	σ_{f}(b)	$\sigma_{n\gamma}$(b)
9.000+3	2.728	1.169
9.150+3	3.269	1.341
9.600+3	3.064	1.250
1.000+4	2.661	1.092
1.040+4	2.730	1.163
1.065+4	2.859	1.169
1.085+4	2.724	1.188
1.120+4	2.871	1.184
1.165+4	2.582	1.104
1.200+4	2.607	1.135
1.240+4	2.380	1.100
1.280+4	2.518	1.075
1.325+4	2.860	1.046
1.370+4	2.566	1.012
1.430+4	2.520	1.008
1.480+4	2.654	0.904
1.530+4	2.294	0.918
1.600+4	2.359	0.963
1.720+4	2.187	0.984
1.790+4	2.365	0.929
1.840+4	2.411	0.840

4.0 Evaluation of $\bar{\nu}_p$

Evaluation of $\bar{\nu}$ prompt for ^{235}U was carried out by assuming ^{252}Cf $\bar{\nu}_p$ = 3.757±0.015 and ^{235}U $\bar{\nu}_p$ (thermal) = 2.420±0.012 as recommended by the Standards and Normalization Subcommittee of CSEWG.[46] Data uncertainties in the standard values were folded into the errors in different experimental data sets while making the least squares fit. The data sets[47-62] used in this evaluation are given in Table X. The data of Colvin and Sowerby,[49] Conde,[50] Hopkins and Diven[56] and Mather el al.[57] were corrected for delayed γ-rays and fission neutron specta differences as suggested by Boldeman.[63] Similarly, the Boldeman[53] and Soleilhac[61] data were mulitiplied by 1.0021 as suggested by Boldeman[53] to allow for the current best representation of the fission spectrum as a Watt spectrum. The Soleilhac data[60] were renormalized to the 1.87 MeV value in the Boldeman[53] paper as suggested by Boldeman.[64]

The renormalized data plots are shown in Figs. 20 and 21. The data were fitted with a least-squares program using inverse of the data variances as weights. Straight line fits were initially made between 0-2.0 MeV, 2-6.0 MeV and 6.0-20.0 MeV as there appears to be breaks in the data at 2 and 6 MeV. From the 0-2.0 MeV fit, the zero energy intercept was obtained to be 2.418±.002 which is in quite good agreement with the assumed thermal value of 2.420±.012. Hence, in the data files a constant $\bar{\nu}_p$ = 2.420 is given from 1.0E-05 eV to 25 keV joined to the straight line obtained from the fit up to 2.0 MeV. From 2

Table IV

Low Energy Fission Integrals for ^{235}U

Author & Data Set	Thermal[a] Fit	$I^{10}_{7.4}$ (1)	$I^{11}_{7.8}$ (2)	$\frac{(2)}{(1)}$	$I^{11}_{7.8}$ Relative to Version V Standards	Error
Deruytter & Wagemans AN/SN-20131/2	569.8 ± 2.3	220.47	237.35	1.07656	243.07	1%
Czirr Private Communication April 30'76	585.0 ± 2.6	225.86	242.27	1.07266	240.57	1%
Gwin AN/SN-10267/24	580.05 ± 2.0	217.49	234.62	1.07876	235.92	1.5%
ORNL-RPI AN/SN-10270/6	574.1 ± 2.3	221.24	237.40	1.07304	241.30	2%

2.1893±0.1552 (MeV^{-1}) and E'_{U-235} = 2.016±.047. Further the ratio $\bar{E}'_{Pu239}/E'_{U-235}$ was found to be equal to 1.04. Though this ratio between the mean energies of ^{239}Pu and ^{235}U had been obtained from data measured for low incident neutron energies, for want of any experimental information, it was decided to maintain the same ratio for all incident neutron energies. The evaluation of the prompt fission neutron spectrum for ^{239}Pu for ENDF/B-V has been described by Kujawski[45] in terms of an energy dependent Watt spectrum. These parameters are given in Table IX along with $\bar{E}_{Pu-239}$. From this Table, one could calculate the mean energy of the ^{235}U Watt spectrum such that $\bar{E}_{Pu-239}/\bar{E}_{U-235}$ = 1.04 and knowing the mean energy, determine the parameters a and b consistent with it. At low energies, a was set equal to 0.988 a value obtained by Adams and b could be calculated consistent with $\bar{E}'$. As in the case of ^{239}Pu the Watt spectrum parameters are kept constant from 1.0E-05 eV to 1.5 MeV and a small energy dependence, similar to the one in the ^{239}Pu parameters, is built into them at higher energies. Future experimental data will have to decide whether this energy dependenc is correct or not. The parameters given in Table IX for ^{235}U are used to describe the fission spectrum due to first, second and third chance fission. The boil off neutrons for second and third chance fission are described by an evaporation type spectrum

$$f(E') \sim E' e^{-E'/\theta(E)}$$

Table V

Fission Integral of ^{235}U from 0.1-1.0 keV

Author	I (b-eV)[a]	I' (b-eV)[b]	I/I'
Gwin	1.1799E+04	1.0515E+04	1.12211
Czirr	1.1403E+04	1.0162E+04	1.12212
ORNL-RPI	1.2399E+04	1.1063E+04	1.12076
Wasson	1.1815E+04	1.0534E+04	---
Wagemans	1.2204E+04	---	---
Mean Unweighted.	1.1924E+04		
Blons	1.2333E+04	1.0995E+04	1.12169
Lemley	1.1782E+04	1.0509E+04	1.12113
		Mean	1.12156

$^{a}I = \int_{.1\ keV}^{1\ keV} \sigma_f dE$

$^{b}I' = \int_{.1\ keV}^{.3\ keV} \sigma_f dE + \int_{.4\ keV}^{1\ keV} \sigma_f dE$

the capture cross section and the grid points used for the unresolved resonance region analysis are shown in Figs. 13-19. The input used at grid points are given in Table III.

d. Capture Cross Section 25 keV to 20 MeV

This was determined by using the capture to fission ratio for the Version IV evaluation and multiplying it by the fission cross section for Version V.

Table VI (Cont'd)

Bin Limits (keV)	Gwin	Czirr	Wasson	Perez & ORNL-RPI	Blons	Wagemen & Deruytter	Gayther	Average $\sigma(n,f)(b)$
100–110	1.614		1.502				1.539	1.568
110–120	1.612		1.462				1.463	1.527
120–130	1.591		1.465				1.475	1.525
130–140	1.402		1.387				1.446	1.426
140–150	1.408		1.389				1.405	1.415
150–160	1.362		1.413				1.421	1.413
160–170	1.385		1.368				1.364	1.386
170–180	1.354		1.352				1.334	1.360
		1.165						
180–190	1.331		1.403				1.304	1.359
190–200	1.198		1.305				1.305	1.282

*Based on σ_f (0.0253eV) = 583.54 b.

$$I_{7.8eV}^{11.0eV} = 241.2 \pm 1.6 \text{ b-eV}$$

$$I_{0.1keV}^{1.0keV} = 1.1924 \times 10^4 \text{ b-eV}$$

$$I_{10keV}^{50keV} = 8.339 \times 10^4 \text{ b-eV}$$

Fission Cross Section from 100 keV-20 MeV

This was evaluated by W.P. Poenitz[6] in conjunction with the Normalization and Standards Subcommittee of CSEWG. The details of this evaluation have been published recently.

2.2 Capture Cross Section

a. Capture Cross Section 1.0E-05 eV to 1.0 eV

The capture cross section in this energy region is from the Leonard evaluation[5] with modifications from 0.85 eV to 1.0 eV in order to join smoothly with the doppler unbroadened capture cross section obtained from the resolved resonance parameters at 1.0 eV. The 0.0253 eV capture cross section is 98.38±0.76 b.

b. Capture Cross Section 1.0 eV to 82.0 eV

The resolved resonance parameters and the background cross section in File 3 together give the capture cross section in this region. The resolved resonance parameters are from the analysis by Smith and Young.[3]

c. Capture Cross Section 82.0 eV to 25 keV

The analysis used here parallels that used for the fission cross section and described in Section 2.1. It consists of first, energy shifting different data sets with respect to one another and then averaging the fine structure to arrive at a consensus structure corresponding to all the data sets and second, renormalizing the different data sets to ENDF/B-V standards to determine broad-bin averages.

Table VII (Cont'd)

Average ^{235}U Fission Cross-Section 0.1-100 keV

Energy Bin Limits (keV)	$<\sigma_f>$ (b)
80.0 - 90.0	1.558
90.0 - 100.0	1.572

$I_{7.8}^{11.0} = 240.0$ b-eV. These data were renormalized to $I_{7.8}^{11.0} = 241.2$ b-eV and the ENDF/B-V $^{10}B(n,\alpha)$ cross section. The results thus obtained are shown in Table V. There is a spread of about 9% in the fission integral from 0.1-1.0 keV though the precision claimed by the individual experiments are much smaller. An unweighted mean of the five data sets listed in Table V is 1.1924×10^4 b-eV. The average cross sections from 100 eV to 1 keV are shown in Fig. 10. The Blons data[16] were normalized to this fission integral. Similarly, the data of Perez et al.[33,34] at higher energies were normalized to the same integral. The average cross sections thus obtained from 1 to 10 keV are shown in Fig. 11. An average of the fission integrals of Gwin, Czirr, Perez, Blons and Wagemans between 10 and 50 keV; $I_{10}^{50} = 8.339 \times 10^4$ b-eV was used to normalize the high energy data of Wasson from 5-800 keV measured with respect to hydrogen. These data have been used in the present evaluation above 5 keV as suggested by Wasson though there are some data by the same author measured with repsect to $^6Li(n,\alpha)$ and extending up to 70 keV. The average fission integral between 10-50 keV was also used to normalize the Gayther[35] data. Lemley[15] data were not used in this evaluation as the raw data were not available to correct for the (n,α) angular distribution in the flux monitor using ENDF/B-V evaluation. It is estimated[36] that this correction amounts to about +3% at 100 keV, though it decreases at lower energies. Thus, from 10-100 keV mean of the data of Gwin,

Table IX

Fission Spectrum Parameters for ^{239}Pu and ^{235}U

E_i(Mev)	^{239}Pu a(meV)	b(MeV^{-1})	$\bar{E}$(nf)(MeV)	^{235}U a(MeV)	b(Mev^{-1})	$\bar{E}$(nf)(MeV)
10^{-11}	0.966	2.842	2.112	0.988	2.249	2.031
1.5	0.966	2.842	2.112	0.988	2.249	2.031
6.0	1.028	2.509	2.205	1.047	2.005	2.120
14.0	1.138	2.048	2.370	1.153	1.653	2.279
20.0	1.218	1.788	2.490	1.231	1.446	2.394

for example a linac, it could be normalized to the accurately known thermal value. Therefore, it was decided to start from the low-energy region with a common thermal normalization and determine average fission cross section in the eV region. This average in the eV region could be used to renormalize higher energy data to give an average in the keV region and so on, so that different data sets could be represented in terms of a common "basis" for comparison. Such data could then be combined with absolute point-wise measurements to arrive at what would be a final evaluation of the data.

Fission cross section data which extend down to thermal energies were normalized to a common 2200 m/sec value of 583.54 b to obtain an average of the fission integral between 7.8 eV-11.0eV which has been suggested by Deruytter[26] as a possible region for cross-normalization of various data sets. The data sets considered are by Deruytter and Wagemans,[26] Czirr,[27] Gwin,[28] de Saussure et al.[14] Bowman[29] and Shore and Sailor.[30] The fission integrals from 7.4-10.0 eV ($I_{7.4}^{10.0}$) and from 7.8-11.0 eV ($I_{7.8}^{11.0}$) obtained from these data sets are given in Table IV. The second column of this Table gives the thermal cross sections of the different data sets as obtained by a reanalysis and fit to these data by Leonard[5] and were used to renormalize the data. The third and fourth columns give the fission integrals as obtained from the CSISRS (Cross Section Information Storage and Retrieval System maintained by the National Nuclear Data Center at Brookhaven) data and column six gives the fission inte-

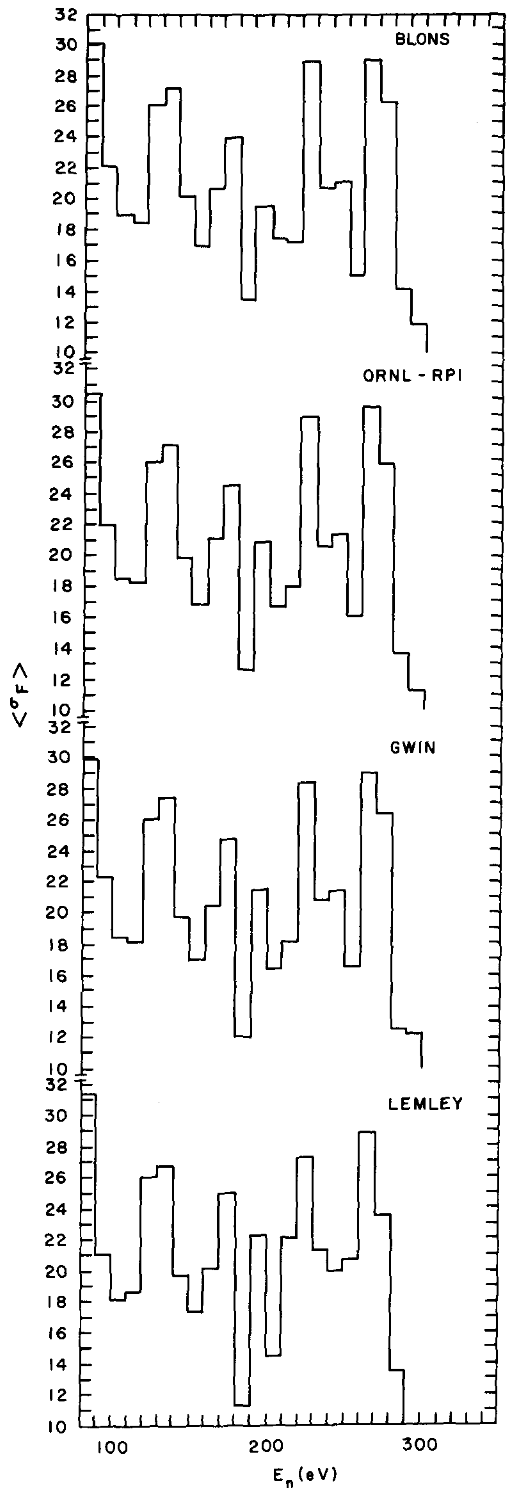

Figure 1. Blons, ORNL-RPI, Gwin and Lemley Data 80-300 eV with no Energy Shift

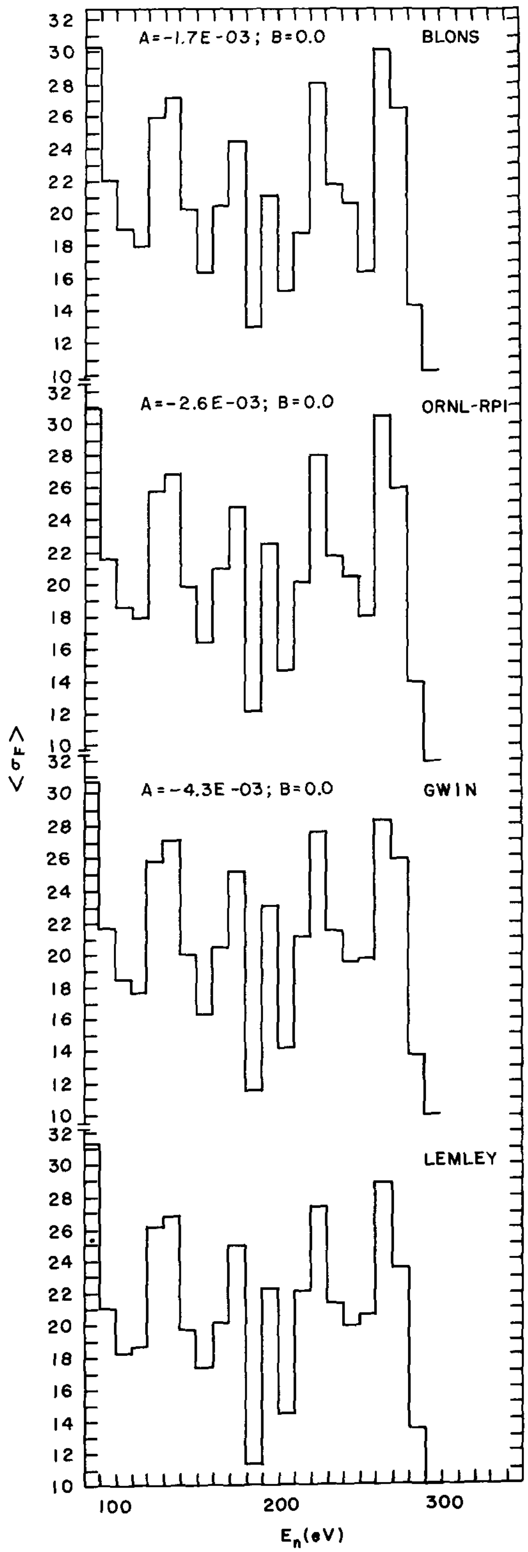

Figure 2. Blons, ORNL-RPI, Gwin and Lemley Data 80-300 eV with Optimum-Energy Shift

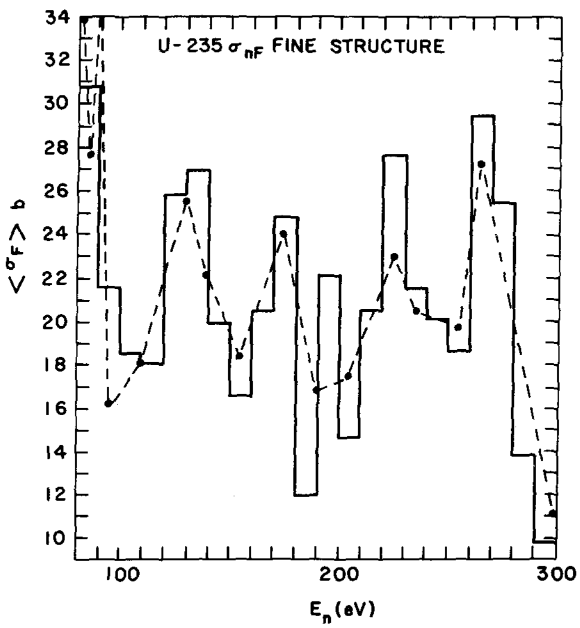

Figure 3. Fission Cross Section Fine Structure
80-300 eV

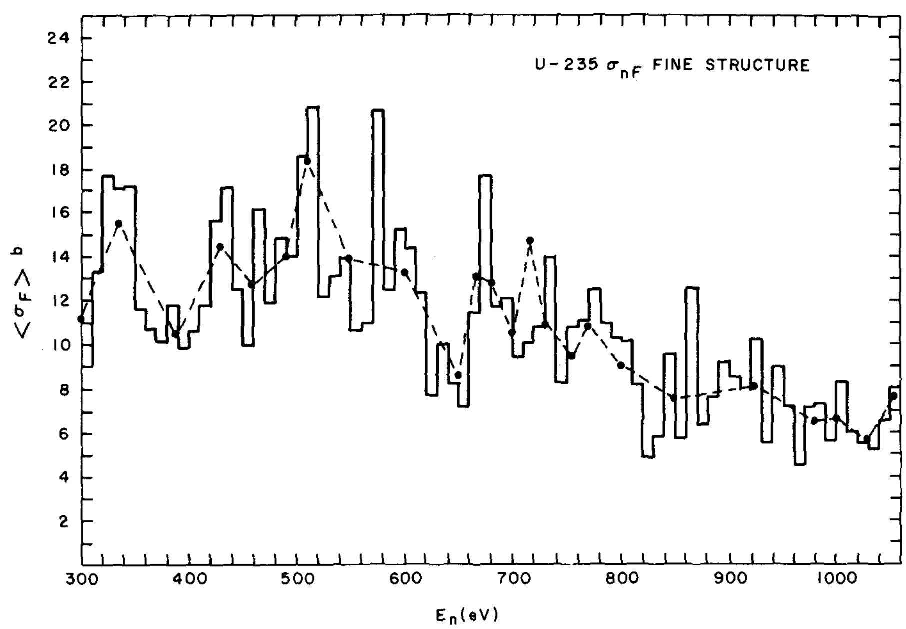

Figure 4. Fission Cross Section Fine Structure
300-1060 eV

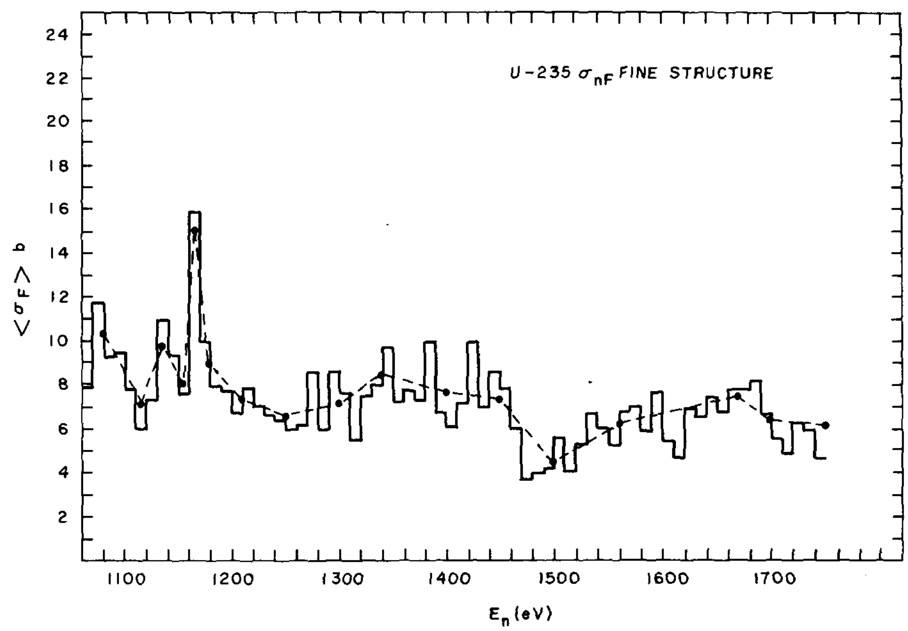

Figure 5. Fission Cross Section Fine Structure
1060-1750 eV

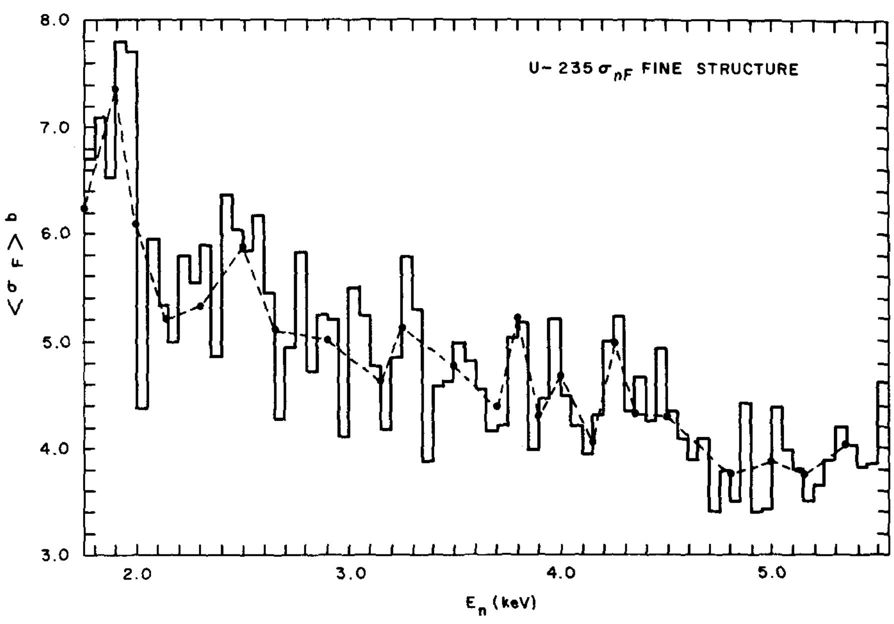

Figure 6. Fission Cross Section Fine Structure
1.75-5.55 keV

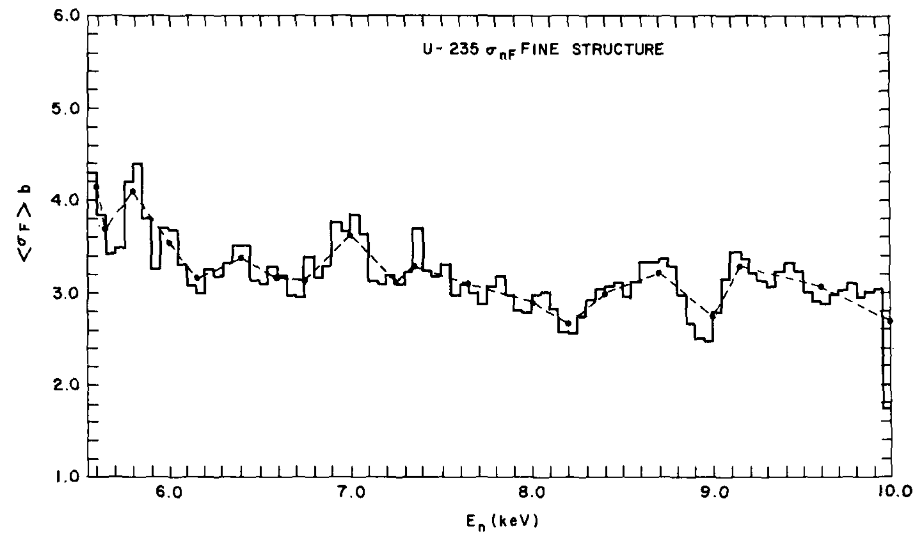

Figure 7. Fission Cross Section Fine Structure
5.55-10.0 keV

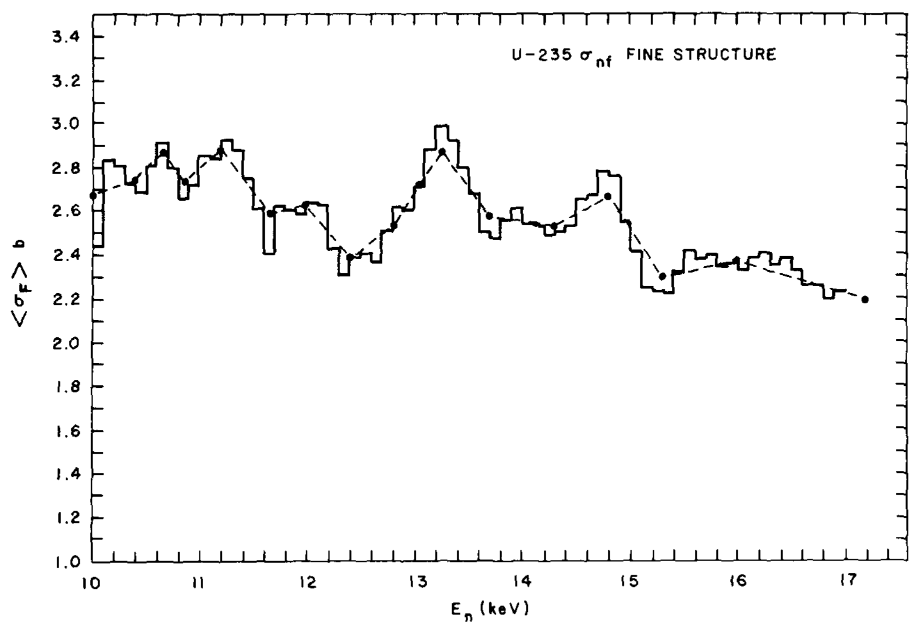

Figure 8. Fission Cross Section Fine Structure
10.0-17.0 keV

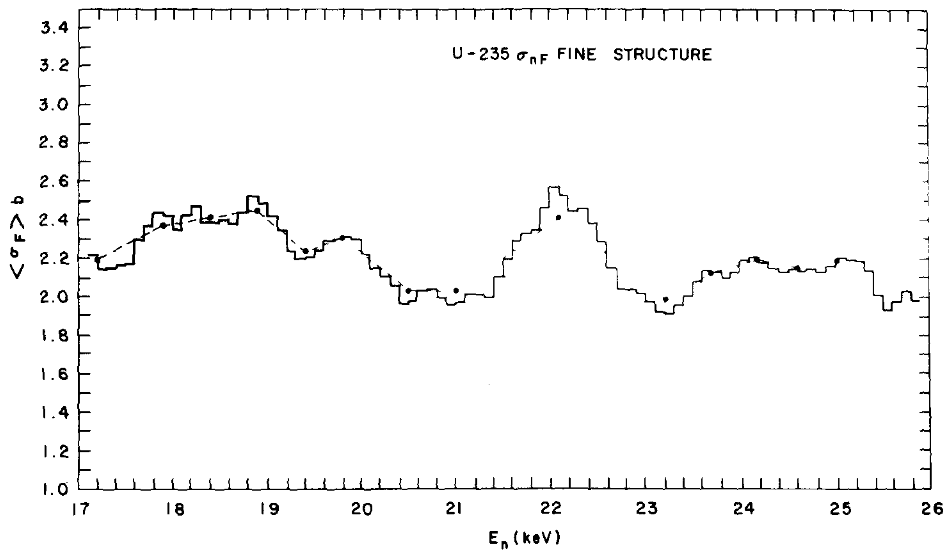

Figure 9. Fission Cross Section Fine Structure
17-26 keV

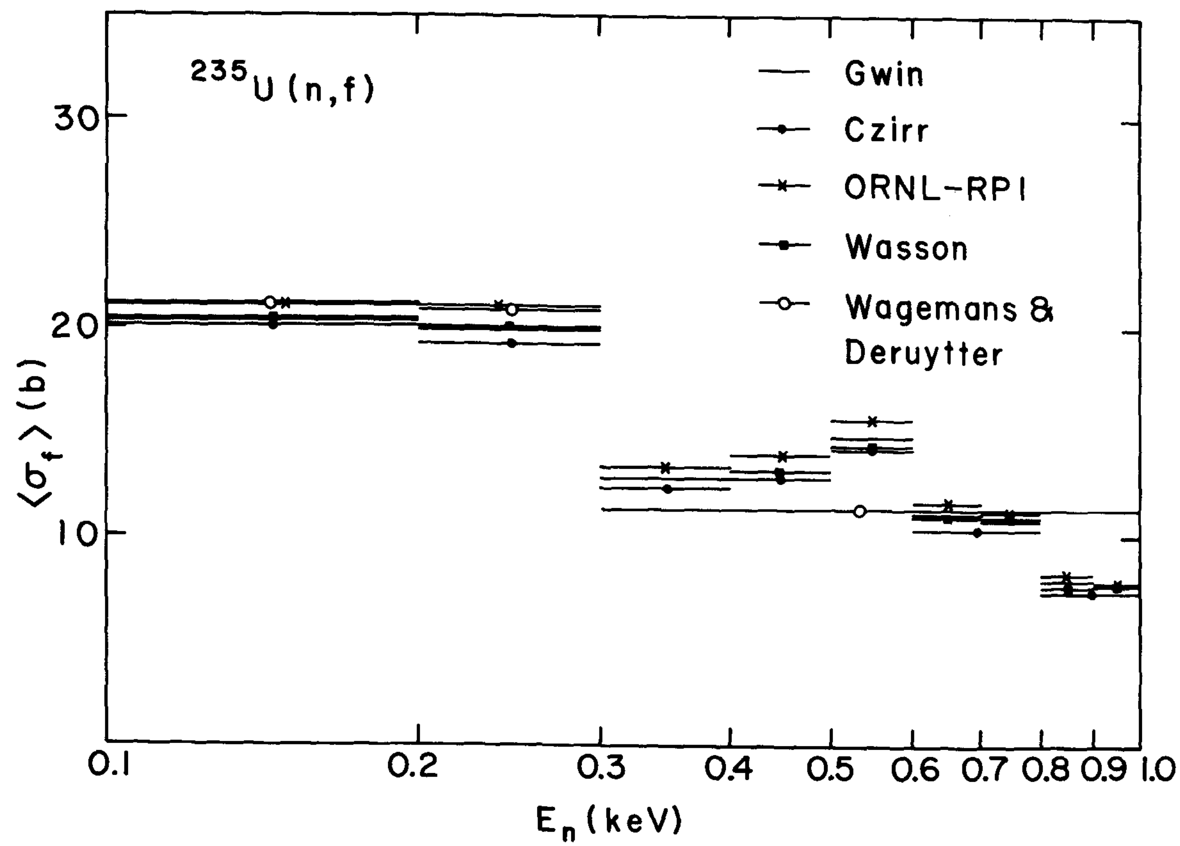

Figure 10. Average Fission Cross Section of ^{235}U from 0.1-1.0 keV

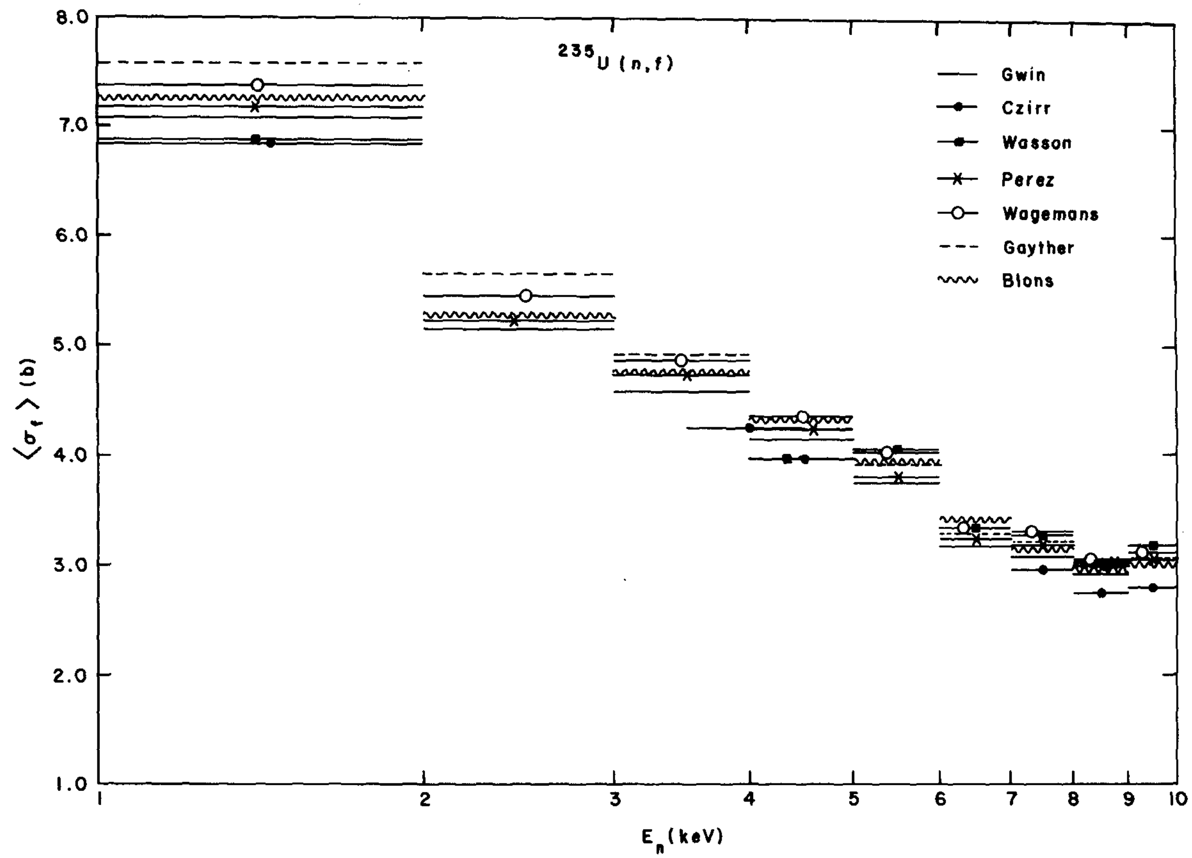

Figure 11. Average Fission Cross Section of ^{235}U from 1-10 keV

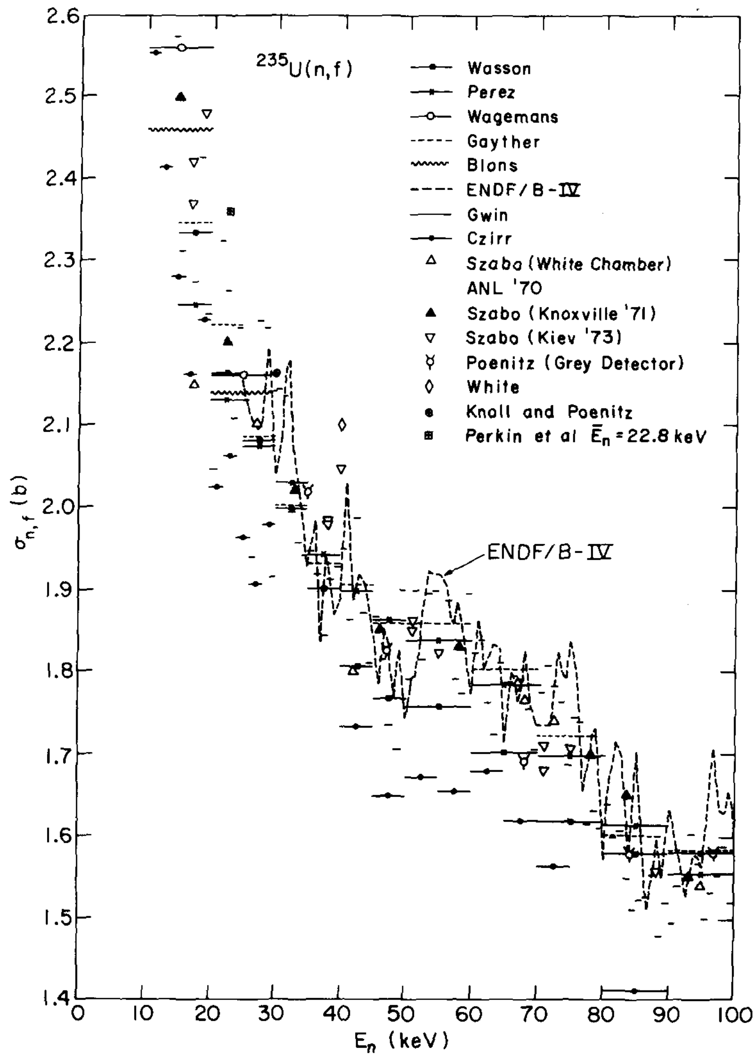

Figure 12. Fission Cross Section of ^{235}U from 10-100 keV

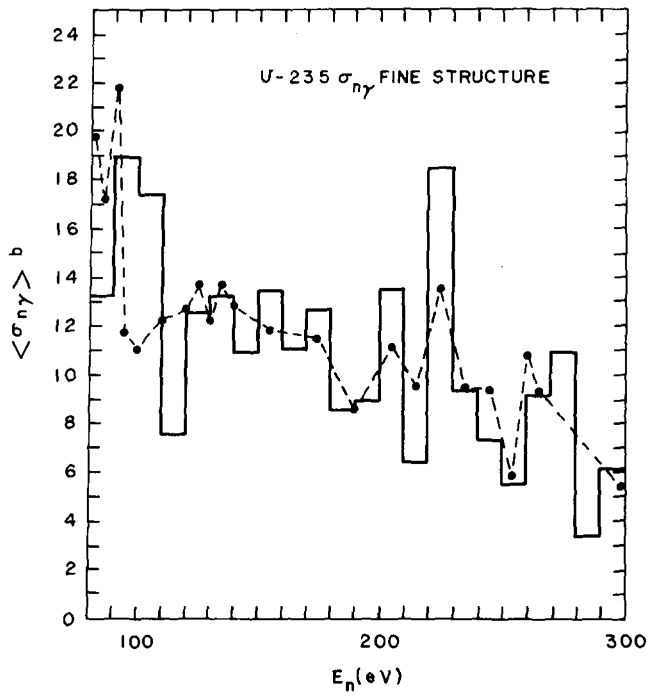

Figure 13. Capture Cross Section Fine Structure 80-300 eV

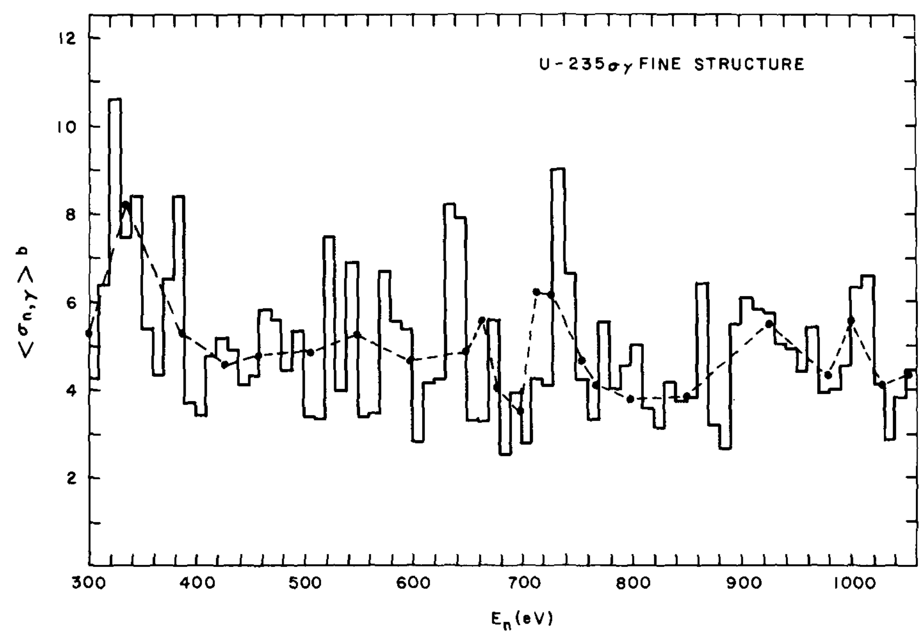

Figure 14. Capture Cross Section Fine Structure 300-1060 eV

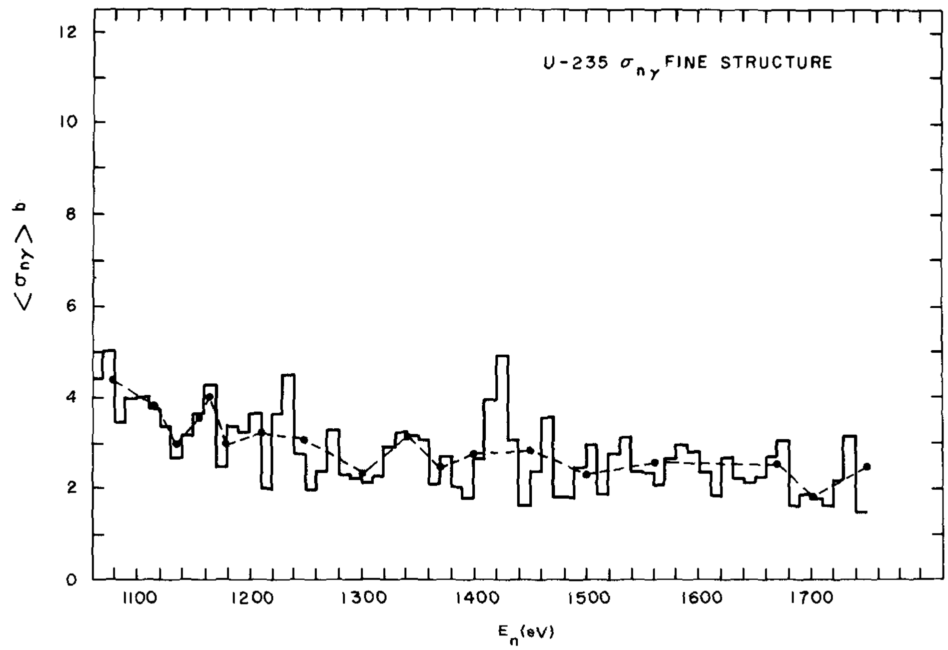

Figure 15. Capture Cross Section Fine Structure
1060-1750 eV

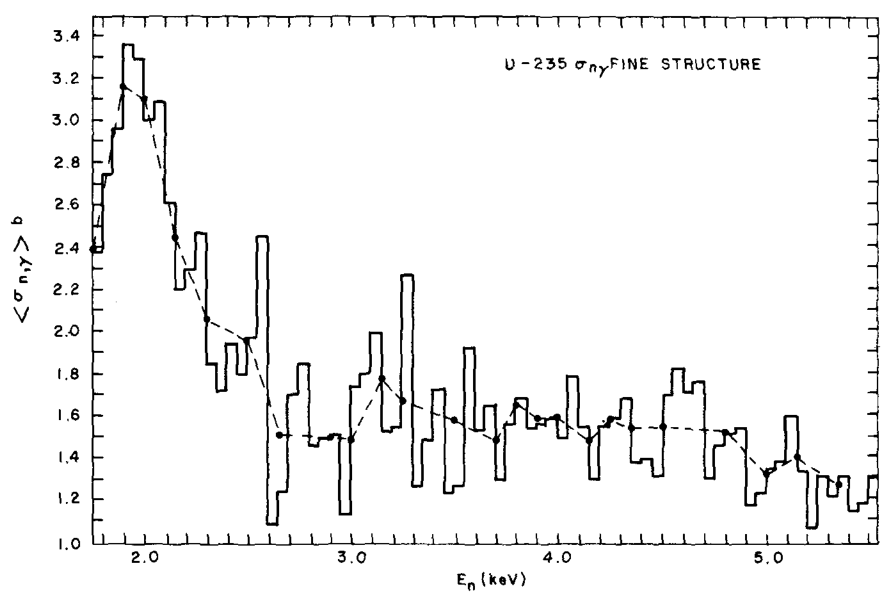

Figure 16. Capture Cross Section Fine Structure
1.75-5.55 keV

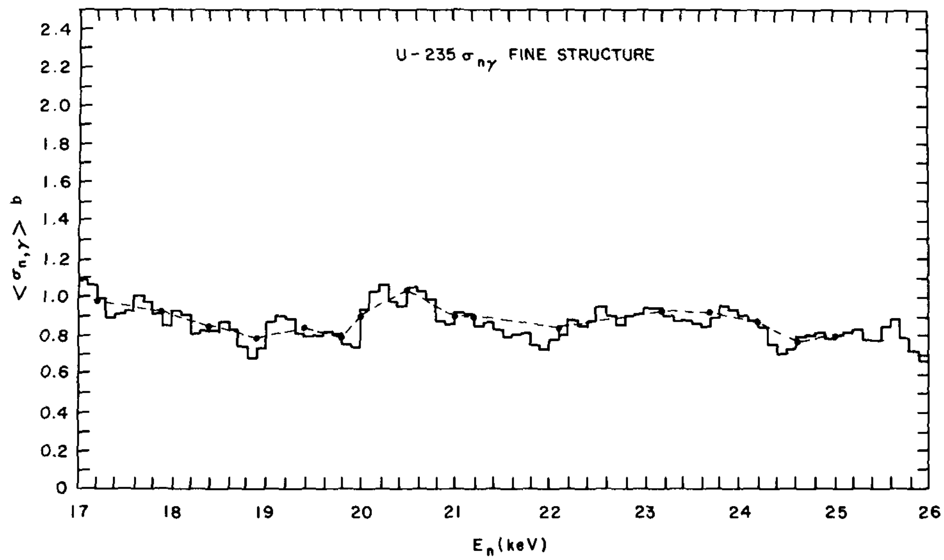

Figure 19. Capture Cross Section Fine Structure
17-26 keV

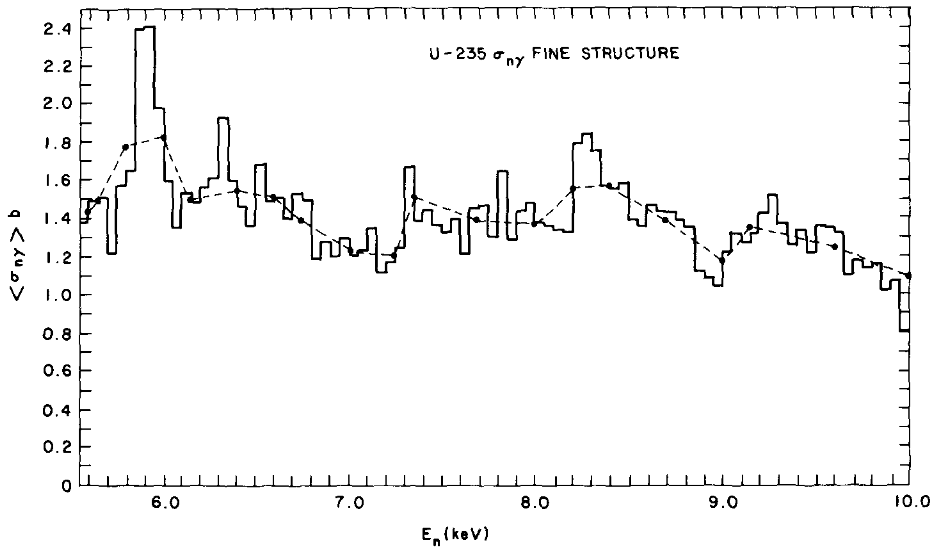

Figure 17. *Capture Cross Section Fine Structure*
5.55-10.0 keV

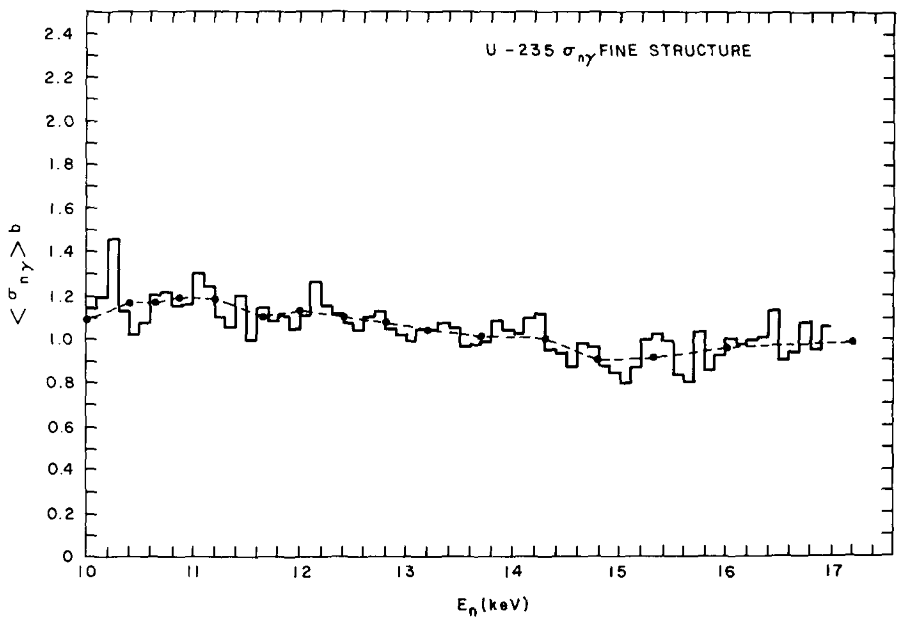

Figure 18. *Capture Cross Section Fine Structure*
10-17.0 keV

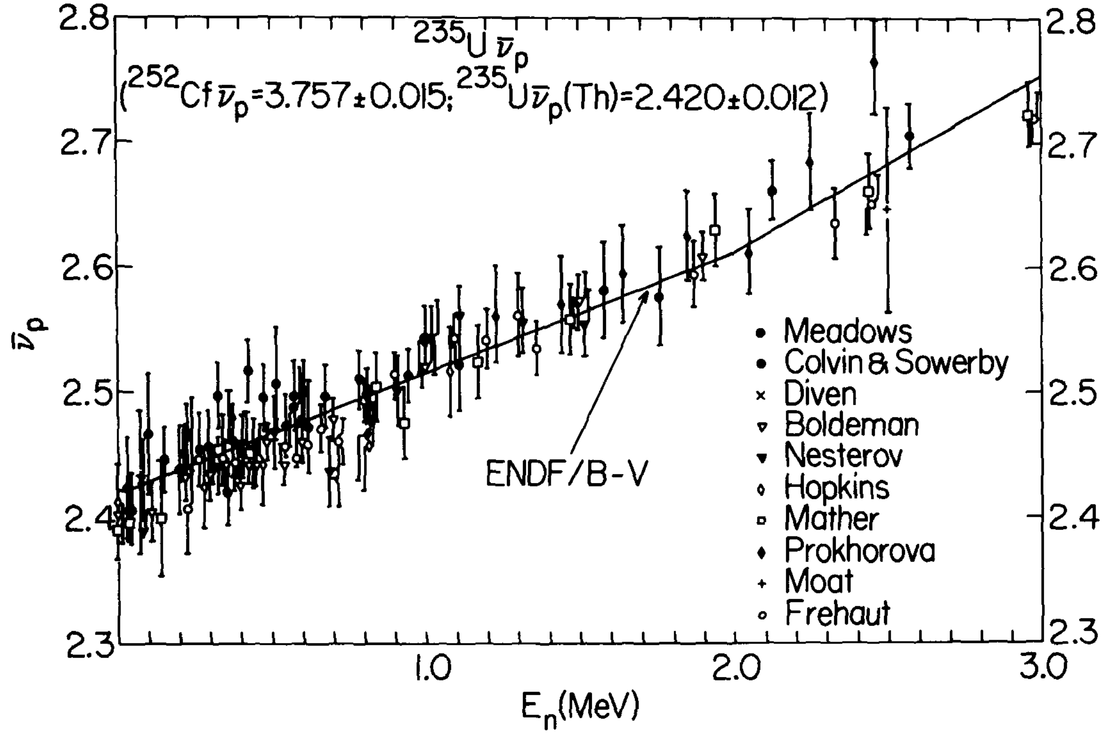

Figure 20. Prompt $\bar{\nu}$ Data and Fit 0-3.0 MeV

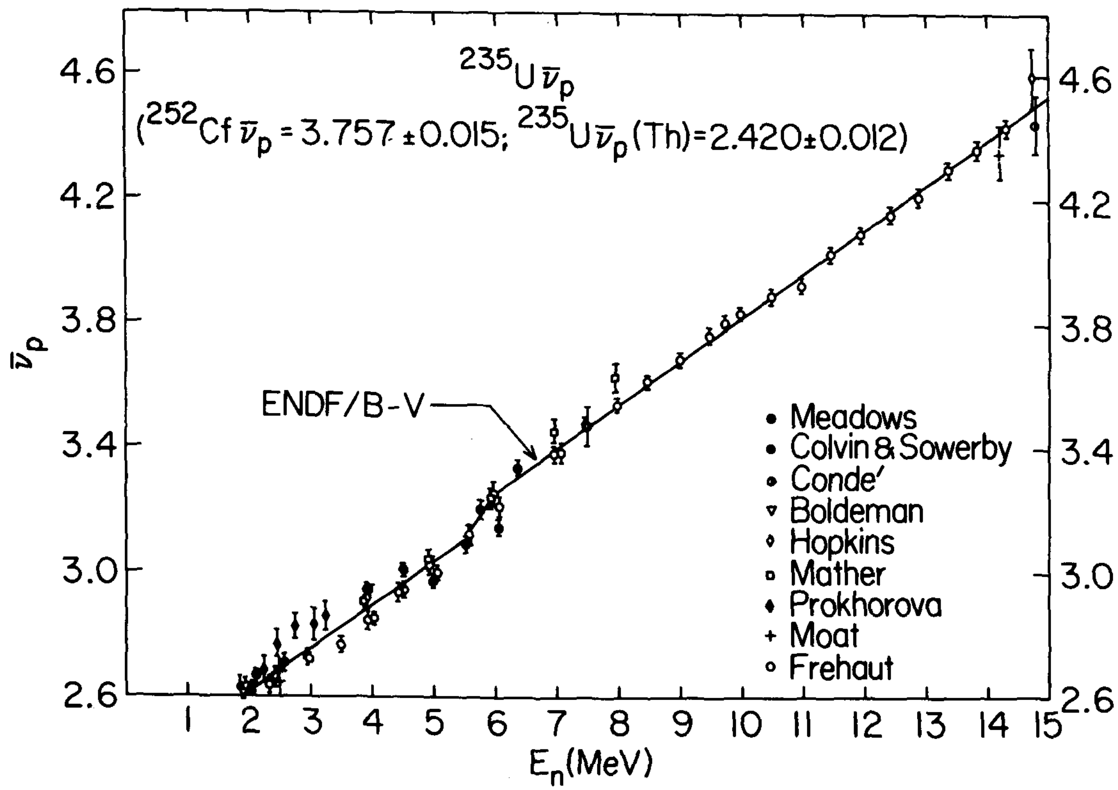

Figure 21. Prompt $\bar{\nu}$ Data and Fit 2-15 MeV.

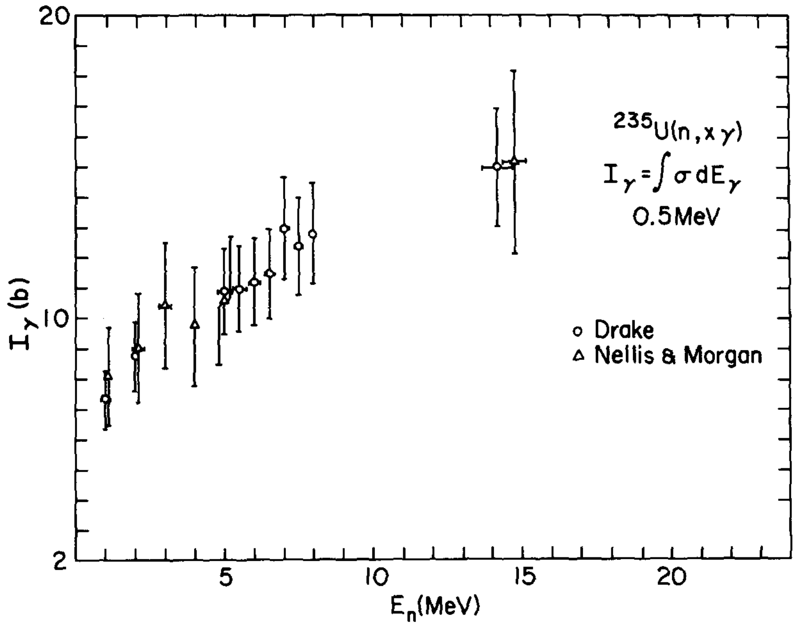

Figure 22. Gamma Ray Production Cross Section for ^{235}U

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