291
1-5-78
1-19 d
Germany
Japan
UK, d
+ Special ENDF Distr.

Sh. 1723

ORNL/TM-6152
(ENDF-257)

Evaluation of the ^{238}U Neutron Cross Sections for Incident Neutron Energies up to 4 keV

G. de Saussure
D. K. Olsen
R. B. Perez
F. C. Difilippo

EB

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION · FOR THE DEPARTMENT OF ENERGY

DISCLAIMER

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy $6.50; Microfiche $3.00
6.00

ORNL/TM-6152
(ENDF-257)
Dist. Category UC-79d

Contract No. W-7405-eng-26

Neutron Physics Division

EVALUATION OF THE ^{238}U NEUTRON CROSS SECTIONS FOR INCIDENT NEUTRON ENERGIES UP TO 4 keV

G. de Saussure, D. K. Olsen, R. B. Perez, and F. C. Difilippo*

*On assignment from Comisión Nacional de Energía Atómica, Argentina.

Date Published: January 1978

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

TABLE OF CONTENTS

	Page No.
Abstract	vii
1. Introduction	1
2. Recent Measurements and Analyses of ^{238}U Cross Sections	2
3. Evaluation of the Resonance Parameters for the Levels with Energies Between 1 and 4000 eV	3
A. General Considerations	3
B. Determination of the Level Energies	10
C. Neutron Widths	14
D. Capture Widths	17
E. Fission Widths	19
F. Angular Momentum Assignment	23
G. Parameters of the Low Energy Resonances	24
H. Resonance Formalism and Scattering Radius	31
4. Evaluation of the Smooth Backgrounds (File 3)	33
5. Fine Adjustments to the Parameters and Smooth Backgrounds	44
6. Capture Cross Sections	45
7. Distribution of the Resonance Parameters	52
A. s-Wave Levels	52
B. p-Wave Levels	60
8. Estimated Uncertainties	68
9. Conclusions	80
References	85

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

ACKNOWLEDGMENT

The authors wish to acknowledge many helpful discussions with the participants of the Seminar on ^{238}U Resonance Capture and are particularly indebted to F. Poortmans, G. Rohr, and H. Weigmann of the BCMN, Geel, Belgium; to R. C. Block and K. Kobayashi of RPI; to R. E. Chrien and H. I. Liou of BNL and D. Finch of SRL for communication of the results of their work prior to publication.

The authors would also like to thank R. Q. Wright for considerable help, especially in putting this evaluation in the ENDF/B format.

Very helpful comments were provided by R. L. Macklin, R. W. Peelle, and C. R. Weisbin who reviewed the report.

Finally the authors would like to extend special thanks to Erma Howe who typed and organized this report.

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

ABSTRACT

This report describes an evaluation of the ^{238}U cross sections below 4 keV. Recent measurements and reanalyses of older data are discussed. Evaluated resonance parameters are obtained for 164 s-wave and 280 p-wave levels. The capture widths of the first three s-wave levels are significantly lower than in the ENDF/B-IV evaluation. The s-wave strength function above 1.5 keV is systematically larger than in ENDF/B-IV. Statistical and systematic uncertainties are evaluated for the resonance parameters and for the smooth backgrounds. The statistical distributions of the resonance parameters are compared with theoretically expected distributions.

1. INTRODUCTION

In this report we discuss an evaluation of the ^{238}U cross sections below 4 keV, intended for inclusion in ENDF/B-V.

These cross sections were evaluated for ENDF/B-IV by F. J. McCrosson[C1] in September 1973. Since that time a number of important new measurements of the low energy ^{238}U cross sections have been reported,[B21-B33] and some older measurements have been carefully reexamined.[A7]

The ^{238}U resonance parameters are particularly important to the calculation of the Doppler effect in fast reactors and of the conversion ratio in thermal reactors. Much of the recent interest in the reevaluation of these parameters has arisen from the apparent inability of the ENDF/B data to predict the ^{238}U capture rate in thermal critical lattices. New precise measurements and new analyses of older measurements have been greatly stimulated by a "Specialists Meeting on Resonance Parameters of Fertile Nuclei and ^{239}Pu" held in Saclay on May 20-22, 1974[A5] and by a "Seminar on ^{238}U Resonance Capture" held in Brookhaven National Laboratory on March 18-20, 1975.[A7] The proceedings of these meetings contain considerable information on the experimental differential measurements and on the utilization of the data for the analysis of integral experiments.

In the next section of this report we briefly review measurements and analyses of the ^{238}U cross sections below 4 keV, performed since 1974. Earlier experiments have been reviewed by Moxon.[C5] In the third section we discuss the evaluation of the resonance parameters. Smooth backgrounds (File 3) are discussed in Section 4. The distribution of the evaluated parameters is examined in Section 5 and a discussion of the errors is presented in Section 6.

2. RECENT MEASUREMENTS AND ANALYSES OF ^{238}U CROSS SECTIONS

Measurements of the ^{238}U resonance parameters done before 1974 have been reviewed and discussed by M. C. Moxon.[C5] Since then extensive series of measurements have been reported by Nakajima et al.,[B26] Olsen et al.,[B31] and Poortmans et al.[B32] These three series of measurements extend to energies well above 4 keV, but the analysis of the Geel measurements is not yet completed. Liou and Chrien[B30] have performed transmission, self-indication and gamma-ray spectra measurements for epithermal neutron energies and have obtained resonance parameters for the s-wave levels up to 116.85 eV. Corvi, Rohr, and Weigmann[B25] were able to make many p-wave assignments in the neutron energy range from 10 to 1600 eV by measuring the fraction of capture gamma rays above 4.3 MeV. Subthreshold fission in ^{238}U below 4 keV has recently been investigated by Block et al.,[B27] Blons, Mazur, and Paya,[B28] Wartena, Weigmann, and Migneco,[B24] Difilippo et al.,[B33] and Slovacek et al.[B29] Finally a series of self-indication measurements was recently completed at RPI.[B34] The analyses of these measurements by Block et al. and by Finch[D1] are still preliminary. Some experimental details of the recent measurements are summarized in Table I.

Some of the older measurements have recently been reexamined. The very high accuracy of the resonance parameters of the 6.67-eV level reported by Jackson and Lynn[B8] has been questioned by a group of experimentalists at the "Seminar on ^{238}U Resonance Capture." In their view "this high accuracy is not supported by any details reported in the paper and is judged to be unrealistic."[A7] Liou and

Table I. Experimental Details of Recent Measurements

(For experiments prior to 1974 see Moxon's review, Ref. C5)

Author, Year, Laboratory	Ref.	Energy Range (eV)	Type of Measurements	Detectors	Samples	Type of Analysis	Comments
Corvi, Rohr, Weigmann (75) Euratom, Geel, Belgium	B25	10-1600	Capture and $\sigma(E,E_\gamma)$ Linac, 50 m	NaI(Tl)	13.9 g/cm^2 and 4.64 g/cm^2	Area	P-wave assignments
Nakajima et al. (75) JAERI, Japan	B25	20-4700	Transmission, Linac, 190 m	1.25 cm thick ^{6}Li glass	.00725, .014, .0236 atom/b N.U.	Atta Harvey Area	One sample at 77^{o}K
Liou and Chrien (76) BNL	B30	<120	Transmission, Self-indication, capture fast chopper	NaI + ^{10}B and Ge Li	from 8.6.10^{-5} to .09 atom/b	Area & multi-level shape fits	---
Olsen et al. (77) ORNL	B31	1-4000	Transmission, Linac 40 and 150 m	1 mm and 2.5 cm thick ^{6}Li glass	from 1.85.10^{-4} to 3.62 atom/b	SIOB: Multilevel shape analysis	---
Poortmans et al. (77) Euratom, Geel, Belgium	B32	1-4270	Transmission, capture, scattering, Linac 30 and 60 m	C_6F_6 liquid scint. for capture ^{3}He gas scint. for scattering and transmission	from 10^{-5} to .03 atom/b	Atta Harvey shape and area; & SIOB multilevel shape	Some samples at 77^{o}K. Data Preliminary
Block et al. (77) RPI	B34		Self-indication Linac 25 m	Large liquid scint.	.08 to 1.3 cm thick	multilevel fits	Analysis incomplete
Block et al. (73) RPI	B21	>600	Subthreshold fission Linac, 10 m	Ionization fission chambers	---	Area	---
Wartena, Weigmann, Migneco (75) Euratom, Geel, Belgium	B24	>600	Subthreshold fission Linac 30 m	Liquid-scint. (to detect prompt fission gammas)	250g ^{238}U sample	Area	
Blons, Mazur, Paya (75) Saclay, France	B28	>600	Subthreshold fission Linac 22.4 & 52 m	gas-scint.	---		---
Slovacek et al. (77) RPI	B29	>1	Subthreshold fission slowing down spect.	Ionization fission chamber	---	Area	Includes estimate of thermal fission cross sec.
Difilippo et al. (77) ORNL	B33	>1	Subthreshold fission Linac 20 & 40 m	Ionization fission chamber	4.7g ^{238}U in chamber	Area	Relatively good resolution

Chrien[B30] have carefully reviewed the work of Jackson and Lynn and have noted that these authors failed to account for the increase in resonance parameter error required by the uncertainty in the vibrational parameter. Liou and Chrien estimate that the uncertainty in the width of the 6.67-eV level from the measurement of Jackson and Lynn should be more than three times as large as that given by those authors.

Derrien[D2,D3] and Ribon[D2] have reanalyzed some of the transmission measurements of Rahn et al.[B20] and of Carraro and Kolar[B17] using least-square shape analysis. The neutron widths obtained by their shape analysis are considerably different than those obtained by area analysis. Between 1450 and 1760 eV the neutron widths obtained by Derrien and Ribon from the data of Carraro and Kolar are 16% smaller than those given by Carraro and Kolar. Between 2.5 and 2.8 keV Derrien's values of Γ_n obtained from the analysis of the transmission measurements of Rahn et al. are 14% higher than those given by Rahn et al. Derrien attributes these differences to errors in the transmission backgrounds in the measurements. The shape analysis technique can "fit" a residual transmission background and hence should be more reliable.

The comparison between shape analysis and area analysis results is illustrated in Tables II and III (taken from the paper of Derrien). It is noteworthy that some values of Γ_n obtained from the same data, by the two methods of analysis, differ by an amount larger than their quoted uncertainties.

Table II. ^{238}U Neutron Widths for Large Resonances Between 1450 eV and 1760 eV

Energy eV	Shape analysis of Geel data (2 thicknesses) Γ_n, meV	Shape analysis of Columbia data (3 thicknesses) Γ_n, meV	Geel published values B17 Γ_n, meV	Columbia published values B20 Γ_n, meV
1473.4	114 ± 2	108 ± 2	125 ± 8	125 ± 10
1522.3	215 ± 4	236 ± 3	260 ± 15	240 ± 15
1597.5	309 ± 6	352 ± 4	351 ± 40	355 ± 25
1622.3	97 ± 2	88 ± 2	116 ± 15	68 ± 14
1637.4	50 ± 1	46 ± 2	60 ± 5	50 ± 8
1662.0	201 ± 4	214 ± 4	241 ± 20	171 ± 20
1687.3	98 ± 2	97 ± 2	104 ± 9	92 ± 10
1709.0	81 ± 2	77 ± 2	94 ± 7	86 ± 8
1755.2	121 ± 3	116 ± 3	135 ± 10	105 ± 10
$\Sigma\Gamma_n$	1286	1334	1486	1292

(This Table, including the comments, is reproduced from the paper of H. Derrien, Ref. D3)

In the shape analysis of Geel data the adjusted background parameters a were negligible ($\leq 10^{-3}$).

In the shape analysis of Columbia the adjusted background parameters a were equal to:

0.0011 for 0.084 at/b sample;
-0.010 for 0.0348 at/b sample;
0.027 for 0.0084 at/b sample.

For the signification of the parameter a see comments on Table III.

Table III. Γ_n Values for Large Resonances Between 2.5 keV and 2.8 keV

Energy eV	Shape analysis on Geel transmissions	CARRARO et al. results (Helsinki)	Shape analysis on Columbia transmissions	RAHN et al. results
2547.2	716±30	706±36	675±27	550±55
2558.5	282±12	234±10	271±27	230±30
2579.9	439±22	394±20	436±27	340±39
2599.0	760±38	790±50	795±42	740±45
2671.3	281±14	280±10	265±24	270±20
2716.5	171±8	170±10	155±18	145±14
$\Sigma\,\Gamma_n$	2649	2574	2596	2275

(This Table, including the comments, is reproduced from the paper of Derrien, Ref. D3)

COMMENTS ON TABLE III

The Geel shape analysis has been done on the 0.011 at/b sample; no background correction is needed; but the normalization coefficient is equal to 0.975. The Columbia shape analysis has been done on the 0.084 at/b and 0.035 at/b samples; the background corrections are respectively equal to 0.007 and 0.013, at 2600 eV neutron energy.

The theoretical formulation of the transmission used in the shape analysis is the following:

$$T_r = a + c\left(e^{-n\sigma_\Delta}\right) * R$$

σ_Δ is the usual Breit-Wigner one level formulation of the total cross section, broadened by the Doppler effects, plus one term taking into account the level-level interference in the neutron channel; R is the resolution function, a the background parameter and c the normalization coefficient.

Recently Olsen et al.,[B31] Liou and Chrien[B30] and Finch[D1] have stressed the importance of multilevel effects in obtaining resonance parameters from transmission data and in describing neutron transmission through thick ^{238}U samples. For instance, Olsen et al. have shown that a shape analysis of their transmission data converges towards the values of $\Gamma_n = 1.39$ mV, $\Gamma_\gamma = 25.1$ mV for the level at 6.67 eV, when multilevel effects are ignored. When multilevel effects are taken into account, the analysis of the same data converges toward the values $\Gamma_n = 1.48$ mV and $\Gamma_\gamma = 23.0$ mV.

3. EVALUATION OF THE RESONANCE PARAMETERS FOR THE LEVELS WITH ENERGIES BETWEEN 1 AND 4000 eV

A. General Considerations

Since 1955, between 30 and 35 independent determinations of the ^{238}U resonance parameters have been reported.[B1-B34] Most of the earlier experiments[B1-B10] cover only the low energy resonances, up to 1 keV. Among the more recent experiments six sets of measurements extend to 4 keV and above.[B11,B17,B20,B26,B31,B32] The comparison of the resonance parameters from the different experiments often shows discrepancies considerably larger than the estimated uncertainties and sometimes systematic. The reasons for these discrepancies are often not understood.

The evaluation of resonance parameters can be done in several ways, including the selection of the values from one single measurement estimated to be the most accurate, or, at the other extreme, averaging the results of all available measurements, weighting each by the inverse square of the reported error. The latter approach was followed by Moxon in his 1974 evaluation[C5] and the former approach was used by McCrosson[C1] for evaluating neutron widths. We believe that the best estimate of the value of the resonance parameters can be obtained by averaging results from a number of independent measurements. Before averaging we have attempted to correct individual measurements for suspected systematic errors and have tried to weight the measurements in a consistent way.

Pitterle et al.[C1] have observed the existence of systematic differences among resonance parameters reported by different measurers and have tried to "correct" the experimental data for the systematic effects by a regression analysis technique. We have used a very smiliar approach here.

Unfortunately there is no uniform method of estimating and reporting the uncertainty in a resonance parameter derived from a set of measurements. In the most recent experiments statistical uncertainties have become relatively unimportant due to the high intensity of presently available neutron sources. Hence the uncertainties are mostly systematic and often due to poorly known causes: undetected backgrounds, method of analysis, and so on. Some authors report only statistical errors, others combine them with estimated systematic errors; many authors report errors as generated by a resonance analysis computer code, on the basis of some goodness of fit criterion that has more to do with the model used to analyze the data than with the systematic errors in the measurements.

Since there are inconsistencies in the methods used by different authors to estimate and report their errors, it does not seem justified to weight each determination of a parameter by the inverse square of the reported error. We have attempted to weight the different experiments consistently by giving more weight to those experiments for which the parameters, corrected for systematic effects, agree well with the average of the other experiments.

Above 200 eV we have considered only data reported since 1967,[B14-B34] except for the data reported in 1964 by Garg et al.[B11] which cover an extensive energy range (6 to 3900 eV). We think that the inclusion of older data in our evaluation would not have improved the precision because these earlier results are likely to have large systematic errors which are difficult to assess because statistical errors are also large and because many of the measurements cover only a resitricted energy range.

Most transmission, self-indication, capture or scattering measurements yield strongly correlated values of Γ_γ and Γ_n for a given resonance; in fact, many measurements yield only a relation between those two widths.[D4] Nevertheless we observed no significant external correlation between the values of Γ_γ and Γ_n reported by different authors. The absence of such external correlations is partly due to the fact that each value is based on a number of experiments that have different internal correlations between the widths, and partly due to the fact that the capture widths have relatively large uncertainties obscuring any possible correlation. Since no important external correlations were observed between the capture and neutron widths, these two widths were evaluated independently.

B. Determination of the Level Energies

The energy scales of the various measurements were aligned on the energy scale of the 150-m time-of-flight measurement of

Olsen et al.[B31] This energy scale was selected as a standard because it is well documented and has been extensively compared with other energy scales.[D5] In Table IV a comparison is shown of the energies of some typical resonances as obtained by Olsen et al. and by other laboratories. The position of most levels, as given by Olsen et al. is intermediate between those given by Rahn et al.[B20] and by Poortmans et al.[B23]

The following procedure is used to align the energy scale of the $k^{\underline{th}}$ experiment to that of Olsen et al. The energy of of $j^{\underline{th}}$ level reported by the $k^{\underline{th}}$ experimenter, E'_{kj}, is assumed to be related to the energy reported by Olsen et al. for that level, E^*_j by the relation:

$$E^*_j = E'_{kj}\,(\alpha_k + \beta_k\, E'^{\frac{1}{2}}_{kj}) \text{ where } j = 1,\ldots,N_k \qquad (1)$$

N_k is the number of level energies reported by the $k^{\underline{th}}$ experimenter. The structure of equation (1) is justified by analysis of the sources of uncertainties in the time-of-flight technique.[D6] The values of α_k and β_k were obtained by minimizing

$$\sum_{j=1}^{N_k} W_j \left[E^*_j - E'_{kj}\,(\alpha_k + \beta_k\, E'^{\frac{1}{2}}_{kj})\right]^2 \qquad (2)$$

where the sum is carried over a number of large levels which are easily identified. The weights w_j were taken inversely proportional to the square of the uncertainties reported by the $k^{\underline{th}}$ experimenter. Rohr et al.[B16] and Poortmans et al.[B32] do not report uncertainties associated with the resonance

Table IV. Comparison of the Energies of Selected Resonances

(All energies in eV)

Olsen et al.	Corvi et al.[a,b]	Rahn et al.	James et al.[b]
145.63 ± .03	145.68 ± .10	145.57 ± .15	145.603 ± .021
463.14 ± .14	463.62 ± .4	462.8 ± .4	463.12 ± .14
619.95 ± .19	620.18 ± .2	619.75 ± .35	
708.27 ± .22	708.59 ± .25	707.9 ± .4	708.18 ± .45
905.03 ± .19	905.47 ± .30	904.5 ± .3	
1419.76 ± .29	1420.7 ± .3	1419.2 ± .3	1419.88 ± .46
1473.82 ± .31	1474.6 ± .3	1473.4 ± .4	
1638.07 ± .34	1639.1 ± .3	1637.4 ± .5	
2030.49 ± .43	2031.9 ± .3	2029.8 ± .6	
2145.56 ± .45	2146.7 ± .3	2144.6 ± .6	
2489.18 ± .43	2490.8 ± .4	2488.4 ± .7	2489.50 ± .71
2672.22 ± .56	2674.0 ± .8	2671.3 ± .9	
2865.39 ± .60	2867.5 ± .8	2864.1 ± .9	
3205.81 ± .67	3208.1 ±1.0	3204.9 ±1.1	
3458.14 ± .73	3461.0 ±1.2	3456.3 ±1.3	
3574.04 ± .75	3576.6 ±1.2	3572.3 ±1.3	

a) Private communication from F. Corvi to G. D. James (1977).
b) Private communication from G. D. James (1977).

Table V. Parameters for Energy Scales Alignment

All energy scales are aligned on the scale of Olsen et al.[B31] by the relation:

$$E^* = E_k \left(\alpha_k + \beta_k E_k^{1/2}\right)$$

the values of α_k and β_k are tabulated below:

Experiment and Year	Ref.	α_k	$10^4 \times \beta_k$ ($eV^{-1/2}$)	$\alpha_k + \beta_k (4000)^{1/2}$
Garg et al. (64)	B11	.999658	.08653	1.000205
Glass et al. (68)	B14	.999658	.08653	1.000205
Rohr et al. (70)	B16	.998714	.18726	.999898
Carraro & Kolar (70)	B17	1.000312	-.20615	.999008
Maletski et al. (72)	B19	1.000625	-.83687	.995332
Rahn et al. (72)	B20	1.000340	.00290	1.000358
Corvi et al. (75)	B25	.999428	.07633	.999911
Nakajima et al. (75)	B26	1.000340	.00290	1.000358
Liou and Chrien (77)	B30	1.	0.	1.
Olsen et al. (77)	B31	1.	0.	1. (standard)
Poortmans et al. (77)	B32	.999428	.07633	.999911

(The number of levels given in Ref. B30 is not sufficient for determining α_k and β_k.)

energies. For these two measurements the energy uncertainties were assumed to be the same as those given by Carraro and Kolar.[B17] In Table V the values of α_k and β_k for a number of measurements are listed. Note that all corrections are much smaller than 1%. The values of the level energies were obtained by averaging the various independent determinations after realignment of the energy scales.

C. Neutron Widths

We have obtained $\langle \Gamma_{nj} \rangle$, the average value of the neutron width of the $j^{\underline{th}}$ level, as:

$$\langle \Gamma_{nj} \rangle = \frac{\sum\limits_k \frac{\Gamma^*_{njk}}{\delta^{*2}_{jk}}}{\sum\limits_k \frac{1}{\delta^{*2}_{jk}}} \tag{3}$$

where:

$$\Gamma^*_{njk} = \Gamma_{njk} (a_k + b_k E_{jk}) \tag{4}$$

$$\delta^*_{jk} = C_k \delta_{jk} \tag{5}$$

and where $\Gamma_{njk} \pm \delta_{jk}$ is the $k^{\underline{th}}$ experimenter's determination of the neutron width of the $j^{\underline{th}}$ level, with its reported standard deviation, and E_{jk} is the energy of the level, after alignment of the energy scale.

The parameters a_k and b_k are intended to correct the results of the $k^{\underline{th}}$ experiment for possible systematic effects and were obtained by minimizing with respect to a_k and b_k the quantity

$$S_k = \sum_{j=1}^{N_k} \frac{[\langle\Gamma_{nj}\rangle - \Gamma_{njk}(a_k + b_k E_{jk})]^2}{C_k^2 \quad \delta_{jk}^2} \qquad (6)$$

The parameters C_k are intended to give consistent weights to the various experiments and were obtained from the relation:

$$\frac{1}{N_k - 1} \sum_{j=1}^{N_k} \frac{[\langle\Gamma_{nj}\rangle - \Gamma_{njk}(a_k + b_k E_{jk})]^2}{C_k^2 \quad \delta_{jk}^2} = 1 \qquad (7)$$

The sums in (6) and (7) were carried over the s-wave levels. The equations (3) to (7) are coupled and were solved by successive iterations. The values of N_k, a_k, b_k, and C_k for the eleven measurements considered are listed in Table VI. For the experiments of Glass et al.[B14], Corvi et al.[B25], and Liou and Chrien[B30] the values of a_k, b_k, and C_k could not be determined by the method just discussed, because these experiments did not report values of Γ_n for a sufficient number of large levels. The values of a_k, b_k, and C_k for these measurements were assigned somewhat arbitrarily and are shown in Table VI.

The systematic trends in the values of Γ_n reported by different experimenters are illustrated in Fig. 1. The left

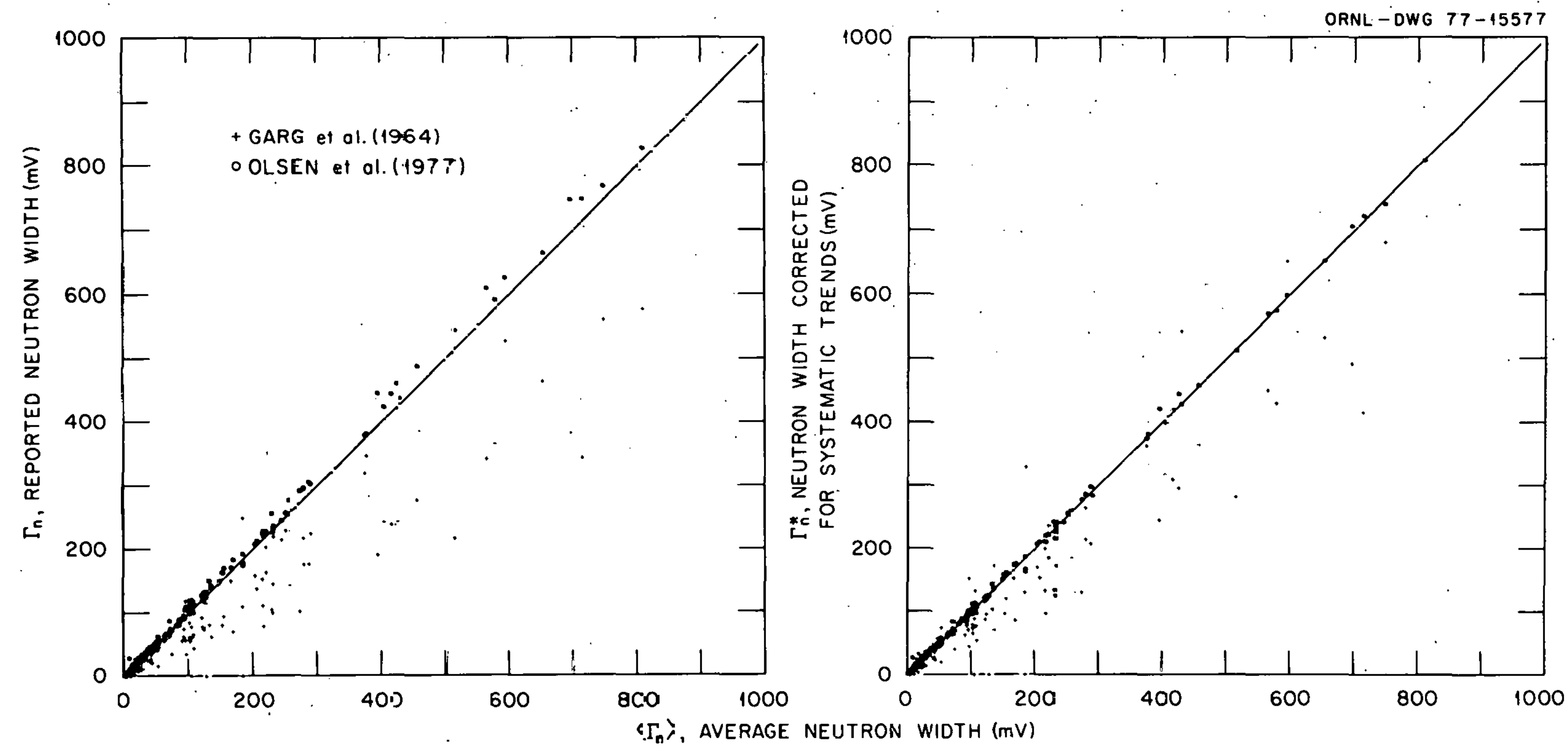

Fig. 1. Systematic trends in the measured values of Γ_n. The left part of the figure shows the values of Γ_n reported by Garg et al.[B11] and by Olsen et al.[B31] against corresponding values obtained by averaging eleven measurements. The values of Garg et al. tend to be lower than average whereas those of Olsen et al. tend to be higher than average, with the difference increasing with increasing Γ_n. In the right part of the figure, the corresponding values of Γ_n^*, i.e., Γ_n corrected for systematic trends are plotted against the average value of Γ_n.

part of the figure shows the values of Γ_n reported by Garg et al.[B11] and by Olsen et al.[B31] against corresponding values obtained by averaging eleven measurements as just discussed. The values of Garg et al. tend to be lower than average whereas those of Olsen et al. tend to be higher than average, with the difference increasing with increasing Γ_n. In the right part of the figure, the corresponding values of Γ_n^*, i.e., Γ_n corrected for systematic trends, are plotted against the average values of Γ_n.

In the averages defined by equation (3) each experiment is given a weight inversely proportional to C_k^2. The method used to determine C_k, equation (7) corresponds to a requirement that χ^2 per degree of freedom be approximately equal to unity for the levels selected for the adjustment, after correction for systematic trends. As may be seen in Table VI the older experiment of Garg et al.[B11] is downweighted by a factor of 21, the experiment of Nakajima et al.[B26] is upweighted by a factor of 1.34, presumably because those authors overestimated their errors.

D. Capture Widths

In most experiments the capture widths have been determined only for selected levels at low energies. Above 1 keV, resolution and Doppler broadening prevent the reliable determination of resonance widths by shape analysis, and capture widths have been obtained only for a few levels with relatively large neutron

Table VI. Parameters for Correction of Systematic Trends in Γ_n

Corrected values $\Gamma^*_{njk} = \Gamma_{njk} \ (a_k + b_k E_{jk})$ (see equation 4)

$\delta^*_{jk} = C_k \delta_{jk}$ (see equation 5)

Experiment	Ref.	a_k	$10^3 b_k$ ($eV^{-1/2}$)	C_k	a_k+b_k *4000 (1)
Garg et al. (64)	B11	.99755	.08252	4.64	1.3276
Glass et al. (68)	B14	1.	0.	2.	
Rohr et al. (70)	B16	.98039	.08432	.87	
Carraro & Kolar (70)	B17	.97853	.00255	.75	.98873
Maletski et al. (72)	B19	1.0074	.17217	1.31	
Rahn et al. (72)	B20	1.0085	.05600	1.26	1.2325
Corvi et al. (75)	B25	1.	0.	2.	
Nakajima et al. (75)	B26	.97176	.03171	.86	1.0986
Liou & Chrien (77)	B30	1.	0.	1.	
Olsen et al. (77)	B31	1.0195	-.02192	1.47	.9318
Poortmans et al. (77)	B32	.99313	-.00689	1.06	.9656

(The coefficients for Ref. B14, B25, and B30 could not be obtained from the reduced number of parameters given and were assigned arbitrarily, see text.)

(1) Given only for the experiments reporting data up to 4 keV.

widths; and for these, the uncertainties are large (10% or more). For this reason the statistical tests which were performed on the neutron widths could not be applied to the capture widths.

The capture widths were obtained from the values reported by Rohr, Weigmann, and Winter,[B16] Maletski et al.,[B19] Rahn et al.,[B20] Liou and Chrien,[B30] Poortmans et al.,[B32] and Olsen et al.[B31] For those levels for which more than one determination of the width existed, the evaluated value was obtained by averaging, weighting by the inverse square of the reported error. For the many levels for which no value was reported, a value of 23.5 mV was assumed. This is the value that had been assumed by the ENDF/B-III and ENDF/B-IV evaluators;[C1] it is consistent with the average value 23.55 mV recently evaluated by Rahn and Havens[D7] and with the value 23.43 mV $\pm$ .11 mV (stat) $\pm$ .70 mV (syst) obtained by Poortmans et al.[B32]

E. Fission Widths

For the levels at 6.67 eV, 20.9 eV and 36.7 eV, the consistent subthreshold widths obtained by Slovacek et al.[B29] and by Difilippo et al.[B33] were averaged. For the other levels the widths obtained by Difilippo et al.[B33] were used. The measurements of Difilippo et al. have appreciably better energy resolution than previous experiments, which permits a resolution of all the "clusters" below 4 keV into their Class 1 level components. The two main subthreshold clusters below 4 keV are illustrated in Figs. 2, 3, and 4.

ORNL-DWG 76-7649R2

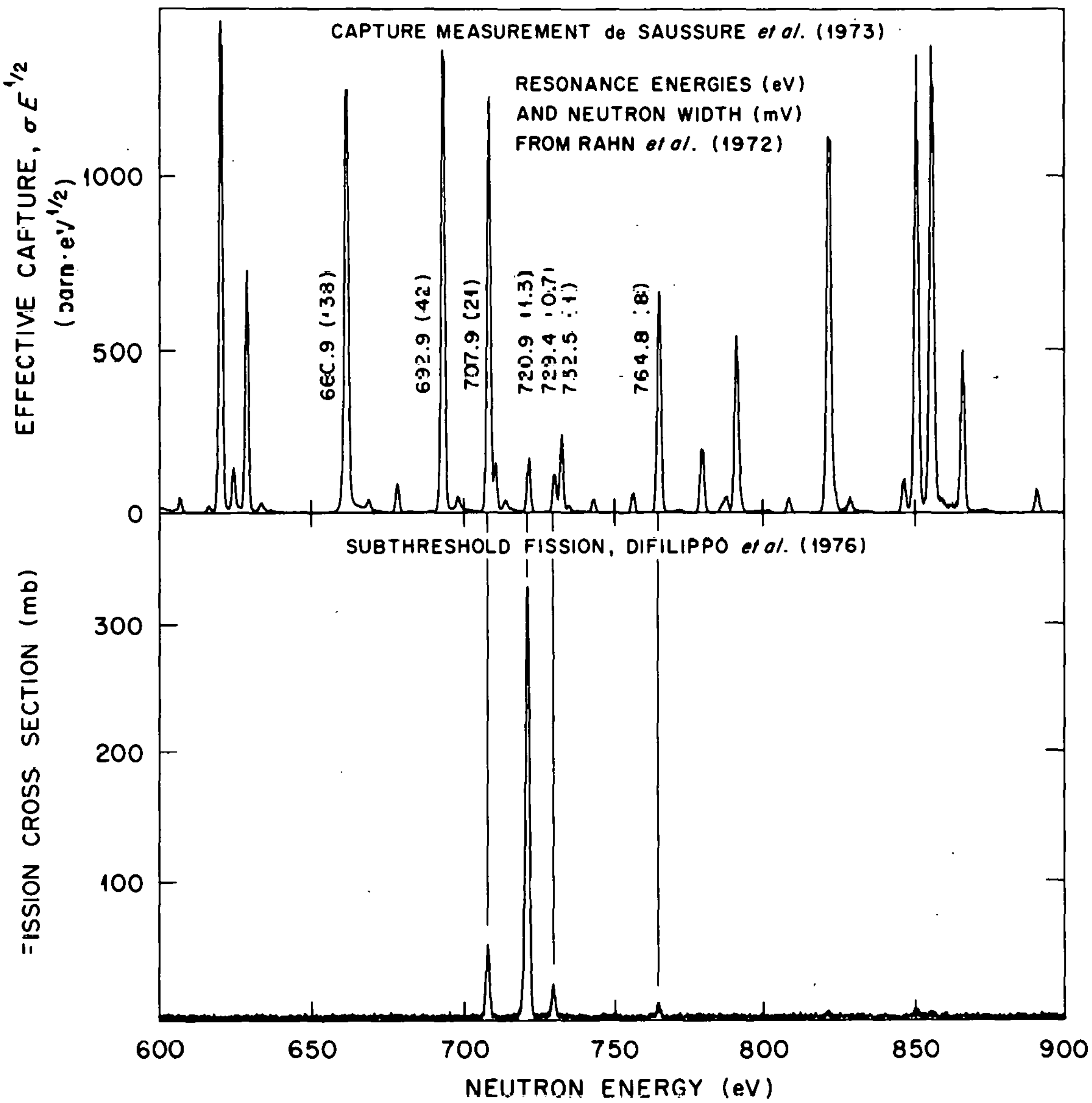

Fig. 2. High resolution ^{238}U capture and fission cross sections in the neighborhood of the subthreshold fission cluster near 720 eV. The lower part of the figure shows the fission cross section, the upper part, the effective capture cross section (multiplied by $E^{\frac{1}{2}}$) on the same energy scale. The levels at 720.9 eV, 729.4 eV, and 764.8 eV are taken to be s-wave levels because they are part of the same subthreshold fission cluster as the known s-wave level at 707.9 eV.

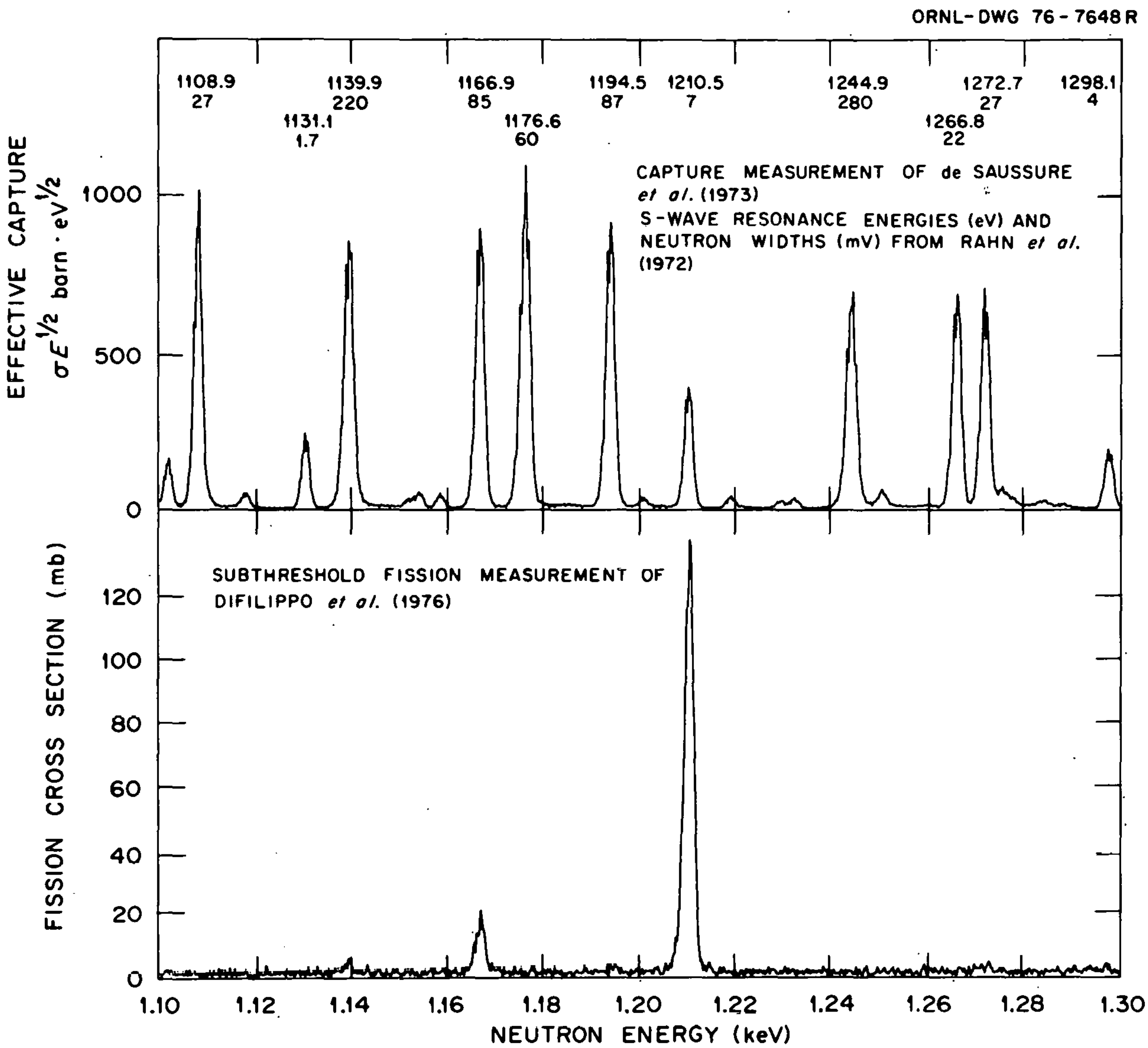

Fig. 3. High resolution ^{238}U capture and fission cross sections in the neighborhood of the subthreshold fission cluster near 1200 eV. The lower part of the figure shows the fission cross sections, the upper part the effective capture cross section (multiplied by $E^{\frac{1}{2}}$) on the same energy scale.

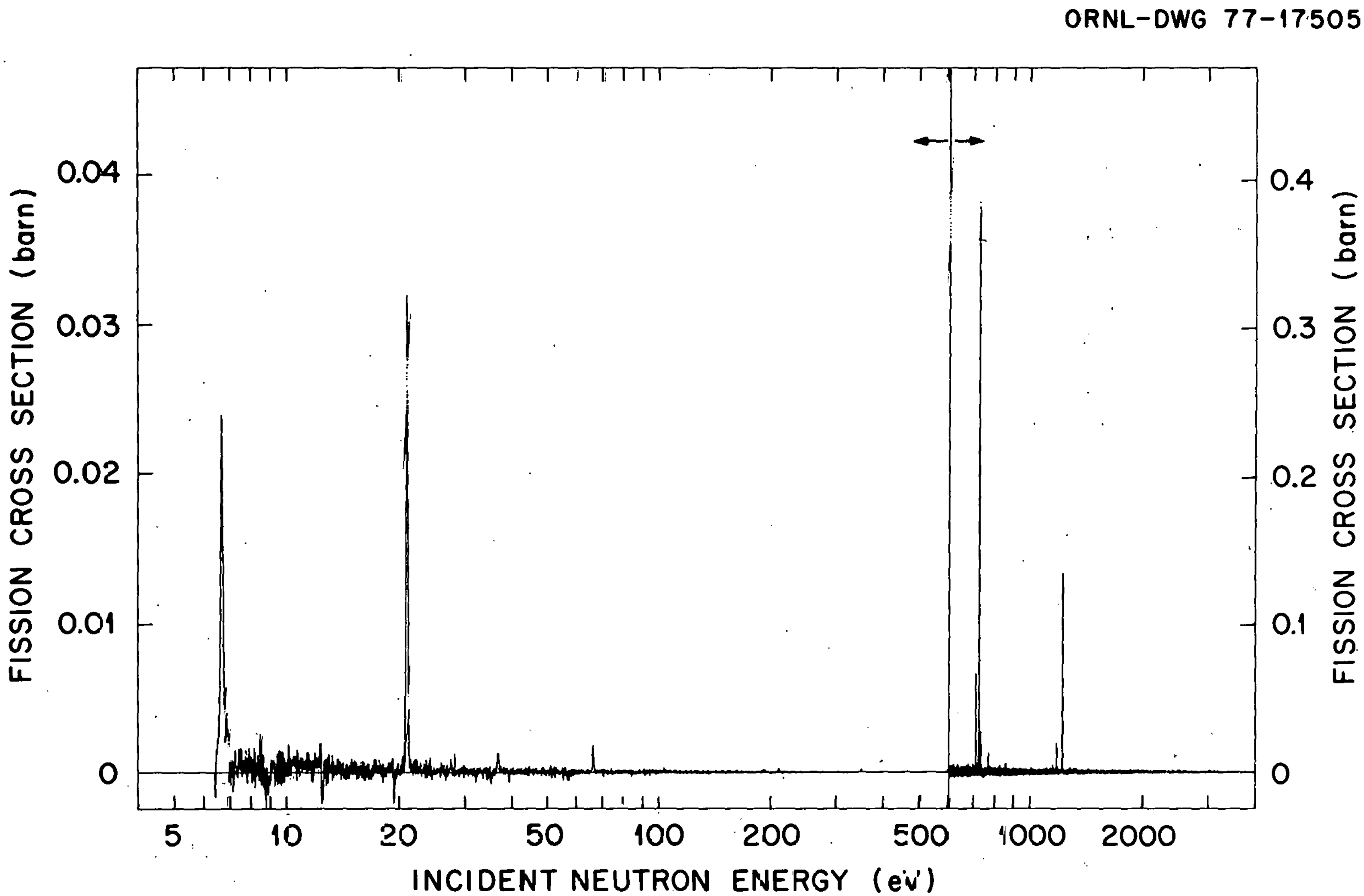

Fig. 4. Fission cross section below 4 keV. Note that there is a factor 10 change in the ordinate scale at 600 eV. A small background due to ^{235}U contaminant was substracted from the data, hence there are large statistical fluctuations near 8.8, 12.4 and 19.3 eV where ^{235}U has large fission resonances.

F. Angular Momentum Assignment

Those levels which have large neutron widths (a few mV) can be identified as s- or p-wave levels from the depth of the interference minimum between the resonance and potential scattering. For many levels with smaller neutron width such an identification is not possible. Corvi, Rohr, and Weigmann[B25] were able to identify 57 levels below 1600 eV as p-waves by measuring the fraction of capture gamma rays above 4.3 MeV. It is reasonable to assume that all levels which belong to a subthreshold fission cluster have the same parity and angular momentum; since in the two clusters below 4 keV at least one level can be identified as an s-wave, all the levels with an observable subthreshold fission component were taken to be s-waves.

For many small levels no unambiguous angular momentum assignment could be given. The angular momentum of those levels was then evaluated according to the following criteria: (1) All observed levels below 4 keV were assumed to be either s-wave or p-wave levels. This is reasonable, since the height of the penetration barriers below 4 keV make the neutron widths excited by neutrons of higher angular momenta exceedingly small. (2) The Bayes's conditional probability that a resonance be excited by p-wave neutrons, $P(p, g\Gamma_n)$, was computed for all the levels, following the method described by Bollinger and Thomas.[B15] All the levels with $P(p, g\Gamma_n) < .5$ were assumed to be excited by s-wave neutrons. (3) In order to satisfy the Δ_3 statistic[D8] for the s-wave levels in the interval 0-4 keV, a few levels with $P(p,g\Gamma_n) > .5$ had to be taken as s-wave levels. Those levels were chosen to minimize the product of their probabilities to be excited by p-wave neutrons. The energy, neutron width and value of $P(p,g\Gamma_n)$ of the s-wave levels with $P(p,g\Gamma_n) > .5$ are given in Table VII. It should be clear that the division of levels with small neutron widths into s- and p-wave levels is not unique and is based on rather weak probability criteria.

G. Parameters of the Low Energy Resonances

The neutron and capture widths of the first six large s-wave levels and of the p-wave level at 10.24 eV have been evaluated in more detail. These parameters are particularly important for the calculation of thermal reactor performance.[A7,D9] A comparison of the reported parameters of these seven levels illustrates the difficulties in evaluating best values. Measurements of these parameters have been reported for more than 20 years. Most of the experimental values as well as a few evaluations are given in Tables VIII and IX.

There are very large discrepancies between some of the values reported for the capture widths. For the important level at 6.67 eV there are at least five standard deviations between the value of Jackson and Lynn,[B8] 27.2 $\pm$ 0.4 mV, and that of Liou and Chrien,[B30] 21.8 $\pm$ 1.0 mV. Similar discrepancies exist for the other levels.

Table VII. s-Wave Levels with Small Neutron Widths

Energy (eV)	Neutron Width (mV)	$P(p,g\Gamma_n)$	Comment
2787.4	13.29	.62	
1565.4	5.50	.69	
3492.6	14.34	.72	
1298.6	3.59	.77	
3169.8	10.89	.78	
2806.4	9.28	.78	
721.59	1.64	.78	Subthreshold Fission
3831.6	11.66	.82	
3219.7	9.19	.82	
1550.6	3.40	.85	
1953.8	3.94	.87	
730.15	1.13	.89	Subthreshold Fission
1913.3	1.71	.93	
1867.6	.88	.95	

$P(p,g\Gamma_n)$ is the Bayes's conditional probability that the resonance is excited by p-wave neutrons (see text and reference B15). The levels listed above have all $P(p,g\Gamma_n)>.5$; they were nevertheless taken as s-wave levels either because they were observed in subthreshold fission groups, or to satisfy the Δ_3 statistics for level spacings.

Table VIII. Comparison of Measured and Evaluated Neutron Widths
(Widths are given in mV)

	Year	Ref.	E_0 (eV) 6.67	20.9	36.7	66.0	80.7	102.5	10.2
Harvey et al.	55	B1		8.5±.4	32.5±1.9	25±2			
Levin	56	B2	1.54±.10	8.3±.7	30±4				
Lynn	56	B3	1.4±.1	8.7±.3	28.6±1.5	22.6±1.5	1.8±.6	57.5±3	
Fluharty	56	B4		10.3±.2	32.6±9	25.4±7	2.34±.80	69±20	
Bollinger	57	B5	1.45±.12	9.9±.4	34±2.3	23.5±1.5	2.1±.2	74±5	.0014
Radkevich	57	B6	1.15±.04	6.35±.59	22±3.5	19.1±4.5	2.7±1.1		
Jackson	62	B8	1.52±.01						
Moxon	62	B9			34.5±3	23.5±1.5	1.8±.3	69±3	
Firk	63	B10			31±.9	25.1±1.2		65.9±2	
Garg	64	B11	1.52±.01	8.7±.3	31±.9	25±1	2.06±.17	65.9±2	
Ashgar	66	B13	1.578±.1	9.34±.5	30.95±1.17	22.74±.77	1.85±.15	58.64±2	.0014
Rohr	68	B16				24.8±1.5		72.6±.5	
Carraro	71	B17				25.3±1	2±1.5	69.5±7	
Maletski	72	B19				24.0±1.5	2.2±.2	70±3	
Rahn	72	B20	1.52±.05	8.5±.78	38±2	26±2	1.71±.18	70±4	.00177±.0004
Nakajima	75	B26		10.1±1.0	33.4±1.7	25.5±1.3	2.25±.18	71.3±4.3	
Liou	77	B30	1.50±.03	9.86±.50	33.3±1.2	25.6±1.8	2.16±.16	68±5	.00165±.00015
Olsen	77	B31	1.480±.032	10.16±.21	33.76±.70	24.37±.53	1.823±.046	70.9±1.6	.00169±.00005
Poortmans	77	B32		10.2±.1	34.1±.5	23.9±.8	1.81±.08	70±2	.00167±.00004
BNL-325	65	C2	1.52±.02	8.5±.5	31±.9	25±1.2	2±.2	68±3	.0014
	73	C2	1.52±.02	8.7±.5	32±1	26±1.5	2±.2	70±3	.00156±.00001
Moxon	74	C5	1.51±.009	8.97±.175	31.6±.5	24±.4	1.96±.07	70.8±.4	.00156±.00001
ENDF/B-IV	75	C1	1.50	8.8	31.1	25.3	2	71	.00156
This Evaluation*	77		1.510±.015	10.12±.10	33.9±.4	24.6±.4	1.91±.04	71.6±.4	.00167±.00004

*Error given here is statistical (uncorrelated) standard deviation also given in Table XXII and XXIII.

Table IX. Comparison of Measured and Evaluated Capture Widths
(Widths are given in mV)

	Year	Ref. E_0(eV)	6.67	20.9	36.7	66.0	80.7	102.5	10.2
Harvey et al.	55	B1		25±5	29±9	17±10			
Levin	56	B2	24±2	30±6	40±20				
Lynn	56	B3	26.1±1.5	28.8±2.3	24.9±4.2	18.6±2.7		15.5±5.4	
Fluharty	56	B4		25.9±12	27.7±24	39.1±26		24±26	
Bollinger	57	B5	26±3	21.9±2.3	29±10	25.6±9			
Radkevich	57	B6	21.15±1.30	36±3.5	34±10	25.5±12	21±15		
Rosen	60	B7						21±6	
Jackson	62	B8	27.2±.4						
Moxon	62	B9			21.2±3.5	24.1±2		24.1±2	
Firk	63	B10			31.3±2.2	25.1±1.6		30.6±3.3	
Michaudon	65	B12	23±1	23±1	23±1				
Ashgar	66	B13	23.43±10.12	33.83±4	26.33±3	26.07±2	21.17±10	25.95±2	
Glass	68	B14			20.9±6	17.35±4		24.9±5	
Rohr	68	B16				19.6±3		26.1±2.3	
Maletski	72	B19				25±2		26±2	
Rahn	72	B20		22±3	23±2	21±2		28±3	
Liou	77	B30	21.8±1	23.5±1.5	23.6±2	22.2±2	23.7±2.5	24.3±2.5	
Olsen	77	B31	23±.8	22.8±.8	22.9±.8	23.2±.8	24.3±1.3	24.1±.9	22.2±2
Poortmans	77	B32		23.2±.6	22.9±.3	24.0±.4		24.3±.4	
BNL-325	65	C2	26±2	26±4	26±4	24±2	21±15	24±3	
	73	C2	26±2	25±3	25±2	22±2		26±2	
Moxon	74	C5	26.9±.37	25.7±1	26.55±1.2	23.56±.76	21.17±8.9	25.78±.94	
ENDF/B-IV	75	C1	25.6	26.8	26.0	23.5	23.5	26.0	23.5
This Evaluation*	77		22.5±.6	23.1±.5	22.9±.3	23.7±.3	24.2±1.2	24.4±.3	23.5

*Error given here is statistical (uncorrelated) standard deviation also given in Table XXII.

For these seven levels, there is no significant systematic trend associated with a particular experiment. The radiation widths of Lynn and Pattenden[B3] are higher than average for the levels at 6.67 eV and 20.9 eV but the reverse is true for the levels at 66.0 and 102.5 eV. Inversely, the radiation widths of Rahn et al.[B20] are lower than average at 66.0 eV but higher at 102.5 eV.

The measurements reported since 1970 give consistent results but, for the first three s-wave levels, the values from these recent measurements are significantly different from the averages of the earlier measurements. The capture widths obtained in all of the recent measurements are at least 10% lower than that of all the older evaluations. For the levels at 20.9 eV and 36.7 eV the neutron widths obtained in the four most recent measurements [B20, B30-32] are very consistent but are approximately 10% higher than the corresponding widths reported in earlier experiments.[C2]

There are valid reasons to ignore, or at least down weight, the older measurements. Modern time-of-flight techniques provide much better energy resolutions and higher neutron intensities than were available a decade ago. Recent measurements were also done with a wide range of thicknesses and often with highly depleted uranium thus reducing corrections for ^{235}U contaminant. In Figs. 5 and 6 we compare the transmission data of Firk, Lynn, and Moxon[B10] with those of Olsen et al.[B31] in the vicinity of

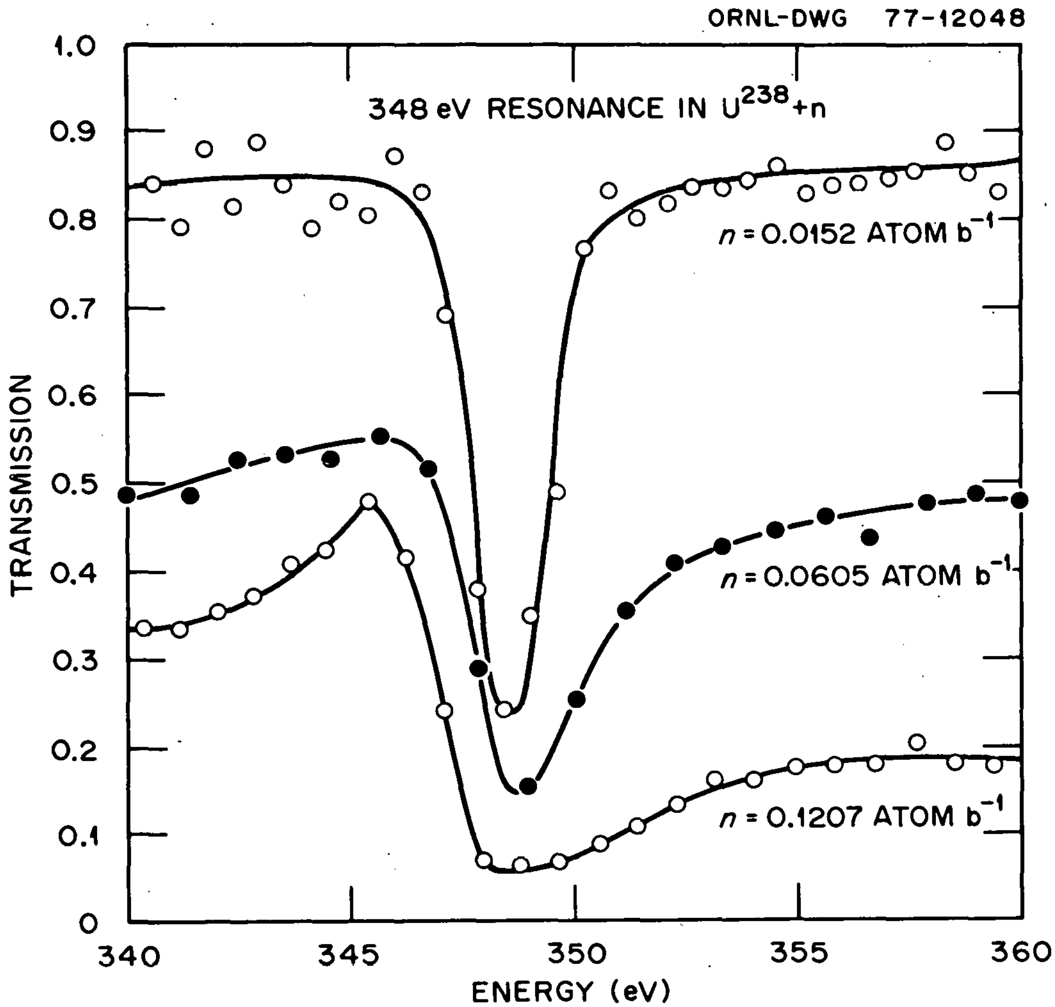

Fig. 5. Typical resonance transmission curves in the region of neutron energy 340 eV to 360 eV. This figure was published by Firk, Lynn, and Moxon in 1962. A comparison with Fig. 6 illustrates the improvement in statistical accuracy and in energy resolution obtained in the past 15 years.

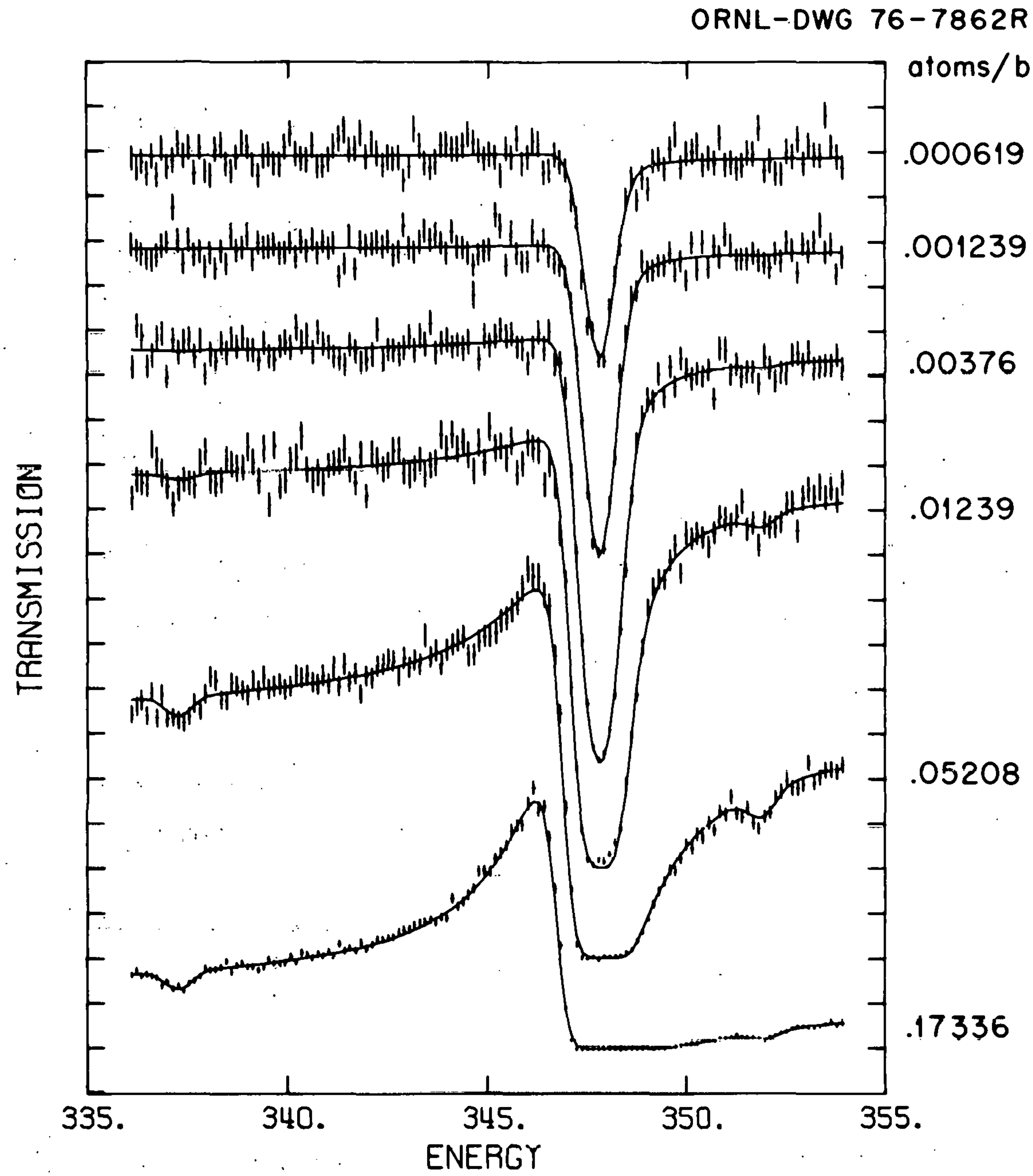

Fig. 6. Resonance transmission curves in the region of neutron energy 335 eV to 355 eV. This figure was recently published by Olsen et al. The solid lines represent a simultaneous least-square fit to the transmissions through seven sample thicknesses.

350 eV. The improvements in resolution, statistical accuracy and number of samples used are evident.

Many of the early values of the resonance parameters were obtained using scattering and capture measurements where multiple scattering corrections were ignored or roughly approximated, whereas the most recent values were derived primarily from precise transmission measurements which do not require multiple scattering corrections.

In Section 2 we have referred to the recent reexamination of the work of Lynn and Jackson.

H. Resonance Formalism and Scattering Radius

We have followed the structure[D10] of the ENDF/B-IV evaluation of ^{238}U:[C1] below 1 eV the cross sections are defined entirely by their File 3 contribution; above 1 eV the smooth cross section contributions of File 3 are added to a resonance contribution from File 2. The evaluation of the File 3 smooth cross sections will be discussed in the next section.

The resonance contributions should be computed by the Breit-Wigner multilevel formula. Olsen et al.,[B31] Liou and Chrien,[B30] and Finch[D1] have recently stressed the importance of using a multilevel formula to obtain an accurate representation of the transmission through thick samples of ^{238}U. DeSaussure et al.[D11] have shown that for ^{238}U the Breit-Wigner multilevel formula approximates very accurately the more exact multilevel formulae.

In order to improve the representation of the cross sections just above 1 eV and just below 4000 eV, two "outside" s-wave levels are included in File 2, in addition to the levels with energies between 1 and 4000 eV. The parameters for the level at 4040 eV were evaluated by the same methods as used for the levels between 1 and 4000 eV. The parameters of the bound level were adjusted to yield the measured cross sections at thermal energies, as will be discussed in the next section.

The value of the effective scattering radius was evaluated as $.944 \times 10^{-12}$ cm. This value is somewhat higher than the value $.9184 \times 10^{-12}$ cm evaluated by T. A. Pitterle for ENDF/B-II,[C1] but it is more consistent with the recent measurements of Rahn et al.[B20] and Olsen et al.[B31] In Table X are listed a few values reported for the effective scattering radius of ^{238}U.[B5,B20,B31,D12-15]

Table X. Measured and Evaluated Values of the ^{238}U Effective Scattering Radius $\hat{a}$

Author*	Year	$\hat{a}$ in 10^{-12} cm
Hughes and Pilcher	1956	.93
Bollinger et al.	1957	.91
Hughes and Zimmerman	1959	$.922 \pm .020$
Lynn	1963	$.918 \pm .013$
Utley	1964	.9184
Divadeenam	1968	.911
Rahn et al.	1972	$.96 \pm .03$
Olsen et al.	1976	$.944 \pm .005$
ENDF/B II, III, IV	1970	.9184
BNL-325	1973	$.94 \pm .03$
This Evaluation	1977	$.944 \pm .025$

*References are given in the text.

4. EVALUATION OF THE SMOOTH BACKGROUNDS (File 3)

As previously stated, we have followed the structure [D10] of the ENDF/B-IV evaluation of ^{238}U.[C1] Below 1 eV the cross sections are defined entirely by their File 3 contribution. Above 1 eV the smooth cross section contributions of File 3 are added to a resonance contribution from File 2.

In addition to the contribution of the levels of File 2 below 1 eV, File 3 represents the contribution of those levels which are not included in File 2, either because their resonance energy is outside the range 1 to 4000 eV (only two "outside levels" were included in File 2), or because those levels were not detected experimentally because they are very small or "overlapped" by large levels.

The contributions of the levels in the range from 4000 to 4500 eV were obtained by evaluating the resonance parameters of the main levels in this range, using the same methods that were used for the evaluation of the parameters in the range 1 to 4000 eV. The parameters of the main levels with energies in the range 4 to 4.5 keV are given in Table XI. The first of these levels was included in File 2. The contributions of the other levels given in Table XI to the cross sections below 4 keV were computed with the single level Breit-Wigner formula and included in File 3.

The contributions of the bound levels and of the levels above 4.5 keV were computed by assuming a bound level at -20 eV and a "picket fence" of uniform equidistant levels extending from $-\infty$ to -20 eV and from 4.5 keV to $+\infty$. The cross sections due to such a

Table XI. Principal s-Wave Levels with Energies between 4 and 4.5 keV

E_0 (keV)	Γ_n (mV)
4.041	64.1
4.064	19.6
4.090	95.3
4.125	41.5
4.132	16.8
4.169	192.3
4.179	32.2
4.210	40.4
4.258	32.7
4.300	143.9
4.307	115.8
4.325	87.4
4.371	158.3
4.376	139.6
4.398	176.4
4.436	103.0
4.512	608.1

All of the above levels are assumed to have a capture width of 23.5 mV.

picket fence of levels can be approximated analytically, as shown by deSaussure et al.[D11] The parameters of the assumed level at -20 eV and the "strengths" of the uniform picket fence were adjusted to yield the measured total and capture cross sections at .0253 eV.

The resonance parameters of the level assumed at -20 eV and the parameters used in computing the contribution of the picket fence of uniform levels are given in Table XII. The reduced neutron width of the level at -20 eV was chosen ten times smaller than the average s-wave reduced neutron width in the resolved region. Even so the contribution of the picket fence to the capture and scattering cross sections had to be reduced by the factors FGC and FGN defined in Table XII, to yield the measured values of the cross sections at .0253 eV. Leonard[D16-17] and Olsen et al.[B31] have already noted that the local strength-function of the bound levels near the binding energy is appreciably lower than the average s-wave strength function over the resonance region.

The various contributions to the computed capture and total cross sections at .0253 eV are listed in Tables XIII and XIV, where these computed cross sections are also compred to "measured" values obtained from the 1973 edition of BNL-325.[C2] These "measured" values were really evaluated from the existing direct measurements. The measurements of the thermal capture cross section are summarized in Table XV, taken from the article of Hunt, Robertson, and Ryves.[D18] The total cross section in the thermal group corresponds to a coherent scattering amplitude of $(0.84 \pm 0.01)\ 10^{-12}$ cm, a value in agreement with

Table XII. Contributions to the Smooth Scattering and Capture Cross Sections

---

1. Picket fences of uniform levels extending from $-\infty$ to $E^- = -20$ eV and from $E^+ = 4512$ eV to $+\infty$, with level spacing D = 24.8 eV, reduced neutron width $\Gamma_n^o = 2.88$ mV and capture width $\Gamma_\gamma = 23.5$ mV. The contributions to the scattering and capture cross sections are approximated as (see Ref. D11):

$$\sigma_n^\infty = \text{FGN} \cdot \text{cs} \cdot \left[\Gamma_n^o f_1 - 4\, k_o \hat{a}\, f_2\right] \qquad \sigma_\gamma^\infty = \text{FGC} \cdot \frac{\text{cs}}{E^{1/2}}\, \Gamma_\gamma\, f_1$$

$$f_1 = \frac{E^+ - E^- + D}{(E^+ - E + \tfrac{1}{2}D)(E - E^- + \tfrac{1}{2}D)} \qquad f_2 = \ln\left(\frac{E - E^- + .582D}{E^+ - E + .582D}\right)$$

where FGN = .557 and FGC = .827 are adjustment factors discussed in the text, $k_o = 2.1875 \cdot 10^9$ cm^{-1} in the neutron wave number at 1 eV, $\hat{a} = .944 \times 10^{-12}$ cm is the effective scattering radius, and $\text{cs} = \dfrac{\pi \Gamma_n^o}{k_o^2 D} \doteq 77.3$ barn.

2. Levels with energies between 4040 and 4512 eV, parameters given in Table XI.

3. Below 1 eV, levels of File 2, including an assumed bound level $E_o = -20$ eV, $\Gamma_n^o = .287$ mV, $\Gamma_\gamma = 23.5$ mV; and an outside level at $E_o = 4040$ eV, first level given in Table XI.

4. Unresolved p-wave above 1 keV: 1000 $< E <$ 1340 eV $\quad \sigma_\gamma^{ur} = (E-1000) \cdot .3994$ mb

$E > 1340$ eV $\quad \sigma_\gamma^{ur} = 3.71\, E^{1/2}$ mb

Table XIII. Computed and Measured Cross Sections at .0253 eV

	$\sigma(n,\gamma)$ b.	$\sigma(n,n)$ b.	σ_t b.
1. Picket Fences Contribution	.295	1.741	2.036
2. Resolved Levels of File 2 (includes potential scattering)	2.405	7.198	9.603
3. Levels with Energies Between 4040 and 4512 eV	0	-.038	-.038
Total	2.700	8.901	11.601
Evaluated from direct measurements (from Ref. C2 and Table XIV)	2.70±.02	8.90±.16	11.60±.16

Table XIV. Computed and Measured Scattering Length at .0253 eV

Computed Scattering Cross Section (see Table XIII)	8.901 b.
Corresponding Scattering Length: $a_{coh} = \left[\frac{\sigma}{4\pi}\right]^{1/2}$	$.842 \times 10^{-12}$ cm
Direct Measurements: (in 10^{-12} cm)	
Atoji (1961)	.851±.022
Roof et al. (1962)	.84±.02
Willis (1963)	.850±.006

Table XV. Measurements of the ^{238}U Thermal Capture Cross Section

Reference	$\sigma(n,\gamma)$ (barn)	Methods and Comments
Harris, Rose, and Schroeder (1954)	2.71±0.05	Reactivity measurements in CP3 using a sample of very low ^{238}U content. Cd ratio measurements by activation to correct for resonance absorption. Revised using $\sigma_A(B)$ = 757.7 b at 2200 m/sec for the standard.
Egelstaff (1954)	2.8±0.10	Transmission measurements with a slow neutron chopper. Sample of very low ^{235}U content was used.
Crocker (1955)	2.72±0.10	Activation in a thermal spectrum with $\sigma_0[Au]$ = 98.8 b. Corrected for fission activity by Ryves (1959).
Small (1955)	2.72±0.06	Local oscillator in well moderated spectrum. Measurements with natural and depleted uranium. Revised assuming $\sigma_A(M_nSO_4)$ = 13.73 b.
Cocking and Egelstaff (1955)	2.69±0.04	Transmission measurements using cold neutrons from a Bi filter extrapolated to 2200 m/sec. Sample was of a very low ^{235}U content.
Egelstaff and Hall (1955)	2.69±0.04	Transmission measurements at long wavelengths with slow neutron chopper. Sample was of very low ^{235}U content.
Palevsky (1955)	2.73±0.07	Transmission measurements at long wavelengths with slow neutron chopper. Sample was of natural uranium.
Bingham, Durham, and Ungrin (1968)	2.721±0.016	Relative to thermal fission cross section of ^{235}U.
Hunt _et al_. (1969)	2.69±0.03	Activation in a thermal spectrum <0.005% ^{235}U.

the results of three neutron diffraction measurements.[D19] The potential scattering cross section corresponds to an effective scattering radius of .944 x 10^{-12} cm as evaluated in the previous section.

The contribution to the cross sections of s-wave levels with energies between 1 and 4000 eV, which have not been observed experimentally, was estimated to be negligible. The contribution of missed p-wave levels to the capture cross section was estimated as follows: Figure 7 is a plot of the cumulative sums of the p-wave reduced neutron widths versus energy. The slope of the curve should be proportional to the p-wave strength-function, which sould be roughly constant. Above 1.5 keV the slope decreases, probably because a number of p-wave levels are missed due to the poorer energy resolution of the measurements, causing an increased overlap of p-wave and s-wave levels and also because the measurements of Corvi, Rohr and Weigmann[B25] from which many of the evaluated p-wave levels were obtained, ends at 1550 eV. The strength of the missed p-wave levels was estimated by extrapolating the slope of the curve of Fig. 7 from the region below 1.3 keV to the region between 1.3 and 4 keV. The calculation of the contribution of these missed p-wave levels to the capture cross section is outlined in Table XVI. This contribution was included as a smooth capture cross section in File 3.

From 1 to 4000 eV the subthreshold fission cross section was evaluated to be the fission cross section computed from the parameters listed in File 2, so that the fission component of File 3 was set identically zero above 1 eV. Below 1 eV the fission cross section

ORNL-DWG 77-12052R

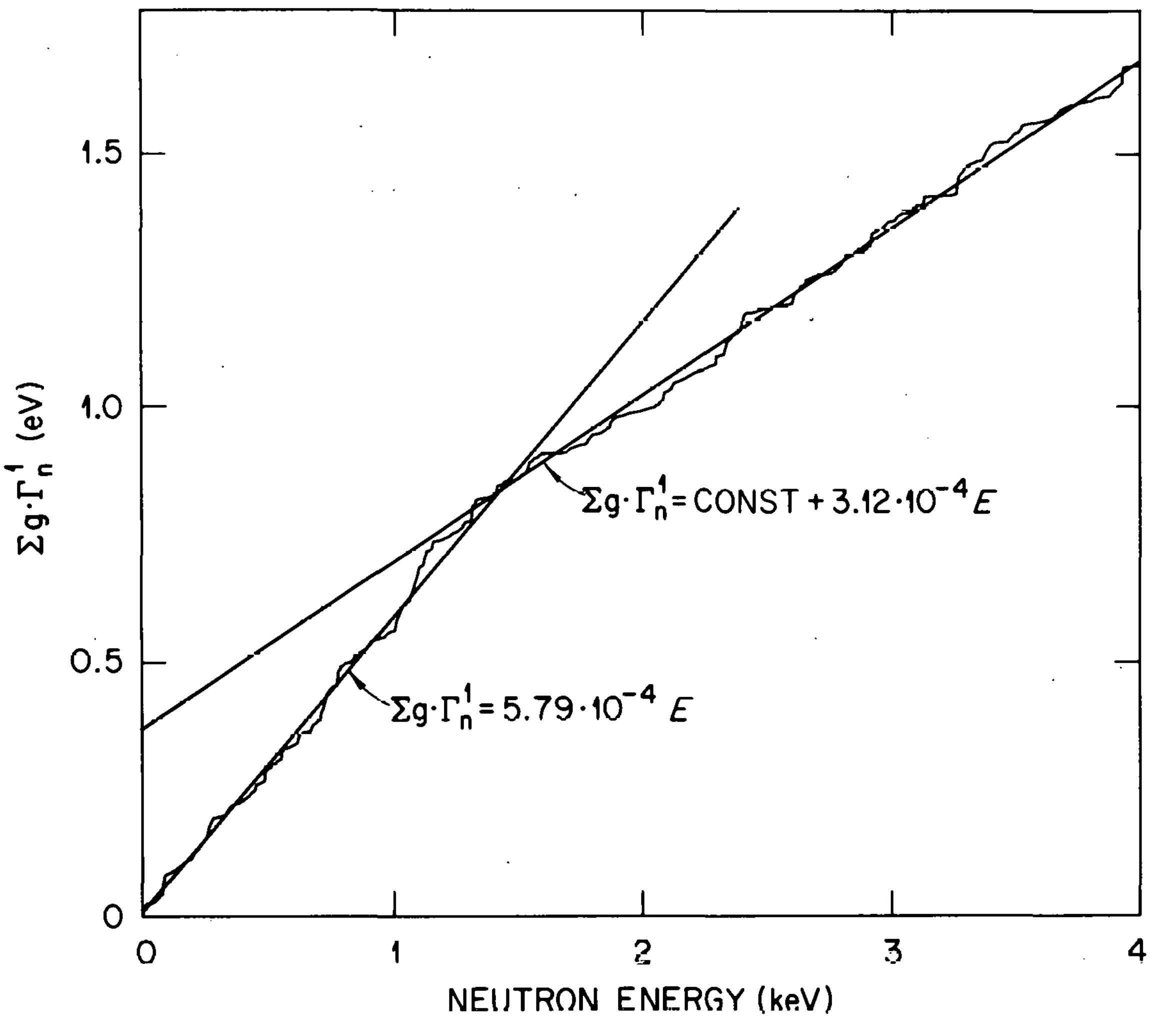

Fig. 7. Cumulative sum of the p-wave reduced widths vs neutron energy. The slope decreases near 1500 eV, probably because many small levels are missed, due to the increasingly poor resolution of the time-of-flight measurements.

Table XVI. Missed p-Wave Capture Above 1 keV

The average p-wave capture cross section is given by:

$$\langle \sigma_{n\gamma}(\ell=1) \rangle = \frac{2\pi^2}{k^2}\frac{1}{D^1} \quad \left\langle \frac{g\Gamma_n \Gamma_\gamma}{\Gamma} \right\rangle_{\ell=1} \cong \frac{2\pi^2}{k^2} \quad \frac{\langle g\Gamma_n \rangle_{\ell=1}}{D^1}$$

(since for p-wave $\Gamma_n \ll \Gamma_\gamma$ and hence $\Gamma \cong \Gamma_\gamma$)

Using the definition of the p-wave strength function:

$$S^1 = \frac{\langle g\Gamma_n^1 \rangle}{3D^1} = \frac{(kR)^2}{1+(kR)^2} \cdot \frac{\langle g\Gamma_n \rangle_{\ell=1}}{3D^1} \, . E^{1/2}$$

we obtain:

$$\langle \sigma_{n\gamma}(\ell=1) \rangle \cong 6\pi^2 R^2 S^1 \; E^{1/2}, \text{ since } (kR)^2 \ll 1 \; .$$

(where $R = .84 \times 10^{-12}$ cm is the nuclear radius)

From Fig. 7 we see that below 1 keV $S^1 \cong 1.93 \times 10^{-4}$, above 1.34 keV $S^1 \cong 1.04 \; 10^{-4}$, so that the missed p-wave capture above 1.34 keV is:

$$6\pi^2 R^2 \times .89 \times 10^{-4} \; E^{1/2} = 3.71 \; E^{1/2} \text{ mb}$$

(where E is in eV)

was evaluated to be proportional to $E^{-\frac{1}{2}}$. The fission cross section at .0253 eV was evaluated as 1.5 times the contribution of the levels with energies between 1 and 4000 eV. The contribution of the bound levels was somewhat arbitrarily evaluated to be only 50% of that of the positive levels, since much of the contribution of the positive levels comes from the first few s-wave levels, and there are strong indications, as discussed above, that the local strength function of the bound levels near the binding energy is smaller than the strength function averaged over the resolved range. The contributions of the positive energy levels to the fission cross section at .0253 eV are given in Table XVII, where the result of this evaluation is also compared with other evaluations.[B18,B29]

Table XVII. The ^{238}U Thermal Fission Cross Section

1. Contributions of levels with energies between 1 and 4000 eV

Eo(eV)	Γ_n(mV)	$\Gamma_f(10^{-9}$eV)	$\delta\sigma_f^{(a)}$(μb)
6.672	1.510	10.33	0.5599
20.86	10.12	59.95	1.260
36.67	33.91	8.877	0.1526
66.01	24.61	51.48	0.1477
80.73	1.907	66.15	0.8892E-02
102.5	71.64	12.25	0.3405E-01
189.6	167.0	47.72	0.6645E-01
208.5	49.60	88.09	0.2873E-01
237.3	26.48	60.03	0.7564E-02
347.8	81.73	267.6	0.4002E-01
376.9	1.148	205.4	0.3529E-03
463.1	5.494	1474.	0.7243E-02
478.4	4.188	240.9	0.8319E-03
518.3	49.60	292.6	0.9795E-02
535.3	44.28	367.0	0.1012E-01
595.0	86.41	1099.	0.4539E-01
619.9	30.76	214.7	0.2849E-02
708.3	21.79	0.2564E 05	0.1727
721.6	1.720	0.1096E 07	0.5563
730.1	0.9341	0.9261E 05	0.2479E-01
765.1	7.767	5945.	0.1177E-01
851.0	62.91	1215.	0.1493E-01
856.1	86.17	1107.	0.1836E-01
1140.	233.1	1595.	0.3497E-01
1168.	87.71	0.1171E 05	0.9093E-01
1211.	9.193	0.2734E 06	0.2033
1267.	29.17	4282.	0.9023E-02

Total contribution of levels with energies between 1 and 4000 eV	3.52 μb
Estimated contribution of bound levels and levels above 4000 eV	1.76 μb
Total thermal fission cross section	5.28 μb
Silbert and Bergen	3 ± 5 μb
Slovacek et al.*	2.7 ± .3 μb

*Contribution from positive energy levels only.

(a) $\delta\sigma_f = 4127550. \dfrac{\Gamma_n\Gamma_f}{E_o^{5/2}}$ in barns

5. FINE ADJUSTMENTS TO THE PARAMETERS AND SMOOTH BACKGROUNDS

In Sections 3 and 4 we have described the evaluation of the resonance parameters and of the background files. Some fine adjustments to these evaluations were then performed on the basis of a direct comparison of calculated and measured transmission through a thick sample of ^{238}U and of high resolution capture data. The thick sample transmission experiments were done by Olsen et al.[B31] with a sample of .175 at/b, both on flight paths of 40 m and 150 m. The capture data were taken by deSaussure et al.[D20] on a 40-m flight path.

The fine adjustments consisted mostly in small changes in the scattering cross section background (File 3) near the boundaries of the resolved range, and in the removal or addition of very small levels. A few levels which had been reported by only one set of experimenters and which could not be observed--neither in the thick sample transmission measurement nor in the capture data--were removed from the file. A few levels which had not been reported previously but which could be observed clearly both in the transmission and capture data were added to the file. The neutron widths of these levels were estimated from the transmission dips and capture peaks.

6. CAPTURE CROSS SECTIONS

The infinitely dilute capture cross section was integrated over 100-eV-wide intervals below 1-keV- and over 1-keV-wide intervals above 1 keV. The contributions of the s-wave levels, p-wave levels, and "missed" p-wave levels are listed separately in Table XVIII where they are compared with direct measurements of the infinitely dilute capture.[D20-22] The computed values given in Table XVIII were obtained analytically using the relation:

$$\int \sigma_{\gamma j} \ dE \cong 2g \frac{\pi^2}{k_0^2} \frac{\Gamma_{\gamma j} \Gamma_{nj}}{E_{oj} \Gamma_j} \qquad (8)$$

for the contribution of the $j^{\underline{th}}$ level to the capture cross section, where $k_o = 2.1875 \times 10^9 \text{ cm}^{-1}$ is the reduced wave number at 1 eV; the other symbols have their usual meaning. In the calculation, the entire contribution defined by equation (8) was assigned to the interval containing the resonance energy E_{oj}, this assumes that the effects of resonance tails across energy intervals cancel. The contribution of the missed p-waves were obtained analytically as indicated in Table XVI. This is the only appreciable contribution due to File 3.

Above 1 keV the capture cross section computed from this evaluation is consistent with that directly measured by Moxon,[D22] is about 8% lower than that measured by deSaussure et al.,[D20] and 13% higher than that obtained by Friesenhahn et al.[D21] Below 900 eV the computed cross section is generally lower than the direct measurements of Moxon and of deSaussure et al. The discrepancies between

Table XVIII. Computed and Measured Average Capture Cross Section*

Energy Interval (eV)	Contributions of: s-wave	resolved p-wave	unresolved p-wave	Total Computed Average Capture	Directly Measured Average Capture: Moxon	Friesenhahn et al.	deSaussure et al.
0 - 100	46.5	.07		46.6			
100 - 200	17.1	.05		17.2			18.72±.44
200 - 300	8.49	.17		8.67			9.77±.30
300 - 400	2.88	.08		2.96			3.40±.17
400 - 500	2.46	.19		2.65			3.12±.15
500 - 600	4.83	.13		4.96	4.97±.13		5.39±.17
600 - 700	3.43	.18		3.61	3.75±.11		4.02±.14
700 - 800	1.36	.39		1.75	2.105±.08		2.10±.12
800 - 900	2.83	.13		2.96	3.37±.10		3.29±.12
900 - 1000	4.10	.14		4.24	3.64±.11		4.54±.14
1000 - 2000	1.62	.20	.10	1.93	1.97±.08	1.70±.20	2.12±.09
2000 - 3000	1.07	.22	.19	1.47	1.48±.07	1.33±.13	1.56±.08
3000 - 4000	.865	.195	.219	1.28	1.23±.06	1.06±.08	1.31±.07

*All values given in barns

measured and computed capture cross sections, particularly below 1 keV, exceed the quoted uncertainties on the measurements and the estimated uncertainties in the calculation and are not understood. In Figs. 8 to 11, the capture probability measured by deSaussure et al.[D20] is compared with a Monte-Carlo calculation based on this evaluation.

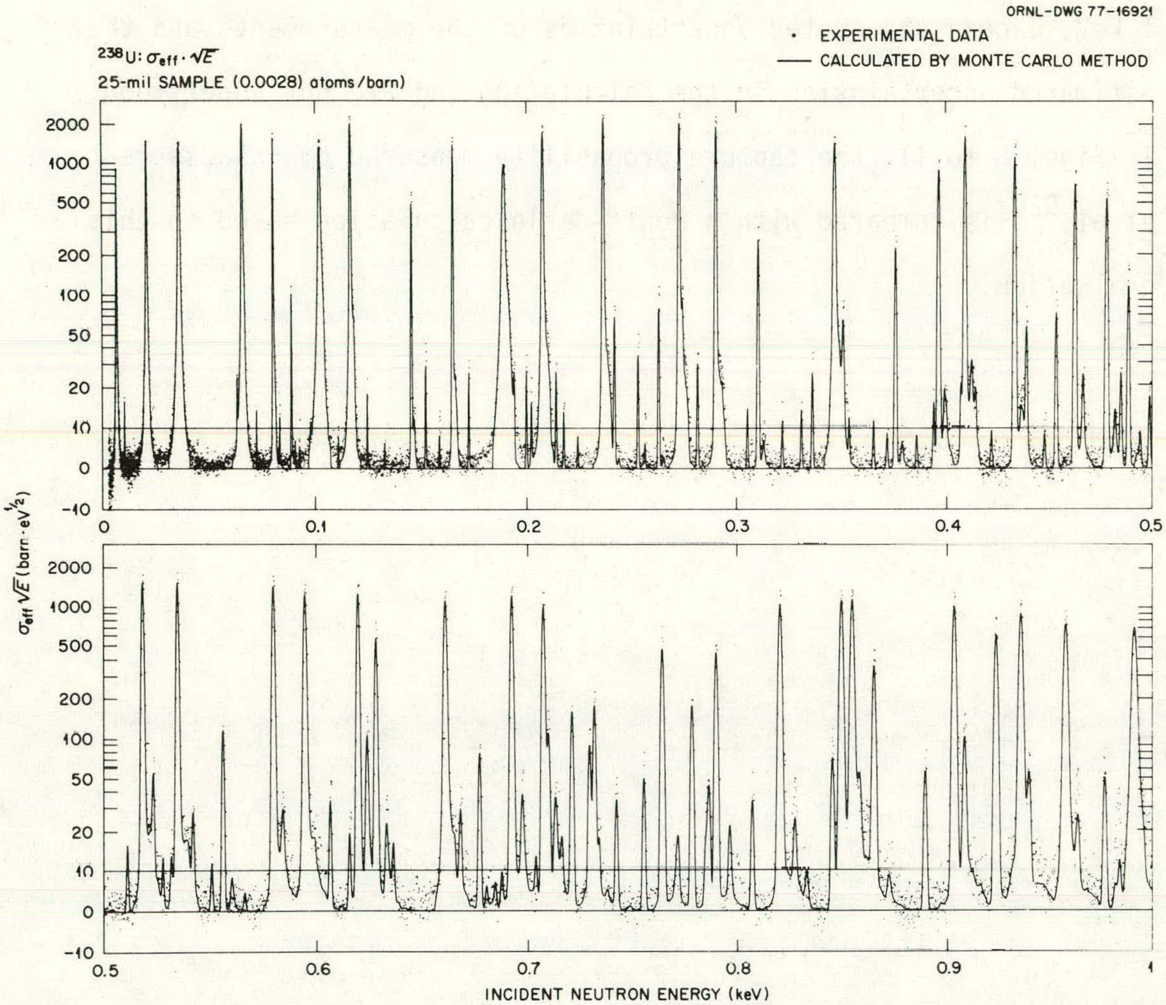

Fig. 8. Comparison of the measured and computed capture probabilities for a ^{238}U sample of .0028 atoms/barn and for incident neutron energies up to 1.0 keV. The ordinate is the probability of capture multiplied by the square root of the energy and divided by the sample thickness in atoms/barn. The calculation was done with the Monte Carlo code MULTSCA using the resonance parameters of this evaluation. Note that the ordinate is linear from -10 to +10 barn x eV$^{1/2}$ and logarithmic above 10 barn x eV$^{1/2}$.

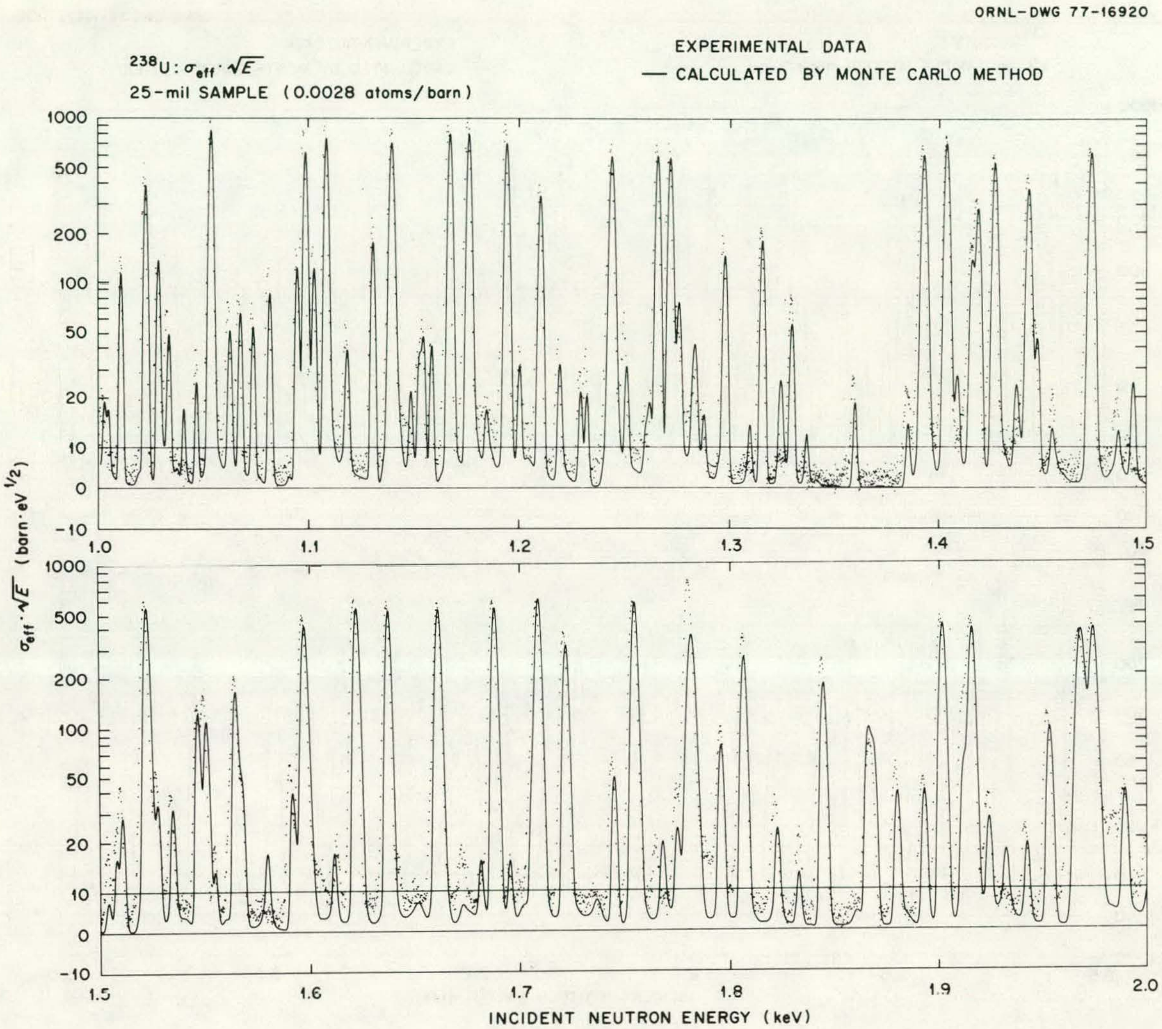

Fig. 9. Comparison of the measured and computed capture probabilities for a ^{238}U sample of .0028 atoms/barn and for incident neutron energies from 1 to 2 keV. The ordinate is the probability of capture multiplied by the square root of the energy and divided by the sample thickness in atoms/barn. The calculation was done with the Monte Carlo code MULTSCA using the resonance parameters of this evaluation. Note that the ordinate is linear from -10 to +10 barn x $eV^{\frac{1}{2}}$ and logarithmic above 10 barn x $eV^{\frac{1}{2}}$.

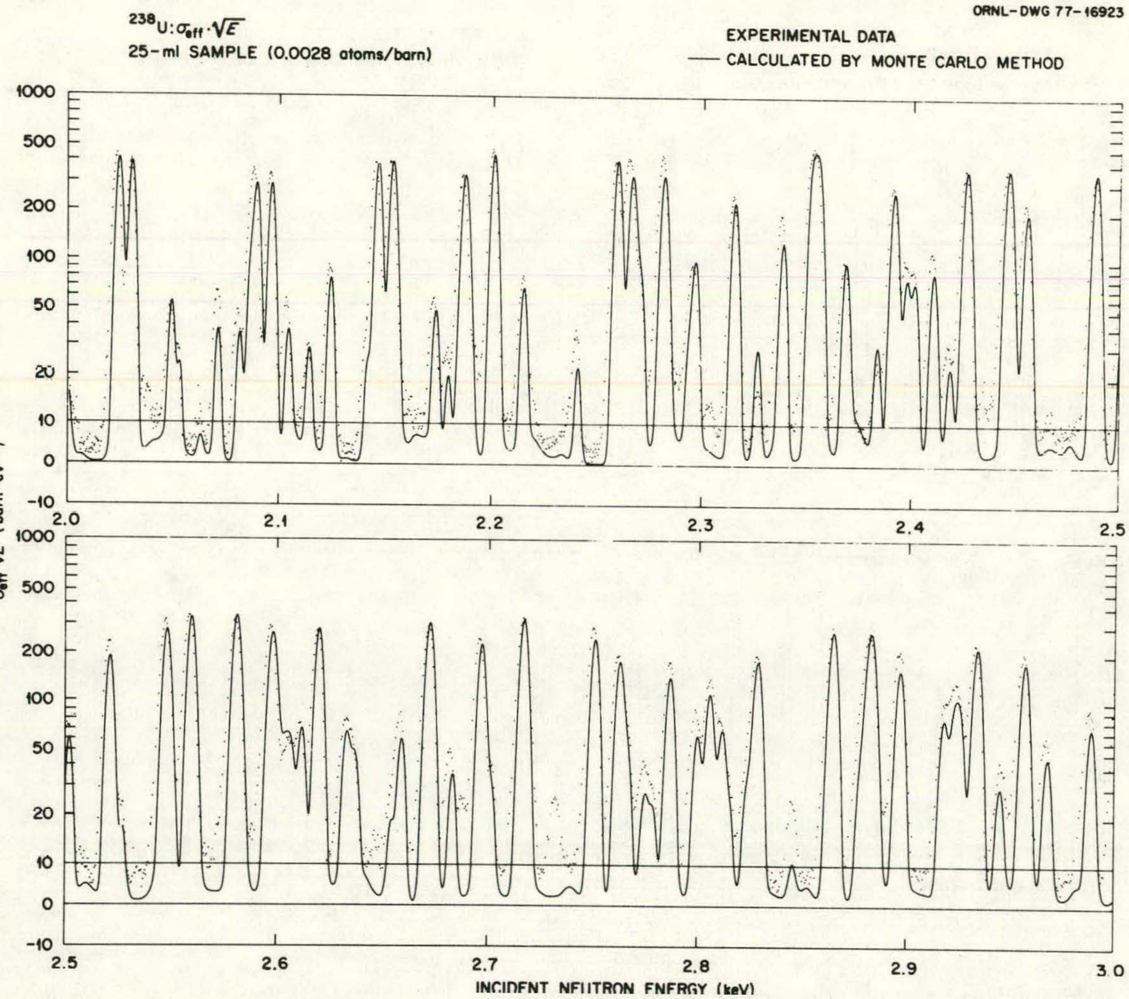

Fig. 10. Comparison of the measured and computed capture probabilities for a ^{238}U sample of .0028 atoms/barn and for incident neutron energies from 2 to 3 keV. The ordinate is the probability of capture multiplied by the square root of the energy and divided by the sample thickness in atoms/barn. The calculation was done with the Monte Carlo code MULTSCA using the resonance parameters of this evaluation. Note that the ordinate is linear from -10 to +10 barn x $eV^{1/2}$ and logarithmic above 10 barn x $eV^{1/2}$.

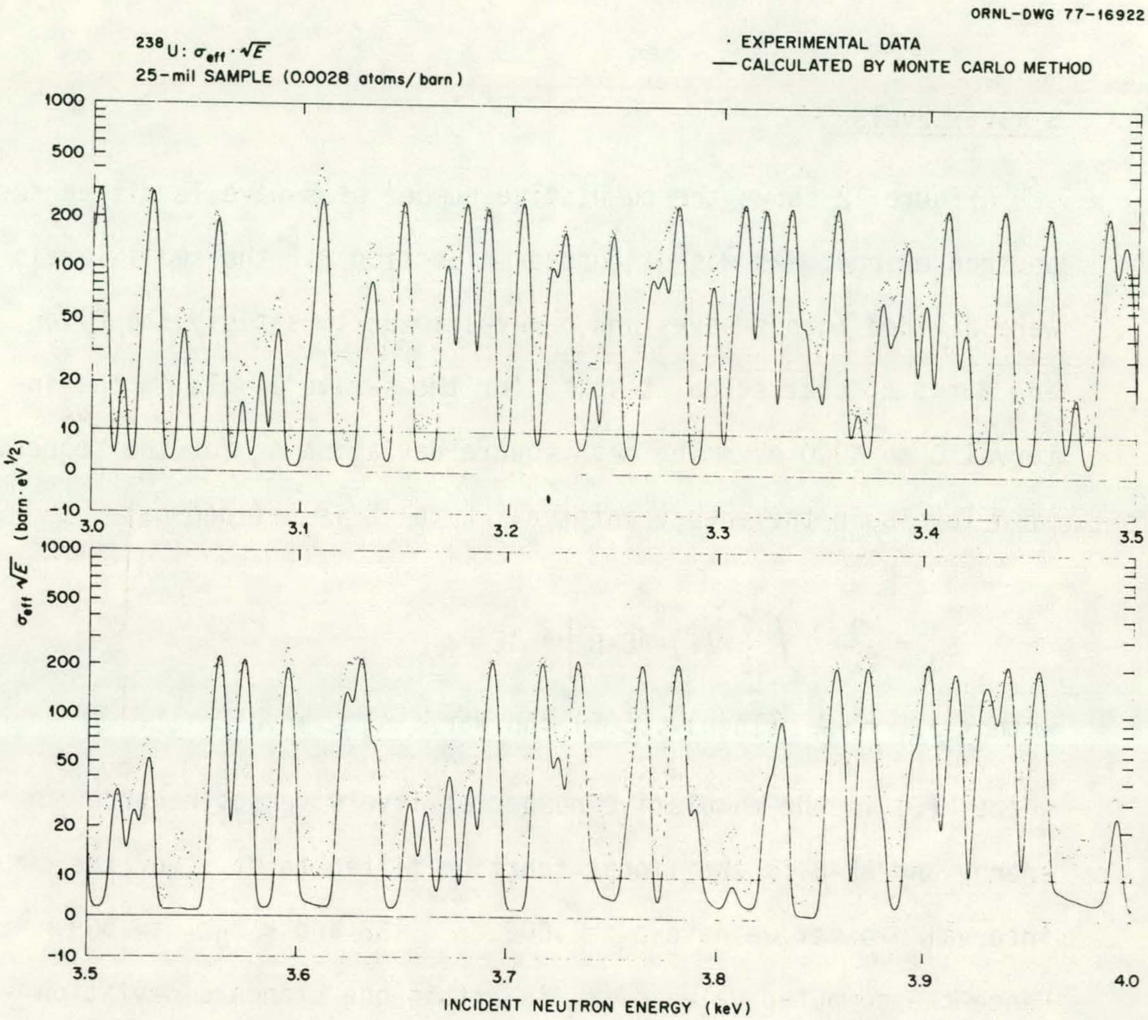

Fig. 11. Comparison of the measured and computed capture probabilities for a ^{238}U sample of .0028 atoms/barn and for incident neutron energies from 3 to 4 keV. The ordinate is the probability of capture multiplied by the square root of the energy and divided by the sample thickness in atoms/barn. The calculation was done with the Monte Carlo code MULTSCA using the resonance parameters of this evaluation. Note that the ordinate is linear from -10 to +10 barn x $eV^{\frac{1}{2}}$ and logarithmic above 10 barn x $eV^{\frac{1}{2}}$.

7. DISTRIBUTION OF THE RESONANCE PARAMETERS

A. S-wave Levels

Figure 12 shows the cumulative number of s-wave levels versus neutron energy. As was discussed in Section 3.F the small levels were divided into s-waves and p-waves so as to satisfy the Dyson and Metha Δ_3 statistical test,[D8] for the s-wave levels in the interval 0 to 4000 eV. The mean square deviation Δ_3 for the sequence of n levels in the energy interval -L to +L is defined as:

$$\Delta_3 = \frac{1}{2L} \int_{-L}^{L} \left[N(E)-AE-B \right]^2 \delta E \qquad (9)$$

with $\langle \Delta_3 \rangle = \frac{1}{\pi^2} (\ln(n)-.0686)$ and var $\langle \Delta_3 \rangle = .012$

where N(E) is the cumulative number of levels versus neutron energy and AE-B is the linear function fitted to it. For the interval 0-4 keV we have $\Delta_3 = .606$; n = 162 and $\langle \Delta_3 \rangle = .509$. Hence the computed value of Δ_3 is within one standard deviation of the most probable value $\langle \Delta_3 \rangle$.

The average s-wave level spacing $\overline{D^0}$ can best be obtained from the Dyson and Metha linear statistics W:[D8]

$$W = \sum_{j=1}^{n} \left[1-\left(\frac{E_j}{L}\right)^2 \right]^{\frac{1}{2}} \text{ with } \langle W \rangle = \frac{\pi L}{2\bar{D}} \text{ and var } \langle W \rangle = 1/2 \qquad (10)$$

which yields a value $\overline{D^0} = 24.78 \pm .14$ eV. Of course, the error estimate is the "sampling error" associated with the statistics

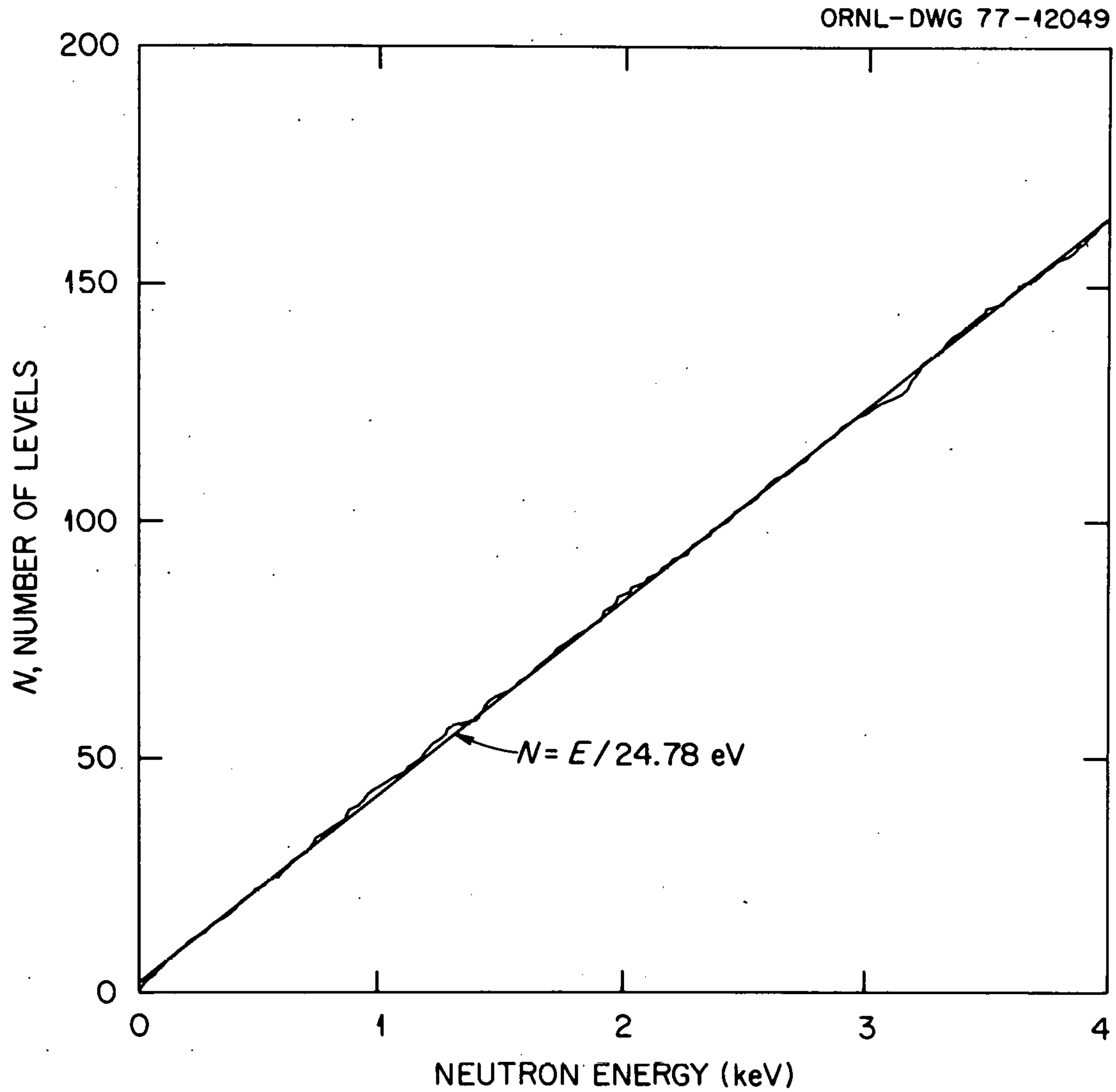

Fig. 12. Cumulative number of s-wave levels vs neutron energy. The solid line is a linear fit to N(E) and corresponds to an average spacing of 24.78 eV.

of the energy levels and does not include a possible error associated with an incorrect distribution of the small levels between s- and p-waves. This error is estimated to be $\pm$ 2 eV.

The value of $\overline{D^o}$ obtained in this evaluation is larger than the 20.8 eV given by Rahn et al.[B20] and the 21.05 eV of ENDF/B-IV.[C1] The reason is that a number of small levels which had been assumed to be s-wave by Rahn et al., and by the evaluator of ENDF/B-IV have since been shown to be more likely p-wave, by the work of Corvi, Rohr and Weigmann.[B25] For the interval 1 to 2 keV the present evaluation yields a spacing of 22.9 $\pm$ 1.8 eV in good agreement with the value 22.4 $\pm$ 1.0 eV obtained by Corvi et al.

In Fig. 13 the observed distribution of s-wave nearest-neighbor spacings is compared with a Wigner distribution for one population.[D23]

$$P(x) = \frac{\pi}{2}\, x\, e^{-\frac{\pi}{4} x^2} \qquad x = \frac{S}{\overline{D^o}} \tag{11}$$

where x is the ratio of the spacing S to the average spacing $\overline{D^o}$. The agreement between the observed distribution and the Wigner distribution is good, except that one large spacing is observed with a value of x between 3.8 and 4.0. The probability to observe a spacing in this range, with 161 spacings, is only 1.4×10^{-3}. The spacing is that between the s-wave levels at 1298.7 eV and 1393.8 eV. Eight small levels have been observed in this interval, but the most important levels at 1317 eV, 1331.5 eV, and 1386.1 eV have been shown to be likely p-waves by Corvi, Rohr, and Weigmann.[B25]

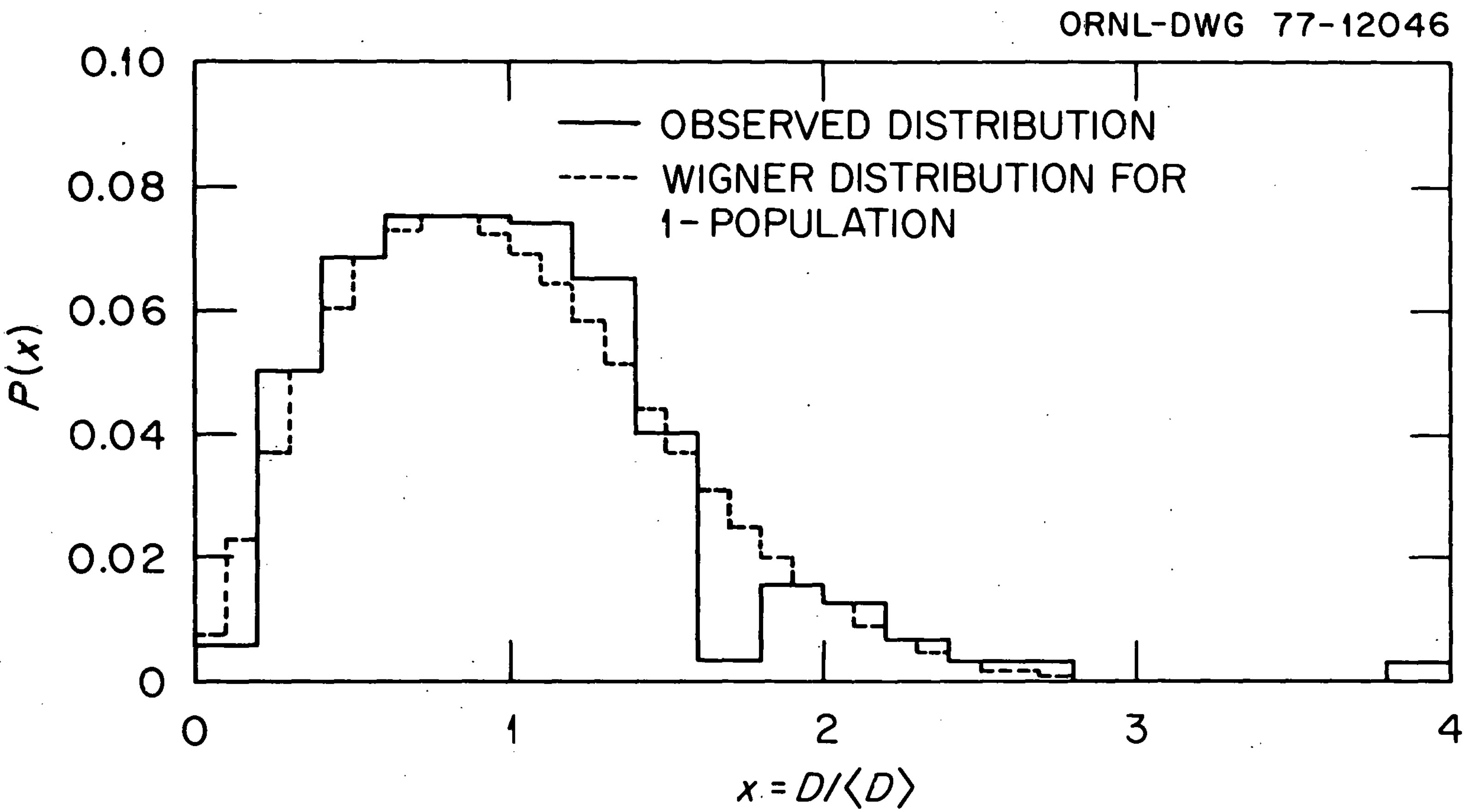

Fig. 13. Nearest neighbor spacing distribution of s-wave levels. The observed distribution (solid line) is compared with a Wigner distribution for one population (dashed line).

The remaining levels have neutron widths smaller than .6 mV hence are very unlikely to be s-wave levels.[B15] If a level had been added at 1360.7 eV, the computed value of Δ_3, equation (9), would have become .650 for a most probable value $\langle \Delta_3 \rangle = .509$ and a standard deviation of .1095.

Figure 14 shows the cumulative sum of the s-wave reduced neutron widths versus energy. The slope of the curve determines the s-wave strength function. The cumulative sum of reduced widths does not behave very linearly with respect to energy so that the "local strength function" varies considerably from one energy region to another. This variation of the local strength function with energy has already been observed by Carraro and Kolar,[B17] Rahn et al.[B20] and by McCrosson.[C1] In Table XIX we give a few recent determinations of the s-wave strength function, S^o. Above 1 keV the values obtained in this evaluation are approximately 10% higher than those of ENDF/B-IV because ENDF/B-IV is mostly based on the measurements of Rahn et al.[B20] whereas the more recent measurements of Nakajima et al.,[B26] Poortmans et al.[B32] and Olsen et al.[B31] all yield values of Γ_n somewhat larger, on the average, than those of Rahn et al. as indicated in Table VI.

In Fig. 15 the integral distribution of s-wave reduced neutron widths:

$$P(x) = \frac{1}{N_T} \int_x^\infty N(Z)\, dZ \quad \text{with } N_T = \int_0^\infty N(Z)\, dZ \qquad (12)$$

Table XIX. Comparison of s-Wave Strength Functions

(All values are multiplied by 10^4)

Energy Interval (keV)	Carraro[1] and Kolar	Rahn[1] et al.	Olsen[1] et al.	Poortmans[1] et al.	ENDF/B-IV	This Evaluation
0- .5	(1.02)[2]	1.065	1.001	.992	1.014	1.006
.5-1	1.041	.996	1.009	.996	.997	1.004
1-1.5	.924	.894	.932	.927	.861	.927
1.5-2	1.586	1.452	1.597	1.617	1.452	1.566
2-2.5	1.029	.912	1.024	1.019	.933	.988
2.5-3	1.473	1.294	1.551	1.441	1.258	1.461
3-3.5	1.176	.983	1.261	1.150	.895	1.172
3.5-4	1.267	1.009	1.293	1.250	1.088	1.221
0-4	1.190	1.075	1.208	1.175	1.062	1.168

(1) These values were obtained by adding the reduced neutron widths reported by the indicated authors for the levels assigned to s-wave in the present evaluation.

(2) Carraro and Kolar do not report neutron widths for the first three s-wave levels. The values of this evaluation were used for these three levels in computing the strength function.

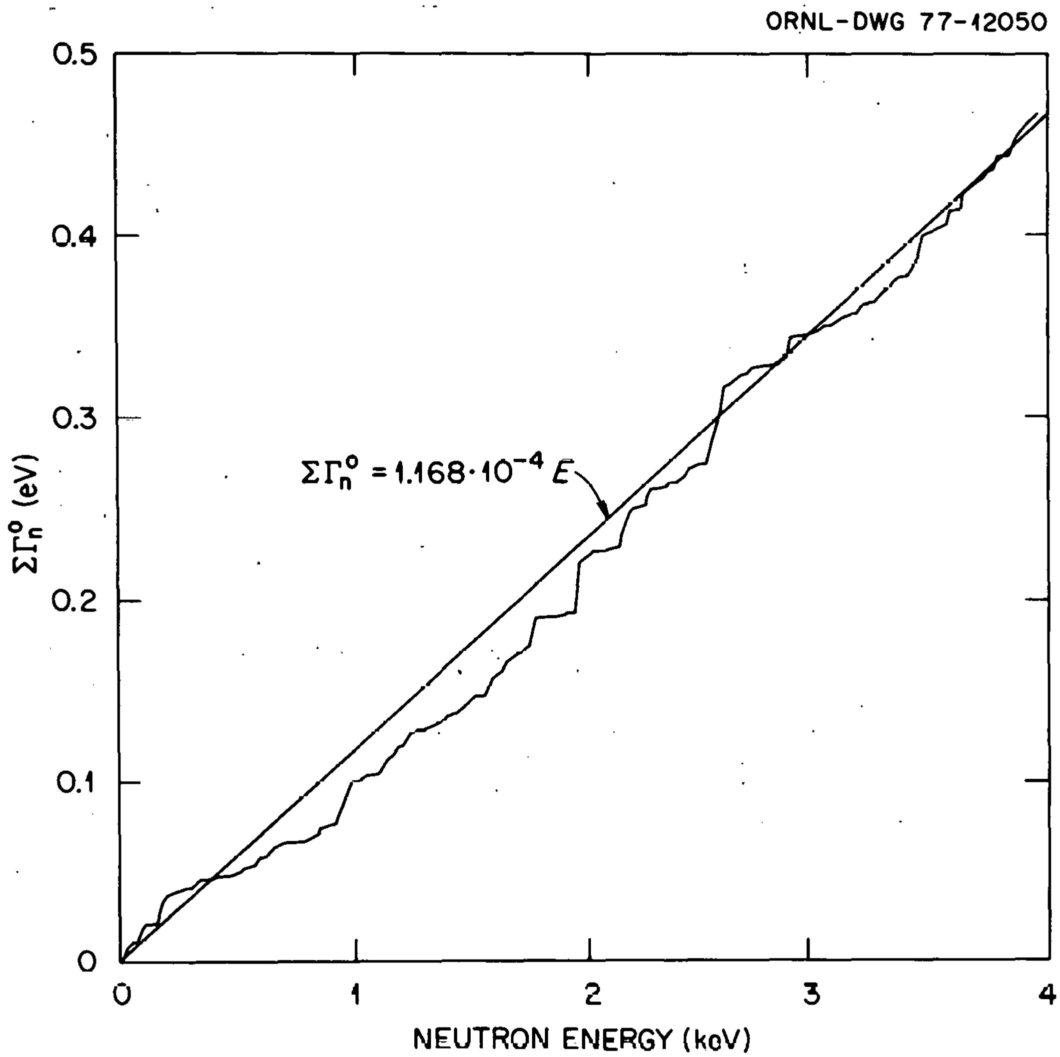

Fig. 14. Cumulative sum of the s-wave reduced neutron widths vs energy. The slope of the curve determines the s-wave strength function.

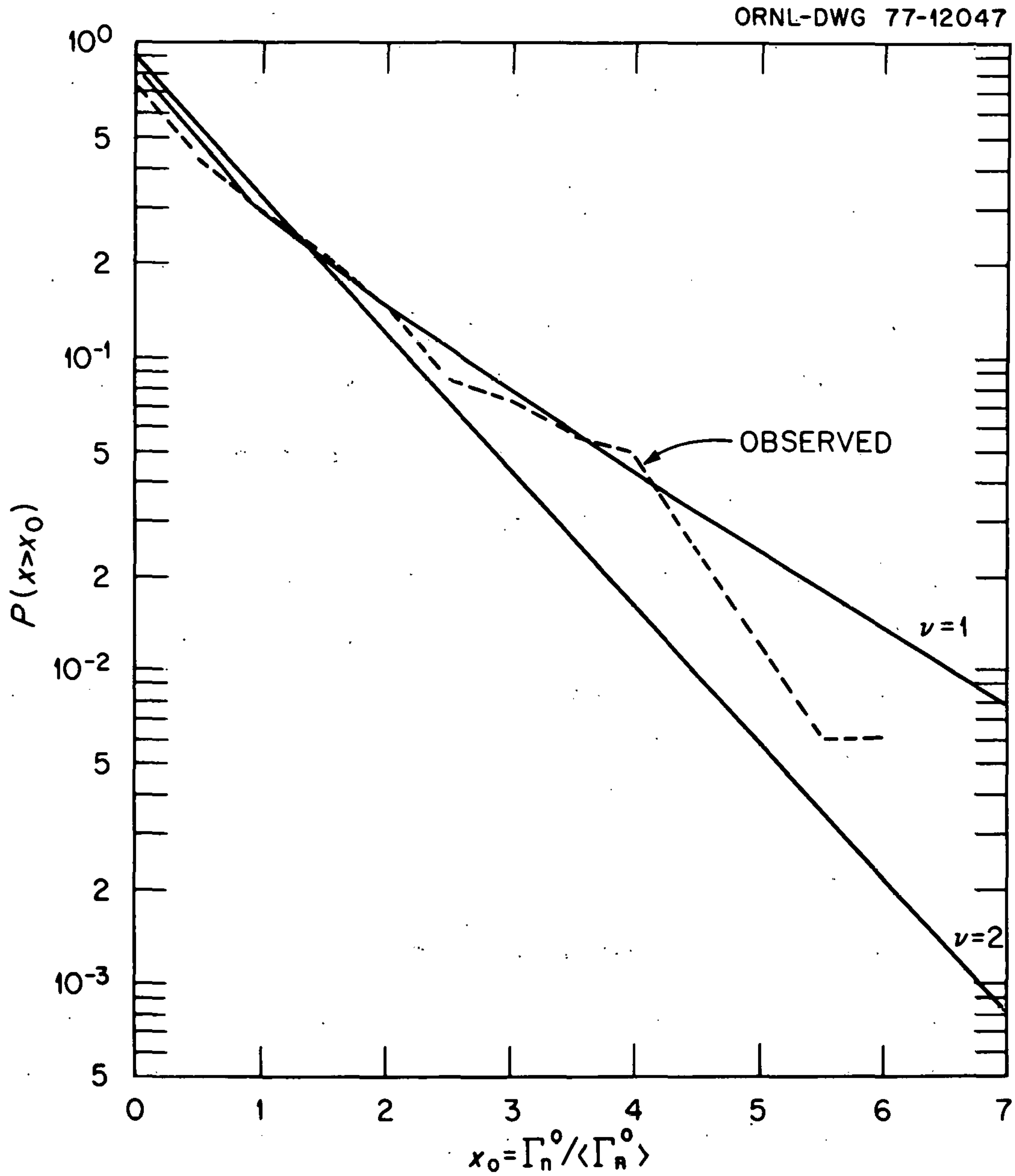

Fig. 15. Integral distribution of s-wave reduced neutron widths. The observed distribution is represented by the dashed line. The solid lines correspond to χ^2 distribution laws with 1 and 2 degrees of freedom respectively. The observed distribution seems to agree better with the ν=1 distribution law (Porter-Thomas Distribution).

where $Z = \frac{\Gamma_n^o}{\langle\Gamma_n^o\rangle}$, is compared to integral distributions corresponding to χ^2 distribution laws[D24] with $\nu = 1$ and $\nu = 2$

$$P_\nu(x) = \frac{\nu}{2\Gamma(\frac{\nu}{2})} \int_x^\infty (\frac{1}{2} Z\nu)^{\frac{1}{2}\nu-1} e^{-\frac{1}{2}Z\nu} dZ \qquad (13)$$

The observed distribution seems in better agreement with the distribution corresponding to $\nu = 1$ (Porter-Thomas distribution).

As was explained in Section 3.D the capture widths of most s-wave levels have not been measured, and a value of $\Gamma_\gamma = 23.5$ mV was assigned to those levels. The average value of the capture width of those levels for which one or more measurements were reported was found to be 23.23 mV with a variance $\langle\Gamma_\gamma^2\rangle - \langle\Gamma_\gamma\rangle^2$ of 4.61 mV^2.

B. <u>P-wave Levels</u>

Figure 16 is a histogram of the cumulative number of p-wave levels versus neutron energy. Up to 800 eV the histogram increases approximately linearly with energy. Above 800 eV, the slope decreases with increasing energy, probably because an increasing fraction of small levels are not detected, since the energy resolution deteriorates with increasing energy.

The average p-wave level spacing was obtained over the interval 0 to 800 eV as $\bar{D}^1 = 8.91 \pm .1$ eV. The error is the sampling error

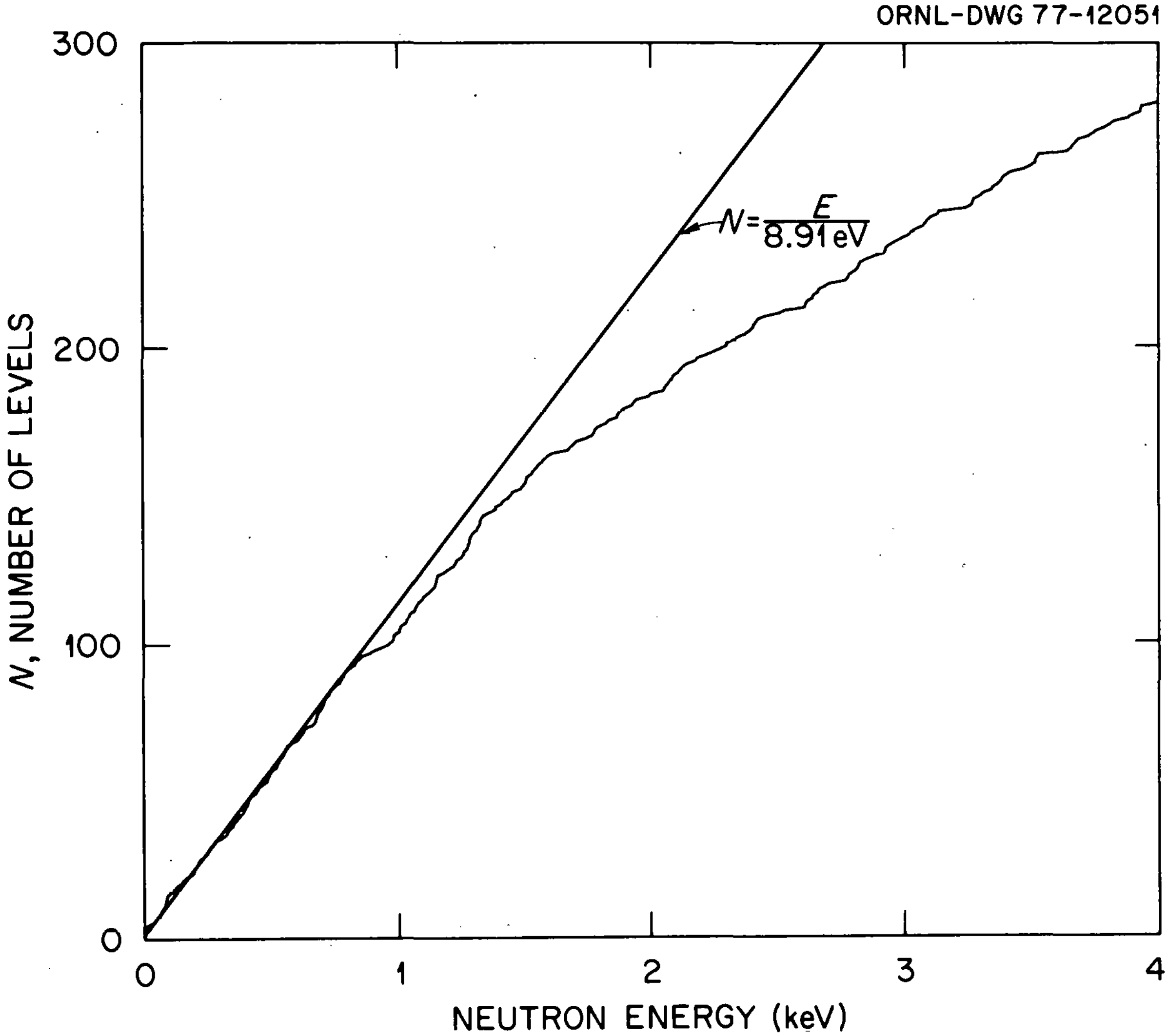

Fig. 16. Histogram of the cumulative number of p-wave levels vs neutron energy. Up to 800 eV, the histogram increases approximately linearly with energy. Above 800 eV, the slope decreases with increasing energy, probably because an increasing fraction of small levels are not detected, since the energy resolution deteriorates with increasing energy.

only. This value is not very different from the value $\overline{D^o}/3=$ 8.3 eV which would be expected if the density of states were proportional to 2J + 1 and independent of parity where J is the spin of the state.[B15]

In Fig. 17 the nearest neighbor spacings distribution of p-wave levels below 800 eV is compared to a Wigner distribution for two populations with a ratio of level densities $\rho = 2$.

$$P(\rho,x) = P_s(r_1,r_2,x) + P_s(r_2,r_1,x) + \frac{2\rho}{(\rho+1)^2}\, e^{\frac{-\pi}{4} x^2 \frac{\rho^2+1}{(\rho+1)^2}} \tag{14}$$

with:

$$P_s(r_1,r_2,x) = \frac{\pi}{2}\, r_1^3\, x \left[1 - \mathrm{erf}\left(\sqrt{\frac{\pi}{2}}\, r_2\, x\right)\right] e^{\frac{-\pi}{4} x^2 r_1^2} \tag{15}$$

and $r_1 = \frac{\rho}{1+\rho}$, $r_2 = \frac{1}{1+\rho}$

The distribution law (14) has been discussed by Gurevitch and Pevzner[D25] and Harvey and Hughes.[D26] P-wave neutrons may form ^{239}U states with J = 1/2 and J = 3/2; if the density of states is proportional to 2J + 1, the ratio ρ of the two populations is 2. The agreement between the observed and expected nearest neighbors distributions is considered reasonable.

The cumulative sum of the p-wave reduced neutron widths is shown in Fig. 7. If all the p-wave levels were detected experimentally, the p-wave strength function would be proportional to the "slope" of the histogram shown in Fig. 7. This slope is approximately constant up to 1500 eV. Above that energy it decreases

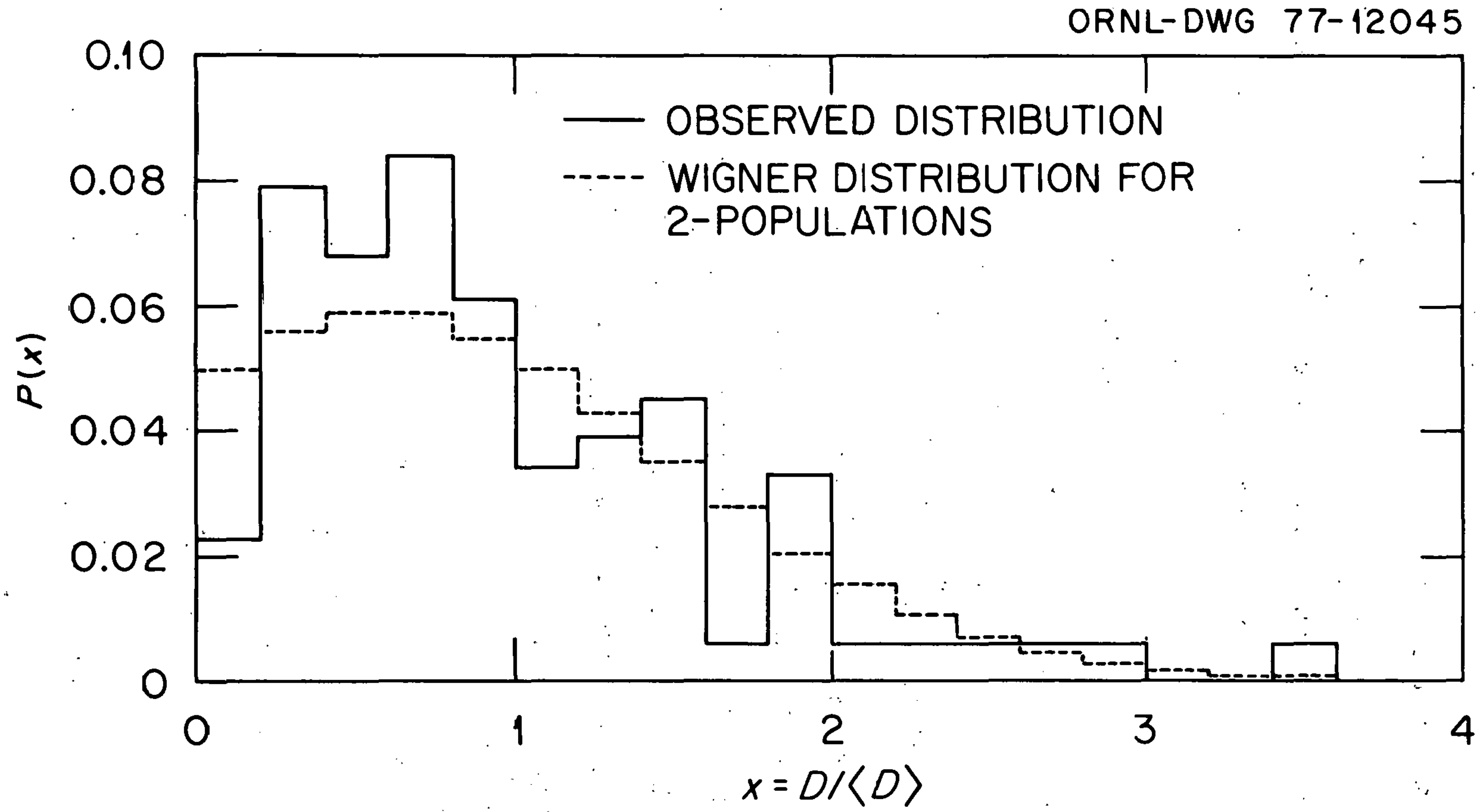

Fig. 17. Nearest neighbor spacing distribution of the p-wave levels below 800 eV. The solid line represents the observed distribution. The dashed line represents the expected distribution for two populations (J=1/2 and J=3/2).

sharply and this is interpreted as indicating that many p-wave levels are missed above 1500 eV, because of the increasingly poorer resolution of the time-of-flight measurements and because the measurements of Corvi, Rohr and Weigmann[B25] from which many of the evaluated p-wave levels were obtained, extends only to 1550 eV.

The p-wave strength function was evaluated from the slope of the histogram of Fig. 7 below 1500 eV as:

$$S^1 = \frac{1}{3}\left(\frac{N-1}{N}\right)\frac{1}{(k_oR)^2}\;\frac{\sum_{n=1}^{N} g\,\frac{\Gamma_n}{E_o^{3/2}}}{E_o(N)-E_o(1)} = (1.93 \pm .5) \times 10^{-4} \qquad (16)$$

where k_o is the reduced wave number at 1 eV, previously defined and where $R = .84 \times 10^{-12}$ cm is the channel radius. The uncertainty in the strength function was estimated from the variations in the slope of the histogram of Fig. 7. The value of S^1 obtained here is consistent with ENDF/B-IV below 500 eV (1.89×10^{-4}) and with the values given by Rahn et al.[B20] (1.4×10^{-4}) and by Corvi et al.[B25] ($2.3^{+.5}_{-.4} \times 10^{-4}$).

The average p-wave reduced neutron width can be obtained as:

$$\langle g\Gamma_n^1 \rangle = 3\, D^1 S^1 = 5.2 \pm 1.4 \text{ mV} \qquad (17)$$

this value is larger than that estimated by Rahn et al. (2.95 mV) but in very good agreement with that obtained by Corvi et al. ($5.42^{+1.11}_{-.86}$ mV). The value corresponds to an average p-wave reduced neutron width of 5.2 mV for the J = 1/2 states and of 2.6 mV for the J = 3/2 states.

In Fig. 18 the integral distribution of the variable $Z = g\Gamma_n^1 / \langle g\Gamma_n^1 \rangle$ is compared to integral distributions corresponding to χ^2 distributions with $\nu = 1$ and $\nu = 2$ (equation 13). Only p-wave levels up to 800 eV were used in obtaining the observed distribution of Fig. 18. The observed distribution is consistent with a $\nu = 1$ (Porter-Thomas) distribution for $g\Gamma_n^1$, as predicted by Bollinger and Thomas.[B15] In Table XX we summarize the values obtained for the s-wave and p-wave average resonance parameters.

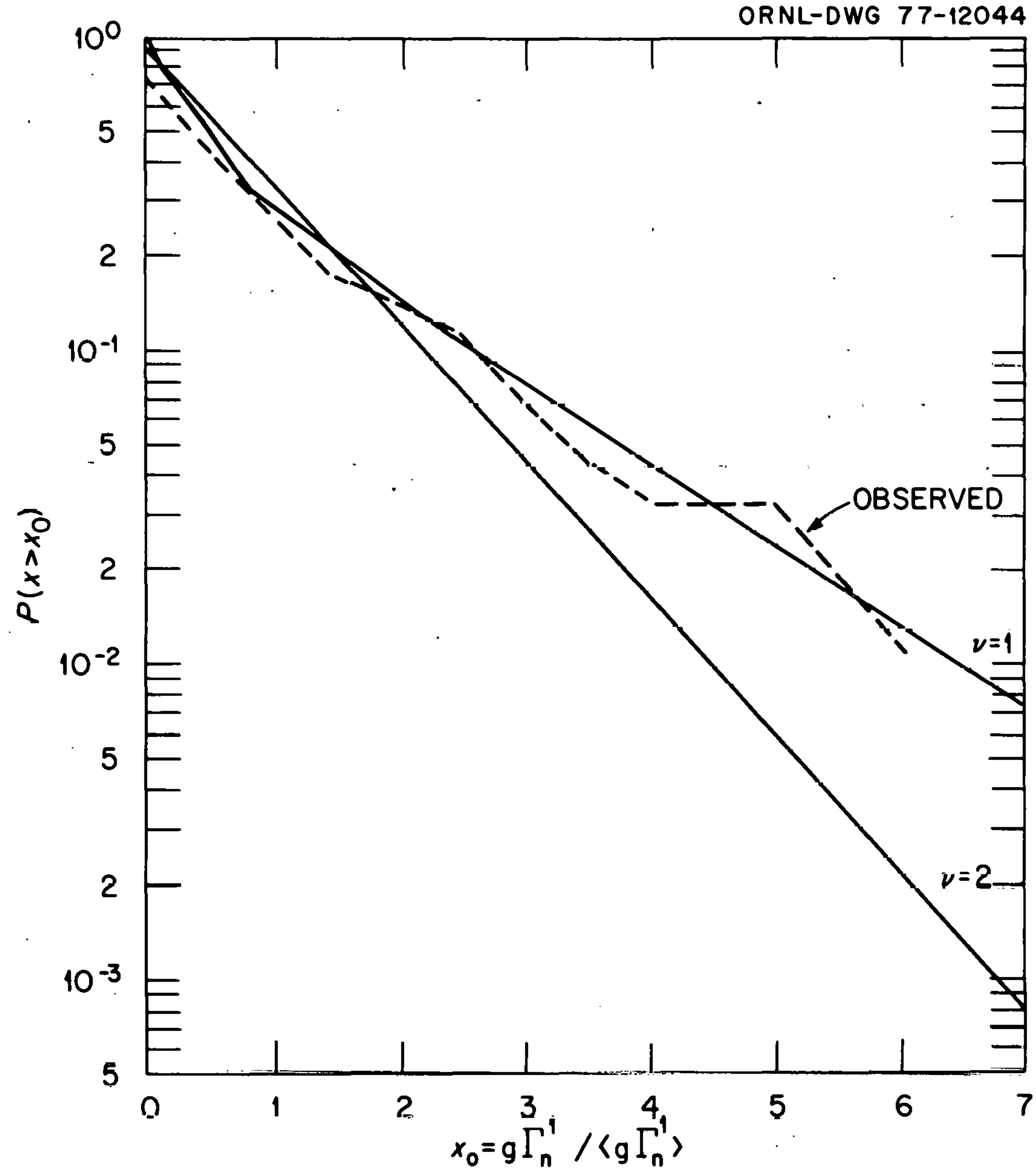

Fig. 18. Integral distribution of the p-wave reduced neutron widths below 800 eV. The solid lines correspond to χ^2 distribution laws with 1 and 2 degrees of freedom, respectively. The observed distribution agrees better with the ν=1 distribution law (Porter-Thomas distribution).

Table XX. Average Resonance Parameters

	ENDF/B-III	ENDF/B-IV	This Evaluation
I. s-wave Levels			
Number of levels below 4 keV	199	190	162
Average spacing D^o (eV)	20.1	21.05	24.8±2
Strength function S^o (X 10^4)	1.045	1.062	1.168±.02
Average neutron width $\langle \Gamma_n^o \rangle$ (mV)	2.090	2.224	2.88±.24
II. p-wave Levels			
Number of levels below 4 keV	258	220	280
Average spacing D^1 at low energy (eV)			8.91±.1 (a)
Strength function S^1 at low energy (X 10^4)		1.89 (b)	1.93±.5 (c)
Average neutron width $\langle g\Gamma_n^1 \rangle$ (mV)			5.2±1.4 (a)
(a) below 800 eV			
(b) below 500 eV			
(c) below 1500 eV			

8. ESTIMATED UNCERTAINTIES

In principle the uncertainty associated with a particular measurement of a parameter can be obtained by a careful analysis of the possible sources of error in the measurement. This analysis is best done by the experimenter performing the measurement, and presumably this is the method used to obtain the errors reported. However, as we have already stated in Section 3, the method generally does not lead to a correct estimate of the uncertainties. This is evident from the fact that data from different experiments often differ by amounts far exceeding the estimated uncertainties as illustrated in Tables II, III, VIII and IX for example. In Table XXI we compare the neutron widths of the larger levels between 3500 and 4000 eV from Garg et al.[B11] and Carraro and Kolar.[B17] It is interesting to note that of the 13 levels given, the neutron widths as given by Garg et al. and by Carraro and Kolar are consistent within the errors given only in one case.

Since the "internal" error estimates given by the measurers can be shown to be often unreliable, it seems more appropriate to evaluate the errors "externally," that is from the dispersion between results from independent measurements.

The methods used to evaluate the errors parallels the methods described in Section 3 and used to evaluate the "best values." We distinguish between "statistical" errors which are uncorrelated from one resonance to the next, and "systematic" errors which are correlated over energy.

Table XXI. Comparison of Two Sets of Neutron Widths Between 3.5 and 4.0 keV

Eo (eV)	Γ_n(mV)	
	Garg et al.	Carraro and Kolar
3561	143 ± 48	256 ± 20
3574	239 ± 60	420 ± 30
3595	15.6 ± 3	47.5 ± 7
3630	217 ± 30	559 ± 55
3693	243 ± 61	415 ± 20
3717	61 ± 15	102 ± 10
3734	153 ± 61	225 ± 10
3765	34 ± 6	94 ± 5
3782	277 ± 62	466 ± 25
3832	6.2 ± 3.1	12.6 ± 2.5
3858	342 ± 62	560 ± 30
3873	249 ± 93	201 ± 10
3902	225 ± 3.75	327 ± 30

The "statistical" error δ_j of the $j^{\underline{th}}$ parameter was obtained from the relation

$$\frac{1}{\delta_j^2} = \sum_k \frac{1}{\delta^{*2}_{jk}} \tag{18}$$

where the δ^*_{jk} are defined in equation 5. The statistical errors obtained for the s-wave and p-wave levels are listed in Tables XXII and XXIII respectively. A number of capture widths have not been measured and have been assigned a value of 23.5 mV. For these parameters no statistical error can be obtained, but a reasonable uncorrelated uncertainty for these capture widths is estimated to be $\pm$ 2.35 mV. This corresponds to a χ^2 distribution with ν=200 for the capture widths.[D24]

The systematic relative error on the level energies is estimated to be:

$$\frac{\delta E}{E} = 2.5 \times 10^{-4} \tag{19}$$

and is, of course, fully correlated with respect to energy. As was stated in Section 3B the level energies were aligned on the scale given by Olsen et al.[B31] Below 4 keV the error in the energy scale of time-of-flight experiments is mostly due to the uncertainty in flight path length. This length uncertainty in the measurement of Olsen et al. is estimated to produce a relative energy uncertainty of 2.0 X 10^{-4}. However, a comparison of recently determined energy scales suggests that the relative energy uncertainty given above is more realistic. The recent work concerning neutron energy standards has been reviewed by G. D. James.[D5]

Table XXII-a. s-Wave Resonance Parameters and Their Uncorrelated Standard Deviations[1] (All values in eV.)

	E_0	δE_0	Γ_n	$\delta\Gamma_n$	Γ_γ	$\delta\Gamma_\gamma$
1	-2.00000E 01	0.0	1.284E-03	0.0	2.350E-02	0.0
2	6.67200E 00	2.04E-04	1.510E-03	1.50E-05	2.253E-02	6.25E-04
3	2.08640E 01	2.04E-04	1.012E-02	9.69E-05	2.307E-02	4.52E-04
4	3.66710E 01	2.04E-04	3.391E-02	4.12E-04	2.292E-02	2.76E-04
5	6.60150E 01	2.04E-04	2.461E-02	3.79E-04	2.369E-02	3.40E-04
6	8.07290E 01	2.04E-04	1.907E-03	4.19E-05	2.417E-02	1.15E-03
7	1.02536E 02	2.04E-03	7.164E-02	4.10E-04	2.441E-02	3.49E-04
8	1.16874E 02	2.04E-03	2.754E-02	3.01E-04	2.267E-02	4.41E-04
9	1.45630E 02	2.04E-03	9.119E-04	1.89E-05	2.220E-02	3.50E-03
10	1.65258E 02	2.04E-03	3.400E-03	7.38E-05	2.336E-02	2.01E-03
11	1.89636E 02	2.04E-03	1.670E-01	1.73E-03	2.305E-02	4.87E-04
12	2.08474E 02	2.04E-03	4.960E-02	7.85E-04	2.282E-02	4.09E-04
13	2.37342E 02	2.04E-03	2.648E-02	4.51E-04	2.475E-02	4.67E-04
14	2.73621E 02	2.04E-03	2.593E-02	4.14E-04	2.273E-02	5.00E-04
15	2.90961E 02	2.04E-03	1.647E-02	3.45E-04	2.265E-02	5.39E-04
16	3.11281E 02	2.04E-03	1.026E-03	3.00E-05	2.350E-02	2.35E 00
17	3.47751E 02	2.04E-03	8.173E-02	1.05E-03	2.275E-02	2.89E-04
18	3.76892E 02	2.04E-03	1.148E-03	2.40E-05	2.350E-02	2.35E 00
19	3.97583E 02	2.04E-03	6.258E-03	1.42E-04	2.383E-02	3.93E-03
20	4.10205E 02	2.04E-03	2.018E-02	3.02E-04	2.371E-02	5.27E-04
21	4.34036E 02	2.04E-03	9.817E-03	1.83E-04	2.329E-02	5.68E-04
22	4.63138E 02	2.04E-03	5.494E-03	1.48E-04	2.350E-02	1.20E-03
23	4.78400E 02	2.04E-03	4.188E-03	1.02E-04	2.350E-02	2.35E 00
24	5.18334E 02	2.04E-03	4.960E-02	7.50E-04	2.359E-02	5.02E-04
25	5.35276E 02	2.04E-03	4.428E-02	7.41E-04	2.382E-02	2.85E-04
26	5.80082E 02	2.04E-03	4.123E-02	7.92E-04	2.480E-02	4.50E-04
27	5.95014E 02	2.04E-03	8.641E-02	1.32E-03	2.314E-02	2.82E-04
28	6.19948E 02	2.04E-03	3.076E-02	5.10E-04	2.332E-02	3.78E-04
29	6.28529E 02	2.04E-03	6.249E-03	1.08E-04	2.350E-02	2.35E 00
30	6.61149E 02	2.04E-03	1.280E-01	2.03E-03	2.537E-02	9.73E-04
31	6.93050E 02	2.04E-03	4.222E-02	8.38E-04	2.350E-02	4.50E-04
32	7.08273E 02	2.04E-03	2.179E-02	5.89E-04	2.345E-02	5.52E-04
33	7.21586E 02	4.09E-03	1.720E-03	5.58E-05	2.350E-02	2.35E 00
34	7.30147E 02	6.12E-03	9.341E-04	4.76E-05	2.350E-02	2.35E 00
35	7.65055E 02	2.04E-03	7.767E-03	2.77E-04	1.700E-02	2.00E-03
36	7.90821E 02	4.09E-03	6.618E-03	1.23E-04	2.350E-02	2.35E 00
37	8.21559E 02	2.04E-03	6.549E-02	1.33E-03	2.272E-02	5.36E-04
38	8.50986E 02	2.04E-03	6.291E-02	1.46E-03	2.552E-02	7.56E-04
39	8.56077E 02	2.04E-03	8.617E-02	1.98E-03	2.355E-02	7.31E-04
40	8.66420E 02	4.09E-03	5.533E-03	2.00E-04	2.350E-02	2.35E 00
41	9.05031E 02	2.04E-03	5.457E-02	1.05E-03	2.461E-02	1.25E-03
42	9.25110E 02	4.09E-03	1.360E-02	4.60E-04	2.500E-02	4.00E-03
43	9.37020E 02	2.04E-03	1.493E-01	2.21E-03	2.366E-02	5.78E-04
44	9.58520E 02	2.04E-03	2.038E-01	3.21E-03	2.285E-02	7.16E-04
45	9.91630E 02	2.04E-03	3.773E-01	3.78E-03	2.989E-02	1.36E-03
46	1.02296E 03	6.13E-03	8.442E-03	3.35E-04	2.350E-02	2.35E 00
47	1.05445E 03	2.04E-03	9.393E-02	1.95E-03	2.311E-02	4.61E-04
48	1.09862E 03	4.09E-03	2.195E-02	6.83E-04	2.350E-02	2.12E-03
49	1.10906E 03	4.09E-03	3.361E-02	8.58E-04	2.400E-02	2.00E-03
50	1.14035E 03	2.04E-03	2.331E-01	3.20E-03	2.382E-02	7.21E-04
51	1.16763E 03	4.09E-03	8.771E-02	2.32E-03	2.410E-02	4.79E-04
52	1.17707E 03	4.09E-03	7.016E-02	1.84E-03	2.200E-02	1.66E-03
53	1.19481E 03	4.09E-03	9.486E-02	2.02E-03	2.040E-02	1.79E-03
54	1.21111E 03	6.13E-03	9.193E-03	2.80E-04	2.350E-02	2.35E 00
55	1.24506E 03	2.04E-03	2.521E-01	4.10E-03	2.271E-02	7.43E-04
56	1.26704E 03	4.09E-03	2.917E-02	7.02E-04	2.402E-02	1.09E-03
57	1.27297E 03	6.13E-03	2.847E-02	8.26E-04	2.288E-02	1.09E-03
58	1.29862E 03	1.22E-02	3.576E-03	2.84E-04	2.350E-02	2.35E 00
59	1.39381E 03	4.09E-03	2.075E-01	3.66E-03	2.427E-02	7.73E-04
60	1.40543E 03	4.09E-03	7.198E-02	1.82E-03	2.552E-02	7.43E-04
61	1.41976E 03	8.16E-03	9.361E-03	4.43E-04	2.350E-02	2.35E 00
62	1.42801E 03	4.09E-03	2.856E-02	8.95E-04	2.555E-02	9.49E-04
63	1.44405E 03	6.13E-03	1.626E-02	6.90E-04	2.200E-02	3.00E-03
64	1.47382E 03	4.09E-03	1.223E-01	2.67E-03	2.387E-02	5.88E-04
65	1.52270E 03	4.09E-03	2.452E-01	4.24E-03	2.388E-02	1.47E-03
66	1.55059E 03	1.22E-02	3.372E-03	2.73E-04	2.350E-02	2.35E 00
67	1.56549E 03	1.02E-02	5.519E-03	3.20E-04	2.350E-02	2.35E 00
68	1.59789E 03	4.09E-03	3.747E-01	6.56E-03	2.223E-02	6.90E-04
69	1.62267E 03	4.09E-03	1.019E-01	2.65E-03	2.232E-02	6.82E-04
70	1.63807E 03	4.09E-03	5.183E-02	1.56E-03	2.298E-02	6.82E-04
71	1.66245E 03	4.09E-03	2.211E-01	4.58E-03	2.419E-02	7.84E-04
72	1.68876E 03	4.09E-03	1.053E-01	2.57E-03	2.355E-02	6.82E-04
73	1.70985E 03	4.09E-03	9.031E-02	2.61E-03	2.800E-02	5.00E-03
74	1.72289E 03	6.13E-03	1.727E-02	7.71E-04	2.210E-02	2.00E-03
75	1.75589E 03	4.09E-03	1.365E-01	2.98E-03	2.700E-02	4.00E-03
76	1.78269E 03	4.09E-03	6.532E-01	9.45E-03	2.350E-02	2.35E 00
77	1.80840E 03	8.17E-03	1.843E-02	9.15E-04	1.700E-02	5.00E-03
78	1.84610E 03	8.17E-03	1.060E-02	5.55E-04	1.500E-02	5.00E-03
79	1.86760E 03	8.38E-02	8.807E-04	4.41E-04	2.350E-02	2.35E 00
80	1.90283E 03	4.09E-03	4.438E-02	1.41E-03	2.465E-02	9.70E-04
81	1.91327E 03	1.43E-02	2.221E-03	3.07E-04	2.350E-02	2.35E 00
82	1.91716E 03	4.09E-03	3.975E-02	1.56E-03	2.313E-02	1.44E-03

[1] For the fission widths, see Table XXII-b.

Table XXII-a. (Continued)

	E_o	δE_o	Γ_n	$\delta\Gamma_n$	Γ_γ	$\delta\Gamma_\gamma$
83	1.95378E 03	1.43E-02	4.192E-03	1.68E-04	2.350E-02	2.35E 00
84	1.96898E 03	4.09E-03	8.094E-01	8.79E-03	3.000E-02	1.00E-02
85	1.97491E 03	4.09E-03	4.293E-01	5.49E-03	2.350E-02	2.35E 00
86	2.02368E 03	4.09E-03	2.211E-01	5.74E-03	2.348E-02	9.70E-04
87	2.03049E 03	8.17E-03	4.757E-02	2.32E-03	2.471E-02	1.17E-03
88	2.08862E 03	8.17E-03	2.485E-02	1.22E-03	2.200E-02	4.00E-03
89	2.09629E 03	8.17E-03	2.454E-02	1.25E-03	2.350E-02	2.35E 00
90	2.14556E 03	4.09E-03	7.436E-02	2.24E-03	2.378E-02	1.07E-03
91	2.15276E 03	4.09E-03	2.881E-01	5.28E-03	2.438E-02	7.96E-04
92	2.18658E 03	4.09E-03	5.784E-01	8.59E-03	2.420E-02	9.90E-04
93	2.20126E 03	6.13E-03	1.064E-01	3.61E-03	2.600E-02	5.00E-03
94	2.25970E 03	1.22E-02	1.081E-01	3.93E-03	2.540E-02	1.00E-03
95	2.26654E 03	8.17E-03	2.321E-01	6.89E-03	2.000E-02	5.00E-03
96	2.28192E 03	8.17E-03	1.844E-01	5.08E-03	1.800E-02	5.00E-03
97	2.31594E 03	1.43E-02	1.937E-02	1.21E-03	2.350E-02	2.35E 00
98	2.35274E 03	8.17E-03	5.346E-02	2.80E-03	2.800E-02	5.00E-03
99	2.35573E 03	1.02E-02	7.131E-02	3.26E-03	2.400E-02	5.00E-03
100	2.39198E 03	1.02E-02	2.977E-02	1.06E-03	2.350E-02	2.35E 00
101	2.42689E 03	6.13E-03	1.533E-01	4.71E-03	2.350E-02	2.35E 00
102	2.44670E 03	6.13E-03	2.165E-01	5.55E-03	2.350E-02	1.20E-03
103	2.45575E 03	1.63E-02	1.729E-02	9.55E-04	2.350E-02	2.35E 00
104	2.48918E 03	6.13E-03	1.032E-01	3.02E-03	2.450E-02	1.30E-03
105	2.52149E 03	1.02E-02	1.718E-02	1.03E-03	2.350E-02	2.35E 00
106	2.54819E 03	4.09E-03	7.150E-01	1.04E-02	2.350E-02	2.35E 00
107	2.55959E 03	4.09E-03	2.645E-01	6.27E-03	2.350E-02	2.35E 00
108	2.58115E 03	4.09E-03	4.270E-01	7.24E-03	2.360E-02	2.35E 00
109	2.59761E 03	4.09E-03	7.477E-01	1.39E-02	2.250E-02	1.10E-03
110	2.62005E 03	1.23E-02	4.868E-02	2.20E-03	2.350E-02	2.35E 00
111	2.67222E 03	6.13E-03	2.801E-01	6.26E-03	2.400E-02	1.40E-03
112	2.69650E 03	1.23E-02	2.952E-02	1.50E-03	2.350E-02	2.35E 00
113	2.71733E 03	6.13E-03	1.702E-01	4.98E-03	2.350E-02	2.35E 00
114	2.75074E 03	1.23E-02	4.030E-02	1.71E-03	2.350E-02	2.35E 00
115	2.76266E 03	1.84E-02	1.863E-02	1.07E-03	2.350E-02	2.35E 00
116	2.78742E 03	1.84E-02	1.310E-02	1.15E-03	2.350E-02	2.35E 00
117	2.80638E 03	2.29E-02	9.444E-03	1.16E-03	2.350E-02	2.35E 00
118	2.82932E 03	1.43E-02	1.991E-02	1.27E-03	2.350E-02	2.35E 00
119	2.86539E 03	1.23E-02	2.016E-01	8.91E-03	2.200E-02	1.40E-03
120	2.88278E 03	8.18E-03	5.951E-01	1.53E-02	2.460E-02	1.40E-03
121	2.89722E 03	2.83E-02	1.714E-02	1.55E-03	2.350E-02	2.35E 00
122	2.93365E 03	1.23E-02	3.673E-02	1.88E-03	2.360E-02	1.50E-03
123	2.95693E 03	1.63E-02	2.179E-02	1.79E-03	2.350E-02	2.35E 00
124	3.00362E 03	8.18E-03	1.216E-01	4.19E-03	2.490E-02	1.50E-03
125	3.02861E 03	8.18E-03	1.358E-01	4.22E-03	2.350E-02	2.35E 00
126	3.05965E 03	1.43E-02	3.064E-02	1.78E-03	2.400E-02	3.00E-03
127	3.10991E 03	6.13E-03	2.314E-01	6.42E-03	2.350E-02	2.35E 00
128	3.14903E 03	8.18E-03	1.066E-01	3.48E-03	2.320E-02	1.40E-03
129	3.16979E 03	2.65E-02	1.079E-02	1.08E-03	2.350E-02	2.35E 00
130	3.17883E 03	8.18E-03	9.341E-02	3.13E-03	2.350E-02	2.35E 00
131	3.18891E 03	8.18E-03	1.091E-01	3.54E-03	2.150E-02	2.00E-03
132	3.20881E 03	8.18E-03	9.569E-02	3.19E-03	2.350E-02	2.35E 00
133	3.21970E 03	4.08E-02	1.010E-02	1.01E-03	2.350E-02	2.35E 00
134	3.22039E 03	1.84E-02	2.533E-02	2.30E-03	2.350E-02	2.35E 00
135	3.24886E 03	1.43E-02	2.531E-02	1.42E-03	2.250E-02	2.50E-03
136	3.27951E 03	6.13E-03	2.740E-01	7.95E-03	2.350E-02	2.35E 00
137	3.31218E 03	8.18E-03	1.626E-01	5.04E-03	2.350E-02	2.35E 00
138	3.32164E 03	8.18E-03	1.335E-01	4.98E-03	2.230E-02	2.00E-03
139	3.33366E 03	1.02E-02	1.026E-01	4.23E-03	2.390E-02	1.80E-03
140	3.35881E 03	1.02E-02	1.242E-01	4.49E-03	2.360E-02	1.50E-03
141	3.38975E 03	1.43E-02	2.235E-02	1.44E-03	2.350E-02	2.35E 00
142	3.40877E 03	6.13E-03	2.306E-01	6.20E-03	2.350E-02	2.35E 00
143	3.43645E 03	6.13E-03	3.966E-01	8.13E-03	2.390E-02	1.50E-03
144	3.45814E 03	6.13E-03	6.967E-01	1.25E-02	2.480E-02	2.00E-03
145	3.48580E 03	1.02E-02	9.598E-02	3.53E-03	2.350E-02	2.35E 00
146	3.49259E 03	1.31E 00	1.444E-02	2.74E-02	2.350E-02	2.35E 00
147	3.56159E 03	6.13E-03	2.574E-01	6.65E-03	2.350E-02	2.35E 00
148	3.57404E 03	6.13E-03	4.166E-01	8.59E-03	2.350E-02	2.35E 00
149	3.59502E 03	1.23E-02	5.311E-02	2.72E-03	2.350E-02	2.35E 00
150	3.62324E 03	1.23E-02	2.084E-02	2.01E-03	2.360E-02	2.35E 00
151	3.62980E 03	6.13E-03	5.153E-01	1.40E-02	2.350E-02	2.35E 00
152	3.69319E 03	6.13E-03	4.044E-01	8.64E-03	2.360E-02	2.35E 00
153	3.71680E 03	1.02E-02	1.102E-01	4.21E-03	2.350E-02	2.35E 00
154	3.73421E 03	8.18E-03	2.155E-01	5.32E-03	2.350E-02	2.35E 00
155	3.76511E 03	1.02E-02	9.719E-02	2.98E-03	2.350E-02	2.35E 00
156	3.78196E 03	6.13E-03	4.565E-01	9.59E-03	2.400E-02	2.20E-03
157	3.83159E 03	3.47E-02	1.339E-02	1.05E-03	2.350E-02	2.35E 00
158	3.85779E 03	6.13E-03	5.651E-01	1.22E-02	2.350E-02	2.35E 00
159	3.87310E 03	2.25E-02	1.708E-01	1.07E-02	2.350E-02	2.35E 00
160	3.90222E 03	6.13E-03	2.884E-01	9.35E-03	2.430E-02	2.50E-03
161	3.91503E 03	1.23E-02	1.049E-01	4.03E-03	2.240E-02	2.50E-03
162	3.94006E 03	1.02E-02	1.834E-01	5.90E-03	2.390E-02	2.50E-03
163	3.95494E 03	1.23E-02	1.278E-01	3.91E-03	2.350E-02	2.35E 00
164	4.04103E 03	4.94E-01	6.501E-02	3.55E-03	2.350E-02	2.35E 00

Table XXII-b. s-Wave Resonance Parameters and Their Uncorrelated Standard Deviations

(All values in eV)

	E_0	δE_0	Γ_f	$\delta\Gamma_f$
1	-2.00000E 01	0.0		
2	6.67200E 00	2.04E-04	1.033E-08	1.03E-09
3	2.08640E 01	2.04E-04	5.995E-08	6.00E-09
4	3.66710E 01	2.04E-04	8.877E-09	8.88E-10
5	6.60150E 01	2.04E-04	5.146E-08	5.15E-09
6	8.07290E 01	2.04E-04	6.615E-08	6.61E-09
7	1.02536E 02	2.04E-03	1.225E-08	1.22E-09
8	1.16674E 02	2.04E-03		
9	1.45630E 02	2.04E-03		
10	1.65258E 02	2.04E-03		
11	1.89636E 02	2.04E-03	4.772E-08	4.77E-09
12	2.08474E 02	2.04E-03	8.809E-08	8.81E-09
13	2.37342E 02	2.04E-03	6.003E-08	6.00E-09
14	2.73621E 02	2.04E-03		
15	2.90961E 02	2.04E-03		
16	3.11281E 02	2.04E-03		
17	3.47751E 02	2.04E-03	2.676E-07	2.68E-08
18	3.76692E 02	2.04E-03	2.054E-07	2.05E-08
19	3.97583E 02	2.04E-03		
20	4.10205E 02	2.04E-03		
21	4.34036E 02	2.04E-03		
22	4.63138E 02	2.04E-03	1.474E-06	1.47E-07
23	4.78400E 02	2.04E-03	2.409E-07	2.41E-08
24	5.18334E 02	2.04E-03	2.926E-07	2.93E-08
25	5.35276E 02	2.04E-03	3.670E-07	3.67E-08
26	5.80082E 02	2.04E-03		
27	5.95014E 02	2.04E-03	1.099E-06	1.10E-07
28	6.19548E 02	2.04E-03	2.147E-07	2.15E-08
29	6.28529E 02	2.04E-03		
30	6.61145E 02	2.04E-03		
31	6.93050E 02	2.04E-03		
32	7.08273E 02	2.04E-03	2.564E-05	2.56E-06
33	7.21586E 02	4.09E-03	1.096E-03	1.10E-04
34	7.30147E 02	6.12E-03	9.261E-05	9.26E-06
35	7.65055E 02	2.04E-03	5.945E-06	5.95E-07
36	7.90821E 02	4.09E-03		
37	8.21559E 02	2.04E-03		
38	8.50986E 02	2.04E-03	1.215E-06	1.21E-07
39	8.56077E 02	2.04E-03	1.107E-06	1.11E-07
40	8.66420E 02	4.09E-03		
41	9.05031E 02	2.04E-03		
42	9.25110E 02	4.09E-03		
43	9.37020E 02	2.04E-03		
44	9.58520E 02	2.04E-03		
45	9.91630E 02	2.04E-03		
46	1.02296E 03	6.13E-03		
47	1.05445E 03	2.04E-03		
48	1.09862E 03	4.09E-03		
49	1.10908E 03	4.09E-03		
50	1.14035E 03	2.04E-03	1.595E-06	1.60E-07
51	1.16763E 03	4.09E-03	1.171E-05	1.17E-06
52	1.17707E 03	4.09E-03		
53	1.19481E 03	4.09E-03		
54	1.21111E 03	6.13E-03	2.734E-04	2.73E-05
55	1.24506E 03	2.04E-03		
56	1.26704E 03	4.09E-03	4.282E-06	4.28E-07

Table XXIII. p-Wave Resonance Parameters and Their Uncorrelated Standard Deviation

(All values in eV)

	E_o	δE_o	Γ_n	$\delta\Gamma_n$	Γ_γ	Γ_γ
1	4.40400E 00	2.04E-04	1.121E-07	1.47E-08	2.350E-02	2.35E 00
2	1.02360E 01	2.04E-04	1.674E-06	3.55E-08	2.350E-02	2.35E 00
3	1.13090E 01	4.09E-04	4.002E-07	2.73E-08	2.350E-02	2.35E 00
4	1.62912E 01	1.63E-01	4.966E-08	1.06E-08	2.350E-02	2.35E 00
5	1.95230E 01	4.09E-04	1.393E-06	7.38E-08	2.350E-02	2.35E 00
6	4.51660E 01	4.09E-04	1.963E-06	3.84E-07	2.350E-02	2.35E 00
7	4.96260E 01	6.13E-03	9.691E-07	3.55E-07	2.350E-02	2.35E 00
8	6.35090E 01	8.17E-04	1.031E-05	5.31E-07	2.350E-02	2.35E 00
9	7.27809E 01	7.28E-01	1.000E-05	1.00E-05	2.350E-02	2.35E 00
10	7.43801E 01	7.44E-01	2.700E-06	2.00E-06	2.350E-02	2.35E 00
11	8.36836E 01	1.83E-03	1.081E-05	6.96E-07	2.350E-02	2.35E 00
12	8.92890E 01	1.67E-02	9.489E-05	2.63E-06	2.350E-02	2.35E 00
13	9.09764E 01	9.10E-01	6.000E-06	1.20E-05	2.350E-02	2.35E 00
14	9.30970E 01	4.09E-03	5.932E-06	6.04E-07	2.350E-02	2.35E 00
15	9.61748E 01	9.82E-01	4.800E-06	2.00E-06	2.350E-02	2.35E 00
16	1.11208E 02	8.18E-03	8.399E-06	1.47E-06	2.350E-02	2.35E 00
17	1.24970E 02	6.01E 03	2.298E-06	1.03E-06	2.350E-02	2.35E 00
18	1.33292E 02	1.02E-02	8.651E-06	2.76E-06	2.350E-02	2.35E 00
19	1.52419E 02	4.08E-03	5.075E-05	3.16E-06	2.350E-02	2.35E 00
20	1.58946E 02	6.12E-03	1.533E-05	2.80E-06	2.350E-02	2.35E 00
21	1.73167E 02	4.09E-03	4.677E-05	3.71E-06	2.350E-02	2.35E 00
22	1.94779E 02	1.95E 00	4.965E-05	1.06E-05	2.350E-02	2.35E 00
23	2.00711E 02	5.99E-03	5.846E-05	5.12E-06	2.350E-02	2.35E 00
24	2.03108E 02	5.98E-03	3.584E-05	4.15E-06	2.350E-02	2.35E 00
25	2.14850E 02	7.83E-03	6.214E-05	6.19E-06	2.350E-02	2.35E 00
26	2.18323E 02	1.27E-02	3.136E-05	5.25E-06	2.350E-02	2.35E 00
27	2.24967E 02	2.00E 00	1.986E-05	1.06E-05	2.350E-02	2.35E 00
28	2.42711E 02	4.02E-03	1.871E-04	7.67E-06	2.350E-02	2.35E 00
29	2.53891E 02	4.04E-03	1.082E-04	8.11E-06	2.350E-02	2.35E 00
30	2.57239E 02	1.81E-02	1.723E-05	4.47E-06	2.350E-02	2.35E 00
31	2.63931E 02	4.02E-03	2.580E-04	1.05E-05	2.350E-02	2.35E 00
32	2.75113E 02	6.09E-03	1.825E-04	1.40E-05	2.350E-02	2.35E 00
33	2.82431E 02	6.06E-03	1.043E-04	8.52E-06	2.350E-02	2.35E 00
34	3.06242E 02	2.00E 00	5.000E-05	4.00E-05	2.350E-02	2.35E 00
35	3.22861E 02	1.64E-02	4.326E-05	5.87E-06	2.350E-02	2.35E 00
36	3.31971E 02	1.23E-02	5.342E-05	8.54E-06	2.350E-02	2.35E 00
37	3.37251E 02	6.09E-03	1.049E-04	9.56E-06	2.350E-02	2.35E 00
38	3.51660E 02	8.08E-03	2.224E-04	1.52E-05	2.350E-02	2.35E 00
39	3.54782E 02	1.63E-01	3.596E-05	2.11E-05	2.350E-02	2.35E 00
40	3.66335E 02	2.00E 00	5.000E-05	4.00E-05	2.350E-02	2.35E 00
41	3.72642E 02	8.30E-02	3.906E-05	1.53E-05	2.350E-02	2.35E 00
42	3.87133E 02	2.00E 00	4.000E-05	4.00E-05	2.350E-02	2.35E 00
43	3.95264E 02	2.00E 00	7.070E-05	1.45E-05	2.350E-02	2.35E 00
44	4.00432E 02	2.00E 00	4.000E-05	4.00E-05	2.350E-02	2.35E 00
45	4.08212E 02	1.22E-02	8.312E-05	1.51E-05	2.350E-02	2.35E 00
46	4.13431E 02	2.00E 00	5.000E-06	4.00E-06	2.350E-02	2.35E 00
47	4.15431E 02	2.00E 00	5.000E-05	4.00E-05	2.350E-02	2.35E 00
48	4.22931E 02	2.00E 00	5.000E-05	1.00E-04	2.360E-02	2.35E 00
49	4.39736E 02	6.09E-03	2.896E-04	1.52E-05	2.350E-02	2.35E 00
50	4.48357E 02	2.86E-02	4.815E-05	1.30E-05	2.350E-02	2.35E 00
51	4.54048E 02	4.09E-03	4.264E-04	1.67E-05	2.350E-02	2.35E 00
52	4.67149E 02	2.45E-02	6.419E-05	1.82E-05	2.350E-02	2.35E 00
53	4.85280E 02	1.23E-02	1.464E-04	1.91E-05	2.350E-02	2.35E 00
54	4.88880E 02	4.08E-03	7.623E-04	3.35E-05	2.350E-02	2.35E 00
55	4.94526E 02	2.00E 00	5.000E-05	2.00E-05	2.350E-02	2.35E 00
56	4.98675E 02	1.59E-02	1.087E-04	1.67E-05	2.350E-02	2.35E 00
57	5.11025E 02	2.00E 00	1.000E-04	4.00E-05	2.350E-02	2.35E 00
58	5.23234E 02	8.08E-03	2.768E-04	2.14E-05	2.350E-02	2.35E 00
59	5.28124E 02	2.00E 00	7.000E-05	6.00E-05	2.350E-02	2.35E 00
60	5.32124E 02	2.00E 00	6.404E-05	2.01E-05	2.350E-02	2.36E 00
61	5.42433E 02	1.50E-02	1.532E-04	1.85E-05	2.350E-02	2.36E 00
62	5.50980E 02	2.96E-02	7.937E-05	2.00E-05	2.350E-02	2.35E 00
63	5.56242E 02	1.93E-02	8.709E-04	4.25E-05	2.350E-02	2.36E 00
64	5.60123E 02	2.00E 00	4.500E-05	2.00E-05	2.350E-02	2.35E 00
65	5.66423E 02	2.00E 00	3.300E-05	2.00E-05	2.350E-02	2.35E 00
66	5.84463E 02	4.09E-02	9.775E-05	2.98E-05	2.350E-02	2.35E 00
67	6.06713E 02	1.43E-02	2.700E-04	3.14E-05	2.350E-02	2.36E 00
68	6.15748E 02	1.80E-02	1.461E-04	2.62E-05	2.350E-02	2.35E 00
69	6.24197E 02	6.08E-03	7.980E-04	3.99E-05	2.350E-02	2.35E 00
70	6.33290E 02	3.07E-02	1.261E-04	3.58E-05	2.350E-02	2.35E 00
71	6.36421E 02	2.00E 00	1.200E-04	6.00E-05	2.350E-02	2.35E 00
72	6.68410E 02	2.16E-02	2.045E-04	3.58E-05	2.350E-02	2.35E 00
73	6.77744E 02	8.06E-03	7.264E-04	4.92E-05	2.350E-02	2.35E 00
74	6.81021E 02	2.00E 00	5.190E-05	2.81E-05	2.350E-02	2.35E 00
75	6.85121E 02	2.00E 00	6.000E-05	6.00E-05	2.350E-02	2.35E 00
76	6.88121E 02	2.00E 00	8.000E-05	6.00E-05	2.350E-02	2.35E 00
77	6.98078E 02	2.71E-02	2.736E-04	4.69E-05	2.350E-02	2.35E 00
78	7.04721E 02	2.00E 00	1.000E-04	6.00E-05	2.350E-02	2.35E 00
79	7.10589E 02	5.37E-02	1.048E-03	6.67E-05	2.350E-02	2.35E 00
80	7.13774E 02	2.51E-02	2.219E-04	3.64E-05	2.350E-02	2.35E 00
81	7.16821E 02	2.00E 00	1.000E-04	1.00E-04	2.350E-02	2.35E 00
82	7.32469E 02	4.08E-03	1.954E-03	6.21E-05	2.350E-02	2.35E 00
83	7.34721E 02	2.00E 00	1.625E-04	3.46E-05	2.350E-02	2.35E 00
84	7.43140E 02	1.42E-02	3.537E-04	3.73E-05	2.350E-02	2.35E 00
85	7.56243E 02	1.02E-02	5.358E-04	3.99E-05	2.350E-02	2.35E 00
86	7.72652E 02	2.00E 00	1.390E-04	7.41E-05	2.350E-02	2.35E 00
87	7.79309E 02	4.08E-03	2.129E-03	7.76E-05	2.350E-02	2.35E 00
88	7.85820E 02	5.11E-02	1.365E-04	3.98E-05	2.350E-02	2.35E 00
89	7.87328E 02	3.49E-02	4.605E-04	2.98E-05	2.350E-02	2.35E 00
90	7.97322E 02	2.00E 00	1.300E-04	2.60E-04	2.350E-02	2.35E 00
91	8.08169E 02	1.43E-02	3.826E-04	4.60E-05	2.350E-02	2.35E 00
92	8.28749E 02	2.96E-02	1.780E-04	2.68E-05	2.350E-02	2.35E 00
93	8.34447E 02	2.00E 00	8.833E-05	3.99E-05	2.350E-02	2.35E 00

Table XXIII. (Continued)

	E_0	δE_0	Γ_n	$\delta\Gamma_n$	Γ_γ	Γ_γ
94	8.46656E 02	8.16E-03	8.725E-04	6.30E-05	2.350E-02	2.35E 00
95	8.59521E 02	2.00E 00	4.116E-04	4.19E-05	2.350E-02	2.35E 00
96	8.91228E 02	1.62E-02	7.670E-04	7.07E-05	2.350E-02	2.35E 00
97	9.10018E 02	1.22E-02	1.360E-03	7.09E-05	2.350E-02	2.35E 00
98	9.40936E 02	3.39E-02	6.227E-04	8.83E-05	2.350E-02	2.35E 00
99	9.64446E 02	4.84E-02	2.883E-04	5.35E-05	2.350E-02	2.35E 00
100	9.77363E 02	1.99E-02	7.656E-04	6.66E-05	2.350E-02	2.35E 00
101	9.82423E 02	2.00E 00	8.932E-05	5.29E-05	2.350E-02	2.35E 00
102	9.84483E 02	2.00E 00	1.620E-04	5.12E-05	2.350E-02	2.35E 00
103	1.00337E 03	2.00E 00	2.100E-04	8.00E-05	2.350E-02	2.35E 00
104	1.00500E 03	1.64E-01	1.995E-04	2.94E-04	2.350E-02	2.35E 00
105	1.01145E 03	1.62E-02	1.867E-03	9.98E-05	2.350E-02	2.35E 00
106	1.02912E 03	1.21E-02	2.308E-03	1.09E-04	2.350E-02	2.35E 00
107	1.03382E 03	3.02E-02	7.426E-04	7.54E-05	2.350E-02	2.35E 00
108	1.04103E 03	2.00E 00	2.500E-04	2.00E-04	2.350E-02	2.35E 00
109	1.04731E 03	3.67E-02	3.933E-04	6.00E-05	2.350E-02	2.35E 00
110	1.06268E 03	2.62E-02	7.661E-04	6.97E-05	2.350E-02	2.35E 00
111	1.06768E 03	2.16E-02	1.069E-03	8.42E-05	2.350E-02	2.35E 00
112	1.07407E 03	2.20E-02	9.082E-04	9.16E-05	2.350E-02	2.35E 00
113	1.08172E 03	1.59E-02	1.519E-03	1.05E-04	2.350E-02	2.35E 00
114	1.09519E 03	1.01E-02	2.276E-03	1.24E-04	2.350E-02	2.35E 00
115	1.10290E 03	1.40E-02	2.221E-03	1.10E-04	2.350E-02	2.35E 00
116	1.11897E 03	4.50E-02	5.169E-04	8.92E-05	2.350E-02	2.35E 00
117	1.13137E 03	8.07E-03	3.641E-03	1.81E-04	2.350E-02	2.35E 00
118	1.14544E 03	2.00E 00	9.923E-06	5.29E-06	2.350E-02	2.35E 00
119	1.14864E 03	2.00E 00	2.977E-04	1.06E-04	2.350E-02	2.35E 00
120	1.15268E 03	5.58E-02	5.721E-04	1.30E-04	2.350E-02	2.35E 00
121	1.15509E 03	3.75E-02	8.023E-04	8.25E-05	2.350E-02	2.35E 00
122	1.15935E 03	3.68E-02	7.368E-04	8.92E-05	2.350E-02	2.35E 00
123	1.18475E 03	2.00E 00	2.000E-04	2.00E-04	2.350E-02	2.35E 00
124	1.20135E 03	7.97E-02	5.435E-04	8.14E-05	2.350E-02	2.35E 00
125	1.21988E 03	5.59E-02	5.549E-04	1.51E-04	2.350E-02	2.35E 00
126	1.23006E 03	5.76E-02	3.976E-04	1.51E-04	2.350E-02	2.35E 00
127	1.23309E 03	6.34E-02	4.043E-04	1.14E-04	2.350E-02	2.35E 00
128	1.25155E 03	7.07E-02	5.738E-04	1.32E-04	2.350E-02	2.35E 00
129	1.26092E 03	2.00E 00	1.985E-04	1.06E-04	2.350E-02	2.35E 00
130	1.26296E 03	2.00E 00	3.000E-04	4.00E-04	2.350E-02	2.35E 00
131	1.27660E 03	4.33E-02	7.194E-04	2.57E-04	2.350E-02	2.35E 00
132	1.27702E 03	2.00E 00	6.946E-04	3.71E-04	2.350E-02	2.35E 00
133	1.28362E 03	2.00E 00	3.969E-04	2.12E-04	2.350E-02	2.35E 00
134	1.28548E 03	1.21E-01	4.211E-04	1.30E-04	2.350E-02	2.35E 00
135	1.28932E 03	2.00E 00	2.426E-04	9.36E-05	2.350E-02	2.35E 00
136	1.29622E 03	2.00E 00	9.922E-05	6.35E-05	2.350E-02	2.35E 00
137	1.31099E 03	1.66E-01	2.338E-04	2.37E-04	2.350E-02	2.35E 00
138	1.31701E 03	1.01E-02	4.793E-03	2.54E-04	2.350E-02	2.35E 00
139	1.32485E 03	1.72E-01	1.981E-04	2.94E-04	2.350E-02	2.35E 00
140	1.32596E 03	2.00E 00	4.000E-04	2.00E-04	2.350E-02	2.35E 00
141	1.33147E 03	2.16E-02	1.282E-03	1.00E-04	2.350E-02	2.35E 00
142	1.33797E 03	2.00E 00	2.400E-04	2.00E-04	2.350E-02	2.35E 00
143	1.36066E 03	6.13E-02	4.304E-04	1.72E-04	2.350E-02	2.35E 00
144	1.38632E 03	7.51E-02	2.674E-04	9.14E-05	2.350E-02	2.35E 00
145	1.38710E 03	2.00E 00	8.906E-05	5.21E-05	2.350E-02	2.35E 00
146	1.40998E 03	3.52E-01	5.044E-04	3.99E-04	2.350E-02	2.35E 00
147	1.41692E 03	1.42E-02	3.479E-03	1.92E-04	2.350E-02	2.35E 00
148	1.43809E 03	2.00E 00	4.372E-04	1.05E-04	2.350E-02	2.35E 00
149	1.44768E 03	3.59E-02	1.099E-03	1.97E-04	2.350E-02	2.35E 00
150	1.45478E 03	2.00E 00	1.953E-04	8.60E-05	2.350E-02	2.35E 00
151	1.48677E 03	9.41E-02	1.902E-04	9.07E-05	2.350E-02	2.35E 00
152	1.49449E 03	2.00E 00	6.000E-04	4.00E-04	2.350E-02	2.35E 00
153	1.50427E 03	7.77E-02	1.902E-04	9.07E-05	2.350E-02	2.35E 00
154	1.50810E 03	7.77E-02	3.946E-04	2.94E-04	2.350E-02	2.35E 00
155	1.51097E 03	3.74E-02	7.578E-04	1.32E-04	2.350E-02	2.35E 00
156	1.52775E 03	6.59E-02	7.726E-04	1.51E-04	2.350E-02	2.35E 00
157	1.53485E 03	4.79E-02	7.869E-04	1.78E-04	2.350E-02	2.35E 00
158	1.54721E 03	1.62E-02	3.898E-03	1.85E-04	2.350E-02	2.35E 00
159	1.55527E 03	1.43E-01	3.389E-04	8.92E-05	2.350E-02	2.35E 00
160	1.56621E 03	3.27E-02	1.249E-03	2.15E-04	2.350E-02	2.35E 00
161	1.57960E 03	2.00E 00	4.000E-04	2.00E-04	2.350E-02	2.35E 00
162	1.59152E 03	3.07E-02	1.144E-03	1.92E-04	2.350E-02	2.35E 00
163	1.61161E 03	2.00E 00	4.000E-04	2.00E-04	2.350E-02	2.35E 00
164	1.67270E 03	2.39E-01	9.303E-05	3.13E-05	2.350E-02	2.35E 00
165	1.68232E 03	2.00E 00	4.000E-04	4.00E-04	2.350E-02	2.35E 00
166	1.69599E 03	1.55E-01	4.072E-04	2.96E-04	2.350E-02	2.35E 00
167	1.70670E 03	3.27E-02	1.375E-03	4.41E-04	2.350E-02	2.35E 00
168	1.74967E 03	3.04E-02	1.687E-03	1.87E-04	2.350E-02	2.35E 00
169	1.76864E 03	2.00E 00	5.000E-04	4.00E-04	2.350E-02	2.35E 00
170	1.77641E 03	4.09E-02	6.894E-04	1.91E-04	2.350E-02	2.35E 00
171	1.78134E 03	1.53E-01	1.177E-03	1.03E-03	2.350E-02	2.35E 00
172	1.79747E 03	3.97E-02	2.788E-03	2.95E-04	2.350E-02	2.35E 00
173	1.82360E 03	7.97E-02	7.158E-04	1.49E-04	2.350E-02	2.35E 00
174	1.83416E 03	2.62E-01	4.163E-04	1.82E-04	2.350E-02	2.35E 00
175	1.86656E 03	2.00E 00	2.900E-03	1.00E-03	2.350E-02	2.35E 00
176	1.86953E 03	3.84E-02	2.610E-03	2.78E-04	2.350E-02	2.35E 00
177	1.88109E 03	4.09E-02	1.435E-03	1.87E-04	2.350E-02	2.35E 00
178	1.89385E 03	3.89E-02	1.558E-03	1.87E-04	2.350E-02	2.35E 00
179	1.92542E 03	6.75E-02	9.447E-04	2.50E-04	2.350E-02	2.35E 00
180	1.93337E 03	2.00E 00	4.000E-04	4.00E-04	2.350E-02	2.35E 00
181	1.94275E 03	9.00E-02	6.688E-04	1.72E-04	2.350E-02	2.35E 00
182	1.99000E 03	1.45E-01	1.437E-03	3.51E-04	2.350E-02	2.35E 00
183	2.00067E 03	3.19E-01	4.886E-04	1.89E-04	2.350E-02	2.35E 00
184	2.04901E 03	5.11E-02	2.248E-03	3.67E-04	2.350E-02	2.35E 00
185	2.05275E 03	1.47E-01	8.683E-04	1.99E-04	2.350E-02	2.35E 00
186	2.06334E 03	2.00E 00	2.479E-04	1.59E-04	2.350E-02	2.35E 00

Table XXIII. (Continued)

	E_0	δE_0	Γ_n	$\delta\Gamma_n$	Γ_γ	Γ_γ
187	2.07139E 03	3.66E-02	1.664E-03	1.52E-04	2.350E-02	2.35E 00
188	2.08076E 03	5.32E-02	1.595E-03	1.99E-04	2.350E-02	2.35E 00
189	2.08609E 03	2.29E-02	4.352E-03	5.51E-04	2.350E-02	2.35E 00
190	2.10413E 03	5.52E-02	1.406E-03	1.53E-04	2.350E-02	2.35E 00
191	2.11402E 03	1.55E-01	9.536E-04	3.39E-04	2.350E-02	2.35E 00
192	2.12416E 03	2.89E-02	3.893E-03	3.37E-04	2.350E-02	2.35E 00
193	2.14063E 03	2.00E 00	9.917E-04	5.29E-04	2.350E-02	2.35E 00
194	2.17272E 03	4.62E-02	2.220E-03	1.99E-04	2.350E-02	2.35E 00
195	2.17903E 03	2.00E 00	7.933E-04	4.24E-04	2.350E-02	2.35E 00
196	2.21543E 03	4.50E-02	3.418E-03	2.99E-04	2.350E-02	2.35E 00
197	2.24144E 03	2.07E-01	1.080E-03	2.91E-04	2.350E-02	2.35E 00
198	2.27143E 03	2.00E 00	3.768E-03	3.18E-04	2.350E-02	2.35E 00
199	2.29395E 03	1.47E-01	1.260E-03	1.17E-03	2.350E-02	2.35E 00
200	2.29652E 03	5.89E-02	5.734E-03	3.15E-04	2.350E-02	2.35E 00
201	2.32691E 03	3.13E-01	1.461E-03	2.81E-04	2.350E-02	2.35E 00
202	2.33859E 03	2.03E-02	8.839E-03	8.82E-04	2.350E-02	2.35E 00
203	2.36875E 03	3.84E-02	6.117E-03	6.43E-04	2.350E-02	2.35E 00
204	2.38442E 03	1.92E-01	1.464E-03	4.28E-04	2.350E-02	2.35E 00
205	2.39776E 03	3.87E-02	4.670E-03	2.74E-04	2.350E-02	2.35E 00
206	2.40180E 03	3.87E-02	4.389E-03	6.97E-04	2.350E-02	2.35E 00
207	2.41122E 03	2.64E-02	5.144E-03	3.62E-04	2.350E-02	2.35E 00
208	2.41867E 03	2.04E-01	1.038E-03	3.67E-04	2.350E-02	2.35E 00
209	2.44743E 03	2.00E 00	3.960E 04	2.10E 01	2.360E-02	2.35E 00
210	2.50223E 03	3.68E-02	3.855E-03	3.82E-04	2.350E-02	2.35E 00
211	2.52706E 03	1.29E-01	8.677E-04	5.87E-04	2.350E-02	2.35E 00
212	2.60480E 03	8.44E-01	3.094E-03	1.18E-02	2.350E-02	2.35E 00
213	[illegible]	1.13E-01	3.194E-03	4.19E-04	2.350E-02	2.35E 00
214	2.61205E 03	7.77E-02	4.865E-03	5.17E-04	2.350E-02	2.35E 00
215	2.63270E 03	7.03E-02	4.313E-03	4.67E-04	2.350E-02	2.35E 00
216	2.63681E 03	9.81E-02	2.882E-03	4.92E-04	2.350E-02	2.35E 00
217	2.65403E 03	2.00E 00	9.913E-04	3.18E-04	2.350E-02	2.35E 00
218	2.65866E 03	4.65E-02	4.254E-03	8.63E-04	2.350E-02	2.35E 00
219	2.68276E 03	1.43E-01	2.360E-03	5.83E-04	2.350E-02	2.35E 00
220	2.70199E 03	8.59E-02	1.767E-03	7.87E-04	2.350E-02	2.35E 00
221	2.76665E 03	5.11E-02	3.084E-03	4.07E-04	2.350E-02	2.35E 00
222	2.77483E 03	1.23E-01	1.500E-03	5.40E-04	2.350E-02	2.35E 00
223	2.77873E 03	2.00E 00	1.289E-03	4.24E-04	2.350E-02	2.35E 00
224	2.79954E 03	4.04E-02	4.968E-03	4.53E-04	2.350E-02	2.35E 00
225	2.81163E 03	5.11E-02	5.162E-03	4.83E-04	2.350E-02	2.35E 00
226	2.81620E 03	1.53E-01	1.371E-03	6.01E-04	2.350E-02	2.35E 00
227	2.82353E 03	2.00E 00	1.982E-03	1.06E-03	2.350E-02	2.35E 00
228	2.84554E 03	9.85E-01	5.965E-04	3.18E-04	2.350E-02	2.35E 00
229	2.87760E 03	4.50E-02	2.150E-03	2.99E-04	2.350E-02	2.35E 00
230	2.91837E 03	5.11E-02	7.041E-03	7.50E-04	2.350E-02	2.35E 00
231	2.92267E 03	7.45E-02	6.757E-03	6.48E-04	2.350E-02	2.35E 00
232	2.92559E 03	5.73E-02	6.701E-03	1.64E-03	2.350E-02	2.35E 00
233	2.94531E 03	7.36E-02	2.138E-03	7.87E-04	2.350E-02	2.35E 00
234	2.96756E 03	6.01E-02	3.766E-03	4.63E-04	2.350E-02	2.35E 00
235	2.98860E 03	4.05E-02	6.642E-03	6.06E-04	2.350E-02	2.35E 00
236	3.01517E 03	1.95E-01	1.459E-03	8.93E-04	2.350E-02	2.35E 00
237	3.02470E 03	4.29E-02	4.194E-03	1.17E-03	2.350E-02	2.35E 00
238	3.04380E 03	5.45E-02	3.527E-03	5.29E-04	2.360E-02	2.35E 00
239	3.07228E 03	1.91E-01	1.027E-03	3.07E-04	2.350E-02	2.35E 00
240	3.08113E 03	1.20E-01	1.709E-03	3.98E-04	2.350E-02	2.36E 00
241	3.08871E 03	7.36E-02	3.552E-03	7.87E-04	2.350E-02	2.35E 00
242	3.10356E 03	1.15E-01	2.158E-03	9.45E-04	2.350E-02	2.35E 00
243	3.13041E 03	8.38E-02	3.081E-03	1.12E-03	2.350E-02	2.35E 00
244	3.13388E 03	3.05E-02	8.312E-03	6.08E-04	2.350E-02	2.35E 00
245	3.24045E 03	3.80E-01	1.528E-03	4.83E-04	2.350E-02	2.35E 00
246	3.26402E 03	1.80E-01	1.831E-03	1.03E-03	2.350E-02	2.35E 00
247	3.26753E 03	3.48E-02	9.866E-03	1.13E-03	2.350E-02	2.35E 00
248	3.27329E 03	1.64E-02	1.086E-02	1.42E-03	2.350E-02	2.35E 00
249	3.29748E 03	3.47E-02	9.629E-03	9.21E-04	2.350E-02	2.35E 00
250	3.30781E 03	4.29E-02	4.735E-03	1.32E-03	2.350E-02	2.35E 00
251	3.34122E 03	7.77E-02	4.072E-03	6.03E-04	2.350E-02	2.35E 00
252	3.34682E 03	2.07E-01	1.419E-03	1.47E-03	2.350E-02	2.35E 00
253	3.36657E 03	2.00E 00	8.917E-04	5.29E-04	2.350E-02	2.35E 00
254	3.37829E 03	3.48E-02	7.675E-03	1.17E-03	2.350E-02	2.35E 00
255	3.38379E 03	8.79E-02	3.562E-03	7.87E-04	2.350E-02	2.35E 00
256	3.39527E 03	3.47E-02	7.729E-03	9.61E-04	2.350E-02	2.35E 00
257	3.41780E 03	1.03E-01	4.080E-03	5.75E-04	2.350E-02	2.35E 00
258	3.47058E 03	1.31E 00	1.513E-03	5.47E-03	2.350E-02	2.35E 00
259	3.49571E 03	4.47E-02	1.065E-02	1.07E-03	2.350E-02	2.35E 00
260	3.51346E 03	1.52E-01	1.898E-03	4.96E-04	2.350E-02	2.35E 00
261	3.51486E 03	2.00E 00	1.585E-03	5.29E-04	2.350E-02	2.35E 00
262	3.52226E 03	1.27E-01	2.068E-03	4.98E-04	2.350E-02	2.35E 00
263	3.52853E 03	5.09E-02	6.317E-03	8.61E-04	2.350E-02	2.35E 00
264	3.63693E 03	1.15E-01	7.947E-03	8.27E-04	2.350E-02	2.35E 00
265	3.65422E 03	1.78E-01	2.707E-03	9.08E-04	2.350E-02	2.35E 00
266	3.66240E 03	2.27E-01	2.603E-03	5.91E-04	2.350E-02	2.35E 00
267	3.67334E 03	6.71E-02	5.117E-03	5.88E-04	2.350E-02	2.35E 00
268	3.68324E 03	6.95E-02	4.376E-03	8.59E-04	2.350E-02	2.35E 00
269	3.72469E 03	8.59E-02	7.258E-03	9.26E-04	2.350E-02	2.35E 00
270	3.74199E 03	2.25E-01	8.365E-04	4.15E-04	2.350E-02	2.35E 00
271	3.75891E 03	2.00E 00	1.981E-03	4.24E-04	2.350E-02	2.35E 00
272	3.79112E 03	2.00E 00	2.872E-03	6.35E-04	2.360E-02	2.35E 00
273	3.80922E 03	2.00E 00	6.438E-04	5.29E-04	2.350E-02	2.35E 00
274	3.82569E 03	7.97E-02	4.462E-03	6.91E-04	2.350E-02	2.35E 00
275	3.88037E 03	1.57E-01	2.904E-03	6.18E-04	2.350E-02	2.35E 00
276	3.89476E 03	5.52E-02	8.524E-03	1.80E-03	2.350E-02	2.35E 00
277	3.92790E 03	5.73E-02	1.240E-02	1.65E-03	2.350E-02	2.35E 00
278	3.93033E 03	2.00E 00	1.387E-02	3.18E-03	2.350E-02	2.35E 00
279	3.93336E 03	4.09E-02	1.209E-02	2.10E-03	2.350E-02	2.35E 00
280	3.99294E 03	2.00E 00	2.971E-03	1.59E-03	2.350E-02	2.35E 00

The systematic relative error on the neutron widths appears to increase linearly with energy and is approximately 4% at low energy and 20% near the upper limit of the resolved range. On that basis we estimate the systematic error to be:

$$\frac{\delta\Gamma_{nj}}{\Gamma_{nj}} = .03 + .04\ E_j, \text{ with } E_j \text{ in keV} \qquad (20)$$

This error is taken to be fully correlated over energy and among s- and p-wave levels.

There is reasonable agreement among recent determinations of the average capture width for s-wave, hence we estimate the systematic uncertainty on the capture width of s-wave levels to be .5 mV. This corresponds to an accuracy of approximately 2% for the average s-wave capture width. There is essentially no direct information concerning the p-wave average capture width. In fact the only p-wave capture width for which experimental values are available is that of the level at 10.24 eV. Some argument can be made for a parity dependence of the average capture width.[D27] Hence, the uncertainty in the average value of the capture widths is larger than that for s-wave levels and is somewhat arbitrarily estimated to be ± 5 mV.

There are difficult normalization problems arising in the determination of the subthreshold fission areas, hence it is not surprising to find systematic differences among the data from independent experiments. From the scatter of those data the systematic relative error in the fission widths is estimated to be 20%.

We have already noted in Section 3 that no significant external correlations are observed among the partial widths of a level reported by different authors, in spite of the fact that most measurements will yield strongly correlated values for these partial widths. This was attributed to the fact that most determinations of the partial widths are based on a number of experiments which have different internal correlations, and also the statistical uncertainties on the capture and fission widths are sufficiently large as to obscure possible correlations. We conclude that the correlations between the evaluated values of different partial widths are not significant.

The uncertainty in the scattering radius was estimated at $\pm .025 \times 10^{-12}$ cm from the scatter of the values reported in Table X.

The uncertainties in the smooth backgrounds (File 3) were estimated from the various approximations used in the computation of these backgrounds. The scattering background is estimated to have an uncertainty of $\pm$ 0.2 b. correlated over all energies. The capture background is estimated to have an uncertainty of $\pm$.02 b correlated over all energies, and a second uncertainty of $\pm$ ($.0016E^{\frac{1}{2}}$) b, where E is the neutron energy in eV, also correlated over all energies but not correlated to the first uncertainty. The second uncertainty arises from the possibility of missing small levels or overcompensating for missed levels. The uncertainty in the subthreshold fission background below 1. eV is estimated to be $\pm$ 60%. The estimated systematic errors are summarized in Table XXIV.

Table XXIV. Systematic Uncertainties in the Evaluated Parameters

---

The following systematic uncertainties are correlated over the range 0 to 4 keV. Uncorrelated (statistical) uncertainties are given in Tables XXII and XXIII. See text for details.

1. Energy Scale: $\frac{\delta E_o}{E_o} = 0.00025$

2. Neutron Widths: $\frac{\delta \Gamma_n}{\Gamma_n} = 0.03 + 0.0004\ Eo$ (for s- and p-waves)

3. Capture Widths: $\frac{\delta \Gamma_\gamma}{\Gamma_\gamma} = \begin{cases} 0.05 \text{ for s-wave levels} \\ 0.2 \text{ for p-wave levels} \end{cases}$

4. Fission Widths: $\frac{\delta \Gamma_f}{\Gamma_f} = 0.2$

5. Smooth Scattering Background: $\delta\sigma_n = \pm 0.2b$

6. Smooth Capture Background: $\delta\sigma_\gamma^{(1)} = \pm 0.02b$

7. Capture due to Unresolved Levels: $\delta\sigma_\gamma^{(2)} = \pm .0016E^{1/2}$ in b.

8. Effective Scattering Radius: $\delta\hat{a} = \pm .025 \times 10^{-12}$ cm

(in these expressions, the energy is assumed to be in eV)

---

9. CONCLUSIONS

The present evaluation differs significantly in many respects from ENDF/B-IV. These differences result mostly from new measurements and new analyses of older measurements.

The most significant changes, for computing performance parameters of thermal reactors, are surely the reduction of the capture widths of the first three s-wave levels, by about 15%, and the increased neutron widths of the levels at 20.9 eV and 36.8 eV, by about 10%.

Above 1.5 keV the Γ_n's obtained in this evaluation are on the average 10 to 20% larger than those of ENDF/B-IV. This is because the ENDF/B-IV values were mostly based on the measurements of Rahn et al.[B20] whereas the new measurements of Nakajima et al.,[B26] Poortmans et al.,[B32] and Olsen et al.,[B31] as well as the older measurement of Carraro and Kolar[B17] all yield values of Γ_n larger than those given by Rahn et al. This is illustrated in Fig. 19 where the local s-wave strength function over successive intervals of 500 eV from different measurements are compared.

A number of small levels considered s-wave levels in ENDF/B-IV are here considered as p-wave levels, and vice versa. The ENDF/B-IV angular momentum assignments essentially followed that of Rahn et al.[B20] The different assignments in this evaluation mostly result from the work of Corvi, Rohr and Weigmann[B25] and from a systematic application of the Δ_3 statistic. The present evaluation has 162 s-wave and 258 p-wave levels in the interval 0-4 keV, whereas ENDF/B-IV had 190 s-wave and 220 p-wave levels in the same interval.

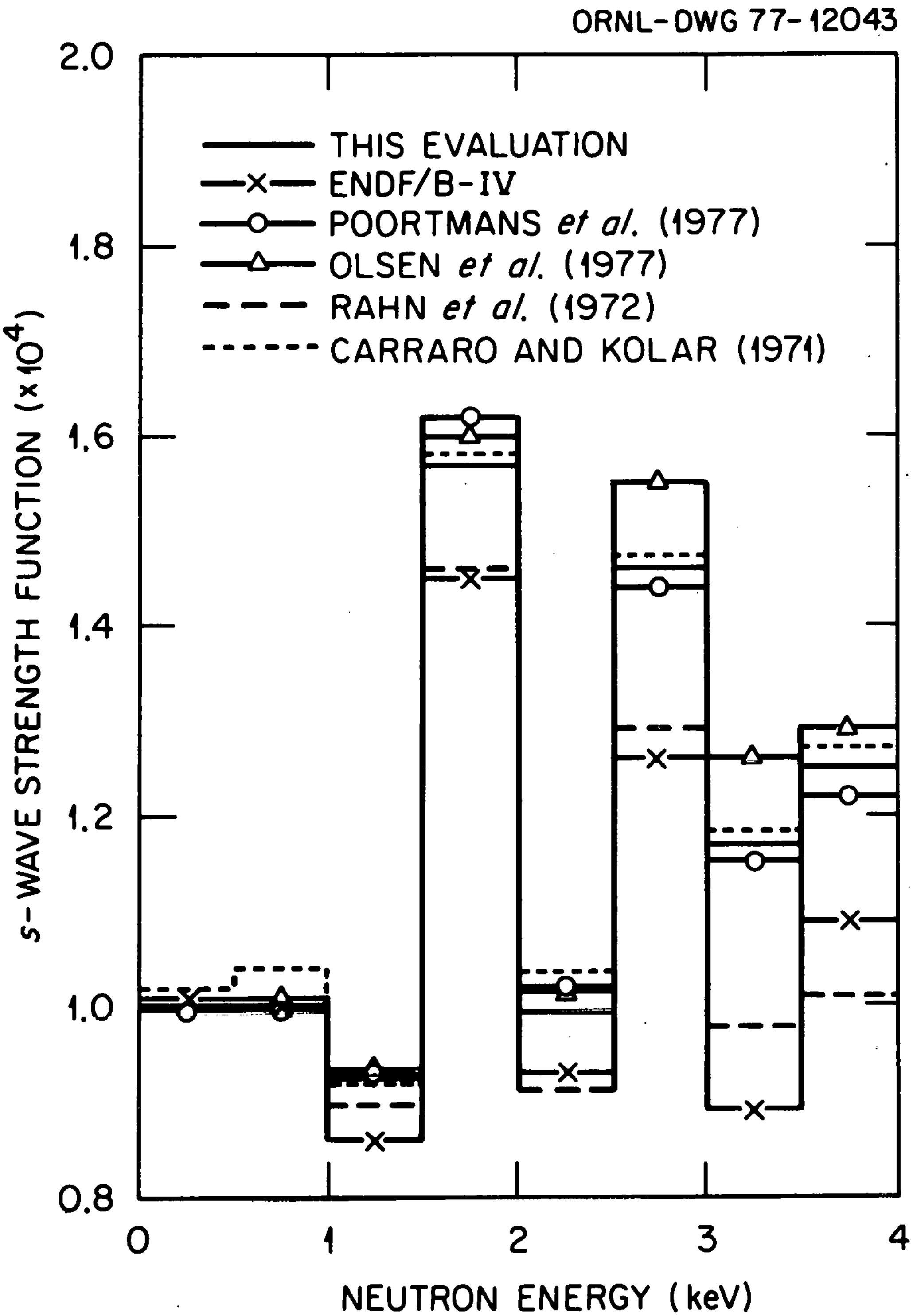

Fig. 19. Comparison of local s-wave strength functions. The values were obtained by adding the reduced neutron widths reported by the author indicated for the levels assigned to s-waves in the present evaluation.

The more precise calculation of the scattering background and the use of a multilevel formula for the calculation of the s-wave contribution will avoid "negative cross sections" and the systematic discrepancies between levels which were present in ENDF/B-IV.[D11]

Finally the recent measurements of Slovacek et al.[B29] and Difilippo et al.[B33] allow a much better definition of the subthreshold fission than what was included in ENDF/B-IV.

A number of problems have been encountered in this evaluation which point to the desirability of further work.

There are systematic discrepancies, often of the order of 20%, among the various values reported for Γ_n, particularly above 1.5 keV. These discrepancies are present even among the most recent measurements. In our opinion the discrepancies result from inadequate methods of analyzing transmission measurements, particularly at high energy where backgrounds are difficult to estimate and where resolution broadening is important and often asymmetric. The work of Derrien[D3] and Ribon[D2] illustrates some of the problems.

The most recent measurements (after 1972) of the capture and neutron widths of the important first few s-wave levels are very consistent but it is somewhat surprising that those recent measurements yield values so much different than the average of older measurements.

As illustrated in Table XVIII there are fairly large discrepancies between the direct measurements of the capture cross section and calculations based on the evaluated resonance parameters. Since there are large discrepancies also among the various direct measurements of capture, we believe the computed values to be more reliable.

Finally, careful measurements of the capture and total cross sections below 1 eV appear very desirable. This energy region is of course very important for thermal reactor calculations. The "thermal cross sections" are well determined by a number of independent measurements, but it is difficult to reconcile these thermal values with any reasonable assumption concerning the bound levels near the binding energy. It is not unlikely that much of the thermal capture is due to a small p-wave level near zero energy. If this were so the capture cross section might not be inversely proportional to the velocity in the thermal region, as is usually assumed.

An attempt was made to evaluate statistical and systematic uncertainties for all the parameters of this evaluation. The evaluation of those uncertainties is based only on differential data. It would be desirable to test the evaluation against integral data such as performance parameters from thermal benchmarks. In Table XXV the infinitely dilute capture resonance integral computed from ENDF/B-IV and from this evaluation are compared with the value reported by BNL-325[C2] and based on direct experimental measurements.[D28] Both evaluated values agree well with the measurements.

An early version of this evaluation was used in a sensitivity analysis of the TRX-2 lattic parameters.[D9] The study indicated that the proposed modifications of the partial widths of the first few s-wave levels improved the agreement between calculated and measured values of the ratio of epithermal-to-thermal ^{238}U captures in TRX-2. This is consistent with the result of similar calculations[A7] based on a reduction of the capture width of the level at 6.67 eV.

Table XXV. Infinite Dilution Capture Resonance Integral

1.	Computation with present evaluation:	
	1/v part of cross section	1.215 b
	Resolved s-wave levels	275.18 b
	Resolved p-wave levels	.81 b
	Cross section above 4 keV (estimated)	2.19 b
	Total	279.4 b
2.	Computed with ENDF/B-IV	278.4 b
3.	Experimental value (BNL-325)	275±5 b

REFERENCES

A. Proceedings of the following conferences contain a number of papers which have been used in this evaluation:

A1. Conference on Neutron Cross Sections and Technology, March 4-7, 1968, Washington, D. C.; see NBS Special Publication 299 (September 1968), also identified as USAEC TIC publication CONF-6860083; hereinafter referred as "CONF-6860083."

A2. Conference on Nuclear Data for Reactors, June 15-19, 1970, Helsinki; see IAEA publication STI/PuB/259, Vienna, 1970; hereinafter referred as "Helsinki-1970."

A3. Conference on Neutron Cross Sections and Technology, March 15-17, 1971, Knoxville, TN; see USAEC DTIE publication CONF-710301; hereinafter referred as "CONF-710301."

A4. National Topical Meeting on New Developments in Reactor Physics and Shielding, September 12-15, 1972, Kiamesha Lake, NY; see USAEC TIC publication CONF-720901; hereinafter referred as "CONF-720901."

A5. Specialists Meeting on Resonance Parameters of Fertile Nuclei and ^{239}Pu," May 20-22, 1974, Saclay; see NEANDC(E) publication 1634, January, 1975; hereinafter referred as "Specialist Meeting - 1974."

A6. Conference on Nuclear Cross Section Technology, March 3-7, 1975, Washington, D. C.; see NBS special publication 425 (October 1975), also identified as USERDA publication CONF-75619216; hereinafter referred as "CONF-75619216."

A7. Seminar on ^{238}U Resonance Capture, March 18-20, 1975, Brookhaven National Laboratory; see BNL publication NCS -50451, ENDF-217 edited by S. Pearlstein (August 1975); hereinafter referred as "ENDF-217-1975."

A8. International Conference on the Interaction of Neutrons and Nuclei, July 6-9, 1976, Lowell, Massachusetts; see USERDA publication TIC CONF-760715; hereinafter referred as "CONF-760715."

B. Measurements of the ^{238}U resonance parameters were obtained from the following references:

B1. J. A. Harvey, D. J. Hughes, R. S. Carter, and V. E. Pilcher, Phys. Rev. 99, 10 (1955); also private communication from J. A. Harvey (1976).

B2. J. S. Levin and D. J. Hughes, Phys. Rev. 101, 1328 (1956).

B3. J. E. Lynn and N. J. Pattenden, Proc. International Conf. on Peaceful Uses of Atomic Energy 4, 210 (1956).

B4. R. G. Fluharty, F. B. Simpson, and O. D. Simpson, Phys. Rev. 103, 1778 (1956).

B5. L. M. Bollinger, R. E. Coté, D. A. Dahlberg, and G. E. Thomas, Phys. Rev. 105, 661 (1957).

B6. I. A. Radkevich, V. V. Vladimirsky, and V. V. Sokolovsky, J. Nuc. Energy 5, 92 (1967).

B7. J. L. Rosen, J. S. Desjardins, J. Rainwater, and W. W. Havens, Phys. Rev. 118, 687 (1960).

B8. H. E. Jackson and J. E. Lynn, Phys. Rev. 127, 461 (1962).

B9. M. C. Moxon and C. M. Mycock (1962); given as private communication (1962) in BNL-325 (1965) (see ref. C2).

B10. F. W. K. Firk, J. E. Lynn, and M. C. Moxon, Nucl. Phys. 41, 614 (1963).

B11. J. B. Garg, J. Rainwater, J. S. Peterson, and W. W. Havens, Phys. Rev. 134, B985 (1964).

B12. A. Michaudon, H. Derrien, P. Ribon, and M. Sanche-Cauvin, Nucl. Phys. 69, 545 (1965).

B13. M. Asghar, C. M. Chaffey, and M. C. Moxon, Nucl. Phys. 85, 305 (1966).

B14. N. W. Glass, A. D. Schelberg, L. D. Tatro, and J. W. Warren, "U-238 Neutron Capture Results from Bomb Source Neutrons," CONF-6860083 Vol. 1, p. 573 (1968) (see ref. A1).

B15. L. M. Bollinger and G. E. Thomas, Phys. Rev. 171, 1293 (1968).

B16. G. Rohr, W. Weigmann, and J. Winter, Helsinki - 1970, 1, 413, (see ref. A2).

B17. G. Carraro and W. Kolar, Helsinki - 1970, 1, 403 (see ref. A2) and CONF-710301 2, 701 (1971) (see ref. A3).

B18. M. G. Silbert and D. W. Bergen, Phys. Rev. C, 4, 220 (1971).

B19. K. L. Maletski, L. B. Pikel'ner, I. M. Salamatin, and E. I. Sharapov. Sovt. J. At. Energy 32, 45 (1972).

B20. F. Rahn, H. S. Camarda, G. Hacken, W. W. Havens, Jr., H. I. Liou, J. Rainwater, M. Slagowitz, and S. Wynchank, Phys. Rev. C, 6, 1854 (1972).

B21. R. C. Block, R. W. Hockenbury, R. E. Slovacek, E. B. Bean, and D. S. Cramer, Phys. Lett. 31, 247 (1973).

B22. H. Ceulemans, "Resonance Scattering Cross Section of ^{238}U below 220 eV," Specialists Meeting - 1974, p. 145 (see ref. A5).

B23. F. Poortmans, L. Mewissen, G. Rohr, H. Weigmann, and G. Vanpraet, "Neutron Scattering Cross Section Measurements on ^{238}U in the Resolved Energy Range," Specialists Meeting - 1974, p.149 (see ref. A5).

B24. J. A. Wartena, H. Weigmann and E. Migneco, CONF-75619216 2, 597 (see ref. A6).

B25. F. Corvi, G. Rohr and H. Weigmann, CONF-75619216 2, 733 (see ref. A6).

B26. Y. Nakajima, A. Asami, M. Mizumoto, T. Fuketa, and H. Takekoshi, CONF-75619216 2, 738 (see ref. A6).

B27. R. C. Block, R. W. Hockenbury, R. E. Slovacek, Series II, Bull. Am. Phys. Soc. 20, 138 (1975); and R. E. Slovacek, D. S. Cramer, E. B. Bean, R. W. Hockenbury, J. R. Valentine, and R. C. Block, Series II, Bull. Am. Phys. Soc. 20, 581 (1975).

B28. J. Blons, C. Mazur and D. Paya, CONF-75619216 2, 642 (see ref. A6).

B29. R. E. Slovacek, D. S. Cramer, E. B. Bean, J. R. Valentine, R. W. Hockenbury, R. C. Block, Nucl. Sci. Eng. 62, 455 (1977).

B30. H. I. Liou, R. E. Chrien, Nucl. Sci. Eng. 62, 463 (1977); and R. E. Chrien, H. I. Liou and J. Kopecky, CONF-760715, p. 1298 (see ref. A8); also private communication from the authors (1976).

B31. D. K. Olsen, G. deSaussure, R. B. Perez, E. G. Silver, F. C. Difilippo, R. W. Ingle, and H. Weaver, Nucl. Sci. Eng. 62, 479 (1977); and D. K. Olsen, G. deSaussure, R. B. Perez, F. C. Difilippo and R. W. Ingle, "Note on ^{238}U + n Resolved Resonance Energies" submitted for publication in Nucl. Sci. Eng. (1977).

B32. F. Poortmans, E. Cornelis, L. Mewissen, G. Rohr, R. Shelley, T. Van der Veen, G. Vanpraet, and H. Weigmann, "Cross Sections and Neutron Resonance Parameters for ^{238}U below 4 keV," p. 1246 CONF-760715 (see ref. A8); also private communication from F. Poortmans (April 1977).

B33. F. C. Difilippo, R. B. Perez, G. deSaussure, D. K. Olsen, and R. W. Ingle, "Measurement of the ^{238}U Subthreshold Fission Cross Section for Incident Neutron Energies between 0.6 and 100 keV," Nucl. Sci. Eng. 63, 153 (1977); also CONF-760715, p. 1401 (see ref. A8) and unpublished work (1977).

B34. R. C. Block, D. R. Harris, and K. Kobayashi, "Recent ^{238}U Self-indication Measurements at RPI," private communication from R. C. Block (January 1977).

C. The following evaluations of the ^{238}U cross sections and resonance parameters are very extensive:

C1. ENDF/B ^{238}U

Version I, Mat 1047

W. A. Wittkopf, D. H. Roy, and A. Z. Livolsi, "^{238}U Neutron Cross Section Data for ENDF/B," ENDF-103 (BAW-316) (May 1967).

Version II, Mat 1107

T. A. Pitterle, "Evaluation of ^{238}U Neutron Cross Sections for ENDF/B Version II File," WARD-4181-1 (March 1971); "Evaluation of ^{238}U Neutron Cross Sections for the ENDF/B File," Helsinki - 1970, p. 687 (see ref. A2).

Version III, Mat 1158

T. A. Pitterle, N. C. Paik, and C. Durston, "Evaluation and Integral Testing of Modifications to ENDF/B Version II Data," WARD-4210T4-1 (December 1971); and C. Durston and T. A. Pitterle, "Evaluation of ^{238}U Neutron Cross Sections for ENDF/B Version III File," WARD-3045T4B2 (April 30, 1972).

Version IV, Mat 1262

F. J. McCrosson, "Evaluation of ^{238}U Cross Sections for ENDF/B-IV" ENDF-217-1975, p. 122 (see ref. A7).

C2. J. R. Stehn, M. D. Goldberg, R. Wiener Chasman, S. F. Mughabghab, B. A. Magurno, and V. M. May, "Neutron Cross Sections" Vol. III, BNL-325, Second Edition (1965); and S. F. Mughabghab and D. I. Garber, "Neutron Cross Sections, Vol. I, Resonance Parameters," BNL-325, Third Edition (1973).

C3. J. J. Schmidt, "Neutron Cross Sections for Reactor Materials," KFK-120, Part I, (1966).

C4. J. Ravier, "Evaluation des Section Efficaces de l' ^{238}U," Cadarache Report PNR/SETR R. .025, Cadarache, France (February 1968).

C5. M. Moxon, "Evaluation of ^{238}U Resonance Parameters" Specialists Meeting - 1974, p. 45 (see ref. A5).

C6. J. R. Askew, "The Current U.K. Position on ^{238}U Resonance Capture" ENDF-217-1975, p. 45, (see ref. A7).

D. Other references are listed below:

D1. D. R. Finch, private communication, October 6, 1976.

D2. H. Derrien and P. Ribon, "On the Shape Analysis of Various ^{232}Th and ^{238}U Transmission Data," Specialists Meeting - 1974, p. 63 (see ref. A5).

D3. H. Derrien, "Comments on ^{238}U Neutron Width Evaluations," ENDF-217-1975, p. 156 (see ref. A7).

D4. Experimental Neutron Resonance Spectroscopy, Edited by J. A. Harvey, Academic Press, New York and London, 1970.

D5. G. D. James, "Neutron Energy Standards," paper presented at "International Specialists Symposium on Neutron Standards and Applications," March 28-31, 1977, NBS (proceedings to be published).

D6. G. deSaussure, R. Gwin, L. W. Weston, R. W. Ingle, R. R. Fullwood, and R. W. Hockenbury, "Simultaneous Measurements of the Neutron Fission and Capture Cross Sections for ^{235}U for Incident Neutron Energies from 0.4 to 3 keV," ORNL-TM-1804 (1967).

D7. F. Rahn and W. W. Havens, Jr., "A Review of the Total Radiation Widths of Neutron Resonances of ^{238}U," EANDC(US)-179/U, European American Nuclear Data Committee.

D8. F. G. Dyson and M. L. Metha, J. Math. Phys. 4, 701 (1963).

D9. E. T. Tomlinson, G. deSaussure and C. R. Weisbin, "Sensitivity Analysis for TRX-2 Lattice Parameters with Emphasis on Epithermal ^{238}U Capture," ERPI NP-346 (1977); and Trans. ANS, June 12-17, 1977.

D10. ENDF/B formats are defined in ENDF-102, "Data Formats and Procedures for the Evaluated Nuclear Data File, ENDF," Revised by D. Garber, C. Dunford, and S. Pearlstein, BNL-NCS-50496 (October 1975 and June 1976).

D11. G. deSaussure, D. K. Olsen, and R. B. Perez, Nucl. Sci. and Eng. 61, 496 (1976).

D12. D. J. Hughes and R. L. Zimmerman, Nuclear Reactions, P. M. Endt and M. Demeur, Eds, Vol. 1, pp. 384-390, North Holland Publishers, Amsterdam (1959); and K. K. Seth, D. J. Hughes, R. L. Zimmerman, and R. C. Garth, Phy. Rev. 110, 692 (1958).

D13. J. E. Lynn, Proc. Phys. Soc. 82, 903 (1963).

D14. M. Divadeenam, unpublished Ph.D. Thesis, Duke University 1968.

D15. C. A. Uttley, Proc. International Conf. on Nucl. Phys., Paris p. 700 (1964); C. A. Uttley, "Total Neutron Cross Section Measurements in Nuclear Data for Reactor," Program at AERE for Period 1, July 1963 - December 31, 1963, EANDC-(UK), 35L, p. 2 (1964).

D16. B. R. Leonard, Jr., "Energy Dependent Cross Sections in the Thermal Regions," CONF-720901, p. 81 (see ref. A4).

D17. B. R. Leonard, Jr., "Thermal Cross Sections of the Fissile and Fertile Nuclei for ENDF/B-II," BNWL-1586 (June 1971).

D18. J. B. Hunt, J. C. Robertson, and T. B. Ryves, Nucl. Energy 23, 705 (1969).

S. P. Harris, D. Rose, and H. D. Schroeder, ANL-LAT-109 (1954).

P. A. Egelstaff, J. Nucl. Energy 1, 92 (1954).

V. S. Crocker, J. Nucl. Energy 1, 234 (1955).

V. G. Small, J. Nucl. Energy 1, 319 (1955).

S. J. Cocking and P. A. Egelstaff, NRDC-84, part 2 (1955).

P. A. Egelstaff and J. W. Hall, NRDC-84, part 2 (1955).

H. Palevsky, unpublished, quoted in Proc. Geneva Conf. 4, 147 (1955).

C. B. Bingham, R. W. Durham, and J. Ungrin, EANDC(Can) 34, (1968).

D19. R. B. Roof, G. P. Arnold, and K. A. Gschneider, Acta. Cryst. 15, 351 (1962).

M. Atoji, J. Chem. Phys. 35, 1950 (1961).

B. T. M. Willis, Proc. Roy. Soc. London A,274, 122 (1963).

D.20 G. deSaussure, E. G. Silver, R. B. Perez, R. Ingle, and H. Weaver, "Measurement of the ^{238}U Capture for Incident Neutron Energies up to 100 keV," (ORNL-TM-4059 (February 1973); also Nucl. Sci. Eng. 51, 385-404 (1973) and subsequent unpublished work (1975).

D21. M. P. Fricke, W. M. Lopez, S. J. Friesenhahn, A. D. Carlson, and D. G. Costello, "Measurements of Cross Sections for the Radioactive Capture of 1 keV to 1 MeV Neutrons by Mo. Rh, Gd, Ta, W, Re, Au, and ^{238}U," Helsinki - 1750, Vol. II, p. 265 (see ref. A2).

D22. M. C. Moxon, "The Neutron Capture Cross Section of ^{238}U in the Energy Region 0.5 to 100 keV," AERE-R-6074 (1969) (see ref. C1 or D20 for 1971 update).

D23. E. P. Wigner, "Proc. Conf. on Neutron Physics by Time-of-Flight, Gatlinburg, TN, 1956," ORNL-2309, 59 (1957).

D24. C. E. Porter and R. G. Thomas, Phys. Rev. 104, 483 (1957).

D25. J. J. Gurevitch and H. S. Pevzner, Soviet Phys. JETP4, 278 (1957).

D26. J. A. Harvey and D. J. Hughes, Phys. Rev. 109, 471 (1958).

D27. See for instance: H. Derrien, "Evaluation of ^{232}Th Resonance Parameters," Specialists Meeting - 1974, p. 73 (see ref. A5); an argument somewhat similiar to that made by Derrien for ^{232}Th could be made for ^{238}U.

D28. J. Hardy, Jr., Nucl. Sci. Eng. 27, 131 (1967).

THIS PAGE

WAS INTENTIONALLY

LEFT BLANK

ORNL/TM-6152
ENDF-257
Dist. Category UC-79d

INTERNAL DISTRIBUTION

1. L. S. Abbott
2. M. A. Bjerke
3. G. T. Chapman
4-28. G. de Saussure
29. J. K. Dickens
30. F. C. Difilippo
31. J. D. Drischler
32. G. F. Flanagan
33. C. Y. Fu
34. H. Goldstein (Consultant)
35. R. Gwin
36. R. W. Ingle
37. D. C. Larson
38. R. L. Macklin
39. F. C. Maienschein
40. J. H. Marable
41. G. L. Morgan
42-56. D. K. Olsen
57. R. W. Peelle
58. F. G. Perey
59-73. R. B. Perez
74. R. W. Roussin
75. E. G. Silver
76. R. R. Spencer
77. M. L. Tobias
78. E. T. Tomlinson
79. J. H. Todd
80. H. Weaver
81. J. E. White
82. C. R. Weisbin
83. L. W. Weston
84. R. Q. Wright
85. A. Zucker
86. P. Greebler (Consultant)
87. W. W. Havens (Consultant)
88. A. F. Henry (Consultant)
89. R. E. Uhrig (Consultant)
90-91. Central Research Library
92. ORNL Y-12 Technical Library
    Document Reference Section
93-94. Laboratory Records Department
95. ORNL Patent Office
96. Laboratory Records (RC)

EXTERNAL DISTRIBUTION

97. DOE Oak Ridge Operations, Research and Technical Support Division, P. O. Box E, Oak Ridge, Tennessee 37830: Director
98. DOE Oak Ridge Operations, Reactor Division, P. O. Box E, Oak Ridge, Tennessee 37830: Director
99-100. DOE Division of Reactor Research and Development, Washington, DC 20545: Director
101-389. For distribution as shown in TID-4500 Distribution Category UC-79d, Liquid Metal Fast Breeder Reactor Physics - Base (62 copies - ENDF distribution)

☆ U.S. GOVERNMENT PRINTING OFFICE: 1977-748-189/341