ORNL/TM-6788
ENDF-277

The ^{238}U Neutron-Induced Fission Cross Section for Incident Neutron Energies Between 5 eV and 3.5 MeV

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

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

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 $4.50; Microfiche $3.00

ORNL/TM-6788
ENDF-277
Dist. Category UC-79d

Contract No. W-7405-eng-26

Engineering Physics Division

THE ^{238}U NEUTRON-INDUCED FISSION CROSS SECTION FOR INCIDENT NEUTRON ENERGIES BETWEEN 5 eV and 3.5 MeV

F. C. Difilippo,[†] R. B. Perez, G. de Saussure, D. K. Olsen, and R. W. Ingle[‡]

Manuscript Completed - February 6, 1979

Date Published: March, 1979

[†]IAEA Fellow now with Comision Nacional de Energia Atomica, Argentina

[‡]Instrumentation and Controls Division

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

ABSTRACT

A measurement of the ^{238}U neutron-induced fission cross section has been performed at the ORELA Linac facility in the neutron energy range between 5 eV and 3.5 MeV. The favorable signal-to-background ratio and high resolution of this experiment resulted in the identification of 85 subthreshold fission resonances or clusters of resonances in the neutron energy region between 5 eV and 200 keV. The fission data below 100 keV are characteristic of a weak coupling situation between Class I and Class II levels. The structure of the fission levels at the 720 eV and 1210 eV fission clusters is discussed. There is an apparent enhancement of the fission cross section at the opening of the 2^+ neutron inelastic channel in U-238 at 45 keV. An enhancement of the subthreshold fission cross section between 100 keV and 200 keV has been tentatively interpreted in terms of the presence of a Class II, partially damped vibrational level. There is a marked structure in the fission cross section above 200 keV up to and including the plateau between 2 and 3.5 MeV.

I. INTRODUCTION

Narrow intermediate structures in the subthreshold region of the neutron-induced fission cross section were first observed in ^{237}Np by Paya et al.[1] and in ^{240}Pu by Migneco and Theobald.[2] An interpretation of these structures was given independently by Weigmann[3] and by Lynn,[4] in terms of the double humped fission barrier proposed by Strutinsky.[5] According to this model the observed intermediate structure arises from the coupling between the Class I states corresponding to the ground-state deformation of the nucleus and the Class II states in the second minimum of the double humped fission barrier. Hence a study of subthreshold fission yields information on the shape of the potential barrier and on the nuclear states at high deformation, as discussed for instance in a recent review of neutron-induced fission by Michaudon.[6]

The $^{238}U(n,f)$ subthreshold fission is an interesting case of weak coupling between the levels of the two potential wells.[6] Although the existence of subthreshold fission in ^{238}U has been known for a long time,[7] only recently has the intermediate structure been observed with good resolution and over an extended energy range.[8-12]

The $^{238}U(n,f)$ measurements presented here cover the energy region from 5 eV to 3.5 MeV with an energy resolution equal to or better than that of most previous measurements. More significant, in order to detect very weak fission levels, it is important to have a favorable signal to background ratio. Most of the background associated with measurements of subthreshold fission in ^{238}U arises from fissions of ^{235}U impurities in the ^{238}U sample. The ^{238}U sample used in the measurements presented here had an exceptionally high ^{238}U isotopic purity[13] and had less than 2 ppm ^{235}U.

The measurements were done by the time-of-flight technique, utilizing the ORELA facility[14] as a pulsed neutron source. The shape of the ^{238}U to ^{235}U fission ratio was obtained from the count rates of sections of the fission chamber containing either ^{238}U or ^{235}U. This fission ratio was normalized to a value .435 ± .004 for the interval from 2.35 to 2.95 MeV, the value obtained in a separate experiment described elsewhere.[15] The ENDF/B-IV description of the $^{235}U(n,f)$-cross section[16] was used to obtain the $^{238}U(n,f)$-cross section from the fission ratio.

A first experiment was done with a flight path of 20 m. The results of that measurement, the equipment and experimental techniques utilized have already been described[12] and hence will not be discussed here. In the present experiment the energy resolution was improved by the following: (1) the flight path was extended from 20 to 40 m, and (2) the time-of-flight spectra from the eight ^{238}U sections of the fission chamber were stored separately and combined after correction for differences in flight path, whereas in our 20 m experiment[12] one common signal had been used for all eight sections.

The computed resolution width as a function of neutron energy for the 40 m experiment is given in Fig. 1. The effect of the improved resolution is illustrated in Fig. 2 where the data from our 20 and 40 m experiments are compared, in the range 700 to 870 eV.

In section II the results of our 40 m experiment are presented in some detail and compared with previously reported data and with a recent evaluation of the ^{238}U fission cross section.[17] In section III we discuss some of the features of the observed cross section.

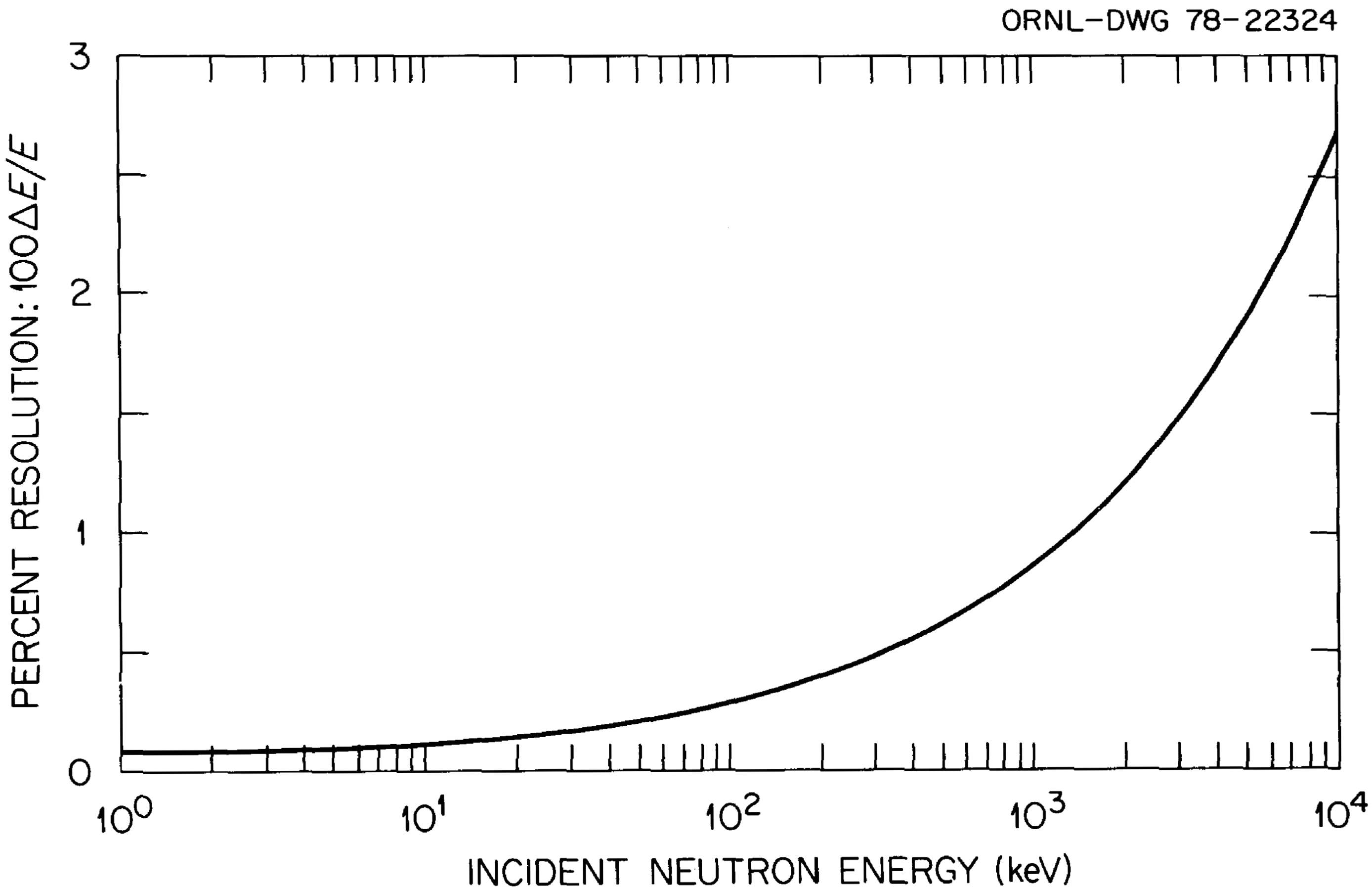

Fig. 1. Experimental energy resolution of the measurement. The resolution width ΔE is the computed e-folding Gaussian broadening width. Below 1 keV most of the broadening is due to the Doppler effect, $\Delta E_D = (4kTE/A)^{1/2}$, above 10 keV the broadening is mostly due to the Linac burst width of 30 ns: $\Delta E_T \approx 8.9 \times 10^{-6} E^{3/2}$, with E in eV.

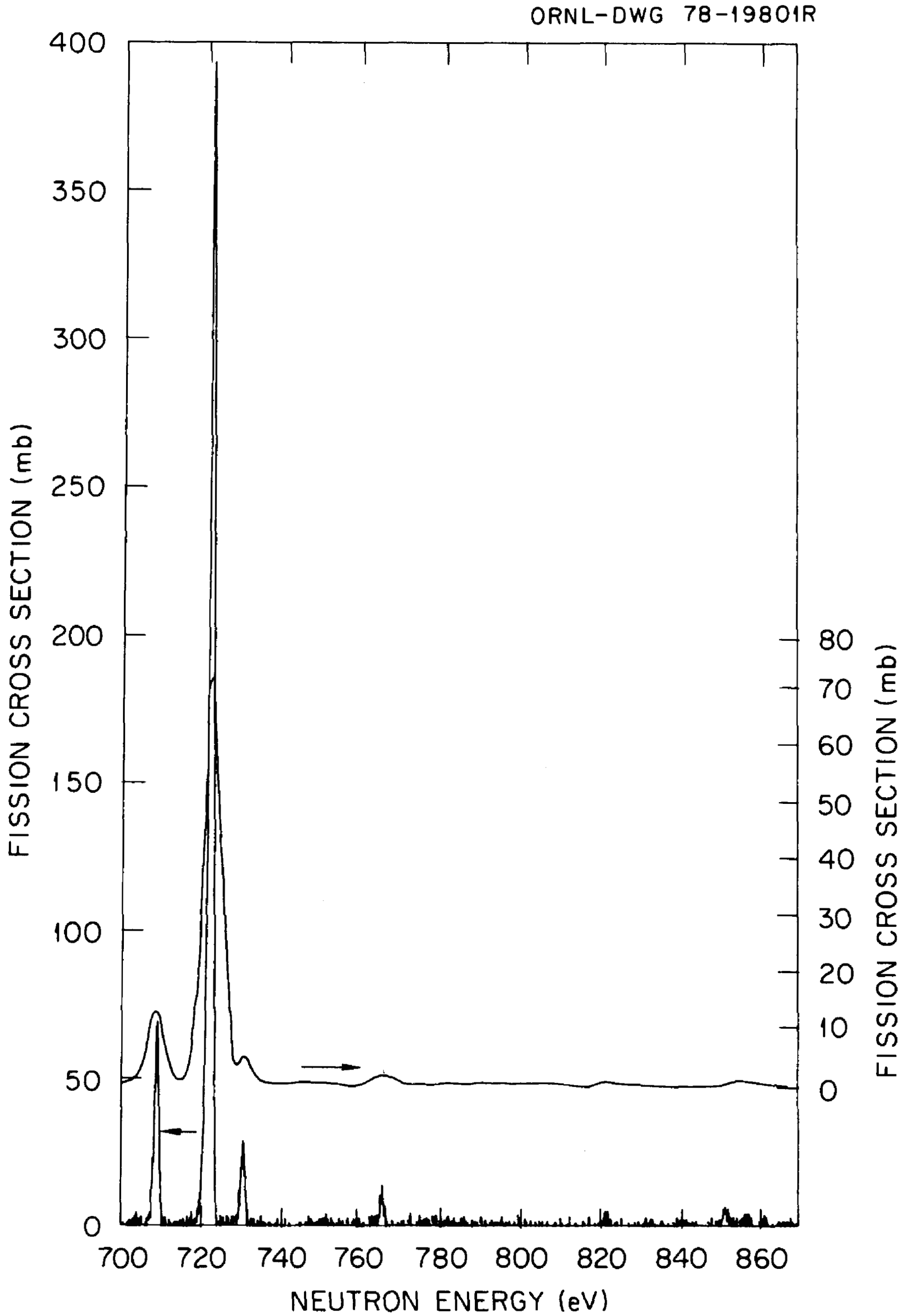

Fig. 2. The $^{238}U(n,f)$-cross section for incident neutron energies between 700 and 870 eV. The upper curve (right scale) shows our previously published low resolution data;[12] the lower curve (left scale) shows the present high resolution data. The improved resolution permits an unambiguous separation of the Class I resonances of the cluster centered at 720 eV.

II. RESULTS

The $^{238}U(n,f)$-cross section between 5 eV and 100 keV is shown in Fig. 3. The levels at 6.7, 20.9, and 36.7 eV had already been observed by Slovacek et al.,[9] but the good signal to background ratio of the present measurement permits the identification of 13 additional fission resonances between 40 and 600 eV. All the Class I levels in the clusters centered around 720 eV and 1.2 keV are well-resolved. Between 5 and 100 keV 36 levels or clusters of levels have been identified.

In Fig. 4 the region 10 to 400 keV is shown in more detail. An enhancement of fission near 120 keV is tentatively interpreted as a contribution from a partially damped vibrational level centered near 145 keV with a width of about 65 keV. A similar structure was observed in the $^{234}U(n,f)$-cross section by James et al.[18]

The fission cross section between 100 keV and 1 MeV and between .4 and 3.6 MeV is shown in Figs. 5 and 6. A large number of measurements have been reported in that range, which have recently been reviewed by Poenitz et al.[17] who evaluated the fission cross section shown as the solid line in Figs. 5 and 6. The comparison indicates a good overall agreement between our data and the evaluation, however, our data show considerably more structure. This is not surprising because the evaluation is based on several data sets where the cross sections were averaged over intervals comparable to the widths of the structures. Our data agree qualitatively with those of Blons et al.,[10] as reported by Cierjacks;[19] but the measurement of Blons et al. has a somewhat better resolution in the high energy region and hence shows more structure.

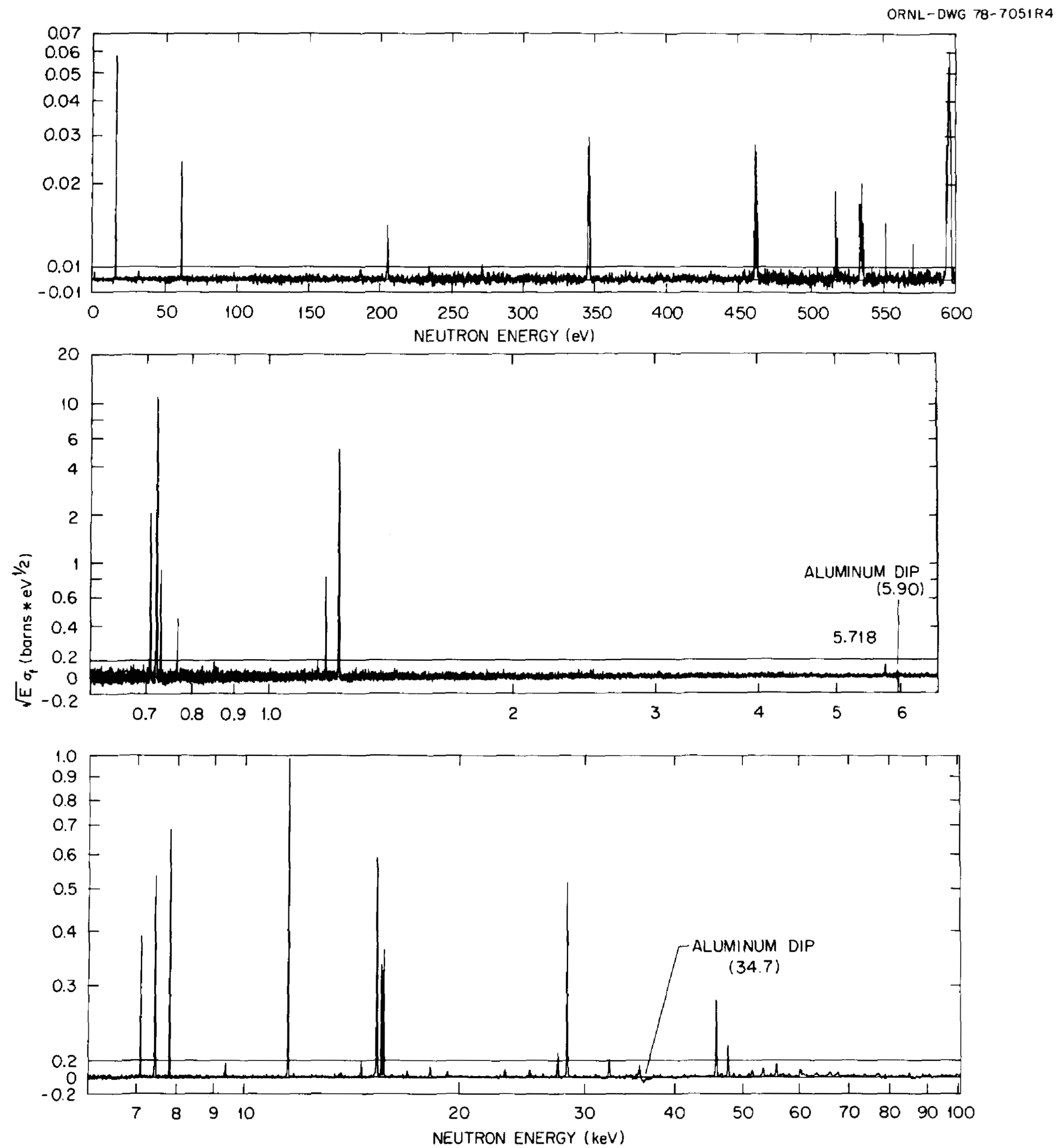

Fig. 3. The $^{238}U(n,f)$-cross section between 5 eV and 100 keV. The fission cross section has been multiplied by $E^{1/2}$ to keep the ordinate scale more uniform. Note that the ordinates change from linear to logarithmic scales. A few negative values, near 35 keV, result from a background overcorrection where aluminum has a large resonance distorting the incident neutron flux, and should be ignored.

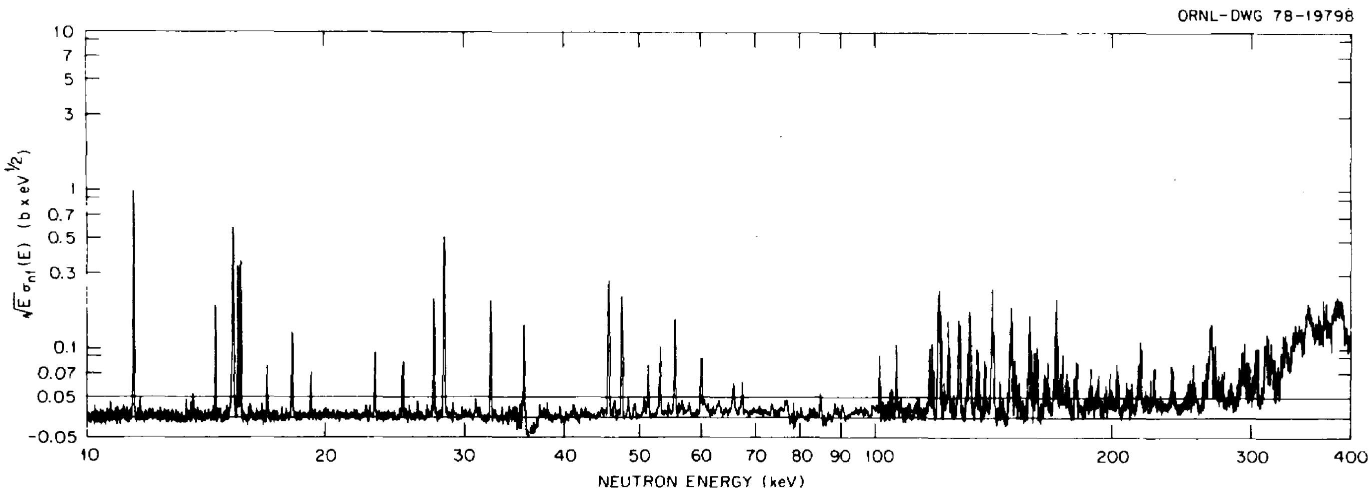

Fig. 4. The $^{238}U(n,f)$-cross section between 10 and 400 keV. The fission cross section has been multiplied by $E^{1/2}$ to keep the ordinate scale more uniform. Note that the ordinate is linear between -0.05 and +0.05 barn $eV^{1/2}$ and logarithmic above 0.05 barn $eV^{1/2}$. The negative values near 35 and 80 keV result from a background overcorrection where aluminum has large resonances distorting the incident neutron flux, and should be ignored. The fission strength enhancement between 120 and 170 keV is tentatively interpreted as resulting from a partially damped vibrational level centered near 145 keV.

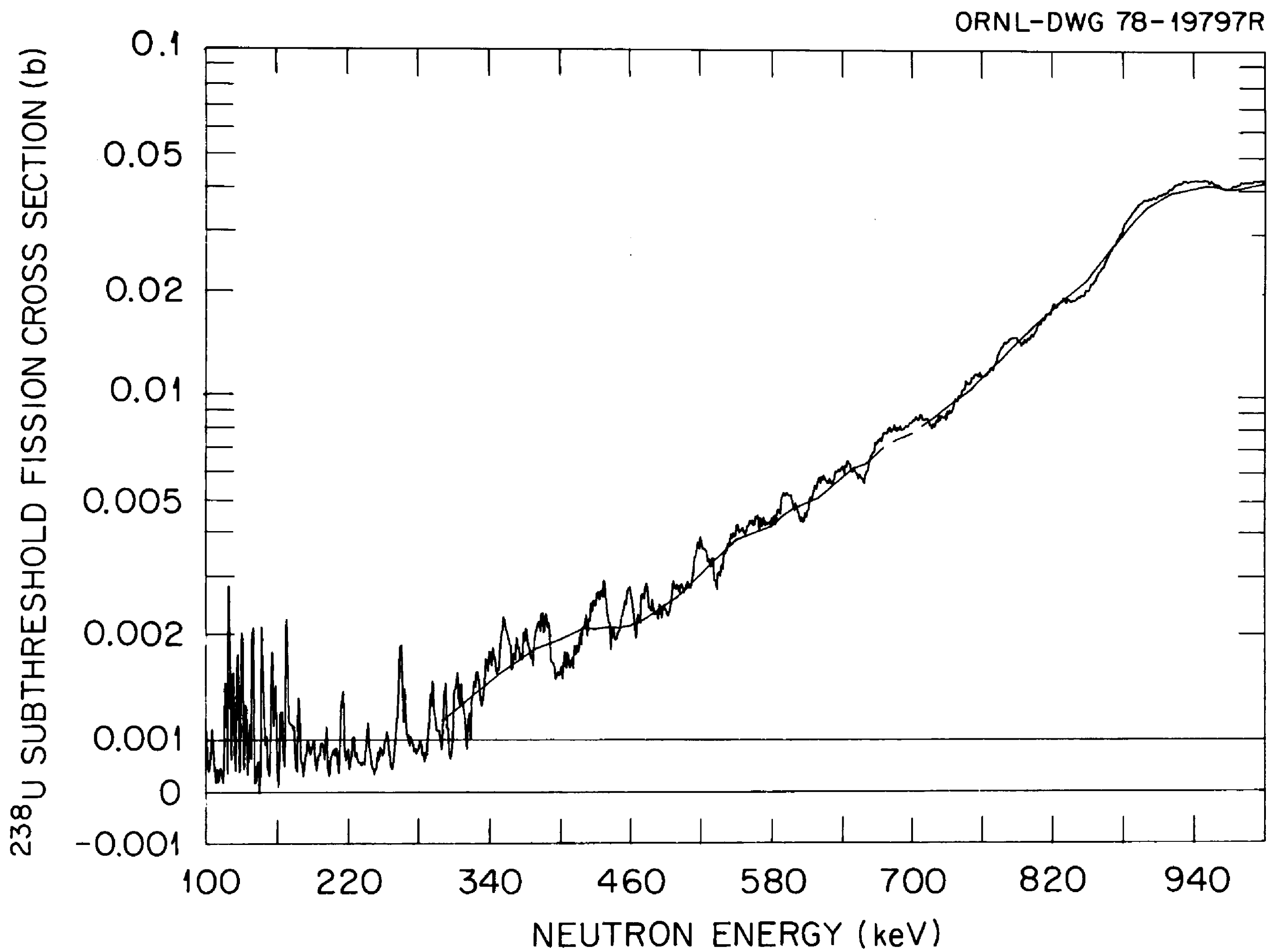

Fig. 5. The $^{238}U(n,f)$-cross section between 100 keV and 1.0 MeV. The smooth curve above 250 keV represents an evaluation of Poenitz et al.[17] Note that the ordinate is linear from 0 to .001 barn and logarithmic above .001 barn.

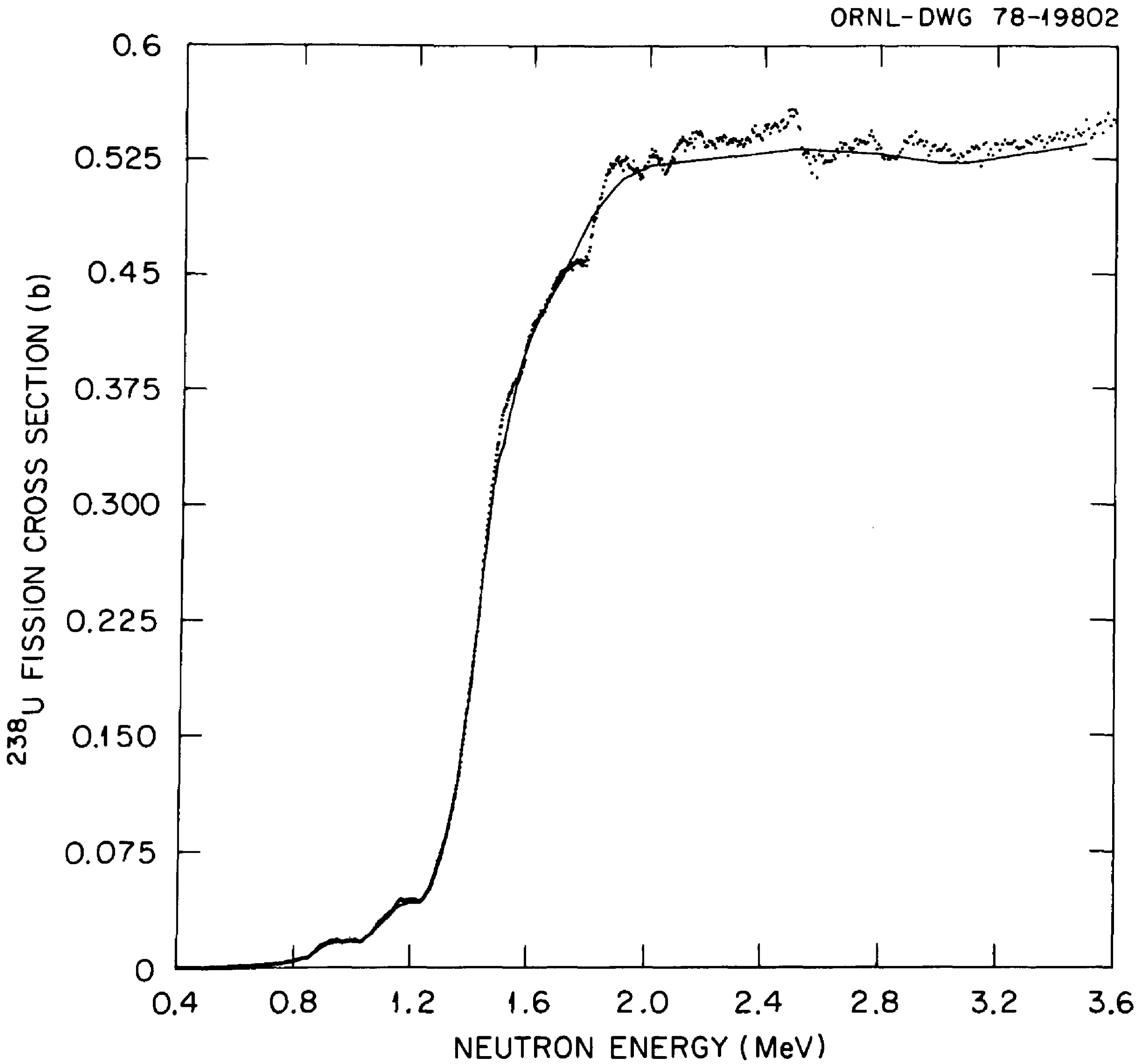

Fig. 6. The ^{238}U(n,f)-cross section between 0.4 and 3.6 MeV. The smooth curve is an evaluation of Poenitz et al.[17] based on a number of recent and older measurements (see text).

The measured $^{238}U(n,f)$-cross section averaged over decimal energy intervals between 700 eV and 3 MeV is given in Table I. A total of 85 fission resonances or clusters of resonances have been identified below 200 keV. The fission areas of the 27 resolved resonances below 2 keV are listed in Table II. The areas of the 36 levels or clusters observed between 2 and 100 keV are listed in Table III, and the areas of the 22 clusters identified between 100 and 200 keV are listed in Table IV. In Table III we have also listed the fission areas obtained in our previous experiment[12] at 20 m. The values given in Table IV of ref. 12 were renormalized upward by 37%, for the following reason: as explained in ref. 12 the fission areas were based on the assumption that the fission efficiencies of the ^{238}U and ^{235}U sections of the chamber were the same. No measurement of this fission ratio efficiency was then available. In the present experiment the fission areas could be obtained in absolute value by normalizing the ^{238}U to ^{235}U fission ratio in the interval 2.35 to 2.95 MeV and this yielded the value of the efficiency ratio.[15] The comparison of Table III shows that there is consistency between our present results and the renormalized 20 m results, but more clusters are observed with the better resolution available at 40 m.

The fission widths Γ_f of the 27 resolved fission resonances below 2 keV have been obtained from the measured fission areas A_f using the relation

$$A_f = \int \sigma_f \, dE = \frac{2\pi^2}{k^2} \, g \, \frac{\Gamma_f \Gamma_n}{\Gamma} \qquad (1)$$

where the symbols have the usual meaning.[20] For this calculation the values of the neutron width Γ_n and total width Γ were taken from our

Table I. The $^{238}U(n,f)$-cross section averaged over decimal intervals between .7 keV and 3 MeV

Energy Interval (keV)	σ_f, Fission Cross Section[a] (mb)	Statistical Error[b] (mb)
.7- .8	7.54	.08
.8- .9	0	.005
.9- 1.	0	.005
1. - 2.	.390	.007
2. - 3.	0	<.005
3. - 4.	0	<.005
4. - 5.	0	<.005
5. - 6.	0	<.005
6. - 7.	0	<.005
7. - 8.	.42	.01
8. - 9.	0	<.005
9. - 10.	.05	<.005
10. - 20.	.133	<.005
20. - 30.	.086	<.005
30. - 40.	.020	<.005
40. - 50.	.088	<.005
50. - 60.	.099	<.005
60. - 70.	.0804	<.005
70. - 80.	.0413	<.005
80. - 90.	.0184	<.005
90. - 100.	.0421	<.005
100. - 200.	.099	<.005
200. - 300.	.088	<.005
300. - 400.	.199	<.005
400. - 500.	.310	<.005
500. - 600.	.640	<.005
600. - 700.	1.28	<.005
700. - 800.	2.76	.005
800. - 900.	7.87	.009
900. - 1000.	16.58	.02
1000. - 2000.	283.0	.1
2000. - 3000.	536.0	.2

[a]The ^{238}U fission cross section was obtained from the measured ($^{238}U/^{235}U$) fission ratio, and the ENDF/B-IV representation of the ^{235}U fission cross section.

[b]It is estimated that systematic errors amount to about 6%. These arise from uncertainties in normalization, in background substraction, and correction for scattering in the structural material of the detector.

Tables II. Measured fission areas and corresponding fission widths of 26 levels below 2 keV

Resonance Energy[a] eV	Fission Area[b] 10^{-6} b × eV	Neutron Widths[a] meV	Total Widths[a] meV	Fission Widths[b] neV
6.672	376± 15	1.510± .015	24.04± .62	9.7± .4
20.86	3290± 66	10.12 ± .10	33.19± .46	55 ± 1
36.67	660± 40	33.91 ± .41	56.83± .50	9.8± .6
66.02	1700± 70	24.61 ± .38	48.30± .51	53 ± 2
80.73	233± 50	1.91 ± .04	26.1 ±1.2	62 ± 13
102.5	392± 78	71.64 ± .41	96.05± .54	13 ± 3
189.6	690± 130	167.0 ±1.7	190.0 ±1.8	36 ± 7
208.5	1120± 130	49.60 ± .79	72.42± .89	83 ± 10
237.3	327± 95	26.48 ± .45	51.23± .65	36 ± 11
347.8	2160± 170	81.73 ±1.10	104.5 ±1.1	233 ± 20
376.9	73± 73	1.148± .024	24.6 ±2.4	140 ±140
463.1	2370± 210	5.49 ± .15	29.0 ±2.4	1405 ±150
478.4	300± 170	4.19 ± .10	27.7 ±2.4	230 ±135
518.3	1250± 190	49.60 ± .75	73.2 ± .9	232 ± 35
535.3	1860± 200	44.28 ± .74	68.1 ± .79	370 ± 40
595.0	5550± 280	86.41 ±1.32	110 ±1.3	1015 ± 50
619.9	550± 150	30.76 ± .51	54.08± .64	144 ± 40
708.3	94900±2700	21.79 ± .59	45.2 ± .81	$(33.8\pm1.0)\times10^3$
721.6	611400±7200	1.72 ± .06	25.2 ±2.4	$(1570\pm100)\times10^3$
730.1	35600±1700	.93 ± .05	24.4 ±2.4	$(166\pm10)\times10^3$
765.1	13000±1100	7.77 ± .28	24.8 ±2.0	7690 ± 780
821.6	900± 530	65.6 ±1.3	88.2 ±1.4	240 ± 140
851.0	9250± 970	62.9 ±1.5	88.4 ±1.7	2680 ± 280
856.1	5370± 700	86.2 ±2.0	109.7 ±2.1	1420 ± 185
1140.	7710± 860	233.1 ±3.2	256.9 ±3.3	2350 ± 260
1168.	43500±2100	87.7 ±2.3	111.8 ±2.3	$(15.7\pm.8)\times10^3$
1211.	341300±5700	9.19 ± .28	32.7 ±2.4	$(356\pm20)\times10^3$

[a]Resonance energies, neutron widths and total widths taken from reference 21.
[b]Fission areas and fission widths obtained from this experiment. Uncertainties given are statistical only.

Table III. Fission areas of clusters observed between 2 and 100 keV

This work		Reference 12[a]	
E_0 (keV)	Fission Area[b] (b × eV)	E_0 (keV)	Fission Area[b] (b × eV)
5.718	.025±.003	5.715	.025±.002
7.098	.075±.004	7.090	.073±.004
7.427	.176±.007	7.430	.184±.008
7.799	.162±.007	7.804	.182±.008
9.348	.047±.004	9.358	.048±.004
11.441	.316±.010	11.43	.378±.038
11.661*	.010±.002		
13.578*	.026±.003		
14.507	.065±.005	14.48	.057±.005
15.252	.346±.011	15.23	.407±.011
15.496*	.141±.007		
15.594	.343±.007	15.56	.345±.010
16.839*	.033±.004		
18.107	.079±.006	18.12	.074±.004
19.145*	.032±.004		
23.028	.063±.006	23.07	.053±.005
25.006	.045±.005	25.03	.037±.005
26.105	.020±.004	26.13	.021±.004
27.399	.150±.009	27.33	.129±.011
28.215	.389±.014	28.23	.353±.021
30.940	.016±.005	30.93	.015±.003
32.322	.160±.010	32.27	.177±.013
35.614	.090±.011	35.67	.083±.008
45.575	.318±.015	45.56	.284±.019
46.381*	.053±.006		
47.408	.248±.015	47.27	.242±.019
48.289*	.046±.006		
49.169*	.047±.006		
50.562	.053±.006	50.53	.059±.009
51.222	.100±.008	51.03	.096±.016
52.763	.155±.011	52.93	.141±.014
54.259	.041±.006		
55.257	.215±.013	55.29	.259±.019
59.658	.218±.013	56.40†	.089±.008
65.658*	.169±.012	57.40†	.065±.010
67.451*	.089±.009	-	-

[a]Renormalized: see text
[b]Statistical error only
*Cluster not observed in the work of Ref. 12.
†Cluster not observed in the present work.

Table IV. Fission areas of clusters observed between 100 and 200 keV

E_0 (keV)	Area (b × eV)	Error[a] (b × eV)
112.9	.106	.013
117.2	.387	.038
119.9	.669	.046
121.8	.123	.019
123.0	.282	.024
124.8	.093	.019
127.2	.443	.039
131.1	.610	.040
133.9	.303	.026
137.1	.210	.017
140.0	.600	.043
143.6	.126	.018
147.7	.503	.032
149.7	.183	.023
151.5	.129	.017
156.1	.526	.029
159.1	.362	.030
164.3	.430	.025
168.9	.749	.038
172.1	.214	.018
174.5	.345	.028
178.9	.327	.018

[a]Statistical error only, systematic errors arising from uncertainties in normalization, background correction and identification of the cluster limits are estimated to amount to 8%.

recent evaluation.[21] The values used for the neutron and total widths and the values obtained for the fission widths are also listed in Table II.

In Table V the fission cross section areas obtained by several experimenters are compared. The discrepancies between the values are somewhat larger than expected.

III. DISCUSSION

Fig. 7 shows the cumulative sum of observed fission clusters as a function of neutron energy, up to 75 keV. Below 35 keV this cumulative sum can be fitted reasonably well by a straight line whose inverse slope corresponds to a spacing of 1.1 ± .1 keV. Between 45 and 55 keV the cumulative sum can again be fitted by a line of inverse slope corresponding to a spacing of 1.3 ± .2 keV. The uncertainties quoted are only sampling errors assuming a Wigner-distribution of levels[22] [i.e., $(0.27\ D^2/N)^{1/2}$]. Between 37 and 45.5 keV there is a surprisingly large gap of about 8 keV with no observable level, see Figs. 3 and 4. (In fact the "gap" starts near 35.7 keV, but we estimate that between 35.7 and 37 keV small levels could be "obscured" by a large aluminum resonance which introduces a perturbation in the neutron flux incident upon our detector, see Fig. 4.) Above 60 keV the slope of the cumulative sum shown in Fig. 7 suggests that many levels are below the detection threshold of our measurements. Above 100 keV a new type of structure appears with relatively larger resonances having an average spacing of 3.3 ± .4 keV; we have already commented on this structure clearly visible in Fig. 4.

Table V. Comparison of fission areas obtained by several experimenters[1]

Resonance Energy (eV)	RPI (ref. 8)	RPI (ref. 9)	Geel (ref. 11)	ORNL[2,3] (ref. 12)	This work[3]
6.672		$(340\pm39)\times10^{-6}$			$(376\pm15)\times10^{-6}$
20.86		$(2880\pm320)\times10^{-6}$			$(3290\pm66)\times10^{-6}$
36.67		$(771\pm97)\times10^{-6}$			$(660\pm40)\times10^{-6}$
708.3			<.07	.094±.007	.0948±.0027
721 6	.31±.08		.26±.04	.56 ±.02	.611 ±.007
730.1			<.03	.026±.002[5]	.036 ±.002
765.1			<.05	.013±.002	.013 ±.002
1108			.05±.02		N.O.[4]
1140			.13±.05	.007±.001	.008 ±.001
1168			.07±.04	.042±.004	.043 ±.002
1176			.06±.03		N.O.
1194			.07±.03		N.O.
1211	.11±.03		.20±.04	.35± .02	.341 ±.006

[1]All areas are given in b × eV
[2]Renormalized (see text)
[3]Uncertainty given is statistical only (1 SD)
[4]N.O. for not observed
[5]This level was not fully resolved in the work of ref. 12, see Fig. 2.

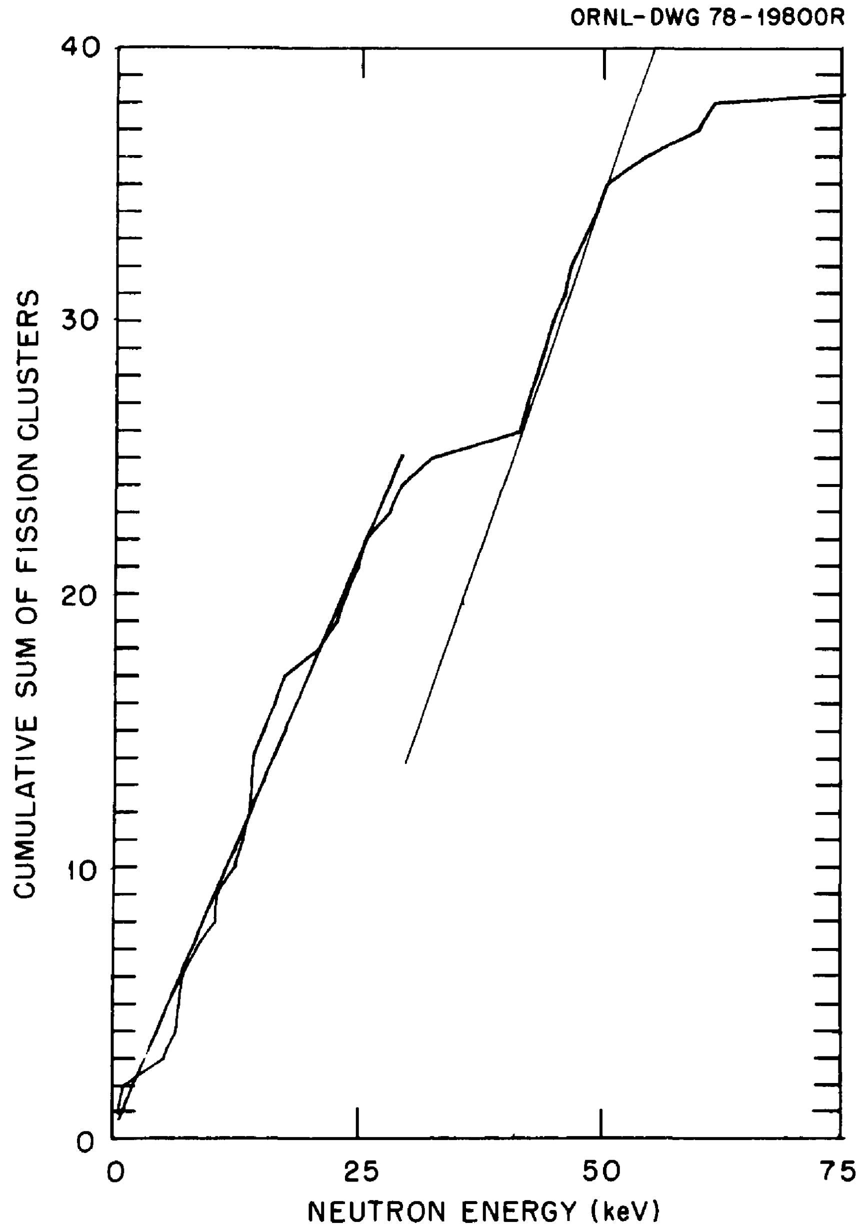

Fig. 7. Cumulative number of fission clusters observed versus incident neutron energy. The 38 clusters are listed in Tables II and III and indicated on Fig. 3. The experimental resolution does not permit to resolve the Class I levels above a few keV. The slopes correspond to Class I spacings of 1.1 keV below 35 keV and 1.3 keV above 45 keV. Above 55 keV a large number of clusters are probably not detected or not resolved. Note the discontinuity between 35 and 45 keV.

From the cumulative sum shown on Fig. 7 we estimate that the average Class II level spacing is of the order of 1 keV. We estimate that we may miss as much as 25% of the levels and that a realistic estimate of the Class II spacing at low energy may be $D_{II} = 1 \pm .25$ keV.

In Fig. 8 the $^{238}U(n,f)$-cross section is compared to the $^{238}U(n,\gamma)$-cross section[23] over the range 20 to 100 keV. There is considerable evidence of intermediate structure in the $^{238}U(n,\gamma)$-cross section,[24] and the comparison shown on the figure was an attempt to determine if the intermediate structures in the fission and capture cross sections could be correlated. No significant "fine correlation" could be observed. Above 45 keV the capture cross section decreases because of the competition with the inelastic scattering channel corresponding to the first 2^+ level in ^{238}U; at 45 keV, there is a discontinuity in the derivative of the cross sections (Wigner cusp[25]) resulting in a rounded step[26] in the capture cross section (the cross section is slightly enhanced just below 45 keV and depressed just above.) Intuitively one would expect a similar behavior in the fission cross section. The data of Fig. 8 show that, on the contrary, the fission is weak below 45 keV and increases sharply near 45 keV, a rather surprising result. It is also possible, of course, that the behavior of the subthreshold fission near 45 keV is not related to the opening of the inelastic channel.

IV. INTERPRETATIONS OF THE CLUSTERS NEAR 720 AND 1210 eV

In this section we discuss several possible interpretations of the two clusters centered near 720 and 1210 eV, respectively.

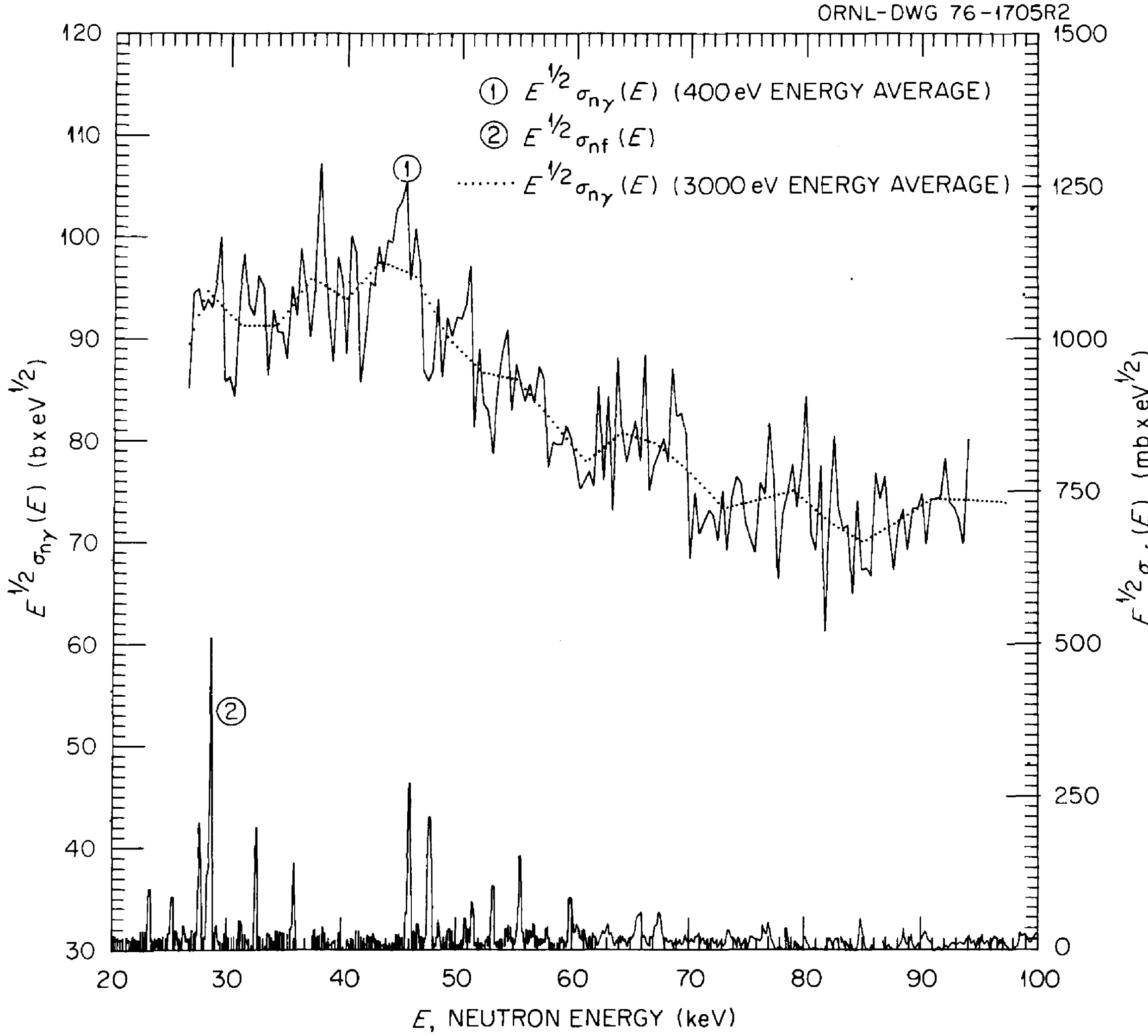

Fig. 8. Comparison of the $^{238}U(n,f)$ cross section (lower curve, right-hand side scale) with the $^{238}U(n,\gamma)$ cross section (upper curve, left-hand side scale). Both cross sections have been multiplied by $E^{1/2}$ to keep the ordinate scale more uniform. The capture cross section is shown averaged over two different energy widths: the capture data averaged over 3 keV wide intervals illustrate the "long-range behavior" of the cross-section. Above 45 keV the capture decreases because of the competition with the inelastic scattering channel corresponding to the first 2^+ level in ^{238}U. Instead the fission is enhanced above 45 keV (see text).

Back et al.[27] have estimated the parameters of the double hump fission barrier of actinides on the basis of measurements of fission probabilities and of a study of the systematic trends of these parameters with respect to A and Z. For the compound nucleus ^{239}U their estimates are given in the second and third columns of Table VI. The last column of the table gives the transmission of each barrier for neutrons of total energy near the binding energy S_n = 4.81 MeV. These transmissions were computed by the usual expression:

$$T = \left\{1 + \exp\left[\frac{2\pi}{\hbar\omega}(V - S_n)\right]\right\}^{-1} \qquad (2)$$

In the following discussion we shall assume the values of the barrier parameters given in Table VI.

In Figs. 9, 10, and 11 the fission cross section is compared to the effective capture cross section[23] over the ranges 5 to 400 eV, 600 to 900 eV and 1.1 to 1.3 keV respectively. The purpose of showing the capture data in these figures is to locate the position of the large s-wave levels. Great care was taken in "aligning" the energy scales of the two measurements. This was done using the 6.67 eV level and the dip near 5.9 keV due to an aluminum resonance. We estimate that the relative energy alignment of our capture and fission data cannot be in error by more than 1 eV at 1 keV. This alignment is confirmed by the observation that the 27 fission resonances below 2 keV, listed in Table II, all line up to better than ± 1 eV with resonances in the capture data.

If we assume the nominal values of the barrier parameters given by Back et al. to be correct, then the transmission through the intermediate

Table VI. Estimated[27] barrier parameters for ^{239}U

Barrier	V/MeV	$h\omega$/MeV	$\frac{2\pi}{h\omega}(V-S_n)$	Transmission
Inner	6.55 ± 0.30	0.90	12.14 ± 2.10	5.3×10^{-6}
Outer	6.30 ± 0.30	0.65	14.40 ± 2.90	5.5×10^{-5}

(S_n = 4.81 MeV, neutron binding energy)

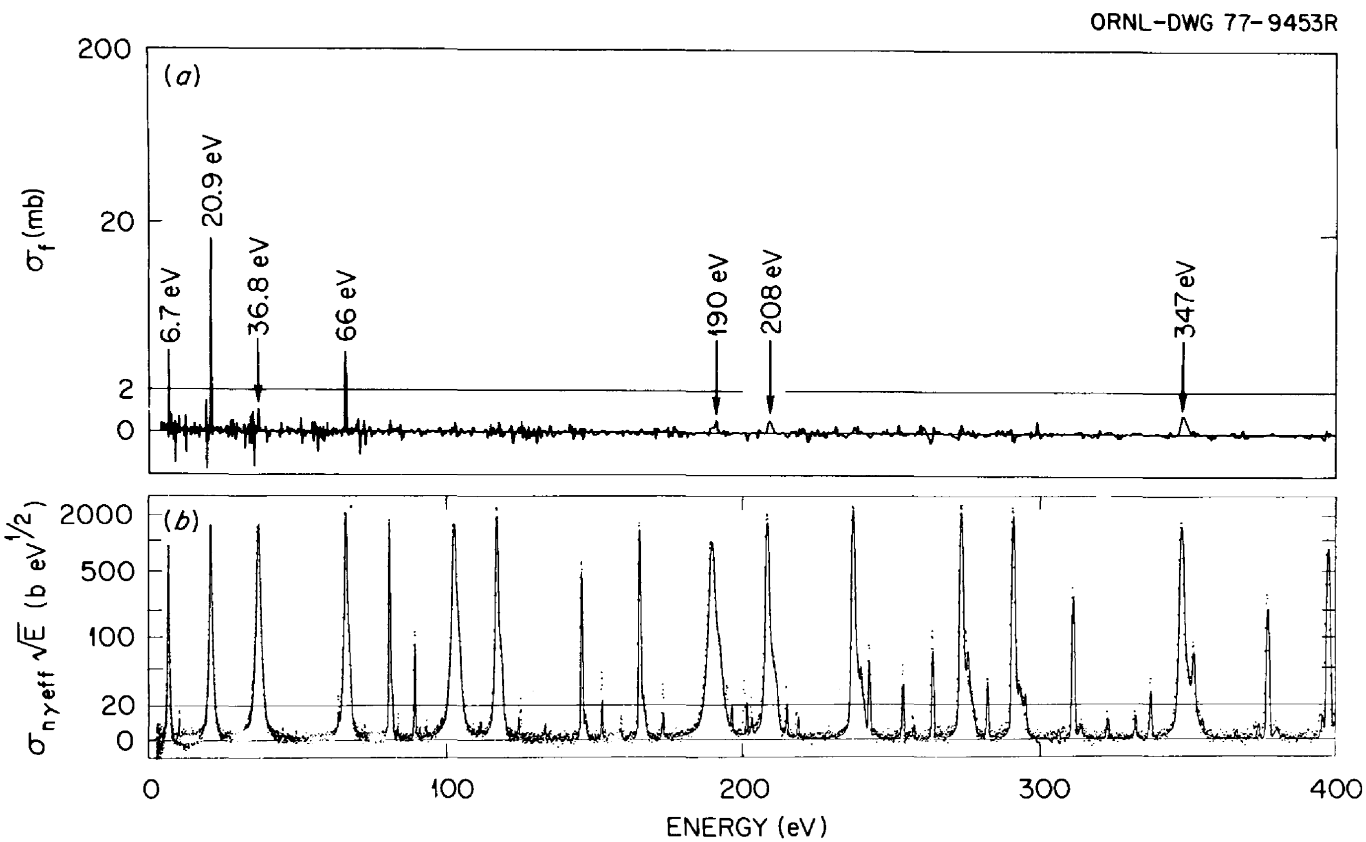

Fig. 9. Comparison of the $^{238}U(n,f)$ and $^{238}U(n,\gamma)$ cross sections for incident neutron energies between 5 and 400 eV. The effective capture cross section[23] is not corrected for self-shielding and multiple scattering and has been multiplied by $E^{1/2}$. The capture data help in locating the position of the s-wave levels. Note that the ordinates change from linear to logarithmic scales. The areas of the fission resonances are given in Table II.

ORNL-DWG 76-7649R3

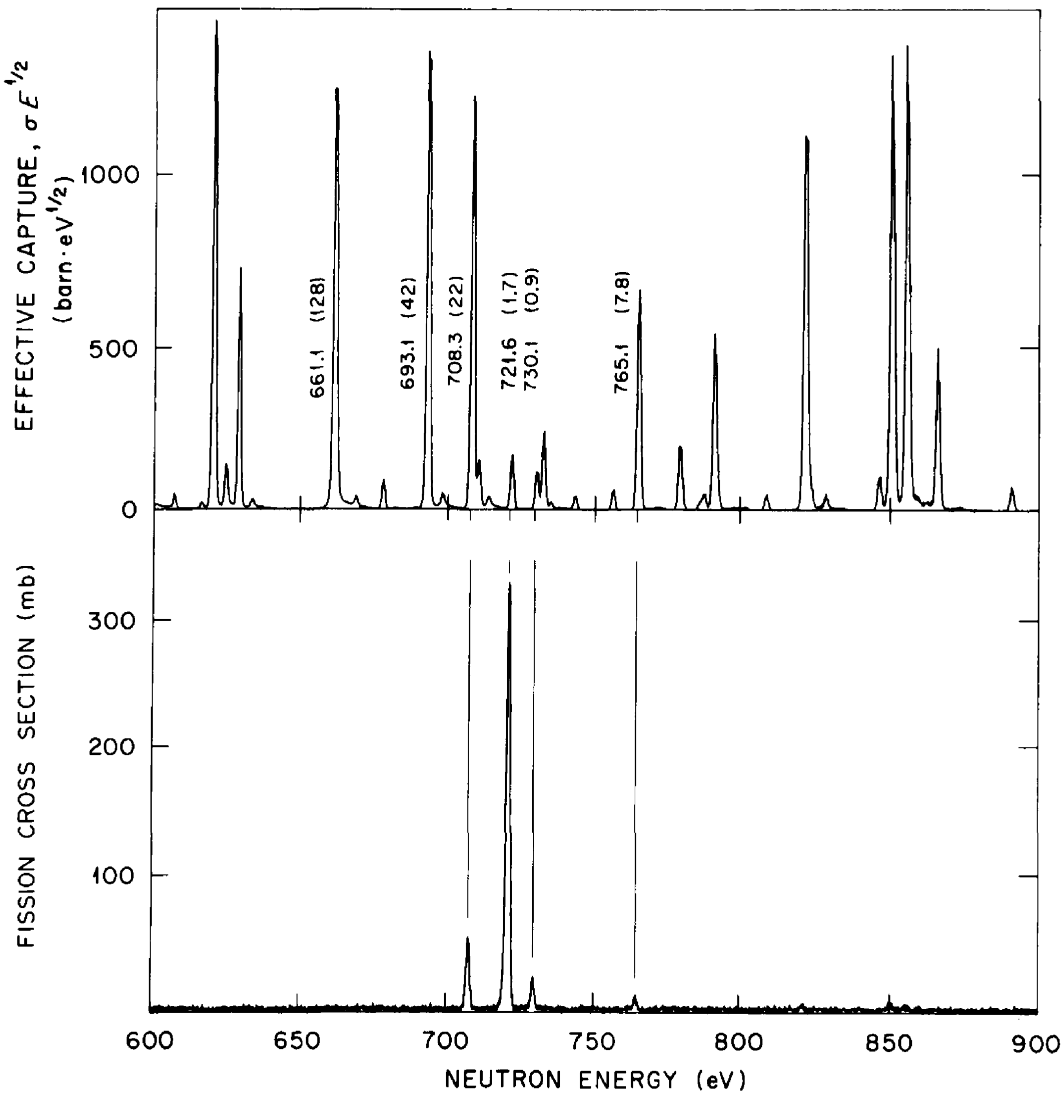

Fig. 10. Comparison of the $^{238}U(n,f)$ and $^{238}U(n,\gamma)$ cross sections for incident neutron energies between 600 and 900 eV. The effective capture cross section[23] is not corrected for self-shielding and multiple scattering and has been multiplied by $E^{1/2}$. The resonance energies in eV and neutron widths in meV are from our recent evaluation.[21] Note that all the fission resonances are aligned with well-known s-wave levels. The areas of the fission resonances are given in Table II.

ORNL-DWG 76-7648R2

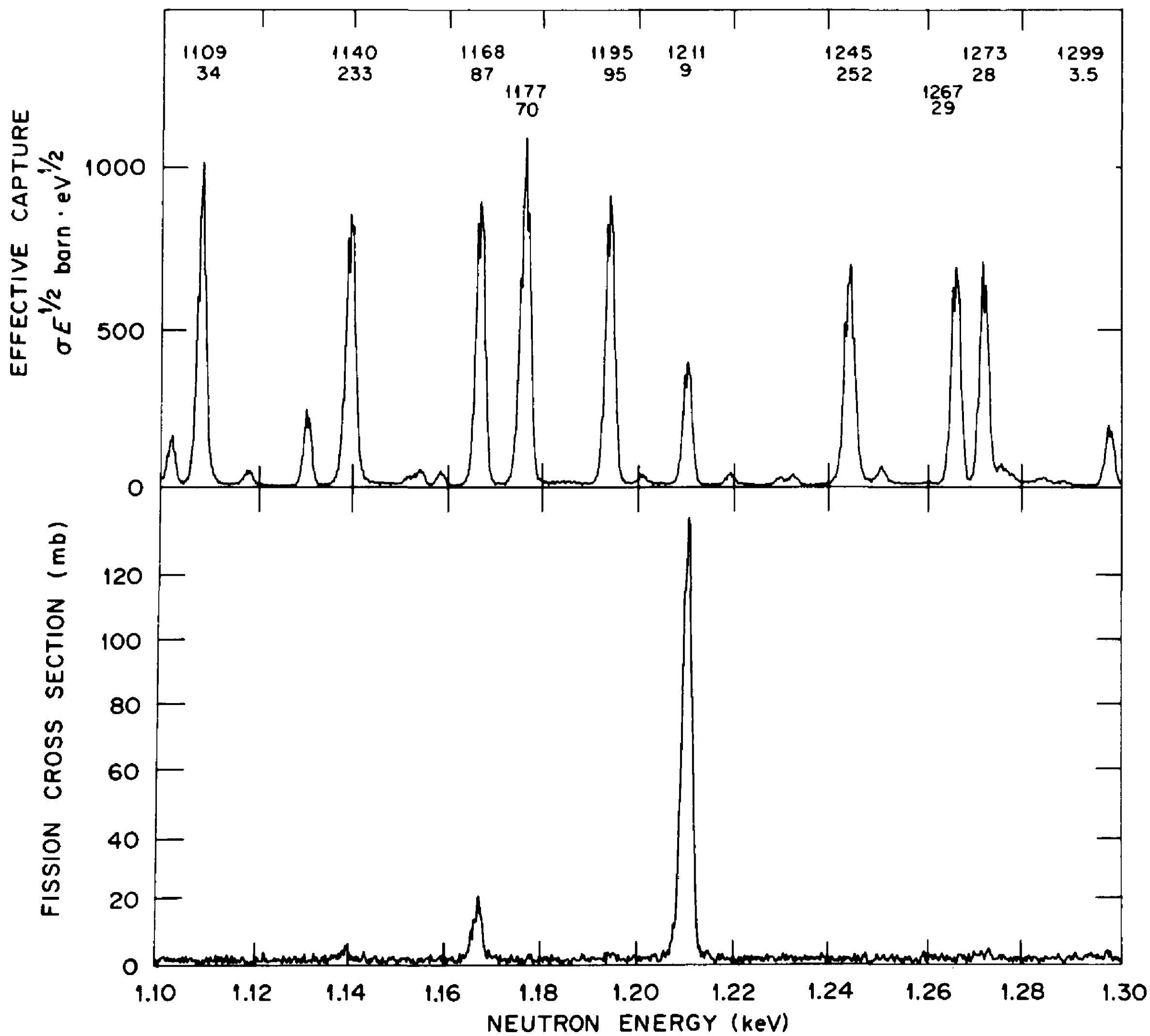

Fig. 11. Comparison of the $^{238}U(n,f)$ and $^{238}U(n,\gamma)$ cross section for incident neutron energies between 1.1 and 1.3 keV. The effective capture cross section[23] is not corrected for self-shielding and multiple scattering and has been multiplied by $E^{1/2}$. The resonance energies in eV and neutron widths in meV are from our recent evaluation.[21] The areas of the fission resonances are given in Table II.

barrier is much larger than that through the outer barrier, hence the spreading width is much larger than the escape width. In this situation, as indicated by Weigmann et al.,[29] a central resonance in each cluster carries most of the fission width and is predominantly Class II.

As indicated in Table II and illustrated in Figs. 10 and 11, in both clusters one level carries indeed more than 85% of the fission width.

Lynn[28] has used perturbation theory to estimate the neutron width $\Gamma_{n,II}$ of the predominantly Class II state:

$$\Gamma_{n,II} \approx \frac{D_{II}}{D_I} \frac{\Gamma_{n,I}}{4} T_A \tag{3}$$

where $D_I \approx 25$ eV and $D_{II} \approx 1$ keV are the Class I and Class II level spacings respectively, $\Gamma_{n,I} \approx 90$ meV is the Class I average neutron width and $T_A \approx 5 \cdot 10^{-6}$ is the transmission of the intermediate barrier. A value $\Gamma_{n,II} \approx .005$ meV is obtained, which is about 300 times smaller than the neutron width of the 722 eV level and 2000 times smaller than that of the 1211 eV level.

Block et al.[8] had already observed the clusters near 720 and 1210 eV with an energy resolution of about 10 eV near 720 eV, and had assigned the main fission resonances to the well-known s-wave levels at 722 and 1211 eV. Commenting on the difference between the value of the neutron width of those two levels and the estimated magnitude of a predominantly Class II level, Lynn[28] suggested that the fission resonances near 720 and 1210 eV were not the well-known s-wave levels to which they had been assigned but were instead resonances with smaller neutron widths, so far unobserved in capture or transmission measurements.

This hypothesis seems however difficult to reconcile with the data presented here; it would require that in both clusters the predominantly Class II level be very close ($E_{II} - E_I < 1$ eV) to a well-known s-wave level.

It seems more likely that the predominantly Class II levels are not observed because their small neutron widths result in fission areas below the detection threshold of our measurement. We estimate this threshold for a narrow resonance ($\Gamma < .5$ eV) around 700 eV to be $5 \cdot 10^{-4}$ b•eV, hence, from Eq. (1) it can be seen that we could probably not detect a level with a neutron width smaller than 10^{-7} eV, regardless of the value of the fission width. Such a value for the neutron width of a predominantly Class II state is not unreasonable; it is 50 times smaller than the perturbation theory estimate, Eq. (3), but there are large uncertainties in that estimate. In particular it was based on a picket fence model of Class I states with uniform width of 90 meV (corresponding to an average reduced neutron width[21] of 3 meV) whereas the Class I levels near 720 eV happen to have neutron widths averaging only about 14 meV.

Another possible interpretation of the clusters near 720 and 1210 eV is based on the assumption that the transmission through the outer potential barrier is larger than that through the inner barrier. This assumption is inconsistent with the nominal values of the barrier parameters estimated by Back et al. and given in Table VI, but can be made consistent with these estimates within the uncertainties given. If the transmission through the outer potential barrier is larger, then the escape width is larger than the spreading width and the predominantly

Class II levels decay mostly by fission and are essentially unobservable in the cross section because of their broad width and low peak value.

Weigmann et al.[29] have argued that the gamma-ray spectrum of neutron capture in a predominantly Class II level should be softer than that of a Class I level. Their study of the gamma-ray spectra of the levels at 722 and 1211 eV indicated that these spectra were consistent with those of other Class I levels and inconsistent with the spectra expected from Class II levels; hence these authors concluded that the levels near 722 and 1211 eV were essentially Class I levels. Browne[30] has also investigated the gamma-ray spectrum of the 722 eV level and, contrary to Weigmann et al., he finds this spectrum significantly softer than that of nearly Class I levels and concludes that the 722 eV level is almost pure Class II.

There is clearly a need for additional work to resolve this discrepancy. If we accept the perturbation estimate of the predominantly Class II neutron width, our interpretation of the clusters is consistent with that of Weigmann et al., and for the level at 722 eV it is in contradiction with the conclusion of Browne.

As can be seen in Fig. 9 and in Table II, several s-wave levels dispersed throughout the resolved resonance region exhibit subthreshold fission with small but significant fission widths. The width corresponding to direct penetration through the double humped fission barrier was estimated using the expression given by Gai et al.,[31] $\Gamma_{min} = D_I T_A T_B / 8\pi$, where T_A and T_B represent the transmission through the first and second barrier respectively. These transmissions were computed using the parameter of Back et al. given in Table VI and the expression given in Eq. (2).

The value obtained, $\Gamma_{min} = 2.8 \cdot 10^{-11}$ eV is a few orders of magnitude smaller than the values of the fission widths observed which range from 10^{-8} to $25 \cdot 10^{-8}$ eV, in the interval 5 to 600 eV. It seems also unlikely that these levels, particularly the levels between 400 and 500 eV, would have such a large fission width through coupling to the Class II level near 720 eV or to a Class II level near the neutron binding energy. At the present time, we have no satisfactory explanation for the magnitude of these fission widths.

V. CONCLUSIONS

We present the results of good resolution, low background measurements of the $^{238}U(n,f)$ cross section from 5 eV to 3.5 MeV. The subthreshold region of the cross section is rich with structures which vary with the incident neutron energy. At the opening of the inelastic scattering channel near 45 keV there is a discontinuity in the derivative of the cross section. One would expect the subthreshold fission to decrease just above 45 keV, due to the competition with the new channel; instead a marked and sudden increase is observed.

Below 30 keV the subthreshold fission cross section shows the characteristic pattern of a very weak coupling between the Class I and Class II states. A value $D_{II} = 1 \pm .25$ keV is obtained for the Class II level spacing.

Several possible interpretations of the well-known clusters centered near 720 and 1210 eV are discussed. The predominantly Class II level of these clusters may be below the detection threshold of the measurements, either due to the small value of its neutron width, or due to the large value of its total width (mostly escape width).

A small but significant fission width can be measured for many of the low energy s-wave levels. These widths appear too large to be due to direct penetration through the double humped barrier.

ACKNOWLEDGMENTS

We are indebted to the ORNL Thermonuclear Division for the loan of a ^{238}U fission chamber with unusually high isotopic purity, and to F. Gillespie for preparing this chamber.

We are also indebted to H. Todd and the ORELA staff for the operation of the Linac, to J. G. Craven for his help with the ORELA data acquisition system and to H. Weaver for his considerable assistance in the installation of the equipment.

Finally, we are indebted to R. L. Macklin, R. W. Peelle, and S. Raman for many fruitful discussions.

REFERENCES

1. D. Paya, H. Derrien, A. Fubini, A. Michaudon, and P. Ribon, *Proc. Conf. Nuclear Data for Reactors,* Paris, Oct. 1966, Vol. II, p. 128, International Atomic Energy Agency, Vienna (1967).

2. E. Migneco and J. P. Theobald, *Nucl. Phys.,* A112, 603 (1968).

3. H. Weigmann, *Z. Phys.,* 214, 7 (1968).

4. J. E. Lynn, "Structure in Sub-Threshold Fission Modes," AERE-R5891, U. K. Atomic Energy Authority, Harwell (1968); see also J. E. Lynn, "Structure Phenomena in Near-Barrier Fission Reactions," Second IAEA Symposium on Physics and Chemistry of Fission, Vienna 28 July-1 Aug., 1969, p. 249, International Atomic Energy Agency, Vienna (1969).

5. V. M. Strutinsky, *Nucl. Phys.,* A95, 420 (1967); also Nucl. Phys., A122 1 (1968).

6. A. Michaudon, "Neutrons and Fissions," *Proc. Int. Conf. on the Interactions of Neutrons with Nuclei,* Lowell, Mass., July 6-9, 1976, CONF-760715-PI, Vol. 1, page 641.

7. M. G. Silbert and D. W. Bergen, *Phys. Rev.,* C4, 220 (1971).

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

9. R. E. Slovacek, D. S. Cramer, E. B. Bean, R. W. Hockenbury, J. R. Valentine and R. C. Block, *Bull. Am. Phys. Soc., Series II,* 20, 581, (1975). See also R. E. Slovacek, D. S. Cramer, E. B. Bean, J. R. Valentine, R. W. Hockenbury and R. C. Block, *Nucl. Sci. and Eng.* 62, 455 (1977).

10. J. Blons, C. Mazur, and D. Paya, *Proc. Conf. Nuclear Cross Sections and Technology*, Washington, D. C. Mar. 1975, National Bureau of Standards Special Publication 425, p. 642 (1975).

11. J. A. Wartena, H. Weigmann and E. Migneco, *Proc. Conf. Nuclear Cross Sections and Technology*, Washington, D. C., Mar. 1975, National Bureau of Standards Special Publication 425, p. 597 (1975).

12. F. C. Difilippo, R. B. Perez, G. de Saussure, D. K. Olsen, and R. W. Ingle, *Trans. Am. Nucl. Soc.*, 23, 499 (1976). Also, *Nucl. Sci. Eng.* 63, 153 (1977).

13. We are indebted to the ORNL Thermonuclear Division for the loan of this high purity sample.

14. F. C. Maienschein, *Energia Nuclear*, 79, 533 (1972) English translation in ORNL-TM-3833 (1972).

15. F. C. Difilippo, R. B. Perez, G. de Saussure, D. K. Olsen, R. W. Ingle, *Nucl. Sci. Eng.*, 68, p. 43 (1978).

16. Evaluated Nuclear Data File, Version IV, of the National Neutron Cross Section Center. Principal evaluators for ^{235}U MAT-1261 are L. Stewart, H. Alter and R. Hunter.

17. W. Poenitz, E. Pennington, A. B. Smith and R. Howerton, "Evaluated Fast Neutron Cross Sections of U-238," Argonne National Laboratory Report ANL/NDM-32 (October 1977). See also Supplement to ANL-76-90, "Proceedings of the NEANDC/NEACRP Specialists Meeting on Fast Neutron Fission Cross Sections of U-233, U-235, U-238, and Pu-239," June 28-30, 1976. Edited by W. P. Poenitz and A. B. Smith, where many of the recent measurements of the ^{238}U(n,f) cross section are compared.

18. G. D. James, J. W. T. Dabbs, J. A. Harvey, N. W. Hill and R. H. Schindler, *Phys. Rev.*, C15, 2083 (1977).

19. S. Cierjacks, in Neutron Standards and Applications, *Proceedings of a Symposium*, National Bureau of Standard Special Publication 493 (1977) p. 278.

20. see for instance, "Experimental Neutron Resonance Spectroscopy," J. A. Harvey, editor, Academic Press, New York (1970).

21. G. de Saussure, D. K. Olsen, R. B. Perez, F. C. Difilippo, "Evaluation of the ^{238}U Neutron Cross Sections for Incident Neutron Energies up to 4 keV," ORNL/TM-6152 (ENDF-257), January 1978. Accepted for publication in *Progress in Nuclear Energy* (1979).

22. E. P. Wigner, in *Proceedings of the Conference on Neutron Physics by Time-of-Flight*, Gatlinburg, Tennessee, 1956 [Oak Ridge National Laboratory Report, ORNL-2309, unpublished.]

23. G. de Saussure, E. G. Silver, R. B. Perez, R. Ingle, and H. Weaver, *Nucl. Sci. Eng.*, 51, p. 385 (1973).

24. R. R. Spencer and F. Kaeppeler, "Measurement of the ^{238}U Capture Cross Section Shape in the Neutron Energy Region 20 to 550 keV," *Proc. Conf. Nuclear Cross Sections and Technology*, Washington, D. C., March 1975, National Bureau of Standards Special Publication 425, p. 620 (1975); also R. B. Perez, G. de Saussure, R. L. Macklin and J. Halperin, "Statistical Tests for the Detection of Intermediate Structure Application to the Structure of the ^{238}U Neutron Capture Cross Section between 5 keV and .1 MeV," submitted to *Phys. Rev.* (1978).

25. E. P. Wigner, *Phys. Rev.*, 73, 1002 (1948).

26. R. G. Newton, "Scattering Theory of Waves and Particles," McGraw-Hill, 1966 p. 533.

27. B. B. Back, O. Hansen, G. C. Britt, J. D. Garrett, and B. Leroux, "Experimental Fission Barriers for Actinide Nuclei," in *Proc. Symp. Physics and Chemistry of Fission*, Rochester, 1973, p. 3, International Atomic Energy Agency, Vienna (1974).

28. J. E. Lynn, "Intermediate Structure in the Sub-barrier Fission Cross Section of ^{238}U," Harwell Report UKNDC-NSC (74) p. 2, and NEANDC(UK) 162 AL.

29. H. Weigmann, G. Rohr, T. Vander Veen, G. Vanpraet, "Neutron Resonance Capture Investigations as a Means of Studying the Coupling Conditions in Sub-barrier Fission," in *Second International Symposium on Neutron Capture Gamma Ray Spectroscopy and Related Topics*, p. 673, Petten (N. H.), 1974.

30. J. C. Browne, "Evidence for 2nd Well γ-decay of Subthreshold Fission Resonances in ^{238}U," Contributed paper PBI/J4, Vol. II, p. 1402, *Proc. of the Internat. Conf. on the Interaction of Neutron with Nuclei*, Lowell, Mass., July 6-9, 1976, CONF-760715-P2, T.I.C., ERDA.

31. E. V. Gai, A. V. Ignatuk, N. K. Rabotnov, G. N. Smirenkin, *Proceedings of the Second Int. Symposium on the Physics and Chemistry of Fission*, Vienna, Austria, 1969 (IAEA, Vienna, 1969) paper No. SM/122/132.

ORNL/TM-6788
ENDF-277
Dist. Category UC-79d

INTERNAL DISTRIBUTION

1. L. S. Abbott
2. G. T. Chapman
3. J. Craven
4-13. G. de Saussure
14. J. K. Dickens
15-24. F. C. Difilippo
25. G. F. Flanagan
26. R. Gwin
27. J. Halperin
28. J. A. Harvey
29. N. W. Hill
30. D. J. Horen
31. R. W. Ingle
32. C. H. Johnson
33. D. C. Larson
34. R. L. Macklin
35. F. C. Maienschein
36. B. F. Maskewitz
37. A. G. Mitchell
38-42. D. K. Olsen
43-63. R. W. Peelle
64. F. G. Perey
65-74. R. B. Perez
75. S. Raman
76. E. G. Silver
77. R. R. Spencer
78. J. H. Todd
79. H. Weaver
80. C. R. Weisbin
81. L. W. Weston
82. R. Q. Wright
83. A. Zucker
84. P. Greebler (consultant)
85. W. B. Loewenstein (consultant)
86. R. E. Uhrig (consultant)
87. R. Wilson (consultant)
88-89. Central Research Library
90. ORNL Y-12 Technical Library Document Reference Section
91-92. Laboratory Records Department
93. ORNL Patent Office
94. Laboratory Records (RC)

EXTERNAL DISTRIBUTION

95. DOE Oak Ridge Operations, Research and Technical Support Division, P. O. Box E, Oak Ridge, Tennessee 37830: Director
96. Office of Assistant Manager, Energy Research and Development, DOE-ORO, Oak Ridge, Tennessee 37830
97-98. DOE Division of Reactor Research and Development, Washington, D.C. 20545: Director
99-418. For distribution as shown in TID-4500 Distribution Category UC-79d, Liquid Metal Fast Breeder Reactor Physics - Base (60 Copies - ENDF distribution)