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Problems and Progress Regarding Resonance Parameterization of ^{235}U and ^{239}Pu for ENDF/B

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Abstract

The procedures used to obtain the resolved and unresolved resonance parameterization of ^{235}U and ^{239}Pu contained in the U.S. Evaluated Nuclear Data File ENDF/B-V are reviewed. For ^{235}U, recommendations are made to improve the representation by including information on resonance spins and fission-channel vector orientations, and some preliminary results are presented. We review evidence that it is the fission channels rather than the spins of the resonances that lead to differences in fission mass distributions, the number of neutrons emitted per fission, and fission kinetic energies. The improved parameterization may thus have physics content that will prove of interest in future applications.

I. Status of ENDF/B

In the early years of the development of the U.S. Evaluated Nuclear Data File, ENDF/B, the reduced R-matrix representation of resolved-resonance cross sections of fissile nuclei was an approved alternative description. It was never used, however, because it led to difficulties in processing the data, in particular in the treatment of Doppler broadening. The recommended procedurewas to use a single-level formulation to calculate symmetric resonance poles, and to correct for possible asymmetries in the cross-section shapes about the poles by adding a pointwise contribution from a tabulated file (File 3). Doppler broadening of the symmetric poles could be easily carried out using Voigt profiles, and it was expected that the File-3 contribution would be small enough that the Doppler broadening could be neglected.

This procedure worked reasonably well. For ^{235}U, Smith and Young[1] provided a resonance evaluation below 82 eV that was approved for inclusion in ENDF/B-III. There was only fragmentary information available at that time on the resonance spins, but for ^{235}U, with a spin of 7/2, this deficiency was not thought to be of primary importance, and the Smith-Young evaluation was found to give a reasonably consistent description of the total and partial cross sections.

For ^{239}Pu, Simpson and Simpson[2] carried out a preliminary evaluation to 300 eV for ENDF/B-III, finding that it was impossible to achieve an internally consistent description of the measured total and partial cross sections. Derrien[3] attributed this difficulty to the fact that the Simpson-Simpson evaluation also did not contain resonance-spin information. The Simpson-Simpson evaluation was then revised by Smith, Kinsey, and Garber,[4] who found that the internal inconsistencies were not removed by an improved spin treatment, and concluded that the problem is one of consistency among total cross section measurements using different sample thicknesses. The total cross section data file had been constructed as weighted averages of total cross sections deduced from transmission measurements on several samples of different thicknesses. This weighting procedure does not appear to treat properly the problems associated with uncertainties in the knowledge of the number of atoms in the samples. When such a mixed set of total cross section data is included in a multiple fit with both fission and capture data, the inconsistencies in the total cross section data are revealed. In reality it is improper to use such a total cross section file directly in a multi-cross section fit. A better procedure would be to fit the transmission data from all of the individual sample thicknesses, along with the partial cross sections. However, the transmission data are usually not available in the necessary detail.

The fit by Smith et al. was not a complete reanalysis of the data, but a revision of the Simpson and Simpson parameters with spins assigned to the resonances. In general the total widths were retained, with adjustments made to the fission and capture widths to yield the ratios of capture to fission indicated by Gwin's ORELA data[5]. Since these data had not yet been completely reduced, fission and capture normalizations were based on data from the single run selected by Gwin as being best for this purpose. While this evaluation was not documented, and there are some areas where the fit is rather unsatisfactory, it was approved for inclusion in ENDF/B-IV and continued in ENDF/B-V, the current version.

Perhaps the most stringent testing of the resonance region evaluations of ^{235}U and ^{239}Pu was done by Koenig and Carter,[6] and by Cullen and Plechaty,[7] who used the ENDF/B-III evaluations to calculate resonance-self-shielded fission measurements of Bramblett and Czirr.[8,9] The results of these data-testing calculations were somewhat surprising: The ^{239}Pu resonance evaluation of ENDF/B-III was found to give rather good agreement with the Czirr-Bramblett measurements on ^{239}Pu, while the ^{235}U evaluation seemed to overpredict the measured self-shielded fission rates on ^{235}U by 20-30%. This discrepancy for ^{235}U was a source of concern for many years. In their review paper at the Harwell conference in 1978, Keyworth and Moore[10] carried out an assessment for various evaluations of resonance parameters for ^{235}U and concluded that there is no adjustment of parameters consistent with the body of microscopic data that could give agreement with the Bramblett-Czirr measurement. They recommended as a first step that this measurement be repeated and verified. This was done by Czirr,[11] who found that the earlier measurements were not corrected properly for background, and that the discrepancy was largely removed if one compared calculations based on the existing evaluations with the results of his remeasurement.

No attempt was made to improve the ^{235}U resonance parameter set for ENDF/B-IV. For ENDF/B-V, it was first proposed to use the evaluation of Reynolds[12] for ^{235}U. The Reynolds evaluation is an R-matrix analysis below 60 eV and does contain the preliminary resonance spin assignments of Keyworth et al.[13] However, two obstacles to the incorporation of the Reynolds parameters presented themselves. The first was a consequence of the exclusive utilization of the fission and capture data of Perez et al.[14] in the fitting procedure. As is the case with many measurements in which boron filters are used to suppress backgrounds, the Perez data become progressively low in the region of the cutoff of the boron filter. Unfortunately the cutoff region almost exactly corresponds to the energy span of the Reynolds evaluation In the intermediate normalization region 7.8-11 eV the fission integral of the Perez data is 8% lower than the best value based on the comparison of all of the known measurements. The second problem with the Reynolds parameter set was a reluctance on the part of the Cross Sections Evaluation Working Group (CSEWG) to decrease the span of the resolved resonance region from 82 to 60 eV. An effort was made to utilize Adler-Adler parameters, converted from the Reich-Moore parameters through the program POLLA, from 1-82 eV. Below 60 eV the Reynolds parameters would be used. From 60 to 82 eV the parameters would be taken from the multilevel fit by Smith[1], which was tailored to yield very closely the same description of cross sections as the single-level representation of Smith and Young. However, the mixed set of Adler-Adler parameters was found to generate rather severe interference anomalies, and the approach was finally abandoned.

The current version of the U.S. Evaluated Nuclear Data File, ENDF/B-V, contains the Smith-Young[1] parameter set for ^{235}U and the Smith, Kinsey, and Garber[4] set for ^{239}Pu. Neither of these is completely satisfactory, as noted above, for the following reasons: 1) The ^{235}U parameter set does not contain spin information, and the single-level description plus smooth background lends itself to accurate Doppler broadening only if kernel broadening is performed on the complete cross sections obtained by adding the smooth files to the resonance calculations. 2) The ^{239}Pu set represents an uncompleted analysis, as the effort was terminated by the time considerations, not by the adequacy of the fit. There are several regions involving overlapping resonances in which the fit is poor. These regions should be cleaned up, and the fit extended to approximately 700 eV, incorporating the fission and capture data of Gwin et al.[15]

The restriction to a single-level or Kapur-Peierls description of the resonance cross sections of fissile nuclei in future versions of ENDF/B appears unlikely to be removed. Fröhner[15] recently noted that an important simplification would result if one were to use Turing's method for analytical Doppler broadening of the Reich-Moore or reduced R-matrix parameterization. This method was studied some years ago by Bhat and Lee-Whiting[16]; its adoption would effectively obviate the necessity for the simpler descriptions. We feel that this approach is desirable, in that it also seems to offer the possibility of including in the evaluation physical information, such as the detailed energy dependence of ν, that is presently included only in a limited pointwise representation. But there appears to be considerable reluctance in the user community to implement the code changes required for a multiple-channel R-matrix evaluation for ^{235}U as a part of ENDF/B. The question is to be decided at the October 21-22 meeting of CSEWG.

For (^{235}U + n) in the unresolved resonance region (82 eV to 25 keV), a complete re-evaluation was carried out for ENDF/B-V by Bhat and Moore.[17] In order to provide a consistent energy scale, fission data of Keyworth et al.,[18] Perez et al.,[14] and Gwin et al.[19] were shifted to match the energy scale of Lemley et al.[20] by maximizing the correlation coefficients between the data sets, and then averages were taken to obtain the absorption and fission cross sections from the Perez et al., Gwin et al., and Lemley et al. sets. After correcting for p-wave fission, the spin-dependence of the unresolved-resonance s-wave fission cross section was obtained by normalizing the spin-separated fission cross sections of Keyworth et al.[18] to the average fission cross section of Perez, Gwin, and Lemley et al. Finally, with the unresolved resonance code UR of Pennington,[21] a set of spin-dependent s-wave average resonance parameters was obtained by simultaneously fitting the absorption and spin-dependent fission cross sections. The intermediate structure in (^{235}U + n) is thus described below 25 keV in this evaluation as an s-wave phenomenon; the evaluation was accepted for inclusion in ENDF/B-V.

The ENDF/B-V representation of the unresolved resonance region for ^{239}Pu (300 eV to 25 keV) is considered to be inadequate. The situation was reviewed by Weston[22] at a recent evaluation conference at Brookhaven National Laboratory. The fission cross sections are thought to be too high, the energy scale is thought to be incorrect, and the capture-to-fission ratio has the wrong shape. Weston attributes the problem to an inadequate treatment of inelastic scattering, recommending a re-evaluation that takes into account recent measurements by Haouat et al.[23]

At a meeting at Brookhaven National Laboratory on May 14-15, 1981, the U.S. Cross Sections Evaluation Working Group (CSEWG) reviewed progress in data testing of ENDF/B-V and set tentative goals for the future. According to the summary of the meeting made by the chairman (S. Pearlstein), plans for ENDF/B-VI (the next version) are as follows:

> The milestone tasks for ENDF/B-VI include fixing of formats, completion of standards, definition of objectives, upgrading of codes, completion of evaluations, and data testing. Because the results of data testing ENDF/B-V are not yet complete and interpreted the goals for ENDF/B-VI cannot be detailed. Therefore, the Executive Committee agreed that only the following tasks could be scheduled at this time:

Formats fixed	Spring 1982
Standards complete	Spring 1983
ENDF/B-VI goals detailed	Fall 1982-Spring 1983

At the same meeting, the CSEWG subcommittee on General Purpose Evaluations considered minimum goals for ENDF/B-VI heavy nuclide evaluations. L. Weston and L. Stewart provided a list of such goals to form the basis for the discussion; this list contained the following items in the resolved and unresolved resonance regions for ^{235}U and ^{239}Pu:

92 U-235	0 - 1 eV	Compare thermal shape with prediction using resolved parameters. New measurements are needed (Weston).
	1 - 100 eV	Multilevel representation must replace the Version V (really III) single-level Breit-Wigner. This requires a reanalysis using recent experimental data. Check for reasonable x/s for normalization integral between 7.8 and 11 eV (de Saussure).
	Unresolved	Check end points and for possible improvements. for possible for possible improvements.
94 Pu-239	0 - 1 eV	Compare thermal shape with that calculated from resonance parameters. New measurements needed (Weston).
	300 eV - 200 keV	Cross sections are inconsistant. New evaluation needed. Representation of inelastic levels is poor. See B-III data (Weston).

II. Fission Channels and Scission-Point Variables

The fission process is often pictured as occurring in multiple stages. For low-energy neutron-induced fission, the first stage is the formation of a compound nucleus, where the excitation energy afforded by the binding energy of the incident neutron is shared among the nucleons. Connected with this stage are resonance properties such as neutrons widths, spins, and resonance spacings. The second stage (perhaps given in detail by several sequential stages) is the crossing of a double- or triple-humped barrier. At the tops of these barriers the nucleus is relatively cold, the excitation energy being largely taken up by the potential energy of the mass surface. Only a few modes of motion are allowed, and the average fission width is determined by the sums of partial widths in the few channels or saddle-point states that may exist. The angular distributions of the fragments are assumed to be related to the channel structure at the outer barrier. The next stage is the transition from the outer saddle point to scission, beyond which the nuclear interaction between the nascent fragments vanishes, by definition. It follows that at scission the primary fission-fragment mass and charge distributions have been established. The time required for and the nature of the saddle-to-scission transition remains an open question, but there is evidence that the mass, charge, and kinetic-energy distributions do depend on the fission-channel configuration at the outer barrier. After scission, as the fragments separate under the influence of long-range coulomb forces, they reorient themselves from the possibly highly deformed scission-point configuration and emit most of the prompt neutrons and prompt fission-gamma radiation.

There is a small but significant variation of all these scission-point variables with neutron energy in the resonance region for neutron-induced fission of both ^{235}U and ^{239}Pu. For ^{239}Pu, the observed variations in both the mass distributions and in ν are found to be spin dependent.[24,25] Frehaut and Shackleton[25] found that the variation in ν is anticorrelated with the prompt fission-gamma yield and depends on the size of the fission width; they suggested that the variation in ν is dominated by competition of the (n,f) and (n,γf) processes. For ^{235}U, the variations in the mass distributions[26] and ν[27,28] are smaller than for ^{239}Pu, and do not appear to depend on the resonance spin, but on the fission channel properties. While it is well known[29] that the mass-distribution variation in (^{235}U + n) is strongly correlated with the fission channel properties, evidence that the variation in ν is similarly correlated has not appeared in the literature and deserves to be reviewed. Pattenden and Postma[30] provided the definitive measurement of the fission channel structure of (^{235}U + n). Following the preliminary work of Dabbs et al.,[31,32] they measured the anisotropy of fission fragments emitted by an aligned sample of ^{235}U irradiated by neutrons at the Harwell linear accelerator. The fragment anistropy is described in terms of A_2, the coefficient of the second Legendre term in the angular distribution expansion, and depends strongly on the K-value of the channel. For ^{235}U, with spin $7/2^-$, the Pattenden-Postma data suggest that neutron-induced fission takes place for 3- resonances in three open channels with K = 0,1,2, and for 4- resonances in two open channels with K = 1,2. Pattenden and Postma measured anisotropies and reported A_2 values for 61 resonances in (^{235}U + n); these values are strongly correlated[29] with variations in the mass distribution of (^{235}U + n) fission measured by Cowan et al.[26]

The variation of ν for (^{235}U + n) was measured by Howe et al.[27] and by Reed et al.[28]. Howe et al. compared their results, by calculating correlation coefficients, with the resonance spins determined by Keyworth et al.,[18] and with the Pattenden-Postma fission-channel angular anisotropies, and concluded that no significant correlation exists. Reed et al.[28] used a different technique, similar to that developed by Weinstein et al.[33] If we calculate the correlation coefficient of the ν measurements of Howe et al.

and of Reed et al., we conclude that the variation is significant and that the two experimental data sets are measures of the same quantity. In other words, we can assume that an average of the Howe et al. and Reed et al. data is likely to be a more nearly accurate representation of the energy dependence of ν than either individual set. The energy dependence of this average, the A values of Pattenden and Postma, the mass distribution variations of Cowan et al,[26] and the effective J values of Keyworth et al. are shown in Table I. The correlation of ν with resonance spin is not significant, but the correlation of ν with the mass distribution measure R is significant at the 0.5% level (i.e., there is a probability of only 0.5% that the sampling of values of ν and R are randomly distributed). The correlation of R and the fission-changed measure A_2 is significant at the 10^{-5} level. We conclude that it is the fission channel properties that lead to the measured variation in ν.

Studies by Auchampaugh[34] have shown that reduced R-matrix fitting of fission cross sections, when there are more than a single open fission-channel, is completely non-unique, in that there are many solutions with different relative fission-vector orientations that give equivalently good fits to the data. In a two-fission-channel description, the number of such solutions was estimated by Adler and Adler[35] as (N-1)(N-2)/2 + 1, where N is the number of levels. However, if the angular distributions of Pattenden and Postma are used as a constraint in such a two-fission-channel description, the fits can be unique.

We expect that a significant improvement in the resonance parameters of (^{235}U + n) can be made. The deficiencies noted in the previous section should be corrected. If carried out under the constraint of a two-fission-channel reduced R-matrix representation, the parameterization should reflect the fission-vector orientations that describe the Pattenden-Postma angular distributions. We feel that such an approach could also describe, at least to first order, the energy dependence of certain scission point variables such as ν and the fragment mass and kinetic energy distributions.

A preliminary analysis of this type has been attempted; the results are given in Table II and shown in Figs. 1-5. We fitted only the spin-separated fission cross sections of Keyworth et al,[18] using as initial-guess parameters the recommended values of Moore et al.,[36] in which the initial-guess fission-vector orientations were chosen to reflect the Pattenden-Postma fission-fragment anisotropies.

A comparison of the preliminary set of Table II with other evaluations shows that most of the narrow resonances listed have fission widths that are too high and neutron widths that are correspondingly too low (such that the resonance fission areas are preserved). This is undoubtedly a consequence of using a slightly incorrect resolution or Doppler width in the fitting. This kind of deficiency can easily be corrected by including total and/or capture cross section data in the fitting.

There are three other modifications that should be made to the set in Table II: 1) In the vicinity of the strong resonance in ^{139}La at 72 eV, Keyworth's data do not describe the actual fission cross section, and one should use a different data set. 2) The fission-width vector orientations are not always given correctly. For example, as shown in Fig. 6, in the region around the 8.8 eV resonance, a clockwise rotation of the vectors by 30^{o} would more nearly represent the Pattenden-Postma results. Between 15 and 20 eV, the vector orientations are given adequately for three of the four strong 4- resonances, but we were unable to achieve a fit that would describe the 15.6 eV resonance as being mostly in the K=1 channel. 3) No fitting was done over the 0.3 eV resonance. Here the Pattenden-Postma data suggest that the fission widths are about equally divided between K=0 or 1 and K=2, with constructive interference above the 0.3 eV resonance in the K=2 channel. While the preliminary parameters of Table I should not be considered definitive, they are expected to prove useful as starting parameters for a more nearly complete analysis.

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Table I. The energy dependence from resonance to resonance of $\bar{\nu}$ (ref. 27, 28), the fragment angular anisotropy measure A_2 (ref. 30), the mass distribution measure R(ref. 26), and the effective spin (ref. 36).

Energy (eV)	Relative $\bar{\nu}$	$-A_2$	R	Jeff	Energy (eV)	Relative $\bar{\nu}$	$-A_2$	R	Jeff
0.29	1.0025	1.35	-	3.20	24.25	0.9962	1.50	1.100	3.00
1.14	1.0022	1.63	-	3.76	24.50	0.9968	-	-	3.04
2.03	0.9929	1.87	-	3.44	25.2-25.6	0.9995	0.97	1.032	3.00
2.84	0.992	-	-	3.6	26.49	1.0008	1.55	0.619	3.37
3.14	1.0053	1.60	-	3.33	27.82	1.0020	1.70	0.554	3.92
3.61	1.0055	1.96	-	3.83	28.36	1.0050	1.25	1.250	3.01
4.84	0.9869	1.74	-	3.53	29.65	1.0017	1.71	0.943	3.74
6.21	1.0045	0.96	-	3.22	30.6-30.9	0.9962	2.04	0.441	3.78
6.39	0.9983	1.70	-	3.65	32.07	0.9984	1.88	0.708	3.71
7.08	0.9994	2.29	-	3.83	33.53	0.9967	2.11	0.401	3.95
8.78	0.9992	1.78	-	3.87	34.4-34.8	1.0024	1.42	0.934	3.46
9.28	0.9985	1.81	-	3.74	35.20	1.0013	0.99	1.027	3.29
10.18	0.9914	1.89	-	3.83	36.5	-	0.93	1.344	3.26
11.66	0.9918	1.84	-	3.74	38.36	-	1.01	1.038	3.75
12.39	0.9941	1.17	-	3.10	39.41	0.9985	1.71	1.008	4.00
12.85	1.0026	1.91	-	3.81	41.3-42.7	0.9987	1.16	-	3.42
14.0-14.5	0.9955	1.20	-	3.10	43.4-45.8	0.9972	1.53	0.784	3.50
15.40	0.9930	2.11	-	3.86	46.8-47.0	1.0015	1.81	0.620	3.88
16.08	0.9894	1.87	-	3.91	48.0-49.4	1.0003	1.54	0.807	3.41
16.68	0.9944	2.27	-	3.99	50.5-52.2	0.9984	1.04	0.906	3.31
18.05	0.9958	1.64	-	3.34	55.1-56.5	0.9996	1.93	-	3.77
19.30	0.9941	1.82	0.402	3.83	57.8-58.7	0.9930	1.74	0.649	3.44
21.07	0.9976	1.93	0.517	3.47	59.8-61.2	0.9918	2.28	0.652	3.40
22.94	0.9962	2.15	0.374	3.93	63.6-64.3	0.9950	-	-	3.72
23.4-23.6	0.9982	2.16	0.404	3.19	65.8-67.3	1.0126	-	1.119	3.56

Correlation coefficients and significance levels (2-sided distribution):

$\rho(\bar{\nu},A_2)$ = +0.342 with 54 degrees of freedom. Significance level = 0.01.

$\rho(\bar{\nu},R)$ = 0.553 with 23 degrees of freedom. Significance level = 0.005.

$\rho(\bar{\nu}, Jeff)$ = -0.089 with 46 degrees of freedom.

$\rho(A_2,R)$ = +0.817 with 22 degrees of freedom. Significance level ~ 10^{-5}.

$\rho(A_2,Jeff)$ = -0.641 with 44 degrees of freedom. Significance level ~ 10^{-5}.

$\rho(R,Jeff)$ = -0.500 with 23 degrees of freedom. Significance level = 0.01.

Table II. Reduced R-matrix parameters that give the solid curves in Figs. 1-5. For all resonances, the radiation width was taken as 35 meV. The signs on the quantities Γ_{f1} and Γ_{f2} (and occasionally Γ_n) are the signs to be associated with the products $\sqrt{\Gamma_a \Gamma_b}$ in a three-reaction-channel reduced R-matrix description.

E_0(eV)	Γ_n(meV)	Γ_{f1}(meV)	Γ_{f2}(meV)	J
-2.000	1.0245	273.3	-407.9	4
-0.250	0.0727	-150.0	1.1	3
0.285	0.0036	-51.2	-35.2	3
1.129	0.0141	16.8	91.2	4
2.[illegible]72	0.0042	-20.2	10.2	3
2.781	0.0012	50.7	-60.4	4
3.089	0.0266	158.1	55.3	3
3.517	0.0064	-243.2	-196.7	3
3.613	0.0419	-40.6	2.3	4
4.845	0.0339	2.0	-4.4	4
5.481	0.0204	-8.9	-453.1	4
6.186	0.0730	42.2	150.[illegible]	3
6.379	0.1686	15.5	0.3	4
7.08[illegible]	0.1054	-23.2	13.6	4
7.162	0.0025	-209.4	-163.6	3
7.617	0.0037	1.0	324.8	4
8.772	0.9052	8.4	85.7	4
8.922	0.1151	-27[illegible].0	163.3	3
9.274	0.1063	69.3	[illegible].1	4
9.721	0.1057	339.3	150.0	3
10.150	0.0604	-41.8	-57.9	4
10.589	0.0143	380.9	1.3	4
10.852	0.0029	-589.4	-183.3	3
11.667	0.3331	-0.1	6.0	4
12.384	1.3082	-3.3	21.8	3
12.430	0.0456	-242.1	23.3	4
12.873	0.0657	120.4	-6.7	4
13.243	0.0334	-42.6	-67.7	4
13.925	0.6503	44.2	506.8	3
14.[illegible]52	0.2613	-2.6	1.8	3
14.996	0.0018	784.6	-40.3	3
15.395	0.1323	-26.7	32.5	4
16.073	0.2912	10.5	-5.0	4
16.642	0.2368	108.6	3.0	4
18.022	0.2621	58.4	-46.3	3
18.024	0.1108	40.8	159.3	4
19.001	0.2114	-1.2	-0.0	4
19.278	2.3476	-29.6	32.4	4
19.365	0.3779	-399.4	[illegible].1	3
20.152	0.0868	-135.7	-62.8	4
20.504	0.1534	53.1	-44.2	4
21.053	1.0610	-27.8	-9.9	4
21.963	0.0637	136.6	743.3	3
22.292	0.0201	0.1	375.6	4
22.923	0.3576	21.3	-48.8	4
23.386	1.6417	2.5	0.[illegible]	4
23.589	0.9350	239.9	-2.5	3
24.204	0.2521	13.0	66.8	3
24.818	0.0640	155.4	285.9	4
25.186	0.5272	203.6	20.9	4
25.493	1.2138	-218.7	443.6	3
26.310	0.1886	-102.6	260.6	3
26.475	0.2925	12.8	-127.6	4
27.223	0.0288	0.8	-59.4	3
27.774	0.5503	-83.0	-20.0	4
28.384	0.2368	-4.8	-215.2	3
28.679	0.0594	124.9	8.4	4
28.903	0.0153	-48.9	-31.7	3
29.625	0.1064	-39.5	-21.4	4
30.596	0.2130	41.9	-102.0	3
30.839	0.3091	-1.4	54.9	4
32.032	1.0126	-84.0	11.4	4
32.056	0.4625	-54.3	1.0	3
32.4[illegible]1	0.0112	-132.2	-1515.0	4
33.498	1.1136	51.2	2.8	4
34.337	1.2298	-2.2	-70.0	4
34.678	1.1069	-445.9	-15.0	3
34.893	0.3665	44.1	0.1	3
35.0[illegible]7	3.0976	0.1	-340.7	3
35.165	1.6098	31.3	6.7	4
36.310	0.0997	-329.7	1761.5	4
38.[illegible]74	0.1696	424.6	1103.8	3
38.328	0.3402	-129.7	-219.7	4
39.386	1.8950	-29.9	47.9	4
39.870	0.3927	182.8	35.8	3
40.494	0.3531	-36.3	-168.5	4
41.071	0.3370	-169.3	377.9	4
41.363	0.5259	-33.7	-337.6	3
[illegible]	0.6707	-7.0	18.4	3
42.204	0.3171	41.0	-115.9	4
42.429	0.0709	3.1	6.6	3
42.696	0.1220	-80.6	111.2	4
43.357	0.3410	-54.7	16.6	3
43.912	0.3772	-11.9	-195.3	4
44.547	0.4741	-115.5	10.4	4
44.786	1.4068	373.0	393.4	3
45.746	0.1614	120.4	1.4	4
46.785	0.9109	1.5	-163.7	4
46.968	0.4790	-47.8	-19.1	4
47.937	0.5843	-29.4	105.7	4
48.104	0.1431	-162.9	-1026.1	3
48.301	0.7860	310.1	40.4	3
48.409	0.3139	-376.5	-628.3	4
48.760	0.8000	-0.5	-59.9	3
49.402	0.2948	-34.7	22.9	4
49.746	-.0001	433.9	93.6	4
50.337	0.1276	21.2	29.8	3
50.439	0.8014	-67.0	0.3	3
51.068	0.9247	6.3	346.8	3
51.733	2.1042	-2.8	132.3	4

Table II. (Con't.)

E_o(eV)	Γ_n(meV)	Γ_{f1}(meV)	Γ_{f2}(meV)	J
51.647	0.5992	310.8	4.0	4
52.159	1.7391	2.0	284.0	3
52.338	0.4869	-86.2	188.4	4
53.452	0.5530	-0.0	149.3	3
53.985	0.3697	66.1	461.9	4
54.893	0.8452	-15.0	118.3	3
55.059	2.5593	0.0	17.7	4
55.765	2.0490	-236.5	21.4	4
55.954	0.6482	411.4	2.9	3
56.471	2.8492	33.6	53.5	4
56.525	0.9277	-238.5	-221.9	3
57.736	0.5564	-54.0	88.0	3
57.779	0.4875	-99.1	161.7	4
58.028	1.1663	40.7	4.2	3
58.617	1.1583	4.1	155.2	4
59.736	0.3212	426.7	-34.6	4
60.144	0.9692	61.1	168.1	3
60.791	0.5230	4.8	205.3	4
61.096	0.7861	11.7	0.3	3
61.412	0.2511	4.5	314.1	4
61.775	0.1602	-16.4	134.6	3
62.418	0.0774	47.4	139.6	4
62.866	0.0301	-317.6	484.4	3
63.562	0.8192	438.0	110.5	3
63.923	0.4481	-526.8	64.6	4
64.253	1.4745	-0.0	-3.7	4
64.801	0.1178	-6.5	1.7	4
65.458	0.1630	-473.5	733.6	4
65.708	1.8572	-0.0	3.3	3
65.957	0.2886	-568.2	237.5	4
66.366	1.9925	-0.4	4.0	4
66.689	0.0486	796.7	125.6	3
67.155	0.31[illegible]	0.2	-1.7	4
67.578	-.0903	10.8	-14.9	4
68.071	-.0088	-397.3	270.6	4
68.345	0.0838	40.7	0.9	3
69.259	0.3999	-173.2	37.4	[illegible]
70.223	3.3063	1.7	-9.1	4
70.436	3.8378	-3.9	8.4	3
70.452	1.7285	140.[illegible]	1391.1	4
70.696	2.0749	50.3	105.4	3
71.464	0.3209	-226.3	30.5	4
72.437	0.9670	181.3	178.2	4
72.820	0.1836	328.2	58.0	3
74.440	[illegible].5305	-147.8	41.2	3
74.540	0.8395	-170.4	47.5	4
74.995	0.3880	-17.5	15.3	4
75.465	1.6398	291.3	14.2	3
76.751	0.2667	1127.1	87.0	3
77.461	0.6603	194.4	26.9	4
77.941	0.8954	192.7	10.0	3
78.143	0.3436	-27.5	0.1	4
78.396	0.2033	1.9	0.0	3
79.591	0.3861	-8.7	-158.8	4
79.758	1.3304	0.8	-1.6	3
80.287	0.7375	-0.0	-140.4	3
80.962	0.2473	369.1	643.1	4
81.392	0.7790	-58.9	-75.5	3
82.367	0.7778	-0.6	-5.0	3
82.656	0.4001	-87.7	4.9	4
83.545	0.9595	-13.1	-0.9	3
84.001	2.6240	261.8	-198.4	4
84.345	1.8315	-224.6	-115.0	3
84.873	1.2939	-0.1	7.5	4
85.208	0.6674	-12.3	14.9	3
85.643	0.5783	-377.1	-52.3	4
86.905	0.5951	-2.4	6.3	3
87.064	0.1324	12.2	-553.9	4
87.785	0.3524	-159.5	279.4	3
88.165	0.3441	-1379.9	4.9	4
88.719	3.3162	-0.9	598.7	3
88.889	1.4827	-10.5	-4.6	4
89.740	0.5641	8.2	-5.4	3
90.118	0.8760	48.3	145.9	4
90.434	3.7716	-3.5	-0.3	4
91.167	3.4279	-2.0	448.9	3
92.037	0.7001	-138.7	-98.7	4
92.525	1.4740	0.1	35.8	4
92.700	-.0949	83.9	63.4	3
93.164	0.4520	157.0	310.5	3
93.374	3.3471	0.6	-3.4	4
94.454	0.2881	19.5	287.7	4
94.766	0.4761	21.0	48.4	3
95.133	0.3912	40.2	-22.2	4
95.500	0.6719	-21.8	26.7	4
95.805	0.5996	33.6	210.2	3
96.051	0.2709	24.6	57.5	4
96.331	0.9868	15.5	400.1	3
97.606	0.3130	-43.4	33.8	4
98.019	2.3619	-68.0	82.5	3
99.446	0.4954	-25.6	0.1	3
100.560	1.8084	134.8	-89.6	4

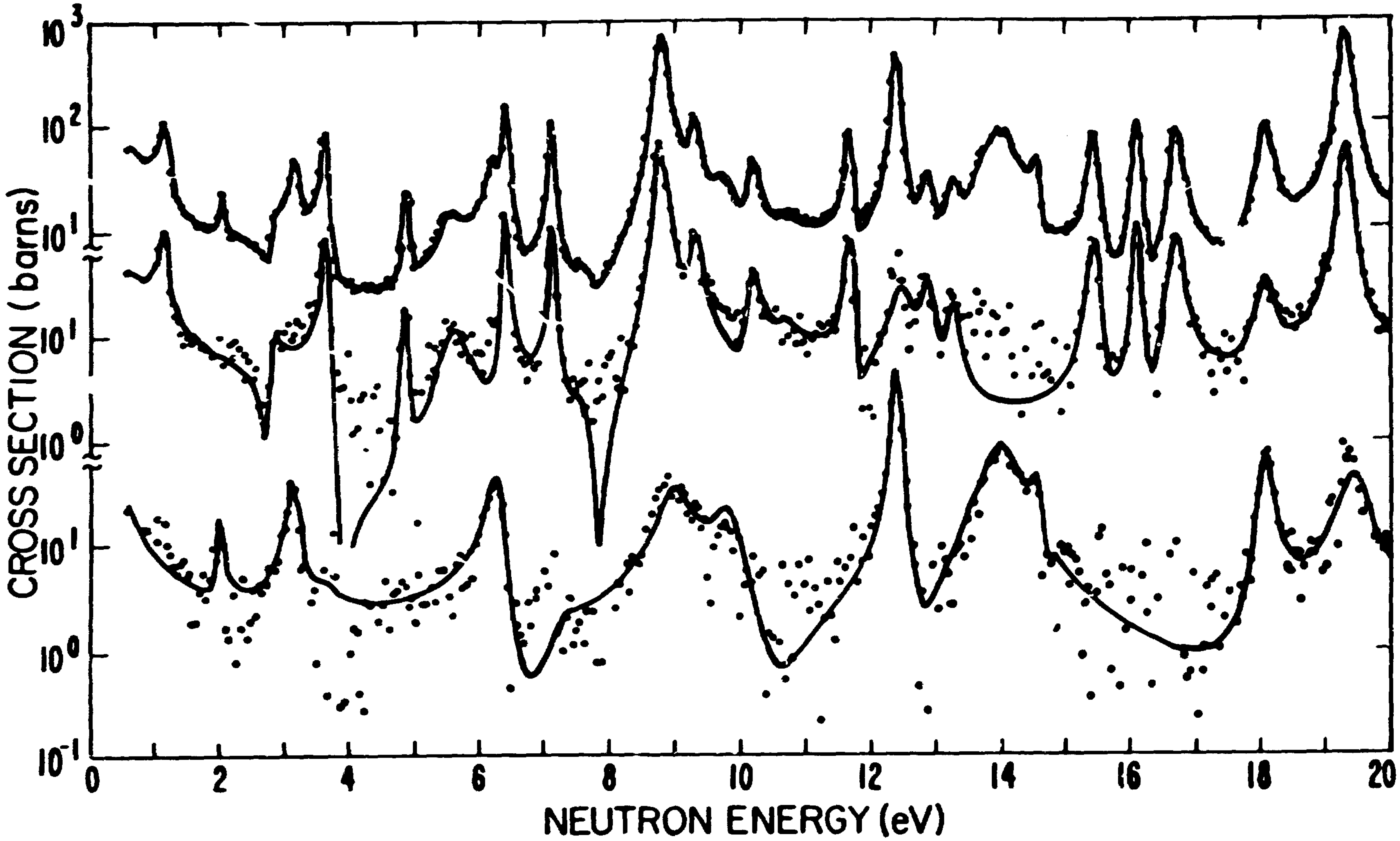

Fig. 1. The fission cross section of ^{235}U below 20 eV. The lowest curve shows the spin 3 cross section, calculated from the reduced R-matrix parameters of table II; the middle curve is the spin 4 cross section; and the top curve is the sum of the other two. Data points above 1 eV are the measurements of Keyworth et al.

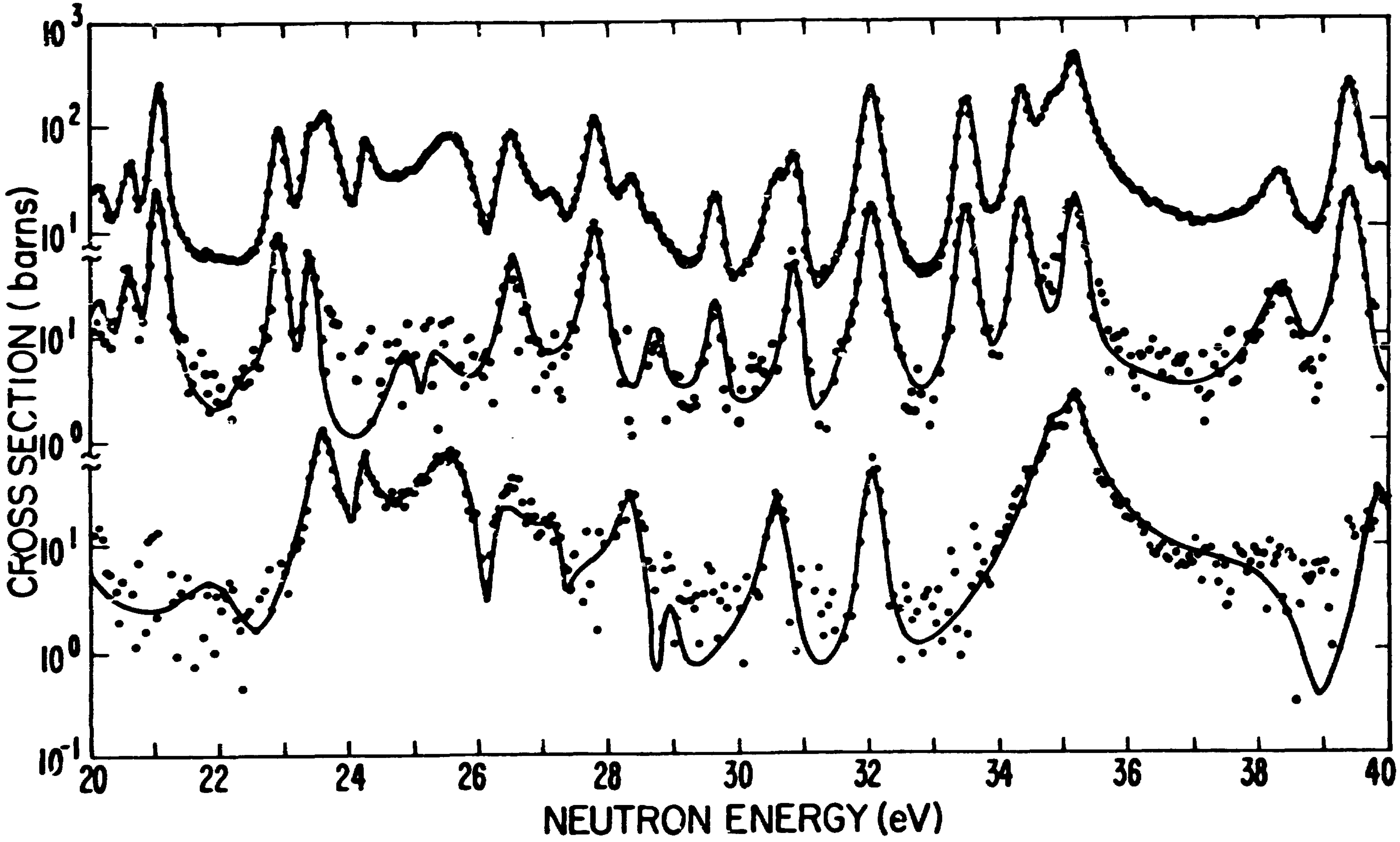

Fig. 2. The fission cross section of ^{235}U from 20 to 40 eV, as in Fig. 1.

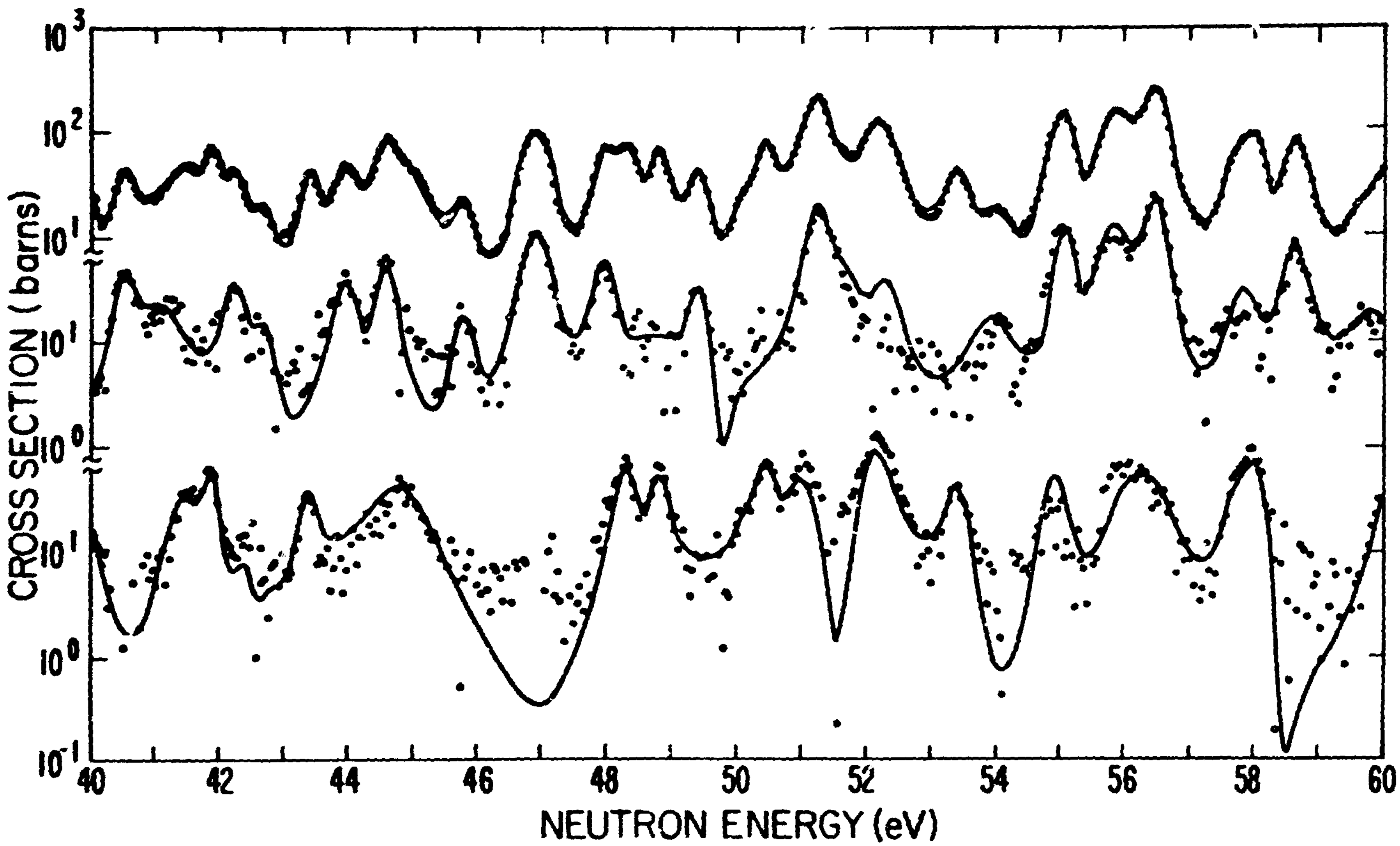

Fig. 3. The fission cross section of ^{235}U from 40 to 60 eV, as in Fig. 1.

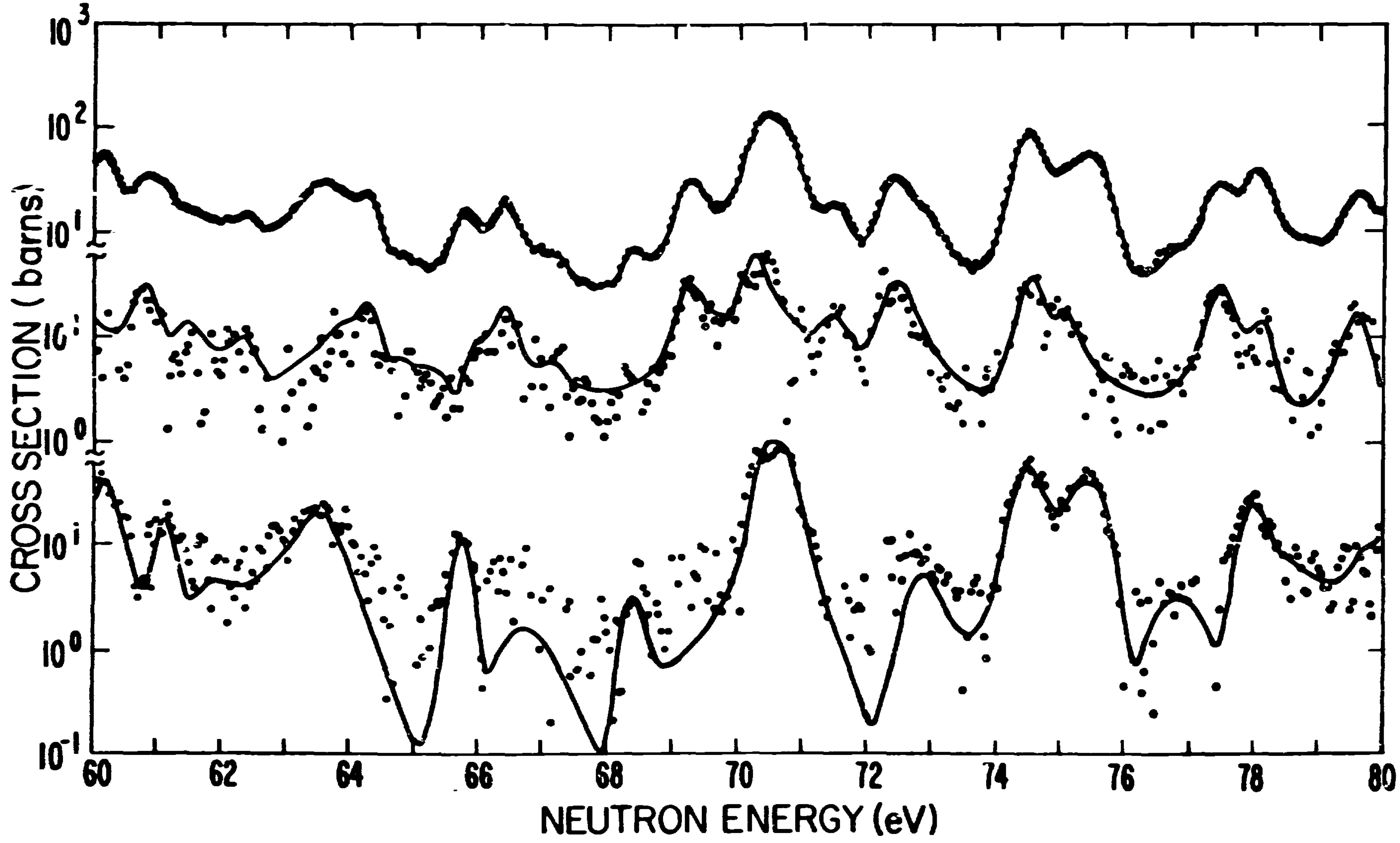

Fig. 4. The fission cross section of ^{235}U from 60 to 80 eV, as in Fig. 1.

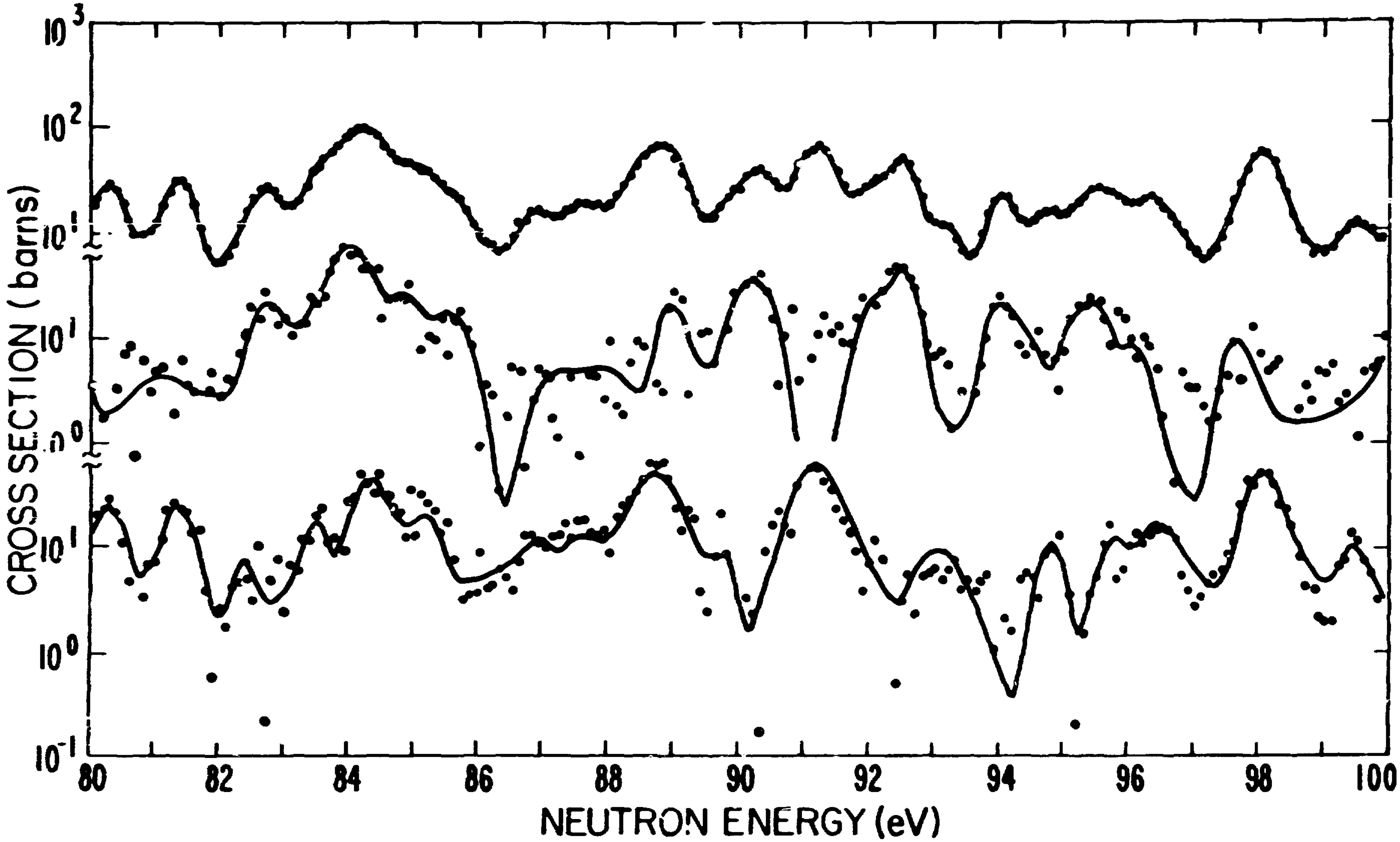

Fig. 5. The fission cross section of ^{235}U from 80 to 100 eV, as in Fig. 1.

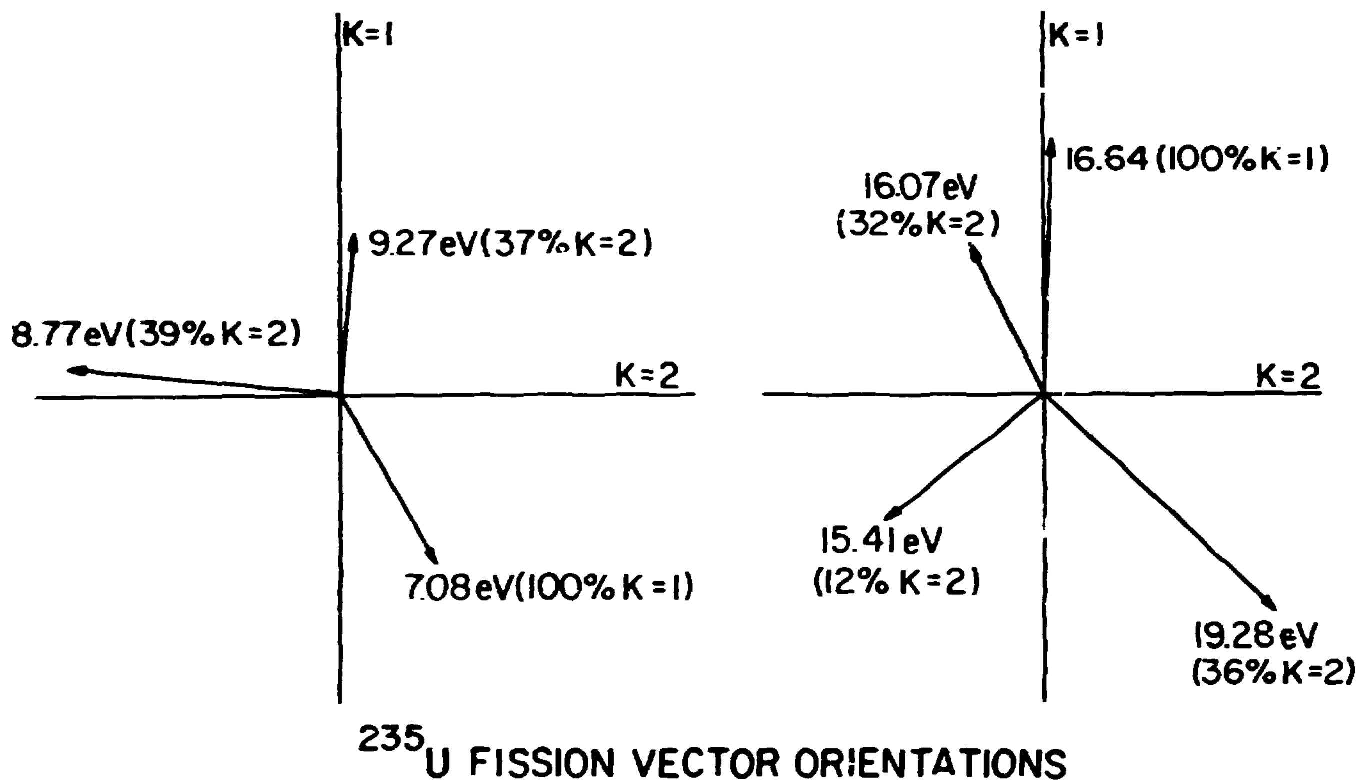

Fig. 6. Fission-width vector orientations for 4- resonances in ^{235}U near 8 and 19 eV, from Table II. These two energy regions are not strongly interdependent, so that a 30° clockwise rotation of all the vectors in Fig. 6A can be done without affecting the vector orientation in 6b appreciably.