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PRESENT STATUS OF CROSS SECTION DATA OF THE FISSILE AND FERTILE ISOTOPES FOR FAST REACTORS*

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ABSTRACT

We review the status of the most relevant neutron cross sections for the design of fast breeder reactors.

I. INTRODUCTION

In this paper we shall review the status of five cross sections: the fission cross section of U-235, because it is so widely used as a standard with respect to which other fission and capture cross sections are measured, and the fission and capture cross sections of U-238 and Pu-239, since these cross sections control the neutron balance of a fast breeder reactor and hence are fundamental to the calculation of the criticality constant and of the breeding ratio (1).

Because of space limitations we will omit from our review some less important cross sections, such as those for the higher plutonium isotopes (Pu-240, 241, 242).

We shall also concentrate on the neutron energy region from 1 keV to 10 MeV since this is the region where most reactions take place in a fast reactor. This is not to imply, however, that the region below 1 keV is not important for the development of fast reactors; quite to the contrary, that low energy region is of prime importance in at least two respects:

1. A large number of good recent cross-section measurements, particularly below a few hundred keV, are really "shape" measurements which need to be normalized at low energy where absolute measurements can be done by the saturated resonance technique (2) or with respect to the well-known 2200 m/sec values (3); clearly the absolute values at high energies derived from these shape measurements are only as good as the cross sections in the normalization range.

2. The resonance structure of the heavy elements can best be interpreted at low energies where the resonances can be resolved and the spin of most levels can be determined (4). At the present time a knowledge of the

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statistical properties of the resonance structure is required to compute self-shielding effects in the unresolved resonance energy range properly (5).

This status report is not an evaluation. Excellent and complete evaluations have recently been performed by CSWEG in the U.S. (6), by Sowerby et al. (7) in the U.K. and by Abagyan, Nicolaev et al. (8) in the U.S.S.R. Our purpose is more to comment on the progress that has been made in recent years in our knowledge of the cross sections, and on the problems and discrepancies that still need to be resolved.

In reviewing the present status of cross-section data it seemed instructive to take an historical perspective by comparing our present knowledge with that of a few years ago. In 1970 W. G. Davey (9) presented an excellent paper on the "Status of Important Heavy Elements Nuclear Data above the Resonance Region" for the Second International Conference on Nuclear Data for Reactors. We find it instructive to compare the present status of cross-section data with that of four years ago, as defined by Davey's paper (10).

For most of the cross sections discussed here it is convenient to divide the neutron energy range in two groups: the region from 1 to 100 keV and that from .1 to 10 MeV. Of course many measurements span across the 100 keV boundary; nevertheless, below 100 keV most recent measurements are "shape measurements," normalized at low energy, done with "white" neutron spectra, by the time-of-flight technique, often relative to the $^{6}Li(n,\alpha)$, the $^{10}B(n,\alpha)$ and the $^{10}B(n,\alpha^*)$ reaction cross sections. Above 100 keV most measurements have been done with nearly monoenergetic neutron sources and are absolute ratio measurements, relative to the H(n,p) cross section or the fission cross section of U-235.

II. THE U-235 FISSION CROSS SECTION

1. The region from 1 to 100 keV

In Fig. 1 we compare the 1968 evaluation of W. G. Davey (10) (solid line) to the most recent U.S. evaluation, ENDF/B-IV (broken line). A few typical data points are also shown. (A plot of all the data available would result in a most confusing picture.) The data prior to 1970 are represented as full symbols, the recent data as open symbols. Table I lists some of the most important measurements done since 1970.

There are two striking features of Fig. 1 about which we shall now comment:

A. Whereas Davey's evaluation is a smooth curve, the ENDF/B-IV evaluation shows a considerable amount of structure.

Indeed, until 1970, most data on the fission cross section of U-235 above a few keV had been obtained with nearly monoenergetic neutron sources or with relatively poor energy resolution, so that any existing structure could not have been observed.

In 1970 Patrick, Sowerby and Schomberg (11) first called attention to the structure in the fission cross section of U-235, which persists well

above 100 keV. Also in 1970, Bowman, Stelts and Baglan (12) presented relative data obtained with very good time resolution, which dramatically illustrated this structure. In recent years this structure has been confirmed and investigated by many time-of-flight measurements (13,14); the details with which it is now known are illustrated by Figs. 2 and 3 in which results from different experiments are compared.

Similar structure has been observed in the total (15) and capture (16) cross sections and statistical tests have shown that it implied some intermediate structure in the neutron or fission channels, such as would result from the coupling between levels in the first and second wells of the fission potential barrier (17).

Patrick et al. (11) and Bowman et al. (12) have pointed out that the structure implies some limitations on the usefulness of U-235 as a standard below a few hundred keV; in particular, measurements done with nearly monoenergetic sources of neutrons should be reinterpreted with care.

B. The second striking feature of Fig. 1 is that the ENDF/B-IV evaluation is systematically lower than Davey's evaluation (by about 7% in the interval 10 to 100 keV). Yet Davey's evaluation was going through the lowest measurements available at the time, those of White (18) and Perkin et al. (19). Since 1970 a large number of new measurements have been completed which for the most part yielded values lower than those of Davey's 1968 evaluation.

Many of the new measurements listed in Table I were done with the time-of-flight technique, with white neutron sources (Linacs, nuclear explosions), and with very good energy resolution. These measurements were done relative to the $^{6}Li(n,\alpha)$ or $^{10}B(n,\alpha)$ reaction cross sections and normalized at some reference energy. The errors quoted by the experimenters vary from 3 to 8% but much of this error is due to uncertainties in the normalization (20), and hence is correlated over the entire energy region. This is illustrated in Table II. In this table we list the cross sections averaged over decimal energy groups for four different measurements (13, 21-23). For each measurement the first column gives the group cross sections obtained from the data as reported by the measurer, the second column gives the group cross section as obtained from the data renormalized to the average value between the four measurements, for the integral from 1 to 100 keV. In the last two columns of Table II we give the average percent difference between the original group cross sections and the renormalized group cross sections. The average discrepancy between the original group cross sections is 3.6%, that between the renormalized group cross sections is only 1.6%. This indicates that for this decimal group structure the "shape" is known to better than 2% whereas the normalization is only known to 3%.

Another estimate of the precision with which we presently know the cross section of U-235 from 1 to 100 keV can be obtained by comparing recent independent evaluations. The most recent U.S. (6), U.K. (7) and U.S.S.R. (8) evaluations are compared in Fig. 4. A few typical data points, with their uncertainties, are also shown, for comparison. Note that below 10 keV the U.K. and U.S.S.R. evaluations show much less structure than the U.S. evaluation; this is, however, in the unresolved (statistical) resonance range, and it is not clear to what extent the fluctuations should be represented in that region.

2. The region from .1 to 10 MeV

In Fig. 5 we compare Davey's 1968 evaluation (10) to ENDF/B-IV (6). Selected typical experimental data are also shown; the full symbols correspond to data prior to 1970, the open symbols to recent data; the most extensive measurements since 1970 are listed in Table I. From 100 to 350 keV ENDF/B-IV is somewhat lower than was Davey's evaluation; this is the same situation as below 100 keV, namely all the new data are lower than the data available in 1968. Above 2.5 MeV, on the contrary, the ENDF/B-IV evaluation is higher than was Davey's evaluation; this is mostly because whereas Davey's evaluation followed the 1967 data of Hansen et al. (24), ENDF/B-IV is based on new measurements of Hansen et al. (25) and Poenitz (26). Between 1.8 and 3.5 MeV there is excellent agreement between the recent data of Poenitz (26), which have a 3% precision, and the preliminary data of Hansen et al. (25), which have a precision better than 1.5%. Below 1.5 MeV the data of Poenitz are systematically lower than those of Hansen et al., but the difference never exceeds 4%.

In Fig. 6 we compare the most recent U.K. evaluation (7) to ENDF/B-IV. There are some fairly large discrepancies between the two evaluations, particularly just below 2 MeV, where the difference between the two evaluations is of the order of 5%. Of course the most recent data of Hansen et al. (25) and of Poenitz (26) were not available when the U.K. evaluation was done, whereas these data were heavily weighted in the ENDF/B-IV evaluation. This explains the discrepancy between the two evaluations near 2 MeV, but the overall situation is unsatisfactory, because Sowerby et al. have performed a simultaneous evaluation of a number of fission and capture cross sections and their ratios; this simultaneous evaluation yields for U-235 a fission cross section which, in the region near 2 MeV is quite consistent with the 1957 data of Diven (27), but is inconsistent with the more recent measurements of Poenitz and Hansen et al., and hence with ENDF/B-IV.

It is very difficult to estimate realistically the uncertainty in our present knowledge of the U-235 fission cross section. In 1957 Allen and Ferguson (28) quoted an absolute error of 3 to 5%; in 1965 White (18) estimated a 3% error for his data; in 1970 Poenitz (29) reported some values with a 3.5% precision; in 1974 the ENDF/B-IV evaluators (6) estimate that the uncertainty below 5 MeV varies between 3 and 5%. Hence, in the past 17 years the errors quoted have not been much reduced! Furthermore there are differences in the values reported for the cross section which are large compared to the quoted errors; the value of the cross section at 550 keV was given by Allen and Ferguson (28) in 1957 as 1.220 ± .043 b., by Poenitz (29) in 1970 as 1.085 ± .043 b. and is evaluated in ENDF/B-IV as 1.159 ± .046 b.!

In spite of the fact that the quoted error in the past 17 years has remained around 4%, there is no doubt that we have considerably improved our knowledge of the U-235 fission cross section, particularly in the past four years. Below 100 keV the structure of the cross section has been reproducibly identified and measured with good resolution, so that the shape of the cross section is probably known to better than 2%; there remains an uncertainty in normalization of the order of 4%, but the nature of this uncertainty has been well identified and its magnitude will probably be reduced in the next few years by experiments now in progress or planned. In the range .1 to 1 MeV it is gratifying that the extensive measurements of Szabo

et al. (30), Gayther et al. (23), and Poenitz (26) all with uncertainties in the 3 to 4% range, agree well within this error. In the range 1 to 6 MeV the new data of Hansen et al. (25) with uncertainties between 1 and 1.5% should considerably improve our knowledge of the cross section. From 2 to 3.5 MeV these data by Hansen et al. (25) agree very well with those of Poenitz (26). Above 6 MeV there are no new measurements, and some are badly needed.

Even though our knowledge of the U-235 fission cross section has much improved in the past four years, it is clear that more precise measurements are required to achieve the 1% accuracy requested from 1 keV to 1 MeV (31). Precision measurements are in progress or planned at Karlsruhe (32), Livermore (33), ORNL (34), Harwell (35), Bruyères-le-Châtel (36) and probably in other laboratories, so that the next few years should see a further improvement in our knowledge of this most important cross section.

III. THE U-238 FISSION CROSS SECTION

Most measurements of the U-238 fission cross section have been made relative to the U-235 fission cross section, so that the ratio of the two cross sections is better known than the absolute value of either cross section, and the errors in the two cross sections are almost entirely correlated.

Measurements prior to 1970 have been extensively reviewed by Davey (10). In 1972 Poenitz and Armani (37) reported new measurements covering the range 2 to 3 MeV with 2% accuracy and Meadows (38) reported measurements from 1 to 5 MeV with accuracies ranging from 1 to 4%. Cierjacks (32) reported extensive preliminary data extending from .8 to 30 MeV. These three ratio measurements seem to be in agreement with Davey's 1968 evaluation of the ratio. Further measurements of the ratio, from the subthreshold region to 1 MeV, are in progress at Saclay (39) and at Livermore (40).

Sowerby (7) has recommended that the absolute value of the U-238 fission cross section be measured above 2 MeV; since U-238 is not fissionable at thermal energies, background problems would be less severe in U-238 measurements than in U-235 measurements. The U-235 cross section could then be derived from the ratio measurements.

A potentially important recent development concerning the U-238 fission cross section is the discovery in 1971 by Silbert and Bergen (41) of the subthresold fission. This subthreshold fission has recently been measured with good energy resolution and good precision by Block et al. (42). Time-of-flight measurements are also in progress at Saclay (39).

The importance of the subthreshold fission in U-238 for the development of fast reactors has probably not yet been fully assessed.

IV. THE U-238 CAPTURE CROSS SECTION

1. The region from 1 to 100 keV

Capture cross section measurements usually have larger errors than

fission cross section measurements because the capture gamma rays are more difficult to detect than the fission fragments or the prompt fission neutrons. If the activation technique is used to detect capture, the data have poor energy resolution and hence are not very useful in the region where the cross section has fine or intermediate structure. Recent U-238 capture cross section measurements quote uncertainties in the 5 to 10% range, but often discrepancies between data are larger, indicating that some sources of error have not been properly identified.

Before 1970 all the measurements of the U-238 capture cross section but one, that of Moxon (43), had been done with nearly monoenergetic neutron sources and most of those measurements had been done relative to the U-235 fission cross section. The interpretation of such measurements is complicated not only because of the structure in the U-235 fission cross section, which we have already discussed, but also because the U-238 capture cross section has considerable structure which needs to be measured more accurately and evaluated.

The structure in the U-238 capture cross section is illustrated in Fig. 7, from a recent paper by Spencer and Käppeler (44). In that figure the authors have compared the shape of their preliminary data to that obtained in a recent ORELA measurement (45). Both sets of data have been averaged over intervals of .5 to 1 keV width. The KFK data are not normalized, so that the agreement in magnitude is not significant. We have added to the figure the ENDF/B-IV evaluation (6). Below 45 keV the evalutaion is represented by statistical parameters so that some structure is implied, but clearly the details of this structure are important and need to be represented more directly by the evaluation.

In Fig. 8 we compare the 1970 evaluation of Davey (46) to ENDF/B-IV. We also show some typical experimental data. Data obtained before 1970 are represented by full figures, recent data by open figures. Some error flags have been omitted so as not to overcrowd the figure. Data derived from ratios of the U-238 capture to the U-235 fission or absorption cross sections have been recomputed using ENDF/B-IV values of the U-235 cross sections.

As can be seen on Fig. 8, there are large uncertainties in the data and discrepancies between measurements. ENDF/B-IV is lower than Davey's evaluation partly because recent measurements have yielded lower cross sections, partly because the U-238 capture cross section is correlated to the U-235 fission cross section by the ratio measurements, and the ENDF/B-IV value of the latter cross section is lower than that evaluated by Davey (10).

The recent measurement of Panitkin et al. (47) extends from 24 to 145 keV and was done with nearly monoenergetic neutrons from the $Li^6(p,n)$ reaction, and relative to the U-235 fission cross section. The point of Block et al. (48) was obtained at 24.3 keV with an iron-filtered beam, and relative to Au. As we have already mentioned, these data must be interpreted in the light of the structure in the U-235 fission and U-238 and Au capture cross sections (49). The data of Chelnokov et al. (50) were also obtained relative to the U-235 fission cross section, using a lead slowing down spectrometer.

Only four measurements done with a white neutron source and the time-of-flight technique have been reported. The data of Moxon (43) extend to 200

keV and have uncertainties ranging from 4 to 8%; the data of Fricke et al. (51) extend to 1 MeV with errors of the order of 12%; the data of de Saussure et al. (45) extend to 100 keV, the errors range from 5 to 10%; finally the measurement of Spencer and Käppeler (44) covers the range 20 to 550 keV, but the results are still preliminary. The three first measurements were done with a Linac, were normalized by the saturated resonance technique at 6.7 eV, and were relative to the $^{10}B(n,\alpha)$ or $^{10}B(n,\alpha\gamma)$ reaction up to 80 keV. The results of these three measurements averaged over decimal intervals up to 100 keV are compared in Fig. 9 where we also show ENDF/B-IV.

Figure 9 shows that there are discrepancies between the results of the three measurements. Those discrepancies are substantially larger than the known uncertainties and do not show a consistent pattern: below 5 keV the ORELA data agree within 6% with those of Moxon but are 25% larger than those of Fricke et al.; above 50 keV the ORELA data and those of Fricke et al. agree to within 3% but are 20% larger than those of Moxon! Patrick and Sowerby (52) have recently discussed these discrepancies in great detail.

Carraro and Kolar (53) have recently obtained U-238 resonance parameters up to 5.7 keV by analyzing transmission measurements; Maletski et al. (54) have obtained parameters up to 1.2 keV from transmission and radiative capture experiments and Rahn et al. (55) have obtained parameters up to 4.6 keV from transmission, capture and self-indication measurements. Unfortunately, the resonance parameters are not sufficient to determine the average capture cross section above 1 keV with precision because the parameters of the small p-wave levels cannot be obtained accurately and those many small levels contribute appreciably to the average cross section in the keV region.

Vankov et al. (56) and Byoun et al. (57) have determined average resonance parameters for U-238 by analyzing thick sample transmission and self-indication experiments done with the sample at different temperatures. Those average resonance parameters may then be used to compute the average capture cross section. However, because of space limitation, we cannot review here this very interesting technique and the results obtained.

2. The region from .1 to 1 MeV

In Fig. 10 we compare the 1970 evaluation of the U-238 capture cross section by Davey (46) with the recent evaluation by Sowerby et al. (7) and with ENDF/B-IV (6). Some typical experimental data are also shown, the data older than 1970 as full figures, the recent data as open figures; data derived from ratio measurements with respect to the U-235 fission cross section were recomputed using the ENDF/B-IV value of the U-235 cross section. The considerable differences in the three evaluations below 2 MeV reflect the considerable uncertainty in the cross section; the agreement between the evaluations above 2 MeV reflects the lack of measurements in that region!

The errors in the U-238 capture cross section are strongly correlated to those in the U-235 fission cross section, not only by the precise measurements of the ratio of those two cross sections, such as that of Poenitz (58), but also because some authors have measured the absolute U-238 capture cross section and U-235 fission cross section using the same techniques and the same detectors to determine the incident neutron flux. If an evaluator favors a given set of data for the U-235 fission cross section, it is logical

that he should also give much weight to the U-238 capture cross section obtained in the same installation, by a similar technique.

In the region from .1 to .5 MeV the data of Menlove and Poenitz (59) are about 17% lower than those of Barry, Bunce and White (60). Davey gave much weight to the data of White (18) in his evaluation of the U-235 fission cross section (10). Since the data of White and the data of Barry et al. were obtained "from the same flux," Davey also weighted the data of Barry et al. in his U-238 capture cross section evaluation (46), and he renormalized the values of Menlove and Poenitz to agree better with those of Barry et al. Sowerby et al. (7) performed a simultaneous evaluation of several cross sections including U-238 capture and U-235 fission. For this evaluation they choose to treat the data of Barry et al. as ratio measurements relative to the fission data of White. ENDF/B-IV choose to give more weight to recent data which are mostly independent of the U-235 fission cross section: the data of Fricke et al. (51), of Ryves et al. (61) and the preliminary data of Pearlstein and Moxon (62).

Sowerby et al. (7) estimate that the U-238 capture cross section is known to 7% from .1 to 1 MeV; in the same range ENDF/B-IV (6) estimates an uncertainty of 5%. We think that these estimates are very optimistic, considering that there is more than 20% discrepancy around 1 MeV between the 1973 evaluation of Sowerby et al. and ENDF/B-IV!

In summary, a number of measurements of the U-238 capture cross section have been completed in the past few years; below 100 keV these measurements suggest a considerable amount of fine structure. Over the entire energy range there are discrepancies between measurements that exceed the known uncertainties. Some experimental data are still preliminary (44,62) and new measurements are in progress (63), but it is clear that considerably more work will be needed to achieve the 2 to 3% accuracy requested by reactor physicists (64).

V. THE Pu-239 FISSION CROSS SECTION

1. The region from 1 to 100 keV

Before 1970 all measurements of the Pu-239 fission cross section, except that of Shunk et al. (65), had been done with respect to the U-235 fission cross section and with nearly monoenergetic sources of neutrons.

Since 1970 a number of measurements were completed which used white neutron sources and the time-of-flight technique. The measurements of Blons et al (66), James (67), Schomberg et al. (68), Gwin et al. (69) and Weston and Todd (70) extend to 20 or 30 keV and indicate a large amount of structure below 10 keV. The data of Farrell et al. (71) extend to 1 MeV and the recent data of Gwin et al. (72) to 200 keV. Precision measurements done with nearly monoenergetic neutron sources above 10 keV have been reported by Szabo et al. (73). New measurements of the Pu-239 to U-235 fission cross section ratio were reported by Lehto (74) up to 25 keV, by Pfletschinger and Käppeler (75) from 5 keV to 1 MeV, and by Poenitz (76) at 30 keV.

In Fig. 11 we compare the 1968 evaluation by Davey (10) to the 1973 evaluation of Sowerby et al. (7) and to ENDF/B-IV; a few experimental data points are also shown. The main difference between the 1968 evaluation and the recent evaluations is in the structure below 10 keV. This structure is confirmed by a number of measurements. Sowerby et al. estimate that the accuracy of their evaluation is 4% below 20 keV, and decreases to 7% at 100 keV. Since reactor designers (31) are requesting 2% accuracy from 20 keV to 3 MeV, additional measurements will be needed.

2. The region from .1 to 10 MeV

Most measurements of the Pu-239 fission cross section above 100 keV were done relative to the U-235 fission cross section so that errors in these two cross sections are strongly correlated (77).

In Fig. 12 we compare the 1968 evaluation of the Pu-239 to U-235 fission ratio by Davey (10) with the ratio derived from the ENDF/B-IV cross sections. Although the average values of the ratio from the two evaluations are not very different, ENDF/B-IV indicates some structure between .6 and 6 MeV which was not present in Davey's evaluation. This structure is indicated by some recent measurements: Pfletschinger and Käppeler (75) and Szabo et al. (73) have measured the fission ratio up to 1 MeV, the measurements of Soleilhac et al. (78) and of Poenitz (58) extend to 1.4 MeV whereas the data of Savin et al. (80) and the recent data of Poenitz (76) cover the range up to 5.4 MeV. Above 6 MeV there have been no new measurements since 1970.

The recent data do not agree on the details of the structure in the fission ratio: for instance Savin et al. report a deep dip near 1.3 MeV which is not seen by Poenitz (76), and the results of Soleilhac et al. above 1 MeV are lower than those of other measurements. These discrepancies are probably the reason for the differences between the 1973 evaluation of Sowerby et al. (7) and ENDF/B-IV. These two evaluations are compared in Fig. 13; a few typical data points have also been included. The discrepancies between the two evaluations of the fission ratio, near .8 MeV and from 4 to 5 MeV are of the order of 4%.

As is the case with U-238, the Pu-239 to U-235 fission ratio is better known than the absolute value of either cross section, so that improvements in the accuracy of the U-235 fission cross section will also improve our knowledge of the Pu-239 fission cross section.

VI. THE Pu-239 CAPTURE CROSS SECTION

Since all the measurements of the Pu-239 capture cross section are done relative to or simultaneously with measurements of the Pu-239 fission cross section, it is more significant to discuss the capture cross section in terms of α, the ratio of capture to fission.

Until 1967 alpha for Pu-239 was thought to vary smoothly with energy from a value near .7 at 1 keV to a value near .1 at 100 keV (81). This behavior was inferred from some integral measurements (82) and from two sets of data in the region 10 to 100 keV obtained with nearly monoenergetic neutron sources (83,84). In 1967 Schomberg et al. (85) presented preliminary

results of a measurement done with a white neutron source which indicated that α for Pu-239 varied very rapidly with energy and could be as large or larger than 1.

In recent years a number of measurements of α for Pu-239 have been completed, most of them were done with white neutron sources and with the time-of-flight technique. At the second Conference on Nuclear Data for Reactors in 1970 the earlier measurements were reviewed by a panel of experts (86) and new data were presented by Belaiev et al. (87) up to 10 keV, by Czirr and Lindsey (88) and by Schomberg et al. (68) up to 30 keV; Farrell et al. (71) presented measurements of the capture and fission cross section extending to 1 MeV.

Since 1970 new data on α for Pu-239 were presented by Gwin et al. (69) and Kurov et al. (89) up to 30 keV, by Kononov et al. (90) from 10 keV to 1 MeV, by Bergman et al. (91) up to 50 keV and by Bandl (92) in the range 8 to 60 keV. The most recent data are those of Weston and Todd (70) and Gwin et al. (72) which extend to 200 keV; these data were taken with different techniques and show good agreement within the errors.

In Table III we list the data of Schomberg et al. (68), of Weston and Todd (70) and of Gwin et al. (72) averaged over decimal intervals. There is good agreement between the three sets of data, within the errors, but these errors range from 5 to 30%. The accuracies requested by reactor designers (1,31) range from 3 to 5%, so that additional measurements would be desirable, but it is doubtful that existing techniques can achieve the lower limit of the requested accuracy.

VII. CONCLUSIONS

We have reviewed the recent data on five cross sections which are particularly important to the development of fast reactors.

A comparison of the present status of the data with what was available around 1970 indicates that in the past few years our knowledge of the cross sections has greatly improved.

Below 100 keV the improvement has not been so much in the accuracy with which we know the absolute value of the cross sections, but the improvement resulted from the identification and measurement of the structure in the cross sections and in α, and in the discovery of the subthreshold fission in U-238. This detailed knowledge of the cross sections came from measurements done with white neutron sources and with good energy resolution. The important role of Linacs as neutron sources and of the time-of-flight technique are particularly noteworthy.

Since the accuracy of the data on the U-235 fission cross section has improved and the structure has been identified, the usefulness of that cross section as a standard below 100 keV must be reevaluated. Indeed many of the recent measurements are done relative to the $^{10}B(n,\alpha)$ of $^{6}Li(n,\alpha)$ reaction cross sections.

Above 100 keV the U-235 fission cross section is still the standard with respect to which other cross sections are usually measured. The preliminary data of Los Alamos and the many experiments in progress lead us to believe that the accuracy with which we know this cross section will greatly improve in the next few years, although much work remains to achieve the 1% precision requested by reactor designers.

The uncertainties in the U-238 capture cross section are still in excess of 10%. We believe that measurements now in progress will soon reduce this uncertainty, but many more measurements will be required to achieve the 2 to 3% accuracy requested by reactor designers.

Finally, an examination of the errors quoted in recent evaluations and in measurements indicates that it is very difficult to assess accurately the uncertainties in the data. For sensitivity calculations it is also very important to recognize the correlations in the errors.

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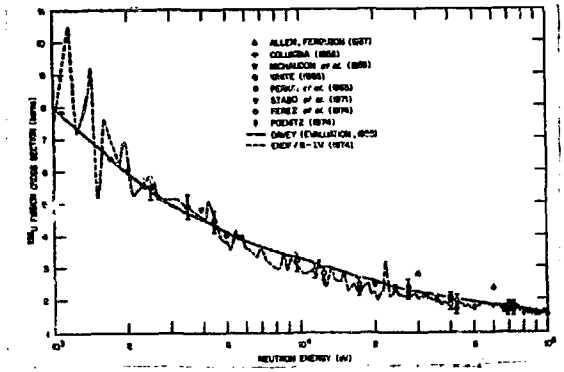
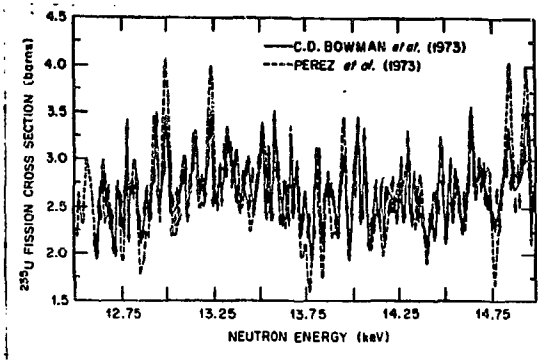
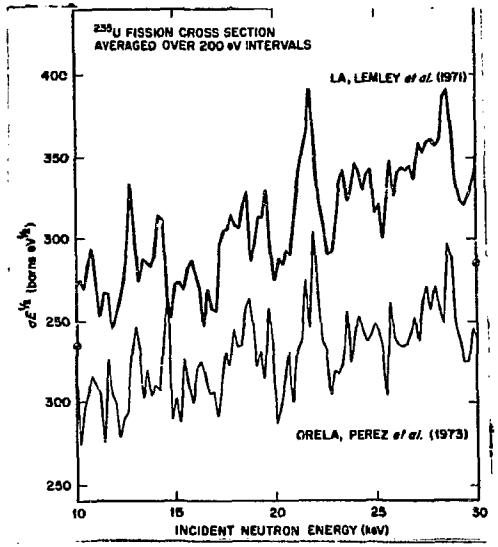


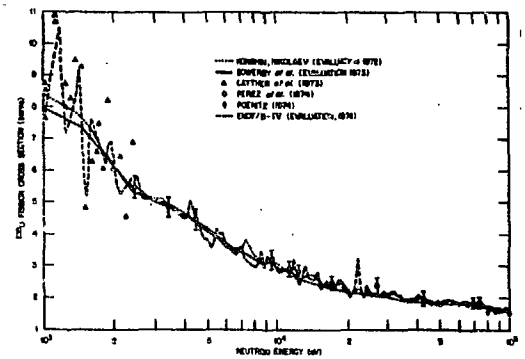
1. Comparison of Two Evaluations of the ^{235}U Fission Cross Section Between 1 and 100 keV. A few experimental data points are also shown.



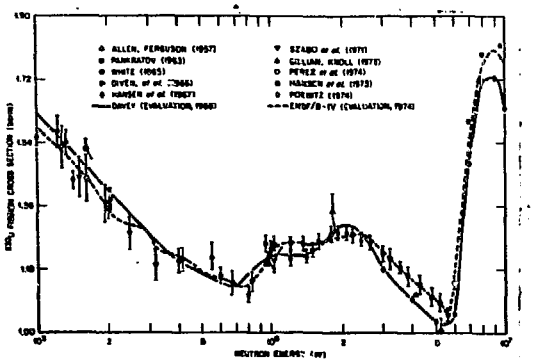
2. Comparison of Two Measurements of the ^{235}U Fission Cross Section Between 12 and 15 keV, Showing Large Fluctuations in the Fission Cross Section.



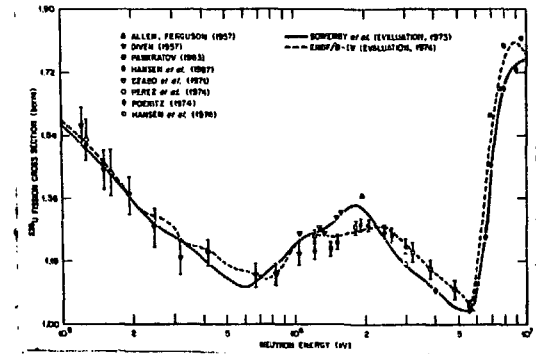
3. Comparison of Two Measurements of the ^{235}U Fission Cross Section Between 10 and 30 keV, Showing Large Fluctuations in the Fission Cross Section. (The vertical scale has been off-set for clarity.)



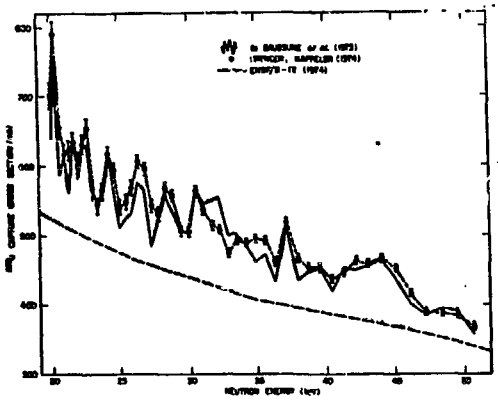
4. Comparison of Three Evaluations of the ^{235}U Fission Cross Sections Between 1 and 100 keV. A few experimental data points are also shown.



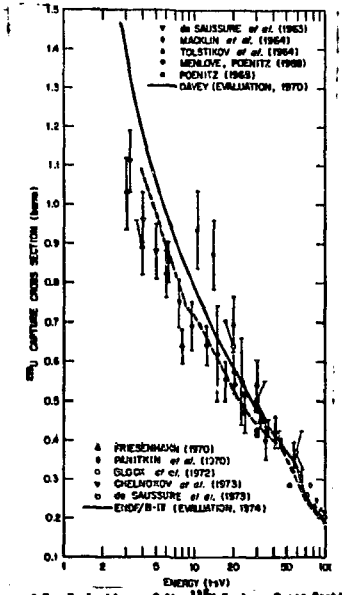
5. Comparison of Two Evaluations of the ^{235}U Fission Cross Section Between .1 and 10 MeV. A few experimental data points are also shown.



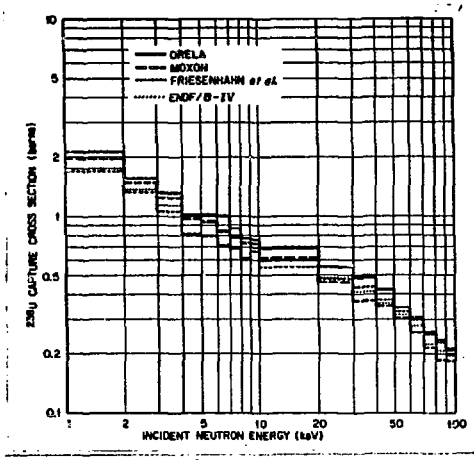
6. Comparison of Two Evaluations of the ^{235}U Fission Cross Section Between .1 and 10 MeV. A few experimental data points are also shown.



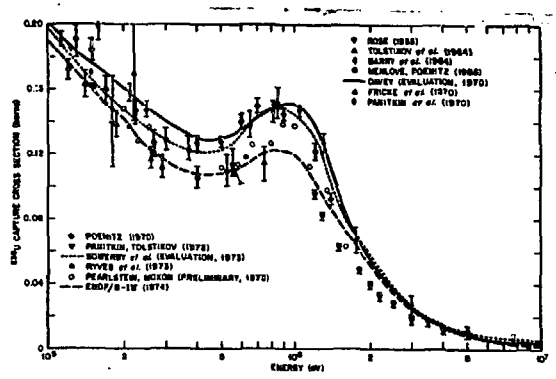
7. Comparison of Two Measurements of the ^{235}U Capture Cross Section Between 20 and 50 keV, Showing Large Fluctuations in the Capture Cross Section. The broken line is the ENDF/B-IV evaluation.



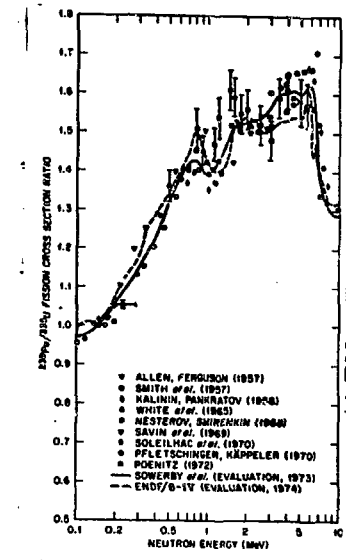
8. Comparison of Two Evaluations of the ^{235}U Capture Cross Section Between 1 and 100 keV. A few experimental data points are also shown.



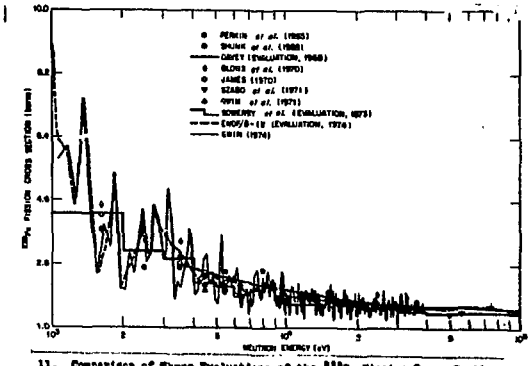
9. Comparison of the ^{238}U Capture Cross Section ENDF/B-IV Evaluation with Three Linac Measurements.



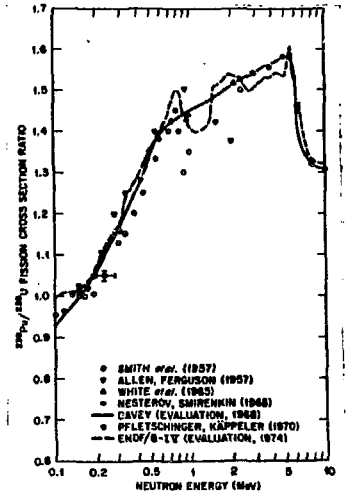
10. Comparison of Three Evaluations of the ^{238}U Capture Cross Section Between .1 and 10 MeV. A few experimental data points are also shown.



13. Comparison of Two Evaluations of the ^{239}Pu/^{235}U Fission Cross Section Ratio. A few experimental data points are also shown.



11. Comparison of Three Evaluations of the ^{239}Pu Fission Cross Section Between 1 and 100 keV. A few experimental data points are also shown.



12. Comparison of Two Evaluations of the ^{239}Pu/^{235}U Fission Cross Section Ratio. A few experimental data points are also shown.

Table I. Some Measurements of the ^{235}U Fission Cross Section Reported Since 1970.

Reference	Year	Energy Range	Approximate Accuracy (%)	Comments
J. Blons et al.[106]	(70)	Below 30 keV	5	Pulsed Linac, time-of-flight technique, relative to $^{10}B(n,\alpha)$, normalized below 1 keV.
F. Kappeler[107]	(70)	440 and 530 keV	3.5	Neutrons from $^{7}Li(p,n)$ reaction, relative to (n,p) cross section.
B. Patrick et al.[11]	(70)	Below 30 keV		Pulsed Linac, time-of-flight technique, relative to $^{6}Li(n,\alpha)$ normalized below 1 keV.
W. P. Poenitz[28]	(70)	552 and 644 keV	4	Neutrons from $^{7}Li(p,n)$ reaction, associated activity technique.
I. Szabo et al.[39]	(70)	17 keV to 1 MeV	3	Neutrons from $^{7}Li(p,n)$ and $T(p,n)$ reactions. Calibrated flux detector.
J. R. Lemley et al.[13]	(71)	Below 100 keV	8	Underground nuclear explosion, relative to $^{6}Li(n,\alpha)$ reaction.
A. E. Samsonov et al.[75]	(71)	Below 45 keV	4 to 7	Lead slowing down time spectrometer.
D. B. Gayther et al.[23]	(72)	1 keV to 1 MeV	4	Pulsed Linac, time-of-flight technique, calibrated flux detector, normalized on 10-30 keV group.
F. Kappeler[108]	(72)	.5 to 1.2 MeV	3.4	Van de Graaff, relative to (n,p) cross section.
D. M. Gilliam[97]	(73)	964 keV	2.3	Na-Be photoneutron source. Track-etch fission detector.
G. Hansen et al.[25]	(73)	1 to 6 MeV	1	Relative to (n,p) cross section.
S. Pearlstein et al.[62]	(73)	80 keV to 1.6 MeV		Neutrons from $^{7}Li(p,n)$ reaction, associated activity method. Results preliminary.
R. B. Perez et al.[24]	(73)	Below 10 keV	8	Pulsed Linac, time-of-flight technique, relative to $^{10}B(n,\alpha)$ reaction. Normalized below 1 keV.
R. Gwin et al.[22]	(74)	Below 100 keV	7	Pulsed Linac, time-of-flight technique, relative to $^{10}B(n,\alpha)$ reaction. Normalized below 1 keV.
R. B. Perez et al.[21]	(74)	Below 200 keV	7	Pulsed Linac, time-of-flight technique, relative to $^{10}B(n,\alpha)$

Table II. Comparison of ^{235}U Fission Cross Sections

Energy Interval (keV)	Perez *et al.*[21]		Gayther *et al.*[23]		Gwin *et al.*[22]		Lemley *et al.*[19]		Percent Difference	
	a	b	a	b	a	b	a	b	c	d
1. TO 2.	7.525	7.259	7.881	7.734	7.080	7.202	6.741	7.013	5.9	3.6
2. TO 3.	5.402	5.211	5.722	5.615	5.140	5.229	5.057	5.261	4.9	3.1
3. TO 4.	4.933	4.759	5.045	4.951	4.580	4.659	4.511	4.693	4.8	2.4
4. TO 5.	4.406	4.250	4.474	4.390	4.080	4.150	4.010	4.172	4.7	2.2
5. TO 6.	3.961	3.821	4.048	3.972	3.720	3.784	3.649	3.796	4.3	2.0
6. TO 7.	3.359	3.240	3.379	3.316	3.140	3.194	3.088	3.212	4.0	1.4
7. TO 8.	3.330	3.212	3.280	3.219	3.050	3.103	3.027	3.149	4.2	1.5
8. TO 9.	3.065	2.957	3.071	3.014	2.880	2.930	2.787	2.899	4.1	1.4
9. TO 10.	3.188	3.075	3.153	3.094	3.010	3.062	3.019	3.141	2.6	1.0
10. TO 20.	2.528	2.439	2.530	2.483	2.460	2.502	2.338	2.432	3.2	1.2
20. TO 30.	2.177	2.100	2.166	2.126	2.110	2.146	2.101	2.186	1.6	1.5
30. TO 40.	2.066	1.993	1.978	1.941	1.940	1.973	1.903	1.980	3.1	1.0
40. TO 50.	1.952	1.883	1.893	1.858	1.820	1.851	1.806	1.879	3.1	0.7
50. TO 60.	1.907	1.840	1.866	1.831	1.820	1.851	1.771	1.842	2.8	0.4
60. TO 70.	1.862	1.796	1.815	1.781	1.760	1.790	1.711	1.780	3.2	0.4
70. TO 80.	1.782	1.719	1.733	1.701	1.710	1.739	1.622	1.687	3.4	1.1
80. TO 90.	1.706	1.646	1.612	1.582	1.590	1.617	1.590	1.654	2.9	1.7
90. TO 100.	1.656	1.597	1.588	1.558	1.560	1.587	1.554	1.617	2.5	1.3
1. TO 100.	2.177	2.100	2.140	2.100	2.064	2.100	2.019	2.100	3.6	1.6

[a]Average cross section, in barns, as reported.

[b]Average cross section, in barns, renormalized to a value of 2.1 b for the interval 1 to 100 keV.

[c]Percent standard deviation of reported average cross section (columns a). Last line is average over the 18 decimal groups.

[d]Percent standard deviation of renormalized average cross section (columns b). Last line is average over the 18 decimal groups.

Table III. The Capture-to-Fission Ratio, α, for ^{239}Pu, Averaged Over Decimal Intervals from 1 to 200 keV

Energy (keV)	Gwin *et al.*[72]	Weston and Todd[70]	Schomberg *et al.*[68]
1 - 2	.84 ± .05	.802 ± .048	.69 ± .10
2 - 3	1.00	.972 ± .058	.92 ± .13
3 - 4	.72	.738 ± .043	.73 ± .12
4 - 5	.87 ± .10	.831 ± .05	.72 ± .11
5 - 6	.82 ± .11	.807 ± .046	.80 ± .11
6 - 7	.79 ± .10	.745 ± .045	.69 ± .12
7 - 8	.64 ± .06	.642 ± .039	.59 ± .10
8 - 9	.54 ± .06	.537 ± .032	.56 ± .09
9 - 10	.55 ± .06	.606 ± .036	.64 ± .10
10 - 20	.48 ± .06	.486 ± .029	.49 ± .07
20 - 30	.35 ± .05	.332 ± .066	.39 ± .06
30 - 40	.30 ± .09	.247 ± .049	
40 - 50	.26 ± .05	.254 ± .051	
50 - 60	.23 ± .05	.246 ± .049	
60 - 70	.23 ± .06	.220 ± .044	
70 - 80	.19 ± .06	.215 ± .043	
80 - 90	.22 ± .09	.200 ± .040	
90 - 100	.17 ± .05	.138 ± .028	
100 - 200	.15 ± .03	.148 ± .030	