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Work supported by the Defense Nuclear Agency under Subtask Code W99QAXPC102 (Cross Section Evaluations) and Work Unit 09 (Cross Section Evaluations and Translations).

CONTENTS

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ABSTRACT

The neutron-induced cross sections for $^{239}Pu$ and $^{240}Pu$ have been evaluated for incident-neutron energies from about 100 keV to 20 MeV. Tabulated values are presented, and recommended curves are compared with the experimental data. These cross sections are merged with the ENDF/B-III evaluated curves from 10-100 keV. Below 10 keV, the ENDF/B-III files are recommended. The complete cross-section sets have been tested by comparing calculated and measured values for a series of integral experiments. These integral results are presented and discussed.

## I. INTRODUCTION

The neutron cross sections for $^{239}Pu$ and $^{240}Pu$ have been studied and values recommended for neutron energies from 100 keV to 20 MeV. These data are available in the ENDF/B format and extrapolate smoothly when combined with the low-energy data on MAT 1159 and MAT 1105, the $^{239}Pu$ and $^{240}Pu$ evaluations, respectively, in ENDF/B-III.

This evaluation effort was concentrated at higher energies with the primary emphasis in two regions: 100 keV to 3 MeV and from 13-15 MeV. Extensions to the representation currently in the ENDF/B files are the treatment of first-, second-, and third-chance fission and the inclusion of "direct-interaction" processes for high-energy neutrons.

The complete evaluations were used in checking an extensive set of integral experiments, including bare and reflected critical assemblies, spectral indices, central core reactivity worths, and leakage spectra. For most of the calculations the processing and neutronics codes were ETOG and DTF, respectively. A few comparisons were run with SIGMA* and MDN,* primarily for high-energy tests where the current ENDF codes are not adequate for handling many processes, for example, multiple-chance fission and spectral representation for direct inelastic scattering.

The cross-section evaluations are discussed in Secs. II and III, with the integral comparisons described in Sec. IV.

## II. PLUTONIUM-239

### A. Total Cross Section

Measurements of the total cross section of $^{239}Pu$ have been presented by Hibdon and Langsdorf,[1] Meads,[2] Bratenahl et al.,[3] Peterson et al.,[4] Foster and Glasgow,[5] and for a number of unpublished Los Alamos results. Recently, Schwartz et al.[6] reported measurements over the energy range from 500 keV to 15 MeV which show good agreement with the higher-energy data of Foster and Glasgow.[5] The evaluated curve above 2.5 MeV is the average of these data, except that above 13 MeV the recommended values lie somewhat above the measurements.

Below approximately 1 MeV, the ENDF/B-III values which lie within the spread of the experimental data (although a bit low) were followed except for minor deviations. The curve between 1.0 and 2.5 MeV was obtained by merging into the average obtained from the measurements by Foster and Glasgow. The recommended curve is shown in Fig. 1.

*Los Alamos Scientific Laboratory (LASL) cross-section processing and neutronics codes.

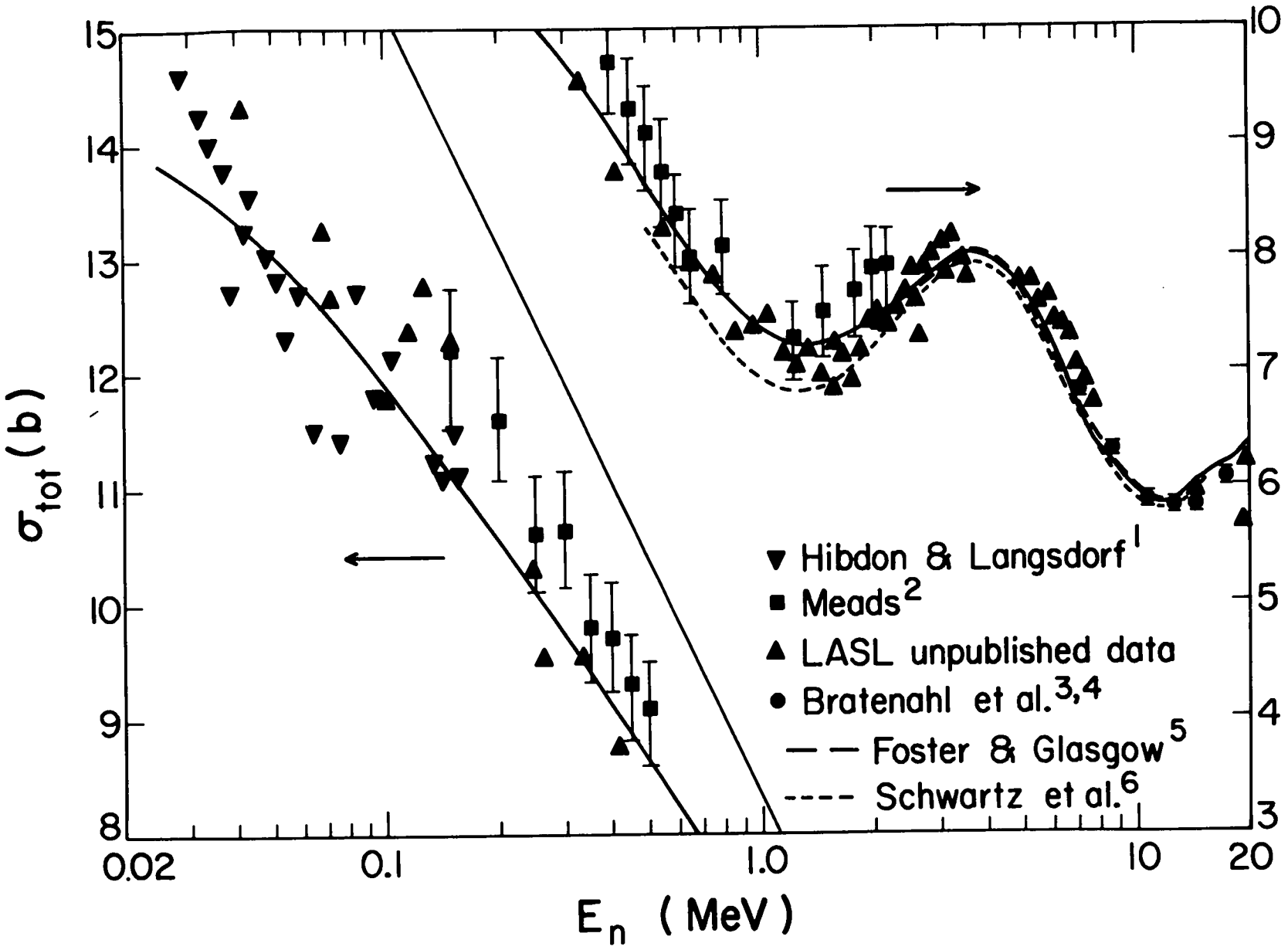


Fig. 1. Total cross section for $^{239}Pu$. The curves representing the data of Foster and Glasgow, and of Schwartz et al. were obtained by averaging their data.

B. Elastic Scattering Cross Section

Knitter and Coppola,[7] Coppola and Knitter,[8] and Allen et al.[9] made measurements of the angular distributions. Above 6-7 MeV, $\sigma_{n,n}$ was obtained by continuously "boot-strapping" nearly all cross sections in order to maintain a smooth curve. Also, the elastic cross section was specified to be greater than one-half of the total cross section at each point. The recommended curve is shown in Fig. 2.

C. Fission Cross Section

The resonance parameters from MAT 1159 of ENDF/B-III were not modified in this evaluation; the fission cross section is represented by resonance parameters up to 25 keV.

In the ENDF/B-III file, the fission cross section is represented by resonance parameters below 25 keV. No attempt has been made here to reevaluate these parameters; instead it is recommended that they be lifted directly from MAT 1159.

Most experimental differential $^{239}Pu$ fission cross sections are measured as a ratio of the fission cross section of $^{239}Pu$ to that of $^{235}U$. In this evaluation, the data of Poenitz,[10,11] Pfletschinger and Käppeler,[12] Soleilac et al.,[13] White et al.,[14] Nesterov and Smirenkin,[15] Savin et al.,[16] Lehto,[17] Smith et al.,[18] and White and Warner[19] were employed. All of these measurements were reported within the past seven years, although the data of Smith et al. result from corrections to an older experiment.

In addition, recent "absolute" measurements have been reported by James,[20] Perkin et al.,[21] and Dubrovina and Shigin.[22] Older measurements by Allen and Ferguson[23] and by Dorofeev and Dobrynin[24] were also used.

Some earlier experiments are not included here on the assumption that they would not appreciably affect the end results. On the basis of the measurements considered, the evaluated curve follows generally the measurements of Savin et al.[16] and Nesterov and Smirenkin,[15] although it falls a bit below their measurements at energies less than 2 MeV. At energies above 1 MeV, the ratio measurements actually

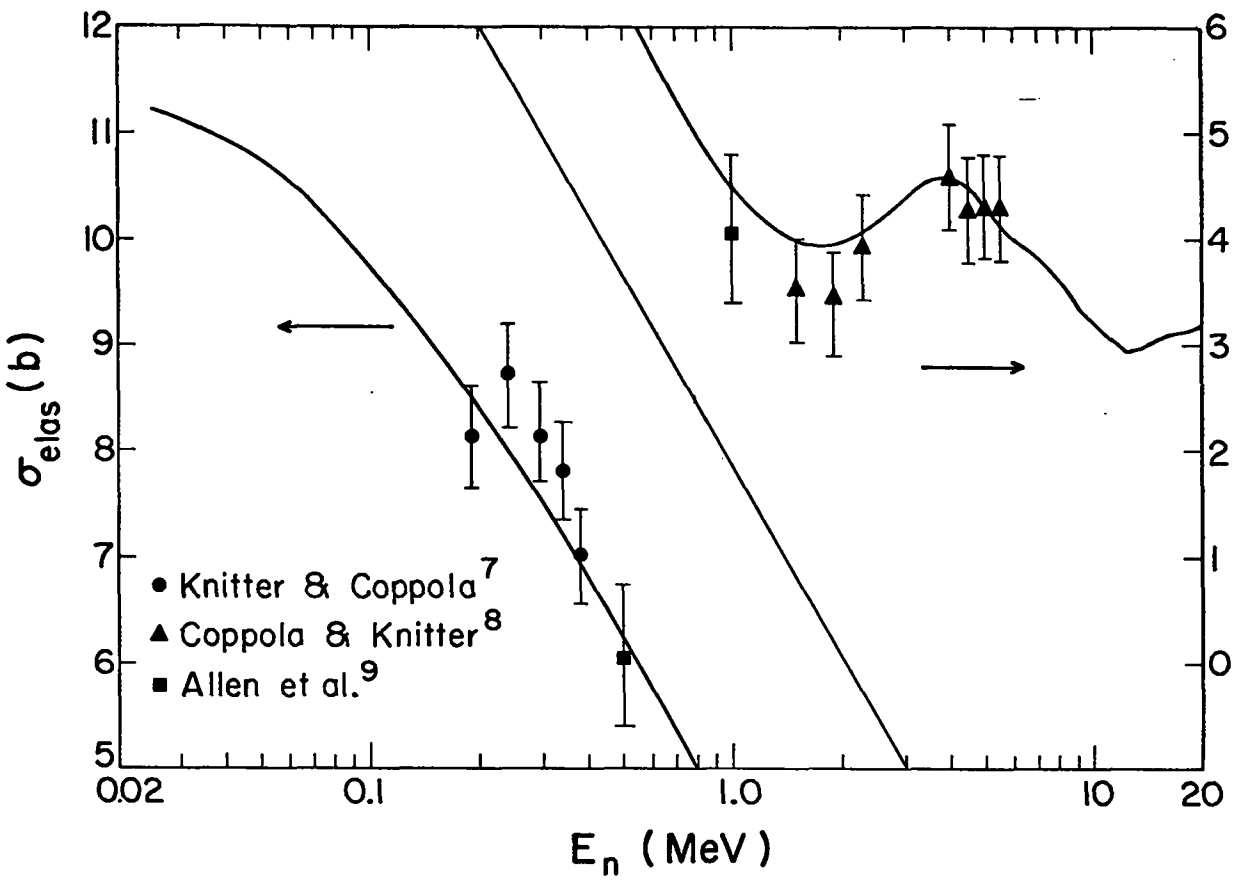


Fig. 2. Elastic-scattering cross section for $^{239}Pu$.

diverge; Soleilac et al.,[13] for example, find a rapidly decreasing ratio while other data indicate an increase.

Above 6-7 MeV, the curve is even more uncertain. The data were taken from Smith et al.,[18] who measured separately the ratio to $^{235}U$ and to $^{238}U$. The latter measurements were converted to ratios with respect to $^{235}U$ via the $^{235}U/^{238}U$ ratios, as evaluated by Pitterle et al.[25] There is also a value at 14.2 MeV from White and Warner.[19] The uncertainties on the data of Smith et al. are relatively large.

Also, Adams et al.[26] measured separately $\sigma_f(^{239}Pu)$ and $\sigma_f(^{235}U)$ relative to $\sigma_f(^{238}U)$ above 12.6 MeV. From these, the ratio $\sigma_f(^{239}Pu)/\sigma_f(^{235}U)$ was obtained. Unfortunately, these measured ratios provide little constraint on the absolute cross section above 1 MeV--precisely that region where "hard spectrum" assembly fluxes are large.

A rather pronounced dip in the ratio between 850 keV and 1.0 MeV is fairly well established. This dip seems to indicate a corresponding increase in the $^{235}U$ fission cross section rather than a drop in the $^{239}Pu$ fission cross section. The recommended curve for the ratio of $\sigma_f(^{239}Pu)$ to $\sigma_f(^{235}U)$ is shown in Figs. 3 and 4.

The $^{235}U$ fission cross section used to obtain the corresponding curve for $^{239}Pu$ was established by Pitterle et al.,[25] and is based largely on recent data (not reviewed here) which tend to raise the curve above 1 MeV and lower it below that point, relative to current published evaluations. The $^{235}U$ fission cross-section evaluation shown in Fig. 5 has <u>not</u> been tested extensively by integral comparisons. Small changes in $^{235}U$ fission can easily be accommodated by adjustments in evaluating the ratio, without doing violence to the uncertainty in either quantity.

The $^{239}Pu$ cross section obtained from this ratio generally falls within the experimental errors of the "absolute" measurements, except that it lies below the data of Dubrovina and Shigin[22] between 80 and about 400 keV and above about 1 MeV. It also lies below the cross sections of Allen and Ferguson[23] at 550 keV and 1.5 MeV. The recommended curve for $\sigma_f(^{239}Pu)$, together with the experimental data, is shown in Fig. 6.

As is well known, the "total" fission cross section (which is the measured quantity) is composed of several processes, referred to as first-, second-, third-, ··· chance fission:

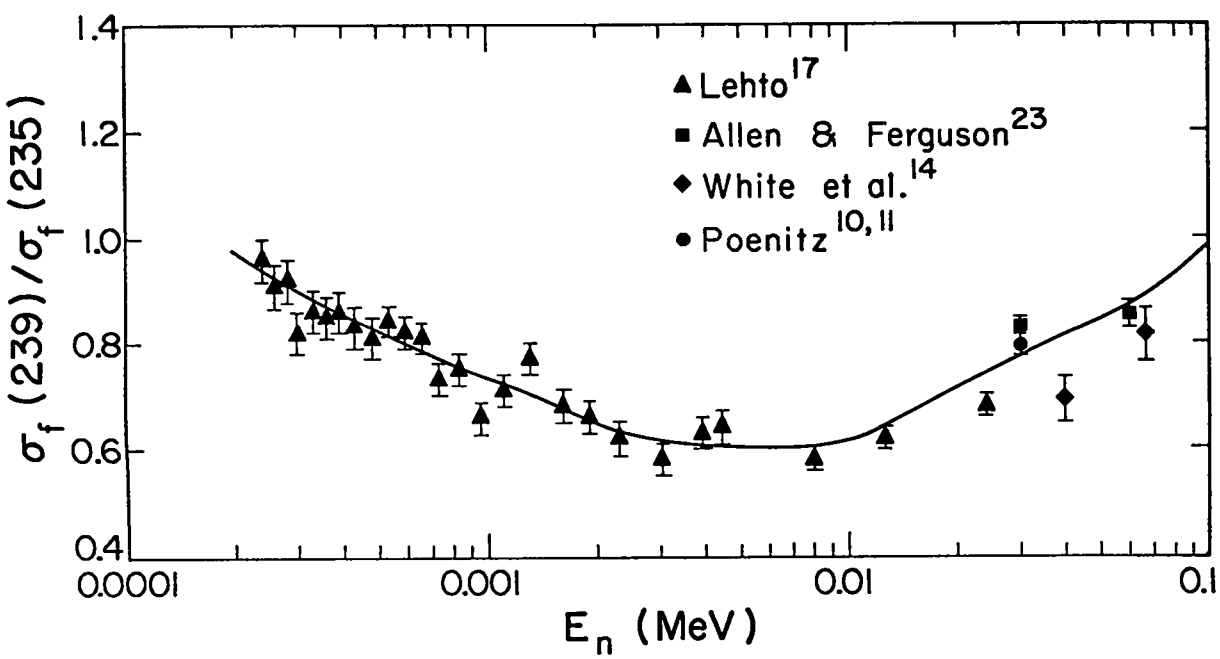


Fig. 3. Ratio of fission cross section for $^{239}Pu$ to that of $^{235}U$, for energies up to 0.1 MeV.

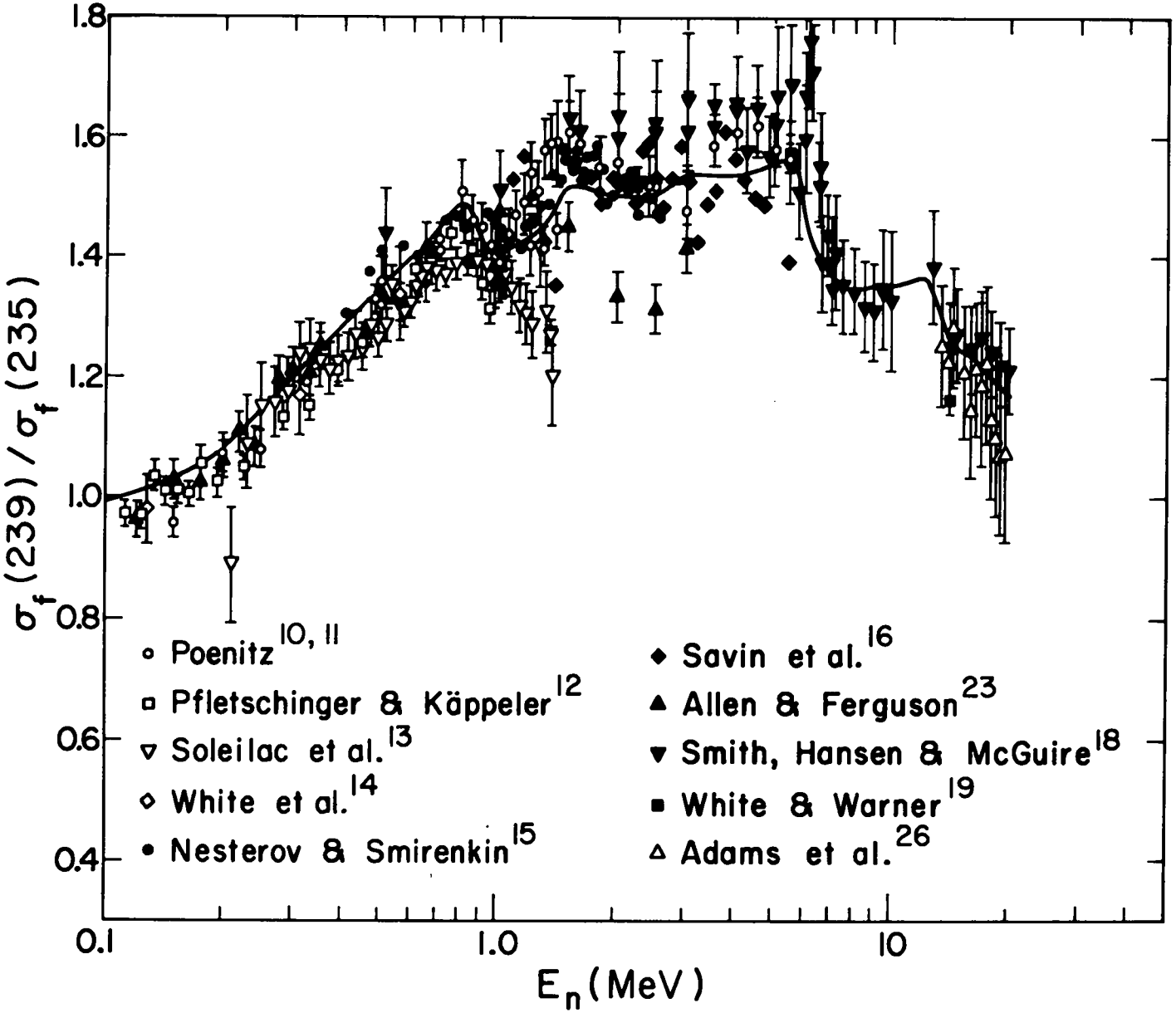


Fig. 4. Ratio of fission cross section for $^{239}Pu$ to that for $^{235}U$, for energies above 0.1 MeV.

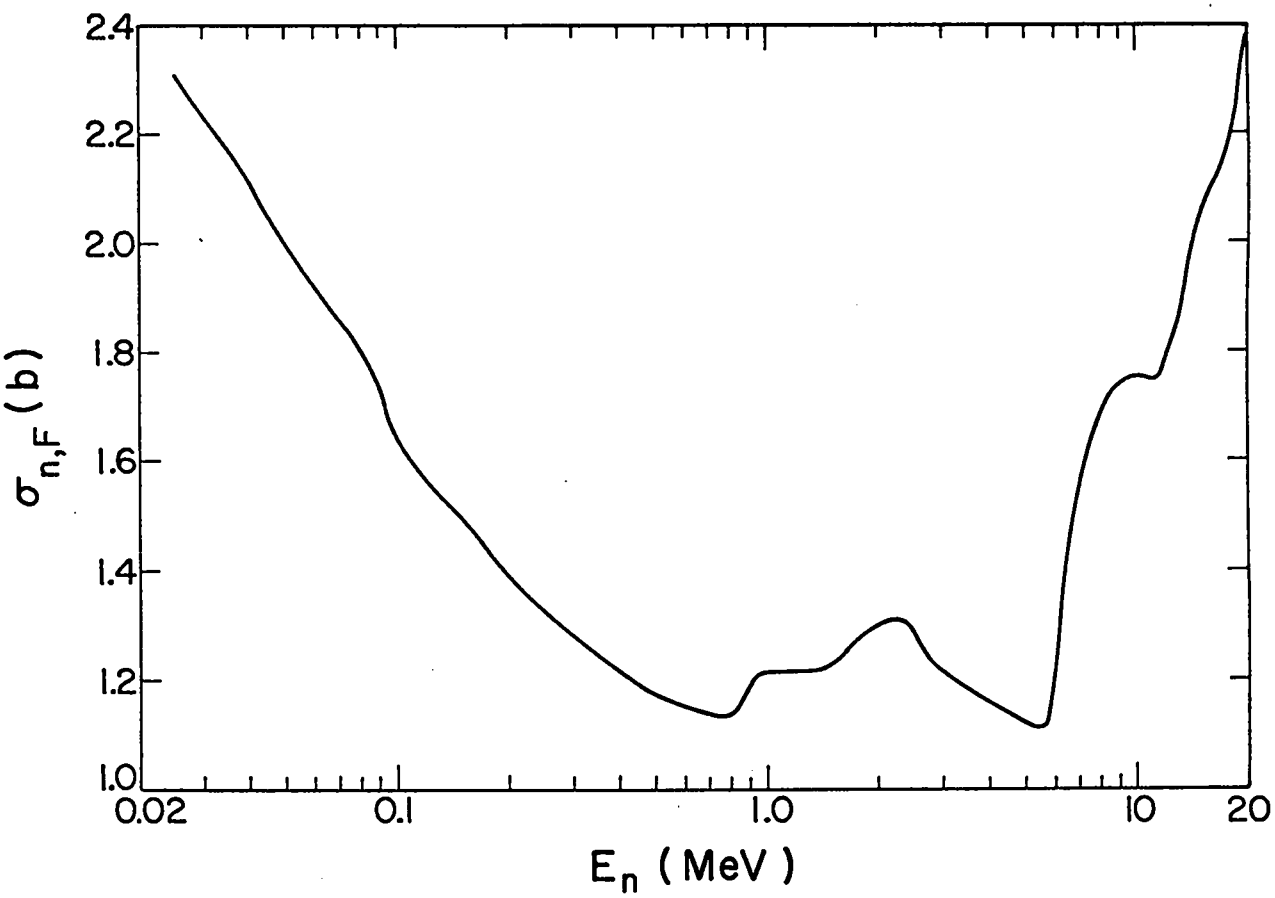


Fig. 5. Fission cross section for $^{235}U$ used as reference.

$$\sigma_{n,F} = \sigma_{n,f} + \sigma_{n,n'f} + \sigma_{n,2nf} + \sigma_{n,3nf} + \cdots \quad , \quad (1)$$

where $\sigma_{n,F}$ is the total fission cross section. $\sigma_{n,f}$ refers to the process whereby fission occurs directly. In the n,n´f reaction (second-chance fission), the compound nucleus initially decays by the emission of a neutron and the residual nucleus then undergoes fission. In n,2nf, two neutrons are emitted prior to fission.

The differentiation of these processes is important because the energy distribution of the prefission neutrons is considerably different from that of the prompt neutrons emitted in the fission process, especially near threshold. That the prefission neutrons are lower in energy than fission neutrons is indicated by the threshold nature of the higher order processes and confirmed by fragmentary experimental evidence.

The n,n´f process is fundamentally an inelastic-scattering reaction, and competes in the sequential mode with the n,n´γ and n,2n channels rather than the n,f channel. This is indicated by a rather sharp rise in the total fission cross section that occurs simultaneously with a sharp drop in the n,n´γ cross section (for those isotopes where such measurements exist). Similarly, the n,2nf process occurs in competition with the n,2nγ and n,3n channels.

Of course, no experimental data exist on the individual fission channels, such as n,n´f, n,2nf, etc. The $^{239}Pu$ fission cross section is relatively constant below the n,n´f threshold* at about 5.5 MeV. Therefore, first-chance fission, $\sigma_{n,f}$, is assumed to be constant from this threshold all the way to 20 MeV. Similarly, the n,n´f cross section is assumed to be constant above the n,2nf threshold at 11.5 MeV. It is emphasized that these assumptions are based on a total lack of measurements and

*Note that the n,n´f and n,2n thresholds are approximately the same. This is also true for the n,2nf and n,3n thresholds.

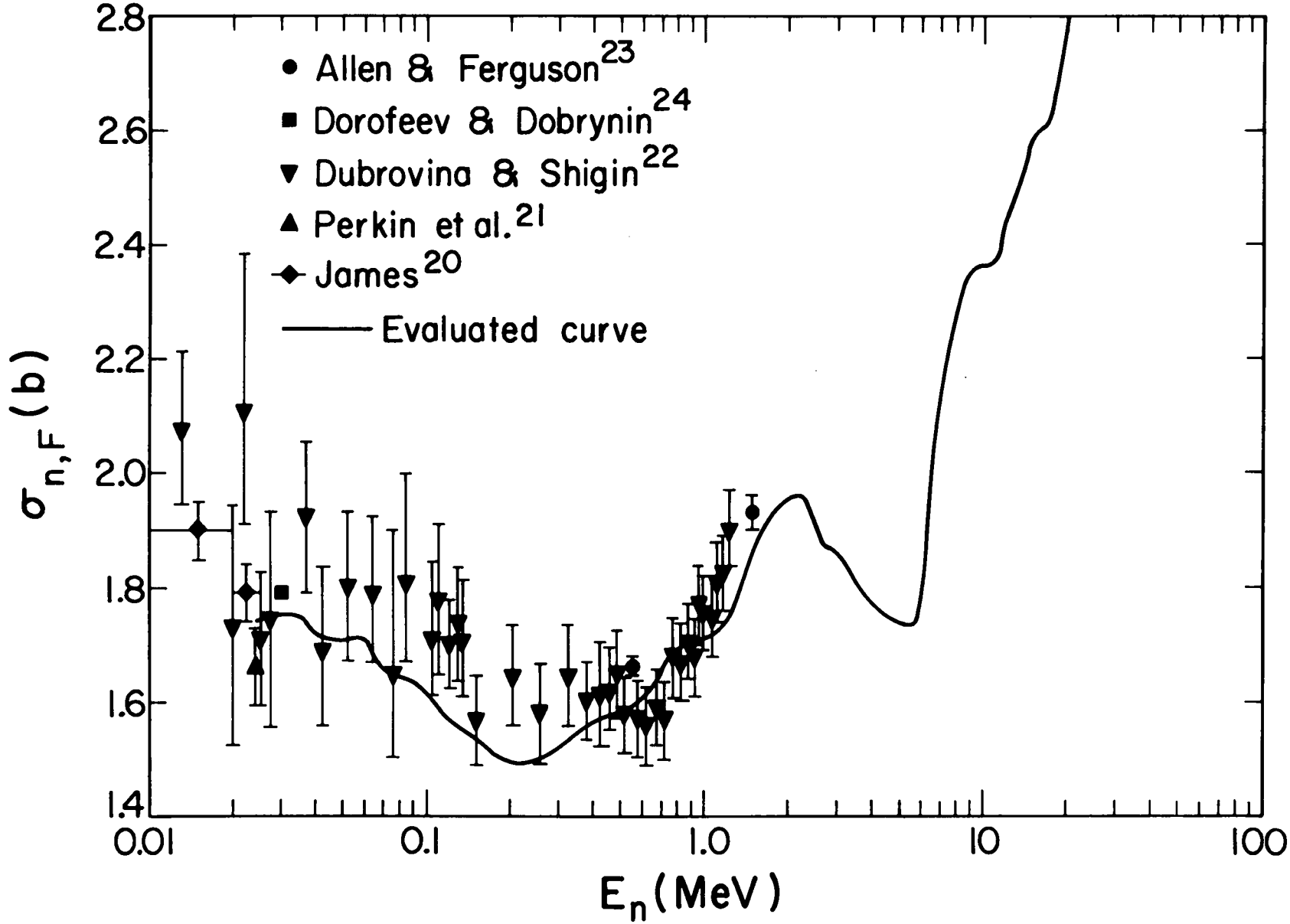


Fig. 6. Fission cross section for $^{239}Pu$ as obtained from the ratio curve in Fig. 4 and the $^{235}U$ fission cross-section curve in Fig. 5. Only the absolute data are plotted.

theoretical understanding. The recommended curves for $\sigma_{n,n'f}$ and $\sigma_{n,2nf}$ are shown in Fig. 7.

D. Mean Number of Prompt Neutrons per Fission

Many recent measurements on $\bar{\nu}$ have been reported, so that $\bar{\nu}$ vs incident neutron energy is fairly well established up to 14.4 MeV. This evaluation is based on the data of Soleilac et al.,[27] Hopkins and Diven,[28] Mather et al.,[29] Colvin and Sowerby,[30] Condé et al.,[31] Savin et al.,[32] and Nesterov et al.,[33] plus the recommended thermal value of Hanna et al.[34] These data were measured with respect to the thermal spontaneous $\bar{\nu}$ for $^{252}$Cf. The ratios obtained were then fitted with a curve that is linear over two regions:

$$\frac{\bar{\nu}(Pu)}{\bar{\nu}(Cf)} = 0.7599 + 0.04009E_n \ , \ 0 \leq E_n \leq 11.5 \text{ MeV}$$

$$= 0.8329 + 0.03374E_n \ , \ 11.5 \leq E_n \leq 20 \text{ MeV}. \quad (2)$$

Assuming $\bar{\nu}$ ($^{252}$Cf) = 3.748,

$$\bar{\nu}(^{239}Pu) = 2.8480 + 0.1502E_n(\text{MeV}), \ 0 \leq E_n \leq 11.5 \text{ MeV}$$

$$= 3.1216 + 0.1237E_n(\text{MeV}) \ ,$$

$$11.5 \text{ MeV} \leq E_n \leq 20.0 \text{ MeV} \ . \quad (3)$$

No experimental data exist between 14.4 and 22.4 MeV. Above the latter energy Soleilac et al.[27] have reported six measurements that indicate a smaller slope; however, the curve fitted to data between 11.5 and 14.4 MeV is consistent with an intercept at 22 MeV. Therefore, the above representation is used up to 20 MeV; the results are given in Fig. 8.

E. Delayed Neutrons from Fission

The delayed neutron fraction, from earlier work summarized by Keepin,[35] appeared to be fairly constant with incident neutron energy, with a thermal value of 0.0061 neutrons/fission and a "fast fission spectrum" value of 0.0063. However, one measurement by Shpakov et al.[36] at 14.5 MeV indicated a significant increase at energies above the fission spectrum neutrons.

Two recent measurements have shown strong indications that the delayed neutron fraction decreases

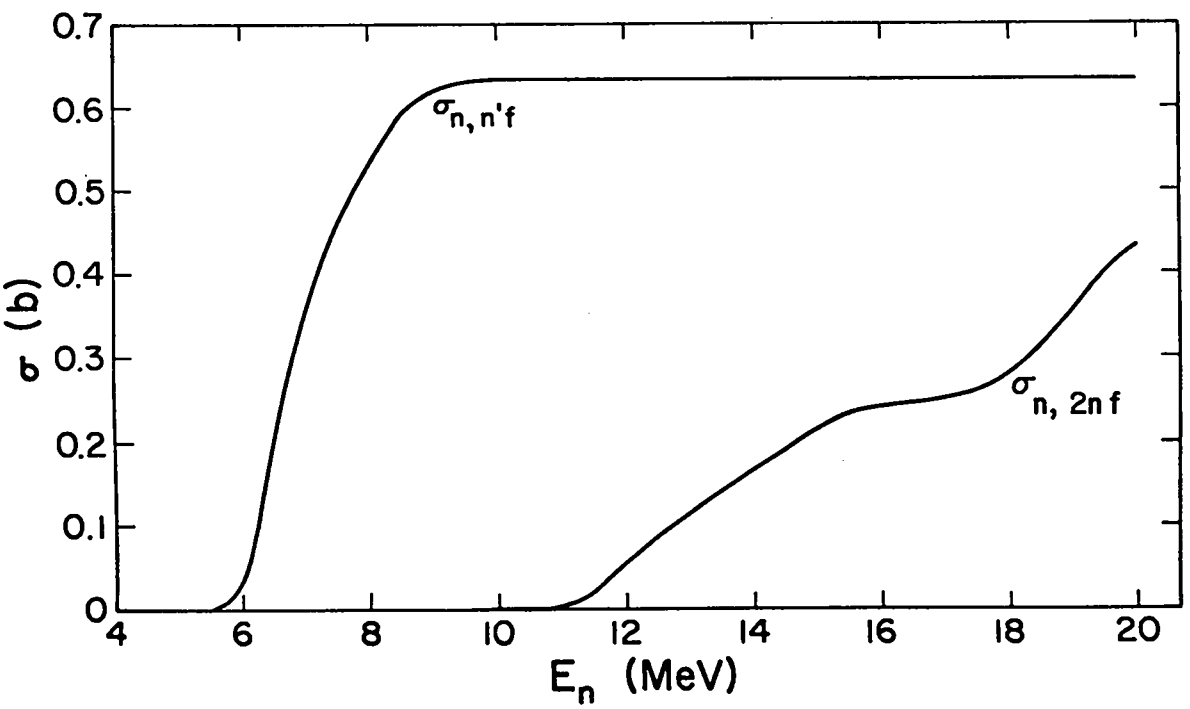


Fig. 7. $\sigma_{n,n'f}$ and $\sigma_{n,2nf}$ for $^{239}$Pu.

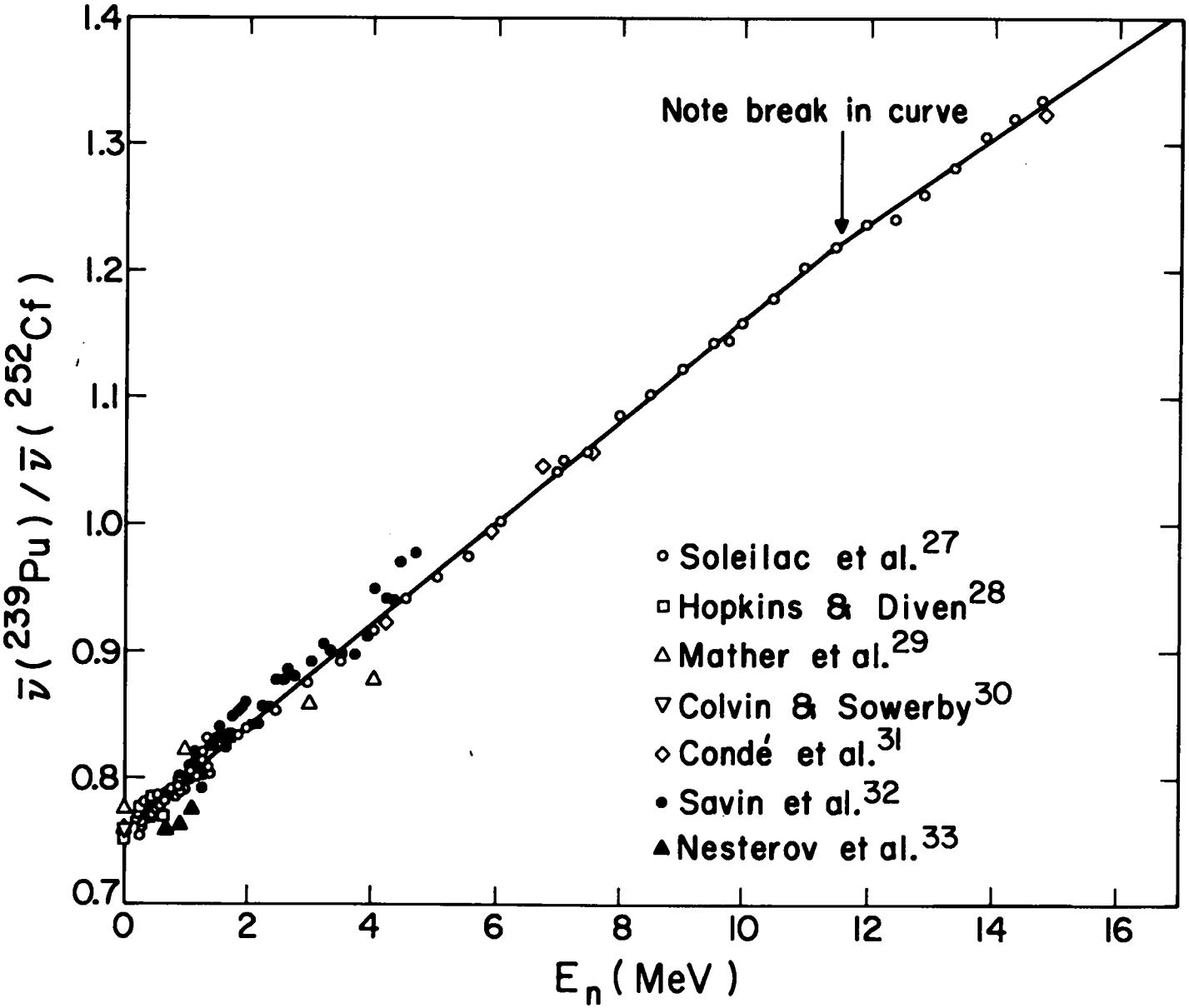


Fig. 8. Ratio of mean number of prompt neutrons per fission for $^{239}Pu$ to the spontaneous fission for $^{252}Cf$.

at higher energies. Evans et al.[37] found a rather abrupt drop in the curve for several isotopes* around 5 MeV, and Masters et al.[38] found a much lower value at 14.9 MeV. The evaluated curve follows the data of Evans et al.[37] and Masters et al.,[38] using the shape of the curve of Evans et al. for $^{235}U$ to interpolate between 3.1 and 14.9 MeV. In the absence of data above 14.9 MeV, it is assumed that the curve is flat between 14.9 and 20.0 MeV.

*They did not measure the delayed fraction for $^{239}Pu$ above 1.8 MeV.

The value at thermal was derived from measurements of Keepin[35] and of Conant and Palmedo.[39] An average of these results agrees well with an extrapolation of the data of Evans et al.[37] The recommended curve is shown in Fig. 9.

The energy distribution of the delayed neutrons is taken from the review by Keepin,[35] who integrated all data over all groups. The recommended curve is shown in Fig. 10.

F. Fission Neutron Energy Distribution

The conventional way to represent the energy distribution of prompt fission neutrons is by a

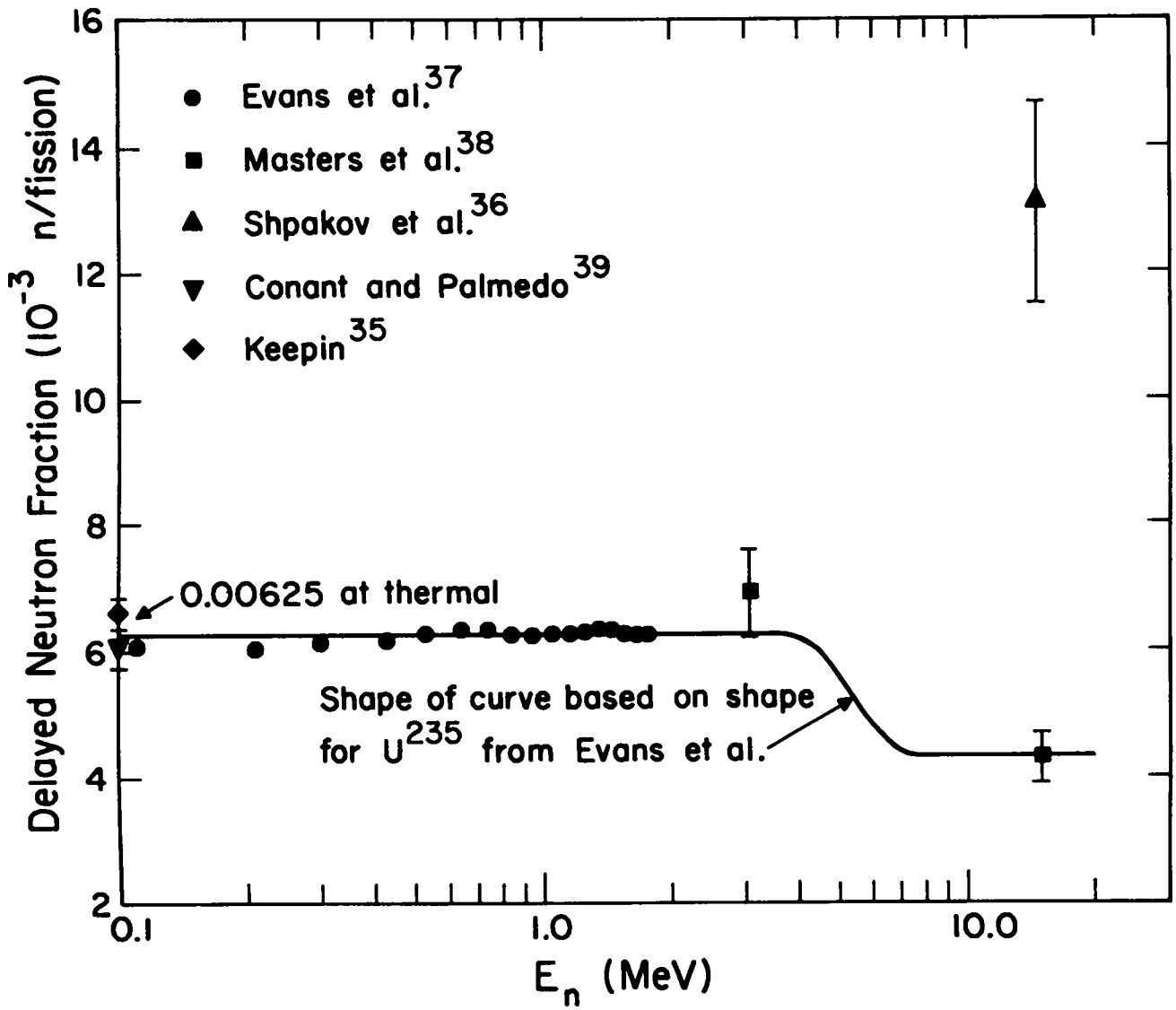


Fig. 9. Delayed neutron fraction for $^{239}Pu$. Data of Conant and Palmedo and of Keepin at thermal are plotted at 0.1 MeV, the lowest energy point on the graph.

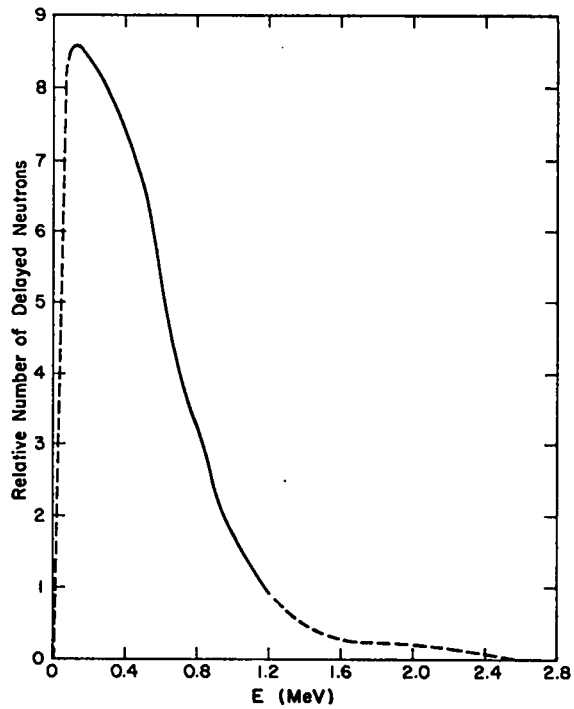


Fig. 10. Relative number of delayed neutron vs final-state neutron energy for $^{239}Pu$.

Maxwellian distribution,

$$F(E) = N E^{1/2} \exp(-E/T_f) \quad , \tag{4}$$

where E is the emitted neutron energy, N is the normalization factor, and $T_f$ is the nuclear temperature. The latter is related to the mean secondary neutron energy by the equation,

$$\bar{E} = \frac{3}{2} T_f \quad . \tag{5}$$

Therefore, the evaluation of the energy distribution consists of evaluating the measurements of $T_f$ as a function of the incident neutron energy, $E_n$.

Values of $T_f$ are given by Barnard et al.,[40] Belov et al.,[41] Zamyatnin et al.,[42] Condé and During,[43] Smirenkin,[44] Coppola and Knitter,[8] and Bertrand and Voignier.[45] Smith[46] found the ratio of $T_f(^{239}Pu)/T_f(^{235}U)$ to be 1.075 at energies of 35-400 keV. Based on the evaluation by Barnard et al.[40] of $T_f(^{235}U)$ = 1.297 MeV, this gives $T_f$ = 1.394 MeV for $^{239}Pu$. The data are tabulated in Table I.

The evaluated temperatures are $T_f$ = 1.39 MeV at thermal energy and $T_f$ = 1.58 MeV at E = 14.0 MeV with

TABLE I

FISSION NEUTRON TEMPERATURES

| Energy (MeV) | Temperature (MeV) | References |
|---|---|---|
| Th | 1.35 ± 0.04 | Belov et al. |
| Th | 1.39 ± 0.01 | Average of several experiments as referenced by Barnard et al. |
| 0.04 | 1.34 ± 0.04 | Condé & During |
| 0.130 | 1.407 ± 0.020 | Barnard et al. |
| 0.035 - 0.400 | 1.394 ± 0.028 | Smith |
| 1.5 | 1.41 ± 0.05 | Coppola & Knitter |
| 1.9 | 1.45 ± 0.04 | Coppola & Knitter |
| 2.3 | 1.52 ± 0.04 | Coppola & Knitter |
| 3.9 | 1.42 ± 0.03 | Smirenkin |
| 4.0 | 1.51 ± 0.07 | Coppola & Knitter |
| 4.5 | 1.69 ± 0.06 | Coppola & Knitter |
| 5.0 | 1.61 ± 0.07 | Coppola & Knitter |
| 5.5 | 1.61 ± 0.05 | Coppola & Knitter |
| 14.0 | 1.58 ± 0.08 | Zamyatnin et al. |
| 14.1 | 1.44 ± 0.15 | Bertrand & Voignier |

values at other energies obtained from a fit to the curve,

$$T_f(E) = A + B[\bar{\nu}(E) + 1]^{1/2} \quad . \tag{6}$$

This effectively ignores the higher points of Coppola and Knitter in favor of the lower (and older) points of Zamyatnin et al. and Smirenkin.

If the form of Eq. (6) is ignored, the data of Coppola and Knitter and of Zamyatnin can be reconciled by a curve which rises rapidly up to about 4-5 MeV, then flattens out to intersect the error bars in the measurement of Zamyatnin. The recommended curve is shown in Fig. 11.

The energy distribution for pre-fission neutrons from the n,n´f and n,2nf processes is based on the energy distribution for n,n´ neutrons (see Sec. II-H).

## G. Radiative Capture Cross Section

The radiative capture cross section is determined almost exclusively from measurements of the ratio, α, with respect to the fission cross sections. This evaluation is based on the measurements of Hopkins and Diven[47] and de Saussure et al.,[48] covering the range above 25 keV. Many measurements have been made in the energy range below 30 keV, the region covered by the resonance parameter representation taken from ENDF/B-III.

The capture cross section was obtained by multiplying pointwise the evaluated curves for α and

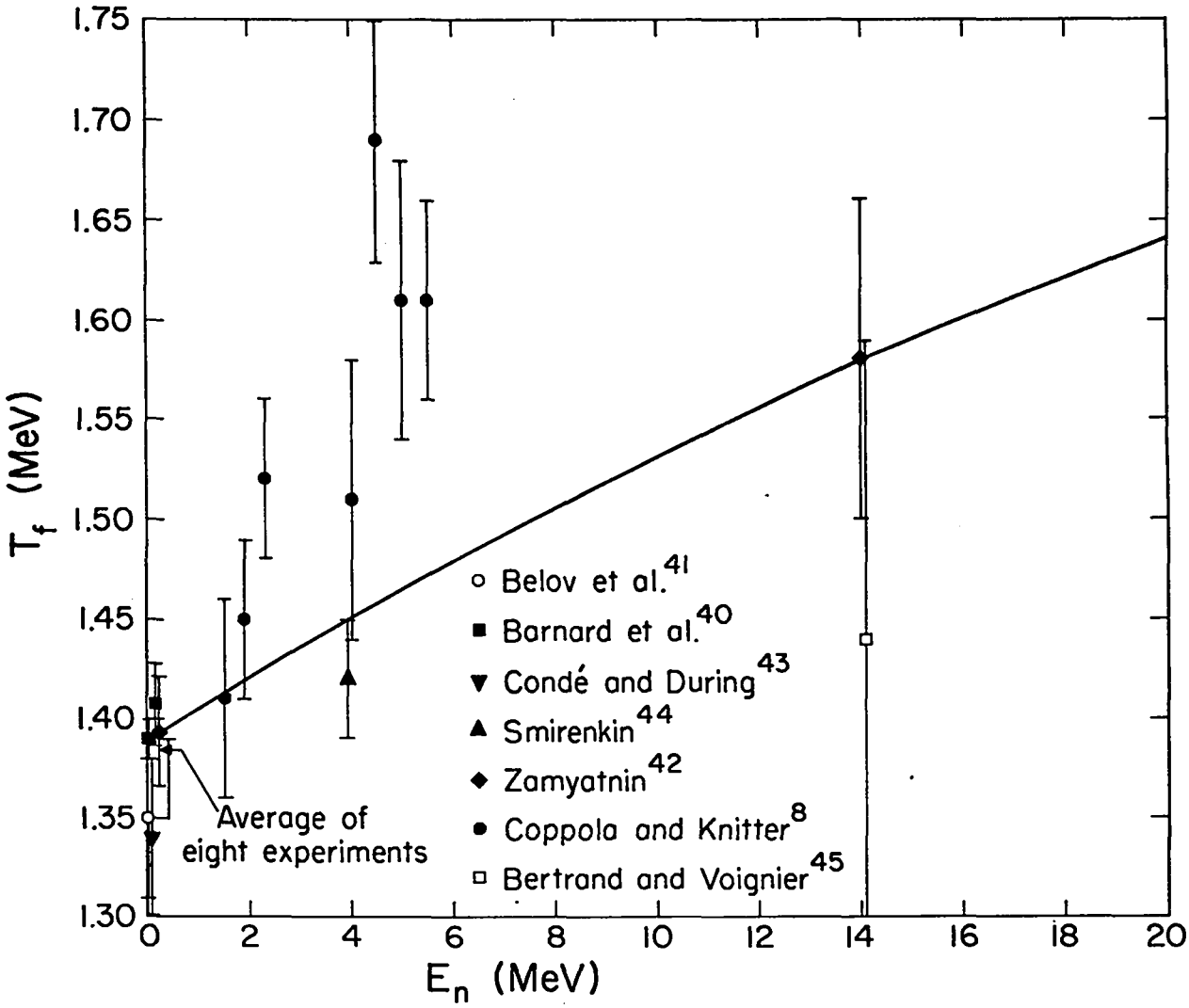


Fig. 11. Fission temperature for $^{239}Pu$.

$\sigma_{n,F}$. The recommended curves for $\alpha$ and $\sigma_{n,\gamma}$ are shown in Figs. 12 and 13, respectively.

H. Inelastic Scattering Cross Section

The inelastic scattering cross section at lower energies was obtained by adding the cross sections for exciting the individual energy levels. No measurements of these level cross sections are available, so those curves were specifically drawn to resemble in shape the curve for energy-level cross sections for other nuclides. The general shapes of the total inelastic cross section and the shapes for the low-energy levels, were based roughly on the evaluation of Hunter et al.[49] The energies of the various excited levels were taken from Lederer et al.[50]

Above the 556-keV level, few levels have been identified. Therefore, above this energy a continuum was introduced which was assumed to give the total inelastic curve in a smooth fashion as a function of energy. At 556 keV, the average final-state energy of the inelastically scattered neutrons was calculated, yielding a value of 0.33 MeV. Thus, $T_1$ = 0.166 MeV was used for the continuum energy-distribution function at 556 keV.

The energy-distribution data of Andreev[51] and Cranberg[52] at about 1.2 and 2.0 MeV can be fitted with temperatures of 0.35 and 0.38 MeV, using the distribution function which describes evaporation processes ($\sigma_{n,n'}$, $2\sigma_{n,2n}$, $3\sigma_{n,3n}$, $\sigma_{n,n'f}$, and $2\sigma_{n,2nf}$):

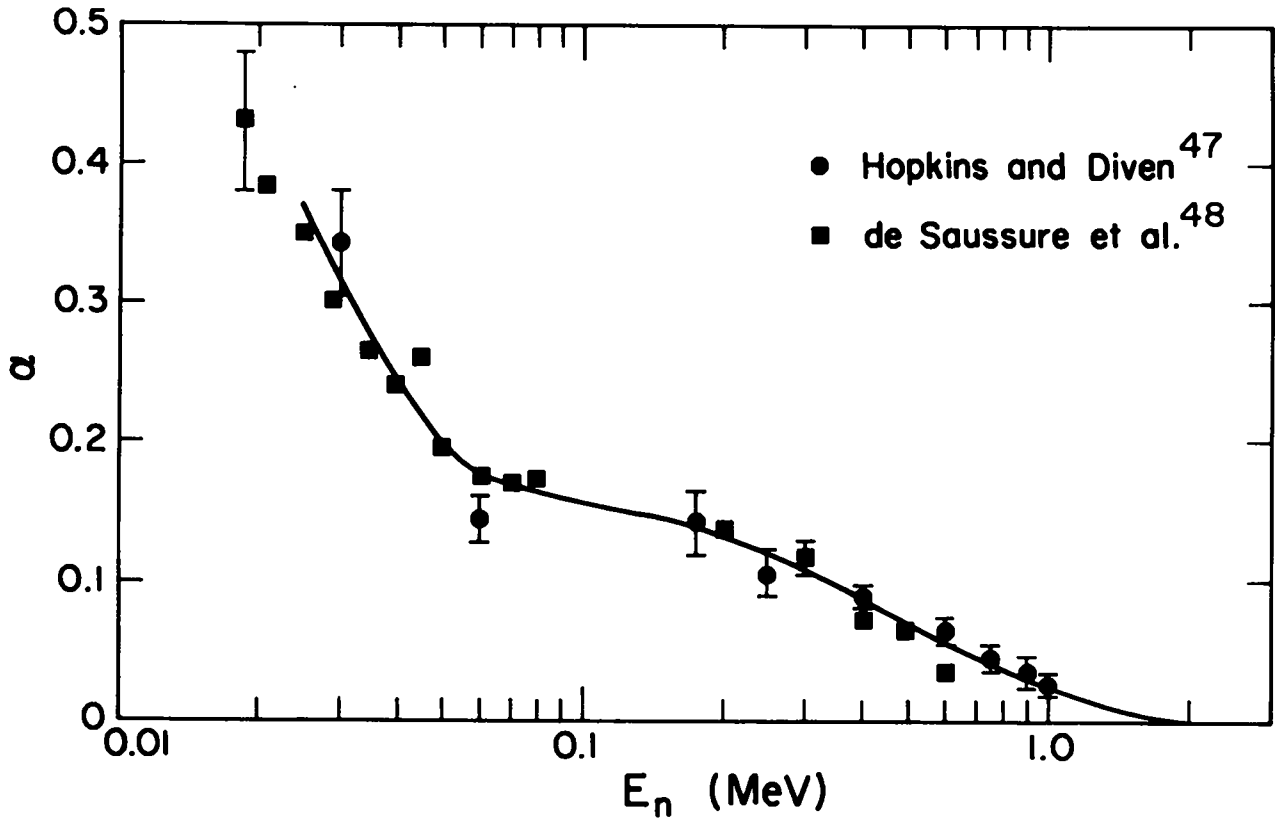


Fig. 12. Ratio of radiative capture cross section to fission cross section (α) for $^{239}Pu$.

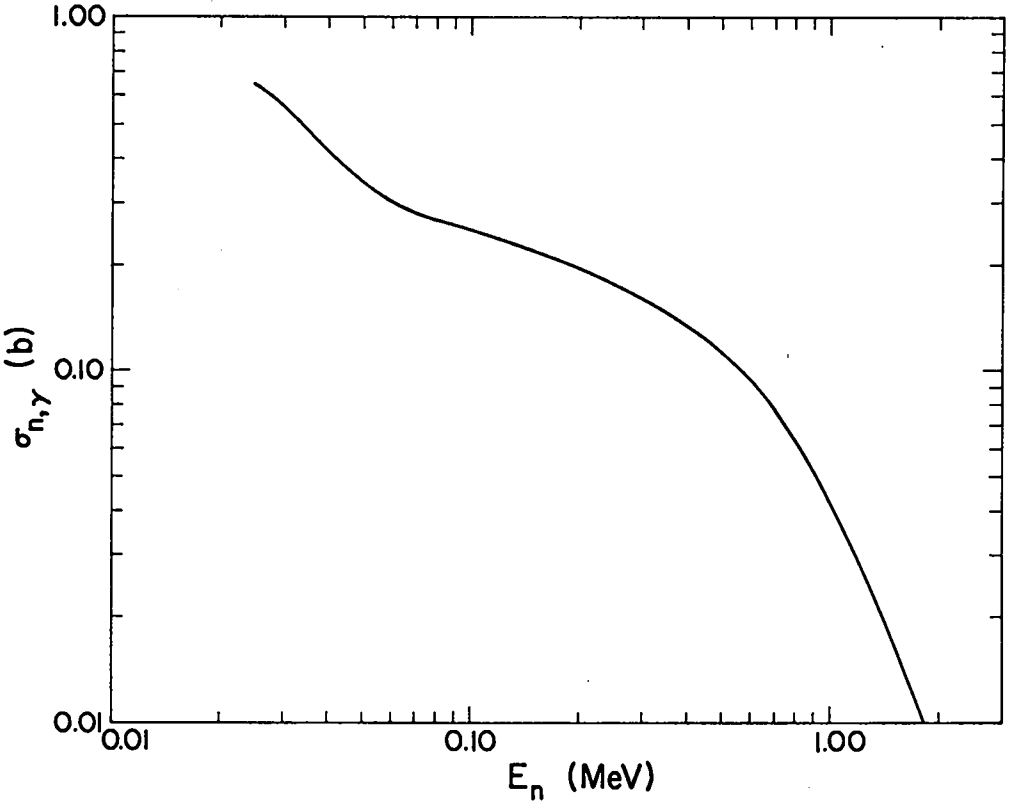


Fig. 13. Radiative capture cross section for $^{239}Pu$.

$$F(E) = NE \exp(-E/T_i) \quad . \qquad (7)$$

At an incident-neutron energy of 14 MeV Zamyatnin et al.[42] measured the neutron energy distribution of all secondary neutrons, including $\sigma_{n,n'}$, $2\sigma_{n,2n}$ and $3\sigma_{n,3n}$, as well as $\bar{\nu}\,\sigma_{n,F}$ neutrons. From these measurements, they derived the spectrum of all evaporation neutrons which was then fitted with a temperature of 0.53 MeV. Coppola and Knitter[8] derived the inelastic energy distribution at incident energies of 1.5-5.5 MeV, by subtracting the fission component from their measured spectra. With their data, a curve of $T_i$ vs $E_n$ (shown in Fig. 14) was obtained. This energy-dependent temperature was used for all evaporation processes, with appropriate modification in the behavior as each energy threshold is reached.

At high energies, inelastic scattering certainly occurs via direct interaction; that is, the incident neutron collides with a nucleon and is scattered, leaving behind a part of its initial energy. Two features are characteristic of such a process. First, the energy loss of the scattered neutron is small compared to the incident energy. Second, the angular distribution of the scattered neutron is predominantly forward-peaked.

This process is displayed in the data of Kammerdiener[53] who measured the angular distribution of inelastically-scattered neutrons at 14 MeV, using ring geometry. According to the usual representation of fission, these high-energy, forward-peaked neutrons can occur only through direct inelastic scattering.

Five levels were arbitrarily introduced (at 1.0, 1.5, 2.0, 2.5, and 3.0 MeV), with cross sections rising to a total of 200 mb at 14 MeV. Each level is associated with an angular distribution that is forward-peaked.* With appropriate threshold modifications the cross sections for each level are taken to be the same above a few MeV. The curves for the various individual levels, the continuum, and the total inelastic cross section are given in Figs. 15 and 16.

I. $\sigma_{n,2n}$ and $\sigma_{n,3n}$

These cross sections are based largely on the evaluation** of Hunter et al.,[49] with thresholds

*See Sec. II-J.

**The final-state energy distribution would perhaps be more physically represented by a different temperature representation for successive neutron emission. This will be taken into account in future evaluations.

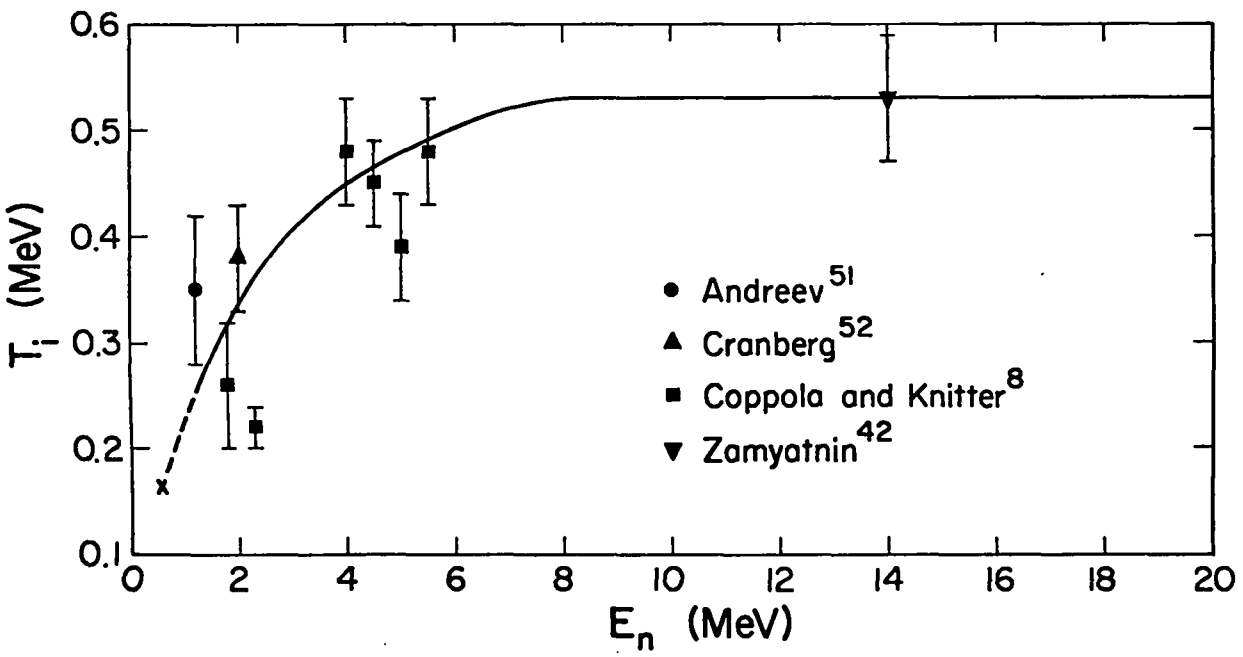


Fig. 14. Inelastic-scattering energy-dependent temperature for $^{239}Pu$.

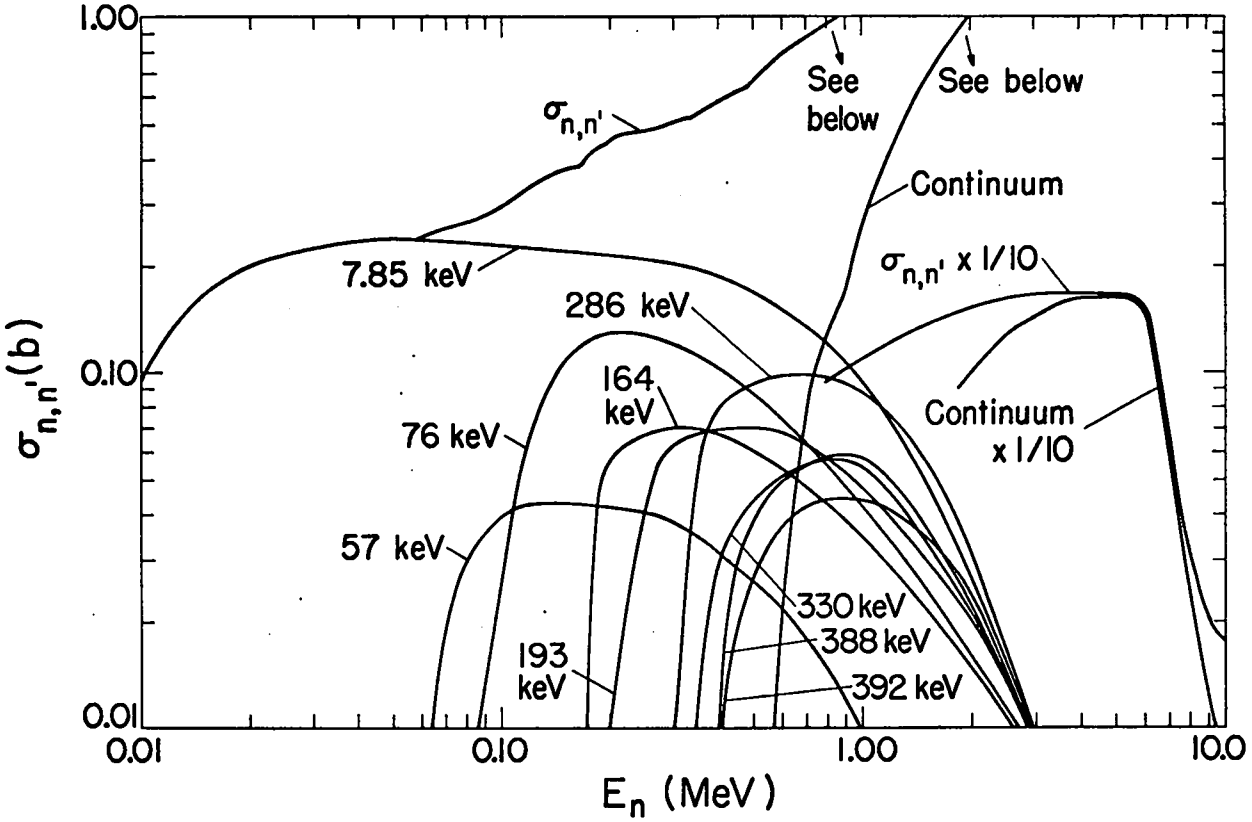


Fig. 15. Inelastic-scattering cross section and continuum cross section, and energy-level cross sections for $^{239}$Pu.

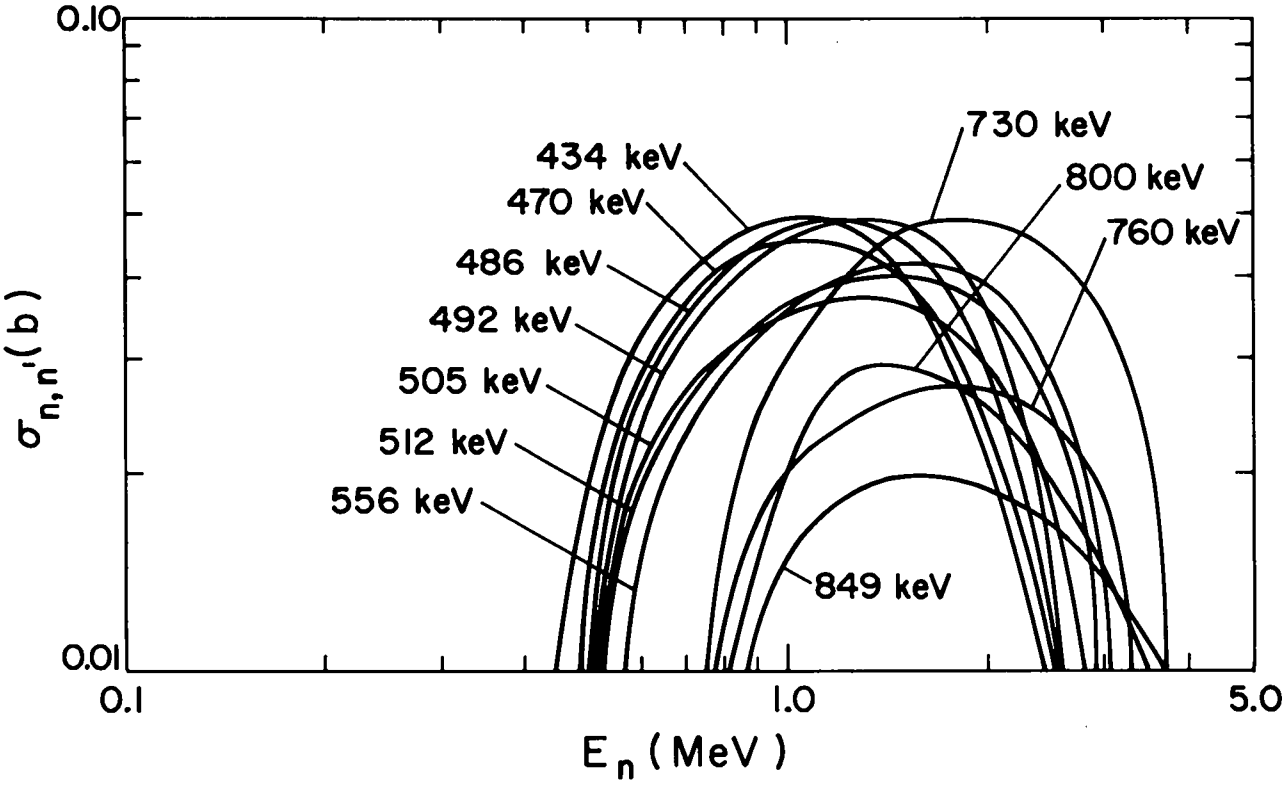


Fig. 16. Energy-level cross sections for $^{239}$Pu.

obtained from Wapstra and Gove.[54] The higher-energy end of $\sigma_{n,2n}$ was based on calculations by Whalen and Worlton.[55] The recommended curves* are given in Fig. 17.

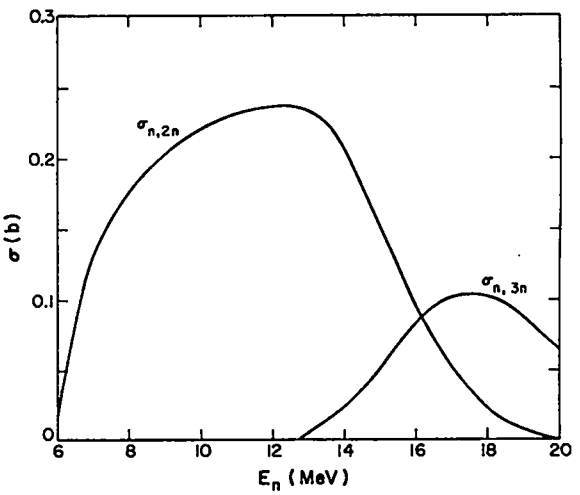


Fig. 17. $\sigma_{n,2n}$ and $\sigma_{n,3n}$ for $^{239}$Pu.

## J. Angular Distributions

The elastic-scattering angular distribution for $^{239}$Pu has been measured by Knitter and Coppola,[7] Coppola and Knitter,[8] Allen et al.,[9] Cranberg,[52] and Kammerdiener.[53] These distributions were fitted by the Legendre expansion,

$$\frac{d\sigma}{d\Omega}(E_n,\theta) = \frac{\sigma_{n,n}(E_n)}{2\pi} \sum_{\ell=0}^{L} \times \{\frac{2\ell+1}{2} a_\ell(E_n) P_\ell(\cos\theta)\} \quad , \qquad (8)$$

where $\sigma_{n,n}$ is the elastic-scattering cross section and $P_\ell(\cos\theta)$ is the $\ell$th Legendre polynomial, $a_0(E_n) \equiv 1.0$. The value of L is determined at each energy by the fit to experimental data, subject to the constraints that L must be even, and the energy-dependent coefficients must extrapolate smoothly over the energy range. The angular distributions at energies between 0.19 and 14 MeV are shown in Figs. 18-35. The graphs of the Legendre coefficients as a function of $E_n$ are given in Figs. 36-39. No attempt was made to remove inelastic contributions from the experimental data.

The Legendre coefficients plotted in Figs. 36-39 were obtained from the initial best fits to the experimental data in Figs. 18-35. These points were then fit with a smooth curve, yielding the final recommended set of Legendre coefficients. These coefficients were used in turn to calculate the angular distributions which are plotted in Figs. 18-35. Thus, the curves shown in Figs. 18-35 are the final recommended angular distributions, not the initial best fits to the experimental data.

The inelastic angular distributions for the constructed direct-interaction levels were based on the elastic distributions at energies below about 2 MeV.

The curves of the Legendre coefficients for the direct-interaction levels as a function of $E_n$ are shown in Fig. 40.

## K. Charged-Particle Cross Sections

Cross sections for the n,α; n,t; n,p; and n,d reactions are taken directly from the ENDF/B-III evaluation. The curves are shown in Fig. 41.

## L. Tabulated Cross Sections

The recommended cross sections are tabulated in Table II. The tabulated values for the various inelastic levels are given in Table III.

*The n,2n and n,3n measurements of Mather et al. (D. S. Mather, P. F. Bampton, R. E. Coles, G. James, and P. J. Nind, "Measurement of (n,2n) Cross Sections for Incident Energies Between 6 and 14 MeV," Atomic Weapons Research Establishment report AWRE O 72/72 and EANDC (UK) 142-AL, November 1972) were received about the time this evaluation was completed. These measurements do not agree with this evaluation. Since their data on $^{238}$U indicate serious discrepancies both in shape and magnitude with earlier experiments, it was decided that these data would not be incorporated in the present evaluation. Furthermore, the $^{239}$Pu measurements were not borne out by integral calculations of Whalen and Worlton, which were factors of two to three lower for $\sigma_{n,2n}$.

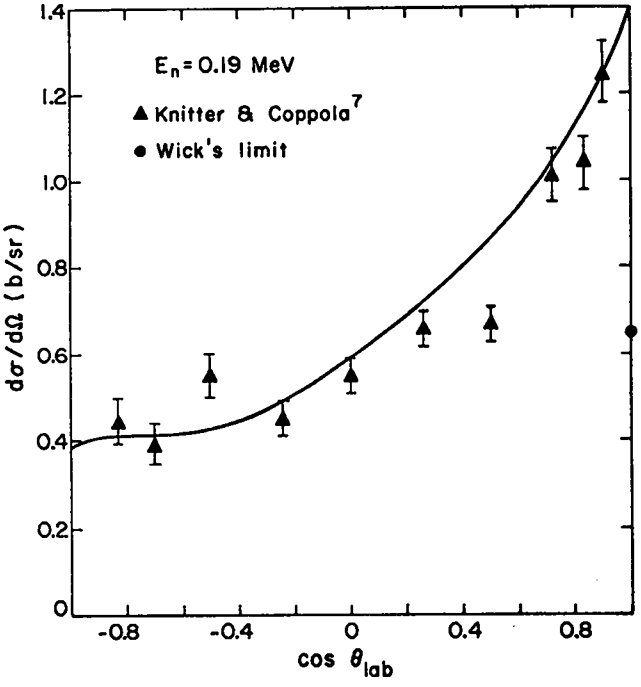


Fig. 18

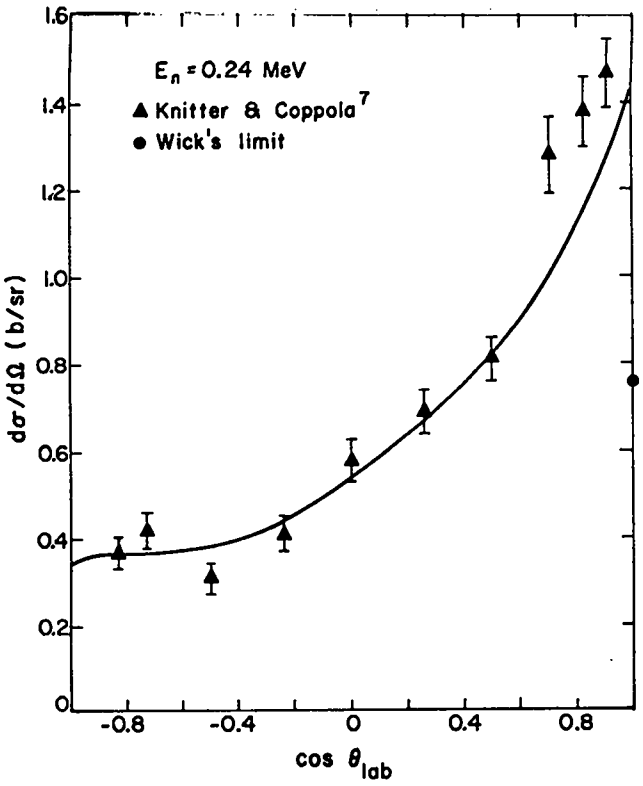


Fig. 19

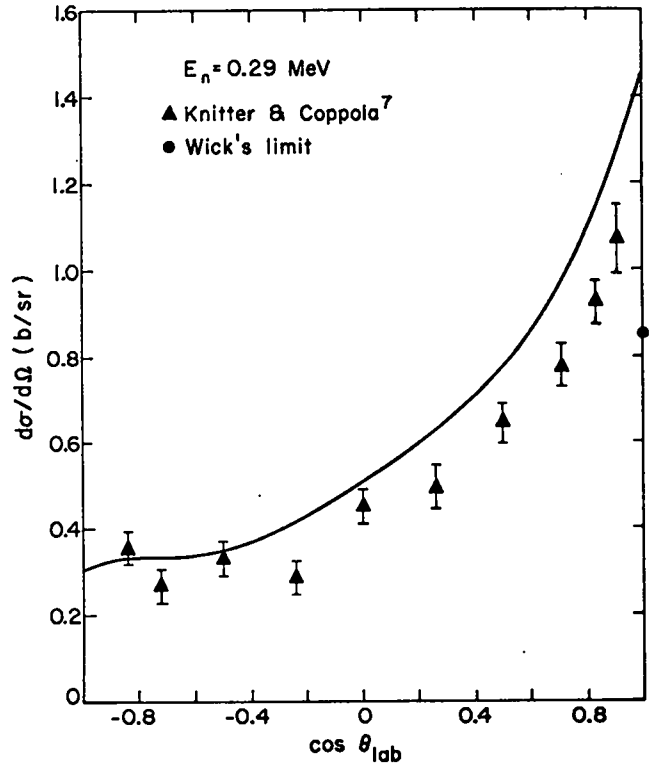


Fig. 20

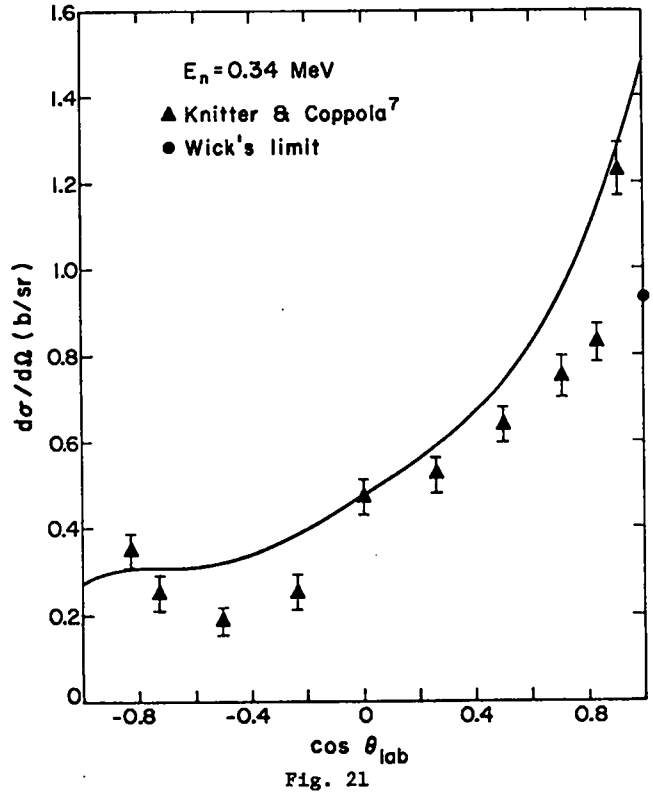


Fig. 21

Figs. 18-21. Elastic-scattering angular distribution for $^{239}Pu$ at 0.19, 0.24, 0.29, and 0.34 MeV, respectively.

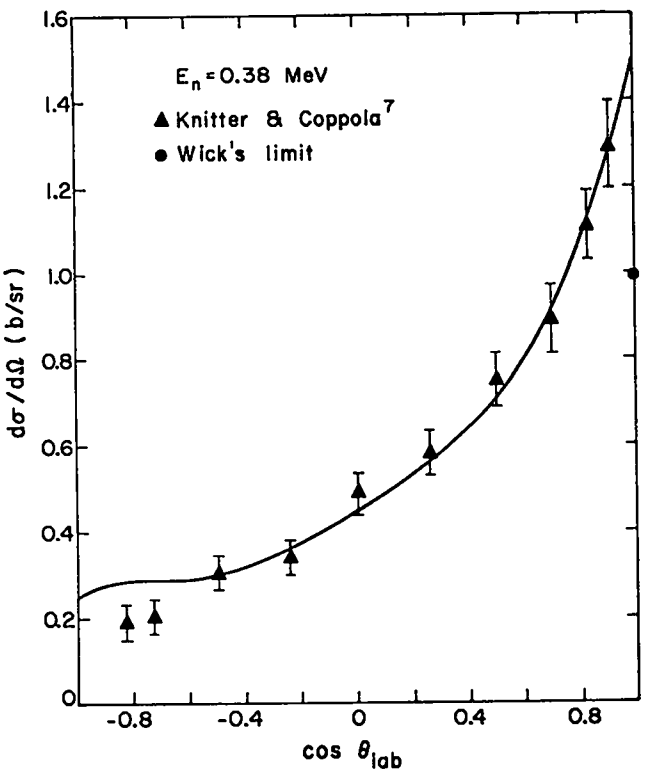


Fig. 22

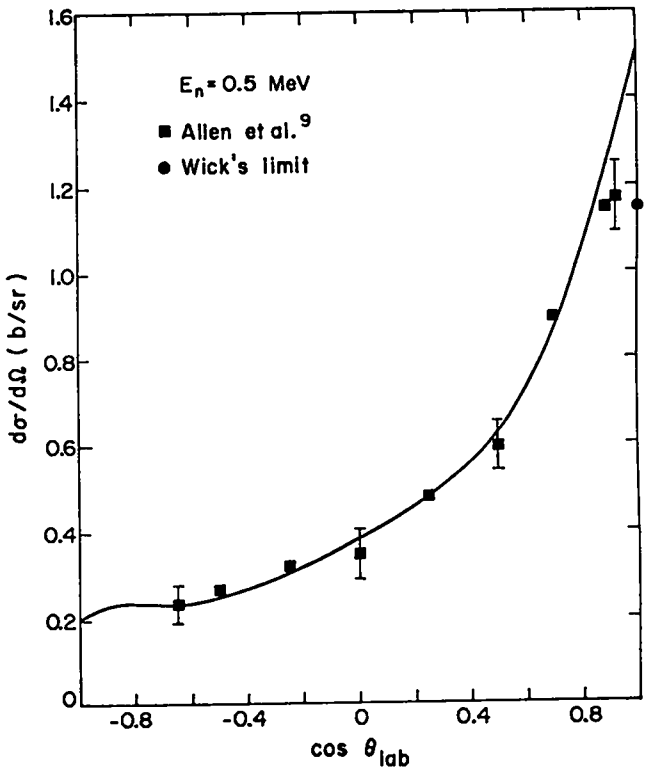


Fig. 23

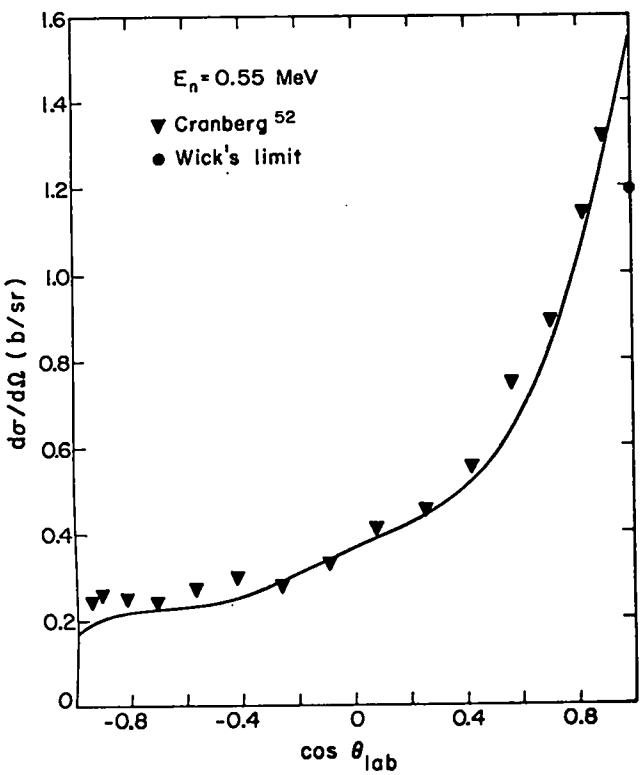


Fig. 24

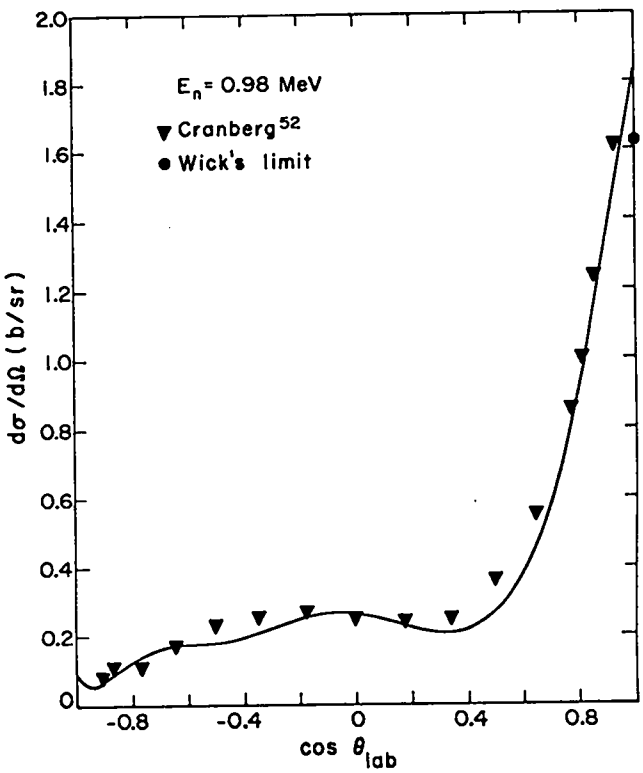


Fig. 25

Figs. 22-25. Elastic-scattering angular distribution for $^{239}Pu$ at 0.38, 0.5, 0.55, and 0.98 MeV, respectively.

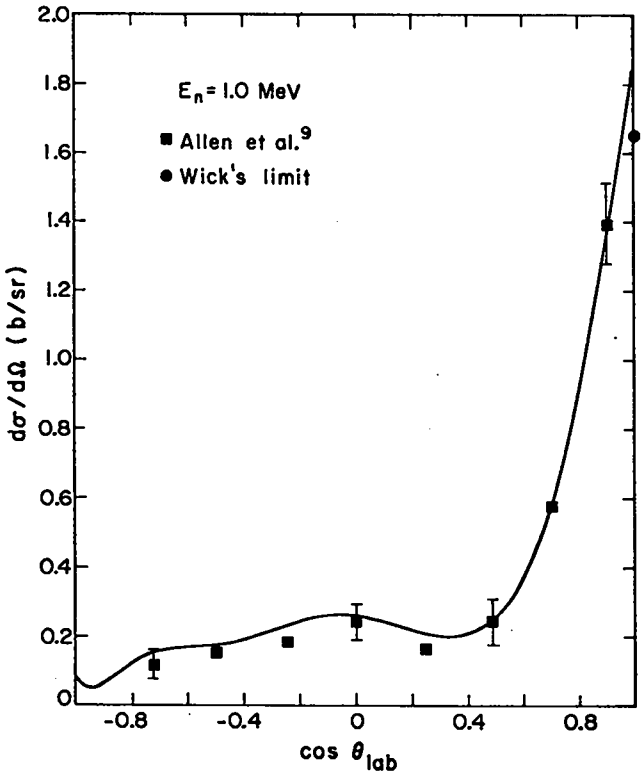


Fig. 26

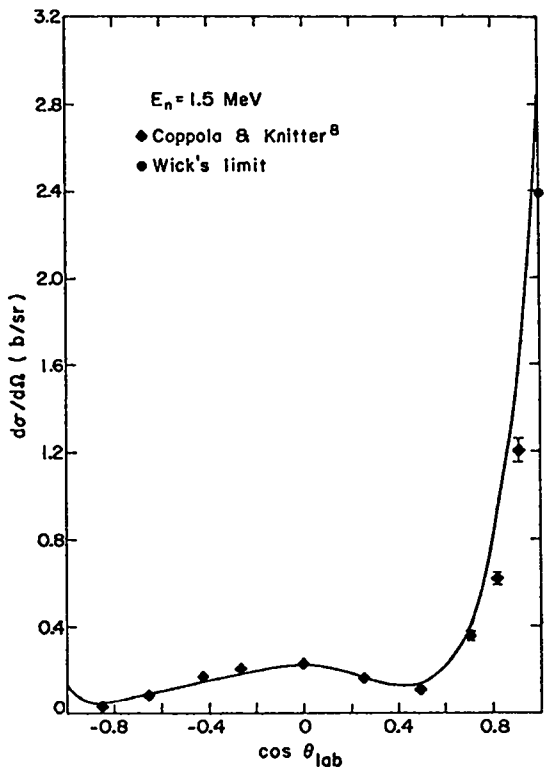


Fig. 27

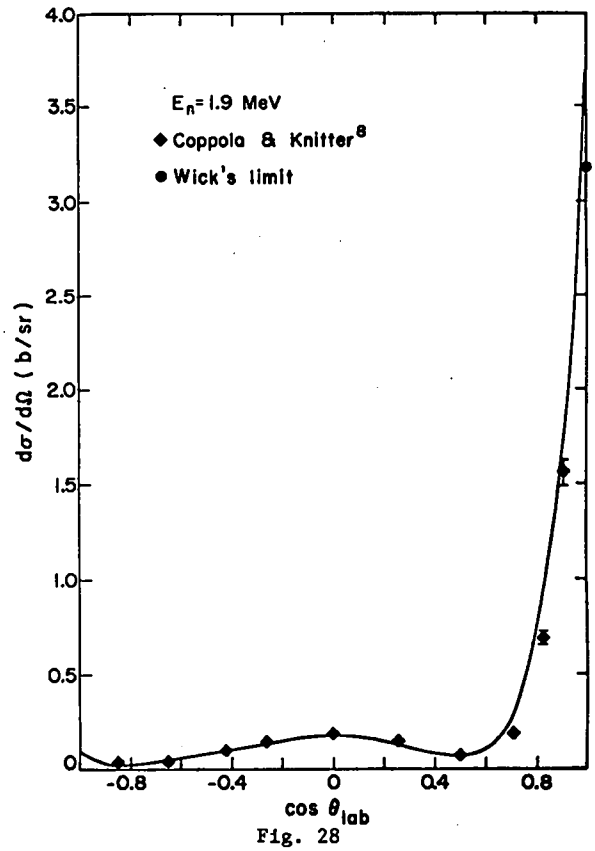


Fig. 28

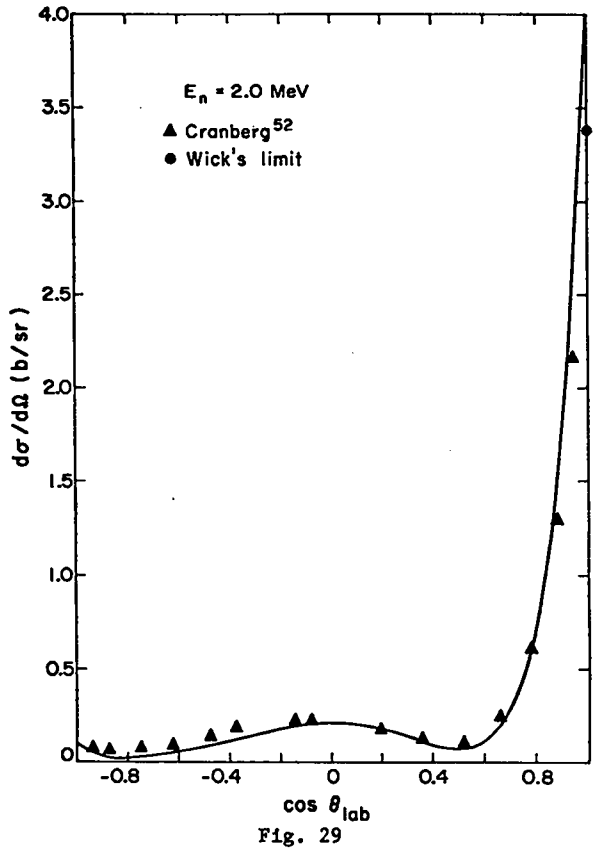


Fig. 29

Figs. 26-29. Elastic-scattering angular distribution for $^{239}$Pu at 1.0, 1.5, 1.9, and 2.0 MeV, respectively.

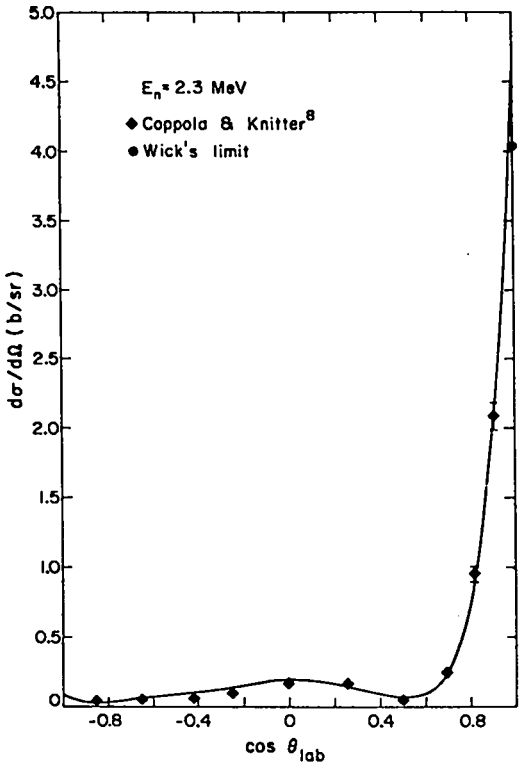


Fig. 30

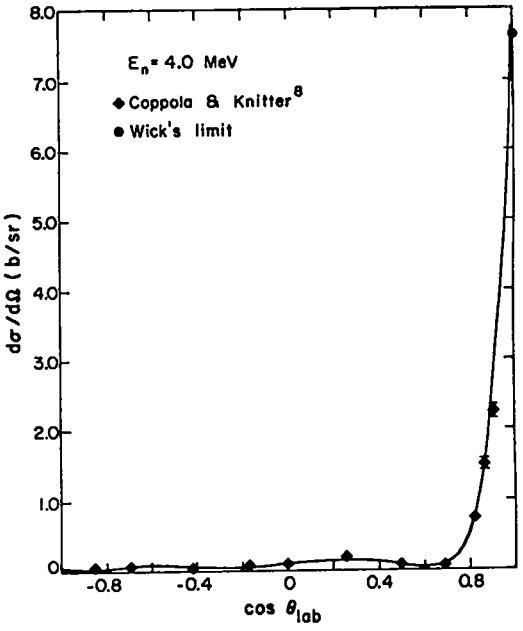


Fig. 31

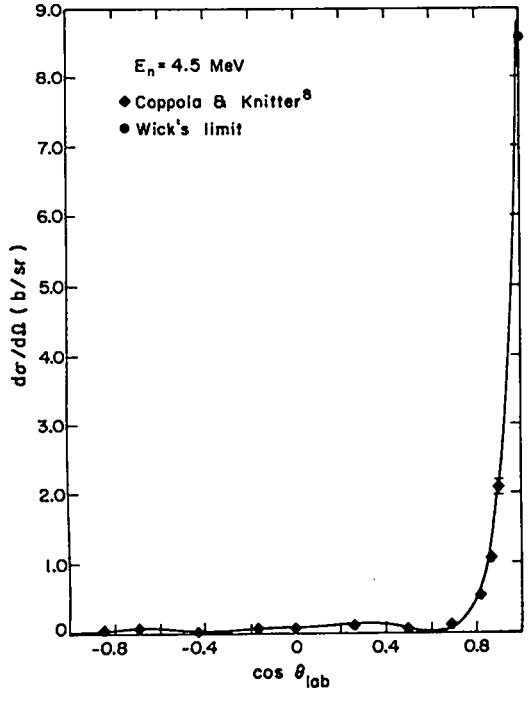


Fig. 32

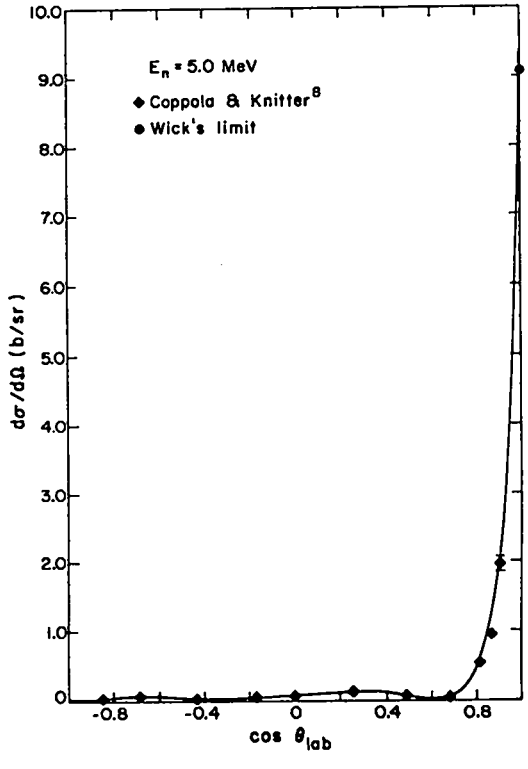


Fig. 33

Figs. 30-33. Elastic-scattering angular distribution for $^{239}Pu$ at 2.3, 4.0, 4.5, and 5.0 MeV, respectively.

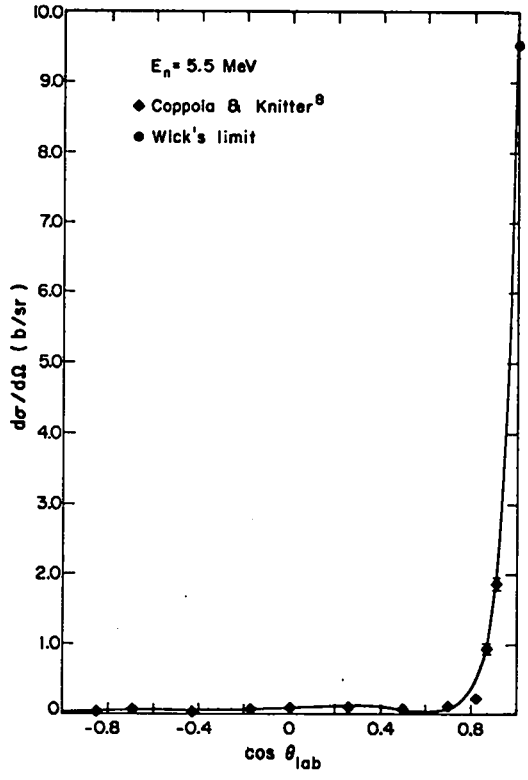


Fig. 34. Elastic-scattering angular distribution for $^{239}Pu$ at 5.5 MeV.

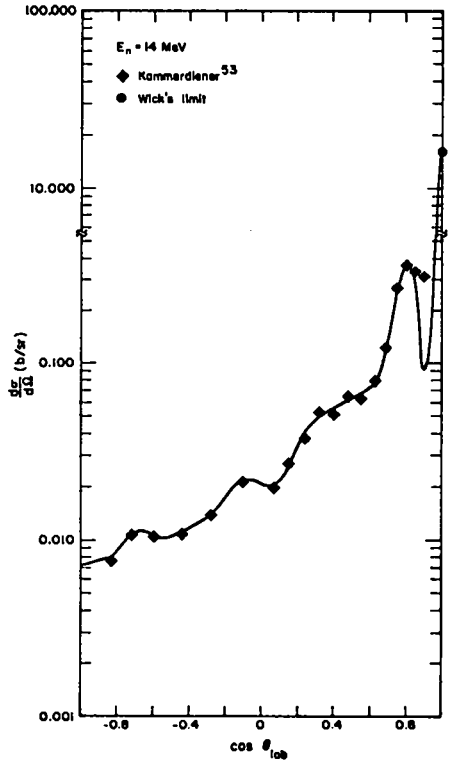


Fig. 35. Elastic-scattering angular distribution for $^{239}Pu$ at 14 MeV.

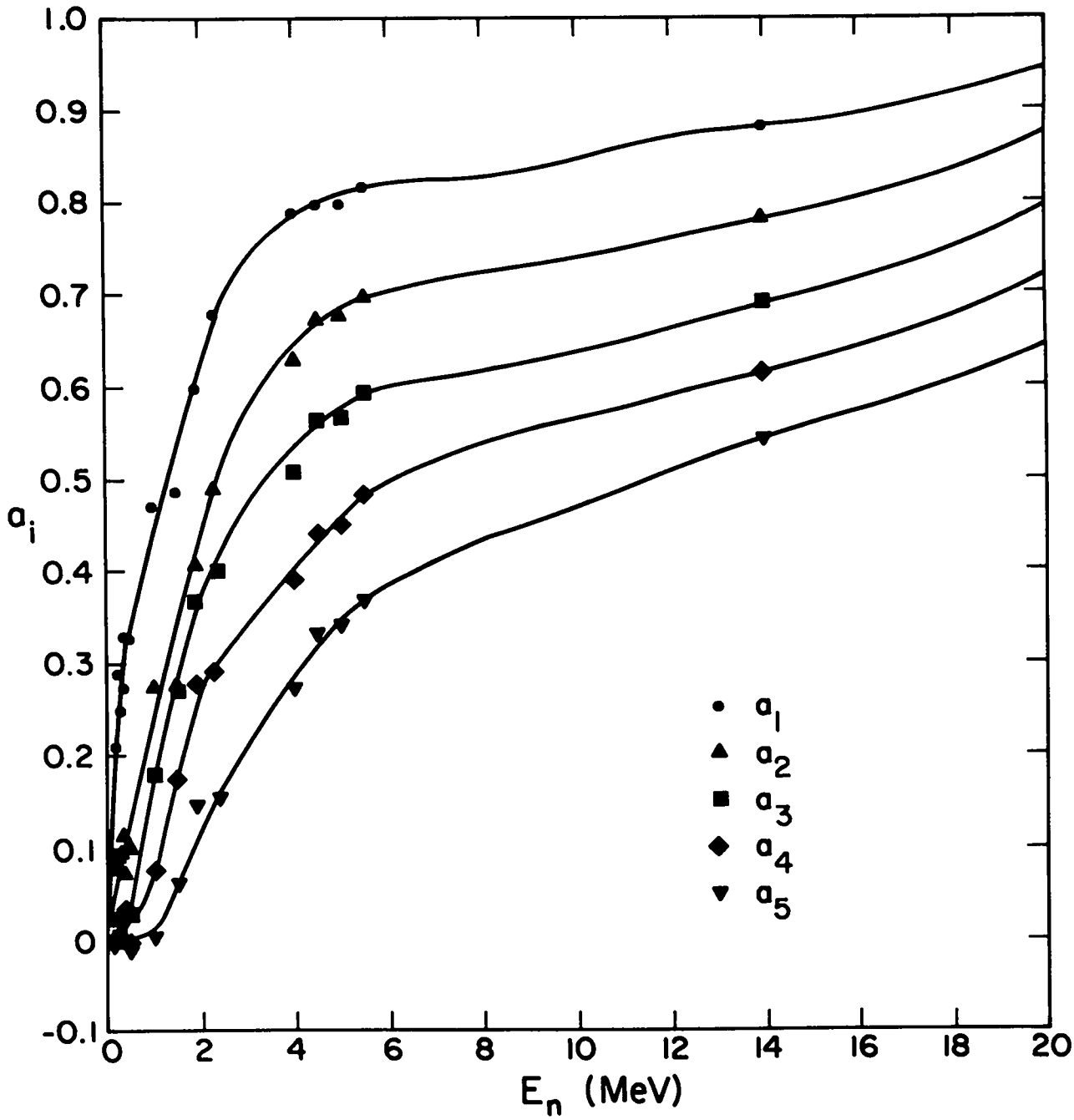


Fig. 36. Legendre polynomial coefficients for elastic-scattering angular distributions for $^{239}Pu$.

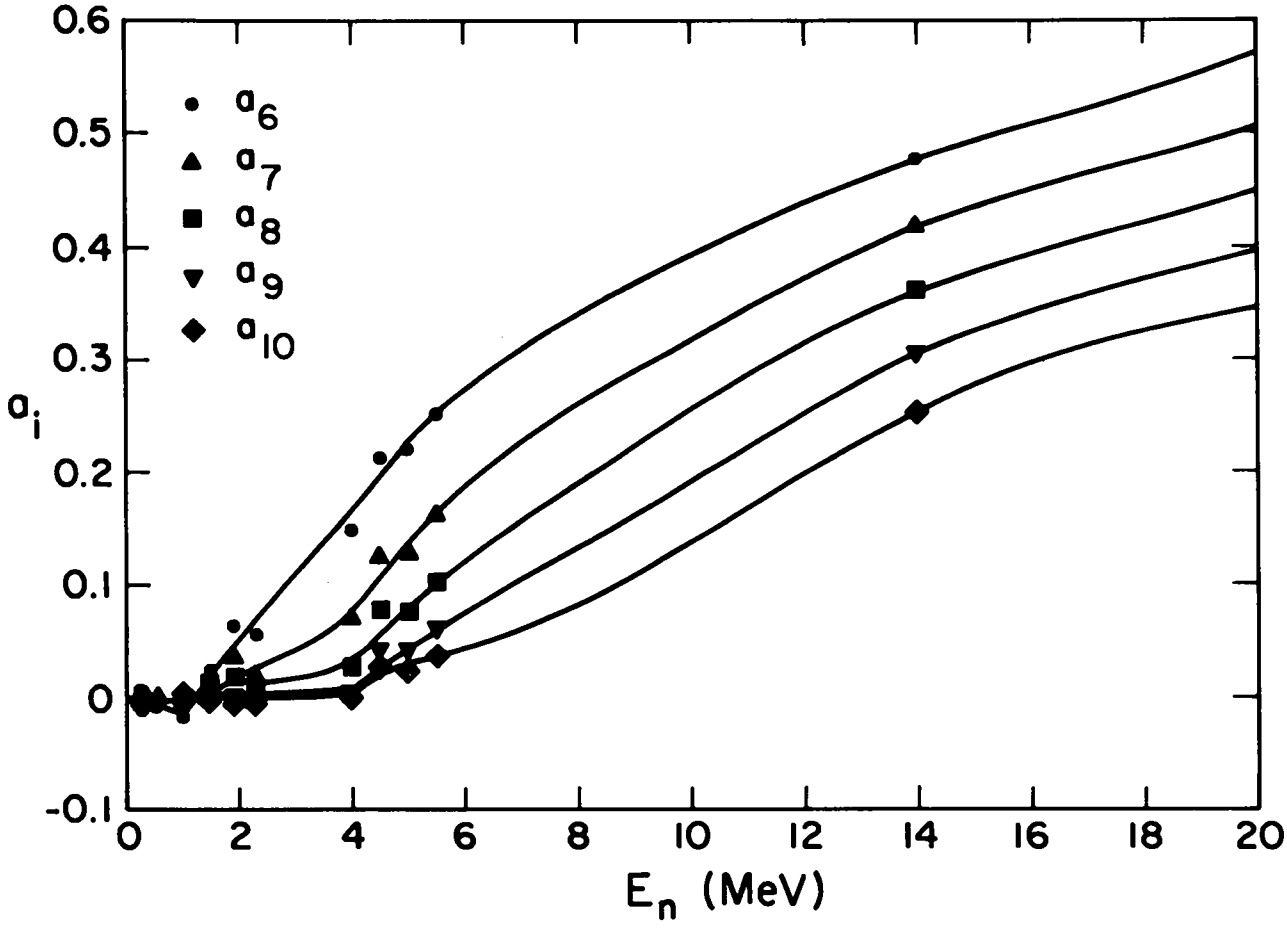


Fig. 37. Legendre Polynomial coefficients for elastic-scattering angular distributions for $^{239}Pu$.

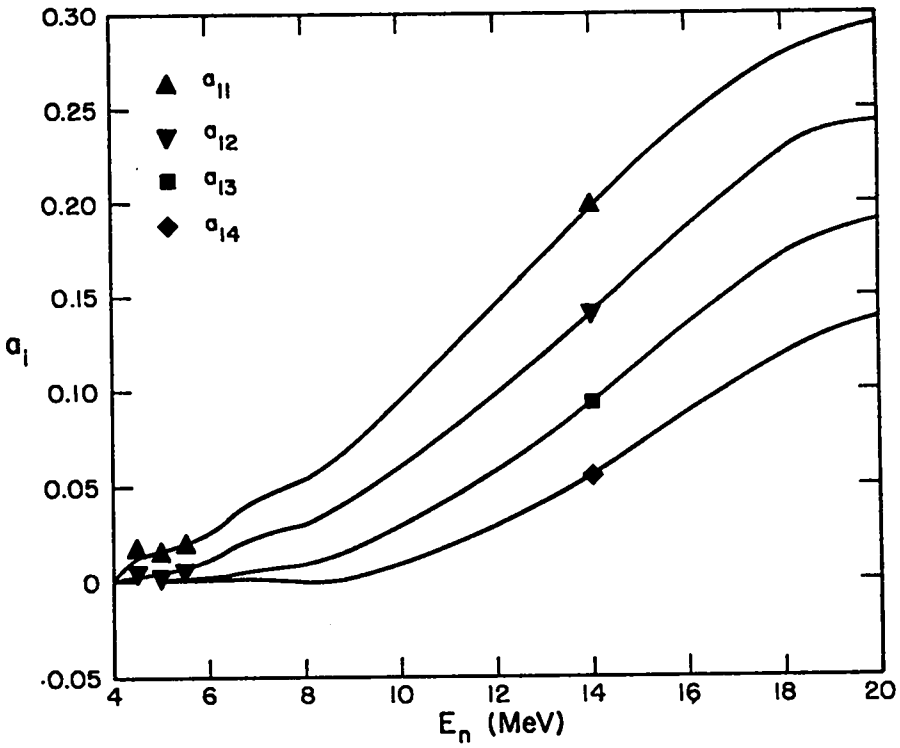


Fig. 38. Legendre polynomial coefficients for elastic-scattering angular distributions for $^{239}Pu$.

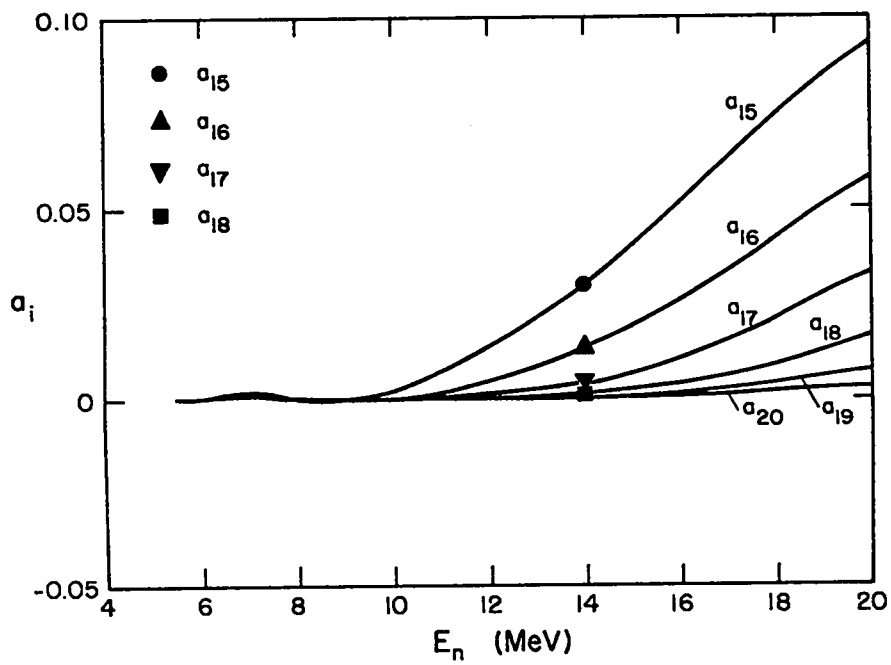


Fig. 39. Legendre polynomial coefficients for elastic-scattering angular distributions for $^{239}Pu$.

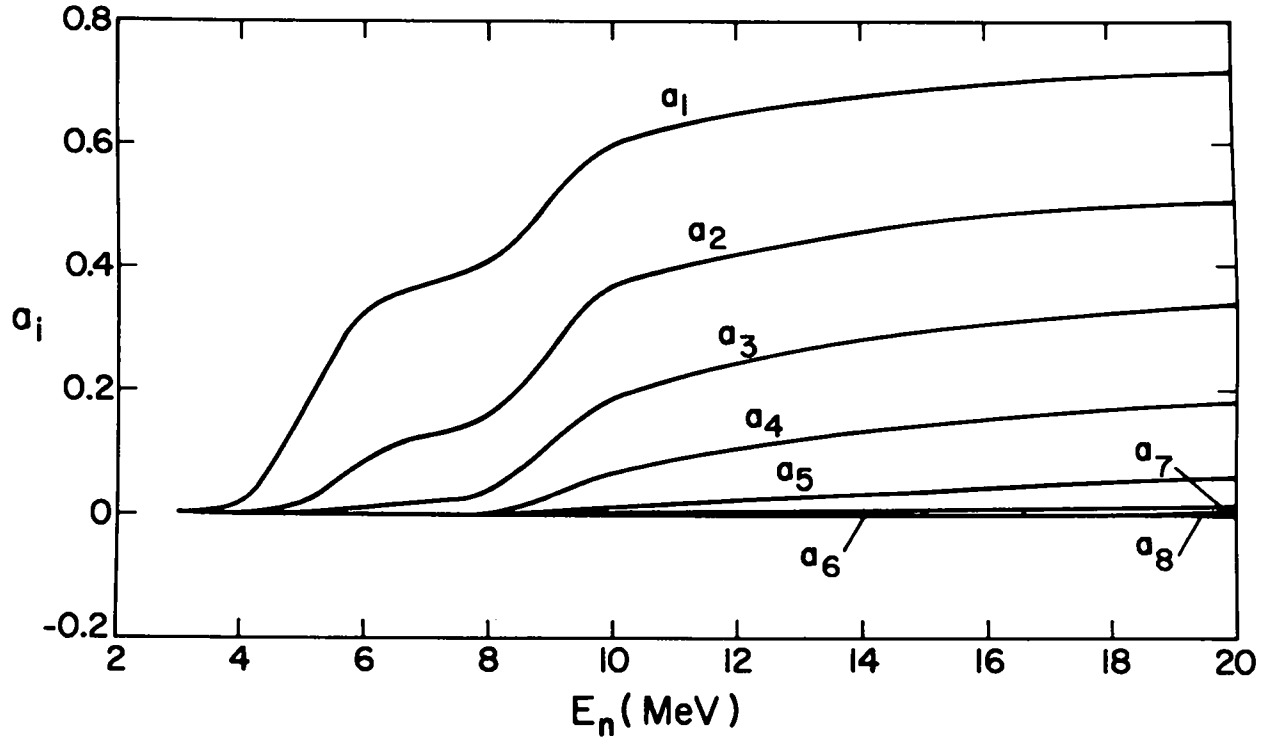


Fig. 40. Legendre polynomial coefficients for direct-interaction inelastic-scattering angular distributions for $^{239}Pu$.

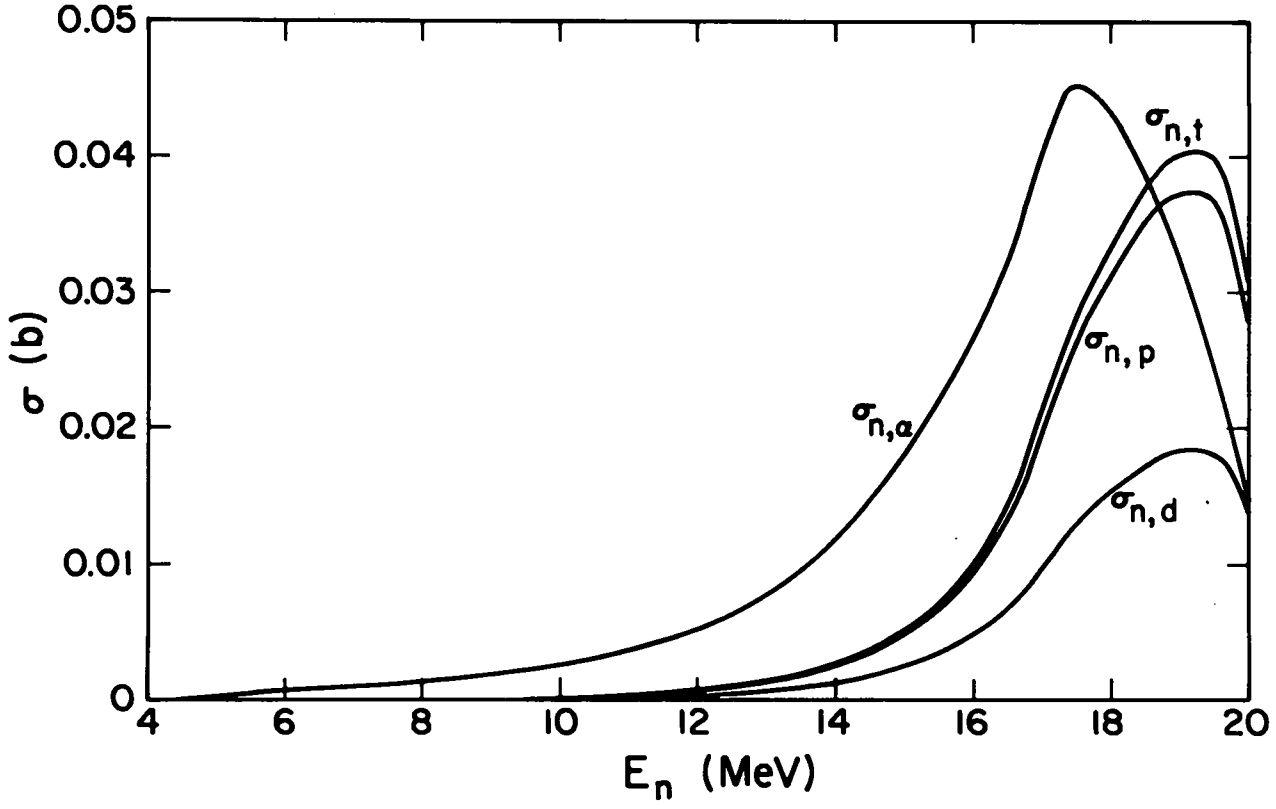


Fig. 41. $\sigma_{n,\alpha}$, $\sigma_{n,t}$, $\sigma_{n,d}$, and $\sigma_{n,p}$ for $^{239}Pu$.

TABLE II

NEUTRON CROSS SECTIONS FOR Pu-239 (IN BARNS)

| E(MeV) | $\sigma_{n,T}$ | $\sigma_{n,n}$ | $\sigma_{n,\gamma}$ | $\sigma_{n,F}$ | $\sigma_{n,n'}$ | $\sigma_{n,2n}$ | $\sigma_{n,3n}$ | $\sigma_{n,f}$ | $\sigma_{n,n'f}$ | $\sigma_{n,2nf}$ | $\sigma_{n,\alpha}$ | $\sigma_{n,p}$ | $\sigma_{n,d}$ | $\sigma_{n,t}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.007883 | | | | | 0.000 | | | | | | | | | |
| 0.0080 | | | | | 0.005 | | | | | | | | | |
| 0.0085 | | | | | 0.027 | | | | | | | | | |
| 0.0090 | | | | | 0.056 | | | | | | | | | |
| 0.0095 | | | | | 0.082 | | | | | | | | | |
| 0.010 | | | | | 0.095 | | | | | | | | | |
| 0.011 | | | | | 0.116 | | | | | | | | | |
| 0.012 | | | | | 0.130 | | | | | | | | | |
| 0.013 | | | | | 0.142 | | | | | | | | | |
| 0.014 | | | | | 0.155 | | | | | | | | | |
| 0.015 | | | | | 0.165 | | | | | | | | | |
| 0.016 | | | | | 0.176 | | | | | | | | | |
| 0.017 | | | | | 0.184 | | | | | | | | | |
| 0.018 | | | | | 0.192 | | | | | | | | | |
| 0.019 | | | | | 0.197 | | | | | | | | | |
| 0.020 | | | | | 0.202 | | | | | | | | | |
| 0.025 | 13.820 | 11.216 | 0.645 | 1.743 | 0.216 | | | | | | | | | |
| 0.030 | 13.640 | 11.105 | 0.560 | 1.750 | 0.225 | | | | | | | | | |
| 0.035 | 13.470 | 11.006 | 0.484 | 1.748 | 0.232 | | | | | | | | | |
| 0.040 | 13.320 | 10.950 | 0.417 | 1.716 | 0.237 | | | | | | | | | |
| 0.045 | 13.170 | 10.852 | 0.371 | 1.708 | 0.239 | | | | | | | | | |
| 0.050 | 13.040 | 10.758 | 0.339 | 1.703 | 0.240 | | | | | | | | | |
| 0.055 | 12.900 | 10.633 | 0.318 | 1.709 | 0.240 | | | | | | | | | |
| 0.057239 | 12.849 | 10.589 | 0.311 | 1.709 | 0.240 | | | | | | | | | |
| 0.060 | 12.780 | 10.524 | 0.304 | 1.708 | 0.244 | | | | | | | | | |
| 0.070 | 12.530 | 10.335 | 0.282 | 1.656 | 0.257 | | | | | | | | | |
| 0.076319 | 12.383 | 10.199 | 0.274 | 1.648 | 0.262 | | | | | | | | | |
| 0.080 | 12.300 | 10.123 | 0.269 | 1.642 | 0.266 | | | | | | | | | |
| 0.090 | 12.090 | 9.914 | 0.261 | 1.634 | 0.281 | | | | | | | | | |
| 0.100 | 11.890 | 9.728 | 0.252 | 1.614 | 0.296 | | | | | | | | | |
| 0.110 | 11.733 | 9.582 | 0.246 | 1.589 | 0.316 | | | | | | | | | |
| 0.120 | 11.540 | 9.399 | 0.241 | 1.564 | 0.336 | | | | | | | | | |
| 0.130 | 11.380 | 9.241 | 0.233 | 1.555 | 0.351 | | | | | | | | | |
| 0.140 | 11.240 | 9.106 | 0.227 | 1.542 | 0.365 | | | | | | | | | |
| 0.150 | 11.095 | 8.965 | 0.221 | 1.534 | 0.375 | | | | | | | | | |
| 0.160 | 10.980 | 8.859 | 0.217 | 1.522 | 0.382 | | | | | | | | | |
| 0.164689 | 10.920 | 8.805 | 0.214 | 1.518 | 0.383 | | | | | | | | | |
| 0.170 | 10.838 | 8.720 | 0.212 | 1.511 | 0.395 | | | | | | | | | |
| 0.180 | 10.740 | 8.611 | 0.206 | 1.502 | 0.421 | | | | | | | | | |
| 0.193811 | 10.592 | 8.454 | 0.200 | 1.495 | 0.443 | | | | | | | | | |
| 0.200 | 10.530 | 8.388 | 0.197 | 1.489 | 0.456 | | | | | | | | | |
| 0.250 | 10.080 | 7.924 | 0.179 | 1.495 | 0.482 | | | | | | | | | |
| 0.287201 | 9.805 | 7.632 | 0.166 | 1.506 | 0.501 | | | | | | | | | |
| 0.300 | 9.720 | 7.535 | 0.162 | 1.514 | 0.509 | | | | | | | | | |
| 0.331386 | 9.513 | 7.304 | 0.154 | 1.534 | 0.521 | | | | | | | | | |
| 0.389630 | 9.182 | 6.914 | 0.138 | 1.560 | 0.570 | | | | | | | | | |
| 0.393646 | 9.163 | 6.892 | 0.136 | 1.561 | 0.574 | | | | | | | | | |
| 0.400 | 9.130 | 6.854 | 0.134 | 1.562 | 0.580 | | | | | | | | | |
| 0.435823 | 8.981 | 6.678 | 0.126 | 1.570 | 0.607 | | | | | | | | | |
| 0.471974 | 8.780 | 6.457 | 0.117 | 1.578 | 0.628 | | | | | | | | | |
| 0.488041 | 8.720 | 6.383 | 0.114 | 1.579 | 0.644 | | | | | | | | | |
| 0.494066 | 8.707 | 6.362 | 0.113 | 1.580 | 0.652 | | | | | | | | | |
| 0.500 | 8.655 | 6.298 | 0.112 | 1.581 | 0.664 | | | | | | | | | |
| 0.507121 | 8.600 | 6.238 | 0.111 | 1.582 | 0.669 | | | | | | | | | |
| 0.514150 | 8.565 | 6.190 | 0.109 | 1.583 | 0.683 | | | | | | | | | |
| 0.558335 | 8.406 | 5.981 | 0.101 | 1.592 | 0.732 | | | | | | | | | |
| 0.600 | 8.258 | 5.774 | 0.093 | 1.603 | 0.788 | | | | | | | | | |
| 0.650 | 8.085 | 5.553 | 0.084 | 1.618 | 0.830 | | | | | | | | | |
| 0.700 | 7.927 | 5.334 | 0.077 | 1.641 | 0.875 | | | | | | | | | |
| 0.733051 | 7.860 | 5.223 | 0.073 | 1.664 | 0.900 | | | | | | | | | |
| 0.763177 | 7.765 | 5.086 | 0.070 | 1.679 | 0.930 | | | | | | | | | |
| 0.803344 | 7.690 | 4.977 | 0.066 | 1.687 | 0.960 | | | | | | | | | |
| 0.852549 | 7.590 | 4.840 | 0.060 | 1.697 | 0.993 | | | | | | | | | |
| 0.900 | 7.500 | 4.717 | 0.053 | 1.700 | 1.030 | | | | | | | | | |
| 0.950 | 7.420 | 4.599 | 0.048 | 1.703 | 1.070 | | | | | | | | | |

TABLE II (Cont'd)

| E(MeV) | $\sigma_{n,T}$ | $\sigma_{n,n}$ | $\sigma_{n,\gamma}$ | $\sigma_{n,F}$ | $\sigma_{n,n'}$ | $\sigma_{n,2n}$ | $\sigma_{n,3n}$ | $\sigma_{n,f}$ | $\sigma_{n,n'f}$ | $\sigma_{n,2nf}$ | $\sigma_{n,\alpha}$ | $\sigma_{n,p}$ | $\sigma_{n,d}$ | $\sigma_{n,t}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.00418 | 7.350 | 4.492 | 0.043 | 1.705 | 1.110 | | | | | | | | | |
| 1.2 | 7.230 | 4.245 | 0.028 | 1.729 | 1.228 | | | | | | | | | |
| 1.4 | 7.220 | 4.077 | 0.020 | 1.801 | 1.322 | | | | | | | | | |
| 1.50627 | 7.240 | 4.000 | 0.0167 | 1.860 | 1.3633 | | | | | | | | | |
| 1.6 | 7.260 | 3.955 | 0.014 | 1.885 | 1.406 | | | | | | | | | |
| 1.8 | 7.340 | 3.942 | 0.010 | 1.925 | 1.463 | | | | | | | | | |
| 2.00836 | 7.450 | 3.979 | 0.006 | 1.950 | 1.515 | | | | | | | | | |
| 2.25 | 7.560 | 4.027 | 0.002 | 1.960 | 1.571 | | | | | | | | | |
| 2.51045 | 7.680 | 4.144 | 0.000 | 1.920 | 1.616 | | | | | | | | | |
| 2.75 | 7.795 | 4.287 | - | 1.866 | 1.642 | | | | | | | | | |
| 3.01254 | 7.895 | 4.379 | - | 1.860 | 1.656 | | | | | | | | | |
| 3.25 | 7.982 | 4.488 | - | 1.834 | 1.660 | | | | | | | | | |
| 3.50 | 8.018 | 4.551 | - | 1.806 | 1.661 | | | | | | | | | |
| 3.75 | 8.040 | 4.592 | - | 1.787 | 1.661 | | | | | | | | | |
| 4.00 | 8.017 | 4.587 | - | 1.769 | 1.661 | | | | | | | | | |
| 4.25 | 7.985 | 4.571 | - | 1.753 | 1.661 | | | | | | | | | |
| 4.50 | 7.900 | 4.491 | - | 1.748 | 1.661 | | | | | | | | | |
| 4.75 | 7.833 | 4.431 | - | 1.741 | 1.661 | | | | | | 0.00 | | | |
| 5.00 | 7.7221 | 4.325 | - | 1.736 | 1.661 | | | | | | 0.0001 | | | |
| 5.25 | 7.5933 | 4.206 | - | 1.733 | 1.654 | | | | | | 0.0003 | | | |
| 5.50 | 7.5125 | 4.141 | - | 1.730 | 1.641 | | | 1.730 | 0.00 | | 0.0005 | | | |
| 5.67965 | 7.4336 | 4.092 | - | 1.731 | 1.610 | 0.000 | | 1.730 | 0.001 | | 0.0006 | | | |
| 5.75 | 7.4137 | 4.079 | - | 1.735 | 1.597 | 0.002 | | 1.730 | 0.005 | | 0.0007 | | | |
| 6.00 | 7.3017 | 4.017 | - | 1.768 | 1.501 | 0.015 | | 1.730 | 0.038 | | 0.0007 | | | |
| 6.25 | 7.0908 | 3.957 | - | 1.837 | 1.250 | 0.046 | | 1.730 | 0.107 | | 0.0008 | | | |
| 6.50 | 6.9408 | 3.910 | - | 1.930 | 1.020 | 0.080 | | 1.730 | 0.200 | | 0.0008 | | | |
| 6.75 | 6.8549 | 3.890 | - | 2.013 | 0.841 | 0.110 | | 1.730 | 0.283 | | 0.0009 | | | |
| 7.00 | 6.7629 | 3.842 | - | 2.090 | 0.700 | 0.130 | | 1.730 | 0.360 | | 0.0009 | | | |
| 7.5 | 6.4811 | 3.724 | - | 2.190 | 0.410 | 0.156 | | 1.730 | 0.460 | | 0.0011 | | | |
| 8.0 | 6.3523 | 3.606 | - | 2.263 | 0.307 | 0.175 | | 1.730 | 0.533 | | 0.0013 | | | |
| 8.5 | 6.2559 | 3.5064 | - | 2.319 | 0.239 | 0.190 | | 1.730 | 0.589 | | 0.0015 | | | |
| 9.0 | 6.1059 | 3.3521 | - | 2.349 | 0.200 | 0.203 | | 1.730 | 0.619 | | 0.0018 | | | |
| 9.5 | 6.0196 | 3.2615 | - | 2.360 | 0.183 | 0.213 | | 1.730 | 0.630 | | 0.0021 | 0.00 | | 0.00 |
| 10.0 | 5.9608 | 3.1980 | - | 2.363 | 0.176 | 0.221 | | 1.730 | 0.633 | | 0.0025 | 0.0001 | | 0.0002 |
| 10.5 | 5.8824 | 3.1149 | - | 2.363 | 0.174 | 0.227 | | 1.730 | 0.633 | 0.000 | 0.0030 | 0.0002 | 0.00 | 0.0003 |
| 11.0 | 5.8524 | 3.0710 | - | 2.367 | 0.178 | 0.232 | - | 1.730 | 0.633 | 0.004 | 0.0036 | 0.0003 | 0.0001 | 0.0004 |
| 11.5 | 5.8431 | 3.0356 | - | 2.384 | 0.183 | 0.235 | - | 1.730 | 0.633 | 0.021 | 0.0043 | 0.0005 | 0.0002 | 0.0005 |
| 12.0 | 5.8333 | 2.9764 | - | 2.422 | 0.191 | 0.237 | - | 1.730 | 0.633 | 0.059 | 0.0052 | 0.0007 | 0.0003 | 0.0007 |
| 12.5 | 5.8420 | 2.9393 | - | 2.454 | 0.202 | 0.238 | - | 1.730 | 0.633 | 0.091 | 0.0063 | 0.0009 | 0.0005 | 0.0010 |
| 12.7069 | 5.8580 | 2.9421 | - | 2.463 | 0.206 | 0.237 | 0.0 | 1.730 | 0.633 | 0.100 | 0.0070 | 0.0011 | 0.0006 | 0.0012 |
| 13.0 | 5.8922 | 2.9471 | - | 2.482 | 0.213 | 0.234 | 0.005 | 1.730 | 0.633 | 0.119 | 0.0077 | 0.0013 | 0.0007 | 0.0014 |
| 13.5 | 5.9562 | 2.9781 | - | 2.503 | 0.221 | 0.226 | 0.014 | 1.730 | 0.633 | 0.140 | 0.0095 | 0.0018 | 0.0009 | 0.0019 |
| 14.0 | 5.9981 | 2.9990 | - | 2.529 | 0.225 | 0.205 | 0.022 | 1.730 | 0.633 | 0.166 | 0.0117 | 0.0025 | 0.0013 | 0.0026 |
| 14.5 | 6.0310 | 3.0155 | - | 2.553 | 0.223 | 0.180 | 0.036 | 1.730 | 0.633 | 0.190 | 0.0145 | 0.0035 | 0.0018 | 0.0037 |
| 15.0 | 6.0700 | 3.0356 | - | 2.580 | 0.221 | 0.152 | 0.051 | 1.730 | 0.633 | 0.217 | 0.0179 | 0.0049 | 0.0025 | 0.0051 |
| 15.5 | 6.1050 | 3.0577 | - | 2.597 | 0.219 | 0.124 | 0.068 | 1.730 | 0.633 | 0.234 | 0.0220 | 0.0068 | 0.0034 | 0.0071 |
| 16.0 | 6.1300 | 3.0802 | - | 2.603 | 0.218 | 0.095 | 0.083 | 1.730 | 0.633 | 0.240 | 0.0267 | 0.0094 | 0.0048 | 0.0099 |
| 16.5 | 6.1600 | 3.1027 | - | 2.608 | 0.2165 | 0.072 | 0.095 | 1.730 | 0.633 | 0.245 | 0.0322 | 0.0131 | 0.0066 | 0.0139 |
| 17.0 | 6.1900 | 3.1176 | - | 2.613 | 0.215 | 0.052 | 0.102 | 1.730 | 0.633 | 0.250 | 0.0403 | 0.0195 | 0.0097 | 0.0209 |
| 17.5 | 6.2150 | 3.1243 | - | 2.624 | 0.214 | 0.036 | 0.104 | 1.730 | 0.633 | 0.261 | 0.0452 | 0.0263 | 0.0131 | 0.0281 |
| 18.0 | 6.2350 | 3.1325 | - | 2.642 | 0.213 | 0.022 | 0.103 | 1.730 | 0.633 | 0.279 | 0.0433 | 0.0310 | 0.0153 | 0.0329 |
| 18.5 | 6.2600 | 3.1367 | - | 2.673 | 0.212 | 0.013 | 0.097 | 1.730 | 0.633 | 0.310 | 0.0388 | 0.0350 | 0.0172 | 0.0373 |
| 19.0 | 6.3052 | 3.1526 | - | 2.719 | 0.2112 | 0.007 | 0.087 | 1.730 | 0.633 | 0.356 | 0.0325 | 0.0373 | 0.0184 | 0.0402 |
| 19.5 | 6.3452 | 3.1726 | - | 2.764 | 0.2105 | 0.003 | 0.076 | 1.730 | 0.633 | 0.401 | 0.0245 | 0.0367 | 0.0181 | 0.0398 |
| 20.0 | 6.3610 | 3.2005 | - | 2.797 | 0.210 | 0.0 | 0.066 | 1.730 | 0.633 | 0.434 | 0.0146 | 0.0281 | 0.0139 | 0.0309 |

Same as $\sigma_{n,F}$ below 5.5 MeV

TABLE III

CROSS SECTIONS FOR INELASTIC LEVELS OF Pu-239 (IN BARNS)

| E(keV) | 7.85 | 57 | 76 | 164 | 193 | 286 | 330 | 388 | 392 | 434 | 470 | 486 | 492 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7.883 | 0.000 | | | | | | | | | | | | |
| 8.0 | 0.005 | | | | | | | | | | | | |
| 8.5 | 0.027 | | | | | | | | | | | | |
| 9.0 | 0.056 | | | | | | | | | | | | |
| 9.5 | 0.082 | | | | | | | | | | | | |
| 10.0 | 0.095 | | | | | | | | | | | | |
| 11.0 | 0.116 | | | | | | | | | | | | |
| 12.0 | 0.130 | | | | | | | | | | | | |
| 13.0 | 0.142 | | | | | | | | | | | | |
| 14.0 | 0.155 | | | | | | | | | | | | |
| 15.0 | 0.165 | | | | | | | | | | | | |
| 16.0 | 0.176 | | | | | | | | | | | | |
| 17.0 | 0.184 | | | | | | | | | | | | |
| 18.0 | 0.192 | | | | | | | | | | | | |
| 19.0 | 0.197 | | | | | | | | | | | | |
| 20.0 | 0.202 | | | | | | | | | | | | |
| 25.0 | 0.216 | | | | | | | | | | | | |
| 30.0 | 0.225 | | | | | | | | | | | | |
| 35.0 | 0.232 | | | | | | | | | | | | |
| 40.0 | 0.237 | | | | | | | | | | | | |
| 45.0 | 0.239 | | | | | | | | | | | | |
| 50.0 | 0.240 | | | | | | | | | | | | |
| 57.239 | 0.240 | 0.000 | | | | | | | | | | | |
| 60.0 | 0.239 | 0.005 | | | | | | | | | | | |
| 70.0 | 0.237 | 0.020 | | | | | | | | | | | |
| 76.319 | 0.235 | 0.027 | 0.000 | | | | | | | | | | |
| 80.0 | 0.234 | 0.0295 | 0.0025 | | | | | | | | | | |
| 90.0 | 0.232 | 0.036 | 0.013 | | | | | | | | | | |
| 100.0 | 0.230 | 0.040 | 0.026 | | | | | | | | | | |
| 110.0 | 0.228 | 0.042 | 0.046 | | | | | | | | | | |
| 120.0 | 0.227 | 0.043 | 0.066 | | | | | | | | | | |
| 130.0 | 0.225 | 0.043 | 0.083 | | | | | | | | | | |
| 140.0 | 0.224 | 0.043 | 0.098 | | | | | | | | | | |
| 150.0 | 0.223 | 0.043 | 0.109 | | | | | | | | | | |
| 160.0 | 0.222 | 0.043 | 0.117 | | | | | | | | | | |
| 164.689 | 0.221 | 0.043 | 0.119 | 0.000 | | | | | | | | | |
| 170.0 | 0.220 | 0.043 | 0.123 | 0.009 | | | | | | | | | |
| 180.0 | 0.219 | 0.043 | 0.127 | 0.032 | | | | | | | | | |
| 193.811 | 0.218 | 0.042 | 0.129 | 0.054 | 0.000 | | | | | | | | |
| 200.0 | 0.217 | 0.042 | 0.130 | 0.057 | 0.010 | | | | | | | | |
| 250.0 | 0.211 | 0.040 | 0.128 | 0.067 | 0.036 | | | | | | | | |
| 287.201 | 0.207 | 0.039 | 0.124 | 0.070 | 0.061 | 0.000 | | | | | | | |
| 300.0 | 0.206 | 0.038 | 0.122 | 0.070 | 0.063 | 0.010 | | | | | | | |
| 331.386 | 0.200 | 0.036 | 0.115 | 0.070 | 0.066 | 0.034 | 0.000 | | | | | | |
| 389.630 | 0.191 | 0.032 | 0.106 | 0.068 | 0.070 | 0.076 | 0.027 | 0.000 | | | | | |
| 393.646 | 0.190 | 0.032 | 0.104 | 0.068 | 0.070 | 0.078 | 0.028 | 0.004 | 0.000 | | | | |
| 400.0 | 0.188 | 0.031 | 0.103 | 0.067 | 0.070 | 0.079 | 0.030 | 0.010 | 0.002 | | | | |
| 435.823 | 0.182 | 0.029 | 0.097 | 0.064 | 0.071 | 0.087 | 0.036 | 0.025 | 0.016 | 0.000 | | | |
| 471.974 | 0.175 | 0.027 | 0.091 | 0.062 | 0.071 | 0.091 | 0.041 | 0.034 | 0.0215 | 0.0145 | 0.000 | | |
| 488.041 | 0.172 | 0.0264 | 0.089 | 0.061 | 0.071 | 0.093 | 0.0423 | 0.037 | 0.024 | 0.0173 | 0.011 | 0.000 | |
| 494.066 | 0.171 | 0.026 | 0.088 | 0.0605 | 0.0707 | 0.0935 | 0.043 | 0.038 | 0.025 | 0.0185 | 0.0123 | 0.0055 | 0.000 |
| 500.0 | 0.169 | 0.0258 | 0.087 | 0.060 | 0.0704 | 0.094 | 0.044 | 0.039 | 0.0258 | 0.0196 | 0.0138 | 0.010 | 0.0056 |
| 507.121 | 0.168 | 0.0255 | 0.086 | 0.0597 | 0.0702 | 0.0944 | 0.0443 | 0.0396 | 0.0267 | 0.0204 | 0.0152 | 0.0110 | 0.008 |
| 514.150 | 0.167 | 0.025 | 0.085 | 0.059 | 0.070 | 0.095 | 0.045 | 0.041 | 0.028 | 0.0215 | 0.0175 | 0.0126 | 0.0107 |
| 558.335 | 0.1585 | 0.023 | 0.0793 | 0.0563 | 0.0694 | 0.097 | 0.0482 | 0.0458 | 0.0335 | 0.0276 | 0.023 | 0.021 | 0.0182 |
| 600.00 | 0.151 | 0.0215 | 0.0741 | 0.0538 | 0.068 | 0.098 | 0.051 | 0.0492 | 0.037 | 0.0322 | 0.0276 | 0.0257 | 0.0233 |
| 650.0 | 0.143 | 0.0195 | 0.069 | 0.0508 | 0.0655 | 0.098 | 0.0536 | 0.0524 | 0.0404 | 0.036 | 0.0326 | 0.0305 | 0.0282 |
| 700.0 | 0.136 | 0.0178 | 0.0641 | 0.0483 | 0.063 | 0.098 | 0.0553 | 0.055 | 0.0423 | 0.040 | 0.036 | 0.0344 | 0.032 |
| 733.051 | 0.131 | 0.0167 | 0.061 | 0.0466 | 0.0615 | 0.098 | 0.0561 | 0.0562 | 0.0433 | 0.0415 | 0.0381 | 0.0371 | 0.0342 |
| 763.177 | 0.126 | 0.0157 | 0.0591 | 0.045 | 0.0595 | 0.098 | 0.0568 | 0.0575 | 0.0438 | 0.0432 | 0.0401 | 0.0385 | 0.0363 |
| 803.344 | 0.121 | 0.0144 | 0.0557 | 0.0434 | 0.0575 | 0.097 | 0.057 | 0.0581 | 0.0442 | 0.045 | 0.042 | 0.041 | 0.0384 |
| 852.549 | 0.113 | 0.0132 | 0.052 | 0.0412 | 0.055 | 0.0955 | 0.057 | 0.0587 | 0.0445 | 0.0468 | 0.0432 | 0.043 | 0.0406 |
| 900.0 | 0.107 | 0.012 | 0.0487 | 0.039 | 0.0523 | 0.093 | 0.057 | 0.059 | 0.0446 | 0.048 | 0.044 | 0.045 | 0.0425 |
| 950.0 | 0.101 | 0.0107 | 0.046 | 0.0373 | 0.0496 | 0.0905 | 0.056 | 0.0584 | 0.0444 | 0.0486 | 0.0446 | 0.0463 | 0.0442 |

| 505 | 512 | 556 | 730 | 760 | 800 | 849 | Continuum | (MeV) 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.000 | | | | | | | | | | | | |
| 0.0057 | 0.000 | | | | | | | | | | | |
| 0.0162 | 0.015 | 0.000 | | | | | 0.000 | | | | | |
| 0.0204 | 0.019 | 0.0152 | | | | | 0.021 | | | | | |
| 0.0238 | 0.0224 | 0.0193 | | | | | 0.045 | | | | | |
| 0.0266 | 0.0254 | 0.0228 | | | | | 0.078 | | | | | |
| 0.028 | 0.027 | 0.0247 | 0.000 | | | | 0.099 | | | | | |
| 0.0293 | 0.0285 | 0.0262 | 0.0115 | 0.000 | | | 0.115 | | | | | |
| 0.0304 | 0.0302 | 0.0285 | 0.0162 | 0.012 | 0.000 | | 0.128 | | | | | |
| 0.0316 | 0.032 | 0.0305 | 0.0205 | 0.0146 | 0.0121 | 0.000 | 0.148 | | | | | |
| 0.0329 | 0.0337 | 0.0332 | 0.0245 | 0.017 | 0.015 | 0.0116 | 0.170 | | | | | |
| 0.0337 | 0.0352 | 0.034 | 0.0275 | 0.0188 | 0.0177 | 0.0135 | 0.212 | | | | | |

TABLE III (Cont'd)

| E(MeV) | 7.85 | 57 | 76 | 164 | 193 | 286 | 330 | 388 | 392 | 434 | 470 | 486 | 492 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1.00418 | 0.094 | 0.009 | 0.043 | 0.0352 | 0.0473 | 0.088 | 0.054 | 0.0575 | 0.044 | 0.049 | 0.045 | 0.0473 | 0.0451 |
| 1.2 | 0.073 | 0.0 | 0.0344 | 0.0295 | 0.0393 | 0.076 | 0.0454 | 0.0496 | 0.041 | 0.0485 | 0.045 | 0.049 | 0.048 |
| 1.4 | 0.046 | - | 0.0276 | 0.0246 | 0.033 | 0.063 | 0.0373 | 0.0412 | 0.037 | 0.0436 | 0.0415 | 0.0468 | 0.0484 |
| 1.50627 | 0.049 | - | 0.0246 | 0.0223 | 0.0297 | 0.0562 | 0.0339 | 0.0370 | 0.0347 | 0.0391 | 0.0391 | 0.0448 | 0.0479 |
| 1.6 | 0.044 | - | 0.0225 | 0.0206 | 0.0277 | 0.051 | 0.0311 | 0.034 | 0.0328 | 0.0355 | 0.037 | 0.0427 | 0.0464 |
| 1.8 | 0.034 | - | 0.0189 | 0.0176 | 0.0235 | 0.0404 | 0.0258 | 0.0275 | 0.0285 | 0.0275 | 0.030 | 0.036 | 0.0417 |
| 2.00836 | 0.027 | - | 0.0162 | 0.0152 | 0.020 | 0.031 | 0.0213 | 0.0225 | 0.0238 | 0.0210 | 0.023 | 0.0282 | 0.0351 |
| 2.25 | 0.020 | - | 0.0134 | 0.0126 | 0.0165 | 0.0222 | 0.0176 | 0.0166 | 0.0184 | 0.0135 | 0.0161 | 0.0191 | 0.0242 |
| 2.51045 | 0.015 | - | 0.0112 | 0.0106 | 0.0135 | 0.0168 | 0.0136 | 0.0136 | 0.0142 | 0.0090 | 0.0103 | 0.0115 | 0.0138 |
| 2.75 | 0.0115 | - | 0.0096 | 0.0090 | 0.0110 | 0.0126 | 0.0110 | 0.0110 | 0.0111 | 0.0075 | 0.0090 | 0.0095 | 0.0090 |
| 3.01254 | 0.008 | - | 0.008 | 0.007 | 0.008 | 0.0097 | 0.008 | 0.008 | 0.008 | 0.005 | 0.007 | 0.008 | 0.006 |
| 3.25 | 0.005 | - | 0.005 | 0.004 | 0.005 | 0.006 | 0.005 | 0.005 | 0.005 | 0.0020 | 0.0040 | 0.0050 | 0.0030 |
| 3.5 | 0.002 | - | 0.002 | 0.001 | 0.002 | 0.0034 | 0.002 | 0.002 | 0.002 | 0.0 | 0.001 | 0.002 | 0.001 |
| 3.75 | 0.000 | - | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | - | 0.000 | 0.000 | 0.000 |
| 4.0 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4.25 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4.5 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 4.75 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5.0 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5.25 | - | - | - | - | - | - | - | - | - | - | - | - | - |
| 5.5 | - | - | - | - | - | - | - | - | - | - | - | - | - |

*Above this energy, the cross sections for these levels are identical.

| E(MeV) | Continuum | Direct Interaction | E(MeV) | Continuum | Direct Interaction | E(MeV) | Continuum | Direct Interaction |
|---|---|---|---|---|---|---|---|---|
| 5.67965 | 1.581 | 0.029 | 11.5 | 0.045 | 0.138 | 18.5 | 0.012 | 0.200 |
| 5.75 | 1.567 | 0.030 | 12.0 | 0.039 | 0.152 | 19.0 | 0.0112 | 0.200 |
| 6.00 | 1.467 | 0.034 | 12.5 | 0.035 | 0.167 | 19.5 | 0.0105 | 0.200 |
| 6.25 | 1.212 | 0.038 | 12.7069 | 0.033 | 0.173 | 20.0 | 0.0100 | 0.200 |
| 6.50 | 0.978 | 0.042 | 13.0 | 0.031 | 0.182 | | | |
| 6.75 | 0.795 | 0.046 | 13.5 | 0.028 | 0.193 | | | |
| 7.00 | 0.650 | 0.050 | 14.0 | 0.025 | 0.200 | | | |
| 7.5 | 0.353 | 0.057 | 14.5 | 0.023 | 0.200 | | | |
| 8.0 | 0.242 | 0.065 | 15.0 | 0.021 | 0.200 | | | |
| 8.5 | 0.166 | 0.073 | 15.5 | 0.019 | 0.200 | | | |
| 9.0 | 0.119 | 0.081 | 16.0 | 0.018 | 0.200 | | | |
| 9.5 | 0.093 | 0.090 | 16.5 | 0.0165 | 0.200 | | | |
| 10.0 | 0.076 | 0.100 | 17.0 | 0.015 | 0.200 | | | |
| 10.5 | 0.062 | 0.112 | 17.5 | 0.014 | 0.200 | | | |
| 11.0 | 0.053 | 0.125 | 18.0 | 0.013 | 0.200 | | | |

| 505 | 512 | 556 | 730 | 760 | 800 | 849 | Continuum | (MeV) 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0345 | 0.0363 | 0.0354 | 0.030 | 0.0202 | 0.0202 | 0.015 | 0.260 | 0.000 | | | | |
| 0.0368 | 0.039 | 0.0397 | 0.0385 | 0.0235 | 0.0277 | 0.0181 | 0.4255 | 0.0005 | | | | |
| 0.037 | 0.040 | 0.0416 | 0.0452 | 0.0256 | 0.0291 | 0.0195 | 0.5825 | 0.0015 | | | | |
| 0.0360 | 0.0400 | 0.0416 | 0.0471 | 0.0264 | 0.0289 | 0.0197 | 0.6633 | 0.002 | 0.000 | | | |
| 0.0352 | 0.0398 | 0.0416 | 0.0481 | 0.0267 | 0.0284 | 0.0199 | 0.738 | 0.0025 | 0.0005 | | | |
| 0.0325 | 0.038 | 0.0407 | 0.0489 | 0.027 | 0.027 | 0.0195 | 0.874 | 0.003 | 0.001 | | | |
| 0.0292 | 0.0356 | 0.0388 | 0.0482 | 0.0268 | 0.0252 | 0.0189 | 1.003 | 0.0035 | 0.0015 | 0.000 | | |
| 0.0244 | 0.0304 | 0.0343 | 0.0465 | 0.0257 | 0.0224 | 0.0178 | 1.1533 | 0.0037 | 0.0018 | 0.0005 | | |
| 0.0185 | 0.0245 | 0.0275 | 0.0436 | 0.0239 | 0.0192 | 0.0167 | 1.282 | 0.004 | 0.002 | 0.001 | 0.000 | |
| 0.0110 | 0.0175 | 0.0209 | 0.0396 | 0.0213 | 0.0166 | 0.0152 | 1.3706 | 0.0041 | 0.0021 | 0.0012 | 0.0001 | |
| 0.008 | 0.007 | 0.0132 | 0.035 | 0.0179 | 0.0144 | 0.0138 | 1.448 | 0.0042 | 0.0022 | 0.0013 | 0.0003 | 0.000 |
| 0.0050 | 0.0040 | 0.0080 | 0.0280 | 0.0110 | 0.0119 | 0.0123 | 1.5163 | 0.0042 | 0.0025 | 0.0015 | 0.0007 | 0.0006 |
| 0.002 | 0.001 | 0.004 | 0.0216 | 0.006 | 0.0100 | 0.0110 | 1.574 | 0.0043 | 0.0028 | 0.0017 | 0.0012 | 0.0010 |
| 0.000 | 0.000 | 0.000 | 0.0090 | 0.0030 | 0.0070 | 0.0090 | 1.6208 | 0.0044 | 0.0031 | 0.0020 | 0.0015 | 0.0012 |
| - | - | - | 0.0 | 0.000 | 0.004 | 0.008 | 1.6355 | 0.0045 | 0.0035 | 0.0023 | 0.0017 | 0.0015 |
| - | - | - | - | - | 0.0010 | 0.0050 | 1.6403 | 0.0046 | 0.0037 | 0.0026 | 0.0020 | 0.0018 |
| - | - | - | - | - | 0.0 | 0.002 | 1.643 | 0.0047 | 0.0040 | 0.0030 | 0.0023 | 0.0020 |
| - | - | - | - | - | - | 0.000 | 1.643 | 0.0048 | 0.0043 | 0.0035 | 0.0029 | 0.0025 |
| - | - | - | - | - | - | - | 1.641 | 0.0050 | 0.0045 | 0.0040 | 0.0035 | 0.0030 |
| - | - | - | - | - | - | - | 1.631 | 0.0050 | 0.0049 | 0.0046 | 0.0044 | 0.0041 |
| - | - | - | - | - | - | - | 1.614 | 0.0054* | 0.0054* | 0.0054* | 0.0054* | 0.0054* |

## III. PLUTONIUM-240

### A. Total Cross Section

The only reported measurements of the total cross section are those by Smith et al.[56] Above 1.5 MeV, the total is taken to be the sum of the partial cross sections, following the shape of the curve for the total cross sections of $^{238}U$ and for $^{239}Pu$. The results are shown in Fig. 42.

### B. Elastic-Scattering Cross Sections

Elastic-scattering cross sections obtained by integrating the differential elastic cross section over all angles are given by Smith et al.[56] The evaluated curve follows the experiments closely up to about 1 MeV, where the scatter in the data becomes quite large. Above 1-1.5 MeV, the elastic-scattering cross section was obtained by subtracting the nonelastic cross section from the total. The recommended curve is shown in Fig. 43.

Smith et al.[56] measured the angular distribution for elastic scattering plus some inelastic contributions. However, the results are presented in terms of Legendre polynomial coefficients, obtained from fitting each measurement. A 5th-order fit was made at each energy, a limit that is both too low (in comparison with the results for neighboring nuclides) and odd, in violation of physical principles and ENDF/B procedures. In the absence of the original data (in units of mb/sr) a refitting procedure could not be performed; hence, these data were not used in this evaluation. On the basis of nuclear systematics, the angular distributions for $^{239}Pu$ were used for $^{240}Pu$.

### C. Fission Cross Section

Measurements of the fission cross section of $^{240}Pu$ have been reported by White and Warner,[19] Savin et al.,[16,57] Dorofeev and Dobrynin,[24] Perkin et al.,[21] Ruddick and White,[58] Smith et al.,[18] Nesterov and Smirenkin,[59] and Gilboy and Knoll.[60] Some of these measurements were ratios of the fission cross section of $^{240}Pu$ relative to that of $^{235}U$; all of them, however, have been reduced to absolute cross sections by multiplying by the appropriate fission cross sections as described in the evaluation of the neutron cross sections of $^{239}Pu$ (Sec. II-C).

The evaluated curve follows the experimental average up to about 400 keV. Above that energy, the experimental measurements do not show good agreement, although the spread is not extreme. The recommended curve tends to follow the measurements of Savin et al.[57] above 500 keV.

The point of White and Warner[19] at 14.1 MeV establishes the absolute value of the curve in the high-energy region; the general shape of the curve above about 5 MeV was taken from the curve for $^{239}Pu$. The recommended curves are shown in Figs. 44 and 45.

### D. Mean Number of Prompt Neutrons from Fission

Measurements of $\bar{\nu}$ are given by Savin et al.,[16] Kuzminov,[61] and de Vroey et al.[62] These were reduced to ratios of $\bar{\nu}$ for $^{240}Pu$ to the spontaneous fission $\bar{\nu}$ for $^{252}Cf$. A fit to the data of Savin et al. and de Vroey et al. below 4 MeV yields a straight line that is inconsistent with the measurements of Kuzminov, especially near 15 MeV. In view of the above inconsistency and the difficulty of establishing a two-segment linear fit without measurements between 4 and 15 MeV, this evaluation is based only on the data of Savin et al. and de Vroey et al., although it is questionable to disregard the only high-energy measurement available. The ratio of $\bar{\nu}$ for $^{240}Pu$ to that of $^{252}Cf$ is given by

$$\frac{\bar{\nu}(^{240}Pu)}{\bar{\nu}(^{252}Cf)} = 0.773 + 0.0382E_n \text{ (MeV)} ,$$

$$0 \leq E_n \leq 20 \text{ MeV} . \qquad (9)$$

Based on $\bar{\nu}$ for $^{252}Cf$ of 3.748,

$$\bar{\nu}(^{240}Pu) = 2.897 + 0.143E_n \text{ (MeV)} . \qquad (10)$$

The recommended curve is shown in Fig. 46.

### E. Delayed Neutrons from Fission

Keepin[35] gives a value of 0.0088 for the delayed neutron fraction in the fission spectrum. In the absence of data to the contrary, the shape of the curve for the delayed neutron fraction as a function of energy is taken to be the same as that for $^{239}Pu$ (see Fig. 9). The final-state energy distribution given by Keepin is essentially the same as that for $^{239}Pu$ (see Fig. 10).

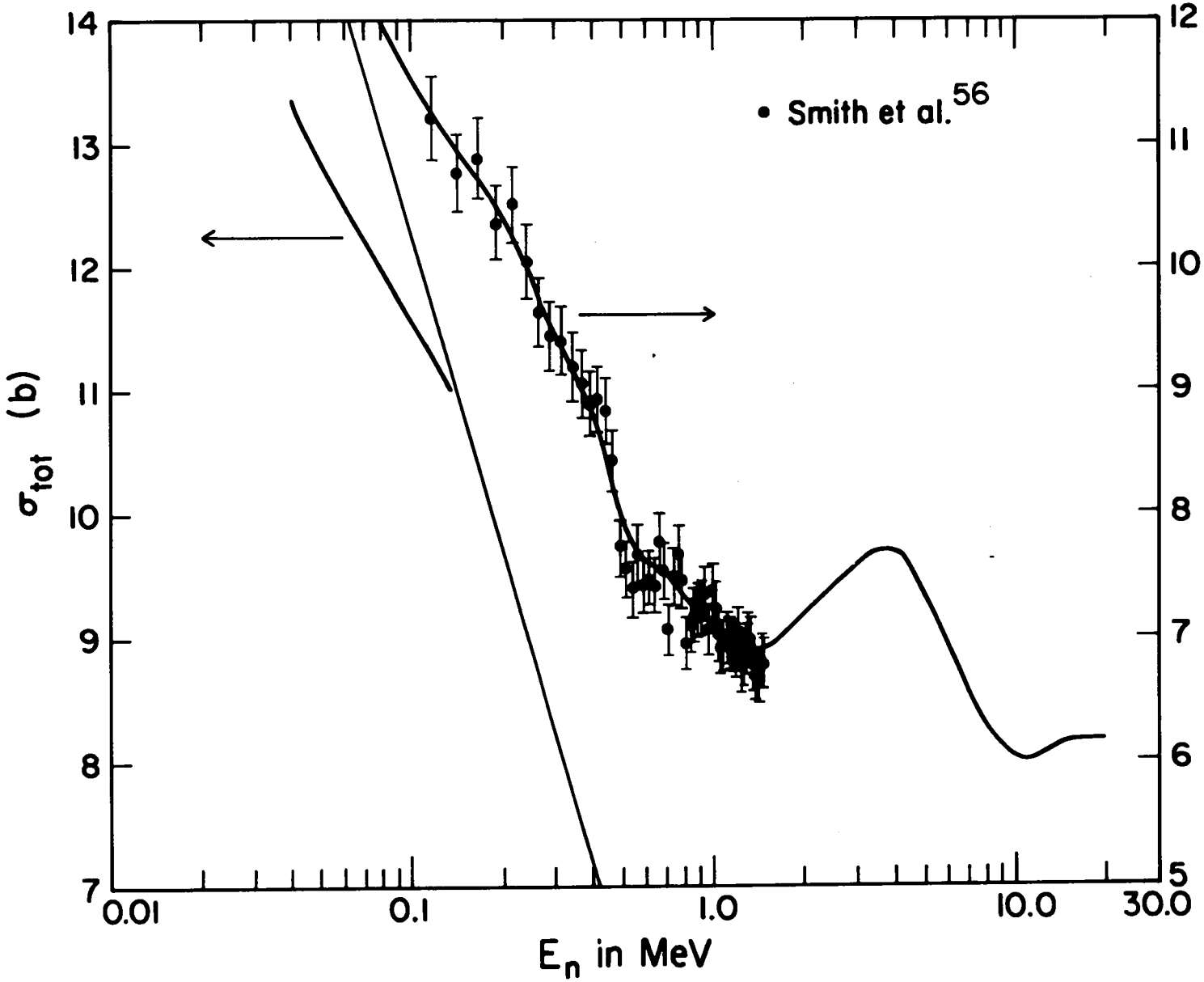


Fig. 42. Total cross section for $^{240}Pu$.

F. Fission Neutron Energy Distribution

Because there are no measurements of the energy distributions for neutron-induced fission of $^{240}Pu$, the nuclear temperature for various incident-neutron energies was calculated from the relation given by Terrell:[63]

$$T_f(E_n) \cong 0.50 + 0.43\ (\bar{\nu} + 1)^{1/2} \quad , \qquad (11)$$

where $\bar{\nu}$ as a function of $E_n$ is given by Eq. 10. Equation (11) gives, for example, $T_f(0) = 1.355$ MeV, $T_f(14\ \text{MeV}) = 1.547$ MeV, and $T_f(20\ \text{MeV}) = 1.619$ MeV. The curve of $T_f$ vs $E_n$ is shown in Fig. 47.

Again, the fission process is represented by the relation,

$$\sigma_{n,F} = \sigma_{n,f} + \sigma_{n,n'f} + \sigma_{n,2nf} + \cdots \qquad (12)$$

The prefission neutron energy distributions are taken to be the same as those for inelastic scattering (see Sec. III-G), with appropriate threshold modifications.

G. Inelastic Scattering

The level energies for $^{240}Pu$ were taken from Lederer et al.[50] Measurements of the cross sections for exciting levels in the ranges 42 ± 5, 140 ± 10, 300 ± 20, 600 ± 20, and 900 ± 50 keV were reported by Smith et al.[56] These measurements give results for the energy levels at 43, 142, 296, and 599 keV, and provide a check on the sum of the levels at 863, 903, and 945 keV.

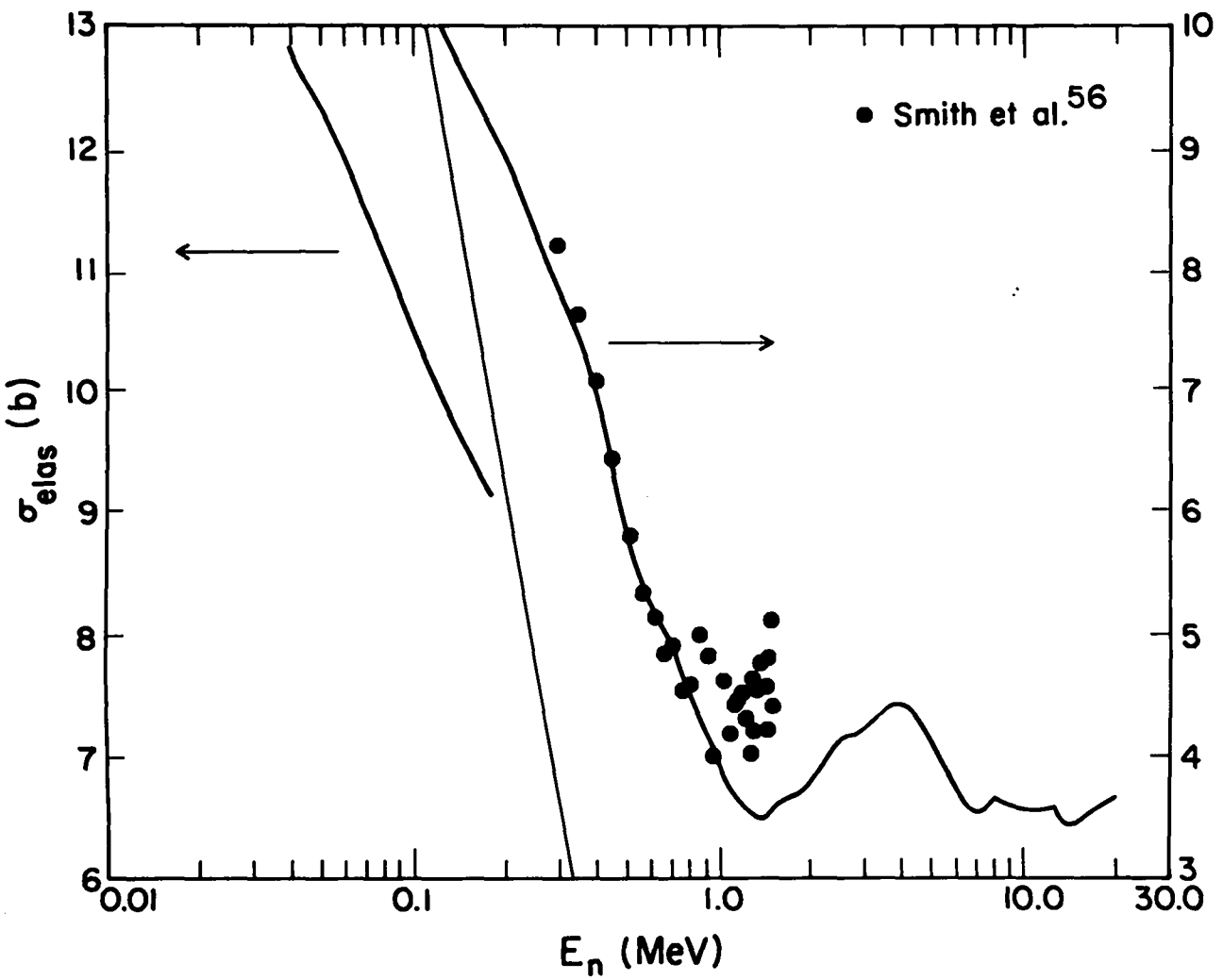


Fig. 43. Elastic-scattering cross section for $^{240}Pu$.

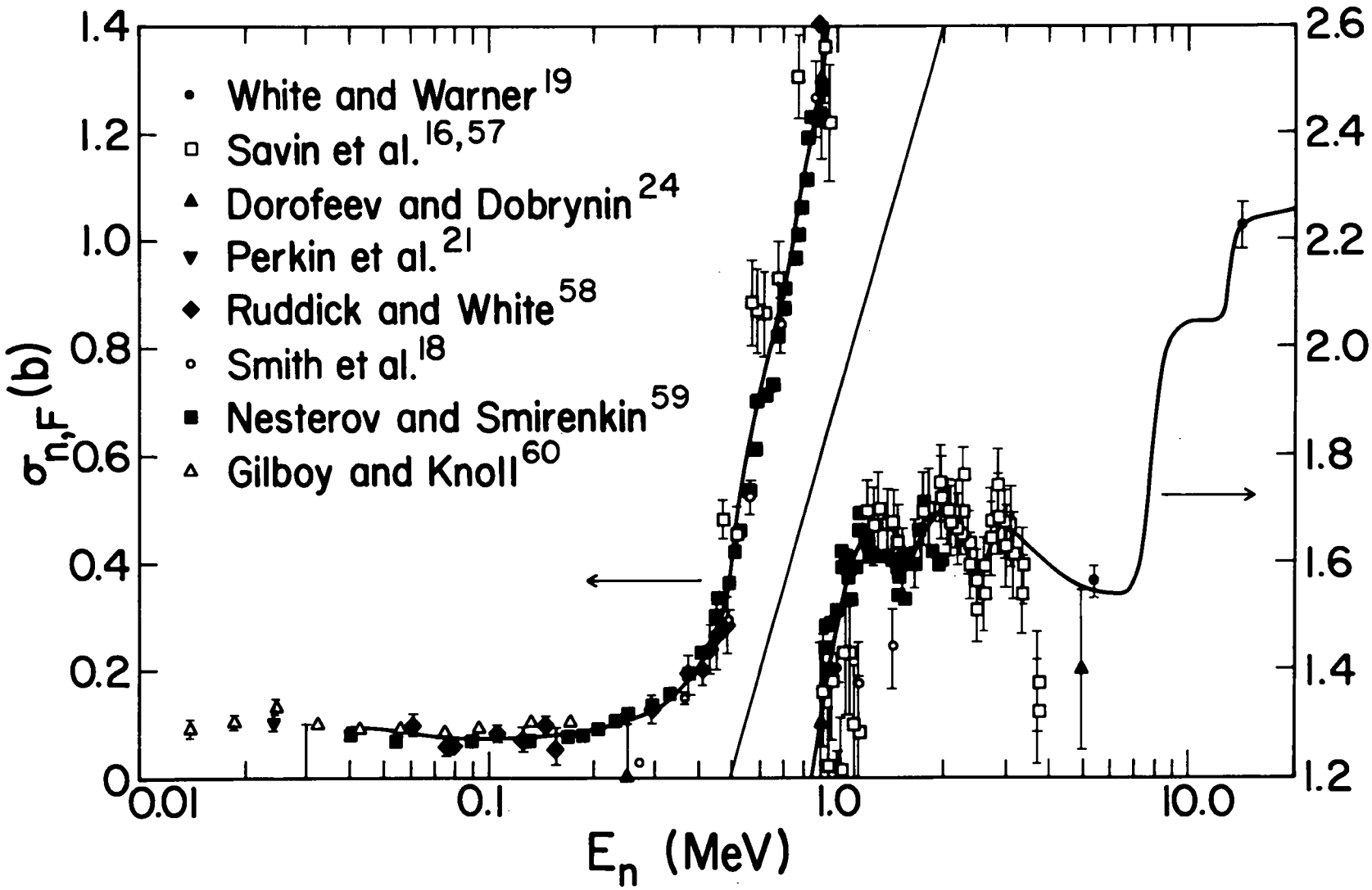


Fig. 44. Fission cross section for $^{240}Pu$. All measurements made relative to other cross sections have been reduced to fission cross sections by means of appropriate ratio curves.

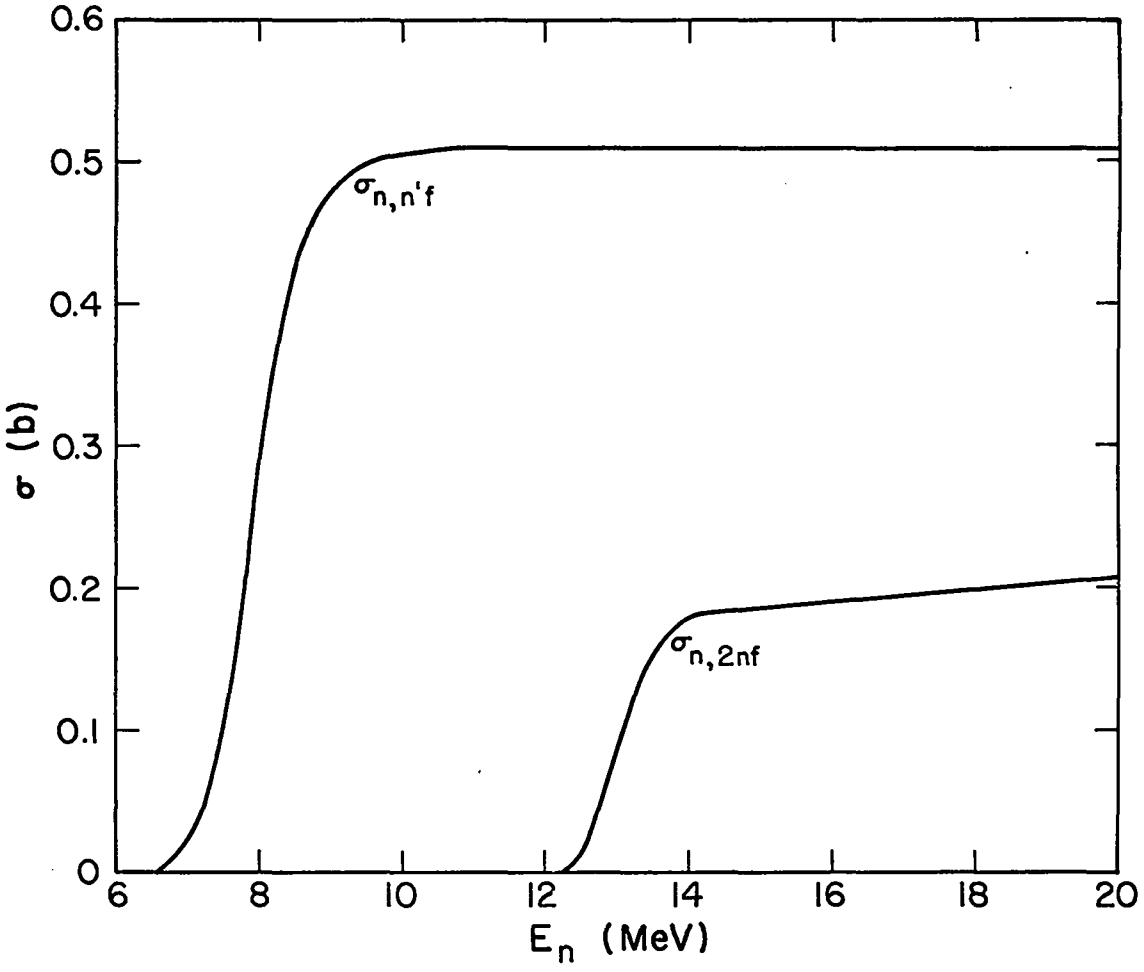


Fig. 45. $\sigma_{n,n'f}$ and $\sigma_{n,2nf}$ for $^{240}Pu$.

A continuum was introduced along with the level at 945 keV to account for the unresolved energy levels above that energy. At an incident energy of 940 keV, the average neutron energy obtained from the levels is 760 keV. Thus, the temperature for the continuum distribution was taken to be 380 keV at that energy. The curve at high energies was based on the curve for $^{239}Pu$; the results are shown in Fig. 48.

Following the procedure used for $^{239}Pu$, levels were introduced at 2, 3, 4, and 5 MeV to represent direct-interaction inelastic scattering. Angular distributions for those levels were assumed as they were for $^{239}Pu$. The cross sections for the various excited levels, the continuum, and the total inelastic are shown in Figs. 49-51.

H. Radiative Capture Cross Section

The radiative capture cross section for $^{240}Pu$ was evaluated by Pitterle and Yamamoto[64] for inclusion in the ENDF/B-III evaluation (MAT 1105). In the absence of experimental measurements in the energy region of interest, their evaluation* was used, without modification, in this work. The curve is reproduced in Fig. 52.

I. $\sigma_{n,2n}$ and $\sigma_{n,3n}$

In the absence of experimental measurements, these cross sections are assumed to be similar to the cross sections for $^{239}Pu$, with appropriate changes in threshold (see Fig. 53). If the dominant factor in these processes should be the even-odd

*This evaluation is based on calculations, using parameters obtained from resonance-region measurements.

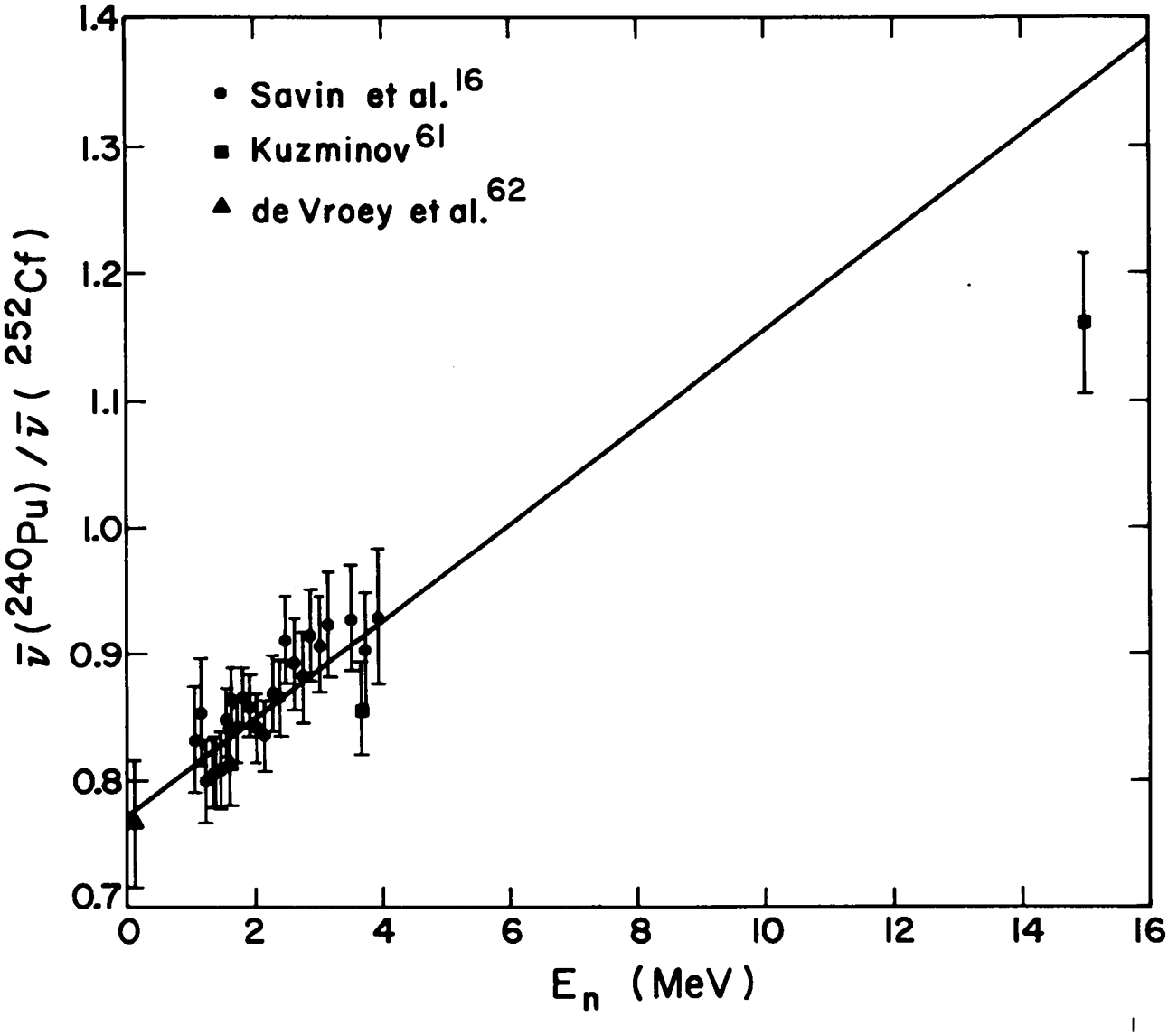


Fig. 46. Ratio of mean number of prompt neutrons per fission for $^{240}Pu$ to the spontaneous value for $^{252}Cf$.

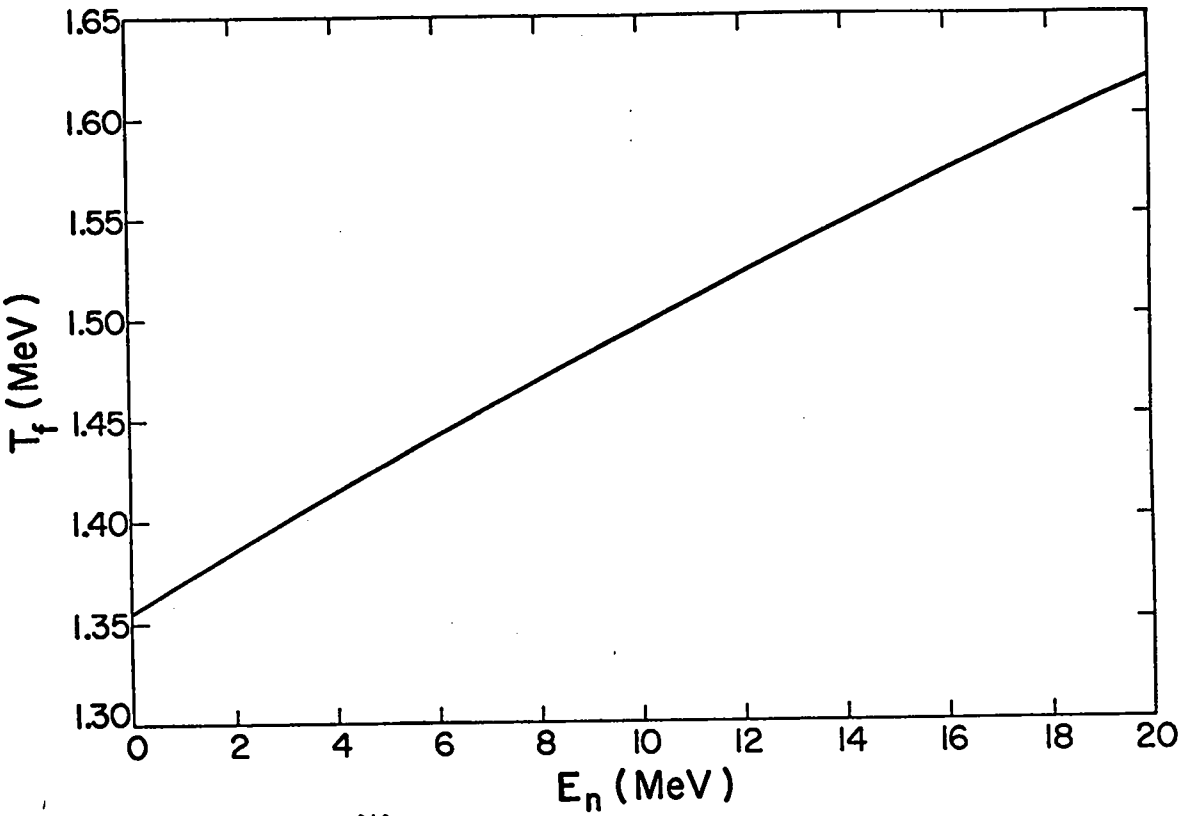


Fig. 47. Fission temperature for $^{240}Pu$.

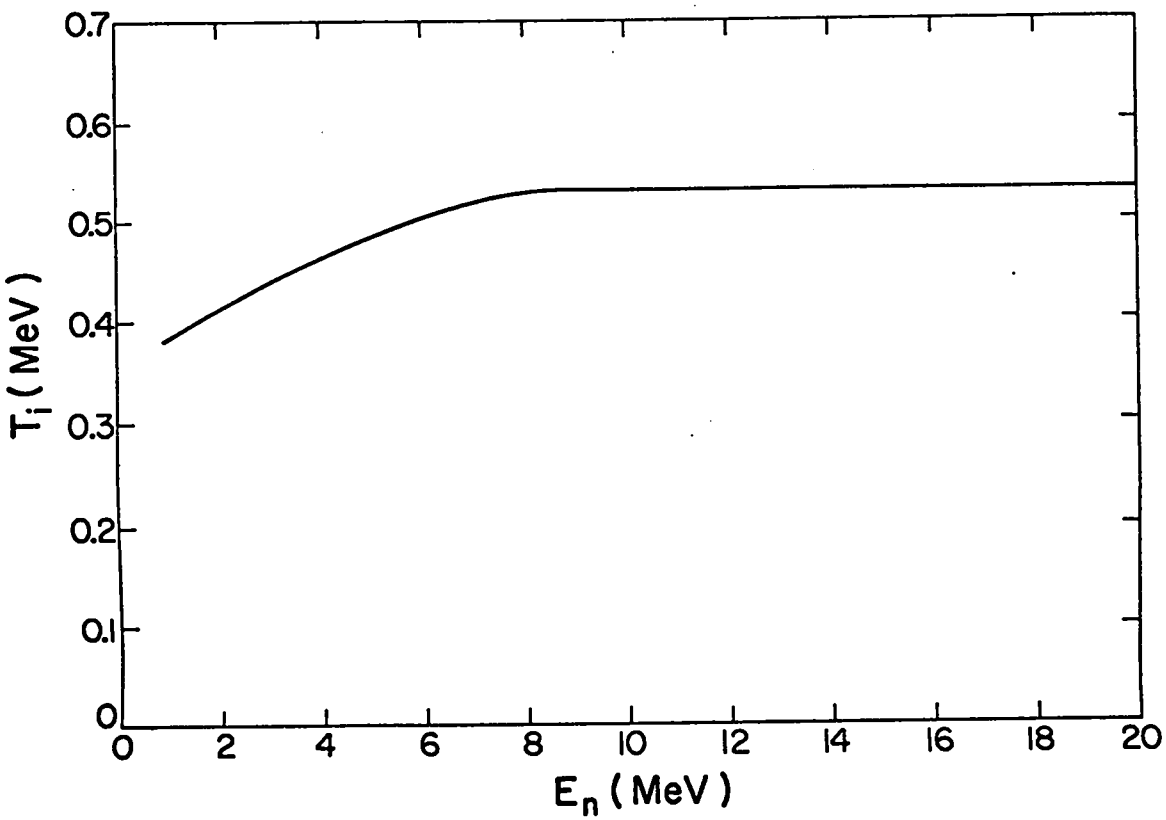


Fig. 48. Inelastic-scattering nuclear temperature for $^{240}Pu$.

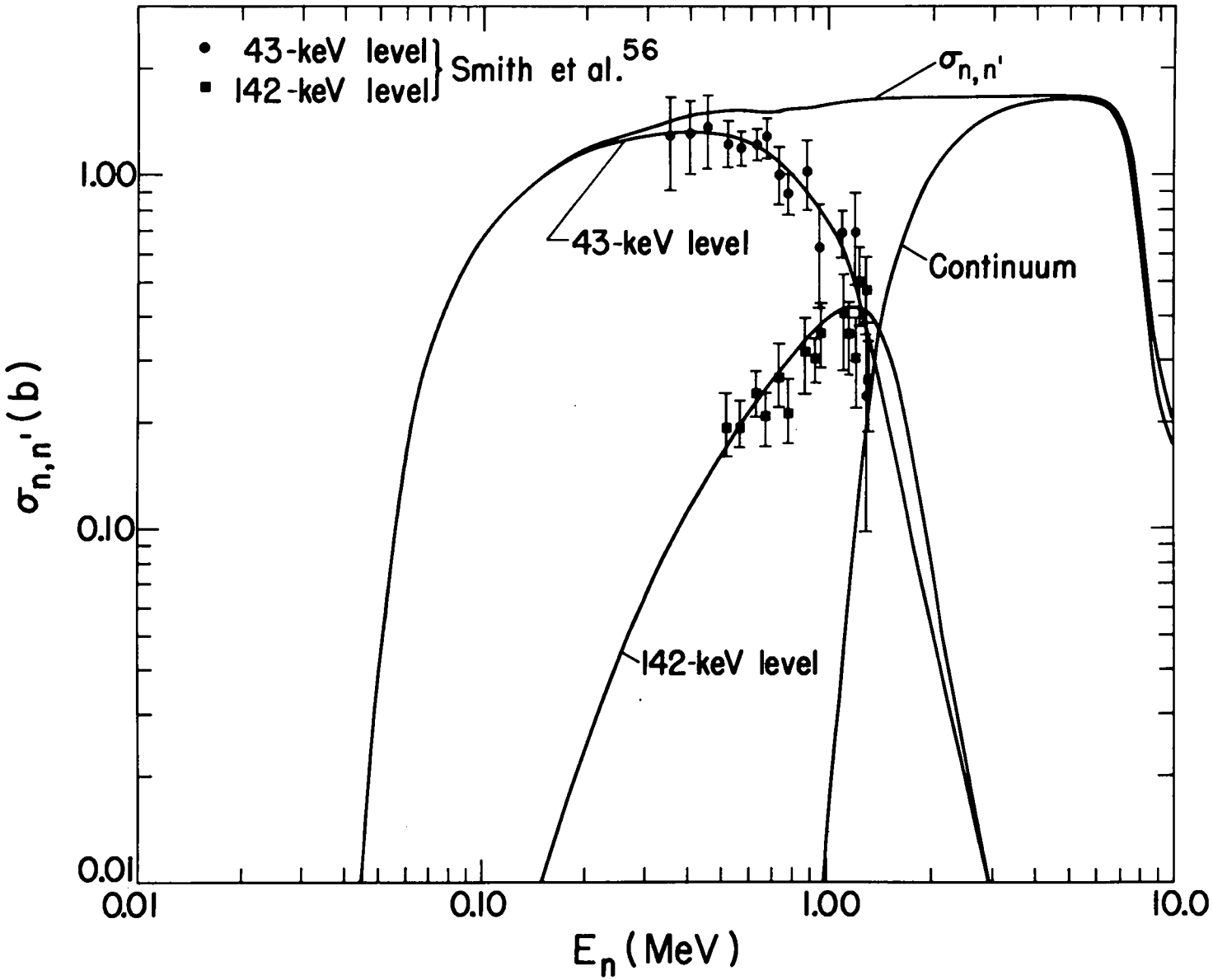


Fig. 49. Inelastic-scattering cross section, continuum cross section and energy-level cross sections for $^{240}Pu$.

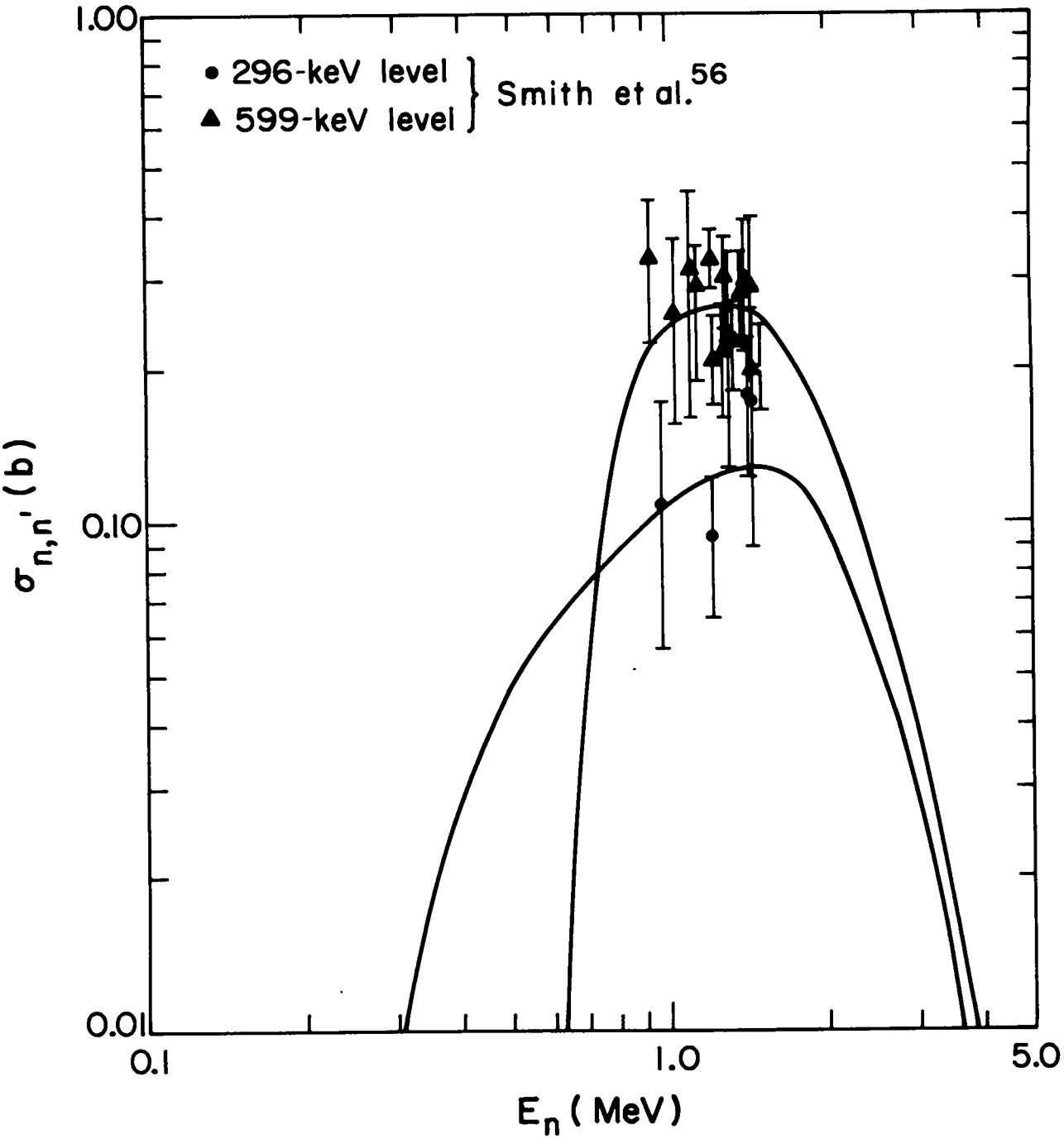


Fig. 50. Energy-level cross sections for $^{240}Pu$.

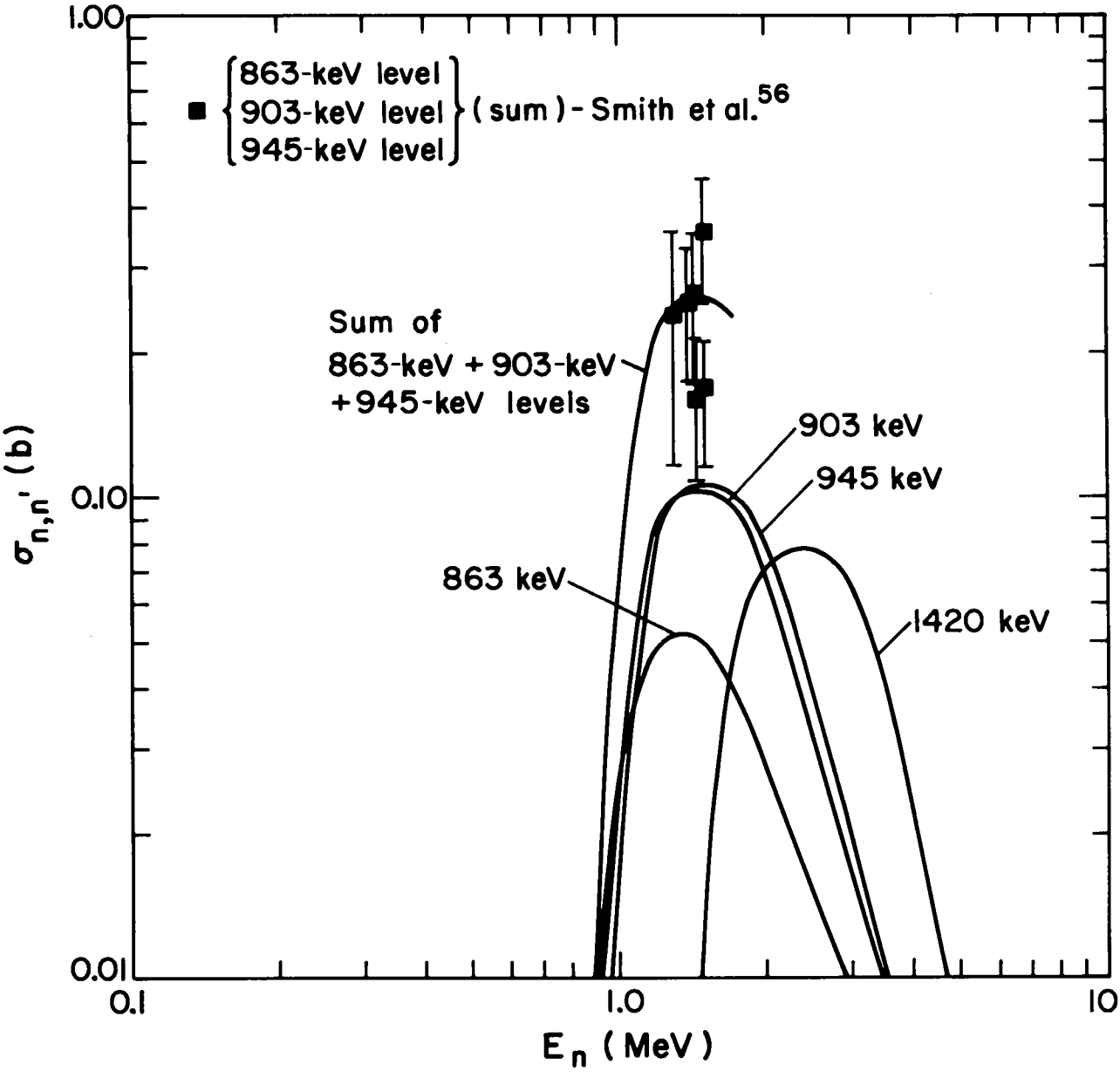


Fig. 51. Energy-level cross sections for $^{240}Pu$.

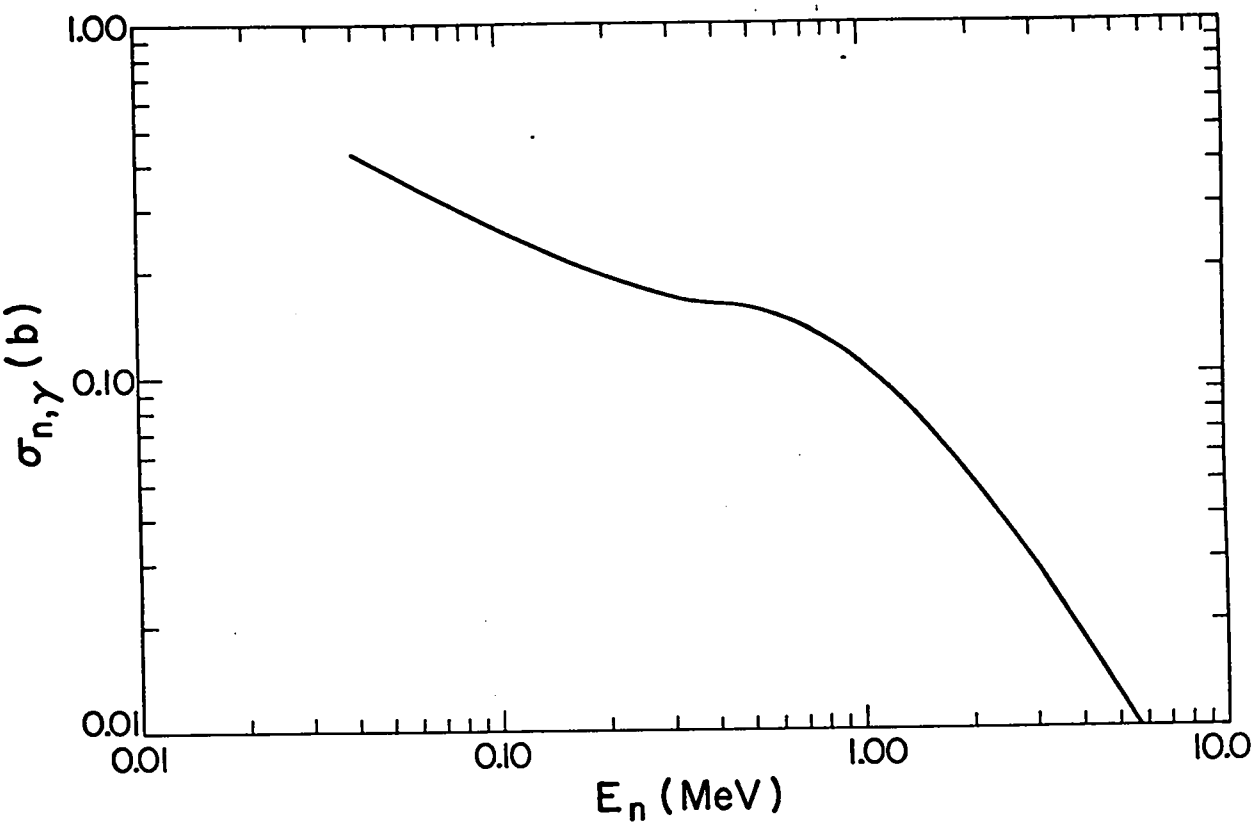


Fig. 52. Radiative-capture cross section for $^{240}Pu$.

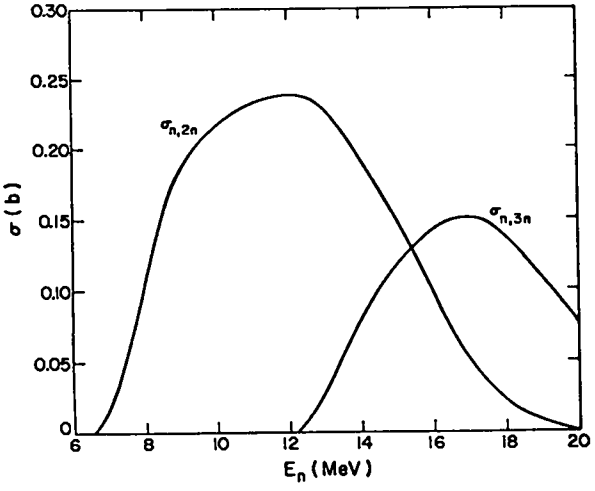


Fig. 53. $\sigma_{n,2n}$ and $\sigma_{n,3n}$ for $^{240}Pu$.

nature of the mass number, then $^{238}U$ might prove to be the better choice.

J. Tabulated Cross Sections

The tabulated values of the cross sections are given in Table IV, while values for the inelastic levels are given in Table V.

TABLE IV

NEUTRON CROSS SECTIONS FOR $^{240}Pu$ (IN BARNS)

| $E_n$ (MeV) | $\sigma_{n,T}$ | $\sigma_{n,n}$ | $\sigma_{n,\gamma}$ | $\sigma_{n,F}$ | $\sigma_{n,n'}$ | $\sigma_{n,2n}$ | $\sigma_{n,3n}$ | $\sigma_{n,f}$ | $\sigma_{n,n'f}$ | $\sigma_{n,2nf}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.040 | 13.356 | 12.8315 | 0.430 | 0.0945 | | | | | | |
| 0.043172 | 13.1323 | 12.630 | 0.410 | 0.0923 | 0.000 | | | | | |
| 0.050 | 12.851 | 12.3424 | 0.380 | 0.0912 | 0.0374 | | | | | |
| 0.055 | 12.664 | 12.132 | 0.362 | 0.0880 | 0.0820 | | | | | |
| 0.060 | 12.507 | 11.920 | 0.343 | 0.083 | 0.161 | | | | | |
| 0.065 | 12.361 | 11.710 | 0.330 | 0.080 | 0.241 | | | | | |
| 0.070 | 12.209 | 11.494 | 0.318 | 0.079 | 0.318 | | | | | |
| 0.075 | 12.096 | 11.330 | 0.306 | 0.078 | 0.382 | | | | | |
| 0.080 | 11.991 | 11.175 | 0.297 | 0.076 | 0.443 | | | | | |
| 0.085 | 11.858 | 10.992 | 0.288 | 0.074 | 0.504 | | | | | |
| 0.090 | 11.742 | 10.827 | 0.278 | 0.072 | 0.565 | | | | | |
| 0.100 | 11.505 | 10.505 | 0.265 | 0.071 | 0.664 | | | | | |
| 0.110 | 11.338 | 10.274 | 0.252 | 0.070 | 0.742 | | | | | |
| 0.120 | 11.193 | 10.066 | 0.242 | 0.071 | 0.814 | | | | | |
| 0.130 | 11.059 | 9.875 | 0.233 | 0.073 | 0.878 | | | | | |
| 0.140 | 10.944 | 9.709 | 0.224 | 0.075 | 0.936 | | | | | |
| 0.142596 | 10.916 | 9.666 | 0.223 | 0.076 | 0.951 | | | | | |
| 0.150 | 10.831 | 9.533 | 0.218 | 0.078 | 1.002 | | | | | |
| 0.160 | 10.747 | 9.4168 | 0.212 | 0.080 | 1.0382 | | | | | |
| 0.170 | 10.654 | 9.2849 | 0.206 | 0.082 | 1.0811 | | | | | |
| 0.180 | 10.558 | 9.1449 | 0.202 | 0.084 | 1.1271 | | | | | |
| 0.190 | 10.461 | 9.0228 | 0.198 | 0.087 | 1.1532 | | | | | |
| 0.200 | 10.392 | 8.9224 | 0.194 | 0.091 | 1.1846 | | | | | |
| 0.22 | 10.211 | 8.6972 | 0.188 | 0.098 | 1.2278 | | | | | |
| 0.24 | 10.006 | 8.4573 | 0.183 | 0.104 | 1.2617 | | | | | |
| 0.26 | 9.807 | 8.2281 | 0.179 | 0.111 | 1.2889 | | | | | |
| 0.28 | 9.611 | 8.0042 | 0.175 | 0.118 | 1.3138 | | | | | |
| 0.297243 | 9.498 | 7.8665 | 0.173 | 0.123 | 1.3355 | | | | | |
| 0.30 | 9.466 | 7.8239 | 0.172 | 0.128 | 1.3421 | | | | | |
| 0.35 | 9.149 | 7.4307 | 0.164 | 0.158 | 1.3963 | | | | | |
| 0.40 | 8.801 | 6.9910 | 0.161 | 0.198 | 1.4510 | | | | | |
| 0.45 | 8.331 | 6.4211 | 0.162 | 0.261 | 1.4869 | | | | | |
| 0.50 | 7.908 | 5.8400 | 0.159 | 0.403 | 1.5060 | | | | | |
| 0.55 | 7.723 | 5.4706 | 0.153 | 0.585 | 1.5144 | | | | | |
| 0.601516 | 7.578 | 5.2225 | 0.1485 | 0.704 | 1.5030 | | | | | |
| 0.65 | 7.531 | 5.0801 | 0.144 | 0.807 | 1.4999 | | | | | |
| 0.70 | 7.510 | 4.9682 | 0.139 | 0.904 | 1.4988 | | | | | |
| 0.75 | 7.398 | 4.7370 | 0.133 | 1.012 | 1.516 | | | | | |
| 0.80 | 7.309 | 4.536 | 0.128 | 1.107 | 1.538 | | | | | |
| 0.85 | 7.254 | 4.384 | 0.123 | 1.208 | 1.539 | | | | | |
| 0.866525 | 7.247 | 4.354 | 0.121 | 1.231 | 1.541 | | | | | |
| 0.906793 | 7.191 | 4.2255 | 0.117 | 1.308 | 1.5405 | | | | | |
| 0.948969 | 7.172 | 4.1003 | 0.112 | 1.406 | 1.5537 | | | | | |
| 1.00 | 7.121 | 3.9530 | 0.108 | 1.483 | 1.5770 | | | | | |
| 1.1 | 7.005 | 3.7107 | 0.099 | 1.596 | 1.5993 | | | | | |
| 1.2 | 6.942 | 3.5949 | 0.091 | 1.647 | 1.6091 | | | | | |
| 1.3 | 6.910 | 3.5260 | 0.085 | 1.679 | 1.620 | | | | | |
| 1.4 | 6.898 | 3.5000 | 0.079 | 1.679 | 1.640 | | | | | |
| 1.42596 | 6.901 | 3.5080 | 0.078 | 1.670 | 1.645 | | | | | |
| 1.5 | 6.911 | 3.5660 | 0.073 | 1.622 | 1.650 | | | | | |

TABLE IV (Cont'd)

| $E_n$ (MeV) | $\sigma_{n,T}$ | $\sigma_{n,n}$ | $\sigma_{n,\gamma}$ | $\sigma_{n,F}$ | $\sigma_{n,n'}$ | $\sigma_{n,2n}$ | $\sigma_{n,3n}$ | $\sigma_{n,f}$ | $\sigma_{n,n'f}$ | $\sigma_{n,2nf}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1.6 | 6.946 | 3.6230 | 0.068 | 1.605 | 1.650 | | | | | |
| 1.7 | 7.015 | 3.6740 | 0.063 | 1.628 | 1.650 | | | | | |
| 1.8 | 7.069 | 3.6975 | 0.0595 | 1.662 | 1.650 | | | | | |
| 1.9 | 7.134 | 3.7390 | 0.0560 | 1.689 | 1.650 | | | | | |
| 2.00833 | 7.187 | 3.7905 | 0.0525 | 1.694 | 1.650 | | | | | |
| 2.2 | 7.292 | 3.9265 | 0.0465 | 1.669 | 1.650 | | | | | |
| 2.4 | 7.374 | 4.0770 | 0.0410 | 1.606 | 1.650 | | | | | |
| 2.5 | 7.404 | 4.1478 | 0.0392 | 1.567 | 1.650 | | | | | |
| 2.6 | 7.439 | 4.1728 | 0.0372 | 1.579 | 1.650 | | | | | |
| 2.8 | 7.528 | 4.1968 | 0.0332 | 1.648 | 1.650 | | | | | |
| 3.01250 | 7.591 | 4.2393 | 0.0297 | 1.672 | 1.650 | | | | | |
| 3.5 | 7.695 | 4.3887 | 0.0233 | 1.633 | 1.650 | | | | | |
| 4.01667 | 7.696 | 4.4286 | 0.0184 | 1.599 | 1.650 | | | | | |
| 4.5 | 7.553 | 4.3172 | 0.0148 | 1.571 | 1.650 | | | | | |
| 5.02083 | 7.309 | 4.0946 | 0.0124 | 1.552 | 1.650 | | | | | |
| 5.5 | 7.093 | 3.9092 | 0.0108 | 1.543 | 1.630 | | | | | |
| 6.0 | 6.898 | 3.7276 | 0.0094 | 1.541 | 1.620 | | | | | |
| 6.5 | 6.699 | 3.5906 | 0.0084 | 1.540 | 1.560 | | | 1.540 | | |
| 6.56072 | 6.668 | 3.5797 | 0.0083 | 1.540 | 1.540 | 0.000 | | 1.540 | 0.000 | |
| 7.0 | 6.519 | 3.5334 | 0.0076 | 1.561 | 1.400 | 0.017 | | | 0.021 | |
| 7.5 | 6.388 | 3.5881 | 0.0069 | 1.635 | 1.105 | 0.053 | | | 0.095 | |
| 8.0 | 6.292 | 3.6507 | 0.0063 | 1.822 | 0.710 | 0.103 | | | 0.282 | |
| 8.5 | 6.198 | 3.6192 | 0.0058 | 1.963 | 0.455 | 0.155 | | | 0.423 | |
| 9.0 | 6.121 | 3.5976 | 0.0054 | 2.019 | 0.312 | 0.187 | | | 0.479 | |
| 9.5 | 6.072 | 3.5819 | 0.0051 | 2.040 | 0.242 | 0.203 | | | 0.500 | |
| 10.0 | 6.022 | 3.5542 | 0.0048 | 2.045 | 0.200 | 0.218 | | | 0.505 | |
| 10.5 | 6.004 | 3.5539 | 0.0045 | 2.048 | 0.1716 | 0.226 | | | 0.508 | |
| 11.0 | 6.006 | 3.5608 | 0.0042 | 2.050 | 0.1590 | 0.232 | | | 0.510 | |
| 11.5 | 6.012 | 3.5667 | 0.0039 | 2.050 | 0.1554 | 0.236 | | | | |
| 12.0 | 6.026 | 3.5738 | 0.0036 | 2.050 | 0.1606 | 0.238 | | | | |
| 12.2398 | 6.039 | 3.5833 | 0.0035 | 2.050 | 0.1642 | 0.238 | 0.000 | | | 0.000 |
| 12.5 | 6.058 | 3.5791 | 0.0033 | 2.062 | 0.1686 | 0.236 | 0.009 | 1.540 | 0.510 | 0.012 |
| 13.0 | 6.069 | 3.4994 | 0.0030 | 2.135 | 0.1766 | 0.227 | 0.028 | 1.540 | 0.510 | 0.085 |
| 13.5 | 6.100 | 3.4469 | 0.0027 | 2.202 | 0.1824 | 0.211 | 0.055 | | | 0.152 |
| 14.0 | 6.117 | 3.4286 | 0.0024 | 2.230 | 0.1850 | 0.192 | 0.079 | | | 0.180 |
| 14.5 | 6.136 | 3.4429 | 0.0021 | 2.235 | 0.1830 | 0.173 | 0.100 | | | 0.185 |
| 15.0 | 6.147 | 3.4562 | 0.0018 | 2.239 | 0.1810 | 0.152 | 0.117 | | | 0.189 |
| 15.5 | 6.158 | 3.4805 | 0.0015 | 2.241 | 0.1790 | 0.124 | 0.132 | | | 0.191 |
| 16.0 | 6.167 | 3.5088 | 0.0012 | 2.243 | 0.1780 | 0.095 | 0.141 | | | 0.193 |
| 16.5 | 6.172 | 3.5296 | 0.0009 | 2.245 | 0.1765 | 0.072 | 0.148 | | | 0.195 |
| 17.0 | 6.175 | 3.5504 | 0.0006 | 2.247 | 0.1750 | 0.052 | 0.150 | | | 0.197 |
| 17.5 | 6.177 | 3.5707 | 0.0003 | 2.249 | 0.1740 | 0.036 | 0.147 | | | 0.199 |
| 18.0 | 6.178 | 3.5950 | 0.0000 | 2.251 | 0.1730 | 0.022 | 0.137 | | | 0.201 |
| 18.5 | 6.178 | 3.6180 | - | 2.253 | 0.1720 | 0.013 | 0.122 | | | 0.203 |
| 19.0 | 6.178 | 3.6338 | - | 2.255 | 0.1712 | 0.007 | 0.111 | | | 0.205 |
| 19.5 | 6.178 | 3.6535 | - | 2.257 | 0.1705 | 0.003 | 0.094 | | | 0.207 |
| 20.0 | 6.178 | 3.6750 | - | 2.258 | 0.1700 | 0.000 | 0.075 | 1.540 | 0.510 | 0.208 |

Same as $\sigma_{n,F}$ below 6.56072 MeV

TABLE V

CROSS SECTIONS FOR INELASTIC LEVELS OF $^{240}Pu$ (IN BARNS)

| $E_n$ (MeV) | 43 | 142 | 296 | 599 | 863 | 903 | 945 | 1420 | 2000 | 3000 | 4000 | 5000 | Continuum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.043172 | 0.000 | | | | | | | | | | | | |
| 0.050 | 0.0374 | | | | | | | | | | | | |
| 0.055 | 0.082 | | | | | | | | | | | | |
| 0.060 | 0.161 | | | | | | | | | | | | |
| 0.065 | 0.241 | | | | | | | | | | | | |
| 0.070 | 0.318 | | | | | | | | | | | | |
| 0.075 | 0.382 | | | | | | | | | | | | |
| 0.080 | 0.443 | | | | | | | | | | | | |
| 0.085 | 0.504 | | | | | | | | | | | | |
| 0.090 | 0.565 | | | | | | | | | | | | |
| 0.100 | 0.664 | | | | | | | | | | | | |
| 0.110 | 0.742 | | | | | | | | | | | | |
| 0.120 | 0.814 | | | | | | | | | | | | |
| 0.130 | 0.878 | | | | | | | | | | | | |
| 0.140 | 0.936 | | | | | | | | | | | | |
| 0.142596 | 0.951 | 0.000 | | | | | | | | | | | |
| 0.150 | 0.992 | 0.0100 | | | | | | | | | | | |
| 0.160 | 1.026 | 0.0122 | | | | | | | | | | | |
| 0.170 | 1.066 | 0.0151 | | | | | | | | | | | |
| 0.180 | 1.109 | 0.0181 | | | | | | | | | | | |
| 0.190 | 1.132 | 0.0212 | | | | | | | | | | | |
| 0.200 | 1.160 | 0.0246 | | | | | | | | | | | |
| 0.22 | 1.196 | 0.0318 | | | | | | | | | | | |
| 0.24 | 1.223 | 0.0387 | | | | | | | | | | | |
| 0.26 | 1.242 | 0.0469 | | | | | | | | | | | |
| 0.28 | 1.259 | 0.0548 | | | | | | | | | | | |
| 0.297243 | 1.273 | 0.0625 | 0.000 | | | | | | | | | | |
| 0.30 | 1.274 | 0.0641 | 0.0040 | | | | | | | | | | |
| 0.35 | 1.290 | 0.088 | 0.0183 | | | | | | | | | | |
| 0.40 | 1.310 | 0.112 | 0.0290 | | | | | | | | | | |
| 0.45 | 1.310 | 0.138 | 0.0389 | | | | | | | | | | |
| 0.50 | 1.295 | 0.163 | 0.0480 | | | | | | | | | | |
| 0.55 | 1.270 | 0.189 | 0.0554 | | | | | | | | | | |
| 0.601516 | 1.224 | 0.215 | 0.0640 | 0.000 | | | | | | | | | |
| 0.65 | 1.173 | 0.238 | 0.0704 | 0.0185 | | | | | | | | | |
| 0.70 | 1.110 | 0.263 | 0.0768 | 0.0490 | | | | | | | | | |
| 0.75 | 1.045 | 0.286 | 0.083 | 0.102 | | | | | | | | | |
| 0.80 | 0.998 | 0.310 | 0.089 | 0.141 | | | | | | | | | |
| 0.85 | 0.931 | 0.333 | 0.094 | 0.181 | | | | | | | | | |
| 0.866525 | 0.914 | 0.341 | 0.096 | 0.190 | 0.000 | | | | | | | | |
| 0.906793 | 0.860 | 0.358 | 0.100 | 0.211 | 0.0115 | 0.000 | | | | | | | |
| 0.948969 | 0.817 | 0.375 | 0.104 | 0.227 | 0.0172 | 0.0135 | 0.000 | | | | | | 0.000 |
| 1.0 | 0.760 | 0.393 | 0.108 | 0.239 | 0.0245 | 0.0243 | 0.0164 | | | | | | 0.0118 |
| 1.1 | 0.634 | 0.417 | 0.115 | 0.256 | 0.0390 | 0.0580 | 0.0455 | | | | | | 0.0348 |
| 1.2 | 0.498 | 0.423 | 0.121 | 0.263 | 0.0491 | 0.0890 | 0.0810 | | | | | | 0.0850 |
| 1.3 | 0.369 | 0.410 | 0.126 | 0.266 | 0.0520 | 0.0995 | 0.1005 | | | | | | 0.1970 |
| 1.4 | 0.279 | 0.369 | 0.127 | 0.262 | 0.0519 | 0.1020 | 0.1050 | | | | | | 0.3441 |
| 1.42596 | 0.252 | 0.356 | 0.1273 | 0.261 | 0.0513 | 0.1022 | 0.1057 | 0.000 | | | | | 0.3895 |
| 1.5 | 0.202 | 0.312 | 0.127 | 0.254 | 0.0499 | 0.1018 | 0.1060 | 0.0142 | | | | | 0.4831 |
| 1.6 | 0.151 | 0.251 | 0.126 | 0.237 | 0.0461 | 0.1004 | 0.1055 | 0.0284 | | | | | 0.6046 |
| 1.7 | 0.115 | 0.194 | 0.123 | 0.215 | 0.0412 | 0.0962 | 0.1024 | 0.0448 | | | | | 0.7184 |
| 1.8 | 0.088 | 0.144 | 0.116 | 0.196 | 0.0363 | 0.0880 | 0.0965 | 0.0568 | | | | | 0.8284 |
| 1.9 | 0.070 | 0.107 | 0.110 | 0.174 | 0.0315 | 0.0780 | 0.0883 | 0.0650 | | | | | 0.9262 |
| 2.00833 | 0.054 | 0.079 | 0.098 | 0.153 | 0.0277 | 0.0670 | 0.0797 | 0.0703 | 0.000 | | | | 1.0213 |
| 2.2 | 0.0356 | 0.0457 | 0.0777 | 0.120 | 0.0211 | 0.0492 | 0.0607 | 0.0775 | 0.0004 | | | | 1.1621 |
| 2.4 | 0.0257 | 0.0296 | 0.0623 | 0.0904 | 0.0170 | 0.0373 | 0.0457 | 0.0784 | 0.0008 | | | | 1.2628 |
| 2.5 | 0.0215 | 0.0244 | 0.0547 | 0.0800 | 0.0151 | 0.0322 | 0.0393 | 0.0780 | 0.0010 | | | | 1.3038 |
| 2.6 | 0.0178 | 0.0202 | 0.0484 | 0.0696 | 0.0136 | 0.0276 | 0.0346 | 0.0763 | 0.0011 | | | | 1.3408 |
| 2.8 | 0.0125 | 0.0133 | 0.0376 | 0.0519 | 0.0111 | 0.0210 | 0.0262 | 0.0718 | 0.0012 | | | | 1.4034 |
| 3.01250 | 0.0090 | 0.0090 | 0.0272 | 0.0380 | 0.0092 | 0.0165 | 0.0200 | 0.0643 | 0.0013 | 0.000 | | | 1.4555 |

TABLE V (Cont'd)

| $E_n$ (MeV) | 43 | 142 | 296 | 599 | 863 | 903 | 945 | 1420 | 2000 | 3000 | 4000 | 5000 | Continuum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3.5 | 0.000 | 0.000 | 0.0129 | 0.0180 | 0.0060 | 0.0098 | 0.0160 | 0.0403 | 0.0017 | 0.0010 | | | 1.5497 |
| 4.01667 | | | 0.0070 | 0.0090 | 0.000 | 0.0070 | 0.0070 | 0.0227 | 0.0023 | 0.0015 | 0.000 | | 1.5935 |
| 4.5 | | | 0.000 | 0.000 | | 0.000 | 0.000 | 0.0126 | 0.0030 | 0.0020 | 0.0010 | | 1.6314 |
| 5.02083 | | | | | | | | 0.0080 | 0.0040 | 0.0030 | 0.0015 | 0.000 | 1.6335 |
| 5.5 | | | | | | | | 0.000 | 0.0054 | 0.0054 | 0.0030 | 0.0010 | 1.6152 |
| 6.0 | | | | | | | | | 0.0075 | 0.0075 | 0.0060 | 0.0040 | 1.5950 |
| 6.5 | | | | | | | | | 0.0090 | 0.0090 | 0.0090 | 0.0080 | 1.5250 |
| 6.56072 | | | | | | | | | 0.0092 | 0.0092 | 0.0092 | 0.0083 | 1.5041 |
| 7.0 | | | | | | | | | 0.0110* | 0.0110* | 0.0110* | 0.0110* | 1.3560* |

*Above this energy, the cross sections for these levels are identical.

| $E_n$ (MeV) | Direct Interaction | Continuum |
|---|---|---|
| 7.5 | 0.0456 | 1.0594 |
| 8.0 | 0.0520 | 0.6580 |
| 8.5 | 0.0584 | 0.3966 |
| 9.0 | 0.0648 | 0.2472 |
| 9.5 | 0.0720 | 0.1700 |
| 10.0 | 0.0800 | 0.1200 |
| 10.5 | 0.0896 | 0.0820 |
| 11.0 | 0.1000 | 0.0590 |
| 11.5 | 0.1104 | 0.045 |
| 12.0 | 0.1216 | 0.039 |
| 12.2398 | 0.1272 | 0.037 |
| 12.5 | 0.1336 | 0.035 |
| 13.0 | 0.1456 | 0.031 |
| 13.5 | 0.1544 | 0.0280 |
| 14.0 | 0.1600 | 0.0250 |
| 14.5 | 0.1600 | 0.0230 |
| 15.0 | 0.1600 | 0.0210 |
| 15.5 | 0.1600 | 0.0190 |
| 16.0 | 0.1600 | 0.0180 |
| 16.5 | 0.1600 | 0.0165 |
| 17.0 | 0.1600 | 0.0150 |
| 17.5 | 0.1600 | 0.0140 |
| 18.0 | 0.1600 | 0.0130 |
| 18.5 | 0.1600 | 0.0120 |
| 19.0 | 0.1600 | 0.0112 |
| 19.5 | 0.1600 | 0.0105 |
| 20.0 | 0.1600 | 0.0100 |

## IV. INTEGRAL TESTING

The evaluated microscopic cross sections for $^{239}Pu$ and $^{240}Pu$ were processed from ENDF/B tapes by ETOG (Ref. 65) into 30-group cross-section sets. ETOG is adequate for these calculations, since the spectra lie predominantly below the prefission threshold. The energy boundaries for this 30-group structure are given in Table VI. These group averaged cross sections were then used to calculate the eigenvalues of several bare and reflected plutonium assemblies which were measured to be delayed critical. Descriptive information on these assemblies is provided in Table VII. For the calculations mentioned above, cross sections for nuclides other than $^{239}Pu$ and $^{240}Pu$ were taken from the LASL-TD-Division Library. This library has been discussed in References 66-69.

The eigenvalue calculations were performed with the DTF (Ref. 70) code in spherical geometry; an $S_{16}$ angular quadrature was used. All cross sections were 30-group, $P_1$ transport-corrected (two-table). A summary of the calculated eigenvalues is given in Table VIII. The results for all assemblies (with

TABLE VI

ENERGY BOUNDARIES AND LETHARGY WIDTHS FOR THE 30-GROUP STRUCTURE ($E_{max}$ = 17 MeV)

| Group | $E_g$ (Lower Boundary) | | $\Delta U_g$ |
|---|---|---|---|
| 1 | 15.0 | MeV | 0.13 |
| 2 | 13.5 | | 0.11 |
| 3 | 12.0 | | 0.12 |
| 4 | 10.0 | | 0.18 |
| 5 | 7.79 | | 0.25 |
| 6 | 6.07 | | 0.25 |
| 7 | 3.68 | | 0.50 |
| 8 | 2.865 | | 0.25 |
| 9 | 2.232 | | 0.25 |
| 10 | 1.738 | | 0.25 |
| 11 | 1.353 | | 0.25 |
| 12 | 0.823 | | 0.50 |
| 13 | 0.50 | | 0.50 |
| 14 | 0.303 | | 0.50 |
| 15 | 0.184 | | 0.50 |
| 16 | 0.0676 | | 1.00 |
| 17 | 0.0248 | | 1.00 |
| 18 | 0.00912 | | 1.00 |
| 19 | 0.00335 | | 1.00 |
| 20 | 0.001235 | | 1.00 |
| 21 | 454.0 | eV | 1.00 |
| 22 | 167.0 | | 1.00 |
| 23 | 61.4 | | 1.00 |
| 24 | 22.6 | | 1.00 |
| 25 | 8.32 | | 1.00 |
| 26 | 3.06 | | 1.00 |
| 27 | 1.13 | | 1.00 |
| 28 | 0.414 | | 1.00 |
| 29 | 0.152 | | 1.00 |
| 30 | 0.000139 | | 7.00 |

TABLE VII

CRITICAL ASSEMBLIES USED FOR INTEGRAL TESTING OF Pu CROSS-SECTION DATA

| Assembly | Ref. | Core Mass (kg) | Reflector Material | Reflector Thickness (cm) |
|---|---|---|---|---|
| Jezebel | 73 | 16.57 | - | - |
| Dirty Jezebel | 73 | 18.82 | - | - |
| U - Ref. - Pu#1 | 74 | 8.48 | $NAT_U$ | 4.128 |
| U - Ref. - Pu#2 | 74 | 6.28 | $NAT_U$ | 11.684 |
| U - Ref. - Pu#3 | 74 | 6.06 | $NAT_U$ | 19.609 |
| Be - Ref. - Pu | 74 | 8.48 | Be* | 3.688 |
| W - Ref. - Pu | 74 | 8.48 | W** | 4.699 |
| VERA - 11 - A | 75 | 63.67 | $NAT_U$*** | 43.0 |
| ZEBRA - Core 3 | 75 | 835.7 | $NAT_U$*** | 30.5 |

* 2% oxygen
** 5.5% Ni, 2.5% Cu, 0.7% Zr
*** See Ref. 75 for impurities

TABLE VIII

CALCULATED EIGENVALUES FOR THE Pu CRITICAL ASSEMBLIES

| Assembly | Eigenvalue ($k_{eff}$) |
|---|---|
| Jezebel | 0.9995 |
| Dirty Jezebel | 1.0024 |
| U - Ref. - Pu#1 | 0.9945 |
| U - Ref. - Pu#2 | 1.0010 |
| U - Ref. - Pu#3 | 0.9969 |
| Be - Ref. - Pu | 1.0009 |
| W - Ref. - Pu | 1.0022 |
| VERA - 11A | 1.0005 |
| ZEBRA CORE-3 | 1.0083 |

the exception of ZEBRA CORE-3) are seen to fall within ± 0.5% of critical ($k_{eff}$ = 1). The eigenvalues for VERA-11A and ZEBRA CORE-3 were corrected for resonance self-shielding effects; these correction factors were described in a previous paper.[67]

The central-core-replacement reactivity of plutonium in the Jezebel assembly has been measured by Engle et al.,[71] using cylindrical samples 0.5 in. in diameter and 0.5 in. long. The sample was represented by a sphere of equal volume for calculational purposes. The plutonium central-core-replacement worth in the center of Jezebel was calculated to be 1451 ¢/g-mole, using a calculated value of the dollar of Δk = k(prompt critical) - k(delayed critical) = 0.00197. Here k(prompt critical) and k(delayed critical) refer to the calculated reactivities of Jezebel in its prompt-critical and delayed-critical configurations. See Ref. 72 for a more detailed discussion of central-core-replacement calculations. This worth compares quite well with the measured value of 1439 ¢/g-mole, i.e., an error of less than 1%.

## V. DISCUSSION

In any evaluation program, cut-off dates for consideration of experimental data must be assigned, otherwise it is impossible to incorporate each set of additional results without starting the program anew. For the present work, some important experimental results were received too late for proper assessment. A few unincorporated examples on $^{239}Pu$ are: The total cross section of Schwartz et al.,[6] the n,2n and n,3n cross sections of Mather et al., and the correction to $\bar{\nu}$ by Frehaut et al. Also, there are many measurements on $^{235}U$ fission which now require a reevaluation of the primary standard cross section. Fortunately, the new measurements on $\bar{\nu}$ for $^{240}Pu$ are in reasonable agreement with the curve chosen here, thereby verifying that the high-energy measurement of Kuzminov[61] should be ignored.

Another experiment that casts some doubt on the present evaluation is described by Auchampaugh and Ragan (LASL, private communication). Their very preliminary results on the fission neutron spectra as a function of energy indicate no change in the nuclear temperature as the incident-neutron energy is increased. In addition, the temperatures found for $^{235}U$, $^{238}U$, and $^{239}Pu$ are not those commonly used in evaluations today. These experiments are being continued and should be studied extensively before revisions are made to the work described here.

Other problems were encountered in this evaluation. Because both the shape and magnitude of many of the partial cross sections are "guessed" over a wide energy range, the structure produced in some of the partial cross sections is often inadvertent and has no physical meaning. While attempts were made to keep such structure to a minimum, it was not removed entirely and is especially apparent in the elastic scattering for $^{240}Pu$, where the elastic was obtained by subtracting the rest of the partials from the total cross section.

Also, the energy-dependent charged-particle cross sections employed in this evaluation were lifted directly from the ENDF/B-III evaluated files. These have not been verified experimentally at any energy either in shape or magnitude. Since the sum of these cross sections approaches 200 mb at 20 MeV, they make a significant contribution to $\sigma_{tot}$ and therefore should be checked.

Insofar as the high-energy direct-interaction cross sections are concerned, a recent calculation indicates that a better "guess" would be to spread these interaction cross sections over a wider excitation energy. In the next pass, therefore, the level energies may be chosen at 1-MeV intervals rather than at the 500-keV intervals presently used.

It is obviously extremely difficult to make a realistic assessment of the probable errors to be assigned to the differential data. With very few exceptions, the differential data are not well established by experimental measurements. The section on integral calculations does include some verification that the low-energy differential data evaluation may not be as far off as the individual measurements might indicate. The estimated errors in Tables IX and X, however, are based on the microscopic data.

Integral tests, such as calculation of the reactivity of Jezebel, restrict the combined errors from Tables IX and X. For example, one cannot raise the fission cross section at all energies by the uncertainties indicated and still retain the capability of calculating the Jezebel reactivity. This restriction applies more strictly to $\sigma_{n,F}$ and $\bar{\nu}$ than to the other parameters listed. The uncertainties listed in these tables were obtained by considering

TABLE IX

ESTIMATED UNCERTAINTIES IN EVALUATED CROSS SECTIONS OF $^{239}Pu$ (IN PERCENT)

| Nuclear Parameter | ENDF/B Designation | Neutron Energy (MeV) 0.03 | 0.1 | 0.5 | 1 | 2 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|---|---|---|
| $\sigma_{TOT}$ | MF = 3, MT = 1 | ± 5 | ± 5 | ± 4 | ± 5 | ± 4 | ± 2 | ± 3 | ± 4 |
| $\sigma_{ELAS}$ | MF = 3, MT = 2 | 20 | 20 | 10 | 10 | 10 | 15 | 15 | 15 |
| $\sigma_{n,F}$ | MF = 3, MT = 18 | 7 | 4 | 4 | 7 | 5 | 5 | 7 | 10 |
| $\sigma_{n,\gamma}$ | MF = 3, MT = 102 | 15 | 10 | 10 | 10 | - | - | - | - |
| $\sigma_{n,n'}$ | MF = 3, MT = 4 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| $\sigma_{n,2n}$ | MF = 3, MT = 16 | - | - | - | - | - | 20 | 30 | 30 |
| $\sigma_{n,3n}$ | MF = 3, MT = 17 | - | - | - | - | - | - | × 2 | × 2 |
| $\bar{\nu}$ | MF = 1, MT = 452 | 1.5 | 1.5 | 1.5 | 2.0 | 2.0 | 2.0 | 3.0 | 3.0 |

TABLE X

ESTIMATED UNCERTAINTIES IN EVALUATED CROSS SECTIONS OF $^{240}Pu$ (IN PERCENT)

| Nuclear Parameter | ENDF/B Designation | Neutron Energy (MeV) 0.05 | 0.1 | 0.5 | 1 | 2 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|---|---|---|
| $\sigma_{TOT}$ | MF = 3, MT = 1 | ± 20 | ± 4 | ± 4 | ± 4 | ± 5 | ± 20 | ± 20 | ± 20 |
| $\sigma_{ELAS}$ | MF = 3, MT = 2 | 20 | 20 | 10 | 15 | 15 | 15 | 15 | 15 |
| $\sigma_{n,F}$ | MF = 3, MT = 18 | 15 | 20 | 20 | 10 | 4 | 15 | 5 | 15 |
| $\sigma_{n,\gamma}$ | MF = 3, MT = 102 | × 2 | × 2 | × 2 | × 2 | × 2 | - | - | - |
| $\sigma_{n,n'}$ | MF = 3, MT = 4 | 30 | 30 | 15 | 15 | 20 | 30 | 30 | 30 |
| $\sigma_{n,2n}$ | MF = 3, MT = 16 | - | - | - | - | - | × 2 | × 2 | × 2 |
| $\sigma_{n,3n}$ | MF = 3, MT = 17 | - | - | - | - | - | - | × 2 | × 2 |
| $\bar{\nu}$ | MF = 1, MT = 452 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 7.0 | 10.0 | 15.0 |

each parameter individually. These integral tests, therefore, give some indication that the cross sections below 3-4 MeV may be less uncertain than indicated above. It is recognized, however, that integral checks cannot uniquely reduce the microscopic uncertainties.

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