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PROMPT-NEUTRON SPECTRA AND
DELAYED-NEUTRON SPECTRA FROM FISSION:
SOME COMMENTS ON CURRENT KNOWLEDGE

by

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ABSTRACT

In partial response to a request for critical examination of current knowledge concerning nuclear constants important in fast-reactor physics, work on energy spectra of prompt and delayed fission neutrons was surveyed. The survey covered prompt-neutron spectra for ^{235}U , ^{233}U , ^{239}Pu , ^{241}Pu , ^{238}U , and ^{232}Th irradiated by thermal and high-energy neutrons, and for spontaneous fission of ^{252}Cf , ^{240}Pu , ^{242}Pu , and ^{244}Cm . Although delayed neutron investigations have concentrated on ^{235}U , these spectra are poorly known, with insufficient information for extrapolating to other nuclides. Further, reactor-dynamics calculations indicate that the spectral uncertainties can be important for reactor physics. Many measurements have been made of prompt-neutron spectra, but there is extensive disagreement (outside of statistical error) among these, most likely due to systematic errors in energy calibration of the neutron detectors. Though large shifts in the spectra used in calculations can have important effects in reactor physics, the actual spectra probably do not differ markedly from some average of existing results. Definitive measurements on either prompt- or delayed-neutron spectra would require large undertakings. Data on variation of spectra with neutron-bombarding energy (E_n) is relatively poor. A more reliable value of $d\bar{E}/dE_n$ ($\bar{E}$ = mean energy of fission neutrons) is derivable by evaluating $(d\bar{E}/d\bar{\nu}_p)(d\bar{\nu}_p/dE_n)$, where $\bar{\nu}_p$ = number of prompt neutrons per fission. Terrell's semitheoretical relation, now experimentally substantiated, yields $d\bar{E}/d\bar{\nu}_p$, and measured values of $d\bar{\nu}_p/dE_n$ are available.

I. INTRODUCTION

This report has been prepared as a partial response to a request for a critical examination of current knowledge about some nuclear constants of interest to fast-reactor physicists. (See also companion reports Refs. 1 and 2.) In this report, we summarize current information on the two kinds of fission-neutron spectra:

1. Energy spectra of the neutrons from delayed-neutron emitters.
2. Energy spectra of prompt neutrons emitted in the fission of various nuclides, fissioned by both thermal and higher-energy neutrons.

The data have been gathered from published work and, insofar as feasible, from unpublished private communications. In summary, the information on delayed-neutron spectra is poor, and important improvement in reactor calculations would probably be feasible with better data. Information on the prompt-neutron spectra is somewhat better, but discordance of results from different laboratories indicates that definitive measurements have yet to be made. Clearing up these uncertainties would improve the accuracy of reaction calculations.

II. DELAYED-NEUTRON SPECTRA

The available experimental data are exceedingly sparse, of poor quality, and mostly quite old. Further, most of the measurements have been limited to ^{235}U delayed neutrons. The parameters entering theoretical analysis are known poorly, and at present, theory cannot be used to give useful results.

The older experiments include Refs. 3-6 and are limited to measurements on ^{235}U . In each of these experiments, a sample was irradiated in a reactor for a predetermined time T_R and then transferred (via rabbit) to the measuring system and allowed to decay for the time T_D before recording started. These measurements are:

Ref. 3. For T_R values from 0.5 to 50 sec and T_D values from 0.8 to 3.3 sec, proton recoils were measured in a hydrogen-filled cloud chamber. Spectra were observed. Energy resolution was of the order of 100 keV, partially caused by poor statistics.

Ref. 4. For T_R values from 1 sec to 5 min and T_D values up to 5 min, the authors examined the attenuation of neutron intensity with distance in paraffin and compared the attenuation slopes to those derived from standard monoenergetic (γ, n) sources. Only mean neutron energies were derived, with a resolution of the order of 100 keV.

Ref. 5. For $T_R = T_D = 1$ sec, proton recoils were measured in a CH_4 cloud chamber. Spectra were observed.

Ref. 6. For T_R values from 1.4 to 100 sec and T_D values from 2 to 200 sec, pulse heights were measured in a ^3He -filled proportional counter. Spectra were observed, with a resolution of about 90 keV.

Where T_R was varied, the data enabled experimenters to extract the spectra of the various half-life groups. Results from Ref. 6 have the highest quality, but have not been checked with subsequent measurements by other experimenters.

The measurements in these references suffer from several defects:

1. Resolution was poor, so it is not clear whether the spectra are really continuous (as observed) or have a line structure.
2. The magnitude of systematic effects from uncorrected background is uncertain. It is particularly uncertain whether much of the low- and high-energy portions of the observed spectra derive from scattered prompt neutrons. The ^3He spectrometer in Ref. 6 is especially susceptible to scattered low-energy neutrons. Part of the apparent high-energy spectra may be due to prompt neutrons arising from fission in the sample itself, fission caused by the delayed neutrons.
3. The accuracy of separating the spectra of the various groups is uncertain.

Later experiments⁷⁻¹⁰ have not cleared up the uncertainties. These experiments introduced the technique of neutron time of flight, triggering each flight-time measurement with beta-decay detection from the precursor. The method involves coincidence measurement and suffers from poor signal-to-noise ratio caused by the intense accidental coincidence rate. The results differ markedly from those in Refs. 3-6. That the observed line structure differs from the previously observed continuous spectra could possibly be explained on the basis of improved resolution. In Ref. 10, for example, resolution varied from 6% at 100 keV to 20% at 500 keV. However, the observed distribution is also much different; e.g., the concentrations of neutrons at high energies (800 keV and above) do not agree at all.

Theoretical analyses cannot now provide definitive information. At best, they are capable of being adjusted so as to check with some of the experimental data. (See, e.g., Ref. 11.)

Analyses such as those in Refs. 12 and 13 show that accurate calculation of the transient behavior of fast reactors requires better information about delayed-neutron spectra than is now available. It is further clear

from the history of this field that such information will not be forthcoming unless a determined effort is made, one involving considerable resources and manpower. What is needed is a well-supported experiment of good promise, pushed to its limit. An interesting concept is the Bandsaw idea in Ref. 14. However, since correct and unambiguous delayed-neutron spectra will be difficult to determine with any method, it would be desirable to make the measurements using several different basic approaches. This is the only way to ensure that the serious systematic errors mentioned will be picked up.

For the purposes of reactor application, the goals of such experiments should be to get accurate information on the following:

- I. What fraction of the delayed neutrons have energies above the thresholds of fertile materials like ^{238}U , ^{232}Th , and ^{240}Pu ?
- II. What kind of structure exists in the spectra, and what are the true intensities at both the high and low ends of each spectrum?
- III. What are the spectra of specific precursors? Up to now, only mixtures are known, coming from precursors of similar half-life values.

The immediate goal should be to attain aims I and II and to develop III as restricted to the six "traditional" groups, such as those listed in Table I. However, each of these groups is an unseparated mixture of a number of precursors. Hence, because of the shift in relative precursor concentrations with fissioning nuclide and bombarding energy, the ability to predict the delayed-neutron spectra for a wide variety of fissioning nuclides and bombarding energies will not be attainable until the spectra from individual precursors are measured. Because of the difficulty in separating exponentially decaying components, accurate characterization of individual components is not feasible until the precursors have been separated, or at least concentrated. Such measurements probably require on-line mass separation and will involve a major program.

TABLE I. Mean Energies of the Delayed-neutron Groups for ^{235}U Fission¹⁵

Group Index, i	Half-life, sec	Mean Energy, keV		
		Hughes <u>et al.</u> ⁴	Burgy <u>et al.</u> ³	Batchelor and Hyder ⁶
1	55.7	250 ± 60	300 ± 60	250 ± 20
2	22.7	560 ± 60	670 ± 60	460 ± 10
3	6.2	430 ± 60	650 ± 100	405 ± 20
4	2.3	620 ± 60	910 ± 90	450 ± 20
5	0.61	420 ± 60	400 ± 70	
6	0.23			

Despite the defects of the data now in existence, these data are all that are available and are presented below. The bulk of the information is derived from ^{235}U thermal fission alone.

Group 1 (the 55-sec component) is the only group that has been unambiguously assigned to a single precursor, ^{87}Br . Each of the other five "traditional" groups are actually composites derived from several precursors. Since the relative concentrations of various precursors change with both the fissioning nucleus and with the energy of the neutron causing fission, the data are of less value for other than thermal ^{235}U fission.

The results from Refs. 3-6 are given here in the form of Ref. 6 spectra in Fig. 1 as well as a summary in Table I, originally prepared by Keepin,¹⁶ and reproduced with more recent half-life values in Ref. 15. Figure 2 reproduces a spectrum from Ref. 8, and Figs. 3 and 4 from Ref. 10. The spectrum in Fig. 2 is presumably a mixture of spectra from the "traditional" groups 2 and 3 (see Table I). Figure 3 represents delayed neutrons from ^{252}Cf , which does not have the same groups as ^{235}U . This spectrum should correspond most closely to a mixture of the "traditional" groups 4 and 5. Figure 4 shows a comparison to that spectrum of Ref. 6 which presumably most closely corresponds to the results here. Table II lists the observed neutron lines.

Fig. 1. Delayed-neutron Spectra of Various Groups.⁶
ANL Neg. No. 121-7227.

Fig. 2. Delayed-neutron Energy Spectrum.⁸
ANL Neg. No. 121-7224 Rev. 1.

Fig. 3

Time-of-flight Spectra of Delayed Neutrons from ^{252}Cf after Background Subtraction and Nine-channel Smoothing of the Raw Data.¹⁰ Expected electronics resolution shown as error bars below spectra. ANL Neg. No. 121-7226 Rev. 1.

Fig. 4. Neutron Spectra for 2-sec Group from Batchelor and Hyder⁶ and from Ref. 10 (bottom curve).
ANL Neg. No. 121-7228.

TABLE II. Energies of Possible Neutron Peaks¹⁰

Energy, MeV	Energy, MeV
0.095 ± 0.007	0.225 ± 0.026
0.104 ± 0.008	0.240 ± 0.018
0.135 ± 0.010	0.265 ± 0.034
0.158 ± 0.016	0.340 ± 0.051
0.188 ± 0.020	0.430 ± 0.064
0.205 ± 0.023	

III. PROMPT-NEUTRON SPECTRA

A. General

Despite the many measurements made of prompt spectra, results of different experimenters disagree by amounts exceeding the author-assigned errors. This is a clear indication of systematic errors still to be isolated. The general features of the spectra are known, but accurate relative intensities are not well characterized, particularly at high energies (>7 MeV), where intensities are low, and at low energies (≤ 0.5 MeV), where scattering causes large background effects.

Theory is of little value, except for rationalizing observed spectra. At best, theory can suggest the functional form to be used to describe experimental spectra. Even here, several possibilities occur, depending upon the arbitrary assumptions and approximations made.

B. Functional Form Used to Describe Prompt Spectra

On the basis of theory,¹⁷ two forms have been suggested and used to describe prompt spectra. One is the Watt distribution,¹⁸ the other is a Maxwell distribution.

The Watt distribution has the form

$$N_w(E) dE = K_1 e^{-bE} \sinh \sqrt{CE} dE, \quad (1)$$

which is normalized to unity if

$$K_1 = 2e^{-\frac{1}{4}a} \frac{b}{\sqrt{a\pi}}, \quad (2)$$

where $a = C/b$. The mean and variance are

$$\bar{E}_w = \frac{1}{b} \left(\frac{3}{2} + \frac{1}{4}a \right) \quad (3a)$$

and

$$\sigma_w^2(E) = \frac{1}{2b^2} (3 + a). \quad (3b)$$

A measure of the ratio of the width of the distribution curve to its mean value is*

*This ratio provides a crude description of the shape of the distribution.

$$R_W = \frac{\sigma_W(E)}{\bar{E}_W} = \sqrt{\frac{2}{3}} \theta, \quad \theta = \frac{\sqrt{1 + \frac{1}{3}a}}{1 + \frac{1}{6}a}. \quad (4)$$

$\bar{E}_W$ may thus be estimated if $N(E)$ data is least-squares fitted to Eq. 1.*

The Maxwell distribution is

$$N_M(E) dE = K_2 \sqrt{E} e^{-E/T}, \quad (5)$$

which is normalized if

$$K_2 = \frac{1}{T^{3/2} \Gamma(\frac{3}{2})}, \quad (6)$$

with $\Gamma(\frac{3}{2}) = \frac{1}{2}\sqrt{\pi}$. The mean and variance are

$$\bar{E}_M = \frac{3}{2} T \quad (7a)$$

and

$$\sigma_M^2(E) = \frac{3}{2} T^2. \quad (7b)$$

The peak or mode is at

$$E = \frac{1}{2} T = \frac{1}{3} \bar{E}_M, \quad (7c)$$

and the ratio of width to mean value is

$$R_M = \frac{\sigma_M(E)}{\bar{E}_M} = \sqrt{\frac{2}{3}}. \quad (8)$$

$\bar{E}_M$ may thus be estimated if $N(E)$ data are fitted to Eq. 5.

Since $\theta < 1$, we have $R_W < R_M$ for any (C,b) combination; hence, for a given $\bar{E}$, the Watt distribution is narrower than the Maxwellian. For example,

*It should be noted (as it has not by some authors) that when a and C are estimated by least-squares curve fitting, giving estimates $\hat{a}$ and $\hat{C}$, these estimates are highly correlated. The usual nonlinear least-squares programs yield a variance-covariance matrix which not only contains the squared errors, $\sigma^2(\hat{a})$ and $\sigma^2(\hat{C})$, but also the correlation term $\text{cov}(\hat{a}, \hat{C})$. In the calculation of the corresponding error in $\bar{E}$, the covariance term should be included as

$$\sigma^2(\bar{E}) = \left(\frac{\partial \bar{E}}{\partial a} \right)^2 \sigma^2(\hat{a}) + \left(\frac{\partial \bar{E}}{\partial C} \right)^2 \sigma^2(\hat{C}) + 2 \frac{\partial \bar{E}}{\partial a} \frac{\partial \bar{E}}{\partial C} \text{cov}(\hat{a}, \hat{C}).$$

$$a = 2, \quad \theta = 0.9688;$$

$$a = 2.3, \quad \theta = 0.9608.$$

These are two a-values that have been used by experimenters.

Several experimenters have noted that with appropriate choices of parameters, both $N_W(E)$ and $N_M(E)$ fit observed distributions within experimental error. Since there is no overriding theoretical reason for using one or the other form, the Maxwellian is now most commonly used to provide a convenient analytical form for describing experimental measurements. Since it is a one-parameter distribution, it is easier to use. We note at the end of this section that the use of such a one-parameter curve can lead to a lack of flexibility in making very close fits to experimental data.

Since some experimental measurements have been reported in the $N_W(E)$ form, it is of interest to determine the best way of translating the $N_W(E)$ description to an $N_M(E)$ one. How this is done depends upon what quality of the $N_W(E)$ curve is to be equated to the corresponding quality of the $N_M(E)$ curve, e.g., the position of the peak, the value of $\bar{E}$, or the average slope of a plot of $\ln \{N_W(E)/\sqrt{E}\}$ versus E over the range E_1 to E_2 . Several of these approaches have been used by various authors.

For the Maxwellian, the fact that the relation

$$\ln \frac{N_M}{\sqrt{E}} = \ln K_2 - \frac{1}{T} E \quad (9)$$

is a straight line suggests that a corresponding fitting to $N_W(E)$ would yield a T value of the best-fitting Maxwellian. By least-squares fitting a particular Watts curve (chosen C, b) to Eq. 9 over the range ΔE (0.2-7.0 MeV), where the bulk of the neutrons lie and where the two forms superimpose best, we find that the resulting slope corresponds to the value that equates the $\bar{E}$ values. Thus, if data are described by a Watts curve with (C, b) parameter values, the Maxwellian that best fits (in the region ΔE) is derived by setting

$$\bar{E}_M = \bar{E}_W,$$

or

$$T = \frac{1}{b} \left(1 + \frac{1}{6} a\right). \quad (10)$$

With this relation, Table III shows the ratios N_W/N_M for a particular case used by Watt: $C = 2.00$, $b = 1.00$ (hence, $T = \frac{4}{3}$, $\bar{E} = 2.00$ MeV). The systematic deviations are evident, indicating that, for the same $\bar{E}$ value,

N_W is more peaked and narrower than N_M . [From the discussion above, $\sigma_W/\bar{E}_W = 0.969(\sigma_M/\bar{E}_M)$.] With few exceptions, published experimental data have been presented only in the log-plot corresponding to Eq. 9, and this is too condensed to show such differences as appear in Table III.

TABLE III. Comparison of Intensities of Watt and Maxwellian Spectra

E, MeV	N_M	N_W/N_M	E, MeV	N_M	N_W/N_M
0.1	0.215	0.941	3.6	0.0935	1.030
0.2	0.282	0.949	4.0	0.0730	1.024
0.3	0.321	0.956	4.5	0.0532	1.012
0.4	0.343	0.962	5.0	0.0385	0.998
0.5	0.356	0.968	5.5	0.0278	0.980
0.6	0.362	0.974	6.0	0.0199	0.960
0.7	0.363	0.980	6.5	0.0143	0.938
0.8	0.360	0.985	7.0	0.0102	0.914
0.9	0.354	0.990	7.5	0.00723	0.889
1.0	0.346	0.995	8.0	0.00513	0.862
1.2	0.326	1.004	8.5	0.00364	0.835
1.4	0.303	1.011	9.0	0.00257	0.807
1.6	0.279	1.017	10.0	0.00128	0.750
1.8	0.255	1.025	11.0	0.00063	0.693
2.0	0.231	1.027	12.0	0.00031	0.637
2.4	0.188	1.033	13.0	0.00015	0.582
2.8	0.150	1.035	14.0	0.00007	0.529
3.2	0.119	1.034			

Where experimental data have been accurate enough to warrant examining the adequacy of the Maxwellian form, differences between the $N_M(E)$ form and the experimental distribution have sometimes appeared, particularly at high and low neutron energies. If desired, it should be feasible to fit such data with a combination of Maxwellians

$$N_M(E) = \alpha_1 K_1 \sqrt{E} e^{-E/T_1} + \alpha_2 K_2 \sqrt{E} e^{-E/T_2}, \quad (11)$$

with $\alpha_1 + \alpha_2 = 1$. At this point in time, however, the usefulness of such sophistication is doubtful, in the light of the serious question concerning the existence of systematic experimental errors in the observed neutron spectra.

C. Experimental Methods

The methods used for spectrum examination may be divided into differential and integral types. In a differential measurement, such as in the proton-recoil or time-of-flight method, the relative number of neutrons having a given energy are detected. Corrections needed for the detector's

energy resolution are relatively modest; i.e., the effects of neutrons of different energies are only moderately superimposed.

In integral measurements, on the other hand, the effects of neutrons of various energies are heavily combined, and an extensive unfolding process is required to extract the spectral shape. The resolution is much inferior to that of the differential method for arbitrary spectral shapes, but the integral method can yield useful results where the distribution is of a defined shape and very broad, as with the Maxwellian. These methods can be used to determine whether $N(E)$ differs grossly from the assumed Maxwellian, but are most useful for determining $\bar{E}$, assuming $N_M(E)$ is the correct form.

The various differential measurements differ in the method used for determining neutron energy, and/or in the method used for determining the detector efficiency at that energy. In one approach, energies have been measured by range determination of those collided protons recoiling into the forward angle. Although cloud chambers have been used, their stopping power is poor, except for the lowest energies (<1 MeV), and nuclear emulsions have been the most useful. Detector efficiency is calculated from the published (n,p) scattering cross section and certain corrections, such as the estimated loss of long tracks through the emulsion surface. Aside from the inherent systematic uncertainties in such a measurement, the method also suffers from the fact that only a limited number of tracks can be examined (10,000 is a very large number), thus limiting the statistical accuracy available at each energy.

In the other commonly used method, neutron energy is measured by time of flight. Zero time for the flight is determined either (1) by use of a pulsed accelerator, (2) by detection of fission fragment in an ion chamber, gas-scintillator chamber, or silicon detector, or (3) by detection of electrons released by fission fragment in a very thin foil near the source.

A neutron detector at the end of the flight path provides the stop pulse. Most commonly used are hydrogen-containing scintillators, with measurement of proton recoils serving for detection. Although the (n,p) scattering cross section can be used to calculate the scintillator efficiency, important corrections are necessary because of the finite boundaries of the detector and because of multiple scattering.* The

*For example, in Ref. 19, the efficiency versus energy for a 1-cm-thick Pilot B plastic scintillator was calculated by measuring neutron energy through time of flight and comparing the number of detected counts with the scattering predicted from the published (n,p) and (n,C) scattering cross sections. Using a ^{252}Cf source, correcting for solid angle, and then integrating over the velocity range covered by the experiment, the authors of Ref. 19 calculated that they should have measured 89.7% of the neutrons per fission. Then (assuming $\bar{\nu}(^{252}\text{Cf}) = 3.82$), this should have given 3.43 observed neutrons per fission. Instead they measured 3.77, which was 10% too high. They arbitrarily assumed the shape of the measured efficiency-versus-energy relation to hold, but decreased each absolute value by 10%. (Actually, because it is now believed that $\bar{\nu} = 3.74$ is closer to the correct value for ^{252}Cf , the discrepancy is about 12.5%.)

scintillator detector is sometimes calibrated against a long counter whose efficiency varies little with energy, and this variation can be calibrated with reactions of known cross section. (Because proton-recoil tracks become too small for reliable detection at low neutron energies, detectors utilizing exothermic neutron reactions--such as $n + {}^6\text{Li}$, as in Ref. 20, or $n + {}^3\text{He}$, as in Ref. 21--have been used in this region. The efficiency is calculated from the known cross section.)

Energy measurement by range or time of flight is probably fairly adequate, though improvements would be desirable at both high and low neutron energies. The discrepancies among published spectral measurements are most likely due to systematic errors in the detection-efficiency curves.

Several different kinds of integral measurements have been made. In one, a target of fissionable material is exposed to thermal neutrons from a reactor, and activation detectors are placed very close to the target. If a series of detectors is used with different thresholds, a knowledge of the relative excitation functions for each detector material allows an unfolding of the observed measured activities to give $N(E)$. Accurate evaluation of $N(E)$ requires that the cross-section-versus-energy relation of each detector be known accurately, not only relatively, but absolutely, and that the resultant activities be accurately counted. Both requirements are difficult to satisfy.

In a second method,^{22,23} a neutron-sensitive scintillator is placed in the center of a polyethylene sphere of radius R at a distance L from the neutron source ($L > R$). The scintillator used is sensitive primarily to thermal neutrons, so the counting rate is a function of neutron intensity, R , and initial neutron energy, since neutrons of higher energy require more moderation before thermalization. With a sequence of spheres of radii $R_1, \dots, R_5$, calibrated against neutrons of known energy and with detection efficiency cross-calibrated against a long counter, counting-rate ratios serve to evaluate $\bar{E}$ for an assumed Maxwellian spectrum.

In a third method,²⁴ thus far applied only to ${}^{252}\text{Cf}$, measurements are made of the scattering intensity of neutrons from targets of varying C and H content. A MnSO_4 bath is used to integrate over all scattering angles. Assuming a Maxwellian spectrum, the best fit of $T = \frac{2}{3}\bar{E}$ is made to the observed variation of scattered intensity with target size. The basic calibration is against published values of the (n,p) and (n,C) scattering cross sections as a function of energy.

D. Measured Fission-neutron Spectrum

The tables in the appendix give results for spectrum measurements made within the last 10 years, and a few of the more accurate ones made before 1960. Since most of these results were fitted to Maxwellian

distributions, it is sufficient to list the $\bar{E}$ values. Where the measurements were of sufficient precision, it is also indicated whether deviations from a Maxwellian were found in the most sensitive regions: low energy (<0.5 MeV) and high energy ($>7-8$ MeV).

From these tables, it is evident that even the neutron spectrum for ^{235}U thermal fission or for ^{252}Cf spontaneous fission cannot be said to have been reliably established over the whole energy range. The situation is worse for the other nuclides.

The most serious source of discrepancy is probably the efficiency calibration of the neutron detector. Aside from the accuracy of the neutron cross-section-versus-energy curves used for calibration, insufficient consideration has sometimes been given in time-of-flight measurements to the effects of the circuitry; e.g., the effect of discriminator bias has sometimes not been folded in. Some of the differences in the tables may also stem from the neglect of (or inadequate correction for) the effect of the shielding materials in their scattering-back of neutrons that have escaped from the scintillator. Where fission gammas are used for calibrating zero flight time in the time-of-flight method, a walk correction is often neglected--this can seriously distort the high-energy part of the spectrum.

Integral methods (with the partial exception of those using threshold detectors) are less sensitive than differential methods. Further, since noticeable deviations are most likely at high and low energies, the energy range covered and the measurement accuracies in these regions play an important role in the discernibility of a deviation.

E. Spread in $\bar{E}$ Values and Effect on Predicted Spectrum

The tables in the appendix indicate that there is a sizable spread in the measured $\bar{E}$ values, and this spread is even larger if the error bands are included, as indicated in Table IV.

TABLE IV Spread in Measured $\bar{E}$ Values for Thermal-neutron Fission^a
(all values in MeV)

^{235}U		^{233}U		^{239}Pu		^{252}Cf	
$\bar{E}$	Range	$\bar{E}$	Range	$\bar{E}$	Range	$\bar{E}$	Range
1 935		1 87	1 83-1 91	2 110	2 080-2 140	2 35	2 24-2 46
1 981		2 00	1 98-2 02	2 01	1 95 2 07	2 34	2 29-2 39
1 945	1 900 1 990	1 983	1 973-1 993	2 033	1 973-2 093	2 085	2 025-2 145
1 86	1 80-1 92	2 034	1 964-2 104	2 078	2 018-2 148	2 388	
1 998	1 918-2 068	1 979		2 021		2 050	2 020 2 120
1 935				2 018	1 998-2 038	2 085	2 025-2 145
1 95	1 92-1 98			2 019	1 989-2 049		
2 30 ^b	2 23-2 37						
Arithmetic average	Total range 1 80-2 068	Arithmetic average	Total range 1 83-2 104	Arithmetic average	Total range 1 950-2 148	Arithmetic average	Total range 2 020 2 46
1 943		1 973		2 041		2 216	
ENDF/B value 1 95 ^c		ENDF/B value 1 96 ^c		ENDF/B value 2 115 ^{c,d}			

^aThe range is taken from Tables A 1-A 4 giving $\bar{E} \pm \Delta\bar{E}$ to $\bar{E} + \Delta\bar{E}$, where $\pm\Delta\bar{E}$ are the listed errors in the tables

^bThis value is so discrepant that it has not been included in the summary values

^cFrom Ref 25

^dReference 25 accepts the value from Ref 26

It is of some interest to examine what shifts in relative intensity follow from changes of this magnitude in $\bar{E}$. Assuming that the neutron spectrum follows the Maxwellian form, we have calculated the shift in relative intensity over the total range of $\bar{E}$ values for ^{235}U indicated in Table IV. Table V shows the ratio $N_M(E, \bar{E}_i)/N_M(E, \bar{E}_{av})$, where $\bar{E}_{av}$ is the arithmetic

TABLE V Relative Intensities for Neutron Spectra of Several $\bar{E}$ Values for ^{235}U

E	N_M for $\bar{E} = 1\,943\text{ MeV}$		$N_M(\bar{E}_1)$			
	N_M	N_M	$N_M(\bar{E} = 1\,943\text{ MeV})$			
		$N_M(\text{peak})$	$\bar{E} = 1\,800\text{ MeV}$	$\bar{E} = 1\,872\text{ MeV}$	$\bar{E} = 2\,005\text{ MeV}$	$\bar{E} = 2\,068\text{ MeV}$
0 1	0 224	0 600	1 115	1 054	0 956	0 915
0 2	0 293	0 786	1 108	1 051	0 959	0 919
0 3	0 333	0 893	1 101	1 048	0 961	0 924
0 4	0 355	0 952	1 094	1 045	0 963	0 928
0 5	0 368	0 987	1 088	1 042	0 965	0 932
0 6	0 373	1 000	1 081	1 039	0 968	0 937
0 7	0 373	1 000	1 074	1 036	0 970	0 941
0 8	0 369	0 989	1 068	1 033	0 972	0 945
0 9	0 362	0 971	1 061	1 030	0 975	0 950
1 0	0 354	0 949	1 055	1 027	0 977	0 954
1 1	0 343	0 920	1 048	1 024	0 979	0 959
1 2	0 332	0 890	1 042	1 021	0 982	0 963
1 3	0 320	0 858	1 036	1 018	0 984	0 968
1 4	0 307	0 823	1 029	1 015	0 986	0 972
1 5	0 294	0 788	1 023	1 012	0 989	0 977
1 6	0 281	0 753	1 017	1 009	0 991	0 981
1 7	0 269	0 721	1 010	1 006	0 993	0 986
1 8	0 256	0 686	1 004	1 003	0 996	0 991
1 9	0 243	0 651	0 998	1 000	0 998	0 995
2 0	0 231	0 619	0 992	0 997	1 001	1 000
2 2	0 208	0 558	0 980	0 991	1 005	1 009
2 4	0 186	0 498	0 968	0 986	1 010	1 019
2 6	0 166	0 445	0 956	0 980	1 015	1 028
2 8	0 147	0 394	0 945	0 974	1 020	1 038
3 0	0 131	0 351	0 933	0 969	1 025	1 048
3 2	0 1158	0 310	0 922	0 963	1 030	1 057
3 4	0 1023	0 274	0 910	0 957	1 035	1 067
3 6	0 0902	0 242	0 899	0 952	1 040	1 077
3 8	0 0794	0 213	0 888	0 946	1 045	1 087
4 0	0 0698	0 187	0 878	0 941	1 050	1 098
4 5	0 0503	0 135	0 851	0 927	1 062	1 124
5 0	0 0361	0 097	0 825	0 913	1 075	1 150
5 5	0 0257	0 069	0 800	0 900	1 088	1 177
6 0	0 0183	0 049	0 776	0 887	1 101	1 205
6 5	0 0129	0 0346	0 753	0 874	1 114	1 233
7 0	0 00910	0 0244	0 730	0 861	1 127	1 263
8 0	0 00450	0 0120	0 687	0 837	1 155	1 323
9 0	0 00220	0 0059	0 646	0 812	1 183	1 386
10 0	0 00107	0 0029	0 607	0 789	1 211	1 452
11 0	0 00052	0 00139	0 571	0 764	1 243	1 529
12 0	0 00025	0 00067	0 537	0 744	1 270	1 594
13 0	0 00012	0 00032	0 505	0 723	1 301	1 670

average (1.943) in Table IV, and $\bar{E}_i$ is taken at several values including the endpoints of the total range in Table IV. For a deviation of $\pm 3.5\%$ in $\bar{E}$, $N_M(E)$ changes by more than 5% below 0.1 MeV and above 4.0 MeV; for a deviation of $\pm 7\%$ in $\bar{E}$, $N_M(E)$ changes by more than 5% below 1.0 MeV and above 3.0 MeV. (For a comment on the significance of changes of this magnitude, see Sect. G below.) The results are shown graphically in Fig. 5.

Fig. 5

Graphical Presentation of Table V. The neutron-energy distributions are taken to follow the Maxwellian $N_M(E)$ of Eq. 5. Curves I-IV give intensity ratios as a function of neutron energy; at a given neutron energy E , the ordinate is the ratio between the intensity at a selected $\bar{E}$ value to that at the standard $\bar{E}$ value 1.943, i.e., $N_M(\bar{E})/N_M(1.943)$ as a function of E . Curve V gives N_M as a function of E for the standard distribution ($\bar{E} = 1.943$ MeV). Curve VI is the same distribution with a logarithmic intensity scale. ANL Neg. No. 121-7325.

F. Changes in Neutron Spectrum due to Increase in E_n , the Energy of the Neutron Causing Fission

Relatively poor data are available on changes of $\bar{E}$ with E_n . That $\bar{E}$ increases with E_n has been unambiguously observed (see, e.g., Fig. 6), but the magnitude of the coefficient is not known accurately, nor has the linearity of the relation been established.

The coefficient may be evaluated from the data in Table A.6 (in conjunction with the thermal fission data) and also from the difference between $\bar{E}$ (^{240}Pu , spontaneous) and $\bar{E}$ (^{239}Pu + thermal n) in conjunction with the binding energy of the last neutron in ^{240}Pu .

Fig. 6. Energy Variation of Mean Fission Neutron Energy $\bar{E}$ with Variation of Bombarding Neutron Energy E_n . ANL Neg. No. 121-7223.

in $\bar{E}$ itself. However, $d\bar{E}/dE_n$ is certainly positive, and approximate values may be used to give a self-consistent range of $\bar{E}$ values.

If the value of $\bar{E}_{40}$ (^{240}Pu , spontaneous) and $\bar{E}_{49}$ (^{239}Pu + thermal n) were known accurately, then $d\bar{E}/dE_n = (\bar{E}_{49} - \bar{E}_{40})/6.38$. This value of the neutron binding energy is taken from Ref. 27. Since the ^{240}Pu measurement was made with the Bramblett sphere method (see Table A.5), we attempt to avoid the effect of systematic errors by using the ^{239}Pu value derived by the same method (see Table A.3). These give $d\bar{E}/dE_n = 0.043 \pm 0.014$ MeV/MeV, in disagreement with Fig. 6.

Since both kinds of results are subject to large errors, it may be more fruitful to evaluate $d\bar{E}/dE_n$ in a somewhat indirect manner. This is feasible through the use of data on $\bar{\nu}_p$, the number of prompt neutrons emitted per fission. The basis of the relation is the fact that when the average fission-fragment excitation energy goes up, for whatever reason, both $\bar{E}$ and $\bar{\nu}_p$ are increased. The experimentally derived relationship between $\bar{E}$ and $\bar{\nu}_p$ may then be combined with measured values of $d\bar{\nu}_p/dE_n$ to give the desired $d\bar{E}/dE_n$.

The quantity $d\bar{\nu}_p/dE_n$ can be more accurately evaluated than $d\bar{E}/dE_n$ simply because relative $\bar{\nu}_p$ values are more accurately measurable than are

If the results of the Russian measurements with 14-MeV neutrons given in the appendix can be taken at their face value,* a rough combination with thermal-neutron fission results indicates that $d\bar{E}/dE_n$ is approximately 0.02 MeV/MeV (see Fig. 6). The large error in the Russian values and the spread in the existing thermal values make the error in the value of $d\bar{E}/dE_n$ quite large. Because of the present status of experimental results as listed in the appendix, the usefulness of a coefficient of this magnitude at present is somewhat questionable. That is, over a range of a few MeV in E_n , the $\bar{E}$ variation predicted by this coefficient is of the same order as the uncertainty

*Aside from the errors inherent in the methods used for neutron-intensity measurements, these results have the added possibility of significant systematic error, since the form of $N(E)$ is extractable only after subtracting the evaporation neutrons of a hypothesized distribution form.

$\bar{E}$ values. The accuracy in determining the relationship of $\bar{E}$ to $\bar{\nu}_p$ is improved by extending the range of $\bar{\nu}_p$ as much as possible. This is effected by taking advantage of the fact that $\bar{\nu}_p$ increases with both E_n and Z .

The following semitheoretical relationship has been given by Terrell:^{17,28,29}

$$\bar{E} = 0.74 \pm 0.653 \sqrt{\bar{\nu}_p + 1}. \quad (12)$$

Figure 7 shows a curve of Eq. 12 analogous to one given by Terrell for thermal fission and spontaneous fission alone; this one (from Ref. 26) includes more recent data and the higher E_n values given in Table A.6.

Fig. 7. Variation of the Averaged Experimental Values of the Energy Parameter T with the Average Number of Neutrons per Fission $\bar{\nu}$ (from Ref. 26). ANL Neg. No. 121-7225.

The relation between the bombarding energy E_n and $\bar{\nu}_p$ has been the subject of many experiments, with results listed in Table VI. Of these, the most recent and most careful measurements are given in Ref. 30.

From Eq. 12,

$$\frac{d\bar{E}}{d\bar{\nu}_p} = \frac{0.327}{\sqrt{\bar{\nu}_p + 1}} = \frac{0.213}{\bar{E} - 0.74}. \quad (13)$$

Then,

$$\frac{d\bar{E}}{dE_n} = \frac{d\bar{E}}{d\bar{\nu}_p} \frac{d\bar{\nu}_p}{dE_n}, \quad (14)$$

where $d\bar{\nu}_p/dE_n$ is given in Table VI. At least for a first approximation, $\bar{E}$ (or $\bar{\nu}_p$) may be taken as the value at the lower end of the E_n range considered.

TABLE VI. Values of $d\nu/dE_n$ for Several Nuclides

Nuclide	Ref.	Year	Energy Range of E_n , MeV	$\frac{d\bar{\nu}_p}{dE_n}$
^{232}Th	31	1965	1.6-15	0.154
	32	1965	2-4	0.096 ± 0.009
^{233}U	33	1958	0-15	0.124 ± 0.011
	34	1963	0-1.08	0.085
	32	1965	0-4	0.105 ± 0.021
			1-4	0.139 ± 0.019
^{234}U	32	1965	1-4	0.135 ± 0.025
^{235}U	33	1958	0-15	0.135 ± 0.012
	35	1962	0.03-1.76	0.097 ± 0.008
	34	1963	0-2	0.085
			2-14	0.160
	36	1964	0-3	0.109 ± 0.006
			3-8	0.181 ± 0.005
	37	1965	2-15	0.147
	38	1967	0.04-1.0	0.14 ^a
			0-5	0.134 ± 0.004
	39	1967	1-2	0.06
			2-3.2	0.15
	30	1969	1.3-5.1	0.129 ± 0.004
			5.1-7.5	0.200 ± 0.004
			7.5-10.0	0.140 ± 0.003
^{238}U			10.5-14.8	0.138 ± 0.005
			7.5-14.8	0.135 ± 0.002
	40	1964	1.5-15	0.154
	32	1965	1.4-4	0.152 ± 0.009
	30	1969	1.3-14.8	0.155 ± 0.002
^{239}Pu	33	1958	0-15	0.121 ± 0.013
	34	1963	0-14.5	0.160
	32	1965	0-4	0.098 ± 0.011
	30	1969	1.3-5.1	0.152 ± 0.003
			6.1-12	0.152 ± 0.002
			12.4-14.8	0.154 ± 0.001
			1.3-14.8	0.150 ± 0.001

^aData indicate that $d\nu/dE_n$ may not remain constant at low energies, but may take a high value of 0.25, only to flatten out somewhat at 0.6 MeV.

It is clear from Table VI that the average slope depends upon the E_n range measured, and the curve of $\bar{\nu}_p$ versus E_n does not have a single slope from $E_n = 0$ to $E_n = 10$ MeV or more. As an example, however, let us take for ^{235}U , $d\bar{\nu}_p/dE_n \approx 0.13$ and $\bar{E} = 1.95$; then, from Eqs. 13 and 14, $d\bar{E}/d\bar{\nu}_p = 0.176$ and $d\bar{E}/dE_n = 0.023$. This value is close to the directly measured quantities in Fig. 6 for ^{233}U , ^{238}U , and ^{239}Pu , but disagrees with the ^{235}U curve. (The dotted line represents the 0.023 slope, a poor fit to the ^{235}U data.)

In the light of the present uncertainties in the absolute $\bar{E}$ values, Eq. 14 may serve to give adequate values of $d\bar{E}/dE_n$ where this is needed. Some values taken from the compilation in Ref. 25 are given in Table VII.

TABLE VII. Values of $d\bar{E}/dE_n$ from ENDF/B²⁵

Nuclide	Energy Range of E_n , MeV	$\frac{d\bar{E}}{dE_n}$, MeV/MeV
^{232}Th	1.2-15	0.0252
^{233}U	0-15	0.0196
^{235}U	0-15	0.0219
^{238}U	1-15	0.0233
^{239}Pu	0-15	0.0152
^{241}Pu	0-1	0.0233
	1-15	0.0207
		} 0.0209

G. Discussion

As mentioned in Sect. E above, the tables in the appendix indicate that the prompt-neutron spectrum is not known accurately, although the general features are well established. We have made no attempt to choose a "best" spectrum from the various determinations. Aside from other considerations, detailed comparison of the spectra was made difficult because most of the published work with differential measurements contained no tabulations, but only difficult-to-read logarithmic plots. Even more important, however, is the likelihood that the deviations between the various reported results were due to systematic errors in the energy calibrations of the neutron detectors. Only with a detailed reexamination and recalibration of each experiment might it be possible to resolve such differences. At present, in the absence of a suitable method for choosing a "best" spectrum, a Maxwellian distribution with its $\bar{E}$ taken as the arithmetic average (see Table IV) may be the best practical choice.

For a comparison, also listed are the values recommended by the AEC's Cross-Section Evaluation Working Group.²⁵

Both Refs. 41 and 42 show that the calculated results for certain fast assemblies can be markedly different when fairly large changes are made in the $\bar{E}$ value used. Thus, in Ref. 42, calculations were made on the effect of shifting $\bar{E}$ (^{235}U) from the value 1.910 to 2.115 MeV. [This difference (~ 0.2 MeV) is not quite as large as the maximum range considered in Sect. E and in Tables IV and V.] For the critical assemblies considered, k_{eff} changed markedly, especially for cores with a high ^{238}U content. In Ref. 41, the effect of shifting $\bar{E}$ (^{239}Pu) from 2.04 to 2.19 MeV was examined on a critical assembly (SEFOR) with 11% ^{238}U , and here, as might be expected, the major effect was a 4% shift in the effective delay fraction. These calculations probably suffice to indicate that improvement in $N(E)$ determination might help the fast-reactor theorists. However, it is unlikely that the uncertainty in the average energy of the ^{235}U spectrum is as large as the shift used in these calculations. Further calculations involving the effect of changes in spectral shape might be worthwhile.

If such lack of agreement between theory and experiment associated with critical assemblies is of sufficient importance, suitable experiments for improving our knowledge of $N(E)$ can probably be carried out. However, in the light of all the work done already, it is clear that new experiments that carefully avoid systematic errors will require a large and well-thought-out program. Although the integral method using activation detectors is more versatile in spectral measurements of various types, a differential method, being basically subject to fewer corrections, is more desirable. The time-of-flight method, with improvements in circuitry, antiscattering provisions, and better detector calibration, is most likely to be refinable to give the desired accuracy in the fission-neutron spectrum.

APPENDIX

Tabulated Results of Measurements on Neutron Spectra (See Sect. III.D for description.)

TABLE A 1 Measurements on Neutron Spectrum from Thermal-neutron Fission of ^{235}U

Energy Range Covered, MeV	Type of Method ^a	Method ^b	Ref	Date	$\bar{E}$ MeV	Deviation ^c	Neutron Detector Calibrated Relative to ^d	Statistical Error Estimate in N/E ^e	Systematic Error Estimate ^f
0.18-2.7	Diff	TOF(I OS)					Long counter (n,p)	1-1.5% 0.2-2.5 MeV	
0.35-12		Emulsion	43	1956	1.935 - 1.9819	None		3-11% 0.3-7 MeV	4-6% 0.4->3 MeV
0.3-4	Diff	TOF(P OS)	26	1965	1.945 $\pm$ 0.045	None	Long counter (<2.3 MeV) (n,p) and Monte Carlo calculation for >2.3 MeV	Small	-
0.3-7.5	Diff	TOF(P, OS)	44, 45	1965	1.86 $\pm$ 0.06	None	0.5-4.5 MeV--long-counter calibration with T(p,n) 4.5-6 MeV-- long-counter calibration with D(d,n)	Small to 10% 0.3-7.5 MeV	-
6-20	Diff	p-recoil solid-state spectrometer	46	1967	1.95 $\pm$ 0.03	None	(n,p)	Small	-
0-4	Int	Bramblett spheres + IS(^{6}Li)	22, 23	1961	1.998 $\pm$ 0.070	None	Long counter and illumination correction Long-counter calibration with d(d,n) 4.5-7.5 MeV	-	$\pm 4\%$ 0.1-7 MeV (from Ref. 22)
0->11	Int	Measuring induced radioactivity of threshold detectors	47	1968	1.935 ^h	$N_0 > N_M$ below 1 MeV $N_0 < N_M$ above 6 MeV	$^{235}\text{U}(n,f)$, $^{238}\text{U}(n,f)$, $^{237}\text{Np}(n,f)$, $^{31}\text{P}(n,p)$, $^{27}\text{Al}(n,p)$, $^{56}\text{Fe}(n,p)$, $^{27}\text{Al}(n,\alpha)$, $^{63}\text{Cu}(n,2n)$	-	-
0-12	Int	Radioactivity of threshold detectors	48	1969	2.30 $\pm$ 0.07	$N_0 < N_M$ below 1.5 MeV $N_0 > N_M$ above 1.5 MeV	As in Ref. 47, plus $^{115}\text{In}(n,n')$, $^{63}\text{Cu}(n,\gamma)$, $^{197}\text{Au}(n,\gamma)$	-	-

^a Differential (Diff) or Integral (Int)^b TOF = time of flight. This is followed by two letters, e.g., (A,B). A is the fragment detector or initiating event (although by electronic delay it may serve as stop pulse). I = ion chamber, G = gas scintillator, SS = silicon solid-state detector, SE = secondary electron detector, P = pulsed accelerator, γ = detection of fission gammas. B is the neutron detector. OS = organic scintillator, IS = inorganic scintillator, loaded with a nuclide giving an exothermic reaction with neutrons.^c Observed deviation from Maxwellian shape. N_0 = observed intensity at neutron energy E . N_M = intensity predicted from the Maxwellian form derived from the observed E value.^d Where a long counter is used, its response is quite flat with energy, usually deviating <5-10% over the measured spectrum. It may be used as a primary standard with sensitivity taken as energy independent (and this is so if no more information is given), or its residual deviation may in turn be calibrated against published spectra as listed here.^e Appropriate only for the differential measurements. As given by the authors or derived from the published curves. Given here as minimum to maximum errors over the indicated range, $E_{\min}$ - $E_{\max}$. For neutron energies $>E_{\max}$, statistical errors are even greater because of lower intensity (see Table III). Emulsion measurements have relatively large statistical errors because it is practicable to individually examine only a limited number of tracks.^f Given here only where provided by the authors. Due to uncertainties in the calibrating cross sections and in the corrections.^g The spectrum is reported to fit a Maxwellian with $T = 1/0.775$, hence, $\bar{E} = 1.935$, from Eq. 7a. It is also reported to fit a Watts curve, with $a = 1/0.965$ and $C = 2.29$, hence, $\bar{E} = 1.981$, from Eq. 3a. No error estimates were given.^h No error estimate given.

TABLE A 2 Measurements on Neutron Spectrum from Thermal-neutron Fission of ^{235}U

Energy Range Covered, MeV	Type of Method ^a	Method ^b	Ref	Date	$\bar{E}$, ^c MeV	Deviation ^d	Neutron Detector Calibrated Relative to ^e	Statistical Error Estimate in N(E) ^f	Systematic Error Estimate ^g
0.3-5 1.2-7	Diff	TOF(G, OS) Emulsion ^h	49	1959	1.87 ± 0.04	$N_0 > N_M$ for $E < 2$ MeV and $E > 5$ MeV ⁱ	^{235}U spectrum taken to be perfect Maxwellian with $\bar{E} = 1.951$ ⁱ	Several percent 8-15% 2-5 MeV	-
0.7-11.5	Int	Induced radioactivity of threshold detectors	50	1958	$\bar{E}_{235} + 0.06 \pm 0.02$ (2.00)	None	$^{141}\text{Pr}(n, 2n)$, $^{27}\text{Al}(n, p)$, $^{31}\text{P}(n, p)$, $^{232}\text{Th}(n, f)$, $^{238}\text{U}(n, f)$, $^{237}\text{Np}(n, f)$ Measured only difference from ^{235}U spectrum	-	-
0-11	Int	Induced radioactivity of threshold detectors	47	1968	$\bar{E}_{235} + 0.040 \pm 0.010$ (1.983)	None	See Table A 1	-	-
0-4	Int	Bramblett spheres + IS(^6Li)	22, 23	1961	2.034 ± 0.070 and $\bar{E}_{235} + 0.036 \pm 0.009$ (1.979)	None	See Table A 1	-	See Table A 1

^aDifferential (Diff) or Integral (Int)^bTOF = time of flight. This is followed by two letters, e.g. (A B). A is the fragment detector or initiating event (although by electronic delay it may serve as stop pulse). I = ion chamber. G = gas scintillator, SS = silicon solid-state detector, SE = secondary electron detector, P = pulsed accelerator. γ = detection of fission gammas. B is the neutron detector. OS = organic scintillator, IS = inorganic scintillator, loaded with a nuclide giving an exothermic reaction with neutrons.^cA number of measurements have been made only relative to the ^{235}U spectrum. Results for these are given in the form $\bar{E}_{235} + \Delta E - \bar{E}_{233}$. The calibration column notes the relative measurement. In the $\bar{E}$ column is given (in parentheses) a value $\bar{E}_{233} = 1.943 + \Delta E$ where 1.943 is the average of all values in Table A 1.^dObserved deviation from Maxwellian shape. N_0 = observed intensity at neutron energy E . N_M = intensity predicted from the Maxwellian form derived from the observed $\bar{E}$ value.^eWhere a long counter is used, its response is quite flat with energy, usually deviating <5-10% over the measured spectrum. It may be used as a primary standard with sensitivity taken as energy independent (and this is so if no more information is given), or its residual deviation may in turn be calibrated against published spectra as listed here.^fAppropriate only for the differential measurements. As given by the authors or derived from the published curves. Given here as minimum to maximum errors over the indicated range $E_{\min} - E_{\max}$. For neutron energies $> E_{\max}$, statistical errors are even greater because of lower intensity (see Table III). Emulsion measurements have relatively large statistical errors because it is practicable to individually examine only a limited number of tracks.^gGiven here only where provided by the authors. Due to uncertainties in the calibrating cross sections and in the corrections.^hCorrections are of the same type as made in Ref. 43.ⁱMeasurements made relative to $N(^{235}\text{U})$ assumed to obey a Maxwellian.TABLE A 3 Measurements on Neutron Spectrum from Thermal-neutron Fission of ^{239}Pu

Energy Range Covered, MeV	Type of Method ^a	Method ^b	Ref	Date	$\bar{E}$, ^c MeV	Deviation ^d	Neutron Detector Calibrated Relative to ^e	Statistical Error Estimate in N(E) ^f	Systematic Error Estimate ^g
0.15-5.5	Diff	TOF(P, OS)	26	1965	2.110 ± 0.030	None	See Table A 1	Small	
0.3-7.5	Diff	TOF(P, OS)	44, 45	1965	2.01 ± 0.06	None	See Table A 1	See Table A 1	
0.5-7	Diff	TOF(γ , OS)	51	1969	$\bar{E}_{235} + 0.090 \pm 0.060$ (2.033)	None	Relative to ^{235}U spectrum taken to be Maxwellian	-	-
0-4	Int	Bramblett spheres + IS(^6Li)	22, 23	1961	2.078 ± 0.070 or $\bar{E}_{235} + 0.078 \pm 0.009$ (2.021)	None	See Table A 1	-	See Table A 1
0.7-11.5	Int	Induced radioactivity of threshold detectors	50	1958	$\bar{E}_{235} + 0.075 \pm 0.02$ (2.018)	None	See Table A 2		
0-11	Int	Induced radioactivity of threshold detectors	47	1968	$\bar{E}_{235} + 0.076 \pm 0.003$ (2.019)	-	See Table A 1	-	-

^aDifferential (Diff) or Integral (Int)^bTOF = time of flight. This is followed by two letters, e.g. (A B). A is the fragment detector or initiating event (although by electronic delay it may serve as stop pulse). I = ion chamber. G = gas scintillator, SS = silicon solid state detector, SE = secondary electron detector, P = pulsed accelerator. γ = detection of fission gammas. B is the neutron detector. OS = organic scintillator, IS = inorganic scintillator, loaded with a nuclide giving an exothermic reaction with neutrons.^cA number of measurements have been made only relative to the ^{235}U spectrum. Results for these are given in the form $\bar{E}_{239} = \bar{E}_{235} + \Delta E$. In the $\bar{E}$ column is given (in parentheses) a value $\bar{E}_{239} = 1.943 + \Delta E$ where 1.943 is the average of all the values in Table A 1.^dObserved deviation from Maxwellian shape. N_0 = observed intensity at neutron energy E . N_M = intensity predicted from the Maxwellian form derived from the observed $\bar{E}$ value.^eWhere a long counter is used, its response is quite flat with energy, usually deviating <5-10% over the measured spectrum. It may be used as a primary standard with sensitivity taken as energy independent (and this is so if no more information is given), or its residual deviation may in turn be calibrated against published spectra as listed here.^fAppropriate only for the differential measurements. As given by the authors or derived from the published curves. Given here as minimum to maximum errors over the indicated range, $E_{\min} - E_{\max}$. For neutron energies $> E_{\max}$, statistical errors are even greater because of lower intensity (see Table III). Emulsion measurements have relatively large statistical errors because it is practicable to individually examine only a limited number of tracks.^gGiven here only where provided by the authors. Due to uncertainties in the calibrating cross sections and in the corrections.

TABLE A 4 Measurements on Neutron Spectrum from Spontaneous Fission of ^{252}Cf

Energy Range Covered, MeV	Type of Method ^a	Method ^b	Ref	Date	$\bar{E}$, MeV	Deviation ^c	Neutron Detector Calibrated Relative to ^d	Statistical Error Estimate in $N(E)$ ^e	Systematic Error Estimate ^f
0.2-3, 2-7	Diff	TOF(G, OS) Emulsion ^g	52	1957	2.35 ± 0.11^h	-	Long counter (n,p)	5% 10-15%	-
0.5-12 ⁱ	Diff	TOF(SE, OS)	19	1962	2.34 ± 0.05	Distribution is narrower than $N_M(E)$	(n,p) and (n,C) ^k	-	-
0.07-7.5	Diff	TOF(G, OS) and (G, IS)	44, 45	1965	2.085 ± 0.060	None	0.07-1.1 MeV-- ^6Li glass detector, hence against $^6\text{Li}(n,^3\text{H})$ and multiple-scattering correction for OS calibration See Table A 1	10% below 0.7 MeV Small to 10%, 0.3-7.5 MeV	-
0.003-15	Diff	TOF(G, OS) and (G, IS)	20	1967	2.388^l	$N_0 < N_M$ for $E > 10$ MeV $N_0 > N_M$ for $E < 0.6$ MeV	0.003-2.6 MeV-- ^6Li glass detector against $^6\text{Li}(n,^3\text{H})$ 1-15 MeV, OS (n,p)	Small, 0.5-10 MeV	-
0-4	Int	Bramblett spheres + IS(^6Li)	22, 23	1961	2.050 ± 0.070	None	See Table A 1	-	-
-	Int	No. of scattered neutrons as a function of absorber length, MnSO_4 bath detector	24	1969	2.085 ± 0.060	-	(n,p) and (n,C)	-	-

^aDifferential (Diff) or Integral (Int)

^bTOF = time of flight. This is followed by two letters e.g., (A, B). A is the fragment detector or initiating event (although by electronic delay, it may serve as stop pulse). I = ion chamber, G = gas scintillator, SS = silicon solid-state detector, SE = secondary electron detector, P = pulsed accelerator, γ = detection of fission gammas. B is the neutron detector. OS = organic scintillator, IS = inorganic scintillator, loaded with a nuclide giving an exothermic reaction with neutrons.

^cObserved deviation from Maxwellian shape. N_0 = observed intensity at neutron energy E . N_M = intensity predicted from the Maxwellian form derived from the observed $\bar{E}$ value.

^dWhere a long counter is used, its response is quite flat with energy, usually deviating <5-10% over the measured spectrum. It may be used as a primary standard with sensitivity taken as energy independent (and this is so if no more information is given), or its residual deviation may in turn be calibrated against published spectra as listed here.

^eAppropriate only for the differential measurements. As given by the authors or derived from the published curves. Given here as minimum to maximum errors over the indicated range, $E_{\min} - E_{\max}$. For neutron energies $> E_{\max}$, statistical errors are even greater because of lower intensity (see Table III). Emulsion measurements have relatively large statistical errors because it is practicable to individually examine only a limited number of tracks.

^fGiven here only where provided by the authors. Due to uncertainties in the calibrating cross sections and in the corrections.

^gCorrections are of the same type as in Ref. 43.

^hResults are given in the Watts form. $\bar{E}$ has been calculated from Eq. 3a. The error estimate in b and C was given, but this is not sufficient to calculate the error in $\bar{E}$, since the least-squares correlation term, $\text{cov}(b, C)$ was not given. Because the b and C estimates are highly correlated (this is due to the form of the equation), the relation

$$\sigma^2(\bar{E}) = \left(\frac{\partial \bar{E}}{\partial a}\right)^2 \sigma^2(a) + \left(\frac{\partial \bar{E}}{\partial C}\right)^2 \sigma^2(C) + 2\left(\frac{\partial \bar{E}}{\partial a}\right)\left(\frac{\partial \bar{E}}{\partial C}\right) \text{cov}(a, C)$$

should be used. I have guessed at the error here, assuming that the correlation term is negative.

ⁱFor a Maxwellian $\sigma_M(E)/\bar{E}_M = \sqrt{\frac{2}{3}} = 0.816$, as in Eq. 8. The observed value of $\sigma_M(E)/\bar{E}_M$ was 0.74. No further details were given, e.g., how extrapolation was made to give the extreme values at high E and low E . These are very important in evaluating the second moment $\sigma_M^2(E)$, so a faulty extrapolation might grossly reduce the observed second moment. This is not a good measure of the fit of $N_M(E)$ to the observed distribution.

^jEstimated range.

^kAlso see footnote on page 17.

^lFor a Maxwellian fitted only over the range 0.5-10.0 MeV, where the fit is good. If fitted to $N_M(E)$ over the whole range, $\bar{E} = 2.350$, but the fit is nowhere close.

TABLE A 5 Measurements on Neutron Spectrum from ^{241}Pu Thermal Fission and from Spontaneous Fission of Several Nuclides

Nuclide	Energy Range Covered MeV	Type of Method ^a	Method ^b	Ref	Date	$\bar{E}$ MeV	Deviation ^c	Neutron Detector Calibrated Relative to
^{241}Pu + thermal neutron	0.3-6 1.6-7	Diff	TOF(G OS)	53	1961	2.002 ± 0.051	None	^{235}U spectrum assumed to be perfect Maxwellian with $\bar{E} = 1.935$
^{240}Pu spont fis	0-4	Int	Bramblett spheres + IS(^6Li)	22 23	1961	1.783 ± 0.070	-	See Table A 1
^{244}Cm spont fis	0.5-6	Diff	^3He detector and solid state detectors	21	1965	2.187 ± 0.093^d	$N_0 > N_M$ below 0.9 MeV ^d	$^3\text{He}(n, p)$
^{244}Cm spont fis	0.3-6.3	Diff	TOF(OS) zero time from fission-gamma-ray peak	51	1969	2.06 ± 0.06	-	Relative to the ^{235}U spectrum assumed Maxwellian
^{242}Pu spont fis	0.5-5					1.81 ± 0.10		Relative to the ^{244}Cm spectrum assumed Maxwellian

^aDifferential (Diff) or Integral (Int)^bTOF = time of flight. This is followed by two letters e.g. (A B). A is the fragment detector or initiating event (although by electronic delay it may serve as stop pulse). I = ion chamber. G = gas scintillator. SS = silicon solid-state detector. SE = secondary electron detector. P = pulsed accelerator. γ = detection of fission gammas. B is the neutron detector. OS = organic scintillator. IS = inorganic scintillator loaded with a nuclide giving an exothermic reaction with neutrons.^cObserved deviation from Maxwellian shape. N_0 = observed intensity at neutron energy E . N_M = intensity predicted from the Maxwellian form derived from the observed $\bar{E}$ value.^dHerold, the author of Ref. 21, is not responsible for these results. He kindly supplied us with his original data and this is the result of our least-squares fit to $N_M(E)$.TABLE A 6 Measurements on Neutron Spectrum from Fission Induced by Neutrons of Above-thermal Energies
(Differential type of method only)

Nuclide	Energy of Bombarding Neutron MeV	Energy Range Covered in Spectrum MeV	Method	Ref	Date	$\bar{E}$ MeV	Neutron Detector Calibrated Relative to
^{235}U	1.50	0.6-5.5	TOF(P OS)	44 45	1965	1.875 ± 0.06	See Table A 1
	14	0.5-6.5	Emulsion ^a	54	1958	2.075 ± 0.090	(n, p)
	14.3	0.5-5	TOF(P OS) ^a	55	1960	2.090 ± 0.045	D(d, n) ^3He using the method of Ref. 56
^{239}Pu	14.0	0.6-6.5	As above	54	1958	2.375 ± 0.120	As above
^{233}U	14.0	1-6	As above	54	1958	2.30 ± 0.12	As above
^{238}U	2.09 4.91	~0.15-9	TOF(I OS)	26	1965	1.935 ± 0.045 2.130 ± 0.045	See Table A 1
	14.0	0.6-5.5	As above	54	1958	2.32 ± 0.12	As above
	14.3	0.5-5	As above	55	1960	2.240 ± 0.045	As above
^{232}Th	14.0	0.6-4	As above	54	1958	2.30	As above

^aThe method has a built-in inaccuracy because it requires semigraphical separation of the fission spectrum from evaporation neutrons.

REFERENCES

1. J. P. Unik and J. E. Gindler, *A Critical Review of the Energy Released in Nuclear Fission*, ANL-7748 (to be published).
2. K. F. Flynn and L. E. Glendenin, *Yields of Fission Products for Several Fissile Nuclides at Various Incident Neutron Energies*, ANL-7749 (to be published).
3. M. Burgy, L. A. Pardue, H. B. Willard, and E. O. Wollan, *Energies of the Delayed Neutrons from ^{235}U Fission Products*, MDDC-16 (June 1946). Abstract in Phys. Rev. 70, 104 (1946).
4. D. J. Hughes, J. Dabbs, A. Cahn, and D. Hall, *Delayed Neutrons from Fission of ^{235}U* , Phys. Rev. 73, 111-124 (1948).
5. T. W. Bonner, S. J. Bame, Jr., and J. E. Evans, *Energy of the Delayed Neutrons from the Fission of ^{235}U* , Phys. Rev. 101, 1514-1515 (1956).
6. R. Batchelor and H. R. McK. Hyder, *The Energy of Delayed Neutrons from Fission*, J. Nucl. Energy 3, 7-17 (1956).
7. N. G. Chrysochoides, A. J. Nicolitsas, N. N. Papadopoulos, C. C. Zikides, and C. A. Mitsonias, "Work in Greece on Delayed Neutrons," *Proc. 1967 Conference on Delayed Fission Neutrons*, IAEA, Vienna (1968), pp. 213-227.
8. N. G. Chrysochoides, N. N. Papadopoulos, and C. C. Zikides, *Delayed Neutron Spectrum Measurement*, Democritus Nuclear Research Center Reactor Department, final report, Contract No. 297/R2/RB (July 1968).
9. E. T. Chulick, E. Eichler, P. L. Reeder, and C. E. Bemis, Jr., "Delayed-Neutron Energy Spectra and Group Abundances from the Spontaneous Fission of ^{252}Cf ," *Chemistry Division Annual Progress Report for Period Ending May 20, 1969*, ORNL-4437, p. 24 (Sept 1969).
10. Eugene T. Chulick, *Delayed-Neutrons from ^3He and ^4He Induced Fission of ^{238}U , ^{232}Th , ^{209}Bi and from Spontaneous Fission of ^{252}Cf* , Ph.D. thesis, Washington University (Sept 1969).
11. H. Gauvin and R. de Turreil, "Emission de Neutrons Retardés: Calcul des Spectres d'Energie et des Probabilités d'Emission des Précurseurs," *Proc. Second Sympos. Phys. and Chem. Fission*, IAEA, Vienna (1969), pp. 621-636.
12. S. Yiftah and D. Saphier, "The Importance of Exact Delayed Neutron Data in Fast Reactor Dynamic Behavior," *Proc. 1967 Conference on Delayed Fission Neutrons*, IAEA, Vienna, pp. 23-31 (1968).
13. S. Yiftah and D. Saphier, *The Effect of the Delayed Neutron Spectra Uncertainties on Fast Reactor Dynamics and Stability*, Trans. Amer. Nucl. Soc. 11, 568-569 (1968).
14. G. S. Brunson and R. J. Huber, "Bandsaw--A Proposal for Remeasuring Delayed Neutron Energies, Yields, and Half-Lives in AFSR-Type Reactors," *Proc. 1967 Conference on Delayed Fission Neutrons*, IAEA, Vienna, pp. 229-237 (1968).
15. "Fission Properties," Sec. 1, *Reactor Physics Constants*, ANL-5800, 2nd ed., July 1963, p. 19.

16. G. R. Keepin, "Delayed Neutrons," Chap. 7, *Progress in Nuclear Energy I, Physics and Mathematics*, pp. 191-225 (1956).
17. James Terrell, *Fission Neutron Spectra and Nuclear Temperatures*, Phys. Rev. 113, 527-541 (1959).
18. B. E. Watt, *Energy Spectrum of Neutrons from Fissions Induced by Thermal Neutrons*, Phys. Rev. 87, 1037-1041 (1952); AECD-3073 (Feb 1951).
19. H. R. Bowman, S. G. Thompson, J. C. D. Milton, and W. J. Swiatecki, *Velocity and Angular Distributions of Prompt Neutrons from Spontaneous Fission of ^{252}Cf* , Phys. Rev. 126, 2120-2136 (1962).
20. J. W. Meadows, *^{252}Cf Fission Neutron Spectrum from 0.003 to 15.0 MeV*, Phys. Rev. 157, 1076-1082 (1967).
21. T. R. Herold, *Energy Spectra of Neutrons and Gamma Rays from Spontaneous Fission of ^{244}Cm* , Savannah River Laboratory Report DP-949 (July 1965).
22. R. L. Bramblett, R. I. Ewing, and T. W. Bonner, *A New Type of Neutron Spectrometer*, Nucl. Instrum and Meth. 9, 1-12 (1960).
23. T. W. Bonner, *Measurements of Neutron Spectra from Fission*, Nucl. Phys. 23, 116-121 (1961).
24. L. Green, *Transmission Measurement of the ^{252}Cf Fission-Neutron Spectrum*, WAPD-TM-830 (Mar 1969). Summarized in Trans. Amer. Nucl. Soc. 11(2), 606-607 (1968).
25. *ENDF/B Version II Data*, AEC Cross-Section Evaluation Working Group, Brookhaven National Laboratory (summer 1970).
26. E. Barnard, A. T. G. Ferguson, W. R. McMurray, and I. J. Van Heerden, *Time-of-Flight Measurements of Neutron Spectra from the Fission of ^{235}U , ^{238}U , ^{239}Pu* , Nucl. Phys. 71, 228-240 (1965).
27. F. Everling, L. A. Koenig, J. H. E. Mattauch, and A. H. Wapstra, *Relative Nuclidic Masses*, Nucl. Phys. 18, 529-569 (1960).
28. J. Terrell, *Neutron Yields from Individual Fission Fragments*, Phys. Rev. 127, 880-904 (1962).
29. J. Terrell, "Prompt Neutrons from Fission," *Proc. Conference on Physics and Chemistry of Fission*, Vol. II, IAEA, Vienna, pp. 3-24 (1965).
30. M. Soleilhac, J. Frehaut, and J. Gauriau, *Energy Dependence of $\bar{\nu}_p$ for Neutron-Induced Fission of ^{235}U , ^{238}U and ^{239}Pu from 1.3 to 15 MeV*, J. Nucl. Eng. 23, 257-282 (1969).
31. H. Condé and M. Holmberg, *Average Number of Prompt Neutrons Emitted in the Neutron Induced Fission of ^{232}Th* , Ark.f.Fys 29, 33-43 (1965).
32. D. S. Mather, P. Fieldhouse, and A. Moat, *Measurement of Prompt $\bar{\nu}$ for the Neutron-Induced Fission of ^{232}Th , ^{233}U , ^{234}U , ^{238}U and ^{239}Pu* , Nucl. Phys. 66, 149-160 (1965).
33. G. N. Smirenkin, I. I. Bondarenko, L. S. Kutsaeva, Kh. D. Mischchenko, L. I. Prokhorova, and B. P. Shemetenko, *Average Number of Prompt Neutrons from the Fission of ^{233}U , ^{235}U , and ^{239}Pu by 4 and 15 MeV Neutrons*, Atomnaya Energya 4, 188 (1958); transl, J. Nucl. Eng. 9, 155-157 (1959).
34. J. C. Hopkins and B. C. Diven, *Prompt Neutrons from Fission*, Nucl. Phys. 48, 433-442 (1963).

35. J. W. Meadows and J. F. Whalen, *Energy Dependence of $\bar{\nu}_p$ for Neutron-Induced Fission of ^{235}U* , Phys. Rev. 126, 197-201 (1962).
36. D. S. Mather, P. Fieldhouse, and A. Moat, *Average Number of Prompt Neutrons from ^{235}U Fission Induced by Neutrons from Thermal to 8 MeV*, Phys. Rev. 133B, 1403-1420 (1964).
37. H. Condé, *Average Number of Neutrons from the Fission of ^{235}U* , Ark.f.Fys. 29, 293-299 (1965).
38. J. W. Meadows and J. F. Whalen, *Energy Dependence of $\bar{\nu}_p$ for Neutron-Induced Fission of ^{235}U below 1.0 MeV*, J. Nucl. Eng. 21, 157-169 (1967).
39. L. I. Prokhorova, G. N. Smirenkin, and D. L. Zhilak, "Channelling Effects in the Energy Dependence of $\bar{\nu}$ for ^{235}U and ^{232}Th ," *Proc. Conference Nuclear Data for Reactors*, Vol. II, IAEA, Vienna, pp. 67-73 (1967).
40. I. Asplund Nilsson, H. Condé, and N. Starfelt, *$\bar{\nu}$ of ^{238}U from 1.5 to 15 MeV*, Nucl. Sci. Eng. 20, 527-535 (1964).
41. G. R. Keepin, "Delayed Fission Neutron Data in Reactor Physics and Design," *Proc. 1967 Conference on Delayed Fission Neutrons*, IAEA, Vienna, pp. 3-22 (1968).
42. J. M. Kallfelz, B. A. Zolotar, and B. R. Sehgal, "Modifications to Fissile Element Cross Sections and Their Influence on Calculated Fast Reactor Parameters," *Proc. EACRP Meeting*, West Berlin, Germany (Nov 1969); ANL internal report EACRP-L-77.
43. L. Cranberg, G. Frye, N. Nereson, and L. Rosen, *Fission Neutron Spectrum of ^{235}U* , Phys. Rev. 103, 662-670 (1956).
44. H. Condé, G. During, and J. Hansen, *Fission Neutron Spectra. I. A Neutron Detector for Fast Time-of-Flight Spectroscopy*, Ark. f. Fys. 29, 307-312 (1965).
45. H. Condé and G. During, *Fission Neutron Spectra. II. Fission Neutron Spectra of ^{235}U , ^{239}Pu , ^{252}Cf* , Ark. f. Fys. 29, 313-319 (1965).
46. G. G. Sherwood, *^{235}U Fission Neutron Spectrum--6 to 20 MeV*, Trans. Am. Nucl. Soc. 10 (No. 2), 555 (1967); L. Harris, G. Sherwood, and J. S. King, *Fast Neutron Spectra in Water and Graphite*, Nucl. Sci. Eng. 26, 571-573 (1966).
47. James A. Grundl, *A Study of Fission-Neutron Spectra with High-Energy Activation Detectors. I. Detector Development and Excitation Measurements. II. Fission Spectra*, Nucl. Sci. Eng. 31, 39-53, 191-206 (1968).
48. W. N. McElroy, *Implications of Recent Fission-Averaged Cross-Section Measurements*, Nucl. Sci. Eng. 36, 109-113 (1969).
49. A. B. Smith, P. R. Fields, and R. K. Sjoblom, *Precise Determination of the ^{233}U Fission Neutron Spectrum*, Phys. Rev. 114, 1351-1353 (1959).
50. V. P. Kovalev, V. N. Andreev, M. N. Nikolaev, and A. G. Guseinov, *Comparison of Neutron Spectra in the Fission of ^{233}U , ^{235}U , ^{239}Pu* , Sovt. Phys. JETP 6(33), No. 4, 825-826 (1958).
51. L. M. Belov, M. V. Blinov, N. M. Kazarinov, A. S. Krivokhatskii, and A. N. Protopopov, *Fission Neutron Spectra of ^{244}Cm , ^{242}Pu , ^{239}Pu* , Yadern. Fiz. 9(4), 727-731 (1969).

52. A. B. Smith, P. R. Fields, and J. H. Roberts, *Spontaneous Fission Neutron Spectrum of ^{252}Cf* , Phys. Rev. 108, 411-413 (1957).
53. A. B. Smith, R. K. Sjoblom, and J. H. Roberts, *Prompt Fission Neutron Spectrum of ^{241}Pu* , Phys. Rev. 123, 2140-2142 (1961).
54. Iu. S. Zamiatnin, I. N. Safina, E. K. Gutnikova, and N. I. Ivanova, *Spectra of Neutrons Produced by 14-MeV Neutrons in Fissile Materials*, Sovt. J. Atomic Energy 4, 443-449 (1958).
55. Yu. A. Vasil'ev, Yu. S. Zamyatnin, Yu. I. Il'in, E. I. Sirotinin, P. V. Toropov, and E. F. Fomushkin, *Measurements of the Spectra and Average Number of Neutrons Emitted in the Fission of ^{235}U and ^{238}U Induced by 14.3 MeV Neutrons*, Soviet Physics JETP 11, 483-492 (1960).
56. J. E. Hardy, *Response of a Liquid Scintillator to Fast Neutrons and γ -Radiation*, Rev. Sci. Instrum. 29, 705-709 (1958).