LA-7739-C (ENDF-278)
Conference Proceedings

Special Distribution
Issued: March 1979

Summary of Fission Spectrum Workshop

held at the National Neutron Cross Section Center

Brookhaven National Laboratory

October 23, 1978

Leona Stewart, Chairman

ATTENDEES

J. C. Browne, Lawrence Livermore Laboratory
M. Bhat, Brookhaven National Laboratory
C. Eisenhauer, National Bureau Standards
J. Hardy, Jr., Bettis Atomic Power Laboratory
B. R. Leonard, Jr., Battelle Pacific Northwest
D. Mathews, General Atomic Company
J. R. Nix, Los Alamos Scientific Laboratory
D. Olsen, Oak Ridge National Laboratory
Sol Pearlstein, Brookhaven National Laboratory
R. W. Peelle, Oak Ridge National Laboratory
E. Pennington, Argonne National Laboratory
W. P. Poenitz, Argonne National Laboratory
J. R. Smith, EG&G, Idaho Falls
L. Stewart, Los Alamos Scientific Laboratory, Chairman
P. G. Young, Los Alamos Scientific Laboratory

SUMMARY OF FISSION SPECTRUM WORKSHOP
held at the National Neutron Cross Section Center
Brookhaven National Laboratory
October 23, 1978

by

Leona Stewart
Chairman

ABSTRACT

In response to an action by the Standards Subcommittee of the Cross Section Evaluation Working Group, a workshop was convened to determine the status of available information on prompt fission neutron spectra. The experimental data were reviewed and theoretical models were developed. The current ENDF/B fission neutron spectra files were summarized. Further work is currently under way, especially to provide a better theoretical tool to represent energy-dependent fission spectra.

I. INTRODUCTION

This workshop covered a full day with much audience participation. It would be impossible to provide a complete summary and, in fact, the outline here does not include many items from my notes since the subjects are to be covered in invited papers planned for the Reactor Physics Division Special Session on Prompt Fission Neutron Spectra at the Atlanta ANS Meeting (June 3-8, 1979). In fact, most of the information presented at our Workshop will be covered at the Atlanta ANS Meeting. The Agenda for this Workshop is given in the Appendix.

II. FISSION SPECTRUM WORKSHOP

A. General (Leona Stewart)

The impetus for this meeting was to establish the status of fission neutron spectra, both prompt and delayed, and the energy-dependent delayed yields based on the needs of the evaluators of fissile and fertile materials. Due to time limitations and the fact that few of the people present were cognizant of the status pertaining to delayed neutron yields and spectra, only the prompt spectra were discussed at this particular workshop. Neither the prompt nor delayed gammas associated with the fission process were included on the agenda, although the γ yields and spectra are also important in the evaluation process.

The needs of the evaluators were summarized and the point stressed that almost nothing is known about the dependence of the prompt fission spectra upon incident neutron energy since energy-dependent experimental measurements available today are sparse and the few data sets which exist are inconclusive. That the shape and average energy of the fission neutron spectrum is important has been ably demonstrated for several thermal reactor systems by Steen[1] and Hardy et al.[2] at Bettis. Some work has also been undertaken on fast-reactor systems.[3] Both the shape and average energy are important in predicting reaction-rate ratios in fast-reactor benchmarks, especially for reactions dominated by threshold effects.

The Evaluated Nuclear Data File, Version B (ENDF/B) has provision for several types of spectral information. For the prompt neutron fission spectra, Version V has been updated to allow an energy-dependent Watt formalism and this form is recommended for the important fissile and fertile isotopes: Th-232, U-233, U-235, U-238, and Pu-239. Although the Watt formalism can be used for all Version V evaluations, most of the fissile and fertile species will have the simpler Maxwellian form carried over from Version IV. These two expressions are given below.

1. Energy-dependent Maxwellian

$$F(E_{n'}) = C(E_0)\sqrt{E_{n'}}\; e^{-E_{n'}/T(E_0)} \; ; \quad \bar{E}_{n'} = 3T/2 \quad ,$$

where C is the normalization constant, and T is the so-called temperature of the distribution function, at the incident neutron energy E_0.

2. Energy-dependent Watt formalism

$$F(E_{n'}) = D(E_0)\; e^{-E_{n'}/a(E_0)} \sinh\sqrt{b(E_0)E_{n'}} \; ; \quad \bar{E}_{n'} = 3a/2 + ba^2/4 \quad ,$$

where D is the normalization constant.

Strictly speaking, other formats for fission neutron energy spectra are allowed in ENDF/B. In fact, above the first-, second-, and third-chance fission thresholds, a combination of two or more spectra are required. As an example of the representation of the spectrum associated with second-chance fission, (n,n'f), the first neutron is generally assumed to be evaporated from the compound nucleus X, leaving the target nucleus Y at an excitation energy high enough to fission. Therefore, the prompt spectrum associated with the second-chance fission process consists of the combination of the inelastically scattered neutron from the target Y and the neutron spectrum from the fissioning of the target nucleus Y. To this spectrum must be added the contribution from first-chance fission through the compound nucleus.

To properly represent the fission process, the evaluator must provide the total fission cross section as a function of incident neutron energy in ENDF File 3, MT=18, where MT is the reaction index. The total fission cross section is the sum of all partial fission cross sections such as (n,n'f) (MT=20), (n,2nf) (MT=21), (n,3nf), etc., along with the direct fission of the compound nucleus usually represented as (n,f) (MT=19). The average number of prompt ($\bar{\nu}_p$) and delayed ($\bar{\nu}_d$) neutrons per fission along with their sum are placed in File 1 in retrievable form. Since few neutrons appear in a fission reactor spectrum above the second-chance fission threshold, thermal and fast-reactor calculations can usually be simplified to the treatment of first-chance fission alone.

B. Theoretical (Ray Nix)

Ray Nix introduced a theoretical derivation representing the prompt fission spectra. The derivation, based on physical grounds, was reduced to a Watt distribution upon the application of several simplyfing assumptions.* He pointed out that the Watt formalism is a better representation of the prompt spectra than the Maxwellian function used for most ENDF materials. However, the Watt parameters chosen for ENDF/B-V were based on fits to data rather than physics constants; therefore, a better understanding of the physical derivation is most important.

*These assumptions are currently being tested and further developments will be presented at the forthcoming Atlanta ANS Meeting.

Briefly, Nix derived spectral parameters by starting with the Weisskopf formalism for the evaporation of neutrons in the center-of-mass system for a highly excited nucleus at a single temperature T.

$$\phi(\varepsilon) = k_0\ \sigma(\varepsilon)\ \varepsilon\ e^{-\varepsilon/T} \quad ,$$

where ε is the emitted neutron energy, k is the normalization constant, and $\sigma(\varepsilon)$ is the compound nucleus cross section for the inverse process and is assumed to be independent of energy. The probability p(T), corresponding to the distribution of fission-fragment excitation energy, is approximated by a linear function of T from T = 0 to the upper limit T_{max}.

The spectrum $\Phi(\varepsilon)$ obtained by integrating over T is given in terms of an exponential integral, which is approximated by the functional form

$$\Phi(\varepsilon) = k_1\ \sqrt{\varepsilon}\ e^{-\varepsilon/T_{ef}} \quad .$$

The average energy $\bar{\varepsilon}$ corresponding to the original and approximate forms for $\Phi(\varepsilon)$ is

$$\bar{\varepsilon} = \frac{4}{3} T_{max} = \frac{3}{2} T_{ef} \quad ,$$

which leads to the relationship

$$T_{ef} = \frac{8}{9} T_{max} \quad .$$

Transformation into the laboratory system reduces to the Watt distribution

$$N(E) = k_2\ e^{-E/T_{ef}}\ \sinh\left(2\sqrt{EE_F}\ /\ T_{ef}\right) \quad ,$$

where E is the emitted neutron energy in the laboratory system and E_F is the average fission-fragment kinetic energy per nucleon. The two constants E_F and T_{ef} need not be adjusted to reproduce prompt fission neutron spectra, but can instead be determined a priori from other physical considerations.

(The derivation will be given in detail in a forthcoming paper by Nix and Madland; to be published. In addition, the assumptions used in the derivations themselves will be studied to show the magnitude effects.)

For a fixed (Z,A), it is reasonable to make the further assumption that E_F is constant with increasing neutron energy; that is, the extra energy goes into excitation energy. Then using the thermal measurements to determine T_{ef}, one approximates the energy dependence of T_{ef} by

$$T_{ef} \approx T_{ef}^{0} + \frac{4}{9} \frac{E_n}{aT_{ef}^{0}} \quad ,$$

where $a \approx A/8$ MeV.

As mentioned earlier, the Watt formalism has been used for several ENDF/B-V materials but no physical interpretations were taken into account in deriving the two constants T_{ef} and E_F. Therefore, further work is under way to check the validity of the approximations for the Watt derivation and also to check the changes which could be incorporated into ENDF/B-VI to give physical significance to the parameters.

C. Experimental

1. Review of Available Data (John Browne). The experimental problems of measuring prompt fission spectra were outlined in detail by John Browne. Everyone agreed that experiments are difficult to perform and, in fact, very few measurements exist which satisfy minimum criteria. The following problems were outlined by Browne with others contributing from the floor:

a. Was (n,γ) discrimination used? If so, was it properly taken into account?

b. Was the detector efficiency measured? If so, how and exactly what data were used as the Standard? As an example, was the (n,p) assumed isotropic in the efficiency measurement? Were relativistic corrections applied? If the detector efficiency was calculated but not measured, then how well could the calculated efficiency be determined?

c. How was the energy scale determined? Very little information, if any, is given in most reports. Even though the energy scale was accurately determined, resolution effects inherently lead to a biased shape for N(E) especially at high energies where the statistics are poor and the resolution effects large. Bo Leonard suggested these effects can be as high as 10-20% if no attempt is made to correct for resolution.

d. The energy scales are determined differently for TOF using a spontaneous fission source and that for a neutron-induced fission event. Questions have arisen regarding shape corrections which should be applied for Cf-252. (Whether this problem has been resolved was not known at the time of the meeting).

e. Angular distribution effects of the neutrons emitted from neutron-induced fission have not been studied in enough detail. Since the fission-fragments, themselves, are very anisotropic, depending upon (Z,A) and incident neutron energy and most of the neutrons are emitted from the moving fragments, angular distribution effects may be important at some energies.

f. For the experiments John Browne reviewed, he found that the sample thicknesses used varied greatly yet the data reduction analysis was not always performed in a consistent way. The samples were sometimes solid cylinders and other times hollow cylinders.

g. Whether or not air scattering, multiple scattering in the target, and other corrections were properly made is not always clear.

h. The dependence of the prompt neutron spectrum upon incident neutron energy is not well determined experimentally, even below the 2nd-chance fission threshold. Above this threshold, the spectrum is expected to have three components but this has not been determined experimentally.

i. The energy range covered by the measurements also varies greatly; for example, neutrons from 1-5 MeV may be detected in one experiment and from 0.5 to 15 MeV in another. These data are always relative and difficult to compare directly without some choice of normalization between the two. Even more important, different runs of the same experiment often disagree, and/or give results well outside the errors assigned to the average values.

j. The methods used for obtaining the average energy of the fission spectrum neutrons are not always equivalent yet often the analytic parameters and average energies are the only data published. If the data cover a wide enough range, the average energy should be checked by simple numerical integration of the results as measured.

Browne also discussed briefly Hauser-Feshbach calculations[4] which he had described in a paper published several years ago. He presented a summary outlining problems he found in recent experimental papers on fission spectra. The group completely endorsed the idea that experimentalists should include brief comments in their write-ups to insure that their data could be employed in a consistent manner.

<u>2. Fission Spectrum Effects in $\bar{\nu}$ Measurements (J. Richard Smith)</u>. The effect of the fission spectrum upon $\bar{\nu}$ measurements is concerned principally with neutron leakage in the experiment involved. In manganese bath measurements the

neutron loss through leakage is usually near 0.25% for a fission spectrum. Differences in spectrum shape have some effect on this figure, but in view of the small size of the correction, small changes in the shape of the assumed spectrum are of relatively minor importance.

Spectral shape has a greater effect in liquid scintillators whose efficiency for fission spectrum neutrons is near 85%. In these experiments a neutron efficiency as a function of neutron energy and angle of entry into the bath is established by observing the capture probability in the tank of neutrons which have been scattered by hydrogen in a recoil proton detector. The incident neutron energy is known either by time-of-flight or reaction kinematics so the energy and angle of the scattered neutron can be deduced from the pulse height in the proton recoil detector. As these efficiency measurements can cover only a limited portion of the scintillator's solid angle, Monte Carlo calculations, normalized to the measured efficiencies, are used to complete the picture. The efficiency relation thus determined must then be folded into the fission spectrum to determine the probability of observing an event in a $\bar{\nu}$ measurement. Boldeman modified his ^{252}Cf $\bar{\nu}$ value by 0.1 to 0.2% when he received evidence that the average energy of the fission spectrum was higher than he had assumed. Frehaut has noted that changing to a Watt spectrum would change his $\bar{\nu}$ values by 0.21%. These are sizeable changes for a quantity for which better than 0.5% accuracy is desired.

D. Energy Dependence of the Prompt Spectra

For the time being, theoretical treatment will be further pursued and checks made against the few experiments which exist. The general consensus is that we have a long road ahead before we can place confidence in our data on energy-dependent spectra.

E. Status of Delayed Yields and Spectra

This item was put off until a later date since the people apprised of the problem did not attend this special session.

F. NBS Standard Spectra (Charles Eisenhauer)

Eisenhauer has developed "Standard" spectra for U-235 at thermal and for spontaneous fission of Cf-252. These spectra are represented by a segmented formalism. That is, the spectra have been split into energy intervals based on activation measurements and then each segment expanded analytically in powers of E. The result is essentially a correction to a Maxwellian distribution. It was noted, however, that the "corrected" Maxwellian for U-235 is very close to the Watt distribution except for a large number of neutrons below 1 MeV often but not always seen in recent measurements. Eisenhauer has under way a new analysis for both U-235 (thermal only) and for Cf-252 and close coordination with CSEWG will be maintained in any reanalysis of the NBS standards. The large proportion of neutrons below 1 MeV has surfaced in many experiments and must be considered by all users and evaluators, not restricted to NBS standards applications.

G. Adjourned

The meeting was adjourned with the recommendation that experimental and theoretical work should continue with the hope that the ENDF/B-VI files could be improved. In addition, better physical understanding of the fission process would be very useful in the evaluation procedures.

ACKNOWLEDGMENTS

The participation and contributions of those attending the workshop are gratefully appreciated.

REFERENCES

1. N. M. Steen, "Status of Nuclear Data for ^{232}Th and ^{233}U," Trans. Am. Nucl. Soc. 28, 712 (1978).

2. J. Hardy, Jr., "The Performance of ENDF/B Data in Thermal Reactor Benchmark Testing - Some Results with Version IV and Prospects for Version V," Trans. Am. Nucl. Soc. 28, 736 (1978); See also; J. Hardy, Jr., J. J. Ullo, and N. M. Steen, "Integral Testing of Thorium and ^{233}U Data for Thermal Reactors," Trans. Am. Nucl. Soc. 28, 714 (1978).

3. E. Kujawski and L. Stewart, "The Prompt-Neutron Fission Spectrum for ^{239}Pu," Trans. Am. Nucl. Soc. 24, 453 (1976).

4. J. C. Browne and F. S. Dietrich, "Hauser-Feshbach Calculation of the ^{252}Cf Spontaneous-Fission Neutron Spectrum," Phys. Rev. C10, 2545 (1974).

APPENDIX

NEUTRON INDUCED FISSION SPECTRA WORKSHOP

October 23, 1978

Building 197
National Nuclear Data Center
Brookhaven National Laboratory

Lee Stewart (LASL), Chairman

9:00 a.m.	Introduction	Stewart, LASL
9:10 a.m.	Outline of information needed by evaluators of fissile-fertile isotopes	All
9:30 a.m.	Theoretical aspects	Ray Nix, LASL
10:00 a.m.	Experimental - Background and new data	John Browne, LLL
10:30 a.m.	Coffee	
10:50 a.m.	Energy dependence of the prompt spectrum	All
11:20 a.m.	Status of delayed yields and spectra	Postponed
11:50 a.m.	LUNCH	
1:15 p.m.	Discussion - Outlined present status and knowledge	All
3:00 p.m.	Coffee	
3:20 p.m.	Recommendations: Experimental Theoretical	All
4:00 p.m.	NBS Standard spectra	Eisenhauer, NBS
4:30 p.m.	Effect of prompt spectrum on $\bar{\nu}_p$	Smith, INEL