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ANL/NDM-74

Evaluation of the ^{238}U Neutron Total Cross Section

by

A. Smith, W. Poenitz, and R. Howerton

December 1982

ARGONNE NATIONAL LABORATORY,
ARGONNE, ILLINOIS 60439, U.S.A.

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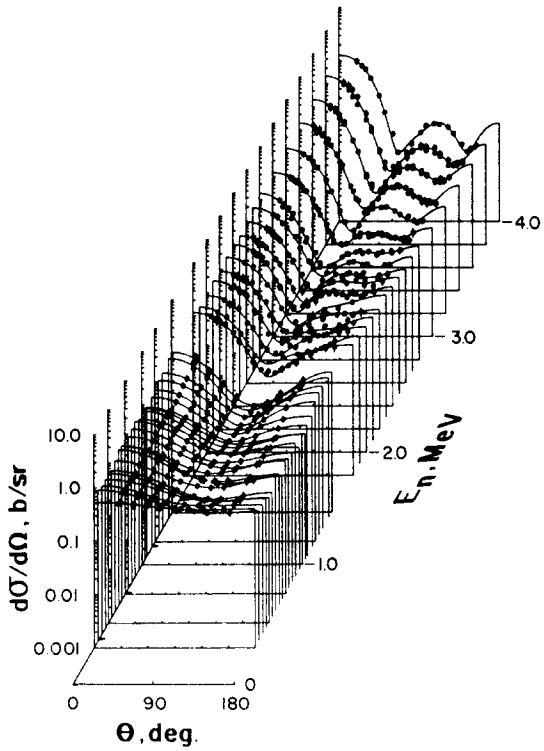

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*This work supported by the U.S. Department of Energy
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ANL/NDM-73 Fast-neutron Elastic Scattering Cross Sections of Elemental Tin by Alan B. Smith, Carl Budtz-Jørgensen and Peter T. Guenther, July 1982.

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EVALUATION OF THE ^{238}U NEUTRON TOTAL CROSS SECTION*

by

A. Smith, W. P. Poenitz, and R. J. Howerton

ABSTRACT

Experimental energy-averaged neutron total cross sections of ^{238}U were evaluated from 0.044 to 20.0 MeV using rigorous numerical methods. The evaluated results are presented together with the associated uncertainties and correlation matrix. They indicate that this energy-averaged neutron total cross section is known to better than 1% over wide energy regions. There are somewhat larger uncertainties at low energies (e.g., $\lesssim$ 0.2 MeV), near 8 MeV and above 15 MeV. The present evaluation is compared with values given in ENDF/B-V.

*This work supported by the U.S. Department of Energy.

I. INTRODUCTION

Precise knowledge of the energy-averaged neutron total cross sections of ^{238}U is important to: i) macroscopic neutron transport, where the total cross section governs the mean-free-path, ii) evaluation, where the cross section is the envelope to which the partial cross sections must conform, and iii) model development, where the total cross section forms a benchmark for testing model parameters. Here we assume the energy-averaged region extends upward in the energy from the inelastic-scattering threshold (45 keV). At lower energies, resolved and unresolved resonance treatments are more appropriate. The upper-energy limit of evaluations relevant to fission-energy systems is conventionally set at 20 MeV and is accepted in this work.

That the ^{238}U energy-averaged neutron total cross section should be well known was recognized at the recent NEANDC Specialist's Meeting on Fast-Neutron Scattering on Actinide Nuclei[1], and there it was recommended that a rigorous evaluation be undertaken in an effort to quantify the contemporary accuracies. This work is in response to that recommendation.

II. OUTLINE OF THE DATA BASE

The majority of the data base was assembled from the numerical data files of the Lawrence Livermore National Laboratory.[2] A few additional data sets were identified in CINDA[3], extracted from professional journals and/or reports, and added to the data base. Several more data sets are known to exist but they have not been formally reported and their authors did not choose to make them available through private communication. The complete experimental data base, outlined in the Appendix, consisted of 33 sets. All were the result of transmission measurements using either white- or monoenergetic-neutron sources. They span a period of approximately three decades. Only two of the sets are more recent than 1974, and only one of these extends above 0.1 MeV. Many are not well specified and their assessment is, to a considerable extent, a subjective exercise.

III. EVALUATION PROCEDURES AND RESULTS

The evaluation proceeded in five steps. First, all of the data sets were inspected using large-scale graphical displays. From this inspection a few data sets were abandoned as: i) being grossly discrepant with the body of the data base, ii) consisting of values with a large scatter widely exceeding statistical uncertainties, and iii) having such large stated uncertainties as to result in a negligible weight in the subsequent evaluation process. Several data sets systematically deviated from the majority of the data in some energy regions. Most of these cases resulted from white-source measurements, and the effect was most prominent in the lower-energy extreme of the data set where background effects could have perturbed the experimental results. In these cases the data set was truncated, deleting regions of obvious qualitative discrepancy. Some data sets were identified as superseded by later and improved work by the same authors. In these instances the earlier and less accurate data were deleted from the data base. At low energies self-shielding effects are a concern.[4] Two sets of data appeared to

give attention to this matter, providing either fully corrected data[4] or sufficient information to make such corrections possible[5]. Thus, other low-energy ($\lesssim$ 0.2 MeV) data sets with results significantly below the more reliable corrected information were abandoned as probably distorted by self shielding. The above qualitative judgements are indicated in the Appendix.

Data, having passed through the above filtering process, were then examined for error specification. Only two sets of data reasonably defined both statistical and systematic uncertainties.[4,5] In these two cases the uncertainties were accepted as stated. For the majority of the data sets only the statistical uncertainties were clearly stated and they were accepted as given by the authors. Where no statistical uncertainty was given a 1-1/2% value was assumed as a conservative estimate of the statistical uncertainty of a typical transmission experiment. Estimates of systematic uncertainties are far more difficult to quantify as they can result from a number of effects; some of the more prominent of these were obviously not recognized by the experimenters. Above 0.2 MeV, in the absence of a specified systematic uncertainty, a value of 1-1/2% was assumed as representative of a measurement with reasonable attention to background, sample properties, deadtime effects, etc. Below 0.2 MeV the systematic uncertainties were assumed to increase linearly with decreasing energy to 3% at 44 keV. This increase was assumed to be an approximate estimate of unknown selfshielding perturbations. In the absence of quantitative specification, the above uncertainty estimates are obviously qualitative generalizations. These estimates may have shortcomings for any one data set but, hopefully, they generally reflect the physical situation. In the absence of more detailed information there is little alternative. One data set appeared to be of excellent relative quality (i.e., the shape was very consistent with the trend body of the data but it was systematically lower in magnitude than the assemblage of data by 2-3 times the above systematic uncertainty estimates. For this set, the systematic uncertainty estimates were increased by a factor of two.

The goal was an evaluated energy-averaged cross section. Below $\approx$ 0.1 MeV structure can be 5% or more in magnitude in a 5 keV average[5] and the structure persists into the MeV region with very much smaller magnitudes.[6] Thus the data were averaged over energy increments that would generally smooth fluctuations while maintaining the overall energy dependence. These increments were; 10 keV < 0.2 MeV, 25 keV from 0.2 to 1.0 MeV, 50 keV from 1.0 to 5.0 MeV, and 100 keV from 5.0 to 20.0 MeV. Since averaging increments generally exceeded the experimental energy resolutions, the energy-averaging increments were considered in the subsequent numerical procedures. The weighted averages and associated statistical uncertainties were constructed assuming weighting factors inversely proportional to the square of the statistical uncertainties. The systematic uncertainties were assumed to be constant over the averaging increment. Thus the systematic uncertainties of the averaged values were taken to be a simple average[5] of the individual components. The averaging procedure also reduced the data base to manageable proportions (some of the input data sets consisted of thousands of individual values).

The above averaged experimental data were evaluated using the numerical procedures as implemented in the Gauss-Markov-Aitken least-squares nuclear-data evaluation program, GMA.[7] The result is the "best" estimate of the global

experimental knowledge of the ^{238}U energy-averaged neutron total cross section, inclusive of uncertainties and correlation matrix. This evaluated result is entirely founded on experiment and may reflect experimental artifacts that are not necessarily physically acceptable.

In order to remove small experimental artifacts from the evaluation and to provide a physically acceptable vehicle for interpolating between evaluated quantities, a conventional spherical optical model was chi-square fitted to the evaluated results, weighting with the respective evaluation uncertainties. Both real and imaginary potential strengths were assumed to have a linear energy dependence. The fitting procedure[8] varied concurrently the eight parameters; real and imaginary, strengths, radii, diffusenesses, and energy dependences. The resulting parameters are given in Table 1. It should be emphasized that they are a parameterization of the evaluation suitable for the assessment of general trends and for interpolation between evaluated quantities. They should not be construed as representative of a general model suitable for all aspects of the fast-neutron interaction with ^{238}U. In fact, the parameters of Table 1 are not conventional and the model gives no attention to the known deformation of the target. These shortcomings do not impair the usefulness of the model in the present context of energy interpolation.

The uncertainties associated with the experimental evaluation are shown in Fig. 1. They are generally less than 1% and increase to 2-3% only in a local region near 0.15 MeV. The optical-model results provide an excellent parameterization of the evaluated experimental results, as shown in Figs. 1 and 2. Generally, the differences between the model- and evaluation-results are smaller than the uncertainties of the latter alone. The model smooths small data and evaluation artifacts. The most prominent of these is near 8 MeV where the model results are $\approx$ 2.5% larger than those of the numerical evaluation. This local artifact was identified as primarily due to one highly weighted data set which appears to have low values in this local region. The model was used to interpolate the numerical-evaluated quantities to a regular energy mesh to obtain the final evaluated results and associated uncertainties (given by the numerical evaluation) given in Table 2. The corresponding correlation matrix is given in Table 3.

IV. COMPARISONS WITH ENDF/B-V

The ENDF/B-V evaluation[9] is so similar to the present results that differences are not clearly evident in graphical comparisons. The ENDF/B-V values are systematically larger than those implied by the present work but by amounts well within the respective uncertainties. Illustrative numerical comparisons are given in Table 4. From 0.2 to 15.0 MeV, the two evaluations agree to better than 1%. At the very lowest and very highest energies the ENDF/B-V values are 1-2% larger than those of the present evaluation. The differences throughout the energy range are well within the respective uncertainties. The uncertainties associated with present evaluation are 4-5 times smaller than those suggested for ENDF/B-V over much of the energy range.[10] ENDF/B-V is a subjective construction based upon graphical representations of much the same data as used in the present work. The latter procedure gave essentially the same result as the numerical methods of the present work but without the detailed uncertainty specifications.

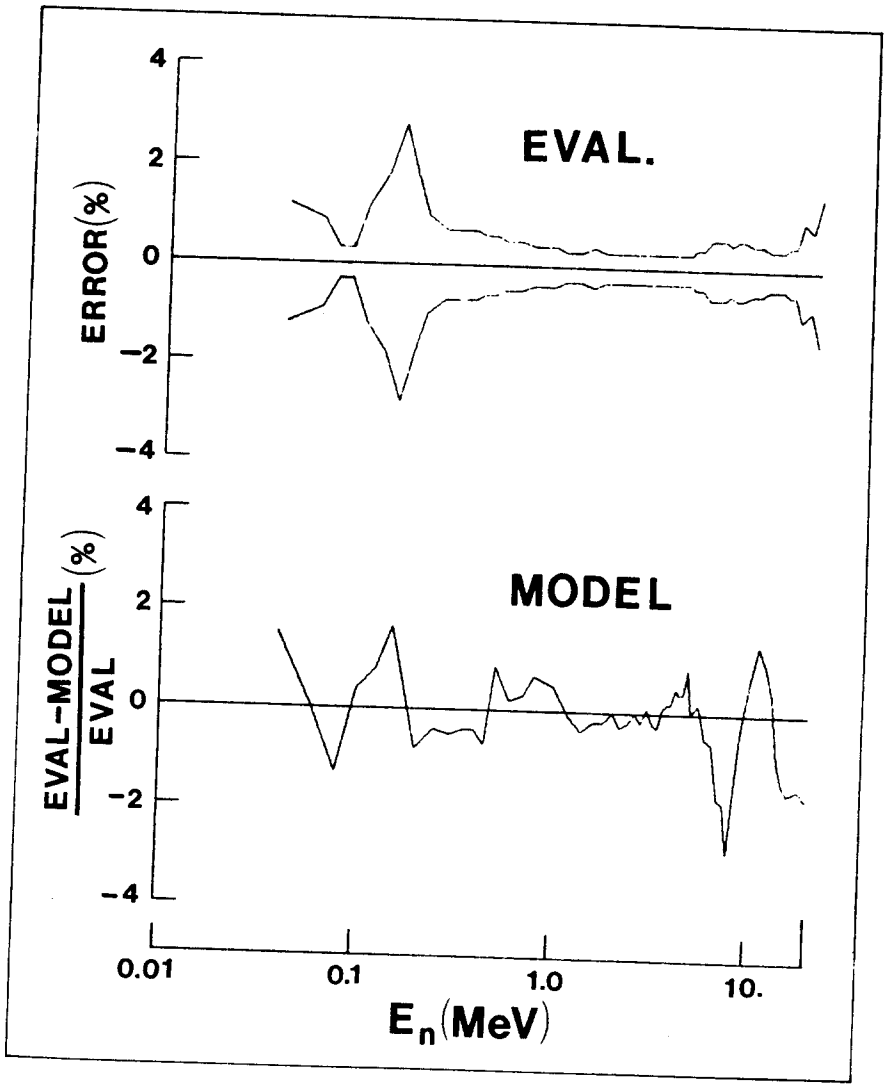

Fig. 1. Experimental-Evaluation Uncertainties (Upper) and Deviation of the Model Result from the Experimental-Evaluation (Lower).

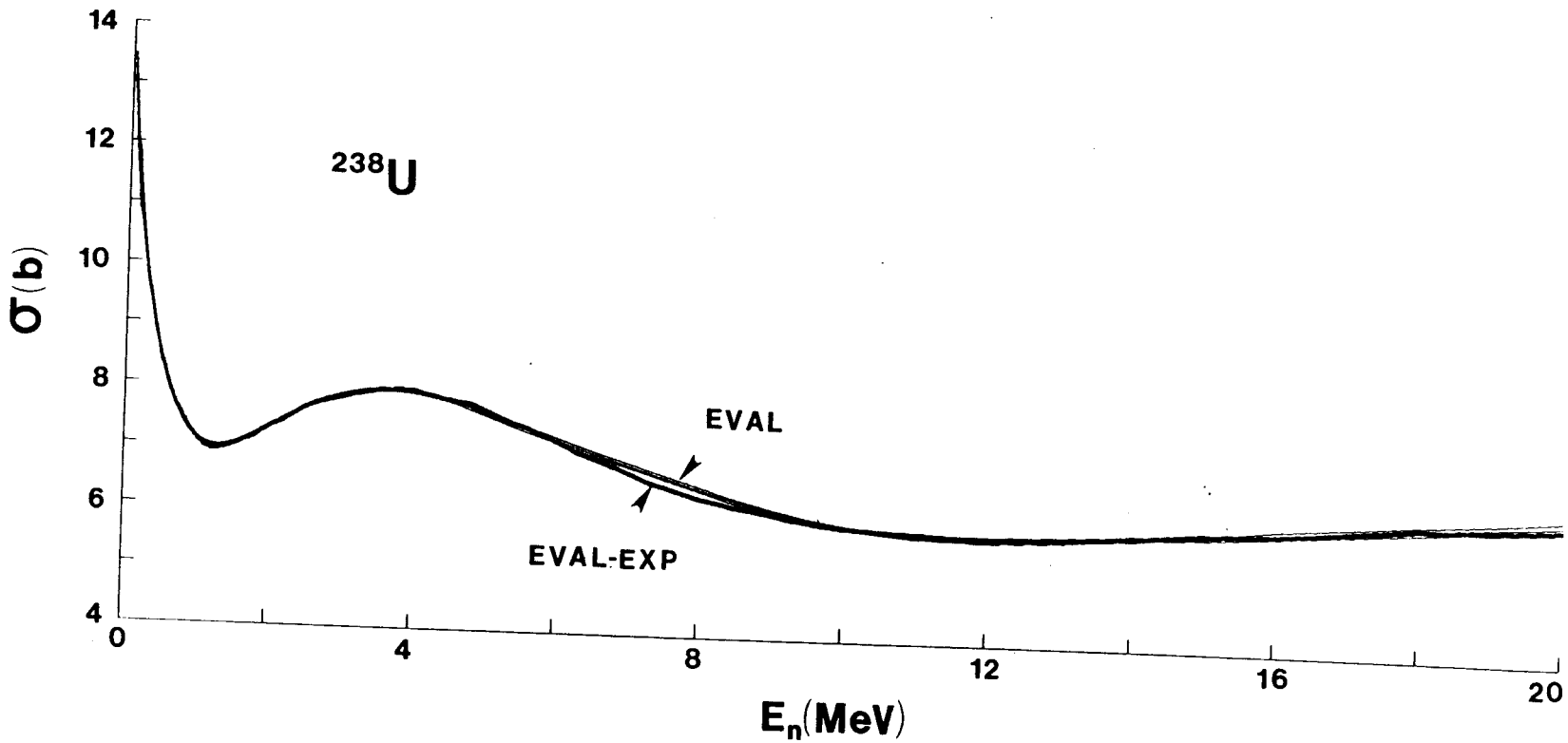

Fig. 2. Evaluated Neutron Total Cross Sections of ^{238}U. Heavy curve indicates the result of the numerical experimental evaluation, the light curves the final evaluation (± uncertainty).

V. CONCLUDING COMMENTS

The present evaluation defines the ^{238}U energy-averaged neutron total cross section to better than 1% over very wide energy ranges with only a limited area near 0.15 MeV where the uncertainties increase to 2-3%. The evaluation gives a reasonable estimate of uncertainty and the associated correlation matrix. The results imply a well known neutron total cross section of essentially a "standard" quality. A model is deduced which gives an excellent parameterization of the evaluation results and which is suitable for interpolating between the evaluated quantities. That model may not be appropriate in other contexts as it is a simple concept. In particular, it ignores collective-deformation effects. The numerical evaluation procedures are rigorous. However, underlying them are subjective judgements necessary for providing the requisite experimental data base. Much of the data base is old with poorly defined (or non-existent) specification of uncertainties, particularly of systematic uncertainties. In a number of instances it appears that very significant systematic uncertainties have escaped the knowledge of the respective experimentalists. Further improvement will require very appreciable new input with detailed attention given to both statistical and systematic uncertainties. That event seems unlikely in the near future. The present results are essentially identical to those of ENDF/B-V. They do provide a quantification of uncertainty that was heretofore lacking.

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8. A. Smith, unpublished data (1969).
   Monoenergetic Source, $E_n = 0.6 - 1.4$ MeV, large scatter, preliminary data, abandoned.

9. S. Mubarakmand et al., Nucl. Instr. and Methods, 115 345 (1974).
   Monoenergetic Source, $E_n = 1.7 - 14.3$ MeV, scattered values, bad shape above $\approx$ 5 MeV, abandoned.

10. R. Batchelor et al., Nucl. Phys., 65 236 (1965).
    Monoenergetic Source, $E_n = 2 - 7$ MeV, few points, used.

11. D. Foster and D. Glasgow, Phys. Rev., C3 604 (1971).
    White Source, $E_n = 2.2 - 15.0$ MeV, used.

12. C. Thibault, CEA-R-3124 (1967).
    Monoenergetic Source, $E_n = 0.1 - 1.5$ MeV, single very low value, abandoned.

13. A Bratenahl et al., Phys. Rev., 110 927 (1950).
    Monoenergetic Source, $E_n = 7 - 14$ MeV, used.

14. D. Didier, J. Phys. and Rad., 22 651 (1961).
    Monoenergetic Source, $E_n = 14.7$ MeV, single value used.

15. J. Peterson et al., Phys. Rev., 120 521 (1960).
    Monoenergetic Source, $E_n = 17.3$ MeV, single value, used.

APPENDIX - DATA BASE (Cont'd.)

15. J. Peterson et al., Phys. Rev., 120 521 (1960).
Monoenergetic Source, E_n = 17.3 MeV, single value, used.

16. W. Poenitz et al., Nucl. Sci. and Eng., 78 333 (1981).
Monoenergetic and White Source, E_n = 0.045 - 4.8 MeV, used.

17. C. Hibdon, ANL unpublished (1953).
Monoenergetic Source, E_n = 0.04 - 0.15 MeV, large scatter, abandoned.

18. V. Filippov et al., ACC-68/17 (1968).
E_n = 0.05 - 0.3 MeV, generally very low magnitudes. Probably distorted by self shielding, abandoned.

19. H. Willard et al., Nucl. Phys., (1950).
Monoenergetic Source, E_n = 0.06 - 1.4 MeV, large scatter, abandoned.

20. R. Henkel et al., Phys. Rev., 94 141 (1954).
Monoenergetic Source, E_n = 0.1 - 20.0 MeV, used.

21. M. Divadeenam et al., Thesis Abstracts, 8 28, 3834 (1968).
Monoenergetic Source, E_n = 0.15 - 0.6 MeV, systematically low above 0.2 MeV and probably distorted by self-shielding at lower energies, abandoned.

22. D. Kopsch et al., Proc. Conf. on Nucl. Data for Reactors, 2 39 (1970)
White Source, E_n = 0.5 - 4.35 MeV, abandoned below 0.7 MeV as systematically too large, used above 0.7 MeV.

23. W. Good et al., Phys. Rev., 59 917 (1941).
Monoenergetic Source, E_n = 0.9 MeV, apparently discrepant single value, abandoned.

24. A. Smith, ANL-7110 (1965).
Monoenergetic Source, E_n = 0.8 - 1.5 MeV, scattered points - poor quality, abandoned.

25. J. Leroy et al., J. Phys., 24 826 (1963).
Monoenergetic Source, E_n = 1.6 - 14.5 MeV, scattered values, abandoned.

26. N. Neneson et al., LA-1655 (1954).
Monoenergetic Source, E_n = 2.9 - 14.1 MeV, reasonable looking data but errors are $\gtrsim$10% therefore abandoned.

27. F. Manero, Anales Fisica 66 271 (1970).
Monoenergetic Source, E_n = 3.5 - 5.1 MeV, used.

28. J. Vervier et al., Nucl. Phys., 6 260 (1958).
Monoenergetic Source, E_n = 13.6 - 14.7 MeV, appears to have both magnitude and shape error, abandoned.

APPENDIX - DATA BASE (Contd.)

29. M. Khaletski, DOK-AKAD-NAUK (USSR) 13 305 (1957).
Monoenergetic Source, E_n = 14.8 MeV, discrepant value, abandoned.

30. P. Bowen et al., Nucl. Phys. 22 640 (1960).
Monoenergetic Source, E_n = 15.8 - 20 MeV, large scatter with large uncertainties, however used.

31. R. Day et al., Phys. Rev., 92 358 (1958).
Monoenergetic Source, E_n = 17.9 - 19.0 MeV, used.

32. D. Syme et al., Ann. Nucl. Energy, 1 305 (1974).
White Source, E_n = 0.8 - 8.9 MeV, shape appears good but normalization is low compared to body of information. Used with increased systematic error for all values (3%).

33. D. Olsen et al., ORNL/TM-5915 (1977).
White Source, $E_n \lesssim 0.1$ MeV, used 5 keV average values corrected to infinitely thin samples assuming linear dependence of self-shielding on sample thickness. The correction may be slightly underestimated.

Table 1. Spherical Optical-Model Parameters for the ^{238}U Evaluation[a]

Real Potential[b]			
Strength[c]	V_o =	43.167	MeV
Radius[d]	R_v =	1.290	F
Diffuseness	a_v =	0.310	F
Imaginary Potential[c]			
Strength[f]	W =	2.313	MeV
Radius	R_w =	1.072	F
Diffuseness	a_w =	1.413	F
Spin-orbit Potential[g]			
Strength	V_s =	6.0	MeV

[a]Explicitly relevant only to the parameterization of the present evaluation.

[b]Saxon form.

[c]Assume energy dependence of form $V = V_o - 0.1046\ E(MeV)$.

[d]All radii expressed in the form $R = R_x A^{1/3}$.

[e]Saxon-derivative form.

[f]Energy dependence of the form $W = W_o + 0.0728\ E(MeV)$.

[g]Thomas form, dimensions same as real potential.

TABLE 2. EVALUATED U-238 NEUTRON TOTAL CROSS SECTIONS

EN(MEV)	XSEC(B)	DXSEC(B)	EN(MEV)	XSEC(B)	DXSEC(B)
0.44000E-01	0.13280E+02	0.19800E+00	0.50000E-01	0.12840E+02	0.13100E+00
0.60000E-01	0.12840E+02	0.11500E+00	0.70000E-01	0.12410E+02	0.11300E+00
0.80000E-01	0.12410E+02	0.11100E+00	0.90000E-01	0.12060E+02	0.12200E+00
0.10000E-00	0.12060E+02	0.14400E+00	0.12000E+00	0.11470E+02	0.21100E+00
0.14000E+00	0.11470E+02	0.32100E+00	0.16000E+00	0.10970E+02	0.32100E+00
0.18000E+00	0.10970E+02	0.19700E+00	0.20000E+00	0.10480E+02	0.10700E+00
0.22500E+00	0.10480E+02	0.89000E-01	0.25000E+00	0.10000E+02	0.71000E-01
0.27500E+00	0.10000E+02	0.69000E-01	0.30000E+00	0.95940E+01	0.68000E-01
0.32500E+00	0.95940E+01	0.67000E-01	0.35000E+00	0.92300E+01	0.66000E-01
0.37500E+00	0.92300E+01	0.60000E-01	0.40000E+00	0.89070E+01	0.54000E-01
0.42500E+00	0.89070E+01	0.53000E-01	0.45000E+00	0.86210E+01	0.52000E-01
0.47500E+00	0.86210E+01	0.47000E-01	0.50000E+00	0.82520E+01	0.42000E-01
0.55000E+00	0.82520E+01	0.41000E-01	0.60000E+00	0.78560E+01	0.40000E-01
0.65000E+00	0.78560E+01	0.36000E-01	0.70000E+00	0.75520E+01	0.31000E-01
0.75000E+00	0.75520E+01	0.30500E-01	0.80000E+00	0.73280E+01	0.30000E-01
0.85000E+00	0.73280E+01	0.29500E-01	0.90000E+00	0.71670E+01	0.29000E-01
0.95000E+00	0.71670E+01	0.25000E-01	0.10000E+01	0.70230E+01	0.21000E-01
0.11000E+01	0.70230E+01	0.21000E-01	0.12000E+01	0.69650E+01	0.21000E-01
0.13000E+01	0.69650E+01	0.24500E-01	0.14000E+01	0.70100E+01	0.28000E-01
0.15000E+01	0.70100E+01	0.24500E-01	0.16000E+01	0.71120E+01	0.21000E-01
0.17000E+01	0.71120E+01	0.21000E-01	0.18000E+01	0.72430E+01	0.22000E-01
0.19000E+01	0.72430E+01	0.22000E-01	0.20000E+01	0.74500E+01	0.22000E-01
0.22000E+01	0.74500E+01	0.22000E-01	0.24000E+01	0.76940E+01	0.22000E-01
0.26000E+01	0.76940E+01	0.23000E-01	0.28000E+01	0.78680E+01	0.23000E-01
0.30000E+01	0.78680E+01	0.23000E-01	0.32000E+01	0.79610E+01	0.23000E-01
0.34000E+01	0.79610E+01	0.23000E-01	0.36000E+01	0.79700E+01	0.23000E-01
0.38000E+01	0.79700E+01	0.23000E-01	0.40000E+01	0.79050E+01	0.23000E-01
0.42000E+01	0.79050E+01	0.23000E-01	0.44000E+01	0.77850E+01	0.23000E-01
0.46000E+01	0.77850E+01	0.31000E-01	0.48000E+01	0.76230E+01	0.31000E-01
0.50000E+01	0.76230E+01	0.30000E-01	0.55000E+01	0.72180E+01	0.44000E-01
0.60000E+01	0.72180E+01	0.43000E-01	0.65000E+01	0.68350E+01	0.42000E-01
0.70000E+01	0.68350E+01	0.34000E-01	0.75000E+01	0.64640E+01	0.36500E-01
0.80000E+01	0.64640E+01	0.39000E-01	0.85000E+01	0.61320E+01	0.35000E-01
0.90000E+01	0.61320E+01	0.31000E-01	0.95000E+01	0.59020E+01	0.30000E-01
0.10000E+02	0.59020E+01	0.29000E-01	0.11000E+02	0.57590E+01	0.23000E-01
0.12000E+02	0.57590E+01	0.23000E-01	0.13000E+02	0.58990E+01	0.23000E-01
0.14000E+02	0.58990E+01	0.29000E-01	0.15000E+02	0.60320E+01	0.29000E-01
0.16000E+02	0.60320E+01	0.61000E-01	0.17000E+02	0.62020E+01	0.62000E-01
0.18000E+02	0.62020E+01	0.63000E-01	0.19000E+02	0.63450E+01	0.63000E-01
0.20000E+02	0.63450E+01	0.80000E-01	0.00000E-01	0.00000E-01	0.00000E-01

TABLE 3. CORRELATION MATRIX (55 X 55)

EN(MEV)	MATRIX-ELEMENT VALUES													
0.044	1.00													
0.060	0.18	1.00												
0.080	0.18	0.17	1.00											
0.100	0.12	0.14	0.11	1.00										
0.125	0.03	0.05	0.03	0.08	1.00									
0.150	0.01	0.03	0.01	0.06	0.06	1.00								
0.175	0.01	0.02	0.01	0.04	0.04	0.04	1.00							
0.200	0.02	0.02	0.02	0.04	0.03	0.03	0.04	1.00						
0.250	0.02	0.03	0.02	0.04	0.04	0.03	0.05	0.11	1.00					
0.300	0.02	0.03	0.02	0.04	0.04	0.02	0.04	0.12	0.14	1.00				
0.350	0.02	0.02	0.02	0.04	0.04	0.02	0.04	0.12	0.13	0.17	1.00			
0.400	0.02	0.03	0.02	0.05	0.04	0.02	0.05	0.12	0.14	0.17	0.18	1.00		
0.450	0.02	0.03	0.02	0.05	0.05	0.02	0.05	0.13	0.15	0.18	0.19	0.20	1.00	
0.500	0.03	0.03	0.03	0.06	0.05	0.03	0.06	0.14	0.17	0.20	0.21	0.22	0.24	1.00
0.600	0.03	0.04	0.03	0.06	0.06	0.03	0.06	0.16	0.19	0.23	0.24	0.25	0.27	0.30
	1.00													
0.700	0.03	0.04	0.03	0.06	0.06	0.03	0.06	0.16	0.18	0.22	0.24	0.24	0.27	0.30
	0.34	1.00												
0.800	0.03	0.04	0.03	0.07	0.06	0.03	0.07	0.17	0.19	0.24	0.25	0.26	0.28	0.32
	0.37	0.39	1.00											
0.900	0.03	0.04	0.03	0.06	0.06	0.03	0.06	0.16	0.19	0.23	0.24	0.25	0.27	0.30
	0.35	0.36	0.41	1.00										
1.000	0.06	0.06	0.05	0.10	0.09	0.04	0.10	0.21	0.26	0.30	0.31	0.33	0.35	0.40
	0.46	0.54	0.59	0.59	1.00									
1.200	0.04	0.05	0.04	0.08	0.08	0.03	0.08	0.17	0.21	0.24	0.25	0.26	0.28	0.32
	0.36	0.37	0.42	0.41	0.75	1.00								
1.400	0.04	0.05	0.04	0.08	0.07	0.03	0.07	0.16	0.19	0.22	0.23	0.24	0.26	0.29
	0.34	0.35	0.39	0.39	0.72	0.56	1.00							
1.600	0.05	0.05	0.04	0.08	0.08	0.03	0.08	0.17	0.20	0.24	0.25	0.26	0.28	0.32
	0.37	0.37	0.42	0.41	0.76	0.59	0.57	1.00						
1.800	0.04	0.05	0.04	0.08	0.08	0.03	0.08	0.16	0.19	0.23	0.23	0.25	0.26	0.30
	0.34	0.35	0.40	0.39	0.74	0.57	0.56	0.60	1.00					
2.000	0.05	0.05	0.04	0.08	0.08	0.03	0.08	0.16	0.20	0.24	0.24	0.26	0.28	0.31
	0.36	0.37	0.41	0.41	0.74	0.58	0.56	0.61	0.60	1.00				
2.200	0.04	0.05	0.04	0.08	0.08	0.03	0.08	0.16	0.19	0.22	0.23	0.24	0.26	0.29
	0.34	0.35	0.39	0.39	0.71	0.56	0.54	0.59	0.58	0.60	1.00			
2.400	0.04	0.05	0.04	0.08	0.07	0.03	0.08	0.15	0.19	0.22	0.23	0.24	0.25	0.29
	0.33	0.34	0.39	0.38	0.70	0.55	0.54	0.58	0.57	0.59	0.57	1.00		
2.600	0.05	0.05	0.04	0.08	0.08	0.03	0.08	0.15	0.19	0.22	0.23	0.24	0.26	0.29
	0.34	0.35	0.39	0.39	0.71	0.56	0.54	0.59	0.58	0.59	0.58	0.58	1.00	
2.800	0.05	0.05	0.04	0.08	0.08	0.03	0.08	0.15	0.19	0.22	0.23	0.24	0.26	0.29
	0.34	0.35	0.39	0.39	0.70	0.55	0.54	0.58	0.57	0.59	0.57	0.58	0.59	1.00
3.000	0.05	0.05	0.05	0.09	0.08	0.03	0.08	0.17	0.20	0.24	0.25	0.26	0.28	0.31
	0.36	0.38	0.43	0.42	0.76	0.60	0.59	0.63	0.62	0.64	0.62	0.63	0.65	0.65
	1.00													
3.200	0.05	0.05	0.05	0.09	0.08	0.03	0.08	0.16	0.20	0.23	0.24	0.25	0.27	0.31
	0.35	0.37	0.42	0.41	0.74	0.59	0.57	0.62	0.61	0.62	0.61	0.61	0.63	0.63

TABLE 3. CONTINUED

EN(MEV)	MATRIX-ELEMENT VALUES													
	0.70	1.00												
3.400	0.05	0.05	0.05	0.08	0.08	0.03	0.08	0.16	0.19	0.23	0.23	0.25	0.26	0.30
	0.35	0.36	0.41	0.40	0.73	0.57	0.56	0.60	0.59	0.61	0.59	0.60	0.62	0.62
	0.68	0.69	1.00											
3.600	0.05	0.05	0.05	0.08	0.08	0.03	0.08	0.16	0.19	0.23	0.23	0.25	0.26	0.30
	0.35	0.36	0.41	0.40	0.72	0.57	0.56	0.60	0.59	0.61	0.59	0.60	0.61	0.62
	0.68	0.67	0.67	1.00										
3.800	0.04	0.05	0.04	0.08	0.08	0.03	0.08	0.15	0.18	0.21	0.22	0.23	0.25	0.28
	0.32	0.34	0.38	0.37	0.67	0.53	0.52	0.56	0.55	0.56	0.55	0.55	0.57	0.57
	0.63	0.62	0.61	0.62	1.00									
4.000	0.05	0.05	0.04	0.08	0.08	0.03	0.08	0.15	0.18	0.21	0.22	0.23	0.24	0.28
	0.32	0.34	0.38	0.37	0.67	0.53	0.52	0.55	0.55	0.56	0.55	0.55	0.57	0.57
	0.63	0.62	0.61	0.62	0.59	1.00								
4.200	0.04	0.05	0.04	0.08	0.08	0.03	0.07	0.14	0.18	0.21	0.21	0.23	0.24	0.27
	0.32	0.33	0.37	0.37	0.66	0.52	0.51	0.55	0.54	0.55	0.54	0.54	0.56	0.56
	0.62	0.61	0.60	0.61	0.58	0.58	1.00							
4.400	0.04	0.05	0.04	0.08	0.07	0.03	0.07	0.14	0.18	0.21	0.21	0.23	0.24	0.27
	0.32	0.33	0.37	0.37	0.66	0.52	0.51	0.55	0.54	0.55	0.54	0.54	0.56	0.56
	0.62	0.61	0.60	0.61	0.58	0.58	0.58	1.00						
4.600	0.04	0.04	0.04	0.07	0.07	0.03	0.07	0.13	0.16	0.19	0.20	0.21	0.22	0.25
	0.29	0.30	0.34	0.34	0.60	0.48	0.47	0.50	0.49	0.50	0.49	0.50	0.52	0.52
	0.57	0.56	0.55	0.55	0.54	0.54	0.53	0.53	1.00					
4.800	0.04	0.05	0.04	0.07	0.07	0.03	0.07	0.13	0.16	0.19	0.19	0.21	0.22	0.25
	0.29	0.30	0.34	0.34	0.59	0.47	0.46	0.49	0.49	0.50	0.49	0.49	0.51	0.51
	0.56	0.55	0.54	0.55	0.53	0.53	0.53	0.53	0.50	1.00				
5.000	0.04	0.04	0.04	0.07	0.07	0.02	0.07	0.13	0.16	0.18	0.19	0.20	0.22	0.24
	0.28	0.30	0.33	0.33	0.59	0.47	0.46	0.49	0.48	0.49	0.48	0.49	0.50	0.50
	0.55	0.54	0.54	0.55	0.53	0.53	0.53	0.53	0.50	0.51	1.00			
5.500	0.02	0.03	0.02	0.04	0.04	0.02	0.04	0.08	0.09	0.11	0.12	0.12	0.13	0.15
	0.17	0.18	0.20	0.20	0.35	0.28	0.27	0.29	0.29	0.30	0.29	0.29	0.30	0.30
	0.33	0.33	0.32	0.32	0.31	0.31	0.30	0.31	0.29	0.28	0.28	1.00		
6.000	0.02	0.03	0.02	0.04	0.04	0.02	0.04	0.08	0.10	0.11	0.12	0.13	0.13	0.15
	0.17	0.18	0.21	0.20	0.35	0.28	0.27	0.29	0.29	0.30	0.29	0.29	0.31	0.31
	0.34	0.33	0.32	0.32	0.31	0.31	0.31	0.31	0.29	0.29	0.28	0.18	1.00	
6.500	0.02	0.02	0.02	0.04	0.04	0.01	0.04	0.07	0.09	0.11	0.11	0.12	0.13	0.14
	0.16	0.17	0.20	0.19	0.34	0.27	0.26	0.28	0.28	0.28	0.28	0.28	0.29	0.29
	0.32	0.31	0.30	0.30	0.30	0.30	0.29	0.29	0.28	0.27	0.27	0.17	0.17	1.00
7.000	0.02	0.03	0.02	0.04	0.04	0.02	0.04	0.08	0.10	0.11	0.12	0.12	0.13	0.15
	0.17	0.18	0.21	0.20	0.36	0.28	0.28	0.29	0.29	0.30	0.29	0.29	0.30	0.30
	0.33	0.33	0.32	0.32	0.31	0.31	0.31	0.31	0.29	0.28	0.28	0.18	0.18	0.17
	1.00													
7.500	0.02	0.02	0.02	0.04	0.04	0.01	0.04	0.07	0.09	0.11	0.11	0.12	0.12	0.14
	0.16	0.17	0.19	0.34	0.27	0.26	0.28	0.27	0.28	0.27	0.27	0.29	0.29	0.31
	0.31	0.30	0.30	0.29	0.29	0.29	0.29	0.27	0.27	0.26	0.17	0.17	0.16	0.16
	0.17	1.00												
8.000	0.03	0.03	0.02	0.04	0.04	0.02	0.04	0.09	0.10	0.12	0.13	0.13	0.14	0.16

TABLE 3. CONTINUED

EN(MEV)	MATRIX-ELEMENT VALUES													
	0.19	0.20	0.23	0.22	0.39	0.31	0.30	0.32	0.32	0.32	0.31	0.32	0.33	0.33
	0.37	0.36	0.35	0.35	0.35	0.34	0.34	0.34	0.32	0.32	0.31	0.20	0.20	0.19
	0.21	0.20	1.00											
9.000	0.03	0.03	0.02	0.04	0.04	0.02	0.04	0.09	0.10	0.12	0.13	0.13	0.14	0.16
	0.19	0.20	0.23	0.22	0.39	0.31	0.30	0.32	0.31	0.32	0.31	0.31	0.33	0.33
	0.36	0.36	0.35	0.35	0.34	0.34	0.33	0.34	0.32	0.31	0.31	0.19	0.20	0.19
	0.23	0.19	0.23	1.00										
10.000	0.03	0.03	0.03	0.05	0.04	0.02	0.05	0.09	0.11	0.13	0.13	0.14	0.15	0.17
	0.20	0.21	0.24	0.23	0.40	0.32	0.31	0.33	0.33	0.34	0.33	0.33	0.35	0.35
	0.38	0.38	0.37	0.37	0.36	0.36	0.35	0.35	0.34	0.33	0.32	0.20	0.20	0.20
	0.21	0.20	0.24	0.25	1.00									
11.000	0.03	0.04	0.03	0.06	0.05	0.02	0.05	0.11	0.13	0.15	0.16	0.17	0.18	0.20
	0.24	0.25	0.28	0.28	0.49	0.39	0.37	0.40	0.39	0.40	0.39	0.40	0.42	0.42
	0.46	0.45	0.44	0.44	0.44	0.43	0.43	0.43	0.41	0.40	0.39	0.25	0.25	0.24
	0.27	0.24	0.30	0.32	0.34	1.00								
12.000	0.03	0.03	0.03	0.06	0.05	0.02	0.05	0.11	0.13	0.15	0.16	0.17	0.18	0.20
	0.23	0.25	0.28	0.27	0.48	0.38	0.37	0.39	0.39	0.40	0.39	0.39	0.41	0.41
	0.45	0.45	0.43	0.43	0.43	0.43	0.42	0.42	0.40	0.39	0.38	0.24	0.24	0.23
	0.25	0.24	0.29	0.30	0.33	0.42	1.00							
13.000	0.03	0.03	0.03	0.05	0.05	0.02	0.05	0.10	0.12	0.14	0.15	0.16	0.17	0.19
	0.22	0.24	0.27	0.26	0.45	0.36	0.35	0.37	0.36	0.37	0.36	0.37	0.39	0.39
	0.42	0.42	0.41	0.41	0.40	0.40	0.39	0.39	0.38	0.37	0.36	0.23	0.23	0.22
	0.25	0.22	0.27	0.29	0.31	0.39	0.39	1.00						
14.000	0.03	0.03	0.02	0.05	0.04	0.02	0.04	0.09	0.11	0.13	0.13	0.14	0.15	0.17
	0.19	0.21	0.24	0.23	0.39	0.31	0.30	0.32	0.32	0.32	0.32	0.32	0.33	0.33
	0.37	0.36	0.35	0.35	0.35	0.35	0.34	0.34	0.32	0.32	0.31	0.20	0.20	0.19
	0.22	0.19	0.24	0.26	0.27	0.34	0.34	0.33	1.00					
15.000	0.03	0.03	0.03	0.06	0.05	0.02	0.05	0.10	0.13	0.15	0.16	0.16	0.17	0.20
	0.23	0.25	0.28	0.27	0.47	0.37	0.36	0.39	0.38	0.39	0.38	0.39	0.41	0.41
	0.45	0.45	0.43	0.43	0.43	0.42	0.42	0.41	0.39	0.39	0.38	0.23	0.23	0.22
	0.24	0.22	0.26	0.26	0.28	0.34	0.34	0.32	0.28	1.00				
16.000	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.04	0.05	0.06	0.06	0.06	0.07	0.08
	0.09	0.13	0.12	0.11	0.17	0.13	0.12	0.13	0.13	0.13	0.13	0.13	0.13	0.13
	0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.13	0.12	0.12	0.11	0.07	0.07	0.07
	0.07	0.07	0.08	0.08	0.09	0.11	0.11	0.11	0.10	0.12	1.00			
18.000	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.03	0.04	0.04	0.04	0.05	0.05	0.06
	0.07	0.09	0.09	0.08	0.12	0.09	0.09	0.10	0.09	0.10	0.09	0.09	0.10	0.09
	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.05	0.05	0.05
	0.05	0.05	0.06	0.06	0.06	0.08	0.08	0.08	0.07	0.08	0.14	1.00		
20.000	0.01	0.01	0.01	0.02	0.01	0.01	0.02	0.03	0.04	0.05	0.05	0.05	0.06	0.06
	0.07	0.11	0.10	0.09	0.14	0.10	0.10	0.11	0.10	0.11	0.10	0.10	0.11	0.11
	0.12	0.11	0.11	0.11	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.06	0.06	0.06
	0.06	0.06	0.06	0.07	0.07	0.09	0.08	0.08	0.07	0.08	0.14	1.00		

TABLE 4. Illustrative Comparisons with ENDF/B-V[9]

Energy (MeV)	$\left[\frac{\text{ENDF-PE}}{\text{PE}}\right]$ in %[a]
0.044	1.5
0.1	1.2
0.2	1.0
0.4	0.6
0.8	0.4
1.0	0.3
1.5	0.3
2.0	0.3
2.5	0.3
3.0	0.3
4.0	0.3
6.0	0.6
8.0	0.6
10.0	0.5
15.0	0.5
20.0	1.3

[a]PE ≡ present evaluation.