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EVALUATION OF U-238 FOR ENDF/B-IV

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INTRODUCTION

In this paper the ENDF/B-IV evaluation of the U-238 cross sections below 4 keV will be discussed. The evaluation was undertaken because the Data Testing Subcommittee of the Cross Section Evaluation Working Group (CSEWG) found ENDF/B-III yielded rather disappointing results for thermal systems. In both D_2O and H_2O moderated lattices of natural or slightly enriched uranium rods, k-eff is underpredicted using Version III by 1.5%. This underprediction has been attributed to a 10% overprediction of U-238 epithermal neutron capture.(1)

These thermal data testing results have raised questions concerning the ENDF/B-III cross sections, since the calculational methods used in the analysis of the benchmark experiments generally have been considered adequate. A number of areas where the Version III U-238 cross sections might be deficient have been proposed, e.g., the existence of systematic errors or spurious p-wave resonances could give rise to excessive U-238 neutron capture. These questions and other details pertaining to the evaluation are described in the present paper.

In the first section of the paper, the thermal cross sections will be discussed. Then the epithermal cross sections will be discussed, particularly the s-wave and p-wave resonances, and the background cross sections. Finally, the impact of the new ENDF/B-IV

evaluations on thermal lattice calculations will be discussed.

DISCUSSION

Thermal Cross Sections (E > 1.0 eV)

The thermal region in the evaluation spans energies below 1 eV. The cross sections in this region are tabulated in File 3. The evaluation for the thermal cross sections followed the procedures employed in the Version II and Version III evaluations, i.e., a multi-level Breit-Wigner formulation was used which incorporated the first nine low energy s-wave resonances plus an appropriate complement of bound levels.[2] The Version IV thermal evaluation differs from ENDF/B-III in two respects: First, the differential capture cross sections were normalized to 2.70 barns at 0.0253 eV, rather than 2.72 barns. Secondly, the thermal break-point was lowered from 5 eV to 1 eV to avoid possible problems in accounting for resonance self-shielding for the 6.67 eV resonance.

The lower capture cross sections are in better agreement with the 1969 measurements of J. B. Hunt, et al., of 2.69 ± 0.03 barns[3] and improve prediction of criticality in the thermal benchmark lattices. They are, however, in poorer agreement with the measurements of C. B. Bingham, et al.,[4] which yielded a value of 2.721 ± 0.016 barns.

In addition, it was intended that the thermal cross sections also include the contributions associated with subthreshold fission as measured by R. C. Block, et al.,[5] but these were inadvertently omitted from File 3. The cross section for fission at 0.0253 eV should be 1.912×10^{-5} barns.[5]

Epithermal Cross Sections (1 eV < E < 4 keV)

The epithermal cross sections between 1 eV and 4 keV are described in terms of single-level, Breit-Wigner, s- and p-wave resonance parameters (File 2) and smooth background cross sections (File 3). Table 1 lists the measurements that were used in the evaluation of the s-wave resonances.

One of the objectives of the present evaluation was to minimize systematic differences as much as possible between the various experiments. Perhaps this could best be done by reanalyzing each of the measurements on a resonance-by-resonance basis using the same analysis technique.[7] However, since this approach would have been too time consuming for the present evaluation, a type of regression analysis was used instead.

In the regression analysis approach, the neutron widths are normalized to a common basis.[8] The measurements of F. Rahn, et al.,[9] and those of G. Carraro and W. Kolar[12] each span the full energy range 1 eV to 4 keV, and thus either could be used as the basis for normalization. The Columbia University data[9] was selected, however, because of the rather large strength functions associated with the G. Carraro and W. Kolan data, particularly at higher energies. The resonance energies and Γ_n values of F. Rahn, et al., provide an appropriate standard since they were obtained from a self-consistent analysis of high resolution transmission, self-indication and Moxon-Rae capture measurements for 7 different U-238 sample thicknesses.

The regression analysis, of course, does not account for systematic errors within the Columbia measurement itself. A final

normalization of the neutron widths was planned to improve the agreement with measured values of ρ^{28} (the ratio of epithermal-to-thermal U-238 neutron captures) for benchmark lattice experiments, but this was dropped when the results were found to be too insensitive to be useful.

Below 1 keV the regression analysis consisted of determining the constant C in the relation

$$Y_i = CX_i, \; i = 1,2, \ldots, N.$$

In this relation X_i denotes the ratio Γ_n/E_0 determined by F. Rahn, et al., for the s-wave resonances and Y_i denotes the same ratio but as determined from one of the other experiments in Table 1. The index N denotes the number of s-wave resonances below 1 keV. A similar procedure was used to normalize the G. Carraro and W. Kolar data to the F. Rahn, et al., data between 1 and 4 keV. The values of C determined from the regression analysis are given in Table 2. Values of C greater than unity indicate measurements having neutron widths which on the average are greater than those of F. Rahn, et al. The neutron widths of each of the experiments were therefore multiplied by the reciprocal of C to remove the systematic differences.

After the neutron widths were normalized by the regression analysis, the resonance parameters were evaluated on a resonance-by-resonance basis to determine E_0, Γ_n, Γ_γ. As part of the evaluation process, the capture resonance integral and the peak capture and total cross sections for each of the various normalized experiments were compared. Tables 3, 4 and 5 give the resonance energies, the normalized neutron widths, and the capture widths for each of the s-wave resonances below 1 keV. The corresponding values for the

capture resonance integral and the peak capture and total cross sections for each of these resonances are listed in Tables 6, 7 and 8.* The appropriate formulas are

Capture Integral: $I_\gamma = \frac{a\pi}{2} g \frac{\Gamma_n \Gamma_\gamma}{\Gamma E_0^2}$

Peak Capture Cross Section: $\sigma_0^\gamma = a\ g \frac{\Gamma_n \Gamma_\gamma}{E_0 \Gamma^2}$

Peak Total Cross Section: $\sigma_0^{total} = a\ g \frac{\Gamma_n}{E_0 \Gamma}$

where the left-hand side of each of the equations is in barns, energy is in eV, g is the statistical spin factor and

$$\Gamma = \Gamma_n + \Gamma_\gamma$$
$$a = 2.6032 \times 10^6 .$$

The resonance parameters which yielded the most consistent values for I_γ, σ_0^γ and σ_0^{total} were selected for the ENDF/B-IV evaluation. Special attention was given to maintaining the coupling between Γ_n and Γ_γ determined in the individual experiments.

Since the ORELA capture measurements[10] are not reported in terms of resonance parameters, these measurements had to be factored into the evaluation by an indirect method. The measured capture probabilities as a function of energy below 4 keV have been compared to Monte Carlo calculations using ENDF/B-III data. A sampling is given in Figure 1. These comparisons of the capture probabilities together with the Version III resonance parameter information in Tables 3-8 provided the needed link to at least qualitatively include the inferences of the ORELA measurements.

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* The tables do not indicate the resonance parameters below 100 eV because these parameters are unchanged from Version III.

Table 9 summarizes the evaluation of the s-wave resonances. It is noted that there is really very little difference between the Version III and Version IV evaluations. The infinite dilution residence intervals in Table 9 were calculated using the narrow resonance approximation. The small differences between the Version III and Version IV infinite dilution resonance integrals probably translate to even smaller differences for effective integrals with high self-shielding.

Before concluding the discussion of the s-wave resonance parameters, it should be noted that the subthreshold fission widths (Γ_f) in ENDF/B-IV are incorrect. Under the assumption that Γ_γ is 23 meV, the ENDF/B-IV compilation gives fission widths of 0.29 and 0.051 meV for the 720 and 1210 eV resonances respectively. But in reference (5) these fission widths correspond to class II levels with radiation widths of 4.9 meV. When the resonances are assigned to the first well of the double-humped fission barrier Γ_γ is 23 meV and Γ_f is 1.2 and 0.12 meV for the 720 and 1210 eV resonances respectively.

The measurements used in the evaluation of the p-wave resonances are listed in Table 10.

Table 11 gives a partial listing of the experimentally determined neutron widths (multiplied by the statistical spin factor, g)* and the resonance energies. The ENDF/B-III p-wave parameters were essentially fitted to the data of G. de Saussure, et al.,[10] and hence provide a measure of the neutron widths for that experiment.

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* The experiments cannot determine g, which can equal either 1 or 2 depending on the spin of the compound nucleus.

Although the experiments themselves do not isolate the s- and p-wave resonances, it is generally easy to distinguish them because the p-wave levels are typically much weaker. As indicated in the table, some experimenters have differed in the assignment of some of the resonances which can be considered as strong p-wave or weak s-wave resonances. With the exception of the resonance at 263.9 eV, the ENDF/B evaluation has used the statistical analysis of F. Rahn, et al.,[9] to distinguish weak levels as p or s. The 263.9 eV resonance must be p-wave to conserve parity since measured spectra for the resonance exhibit E1 radiative transitions to the $5/2^+$ ground state of U-239.[18]

In the evaluation below 1200 eV, a supposed p-wave resonance of an experiment was considered spurious, and hence ignored, if it was not substantiated by another of the experiments considered. ~~Having~~ established the existence of a p-wave resonance, the neutron width was determined by weighting the measured values according to their reported experimental precision. The Version IV p-wave parameters between 1.2 and 4 keV are essentially the same as those in Version III, but with minor modifications to improve the agreement with the ORELA capture cross section measurements.

The p-wave resonance parameter evaluation is summarized in Table 12. Again, only small differences are observed between the Version III and Version IV evaluations. The ENDF/B-IV strength function of 1.39×10^{-4} is based on the p-wave resonances below 500 eV. This value, determined using a channel radius of 8.4 fermi, is consistent with the p-wave strength function obtained from the cross sections in the 10-40 keV range.

The background cross sections between 1 eV and 4 keV which went into File 3 will now be described. A scattering cross section of approximately 2.5 barns was added between 1 eV and the first resonance to provide continuity across the break point at 1 eV. This addition is required because File 2 includes only the positive energy resonances with their associated interference scattering terms. A similar spectrum of bound level resonances exists and is the origin of this additional 2.5 barns contribution. Capture cross sections between 1 and 100 eV were also added to account for the bound level contribution.

In addition, background cross sections between 0.68 and 4.0 keV were added to account for missed p-wave resonances in the resolved region. These background cross sections are compared with those in Version III in Table 13.

CONCLUSION

ENDF/B-III and ENDF/B-IV calculations of k-eff and ρ^{23} for 10 CSEWG thermal benchmark experiments are given in Tables 14 and 15.

The five unreflected spheres of uranyl nitrate solution contain 93 wt % U-235 and serve as a test of the H_2O and U-235 cross sections. The relatively good prediction of criticality for the spheres, particularly for Version IV, indicates that there are no severe problems with the H_2O and U-235 cross sections in thermal systems.

The two H_2O moderated lattices of slightly enriched uranium and three D_2O moderated lattices of natural uranium rods test the U-238 thermal and resonance region capture cross sections, in addition to

the U-235 and moderator cross sections. Although the improvement over Version III is significant, the Version IV calculations still underpredict criticality. Again, this can be traced to the overprediction of ρ^{28}. Reasonably good predictions of criticality would be achieved if the required reduction in epithermal-to-thermal U-238 captures could be accomplished.

Good prediction of criticality could therefore be achieved for the uranyl nitrate solutions and the lattice experiments if epithermal neutron capture in U-238 were reduced to yield agreement with ρ^{28} measurements. In light of the present evaluation, however, the required reductions of the epithermal U-238 capture cross sections appear to be below the bounds established by the precision of present differential measurements. Thus, the difficulties encountered in thermal data testing may be arising, at least in part, from sources other than cross sections.

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TABLE 1

DATA FOR EVALUATION OF s-WAVE RESONANCES

Total and Capture

1. F. Rahn, et al. - Transmission, Self-Indication, Capture (0-4 keV)
2. G. de Saussure, et al. - Capture (0-4 keV)
3. M. Asghar, et al. - Scattering, Capture (0-823 eV)
4. Carraro and Kolar - Transmission (0-4 keV)
5. G. Rohr, et al. - Capture (66-1055 eV)
6. Maletski, et al. - Transmission, Capture (66-1197 eV)

Fission

Block, et al. - Subthreshold Fission

TABLE 2

NORMALIZATION CONSTANTS FOR Γ_n

ΔE, keV	Rahn	Carraro	Rohr	Maletski	Asghar
0 - 1.0	1.0	0.962	0.948	0.919	0.772
1.0 - 1.5	1.0	1.005			
1.5 - 2.0	1.0	1.074			
2.0 - 2.5	1.0	1.022			
2.5 - 3.0	1.0	1.131			
3.0 - 3.5	1.0	1.200			
3.5 - 4.0	1.0	1.245			

TABLE 3

ENERGIES OF s-WAVE RESONANCES (eV)

RAHN	RCHR	CARRARO	MALETSKI	ASGHAR	ENDF/B-III	
0.1025E 03	0.1026E 03	0.1025E 03	0.1024E 03	0.1026E 03	0.1026E 03	1
0.1168E 03	0.1169E 03	0.1169E 03	0.1169E 03	0.1169E 03	0.1169E 03	2
0.1456E 03	0.0	0.1456E 03	0.1458E 03	0.0	0.1456E 03	3
0.1652E 03	0.0	0.1653E 03	0.1654E 03	0.0	0.1653E 03	4
0.1898E 03	0.1896E 03	0.1896E 03	0.1895E 03	0.1896E 03	0.1896E 03	5
0.2085E 03	0.2085E 03	0.2084E 03	0.2084E 03	0.2085E 03	0.2084E 03	6
0.2372E 03	0.2373E 03	0.2373E 03	0.2376E 03	0.2373E 03	0.2373E 03	7
0.2736E 03	0.2736E 03	0.2736E 03	0.2739E 03	0.2736E 03	0.2736E 03	8
0.2910E 03	0.2908E 03	0.2908E 03	0.2912E 03	0.2908E 03	0.2908E 03	9
0.3111E 03	0.0	0.3112E 03	0.3117E 03	0.0	0.3112E 03	10
0.3477E 03	0.3478E 03	0.3478E 03	0.3481E 03	0.3478E 03	0.3478E 03	11
0.3770E 03	0.0	0.3768E 03	0.3770E 03	0.0	0.3768E 03	12
0.3974E 03	0.3976E 03	0.3976E 03	0.3981E 03	0.3976E 03	0.3976E 03	13
0.4102E 03	0.4102E 03	0.4102E 03	0.4107E 03	0.4102E 03	0.4102E 03	14
0.4337E 03	0.4341E 03	0.4342E 03	0.4346E 03	0.4341E 03	0.4341E 03	15
0.4541E 03	0.0	0.4537E 03	0.0	0.0	0.0	16
0.4628E 03	0.0	0.4632E 03	0.4641E 03	0.0	0.4632E 03	17
0.4770E 03	0.0	0.4783E 03	0.4794E 03	0.0	0.4783E 03	18
0.5183E 03	0.5183E 03	0.5183E 03	0.5190E 03	0.5183E 03	0.5183E 03	19
0.5352E 03	0.5352E 03	0.5352E 03	0.5362E 03	0.5352E 03	0.5352E 03	20
0.5559E 03	0.0	0.5561E 03	0.0	0.0	0.0	21
0.5799E 03	0.5800E 03	0.5800E 03	0.5807E 03	0.5800E 03	0.5800E 03	22
0.5948E 03	0.5950E 03	0.5950E 03	0.5948E 03	0.5950E 03	0.5950E 03	23
0.6198E 03	0.6198E 03	0.6198E 03	0.6210E 03	0.6198E 03	0.6198E 03	24
0.6283E 03	0.0	0.6285E 03	0.6290E 03	0.0	0.6285E 03	25
0.6609E 03	0.6611E 03	0.6611E 03	0.6620E 03	0.6611E 03	0.6611E 03	26
0.6929E 03	0.6930E 03	0.6930E 03	0.6940E 03	0.6930E 03	0.6930E 03	27
0.7079E 03	0.7080E 03	0.7080E 03	0.7050E 03	0.0	0.7080E 03	28
0.7209E 03	0.0	0.7214E 03	0.0	0.0	0.7214E 03	29
0.7325E 03	0.0	0.7321E 03	0.7330E 03	0.0	0.7321E 03	30
0.7648E 03	0.0	0.7652E 03	0.7670E 03	0.0	0.7651E 03	31
0.7788E 03	0.0	0.7795E 03	0.0	0.0	0.7795E 03	32
0.7904E 03	0.0	0.7910E 03	0.7920E 03	0.0	0.7910E 03	33
0.8209E 03	0.8218E 03	0.8218E 03	0.8220E 03	0.0	0.8218E 03	34
0.8506E 03	0.8514E 03	0.8514E 03	0.0	0.0	0.8514E 03	35
0.8561E 03	0.8563E 03	0.8563E 03	0.0	0.0	0.8563E 03	36
0.8660E 03	0.0	0.8668E 03	0.8690E 03	0.0	0.8668E 03	37
0.9045E 03	0.9054E 03	0.9054E 03	0.9070E 03	0.0	0.9054E 03	38
0.9245E 03	0.0	0.9254E 03	0.0	0.0	0.9254E 03	39
0.9366E 03	0.9372E 03	0.9372E 03	0.9390E 03	0.0	0.9372E 03	40
0.9580E 03	0.9589E 03	0.9589E 03	0.9600E 03	0.0	0.9589E 03	41
0.9914E 03	0.9919E 03	0.9919E 03	0.0	0.0	0.9919E 03	42

TABLE 4

NORMALIZED s-WAVE NEUTRON WIDTHS (eV)

	RAHN	ROHR	CARRARO	MALETSKI	ASGHAR	ENDF/B-III	
102.47	0.7000E-01	0.7658E-01	0.7225E-01	0.7617E-01	0.7596E-01	0.6950E-01	1
116.82	0.3500E-01	0.2985E-01	0.2827E-01	0.2394E-01	0.2992E-01	0.2720E-01	2
145.57	0.8400E-03	0.0	0.9252E-03	0.9140E-03	0.0	0.8500E-03	3
165.21	0.3080E-02	0.0	0.3534E-02	0.3264E-02	0.0	0.3400E-02	4
189.80	0.1790E 00	0.1780E 00	0.1757E 00	0.1784E 00	0.1725E 00	0.1650E 00	5
208.49	0.5900E-01	0.5169E-01	0.5509E-01	0.5223E-01	0.6489E-01	0.5300E-01	6
237.20	0.3500E-01	0.2753E-01	0.2911E-01	0.2938E-01	0.3238E-01	0.2820E-01	7
275.56	0.2850E-01	0.2700E-01	0.2692E-01	0.2394E-01	0.2689E-01	0.2590E-01	8
291.01	0.1710E-01	0.1698E-01	0.1559E-01	0.1784E-01	0.1810E-01	0.1500E-01	9
311.13	0.1060E-02	0.0	0.1143E-02	0.9793E-03	0.0	0.1100E-02	10
347.74	0.8020E-01	0.8618E-01	0.8690E-01	0.8487E-01	0.7435E-01	0.8360E-01	11
377.03	0.9700E-03	0.0	0.1331E-02	0.9793E-03	0.0	0.1260E-02	12
397.39	0.6000E-02	0.6751E-02	0.6580E-02	0.5114E-02	0.6412E-02	0.6330E-02	13
410.18	0.1900E-01	0.2099E-01	0.2141E-01	0.2176E-01	0.1843E-01	0.2060E-01	14
433.70	0.8750E-02	0.1065E-01	0.9979E-02	0.8705E-02	0.1019E-01	0.9600E-02	15
454.10	0.4300E-03	0.0	0.4782E-03	0.0	0.0	0.0	16
462.80	0.4500E-02	0.0	0.5769E-02	0.5440E-02	0.0	0.5550E-02	17
477.00	0.3050E-02	0.0	0.4127E-02	0.3808E-02	0.0	0.3970E-02	18
518.27	0.4890E-01	0.5158E-01	0.5769E-01	0.4570E-01	0.5065E-01	0.5550E-01	19
535.21	0.4510E-01	0.4536E-01	0.4699E-01	0.5985E-01	0.5026E-01	0.4520E-01	20
555.90	0.7070E-03	0.0	0.7276E-03	0.0	0.0	0.0	21
579.87	0.4090E-01	0.4483E-01	0.4584E-01	0.3917E-01	0.4863E-01	0.4410E-01	22
594.84	0.8510E-01	0.8987E-01	0.8773E-01	0.1012E 00	0.9248E-01	0.8440E-01	23
619.75	0.2750E-01	0.3164E-01	0.3378E-01	0.3591E-01	0.3303E-01	0.3250E-01	24
628.29	0.5260E-02	0.0	0.6965E-02	0.7617E-02	0.0	0.6700E-02	25
660.90	0.1380E 00	0.1300E 00	0.1372E 00	0.1632E 00	0.1356E 00	0.1320E 00	26
692.90	0.4210E-01	0.4462E-01	0.4553E-01	0.4352E-01	0.4106E-01	0.4380E-01	27
707.90	0.2100E-01	0.2352E-01	0.2308E-01	0.2176E-01	0.0	0.2420E-01	28
720.90	0.1340E-02	0.0	0.1518E-02	0.0	0.0	0.1460E-02	29
732.50	0.1080E-02	0.0	0.1653E-02	0.3808E-02	0.0	0.1590E-02	30
764.80	0.8020E-02	0.0	0.5509E-02	0.7617E-02	0.0	0.8000E-02	31
778.80	0.1670E-02	0.0	0.1975E-02	0.0	0.0	0.2200E-02	32
790.40	0.5900E-02	0.0	0.7173E-02	0.6529E-02	0.0	0.8000E-02	33
820.90	0.6500E-01	0.6012E-01	0.7069E-01	0.7181E-01	0.0	0.6530E-01	34
850.60	0.5510E-01	0.5865E-01	0.6757E-01	0.0	0.0	0.6300E-01	35
856.10	0.8110E-01	0.8270E-01	0.9563E-01	0.0	0.0	0.8630E-01	36
866.00	0.5000E-02	0.0	0.6861E-02	0.5440E-02	0.0	0.5700E-02	37
904.50	0.4900E-01	0.5200E-01	0.5873E-01	0.4352E-01	0.0	0.5620E-01	38
924.50	0.9730E-02	0.0	0.1507E-01	0.0	0.0	0.1390E-01	39
936.60	0.1440E 00	0.1366E 00	0.1507E 00	0.1306E 00	0.0	0.1370E 00	40
958.00	0.2030E 00	0.1904E 00	0.2225E 00	0.1415E 00	0.0	0.1960E 00	41
991.40	0.3900E 00	0.3599E 00	0.4200E 00	0.0	0.0	0.3770E 00	42

TABLE 5

s-WAVE CAPTURE WIDTHS (eV)

	RAHN	ROHR	CARRARO	MALETSKI	ASGHAR	ENDF/B-III	
102.47	0.2800E-01	0.2610E-01	0.2355E-01	0.2600E-01	0.2595E-01	0.2610E-01	1
116.82	0.2000E-01	0.2430E-01	0.2355E-01	0.2300E-01	0.2572E-01	0.2430E-01	2
145.57	0.2355E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2350E-01	3
155.21	0.1800E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2350E-01	4
189.80	0.2700E-01	0.2470E-01	0.2355E-01	0.2200E-01	0.2321E-01	0.2470E-01	5
208.49	0.2200E-01	0.2240E-01	0.2355E-01	0.2600E-01	0.2149E-01	0.2350E-01	6
237.20	0.2400E-01	0.2450E-01	0.2355E-01	0.2600E-01	0.1953E-01	0.2450E-01	7
273.56	0.2300E-01	0.2310E-01	0.2355E-01	0.2500E-01	0.2391E-01	0.2350E-01	8
291.01	0.2200E-01	0.2310E-01	0.2355E-01	0.2300E-01	0.2240E-01	0.2350E-01	9
311.13	0.2355E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2350E-01	10
347.74	0.2600E-01	0.2350E-01	0.2355E-01	0.2200E-01	0.2040E-01	0.2500E-01	11
377.03	0.2355E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2350E-01	12
397.39	0.2200E-01	0.2520E-01	0.2355E-01	0.2355E-01	0.3750E-01	0.3000E-01	13
410.18	0.1800E-01	0.2260E-01	0.2355E-01	0.2500E-01	0.2661E-01	0.2350E-01	14
433.70	0.2000E-01	0.2650E-01	0.2355E-01	0.2355E-01	0.2510E-01	0.2650E-01	15
454.10	0.2355E-01	0.0	0.2355E-01	0.0	0.0	0.0	16
462.80	0.2355E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2350E-01	17
477.00	0.2355E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2350E-01	18
518.27	0.2400E-01	0.2440E-01	0.2355E-01	0.2300E-01	0.5120E-02	0.2440E-01	19
535.21	0.2300E-01	0.2470E-01	0.2355E-01	0.2300E-01	0.2930E-01	0.2470E-01	20
555.90	0.2355E-01	0.0	0.2355E-01	0.0	0.0	0.0	21
579.87	0.2100E-01	0.2610E-01	0.2355E-01	0.2300E 02	0.2200E-01	0.2610E-01	22
594.84	0.2000E-01	0.2310E-01	0.2355E-01	0.2400E-01	0.2179E-01	0.2350E-01	23
619.75	0.1900E-01	0.2460E-01	0.2355E-01	0.2400E-01	0.3310E-01	0.2460E-01	24
628.29	0.2355E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2350E-01	25
660.90	0.2900E-01	0.2600E-01	0.2355E-01	0.2200E-01	0.2512E-01	0.2600E-01	26
692.90	0.2200E-01	0.2410E-01	0.2355E-01	0.2400E-01	0.2020E-01	0.2410E-01	27
707.90	0.2100E-01	0.2850E-01	0.2355E-01	0.2600E-01	0.0	0.2850E-01	28
720.93	0.2355E-01	0.0	0.2355E-01	0.0	0.0	0.2350E-01	29
732.50	0.2355E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2350E-01	30
764.80	0.1700E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2850E-01	31
778.80	0.2355E-01	0.0	0.2355E-01	0.0	0.0	0.2350E-01	32
790.40	0.2355E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2850E-01	33
820.90	0.2000E-01	0.2600E-01	0.2355E-01	0.2400E-01	0.0	0.2600E-01	34
850.60	0.2300E-01	0.3090E-01	0.2355E-01	0.0	0.0	0.3090E-01	35
856.10	0.2300E-01	0.2360E-01	0.2355E-01	0.0	0.0	0.2350E-01	36
866.00	0.2355E-01	0.0	0.2355E-01	0.2355E-01	0.0	0.2350E-01	37
904.50	0.2200E-01	0.2680E-01	0.2355E-01	0.2500E-01	0.0	0.2680E-01	38
924.50	0.2500E-01	0.0	0.2355E-01	0.0	0.0	0.2350E-01	39
936.60	0.2500E-01	0.2360E-01	0.2355E-01	0.2400E-01	0.0	0.2350E-01	40
958.00	0.2100E-01	0.2270E-01	0.2355E-01	0.2200E-01	0.0	0.2350E-01	41
991.40	0.3000E-01	0.3070E-01	0.2355E-01	0.0	0.0	0.3070E-01	42

TABLE 6

s-WAVE CAPTURE INTEGRALS (BARNS)

	RAHN	ROHR	CARRARO	MALETSKI	ASGHAR	ENDF/B-III	
102.47	0.7789E 01	0.7561E 01	0.6906E 01	0.7559E 01	0.7513E 01	0.7371E 01	1
116.82	0.3814E 01	0.4008E 01	0.3846E 01	0.3510E 01	0.4139E 01	0.3840E 01	2
145.57	0.1565E 00	0.0	0.1718E 00	0.1692E 00	0.0	0.1654E 00	3
165.21	0.3940E 00	0.0	0.4601E 00	0.4285E 00	0.0	0.4445E 00	4
189.80	0.2663E 01	0.2467E 01	0.2361E 01	0.2230E 01	0.2327E 01	0.2451E 01	5
208.49	0.1507E 01	0.1470E 01	0.1553E 01	0.1634E 01	0.1519E 01	0.1533E 01	6
237.20	0.1035E 01	0.9414E 00	0.9451E 00	0.9991E 00	0.8847E 00	0.9520E 00	7
273.56	0.6998E 00	0.6801E 00	0.6861E 00	0.6665E 00	0.6914E 00	0.6730E 00	8
291.01	0.4646E 00	0.4733E 00	0.4536E 00	0.4646E 00	0.4840E 00	0.4427E 00	9
311.13	0.4285E-01	0.0	0.4604E-01	0.3957E-01	0.0	0.4437E-01	10
347.74	0.6640E 00	0.6242E 00	0.6265E 00	0.5896E 00	0.5411E 00	0.6506E 00	11
377.03	0.2680E-01	0.0	0.3627E-01	0.2705E-01	0.0	0.3444E-01	12
397.39	0.1221E 00	0.1377E 00	0.1330E 00	0.1084E 00	0.1416E 00	0.1352E 00	13
410.18	0.2246E 00	0.2645E 00	0.2725E 00	0.2820E 00	0.2646E 00	0.2668E 00	14
433.70	0.1323E 00	0.1649E 00	0.1520E 00	0.1376E 00	0.1573E 00	0.1529E 00	15
454.10	0.8374E-02	0.0	0.9309E-02	0.0	0.0	0.0	16
462.83	0.7213E-01	0.0	0.8833E-01	0.8390E-01	0.0	0.8557E-01	17
477.00	0.4853E-01	0.0	0.6276E-01	0.5833E-01	0.0	0.6071E-01	18
518.27	0.2451E 00	0.2521E 00	0.2546E 00	0.2323E 00	0.7078E-01	0.2580E 00	19
535.21	0.2174E 00	0.2283E 00	0.2239E 00	0.2363E 00	0.2642E 00	0.2280E 00	20
555.90	0.9083E-02	0.0	0.9334E-02	0.0	0.0	0.0	21
579.87	0.1687E 00	0.2005E 00	0.1891E 00	0.4742E 00	0.1841E 00	0.1993E 00	22
594.84	0.1871E 00	0.2123E 00	0.2145E 00	0.2242E 00	0.2037E 00	0.2123E 00	23
619.75	0.1203E 00	0.1473E 00	0.1477E 00	0.1525E 00	0.1760E 00	0.1490E 00	24
628.29	0.4454E-01	0.0	0.5564E-01	0.5948E-01	0.0	0.5397E-01	25
660.90	0.2243E 00	0.2027E 00	0.1881E 00	0.1809E 00	0.1983E 00	0.2032E 00	26
692.90	0.1231E 00	0.1332E 00	0.1321E 00	0.1313E 00	0.1153E 00	0.1324E 00	27
707.90	0.8568E-01	0.1051E 00	0.9508E-01	0.9637E-01	0.0	0.1068E 00	28
720.90	0.9976E-02	0.0	0.1120E-01	0.0	0.0	0.1080E-01	29
732.50	0.7870E-02	0.0	0.1178E-01	0.2495E-01	0.0	0.1136E-01	30
764.80	0.3810E-01	0.0	0.3118E-01	0.4000E-01	0.0	0.4363E-01	31
778.80	0.1051E-01	0.0	0.1226E-01	0.0	0.0	0.1354E-01	32
790.40	0.3088E-01	0.0	0.3593E-01	0.3332E-01	0.0	0.4082E-01	33
820.90	0.9281E-01	0.1099E 00	0.1070E 00	0.1089E 00	0.0	0.1126E 00	34
850.00	0.9171E-01	0.1142E 00	0.9851E-01	0.0	0.0	0.1169E 00	35
856.10	0.9997E-01	0.1024E 00	0.1054E 00	0.0	0.0	0.1030E 00	36
866.00	0.2249E-01	0.0	0.2891E-01	0.2393E-01	0.0	0.2497E-01	37
904.50	0.7569E-01	0.8822E-01	0.8384E-01	0.7893E-01	0.0	0.9052E-01	38
924.50	0.3351E-01	0.0	0.4388E-01	0.0	0.0	0.4170E-01	39
936.60	0.9930E-01	0.9368E-01	0.9482E-01	0.9402E-01	0.0	0.9339E-01	40
958.00	0.8479E-01	0.9020E-01	0.9470E-01	0.8447E-01	0.0	0.9332E-01	41
991.40	0.1159E 00	0.1176E 00	0.9269E-01	0.0	0.0	0.1180E 00	42

TABLE 7

s-WAVE PEAK CAPTURE CROSS SECTIONS (BARNS)

	RAHN	ROHR	CARRARO	MALETSKI	ASGHAR	ENDF/B-III	
102.47	0.5165E 04	0.4810E 04	0.4706E 04	0.4823E 04	0.4816E 04	0.5036E 04	1
116.82	0.5157E 04	0.5509E 04	0.5522E 04	0.5565E 04	0.5535E 04	0.5549E 04	2
145.57	0.5947E 03	0.0	0.6504E 03	0.6421E 03	0.0	0.6286E 03	3
165.21	0.1966E 04	0.0	0.1787E 04	0.1683E 04	0.0	0.1739E 04	4
189.30	0.1562E 04	0.1469E 04	0.1431E 04	0.1342E 04	0.1435E 04	0.1528E 04	5
208.49	0.2470E 04	0.2634E 04	0.2620E 04	0.2772E 04	0.2333E 04	0.2658E 04	6
237.20	0.2648E 04	0.2733E 04	0.2712E 04	0.2729E 04	0.2574E 04	0.2729E 04	7
273.56	0.2348E 04	0.2364E 04	0.2368E 04	0.2375E 04	0.2370E 04	0.2373E 04	8
291.01	0.2201E 04	0.2186E 04	0.2145E 04	0.2199E 04	0.2213E 04	0.2129E 04	9
311.13	0.3449E 03	0.0	0.3694E 03	0.3201E 03	0.0	0.3573E 03	10
347.74	0.1384E 04	0.1260E 04	0.1256E 04	0.1223E 04	0.1265E 04	0.1326E 04	11
377.03	0.2623E 03	0.0	0.3497E 03	0.2647E 03	0.0	0.3337E 03	12
397.39	0.1103E 04	0.1091E 04	0.1118E 04	0.9585E 03	0.8164E 03	0.9420E 03	13
410.18	0.1585E 04	0.1584E 04	0.1583E 04	0.1577E 04	0.1534E 04	0.1580E 04	14
433.70	0.1271E 04	0.1226E 04	0.1253E 04	0.1180E 04	0.1232E 04	0.1171E 04	15
454.10	0.1010E 03	0.0	0.1119E 03	0.0	0.0	0.0	16
462.80	0.7576E 03	0.0	0.8883E 03	0.8551E 03	0.0	0.8686E 03	17
477.00	0.5540E 03	0.0	0.6905E 03	0.6507E 03	0.0	0.6729E 03	18
518.27	0.1109E 04	0.1095E 04	0.1034E 04	0.1117E 04	0.4188E 03	0.1065E 04	19
535.21	0.1088E 04	0.1110E 04	0.1082E 04	0.9736E 03	0.1132E 04	0.1111E 04	20
555.90	0.1325E 03	0.0	0.1361E 03	0.0	0.0	0.0	21
579.87	0.1006E 04	0.1044E 04	0.1006E 04	0.7609E 01	0.9626E 03	0.1048E 04	22
594.84	0.6743E 03	0.7117E 03	0.7300E 03	0.6782E 03	0.6752E 03	0.7453E 03	23
615.75	0.1012E 04	0.1034E 04	0.1016E 04	0.1007E 04	0.1050E 04	0.1030E 04	24
628.29	0.6184E 03	0.0	0.7295E 03	0.7642E 03	0.0	0.7150E 03	25
660.90	0.5652E 03	0.5470E 03	0.4923E 03	0.4116E 03	0.5192E 03	0.5413E 03	26
692.90	0.8469E 03	0.8554E 03	0.8440E 03	0.8594E 03	0.8302E 03	0.8601E 03	27
707.90	0.9193E 03	0.9108E 03	0.9191E 03	0.9107E 03	0.0	0.9131E 03	28
720.90	0.1839E 03	0.0	0.2053E 03	0.0	0.0	0.1987E 03	29
732.50	0.1490E 03	0.0	0.2179E 03	0.4256E 03	0.0	0.2111E 03	30
764.80	0.7413E 03	0.0	0.5227E 03	0.6267E 03	0.0	0.5823E 03	31
778.80	0.2067E 03	0.0	0.2384E 03	0.0	0.0	0.2614E 03	32
790.40	0.5276E 03	0.0	0.5889E 03	0.5586E 03	0.0	0.5632E 03	33
820.90	0.5706E 03	0.6676E 03	0.5938E 03	0.5946E 03	0.0	0.6452E 03	34
850.60	0.6359E 03	0.6910E 03	0.5860E 03	0.0	0.0	0.6751E 03	35
856.10	0.5234E 03	0.5251E 03	0.4820E 03	0.0	0.0	0.5114E 03	36
866.00	0.4342E 03	0.0	0.5247E 03	0.4567E 03	0.0	0.4718E 03	37
904.50	0.6155E 03	0.6453E 03	0.5874E 03	0.6651E 03	0.0	0.6286E 03	38
924.50	0.5679E 03	0.0	0.6694E 03	0.0	0.0	0.6569E 03	39
936.60	0.3503E 03	0.3489E 03	0.3246E 03	0.3636E 03	0.0	0.3471E 03	40
958.00	0.2309E 03	0.2564E 03	0.2350E 03	0.3159E 03	0.0	0.2395E 03	41
991.40	0.1742E 03	0.1901E 03	0.1320E 03	0.0	0.0	0.1827E 03	42

TABLE 8

s-WAVE PEAK TOTAL CROSS SECTIONS (BARNS)

	RAHN	FCHR	CARRARO	MALETSKI	ASGHAR	ENDF/B-III	
102.47	0.1815E 05	0.1892E 05	0.1914E 05	0.1895E 05	0.1891E 05	0.1845E 05	1
116.82	0.1418E 05	0.1228E 05	0.1215E 05	0.1136E 05	0.1198E 05	0.1176E 05	2
145.57	0.6159E 03	0.0	0.6759E 03	0.6671E 03	0.0	0.6524E 03	3
165.21	0.2302E 04	0.0	0.2055E 04	0.1916E 04	0.0	0.1990E 04	4
189.30	0.1192E 05	0.1206E 05	0.1211E 05	0.1223E 05	0.1210E 05	0.1198E 05	5
208.49	0.9095E 04	0.8710E 04	0.8749E 04	0.8340E 04	0.9379E 04	0.8654E 04	6
237.20	0.6510E 04	0.5804E 04	0.6063E 04	0.5812E 04	0.6843E 04	0.5870E 04	7
273.56	0.5299E 04	0.5128E 04	0.5075E 04	0.4649E 04	0.5036E 04	0.4988E 04	8
291.01	0.3912E 04	0.3793E 04	0.3566E 04	0.3906E 04	0.4000E 04	0.3488E 04	9
311.13	0.3604E 03	0.0	0.3873E 03	0.3334E 03	0.0	0.3743E 03	10
347.74	0.5653E 04	0.5881E 04	0.5890E 04	0.5939E 04	0.5873E 04	0.5762E 04	11
377.03	0.2731E 03	0.0	0.3694E 03	0.2757E 03	0.0	0.3516E 03	12
397.39	0.1404E 04	0.1383E 04	0.1439E 04	0.1167E 04	0.9560E 03	0.1141E 04	13
410.18	0.3259E 04	0.3056E 04	0.3022E 04	0.2950E 04	0.2597E 04	0.2964E 04	14
433.70	0.1827E 04	0.1720E 04	0.1784E 04	0.1617E 04	0.1732E 04	0.1595E 04	15
454.10	0.1328E 03	0.0	0.1142E 03	0.0	0.0	0.0	16
462.30	0.9024E 03	0.0	0.1106E 04	0.1053E 04	0.0	0.1074E 04	17
477.00	0.6258E 03	0.0	0.8115E 03	0.7559E 03	0.0	0.7866E 03	18
518.27	0.3369E 04	0.3410E 04	0.3567E 04	0.3337E 04	0.4561E 04	0.3489E 04	19
535.21	0.3221E 04	0.3149E 04	0.3240E 04	0.3507E 04	0.3073E 04	0.3145E 04	20
555.90	0.1365E 03	0.0	0.1403E 03	0.0	0.0	0.0	21
579.87	0.2966E 04	0.2837E 04	0.2965E 04	0.7622E 01	0.3090E 04	0.2820E 04	22
594.84	0.3544E 04	0.3480E 04	0.3449E 04	0.3538E 04	0.3541E 04	0.3422E 04	23
619.75	0.2499E 04	0.2363E 04	0.2475E 04	0.2513E 04	0.2098E 04	0.2391E 04	24
628.29	0.7565E 03	0.0	0.9453E 03	0.1011E 04	0.0	0.9189E 03	25
660.90	0.3255E 04	0.3281E 04	0.3361E 04	0.3465E 04	0.3322E 04	0.3290E 04	26
692.90	0.2468E 04	0.2439E 04	0.2476E 04	0.2418E 04	0.2518E 04	0.2423E 04	27
707.90	0.1839E 04	0.1663E 04	0.1820E 04	0.1673E 04	0.0	0.1688E 04	28
720.90	0.1944E 03	0.0	0.2185E 03	0.0	0.0	0.2111E 03	29
732.50	0.1558E 03	0.0	0.2332E 03	0.4944E 03	0.0	0.2253E 03	30
764.80	0.1091E 04	0.0	0.6450E 03	0.8294E 03	0.0	0.7457E 03	31
778.80	0.2213E 03	0.0	0.2584E 03	0.0	0.0	0.2859E 03	32
790.40	0.6598E 03	0.0	0.7683E 03	0.7134E 03	0.0	0.7213E 03	33
820.90	0.2425E 04	0.2211E 04	0.2376E 04	0.2374E 04	0.0	0.2266E 04	34
850.60	0.2159E 04	0.2002E 04	0.2267E 04	0.0	0.0	0.2051E 04	35
856.10	0.2369E 04	0.2365E 04	0.2439E 04	0.0	0.0	0.2389E 04	36
866.00	0.5264E 03	0.0	0.6775E 03	0.5622E 03	0.0	0.5862E 03	37
904.50	0.1986E 04	0.1897E 04	0.2052E 04	0.1823E 04	0.0	0.1947E 04	38
924.50	0.7889E 03	0.0	0.1098E 04	0.0	0.0	0.1045E 04	39
936.60	0.2368E 04	0.2368E 04	0.2402E 04	0.2342E 04	0.0	0.2371E 04	40
958.00	0.2463E 04	0.2426E 04	0.2455E 04	0.2347E 04	0.0	0.2424E 04	41
991.40	0.2438E 04	0.2418E 04	0.2485E 04	0.0	0.0	0.2427E 04	42

TABLE 9

SUMMARY OF s-WAVE RESONANCES

Quantity	ENDF/B-III*	ENDF/B-IV
No. of resonances	199	190
$\langle\Gamma_\gamma\rangle$, meV	23.5	23.5
S_0, 10^{-4}		
0-1 keV	1.002	1.005
1-2 keV	1.083	1.109
2-3 keV	1.119	1.122
3.4 keV	0.974	1.013
0-4 keV	1.045	1.062
$\langle D\rangle$, eV		
0-1 keV	20.0	21.3
1-2 keV	20.8	21.3
2-3 keV	18.9	20.8
3-4 keV	20.6	20.8
0-4 keV	20.1	21.05
I_γ, barns		
0-1 keV	269.77	269.37
1-2 keV	1.15	1.12
2-3 keV	0.49	0.45
3-4 keV	0.25	0.25
0-4 keV	271.63	271.19

* From Reference 8.

TABLE 10

DATA FOR EVALUATION OF P-WAVE RESONANCES

1. L. M. Bollinger and G. E. Thomas - Transmission (0-174 eV)
2. F. Rahn, et al. - Transmission, Self-Indication, Capture (0-4 keV)
3. G. de Saussure, et al. - Capture (0-4 keV)
4. J. B. Garg, et al. - Transmission (0-4 keV)
5. H. W. Glass, et al. - Capture (30-2050 eV)

TABLE 11

COMPARISON OF P-WAVE RESONANCES

E_0, eV	$g\Gamma_n$, 10^{-6} eV				
	Bollinger	Glass	Rahn	ENDF/B-III	Recommended
10.22	1.56 ± 0.01		1.77 ± 0.36	1.50	1.56
11.00				.3064	-
11.32	0.358 ± 0.006				-
16.30	0.053 ± 0.015				-
19.50	1.0 ± 0.1		1.37 ± 0.57	0.97	1.00
45.19	0.83 ± 0.15	1.0 ± 0.5	2.0 ± 1.0	3.00	1.00
47.5		0.8 ± 0.8		0.80	-
49.5	0.68 ± 0.23	0.5 ± 0.3		1.50	0.60
56.4		0.6 ± 0.2		1.20	-
57.9	0.48 ± 0.08				-
63.54	5.5 ± 1.5	4.8 ± 2.0	6.0 ± 2.6	17.2	5.50
72.8		10.8 ± 5.0		5.215	-
74.4		2.7 ± 1.0			-
83.57	7.0 ± 0.7	6.4 ± 1.0	4.0 ± 2.0	12.93	6.30
89.19	85.0 ± 4.0	85.0 ± 3.0	89.8 ± 10.9	96.00*	90.00
91.0		6.0 ± 6.0		6.00	6.00
93.3	3.0 ± 0.6	4.0 ± 2.0		12.11	5.00
98.2		4.8 ± 1.0		13.09	8.00

* [illegible] in ENDF/B-III

TABLE 12

SUMMARY OF P-WAVE RESONANCES

Quantity	ENDF/B-III	ENDF/B-IV
No. p-Wave Res.	258	220
S_1, 10^{-4} (Below 500 eV)	--	1.89
I_γ, barns (p-Wave Res)		
0 - 1.0 keV	0.403	0.369
1.0 - 2.0 keV	0.106	0.108
2.0 - 3.0 keV	0.036	0.050
3.0 - 4.0 keV	0.033	0.034
0 - 4.0 keV	0.578	0.561

TABLE 13

BACKGROUND CROSS SECTIONS BETWEEN 0.68 AND 4.0 keV

Energy, eV	Capture Cross Section, barns	
	ENDF/B-III	ENDF/B-IV
680	0	0
700	0.005	0.005
980	0.05	0.02
1000	0.08	0.05
2000	0.16	0.11
2100	0.17	0.12
2500	0.22	0.15
3000	0.25	0.17
4000	0.28	0.19
I_γ, barns (0.68 - 4.0 keV)	0.255	0.171

TABLE 14

CRITICALITY

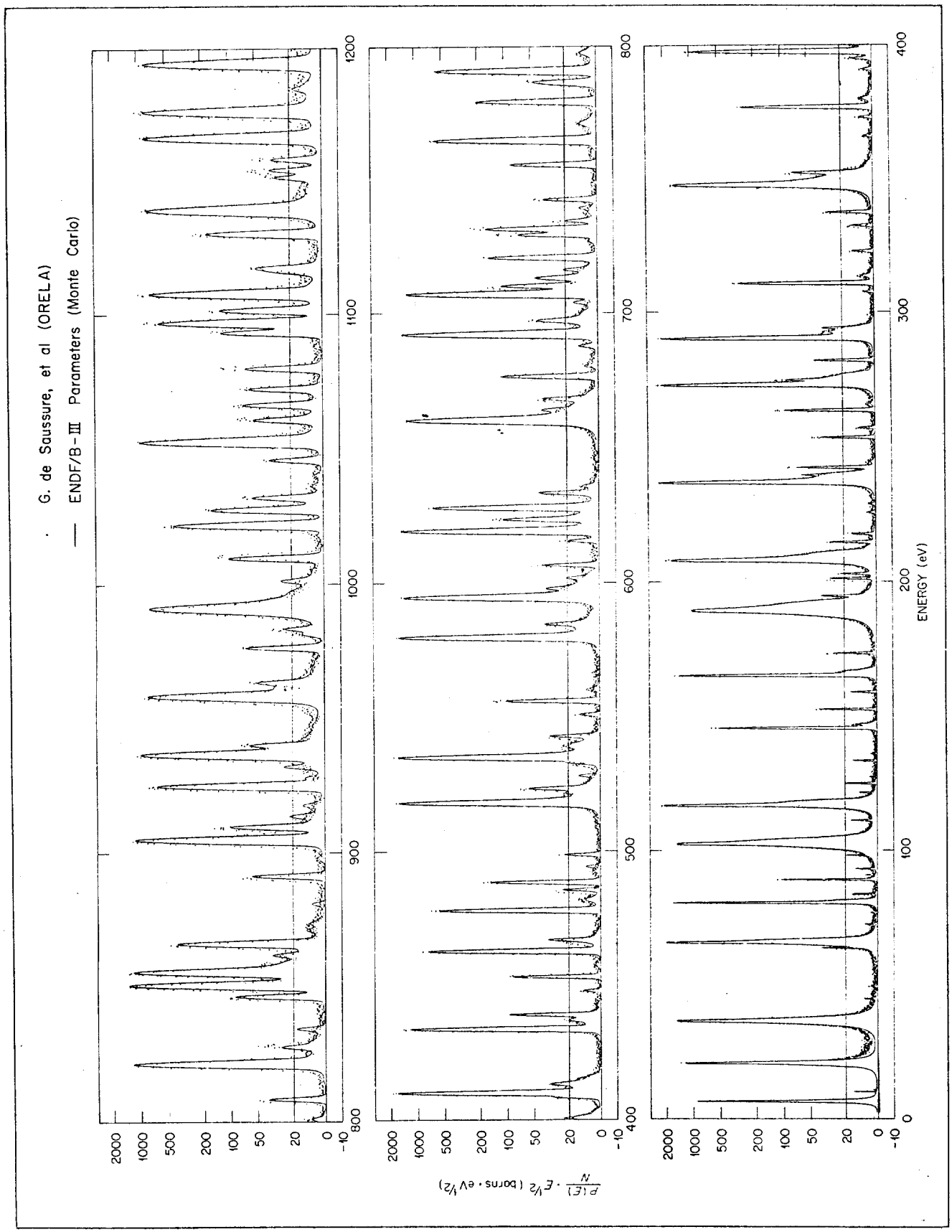
BENCHMARK	DESCRIPTION	Keff (ENDF/B-III)						Keff (ENDF/B-IV)
		ANC	BAPL	CRNL	GGA	ORNL	SRL	SRL
ORNL	Unref. spheres of uranyl nitrate sol.							
-1	H/U-235=1378; R=34.595 cm		0.9965		0.9999		0.9973	0.9996
-2	H/U-235=1177; R=34.595 cm		0.9963		0.9995			
-3	H/U-235=1033; R=34.595 cm		0.9933		0.9963			
-4	H/U-235= 971; R=34.595 cm		0.9947		0.9980		0.9958	0.9976
-10	H/U-235=1835; R=61.011 cm		0.9931		0.9956		0.9935	0.9951
TRX	H_2O moderated U lattices							
-1	Mod/Fuel = 2.35	0.9741	0.9872	0.9808	0.9791	0.985	0.9766	0.9875
-2	Mod/Fuel = 4.02	0.9823	0.9913	0.9876	0.9924	[illegible]	[illegible]	0.9941
MIT	D_2O moderated U lattices							
-1	Mod/Fuel = 20.74			0.9801	0.9880	0.984	0.9705	0.9883
-2	Mod/Fuel = 25.88			0.9804	0.9885	0.971	0.9790	0.9880
-3	Mod/Fuel = 34.59			0.9826	[illegible]	0.975	[illegible]	0.9911

TABLE 15

RATIO OF EPITHERMAL-TO-THERMAL ^{238}U CAPTURES

BENCH-MARK	ρ^{28} (ENDF/B-III) EXP	ANC	BAPL	CRNL	GGA	ORNL	SRL	ρ^{28} (ENDF/B-IV) SRL
TRX-1	1.311	1.438	1.422	1.419	1.416	1.44	1.454	1.417
	±0.020							
TRX-2	0.830	0.906	0.899	0.874	0.877	0.91	0.890	0.868
	±0.015							
MIT-1	0.493			0.5319	0.534	.535	0.5633	0.5464
	±0.008							
MIT-2	0.394			0.4365	0.435	.430	0.4659	0.4483
	±0.002							
MIT-3	0.305			0.3400	0.334	.346	0.3624	0.3490

* Thermal cutoff energy = 0.625 eV

FIGURE 1

ORELA Capture Measurements