NUCLEAR DATA AND MEASUREMENTS SERIES

ANL/NDM-4
^{90}Zr and ^{92}Zr – Neutron Total and Scattering Cross Sections

by

P. Guenther, A. Smith, and J. Whalen

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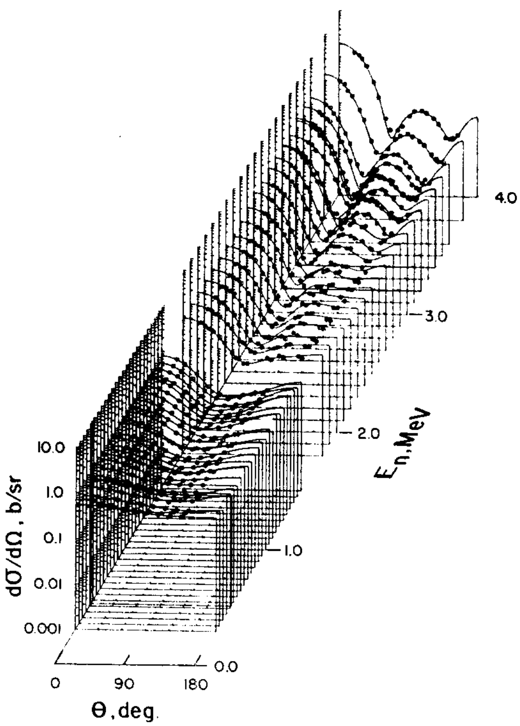

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^{90}Zr and ^{92}Zr; Neutron Total and Scattering Cross Sections[a]

by

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Abstract

Total neutron cross sections of ^{90}Zr and ^{92}Zr were measured from 0.9 to 5.5 MeV and elastic and inelastic neutron scattering cross sections from 1.8 to 4.0 MeV. The inelastic neutron excitations of six states in ^{90}Zr and more than twelve in ^{92}Zr were observed. The experimental results formed the basis of an optical-statistical model interpretation including considerations of the $\left[\frac{N-Z}{A}\right]$ and shell dependence of the optical potential and the effects of resonance width-fluctuation and interference. Comparisons of measured and calculated cross sections suggested new J^{π} assignments for a number of excited states. The experimental and calculational results were incorporated into a limited evaluated data file in the ENDF format including total and scattering cross sections to from 0.8 to 8.0 MeV.

a. This work supported by the U. S. Atomic Energy Commission.

I. INTRODUCTION

Zirconium is a widely used structural material in fission-reactor systems. In these and other applications fast neutron cross sections of zirconium are of high importance (1). More than two thirds of the element consists of the isotopes ^{90}Zr and ^{92}Zr. Therefore, these isotopes make the major contribution to the elemental cross sections. At low energies ($\lesssim$ 1.0 MeV) the neutron total and elastic and inelastic scattering cross sections of the element are reasonably known (2,3,4). However, as the energy increases into the few MeV range the knowledge becomes uncertain and the character of the neutron scattering cross sections becomes very isotope dependent.

The two isotopes ^{90}Zr and ^{92}Zr are situated at and just above the closed shell at N=50, respectively. In this region the density of excited states is changing rapidly, the s-wave strength function near a minimum and the p-wave strength function large (5,6). An optical-model (7,8) description of the neutron-nucleus interaction may be sensitive to both shell and isotopic effects (9,10,11,12) such as have been reported elsewhere (13,14). The properties of the excited states, particularly of ^{90}Zr, are well established to excitations of more than 3.0 MeV (5); thereby alleviating one source of uncertainties in statistical model calculations (15) and improving the potential for a detailed examination of the theoretical concepts (16). The latter are a matter of contemporary basic-physical interest (17). In particular one can expect considerable enhancement of energy-average cross sections for reactions in which the entrance and exit channel fluctuations are strongly correlated and a corresponding reduction in reactions without such correlations. In addition compound-nucleus inelastic neutron scattering cross sections should be enhanced by resonance correlations. These effects imply considerable corrections to the conventional Hauser-Feshbach formula (15). Finally, spectroscopic information for ^{92}Zr is incomplete at excitations $\lesssim$ 3.0 MeV and a careful comparison of measured and calculated neutron inelastic scattering cross sections can guide the selection of J^{π} values.

The present program was undertaken in order to: a) provide nuclear data of high applied relevance, b) examine the shell and isotopic dependence of the optical potential, and c) phenomenologically explore the physical character of the compound-nucleus process.

II. Experimental Methods

The samples employed in the measurements were right metallic cylinders 2 cm in diameter and 2 cm high. They were fabricated out of isotopically separated material enriched to greater than 95 atom/percent. The mass assay is given in Table 1. There were negligible chemical impurities. Herein all cross sections are reported as barns per average atom of the respective samples. Corrections for the effect of minority isotopes should be less than the experimental uncertainties.

The total cross section measurements were made using monoenergetic transmission techniques including fast time-of-flight for background and neutron-source control (18). The neutron scattering measurements were made using a ten-angle time-of-flight system employing flight paths in the range 5.5 to 6.0 meters. The scattering measurements, including those associated with the H(n,n) standard, were corrected for beam attenuation, angular resolution and multiple-event effects using Monte Carlo-calculational procedures (19).

All the measurements employed the $^7Li(p,n)$ neutron source reaction (20). This reaction produces primary and secondary neutron groups in the energy range of the present experiments. Corrections were made for perturbations due to the secondary group where appropriate.

The details of the specific apparatuses employed in these measurements have been described elsewhere (21,22).

III. Experimental Results

A. Total Neutron Cross Sections

The total neutron cross sections of ^{90}Zr and ^{92}Zr were measured from 0.9 to 5.5 MeV at intervals of $\lesssim$ 10 keV with resolutions in the range 5 to 10 keV. The results are summarized in Fig. 1.

The statistical accuracy of the individual measurements varied from 2 to 5 percent. Systematic uncertainties were estimated to be < 3 percent. Concurrent measurements of a carbon reference standard resulted in total cross sections of carbon in agreement with those reported in the literature (23,24). Above several MeV the total cross sections were relatively smooth functions of energy. However, below $\approx$ 1.5 MeV, particularly for ^{90}Zr, fluctuating partially resolved structure becomes evident with increasing magnitudes with decreasing energy. Apparently the only previous total cross section results directly comparable with the present work are the ^{90}Zr values of Stooksberry et al. (25). The agreement with the present work is good as illustrated in Fig. 1. Approximately two thirds of elemental zirconium consists of ^{90}Zr and ^{92}Zr. The relative-isotopic-weighted average of the present results is in good agreement with the reported total cross sections of the natural element (2). The present results do show a difference in total cross section magnitudes between the two isotopes. The difference is approximately that expected from a "size" effect as discussed in Sec. IV, below.

B. Elastic Neutron Scattering Cross Sections

The differential elastic scattering cross sections were measured from 1.8 to 4.0 MeV at intervals of $\lesssim$ 0.2 MeV with energy resolutions of 30 to 50 keV. The measurements were made at twenty scattering angles distributed from < 20 to > 155 deg. The relative energy dependence of each of the ten detector systems was experimentally determined by observation of the H(n,n) scattering process and all zirconium cross section values were determined relative to that of H(n,n) scattering (26). The experimental results are summarized in Fig. 2. Clearly, there is a marked energy and isotopic dependence of these cross sections. The accuracies of the measurements were generally 5 to 10 percent or a few milli-barns/steradian, whichever was larger. For some specific measurements the uncertainties were somewhat larger as qualitatively indicated by the error-bars of Fig. 2. The uncertainty estimates included contributions from systematic perturbations such as those associated with the Monte-Carlo correction procedures. The normalization to the H(n,n) standard cross section was independent at each incident energy and free of absolute flux or detector calibrations (13). Pairs of adjacent data points were usually obtained using the same detector thus were subject to many of the same systematic uncertainties. However, the calibration associated with any pair was essentially independent of that of any other pair. These calibration procedures can result in increased random uncertainties between point-pairs within a given distribution but the method has the advantage of a highly redundant general normalization alleviating some usual systematic uncertainties. The experimental geometry was well controlled and the scattering angle calibrated by direct left-right observation of the energy transfer in scattering from hydrogen. The scattering angles were believed known to ± 1.0 deg. At the higher incident energies this small angular uncertainty can have an effect on the measured values. Cross sections of a carbon reference standard were determined concurrently with the zirconium measurements. The angle integral of the observed carbon cross sections was generally within 5 to 10 percent of the reported total cross sections (23,24).

The angle-integrated elastic scattering cross sections were determined by least-square fitting the measured differential values with a Legendre series. Generally, there were no constraints on the fitting procedures. Particularly, Wick's Limit (27) or similar artifaces were not employed to force the small-angle behavior. The resulting angle-integrated values are outlined in Fig. 1. The uncertainties in these angle-integrated cross sections were estimated to be 5 to 10 percent with the largest contribution due to the extrapolation from the most-forward measured point (at 15 to 20 deg.) to zero degrees. Generally, the angle-integrated elastic scattering cross sections were consistent with the observed total cross sections and explicitly so for ^{90}Zr below the first inelastic scattering threshold as illustrated in Fig. 1.

Comparable previous elastic scattering measurements appear confined to a single ^{90}Zr distribution reported by Stooksberry et al. (25) at 2.1 MeV. The previous data apparently was arbitrarily normalized but it does have an angular-dependent shape consistent with the results of the present work.

C. Inelastic Neutron Scattering Cross Sections

The inelastic neutron scattering cross sections were determined concurrently with those for the elastic process using identical H(n,n) calibration procedures. The scattered neutron velocity resolution of $\sim$ 0.4 nsec/meter was sufficient to resolve most of the reported structure in these two isotopes. The ten detectors had minimum sensitivities varying from $\sim$ 0.2 to 0.8 MeV. Cross sections were accepted when there was a reasonable response from five or more detectors generally implying a scattered neutron energy of greater than 0.5 MeV. Usually 15 to 20 data points were obtained on a given distribution. The various reaction Q-values were determined from the known flight paths, flight times and incident energies and verified by the observation of well known inelastic neutron processes. These Q-value determinations were highly redundant and the final values were taken from a simple average of the measured quantities with the respective uncertainties estimated from the consistency of the measured values. The resulting Q-values were relatively precise but far short of precisions obtainable using other spectroscopic methods (e.g. charged-particle and gamma-ray spectroscopy as illustrated in Ref. 5). The latter are generally preferred for analysis and are the values used in Sec. IV, below. The uncertainties in the measured inelastic cross sections varied with experimental conditions and the magnitudes and the locations of the respective scattered neutron groups. The best differential uncertainties were 5 to 10 percent or a few milli-barns/steradian (whichever was larger). The angle-integrated inelastic cross sections were obtained by least square fitting a Legendre series to the observed differential values. Most of the angular distributions were essentially isotropic. Exceptions were those associated with the excitation of the 0+ states as illustrated by the ^{90}Zr example of Fig. 3. The estimated uncertainties, in the angle integrated values, including systematic effects, were 5 to 10 percent or larger.

The inelastic neutron excitation of more than twenty states was observed. The excitation energies and the corresponding cross sections are summarized in Table 2 and Figs. 4 and 5. The spectroscopic character of these states is discussed in Sec. IV-B, below. The six states observed in ^{90}Zr closely correspond with those reported in the literature (5). Only in the case of the closely spaced 2738 and 2748 keV doublet did the present measurements fail to resolve all the reported levels. Apparently all previous inelastic neutron scattering studies of ^{90}Zr relied upon the gamma-ray detection technique (28,29,30). This method does not always uniquely define the cross sections but even so many of the gamma-ray results compare favorably with the present values as illustrated in Fig. 4. Where there are pronounced discrepancies they are attributable to the effects of gamma-ray branching. Many of the neutron groups observed in neutron scattering from ^{92}Zr were clearly related to well established levels (5). There was no evidence for the tentatively suggested state at $\approx$ 2.15 MeV. The reported 2.34 and 2.39 MeV doublet was observed and also a single group corresponding to an excitation of $\approx$ 2.48 MeV. The latter has been suggested as a doublet with a few keV separation, well beyond the resolution of the present work. A single measurement implied a level at $\approx$ 2.66 MeV. A similar level has been previously suggested from (p,p) scattering measurements (5) but the observed neutron cross sections were small and the present identification was considered very marginal. Neutron groups observed at excitations in the range 2.7 to 3.0 MeV closely correspond to previous spectroscopic results. Above excitations of $\approx$ 3.0 MeV the present results become more speculative. The experimental resolution was not comparable to the complexity of the reported structure and the observed cross sections were probably attributable to contributions from two or more states. There appears to have been only a single previous neutron measurement of inelastic scattering from ^{92}Zr and the result is not in particularly good agreement with the present work (31). Day (32) and Tessler et al. (33) have extensively studied the ^{92}Zr (n;n'γ) process. The latter group gave particular attention to gamma-ray cascades and branching ratios and obtained neutron cross sections for a number of excitations. These are in remarkably good agreement with the present values as illustrated in Fig. 5. The results of Day are consistent with the present values where they are unambiguously related to the neutron cross sections.

IV. Discussion

A. The Optical Model

The optical model interpretation consisted of the derivation of an isotopically dependent potential from each of the experimental data sets with subsequent inspection of the resulting parameters for evidence of isotopic, shell and energy dependence as suggested and reported in previous work (9,10,11,12,13). In addition, the choice of the potentials in this mass-energy range reflects the nature of the compound-nucleus reaction mechanism (15,16,17). The resulting potentials were used for the subsequent interpretation of spectroscopic properties and the formulation of evaluated data files. The present measurements provided an auspicious foundation for such endeavors, with a good definition and scope extending over most neutron exit channels in a sensitive mass-energy range. This was particularly so for ^{90}Zr where the properties of all states were well known to excitations of $\gtrsim$ 3.3 MeV.

The six optical model parameters were determined from a Xi-square fit to each measured elastic scattering distribution over the energy range 2 to 4 MeV. The fitting procedures were inclusive of compound-elastic contributions calculated using the Hauser-Feshbach formula (15) corrected for width fluctuation effects (16,34). The variations in the parameters for a given isotope were small, particularly if the few poor-quality fits were omitted. The parameters were most uncertain at the lowest energies where the data was less reliable and at the highest energies (near 4.0 MeV) where all competing inelastic neutron exit channels were not clearly known. The distribution of parameter values for a given isotope was generally random with no evident energy-dependent trend. The lack of any recognizable energy dependence was not surprising as studies based upon a far wider energy range indicate a relatively small energy dependence of the potential parameters. For example, the work of Engelbrecht and Fiedeldey (35) implied a change from the average real-potential magnitude of +0.3 to -0.3 MeV going from incident energies of 2 to 4 MeV. These are small values, $\lesssim$ 1 percent. The present total cross section measurements extend over a wider energy range than the elastic scattering values. Comparison of measured and calculated total cross sections in this wider context did suggest an energy dependence of the real potential consistent with that of Ref. 35. The final parameter sets for ^{90}Zr and ^{92}Zr were constructed of a simple average of the values obtained from the isotopic Xi-square fits. The results are summarized in Table 3. The parameter uncertainties given in the Table are the RMS deviation from the average assuming equal weighting. These uncertainties are believed to be very conservative as they tend to be biased toward larger magnitudes by a few fits of less desirable quality.

Neutron total and elastic angle-integrated cross sections calculated with the potentials of Table 3 were in agreement with the measured values as illustrated in Fig. 1. In the low-energy limit the calculated $\ell=0$ strength functions were $\approx 0.6 \times 10^{-4}$ and consistent with systematic behavior in this mass region (6). The two average potentials gave a very nice description of the observed elastic scattering angular distributions as illustrated by the curves of Fig. 2. Discrepancies between calculation and experiment were largest at lower energies and may represent true fluctuations in the measured data as clearly evident in the neutron total cross sections at lower energies (see Fig. 1). All of these calculations were inclusive of the width fluctuation correction (16). In addition, the ^{90}Zr results included resonance correlation corrections with the correlation parameter, Q=0.5. This additional correction did not have a large effect on the elastic scattering distributions and was relatively more important in the minima at higher energies as illustrated by the comparisons of Fig. 3. In these latter areas, there are other uncertainties associated with the neglect of competition from unknown inelastic exit channels. Moreover the correlation corrections (34) are only approximations which, at higher energies with a number of channels, may break down and even lead to negative compound-elastic cross sections (17). Such anomalous behavior was observed for large values of the correlation parameter (e.g. Q=1.0) at 4.0 MeV. Despite these uncertainties, it is clear from the inelastic processes that such corrections are relevant as discussed in Sec. IV-B, below.

The potentials for ^{90}Zr and ^{92}Zr of Table 3 are identical within estimated parameter uncertainties. Indeed the differences between the parameter values are less than would be expected assuming the uncertainty estimates are equivalent to standard deviations. This fact tends to support the above premise that the uncertainties are conservative. Lane (11), Becchetti and Greenlees (12) and others (8, 13) have attributed a $\left[\frac{N-Z}{A}\right]$ (or iso-spin) dependence to the optical potential. This conclusion was deduced from basic physical concepts and phenomenological comparisons with measured data. In neutron processes the dependence leads to potential strengths of the form

$$V = V_o - \left(\frac{N-Z}{A}\right)\cdot V_1$$
$$W = W_o - \left(\frac{N-Z}{A}\right)\cdot W_1 \quad (1)$$

where $V_1 \sim 25$ MeV and $W_1 \sim 12$ MeV. These equations imply a difference between ^{90}Zr and ^{92}Zr real potentials of $\delta W \sim 0.49$ MeV and between imaginary potentials of $\delta W \sim 0.23$ MeV. Moreover ^{90}Zr is at the closed shell N=50 and Lane et al. (9) and Vonach et al. (10) have noted reduced optical-potential absorption as shell closures are approached. A similar affect has recently been suggested near A=100 by Guenther et al. (13) where comparisons of ^{92}Mo and ^{100}Mo neutron scattering results indicate an approximately linear shell dependent change of $\delta W \sim 1$-2 MeV over eight mass units. Thus in the present context of neighboring ^{90}Zr and ^{92}Zr both the expected $\left[\frac{N-Z}{A}\right]$ and shell dependence of the potential is much smaller than the uncertainties in the parameter values given in Table 3. Identification of such effects will probably require about a factor of three improvement in the accuracy of the parameters values. This will not be an easy task in this mass-energy range as the requisite experiments are very demanding and, more critically, the fine details of the parameter selection will be influenced by compound-nucleus contributions. The detailed physical understanding of the latter is not certain and is now a matter of considerable theoretical discussion (17,36,37). Until these physical questions can be resolved and put into a useful computational form, it will be difficult, if not impossible, to determine compound-elastic components to accuracies necessary for the selection of potentials sensitive to small $\left[\frac{N-Z}{A}\right]$ and shell effects between neighboring isotopes as in the present case.

B. The Statistical Model and Spectroscopic Parameters

The above optical-model parameters and compound-nucleus concepts were used to calculate the inelastic neutron scattering cross sections. The calculations employed the Hauser-Feshbach formula (15) with corrections for the width-fluctuation and correlation of resonances. These corrections were implemented by means of the computer program NEARREX (34) using the Moldauer θ coefficients given by

$$\langle\theta\rangle = T + Q^{-1}\left[1 - (1-QT)^{\frac{1}{2}}\right]^2 \qquad (2)$$

where T are the conventional transmission coefficients and Q an overlap parameter ranging from zero (for simple width fluctuation corrections) to unity (16). This expression is an approximate representation of the complex physical situation (16,17). It is reasonably valid relatively near the inelastic reaction thresholds with a few open channels and will lead to the correlation enhancement of compound-inelastic cross sections. In the present calculations Q is treated as a free parameter, adjusted to obtain a phenomenological description of the observed cross sections.

The ^{90}Zr interpretation is relatively straightforward as the spectroscopic parameters are well known (5) and the approximation of Eq. 2 is reasonably valid. The calculated cross sections for the excitations of the first two states (1.761 (0+) and 2.186 (2+) MeV) are sensitive to the choice of Q. Values of Q in the range 0.5 to 0.7 are reasonably descriptive of the observed inelastic neutron cross sections as illustrated in Figs. 3 and 4 and also of the observed elastic scattering distributions. As more channels open, Q has less effect and the cross sections calculated with the reported J^{π} values (5) and various values of Q are in reasonable agreement with the measured results as illustrated in Fig. 4. This agreement is inclusive of the unresolved doublet at an excitation of $\stackrel{\sim}{\sim}$ 2.74 MeV.

The interpretation of the ^{92}Zr results is more difficult as the spectroscopic character of the contributing states is not always known, more exit channels are open and the approximation of Eq. 2 becomes less valid. These complexities are not serious near the thresholds of the first two states (0.934 (2+) and 1.383 (0+) MeV) and comparison of measured and calculated results indicates Q-values of 0.5 or larger as illustrated in Fig. 5. At higher energies ($\tilde{\sim}$ 4.0 MeV) the calculations using Q $\tilde{\sim}$ 1.0 become unreliable and the approximations underlying Eq. 2 break down. Again the calculated excitations of the higher-energy excited states are not sensitive to the choice of Q. The J^{π} values of the 1.496 (4+), 1.847 (2+), 2.067 (2+) and 2.340 (3-) MeV states are well known (5) and the calculated cross sections in good agreement with observation. The J^{π} values of reported states at 2.39, 2.48, 2.65, 2.74, 2.82 and 2.85 MeV are uncertain (5). A number of calculations were compared with measured cross section results using a wide range of J^{π} values with iterations extending upward in energy. From the results it is suggested that: the 2.39 MeV state J=1, 2 or 3, J=5 for the 2.48 MeV state and J=2 or 3 for the 2.74 MeV state. The observed cross sections for the unresolved doublet at 2.82 and 2.85 MeV are consistent with a prominent contribution from a single state with J=2, 3 or 4 possibly implying a large J value for the alternate component. No attempt was made to calculate the cross sections for the 2.65 MeV state as its observation was speculative. If present, the corresponding cross sections are small implying large J values. The observed 2.9 MeV state was attributed to the reported doublet at 2.898 (2,3+) and 2.95 MeV. Calculated cross sections based upon the single state with J=2 or 3+ were consistent with the measured values implying a large J-value for the other component of the doublet. The observed state at 3.06 MeV was attributed to the reported 3.04 (2+) level.

However, the cross sections calculated under this premise were smaller than observed. Thus it is possible that the measured values are in error or that there are additional components contributing to the observed cross sections. No attempt was made to correlate the measured and calculated excitations at energies above $\sim$ 3.0 MeV due to the complexities and uncertainties of the experimental results, the contributing structure and the computational methods.

The above calculations can give guidance as to the relative energy dependence of the inelastic cross sections and, when correlated with measured values, suggest spectroscopic parameters. However, the accuracy of prediction of inelastic cross section magnitudes near the first few thresholds independent of experimental normalization is no better than 20 to 30 percent. The uncertainties are due to shortfalls in the basic understanding of resonance width-fluctuations and correlations and the associated computational techniques. These physical factors are contained in the "M" matrix of Refs. 16 and 17. Moldauer has pointed out the fortuitous property of the formulas to tend toward the familiar Hauser-Feshbach result at higher energies (17). The physical situation is not so simple in the region of the present experiments and is the subject of continued theoretical investigation by, for example, Moldauer (17), Kawai et al. (36) and Weidermüller (37).

VI. A Limited Evaluated File in the ENDF/B Format

The above experimental and calculational results were used to develope limited evaluated ^{90}Zr and ^{92}Zr neutronic data files in the ENDF format (38). These files extend from 0.8 to 8.0 MeV and include total and scattering cross sections. It was the intent to make the results of the present work available to the applied user in a recognized format and to set forth a framework for the subsequent formulation of more comprehensive evaluated files as more isotopic data for these isotopes becomes available. Here we briefly outline the basis of these files; the numerical contents of which are given in the appendix.

A. The ^{90}Zr File

This file contains the nine components outlined in Table 4.

The total cross section values from 0.8 to 5.5 MeV were taken from energy averages of the results of the present work. The results of Ref. 25 were also considered. Above 5.5 MeV the file is based upon the above model normalized to measured values over the energy range 5.0 to 5.5 MeV. It generally follows the energy dependence of the elemental cross section (2) but has slightly smaller magnitudes. The uncertainty in the evaluated total cross section is believed $<$ 10 percent over the entire energy range and $<$ 5 percent below 5.0 MeV.

Below the inelastic scattering thresholds the angle-integrated elastic scattering cross sections are made explicitly equivalent to the total cross sections and the associated uncertainties are comparable. Here, and generally throughout these evaluations, contributions from minor reaction channels, such as (n,γ) processes, are ignored. When the requisite information becomes available the files should be appropriately corrected. From the inelastic scattering threshold to 4.0 MeV the angle-integrated elastic scattering was treated as a free parameter, adjusted to assure consistency between inelastic scattering and total cross sections. The results are consistent with the present measured values and probably known to $\lesssim$ 10 percent. Beyond 4.0 MeV the angle-integrated elastic cross section was calculated using the above model with the continuum inelastic component treated as a free parameter. At these higher energies, the estimated uncertainties are $\approx$ 10 percent. The elastic scattering angular distributions are taken directly from the present work extended to both lower and higher energies as required using the above model. The distributions are described in terms of f_ℓ Legendre coefficients expressed in the laboratory system. All evaluated distributions are consistent with Wick's Limit (27).

The discrete inelastic excitation cross sections were evaluated from the measured values (primarily those of the present work) summarized in Fig. 4. Thresholds extended to $\approx$ 3.35 MeV and the 2.77 MeV doublet was treated as a single state. The above model was employed for interpolation to threshold and extrapolation above 4.0 MeV. The latter extrapolation was only qualitative and assumed no pre-compound processes. Some compound-inelastic contribution was retained to 8.0 MeV; for ^{90}Zr, perhaps too much. Generally, these evaluations should be treated with circumspection above the maximum measured energy of 5.5 MeV. The isotropy of inelastic neutron emission is implicit in the evaluation. This is inappropriate for the excitation of the 0+ states at lower energies and is an over simplification at high energies ($\gtrsim$ 6.0 MeV). However, the resulting errors are probably of negligible applied significance. The continuum inelastic component is the simple difference between the above elastic scattering cross sections and the discrete inelastic components. As a first approximation the continuum emission spectrum can be represented by a simple temperature. A more refined approach will use a "harder" continuum distribution as indicated, for example, by high energy macroscopic measurements (39). The uncertainties to be associated with the prominent evaluated inelastic groups are estimated to be $\approx$ 10 percent and become much larger for those contributions of relatively small magnitude. The integrated inelastic cross section and continuum component are probably known to within 10 to 20 percent. At the higher energies this uncertainty is strongly correlated with that of the elastic cross sections.

The final evaluated ^{90}Zr results are summarized in Fig. 6.

B. The ^{92}Zr File

The formulation of the ^{92}Zr file was identical to that of the ^{90}Zr file described above. The various components are defined in Table 5. Some of the detail of the excited structure is truncated. The ^{92}Zr file content is graphically summarized in Fig. 6. The uncertainties are generally equivalent to those of the ^{90}Zr file.

Previous comparable evaluated files for the isotopes ^{90}Zr and ^{92}Zr or for the element zirconium are not readily available precluding critical comparisons. The zircaloy file, MAT-1284, was examined. Qualitative comparisons with the present evaluations are hampered by some ambiguities in reaction Q-values and the fact that the discrete inelastic cross sections of MAT-1284 are truncated to zero-values in a stepwise manner at 3.5 MeV. However qualitative comparisons with selected inelastic cross sections of MAT-1284 near 2.0 MeV indicate reasonable agreement with the recent work considering the presence of other isotopes. The agreement between the total and elastic scattering cross sections of MAT-1284 and the present work is reasonably good.

VI. Concluding Remarks

The present measurements define the neutron total cross sections of ^{90}Zr and ^{92}Zr from below 1.0 MeV to 5.5 MeV and their neutron scattering cross sections from 1.8 to 4.0 MeV. These detailed results provide a foundation for the phenomenological interpretation of neutron processes in a mass-energy region where there is an interplay between direct and compound-nucleus reactions.

Optical potentials specifically appropriate to ^{90}Zr and to ^{92}Zr were deduced from the measured values. The respective potential-parameter sets were, within their small uncertainties, identical. In particular, no significant $\left[\frac{N-Z}{A}\right]$ or shell dependence of the optical potential could be identified within the context of these two neighboring isotopes. Estimates of such dependences, based upon previously reported work, were approximately a factor of three smaller than the estimated uncertainties in the present optical parameter sets. It is suggested that positive identification of such effects in the present energy-isotopic context will be exceedingly difficult as small variations in compound nucleus mechanisms will appreciably influence the parameter selection. The compound-nucleus process, particularly resonance width-fluctuation and correlation properties, may not be sufficiently understood to reliably determine optical parameters with the necessary accuracies of better than a few tenths percent. Moreover, the computational tools for utilizing the theoretical concepts in experimental analysis are not generally available.

Comparison of measured and calculated neutron inelastic scattering cross sections demonstrated the importance of resonance width-fluctuation and correlation corrections to the simple Hauser-Feshbach formula. Careful parameter adjustment resulted in calculated cross sections descriptive of the experimental results. However, uncertainties in the correction procedures are such that it is doubtful that calculations, independent of experiment, can predict inelastic neutron cross sections in this region to better than 20 to 30 percent. Correlation of measured and calculated neutron inelastic excitation cross sections suggested a number of previously uncertain spin values particularly those associated with states in ^{92}Zr at excitations of 2390, 2480, 2740, 2820, 2851, 2898 and 2950 keV.

The experimental and calculational results were used to deduce limited evaluated data files for ^{90}Zr and ^{92}Zr. These files may be of use in some special applications and they provide a foundation for the formulation of more comprehensive evaluated data files as additional data becomes available.

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TABLE 1. SAMPLE COMPOSITION

Sample	Isotope, Atom/Percent				
	90	91	92	94	96
#1(^{90}Zr)	97.72	1.07	0.51	0.56	0.15
#2(^{92}Zr)	2.54	1.04	95.13	1.11	0.18

TABLE 2. OBSERVED INELASTIC NEUTRON EXCITATION ENERGIES IN KEV.

ZR-90		ZR-92	
EXP.	NDS*	EXP.	NDS*
1749 ± 15(0+)	1761(0+)	934 ± 10(2+)	934(2+)
2169 ± 15(2+)	2186(2+)	1375 ± 10(0+)	1383(0+)
2306 ± 20(5−)	2319(5−)	1492 ± 10(4+)	1496(4+)
2732 ± 20(4−) +	2738(4−) +	1838 ± 15(2+)	1847(2+)
(3−)	2748(3−)	2058 ± 15(2+)	2067(2+)
3068 ± 20(4+)	3077(4+)	2320 ± 20(3−)	2340(3−)
3300 ± 20(2+)	3310(2+)	2360 ± 20(1,3)	2390(**)
		2486 ± 20(5)	2480(**)
		2666 ± 30(**)	2650(**)
		2778 ± 30(2,3)	2740(**)
		2867 ± 30(2,4)	2820(**) +
			2851(**)
		2900 ± 40(2,3)	2898(2,3+) +
			2950(**)
		3063 ± 30(**)	3040(2+)
		3187 ± 30	3160 +
			3174 +
			3110 +

		3275 ± 50	3223 +
			3240 +
			3264 +
			3320 +
			----

*Herein NDS refers to the nuclear data sheets as defined in Ref. 5.

**Denotes uncertain or unknown J^{π} assignment.

TABLE 3. OPTICAL MODEL PARAMETERS

^{90}Zr		
V^a = 50.12 ± 0.55[e] MeV	R_v^b = 1.244 ± 0.0075 F	a_v = 0.60 ± 0.055 F
W^c = 5.50 ± 0.48 MeV	R_w^b = 1.250 ± 0.075 F	b_w = 0.53 ± 0.053 F
V_{so}^d = 8.0 MeV		
^{92}Zr		
V = 49.50 ± 0.50 MeV	R_v = 1.238 ± 0.005 F	a_v = 0.606 ± 0.05 F
W = 5.21 ± 0.25 MeV	R_w = 1.340 ± 0.05 F	b_w = 0.550 ± 0.042 F

a. Saxon real form.
b. All radii given in form $r = R.A^{1/3}$.
c. Saxon derivative imaginary form.
d. Thomas spin-orbit form fixed at the same magnitude for both isotopes.
e. All uncertainties are RMS values derived from Xi-square six-parameter fits to the elastic angular distributions over the incident energy range 2.0 to 4.0 MeV as described in text.
The estimates are very conservative.

TABLE 4. EVALUATED CROSS SECTIONS OF ZR-90

No.	Cross Section	EX(MeV)	Threshold(MeV)
1	Total	---	---
2	Elastic	0.0	0.0
3	Inel.-1	1.761	1.780
4	Inel.-2	2.186	2.210
5	Inel.-3	2.319	2.346
6	Inel.-4	2.740	2.770
7	Inel.-5	3.077	3.111
8	Inel.-6	3.310	3.346
9	Continuum Inel.	3.758	3.800

TABLE 5. EVALUATED CROSS SECTIONS OF ZR-92

No.	Cross Section	EX(MeV)	Threshold(MeV)
1	Total	---	---
2	Elastic	0.0	0.0
3	Inel.-1	0.934	0.943
4	Inel.-2	1.383	1.397
5	Inel.-3	1.496	1.511
6	Inel.-4	1.847	1.865
7	Inel.-5	2.067	2.088
8	Inel.-6	2.340	2.363
9	Inel.-7	2.390	2.414
10	Inel.-8	2.480	2.505
11	Inel.-9	2.740	2.767
12	Inel.-10	2.830	2.858
13	Inel.-11	2.900	2.929
14	Inel.-12	3.040	3.070
15	Inel.-13	3.160	3.192
16	Inel.-14	3.270	3.303
17	Continuum Inel.	3.709	3.750

FIGURE CAPTIONS

Fig. 1. Total and elastic scattering cross sections of ^{90}Zr and ^{92}Zr. The present results are indicated by circular (total cross sections) and square (elastic cross sections) data points. Triangles indicate the ^{90}Zr total cross section results of Stooksberry et al. (25). Solid curves indicate the results of model calculations as described in the text.

Fig. 2. Differential elastic scattering cross sections of ^{90}Zr and ^{92}Zr. The measured values are indicated by data points. Curves denote the results of optical-model calculations as described in the text.

Fig. 3. The differential scattering of 3.8 MeV neutrons from ^{90}Zr. Data points indicate the present results for the noted excitation energies. The curves were obtained by calculation using the indicated values of the correlation parameter, Q, as described in the text.

Fig. 4. Inelastic neutron excitation cross sections of ^{90}Zr. Solid data points indicate the present experimental results for the respective excitation energies (in keV). The results of comparable (n;n'γ) measurements are given by: O=Lind and Day (28), Δ=Wagner et al. (29), and += Tucker et al. (30). These previous results are essentially gamma-ray production cross sections. The curves are the results of calculations using correlation parameter, Q, values of 0.0, 0.5 and 1.0 (respectively, the lower-, mid- and upper-curve of each triad) as discussed in Sec. IV of the text.

Fig. 5. Inelastic neutron excitation cross sections of ^{92}Zr. Excitation energies are noted in keV. Solid data points indicate the present results. Previous results are indicated by ○ = Glazkov (31), Δ=Day (32) and +=Tessler et al. (33). The latter two sets of data were obtained from (n;n'γ) measurements. Curves indicate the results

of calculations as described in the text. Where the curves are in pairs the lower one pertains to a correlation parameter, Q=0 and the upper to Q=0.5. Elsewhere, single curves were obtained with Q=0.0.

Fig. 6. Evaluated neutron total and scattering cross sections of ^{90}Zr and ^{92}Zr. The curves summarize the results of the present work.

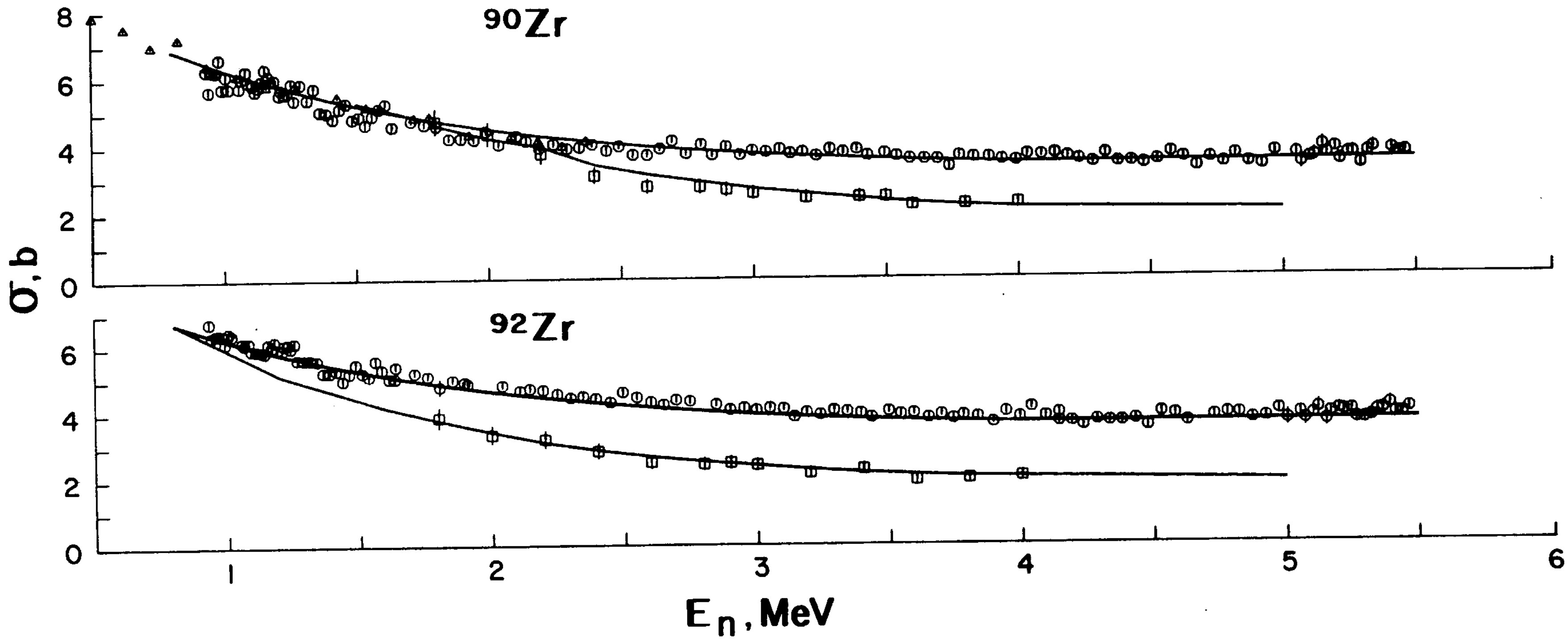
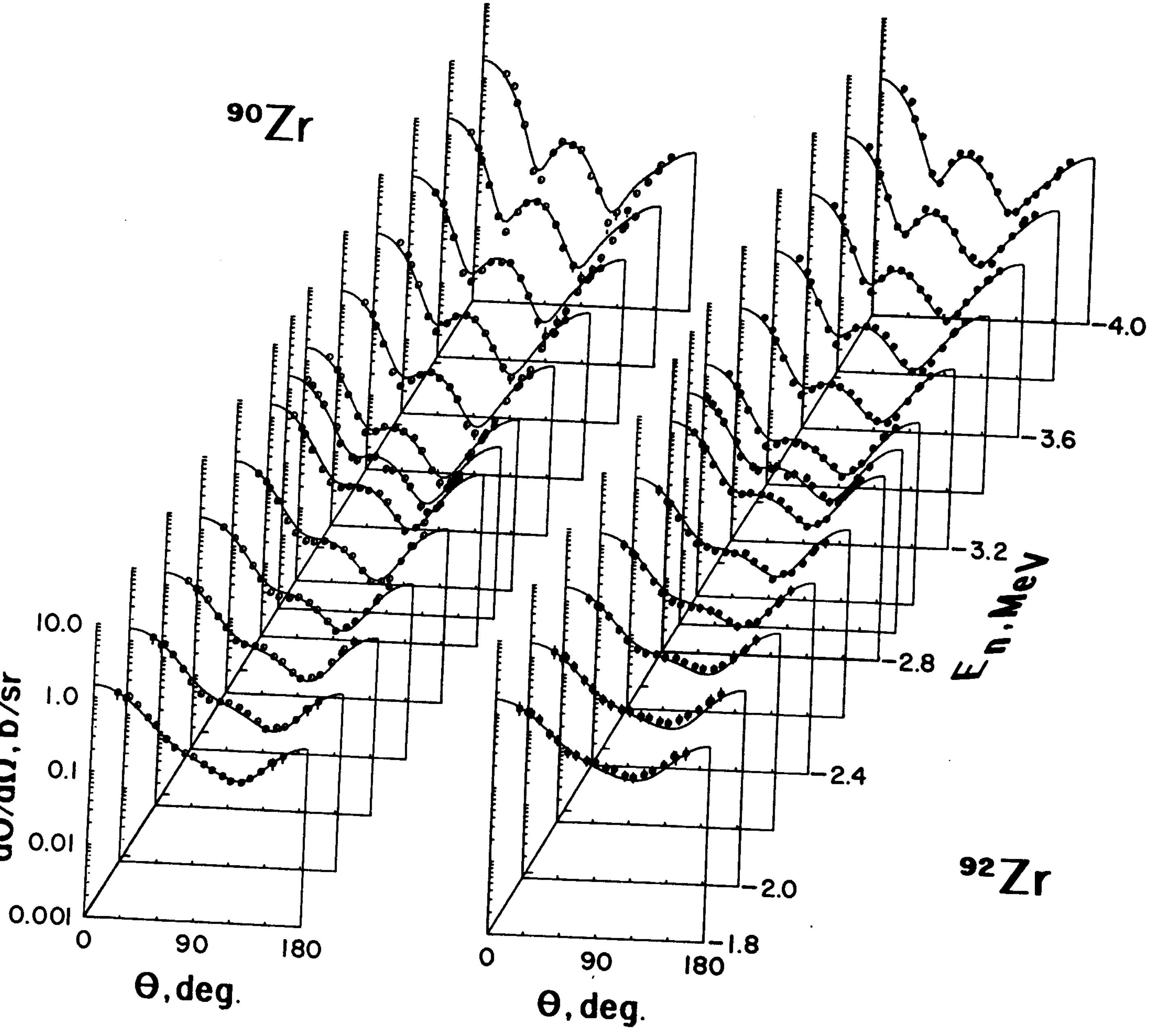
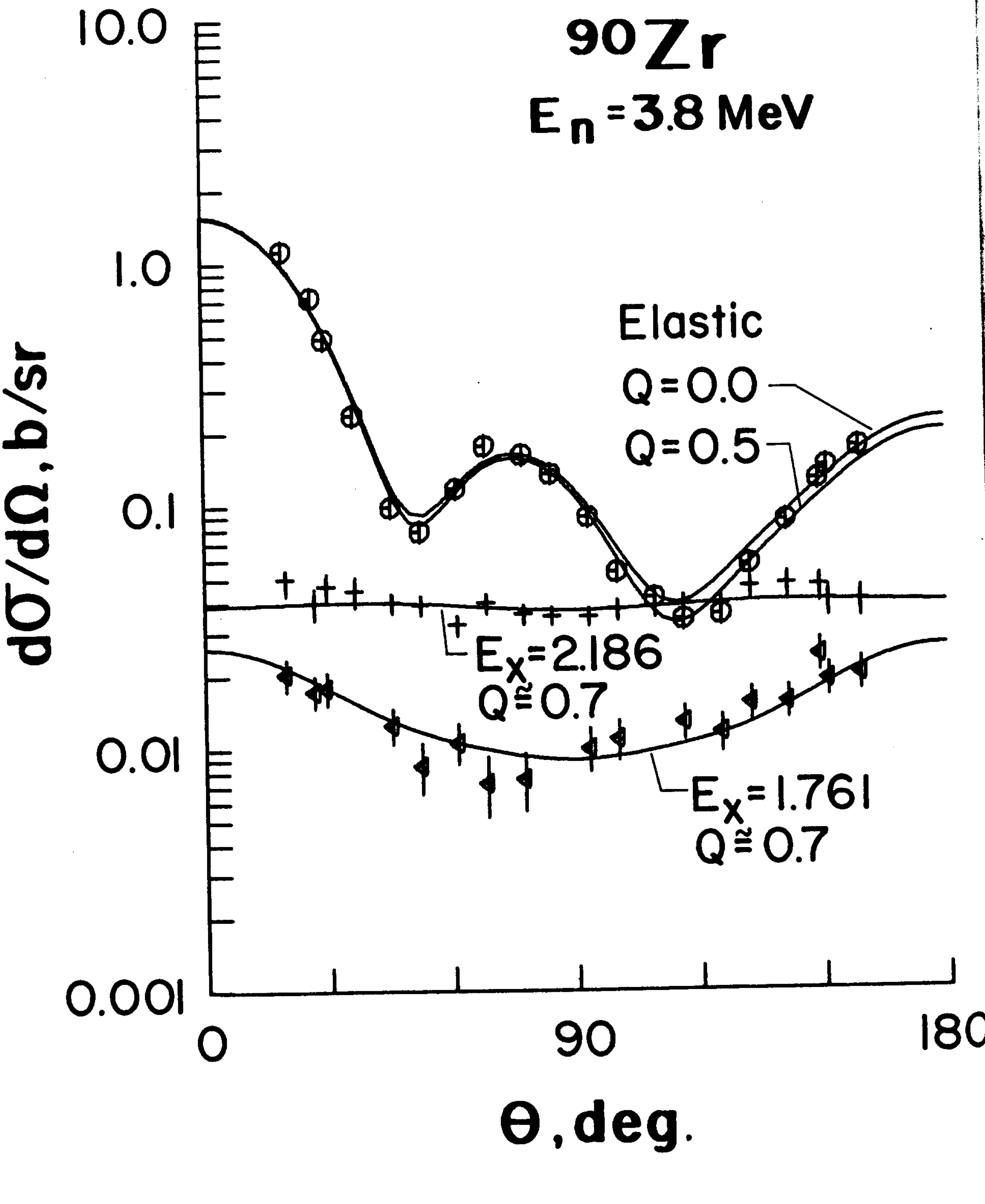


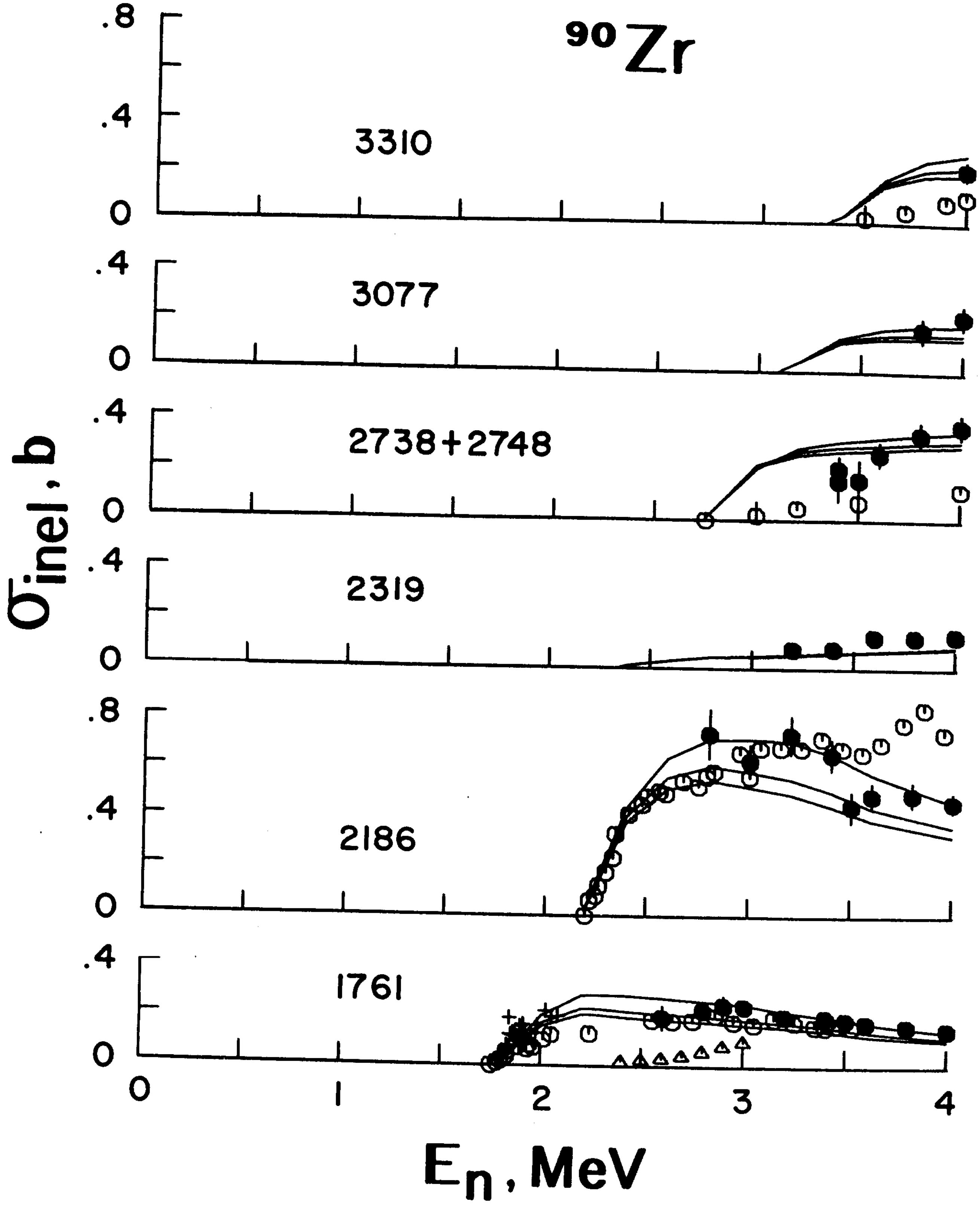
Fig-1



⁹⁰Zr
⁹²Zr
10.0
1.0
0.1
0.01
0.001
dσ/dΩ, b/sr
0
90
180
Θ, deg.
0
90
180
Θ, deg.
1.8
2.0
2.4
2.8
3.2
3.6
4.0
En, MeV

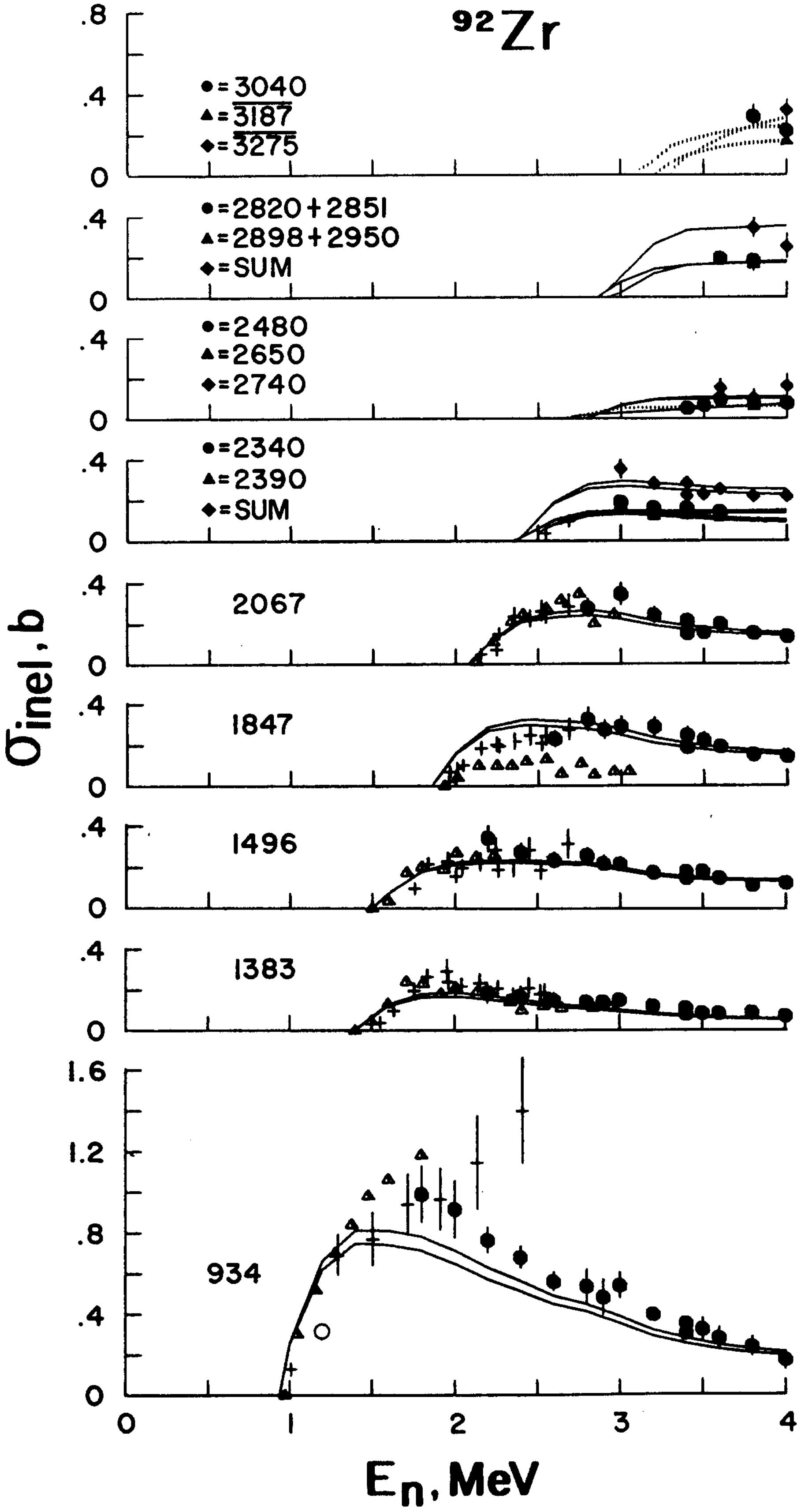


90Zr
En = 3.8 MeV
Elastic
Q = 0.0
Q = 0.5
Ex = 2.186
Q ≅ 0.7
Ex = 1.761
Q ≅ 0.7
10.0
1.0
0.1
0.01
0.001
dσ/dΩ, b/sr
0
90
180
θ, deg.

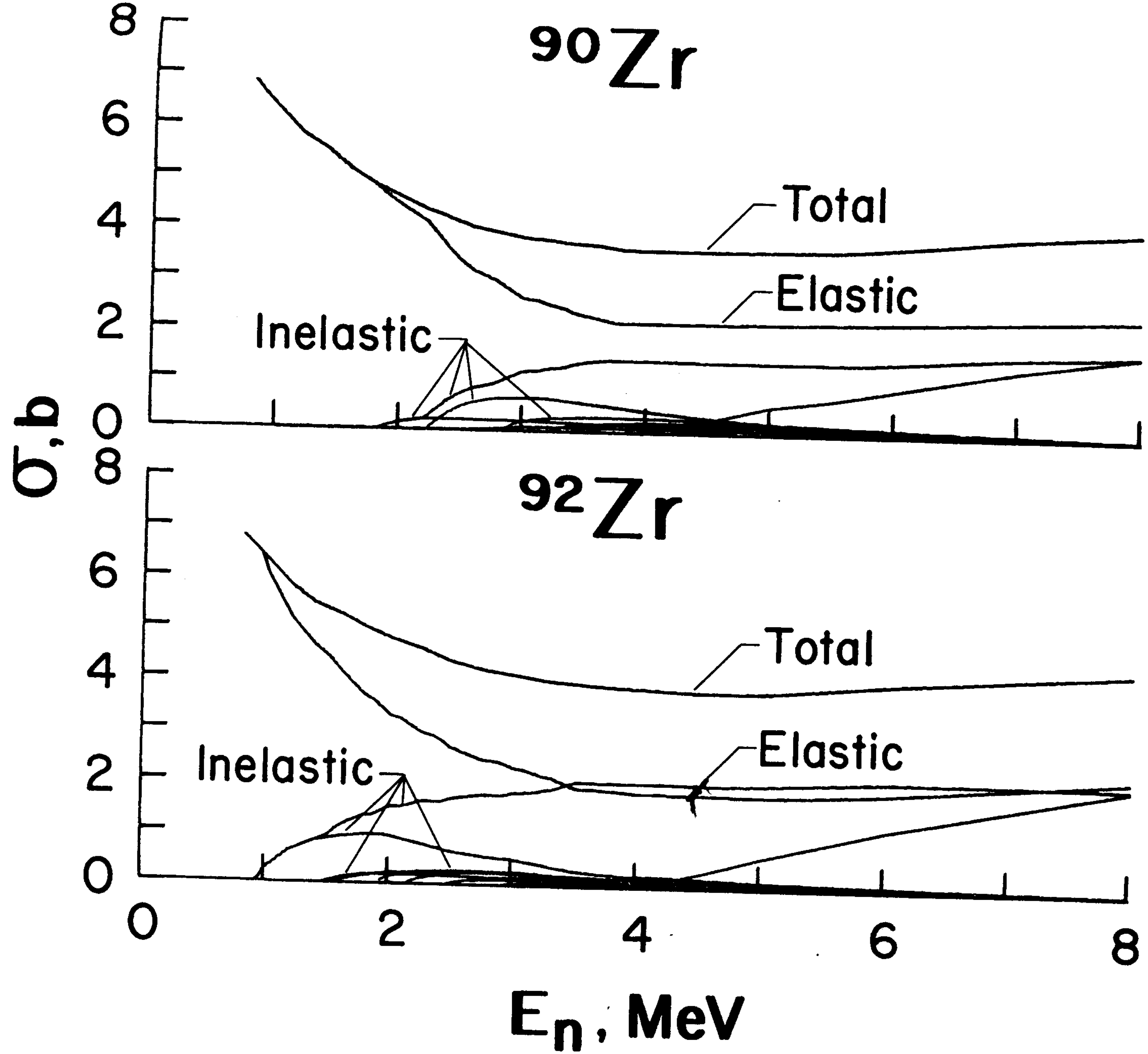


^{90}Zr
3310
3077
2738+2748
2319
2186
1761
σ inel , b
E n , MeV
.8
.4
0
1
2
3
4

Fig - 4



92Zr
● = 3040
▲ = 3187
◆ = 3275
● = 2820 + 2851
▲ = 2898 + 2950
◆ = SUM
● = 2480
▲ = 2650
◆ = 2740
● = 2340
▲ = 2390
◆ = SUM
2067
1847
1496
1383
934
σinel, b
En, MeV



90Zr
Total
Elastic
Inelastic
92Zr
Total
Elastic
Inelastic
σ, b
0
2
4
6
8
En, MeV

						92	3	0	178
4.00920+04	.91905E 02	0	99	0	0	92	3	91	179
0.0 + 0	-3.7097E 06	0	0	1	6	92	3	91	180
6	2					92	3	91	181
.37500E 07	.00000E 00	.40000E 07	.52000E-01	.45000E 07	.30790E 00	92	3	91	182
.50000E 07	.63380E 00	.60000E 07	.12059E 01	.80000E 07	.21000E 01	92	3	91	183
						92	3	0	184
						92	0	0	185
4.00920+04	.91905E 02	0	1	0	0	92	4	2	186
0.0 +00	.91905E 02	0	1	0	0	92	4	2	187
0.0 + 0	0.0 + 0	0	0	1	19	92	4	2	188
19	2					92	4	2	189
.00000E 00	.80000E 06	0	0	6	0	92	4	2	190
.33633E 00	.15846E 00	.16286E-01	.79344E-02	.20800E-03	.98462E-03	92	4	2	191
.00000E 00	.10000E 07	0	0	6	0	92	4	2	192
.36767E 00	.18140E 00	.27586E-01	.13256E-01	.59773E-03	.14100E-02	92	4	2	193
.00000E 00	.12000E 07	0	0	6	0	92	4	2	194
.40133E 00	.20540E 00	.42500E-01	.21600E-01	.15700E-02	.18146E-02	92	4	2	195
.00000E 00	.14000E 07	0	0	6	0	92	4	2	196
.41367E 00	.22800E 00	.57386E-01	.32867E-01	.33682E-02	.27000E-02	92	4	2	197
.00000E 00	.16000E 07	0	0	6	0	92	4	2	198
.42833E 00	.25120E 00	.73843E-01	.46422E-01	.64245E-02	.34500E-02	92	4	2	199
.00000E 00	.18000E 07	0	0	6	0	92	4	2	200
.43533E 00	.27160E 00	.89529E-01	.61456E-01	.10891E-01	.43723E-02	92	4	2	201
.00000E 00	.20000E 07	0	0	6	0	92	4	2	202
.44467E 00	.29120E 00	.10574E 00	.78822E-01	.17318E-01	.59769E-02	92	4	2	203
.00000E 00	.22000E 07	0	0	6	0	92	4	2	204
.45500E 00	.31040E 00	.12224E 00	.98278E-01	.25955E-01	.82615E-02	92	4	2	205
.00000E 00	.24000E 07	0	0	6	0	92	4	2	206
.46167E 00	.32700E 00	.13747E 00	.11844E 00	.36636E-01	.11377E-01	92	4	2	207
.00000E 00	.26000E 07	0	0	6	0	92	4	2	208
.47200E 00	.34300E 00	.15329E 00	.13967E 00	.49864E-01	.15523E-01	92	4	2	209
.00000E 00	.28000E 07	0	0	6	0	92	4	2	210
.47900E 00	.35760E 00	.17114E 00	.16344E 00	.71609E-01	.26500E-01	92	4	2	211
.00000E 00	.30000E 07	0	0	8	0	92	4	2	212
.48667E 00	.36720E 00	.18343E 00	.18156E 00	.82936E-01	.29108E-01	92	4	2	213
.63113E-02	.34659E-02	.00000E 00	.00000E 00	.00000E 00	.00000E 00	92	4	2	214
.00000E 00	.32000E 07	0	0	8	0	92	4	2	215
.49833E 00	.37640E 00	.19800E 00	.20044E 00	.10091E 00	.36015E-01	92	4	2	216
.68933E-02	.32753E-02	.00000E 00	.00000E 00	.00000E 00	.00000E 00	92	4	2	217
.00000E 00	.34000E 07	0	0	8	0	92	4	2	218
.51000E 00	.38640E 00	.21614E 00	.22133E 00	.12436E 00	.48808E-01	92	4	2	219
.15227E-01	.91235E-02	.00000E 00	.00000E 00	.00000E 00	.00000E 00	92	4	2	220
.00000E 00	.36000E 07	0	0	8	0	92	4	2	221
.52900E 00	.40420E 00	.24271E 00	.24578E 00	.15027E 00	.63392E-01	92	4	2	222
.18153E-01	.77353E-02	.00000E 00	.00000E 00	.00000E 00	.00000E 00	92	4	2	223
.00000E 00	.38000E 07	0	0	8	0	92	4	2	224
.53367E 00	.40640E 00	.25457E 00	.25933E 00	.17064E 00	.76008E-01	92	4	2	225
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.00000E 00	.40000E 07	0	0	8	0	92	4	2	227
.54533E 00	.41640E 00	.27271E 00	.27333E 00	.18827E 00	.86000E-01	92	4	2	228
.26780E-01	.11247E-01	.00000E 00	.00000E 00	.00000E 00	.00000E 00	92	4	2	229
.00000E 00	.60000E 07	0	0	10	0	92	4	2	230
.66800E 00	.51340E 00	.41300E 00	.36067E 00	.31282E 00	.19862E 00	92	4	2	231
.89467E-01	.40771E-01	.17800E-01	.63143E-02	.00000E 00	.00000E 00	92	4	2	232
.00000E 00	.80000E 07	0	0	10	0	92	4	2	233
.77067E 00	.62380E 00	.50586E 00	.42744E 00	.35818E 00	.27123E 00	92	4	2	234
.16013E 00	.79706E-01	.36958E-01	.13276E-01	.00000E 00	.00000E 00	92	4	2	235
						92	4	0	236
						92	0	0	237

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0.0     + 0-2.3376E 06          0          6                        92 3  0   121
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0.0     + 0-2.3880E 06          0          7                        92 3 56   127
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                                                      1       6     92 3 57   129
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                                                      1       6     92 3 58   135
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                                                      1       6     92 3 59   141
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.40000E 07 .14300E 00 .50000E 07 .12000E 00 .80000E 07 .00000E 00   92 3 59   143
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.80000E 07 .00000E 00 .00000E 00 .00000E 00 .00000E 00 .00000E 00   92 3 60   150
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.80000E 07 .00000E 00 .00000E 00 .00000E 00 .00000E 00 .00000E 00   92 3 61   157
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0.0     + 0-3.0370E 06          0         12                        92 3 61   159
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                                                      1       5     92 3 63   167
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0,0      + 0-.93286E 06        0          0          1         14 92 3 51  84
        14          2                                             92 3 51  85
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                                                                  92 3  0 114
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0,0      + 0-2,0656E 06        0          0          1          9 92 3 55 116
         9          2                                             92 3 55 117
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EVALUATED ZR-92 FILE

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PARTIAL EVALUATION BY A. SMITH, P. GUENTHER AND J. WHALEN, ANL.   92 1451    4
DOCUMENTATION IN ANL/NDM-4, 1974.                                 92 1451    5
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                                 3         55          6          92 1451   15
                                 3         56          6          92 1451   16
                                 3         57          5          92 1451   17
                                 3         58          5          92 1451   18
                                 3         59          5          92 1451   19
                                 3         60          6          92 1451   20
                                 3         61          6          92 1451   21
                                 3         62          5          92 1451   22
                                 3         63          5          92 1451   23
                                 3         64          5          92 1451   24
                                 3         91          5          92 1451   25
                                 4          2         49          92 1451   26
                                                                  92 1    0   27
                                                                  92 0    0   28
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.70000E 07 .42050E 01 .80000E 07 .43500E 01                       92 3    1   46
                                                                  92 3    0   47
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.00000E 00	.60000E 07	0	0	10	0	90	4	2	163
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.80000E 07 .00000E 00 .00000E 00 .00000E 00 .00000E 00 .00000E 00   90 3 55  101
                                                                    90 3 55  102
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0.0     + 0-3.31  E 06        0          6          0          0    90 3 56  104
      8          2            0          0          1          8    90 3 56  105
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                                                                    90 3 56  109
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      8          2            0          0          1          8    90 3 91  112
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EVALUATED ZR-90 FILE

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PARTIAL EVALUATION BY A. SMITH, P. GUENTHER AND J. WHALEN, ANL.      90 1451
DOCUMENTATION IN ANL/NDM-4, 1974.                                    90 1451
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                                                                     90 0  0
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        36          2                                                90 3  1
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        36          2                                                90 3  2
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