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⁹⁰Zr and ⁹²Zr; Neutron Total and
Scattering Cross Sections^a

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**^{90}Zr and ^{92}Zr ; Neutron Total and
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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.

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1. 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 $\text{H}(n,n)$ standard, were corrected for beam attenuation, angular resolution and multiple-event effects using Monte Carlo-calculational procedures (19).

All the measurements employed the ${}^7\text{Li}(p,n)$ 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 ${}^{90}\text{Zr}$ and ${}^{92}\text{Zr}$ were measured from 0.9 to 5.5 MeV at intervals of ~ 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 ~ 1.5 MeV, particularly for ${}^{90}\text{Zr}$, 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 ${}^{90}\text{Zr}$ 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 ${}^{90}\text{Zr}$ and ${}^{92}\text{Zr}$. 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 ~ 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 artifacts 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 $n(n,n)$ calibration procedures. The scattered

neutron velocity resolution of ~ 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 ~ 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 corre-

sponding 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 ~ 2.15 MeV. The reported 2.34 and 2.39 MeV doublet was observed and also a single group corresponding to an excitation of ~ 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 ~ 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 ~ 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 $^{92}\text{Zr} (n;n'\gamma)$ 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 χ^2 -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, ~ 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 χ^2 -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 $l=0$ strength functions were $\sim 0.6 \times 10^{-4}$ 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 $\left[\frac{N-2}{A}\right]$ (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

$$\begin{aligned} V &= V_0 - \left(\frac{N-Z}{A}\right) \cdot V_1 \\ W &= W_0 - \left(\frac{N-Z}{A}\right) \cdot W_1 \end{aligned} \quad (1)$$

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 effect 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

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

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 ~ 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 (3+) MeV) and comparison of measured and calculated results indicates Q-values of 0.5 or larger as illustrated in Fig. 5. At higher energies (~ 4.0 MeV) the calculations using $Q \sim 1.0$ 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 ~ 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 Weidmüller (37).

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

The above experimental and calculational results were used to develop 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 $\sim$ 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 ~ 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 ~ 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 (~ 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 ~ 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 partic-

ularly 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.

References

1. Compilation of requests for nuclear cross sections, USNDC-6, (1972).
2. M. Goldberg, S. Mughabghab, B. Magurno and V. May, Brookhaven National Laboratory Report, BNL-325, 2nd Ed., Supple. 2 (1966).
3. A. Langsdorf, R. Lane and J. Monahan, Argonne National Laboratory Report, ANL-5567 (Rev.), (1961).
4. D. Reftmann, C. Englebrecht and A. Smith, Nucl. Phys. 48-593 (1963).
5. Nuclear Data Sheets, A-Chains 90 and 92, compiled by J. Ball, M. Johns and K. Way and by D. Kocher and D. Horen.
6. S. Mughabghab and D. Garber, Brookhaven National Laboratory Report, BNL-325, 3rd Ed., Vol. 1, (1973).
7. H. Feshbach, C. Porter and V. Weisskopf, Phys. Rev., 90-166 (1953).
8. P. Hodgson, The Optical Model of Elastic Scattering, Clarendon Press, Oxford (1963).
9. A. Lane, J. Lynn, E. Melkonian and E. Rae, Phys. Rev. Let., 2-424 (1959).
10. W. Vonach, A. Smith and P. Moldauer, Phys. Let., 11-331 (1964).
11. A. Lane, Phys. Rev. Let., 8-171 (1962).
12. F. Becchetti and G. Greenlees, Phys. Rev., 182-1190 (1969).
13. A. Smith, P. Guenther and J. Whalen, Argonne National Laboratory, Report ANL/NDM-7 (1974).
14. D. Lind, Private Communication.
15. W. Hauser and H. Feshbach, Phys. Rev., 87-366 (1952), see also L. Wolfenstein, Phys. Rev., 82-690 (1951).
16. P. Moldauer, Phys. Rev., 135-8642 (1964), see also Phys. Rev., 123-968 (1961) and Phys. Rev., 171-1164 (1968).
17. P. Moldauer, Why the Hauser Feshbach Formula Works, to be published.
18. D. Miller, Fast Neutron Physics, Part 2, P-985, Ed. J. Marion and J. Fowler, Interscience Pub., New York (1963).
19. A. Smith and P. Guenther, PARD-Program for the Acquisition and Reduction of Neutron Scattering Data, Argonne National Laboratory Memorandum (1973), Unpublished.
20. H. Newson and J. Gibbons, Fast Neutron Physics, Part 2, P-1601, see also J. Meadows and D. Smith, Argonne National Laboratory Report, ANL-7938 (1972).
21. J. Whalen, Applied Physics Division Annual Report for 1972, Argonne National Laboratory, to be published.

22. A. Smith, P. Guenther, R. Larsen, C. Nelson, P. Walker and also A. Smith, Applied Physics Division Annual Report for 1972, Argonne National Laboratory, Unpublished.
23. S. Cierjacks, P. Forti, D. Kopsch, L. Kropp, J. Nebe and H. Unseld, Kernforschungszentrum Karlsruhe Report KFK-1000, (1968).
24. R. Schwartz, R. Schranck and H. Heaton, National Bureau of Standards Report, NBS-138 (1974).
25. R. Stooksberry, J. Anderson and M. Goldsmith, Bettis Atomic Power Lab. Report, WAPD-T-2411, (1969).
26. J. Hopkins and G. Breit, Nuclear Data A9-137 (1971).
27. See A. Lane and R. Thomas, Rev. Mod. Phys., 30-257 (1958), P-293.
28. D. Lind and R. Day, Ann. Phys., 12-485 (1961). See also Ref. 2.
29. R. Wagner, E. Shunk and R. Day, Phys. Rev., 130-1926 (1963).
30. A. Tucker, J. Wells and W. Meyerhof, Phys. Rev., B137-1181 (1965).
31. N. Glazkov, Atomnaya Energiya, 15-416 (1963).
32. R. Day as quoted in Ref. 2.
33. G. Tessler, S. Glockstein and E. Carroll, Phys. Rev., C2-2390 (1970).
34. Calculations employed the computer code NEARREX defined in P. Moldauer, C. Engelbrecht and G. Duffy, Argonne National Laboratory Report ANL-6978 (1964).
35. C. Engelbrecht and H. Fiedeldey, Ann. Phys., 42-262 (1967).
36. M. Kawai, A. Kerman and K. McVoy, Ann. Phys., (N. Y.) 75-156 (1973).
37. H. Weidenmüller, Phys. Rev., C9-1202 (1974).
38. Evaluated Nuclear Data File-B (ENDF/B), National Neutron Cross Section Center, Brookhaven National Laboratory.
39. For example, J. Kammerdiener, Lawrence Livermore Laboratory Report, UCRL-51232 (1972).

TABLE 1. SAMPLE COMPOSITION

Sample	Isotope, Atom/Percent				
	90	91	92	94	96
#1(⁹⁰ Zr)	<u>97.72</u>	1.07	0.51	0.56	0.15
#2(⁹² Zr)	2.54	1.04	<u>95.13</u>	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-) + (3-)	2738(4-) + 2748(3-)	1838 ± 15(2+)	1847(2+)
3068 ± 20(4+)	3077(4+)	2058 ± 15(2+)	2067(2+)
3300 ± 20(2+)	3310(2+)	2320 ± 20(3-)	2340(3-)
		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

$V^a = 50.12 \pm 0.55 \text{ MeV}$	$R_V^b = 1.244 \pm 0.0075 \text{ F}$	$a_V = 0.60 \pm 0.055 \text{ F}$
$W^c = 5.50 \pm 0.48 \text{ MeV}$	$R_W^b = 1.250 \pm 0.075 \text{ F}$	$b_W = 0.53 \pm 0.053 \text{ F}$
$V_{so}^d = 8.0 \text{ MeV}$		

 ^{92}Zr

$V = 49.50 \pm 0.50 \text{ MeV}$	$R_V = 1.238 \pm 0.005 \text{ F}$	$a_V = 0.606 \pm 0.05 \text{ F}$
$W = 5.21 \pm 0.25 \text{ MeV}$	$R_W = 1.340 \pm 0.05 \text{ F}$	$b_W = 0.550 \pm 0.042 \text{ F}$

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 χ^2 -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 3.6 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 ($n;n'\gamma$) measurements are given by: $\circ$ -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 $\circ$ = Glazkov (31), Δ =Day (32) and $+$ =Tessler et al. (33). The latter two sets of data were obtained from ($n;n'\gamma$) 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-3

Fig-4

Fig-5

4.00920+04	.91905E 02	0	99	0	0	92 3 0
0.0 + 0-3.7097E 06	0	0	0	1	6	92 3 91 179
6	2					92 3 91 180
.37900E 07	.00000E 00	.40900E 07	.52000E-01	.45000E 07	.30790E 00	92 3 91 181
.50000E 07	.63380E 00	.60800E 07	.12059E 01	.80000E 01	.21000E 01	92 3 91 182
						92 3 0 183
						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	0	1	0	0	92 4 2 187
0.0 + 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
.33643E 00	.15846E 00	.16296E-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	.57356E-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
.18193E-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
.27253E-01	.14382E-01	.00000E 00	.00000E 00			

20800E	07	.00000E	00	.22500E	07	.14000E	00	.25000E	07	.24000E	00	92	3	55	119
.27500E	07	.27500E	00	.30000E	07	.60000E	07	.35000E	07	.16200E	00	92	3	55	119
.40000E	07	.13000E	00	.50000E	07	.26000E	-01	.80000E	07	.00000E	00	92	3	5	121
4.00000E	07	.91905E	02	0	0	6	0	0	0	0	0	92	3	56	123
0.0	+0-2.3373E	06	2	0	0	1	7	6	1	7	6	92	3	56	123
.23630E	07	.00000E	00	.25000E	07	.60000E	-01	.27500E	07	.15000E	00	92	3	56	124
.30000E	07	.18000E	00	.35000E	07	.15000E	00	.40000E	07	.13000E	00	92	3	56	126
.80000E	07	.00000E	00	.00000E	00	.00000E	00	.00000E	06	.00000E	00	92	3	56	127
4.00000E	07	.91905E	02	0	0	7	0	0	0	0	0	92	3	57	129
0.0	+0-2.3380E	06	2	0	0	1	6	6	1	6	6	92	3	57	131
.24140E	07	.00000E	00	.25000E	07	.50000E	-01	.27500E	07	.12000E	00	92	3	57	132
.30000E	07	.13000E	00	.40000E	07	.95000E	-01	.80000E	07	.00000E	00	92	3	0	134
4.00000E	07	.91905E	02	0	0	8	0	0	0	0	0	92	3	58	135
0.0	+0-2.4791E	06	2	0	0	0	1	6	1	6	6	92	3	58	136
.25000E	07	.00000E	00	.30000E	07	.40000E	-01	.35000E	07	.60000E	-01	92	3	58	137
.40000E	07	.70000E	-01	.50000E	07	.50000E	-01	.80000E	07	.00000E	00	92	3	58	139
4.00000E	07	.91905E	02	0	0	9	0	0	0	0	0	92	3	59	141
0.0	+0-2.7373E	06	2	0	0	0	1	6	1	6	6	92	3	59	142
.27670E	07	.00000E	00	.30000E	07	.60000E	-01	.35000E	07	.12500E	00	92	3	59	143
.40000E	07	.14300E	00	.50000E	07	.12000E	00	.80000E	07	.00000E	00	92	3	59	145
4.00000E	07	.91905E	02	0	0	10	0	0	0	0	0	92	3	60	147
0.0	+0-2.8273E	06	2	0	0	0	1	7	6	6	6	92	3	60	149
.28580E	07	.00000E	00	.30000E	07	.40000E	-01	.32500E	07	.12500E	00	92	3	60	150
.35000E	07	.14500E	00	.40000E	07	.15500E	00	.50000E	07	.12500E	00	92	3	60	152
.80000E	07	.00000E	00	.00000E	00	.00000E	00	.00000E	00	.00000E	00	92	3	0	153
4.00000E	07	.91905E	02	0	0	11	0	0	0	0	0	92	3	61	154
0.0	+0-2.8975E	06	2	0	0	1	1	7	6	6	6	92	3	61	155
.29290E	07	.00000E	00	.30000E	07	.35000E	-01	.32500E	07	.13500E	00	92	3	61	157
.35000E	07	.14000E	00	.40000E	07	.14000E	00	.50000E	07	.11000E	00	92	3	61	158
.80000E	07	.00000E	00	.00000E	00	.00000E	00	.00000E	00	.00000E	00	92	3	61	159
4.00000E	07	.91905E	02	0	0	12	0	0	0	0	0	92	3	62	161
0.0	+0-3.0370E	06	2	0	0	0	1								

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.28000E 07	.24183E 01	.28580E 07	.23993E 01	.29290E 07	.23562E 01	92 3 2	59
.30000E 07	.22750E 01	.30700E 07	.22502E 01	.31920E 07	.21685E 01	92 3 2	60
.32000E 07	.21600E 01	.32500E 07	.21071E 01	.33030E 07	.20949E 01	92 3 2	61
.34000E 07	.19987E 01	.35000E 07	.18995E 01	.36000E 07	.18890E 01	92 3 2	62
.37500E 07	.18733E 01	.38000E 07	.18636E 01	.40000E 07	.18250E 01	92 3 2	63
.45000E 07	.18125E 01	.50000E 07	.18000E 01	.60000E 07	.18999E 01	92 3 2	64
.70000E 07	.20799E 01	.80000E 07	.22500E 01			92 3 2	65
						92 3 0	66
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0.0 + 0-.93286E 06		0	0	1	35	92 3 4	68
35	2					92 3 4	69
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.15110E 07	.94765E 00	.16000E 07	.11300E 01	.17000E 07	.12450E 01	92 3 4	72
.18000E 07	.13500E 01	.18650E 07	.13549E 01	.20000E 07	.15250E 01	92 3 4	73
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.24140E 07	.16270E 01	.25000E 07	.16980E 01	.25050E 07	.16992E 01	92 3 4	75
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.28580E 07	.17575E 01	.29290E 07	.17722E 01	.30600E 07	.18250E 01	92 3 4	77
.30700E 07	.18218E 01	.31920E 07	.18547E 01	.32500E 07	.18929E 01	92 3 4	78
.33030E 07	.18945E 01	.35000E 07	.20505E 01	.37500E 07	.20267E 01	92 3 4	79
.40000E 07	.20550E 01	.45000E 07	.20175E 01	.50000E 07	.20580E 01	92 3 4	80
.60000E 07	.21501E 01	.80000E 07	.21000E 01	.00000E 00	.00000E 00	92 3 4	81
						92 3 0	82
4.00920+04	.91905E 02	0	1	0	0	92 3 51	83
0.0 + 0-.93286E 06		0	0	1	14	92 3 51	84
14	2					92 3 51	85
.94300E 06	.00000E 00	.10000E 07	.26000E 00	.12000E 07	.64000E 00	92 3 51	86
.14000E 07	.64000E 00	.16000E 07	.93000E 00	.18000E 07	.97000E 00	92 3 51	87
.20000E 07	.92000E 00	.25000E 07	.64000E 00	.28000E 07	.54000E 00	92 3 51	88
.30000E 07	.50000E 00	.35000E 07	.29000E 00	.40000E 07	.20000E 00	92 3 51	89
.50000E 07	.12000E 00	.80000E 07	.00000E 00	.00000E 00	.00000E 00	92 3 51	90
						92 3 0	91
4.00920+04	.91905E 02	0	2	0	0	92 3 52	92
0.0 + 0-1.3820E 06		0	0	1	10	92 3 52	93
10	2					92 3 52	94
.13970E 07	.00300E 00	.15000E 07	.50000E-01	.16000E 07	.12000E 00	92 3 52	95
.17000E 07	.16500E 00	.18000E 07	.20000E 00	.20000E 07	.20500E 00	92 3 52	96
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.80000E 07	.00300E 00	.00000E 00	.00000E 00	.00000E 00	.00000E 00	92 3 52	98
						92 3 0	99
4.00920+04	.91905E 02	0	3	0	0	92 3 53	100
0.0 + 0-1.4947E 06		0	0	1	10	92 3 53	101
10	2					92 3 53	102
.15110E 07	.00000E 00	.16000E 07	.80000E-01	.18000E 07	.16000E 00	92 3 53	103
.20000E 07	.24000E 00	.22500E 07	.25000E 00	.25000E 07	.25000E 00	92 3 53	104
.50000E 07	.21000E 00	.40000E 07	.14000E 00	.50000E 07	.86000E-01	92 3 53	105
.80000E 07	.00000E 00	.00000E 00	.00000E 00	.00000E 00	.00000E 00	92 3 53	106
						92 3 0	107
4.00920+04	.91905E 07	0	4	0	0	92 3 54	108
0.0 + 0-1.8449E 06		0	0	1	9	92 3 54	109
9	2					92 3 54	110
.18650E 07	.00000E 00	.20000E 07	.16000E 00	.22500E 07	.25000E 00	92 3 54	111
.25000E 07	.29000E 00	.27500E 07	.28000E 00	.30000E 07	.24000E 00	92 3 54	112
.40000E 07	.14000E 00	.50000E 07	.90000E-01	.80000E 07	.06000E 00	92 3 54	113
						92 3 0	114
4.00920+04	.91905E 02	0	5	0	0	92 3 55	115
0.0 + 0-2.0656E 06		0	0	1	9	92 3 55	116
9	2					92 3 55	117

EVALUATED ZR-92 FILE

4.00920+04 .91905E 02	0	0	0	20	92 1451	1
0.0 +00 0.0 +00	0	0	4	0	92 1451	2
-----ZR-92-----						
PARTIAL EVALUATION BY A. SMITH, P. GUENTHER AND J. WHALEN, ANL.						
DOCUMENTATION IN ANL/NDM-4, 1974.						

	1	451	26		92 1451	6
	3	1	18		92 1451	7
	3	2	18		92 1451	8
	3	4	15		92 1451	9
	3	51	8		92 1451	10
	3	52	7		92 1451	11
	3	53	7		92 1451	12
	3	54	6		92 1451	13
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	3	60	6		92 1451	19
	3	61	6		92 1451	20
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	3	64	5		92 1451	23
	3	91	5		92 1451	24
	4	2	49		92 1451	25
					92 1451	26
					92 1 0	27
					92 0 0	28
4.00920+04 .91905E 02	0	99	0	0	92 3 1	29
0.0 + 0 0.0 + 0	0	0	1	44	92 3 1	30
44 2					92 3 1	31
.80000E 06 .68000E 01 .94300E 06 .64425E 01 .10000E 07 .63000E 01					92 3 1	32
.12000E 07 .58000E 01 .13970E 07 .54552E 01 .14000E 07 .54500E 01					92 3 1	33
.15000E 07 .53500E 01 .15110E 07 .53390E 01 .16000E 07 .52500E 01					92 3 1	34
.17000E 07 .51250E 01 .18000E 07 .50000E 01 .18650E 07 .49350E 01					92 3 1	35
.20000E 07 .48000E 01 .20880E 07 .47296E 01 .22000E 07 .46400E 01					92 3 1	36
.22500E 07 .46000E 01 .23630E 07 .44870E 01 .24000E 07 .44500E 01					92 3 1	37
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.37500E 07 .39000E 01 .38000E 07 .38960E 01 .40000E 07 .38800E 01					92 3 1	44
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.70000E 07 .42050E 01 .80000E 07 .43500E 01					92 3 1	46
					92 3 0	47
4.00920+04 .91905E 02	0	0	0	0	92 3 2	48
0.0 + 0 0.0 + 0	0	0	1	44	92 3 2	49
44 2					92 3 2	50
.80000E 06 .68000E 01 .94300E 06 .64425E 01 .10000E 07 .60400E 01					92 3 2	51
.12000E 07 .51600E 01 .13970E 07 .46182E 01 .14000E 07 .46085E 01					92 3 2	52
.15000E 07 .44100E 01 .15110E 07 .43913E 01 .16000E 07 .41200E 01					92 3 2	53
.17000E 07 .38800E 01 .18000E 07 .36500E 01 .16650E 07 .35801E 01					92 3 2	54
.20000E 07 .32750E 01 .20880E 07 .32146E 01 .22000E 07 .30410E 01					92 3 2	55
.22500E 07 .29635E 01 .23630E 07 .28724E 01 .24000E 07 .28264E 01					92 3 2	56
.24140E 07 .28090E 01 .25000E 07 .26520E 01 .25050E 07 .26478E 01					92 3 2	57

4.0090	+04	.89128E 02	0	1	0	0	90	0	0	118
0.0	+06	.89128E 02	0	1	0	0	90	4	2	119
0.0	+0	0.0	+9	0	0	19	90	4	2	120
19		2					90	4	2	121
.00000E 00	.60000E 06	0	0	6	0	0	90	4	2	122
.52523E 00	.15996E 00	.12964E-01	.72944E-02	.12127E-03	.97769E-03	0	90	4	2	123
.00000E 00	.10000E 07	0	0	6	0	0	90	4	2	124
.34000E 03	.18158E 00	.21714E-01	.13399E-01	.43818E-03	.17438E-02	0	90	4	2	125
.00000E 00	.12000E 07	0	0	6	0	0	90	4	2	126
.35367E 00	.20120E 00	.31686E-01	.21511E-01	.11036E-02	.26746E-02	0	90	4	2	127
.00000E 00	.14000E 07	0	0	6	0	0	90	4	2	128
.35353E 00	.21900E 00	.41971E-01	.31356E-01	.23409E-02	.37431E-02	0	90	4	2	129
.00000E 00	.16000E 07	0	0	6	0	0	90	4	2	130
.34733E 00	.23440E 00	.51843E-01	.42476E-01	.42718E-02	.48685E-02	0	90	4	2	131
.00000E 00	.18000E 07	0	0	6	0	0	90	4	2	132
.33967E 00	.24820E 00	.61214E-01	.54789E-01	.70936E-02	.61300E-02	0	90	4	2	133
.00000E 00	.20000E 07	0	0	6	0	0	90	4	2	134
.34067E 00	.26340E 00	.72000E-01	.69900E-01	.11182E-01	.77615E-02	0	90	4	2	135
.00000E 00	.22000E 07	0	0	6	0	0	90	4	2	136
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.00000E 00	.24000E 07	0	0	6	0	0	90	4	2	138
.35867E 00	.29220E 00	.98014E-01	.10189E 00	.24827E-01	.11031E-01	0	90	4	2	139
.00000E 00	.26000E 07	0	0	6	0	0	90	4	2	140
.36633E 00	.30420E 00	.11086E 00	.11933E 00	.34500E-01	.13577E-01	0	90	4	2	141
.00000E 00	.28000E 07	0	0	6	0	0	90	4	2	142
.37133E 00	.31340E 00	.12279E 00	.13600E 00	.45755E-01	.16677E-01	0	90	4	2	143
.00000E 00	.30000E 07	0	0	6	0	0	90	4	2	144
.38300E 00	.32220E 00	.13619E 00	.15356E 00	.56845E-01	.21277E-01	0	90	4	2	145
.12860E-02	.22876E-03	.00000E 00	.00000E 00	.00000E 00	.00000E 00	0	90	4	2	146
.00000E 00	.32000E 07	0	0	6	0	0	90	4	2	147
.39133E 00	.32820E 00	.14814E 00	.16944E 00	.73436E-01	.26492E-01	0	90	4	2	148
.16013E-02	.32665E-03	.00000E 00	.00000E 00	.00000E 00	.00000E 00	0	90	4	2	149
.00000E 00	.34000E 07	0	0	6	0	0	90	4	2	150
.40433E 00	.33400E 00	.16157E 00	.18544E 00	.90082E-01	.32738E-01	0	90	4	2	151
.25660E-02	.55729E-03	.00000E 00	.00000E 00	.00000E 00	.00000E 00	0	90	4	2	152
.00000E 00	.36000E 07	0	0	6	0	0	90	4	2	153
.42233E 00	.34680E 00	.17700E 00	.20244E 00	.10873E 00	.40377E-01	0	90	4	2	154
.35113E-02	.82529E-03	.00000E 00	.00000E 00	.00000E 00	.00000E 00	0	90	4	2	155
.00000E 00	.38000E 07	0	0	6	0	0	90	4	2	156
.43900E 00	.34480E 00	.19029E 00	.21633E 00	.12655E 00	.48485E-01	0	90	4	2	157
.45007E-02	.12800E-02	.00000E 00	.00000E 00	.00000E 00	.00000E 00	0	90	4	2	158
.00000E 00	.40000E 07	0	0	6	0	0	90	4	2	159
.44867E 00	.34900E 00	.22429E 00	.22933E 00	.14455E 00	.57223E-01	0	90	4	2	160
.64227E-02	.18565E-02	.00000E 00	.00000E 00	.00000E 00	.00000E 00	0	90	4	2	161
.00000E 00	.60000E 07	0	0	6	0	0	90	4	2	162
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							90	4	0	168
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4.0090 +04 .89128E 02		0	1	0	0	90 3 0	66
0.0 + 0-1.761 E 06		0	0	1	12	90 3 51	67
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.17800E 07	.00000E 00	.19000E 07	.10630E 00	.20000E 07	.16000E 00	90 3 51	69
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13						90 3 52	76
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.26000E 07	.59000E 00	.28000E 07	.68000E 00	.30000E 07	.68000E 00	90 3 52	78
.32000E 07	.64500E 00	.35000E 07	.56000E 00	.40000E 07	.42000E 00	90 3 52	79
.45000E 07	.36000E 00	.50000E 07	.21000E 00	.60000E 07	.12000E 00	90 3 52	80
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						90 3 0	82
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0.0 + 0-2.319 E 06		0	0	1	6	90 3 53	84
6						90 3 53	85
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						90 3 0	88
4.0090 +04 .89128E 02		0	4	0	0	90 3 54	89
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8						90 3 54	91
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.60000E 07	.12000E 00	.60000E 07	.60000E 00	.00000E 00	.00000E 00	90 3 54	94
						90 3 0	95
4.0090 +04 .89128E 02		0	5	0	0	90 3 55	96
0.0 + 0-3.077 E 06		0	0	1	7	90 3 55	97
7						90 3 55	98
.31110E 07	.00000E 00	.34000E 07	.15000E 00	.38000E 07	.20000E 00	90 3 55	99
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.80000E 07	.60000E 00	.00000E 00	.00000E 00	.00000E 00	.00000E 00	90 3 55	101
						90 3 0	102
4.0090 +04 .89128E 02		0	6	0	0	90 3 56	103
0.0 + 0-3.31 E 06		0	0	1	8	90 3 56	104
8						90 3 56	105
.33460E 07	.00000E 00	.35000E 07	.10000E 00	.37000E 07	.20000E 00	90 3 56	106
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.60000E 07	.11000E 00	.80000E 07	.00000E 00	.00000E 00	.00000E 00	90 3 56	108
						90 3 0	109
4.0090 +04 .89128E 02		0	99	0	0	90 3 91	110
0.0 + 0-3.758 E 06		0	0	1	8	90 3 91	111
8						90 3 91	112
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.50000E 07	.57000E 00	.55000E 07	.72500E 00	.60000E 07	.94000E 00	90 3 91	114
.70000E 07	.13575E 01	.80000E 07	.16950E 01	.00000E 00	.00000E 00	90 3 91	115
						90 3 0	116
						90 3 0	117

EVALUATED 2R-90 FILE

4.00900+04 .89128E 02	0	0	0	12	90 1451	1
0.0 +00 0.0 +00	0	0	4	0	90 1451	2
-----2R-90-----						
PARTIAL EVALUATION BY A. SMITH, P. GUENTHER AND J. WHALEN, ANL.						
DOCUMENTATION IN ANL/NUM-4, 1974.						

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	3	1	15		90 1451	8
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	3	4	13		90 1451	10
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	3	56	6		90 1451	16
	3	91	6		90 1451	17
	4	2	49		90 1451	18
					90 1 0	19
					90 0 0	20
4.0090 +04 .89128E 02	0	99	0	0	90 3 1	21
0.0 + 0 0.0 + 0	0	0	1	36	90 3 1	22
36 2					90 3 1	23
.80000E 06 .60500E 01 .90000E 06 .65500E 01 .10000E 07 .63000E 01					90 3 1	24
.12000E 07 .58000E 01 .14000E 07 .55000E 01 .16000E 07 .51000E 01					90 3 1	25
.17800E 07 .48300E 01 .18000E 07 .48000E 01 .19000E 07 .46850E 01					90 3 1	26
.20000E 07 .45700E 01 .21000E 07 .44600E 01 .22000E 07 .43500E 01					90 3 1	27
.22100E 07 .43415E 01 .23000E 07 .42650E 01 .23460E 07 .42259E 01					90 3 1	28
.24000E 07 .41900E 01 .25000E 07 .40900E 01 .26000E 07 .40000E 01					90 3 1	29
.27700E 07 .39150E 01 .28000E 07 .39000E 01 .30000E 07 .38000E 01					90 3 1	30
.31110E 07 .37778E 01 .32000E 07 .37600E 01 .33460E 07 .37162E 01					90 3 1	31
.34000E 07 .37000E 01 .35000E 07 .36900E 01 .36000E 07 .36800E 01					90 3 1	32
.37000E 07 .36400E 01 .38000E 07 .36000E 01 .40000E 07 .35900E 01					90 3 1	33
.45000E 07 .36000E 01 .50000E 07 .36280E 01 .55000E 07 .36400E 01					90 3 1	34
.60000E 07 .37200E 01 .70000E 07 .39500E 01 .80000E 07 .41000E 01					90 3 1	35
					90 3 0	36
4.0090 +04 .89128E 02	0	0	0	0	90 3 2	37
0.0 + 0 0.0 + 0	0	0	1	36	90 3 2	38
36 2					90 3 2	39
.60000E 06 .68500E 01 .90000E 06 .65500E 01 .10000E 07 .63000E 01					90 3 2	40
.12000E 07 .58000E 01 .14000E 07 .55000E 01 .16000E 07 .51000E 01					90 3 2	41
.17800E 07 .48300E 01 .18000E 07 .47833E 01 .19000E 07 .45850E 01					90 3 2	42
.20000E 07 .44100E 01 .21000E 07 .42600E 01 .22000E 07 .41150E 01					90 3 2	43
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					90 3 0	52
4.0090 +04 .89128E 02	0	99	0	0	90 3 4	53
0.0 + 0-1.761 E 06	0	0	1	28	90 3 4	54
28 2					90 3 4	55
.17800E 07 .00000E 00 .19000E 07 .10000E 00 .20000E 07 .16000E 00					90 3 4	56
.21000E 07 .20000E 00 .22000E 07 .23500E 00 .22100E 07 .23540E 00					90 3 4	57