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Few-MeV NEUTRONS INCIDENT ON YTTRIUM*

by

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and J. Whalen

September, 1982

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

Neutron total and scattering cross sections of elemental yttrium are measured in the few-MeV region with broad resolutions. The total-cross-section measurements extend from ≈ 0.5 to 4.2 MeV in steps of $\lesssim$ 0.1 MeV. Neutron elastic- and inelastic-scattering cross sections are measured from ≈ 1.5 to 4.0 MeV, at incident-neutron energy intervals of $\lesssim$ 50 keV and at ten or more scattering angles distributed between 20 and 160 deg. Inelastically-scattered neutron groups are observed corresponding to the excitation of levels at 909 ± 23, 1504 ± 20, 1747 ± 16, 2224 ± 16, 2567 ± 26, 2889 ± 12 and 3104 ± 10 keV. The experimental results are discussed in terms of the spherical optical-statistical, coupled-channels and core-coupling models and compared with corresponding quantities given in the evaluated nuclear data file ENDF/B-V.

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

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I. INTRODUCTION

This work was undertaken as a part of a comprehensive study of the interaction of few-MeV neutrons with light-mass ($A \approx 100$) fission products. Other aspects of this program are described in Refs. 1-7. Yttrium is mono-isotopic (^{89}Y) and magic in neutron number (N=50). It is at the end of a fission-product decay chain, with chain yields varying from $\approx$ 6% for neutron-induced fission of ^{232}Th to $\approx$ 1.2% for ^{240}Pu fission. Low-lying levels of yttrium, those significantly contributing to the inelastic-scattering of few-MeV neutrons, have been attributed to the coupling of the $p_{1/2}$ proton to excitations of the ^{88}Sr core [8,9] and coulomb-excitation studies suggest that the ^{88}Sr core excitations are, at least in part, of a collective nature.[10] Other core coupling schemes involving the $g_{9/2}$ proton configuration result in large spins and thus have little effect on low-energy neutron scattering. The energies, spins and parities of the levels of both ^{88}Sr and ^{89}Y, at energies relevant to the present study, are given in Ref. 11. The nature of the neutron interaction mechanism is uncertain.

The objectives of the present work were; i) the provision of experimental data for applied use, ii) the derivation of a nuclear model suitable for the prediction of the properties of experimentally inaccessable nuclei[12], and iii) an assessment of the mechanism for interaction of few-MeV neutrons with ^{89}Y. The experimental methods are outlined in Section II. In Section III the experimental results are presented and compared with previously-reported experimental values. The derivation of a model and its implications are discussed in Section IV. Section V compares the present experimental results with the corresponding quantities given in the evaluated nuclear data file, ENDF/B-V.[13]

II. OUTLINE OF THE EXPERIMENTAL METHODS

All the measurement samples were fabricated of elemental metal having no significant chemical impurities. The scattering sample was a cylinder 2 cm in diameter and 2 cm long. The transmission samples were cylinders 2.54 cm in diameter with lengths varying from 1.0 to 4.75 cm. The sample densities were determined to $<$ 1% by precision weight and dimension measurements.

The measurements were made at the Argonne National Laboratory Fast-Neutron-Generator Facility using established apparatuses and procedures. All the measurements employed the $^7Li(p;n)^7Be$ reaction as a neutron source with the lithium-target film adjusted to obtain the desired incident-neutron energy resolutions. The neutron total-cross-section measurements were made using the apparatus, method and geometries described in Refs. 14 and 15. The method provided good background control and made possible the concurrent measurement of the neutron transmission through a number of yttrium samples of varying thickness and through a carbon-verification sample. Dead-time effects were considered and appropriate corrections applied to the data. In scattering effects were assessed and found to be negligibly small. The differential-neutron-scattering measurements were made using the time-of-flight technique and the Argonne ten-angle detection apparatus.[16] Scattered-neutron flight paths were $\approx$ 5.5 m, the neutron burst width was $\approx$ 1 nsec, and the burst repetition rate was 2 MHz. The resulting scattered-neutron resolution was sufficient to separate the elastically-scattered neutron group from all known inelastically-scattered components and to resolve the prominent inelastically-scattered neutron groups. Details of the method are given in Ref. 15. The scattered-neutron measurements were made relative to the well known carbon total cross section[17] using the detector calibration methods described in Ref. 18. The measured differential-scattering values were corrected for multiple-event, beam attenuation, and angular-resolution effects using the methods described in Ref. 19.

III. EXPERIMENTAL RESULTS

A. Neutron Total Cross Sections

The neutron-total-cross-section measurements were made at intervals of $\lesssim$ 100 keV from 0.5 to 4.2 MeV with energy resolutions of 50 to 100 keV. At the lower extreme of the measured energy range the cross section fluctuates and self-shielding is a concern.[14] Thus a number of sample thicknesses were used ranging from 1.0 to 4.75 cm and the effective total cross sections were derived from the observed neutron transmissions through each of the samples in the conventional manner.[20] The statistical uncertainties of the cross sections obtained for each of the individual samples varied from $\approx$ 1 to 5%, depending upon the sample thicknesses. The results were averaged over 100 keV in order to smooth fluctuations. The statistical uncertainties of the averaged cross-section values were $\approx$ 1 to 3%, again depending upon sample thickness. These effective averaged total cross sections are illustrated in Fig. 1. Above $\approx$ 1.0 MeV there is no indication that the total-cross-section results are dependent upon sample thickness. At lower energies there is some evidence of a self-shielding effect with the thinner-sample results tending to be 1 to 2% larger than those obtained with the thicker samples. This trend is consistent with the lower-energy observations of Poenitz et al.[21] In view of the apparent small magnitude of the self-shielding effect, even at the lower energies of the present work, it was ignored.

Low-energy ($\lesssim$ 650 keV) yttrium total cross sections have been measured by Whalen[22] with resolutions of $\approx$ 2 keV. These low-energy results display large fluctuations but their general trend with energy is consistent with the present values (see Fig. 1). Using both white- and monoenergetic-source techniques, Poenitz et al.[21] have recently measured the total cross sections of yttrium overlapping the energy range of the present work. The results of Ref. 21 are consistent with the present values to well within the respective uncertainties, as illustrated in Fig. 1.

B. Neutron Scattering Cross Sections

The differential neutron-scattering cross sections of yttrium were measured at 10 to 20 scattering angles distributed between 20 and 160 degrees at intervals of $\lesssim$ 50 keV from 1.5 to 4.0 MeV. Incident-neutron energy resolutions were generally 50 to 75 keV. In addition, several measurements were made with incident-neutron energy resolutions of $\approx$ 15 keV. The relatively broad incident-neutron resolutions were chosen to reasonably

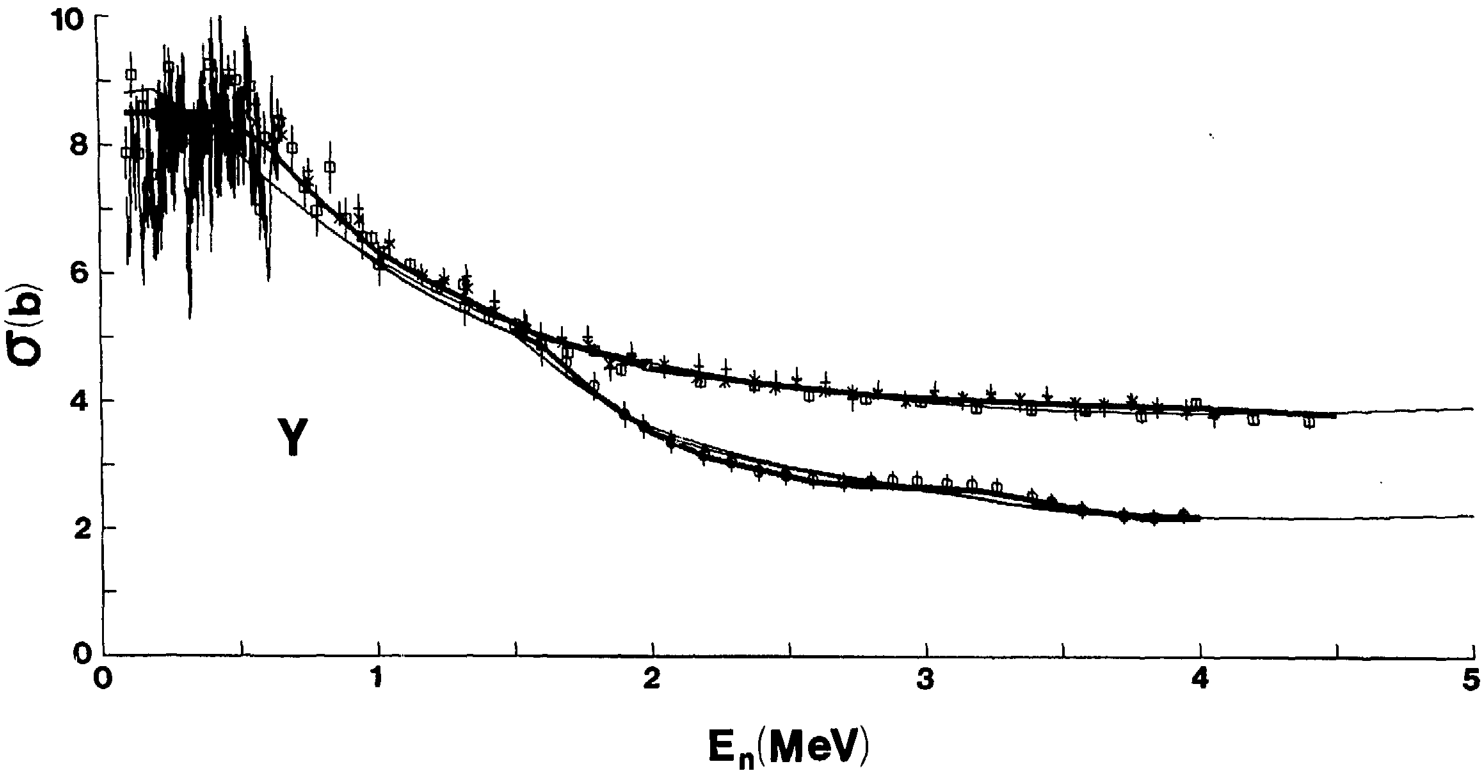

Fig. 1. Neutron Total and Elastic-Scattering Cross Sections of Elemental Yttrium. The present experimental results are noted by; i) X=total cross sections obtained with a 4.75 cm thick sample, ii) +=total cross sections obtained using a 1.0 cm thick sample, and iii) O=angle-integrated elastic-scattering cross sections. The fluctuating curve indicates the total cross sections of Ref. 22 and the symbol those of Ref. 21. Heavy curves denote "eyeguides" constructed through the measured values and light curves the results of calculations. Where there are two calculated results the lower curve references the results of the fitting procedure and the alternate (and larger), calculated results those obtained with a modified width-fluctuation correction, as discussed in the text.

average compound-nucleus (CN) fluctuations while, at the same time, separating the elastically-scattered neutron group from inelastically-scattered components and reasonably resolving the prominent inelastically-scattered neutron groups.

Even with the above relatively-broad energy resolutions, elastic-scattering cross-section fluctuations were evident at energies $\lesssim$ 2.5 MeV. Therefore, the measured differential elastic-scattering cross-section fluctuations were further averaged over 200-keV energy increments in steps of 100 keV. A minimum of three angular distributions were contained in each average and, in some cases, as many as ten. These averaged differential elastic-scattering results are illustrated in Fig. 2. The statistical uncertainties of the individual differential values was $\lesssim$ 2%. Uncertainties due to detector calibrations, including those associated with the reference-carbon-total cross section, were estimated to be less than 3%. The relative angular scale was known to ± 0.1 degree and the absolute angular scale to ± 0.5 degree. Correction procedures introduced a further uncertainty of $\lesssim$ 1%. Thus the overall uncertainties of the individual differential values were $\lesssim$ 5%. The measurements were made in four experimental periods distributed over several years, each with independent experimental arrangements and detector calibrations. The results obtained in these individual measurement periods were consistent to within the above experimental uncertainties. The energy-averaged differential elastic-scattering cross sections were least-square fitted with 6^{th}-order Legendre-Polynomial series with the results illustrated in Fig. 2. These fitting procedures provided the angle-integrated elastic-scattering cross sections shown in Fig. 1. The latter are believed known to $\lesssim$ 5%. The angle-integrated elastic-scattering cross sections follow a relatively smooth energy-dependent behavior. There is a small plateau region between 3.0 and 3.3 MeV which was observed in all measured data sets.

There have been a few previously-reported yttrium elastic-scattering results comparable with the present work. For example, Towle[23] measured differential elastic-scattering cross sections of yttrium at 2.35 MeV. His results are generally consistent with those of the present work to within the respective experimental uncertainties. More generally, the Evaluated Nuclear Data File-B, Version-V, (ENDF/B-V)[13] should be representative of prior knowledge of the neutron interaction with yttrium. Therefore, detailed comparisons of the present results with values given in ENDF/B-V are discussed in Section V.

The inelastic-scattering cross sections were determined concurrently with the elastic-scattering cross sections. Cross sections corresponding to scattered-neutron energies greater than 0.6 MeV were quantitatively determined. Lower-energy neutron groups were observed but the corresponding cross sections were not derived since they would have been sensitive to the exact nature of the detector response functions which were not well known below $\approx$ 0.6 MeV.

The observed inelastic-neutron excitation energies were determined from the measured flight times, incident energies and flight paths. The results of a large number of independent measurements were averaged to obtain the excitation energies given in Table 1. The uncertainties are defined as the RMS deviations of the individual values from the simple means. The seven observed

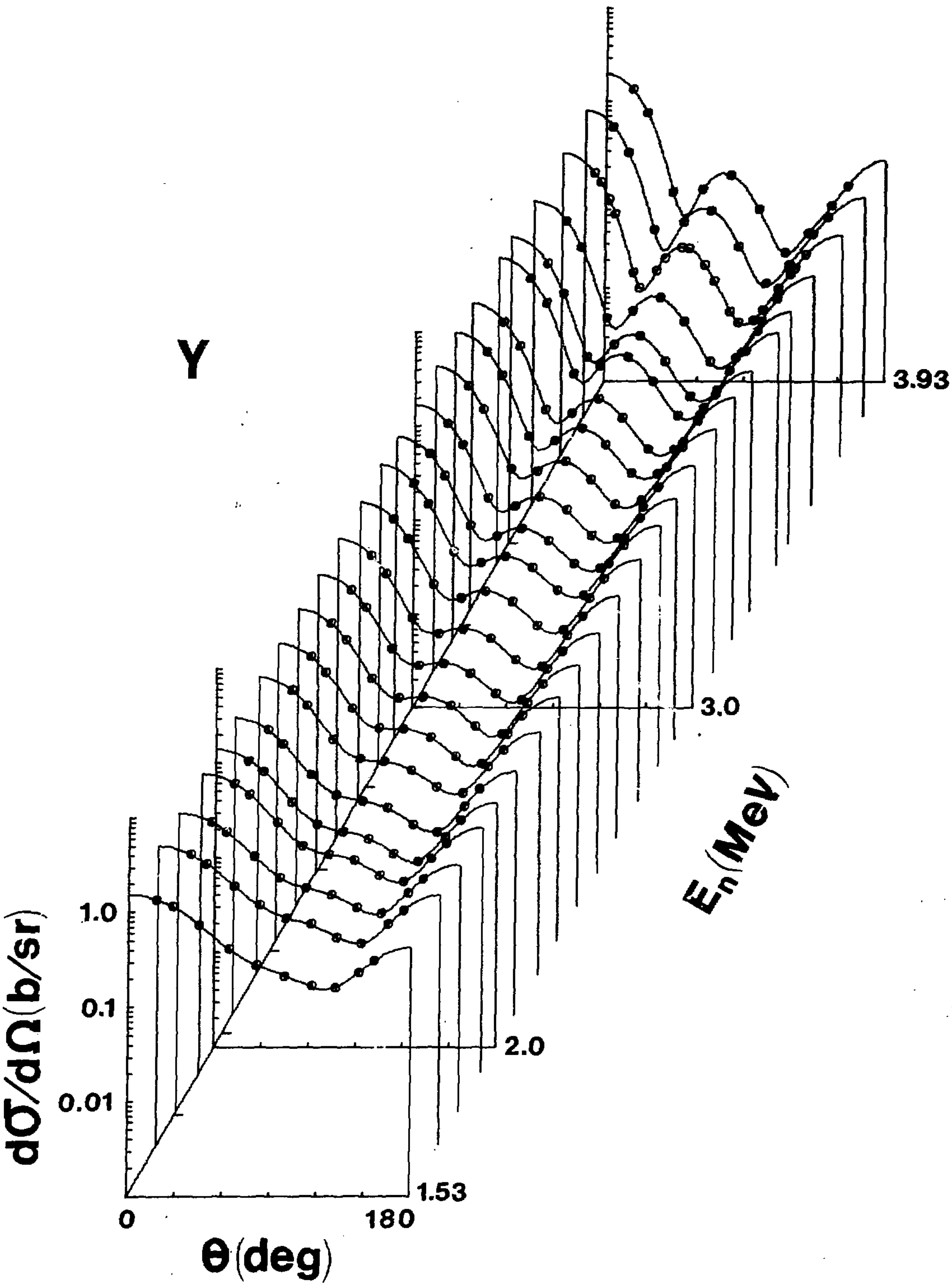

Fig. 2. Differential-Neutron-Elastic-Scattering Cross Sections of Elemental Yttrium. The present experimental results are indicated by data symbols. Curves denote the results of fitting Legendre Polynomial series to the measured values (all values in the laboratory system).

inelastic-neutron groups correspond to previously reported levels in yttrium, as summarized in Ref. 11. The observed 909-keV level is identified with the reported 909(9/2+) keV level and the observed 1504-, 1747-and 2224-keV levels with the reported 1507 (3/2-), 1745(5/2-) and 2222(5/2+) keV levels, respectively. The observed 2567-keV level is probably a composite of contributions from the three reported levels at 2530(7/2+), 2568(11/2+) and 2622(9/2+) keV. Several high-resolution measurements indicated a doublet in this region which was attributed to the unresolved 2530-and 2568-keV levels and the 2622-keV level. The experimentally observed separation was 77 keV. The observed level at 2889 keV was attributed to the composite of the reported 2871(7/2+) and 2881(3/2-) keV levels. There may be an additional contribution from the reported 2893 keV level but the latter is likely of high spin and thus will make a very small contribution to the inelastic-neutron-scattering process. In any event, the reported three levels near 2900 keV would not be resolved in the present experiment. The observed 3104 keV level was attributed to contributions from the three reported levels at 3067(3/2-), 3106(3/2,5/2-) and 3138(3/2,5/2-) keV. Again, several high-resolution measurements indicated a triad of levels in this region with separations of 30 and 33 keV to be compared with the reported separations of 39 and 32 keV, respectively. Several higher-energy excitations were qualitatively observed but not quantitatively assessed due to uncertainties associated with rapidly changing detector sensitivities.

The angle-integrated inelastic-scattering cross sections were deduced from the measured differential values in the same manner as outlined above for elastic scattering. The differential distributions were nearly isotropic thus the Legendre-polynomial fitting procedures were limited to the P_2 term of the series. Some inelastic-scattering cross sections were distorted by contributions originating in the second-neutron group of the $^7Li(p;n)^7Be$ source reaction. In these cases appropriate corrections were made. They were generally of relatively-small magnitude. The resulting angle-integrated inelastic-scattering cross sections, corresponding to the observed levels of Table 1, are illustrated in Fig. 3. The indicated uncertainties have the same origins as outlined above for elastic scattering, with a larger statistical component. An additional contribution to the uncertainties was the above noted source-correction factor. In the best cases, the inelastic-scattering cross-section uncertainties were $< 10\%$ and, in least favorable instances, $> 20\%$.

Some previous studies of inelastic-neutron scattering from yttrium have been reported. The present results are in very good agreement with the (n;n') results reported by Towle[23] and reasonably extrapolate to the higher-energy (n;n') results of Kinney and Perey.[24] The (n;n') results reported by Ramström[25] tend to lie lower than the present results, particularly for the prominent 1504-and 1747-keV excitations. Generally, the present results are in good agreement with those deduced from (n;n',gamma) measurements by Shafroth et al.[9] Graphical comparisons of the present results with the above previously reported data are given in Fig. 3.

The present experimental results provide a relatively comprehensive picture of the interaction of few-MeV neutrons with elemental yttrium, omitting only the relatively small radiative capture cross sections. The cumulative sum of the measured inelastic-scattering cross sections is consistent with the nonelastic cross sections implied by the above measured neutron total

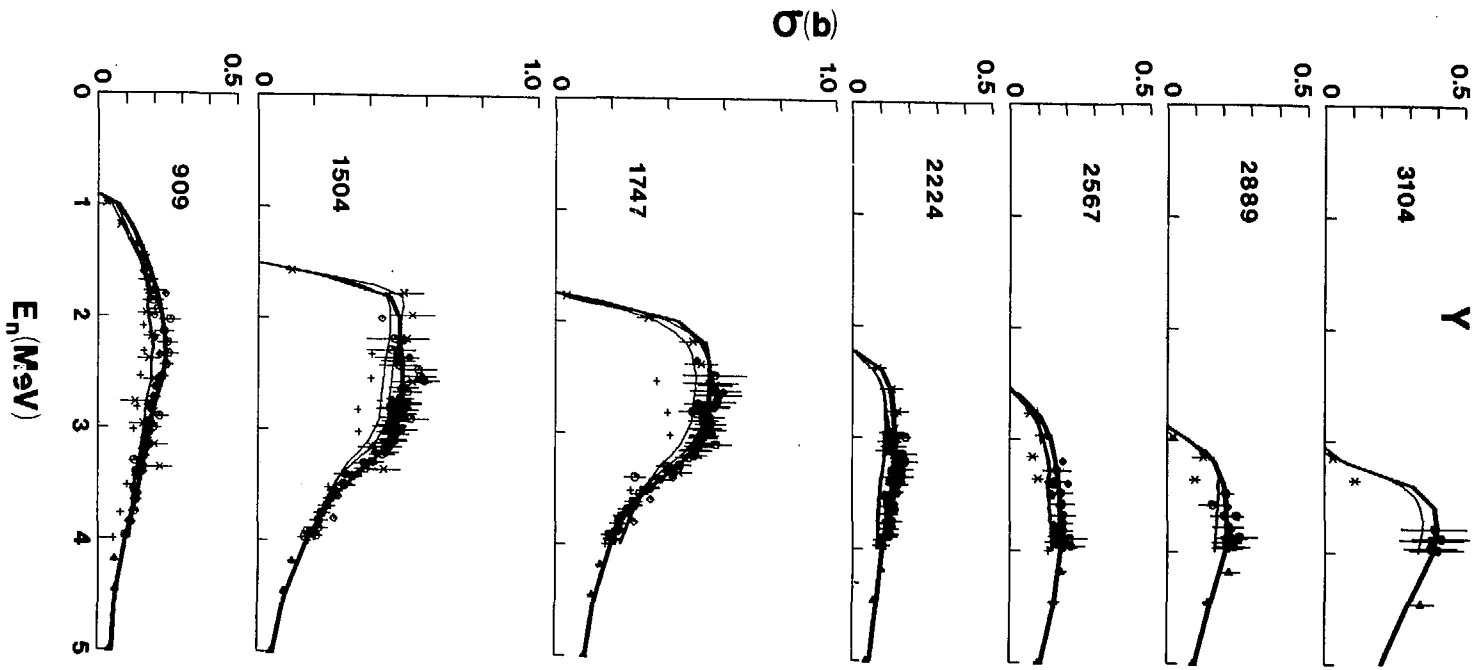

Fig. 3. Inelastic-Neutron-Excitation Cross Sections of Elemental Yttrium. The present experimental results are indicated by 0 symbols, those of Ref. 23 by ◇, Ref. 24 by ◁, Ref. 25 by + and Ref. 9 by X. Observed excitation energies in keV are numerically given in the respective sections of the figure. Heavy curves are "eyeguides" constructed through the present experimental results. Light curves indicate the results of calculations, the lower curve resulting from the fitting procedure and the higher curve from the use of an alternate width-fluctuation correction, as discussed in the text.

and elastic-scattering cross sections to 3.5 MeV to within the experimental uncertainties of the latter two components alone. Above 3.5 MeV, inelastic-scattering contributions not observed in the present measurements distort such comparisons.

IV. INTERPRETATION AND DISCUSSION

An objective of this work was the derivation of a conventional optical-statistical model (OM)[26] suitable for interpolation and extrapolation in this mass-energy region. The parameters of such a model were deduced by concurrently chi-square fitting the measured differential elastic-scattering cross sections (see Fig. 2). A few low-energy total-cross-section values were also inserted into the fitting procedure in order to guide the low-energy behavior of the fitting. Strength functions, inelastic-scattering data and higher-energy total cross sections were not an input to the fitting. The fitting procedure simultaneously varied the six OM parameters; real and imaginary strengths, radii and diffusenesses. Compound-nucleus (CN) processes are a prominent consideration at the energies of the present work. They were calculated using the Hauser-Feshbach formula[27], as modified by Moldauer[28], with the level specifications given in Table 1. Above 3.2 MeV the level properties were represented by the statistical formalism and parameters of Gilbert and Cameron.[29] The statistical representation is relevant to only a limited range of low excitation energies and fluctuations of the statistical parameters can be expected. Therefore, the statistical-parameter temperature was made a variable in the fitting procedure; resulting in a temperature value of 1.4 MeV, considerably larger than indicated by the systematic trends of Ref. 29. The present data span a limited energy dependence of the potential parameters. Therefore, it was assumed that the real-potential strength decreased at the rate of 0.3 MeV/MeV, in accord with frequently encountered "global" optical potentials,[30] and that the imaginary strength was energy independent. The calculations included a spin-orbit potential of the Thomas form with a strength of 6 MeV and geometrical dimensions identical to those of the real potential. The fitting procedures were carried out with the computer program ABAREX.[31] The calculations rapidly converged to the potential parameters given in Table 2. These parameters gave a good description of the measured differential elastic-scattering cross sections, as illustrated in Fig. 4. They also provided a reasonable description of the observed neutron total and angle-integrated elastic-scattering cross sections (see Fig. 1). Of course, they did not reproduce either the fine or intermediate resonance structure evident at low energies. There remains a small systematic discrepancy between measured and calculated angle-integrated elastic-scattering cross sections from $\approx$ 3.0 to 3.3 MeV with differences beyond the experimental uncertainties. This discrepancy may be the above-noted experimental artifact, but it was evident in results obtained in all four measurement periods. These differences correspond to an energy range where the statistical parameterization first enters the calculations and where such a parameterization may not accurately represent the average level structure. The model parameters of Table 2 are reasonably consistent with those recently reported for yttrium by Arthur.[32] The geometric factors are different but the strengths of the two potentials, measured as the integral per nucleon (J/A), are very similar; J/A=451.7 (real) and 60.4 (imaginary) MeV

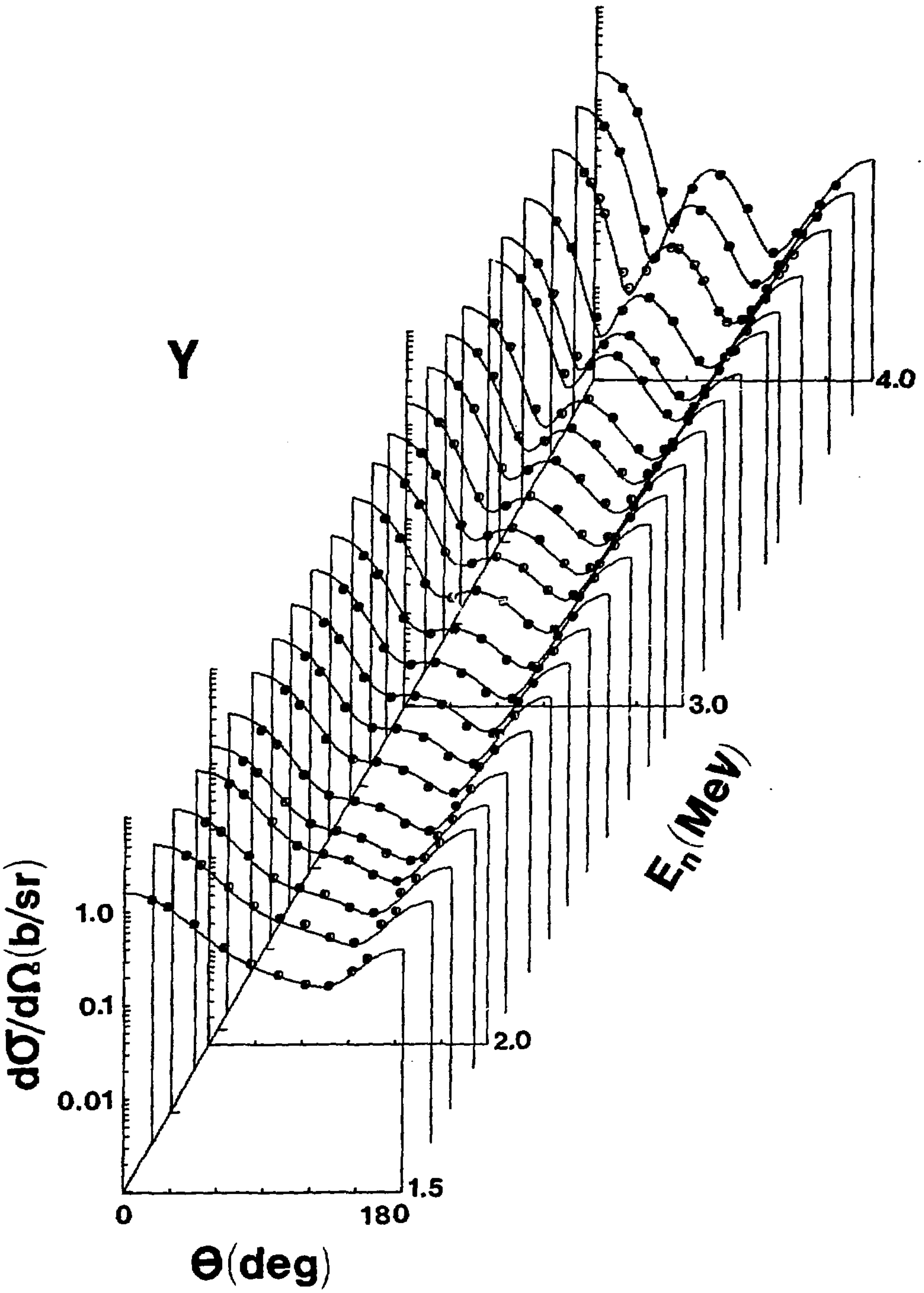

Fig. 4. Comparison of Measured and Calculated Elastic-Scattering Cross Sections of Yttrium. The measured values are indicated by data symbols and the results of the calculations described in the text are denoted by curves.

x F^3 for the present work compared with 444.4 (real) and 57.4 (imaginary) MeV x F^3 for Ref. 32. The present parameters imply an S_0 strength function of 0.5×10^{-4} compared with $0.27(\pm 0.05) \times 10^{-4}$ deduced from low-energy resonance data.[33] That is reasonable agreement in view of what appears to be considerable intermediate-resonance structure at low energies. The present parameters include a relatively large absorption radius, characteristic of that encountered in potentials derived from low-energy and strength-function data[34], and a relatively small absorption strength typical of potentials applicable to regions near shell closures.[35]

The above model is qualitatively descriptive of the observed inelastic-scattering cross sections as illustrated by the lower calculated curves in Fig. 3. Quantitatively, the calculated cross sections for the excitations of the 1504-and 1747-keV levels are significantly smaller than the measured values in the few-MeV region. These CN calculations are sensitive to the exact nature of the width-fluctuation correction. The above fitting procedures used the analytical expression for the width-fluctuation correction given by Engelbrecht and Weidenmüller[36], which is supported by the numerical modeling of Moldauer.[28] In the present application the degree of freedom involved is ≈ 1.9. Alternate choices of the degree of freedom are physically admissable. An extreme case is the simple Hauser-Feshbach formula ($\nu \to \infty$) which leads to calculated inelastic-scattering cross sections much larger than experimentally observed. A modest increase in the degrees of freedom to a value of three, results in calculated inelastic-scattering cross sections that are in relatively good agreement with observation (see the higher calculated curves in Fig. 3). Refitting the elastic-scattering data with that assumption results is only very modest changes in the potential parameters of Table 2 and continues to provide a good description of the measured elastic-scattering cross sections as illustrated in Fig. 5. However, this increase in the degrees of freedom seems to be essentially a pragmatic adjustment with little, if any, physical justification.[37]

The 1504-and 1747-keV levels of yttrium have been attributed to the coupling of a $p_{1/2}$ proton to the excited ^{88}Sr core.[8,9] With this core-coupling model, the 1836(2+) keV level of ^{88}Sr is split to obtain the 1504(3/2-) and 1747(5/2-) keV levels prominently evident in the present inelastic-scattering measurements. The ^{88}Sr core is, to some extent, a collective vibrator and coulomb-excitation measurements indicate $\beta_2 = 0.15$[10]. Such collective vibrations can be expected to carry over to the two ^{89}Y levels. Assuming the core-coupling model, the direct one-phonon vibrational excitations of the 1504- and 1747-keV levels of ^{89}Y were calculated at 2 and 3 MeV with a β_2 extending over the range 0.15 to 0.20. The resulting direct cross sections for the excitation of each level varied from 35 to 40 mb. At ≈ 2.0 MeV the vibrational values, when added to the above spherical results, yield inelastic-excitation cross sections in reasonable agreement with the present observations. The vibrational calculations employed the spherical-model parameters of Table 2. As such, their results must be considered a first approximation since the introduction of the direct-vibrational interaction will effect the choice of model parameters and the transmission coefficients governing the CN contributions to the cross sections. A rigorous assessment of the vibrational concept would require comprehensive fitting procedures, such as carried out above for the spherical model. They were not attempted due to their very appreciable cost in computing. However, even the present approximate approach tends to support the concept of the core-coupling model with its associated direct-vibrational interaction.

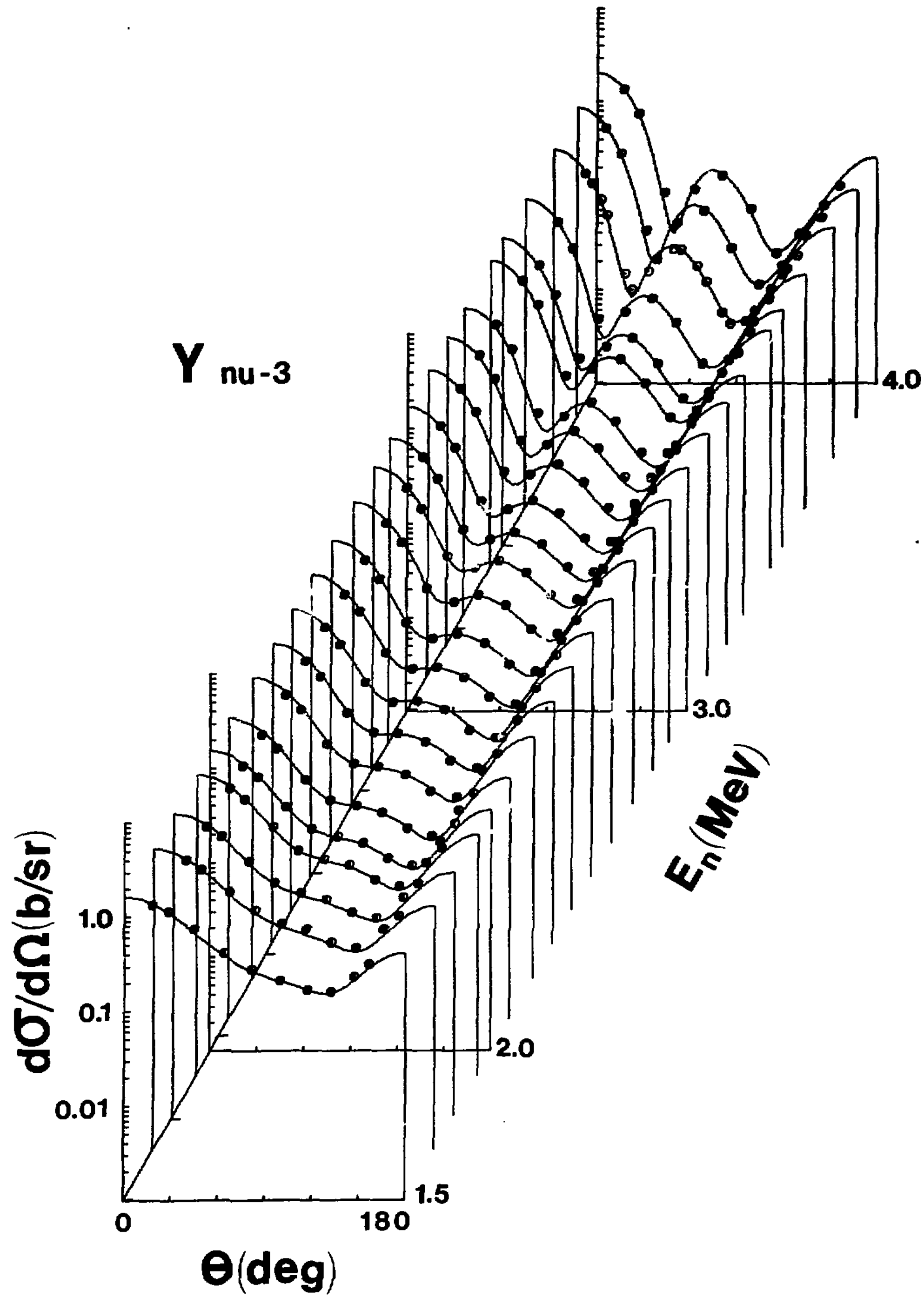

Fig. 5. Comparison of Measured (Symbols) and Calculated (Curves) Elastic-Scattering Cross Sections of Yttrium. The calculations employed a degree of freedom (ηu) = 3 in the width-fluctuation correction, as discussed in the text.

There is some uncertainty in the level structure of ^{89}Y near 3.0 MeV.[11] the J-pi of the 3067-keV level is reported to be 3/2-, but those of the 3106 and 3138 keV levels are uncertain, with 3/2- or 5/2- assignments suggested. The present experimental results are not consistent with 3/2- values for both 3106 and 3138 levels. The best agreement between experiment and calculation is obtained when both are 5/2- or when the sequence is 3106(3/2-) and 3138(5/2-) keV. The several higher-resolution measurements also support the latter choice. However, the appreciable experimental uncertainties preclude a definitive assignment.

V. COMPARISONS WITH ENDF/B-V

The ENDF/B-V evaluation[23] (MAT=9209) considers neutron total and elastic-scattering cross sections and discrete inelastic-scattering cross sections through excitation energies of ≈ 2550 keV. There are considerable differences between the evaluated neutron total cross sections and those obtained in the present measurements, as illustrated in Fig. 6. The differences are both positive and negative, energy dependent and can be ten percent or more at some energies. Furthermore, the evaluated energy-dependent shape is not consistent with either the present experimental or calculational results. These total-cross-section differences are reflected in the elastic-scattering cross sections where the evaluated quantities are significantly different from those indicated by the present results (see Fig. 6). Fortuitously, the evaluated nonelastic cross section is more consistent with that implied by the present work. However, there are very large discrepancies between evaluated inelastic-scattering cross sections and those obtained in the present work (see Fig. 7). For some of the prominent inelastic-excitation functions the differences are nearly factors of two and for some of the minor excitation cross sections they are an order of magnitude or more. It is difficult to explain such large inelastic-scattering discrepancies unless the evaluation is based upon calculations employing spin and parity assignments that are grossly in error. In any event, the inelastic-scattering discrepancies far transcend the commonly stated accuracy goals for fast-breeder-reactor fission-product data.

VI. CONCLUDING COMMENTS

The present experimental results considerably improve the understanding of neutron total, elastic-scattering and inelastic-scattering cross sections of yttrium over an energy range of importance to fast-breeder reactors (FBR). A spherical OM, deduced from the measured values, is descriptive of the observed neutron total and elastic-scattering cross sections and, qualitatively, of the inelastic-scattering cross sections. The model should be an appropriate vehicle for interpolation and extrapolation in this mass-energy region. The model is characterized by absorption which is centered well outside the real radius and is of relatively weak strength. The model underpredicts the cross sections for some of the prominent inelastic-scattered groups. This shortcoming can be alleviated by increasing the degree of freedom employed in the calculation of the width-fluctuation correction. However, a more attractive remedial approach is the core-coupling model with direct-vibrational excitation of the ^{88}Sr core. The resulting direct-excitation

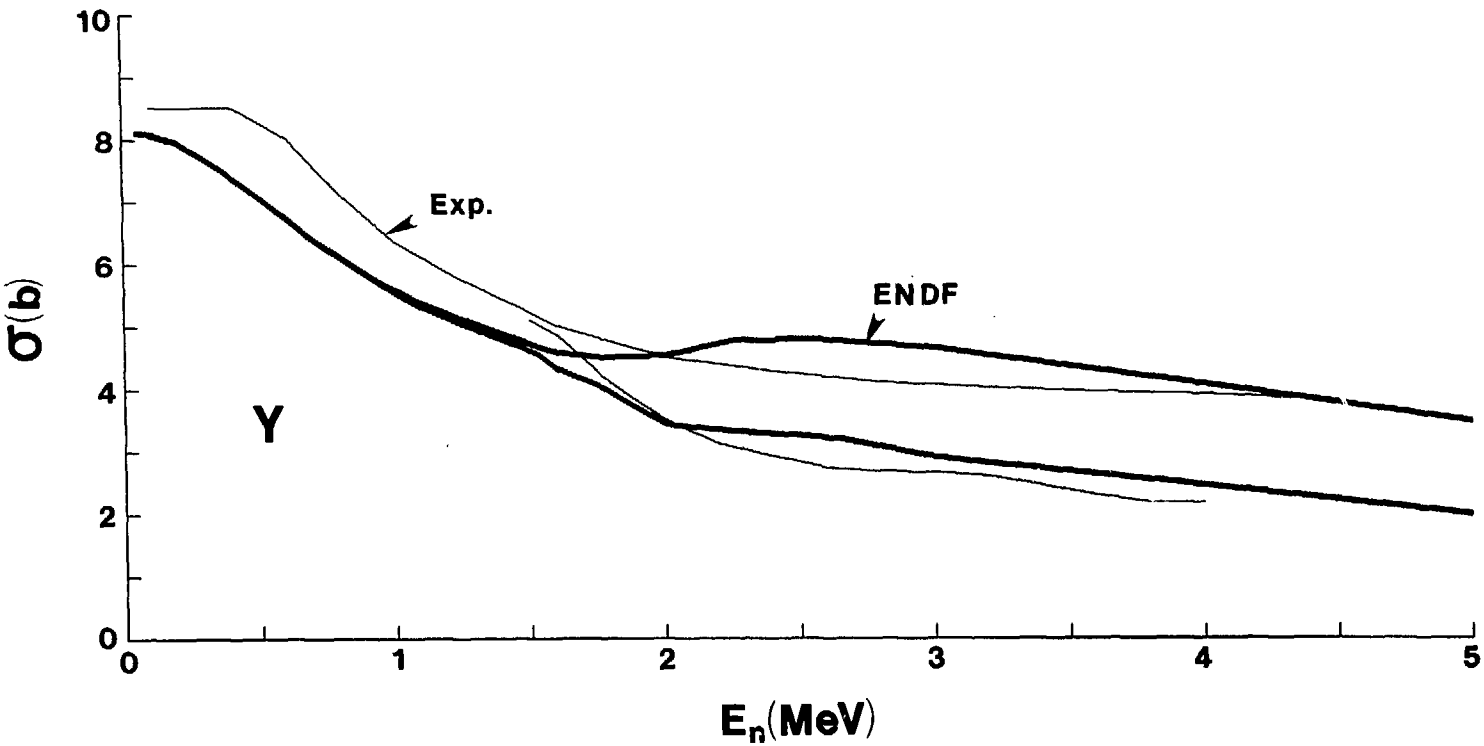

Fig. 6. Comparison of Measured and Evaluated Neutron Total and Elastic-Scattering Cross Sections of Yttrium. The light curves are the "eyeguides" constructed through the present experimental results (see Fig. 1) and the heavy curves ENDF/B-V values.

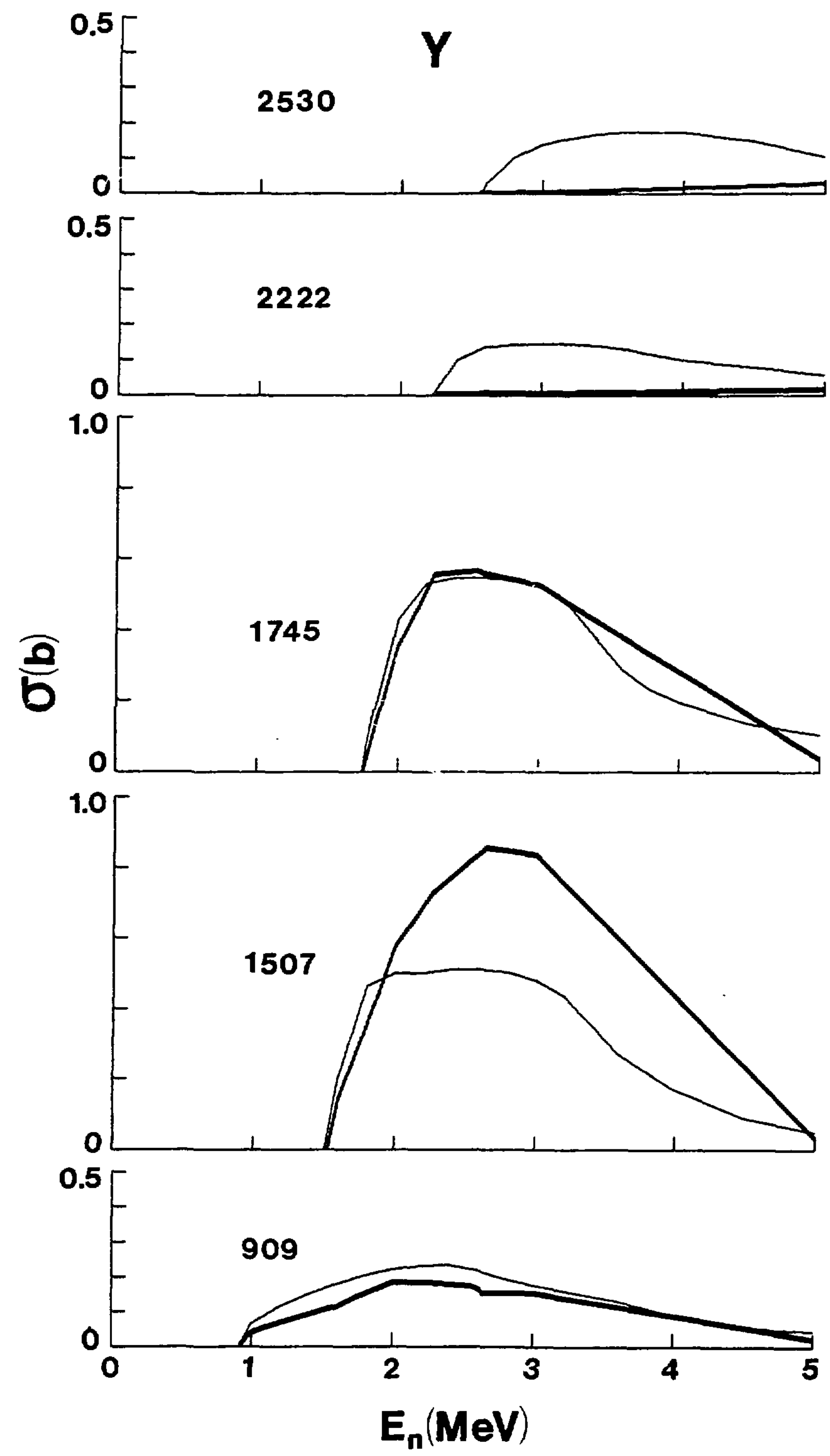

Fig. 7. Comparison of Measured and Evaluated Inelastic-Scattering Cross Sections of Elemental Yttrium. The light curves are the "eyeguides" constructed through the present experimental results (see Fig. 3) and the heavy curves indicated the ENDF/B-V evaluated cross sections.

cross sections are of such a magnitude as to bring calculated inelastic-scattering cross sections into quantitative agreement with observation, and in that sense the present experimental results support the concept of the core-coupling model. The present experimental results offer some guidance toward the resolution of ambiguities in spin and parity assignments at excitation energies of $\approx$ 3.0 MeV. The present experimental neutron total, elastic-scattering and inelastic-scattering cross sections are widely discrepant with respect to the evaluated quantities given by ENDF/B-V by amounts considerably exceeding the accuracies frequently requested for FBR fission-product data.

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Table 1. Observed Neutron Excitation Energies

Group No.	E_x(exp.),keV[a]	E_x(Ref. 11), keV[b]
1	909 ± 23	909(9/2+)
2	1504 ± 20	1507(3/2-)
3	1747 ± 16	1745(5/2-)
4	2224 ± 16	2222(5/2+)
5	2567 ± 26	2530(7/2+)
		2568(11/2+)
		2622(9/2+)
6	2889 ± 12	2871(7/2+)
		2881(3/2-)
		2893(---)
7	3104 ± 10	3067(3/2-)
		3106(3/2,5/2-)
		3138(3/2,5/2-)

[a]Uncertainties defined as RMS deviations of a number of measurements from the simple means.

[b]Underlined spin-parity assignments were used in model derivation.

Table 2. Spherical Optical-Model Parmaeters[a]

Real Potential[b]			
	Strength	V_o = 49.19	MeV
	Radius[c]	R_v = 1.23	F
	Diffuseness	A_v = 0.738	F
	J_v/A_v[d] = 451.8 MeV x F^3		
Imaginary Potential[e]			
	Strength	W = 8.15	MeV
	Radius	R_w = 1.47	F
	Diffuseness	A_w = 0.303	F
	J/A_w = 60.42 MeV x F^3		

[a] Assume spin-orbit term of Thomas form with 6 MeV strength and the geometry of real potential.

[b] Saxon form, assume energy dependence of $V = V_o - 0.3\ E(\text{MeV})$.

[c] All radii expressed as $R = R_i \times A^{1/3}$.

[d] Integral per nucleon.

[e] Saxon-derivative form.

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