INDC-220

EANDC(US)-1066

INDC (US)-3U

REPORT OF THE NCSAC AD-HOC SUBCOMMITTEE ON NEUTRON SCATTERING

Topic #1

April 1968

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I. INTRODUCTION

In attempting to perform a function set forth in its "Frame of Reference" The Nuclear Cross Sections Advisory Committee of the Division of Research U.S.A.E.C. has for many years prepared reports** concerning microscopic cross section and related measurements of use to the nation's nuclear energy and allied efforts. These reports list by element (or isotope if appropriate); the cross sections being requested specifying the energy range and accuracy desired, the name of the requestor of the information and relevant comments concerning the existance of such information or status of measurements known to be in progress or planned.

This material is now stored in a form amenable to computer processing such as updating and automated reproduction. The format has developed over the years and is now considered satisfactory and the information contained is as accurate as can be reasonably expected of a compiler. Nevertheless it has been felt by the NCSAC sub-committee that the objectives of the compilation are only partially being met. For example many requests are of long standing and, because of the way the requests are collected, it is difficult to ascertain the continued validity of the request. Some requests are made for data which

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* This document contains tentative information and should not be referenced without explicit authorization of originators of the particular data.

** "Compilation of Requests for Nuclear Cross Section Measurements" EANDC(US)-103 "U", June, 1967, prepared by A. B. Smith, NCSAC is the latest of these reports.

already exists in the open literature or for which theory would provide adequate information. From the measurers point of view, some requests are either not within the present state of the art or are so difficult that their need should be adequately and further justified before the necessary effort is expended. In some cases the request is ambiguous or perhaps nonsensical. The problems are further compounded by the imperfect or nonexistent lines of communication between requestor and measurer. It has been judged that some more active role of the NCSAC is indicated if the function for which the compilation is designed is to be properly dispatched. Subcommittees of the NCSAC have been appointed in the various measurement disciplines to study the compilation with special attention being paid to alleviating the short comings cited above. One such subcommittee has been charged with elastic and inelastic neutron scattering in the keV-MeV energy range.

There are a great many requests for scattering cross sections in the compilation and to produce a comprehensive detailed study would take an inordinately long time while a study resulting in only generalities would be of little use. It is proposed therefore to attack the request items piecemeal in the hope of stimulating work or revision of the request. The choice of items will be somewhat arbitrary but will in the beginning tend toward requests on elements which fill one or both of the following criteria.

a) Priority I or II*

b) There is sufficient information both experimental and theoretical to perhaps justify removal of request items from the compilation.

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* See Sec. IV EANDC(US)-103 opcit.

Each case study will attempt to

1. Review in the context of the requests the available information on the particular element.
2. Discuss applicable theoretical treatment
3. Compare experimental and theoretical cross sections with ENDF data where available*.
4. Make recommendations to both the requestor and potential measurer designed to hasten the removal of the request from the compilation.

In making these reviews, standard reference sources will be assayed including: a) SCISRS I file; b) CINDA; c) prominent journals and conference proceedings; and d) pertinent private sources. While undertaken with some care, the bibliographic effort should not be taken as definitive.

This document deals with the following specific requests for Neutron Scattering Cross Sections of VANADIUM**.

#82 Differential Elastic Scattering Cross Section

Energy range; 1 - 14 MeV

Priority II

Desired accuracy: 10 percent (at least 20)

Request by: RDT - R. Avery

Comment:

Average of (1 - cos θ) desired

Angular resolution 10 deg., Energy resolution 500 keV

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* Herein ENDF referres to the Evaluated Nuclear Data File, USAEC Division of Reactor Development

** Requests and number taken from WASH-1078

#83 Differential Inelastic Scattering Cross Section

Energy range; threshold to 14 MeV

Priority II

Desired accuracy: 15 percent

Request by: RDT - R. Avery

Comment:

Desire emitted neutron energy resolution 15 percent.

There are no pertinent EANDC requests other than those above.

The following resume' reviews the currently available experimental and theoretical understanding in the context of the above two requests. It is the intent to determine to what extent the requests are satisfied and/or what future course is requisite to provide the desired information. In view of the reactor origin of the requests, the status of pertinent evaluated data as defined in the ENDF-B file is reviewed in the context of the requests and the available physical information.

II. TOTAL NEUTRON CROSS SECTIONS

Initially, it is desirable to establish the total cross sections throughout the energy range of interest so as to provide an envelope of partial cross sections and the quantity that is most easily compared with theory. A number of experimental results are available well defining the total cross section up to 14 MeV with the exception of a small region between 1.5 - 2.0 MeV[1-9,28,29]. Representative of these results are those shown in the upper portion of Fig. 1. (9,6). The lower portion of Fig. 1 shows information taken from the corresponding energy range of the ENDF-B file. This file was prepared before the good resolution results, below 1.5 MeV, were available thus does not show the detailed resonance structure. Such structure information may or may not be useful in reactor design but the detailed experimental data is available should it be needed. The ENDF file reasonably extrapolates the measured data over the interval 1.5 - 2.0 MeV and, within the energy mesh employed, well describes the total cross sections.

III. DIFFERENTIAL ELASTIC SCATTERING CROSS SECTIONS

Relatively definitive differential elastic scattering data is available at incident neutron energies of $\lesssim$ 1.5 MeV[10]. These results are shown in Fig. 2 together with curves taken from the ENDF-B file. At these low energies the cross section displays a great deal of partially resolved structure which is reasonably represented by the ENDF data. Elastic scattering results are also available at energies up to 2.35 MeV as shown in Fig. 3 and at 3.2 MeV (Fig. 4)[11,12]. Very recently results between $\sim$ 2.5 - 8.0 MeV have been reported by Holmqvist and Wiedling[13]; the 8.05 MeV result is indicated in Fig. 5. There are a few other differential elastic scattering measurements at isolated incident energies and scattering angles[14]. From these latter, it is difficult to form a coherent picture of the process and extract information pertinent to the requests. Oddly, 14 MeV elastic scattering angular distributions appear to be very limited though such measurements are well within the capability of a very modest institution[30].

IV. DIFFERENTIAL INELASTIC SCATTERING CROSS SECTIONS

The excited structure of vanadium is reasonably known to excitation energies of $\sim$ 3.0 MeV[15] inclusive of spins and parities of the first four states. This structure, together with prominent gamma-ray transitions is outlined in Fig. 6. The wide separation of the lower states makes it relatively easy to observe discrete scattered neutron groups. Some of the most recent and detailed results[10,11] are summarized in Figs. 3 and 7. More extensive and tentative data is also available from the same authors. The comparable excitation functions contained in the ENDF file are also indicated in Fig. 7. The results of Fig. 3 are substantiated by previous measurements of the 90 deg. excitation cross sections of the 930 and the 1610 keV states at an incident energy of 2.4 MeV[16]. The observed secondary neutron distributions were found to be nearly isotropic with the exception of low (< 1.0 MeV) incident neutron energies where strong and broad resonance structures can lead to significant anisotropies[10].

There is little experimental knowledge of inelastic scattering from vanadium above incident neutron energies of $\sim$ 3.0 MeV. A measurement has been reported at 7.0 MeV yielding a "temperature" of 0.9 MeV and a total inelastic cross section of 1.21 ± 0.11 b[17]. About and beyond this isolated point the situation is obscure, but for scattered measurements using continuum spectra of incident neutrons[18].

The above direct inelastic scattering results are supported by several $(n{:}n'\gamma)$ results[19,20]. The Texas Nuclear Corporation results near 1.0 MeV are in good agreement with the results shown in Fig. 7. The results of Ref. 20 at 1.83, 2.21, and 2.43 MeV tend to be systematically slightly larger than those indicated by direct neutron observation. The discrepancy is not large (< 20%) and not surprising in view of the use of the $Fe(n{:}n'\gamma)$ reaction as the reference standard.

V. CALCULATED EXTRAPOLATION

The equivalent non-local optical potential of Englebrecht and Fiedeldey and statistical formulas were employed to extrapolate the measured results[21-23]. This particular optical potential, shown valid over wide incident energy ranges, has the form:

$$V_c(r) = -(V + iU)\, f_1 - iWf_2$$

$$f_1 = \left(1 + \exp\left[\frac{r - R_1}{a_1}\right]\right)^{-1}, \qquad f_2 = \exp - \left[\frac{(r - R_2)}{a_2}\right]^2$$

$$R_1 = r_1 + r_0 A^{1/3}, \qquad r_0 = 1.16f, \qquad r_1 = 0.6f$$

$$R_2 = R_1 + r_2, \qquad r_2 = 0.5f, \qquad V = V_0 - 0.25E \ (\text{MeV})$$

$$a_1 = 0.62f, \qquad a_2 = 0.5f, \qquad W = W_0 - 0.2E \ (\text{MeV})$$

$$U = +\,0.125E - 0.0004E^2$$

As $E \to 0$, $U \to 0$ and the form is equivalent to that successfully employed by Moldauer[24]. Englebrecht suggests general values of U, V, and W[21]. However, in this application V and W ($U \equiv 0$) were determined from a χ^2 fit of the above potential to the abundant elastic scattering information available at incident energies of < 1.5 MeV. Before fitting, the experimental values (Fig. 2) were averaged over 200 keV intervals to obtain the results of Fig. 8. Even with this averaging procedure structure was evident at energies $\lesssim$ 1.0 MeV and was reflected in fluctuating V and W values as shown in Fig. 8. Above $\sim$ 1.0 MeV, V and W remained fairly constant with energy at V = 42.5 and W = 7.8.

These relatively constant values were used to establish the V_0 and W_0 of the above potential form. All subsequent computations were based upon these "established" values.

The fidelity of the above potential is indicated by the calculated total cross section curve shown in Fig. 1 [25]. The agreement with experiment was judged good over a wide energy range. By "derivational method", the elastic scattering at incident energies $\lesssim$ 1.5 MeV was well described by the potential (Fig. 8). More important, the computed elastic scattering (solid curve), (Figs. 3, 4, and 5) at 2.34, 3.2, and 8.0 MeV, respectively, was descriptive of experiment. The sensitivity of the potential choice was examined by applying other "recommended" potentials. Some of these alternative attempts yielded poorer results as indicated by the example of the dashed curve of Fig. 3 [26]. These comparisons between computed and observed elastic scattering tend to indicate that suitable values can be obtained to $\lesssim$ 9.0 MeV well within the requested upper error limit of 20%.

The calculated inelastic scattering cross sections at 2.34 MeV agreed to within 10-20% with experiment (solid curves, Fig. 3). Below 1.0 MeV the comparison is less happy (see Fig. 7) but this is a region where resonance effects are obviously present and the basic statistical concepts employed become of marginal validity. Attempts to use fluctuation and correlation corrections to achieve a better agreement with experiment were not particularly successful. In any case, below $\sim$ 1.0 MeV the ample experimental results well define the physical situation. At 7.0 MeV, the calculations yield a total inelastic cross section of 1.27b, within the requested 15% of the measured value of 1.21b. Generally, though the inelastic computations yield results that are not in as good agreement with experiment as those obtained for the elastic process, they appear suitable for the extrapolation of measured values to obtain cross sections of the requested 15% accuracy up to incident energies of ∿ 3.0 MeV and possibly higher.*

VI. CONCLUSIONS AND RECOMMENDATIONS

1. Reg. #82. Elastic Scattering

It is believed that available experimental information and careful use of computation satisfies the request to at least 3.0 MeV and possibly to ∿ 9.0 MeV. No more measurements are warranted at incident energies of < 3.0 MeV.

From 8 - 14 MeV the elastic cross section of vanadium remains uncertain. Careful differential measurements are suggested at ∿ 5, ∿ 7, ∿ 10, and ∿ 14 MeV followed by a good model oriented assay. ORNL work now in progress may meet all requirements to ∿ 7.0 MeV[27]. Should the model prove descriptive of the higher energy results and permit reasonable extrapolation no further measurements should be initiated.

None of the above suggested measurements appear beyond present technical capability and there is no sample problem.

2. Reg. #83. Inelastic Scattering

Including work now nearing completion (10,11) available data and reasonable calculation should satisfy the request to ∿ 3.0 MeV. No further measurements at lower energies should be initiated.

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* Throughout this assay (n:x), x ≠ neutron have been ignored. Such processes are not insignificant in vanadium but their omission should not appreciably alter the above conclusions.

Above an incident energy of ~ 3.0 MeV there is almost no information. Differential measurements are suggested at ~ 4, ~ 5, ~ 7, ~ 10, and ~ 14 MeV[27]. A secondary neutron resolution of 1 nsec/m should be technically feasible and will resolve all individual scattered neutron groups up to excitation energies of ~ 2.5 MeV. As for the elastic scattering, above; a proper use of models should provide the necessary extrapolation of the measured values.

There appears no fundamental technical obstacle to obtaining the above results and they could well be pursued concurrently with the elastic scattering measurements.

3. ENDF-B

The present file for vanadium appears remarkably good, particularly in view of the fact that it was prepared prior to the completion of many of the experimental measurements. However, the contents of the file must be continually reviewed and updated if the user is to rapidly realize the benefit of the improved physical understanding. It is suggested that a mechanism for such updating be defined with "open channels" to and from the experimenter.

4. Physical Understanding

The above resume' is based entirely upon applied need. It should be noted that fast neutron induced processes in vanadium are of physical interest as they constitute some of the best examples of intermediate structure in several exit channels. Ultimately, a proper understanding of such phenomena might have a far greater impact on the applied use of neutron data than the satisfying of the explicit requests in question. The above suggested future measurements probably will not provide a reasonable basis for such understanding.

5. Suggest Revision of Requests #82 and #83 to the Following Forms:

82 V-NAT DEL 4 MEV - 14 MEV II 10 PER, 20 ACCEPT.

DIFFERENTIAL ELASTIC SCATTERING CROSS SECTION (ANGLE)

REQ. RDT ANL AVERY

REQ. COM, WANT AVE, OF (1-COS), ANGLE RESOLUTION 0.5 MEV, NEEDED FOR FAST REACTOR CALCULATION.

STATUS, ORL WORKING 5 - 7 MEV

SWE RESULTS TO 8 MEV, SEE PROCEEDINGS OF WASH-TECH-CONF (1968) PAPER E-23,

USE OPTICAL MODEL BASED ON LOW ENERGY SCATTERING AND KNOWN TOTAL X-SEC,

ALD TOWLE HAS SOME RESULTS AT LOWER ENERGIES.

83 V-NAT SIN 3 MEV - 14 MEV II 15 PER

DIFFERENTIAL INELASTIC SCATTERING CROSS SECTION (ENERGY)

REQ. RDT ANL AVERY

REQ COM, FOR FAST REACTOR CALCULATIONS, INCIDENT AND EXIT ENERGY RESOLUTION 15 PER.

STATUS, ORL WORKING IN REGION 5-7 MEV

SWE DATA BEING PROCESSED TO $\sim$ 8.0 MEV,

ALD TOWLE HAS SOME RESULTS AT LOWER ENERGIES

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19. Mathur et al. Private Communication (to be published). Texas Nuclear Corporation Progress Report.

20. D. Barrows, Thesis, University of Kentucky, unpublished.

21. C. Englebrecht and H. Fiedeldey, to be published.

22. Wolfenstein, Phys. Rev. 82, 690 (1951).

23. W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952).

24. P. A. Moldauer, Nucl. Phys. 47, 65 (1963).

25. All computations utilized a modified version of ABACUS II - NEARREX, ANL-6978.

26. L. Rosen, Los Alamos Scientific Laboratory Report, LA-3538-MS

27. Work in progress at ORNL may fulfill all needs at $\sim$ 5.0 - 7.0 MeV.

28. F. Firk et al. Proc. Phys. Soc. 82, 477 (1963).

29. G. Rohr and E. Friedland, Nucl. Phys. A104, 1 (1967).

30. Some 14 MeV Elastic Scattering is Ref. to AFWL-TR65-216, II; See CINDA (1967).

FIGURE CAPTIONS

Fig. 1 Total cross sections of Vanadium from 0.1 to 10.0 MeV. Top, representative experimental results from Ref. 6 and 9. Bottom, ENDF-B file total cross sections noted by square points. Curve indicates results of optical-model calculations as described in Section V of text.

Fig. 2 Measured differential elastic scattering cross sections compared with the ENDF file data.[10] The experimental data is averaged over 50 keV intervals.

Fig. 3 Elastic and inelastic differential scattering cross sections of V at 2.35 MeV[11]. Curves indicate results of calculations as discussed in Sec. V of the text.

Fig. 4 Differential elastic scattering cross sections of V at 3.2 MeV[12].

Fig. 5 Differential elastic scattering from V at 8.05 MeV[13]. ● indicate experimental values and curves the result of calculation as discussed in Sec. V of the text. Figure is qualitative as data was read from small figure of Ref. 13.

Fig. 6 Level structures of Vanadium[13]. Prominent gamma-ray transitions are noted[17].

Fig. 7 Inelastic scattering cross sections of Vanadium; bars from Ref. 10, circles Ref. 11. Solid curves indicate ENDF file content. Dotted lines represented calculated results as per Section V of the text.

Fig. 8 Differential elastic scattering cross sections of Vanadium. The experimental measurements have been averaged over a 200 keV interval to smooth local fluctuations. Solid curves result from a χ^2 fit of an optical potential to the data. The resulting energy dependence of V (real) and W (imaginary) portions of the potential are indicated in the upper part of the figure. The dashed curves indicated results obtained with the "general" potential discussed in Sec. V of the text.

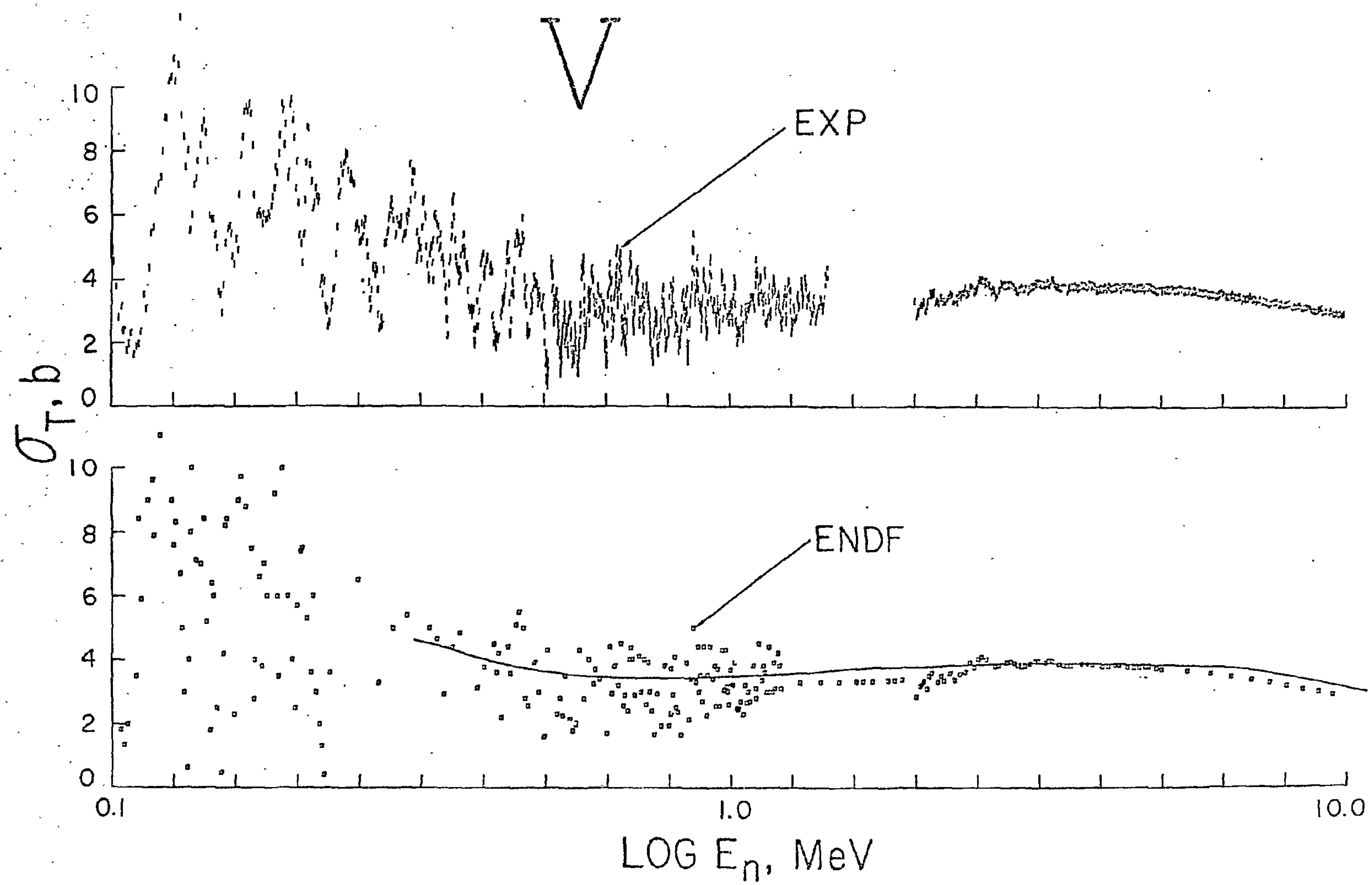
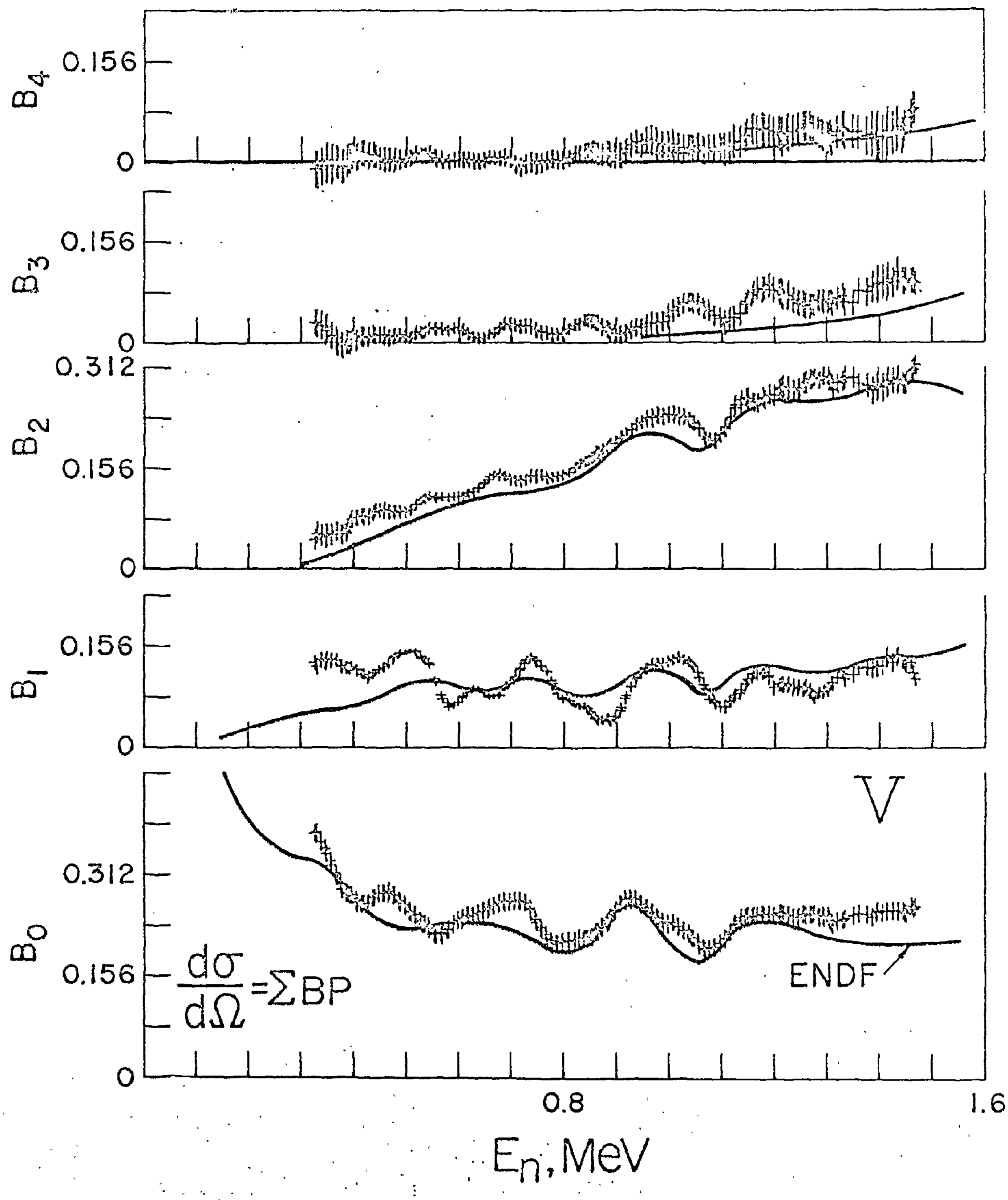


Fig. 1



B4
0.156
0
B3
0.156
0
0.312
B2
0.156
0
B1
0.156
0
V
0.312
B0
0.156
0
$\frac{d\sigma}{d\Omega}=\Sigma BP$
ENDF
0.8
1.6
E_n, MeV

Fig. 2

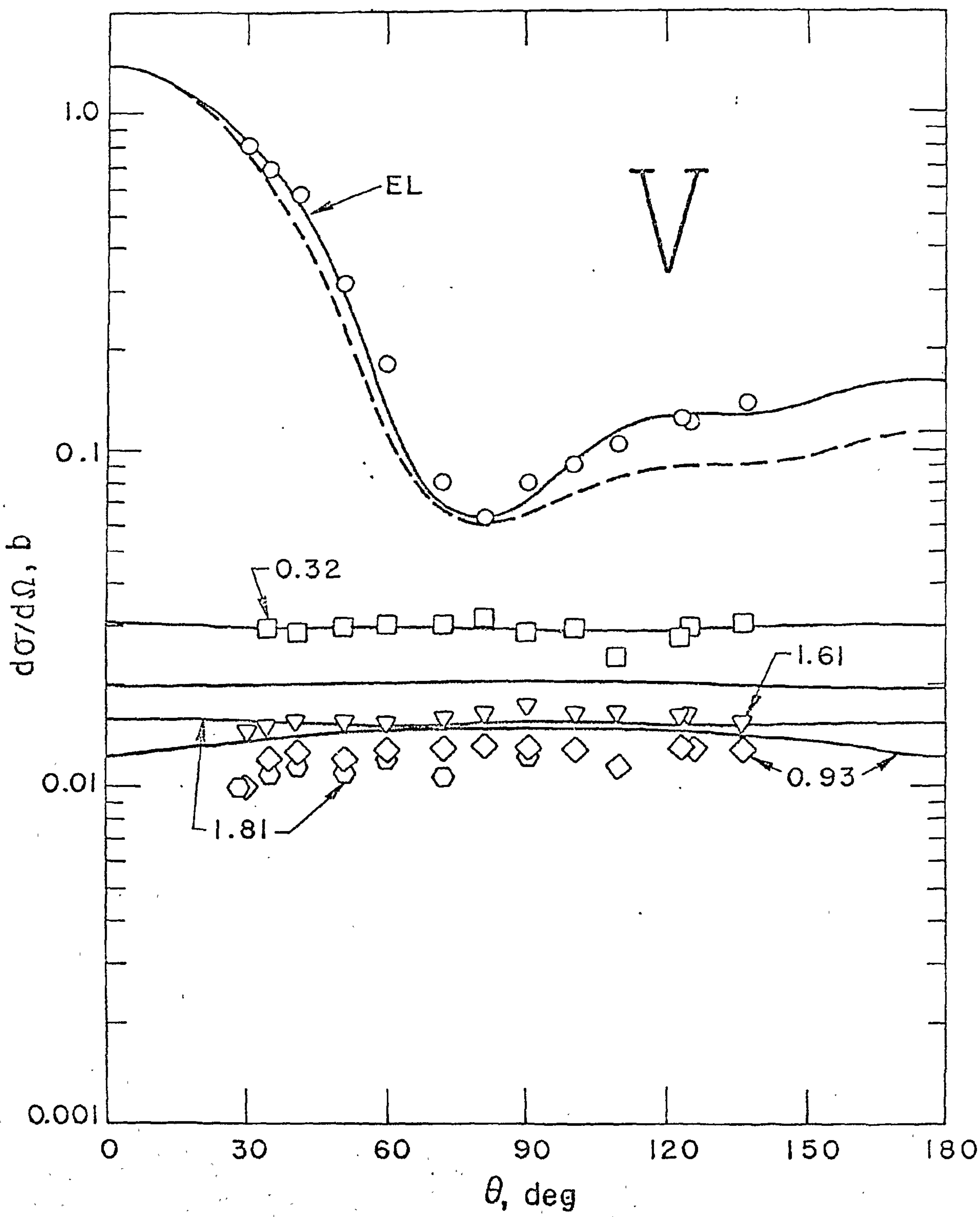

V
EL
0.32
1.61
0.93
1.81
1.0
0.1
0.01
0.001
dσ/dΩ, b
0
30
60
90
120
150
180
θ, deg

Fig. 3

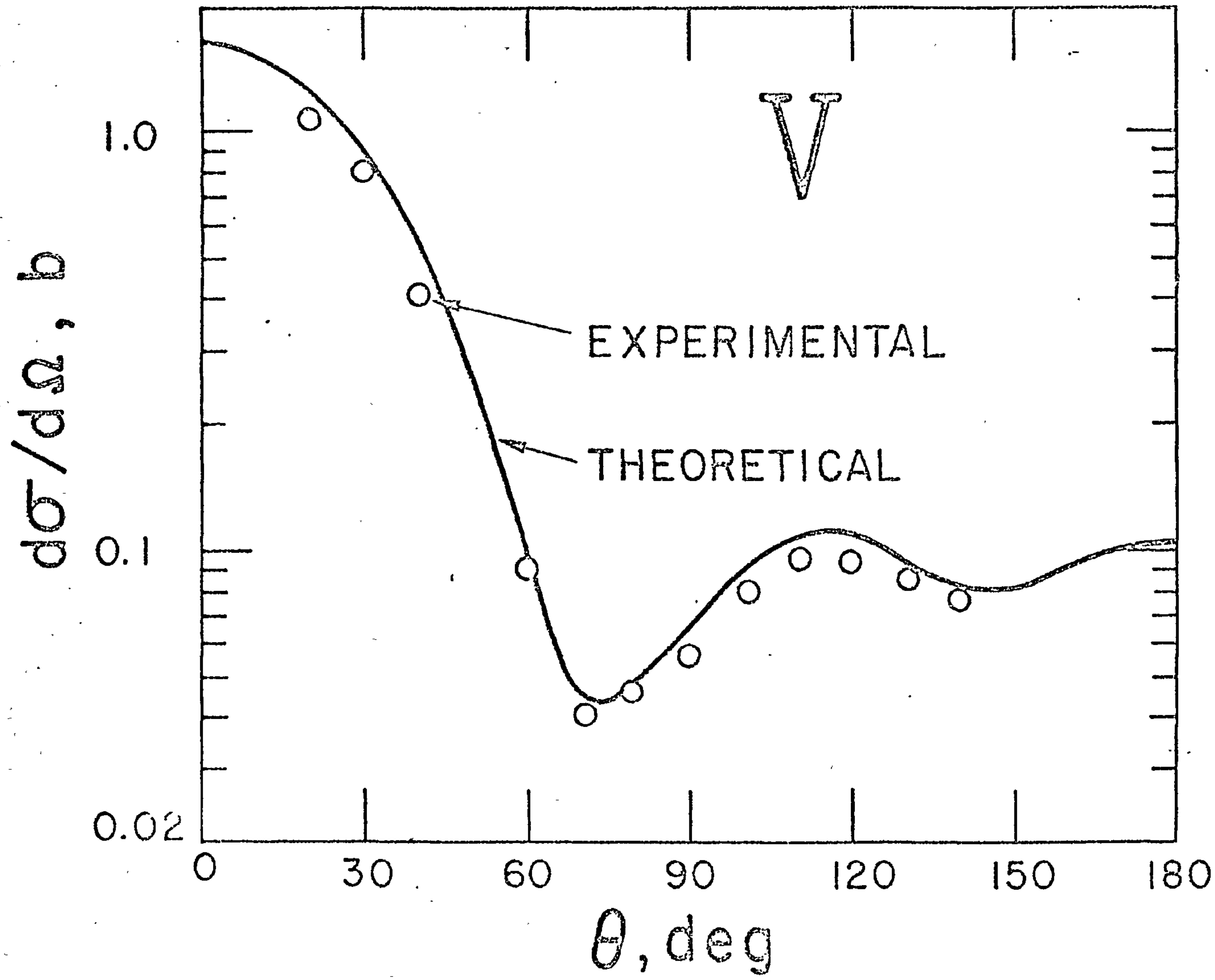
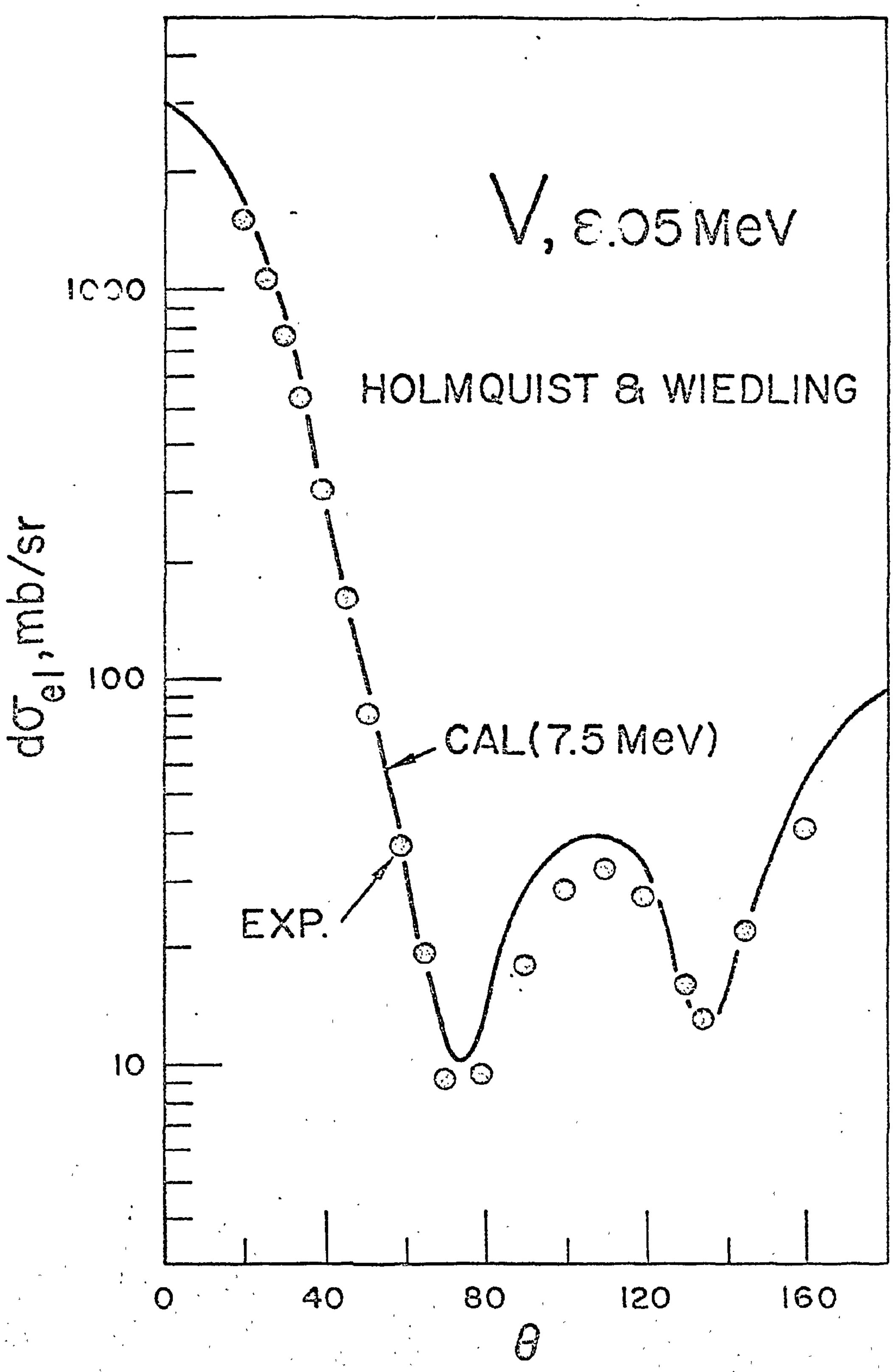

V
EXPERIMENTAL
THEORETICAL
1.0
0.1
0.02
0
30
60
90
120
150
180
dσ/dΩ, b
θ, deg

Fig. 4



V, 8.05 MeV
HOLMQUIST & WIEDLING
CAL(7.5 MeV)
EXP.
1000
100
10
dσ_el, mb/sr
0
40
80
120
160
θ

Fig. 5

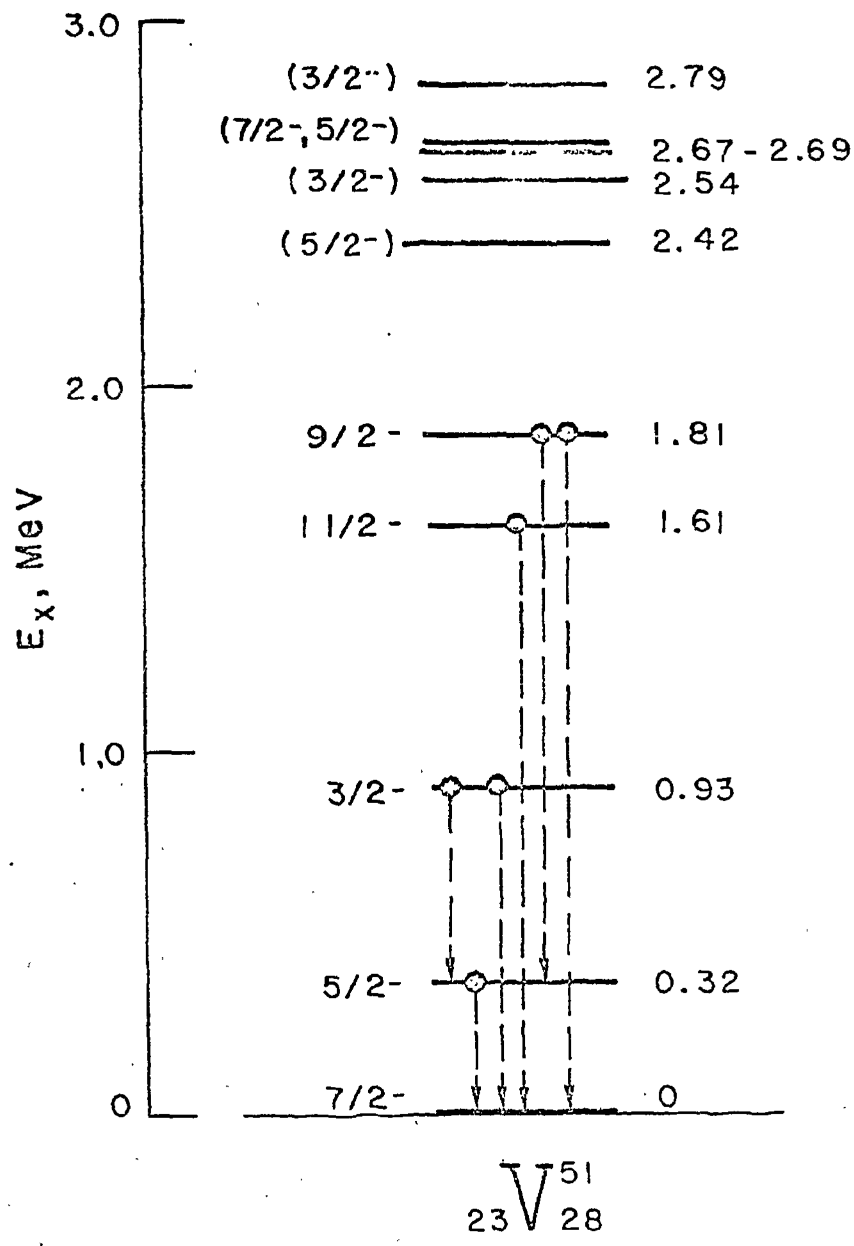

3.0
2.0
1,0
0
Ex, MeV
(3/2⁻)
2.79
(7/2⁻, 5/2⁻)
2.67 - 2.69
(3/2⁻)
2.54
(5/2⁻)
2.42
9/2⁻
1.81
11/2⁻
1.61
3/2⁻
0.93
5/2⁻
0.32
7/2⁻
0
$_{23}V^{51}_{28}$

Fig. 6

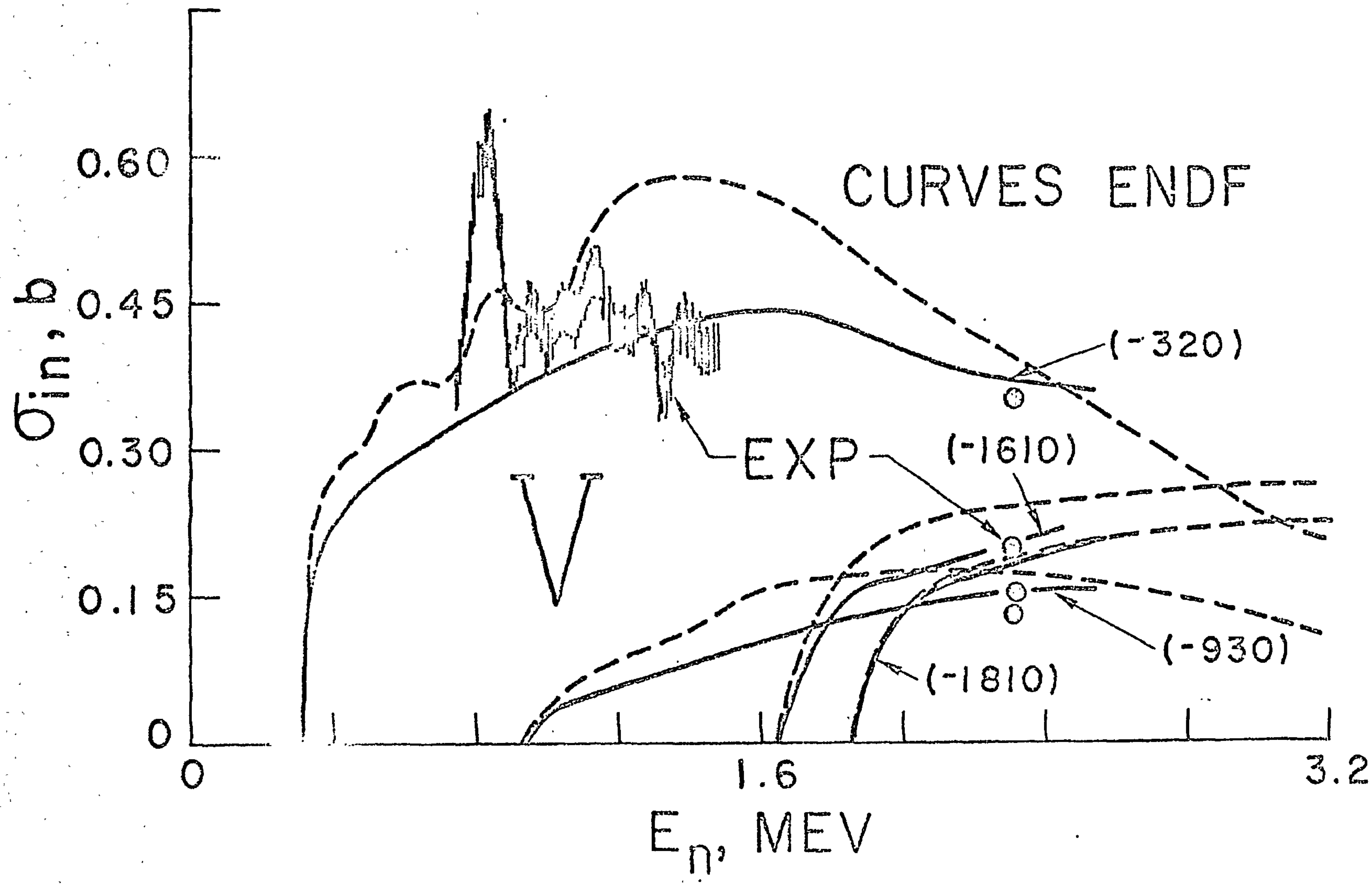
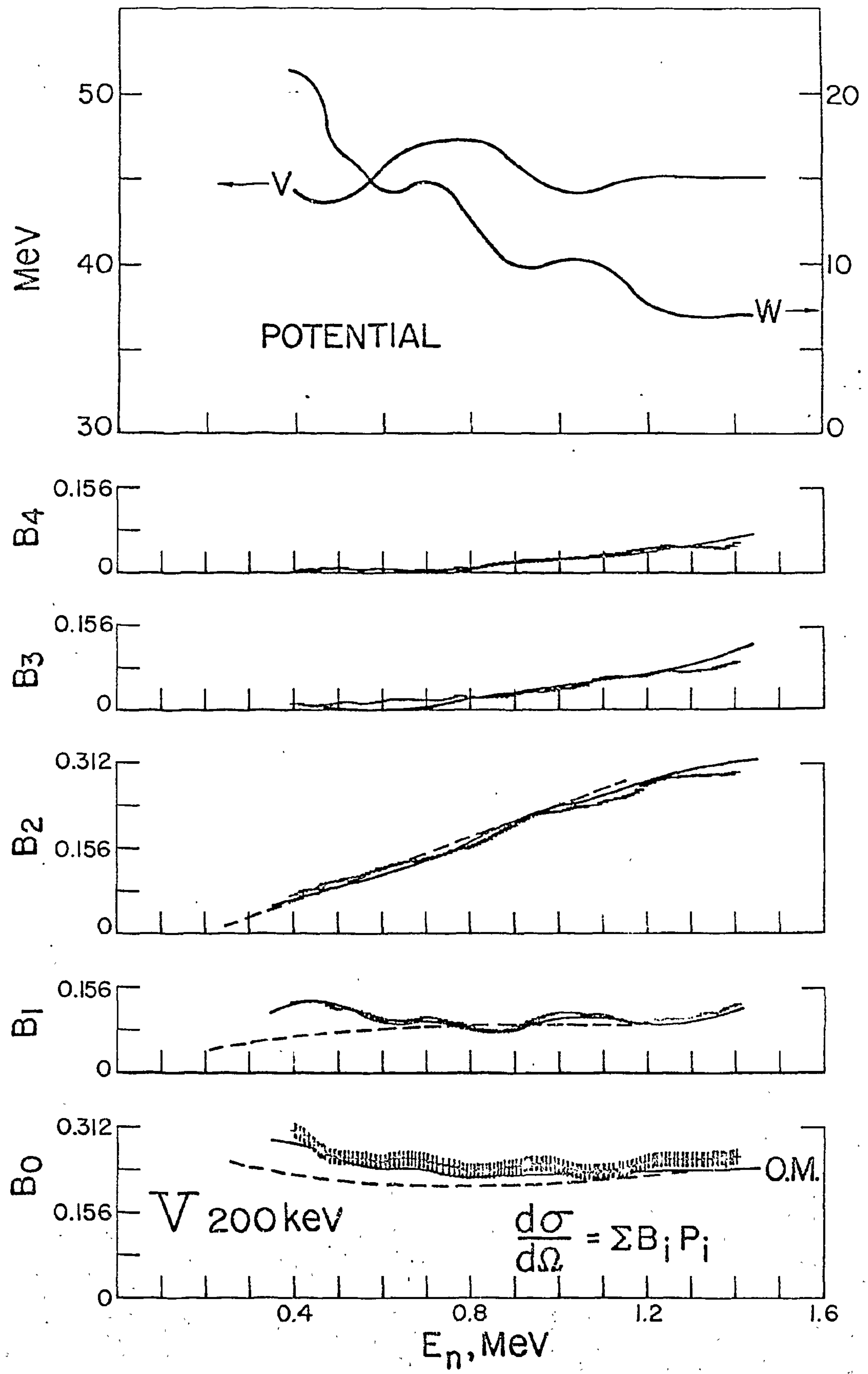

CURVES ENDF
0.60
0.45
0.30
0.15
0
σ_{in}, b
V
EXP
(-320)
(-1610)
(-930)
(-1810)
0
1.6
3.2
E_n, MEV

Fig. 7



MeV
POTENTIAL
V
W
50
40
30
20
10
0
B4
B3
B2
B1
B0
0.156
0.312
0
O.M.
V 200 kev
$\frac{d\sigma}{d\Omega} = \Sigma B_i P_i$
0.4
0.8
1.2
1.6
E_n, MeV

Fig. 8