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(ENDF-121)

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EVALUATED NEUTRON CROSS SECTIONS OF SODIUM-23 FOR THE ENDF/B FILE

T. A. Pitterle

United States Atomic Energy Commission
Contract No. AT(11-1)-865
Project Agreement No. 18

JUNE 1968

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Approved J.B. Nims

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Project Engineer
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SUMMARY

This report describes an evaluation of sodium-23 neutron cross section data carried out for the ENDF/B file. Data were evaluated from 10^{-4} ev to 15 Mev for the following neutron reactions: total, elastic scattering including Legendre polynomial expansions of the angular dependence, nonelastic, inelastic including resolved levels, (n, γ), (n, p), (n, α), and (n, 2n). Graphs of the evaluated data are compared with experimental data in the report.

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I. INTRODUCTION

In 1966, an evaluation of neutron cross sections for sodium was conducted for the ENDF/B data file, where sodium is Material Number 1059. This report describes that evaluation, which was carried out as part of a cooperative effort by the Cross Section Evaluation Working Group (CSEWG), coordinated through the National Neutron Data Center at Brookhaven National Laboratory under the sponsorship of the United States Atomic Energy Commission. References given in the CINDA index (EANDC-66U, July 1, 1966) were considered in this evaluation as well as a few references as late as October, 1966.

In this evaluation, the mass of sodium was taken as 22.991 amu for a neutron mass of 1.008986 amu. The recommended resonance parameters are discussed in Chapter II. Chapters III and IV describe the recommended smooth cross sections and elastic scattering angular expansions. Secondary energy distributions for inelastic scattering and (n, 2n) reactions are discussed in Chapter V and comparisons with other evaluations are considered in Chapter VI. In File 7 of ENDF/B, data are included for free gas thermal scattering law based on the BNL-325-recommended value of 3.13 for the free atom cross section.

Graphs comparing the evaluated and experimental data are included. The ENDF/B data file is available through the National Neutron Data Center at Brookhaven National Laboratory.

This report supersedes the preliminary document, APDA Technical Memorandum No. 42, describing this evaluation.

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II. RESONANCE PARAMETERS

Measurements of the resonance parameters for sodium considered in this analysis are given in Table I. Other measurements, such as the detailed parameters of Hibdon [1] or Stelson,[2] were not included in this evaluation.

A. 2.85 Kev RESONANCE

For the 2.85 kev resonance in Table I, the peak cross section σ_o is the largest value directly measured and not the theoretical height, and ΔE is the resolution quoted by the respective authors. The two most recent measurements of this resonance by Garg [3] and Moxon [4] are seen to disagree on the very important spin assignments; however, the resolutions in both experiments should be sufficient to distinguish between the theoretical peak heights of about 370 and 620 for J=1 and J=2, respectively. Hibdon's [1] assignment of J=2 was made by a linear extrapolation to expected results for a smaller neutron energy spread than obtained experimentally.

Stephenson [5] has calculated a good fit to the experimental data available prior to the measurements of Moxon and Garg for a J=1 spin assignment using the BNL-325-[6] recommended parameters (Γ_n=410 ev) and spin-dependent scattering radii. From measurements of the low energy coherent σ_c and total scattering cross sections σ_n, possible values for the nuclear scattering amplitudes, a_+ for J=2 and a_- for J=1, can be obtained from [5]

$$\begin{aligned} \sigma_n &= 4\pi\left(\frac{A+1}{A}\right)^2 (g_+ a_+^2 + g_- a_-^2) \\ \sigma_c &= 4\pi\left(\frac{A+1}{A}\right)^2 (g_+ a_+ - g_- a_-)^2 \end{aligned} \tag{1}$$

For σ_n = 3.4b and σ_c = 1.55 b,[7] solutions of these equations are $a_+ = \pm 6.21$f (f=fermi 10^{-13}cm), $a_- = \pm 1.38$f, and $a_+ = \pm 1.52$f, $a_- = \pm 8.11$f. The cross sections for each spin state in Equation 1 can be set equal to the corresponding Breit-Wigner expressions evaluated at E=0 to obtain

$$\begin{aligned} 4\pi g_r a_r^2 &= \frac{\pi ƛ_o^2 g_r \Gamma_n^2}{E_o^2 + \Gamma^2/4} - \frac{4\pi ƛ_o g_r R_r \Gamma_n E_o}{E_o^2 + \Gamma^2/4} + 4\pi g_r R_r^2 \\ 4\pi g_{nr} a_{nr}^2 &= 4\pi g_{nr} R_{nr}^2 \end{aligned} \tag{2}$$

TABLE I - EXPERIMENTAL RESONANCE PARAMETERS

E_R, kev	J	ℓ	Γ, ev	$g\Gamma$	Γ_γ, ev	σ_o, barns	ΔE, ev	Other	Ref
2.80	1	0	420	158		380 ± 10	200		8
2.85 ± .04	1	0	405 ± 12	152 ± 5		370 ± 5	150		9
2.95	2	0	220	138		390 ± 25	300		1
2.851	2	0	380 ± 20	238 ± 13		600 ± 60	2		3
2.86 ± .015	1	0	424 ± 13	159 ± 5	0.6	350 ± 25	11		4
2.85					0.6				10
7.6									10
35.5									10
36								$2\pi^2 \bar{\lambda}^2_o g\Gamma_n\Gamma_\gamma/\Gamma$ = 21.0 ev b	12
35.39								$2\pi^2 \bar{\lambda}^2_o g\Gamma_n$ = 60 ev b	13
54.1	3	1	750	656					1
53.3	1	1	1700	638			160		3
54 ± 1	2	1	1200	750 ± 40			900		4
53.4									10
54.0								$2\pi^2 \bar{\lambda}^2_o \dfrac{g\Gamma_n\Gamma_\gamma}{\Gamma}$ = 21 ev b	12
117.8									10
117.6								$2\pi^2 \bar{\lambda}^2_o g\,\Gamma_n$ = 170 ev b	13

where the subscripts r and nr indicate the resonant and nonresonant spin states, respectively. For $\Gamma_n/E_o << 1$, there results

$$a_r \simeq R_r - \frac{\lambda\!\!\!^{-}_o \Gamma_n}{2E_o}$$

For J=1 and Γ_n=410 ev, R(J=1) = 5.02 and R(J=2) = 6.21 represent a solution. Stephenson[5] adjusts these values to R(J=1) = 5.18f and R(J=2) = 5.85f to obtain an improved fit to the experimental data. For J=2 and Γ_n=380 ev, R(J=2) = 6.46f or 5.42f and R(J=1) = 8.11f represent solutions for the radii.

For J=2 and Γ=380 ev, the value of gΓ is inconsistent with the other measurements for this resonance, suggesting the possibility of a smaller width for this resonance. In Figure 1, a comparison is made of calculated total cross sections for a J=2 resonance with Γ_n=380 ev (R_+ = 8.11f, R_- = 5.42f) and Γ_n = 285 ev (R_+ = 8.11f, R_- = 3.93f). Figure 2 compares calculated values for J=1, Γ_n =410 ev (R_+ = 5.85f, R_- = 5.18f)[5] with experimental data. The radii used for the J=2 calculations are based on Equation 2.

Good fits to the experimental data may be possible with assumptions of negative resonances and spin-independent radii; however, negative resonances have not been examined in this evaluation.

For a J=2 spin assignment, the choice of $\Gamma \approx$285 ev yields a better fit to the experimental data than Γ=380 ev. The measurements of Garg[3] plotted in Figures 1 and 2 represent a selection from independent measurements over the same energy range. Other measurements differ by about 25%, although only one measurement over the 2.85 kev resonance is reported. Based on the uncertainties in the current measurements of the Columbia Group,[3] these measurements were not included in the final choice of the evaluated data.

Based on the data of Good,[8] Lynn,[9] and Moxon,[4] a width of Γ_n = 410 ev and a J=1 spin assignment were selected for this evaluation.

Moxon[4] and Block[10] (Ref. 10 assumes J=1, Γ_n=410 ev) have obtained estimates of the capture width for the 2.85 kev resonance. From measurements of the capture yield, both authors have obtained a radiation width of 0.6 ev. They find, however, that the measured capture yield peaks below the resonance peak with a broad low energy tail extending to about 1 kev. An experimental or theoretical explanation for the asymmetry of the capture yield is not presently known. Use of the 0.6 ev radiation width in the single level resonance formulae yields a 0.0253 ev capture cross section and resonance integral considerably larger than present measurements. Scattering resonance integrals (numerical integration of calculated cross section) and capture integrals calculated as

$$I_\gamma = \frac{2\pi^2 \lambda\!\!\!^{-}{}_o^2\, g\Gamma_n \Gamma_\gamma}{E_o \Gamma}$$

are given in Table II.

TABLE II - CALCULATED AND EXPERIMENTAL RESONANCE INTEGRALS, barns

Parameters	Scattering	Absorption (Non 1/v)
E_o = 2.85, J=1, Γ_n =410, Γ_γ =0.336 R(J=1) = 5.18f, R(J=2) = 5.85f	72	0.069
E_o = 2.85, J=2, Γ_n =380, Γ_γ =0.219 R(J=2) = 5.425f, R(J=1) = 8.11f	108	0.075
E_o = 2.85, J=2, Γ_n =285, Γ_γ =0.293 R(J=2) = 3.93f, R(J=1) = 8.11f	86	0.100
E_o = 2.85, J=1, Γ_n =410, Γ_γ =0.60 R(J=1) = 5.18f, R(J=2) = 5.85f	72	0.123
E_o = 35.4, J=3, Γ_n =0.55, Γ_γ =0.3		0.00060
E_o = 53.5, J=2, Γ_n =1200, Γ_γ =0.4		0.00039
Experiment	68 (Ref. 53, 5)	0.075 ± 0.01 (Ref. 54) 0.070 ± 0.01 (Ref. 55)

As noted by Lynn,[9] one can assume that the entire 0.0253 ev capture cross section (0.534 barns, Ref. 6) is due to the 2.85 kev resonance to estimate the radiation width. This procedure, which should represent an upper limit if the single level formula is adequate, yields a value of 0.336 ev for the recommended parameters. Use of this radiation width gives a resonance integral in good agreement with experiment (see Table II). The resonance integral for the recommended parameters as obtained by numerical integration of the calculated capture cross section from 0.5 ev to 40 kev is 0.313 barns including the 1/v contribution and 0.074 barns for the non-1/v integral.

Until further analysis of the measurements of Moxon and Block can be made, a radiation width of 0.336 is recommended and has been used in this analysis. (Note: Since this evaluation was completed, a measurement[11] has been reported yielding a radiation width of 0.34 ev for a J=1 spin assignment and a capture yield consistent with expectations for a single level.)

Included in Table II are resonance integrals for the data of Garg.[3] For this data, the radiation widths were obtained by fitting the 0.0253 ev capture cross section of 0.534 barns and the spin-dependent radii were obtained following the procedures of Stephenson.[5]

B. 35.4 AND 53.5 Kev RESONANCES

For the 35 kev resonance, only integral measurements (LeRigoleur[12] and Ribon[13]) have been reported. Assuming that the angular momentum ℓ is greater than 0 and that the statistical factor g is 7/8, one can obtain the parameters given in Table III. These assumptions have been made in this study to permit an approximate description of the resonance while retaining the integral measurements of References 12 and 13.

TABLE III - RECOMMENDED RESONANCE PARAMETERS

E_o, kev	J	ℓ	Γ_n, ev	Γ_γ, ev	Other
2.85	1	0	410.0	0.336	R(J=1) = 5.18f, R(J=2) = 5.85f
35.4	3	>0	0.55	0.30	
53.5	2	1	1200.0	0.40	

Three measurements for the 54 kev resonance have yielded three different spin assignments. For this analysis, the parameters of Moxon[4] were selected. The capture integral of LeRigoleur[12] was used with the Moxon parameters to obtain an estimate for the radiation width of 0.4 ev.

C. USE OF THE RECOMMENDED PARAMETERS

The recommended parameters are given in Table III. Present ENDF/B format restrictions do not permit use of spin-dependent radii. For the ENDF/B parameters, a radius of 5.278f was chosen to give a potential scattering cross section of 3.5 barns.

These parameters, included in File 2 of the ENDF/B data, are to be used to calculate only the resonance absorption cross section which is additive to the smooth background cross section in File 3 of ENDF/B. The total scattering cross section is included in File 3 as calculated from the recommended parameters using the spin-dependent radii.

The absorption cross sections as calculated from the recommended parameters and the background cross section of File 3 are given in Figures 1 and 3.

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III. SMOOTH CROSS SECTIONS

In this chapter, the smooth cross sections included in Files 3 and 5 of the ENDF/B file are described. These include the total, elastic scattering, inelastic scattering, nonelastic, (n,γ), (n, p), (n,α), and (n, 2n) cross sections.

A. TOTAL CROSS SECTION

The general criteria used in the selection of the recommended total cross section from the experimental data was to select the measurements with the best energy resolution when the accuracy of the measurements is comparable. However, at high energies (i.e., above about 3 Mev for sodium) elastic scattering does not dominate the total cross section and the preference for the best resolution measurements was not always followed. Since the energy resolutions currently available for the nonelastic cross section measurements are considerably less than for the total cross section, nonrealistic oscillations may be obtained for the scattering cross section (difference between total and nonelastic cross sections) when relatively large nonelastic cross sections are subtracted from high-resolution total cross sections. For this reason, the best resolution measurements were not always selected for this evaluation above a few Mev.

From 10^{-3} to 1.5 ev, the total cross section is based principally on the data of Joki [14] and is in agreement with the evaluations of Schmidt [15] and Moorhead.[16] Between 15 and 400 ev, the cross section was smoothly interpolated through the data of Hodgson [17] to agree with the value calculated from the resonance parameters of Table III at 400 ev. In this energy range, the recommended value is 5% to 10% higher than the calculated value. From 400 ev to 30 kev, the cross section is calculated from the 2.85 kev parameters of Table III, using the spin-dependent radii of Stephenson.[5] Between 30 and 100 kev, total cross sections calculated from the resonance parameters of Table III for the 35.4 and 53.5 kev resonances were added to a smooth background cross section extrapolated from 30 kev to the 100 kev measurements of Whalen.[18] The recommended cross section from 1 to 100 kev is in agreement with the data of Lynn [9] from 1 to 12 kev and Merzbacker [19] and Hibdon [1] near 40 kev, as shown in Figure 2, where the recommended curve is compared with experimental data. From 1.5 ev to 65 kev, the total cross section given in File 3 of the ENDF/B data does not include the capture cross section to be computed from resonance parameters.

In the energy range between 0.10 and 0.65 Mev, Whalen [18] has measured the total cross with an energy resolution of better than 1 kev and an accuracy of about 1 to 3%. The measurements of Stelson and Preston [2] in this energy range have a resolution of 2.5 kev and similar accuracy. The measurements of Garg[3] do not indicate comparable accuracy and were not considered in this evaluation. Langsford[20] has reported good resolution measurements; however, the results are only given as a graph of the experimental data, and in this energy range the data cannot be obtained from the graph with an accuracy comparable to the measurements of Whalen. The recommended total cross section is based on the data of Whalen over the entire energy range of these measurements from 0.10 to 0.65 Mev. In Figures 4 and 5, the recommended curve is compared with the experimental data of Whalen[18] and Stelson.[2] In general, good agreement is found between these measurements.

The measurements of Whalen show considerable structure in the cross section although the resolution is not sufficient to clearly separate resonance structure from statistical fluctuations for the small oscillations in the data. The measurements do not appear to support the extremely high-level density indicated by the measurements reported by Hibdon,[1] although a more careful analysis of Whalen's measurements is necessary for a confident conclusion.

Figures 5 and 6 compare the experimental data and recommended total cross section between 0.45 and 2.2 Mev. From 0.65 to 1.0 Mev, the best measurements are those of Langsford[20] (resolution, $\Delta E < 2.5$ kev), Stelson[2] ($\Delta E \gtrsim 3$-5 kev), Vaughn[21] ($\Delta E \gtrsim 5$ kev), and Adair[22] ($\Delta E \gtrsim 20$ kev). The data of Langsford[20] used in this study were obtained from a smooth curve drawn through the data points given in the figure of his report and are representative values only. A consistent trend found in the Langsford data is a shift to lower energies in the energy scale by up to 20 kev, relative to other measurements in the overlapping energy ranges. For this evaluation, an upward adjustment of 10 kev has been applied to the data and is included in the data points plotted in the figures. Up to 1.0 Mev, the measurements are in general agreement except for differences in the energy scale. For this evaluation, the data of Langsford was selected between 0.65 and 1.0, based principally on its better resolution although the data of Stelson and Vaughn may be considered equally reliable.

Between 1.0 and 2.6 Mev, measurements include Langsford[20] ($\Delta E \gtrsim 2.5$ - 9 kev), Vaughn[21] ($\Delta E \gtrsim 5$ kev up to 1.7 Mev), Deconninck[23] ($\Delta E \gtrsim 3.5$ Mev up to 2.0 Mev), Towle and Gilboy[24] ($\Delta E \approx 15$ kev), Meier[25] ($\Delta E \approx 30$ kev), and Leroy[26] ($\Delta E \gtrsim 40$-60 kev). These measurements are shown in Figures 6 and 7. Although the data of Langsford, Vaughn, and Deconninck are of comparable resolution and accuracy, differences of up to about 20% are found between the measurements. Langsford's measurements have better resolution than those of Vaughn over the energy range of Vaughn's data. A smooth curve through Langsford's data was taken as the recommended curve between 1.0 and 2.6 Mev. The choice of the Langsford data over that of Deconninck was arbitrarily made on the basis of probable greater accuracy and to permit continuity in the recommended data from 0.65 to 2.6 Mev.

Above 2.6 Mev, the choice of a smooth curve through the data points given in the graph of Langsford becomes increasingly difficult due to the scatter of the data and the small scale of the graph. For this reason principally, Langsford's data were not used above 2.6 Mev.

Measurements between 2.6 and 15 Mev have been reported by Calvi[27] ($\Delta E \approx 10$ kev) up to 5 Mev, Glasgow and Foster[28] ($\Delta E \approx 30$ to 200 kev), Leroy[26] ($\Delta E \approx 50$ to 500 kev), and Fabiani[29] ($\Delta E \approx 1.5$ kev from 5.4 to 7.5 Mev and then increasing to 15 kev at 8.5 Mev) between 5.4 and 8.5 Mev. These data are graphed in Figures 7 and 8. Between 2.6 and 5.0 Mev, the recommended curve follows the data of Calvi. Although Calvi's measurements have the best resolution of the measurements in this energy range, the data show less structure than the data of Langsford.[20]

Above 5 Mev, the recommended data follows Glasgow and Foster[28] to 15 Mev. The choice of the measurements of Glasgow over those of Fabiani[29] beteen 5.4 and 8.5 Mev was arbitrarily made to avoid the possibility of introducing unrealistic structure in the scattering cross by subtraction of the poor resolution and relatively large nonelastic cross section from the data of Fabiani.

B. (n, v) CROSS SECTION

The BNL-325[6] recommended cross section of 0.534 barns at 0.0253 ev has been used in this evaluation. A 1/v behavior was assumed from 10^{-3} to 1.5 ev.

From 1.5 ev to 65 kev, the capture cross section is to be calculated from the recommended resonance parameters. Above 4.5 kev, a smooth background cross section based on the measurements of LeRigoleur[12] has been included in File 3 of the ENDF/B data and should be added to the values calculated from the resonance parameters. LeRigoleur's results have been renormalized to the Li^{10} $(n, \alpha)T$ values of BNL-325[6] for this evaluation. The cross section calculated from resonance parameters as well as the smooth background cross section is given in Figures 3 and 9.

Above 0.1 Mev, the measurements of Bame and Cubitt[30] were joined with the data of LeRigoleur. From 1 to 15 Mev, Menlove's[31] data were used for the recommended cross section. Figure 9 shows the cross section from 0.1 to 15 Mev.

C. INELASTIC SCATTERING CROSS SECTION

The lowest level for inelastic scattering is at 0.439 Mev followed by a level at 2.078 Mev. In this evaluation, five additional resolved levels have been included at 2.393, 2.641, 2.705, 2.983, and 3.680 Mev. Up to 4 Mev, the total inelastic cross section is based principally on measured values for the known levels.

The best measurements for inelastic scattering from the 0.439 Mev level have been obtained by Chien and Smith[32] up to 1.5 Mev, Towle and Gilboy[33] from 0.5 to 2.0 Mev, Lind and Day[34] to 3.5 Mev, and Shipley[35] to 4.0 Mev. Chien and Smith[32] used time of flight techniques to perform differential, direct measurements of the inelastically scattered neutrons with a resolution of 10 kev. Towle and Gilboy performed direct measurements at energies of 0.98, 1.50, and 2.515 Mev and obtained an excitation curve between 0.5 and 2.0 Mev with a resolution of 20 kev (normalized to the direct measurement at 1.50 Mev) by measurement of the 0.44 Mev γ-ray. Angular distributions are reported by Chien[32] at 1.0, 1.2, and 1.4 Mev and by Towle at 1.0, 1.5 and 2.515. The distributions show moderate but possibly significant deviations from symmetry about 90°, particularly in the 1.4 Mev measurement of Chien.

The experimental data for the 0.439 Mev level are shown in Figure 11. Considering resolution differences for the strong resonance structure, the measurements of Chien and Towle are in satisfactory agreement except between 1.3 and 1.5 Mev. Except for the lower value shown for Towle at 0.98 Mev, the measurements of Towle below 1.5 Mev are relative to his value at 1.5 Mev, while Chien's values are absolute measurements at each energy. If Towle's 1.5 Mev measurement were given a 10% to 15% reduction to obtain agreement with Chien's data at 1.5 Mev, the relative agreement between these two measurements, allowing for resolution differences below 1.3 Mev, would not be seriously altered and would be improved above 1.3 Mev. Other measurements for this level do not appear to be sufficiently accurate to resolve this discrepancy. Based principally on the sensitivity of Towle's measurements to the 1.5 Mev uncertainty, the data of Chien and Smith were selected for this evaluation up to 1.5 Mev.

The data of Towle and Gilboy were used from above 1.5 Mev to 2 Mev, Lind and Day[34] to 3.5 Mev, and Shipley[35] to 4.0 Mev. Lind measured the 0.44 Mev γ-ray cross section which includes contributions from higher levels above 2.1 Mev. The cross section for the 0.439 Mev level was obtained by subtracting Lind's measured cross section for production of a 1.61 Mev gamma (from excitation of the 2.078 Mev level) from his measured value for the 0.44 Mev gamma. The evaluated cross section is shown in Figure 11.

For the 2.078 Mev level, the data of Freeman[36] were used to 2.95 Mev and the Lind[34] data to 3.5 Mev with extrapolation through the point of Towle[33] at 3.97 Mev. In this case, the Lind data were taken as the sum of the measured values for production of the 1.61 and 2.05 Mev gamma rays or by assuming that the 1.61 Mev gamma accounts for 90%[34] of the total cross section for the 2.078 Mev level.

The Freeman[36] data were used for the 2.393 level up to 3 Mev with the Lind[34] data to 3.5 Mev with extrapolation through the Towle[33] point at 3.97 Mev. For this level, the decay scheme of Freeman which indicates 75% decay directly to the ground state was used to extract the total level excitation from the 2.37 Mev gamma production cross section of Lind.[32]

For the 2.641 and 2.983 level excitations, the data of Lind[34] were used for the evaluated cross section. Estimates of the cross sections for the 2.705 and 3.68 Mev levels were taken from Schmidt.[15] The resolved level cross sections are shown in Figures 11, 12, and 13.

From 4 to 10 Mev, the evaluation of Schmidt[15] was used for the total inelastic cross section. This cross section is based on a smooth interpolation from the 4 Mev values to an evaporation theory estimate of Williamson[37] above 8 Mev, which yields a maximum cross section of 0.93 barns at 7.2 Mev.

Two measurements at 14 Mev have been made. Martin[38] measured a value of 0.463 ± 0.056 barns for the production of 0.44 Mev gamma rays. Sukhanov[39] measured the cross section for inelastically scattered neutrons with final energies from 0.6 to 4.0 Mev as 0.45 ± 0.1 barns. Each of these measurements probably include a large fraction of the total inelastic cross section at 14 Mev. In this evaluation, an arbitrary linear extrapolation from 0.8b.[15] at 10 Mev to 0.6b at 15 Mev was used. The total inelastic cross section from 2 to 15 Mev is given in Figure 14.

D. THRESHOLD REACTIONS

Threshold reactions included in this evaluation are given in Table IV along with averages of the recommended cross sections over a Watts fission spectrum.

Available experimental data for the (n, p) reaction are shown in Figure 15. The recommended cross section is based on the data of Williamson[37] from 4 to 5.75 and 9 to 10 Mev, Bass[40] between 5.75 and 9 Mev, and Picard[41] above 14 Mev.

Cross section data for the (n,α) reaction are given in Figure 16. The recommended cross section is based on Bass[40] from 6.75 to 9.0 Mev and Wolfer[42] above 12 Mev with a smooth extrapolation between these data.

The (n, 2n) cross section data are shown in Figure 17. Included in this figure are the measurements of Menlove[43] which became available since this evaluation. The data of Liskien and Paulson[44] were selected for this evaluation. However the measurements of Menlove now seem to confirm a lower value for the (n, 2n) cross section than selected for this evaluation.

TABLE IV - THRESHOLD REACTIONS AND FISSION SPECTRUM AVERAGES

Reaction	Q	Theoretical Threshold	Fission Spectrum Averages, mb Experiment	Calculated
$Na^{23}(n, p)Ne^{23}$	- 3.60	3.76	0.7 (45)	1.3
			1.0 (46)	
$Na^{23}(n, \alpha)F^{20}$	- 3.87	4.04	0.4 (45)	0.56
			0.47 (46)	
$Na^{23}(n, 2n)Na^{22}$	-12.41	12.96	0.006(45)	0.0035

E. NONELASTIC CROSS SECTION

The nonelastic cross section was computed as the sum of the separately evaluated (n,γ), inelastic, and threshold reaction cross sections. Below 0.44 Mev, it is equal to the (n,γ) cross section. From 0.44 to 4 Mev, the nonelastic cross section is approximately equal to the inelastic cross section as the capture cross section is less than one millibarn. Above 4 Mev, Figure 14, the threshold reactions contribute significantly to the nonelastic cross section.

F. SCATTERING CROSS SECTION

The elastic scattering cross section was obtained by subtracting the total nonelastic cross section, computed as a sum of its separately evaluated components, from the evaluated total cross section. The scattering cross section follows closely the structure of the total cross section particularly between 1 kev and about 2 Mev. Over the remainder of the energy range, the scattering cross section is shown in Figures 2, 7, 8, and 3.

IV. ELASTIC SCATTERING ANGULAR EXPANSIONS

Secondary angular distributions for elastic scattering were evaluated as Legendre polynomial expansions with the Legendre coefficients defined by

$$\frac{d\sigma(\mu, E)}{d\Omega} = \frac{\sigma_s(E)}{2\pi} \sum_{\ell=0}^{NL} \frac{2\ell+1}{2} f_\ell(E) P_\ell(\mu)$$

where $f_0(E) = 1$. In this evaluation, coefficients for NL=9 have been obtained in the center of mass coordinate system from 0.01 to 15 Mev. The CHAD code[47] was used to calculate the Legendre coefficients and the average cosine of the scattering angle $\bar{\mu}$ from the angular distributions. In most cases, the experimental data does not include values at 0° and 180° and the data were extrapolated to these angles before fitting the Legendre expansion. Similarly, when the experimental data were reported as Legendre coefficients, the angular distributions were reconstituted from the expansions, extrapolated smoothly to 0° and 180°, and the Legendre expansion was then recalculated.

Below 0.01 Mev, the angular distribution is isotropic in the center of mass system so that the f_ℓ are zero for ℓ greater than zero. From 0.03 to 0.3 Mev, the data of Lane and Monohan[48] were used. From 0.3 to 1.5 Mev, the measurements of Chien and Smith[32] have better resolution (10 kev compared to 25 kev) than the data of Lane[45] and has been corrected for multiple scattering, while the Lane data does not have this correction. As noted by Lane, the multiple scattering correction tends to increase the first two coefficients from about 0.02 (corresponding to similar errors in $\bar{\mu}$) near 30 kev to about 0.1 near 0.8 Mev. In this evaluation the data of Chien[32] were used from 0.3 to 1.5 Mev.

From 1.5 to 2.2 Mev, angular measurements have been made by Elwyn[49] with a resolution of about 100 kev but uncorrected for inelastic or multiple scattering. The data are reported as graphs of the first three Legendre coefficients. In this evaluation, the relative behavior of the Elwyn data was used to extrapolate the coefficients obtained from the Chien data up to 2.2 Mev. This procedure should yield a reasonable estimate of the energy dependence of $\bar{\mu}$ in this energy range.

Above 2.2 Mev, the measurements of Towle and Gilboy[33] at 2.52 and 3.97 Mev were used, along with the distributions calculated by Moorhead.[16] Legendre coefficients for this data were obtained from Dr. Edward Pennington at Argonne National Laboratory.

The experimental and evaluated data for $\bar{\mu}$ are given in Figure 18 and the first six Legendre coefficients are given in Figures 19 and 20.

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V. SECONDARY ENERGY DISTRIBUTIONS

A. INELASTIC SCATTERING

For the resolved level inelastic scattering, the ENDF/B distribution LF=3, which prescribes a discrete energy loss, is used. Present ENDF/B secondary energy distributions do not include a distribution which would permit approximate inclusion of the additional energy loss due to the recoil energy of the target nucleus. As noted by Moorhead,[16] the recoil energy leads to about an 8% lower final neutron energy for sodium scattering than obtained from the discrete energy loss alone.

For the unresolved or statistical inelastic scattering, 1966 ENDF/B format restrictions limit the distribution to a Maxwellian distribution with energy dependent nuclear temperature (LF=9) given by

$$p\,(E' \leftarrow E) = \frac{E'}{\theta^2}\, e^{-E'/\theta}$$

where θ is the nuclear temperature. This distribution is derived from evaporation theory which is based on the assumption of a large number of closely spaced nuclear levels. As sodium has a relatively low level density, the application of evaporation theory is of doubtful validity. For this reason, it is felt that the most appropriate definition of the nuclear temperature would be to approximate the average secondary energy ($2\,\theta$ for Maxwellian). Using the recommended resolved level data, the average value of E'/E at 4 Mev is estimated as 0.515. From the calculated cross sections of Moorhead[16] at 5 Mev, E'/E is obtained as 0.525. Based on these estimates of E'/E, the nuclear temperature for inelastic scattering was estimated at 1/4 the energy at 4 and 5 Mev and to increase approximately as $\sqrt{E}$ above 5 Mev.

B. (n, 2n) REACTION

For neutron energies just above the threshold energy for the (n, 2n) reactions, the maximum energy available for kinetic energy of the emitted neutrons is the excess energy above threshold. It is more likely that only about 0.9 of the excess energy is available for kinetic energy. To estimate the nuclear temperature for a Maxwellian distribution, it is assumed that both emitted neutrons have the same energy and that the average energy of the emitted particles is 0.8 of the maximum available energy. Then

$$\overline{E'} = \frac{0.8(E - E_{TH})}{2} = 2\,\theta$$

$$\theta = 0.2(E - E_{TH})$$

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VI. COMPARISONS WITH OTHER EVALUATIONS

A. PRIOR EVALUATIONS

Among prior evaluations of sodium cross sections are those of the ELMOE[50] code library, Moorhead,[16] and Schmidt.[15] The evaluation of Moorhead uses the Schmidt data extensively. Separate files are included in the ELMOE library tape (maximum energy of 3.68 Mev) labeled BNL-325 data and Hibdon-adjusted data, which differs from the BNL-325 data from 0.066 to 0.835 Mev. For the Hibdon data, a high level density of resonance structure is used, and it appears that even a broad energy average over the Hibdon structure would yield a larger cross section than obtained in the other evaluations. For the 2.85 kev resonance, the previous evaluations used the Hibdon data of Table I. Except for the resolved resonances, the presently evaluated scattering cross section is in qualitative agreement with that of Moorhead although differences in energy resolution are large and complicate comparison.

From 0.3 to 2.0 Mev, the average cosine of the scattering angle in the present evaluation is about 10-20% larger than that of Moorhead and Schmidt, which are based on the data of Reference 51. The sharp increase near 0.7 Mev is present in all evaluations.

The inelastic cross section is in good agreement with the previous evaluations except from 1.35 to 1.55 Mev, where the present data are 20% lower than that of Schmidt.[15] Above 10 Mev, Moorhead[16] assumed a constant value of 0.8 barns compared to the extrapolation to 0.6 barns at 15 Mev for the present evaluation.

For the capture cross section, the most important differences between this evaluation and that of Schmidt are due to differences in the 2.85 kev resonance parameters. This evaluation includes parameters from the 35.4 and 53.5 kev resonances while Schmidt gives a smooth extrapolation through these resonances at two to three times the smooth background of this study from 0.01 to 0.1 Mev.

B. 1966 EVALUATION OF SCHMIDT

In 1966, Schmidt[52] re-evaluated and updated his 1962 evaluation. This later evaluation was conducted concurrently with the present evaluation and was not available for consideration in the present study. Both evaluations are based on essentially the same experimental data except for a few later references used in the present evaluation. The principal differences between these evaluations are discussed below.

1. Resonance Parameters and the Capture Cross Section

Schmidt uses the parameters of Garg[3] for the 2.85 kev resonance with a radiation width of 0.220 obtained by fitting the thermal cross section. For the 54 kev resonance, Schmidt uses the parameters of Hibdon.[1] The measurements of Moxon,[4] which are heavily weighted in the present evaluation, were not published at the time of Schmidt's evaluation.

Schmidt's capture cross section from 4 to 200 kev is based on the smooth capture data of LeRigoleur[12] while the present evaluation uses the capture integrals from LeRigoleur's data combined with a renormalized cross section between resonances. Between resonances, the capture cross section of the present study, although small, is about 30% greater than Schmidt's evaluation. Above 0.2 Mev, the capture cross sections are similar.

2. Total Cross Section

Schmidt's total cross section above 0.1 Mev is based principally on the following references. Stelson and Preston,[2] 0.1 to 0.9 Mev; Vaughn,[21] 0.9 to 1.7 Mev; Deconninck,[23] 1.7 to 2.0 Mev; Langsford,[20] 2.0 to 4.0 Mev, Calvi,[27] 4.0 to 5.4 Mev; Fabiani,[29] 5.4 to 8.5 Mev; and Glasgow[28] above 8.5 Mev. Differences from this evaluation can be inferred from Figures 3 to 7. The data of Whalen[18] below 0.65 Mev were not available to Schmidt at the time of his evaluation.

3. Inelastic Scattering Cross Section

The inelastic scattering cross sections are in general agreement with the following exceptions: between 1.35 and 1.55 Mev, Schmidt uses the data of Towle[24] which is about 20% higher than the data of Chien and Smith[32] used in this evaluation; Schmidt's cross section for the 2.98 Mev level is based on the decay scheme of Endt and van der Leun[51] and is a factor of two greater than the present evaluation; and above 10 Mev, the inelastic cross section of Schmidt decreases to a value of 0.3 barns at 15 Mev based on the calculation of Williamson.[37]

4. Threshold Reactions

Schmidt's evaluation below 10 Mev for the (n, p) and (n,α) reactions is based on the data of Williamson (see Figures 15 and 16) and is generally lower than the present evaluation in this energy range. The detailed data of Bass[40] used in this evaluation was not published at the time of Schmidt's evaluation.

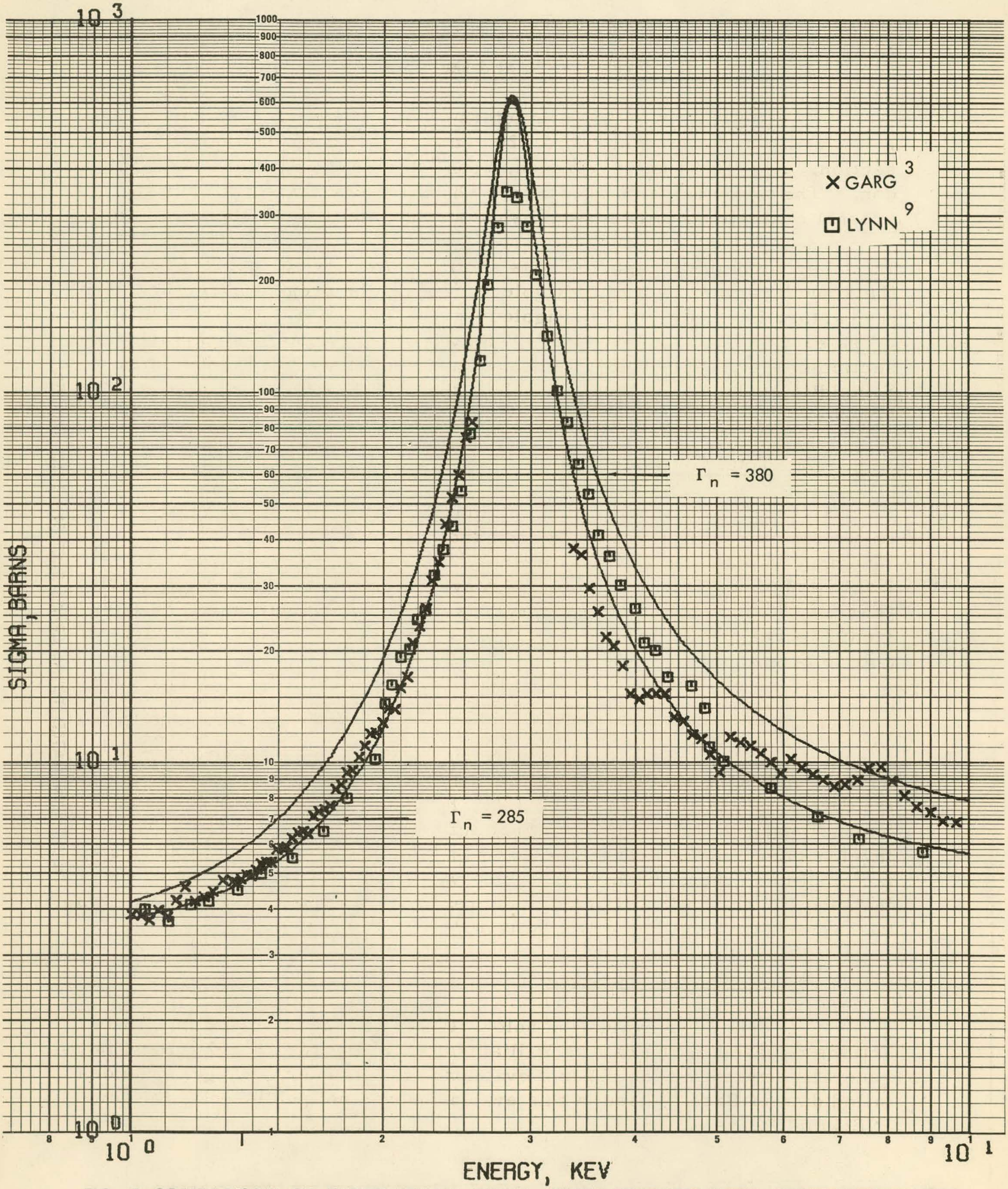

FIG. 1 COMPARISON OF EXPERIMENTAL TOTAL CROSS SECTIONS WITH CALCULATIONS FOR J=2, 2.85 KEV RESONANCE

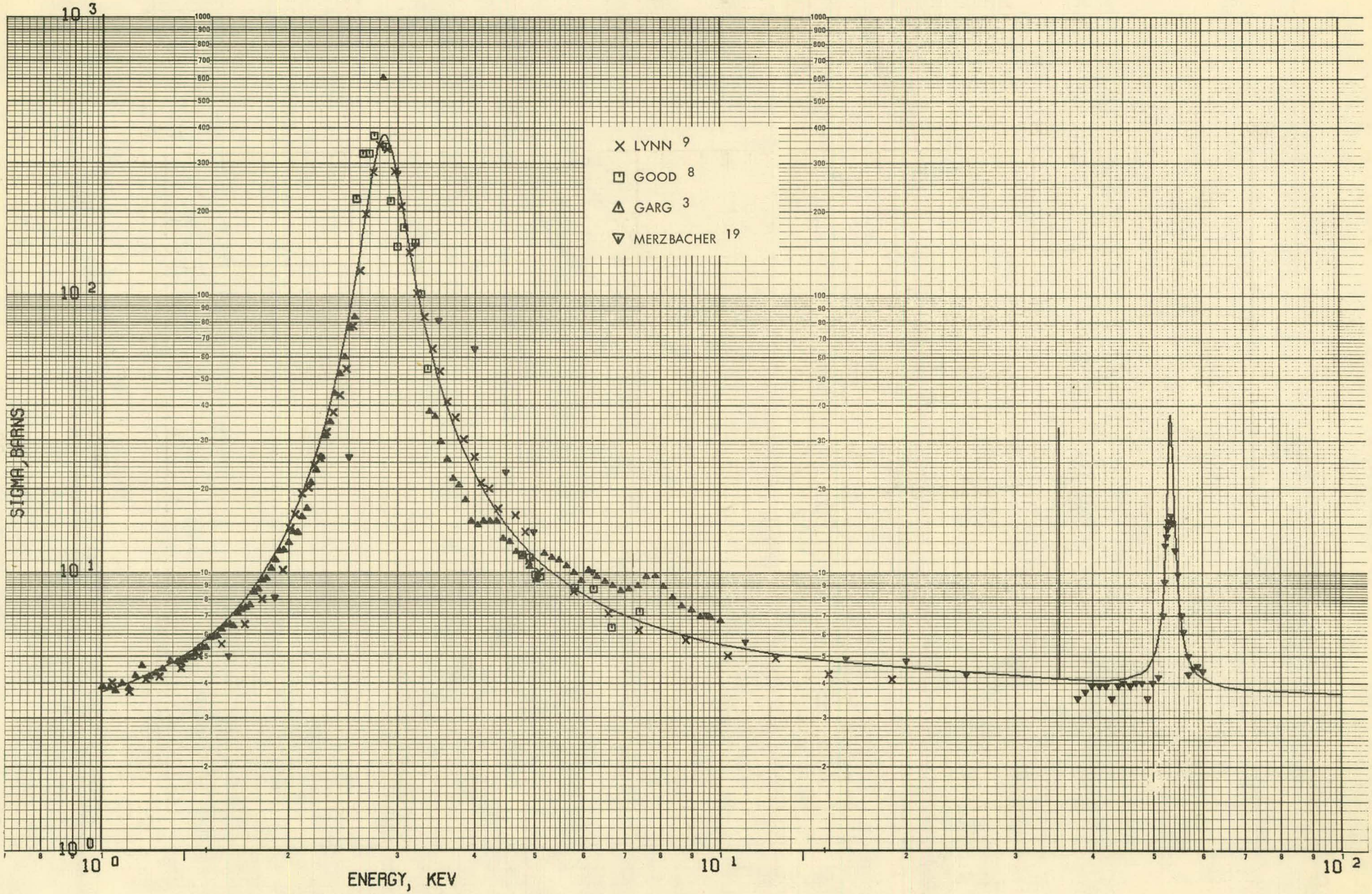

FIG. 2 EVALUATED TOTAL CROSS SECTION, 1 TO 100 KEV

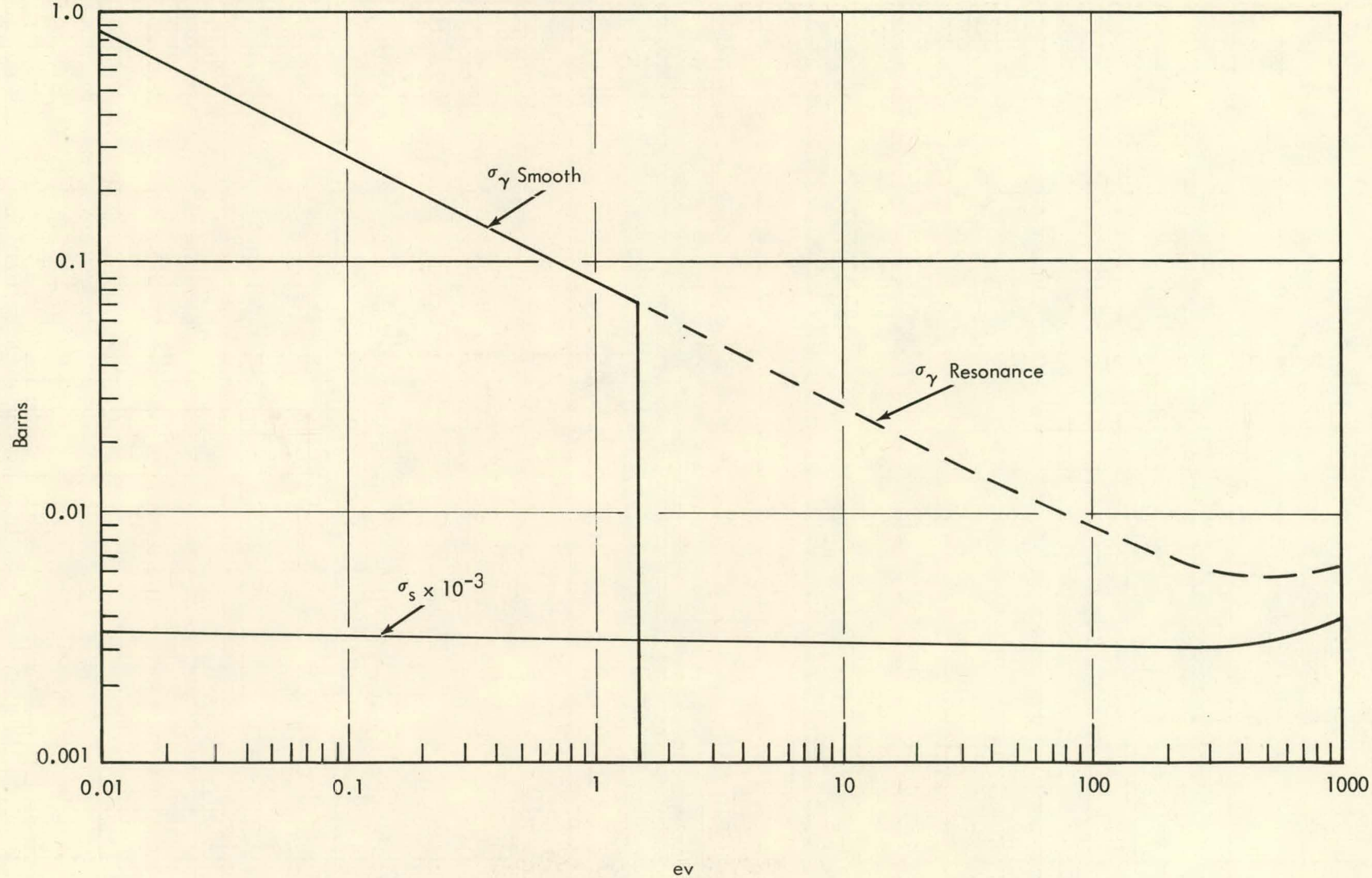

FIG. 3 SCATTERING AND CAPTURE CROSS SECTIONS, 0.01 TO 1000 EV

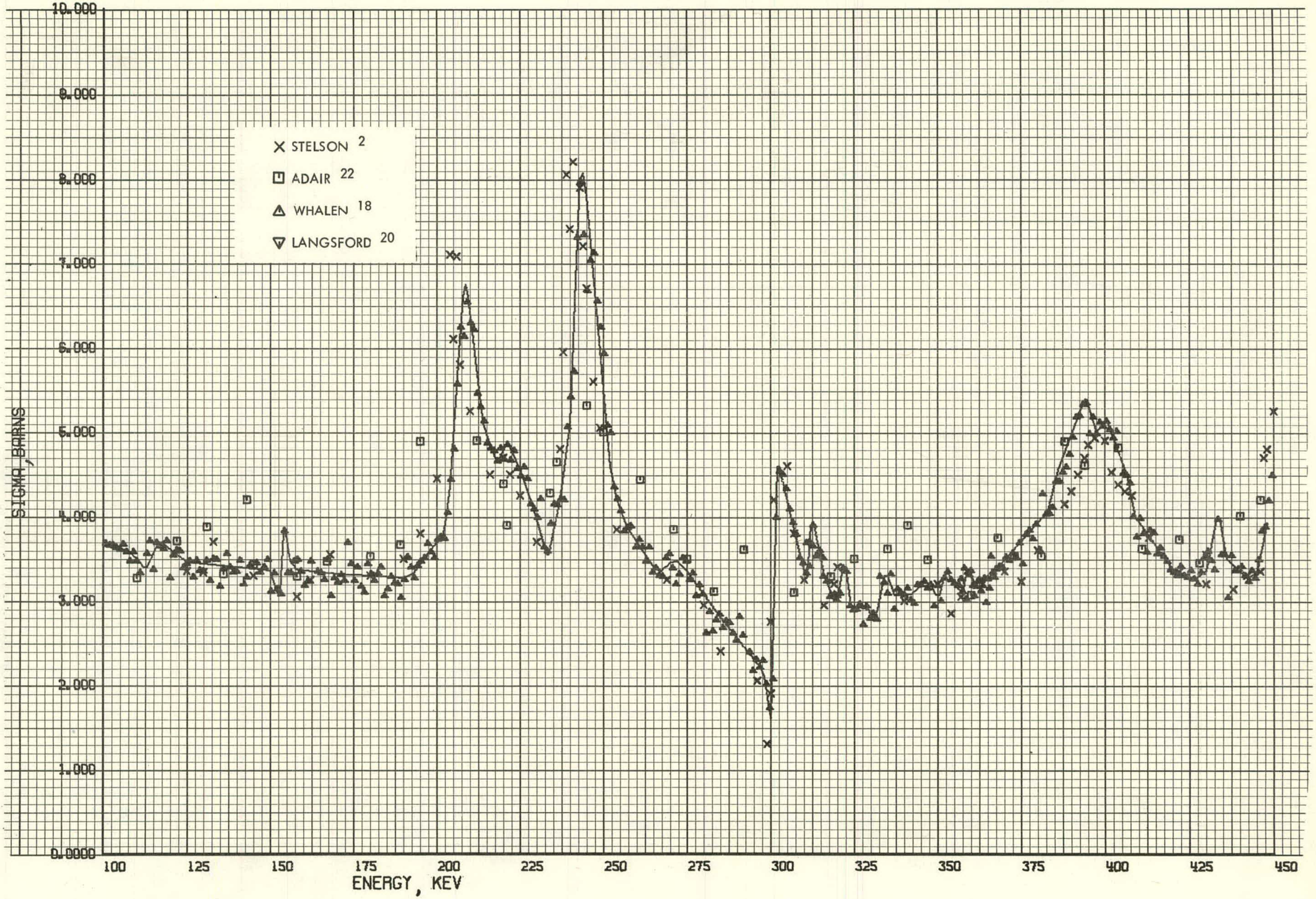

FIG. 4 TOTAL CROSS SECTION, 0.10 TO 0.45 MEV

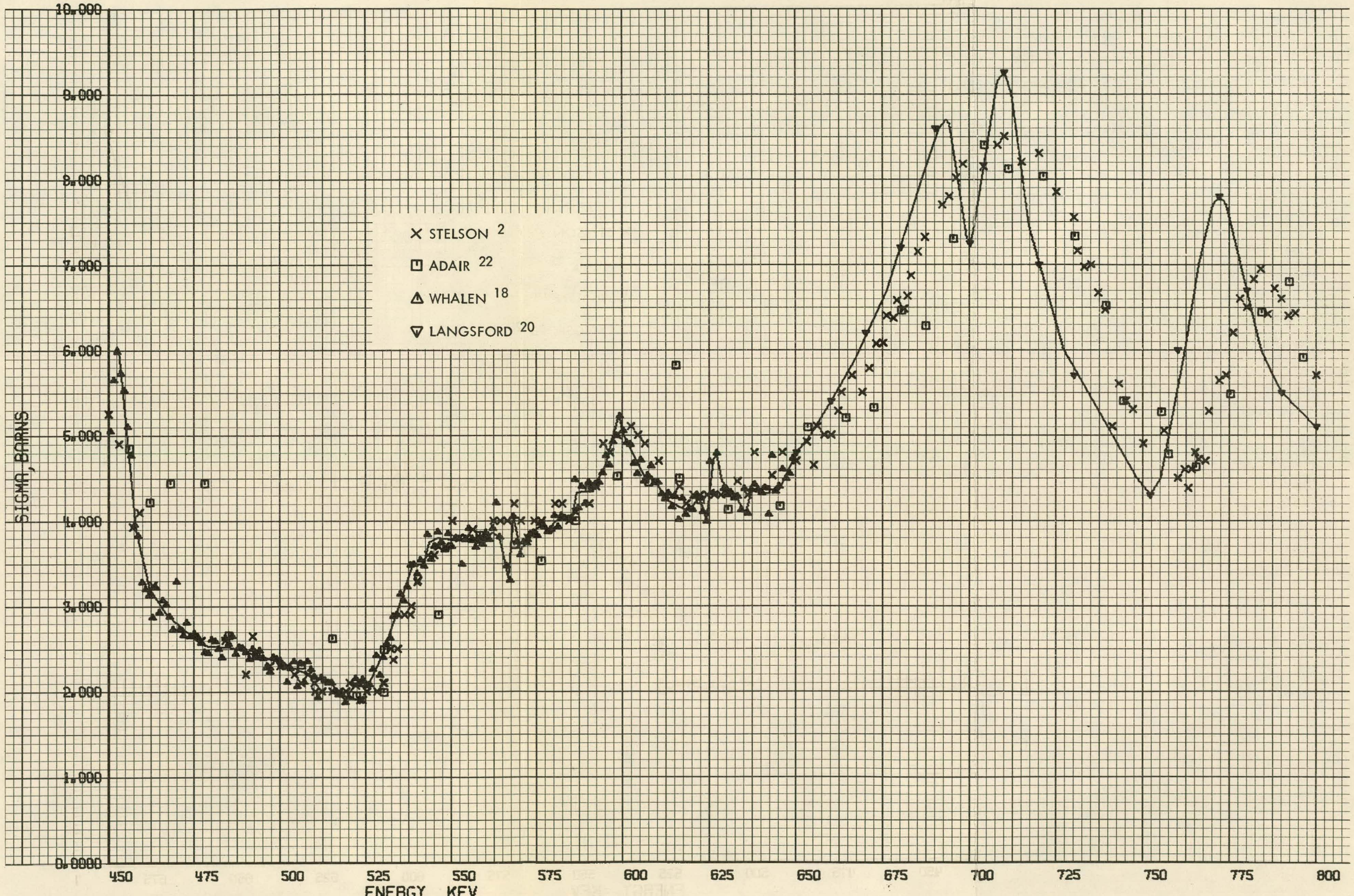

FIG. 5 TOTAL CROSS SECTION, 0.45 TO 0.80 MEV

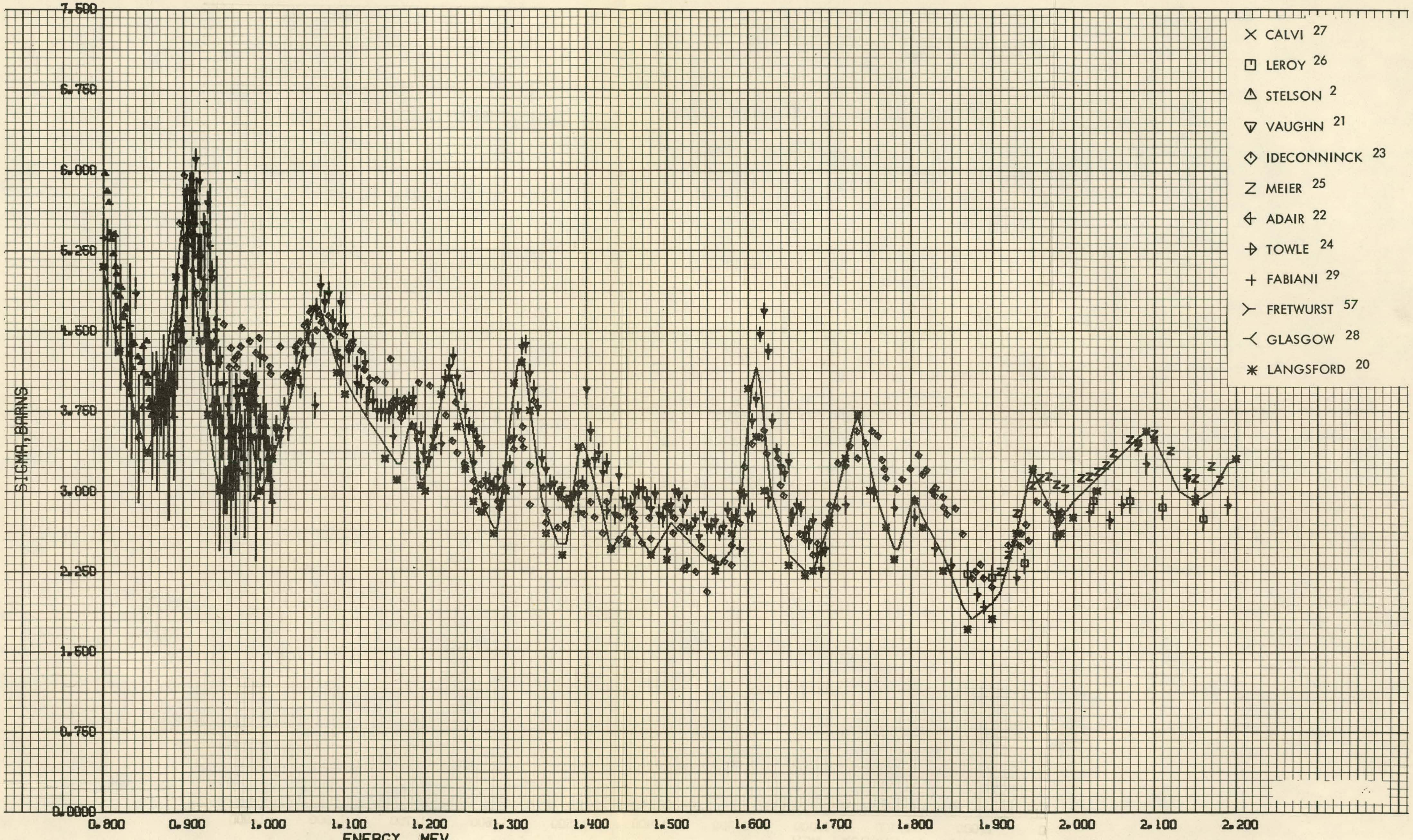

FIG. 6 TOTAL CROSS SECTION, 0.80 TO 2.20 MEV

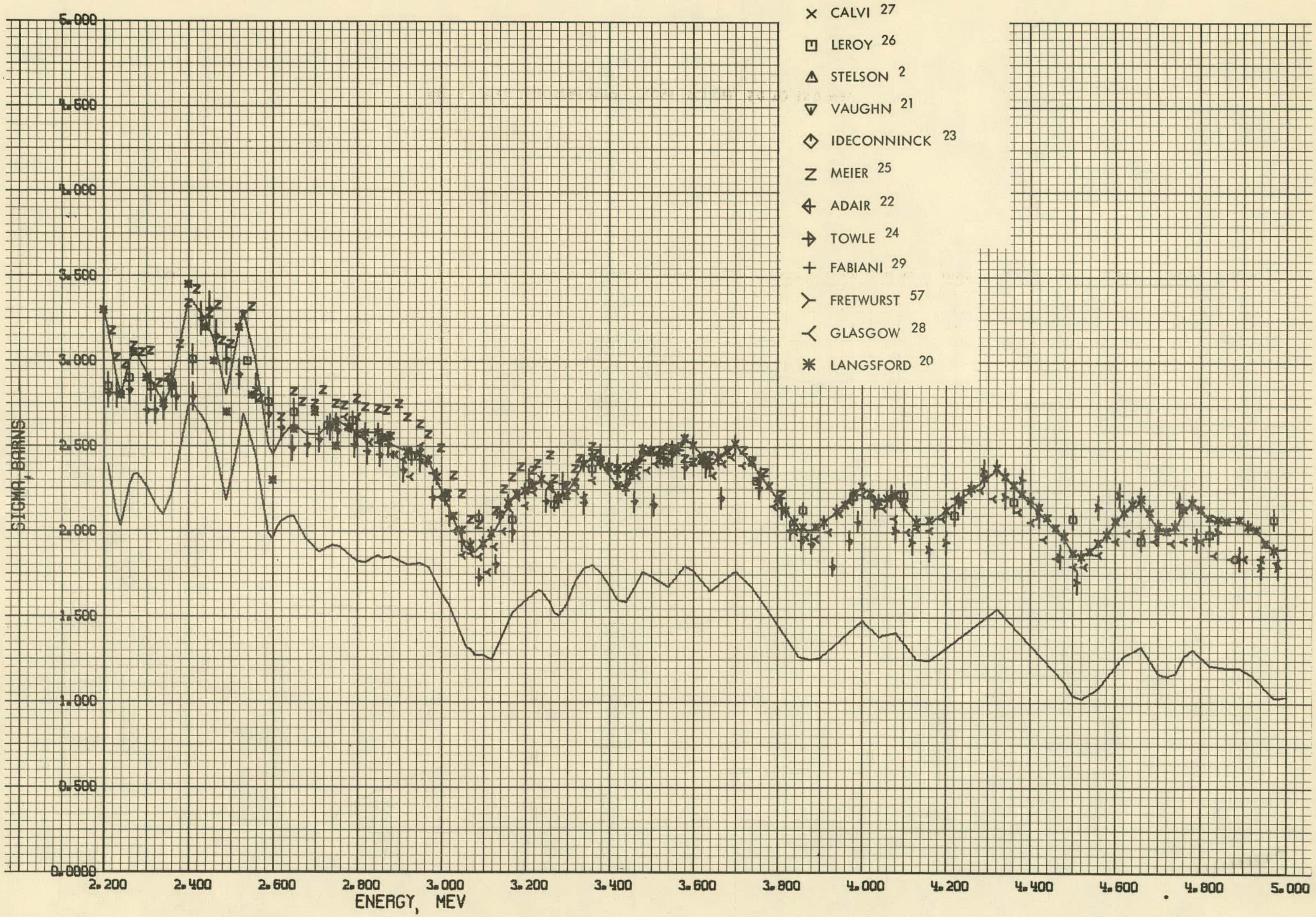

FIG. 7 TOTAL AND SCATTERING CROSS SECTION, 2.2 TO 5.0 MEV

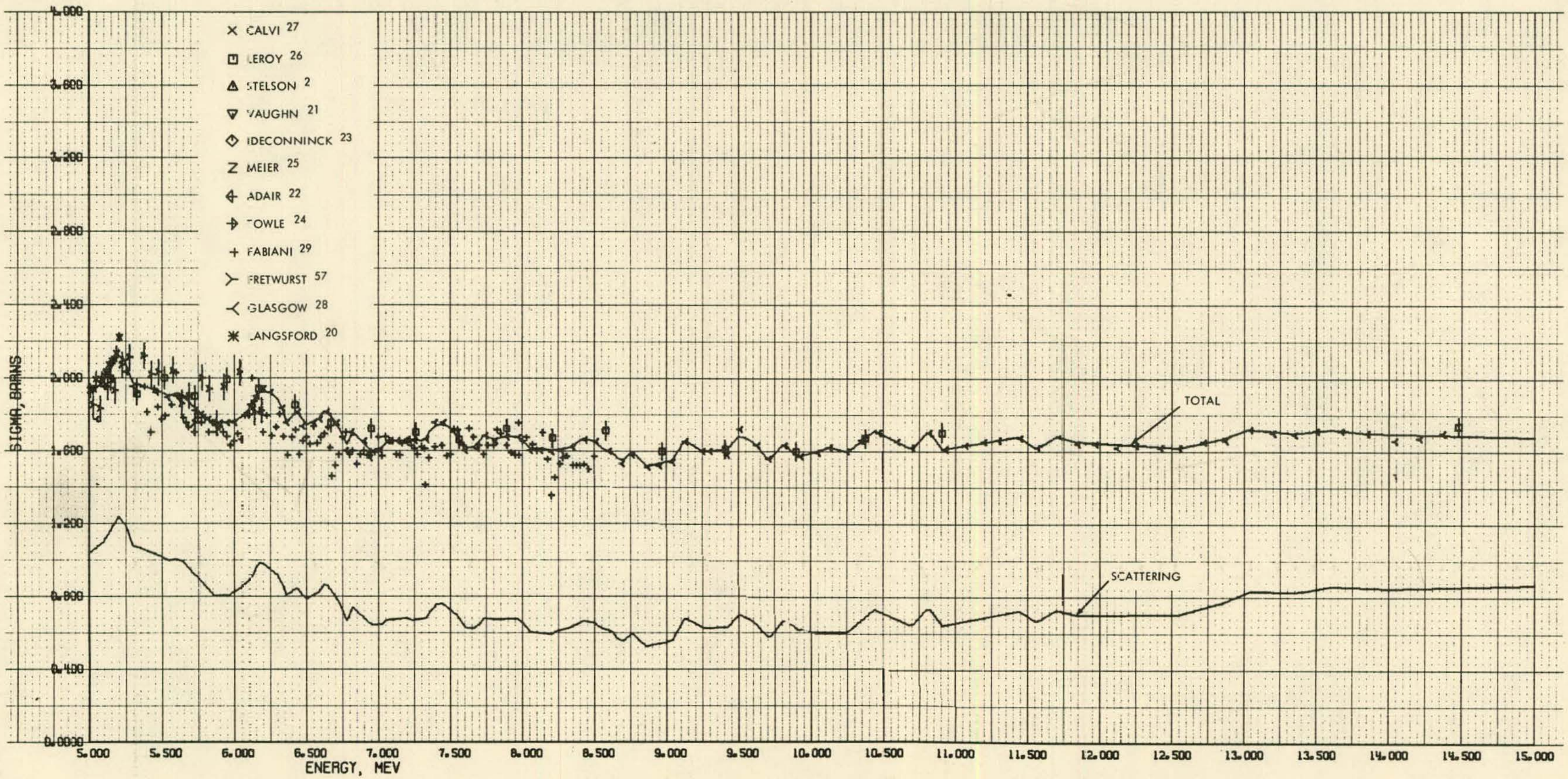

FIG. 8 TOTAL AND SCATTERING CROSS SECTION, 5.0 TO 15.0 MEV

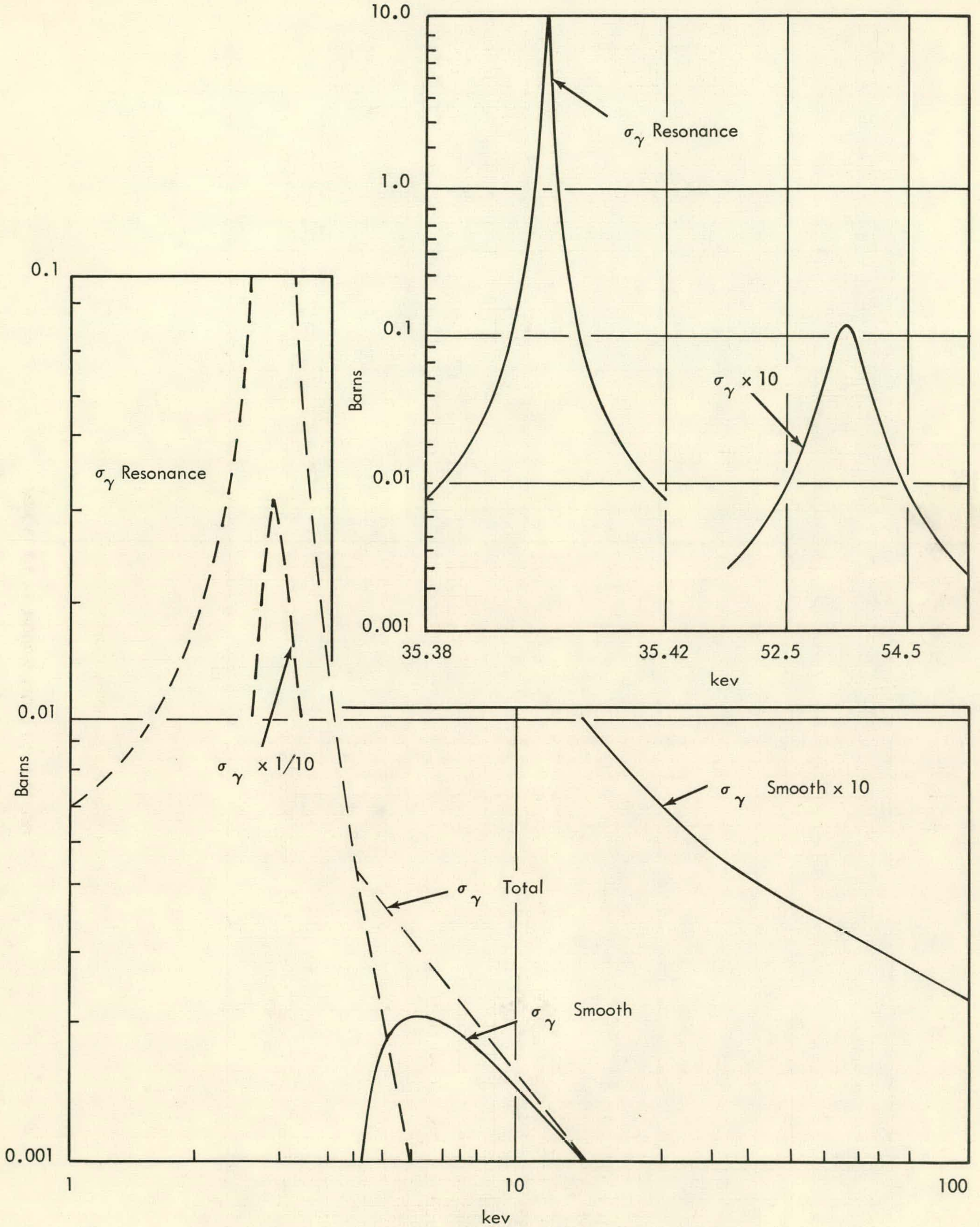

FIG. 9 (n, γ) CROSS SECTION, 1.0 TO 100.0 KEV

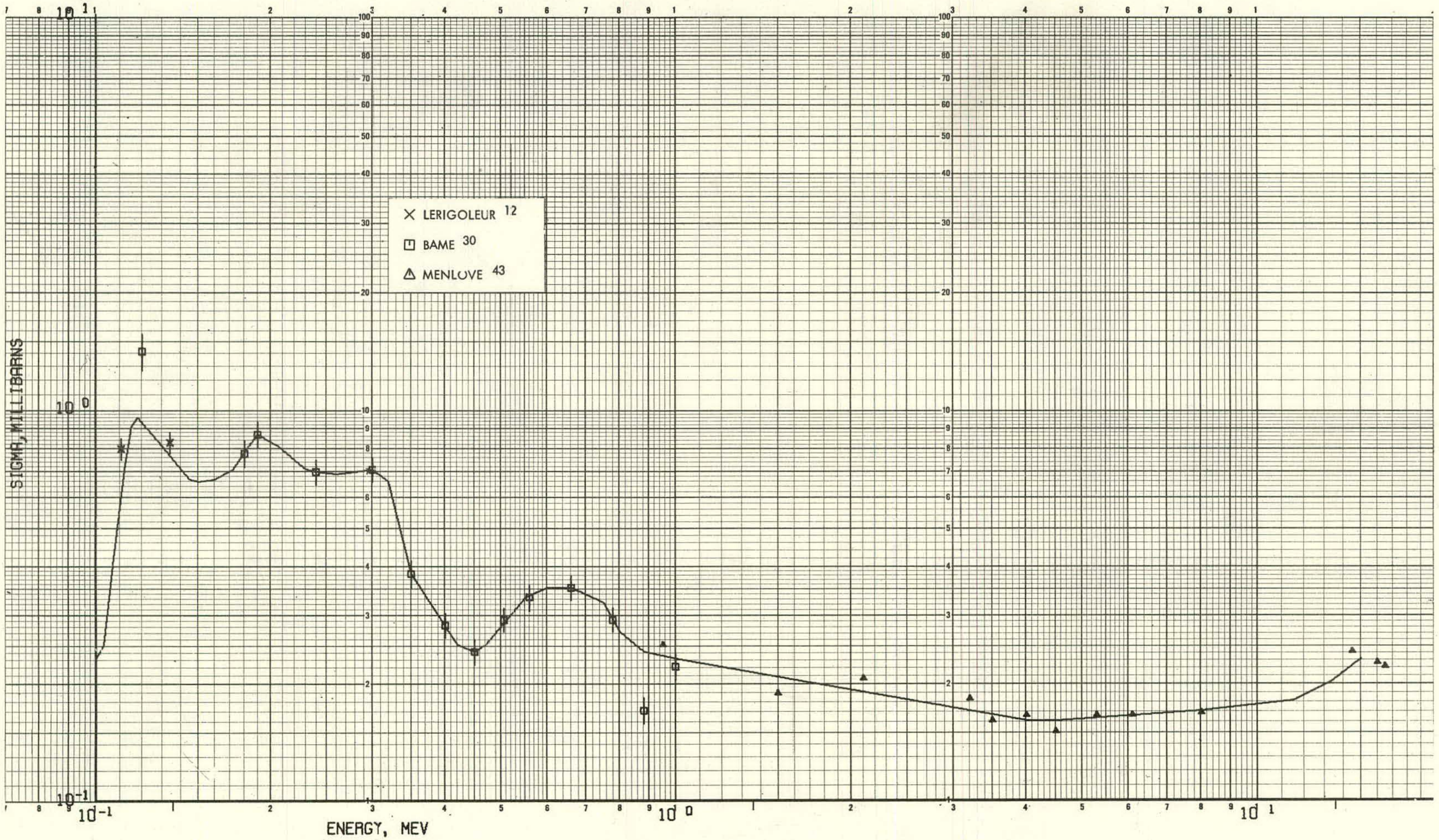

FIG. 10 (n, γ) CROSS SECTION, 1.0 TO 15 MEV

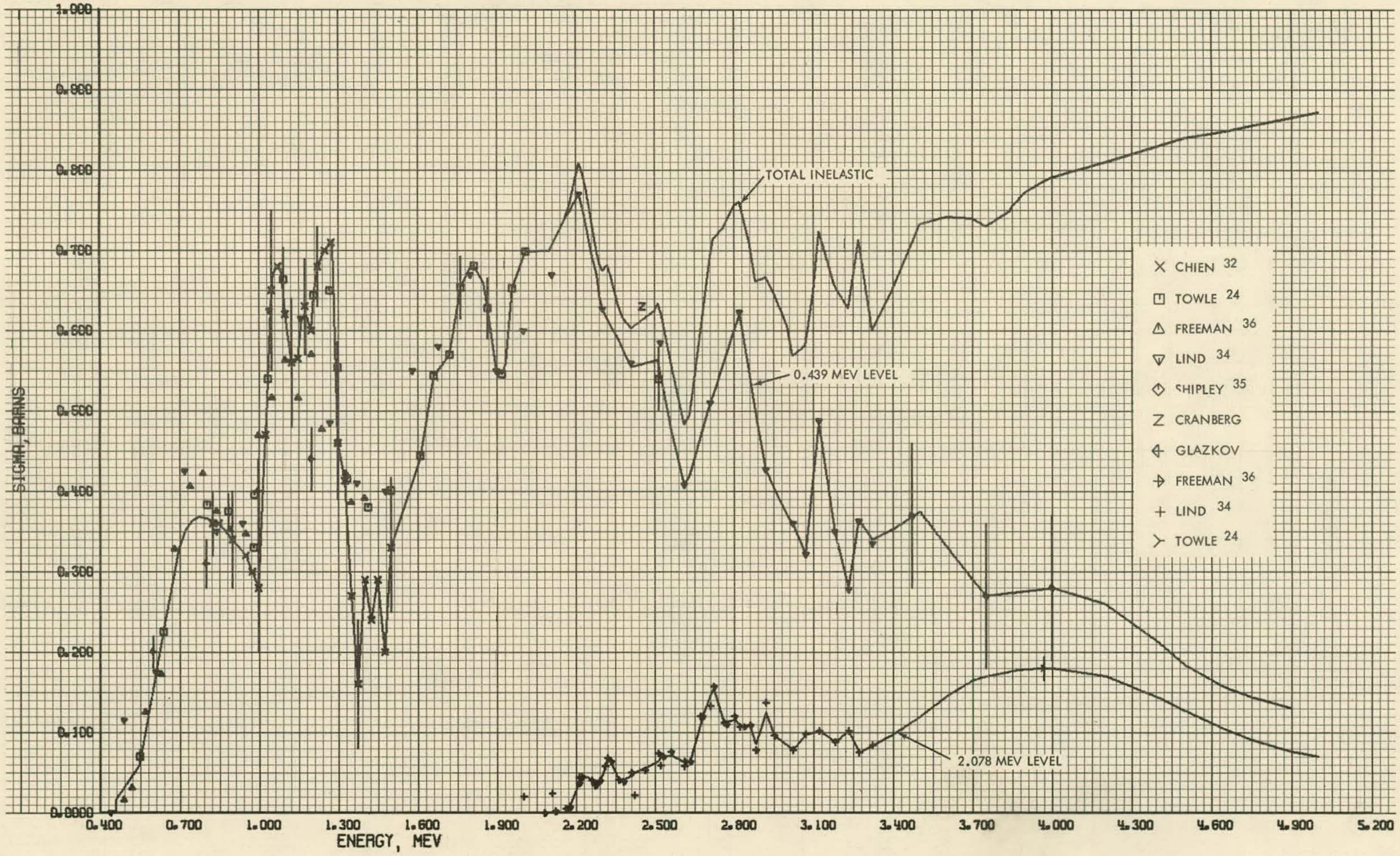

FIG. 11 INELASTIC SCATTERING CROSS SECTIONS, 0.439, 2.078 MEV LEVELS AND TOTAL INELASTIC

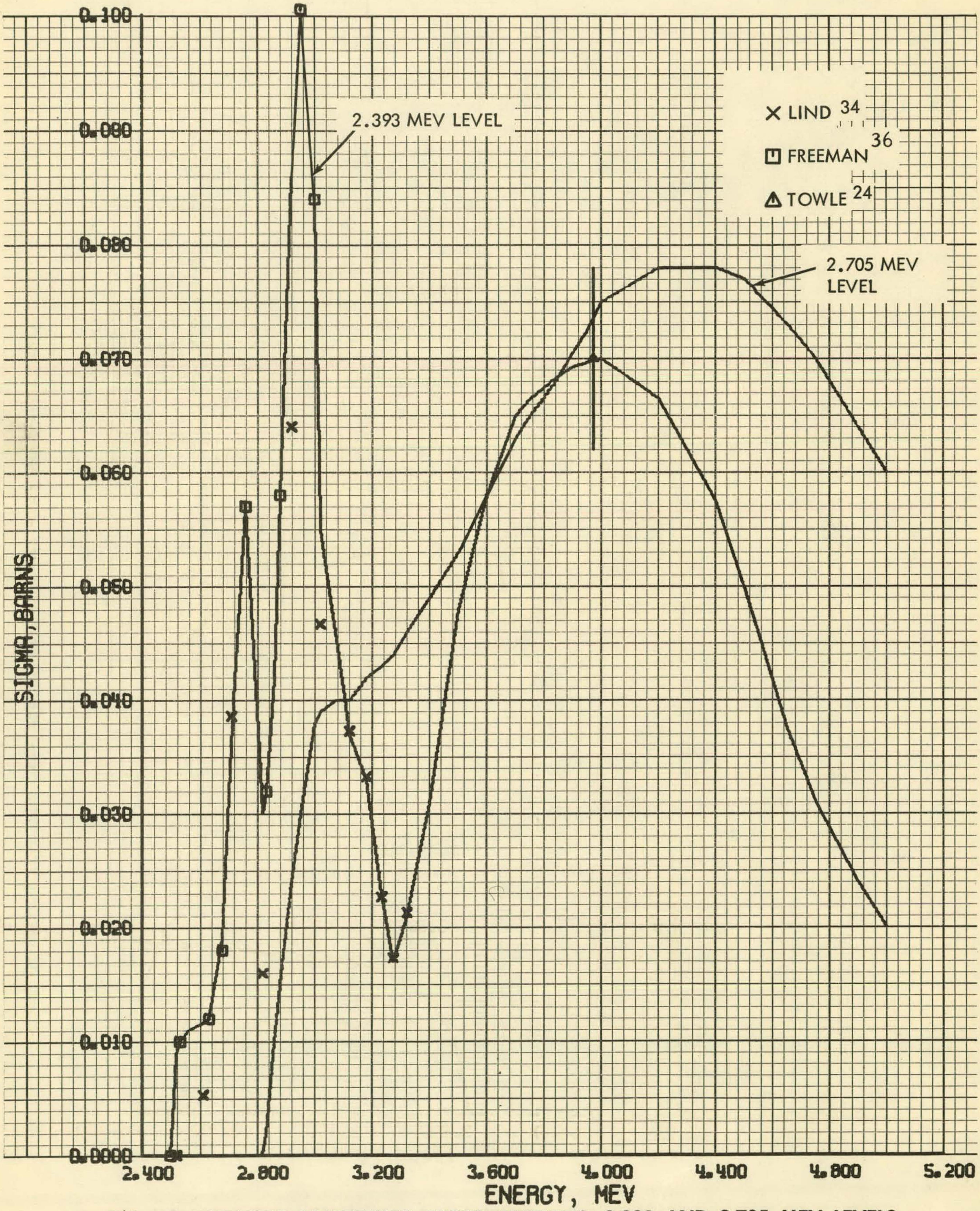

FIG. 12 INELASTIC SCATTERING CROSS SECTIONS, 2.393 AND 2.705 MEV LEVELS

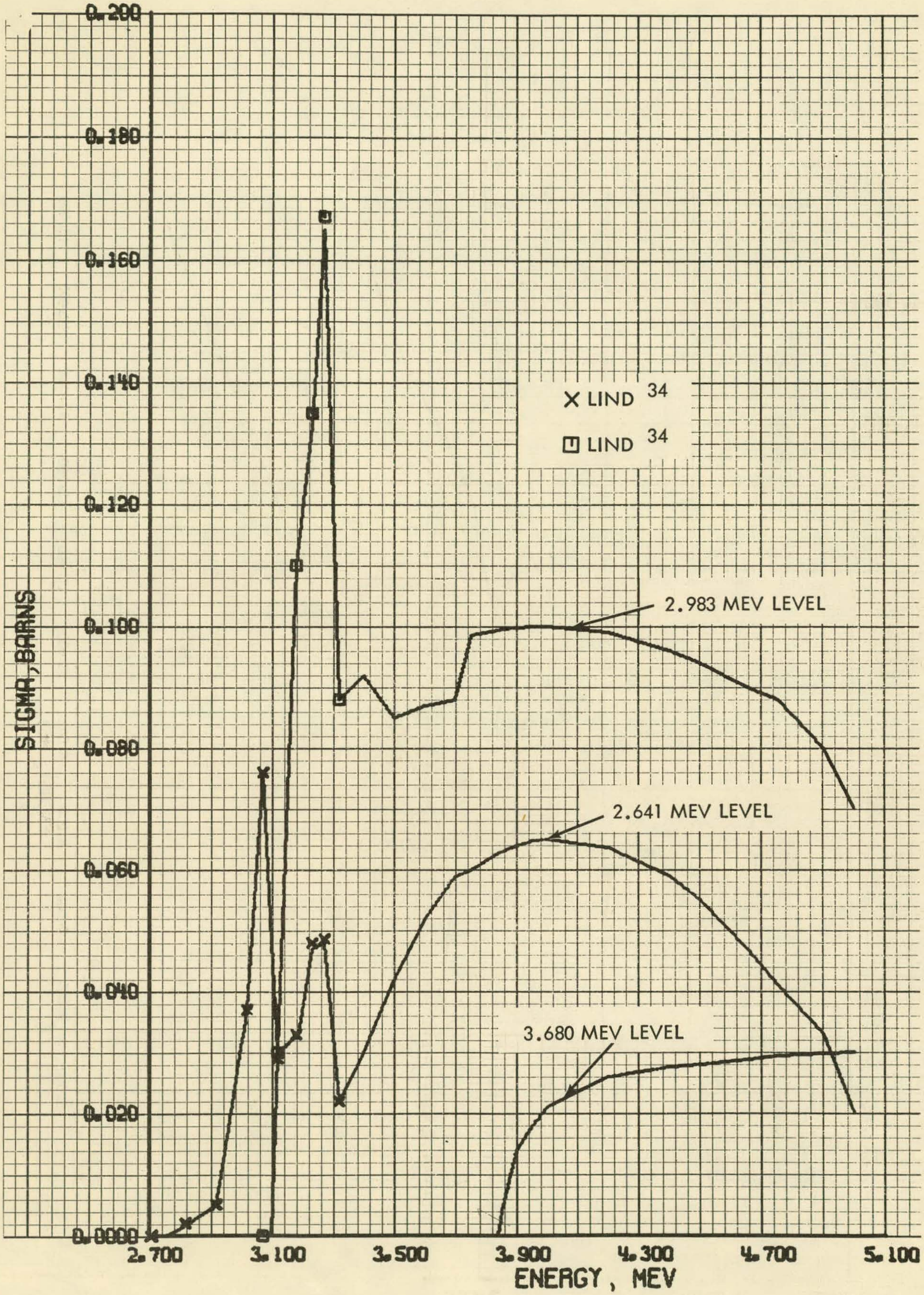

FIG. 13 INELASTIC SCATTERING CROSS SECTIONS, 2.641, 2.983, AND 3.680 MEV LEVELS

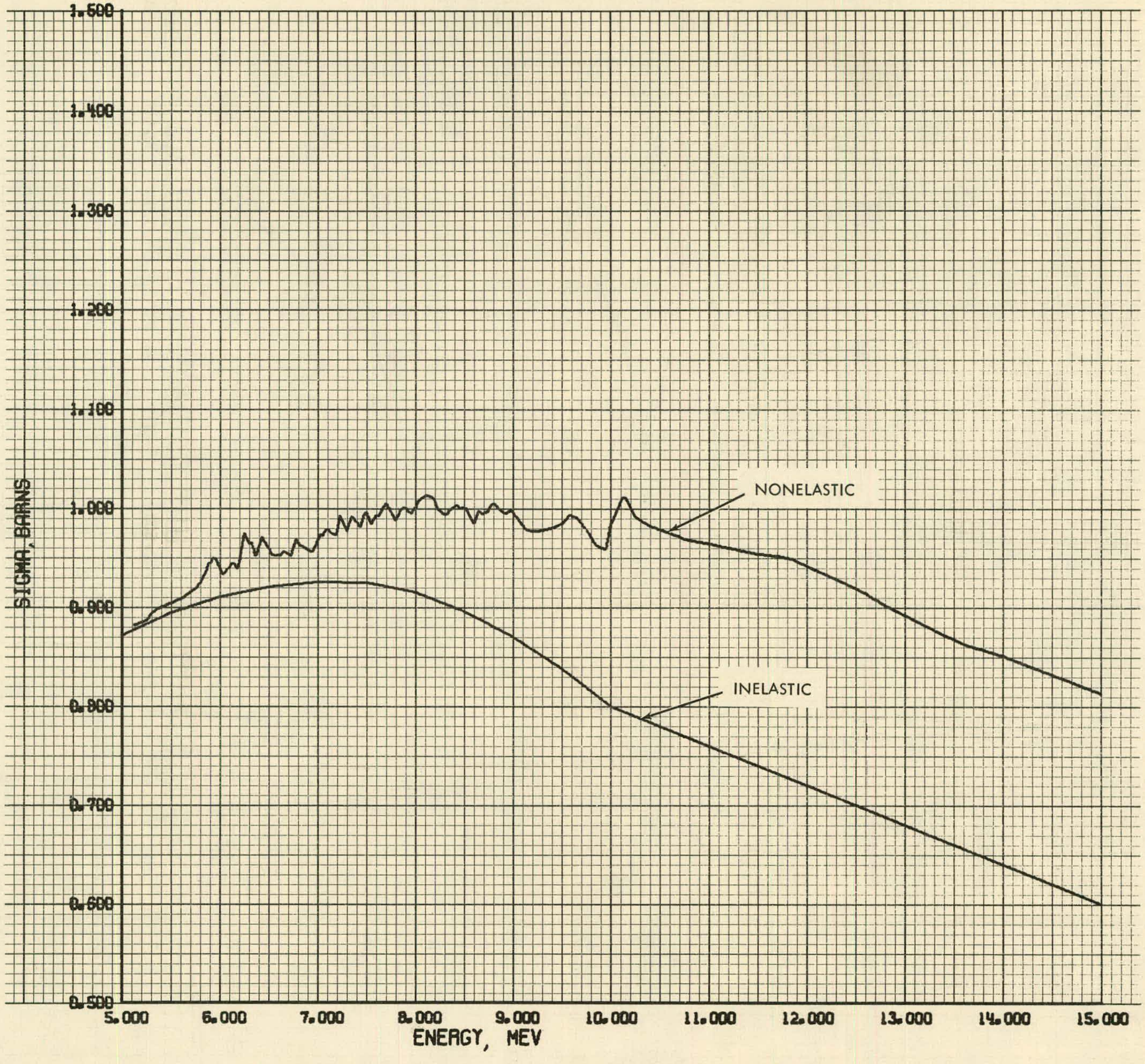

FIG. 14 TOTAL INELASTIC SCATTERING AND NONELASTIC CROSS SECTIONS, 5 TO 15 MEV

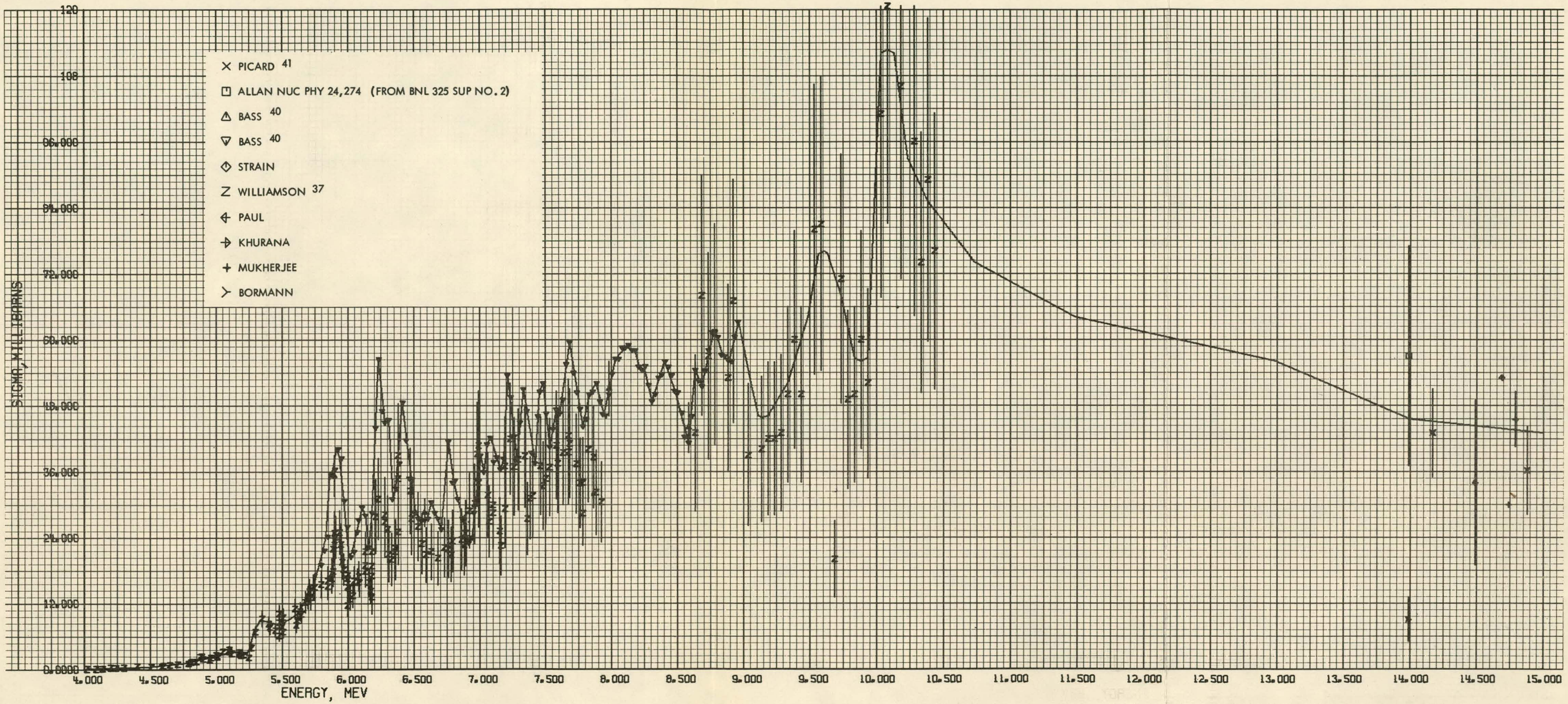

FIG. 15 (n, p) CROSS SECTION

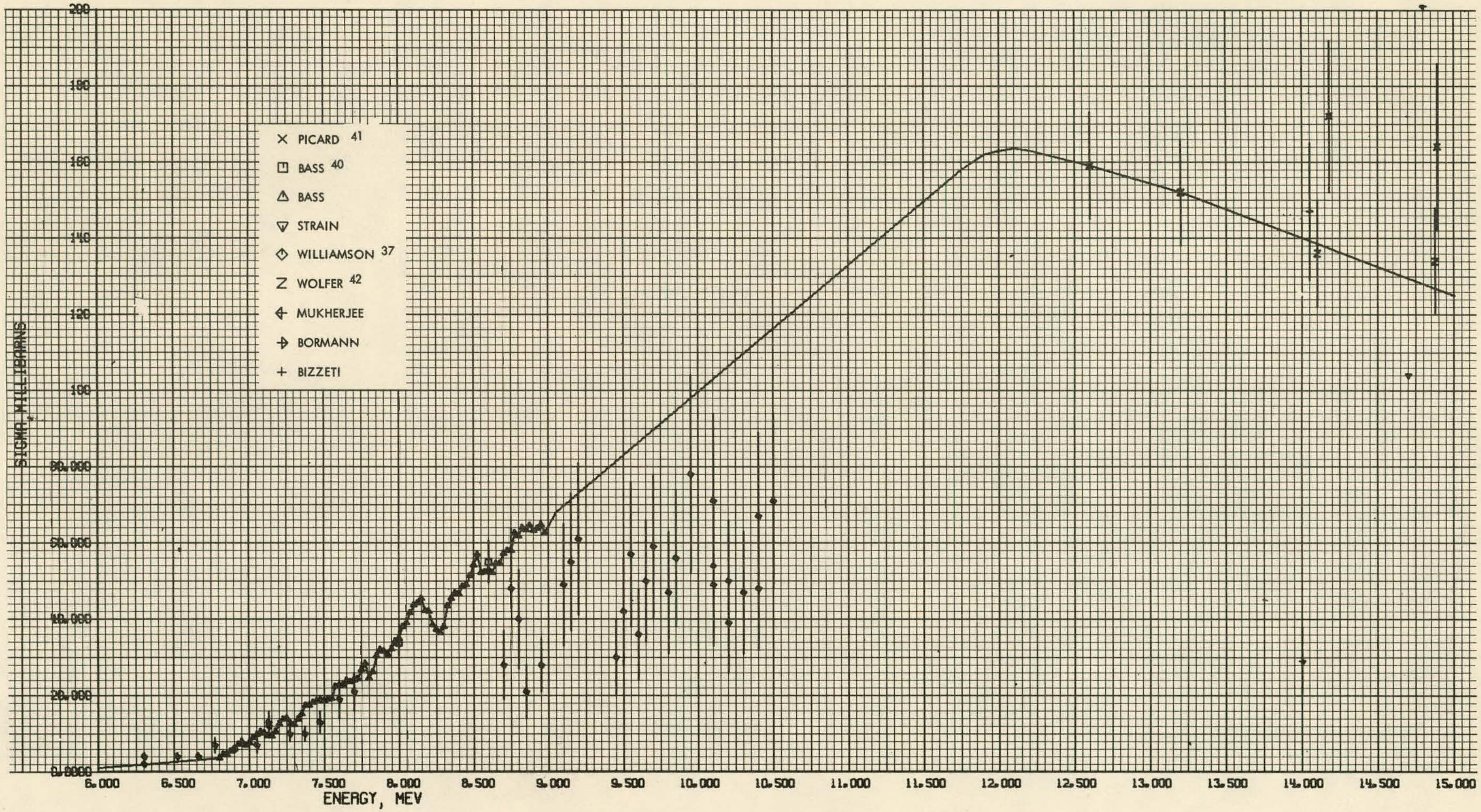

FIG. 16 (n, α) CROSS SECTION

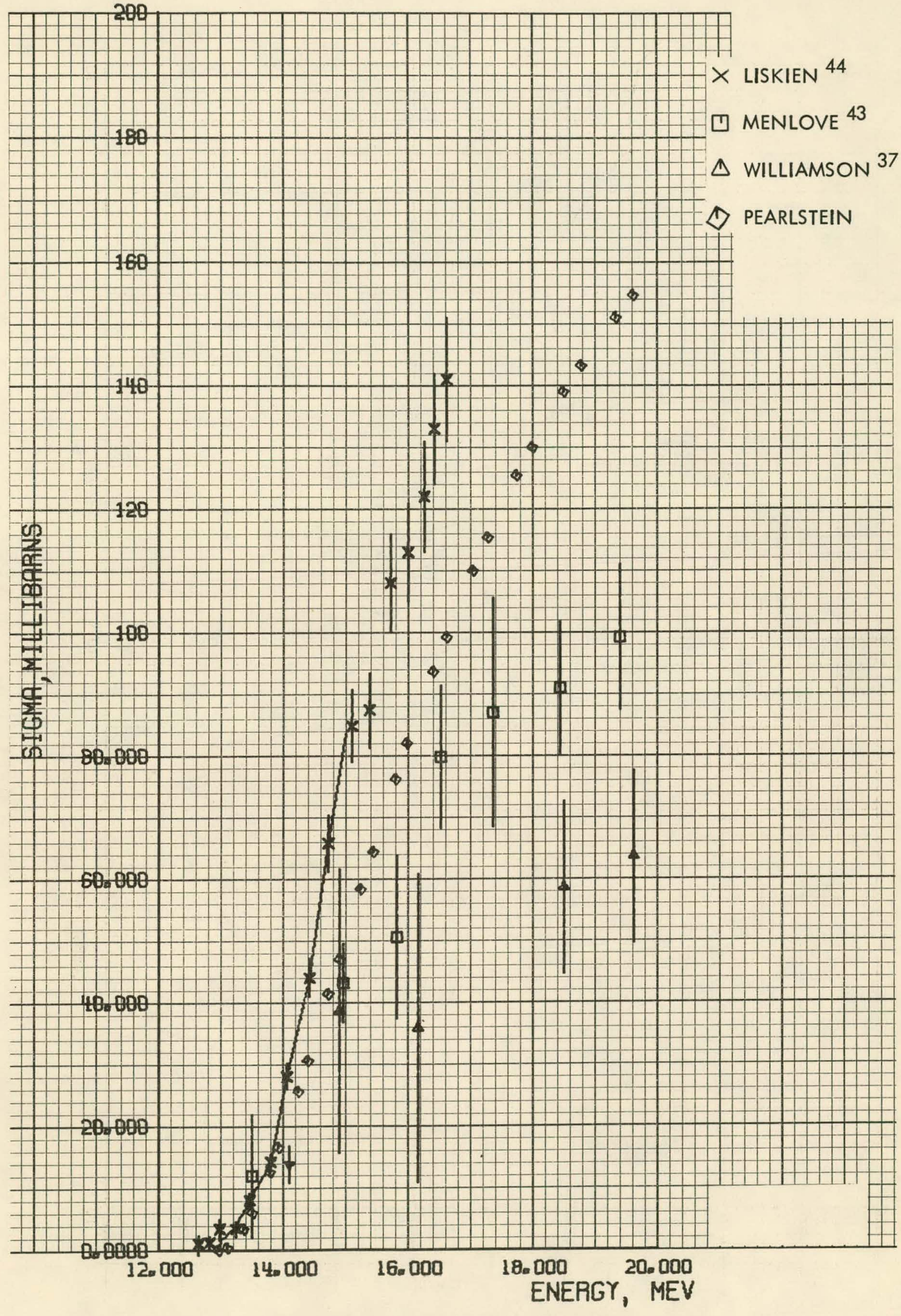

FIG. 17 (n, 2n) CROSS SECTION

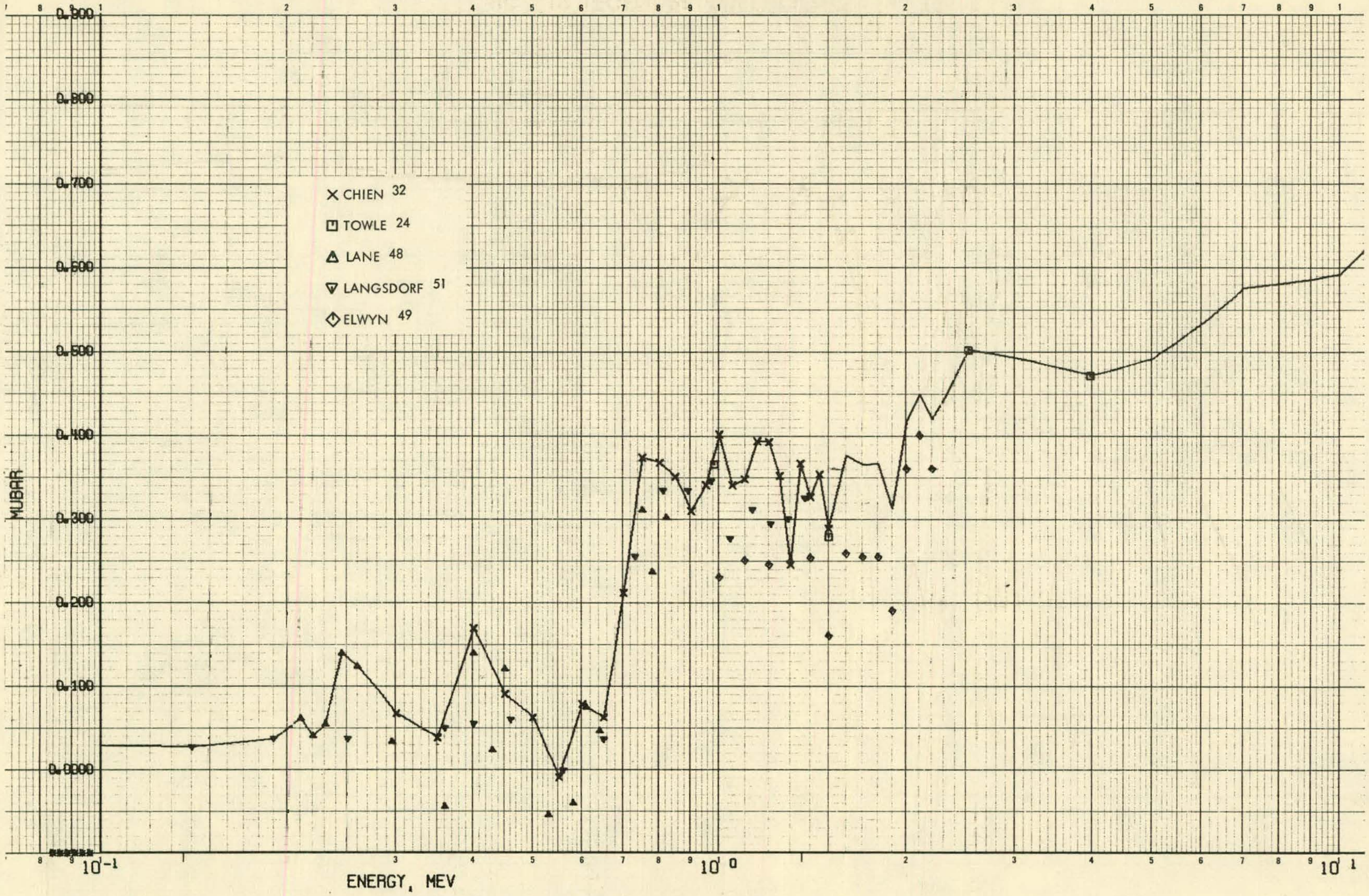

FIG. 18 AVERAGE COSINE OF SCATTERING ANGLE, $\bar{\mu}$

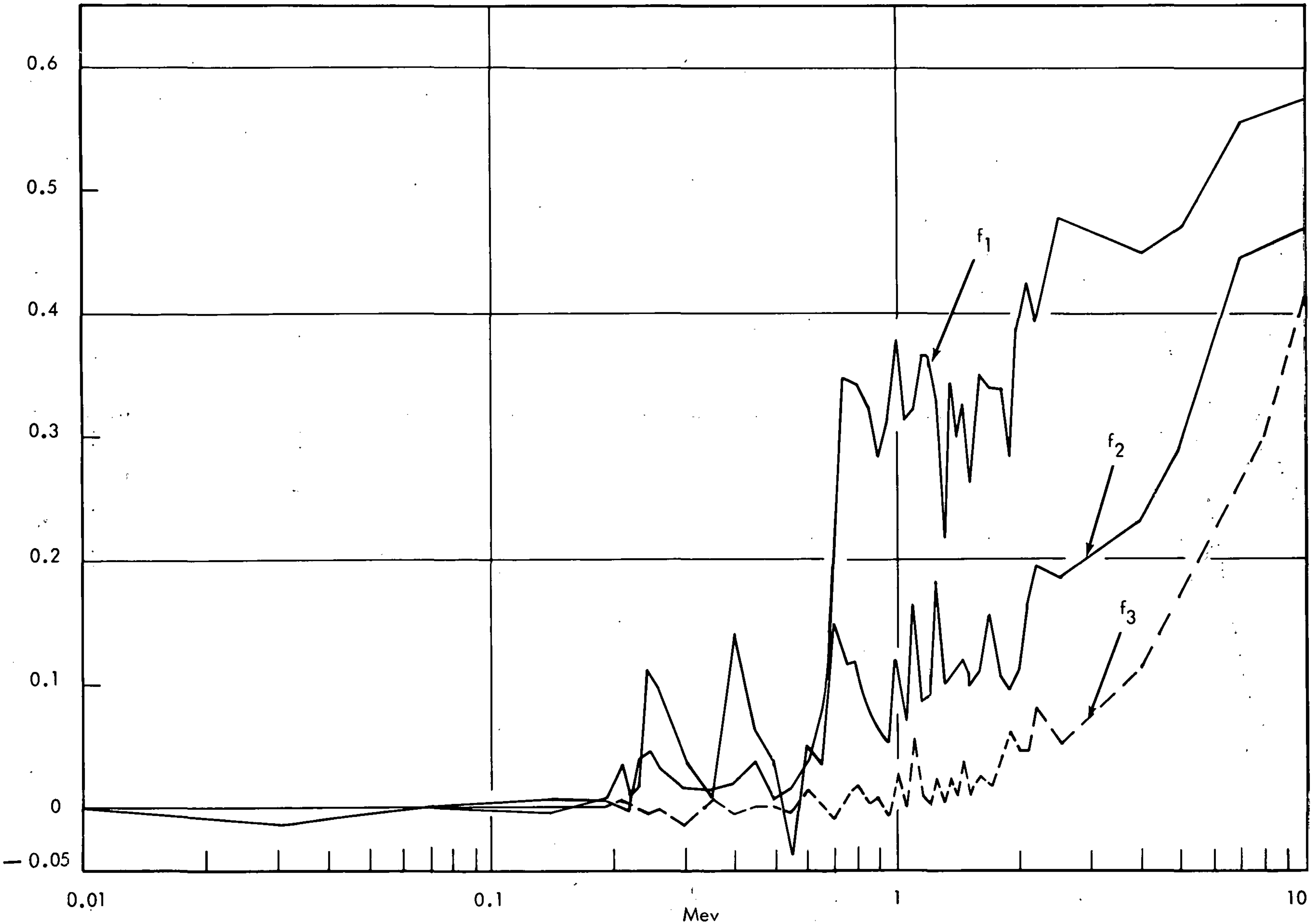

FIG. 19 LEGENDRE COEFFICIENTS f_1 TO f_3

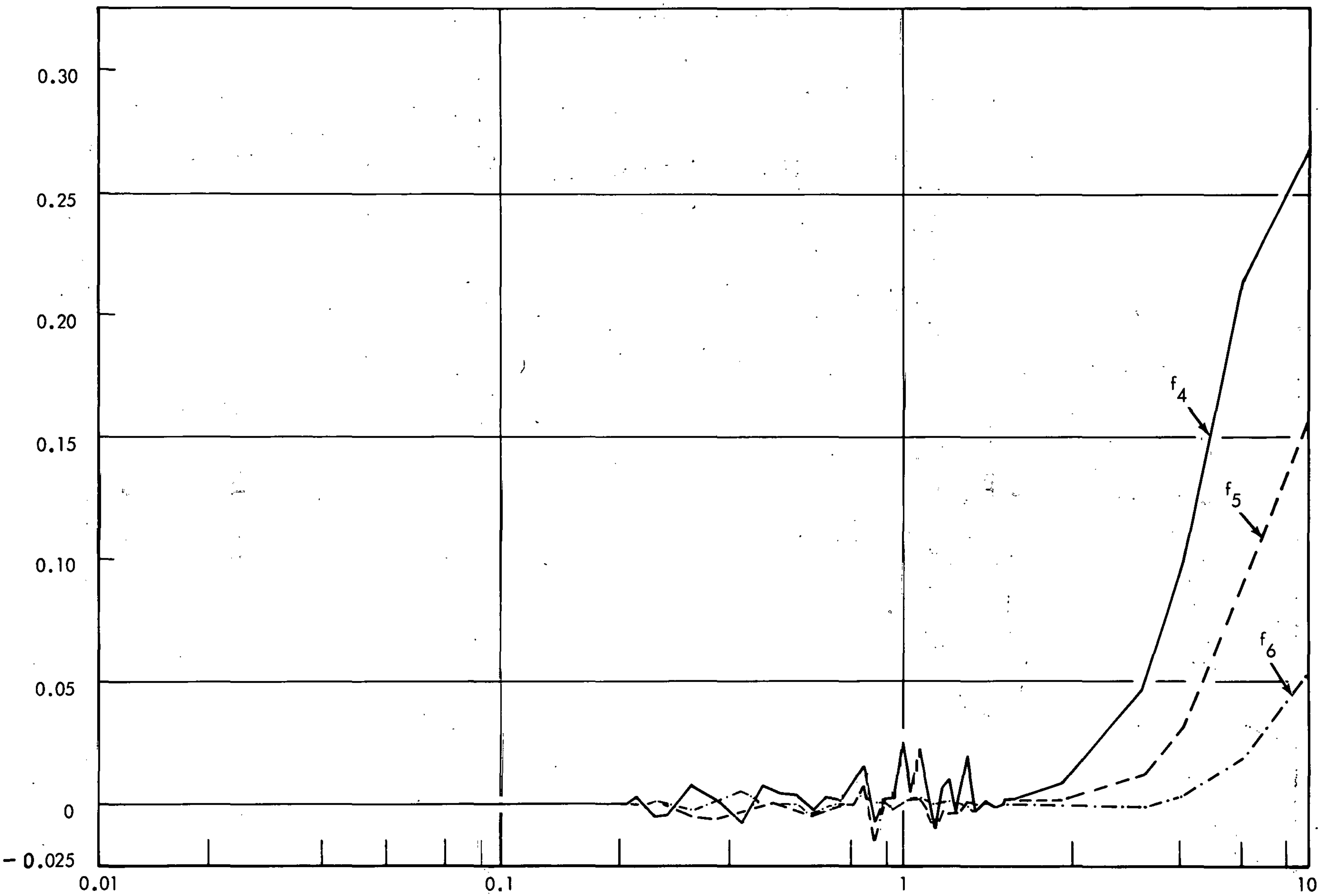

FIG. 20 LEGENDRE COEFFICIENTS f_4 TO f_6

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