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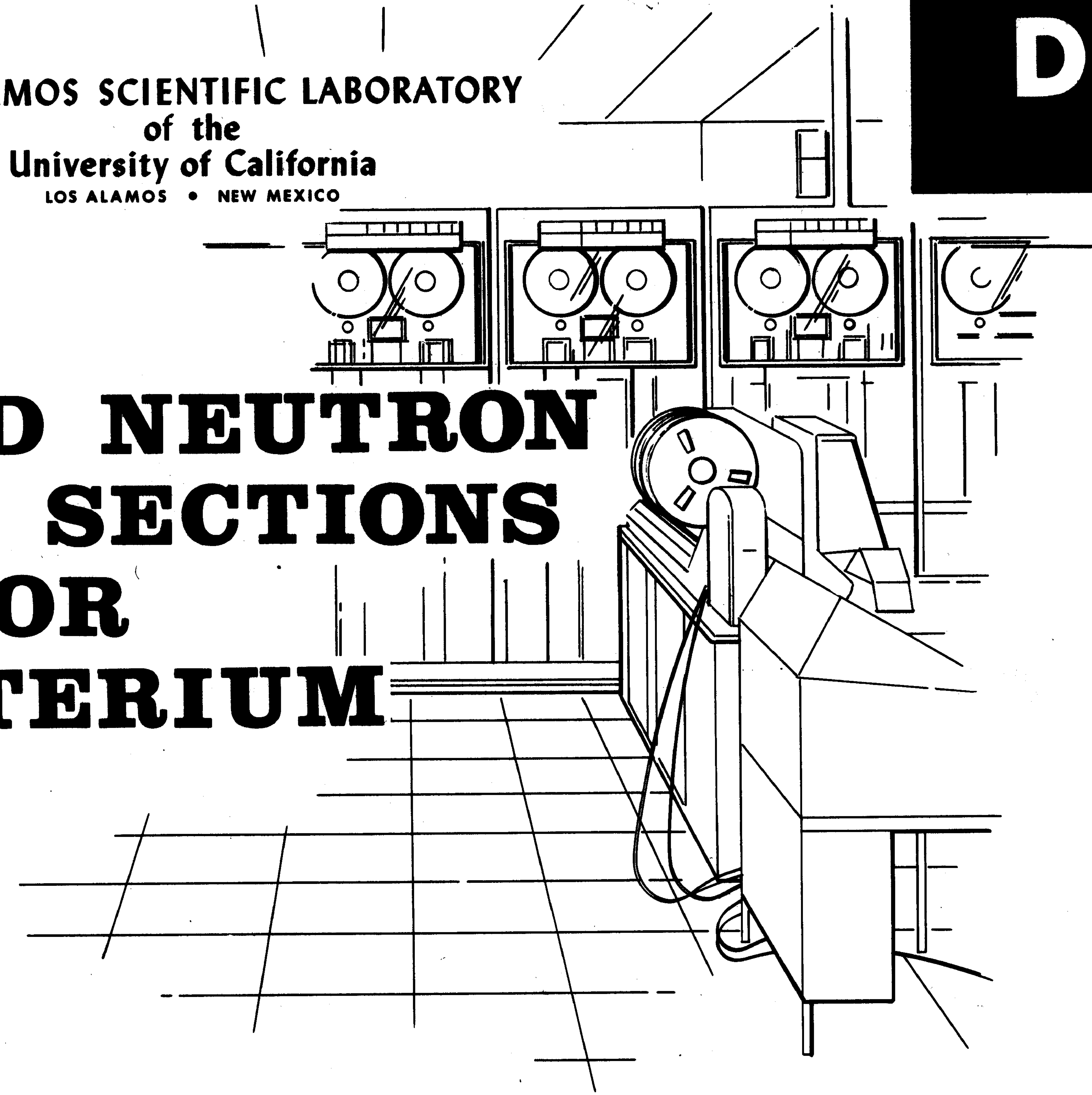

EVALUATED NEUTRON CROSS SECTIONS FOR DEUTERIUM

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by

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FOREWORD

The experimental data compilations available are, at the present time, incomplete for the purposes of an up-to-date evaluation of neutron-deuteron interactions. Most of the experimental information in this report has been obtained from a search of the literature by the authors and from personal contacts with experimentalists. Often the experimental data could not be obtained in numerical form and had to be read from graphical displays; it is hoped that the errors which must inevitably have been introduced by this procedure are small. The literature survey was thought to be exhaustive (the CINDA† references up to the March 15, 1967, Supplement 2 have been examined by one of the authors) but only information judged useful is included in the report. In particular, the profusion of recent break-up cross-section measurements is not fully presented; these data have been studied in detail but were found to be too fragmentary to permit an improvement on phase-space predictions herein.

In recent years, emphasis has been placed on the need for a presentation of the experimental data upon which the evaluation depends; both experimentalists and evaluators have also shown great interest in having all the information on a particular element or isotope collected in one report. It is hoped that the data herein will readily lend themselves to corrections, criticisms, and perusal without the need for further transformations and normalizations. Values are recommended for neutron-deuteron cross sections in the energy range 0.0001 eV to 20 MeV to facilitate neutronics calculations.

With the aim of providing a working manual with a useful "half-life" for both experimentalists and theoreticians, the following specifications have been established:

1. The size of the graph paper and the scales chosen most often permit the inclusion of the standard deviations.
2. Only standard size tracing paper is used.
3. The grids are reproduced and the scales are kept as uniform as possible.
4. The graphs are neither enlarged nor reduced in the printing process.
5. Individual pages can be added or deleted; therefore, corrections and additions can be made when necessary.
6. The angular distributions are plotted in absolute units along with tabular values of both cross sections and probability, thereby facilitating comparison and checking.

Perhaps a "new" evaluation program can begin where this one ends. Any comments, corrections, and criticisms will be welcomed by the authors.

†CINDA 66, EANDC 60 U (July 1, 1966); and CINDA 66, Supplement 2, EANDC 70 U (March 15, 1967).

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The authors thank J. Corner (AWRE) and R. F. Taschek (LASL) for making this collaborative effort possible.

Without the support and encouragement of many people this report would not have been completed. A complete listing of the contributors would be prohibitive in length; a few, however, must be mentioned. We are indebted to E. Bernstein, L. Rodberg, and J. E. Young for the time they spent interpreting the experimental data. We also thank J. D. Seagrave for keeping us posted on the newest data and developments on the three-nucleon system. For many helpful discussions on the subject of radiative capture we thank A. C. Douglas and H. T. Motz. We are most grateful to K. Parker and E. Pendlebury for many useful comments and to J. D. Anderson and W. T. H. van Oers for the discussions, encouragement, and theoretical calculations they so willingly furnished.

The information contained in this report would be greatly reduced in quality were it not for the help of R. B. Lazarus and K. Parker in scrutinizing, checking, and handling the programs and computer operations necessary for an evaluation.

Finally, we express our gratitude to many people at AWRE and LASL for their patience and the effort they expended in following this manuscript from its infancy. In particular, we wish to thank Carol Schweitzer, Luween Smith, Opal Milligan, and Susan Offord.

EVALUATED NEUTRON CROSS SECTIONS FOR DEUTERIUM

I. INTRODUCTION

The interpretation of experimental results obtained from the scattering of neutrons by deuterium is often a difficult task. Since the deuteron is a light nucleus, large energy losses occur in the elastic channel, and the low-energy threshold for break up into a neutron and proton often leads to a significant background of low-energy neutrons in the region above about 5 MeV. At higher incident energies, the (n, 2n) neutrons themselves can produce further (n, 2n) reactions; consequently, in-scattering and multiple-scattering corrections must be applied with great care.

The total, elastic, and (n, 2n) cross sections have been measured over a wide range in the MeV region but none of the cross sections, except that of radiative capture at thermal energies, is well-known below a few hundred keV. Many of the experimental results are in conflict and this is not always resolved by a study of the relevant information. When this evaluation was in its final stages, measurements on the total cross section[1] were completed which disagree with the choices made herein. The sums of the total elastic and reaction cross sections were already consistent with the total cross sections and any change in the total would have involved a radical reappraisal of all the data; this evaluation is, therefore, presented without weight being given to these recent measurements.

Compiling the data needed for this report became laborious because the datum points were sometimes available only from graphs and often could not be interpreted numerically with reasonable accuracy. In addition, precise analyses on the deuterium targets were difficult to perform, especially for those which were low in enrichment or were themselves compounds. In many experiments absolute cross sections had been obtained by observing the "difference" between two targets made of compounds, one target containing ^{1}H and the other ^{2}D; typical examples are H_2O versus D_2O and CH_2 versus CD_2. Gaseous and iced targets had also been employed, in a few instances with highly enriched deuterium.

At low energies the neutron-deuteron potential-scattering cross section is constant and the elastic-scattering angular distributions isotropic; a reliable estimate of the energy below which these conditions should obtain is not available. The relevant references and a discussion of this point are given in Section III.A, Total Cross Sections.

The radiative capture cross section is less than one millibarn at thermal; the only other direct measurement is at 14.4 MeV. Data from the inverse process and theoretical calculations have been employed to supplement the experimental information.

Experimental measurements on the energy and angular distributions of the break-up neutrons are extremely limited. Much of the existing data cover a small region in energy and angle and are often given as relative values; interpretation of the results in terms of cross sections covering the region of interest is difficult. Recommendations have been based on phase-space arguments because a study of the break-up spectra from p-d and n-d interactions gave little insight into the energy and angular dependence of the emitted neutrons as a function of incident neutron energy.

With the recent advances in time-of-flight techniques, total cross sections are often measured using a pulsed beam; this produces a neutron source which is "continuous" in energy (over a well-defined region) and permits a significant energy region to be covered in a "single run." With a target as light as deuterium, the elastically scattered neutrons suffer large energy losses except near zero degrees. This can cause serious errors unless great care is exercised in applying the corrections for room-scattered neutrons, sample and source geometries, and other factors such as target contaminants. The polarizations observed in neutron scattering from deuterium in the MeV region have been quite small, but cognizance should be taken of the magnitude of the polarization effects observed in scattering from the other elements present in targets and detectors,[2] especially carbon.

II. CROSS SECTIONS AND POSSIBLE REACTION MECHANISMS FOR INCIDENT NEUTRONS BELOW 20 MeV

All reactions, except radiative capture, produce neutrons in the exit channel. The Q values used in this report have been calculated using the mass tables of Mattauch et al.[3] The laboratory threshold energy, E_{ths}, for a reaction with negative Q is given by:

$$E_{ths} = \frac{M_n + M_d}{M_d} |Q|,$$

where M_n is the mass of the neutron and M_d the mass of the deuteron. Relative to ^{12}C ($M_{^{12}C} = 12$ amu), the atomic masses quoted by Mattauch et al.[3] are:

$M_n = 1.00866520 \pm 0.0000001$

$M_p = 1.00782519 \pm 0.00000008$

$M_d = 2.01410222 \pm 0.00000012$

$M_{^{16}O} = 15.99491502 \pm 0.00000028$

	Q_{mass} (MeV)	Lab Threshold (MeV)
1. Total Cross Section		
A. Deuteron bound in heavy water molecule, $\sigma^b_{TOT} = \frac{\sigma_{TOT}(D_2O) - \sigma_{TOT}(\text{oxygen})}{2}$		
B. Free Deuteron, $\sigma_{TOT} = \sum_i \sigma_i$		
2. Elastic Scattering, $\sigma_{el} = \int \sigma(\theta) d\Omega$, where $\sigma(\theta)$ is the differential cross section.		
3. Nonelastic Scattering, $\sigma_{NON} = \sigma_{TOT} - \sigma_{el}$; $\sigma_{NON} = \sigma_{n,\gamma} + \sigma_{n,2n}$		
4. Radiative Capture, $\sigma_{n,\gamma}$	+6.2574 ± 0.0001	exothermal
5. D(n,p)2n or $\sigma_{n,2n}$	-2.22452 ± 0.0001	3.339

III. TREATMENT OF EXPERIMENTAL DATA

1. Total Cross Section

A. Deuteron Bound in Heavy Water Molecule

To illustrate molecular binding effects, a "bound" total cross section for deuterium obtained from the n - D_2O total cross section scattering data[4-6] is given in Fig. D_2O-1. The bound cross section was obtained by subtracting the total cross section for free oxygen (a value of 3.8 b was used) from the total scattering cross section for heavy water and dividing this difference by two. The value at 0.0001 eV was obtained by extrapolation.

B. Free Deuteron

Very few of the many measurements of the total cross section for deuterium have been made in the past ten years. At very low energies the data are conflicting; 3.2 b is recommended for the potential scattering cross section at thermal energy because this value gives the best agreement with the "direct measurements" and the cross sections extracted from experiments on D_2O.

Some explanation is necessary to support this value since a more widely acceptable choice in the past has been 3.38 to 3.44 b. A coherent scattering length of (+6.77 ± 0.08 f) was reported by Bartolini et al.[7] at LRL and quoted in the recent edition of BNL-325.[8] This value gave a coherent scattering of 5.76 ± 0.14 b. A measurement of the incoherent scattering by Gissler[9] of 2.25 ± 0.04 b was inconsistent with the coherent scattering even though a value of 3.38 b was selected for the free-atom cross section for deuterium. Recently, however, Donaldson[10] at LRL revised the value quoted in Refs. 7 and 8 for the coherent scattering length to 6.17 ± 0.06 f. With a value of 6.17 f, the potential scattering cross section for the free deuteron calculated from the coherent and incoherent scattering cross sections reported in Refs. 9 and 10 gives 3.12_3 ± 0.05 b. A detailed review of these data, including related experiments and theoretical interpretation, can be found in papers by van Oers and Seagrave.[11]

It seems necessary, therefore, to reduce the scattering cross section to a value of the order of 3.2 b. The value 3.2 is preferred to 3.1 b because the elastic scattering and total cross sections measured near 100 keV indicate a value somewhat higher than 3.1 b. None of the data is conclusive but every indication favors the reduction of the previous value of the cross section by 200 to 250 mb. In fact, the 3.2-b value chosen in this report may be subject to just criticism in that the cross section could have been closer to 3.1 b. The preliminary nature of the change in a_{coh}, however, does not appear to warrant further study at this time.

Above 2.0 MeV, a curve has been calculated from the analytic formula given by Seagrave and Henkel:[12]

$$\sigma_{TOT} = 14.35\left(E_n + 3.6\ \text{MeV}\right)^{-1}\ \text{b}.$$

The shape of this curve is reproduced fairly well by the recent measurements of Glasgow and Foster[1] at Hanford, but the magnitude of the curve is greater by about 5% over the entire energy region from 3 to 13 MeV; below 3 MeV the Hanford data drop even lower, agreeing quite well with the measurements of Willard et al.,[13] which are also considerably lower than the recommended curve. It should be noted, however, that the Hanford data tend to higher values in the energy region of overlap with the ORNL data while falling more rapidly at lower energies than a smoothed curve would predict without entailing noticeable changes in slope. Since independent angular distribution measurements tend to support the higher values of the total cross section and the final values[1] were not yet available when this evaluation was underway, the Hanford data were essentially ignored in the recommended curve. The tabular data have been furnished prior to publication and are shown for comparison in TOT-1-2-5; the values displayed are three-group averages to reduce the number of points and thus improve presentation. Admittedly, this procedure introduces an interdependence in the points, but average values should be more representative than "every third point," or a similar choice. For additional data see Ref. 14.

2. Elastic Scattering

Differential angular distributions have been measured by Allen et al.,[15] Adair et al.,[16] Elwyn et al.,[17] Blanc et al.,[18] Seagrave and Cranberg,[19] Brüllman et al.,[20] Wantuch,[21] Allred et al.,[22] and Seagrave.[23] Preliminary measurements have been available in the region from 5 to 9 MeV from LASL[24] and Rice University,[25] near 14 MeV from UCLA[26] and Zagreb,[27] and from 18 to 24 MeV from LASL;[24] none of these, however, have been released for inclusion in this report. In addition, recoil deuterons have occasionally been observed over a limited angular region but the absolute cross sections have not been determined; the integral values are, of course, not very accurate if a large contribution must be obtained from an extrapolation.

Except near 14 MeV, the region above 5.5 MeV is relatively unexplored; therefore, the p-d data have been employed to extend the analysis to 20 MeV and obtain better estimates of the shape and absolute magnitude of the elastically scattered neutron distributions. No effort has been made to include all the p-d experiments available; instead, the experimental data have been tabulated and plotted only at a sufficient number of energy points to allow reasonable interpolation. Neither n-d nor p-d data are yet available to fill the gap between about 14.5 and 20.6 MeV.

Both the shape of the angular distributions and the magnitude of the integral values have been investigated to check the reliability of the measurements. For the convenience of the reader, the angular distribution curves have been normalized over cosine θ (see pages facing angular distribution curves) and these probability tables should be used in conjunction with the elastic scattering cross section given in Table I.

The absolute cross sections measured by the experimentalists are useful comparisons for evaluation and the curves presented on the angular distributions are integrated and compared with the values obtained by subtracting the nonelastic from the total cross sections (see ELAS-1-2-1). The elastic cross sections in Table I are the differences in the tabulated values of the total and nonelastic cross sections. The significant figures in Table I are not representative of the accuracy implied in this report. The number of significant figures carried in the total cross section was governed by the number of figures necessary to maintain a smoothed function for the nonelastic cross section while insuring that $\sigma_{TOT} \equiv \sigma_{ELAS} + \sigma_{n,2n}$ above 100 eV.

The integral cross sections show very good agreement (with the TOTAL minus NONELASTIC). It should be noted, however, that the measurements made by Seagrave and Cranberg[19] at 2.45 and 3.27 MeV were normalized to the total n-d cross section. Their experimental data were also normalized to a hydrogen differential cross section which gave results which differed by no more than 4%. The 20.57-MeV p-d angular distribution data were represented by a curve which gave a predetermined value (total minus nonelastic) of 400 mb. This curve does appear to fit in a reasonable fashion into the structure seen at lower energies. The other curves were drawn without recourse to fitting procedures or any other method of forcing the "best" integral values.

The data of Blanc et al.[18] do not agree with the distributions at nearby energies either in shape or magnitude and they did not influence this analysis. The UCLA data[26] at 14.3 MeV show excellent agreement with this evaluation, except at small angles where the measured values are larger. The Zagreb data[27] do not include measurements at small angles, but agreement is reasonable over the angular region covered.

It is interesting to note that, as early as 1953, Christian and Gammel[28] used the data on p-d scattering to predict the magnitude and shape of n-d scattering and their estimate is shown for comparison in ANG-1-2-11. Until recently,[29,30] the charge-conjugate reactions were rarely used in evaluating neutron interactions. Since deuterium is a self-conjugate nucleus (Z = N), charge independence implies the same scattering for both incident protons and neutrons.

The Coulomb interaction between the proton and deuteron distorts the shape of the angular distribution and this must be taken into account in the n-d analysis. As this effect is more pronounced at small angles, the integral values are extremely sensitive to how the cross section is extrapolated to zero degrees. The criteria followed were: (a) the changes in the slope of the distributions were minimized, and (b) that the zero-degree cross section conforms to the limitations imposed by Wick's limit.[31]

For convenience the formulae relevant to Wick's limit are reproduced below from LA-3270:[30]

since

$$\sigma(0°) = \left|f_R(0°)\right|^2 + \left|f_I(0°)\right|^2$$

it follows that

$$\sigma(0°) \geq \left|f_I(0°)\right|^2$$

where $f_R(0°)$ and $f_I(0°)$ are the real and imaginary parts, respectively, of the complex scattering amplitude at zero degrees.

It is easily proven[32] that

$$f_I(0°) = \frac{k\sigma_{TOT}}{4\pi},$$

the latter equality being known as the optical theorem. Then,

$$\sigma_W \equiv \frac{k^2\left(\sigma_{TOT}\right)^2}{(4\pi)^2};$$

where

$$k^2 = (2.187)^2 \frac{m_1 m_2^2}{\left(m_1 + m_2\right)^2} E_0 ; \quad \left[\text{units barn}^{-1}, \text{ or } \frac{10^{24}}{\text{cm}^2}\right]$$

for mass m_1 incident on target mass m_2, and E_0 the incident neutron energy in the laboratory system in units of MeV. Then,

$$\sigma_W = \left(3.0276 \times 10^{-2}\, E_0\right) \frac{m_1}{\left(1 + \frac{m_1}{m_2}\right)^2} \left(\sigma_{TOT}\right)^2, \left[\frac{\text{barns}}{\text{sr}}\right]$$

with σ_{TOT} in barns.

Wick's limit has been calculated and plotted on each angular distribution. To assist comparison, the angular distributions above 5.5 MeV are shown in ANG-1-2-19. Except for a slight converging of the zero-degree cross sections at 12 and 14 MeV, the distributions seem to vary smoothly with energy. Van Oers and Brockman[33] calculated the n-d scattering cross sections from phase shifts they obtained in fitting the p-d data; these are reproduced as a composite in ANG-1-2-20. There is very little difference between the two sets of curves except for the minima which were not as deep in the phase shift analyses; in addition, the zero-degree cross sections in this analysis tend toward higher values. Direct comparisons of van Oer's predictions with the experimental data and the evaluated curves chosen herein can be seen in ANG-1-2-17 and ANG-1-2-18. Near 14 MeV, the n-d data seem to be consistently higher at the backward angles than the p-d cross sections, even though the p-d experiment is at a slightly lower incident energy.

3. Nonelastic Scattering

Radiative capture and deuteron break up are the only nonelastic processes. The radiative capture is discussed under Section III 4, and the (n, 2n) cross section under Section III 5.

Above 100 eV, the radiative capture cross section has been assumed to be zero in constructing the values for the total and nonelastic cross sections. The nonelastic cross section is, in this energy region, equal to $\sigma_{n,2n}$.

4. Radiative Capture; $\sigma_{n,\gamma}$

Only at thermal energy and 14.4 MeV are direct measurements of the radiative capture cross sections available. There are, however, experimental data on the inverse reaction, the two-body photodisintegration of the triton. Bösch et al.[34] have measured this cross section for γ rays of 6.7, 7.6 and 9 MeV, and Kosiek et al.[35] for γ-ray energies between 17 and 31 MeV. These measurements, together with the experiments on the two-body photodisintegration of ^{3}He,[36-38] support Gunn and Irving's theoretical treatment of the photoelectric disintegration of three-particle nuclei.[39] For an incident γ ray of energy E_γ, Gunn and Irving give the photoelectric dipole disintegration cross section of ^{3}H, with ejection of a neutron of momentum $p = \sqrt{4/3\, M\left(E_\gamma - Q_t\right)}$, as:

$$\sigma_{T(\gamma,n)D} = 32\left(e^2/\hbar c\right) \frac{E_\gamma\left(E_\gamma - Q_t\right)^{3/2}}{W_D^{5/2}} \frac{\mu_T^{\,4}\hbar^6}{M^3 W_D^3} \{f(\lambda)\}^2,$$

with

$$f(\lambda) = \frac{7\lambda - 2}{\lambda^2(\lambda - 1)^2} - \frac{15}{(\lambda - 1)^3} + \frac{15}{(\lambda - 1)^{7/2}} \cos^{-1}\left(\frac{1}{\sqrt{\lambda}}\right),$$

and $\lambda = \left(ME_\gamma - MQ_t + 3/2\, \mu_T^2\hbar^2\right)/MW_D$. Q_t is the energy required to dissociate the triton into the two-body neutron-deuteron system, M the nuclear mass, and W_D the deuteron binding energy. $1/\mu_T$ is the size parameter of the Gunn-Irving wave function and 2.6 f gives the best phenomenological fit[34] to the experimental data. For the energy range of interest, contributions other than the electric dipole transition should account for less than 1% of the total photodisintegration cross section.[40] In fact, the ground-state wave function of the triton used by Gunn and Irving is symmetric in the position coordinates of the three nucleons which leads to a zero magnetic-dipole contribution.[41] Bösch et al.[42] have improved the agreement of the Gunn-Irving theory with experiment by introducing a small antisymmetry term into the ground-state wave function and calculating the magnetic-dipole and electric-quadrupole contributions. From the magnetic-dipole cross section, the capture cross section at thermal energies can be calculated.[40]

The principle of detailed balance relates the radiative capture and two-body disintegration cross sections as follows:

$$\sigma_{D(n,\gamma)T}\left(E_{nL}\right) = \frac{E_\gamma^2}{2M_c^2\left(E_\gamma - Q_t\right)}\,\sigma_{T(\gamma,n)D}\left(E_\gamma\right)$$

and

$$E_{nL} = 3/2\left(E_\gamma - Q_t\right),$$

where E_{nL} is the laboratory energy of the neutron. At low energies the Gunn-Irving theory gives $\sigma_c \alpha E_{nL}^{1/2}$, whereas one expects $\sigma_c \alpha E_{nL}^{-1/2}$. The lower-energy values were, therefore, obtained by a 1/v extrapolation from thermal to 1 keV. Between 1 keV and 100 keV a smooth curve was used to join the 1/v extrapolation to values obtained from the inverse reaction (γ, n).

At thermal energy, the 506 ± 10 μb cross section recently measured by Merritt et al.[43] has been chosen as the "best" value. Using the Eichmann theory, a calculation of the thermal capture cross section using the magnetic-dipole photodisintegration cross section of Bösch et al.[42] gives 455 μb. The experimental measurement of 29.4 ± 5.8 μb obtained by the Zagreb group[44] at 14.4 MeV is almost a factor of three higher than the extrapolation of a smooth curve obtained from detailed balance calculations on the inverse reaction.

5. $\sigma_{n,2n}$

Experimental measurements on the energy spectra of protons observed when deuterons are bombarded with both protons and neutrons are many and varied. Most of the data, however, cover a very limited region in energy or angle or both, and the only reliable measurements on the total (n, 2n) cross sections come from the coincidence experiments in which timing is used to isolate the (n, 2n) processes from background events.

The low-energy region has been explored by Holmberg and Hansen[45] who find rather low cross sections when compared with this evaluated curve. However, the only other information about the shape of the curve near threshold is that, theoretically, it should be convex. With this in mind, the Holmberg-Hansen data have been used to decide the low-energy shape of the (n, 2n) curve. The coincidence measurements of Catron et al.[46] extend the energy range to 14 MeV.

No information, except what can be inferred from p-d elastic scattering, is available above the 14-MeV region and nothing is known about the energy at which the (n, 2n) cross section would cease its upward climb and tend to decrease with increasing energy. It is hoped that the curve chosen is a reasonable approximation.

6. Emission Spectra as a Function of Angle

There are very few direct measurements[47-49,59] of the differential reaction cross sections of the neutron spectra from n-d break up. Furthermore, the data are confined to 14-MeV incident neutrons and, even for that energy, give a far from complete picture. Some information can be inferred from the more numerous observations of the proton spectra for the D(n, p)2n and D(p, 2p)n reactions, but the overall description is still fragmentary and often contradictory.

Because of these difficulties, the (n, 2n) emission spectra were calculated from a phase-space model using an n-body interaction code programmed for the LASL Maniac II by R. B. Lazarus. Its principles are briefly outlined as follows: if "n" particles are produced in a direct reaction, that is, sequential decay does not occur, then the energy distribution in the center-of-mass system[30] of any <u>one</u> of the "n" particles emitted can be represented by:

$$N\left(E_i\right)dE_i = \text{Constant}\left(E_i\right)^{1/2}\left[E_i(\max) - E_i\right]^{\frac{3}{2}n-4} dE_i,$$

by assuming equal probability in phase space. $E_i(\max)$ is the maximum energy available to particle "i" and depends only on the incident neutron energy and the Q-value of the reaction. The expressions for the energy and angular distributions are analytic functions and the cross sections (as a function of energy and angle) in the laboratory and center-of-mass systems may be obtained by normalizing to a total break-up cross section. In the Appendix, many examples are given of the spectra at particular angles for various neutron bombarding energies. In all cases, the cross section as a function of the cosine of the angle and the cross section as a function of the emitted particle energy are plotted in absolute units in the laboratory system. It should be noted that isotropy in the center-of-mass system is implicit in the phase-space model.

In addition to affording a complete description, the phase-space predictions agree reasonably well with the experimental results.[50] Delves[51] has pointed out that the experimental results for nucleons with incident energies less than 6 MeV differ little from phase-space distributions. Poppe et al.,[52] observing the zero-degree cross sections for neutrons from d+p reactions, found energy spectra very much like the phase-space distributions for 7.5- to 9-MeV incident proton energies.

At higher energies, the experimental spectra diverge from the phase-space predictions. For example, measurements[53] of the D(n, p)2n reaction show peaking in the proton spectrum at the maximum proton energy for small forward angles, which diminishes as the scattering angle increases. There is also a noticeable but lesser peak at lower proton energies; both the low- and the high-energy peaks have been attributed to final-state interactions, the low-energy peak being caused by the final-state interaction of the proton with one of the neutrons and the high-energy peak by the final-state interaction between the two neutrons. According to this theory, the low-energy peak in the proton spectrum must correspond to a high-energy peak in the neutron spectrum, since the low-energy peak is kinematically the process where, in the center-of-mass system, the proton and a neutron are recoiling backwards with small relative momentum, and one of the neutrons is moving forward with maximum energy.

The correlation in the distributions of the secondary neutrons in the D(n, 2n)p reaction is not dealt with in this report. A good treatment for phase-space distributions has been given by Maksimenko and Rozental;[54] Ohlsen[55] discusses the more general problem. To illustrate how correlation shows itself in experimental spectra, data have been excerpted from two references and these data are compared with phase-space predictions for n-d break up (APP-1-2-1 to 1-2-6).

The proton spectra observed[53] from the interaction of neutrons with deuterons are reproduced in APPENDIX-1-2-3 (through -6) at 14.4 MeV. These results, or parts thereof, have been reported in many publications but the data shown herein carry a correction factor which raises the previously published values[56] by approximately 25%.

For two identical particles in the exit channel, much of the structure seen in the spectrum for a single nucleon is "averaged" out. This is evident in the proton production cross-section spectra observed from the interaction of protons with deuterons by Kikuchi et al.[57] These spectra should be similar to the neutron production spectra observed in the D(n, 2n)p reaction.

APPENDIX-1-2-1 shows the proton production cross sections for incident proton energies of 10.1 MeV. The 10° data suggest a small energy-calibration inconsistency (in excess of the 100-keV difference in incident energy) since protons are observed (with significant probability) at energies higher than those allowed by kinematics. The fact that the data at other angles conform quite well with the maximum calculated energies leads to the conclusion that this is not primarily a resolution problem. The integral values of the experimental data are much larger than those obtained from phase-space arguments and the spectra peak at low proton energies, not at the high-energy end. More noticeable, perhaps, is the fact that the integral of the experimental measurements over energy for each angle, up to 48°, has not fallen appreciably with increasing angle. Whether this indicates an extremely large anisotropy or an abnormally large (p, 2p) cross section is not clear. It should be pointed out that the phase-space spectra have already been multiplied by two, for comparison purposes, to account for the difference between a reaction and production cross section.

Proton spectra observed from bombarding deuterons by protons at 13.9 MeV[57] are shown in APPENDIX-1-2-2. Smooth curves drawn through the data by the authors have been reproduced since tabular values of the individual datum points were not available. The authors took the liberty of multiplying the scales by a factor of two to obtain consistency between Figs. 6 and 7 in Ref. 57; that this factor was necessary was also evident in comparing Figs. 7 and 8.

There are two other experiments near 14 MeV which should be mentioned although the tabular values were not available for presentation in this report. Anderson et al.[58] observed the neutrons from the break-up of deuterons by protons while Vedrenne et al.[59] observed the neutrons from the interactions of neutrons with deuterium.

At small angles, the neutron spectra observed by Anderson et al.[58] are quite similar in shape but smaller in absolute magnitude than the proton spectra observed by the Zagreb group[53,56] in the n-d interaction. For neutrons from 3 to 7 MeV, this difference approaches 50% at an angle near 4° using the correction factor of 1.25 suggested by Šlaus.[56] On comparison with the more recent Zagreb measurements of Cerineo et al.,[60] the differences are, indeed, about 50% thereby confirming the need for the correction factor of 1.25 to effect agreement between the two Zagreb experiments.

At higher energies the disagreement between the spectra, though less marked, is still appreciable and leads to quite different integral values for the n-d and p-d break-up cross sections. The neutron spectra[58] from p-d break up show forward and aft peaking which can be attributed, by analogy with the interpretation of the n-d data,[53,60] to p-p and p-n "final state" interactions.

Although the energy of the p-d measurement is a few hundred keV lower than the n-d and the resolutions in the n-d and p-d experiments differ, the disparity in the cross sections is too large to be ascribed to these factors alone. Certainly, the data presently available indicate that, for a given incident energy, the (p, 2p) cross section is lower than the (n, 2n),[61] but the "expected" differences should be larger near threshold where the Coulomb barrier is important and should diminish with increasing energy. Differences between the cross sections of the order implied by these experiments must be ruled out.

In observing the neutrons from n-d break up, Vedrenne et al.[59] find a peak in the spectra which shifts little with increasing angle and with a magnitude that changes by only a factor of two in going from 10° to 80° in the laboratory system. Although it is suggested (see Fig. 4 of Ref. 59) that the integrals of the data over energy are in reasonable agreement with the phase-space-like predictions of Frank and Gammel[62] and with the "accepted" total (n, 2n) cross section, these integrals have been obtained with the assumption that there are no contributions from neutrons emitted below 2.5 to 3 MeV and, at zero degrees, above 9 MeV. Yet in a phase-space model these contributions amount to more than 30% of the total (n, 2n) cross section. If the integral for their experimental data is multiplied by 1/0.7 to take account of this, a total emission cross section of about 460 mb is obtained, which is 100 mb higher than the accepted value of the (n, 2n) emission cross section at 14 MeV. Admittedly, the above "correction" is rather crude, but it suggests that the strange peak in the spectra of the Vedrenne experiment might be caused by other factors, such as source neutrons from d-d reactions.

Apparently all in c.m.

IV. PRESENTATION OF THE RESULTS

The smooth curves on the graphs represent the "best" values chosen for the data library. On the individual graphs each experiment (or quantity) is identified by a short reference notation consisting of the name of one of the authors, the institution (or city or country), and the year of publication (abbreviated to the last two digits).

A complete reference, including any notes or comments which may be of interest, appears on the page facing each display. For the differential cross sections, a tabulation of the cross sections and probabilities represented by the smooth curve is also included on the facing page.

The tabular and graphical results are arranged in the following manner:

1. Total and Integral Values of the Cross Sections

A.	TOTAL		
	(1) Deuteron Bound in Heavy Water	Graph	D_2O-1
	(2) $\sigma_{TOT} = \sigma_{el} + \sigma_{NON}$	Summary: Graphs:	Table 1 TOT-1-2-1 thru -5
B.	$\sigma_{el} = \int \sigma(\theta)\, d\Omega$ (Evaluated and Experimental)	Summary: Graphs:	Table 1 ELAS-1-2-1
C.	$\sigma_{n,\gamma}$ = Radiative Capture	Summary: Graphs:	Table 1 CAP-1-2-1 thru -3
D.	$\sigma_{NON} = \sigma_{n,\gamma} + \sigma_{n,2n}$ (Evaluated and Experimental)	Summary: Graphs:	Table 1 NON-1-2-1 thru -2 ($\sigma_{n,2n}$, only)

2. Differential Cross Sections for Elastic Scattering

A.	E_n = 100 keV	Graph:	ANG-1-2-1
B.	E_n = 200 keV		-2
C.	E_n = 500 keV		-3
D.	E_n = 750 keV		-4
E.	E_n = 1.0 MeV		-5
F.	E_n = 1.2 MeV		-6
G.	E_n = 1.5 MeV		-7
H.	E_n = 1.95 MeV		-8
I.	E_n = 2.45 MeV		-9
J.	E_n = 3.27 MeV		-10
K.	E_n = 3.5 MeV		-11
L.	E_n = 5.6 MeV (obtained from p+D)	Graph:	ANG-1-2-12
M.	E_n = 7.85 MeV (obtained from p+D)		-13
N.	E_n = 9.7 MeV (obtained from p+D)		-14
O.	E_n = 11.5 MeV (obtained from p+D)		-15
P.	E_n = 12.7 MeV (obtained from p+D)		-16
Q.	E_n = 14.1 MeV (obtained from n+D and p+D)		-17
R.	E_n = 20.57 MeV (obtained from p+D)		-18
S.	Composite Evaluated Angular Distribution for E_n = 5.6 to 20.57 MeV		-19
T.	Composite Theoretical Predictions for E_n = 5.6 to 20.57 MeV		-20

3. Break-up Cross Sections

The cross sections for the emission of the neutrons from (n, 2n) processes are calculated and presented in the Appendix in the following manner:

APPENDIX-1-2-1	Graph	10.1 MeV	Exp. and Theory	All angles
2	Graph	13.9 MeV	Exp. and Theory	All angles
3	Graph	14.4 MeV	Exp. and Theory, 4°	
4	Graph	"	Exp. and Theory, 10°	
5	Graph	"	Exp. and Theory, 20°, 30°	
6	Graph	"	Exp. and Theory, 40°, 45°	
7	Graph	"	50°, 60°	
8	Graph	"	70°, 80°, 90°	
9	Graph	"	100°-180°	
10	Graph	"	$\sigma(\theta)$ vs cosine θ	
11	Graph	"	$\sigma(E')$ vs E'	
12	Graph	4.5, 5 and 6 MeV	0°-40°	
13	Graph	"	$\sigma(\theta)$	
14	Graph	"	$\sigma(E')$ vs E'	
15	Graph	7, 8, and 9 MeV	0°, 20°	
16	Graph	"	40°, 90°	
17	Graph	"	$\sigma(\theta)$	
18	Graph	"	$\sigma(E')$ vs E'	
APPENDIX-1-2-19	Graph	10, 11, and 12 MeV	0°, 20°	
20	Graph	"	40°, 90°	

APPENDIX-1-2-21	Graph	10, 11, and 12 MeV	$\sigma(\theta)$ vs cosine θ
22	Graph	"	$\sigma(E')$ vs E'
23	Graph	13, 14, and 15 MeV	0°
24	Graph	"	20°
25	Graph	"	40°-120°
26	Graph	"	$\sigma(\theta)$ vs cosine θ
27	Graph	"	$\sigma(E')$ vs E'
28	Graph	17 and 20.57 MeV	0°, 30°, 60°
29	Graph	"	$\sigma(\theta)$ vs cosine θ
30	Graph	"	$\sigma(E')$ vs E'

REFERENCES

1. D. W. Glasgow and D. G. Foster, Jr., Phys. Rev. 157, 764 (1967).
2. See, for example, the excellent paper on the geometry conditions to minimize in-scattering by D. G. Foster, Jr., and D. W. Glasgow, Nucl. Instr. and Meth. 36, 1 (1965).
3. J. H. E. Mattauch, W. Thiele, A. H. Wapstra, Nucl. Phys. 67, 1 (1965).
4. Brookhaven National Laboratory, slow chopper, unpublished. See D. J. Hughes and Robert B. Schwartz, BNL-325 (second edition).
5. L. J. Rainwater, W. W. Havens, Jr., J. R. Dunning, and C. S. Wu, Phys. Rev. 73, 733 (1948).
6. L. A. Rayburn and E. O. Wollan, Nucl. Phys. 61, 381 (1965).
7. W. Bartolini, R. E. Donaldson, and L. Passell, Bull. Am. Phys. Soc., Series II, 8, 477 (1963).
8. BNL-325, Vol. I, Suppl. 2, Sec. Ed. (1964).
9. W. Gissler, Z. Krist. 118, 149 (1963).
10. R. E. Donaldson, private communication to J. Seagrave, LASL, October 1966; W. Bartolini, R. E. Donaldson, and L. Passell, Bull. Am. Phys. Soc., Series II, 8, 477 (1963).
11. W. T. H. van Oers and J. D. Seagrave, Phys. Letters 24B, 562 (1967); σ_{scat} appearing in this paper should be corrected to read $3.12_6 \pm 0.06$ barns, private communication from J. D. Seagrave; and J. D. Seagrave and W. T. H. van Oers, to appear in Proceedings of the Symposium on Light Nuclei, Few-Body Problems, and Nuclear Forces, held at Brela, Yugoslavia (1967), Gordon and Breach (1968).
12. J. D. Seagrave and R. L. Henkel, Phys. Rev. 98, 666 (1955).
13. H. B. Willard, J. K. Bair, and C. M. Jones, Phys. Letters 9, 339 (1964).
14. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953); W. D. Allen, A. T. G. Ferguson, and J. Roberts, Proc. Phys. Soc. (London) A68, 650 (1955); A. Bratenahl, J. M. Peterson, and J. P. Stoering, Phys. Rev. 110, 927 (1958); J. M. Peterson, A. Bratenahl and J. P. Stoering, Phys. Rev. 120, 521 (1960); R. A. J. Riddle, A. Langsford, P. H. Bowen, and G. C. Cox, Nucl. Phys. 61, 457 (1965); L. S. Goodman, Phys. Rev. 88, 686 (1952); H. L. Poss, E. O. Salant, G. A. Snow, and L. C. L. Yuan, Phys. Rev. 87, 11 (1952); D. I. Meyer and W. Nyer, Los Alamos Scientific Laboratory Report LA-1279 (1951).
15. W. D. Allen, A. T. G. Ferguson, and J. Roberts, Proc. Phys. Soc. (London) A68, 650 (1955).
16. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953).
17. A. J. Elwyn, R. O. Lane, and A. Langsdorf, Jr., Phys. Rev. 128, 779 (1962).
18. D. Blanc, F. Cambou, and G. Vedrenne, J. Phys., Colloque No. 1, C1-71 (1966).
19. J. D. Seagrave and L. Cranberg, Phys. Rev. 105, 1816 (1957).
20. M. Brüllmann, H. J. Gerber, D. Meier, and P. Scherrer, Helv. Phys. Acta 32, 511 (1959).
21. E. Wantuch, Phys. Rev. 84, 169 (1951).
22. J. C. Allred, A. H. Armstrong, R. O. Bondelid, and L. Rosen, Phys. Rev. 88, 433 (1952).
23. J. D. Seagrave, Phys. Rev. 97, 757 (1955).
24. J. D. Seagrave, J. C. Hopkins, and P. W. Keaton, WASH-1071, 126 (1966), preliminary data only.
25. B. E. Bonner, E. B. Paul, and G. C. Phillips, Bull. Am. Phys. Soc., Series II, 11, 303 (1966), and private communication.
26. A. C. Berick, thesis, UCLA (1967).
27. I. Basar, to appear in Proceedings of the Symposium on Light Nuclei, Few-Body Problems, and Nuclear Forces, held at Brela, Yugoslavia (1967), Gordon and Breach (1968), and private communication from P. Tomaš to J. D. Seagrave.
28. R. S. Christian and J. L. Gammel, Phys. Rev. 91, 100 (1953).
29. J. D. Anderson and H. F. Lutz, UCRL-14955 (1966).
30. L. Stewart, Los Alamos Scientific Laboratory Report LA-3270 (1965).
31. G. C. Wick, Atti Acad. d'Ital., 13, 1203 (1943).
32. See, for example, Ta-You Wu and Takashi Ohmura, Quantum Theory of Scattering, Englewood Cliffs, N. J., Prentice Hall, Inc., (1962), pp. 7 and 256.

33. W. T. H. van Oers and K. W. Brockman, Jr., Nucl. Phys. A92, 561 (1967), and private communication.

34. R. Bösch, J. Lang, R. Müller, and W. Wölfli, Phys. Letters 8, 120 (1964).

35. R. Kosiek, D. Müller, and R. Pfeiffer, Phys. Letters 21, 199 (1966).

36. J. B. Warren, K. L. Erdman, L. P. Robertson, D. A. Axen, and J. R. MacDonald, Phys. Rev. 132, 1691 (1963).

37. B. L. Berman, L. J. Koester, Jr., and J. H. Smith, Phys. Rev. 133, B117 (1964).

38. J. R. Steward, R. C. Morrison, and J. S. O'Conell, Yale Electron Accelerator Laboratory internal report (1964).

39. J. C. Gunn and J. Irving, Phil. Mag. 42, 1353 (1951).

40. U. Eichmann, Z. Physik 175, 115 (1963).

41. M. Verde, Helv. Phys. Acta 23, 453 (1950).

42. R. Bösch, J. Lang, R. Müller, and W. Wölfli, Phys. Letters 15, 243 (1965).

43. J. S. Merritt, J. G. V. Taylor, and A. W. Boyd, Nucl. Sci. Eng. 28, 286 (1967).

44. M. Cerineo, K. Ilakovac, I. Šlaus, and P. Tomaš, Phys. Rev. 124, 1947 (1961).

45. M. Holmberg and J. Hansen, IAEA Conf. on Nuclear Data; Microscopic Cross Sections and Other Data Basic for Nuclear Reactors, Paris, October 17-21, 1966, in Nuclear Data for Reactors, IAEA, Vienna, 1967, Vol. I, p. 209.

46. H. C. Catron, M. D. Goldberg, R. W. Hill, J. M. LeBlanc, J. P. Stoering, C. J. Taylor, and M. A. Williamson, Phys. Rev. 123, 218 (1961).

47. S. Messelt, Nucl. Phys. 48, 512 (1963).

48. M. Brüllmann, H. Jung, and D. Meier, Helv. Phys. Acta 37, 220 (1964).

49. H. Jérémie, M. Heyman, and J. Kahane, J. Phys. Rad. 22, 847 (1961).

50. G. C. Phillips, Lecture Series at Zagreb (1965), and W. D. Simpson, Ph.D. thesis, Rice University (May 1965).

51. L. M. Delves, Nucl. Phys. 26, 136 (1961).

52. C. H. Poppe, C. H. Holbrow, and R. R. Borchers, Phys. Rev. 129, 733 (1963).

53. K. Ilakovac, L. G. Kuo, M. Petravić, I. Šlaus, and P. Tomaš, Phys. Rev. Letters 6, 356 (1961), and Nucl. Phys. 43, 254 (1963); the same data were also reported by I. Šlaus, Progress in Fast Neutron Physics, Chicago, Ill., The University of Chicago Press, 1963, p. 61. See also Ref. 56 for the renormalizations made to these data.

54. V. M. Maksimenko and I. L. Rozental, JETP 5, 546 (1957).

55. G. G. Ohlsen, Nucl. Instr. and Meth. 37, 240 (1965).

56. At the suggestion of I. Šlaus, the data herein have been raised by 25% (private communication to Stewart, July 1966). NOTE ADDED IN PROOF: Although Šlaus increased this cross section due to the better independent measurements of Cerineo et al. [Phys. Rev. 133, B948 (1964)], it is interesting to note that he has recently re-presented the results of both experiments without his suggested renormalization. See, for example, I. Šlaus, Rev. Mod. Phys. 39, 575 (1967), Cf. 1 and 2. It seems, therefore, that the absolute values of these cross sections, which already appear large (in terms of the theoretical interpretation and the total (n, 2n) cross section), have not yet been well established.

57. S. Kikuchi, J. Sanada, S. Suwa, I. Hayashi, K. Nisimura, and K. Fukunaga, J. Phys. Soc. (Japan) 15, 749 (1960).

58. J. D. Anderson, C. Wong, J. W. McClure, and B. A. Pohl, Phys. Rev. Letters 15, 66 (1965); J. D. Anderson and H. F. Lutz, UCRL-14955 (1966).

59. G. Vedrenne, D. Blanc, and F. Cambou, Antwerp Conference, 1965.

60. M. Cerineo, K. Ilakovac, I. Šlaus, P. Tomaš, and V. Valković, Phys. Rev. 133, B948 (1964).

61. W. T. H. van Oers and K. W. Brockman, Jr., Nucl. Phys. 47, 338 (1963).

62. R. M. Frank and J. L. Gammel, Phys. Rev. 93, 463 (1954).

TABLE I

EVALUATED NEUTRON CROSS SECTIONS SCATTERED FROM DEUTERIUM

(TABULAR DATA FROM GRAPHS)

ASSUMPTIONS:

For the sake of clarity, the values for $\sigma_{n,\gamma}$ have been neglected in the sums for σ_{NON} and σ_{TOT} for E_n > 100 eV.

	E_0	σ_{TOT} Barns	σ_{el} Barns	σ_{NON} Barns	$\sigma_{n,\gamma}$ μ Barns	$\sigma_{n,2n}$ Barns
eV	1.0×10^{-4}	3.208	3.2	0.008	8000	0
eV	2.53×10^{-2}	3.200506	↓	0.000506	506	↓
eV	1.00×10^{2}	3.200008	↓	0.000008	8	↓
		[Neglecting (n, γ)]	↓	[Neglecting (n, γ)]		↓
keV	1.0	3.2	3.2	0	2.5	↓
keV	2.0	↓	↓	↓	1.76	↓
keV	3.0	↓	↓	↓	1.47	↓
keV	4.0	↓	↓	↓	1.30	↓
keV	5.0	↓	↓	↓	1.19	↓
keV	6.0	↓	↓	↓	1.11	↓
keV	7.0	↓	↓	↓	1.06	↓
keV	8.0	↓	↓	↓	1.03	↓
keV	9.0	↓	↓	↓	1.01	↓
keV	10.0	↓	↓	↓	1.00	↓
keV	11.0	3.195	3.195	↓	0.997	↓
keV	12.0	3.190	3.190	↓	0.995	↓
keV	13.0	3.185	3.185	↓	0.995	↓
keV	15.0	3.180	3.180	↓	0.998	↓
keV	17.0	3.170	3.170	↓	1.01	↓
keV	20.0	3.160	3.160	↓	1.03	↓
keV	25.0	3.145	3.145	↓	1.10	↓
keV	30.0	3.135	3.135	↓	1.15	↓
keV	40.0	3.125	3.125	↓	1.27	↓
keV	50.0	3.120	3.120	↓	1.39	↓
keV	60.0	3.110	3.110	↓	1.50	↓
keV	70.0	3.105	3.105	↓	1.61	↓
keV	80.0	3.100	3.100	↓	1.72	↓
keV	90.0	3.100	3.100	↓	1.82	↓
keV	100.0	3.100	3.100	↓	1.94	↓
keV	150.0	3.10	3.10	↓	2.38	↓
keV	200.0	3.08	3.08	↓	2.74	↓
keV	220.0	3.07	3.07	↓	2.9	↓
keV	250.0	3.05	3.05	↓	3.1	↓
keV	300.0	3.03	3.03	↓	3.33	↓
keV	350.0	3.02	3.02	↓	3.6	↓
keV	400.0	3.005	3.005	↓	3.83	↓
keV	450.0	3.0	3.0	↓	4.0	↓
keV	500.0	2.99	2.99	↓	4.26	↓
keV	550.0	2.975	2.975	↓	4.4	↓
keV	600.0	2.965	2.965	↓	4.64	↓
keV	650.0	2.95	2.95	↓	4.75	↓
keV	700.0	2.945	2.945	↓	4.99	↓
keV	750.0	2.94	2.94	↓	5.1	↓
keV	800.0	2.925	2.925	↓	5.30	↓
keV	850.0	2.915	2.915	↓	5.4	↓
keV	900.0	2.910	2.910	↓	5.55	↓
keV	950.0	2.905	2.905	↓	5.65	↓
keV	1000.0	2.90	2.90	↓	5.86	↓

	E_0 MeV	σ_{TOT} Barns	σ_{el} Barns	σ_{NON} Barns	$\sigma_{n,\gamma}$ μ Barns	$\sigma_{n,2n}$ Barns
MeV	1.2	2.825	2.825	0	6.35	0
MeV	1.5	2.73	2.73	↓	7.0	↓
MeV	1.75	2.64	2.64	↓	7.4	↓
MeV	1.95	2.555	2.555	↓	7.7	↓
MeV	2.0	2.54	2.54	↓	7.82	↓
MeV	2.25	2.445	2.445	↓	8.1	↓
MeV	2.45	2.36	2.36	↓	8.4	↓
MeV	2.5	2.345	2.345	↓	8.5	↓
MeV	2.75	2.25	2.25	↓	8.8	↓
MeV	3.0	2.16	2.16	↓	9.0	↓
MeV	3.27	2.06	2.06	↓	9.1	↓
MeV	3.339	2.05	2.05	↓	9.2	(Thresh.)
MeV	3.4	2.035	2.0338	0.0012	9.3	0.0012
MeV	3.5	2.005	2.0021	0.0029	9.4	0.0029
MeV	3.75	1.945	1.937	0.008	9.6	0.008
MeV	4.0	1.875	1.8625	0.0135	9.7	0.0135
MeV	4.25	1.82	1.801	0.019	9.9	0.019
MeV	4.5	1.77	1.745	0.025	10.0	0.025
MeV	5.0	1.66	1.623	0.037	10.15	0.037
MeV	5.5	1.57	1.5213	0.0487	10.3	0.0487
MeV	5.6	1.555	1.5039	0.0511	10.4	0.0511
MeV	6.0	1.485	1.4248	0.0602	10.5	0.0602
MeV	6.5	1.415	1.3447	0.0713	10.6	0.0713
MeV	7.0	1.35	1.2680	0.0820	10.75	0.0820
MeV	7.25	1.32	1.2320	0.088	10.8	0.088
MeV	7.5	1.29	1.1975	0.0925	10.8	0.0925
MeV	7.85	1.25	1.1505	0.0995	10.75	0.0995
MeV	8.0	1.23	1.1273	0.1027	10.7	0.1027
MeV	8.5	1.175	1.0633	0.1117	10.65	0.1117
MeV	9.0	1.135	1.014	0.121	10.6	0.121
MeV	9.5	1.085	0.9558	0.1292	10.45	0.1292
MeV	9.7	1.075	0.9427	0.1323	10.35	0.1323
MeV	10.0	1.05	0.913	0.137	10.3	0.137
MeV	10.5	1.01	0.866	0.144	10.25	0.144
MeV	11.0	0.975	0.8245	0.1505	10.2	0.1505
MeV	11.5	0.943	0.7865	0.1565	10.1	0.1565
MeV	11.75	0.930	0.7705	0.1595	10.0	0.1595
MeV	12.0	0.912	0.750	0.162	10.0	0.162
MeV	12.17	0.904	0.740	0.164	10.0	0.164
MeV	12.25	0.900	0.7352	0.1648	9.9	0.1648
MeV	12.5	0.883	0.716	0.167	9.9	0.167
MeV	13.0	0.855	0.683	0.172	9.7	0.172
MeV	13.5	0.832	0.656	0.176	9.6	0.176
MeV	14.0	0.810	0.630	0.180	9.5	0.180
MeV	14.1	0.802	0.621	0.181	9.4	0.181
MeV	14.5	0.788	0.6044	0.1836	9.3	0.1836
MeV	15.0	0.768	0.581	0.187	9.2	0.187
MeV	16.0	0.728	0.536	0.1923	9.0	0.1923
MeV	17.0	0.695	0.498	0.197	8.7	0.197
MeV	18.0	0.665	0.4644	0.2006	8.5	0.2006
MeV	19.0	0.635	0.4317	0.2033	8.2	0.2033
MeV	20.0	0.608	0.4027	0.2053	8.1	0.2053
MeV	20.57	0.595	0.389	0.206	8.0	0.206

DATA REFERENCES

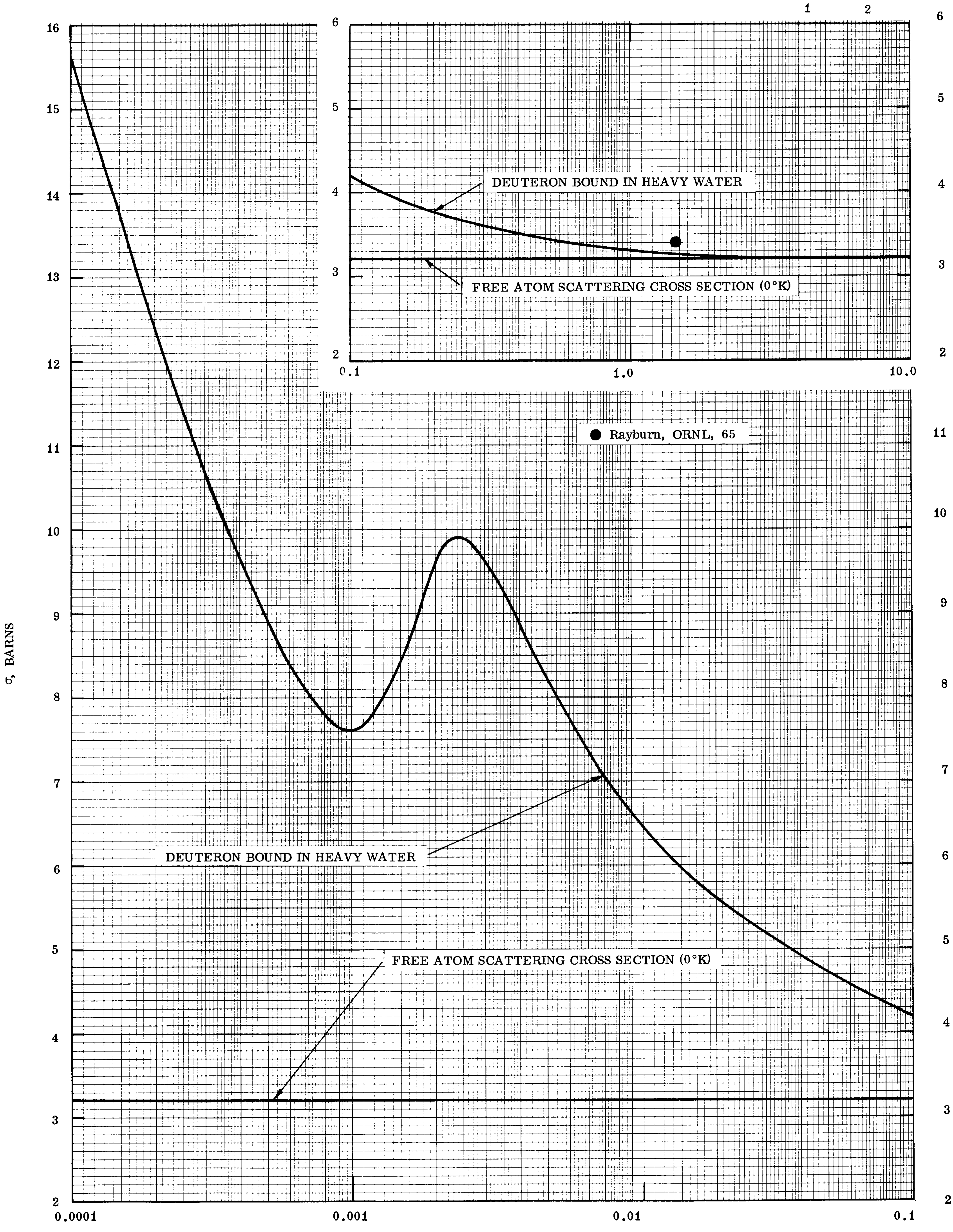
DEUTERON BOUND IN HEAVY WATER

1. ● L. A. Rayburn and E. O. Wollan, Nucl. Phys. 61, 381 (1965). Point obtained from transmission measurements on D_2O and various compounds containing oxygen.

2. ——— Curve obtained by subtracting the low energy total cross section of oxygen from that of D_2O (and dividing by 2); the D_2O totals were those of Rainwater et al., Col. 1948, and BNL (unpublished, see BNL-325, second edition). Below 0.0004 eV the curve was obtained by extrapolation.

TOTAL CROSS SECTION

D Z 1 MASS 2

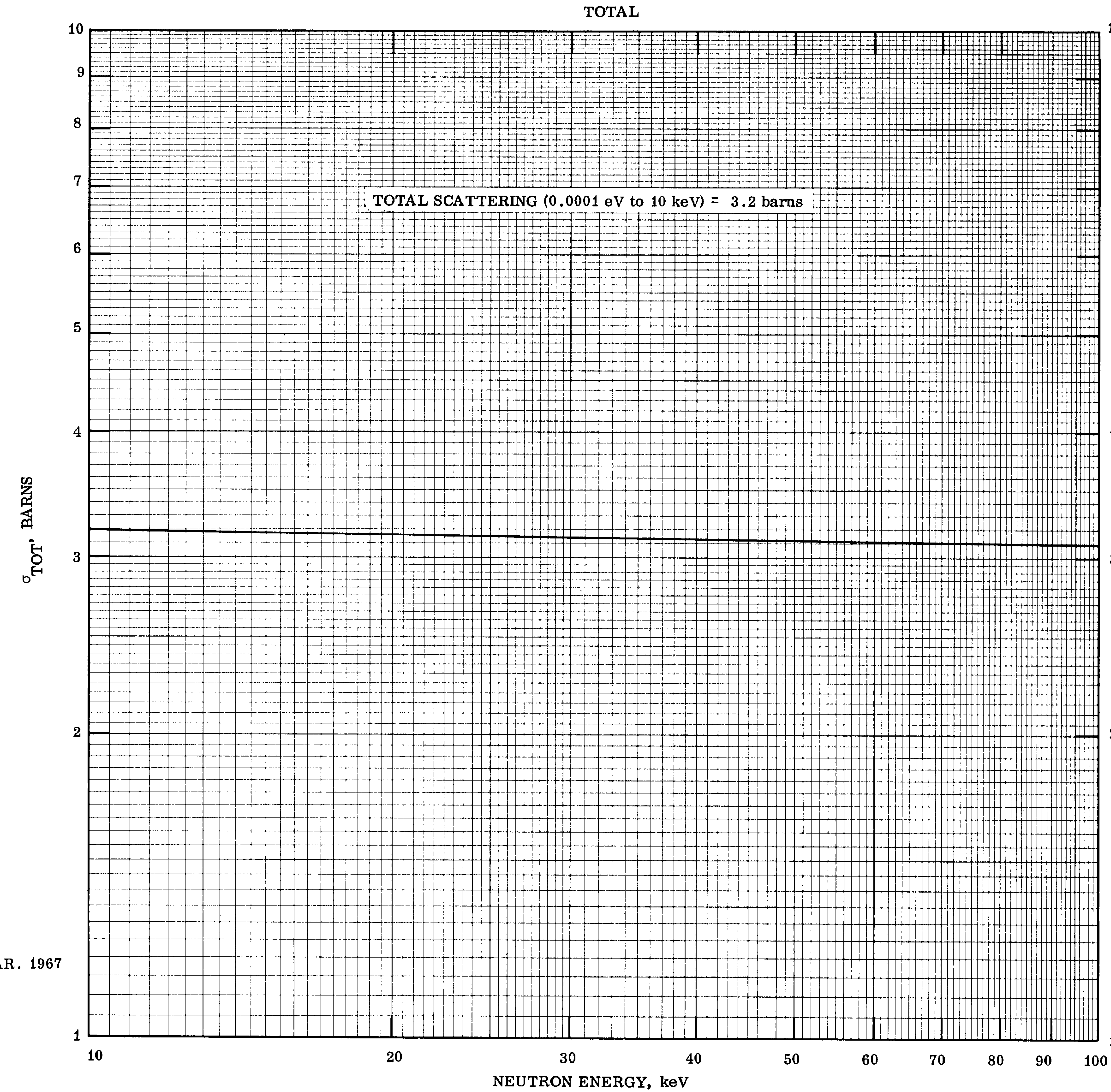


DATA REFERENCE

TOTAL CROSS SECTION

1.——— A potential scattering cross section of 3.2 barns gave relatively good agreement with the values calculated from measurements made on various compounds. A straight line on a log-log basis from 10 to 100 keV was guessed as a smooth extrapolation to the region above 100 keV where old measurements are available.

D Z 1 MASS 2



MAR. 1967

TOT-1-2-1

DATA REFERENCES

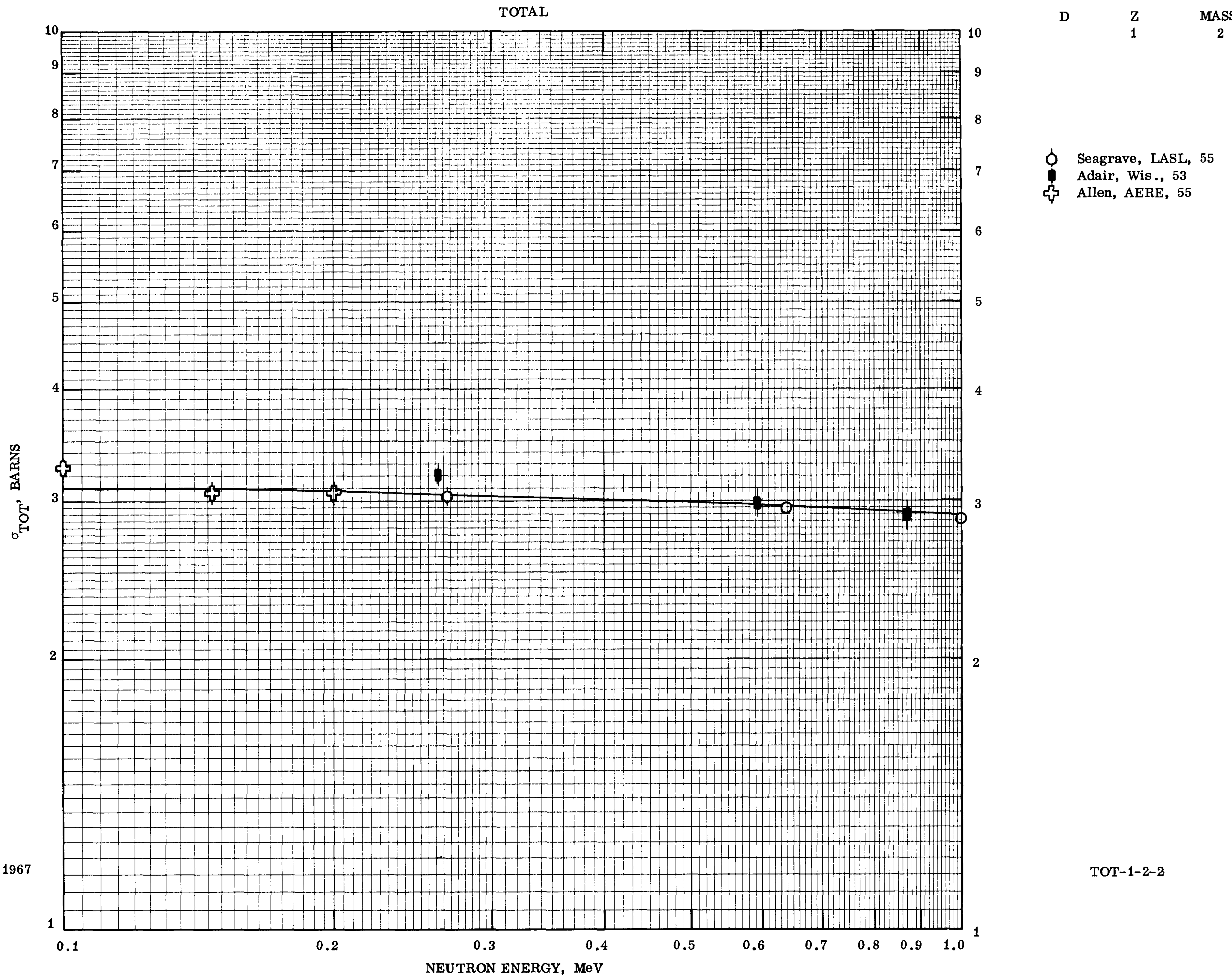
TOTAL CROSS SECTION

1. ϕ J. D. Seagrave and R. L. Henkel, Phys. Rev. 98, 666 (1955). Transmission measurements on deuterium gas using a stilbene scintillator in a conventional photomultiplier assembly.

2. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953). Transmission measurement of the ratio of heavy water to ordinary water. Ionization chamber used as detector.

3. W. D. Allen, A. T. G. Ferguson, and J. Roberts, Proc. Phys. Soc. (London) A68, 650 (1955). Two experiments were performed in which the differences between hydrogen- and deuterium-filled proportional counters were observed, with and without the insertion of a 3/4" lead filter for the gamma rays. On the run with the filter, however, the neutron intensity was reduced 30-40%. The second set of data was ignored since corrections made for the lead filter were not particularly obvious.

D	Z	MASS
	1	2



MAR. 1967

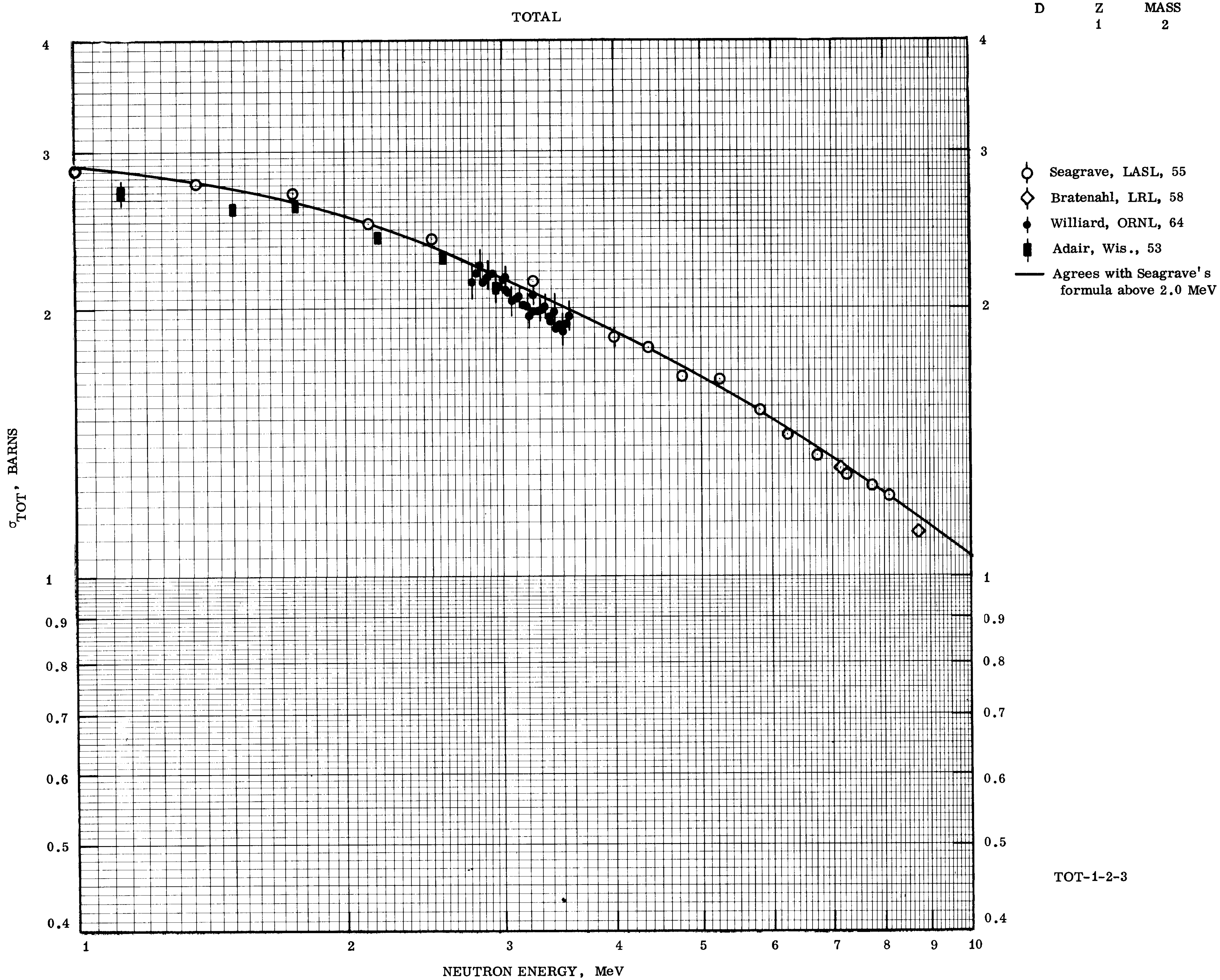
TOT-1-2-2

DATA REFERENCES

TOTAL CROSS SECTIONS

1. J. D. Seagrave and R. L. Henkel, Phys. Rev. 98, 666 (1955). Transmission measurements on deuterium gas using a stilbene scintillator in a conventional photomultiplier assembly.
2. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953). Transmission measurement of the ratio of heavy water to ordinary water. Ionization chamber used as detector.
3. H. B. Willard, J. K. Bair, C. M. Jones, Phys. Letters 9, 339 (1964). T(p, n) neutrons; deuterated polyethylene and graphite samples. Stilbene crystal.
4. A. Bratenahl, J. M. Peterson, and J. P. Stoering, Phys. Rev. 110, 927 (1958). D(d, n) neutrons; monitor and detector were plastic scintillators; scattering corrections applied but no specific information provided on the targets themselves.

D Z 1 MASS 2



MAR. 1967

TOT-1-2-3

DATA REFERENCES

TOTAL CROSS SECTIONS

1. ϕ J. D. Seagrave and R. L. Henkel, Phys. Rev. 98, 666 (1955). Transmission measurements on deuterium gas using a stilbene scintillator in a conventional photomultiplier assembly.

2. ♦ H. B. Willard, J. K. Bair, and C. M. Jones, Phys. Letters 9, 339 (1964). T(p, n) neutrons; deuterated polyethylene and graphite samples; stilbene crystal.

3. ◇ A. Bratenahl, J. M. Peterson, and J. P. Stoering, Phys. Rev. 110, 927 (1958). D(d, n) neutrons; monitor and detector were plastic scintillators. "Scattering corrections" applied but specific information on targets not provided.

4. ● L. S. Goodman, Phys. Rev. 88, 686 (1952). T(d, n) source; biased anthracene crystal detector; no information on target given.

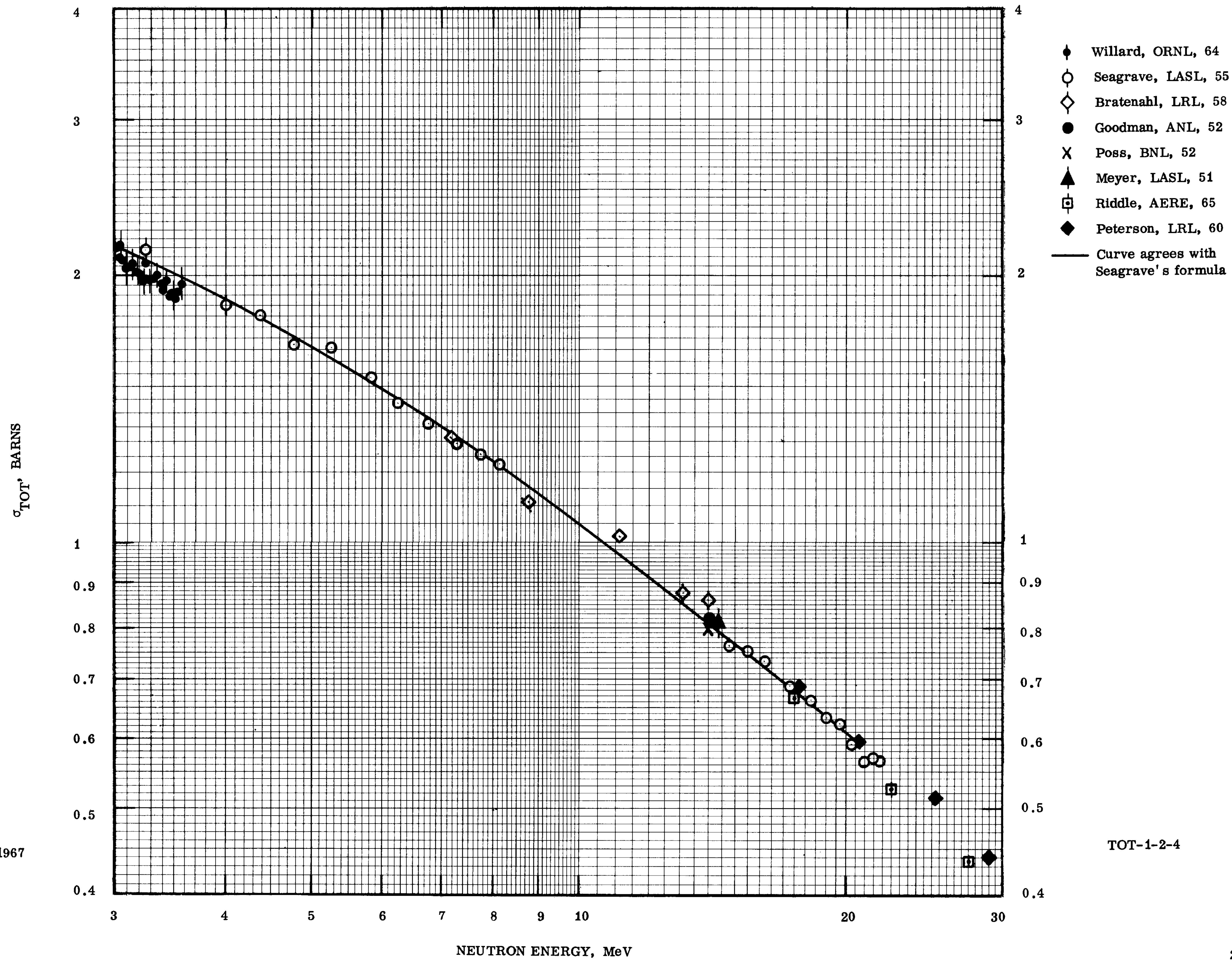
5. X H. L. Poss, E. D. Salant, G. A. Snow, and L. C. L. Yuan, Phys. Rev. 87, 11 (1952). T(d, n) source; liquid scintillator; difference measured between light and heavy water.

6. ▲ D. I. Meyer and W. Nyer, LA-1279 (1951). T(d, n) neutron source; D_2O sample; copper detectors implementing the $^{63}Cu(n, 2n)^{62}Cu$ activity. Scattering corrections estimated and checked experimentally and found to be negligible.

7. ⊡ R. A. J. Riddle, A. Langsdorf, P. H. Bowen, and G. C. Cox, Nucl. Phys. 61, 457 (1965). Source spectrum from 143-MeV protons on Al; scintillation detector used to measure difference between light and heavy water. Time of flight; 26 m flight path.

8. ◆ J. M. Peterson, A. Bratenahl, and J. P. Stoering, Phys. Rev. 120, 521 (1960). T(d, n) source; monitor and detector were plastic scintillators. "Scattering corrections" applied but specific information on targets not provided.

TOTAL



MAR. 1967

TOT-1-2-4

DATA REFERENCES

TOTAL CROSS SECTIONS

1. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953). Transmission measurement of the ratio of heavy water to ordinary water. Ionization chamber used as detector.

2. J. D. Seagrave and R. L. Henkel, Phys. Rev. 98, 666 (1955). Transmission measurements on deuterium gas using a stilbene scintillator in a conventional photomultiplier assembly.

3. H. B. Willard, J. K. Bair, and C. M. Jones, Phys. Letters 9, 339 (1964). T(p, n) neutrons; deuterated polyethylene and graphite samples; stilbene crystal. Due to crowding, only a few of these points are plotted here. All of the points are included on TOT-1-2-3, however.

4. A. Bratenahl, J. M. Peterson, and J. P. Stoering, Phys. Rev. 110, 927 (1958). D(d, n) neutrons; monitor and detector were plastic scintillators. "Scattering corrections" applied but specific information on targets not provided.

5. L. S. Goodman, Phys. Rev. 88, 686 (1952). T(d, n) source; biased anthracene crystal detector; no information on target given.

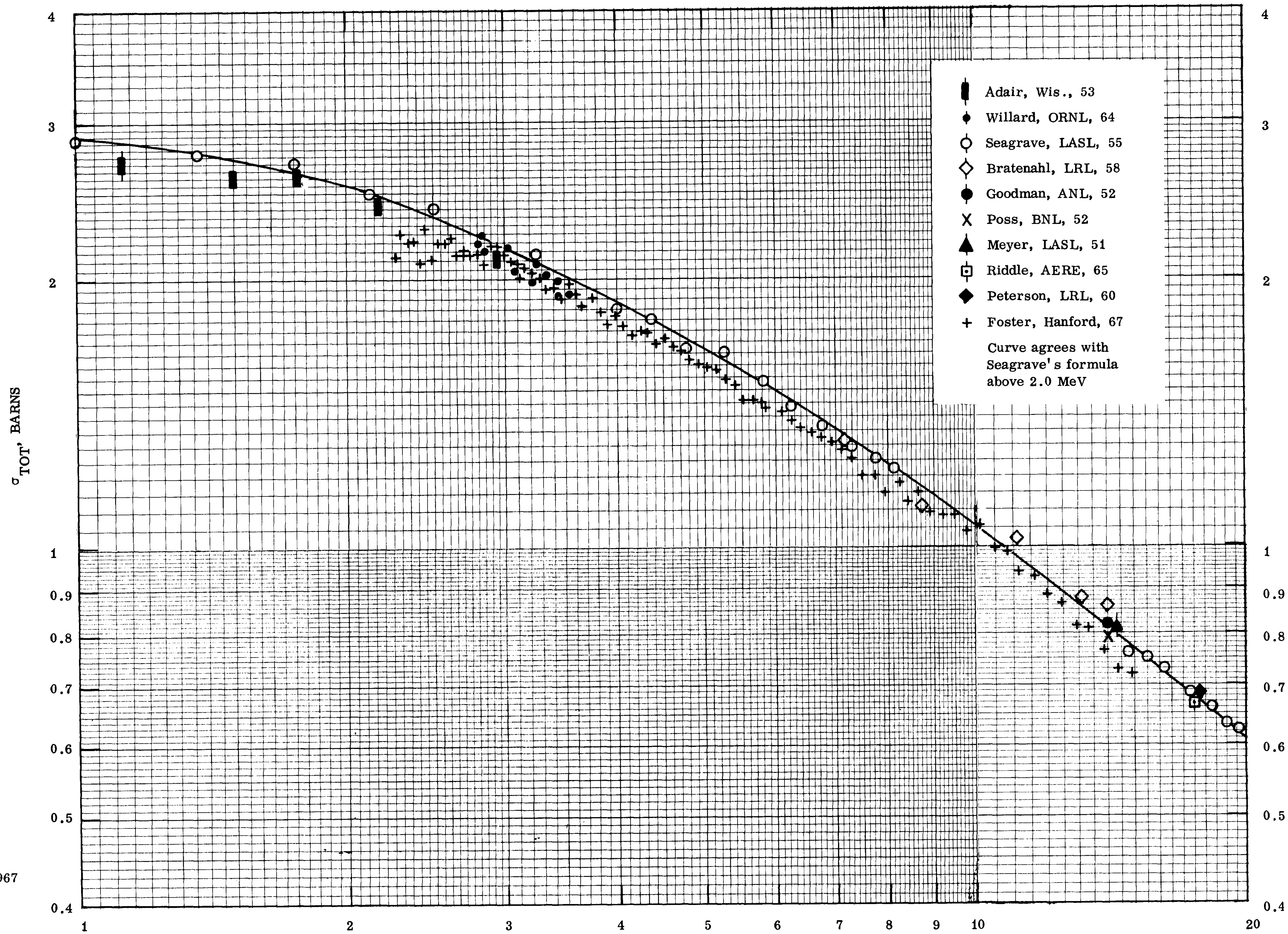
6. H. L. Poss, E. D. Salant, G. A. Snow, and L. C. L. Yuan, Phys. Rev. 87, 11 (1952). T(d, n) source; liquid scintillator; difference measured between light and heavy water.

7. D. I. Meyer and W. Nyer, LA-1279 (1951). T(d, n) neutron source; D_2O sample; copper detectors implementing the $^{63}Cu(n, 2n)^{62}Cu$ activity. Scattering corrections estimated and checked experimentally and found to be negligible.

8. R. A. J. Riddle, A. Langsdorf, P. H. Bowen, and G. C. Cox, Nucl. Phys. 61, 457 (1965). Source spectrum from 143-MeV protons on Al; scintillation detector used to measure difference between light and heavy water. Time of flight; 26 m of flight path.

9. J. M. Peterson, A. Bratenahl, and J. P. Stoering, Phys. Rev. 120, 521 (1960). T(d, n) source; monitor and detector were plastic scintillators. "Scattering corrections" applied but specific information on targets not provided.

10. D. W. Glasgow and D. G. Foster, Jr., Phys. Rev. 157, 764 (1967). Transmission measurement using time of flight, white spectrum; deuterated polyethylene target; liquid scintillator. Scattering corrections applied. The authors are indebted to Graham Foster for making the tabular results available prior to publication. Data plotted represent straight three-group averages.


Adair, Wis., 53
Willard, ORNL, 64
Seagrave, LASL, 55
Bratenahl, LRL, 58
Goodman, ANL, 52
Poss, BNL, 52
Meyer, LASL, 51
Riddle, AERE, 65
Peterson, LRL, 60
Foster, Hanford, 67
Curve agrees with Seagrave's formula above 2.0 MeV
σ_{TOT}, BARNS
NEUTRON ENERGY, MeV
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
1
2
3
4
5
6
7
8
9
10
20

DATA REFERENCES

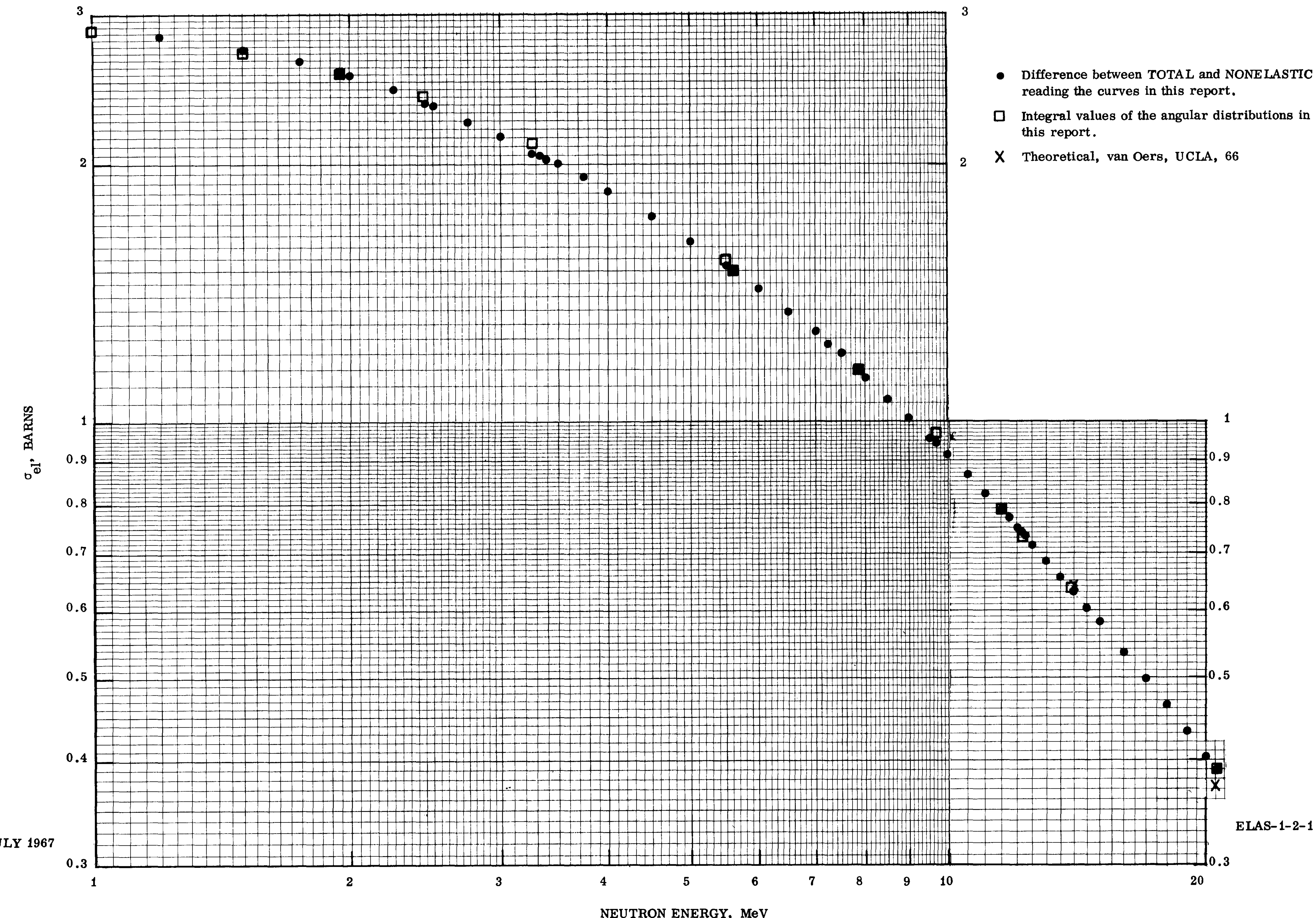
ELASTIC SCATTERING

1. □ To make full use of the information from the data, the elastic angular distributions were constructed independently of the total and nonelastic cross sections. The integrals of the angular distributions (the total elastic cross sections) were then considered along with the total and nonelastic cross-section data to evaluate the individual contributions.

2. ● The differences at various energies between the TOTAL (TOT-1-2-3 to 1-2-4) and NONELASTIC (NON-1-2-2) cross sections as read from the graphs.

3. X Integral values of the n+D angular distributions calculated by W. T. H. van Oers at UCLA (private communication, 1966).

COMPARISON OF ELASTIC SCATTERING INTEGRALS WITH (TOTAL - NONELASTIC)



JULY 1967

ELAS-1-2-1

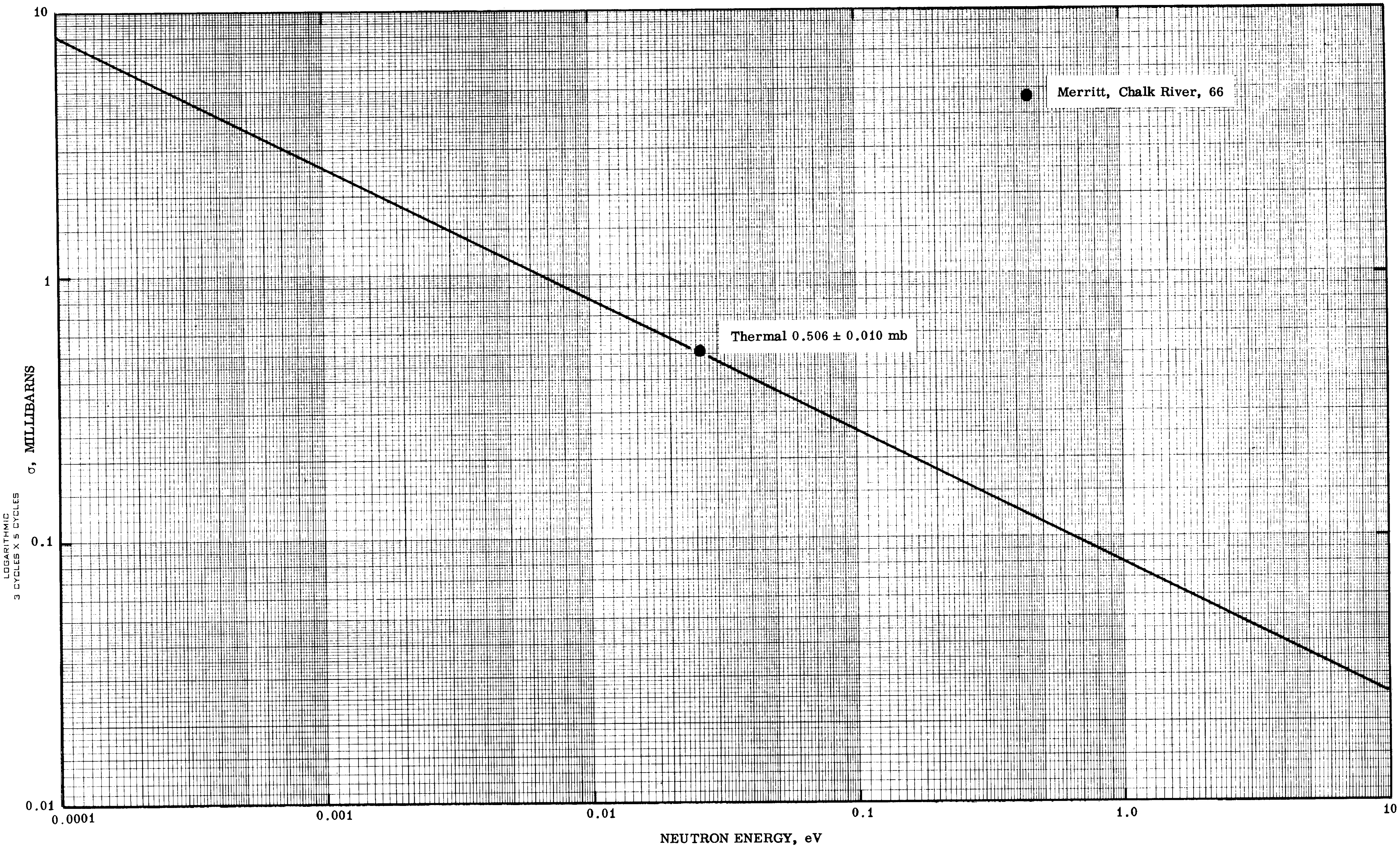
DATA REFERENCES

CAPTURE CROSS SECTIONS

1. ● J. S. Merritt, J. G. V. Taylor, and A. W. Boyd, Nucl. Sci. and Eng. 28, 286 (1967). Observed β's from the tritium produced using differential gas proportional counting techniques; relative to ^{59}Co. Error within size of point.

2.——— Curve follows "1/v" law through Merritt's value.

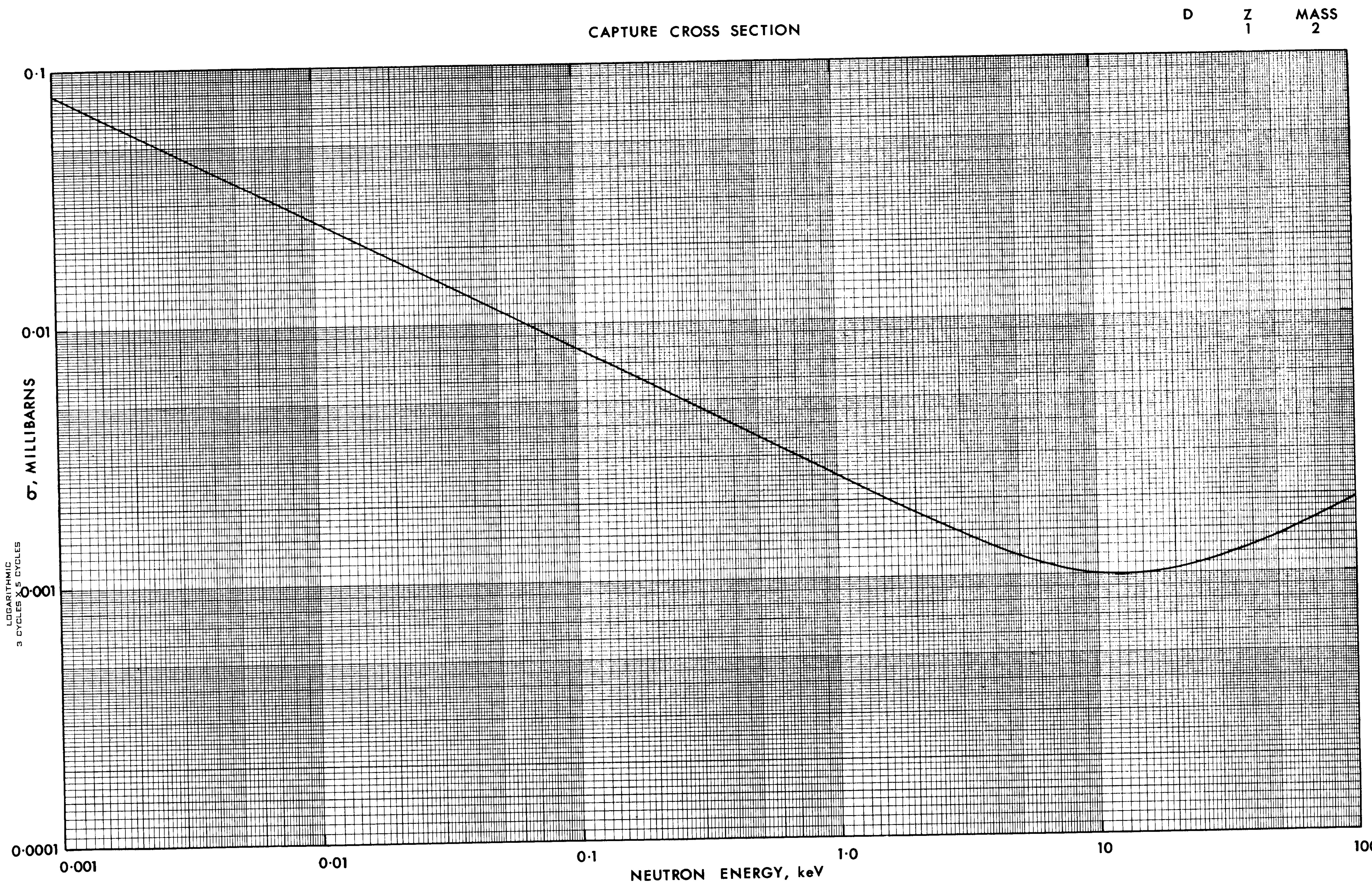
CAPTURE CROSS SECTION



DATA REFERENCE

CAPTURE CROSS SECTIONS

1. ——— Curve obtained by "1/v" law up to 1 keV. Between 1 and 100 keV the curve is a smooth interpolation.


D
Z
1
MASS
2
CAPTURE CROSS SECTION
0·1
0·01
0·001
0·0001
σ, MILLIBARNS
0·001
0·01
0·1
1·0
10
100
NEUTRON ENERGY, keV

CAP-1-2-2

DATA REFERENCES

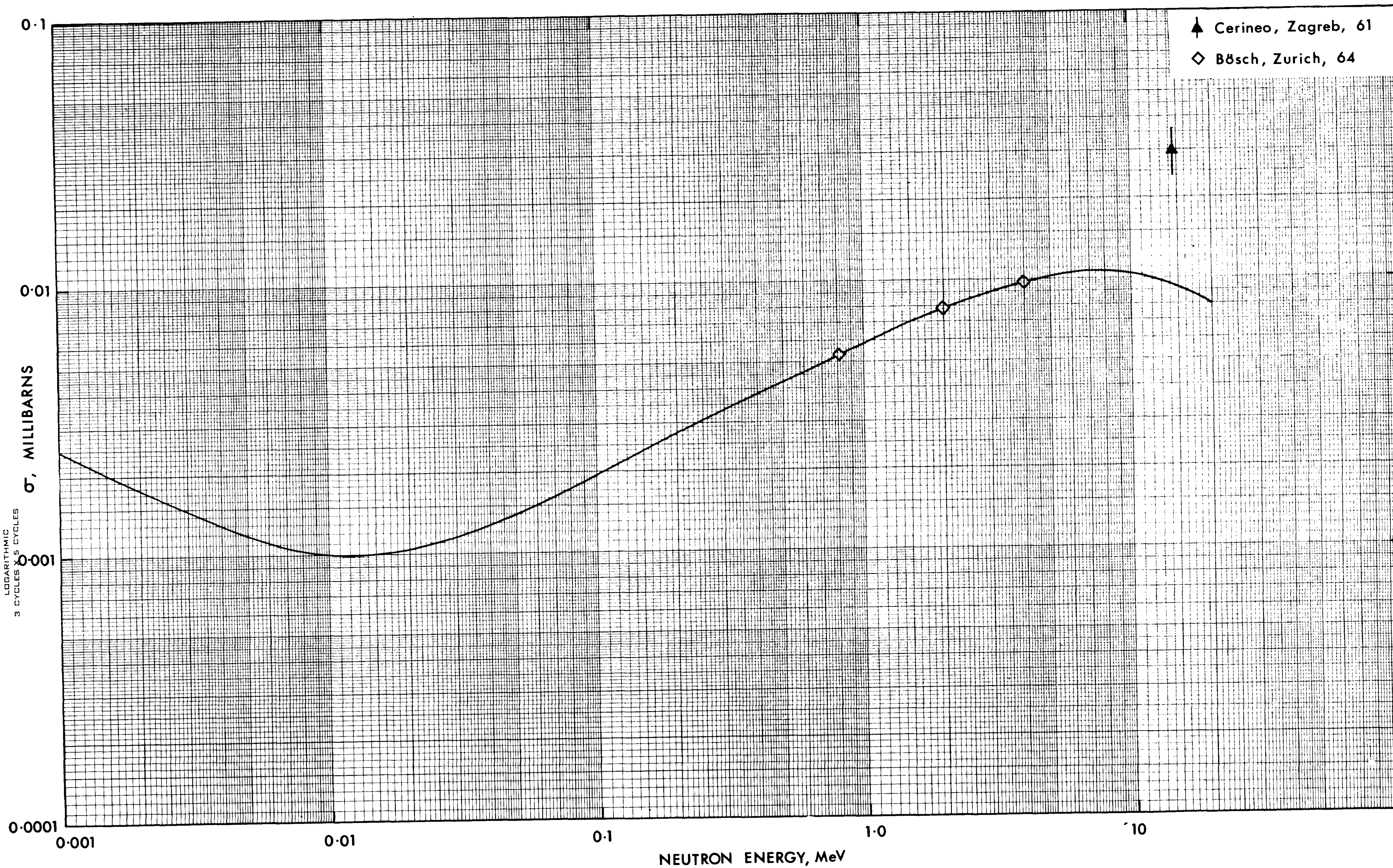
CAPTURE CROSS SECTIONS

1. ▲ M. Cerineo, K. Ilakovac, I. Šlaus and P. Tomaš, Phys. Rev. 124, 1947 (1961). Detected tritons using counter telescope and charged particle discrimination with dE/dx counter.

2. ◇ R. Bösch, J. Lang, R. Müller and W. Wölfli, Phys. Letters 8, 120 (1964) using γ rays from a reactor on a tritium gas target. Points obtained from detailed balance calculations.

3. ——— Curve above 0.1 MeV was calculated by the method given in: J. C. Gunn and J. Irving, Phil. Mag. 335, 1353 (1951).

CAPTURE CROSS SECTION



CAP-1-2-3

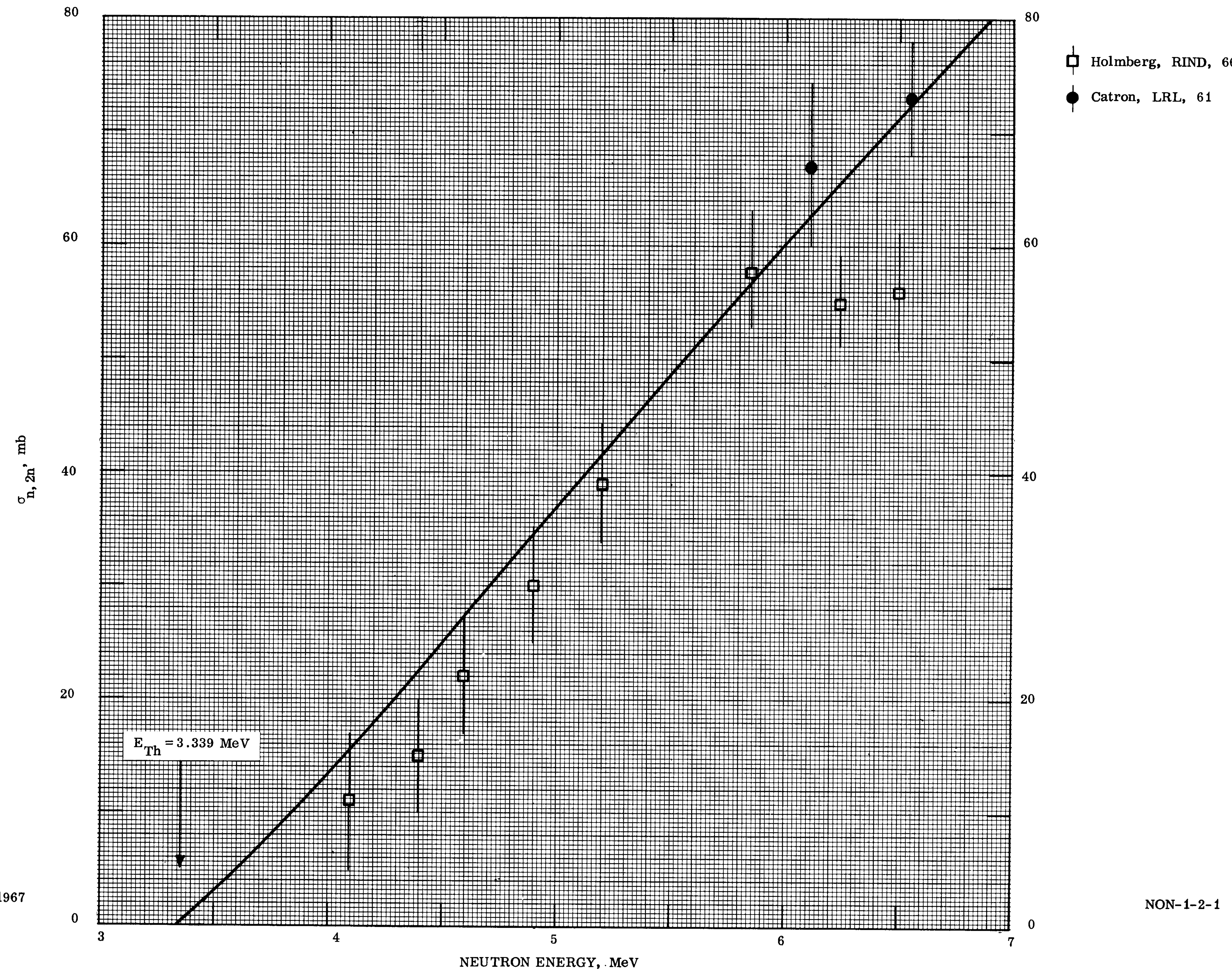
DATA REFERENCES

n, 2n REACTION

1. ⧫ H. C. Catron, M. D. Goldberg, R. W. Hill, J. M. LeBlanc, J. P. Stoering, C. J. Taylor, and M. A. Williamson, Phys. Rev. 123, 218 (1961). Detected neutrons in coincidence in a large liquid scintillator. Efficiency measured relative to $\bar{\nu}$ for ^{244}Cm and ^{252}Cf.

2. ⌑ M. Holmberg and J. Hansén, IAEA Conf. on Nuclear Data; Microscopic Cross Sections and Other Data Basic for Nuclear Reactors, Paris, October 17-21, 1966, paper CN-23/18. Liquid scintillator. Time-to-pulse height converter to measure correlation between capture pulses. Efficiency measured relative to $\bar{\nu}$ for ^{252}Cf.

D(n, 2n) REACTION



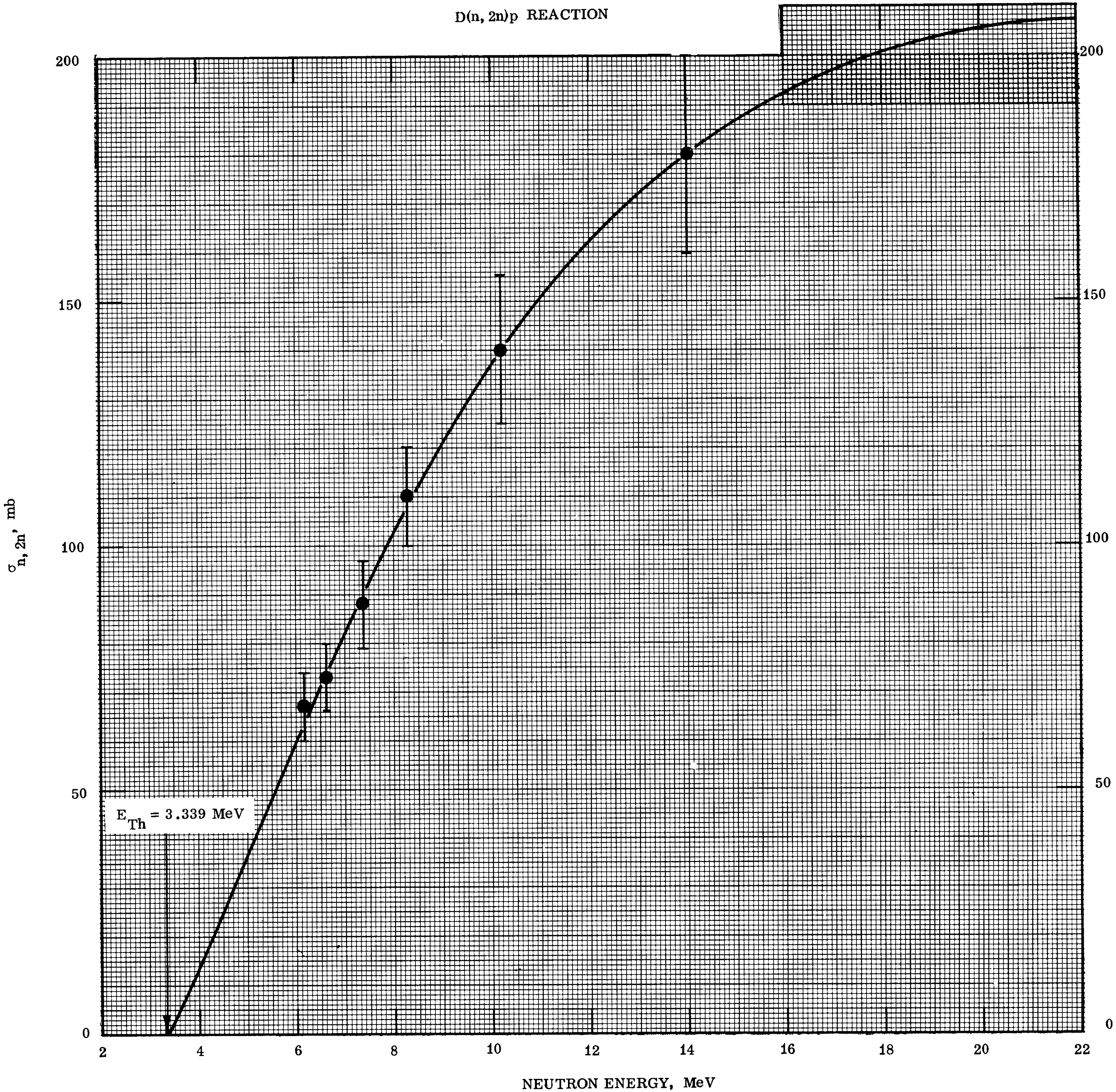
JULY 1967

NON-1-2-1

DATA REFERENCE

n, 2n REACTION

1. ⬤ H. C. Catron, M. D. Goldberg, R. W. Hill, J. M. LeBlanc, J. P. Stoering, C. J. Taylor, and M. A. Williamson, Phys. Rev. 123, 218 (1961). Detected neutrons in coincidence in a large liquid scintillator. Efficiency measured relative to $\bar{\nu}$ for ^{244}Cm and ^{252}Cf.


D(n, 2n)p REACTION
Catron, LRL, 61
$\sigma_{n,2n}$, mb
NEUTRON ENERGY, MeV
E_{Th} = 3.339 MeV
0
50
100
150
200
2
4
6
8
10
12
14
16
18
20
22

D	Z	MASS
	1	2

E_0 = 0.10 MeV

EVALUATED ANGULAR DISTRIBUTIONS
OF
NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	230	0.4291
-1.0	306	0.5709
SUM =	268	0.5000
$\times \sin\theta\, d\theta$ =	536	1.0000
$\times\, d\phi$ =	3.37 barns	
(Comparison with curve), σ_{TOT} =	3.1 barns	

DATA REFERENCE

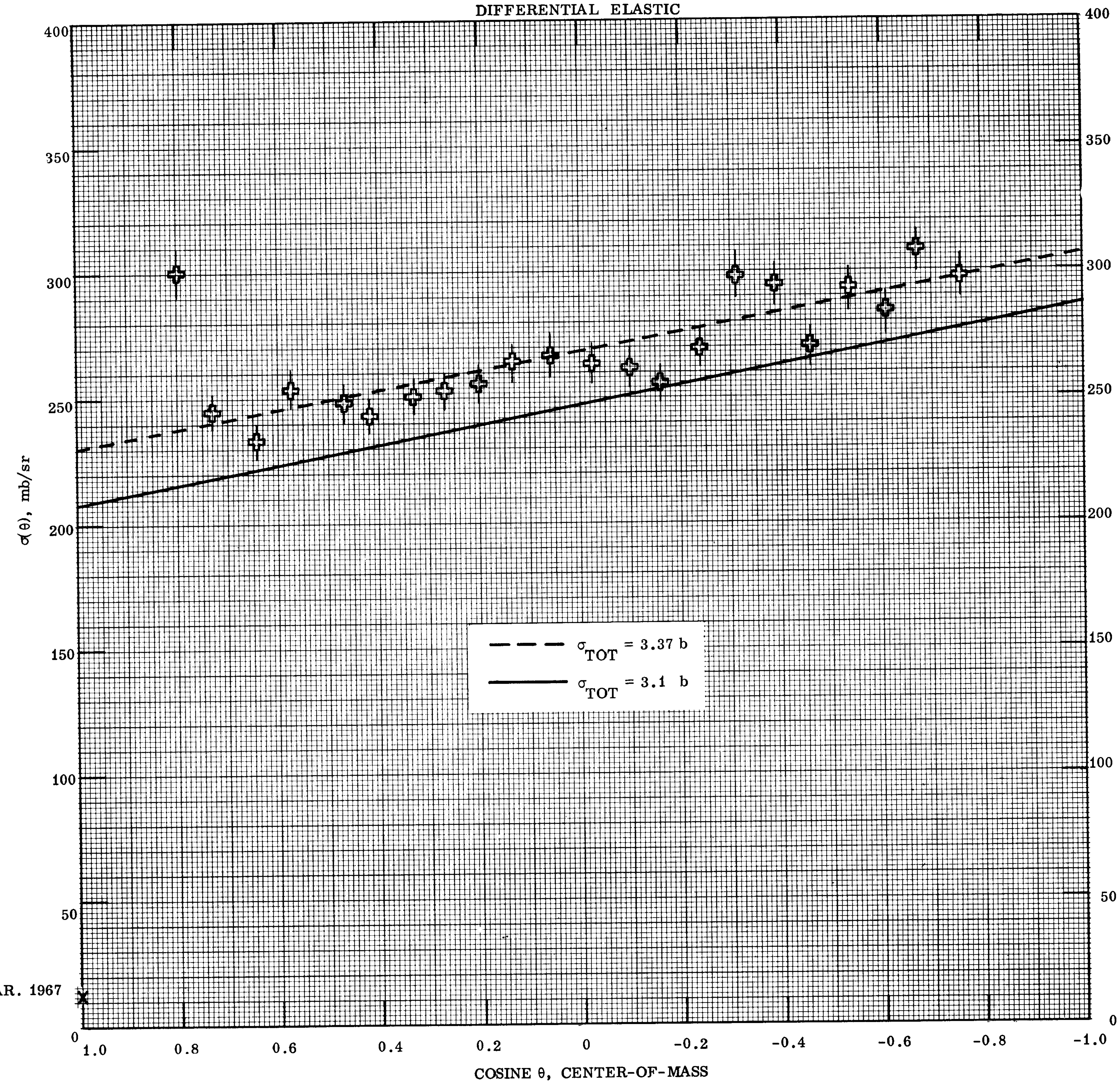
ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. ✠ W. D. Allen, A. T. G. Ferguson, and J. Roberts, Proc. Phys. Soc. (London) A68, 650 (1955).

Measured difference between hydrogen- and deuterium-filled proportional counters.

Since the absolute values are ~8.5% higher than σ_{TOT}, the shape but not the magnitude was used in the evaluation.



n + D ELASTIC SCATTERING

0.10 MeV, Allen, AERE, 55

X $\sigma_w(0°)$ = 13 mb/sr using σ_{TOT} = 3.1 b at 0.1 MeV

MAR. 1967

ANG-1-2-1

D	Z	MASS
	1	2

E_0 = 0.2 MeV

EVALUATED ANGULAR DISTRIBUTIONS OF NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	167	0.3250
0.9	174	0.3386
0.8	182	0.3542
0.7	189	0.3678
0.6	197	0.3834
0.5	205	0.3989
0.4	214	0.4164
0.3	222	0.4320
0.2	231	0.4495
0.1	240	0.4670
0.0	249	0.4846
-0.1	259	0.5040
-0.2	269	0.5235
-0.3	280	0.5449
-0.4	292	0.5682
-0.5	305	0.5935
-0.6	318	0.6188
-0.7	332	0.6461
-0.8	346	0.6733
-0.9	362	0.7044
-1.0	379	0.7375
SUM =	5139	10.0003
× sin θ dθ =	513.9	1.00003
× dϕ =	3.23 barns	
(Comparison with curve), σ_{TOT} =	3.08 barns	

DATA REFERENCE

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

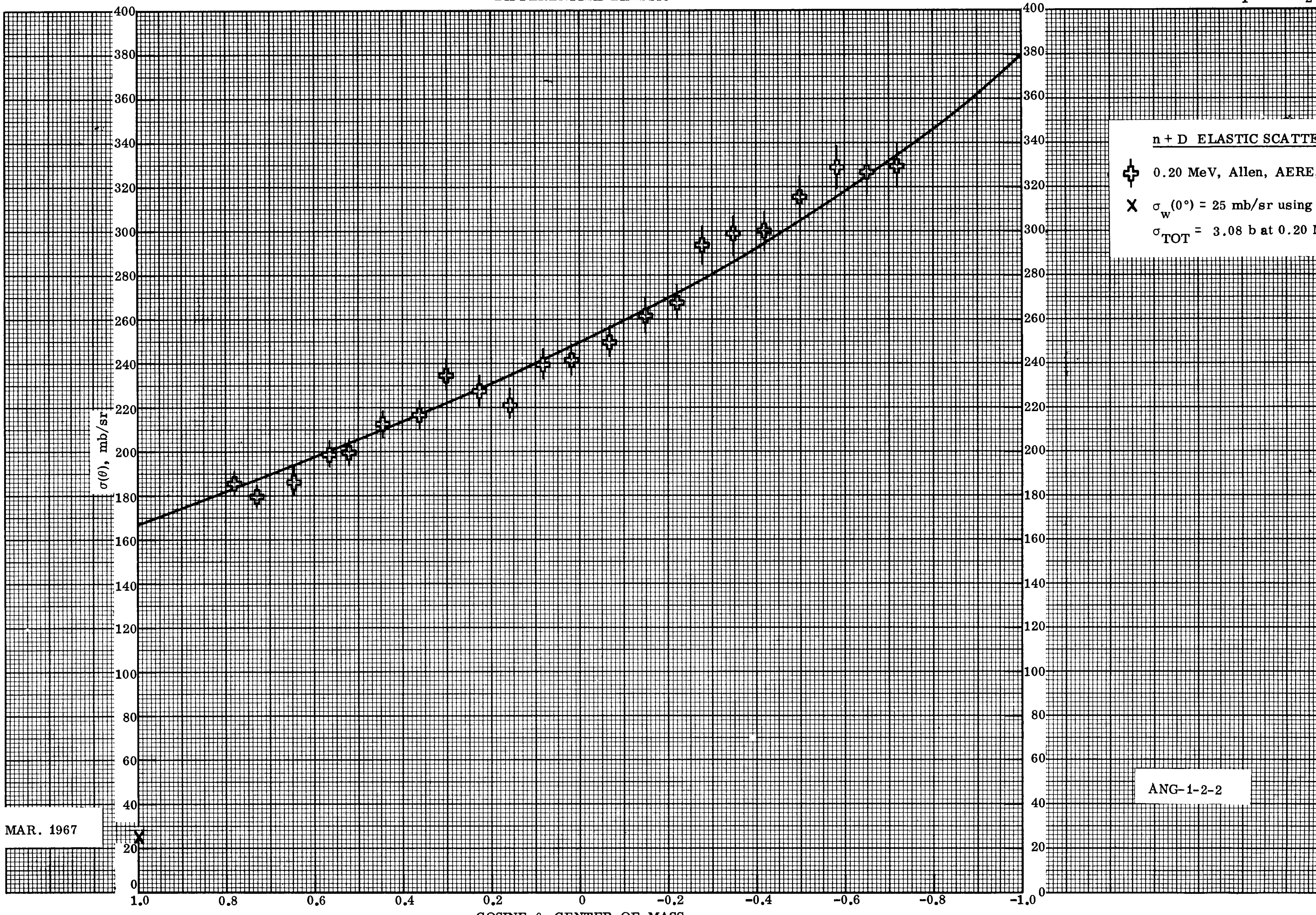
n + D ELASTIC SCATTERING:

1. W. D. Allen, A. T. G. Ferguson, and J. Roberts, Proc. Phys. Soc. (London) A68, 650 (1955).

   Measured difference between hydrogen- and deuterium-filled proportional counters.

D Z MASS
1 2

DIFFERENTIAL ELASTIC



MAR. 1967

ANG-1-2-2

10 X 10 TO THE ½ INCH

D	Z	MASS
	1	2

E_0 = 0.5 MeV

EVALUATED ANGULAR DISTRIBUTIONS
OF
NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	96	0.1935
0.9	105	0.2117
0.8	113	0.2278
0.7	122	0.2460
0.6	131	0.2641
0.5	141	0.2842
0.4	151	0.3044
0.3	162	0.3266
0.2	174	0.3508
0.1	187	0.3770
0.0	202	0.4072
-0.1	217	0.4375
-0.2	236	0.4758
-0.3	256	0.5161
-0.4	282	0.5685
-0.5	315	0.6350
-0.6	357	0.7197
-0.7	410	0.8266
-0.8	475	0.9576
-0.9	553	1.1148
-1.0	644	1.2983
SUM =	4959	9.9973
$\times \sin\theta\, d\theta$ =	495.9	0.99973
$\times d\phi$ =	3.12 barns	
(Comparison with curve), σ_{TOT} =	2.99 barns	

ANG-1-2-3

MARCH 1967

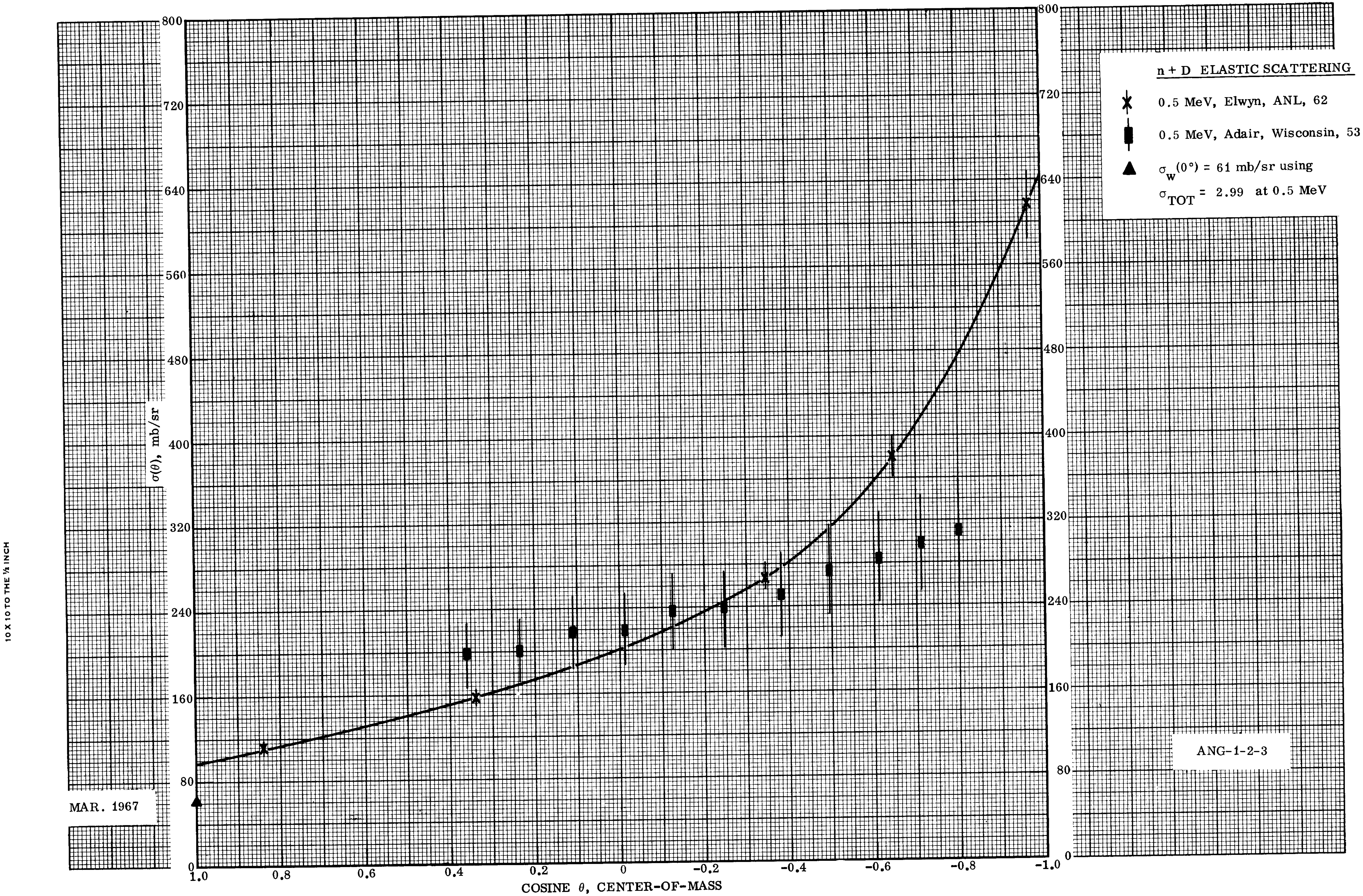
DATA REFERENCES

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. ✗ A. J. Elwyn, R. O. Lane, and A. Langsdorf, Jr., Phys. Rev. 128, 779 (1962). From averaging left and right measurements using CD_2 and C samples. $^7Li(p,n)$ neutron source, corrections applied for $^7Li(p,n)^7Be^*$. Not corrected for multiple scattering or beam attenuation which are small effects. CD_2 target ~96% transmission. BF_3 detectors. Normalized to carbon.

2. ▮ R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953). $^7Li(p,n)$ neutron source. Proportional counter filled with deuterium. $^{10}BF_3$ flux monitor. The angular distribution data at 220 keV have been omitted.


n + D ELASTIC SCATTERING
0.5 MeV, Elwyn, ANL, 62
0.5 MeV, Adair, Wisconsin, 53
$\sigma_w(0°)$ = 61 mb/sr using
σ_{TOT} = 2.99 at 0.5 MeV
ANG-1-2-3
MAR. 1967
$\sigma(\theta)$, mb/sr
COSINE θ, CENTER-OF-MASS
800
720
640
560
480
400
320
240
160
80
0
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
10 X 10 TO THE ½ INCH

D	Z	MASS
	1	2

E_0 = 0.75 MeV

EVALUATED ANGULAR DISTRIBUTIONS
OF
NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	125	0.2641
0.9	126	0.2662
0.8	129	0.2726
0.7	132	0.2789
0.6	135	0.2853
0.5	138	0.2916
0.4	143	0.3022
0.3	149	0.3148
0.2	157	0.3317
0.1	166	0.3508
0.0	177	0.3740
-0.1	191	0.4036
-0.2	206	0.4353
-0.3	227	0.4796
-0.4	251	0.5304
-0.5	289	0.6107
-0.6	333	0.7036
-0.7	388	0.8198
-0.8	462	0.9762
-0.9	546	1.1537
-1.0	648	1.3692
SUM =	4731.5	9.9977
$\times \sin\theta\, d\theta$ =	473.15	0.9998
$\times\, d\phi$ =	2.986 barns	
(Comparison with curve), σ_{TOT} =	2.94 barns	

ANG-1-2-4

MARCH 1967

DATA REFERENCES

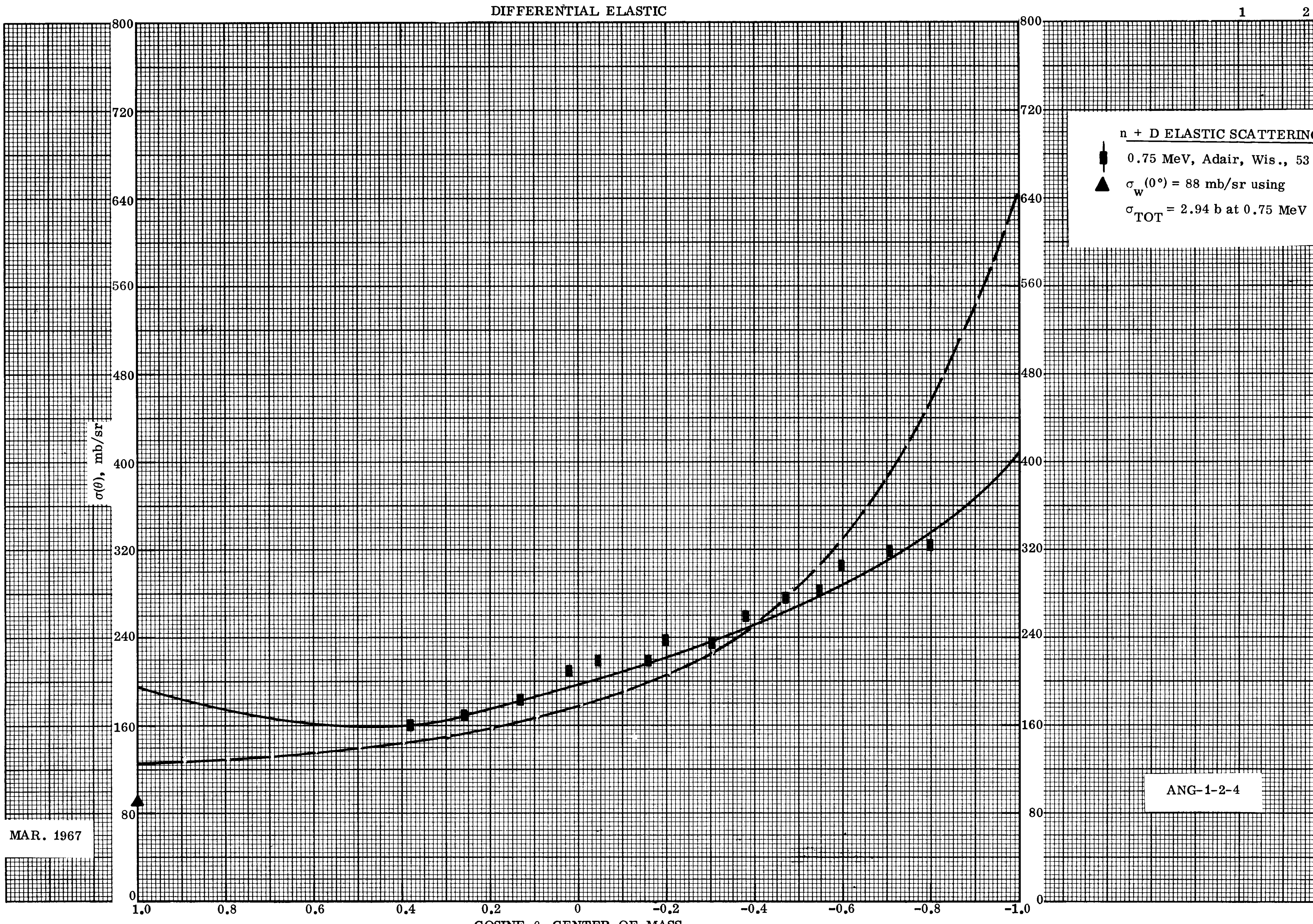
ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953). $^7Li(p,n)$ neutron source. Proportional counter filled with deuterium. $^{10}BF_3$ flux monitor.

2.——— Linear-linear interpolation between Elwyn's data at 0.5 and at 1.0 MeV is considered best representation and values in table taken from this curve.

3.——— Smooth curve through datum points does not give an energy dependence consistent with ANL experimental results at lower and higher energies.



10 X 10 TO THE ½ INCH

D	Z	MASS
	1	2

E_0 = 1.0 MeV

EVALUATED ANGULAR DISTRIBUTIONS
OF
NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	153	0.3343
0.9	147	0.3212
0.8	143	0.3124
0.7	139	0.3037
0.6	136	0.2972
0.5	135	0.2950
0.4	135	0.2950
0.3	136	0.2972
0.2	140	0.3059
0.1	145	0.3168
0.0	154	0.3365
-0.1	166	0.3627
-0.2	183	0.3998
-0.3	207	0.4523
-0.4	237	0.5178
-0.5	271	0.5921
-0.6	318	0.6948
-0.7	379	0.8281
-0.8	454	0.9920
-0.9	547	1.1952
-1.0	657	1.4355
SUM =	4577	10.0006
$\times \sin\theta\, d\theta$ =	457.7	1.00006
$\times\, d\phi$ =	2.88 barns	
(Comparison with curve), σ_{TOT} =	2.90 barns	

ANG-1-2-5

MARCH 1967

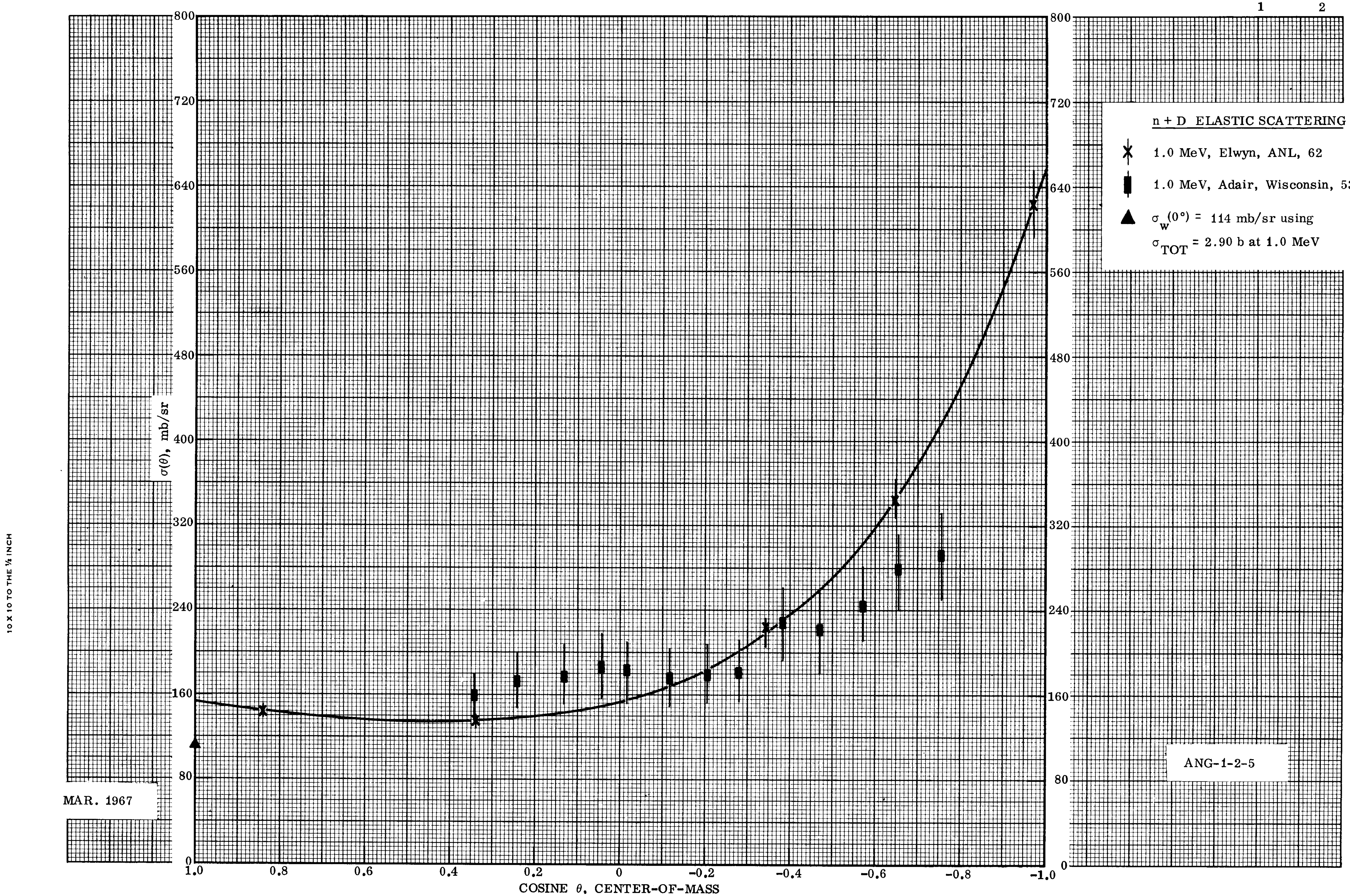
DATA REFERENCES

ELASTIC SCATTERING ANGULAR DISTRIBUTION

n + D ELASTIC SCATTERING:

1. A. J. Elwyn, R. O. Lane, and A. Langsdorf, Jr., Phys. Rev. 128, 779 (1962). From averaging left and right measurements using CD_2 and C samples. $^7Li(p,n)$ neutron source, corrections applied for $^7Li(p,n)^7Be^*$. Not corrected for multiple scattering or beam attenuation which are small effects. CD_2 target ~96% transmission. BF_3 detectors. Normalized to carbon.

2. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953). T(p, n) neutron source. Proportional counter filled with deuterium. and argon mixture. $^{10}BF_3$ flux monitor.


800
720
640
560
480
400
320
240
160
80
0
σ(θ), mb/sr
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
COSINE θ, CENTER-OF-MASS
n + D ELASTIC SCATTERING
1.0 MeV, Elwyn, ANL, 62
1.0 MeV, Adair, Wisconsin, 53
σw(0°) = 114 mb/sr using
σTOT = 2.90 b at 1.0 MeV
ANG-1-2-5
MAR. 1967
10 X 10 TO THE ½ INCH

D	Z	MASS
	1	2

E_0 = 1.2 MeV

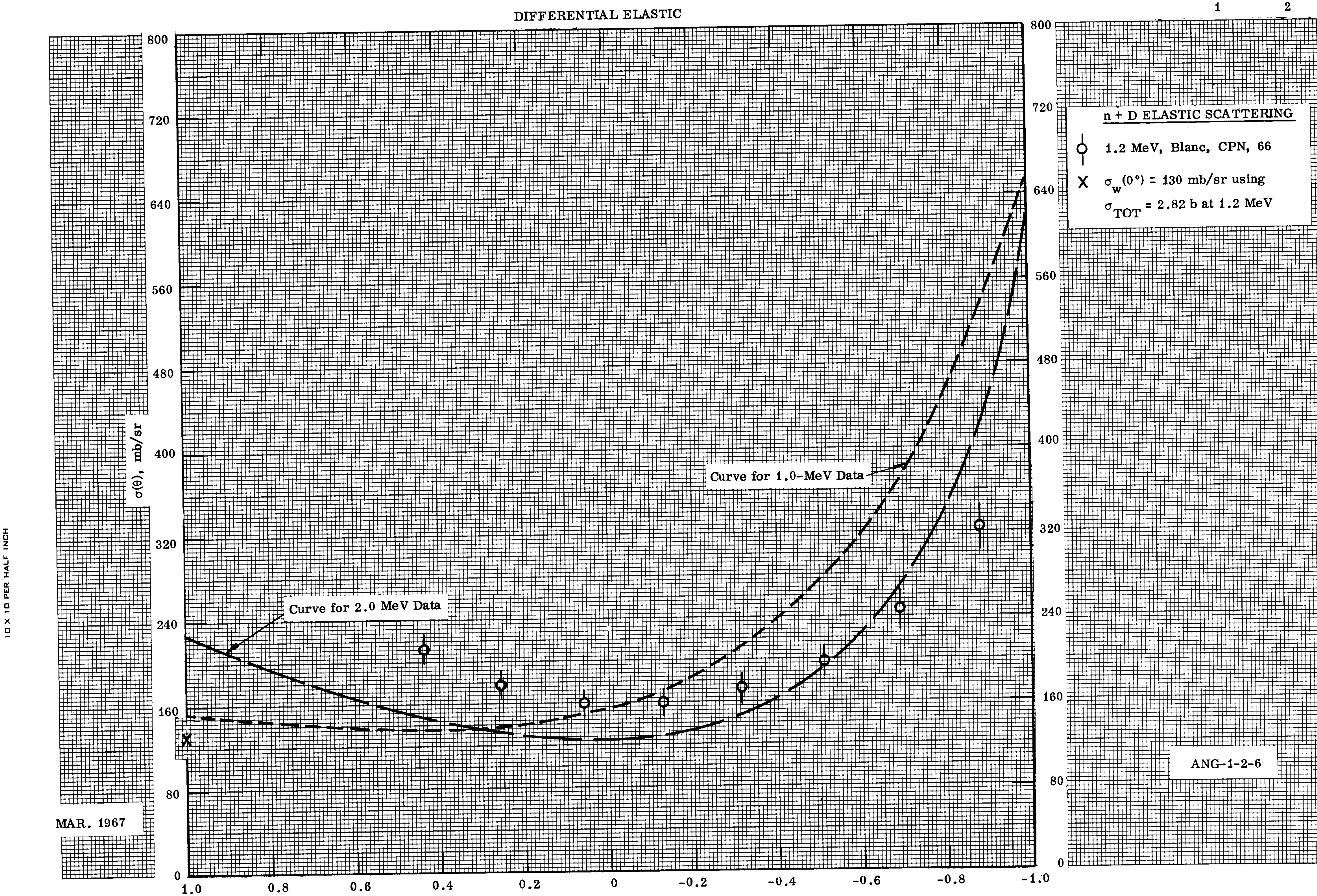
No tabular data given since data not used in analysis.

DATA REFERENCE

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. D. Blanc, F. Cambou, G. Vedrenne, J. Phys., Colloque No. 1, C1-71, (1966). Observed pulse-height distribution using deuterated benzene scintillator as both sample and detector. Applied corrections due to the nonlinear response and finite resolution.


DIFFERENTIAL ELASTIC
n + D ELASTIC SCATTERING
1.2 MeV, Blanc, CPN, 66
σw(0°) = 130 mb/sr using
σTOT = 2.82 b at 1.2 MeV
Curve for 1.0-MeV Data
Curve for 2.0 MeV Data
σ(θ), mb/sr
800
720
640
560
480
400
320
240
160
80
0
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
ANG-1-2-6
MAR. 1967
10 X 10 PER HALF INCH

D Z 1 MASS 2

E_0 = 1.5 MeV

EVALUATED ANGULAR DISTRIBUTIONS
OF
NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	σ(θ) mb/sr	P(θ)
1.0	192	0.4456
0.9	181	0.4201
0.8	172	0.3992
0.7	162	0.3760
0.6	153	0.3551
0.5	146	0.3389
0.4	140	0.3249
0.3	136	0.3157
0.2	135	0.3133
0.1	135	0.3133
0.0	138	0.3203
-0.1	145	0.3365
-0.2	156	0.3621
-0.3	172	0.3992
-0.4	195	0.4526
-0.5	227	0.5269
-0.6	268	0.6220
-0.7	325	0.7543
-0.8	402	0.9330
-0.9	504	1.1698
-1.0	639	1.4831
SUM =	4307.5	9.9975
× sin θ dθ =	430.8	0.99975
× dϕ =	2.71 barns	
(Comparison with curve), σ_{TOT} =	2.73 barns	

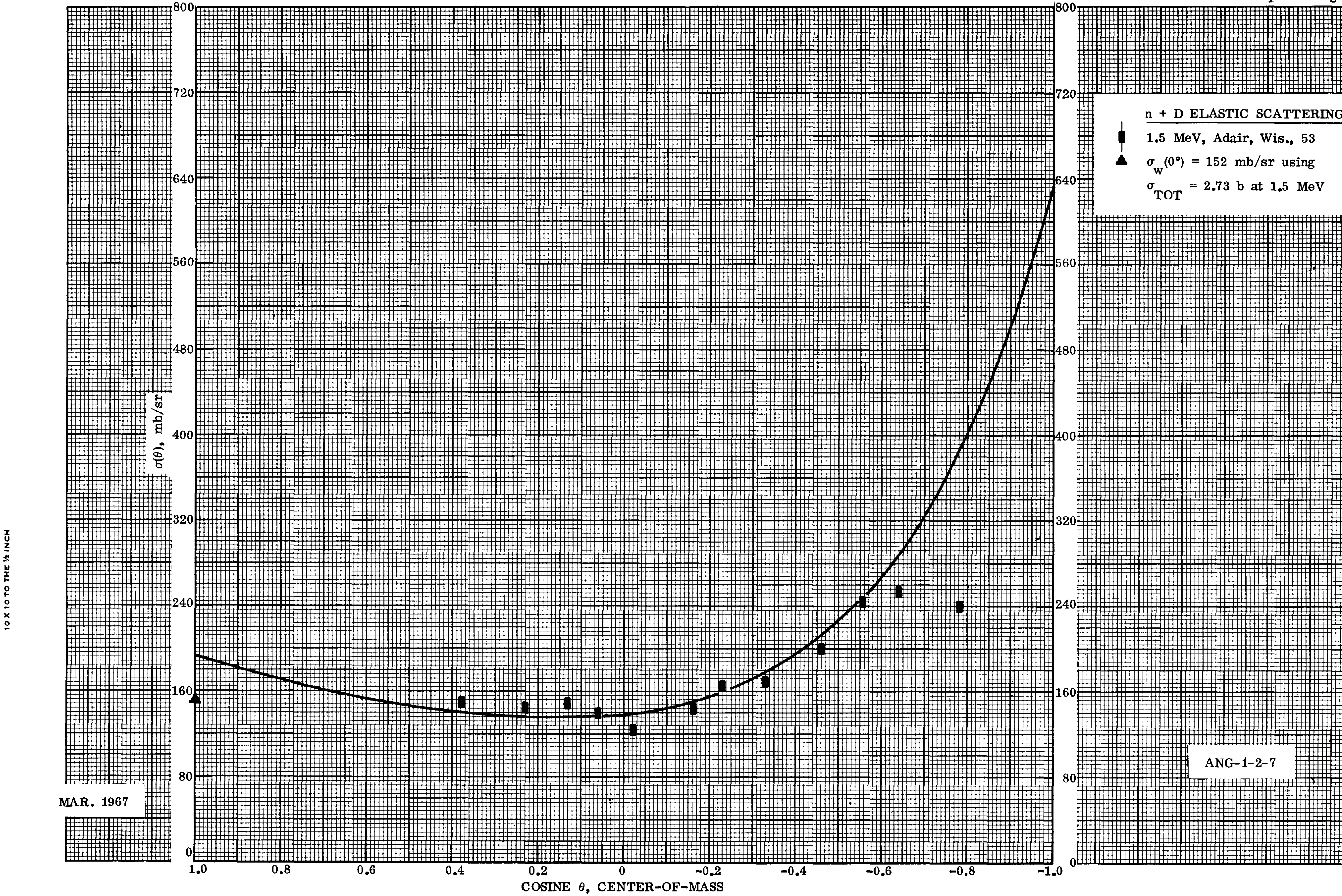
DATA REFERENCE

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953). T(p, n) neutron source. Proportional counter filled with deuterium and argon mixture. $^{10}BF_3$ flux monitor. Since these data agreed very well with a linear-linear interpolation based on the ANL data at 1.0 and 2.0 MeV, except at the most backward angle, the interpolated values are recommended.

DIFFERENTIAL ELASTIC



D	Z	MASS
	1	2

E_0 = 1.95 MeV

EVALUATED ANGULAR DISTRIBUTIONS OF NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	227	0.5614
0.9	212	0.5243
0.8	196	0.4847
0.7	181	0.4476
0.6	168	0.4155
0.5	156	0.3858
0.4	145	0.3586
0.3	137	0.3388
0.2	130	0.3215
0.1	124	0.3066
0.0	122	0.3017
-0.1	124	0.3066
-0.2	131	0.3240
-0.3	143	0.3536
-0.4	160	0.3957
-0.5	187	0.4624
-0.6	222	0.5490
-0.7	275	0.6801
-0.8	352	0.8705
-0.9	456	1.1277
-1.0	619	1.5308
SUM =	4044	10.0008
$\times \sin\theta\, d\theta$ =	404.4	1.00008
$\times\, d\phi$ =	2.54 barns	
(Comparison with curve), σ_{TOT} =	2.555 barns	

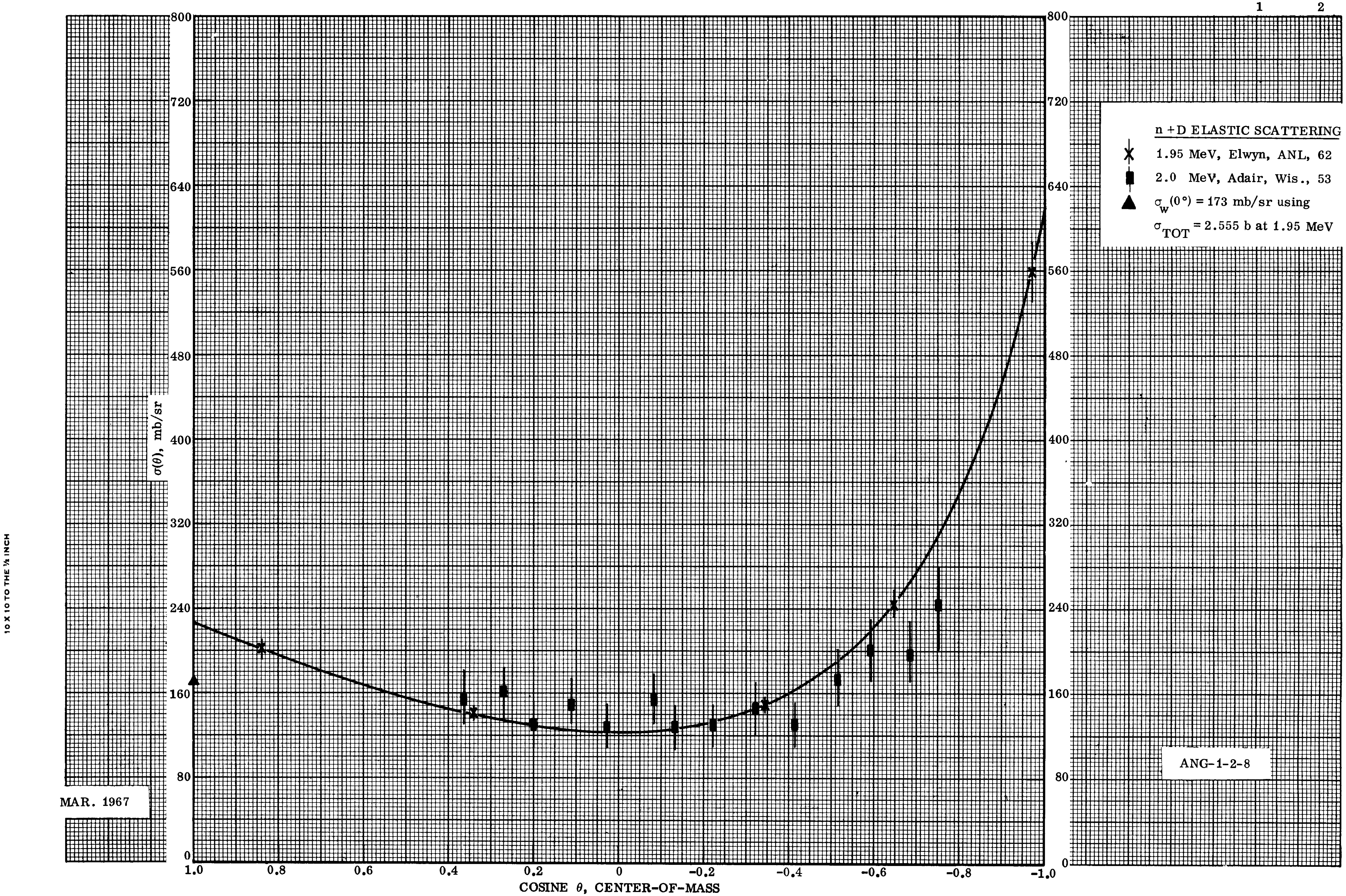
DATA REFERENCES

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. A. J. Elwyn, R. O. Lane, and A. Langsdorf, Jr., Phys. Rev. 128, 779 (1962). From averaging left and right measurements using CD_2 and C samples. $^7Li(p,n)$ neutron source, corrections applied for $^7Li(p,n)^7Be^*$. Not corrected for multiple scattering or beam attenuation which are small effects. CD_2 target ~96% transmission. BF_3 detectors. Normalized to carbon.

2. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953). T(p, n) neutron source. Proportional counter filled with deuterium and argon mixture. $^{10}BF_3$ monitor.



n + D ELASTIC SCATTERING
1.95 MeV, Elwyn, ANL, 62
2.0 MeV, Adair, Wis., 53
$\sigma_w(0°)$ = 173 mb/sr using
σ_{TOT} = 2.555 b at 1.95 MeV
σ(θ), mb/sr
COSINE θ, CENTER-OF-MASS
0
80
160
240
320
400
480
560
640
720
800
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
ANG-1-2-8
MAR. 1967
10 X 10 TO THE ½ INCH

D	Z	MASS
	1	2

E_0 = 2.45 MeV

EVALUATED ANGULAR DISTRIBUTIONS
OF
NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	329	0.8597
0.9	294	0.7682
0.8	261	0.6820
0.7	230	0.6010
0.6	204	0.5330
0.5	181	0.4730
0.4	161	0.4207
0.3	144	0.3763
0.2	131	0.3423
0.1	121	0.3162
0.0	114	0.2979
-0.1	111	0.2900
-0.2	112	0.2926
-0.3	118	0.3083
-0.4	130	0.3397
-0.5	149	0.3893
-0.6	175	0.4573
-0.7	211	0.5513
-0.8	260	0.6794
-0.9	336	0.8780
-1.0	440	1.1497
SUM =	3827.5	10.0012

$\times \sin\theta \, d\theta$ = 382.75

$\times \, d\phi$ = 2.40 barns

(Comparison with curve), σ_{TOT} = 2.36 barns

ANG-1-2-9

MARCH 1967

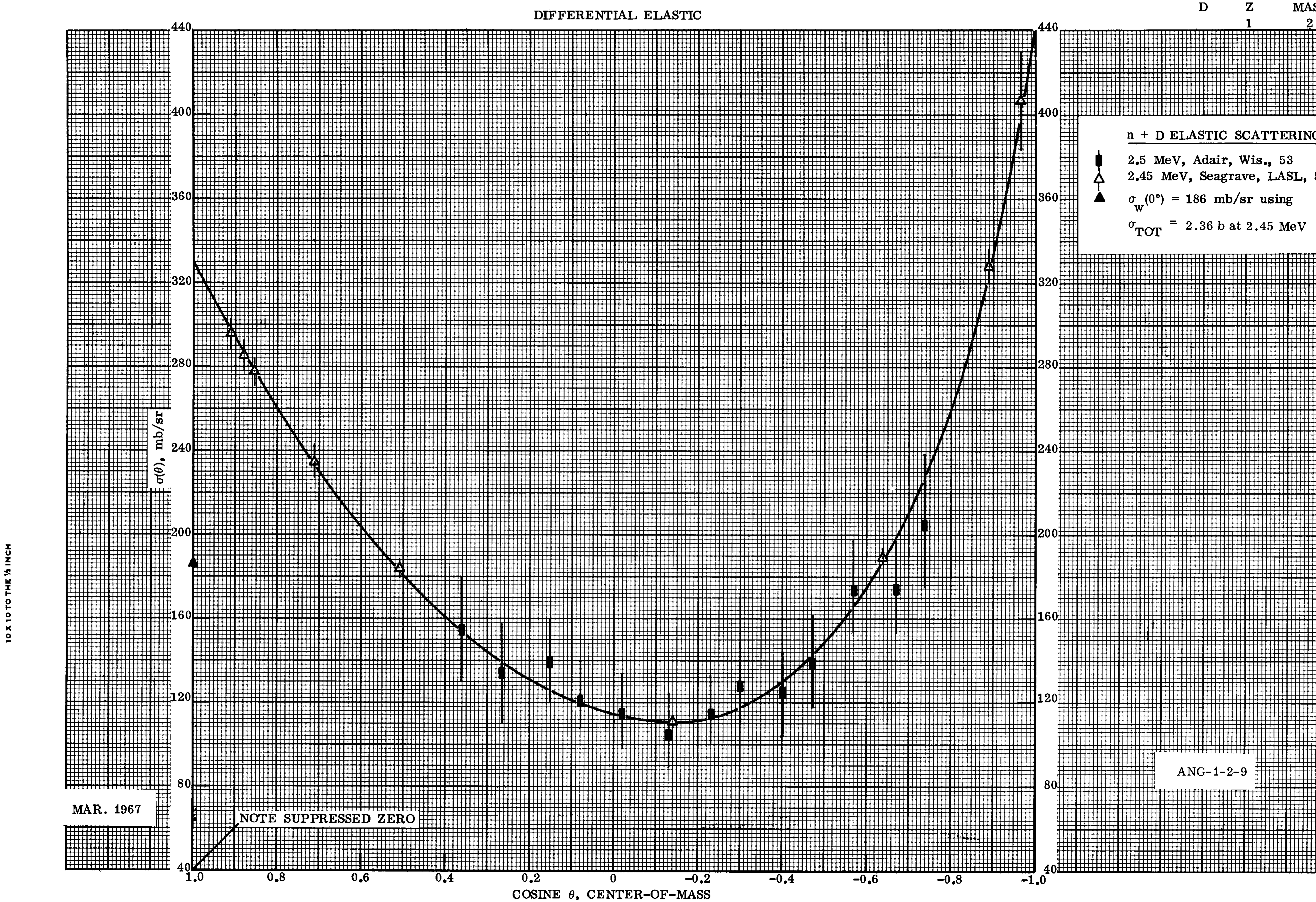
DATA REFERENCES

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. R. K. Adair, A. Okazaki, and M. Walt, Phys. Rev. 89, 1165 (1953). T(p, n) neutron source. Proportional counter filled with deuterium and argon mixture. $^{10}BF_3$ monitor.

2. J. D. Seagrave and L. Cranberg, Phys. Rev. 105, 1816 (1957). Time-of-flight scintillation detector. Normalized to hydrogen at 40°. Final absolute values obtained by normalizing the integral to "accepted values of the total cross section for n-D scattering" which were calculated from the formula for σ_{TOT} found in the paper by J. D. Seagrave and R. L. Henkel, Phys. Rev. 98, 666 (1955). This reads $\sigma_{TOT}(E_n) = 14.35/(E_n + 3.6 \text{ MeV})$.


DIFFERENTIAL ELASTIC
n + D ELASTIC SCATTERING
2.5 MeV, Adair, Wis., 53
2.45 MeV, Seagrave, LASL, 57
σw(0°) = 186 mb/sr using
σTOT = 2.36 b at 2.45 MeV
σ(θ), mb/sr
COSINE θ, CENTER-OF-MASS
NOTE SUPPRESSED ZERO
ANG-1-2-9
MAR. 1967
10 X 10 TO THE ½ INCH
440
400
360
320
280
240
200
160
120
80
40
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0

D	Z	MASS
	1	2

E_0 = 3.27 MeV

EVALUATED ANGULAR DISTRIBUTIONS OF NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	304	0.9007
0.9	277	0.8207
0.8	250	0.7407
0.7	224	0.6637
0.6	199	0.5896
0.5	175	0.5185
0.4	154	0.4563
0.3	135	0.4000
0.2	119	0.3526
0.1	106	0.3141
0.0	97	0.2874
-0.1	92	0.2726
-0.2	90	0.2667
-0.3	92	0.2726
-0.4	98	0.2904
-0.5	109	0.3230
-0.6	127	0.3763
-0.7	161	0.4770
-0.8	222	0.6578
-0.9	307	0.9096
-1.0	379	1.1230
	SUM = 3375	1.00014

$\times \sin\theta \, d\theta$ = 337.5

$\times \, d\phi$ = 2.12 barns

(Comparison with curve, σ_{TOT} = 2.06 barns

ANG-1-2-10

MARCH 1967

DATA REFERENCES

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

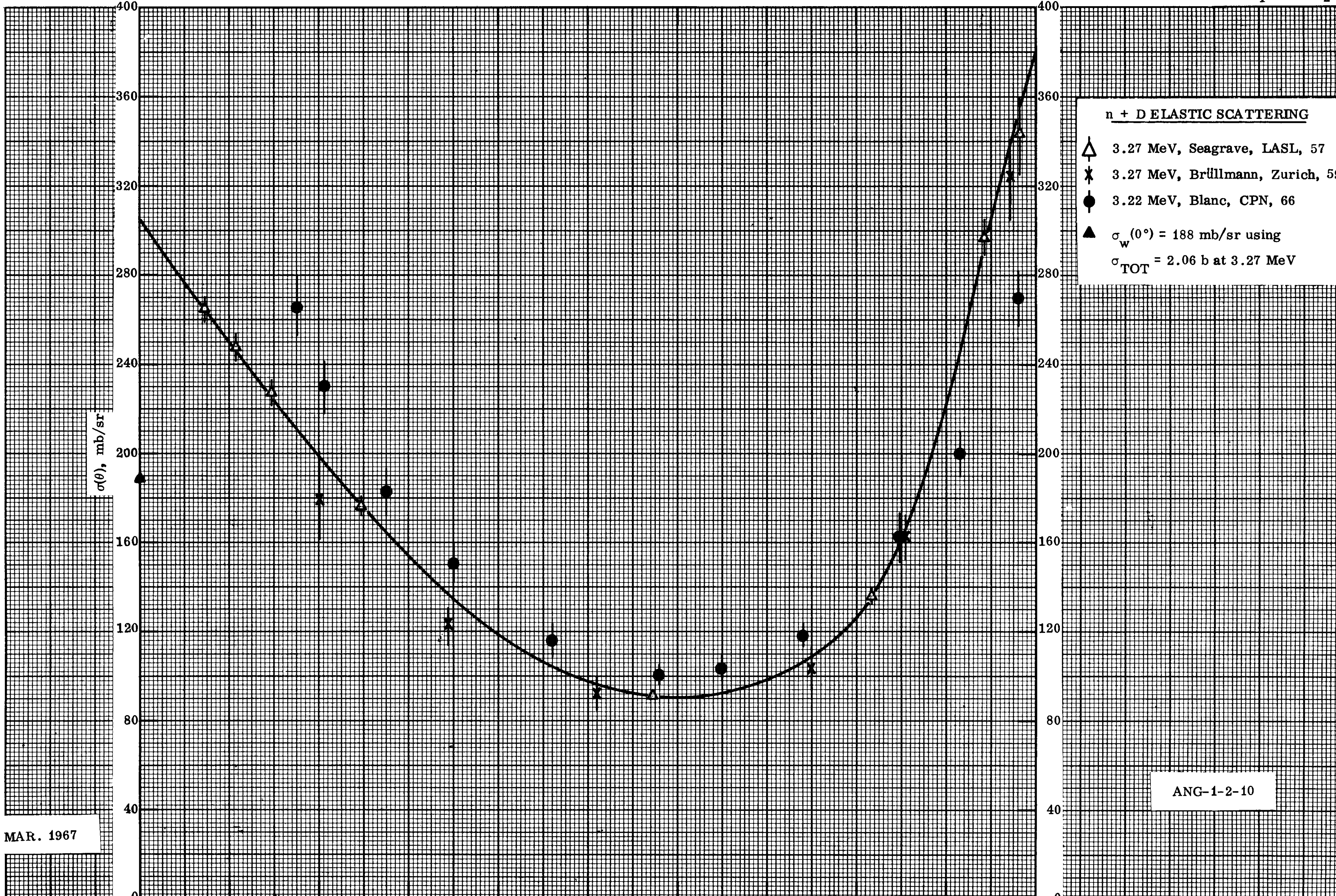
n + D ELASTIC SCATTERING:

1. J. D. Seagrave and L. Cranberg, Phys. Rev. 105, 1816 (1957). Time-of-flight scintillation detector. Normalized to hydrogen at 40°. Final absolute values obtained by normalizing the integral to "accepted values of the total cross section for n-D scattering" which were calculated from the formula for σ_{TOT} found in the paper by J. D. Seagrave and R. L. Henkel, Phys. Rev. 98, 666 (1955). This reads $\sigma_{TOT}(E_n) = 14.35/(E_n + 3.6\text{ MeV})$.

2. M. Brüllmann, H. J. Gerber, D. Meier, and P. Scherrer, Helv. Phys. Acta 32, 511 (1959). Recoil deuterons detected; D(d, n) neutron source. Scintillation counter; deuterated benzene (C_6D_6) target. Plastic scintillator to record the neutrons. Points reproduced from small graph in publication.

3. D. Blanc, F. Cambou, and G. Vedrenne, J. Phys., Colloque No. 1, 71 (1966). Observed pulse-height distribution using deuterated benzene scintillator as both sample and detector. Applied corrections due to the nonlinear response and finite resolution.

DIFFERENTIAL ELASTIC



10 X 10 TO THE ½ INCH

E_0 = 5.5 MeV

EVALUATED ANGULAR DISTRIBUTIONS OF NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	258	1.0598
0.9	239	0.9817
0.8	218	0.8955
0.7	198	0.8133
0.6	177	0.7270
0.5	157	0.6449
0.4	137	0.5627
0.3	116	0.4765
0.2	95	0.3902
0.1	79	0.3245
0.0	64	0.2629
-0.1	53	0.2177
-0.2	46	0.1889
-0.3	44	0.1807
-0.4	47	0.1931
-0.5	55	0.2259
-0.6	67	0.2752
-0.7	89	0.3656
-0.8	125	0.5135
-0.9	179	0.7353
-1.0	241	0.9899
SUM =	2434.5	9.9999

$\times \sin\theta \, d\theta$ = 243.45

$\times \, d\phi$ = 1.53 barns

(Comparison with curve), σ_{ELAS} = 1.52 barns from (TOTAL - NONELASTIC)

DATA REFERENCES

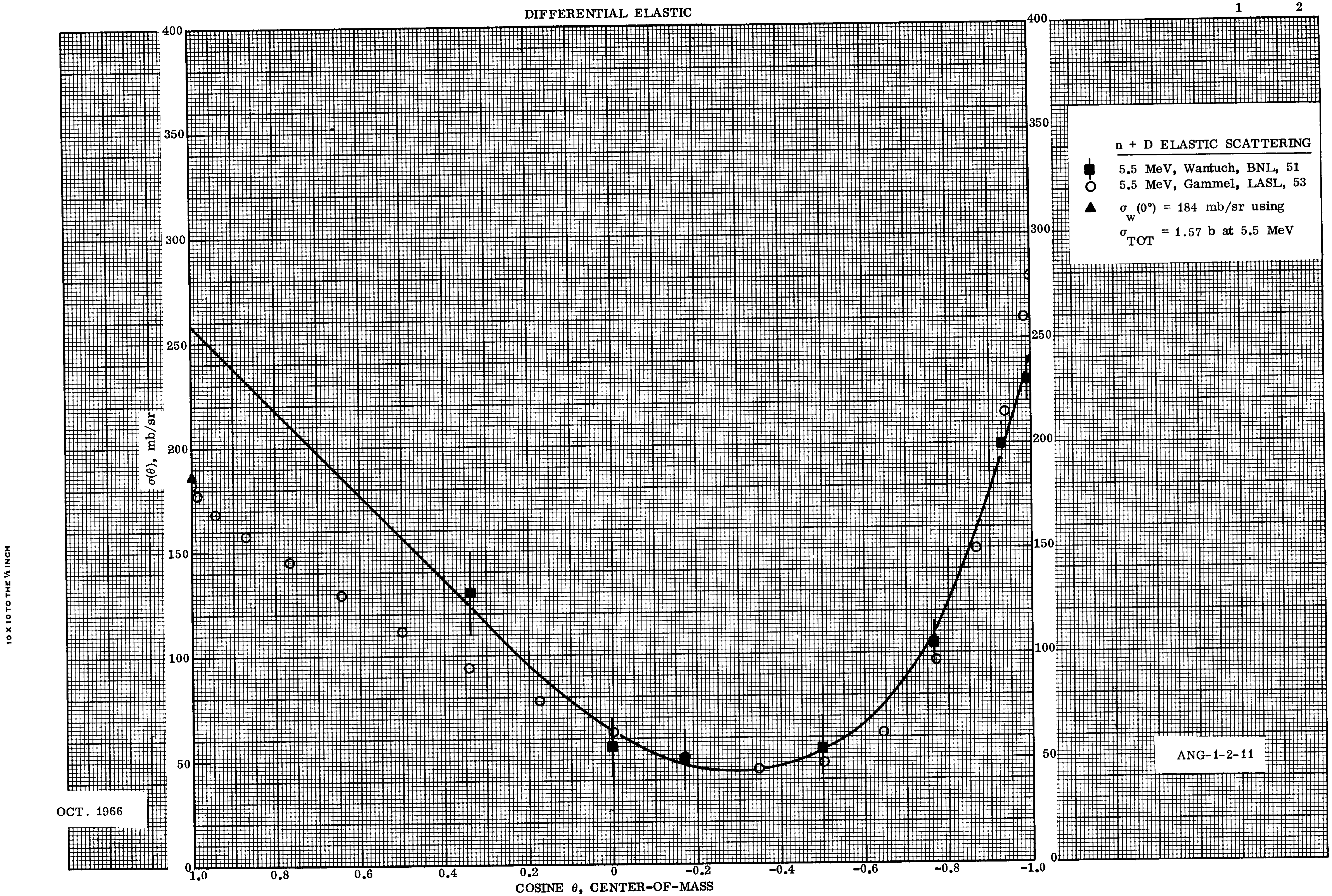
ELASTIC SCATTERING ANGULAR DISTRIBUTION

n + D ELASTIC SCATTERING:

1. ■ E. Wantuch, Phys. Rev. 84, 169 (1951). D(d, n) source; both deuterated paraffin and deuterium gas targets; recoil deuterons detected with counter telescope.

2. ○ R. S. Christian and J. L. Gammel, Phys. Rev. 91, 100 (1953). Points are a theoretical prediction based on p + D data.

NOTE: These data were not used in this analysis; they are shown for comparison purposes only.


DIFFERENTIAL ELASTIC
n + D ELASTIC SCATTERING
5.5 MeV, Wantuch, BNL, 51
5.5 MeV, Gammel, LASL, 53
σ_W(0°) = 184 mb/sr using
σ_TOT = 1.57 b at 5.5 MeV
σ(θ), mb/sr
COSINE θ, CENTER-OF-MASS
ANG-1-2-11
OCT. 1966
10 X 10 TO THE ½ INCH

D Z MASS
1 2

E_0 = 5.6 MeV

EVALUATED ANGULAR DISTRIBUTIONS OF NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	282	1.1889
0.9	238	1.0034
0.8	208	0.8769
0.7	182	0.7673
0.6	157	0.6619
0.5	137	0.5776
0.4	120	0.5059
0.3	105	0.4427
0.2	91	0.3837
0.1	80	0.3373
0.0	69	0.2909
-0.1	61	0.2572
-0.2	55	0.2319
-0.3	51	0.2150
-0.4	51	0.2150
-0.5	55	0.2319
-0.6	65	0.2740
-0.7	83	0.3499
-0.8	113	0.4764
-0.9	172	0.7252
-1.0	276	1.1636
SUM =	2372	10.0003
$\times \sin\theta \, d\theta$ =	237.2	1.00003
$\times d\phi$ =	1.490 barns	

(Comparison with curve), σ_{ELAS} = 1.504 barns from (TOTAL - NONELASTIC)

DATA REFERENCES

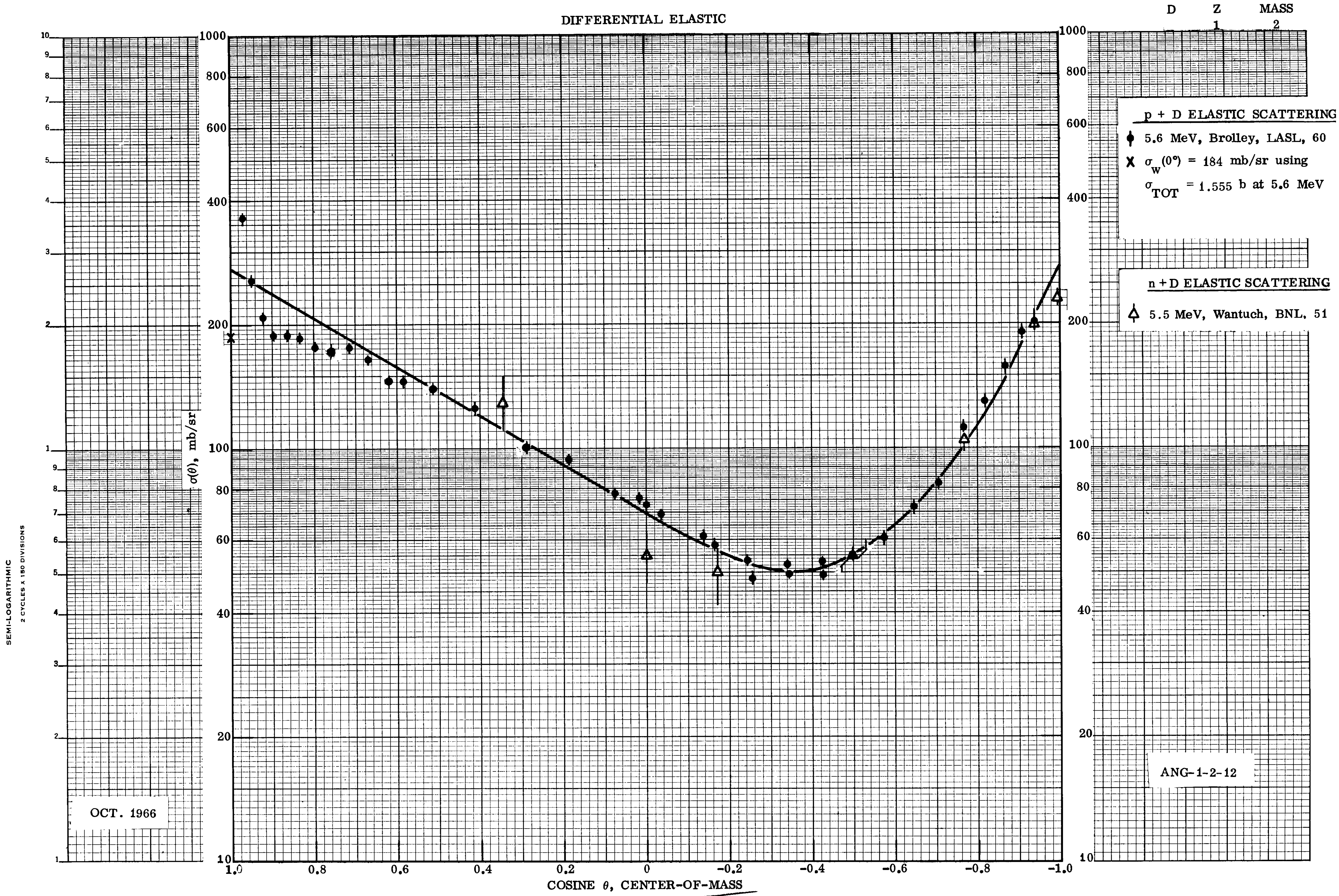
ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. △ E. Wantuch, Phys. Rev. 84, 169 (1951). D(d, n) source; both deuterated paraffin and deuterium gas targets; recoil deuterons detected with counter telescope.

p + D ELASTIC SCATTERING:

2. ● J. E. Brolley, Jr., T. M. Putnam, L. Rosen, and L. Stewart, Phys. Rev. 117, 1307 (1960). Nuclear emulsion techniques; deuterium gas target; protons and recoil deuterons detected.



DIFFERENTIAL ELASTIC
D Z MASS
1 2
p + D ELASTIC SCATTERING
5.6 MeV, Brolley, LASL, 60
X $\sigma_W(0°)$ = 184 mb/sr using
σ_{TOT} = 1.555 b at 5.6 MeV
n + D ELASTIC SCATTERING
5.5 MeV, Wantuch, BNL, 51
σ(θ), mb/sr
COSINE θ, CENTER-OF-MASS
ANG-1-2-12
OCT. 1966
SEMI-LOGARITHMIC
2 CYCLES X 180 DIVISIONS

E_0 = 7.85 MeV

EVALUATED ANGULAR DISTRIBUTIONS OF NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	216	1.1934
0.9	189	1.0442
0.8	166	0.9172
0.7	146	0.8066
0.6	127	0.7017
0.5	111	0.6133
0.4	97	0.5359
0.3	83.5	0.4613
0.2	71.5	0.3950
0.1	62.5	0.3453
0.0	54	0.2984
-0.1	46.9	0.2591
-0.2	40.8	0.2254
-0.3	36	0.1989
-0.4	33	0.1823
-0.5	33	0.1823
-0.6	36.8	0.2033
-0.7	48.2	0.2663
-0.8	72	0.3978
-0.9	126	0.6962
-1.0	243	1.3426
SUM =	1810.0	9.9985
× sin θ dθ =	181.0	0.99985
× dϕ =	1.137 barns	

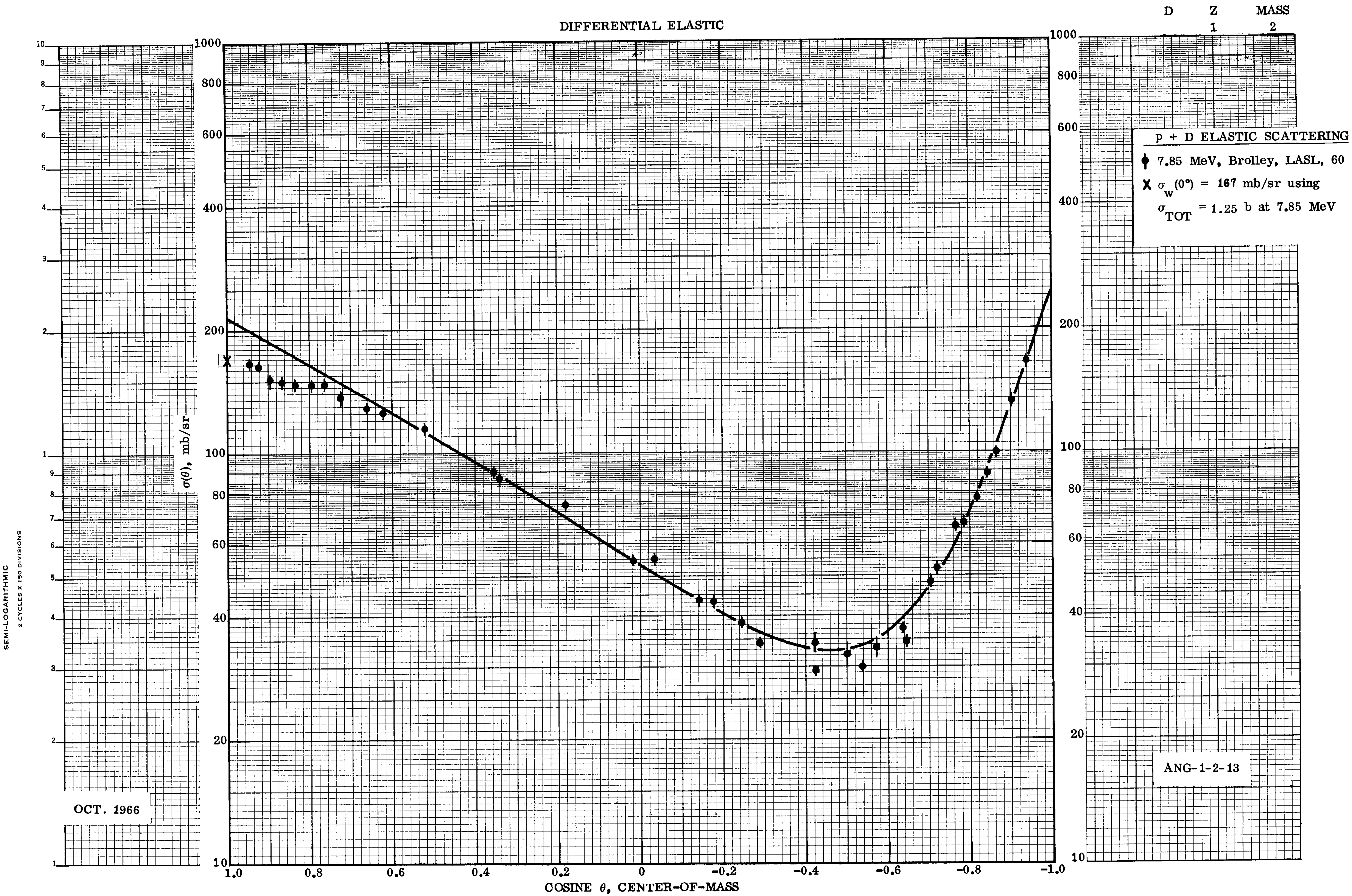
(Comparison with curve), σ_{ELAS} = 1.151 barns from (TOTAL - NONELASTIC)

DATA REFERENCE

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

p + D ELASTIC SCATTERING:

1. J. E. Brolley, Jr., T. M. Putnam, L. Rosen, and L. Stewart, Phys. Rev. 117, 1307 (1960). Nuclear emulsion techniques; deuterium gas target; protons and recoil deuterons detected.



D Z MASS
1 2
DIFFERENTIAL ELASTIC
p + D ELASTIC SCATTERING
7.85 MeV, Brolley, LASL, 60
X $\sigma_W(0°)$ = 167 mb/sr using
σ_{TOT} = 1.25 b at 7.85 MeV
$\sigma(\theta)$, mb/sr
COSINE θ, CENTER-OF-MASS
1000
800
600
400
200
100
80
60
40
20
10
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
SEMI-LOGARITHMIC
2 CYCLES X 150 DIVISIONS
OCT. 1966
ANG-1-2-13

D	Z	MASS
	1	2

E_0 = 9.7 MeV

EVALUATED ANGULAR DISTRIBUTIONS
OF
NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	187	1.2101
0.9	166	1.0742
0.8	146	0.9448
0.7	129	0.8348
0.6	114	0.7377
0.5	99	0.6406
0.4	86.5	0.5597
0.3	75	0.4853
0.2	65	0.4206
0.1	56	0.3624
0.0	47.8	0.3093
-0.1	39.6	0.2562
-0.2	33	0.2135
-0.3	27.9	0.1805
-0.4	23.9	0.1546
-0.5	21.4	0.1385
-0.6	23	0.1488
-0.7	32.6	0.2110
-0.8	55.7	0.3604
-0.9	105	0.6794
-1.0	211	1.3654
SUM =	1545.4	10.0000
$\times \sin\theta\, d\theta$ =	154.54	1.0000
$\times\, d\phi$ =	0.971 barns	

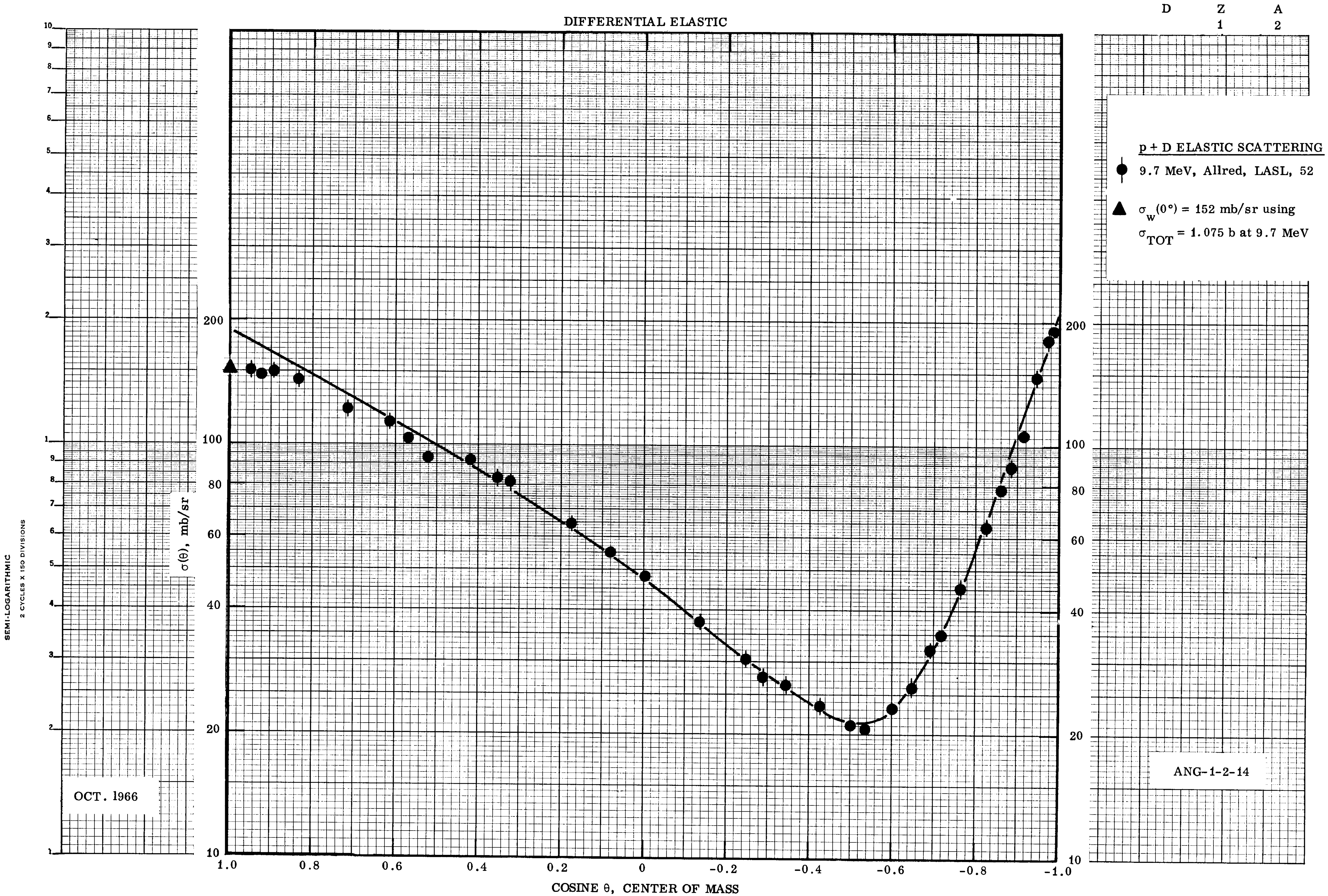
(Comparison with curve), σ_{ELAS} = 0.9427 barns from (TOTAL - NONELASTIC)

DATA REFERENCE

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

p + D ELASTIC SCATTERING:

1. J. C. Allred, A. H. Armstrong, R. O. Bondelid, and L. Rosen, Phys. Rev. 88, 433 (1952). Nuclear emulsion techniques; deuterium gas target; protons and recoil deuterons detected.


D Z A
1 2
DIFFERENTIAL ELASTIC
p + D ELASTIC SCATTERING
9.7 MeV, Allred, LASL, 52
$\sigma_w(0°)$ = 152 mb/sr using
σ_{TOT} = 1.075 b at 9.7 MeV
σ(θ), mb/sr
COSINE θ, CENTER OF MASS
1.0 0.8 0.6 0.4 0.2 0 -0.2 -0.4 -0.6 -0.8 -1.0
10 20 40 60 80 100 200
OCT. 1966
ANG-1-2-14
SEMI-LOGARITHMIC
2 CYCLES X 150 DIVISIONS

D	Z	MASS
	1	2

E_0 = 11.5 MeV

EVALUATED ANGULAR DISTRIBUTIONS OF NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	162	1.2911
0.9	143	1.1397
0.8	126	1.0042
0.7	111	0.8847
0.6	97	0.7731
0.5	85	0.6774
0.4	74	0.5898
0.3	64.5	0.5141
0.2	55.5	0.4423
0.1	47	0.3746
0.0	39.6	0.3156
-0.1	32.8	0.2614
-0.2	26.3	0.2096
-0.3	20.8	0.1658
-0.4	16.2	0.1291
-0.5	12.9	0.1028
-0.6	14.1	0.1124
-0.7	20.5	0.1634
-0.8	37.5	0.2989
-0.9	75	0.5978
-1.0	150	1.1955
SUM =	1254.7	10.0000
$\times \sin\theta\, d\theta$ =	125.47	1.0000
$\times\, d\phi$ =	0.788 barns	

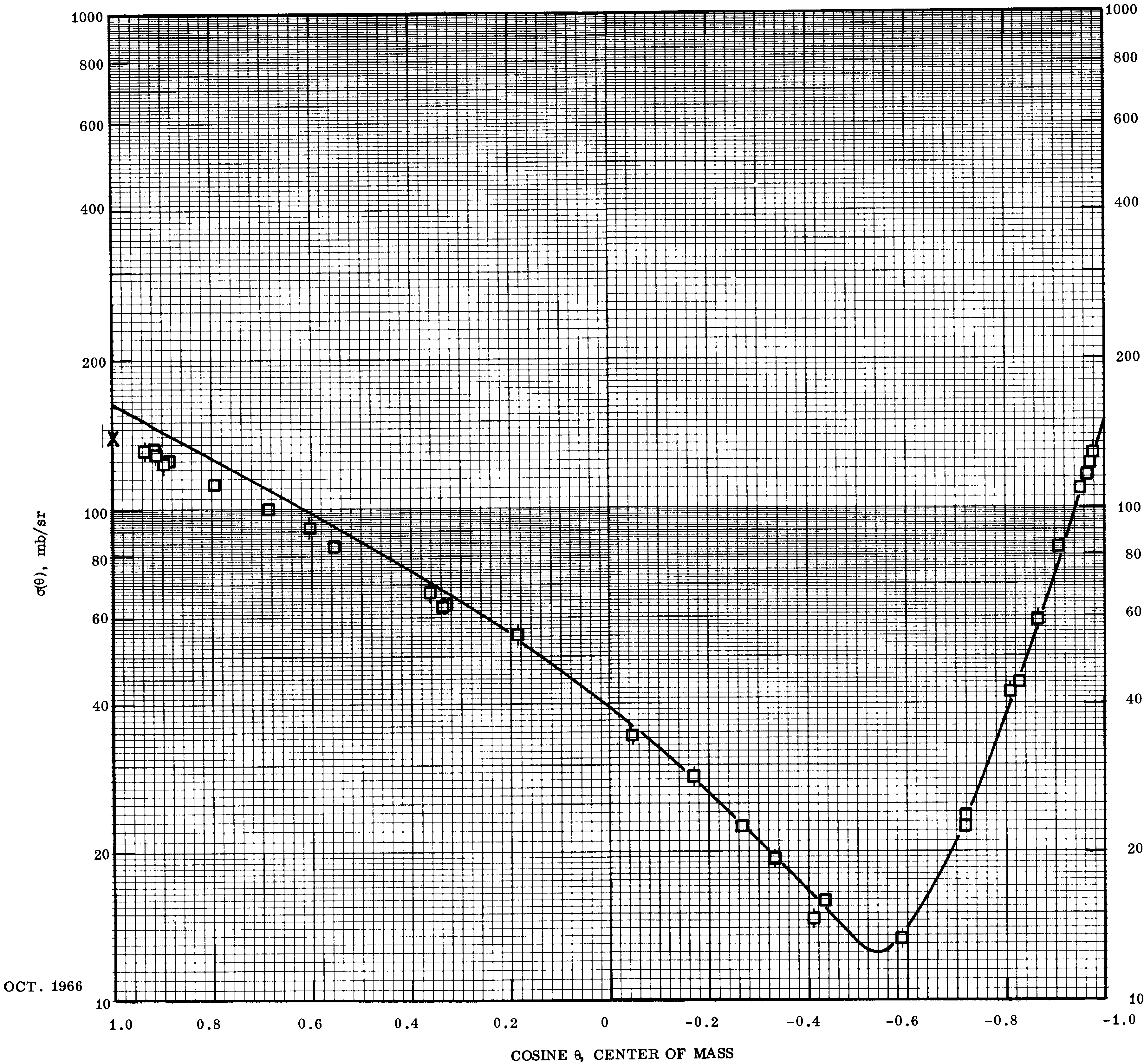
(Comparison with curve), σ_{ELAS} = 0.7865 barns from (TOTAL - NONELASTIC)

DATA REFERENCE

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

p + D ELASTIC SCATTERING:

1. W. T. H. van Oers and K. W. Brockman, Jr., Nuclear Forces and the Few Nucleon Problem, edited by T. C. Griffith and E. A. Power (Pergamon Press, London, 1960) Vol. I, p. 285; (Tabular values, private communication from van Oers, July 1966); 23-MeV deuterons incident.



p + D ELASTIC SCATTERING

11.5 MeV, van Oers, Amsterdam, 66

X $\sigma_W(0°) = 139$ mb/sr using $\sigma_{TOT} = 943$ mb at 11.5 MeV

OCT. 1966

ANG-1-2-15

E_0 = 12.17 MeV

EVALUATED ANGULAR DISTRIBUTIONS OF NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	148	1.2814
0.9	131	1.1342
0.8	116	1.0043
0.7	102	0.8831
0.6	89.5	0.7749
0.5	78	0.6753
0.4	68	0.5887
0.3	59	0.5108
0.2	50.5	0.4372
0.1	42.5	0.3680
0.0	35.5	0.3074
-0.1	29	0.2511
-0.2	23.2	0.2009
-0.3	18.7	0.1619
-0.4	14.8	0.1281
-0.5	12.1	0.1048
-0.6	13	0.1126
-0.7	19.7	0.1706
-0.8	35.5	0.3074
-0.9	71	0.6147
-1.0	144	1.2468
SUM =	1155	10.0001
$\times \sin\theta \, d\theta$ =	115.5	1.00001
$\times \, d\phi$ =	0.726 barns	

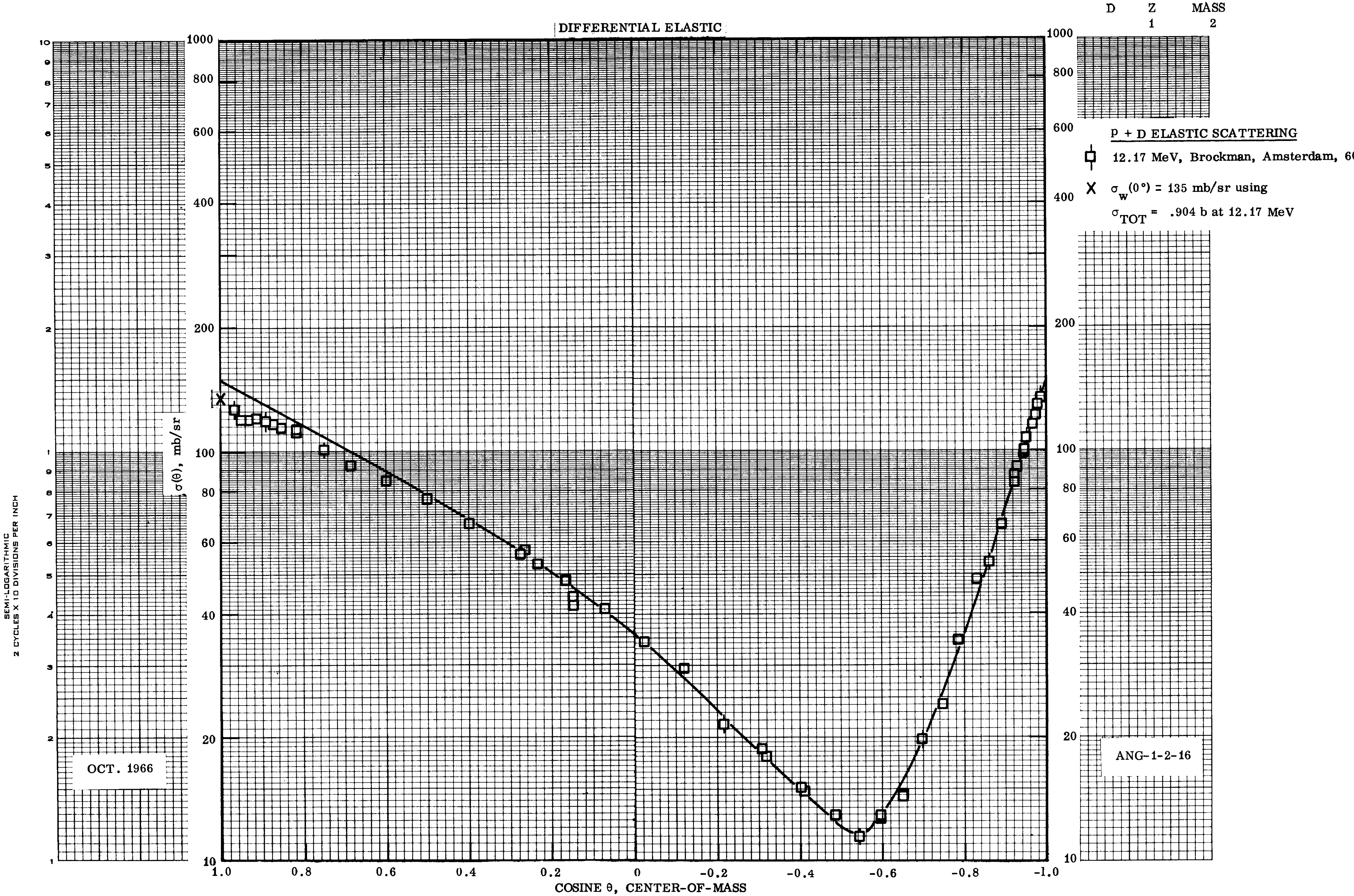
(Comparison with curve), σ_{ELAS} = 0.740 barns from (TOTAL - NONELASTIC)

DATA REFERENCE

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

p + D ELASTIC SCATTERING:

1. W. T. H. van Oers and K. W. Brockman, Jr., Nucl. Phys. 21, 189 (1960). 24.35-MeV incident deuterons. Hydrogen gas target; deuterons and recoil protons detected with CsI scintillation counter. Small angle data normalized by monitoring the beam at 20° (laboratory).


D Z MASS
1 2
DIFFERENTIAL ELASTIC
p + D ELASTIC SCATTERING
12.17 MeV, Brockman, Amsterdam, 60
X $\sigma_w(0°)$ = 135 mb/sr using
σ_{TOT} = .904 b at 12.17 MeV
$\sigma(\theta)$, mb/sr
COSINE θ, CENTER-OF-MASS
OCT. 1966
ANG-1-2-16
SEMI-LOGARITHMIC
2 CYCLES X 10 DIVISIONS PER INCH

D	Z	MASS
	1	2

E_0 = 14.0 MeV

EVALUATED ANGULAR DISTRIBUTIONS OF NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	σ(θ) mb/sr	P(θ)
1.0	148	1.4581
0.9	128	1.2611
0.8	110	1.0837
0.7	95	0.9360
0.6	81.5	0.8030
0.5	70	0.6897
0.4	59.5	0.5862
0.3	50	0.4926
0.2	42.5	0.4187
0.1	35.3	0.3478
0.0	29.2	0.2877
-0.1	23.7	0.2335
-0.2	18.8	0.1852
-0.3	14.5	0.1429
-0.4	11.3	0.1113
-0.5	9.1	0.0897
-0.6	8.5	0.0837
-0.7	12.3	0.1212
-0.8	24.3	0.2394
-0.9	55.0	0.5419
-1.0	125	1.2315
SUM =	1015.0	10.0001
× sin θ dθ =	101.5	1.00001
× dϕ =	0.638 barns	

(Comparison with curve), σ_{ELAS} = 0.630 barns from (TOTAL - NONELASTIC)

DATA REFERENCES

ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. J. C. Allred, A. H. Armstrong, and L. Rosen, Phys. Rev. 91, 90 (1953). T(d, n) neutron source; nuclear emulsion techniques. Deuterated paraffin and deuterated polyethylene targets.

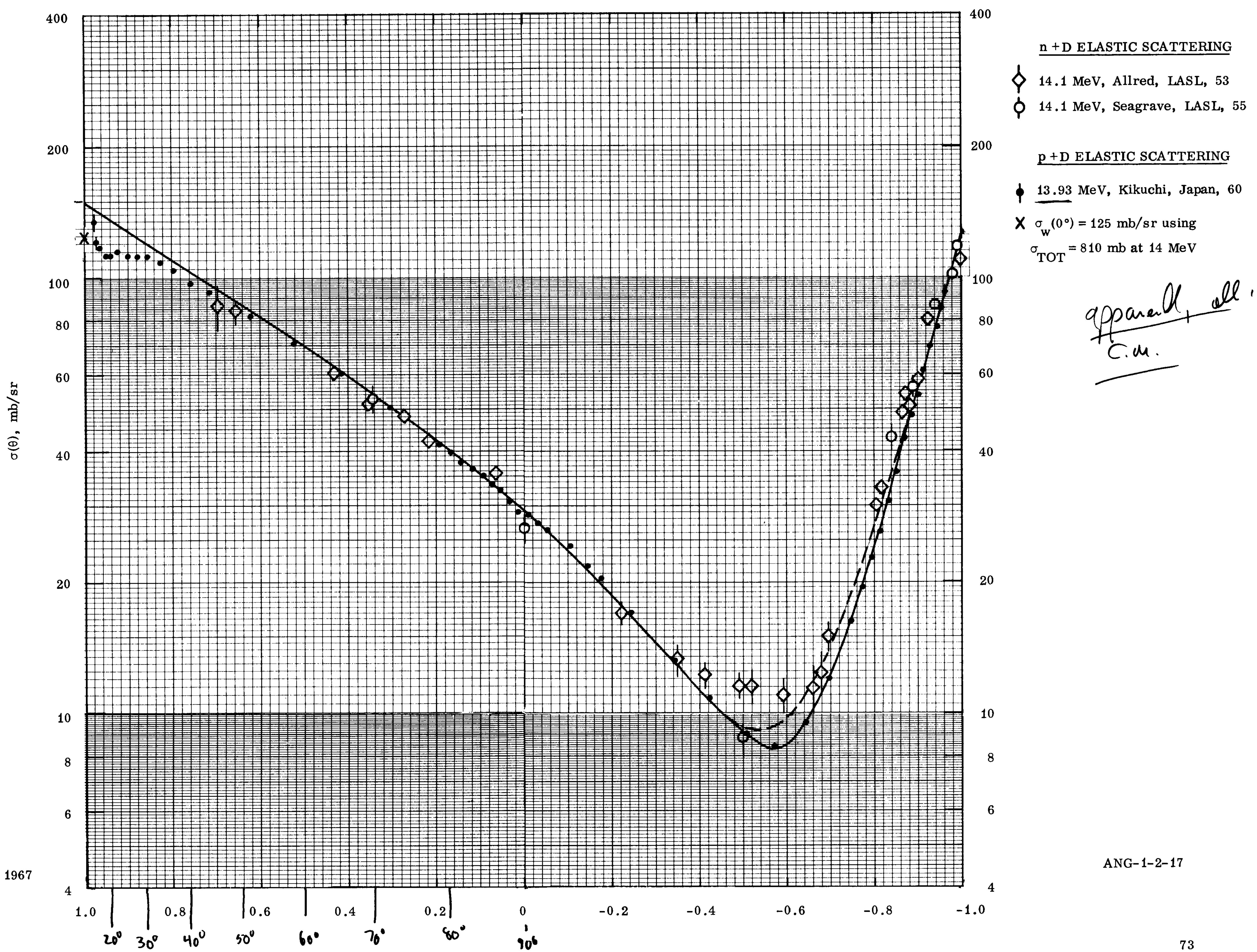
2. J. D. Seagrave, Phys. Rev. 97, 757 (1955). T(d, n) neutron source; deuterated polyethylene targets. Detected recoil deuterons with counter telescope. dE/dx counter for discrimination between protons and deuterons.

——— This curve was chosen since the point by Seagrave near (cosine θ = -0.5) indicates a deep minimum borne out by the p + D data.

— — — Calculated from phase-shift analysis of p + D scattering with the inclusion of Coulomb corrections using Born approximation for $\ell > 1$. One of the authors (L. S.) sincerely appreciates these calculations which were performed by Dr. W. T. H. van Oers at UCLA in October 1966. This curve deviates so slightly at lower angles that the difference between the two cannot be shown on this scale. For a description of the method see W. T. H. van Oers and K. W. Brockman, Jr., Nucl. Phys. A92, 561 (1967).

p + D ELASTIC SCATTERING:

3. S. Kikuchi, J. Sanada, S. Suwa, I. Hayashi, K. Nisimura, and K. Fukinaga, J. Phys. Soc. Japan 15, 9 (1960). Deuterium gas target; NaI and CsI detectors used to detect protons and recoil deuterons. Accuracy quoted 1 to 3%.



FEB. 1967

ANG-1-2-17

D Z 1 MASS 2

E_0 = 20.57 MeV

EVALUATED ANGULAR DISTRIBUTIONS
OF
NEUTRONS ELASTICALLY SCATTERED FROM DEUTERIUM

COSINE θ	$\sigma(\theta)$ mb/sr	$P(\theta)$
1.0	111	1.7924
0.9	93	1.5017
0.8	77	1.2434
0.7	63.5	1.0254
0.6	52.5	0.8478
0.5	43.3	0.6992
0.4	35.7	0.5765
0.3	29.5	0.4764
0.2	24.3	0.3924
0.1	20.2	0.3262
0.0	16.5	0.2664
-0.1	13.5	0.2180
-0.2	10.7	0.1728
-0.3	8.3	0.1340
-0.4	6.1	0.0985
-0.5	4.05	0.0654
-0.6	2.53	0.0409
-0.7	3.5	0.0565
-0.8	8.9	0.1437
-0.9	22.2	0.3585
-1.0	57.0	0.9204
SUM =	619.28	10.0001
$\times \sin\theta\, d\theta$ =	61.928	1.00001
$\times d\phi$ =	0.389 barns	

(Comparison with curve), σ_{ELAS} = 0.389 barns from (TOTAL - NONELASTIC)

NOTE: The above table represents the smooth curve.

ANG-1-2-18

FEB. 1967

DATA REFERENCES

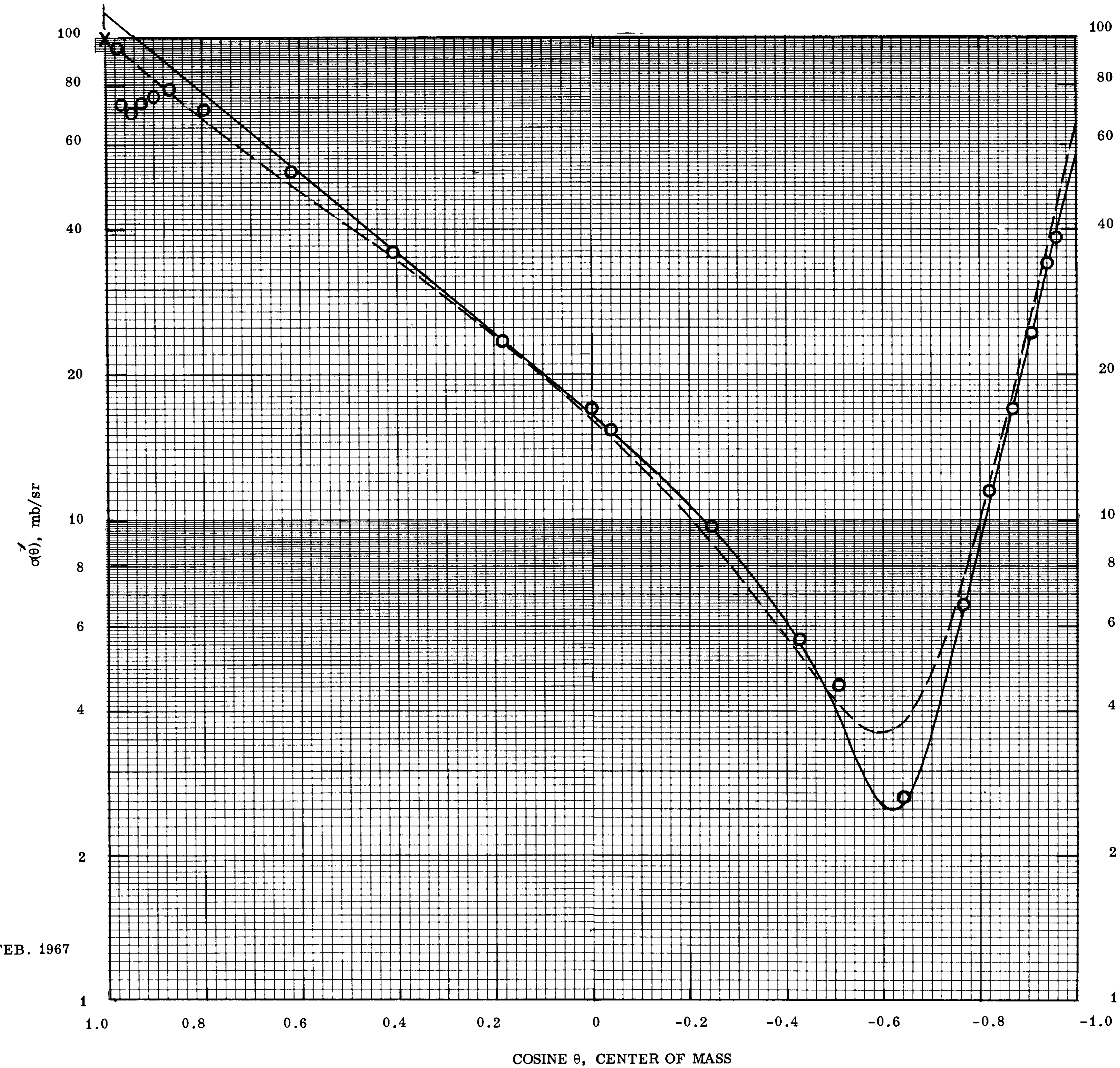
ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

n + D ELASTIC SCATTERING:

1. ——— Calculated from phase-shift analysis of p + D scattering with the inclusion of Coulomb corrections using Born approximation for $\ell > 1$. One of the authors (L.S.) sincerely appreciates these calculations which were performed by Dr. W. T. H. van Oers at UCLA in October 1966.

p + D ELASTIC SCATTERING:

2. ɸ David O. Caldwell and J. Reginald Richardson, Phys. Rev. 98, 28 (1955). Triple coincidence proportional counter telescope; deuterium gas target.



p + D ELASTIC SCATTERING

20.57 MeV, Caldwell, UCLA, 55

(Unless shown, errors are within symbol)

n + D ELASTIC SCATTERING

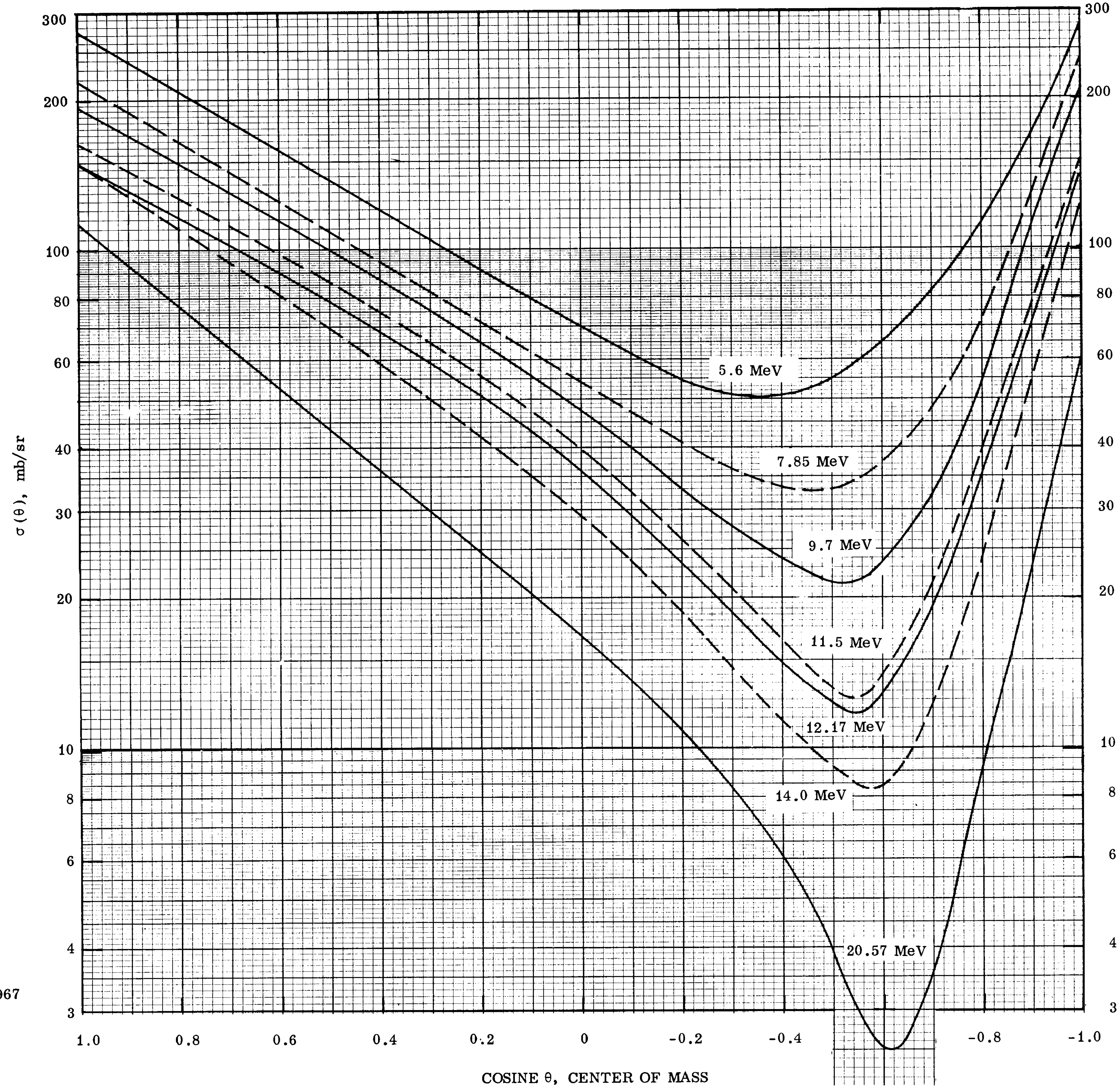
Calculated from phase shift analysis of p + D van Oers, UCLA, 66

X $\sigma_w(0°) = 99$ mb/sr using $\sigma_{TOT} = 0.595$ b at 20.57 MeV

ANG-1-2-18

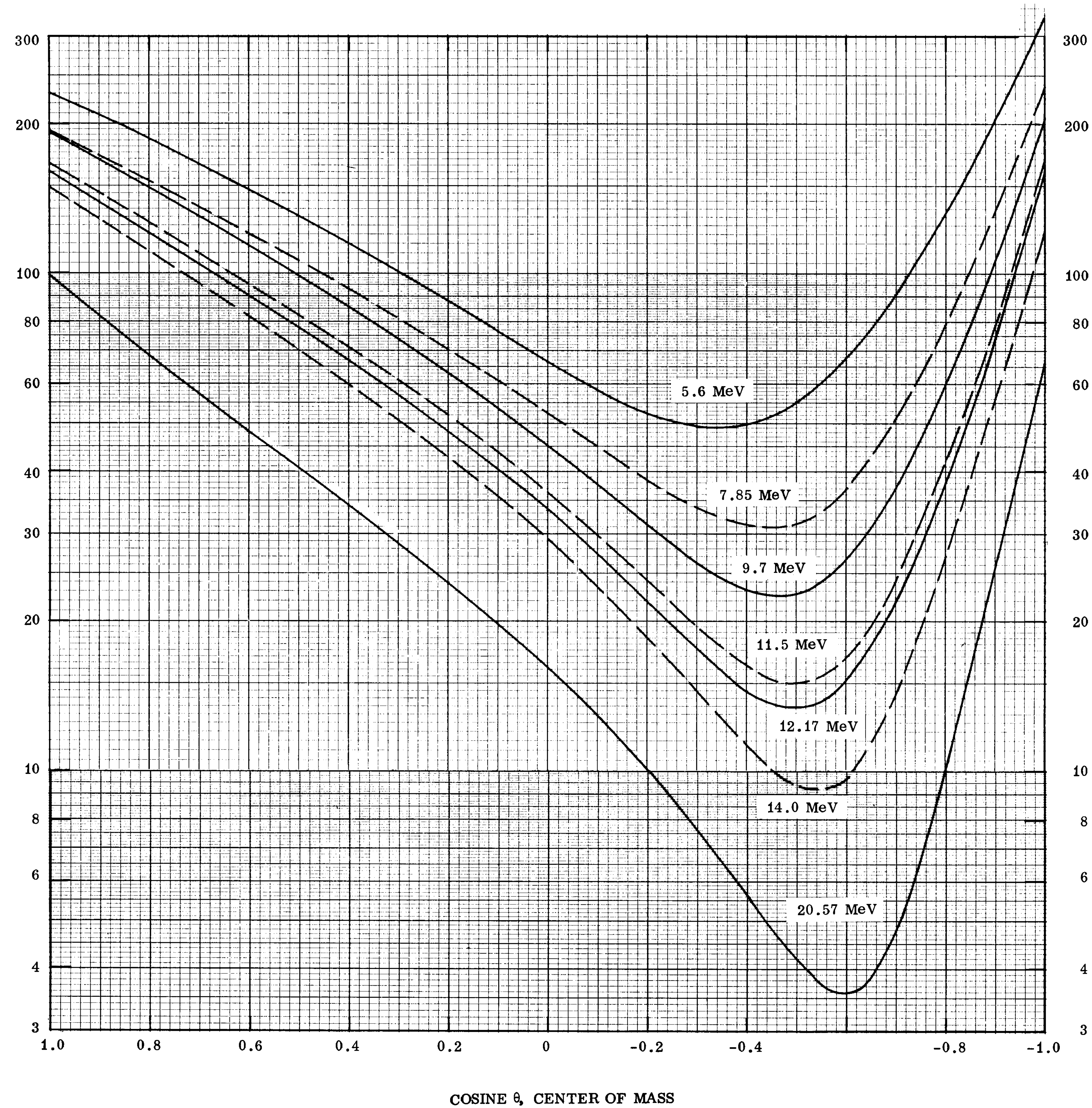
FEB. 1967

COMPOSITE ELASTIC SCATTERING ANGULAR DISTRIBUTIONS FROM 5.6 TO 20.57 MeV



Composite curves reproduced from this evaluation; Horsley and Stewart (1967).

COMPOSITE ELASTIC SCATTERING ANGULAR DISTRIBUTIONS FROM 5.6 TO 20.57 MeV



Composite curves as calculated by van Oers, private communication to Stewart, October 1966. Further information and references can be found on ANG-1-2-17 and -18.

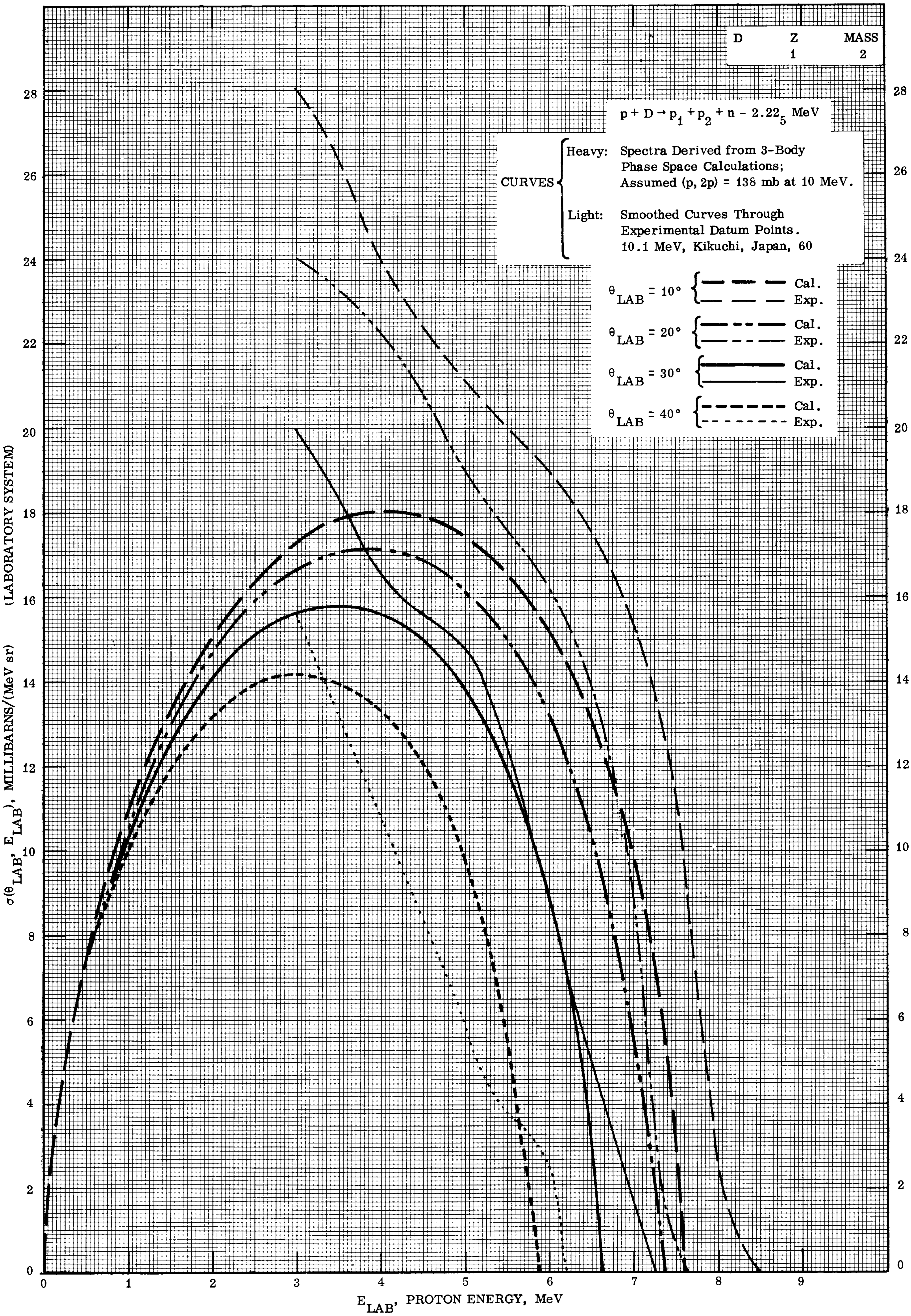
APPENDIX

DATA REFERENCES

$$p + D \rightarrow p_1 + p_2 + n_1 - 2.225 \text{ MeV}$$

Legend	Energy	Reference and Comments
Curves Light	10.1 MeV	S. Kikuchi, J. Sanada, S. Suwa, I. Hayashi, K. Nisimura, and K. Fukunaga, J. Phys. Soc. (Japan) 15, 748 (1960). Detected both protons using proportional and NaI counters (not in coincidence); deuterium gas target. The individual points were not available, therefore the curves as drawn by the experimentalists through their data have been reproduced for comparison. Note: This cross section is twice the reaction cross section and labeled the proton production cross section.
Curves Heavy	10 MeV	Phase space calculation from unfolding the double integral assuming that D(p, n)2p reaction cross section is 138 mb.

PROTON PRODUCTION CROSS SECTIONS FROM p + D BREAKUP $E_p = 10.1$ MeV

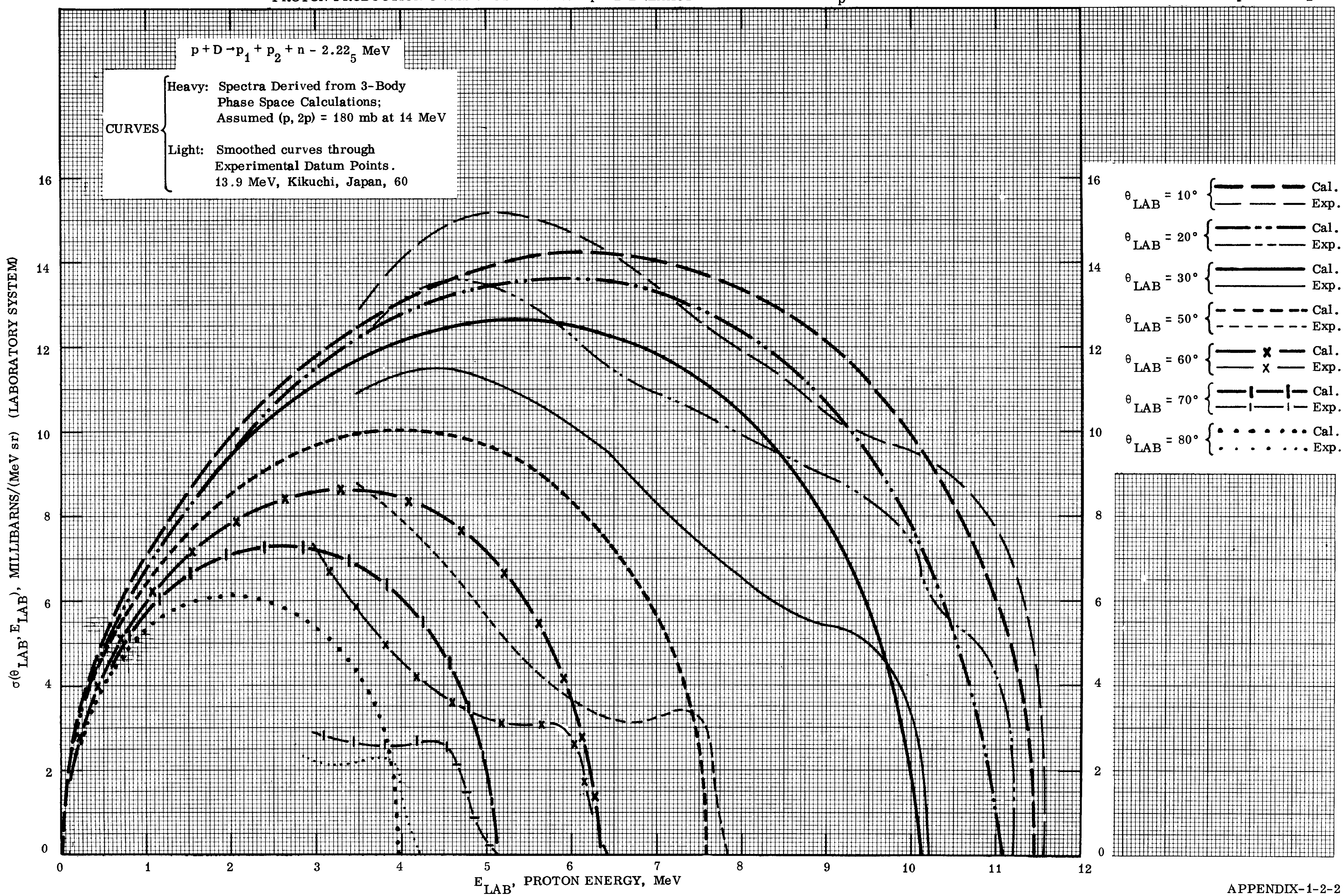


DATA REFERENCES

$$p + D \rightarrow p_1 + p_2 + n_1 - 2.225 \text{ MeV}$$

Legend	Energy	Reference and Comments
Curves Light	13.9 MeV	S. Kikuchi, J. Sanada, S. Suwa, I. Hayashi, K. Nisimura, and K. Fukunaga, J. Phys. Soc. (Japan) 15, 748 (1960). Detected both protons using proportional and NaI counters (not in coincidence); deuterium gas target. The individual points were not available, therefore the curves as drawn by the experimentalists through their data have been reproduced for comparison. Note: This cross section is twice the reaction cross section and labeled the proton production cross section.
Curves Heavy	14 MeV	Phase space calculation from unfolding the double integral assuming that D(p, n)2p reaction cross section is 180 mb.

PROTON PRODUCTION CROSS SECTIONS FROM p + D BREAKUP E_p = 13.9 MeV

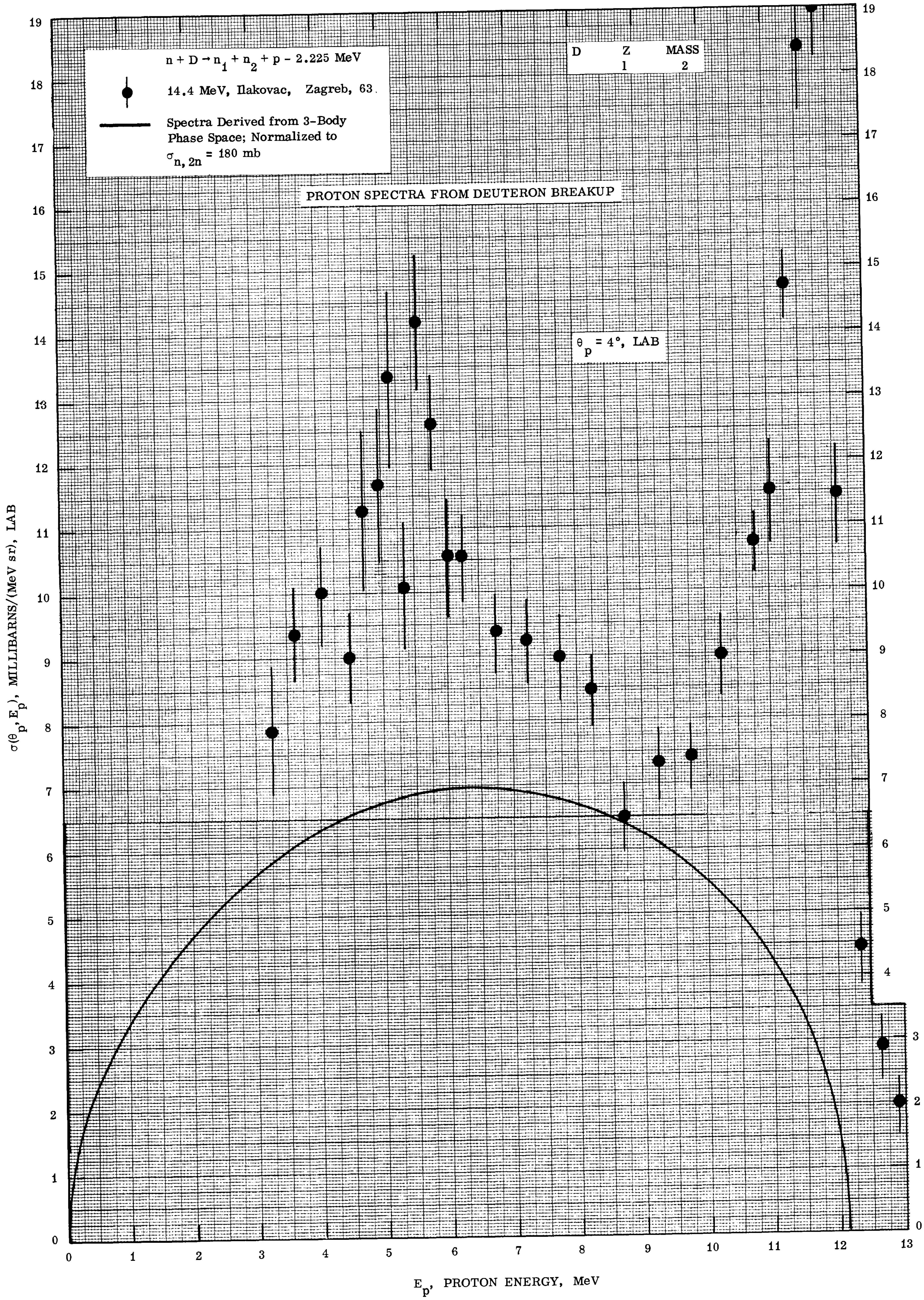


DATA REFERENCES

$$n + D \rightarrow p + n_1 + n_2 - 2.225 \text{ MeV}$$

1. ● 14.4 MeV — K. Ilakovac, L. G. Kuo, M. Petravić, I. Šlaus, and P. Tomaš, Phys. Rev. Letters 6, 356 (1961) and Nucl. Phys. 43, 254 (1963); the same data were also reported by I. Šlaus, Progress in Fast Neutron Physics, Chicago, Ill., The University of Chicago Press, 1963, p. 61. Šlaus describes in the last reference a remeasurement of the proton spectrum near zero degrees which disagrees in absolute value. At the suggestion of Šlaus, the data herein have been raised by 25% (private communication to Stewart, July 1966). Please see also the comments under Ref. 53 and 56. Detected protons using a dE/dx - E counter with a two-dimensional (5 x 20 channel) analyzer.

2. ——— 14.4 MeV — Phase space calculation from unfolding the double integral assuming that the D(n, 2n) reaction cross section is 180 mb.

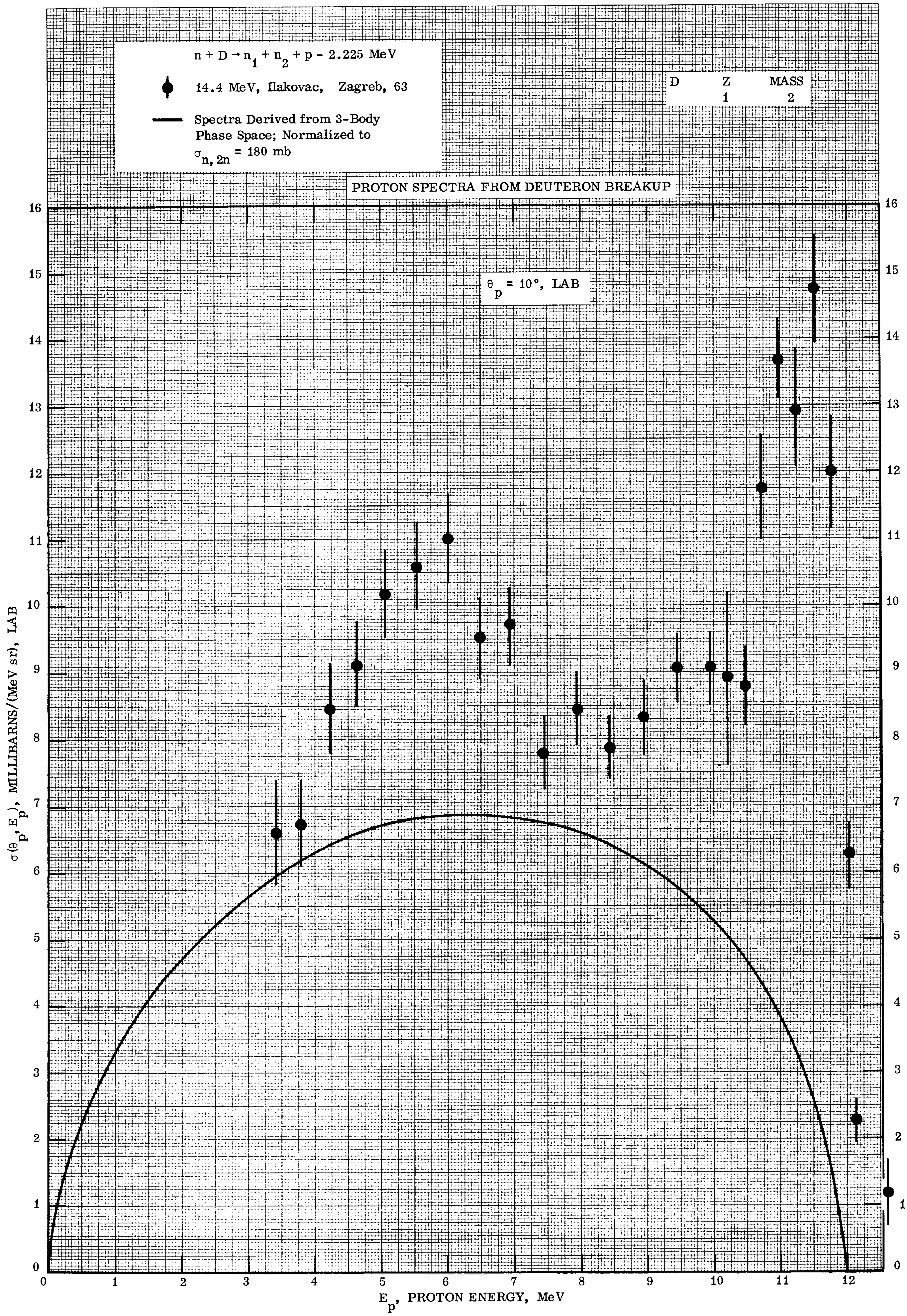

$n + D \rightarrow n_1 + n_2 + p - 2.225$ MeV
14.4 MeV, Ilakovac, Zagreb, 63.
Spectra Derived from 3-Body Phase Space; Normalized to $\sigma_{n,2n}$ = 180 mb
D Z MASS
1 2
PROTON SPECTRA FROM DEUTERON BREAKUP
$\theta_p = 4°$, LAB
$\sigma(\theta_p, E_p)$, MILLIBARNS/(MeV sr), LAB
E_p, PROTON ENERGY, MeV

DATA REFERENCES

$$n + D \rightarrow p + n_1 + n_2 - 2.225 \text{ MeV}$$

1.	⧫	14.4 MeV	K. Ilakovac, L. G. Kuo, M. Petravić, I. Šlaus, and P. Tomaš, Phys. Rev. Letters 6, 356 (1961) and Nucl. Phys. 43, 254 (1963); the same data were also reported by I. Šlaus, Progress in Fast Neutron Physics, Chicago, Ill., The University of Chicago Press, 1963, p. 61. Šlaus describes in the last reference a remeasurement of the proton spectrum near zero degrees which disagrees in absolute value. At the suggestion of Šlaus, the data herein have been raised by 25% (private communication to Stewart, July 1966). Please see also the comments under Ref. 53 and 56. Detected protons using a dE/dx - E counter with a two-dimensional (5 x 20 channel) analyzer.
2.	———	14.4 MeV	Phase space calculation from unfolding the double integral assuming that the D(n, 2n) reaction cross section is 180 mb.

REACTION CROSS SECTION; for Neutron Production, Multiply by Two $E_n = 14.4$ MeV



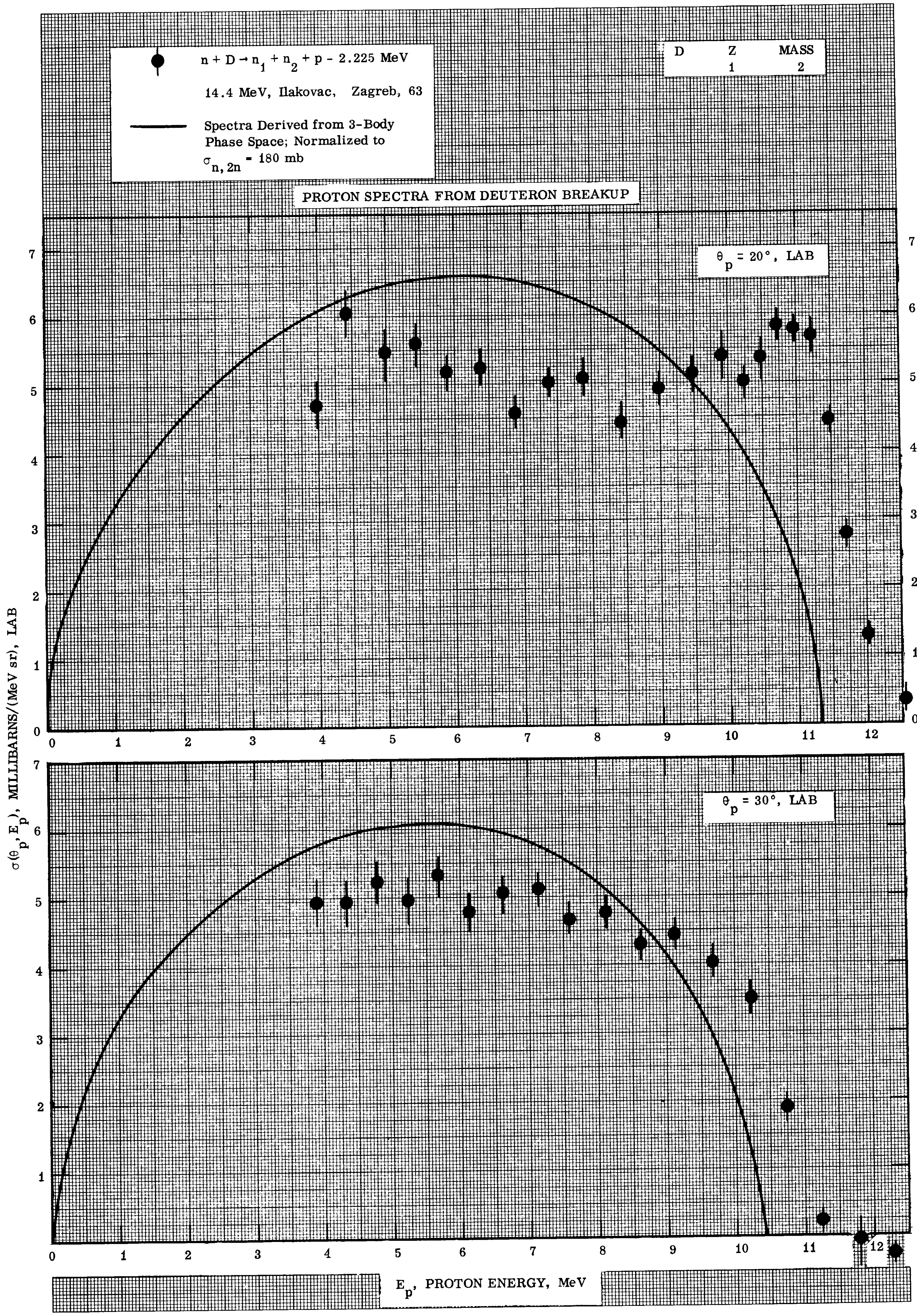
DATA REFERENCES

$n + D \rightarrow p + n_1 + n_2 - 2.225$ MeV

1. 14.4 MeV — K. Ilakovac, L. G. Kuo, M. Petravić, I. Šlaus, and P. Tomaš, Phys. Rev. Letters 6, 356 (1961) and Nucl. Phys. 43, 254 (1963); the same data were also reported by I. Šlaus, Progress in Fast Neutron Physics, Chicago, Ill., The University of Chicago Press, 1963, p. 61. Šlaus describes in the last reference a remeasurement of the proton spectrum near zero degrees which disagrees in absolute value. At the suggestion of Šlaus the data herein have been raised by 25% (private communication to Stewart, July 1966). Please see also the comments under Ref. 53 and 56. Detected protons using a dE/dx - E counter with a two-dimensional (5 x 20 channel) analyzer.

2. 14.4 MeV — Phase space calculation from unfolding the double integral assuming that the D(n, 2n) reaction cross section is 180 mb.

REACTION CROSS SECTION; for Neutron Production, Multiply by Two $E_n = 14.4$ MeV



DATA REFERENCES

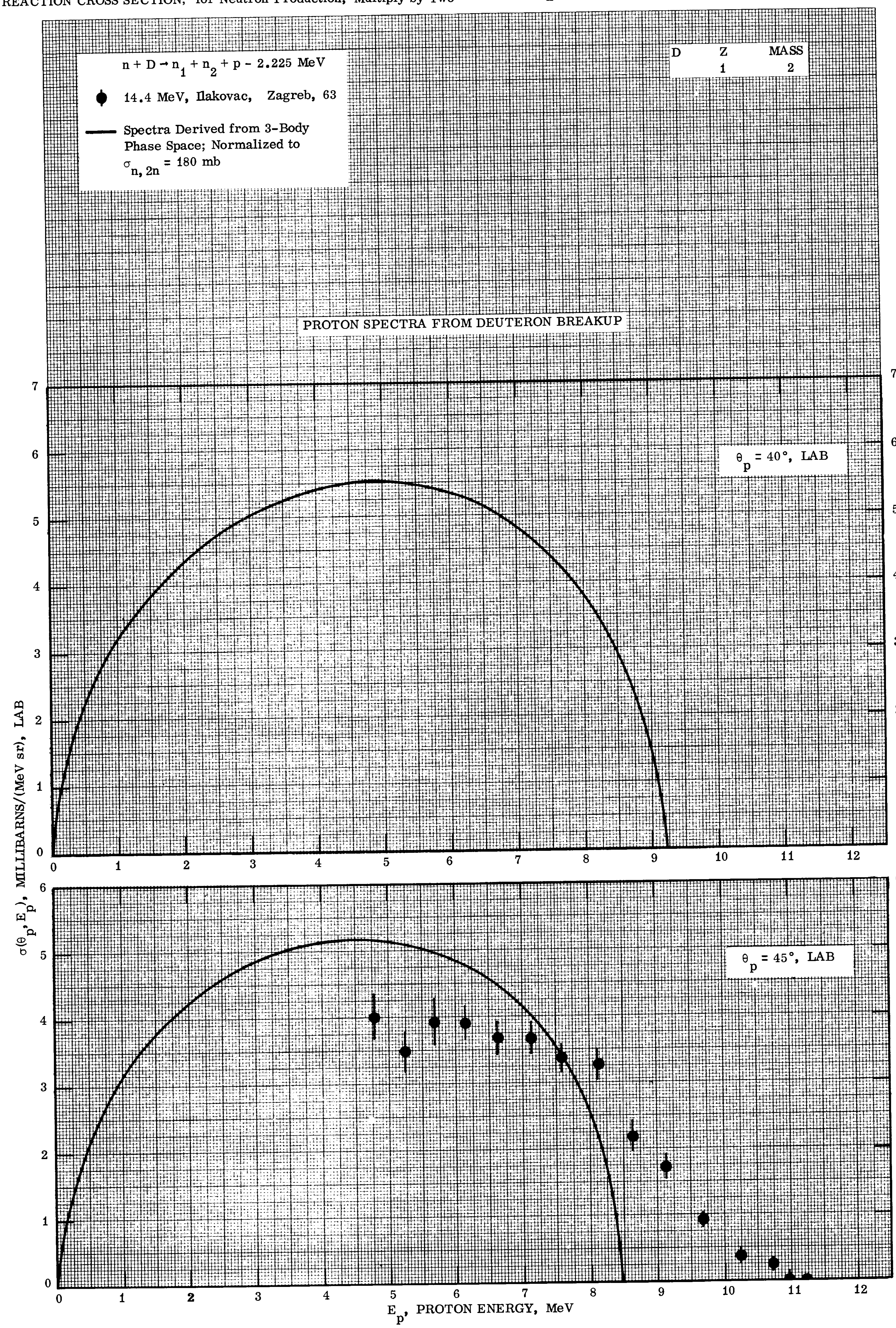
$$n + D \rightarrow p + n_1 + n_2 - 2.225\ \text{MeV}$$

1. ⏀ 14.4 MeV — K. Ilakovac, L. G. Kuo, M. Petravić, I. Šlaus, and P. Tomaš, Phys. Rev. Letters 6, 356 (1961) and Nucl. Phys. 43, 254 (1963); the same data were also reported by I. Šlaus, Progress in Fast Neutron Physics, Chicago, Ill., The University of Chicago Press, 1963, p. 61. Šlaus describes in the last reference a remeasurement of the proton spectrum near zero degrees which disagrees in absolute value. At the suggestion of Šlaus, the data herein have been raised by 25% (private communication to Stewart, July 1966). Please see also the comments under Ref. 53 and 56. Detected protons using a dE/dx - E counter with a two-dimensional (5 x 20 channel) analyzer.

2. ——— 14.4 MeV — Phase space calculation from unfolding the double integral assuming that the D(n, 2n) reaction cross section is 180 mb.

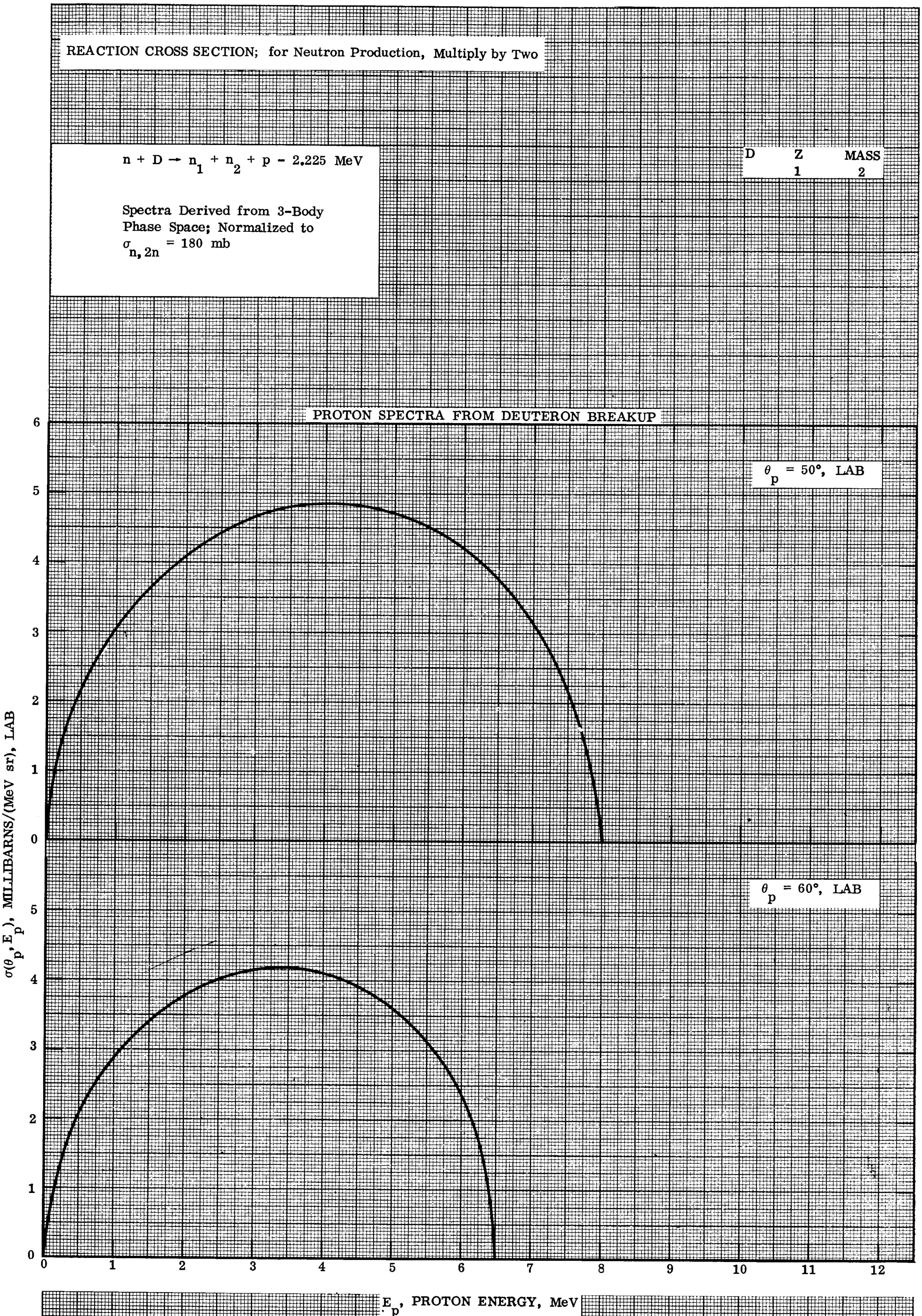
REACTION CROSS SECTION; for Neutron Production, Multiply by Two

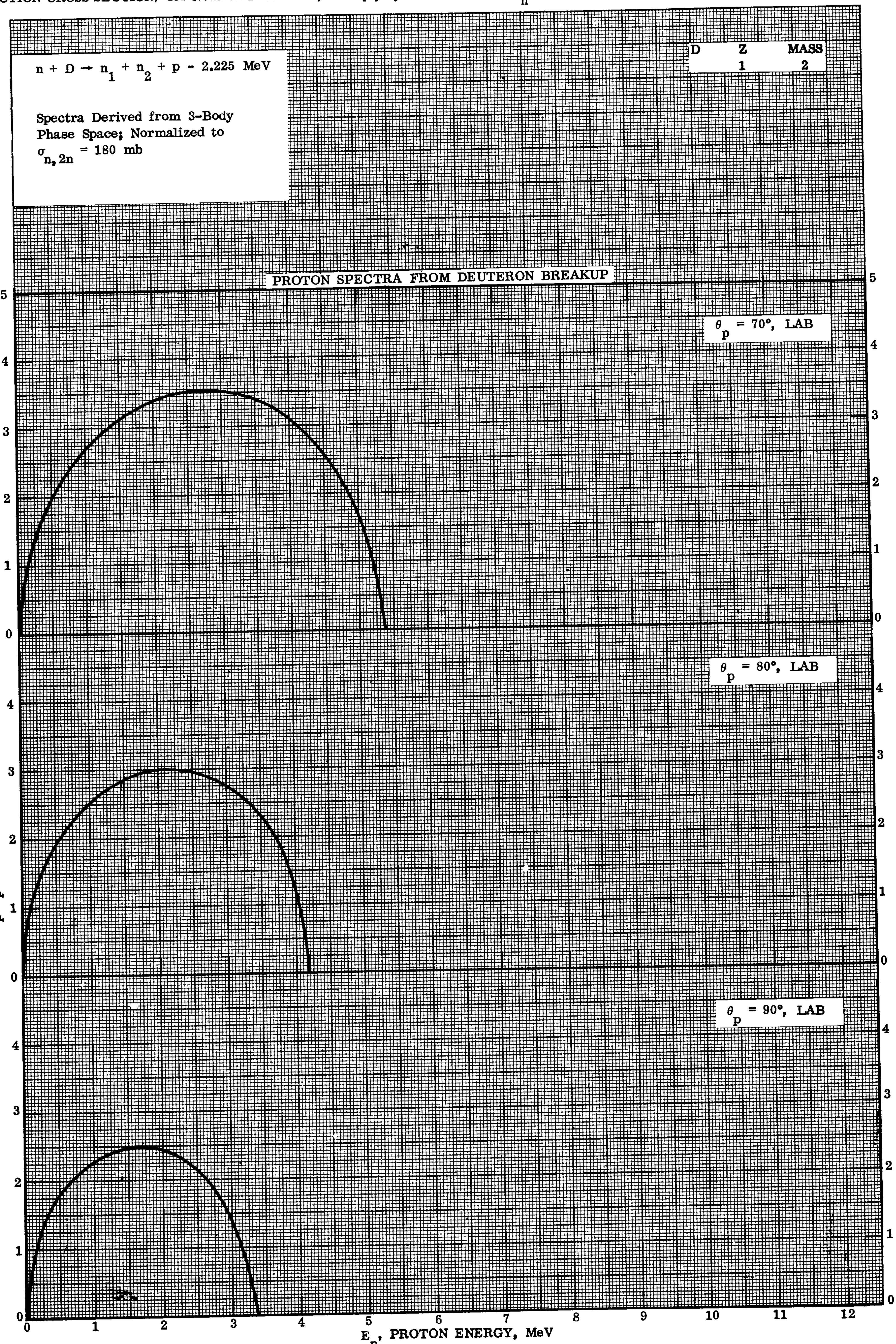
$E_n = 14.4$ MeV



Millimeters, 5 mm lines accented, cm lines heavy.

$E_n = 14.4$ MeV

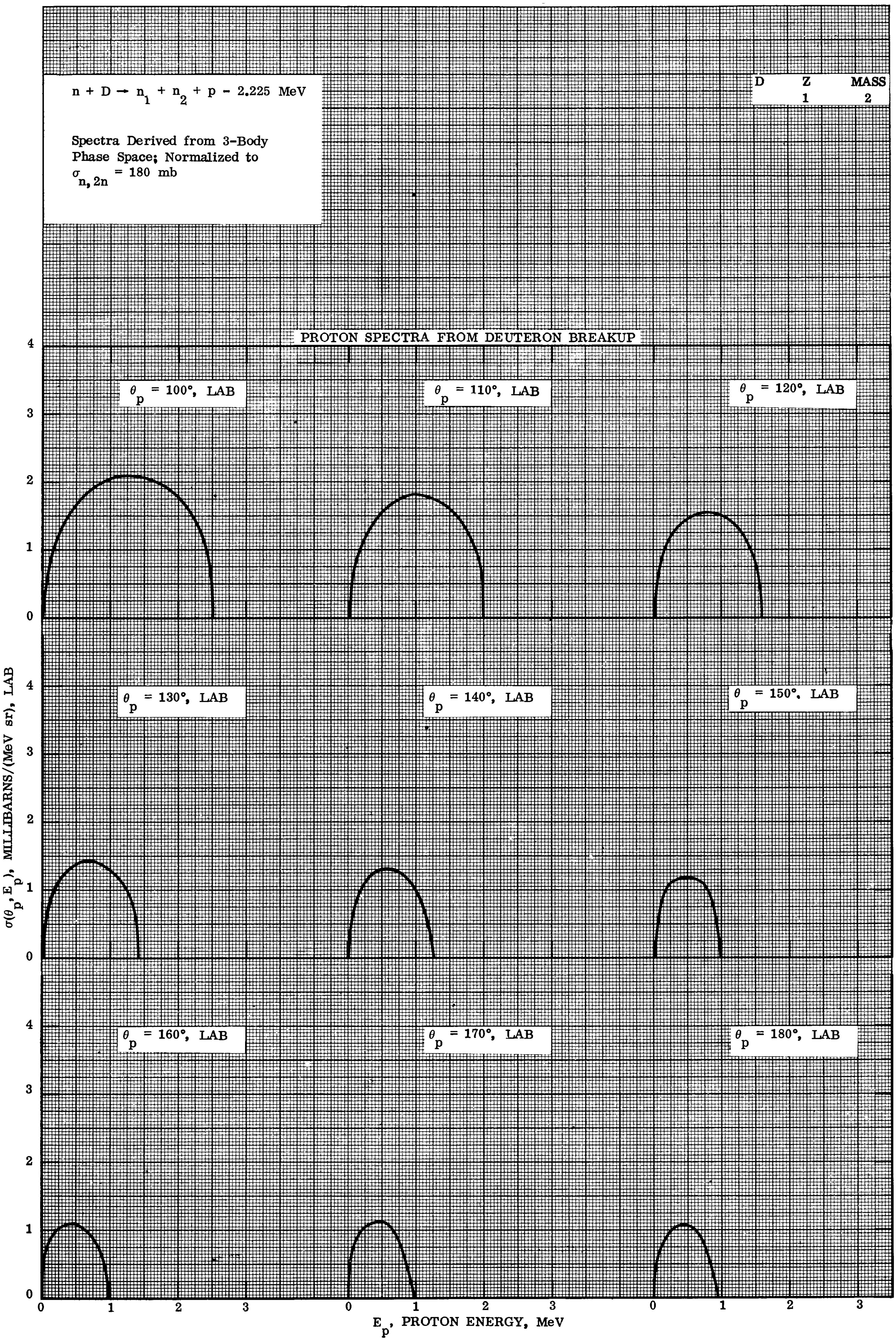




n + D → n_1 + n_2 + p - 2.225 MeV
Spectra Derived from 3-Body Phase Space; Normalized to $\sigma_{n,2n}$ = 180 mb
D Z MASS
1 2
PROTON SPECTRA FROM DEUTERON BREAKUP
θ_p = 70°, LAB
θ_p = 80°, LAB
θ_p = 90°, LAB
$\sigma(\theta_p, E_p)$, MILLIBARNS/(MeV sr), LAB
E_p, PROTON ENERGY, MeV
0 1 2 3 4 5 6 7 8 9 10 11 12

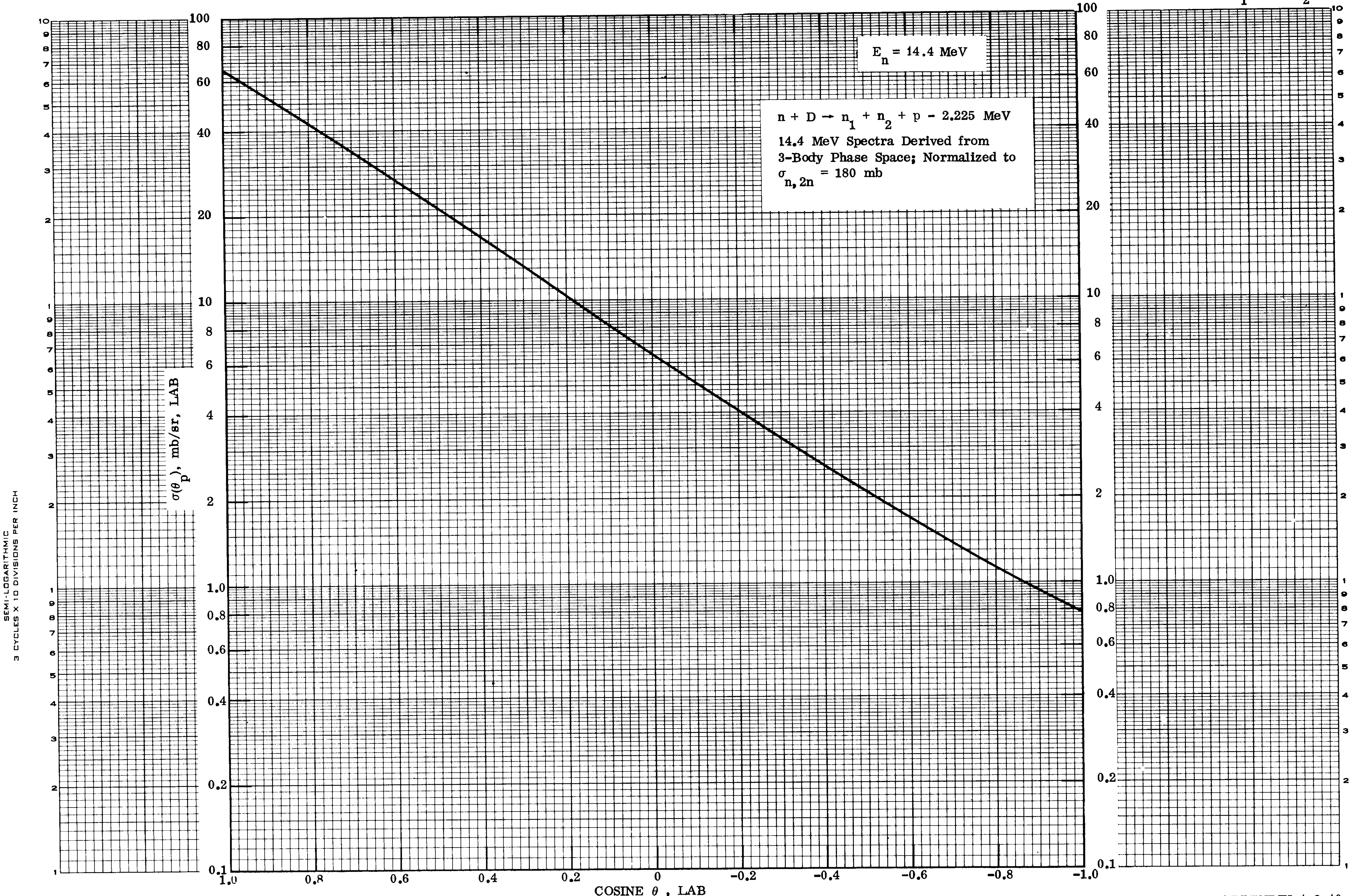
Millimeters, 5 mm lines accented, cm lines heavy.

REACTION CROSS SECTION; for Neutron Production, Multiply by Two $E_n = 14.4$ MeV

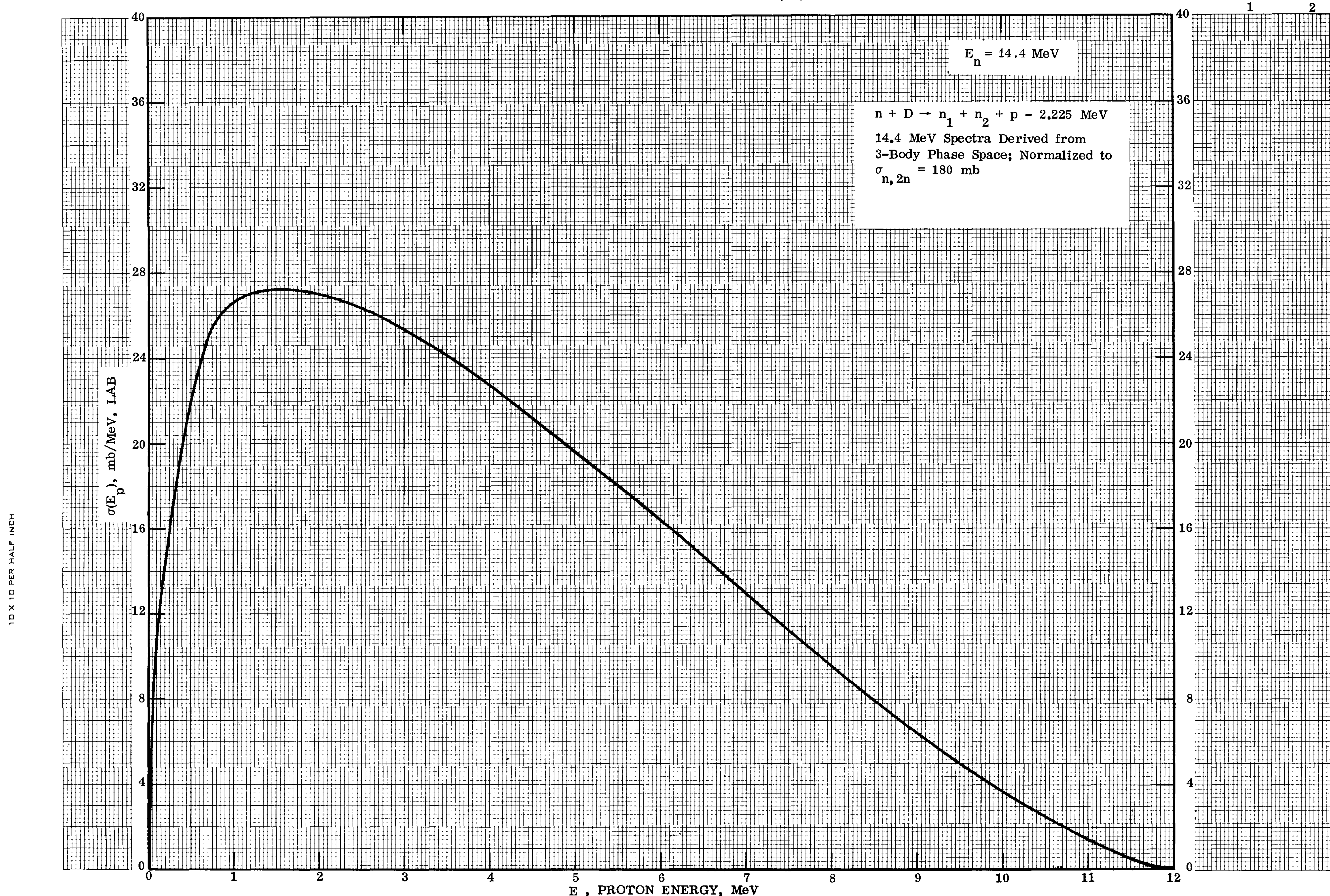


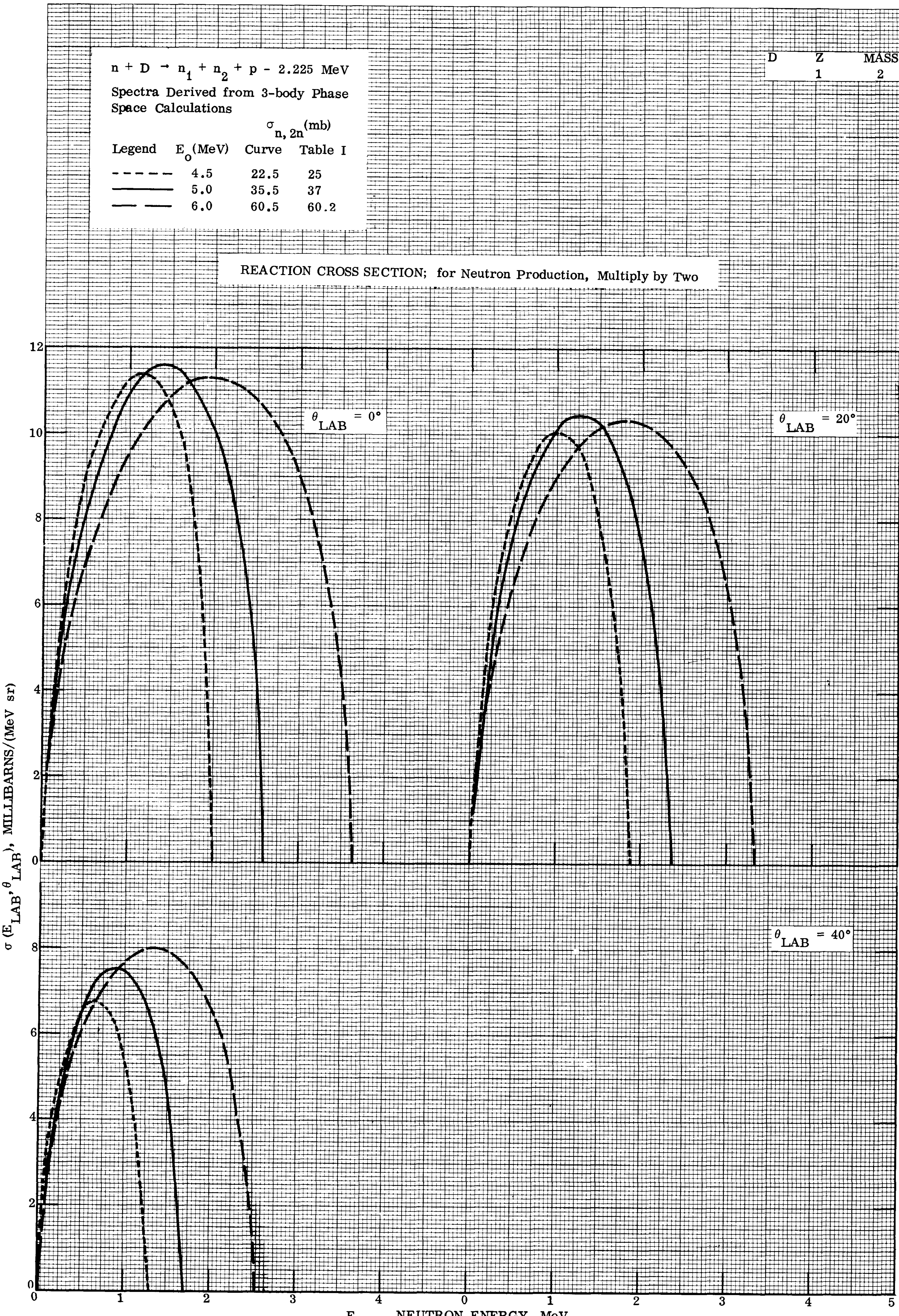
97

REACTION CROSS SECTION; for Neutron Production, Multiply by Two



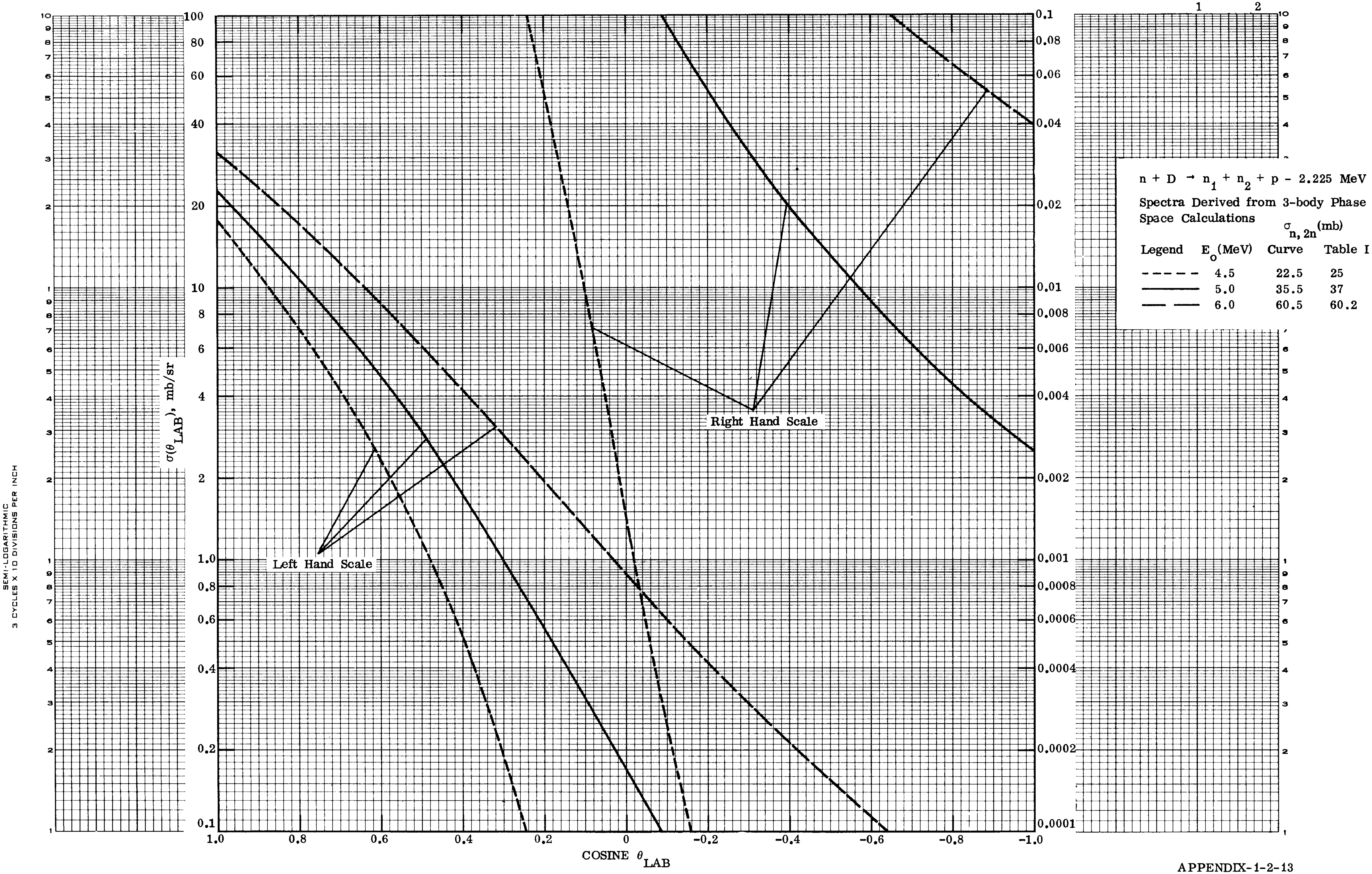
REACTION CROSS SECTION; for Neutron Production, Multiply by Two

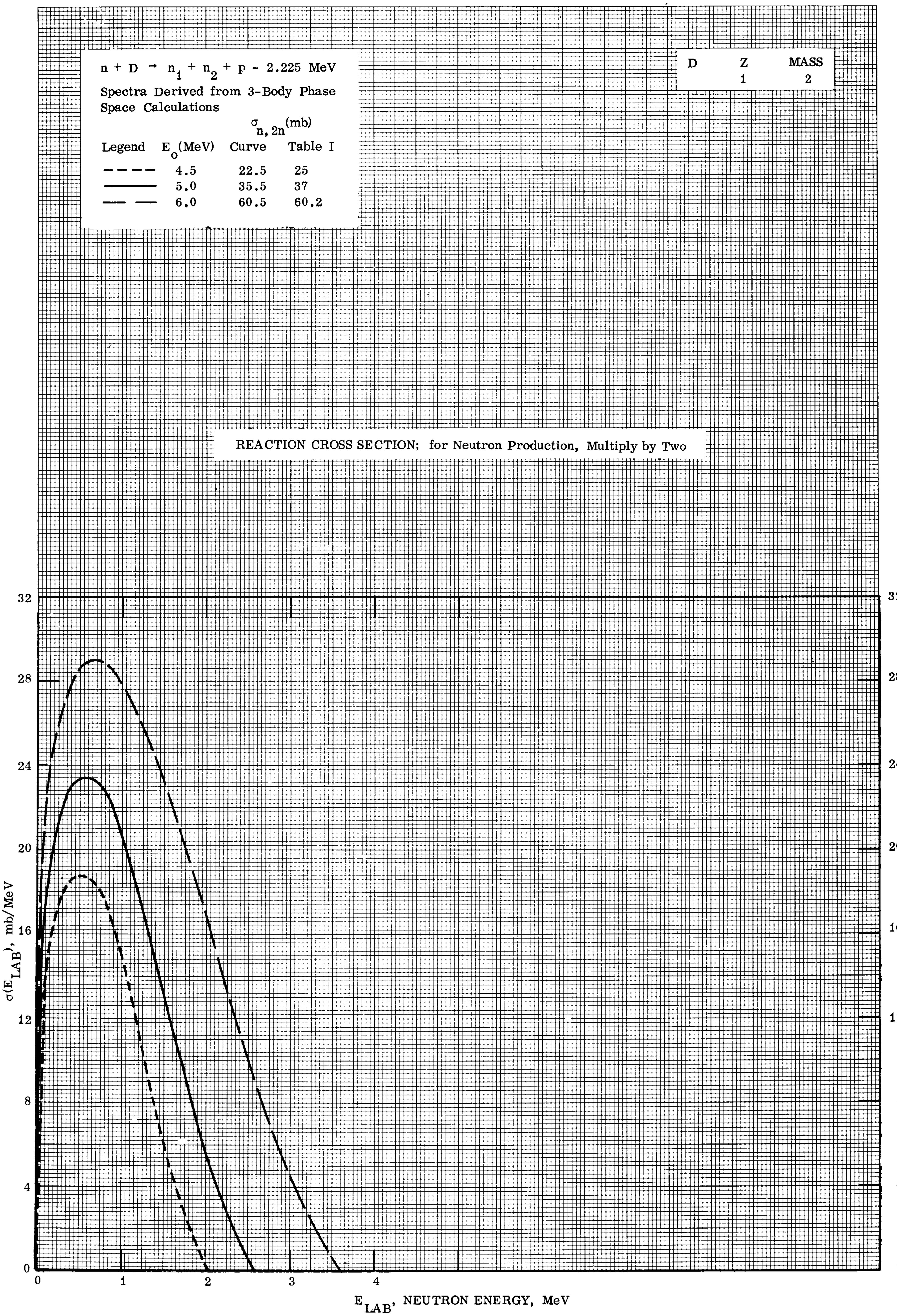


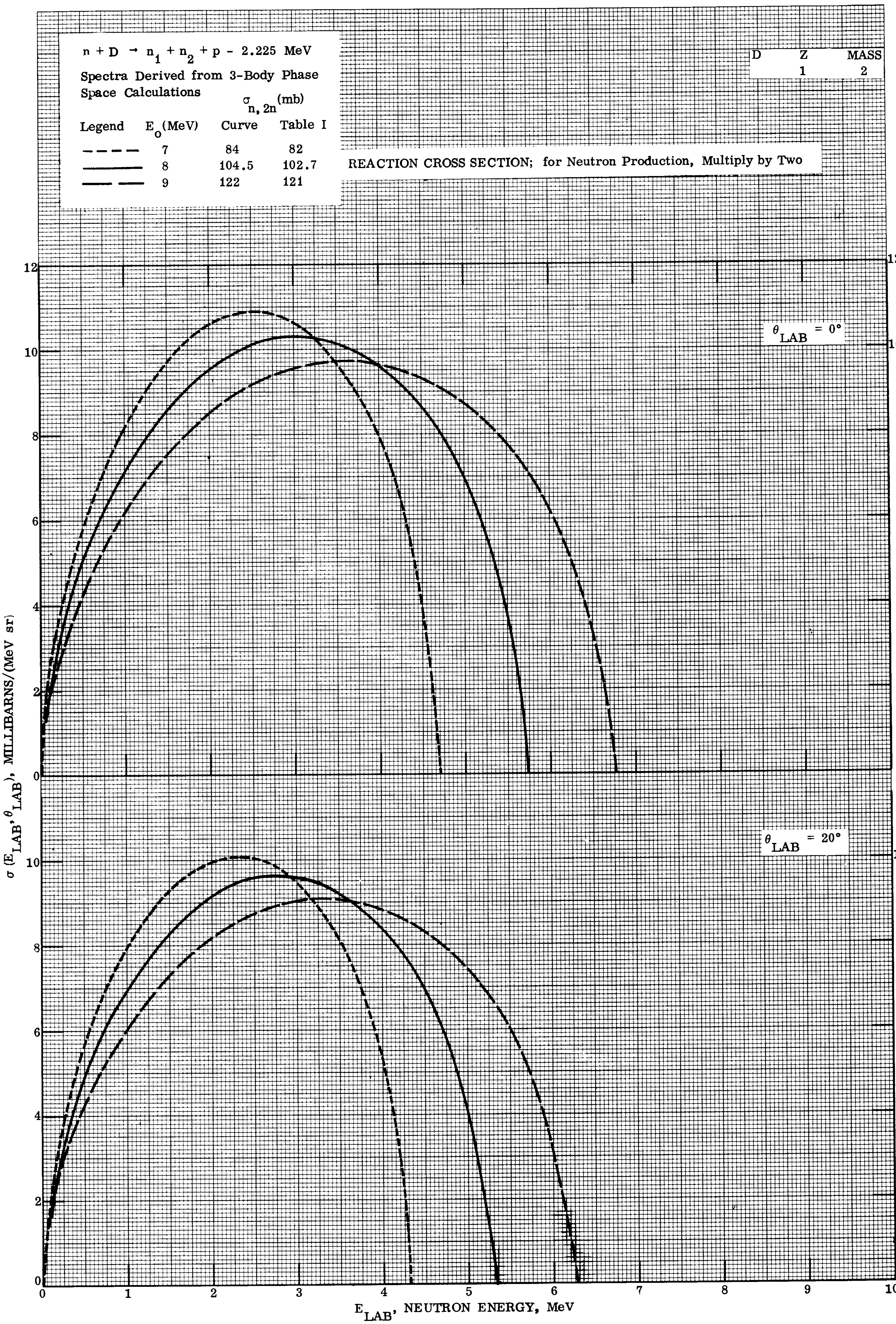


n + D → n1 + n2 + p - 2.225 MeV
Spectra Derived from 3-body Phase Space Calculations
σ n, 2n (mb)
Legend E0(MeV) Curve Table I
4.5 22.5 25
5.0 35.5 37
6.0 60.5 60.2
D Z MASS
1 2
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
θLAB = 0°
θLAB = 20°
θLAB = 40°
σ (ELAB, θLAB), MILLIBARNS/(MeV sr)
ELAB, NEUTRON ENERGY, MeV

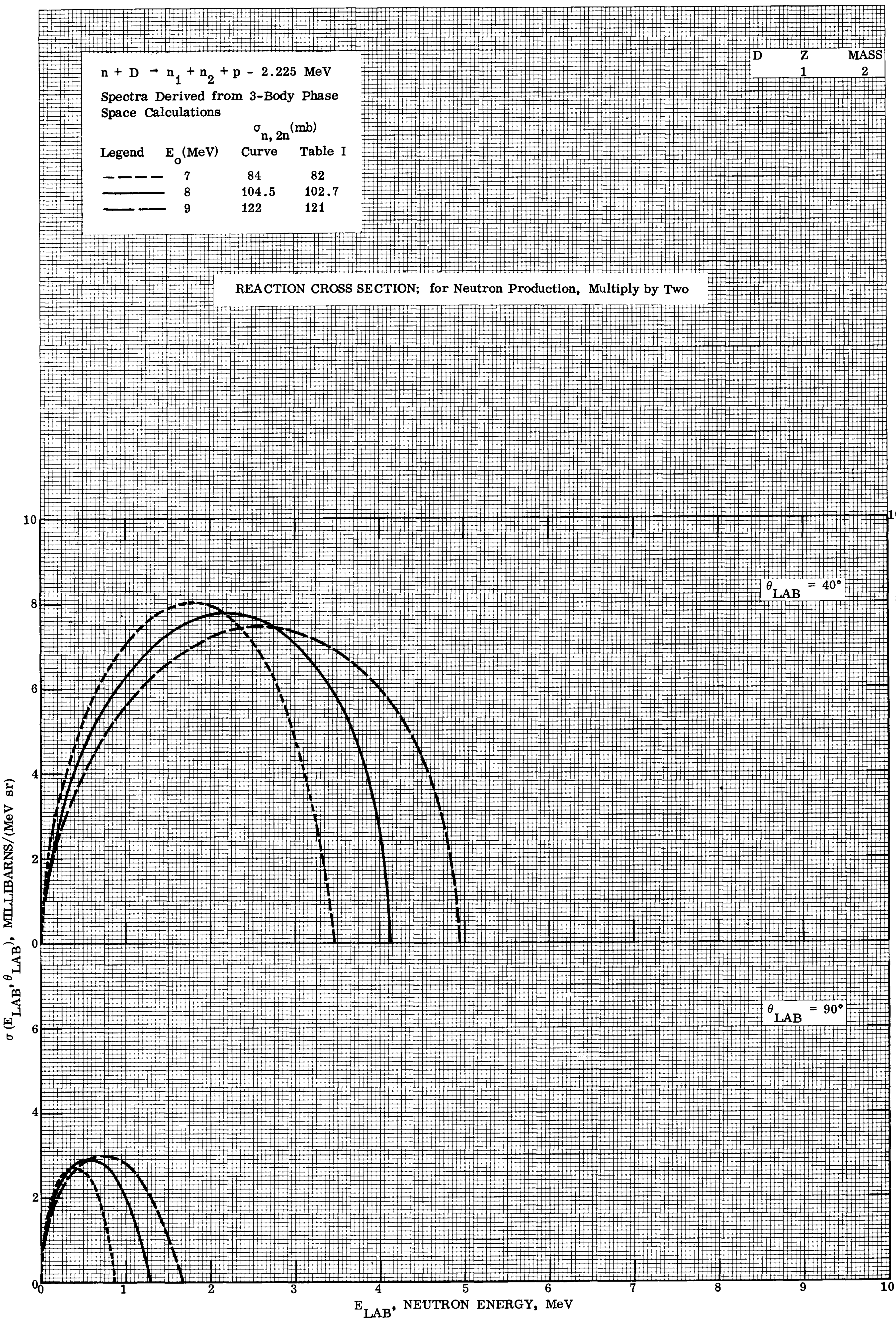
D Z MASS
1 2


n + D → n_1 + n_2 + p - 2.225 MeV
Spectra Derived from 3-body Phase Space Calculations
Legend | E_0(MeV) | $\sigma_{n,2n}$(mb) Curve | Table I
4.5 | 22.5 | 25
5.0 | 35.5 | 37
6.0 | 60.5 | 60.2
Left Hand Scale
Right Hand Scale
$\sigma(\theta_{LAB})$, mb/sr
COSINE θ_{LAB}
100
80
60
40
20
10
8
6
4
2
1.0
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
0.008
0.006
0.004
0.002
0.001
0.0008
0.0006
0.0004
0.0002
0.0001
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
SEMI-LOGARITHMIC
3 CYCLES X 10 DIVISIONS PER INCH


n + D → n1 + n2 + p - 2.225 MeV
Spectra Derived from 3-Body Phase Space Calculations
σn, 2n(mb)
Legend E0(MeV) Curve Table I
- - - - 4.5 22.5 25
——— 5.0 35.5 37
— — 6.0 60.5 60.2
D Z MASS
1 2
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
σ(ELAB), mb/MeV
0
4
8
12
16
20
24
28
32
0
1
2
3
4
ELAB, NEUTRON ENERGY, MeV

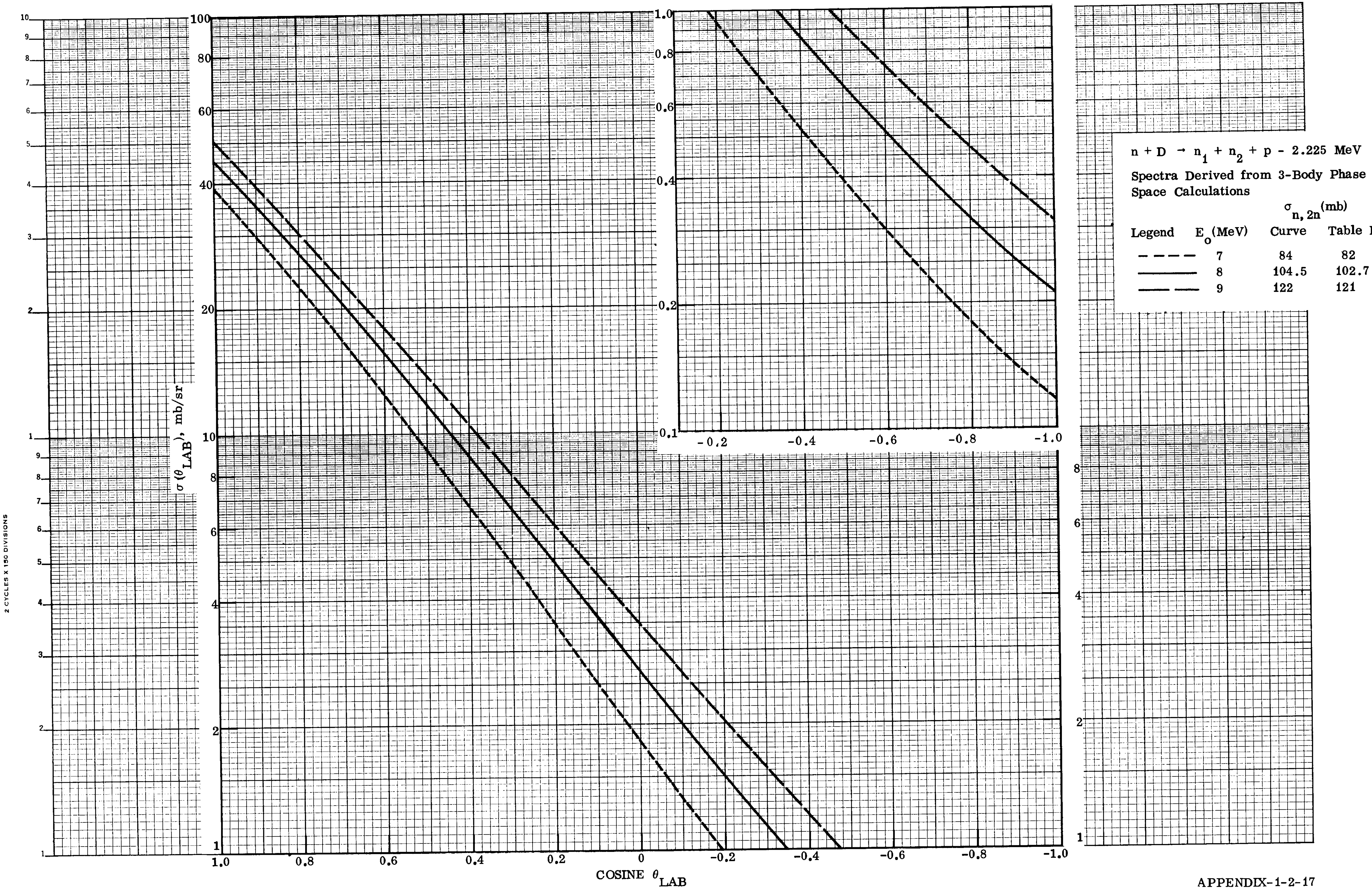


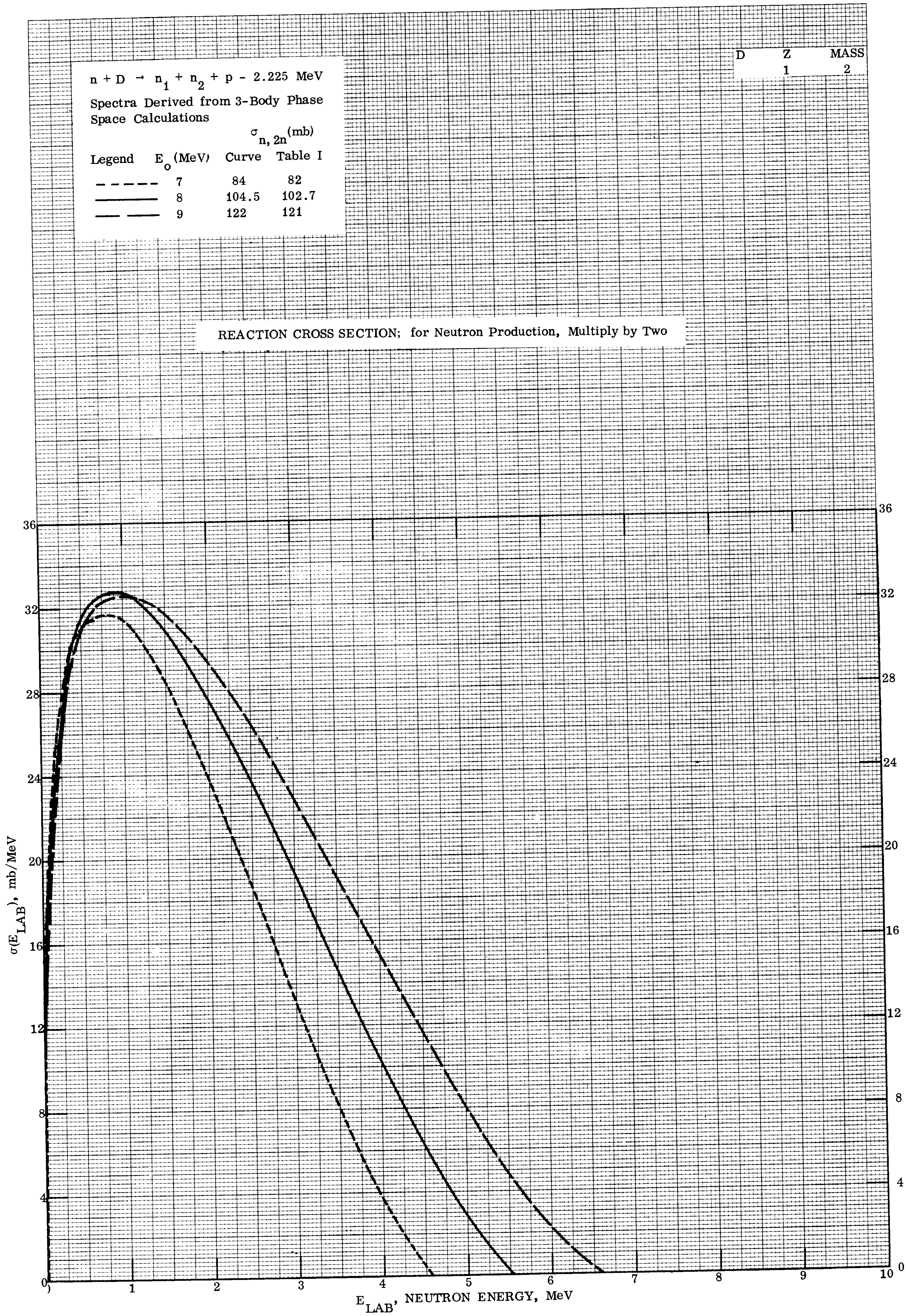
$n + D \rightarrow n_1 + n_2 + p - 2.225$ MeV
Spectra Derived from 3-Body Phase Space Calculations
Legend	E_o(MeV)	$\sigma_{n,2n}$(mb) Curve	Table I
- - - -	7	84	82
———	8	104.5	102.7
— —	9	122	121
D Z MASS
1 2
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
θ_{LAB} = 0°
θ_{LAB} = 20°
σ (E_{LAB}, θ_{LAB}), MILLIBARNS/(MeV sr)
E_{LAB}, NEUTRON ENERGY, MeV

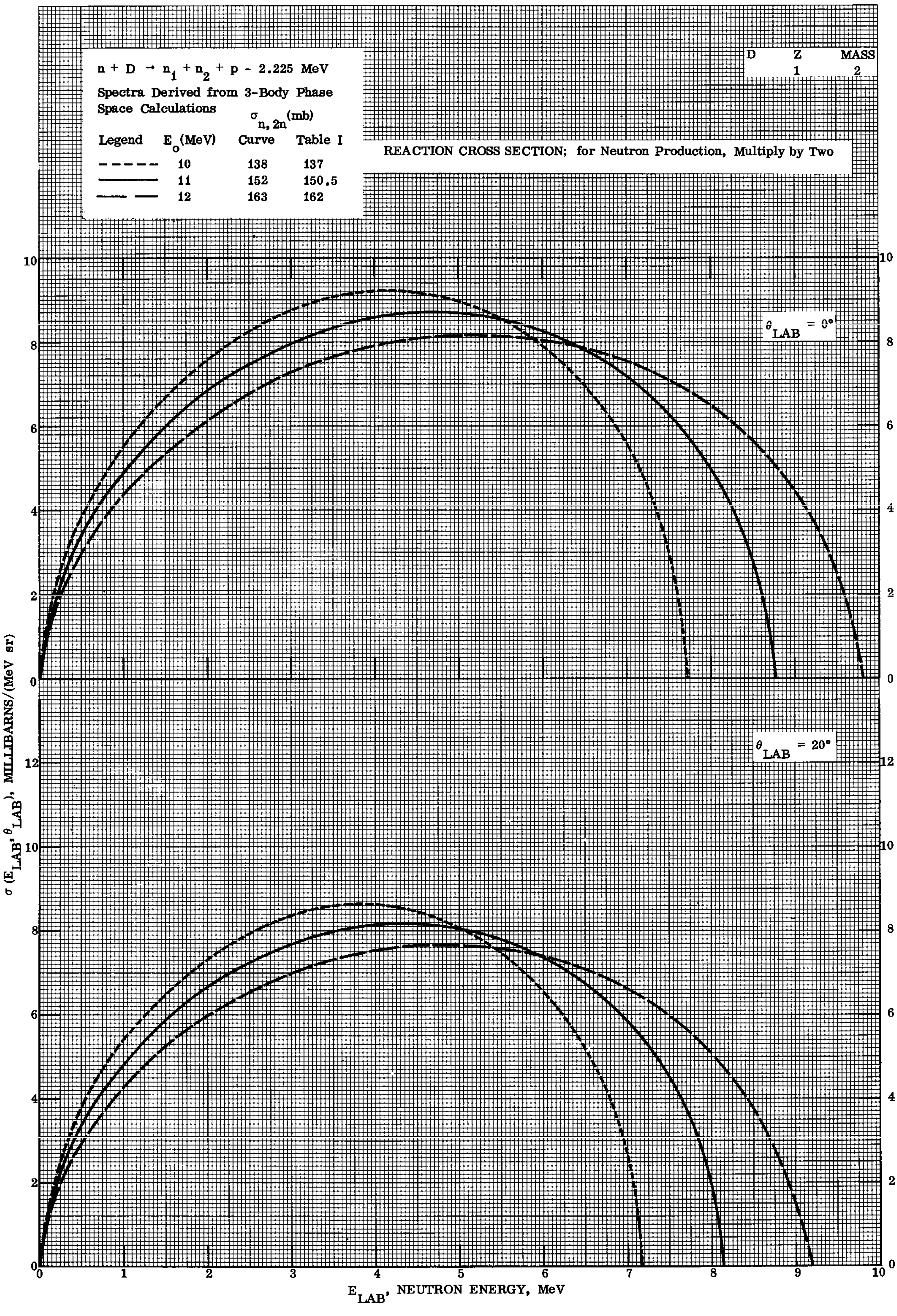

D Z MASS
1 2
n + D → n1 + n2 + p - 2.225 MeV
Spectra Derived from 3-Body Phase Space Calculations
σ n, 2n (mb)
Legend E0 (MeV) Curve Table I
7 84 82
8 104.5 102.7
9 122 121
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
θLAB = 40°
θLAB = 90°
σ (ELAB, θLAB), MILLIBARNS/(MeV sr)
ELAB, NEUTRON ENERGY, MeV
0
1
2
3
4
5
6
7
8
9
10

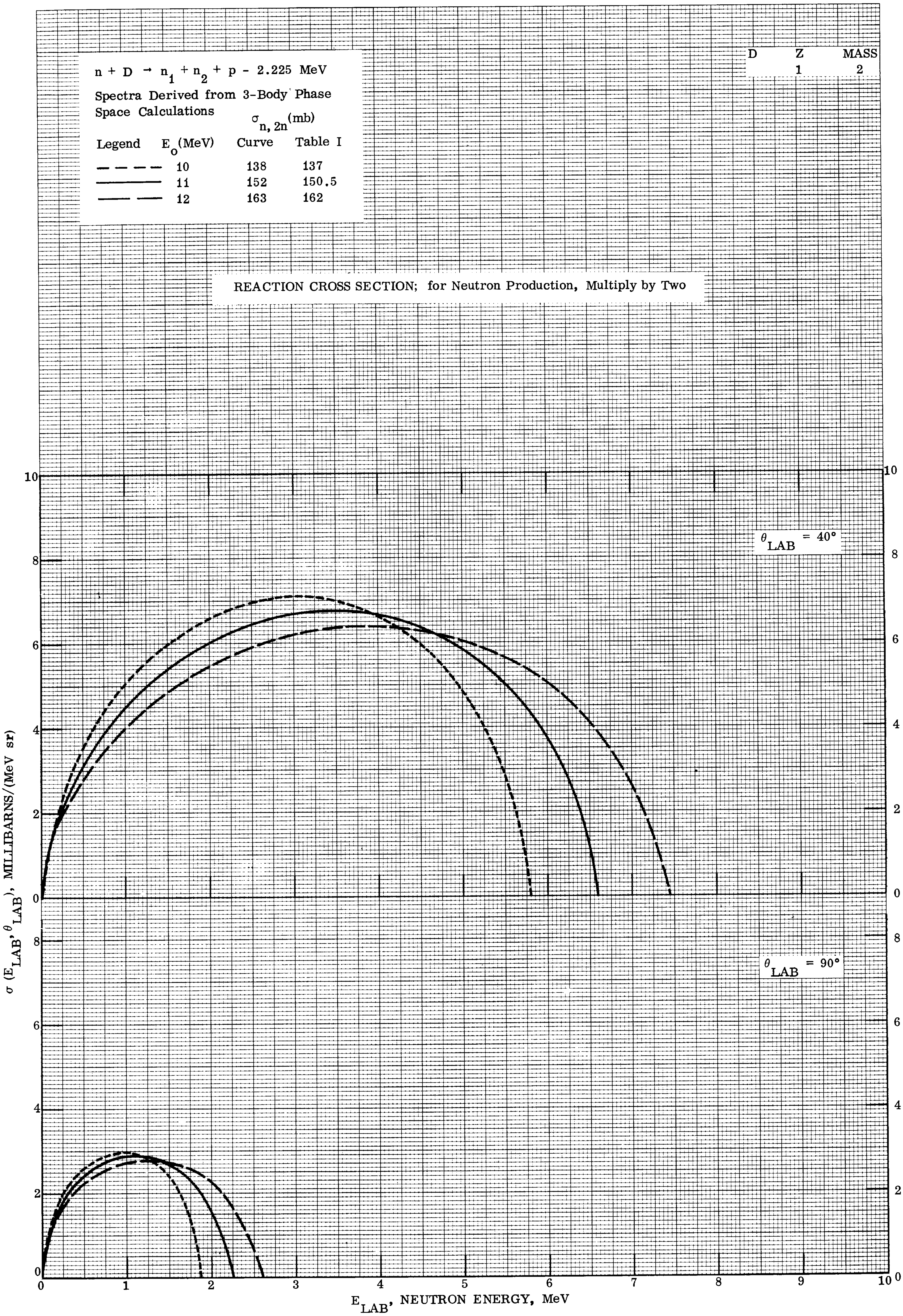
REACTION CROSS SECTION; for Neutron Production, Multiply by Two

D Z 1 MASS 2




n + D → n1 + n2 + p - 2.225 MeV
Spectra Derived from 3-Body Phase Space Calculations
Legend E0 (MeV) σn,2n(mb) Curve Table I
7 84 82
8 104.5 102.7
9 122 121
D Z MASS
1 2
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
σ(ELAB), mb/MeV
ELAB, NEUTRON ENERGY, MeV
0 4 8 12 16 20 24 28 32 36
0 1 2 3 4 5 6 7 8 9 10

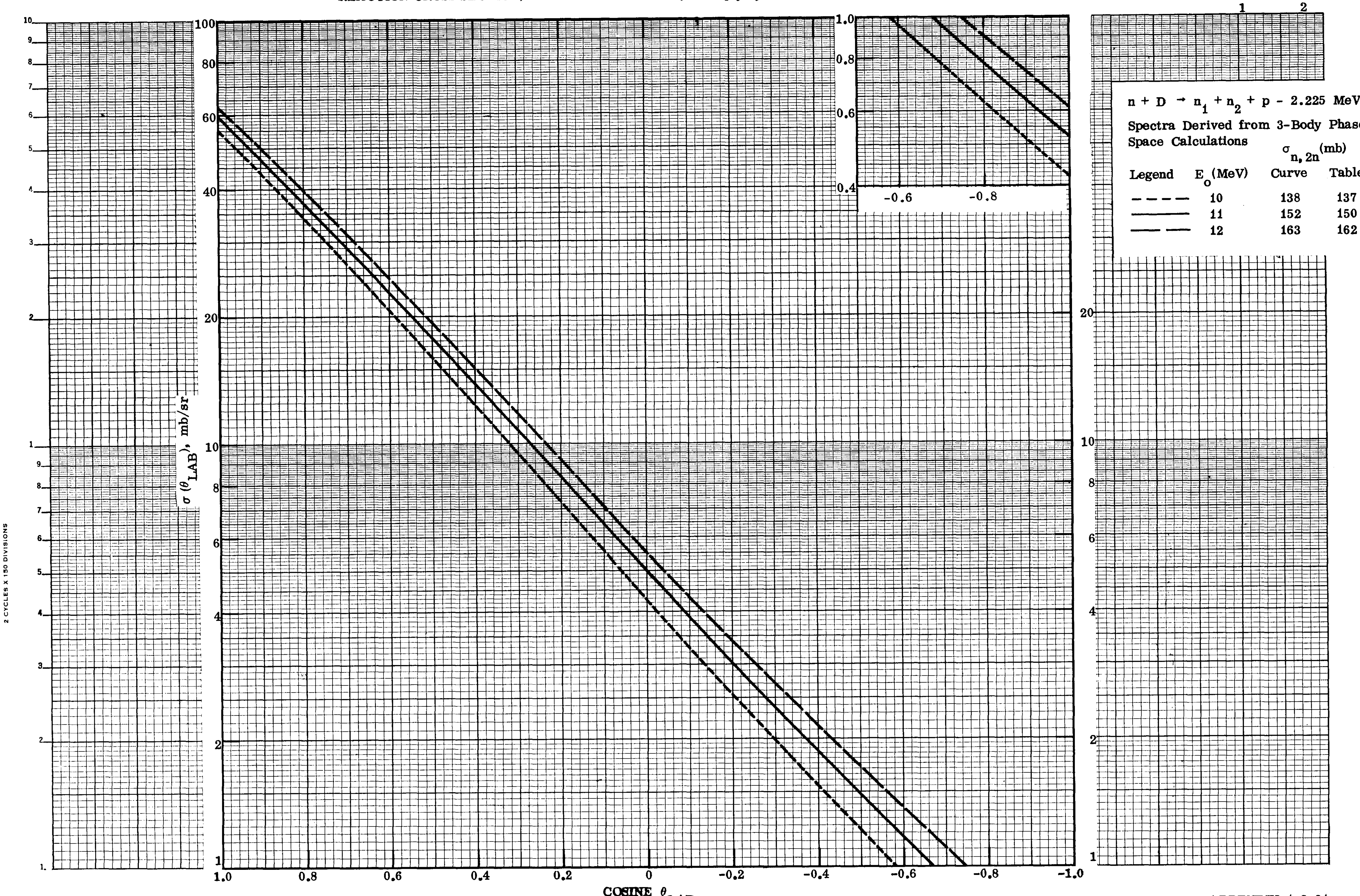

n + D → n_1 + n_2 + p - 2.225 MeV
Spectra Derived from 3-Body Phase Space Calculations
Legend
E_o(MeV)
$\sigma_{n,2n}$(mb)
Curve
Table I
10 138 137
11 152 150.5
12 163 162
D
Z
MASS
1
2
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
θ_{LAB} = 0°
θ_{LAB} = 20°
σ (E_{LAB}, θ_{LAB}), MILLIBARNS/(MeV sr)
E_{LAB}, NEUTRON ENERGY, MeV

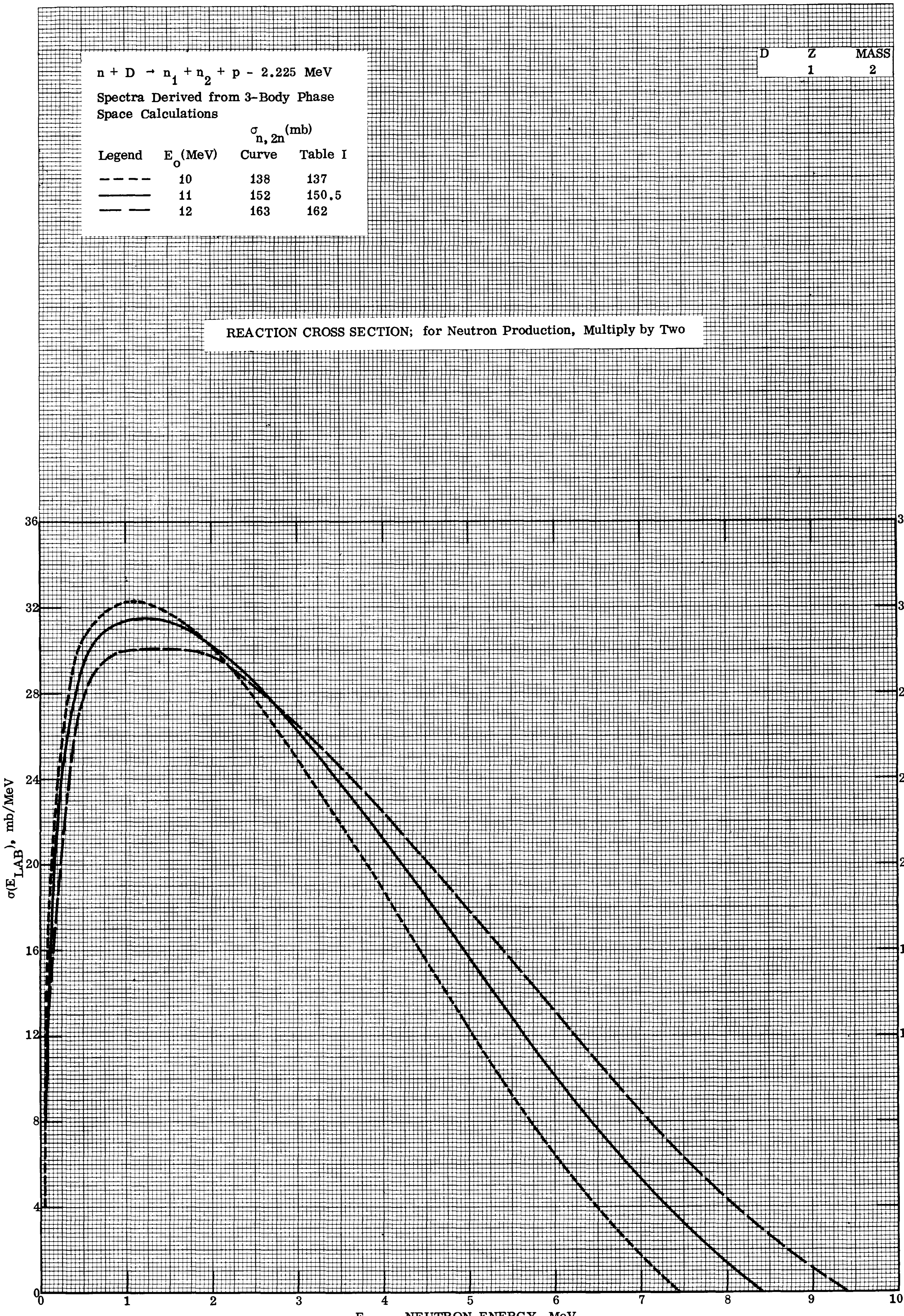


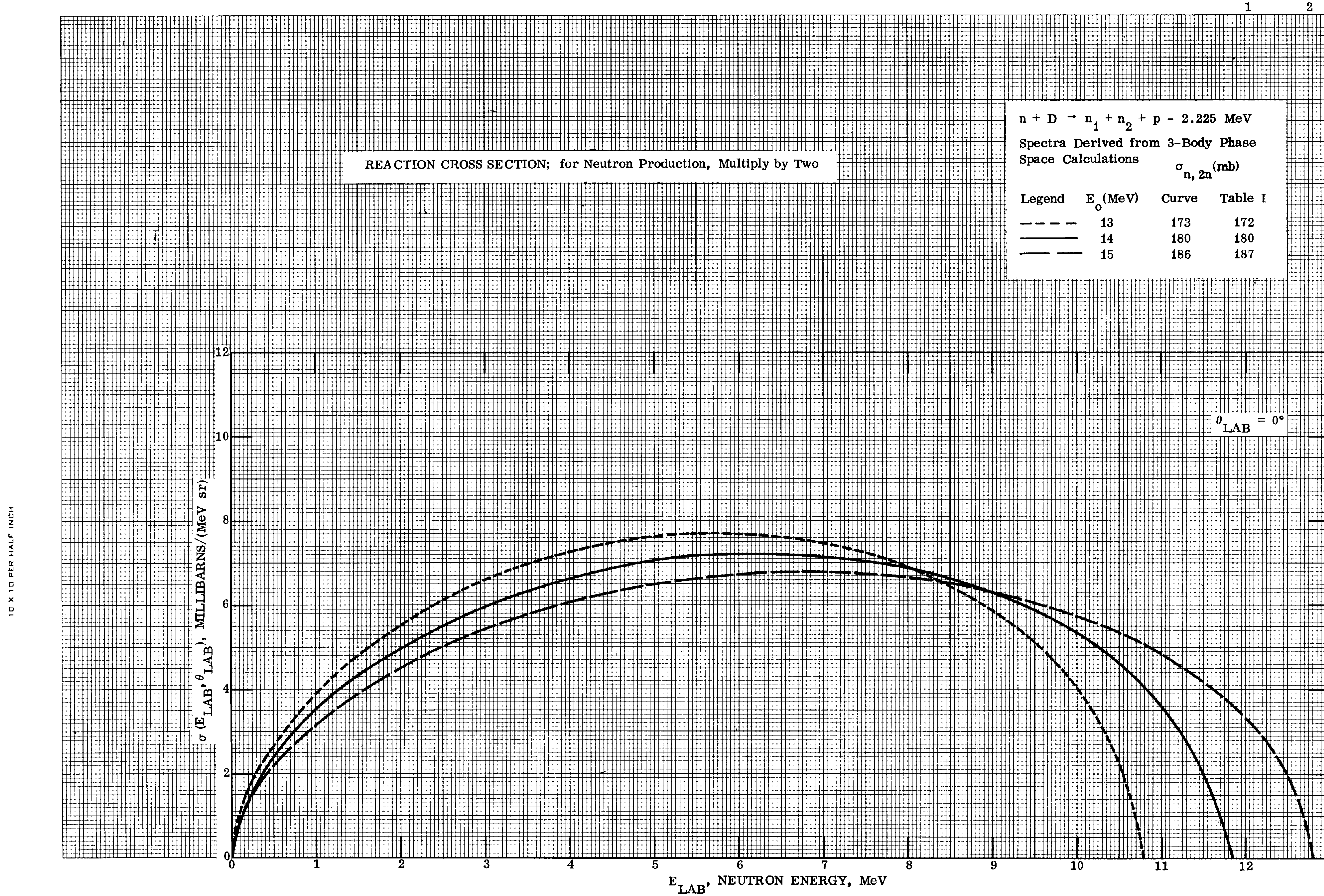
D Z MASS
1 2
n + D → n_1 + n_2 + p - 2.225 MeV
Spectra Derived from 3-Body Phase Space Calculations
Legend E_o(MeV) $\sigma_{n,2n}$(mb) Curve Table I
10 138 137
11 152 150.5
12 163 162
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
θ_{LAB} = 40°
θ_{LAB} = 90°
σ (E_{LAB}, θ_{LAB}), MILLIBARNS/(MeV sr)
E_{LAB}, NEUTRON ENERGY, MeV
0 1 2 3 4 5 6 7 8 9 10
0 2 4 6 8 10

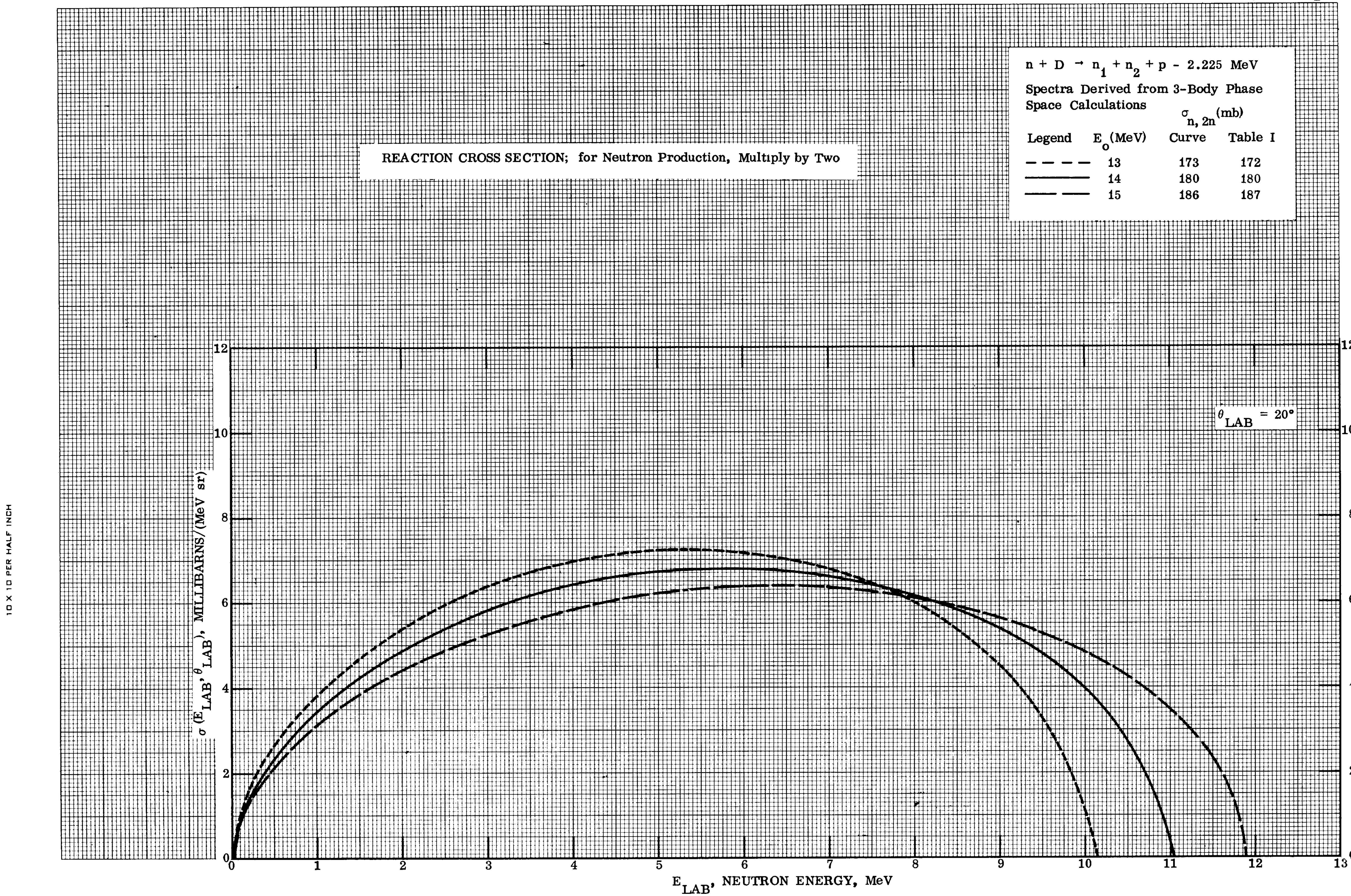
REACTION CROSS SECTION; for Neutron Production, Multiply by Two

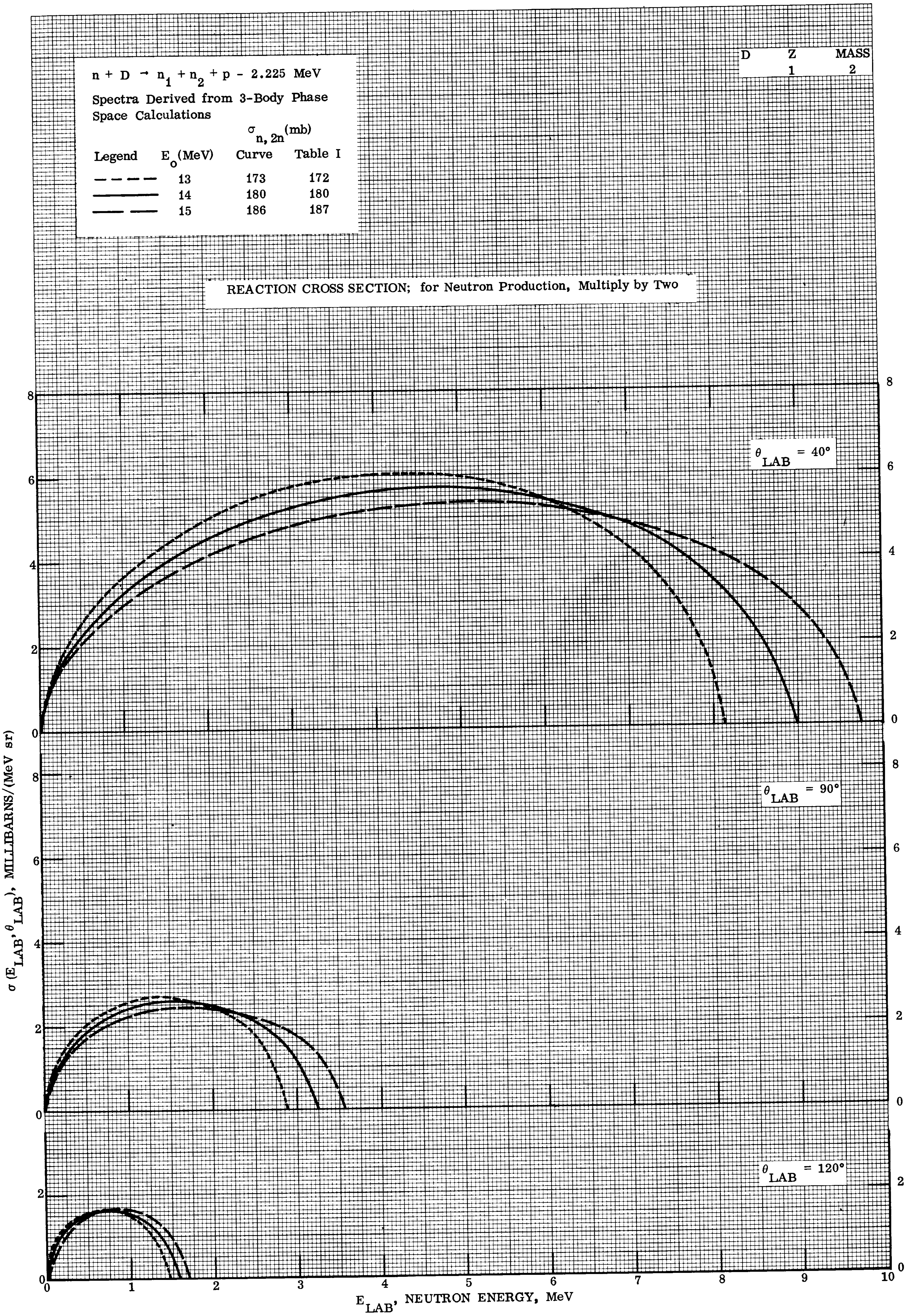
D Z 1 MASS 2




D Z MASS
1 2
n + D → n_1 + n_2 + p - 2.225 MeV
Spectra Derived from 3-Body Phase Space Calculations
$\sigma_{n,2n}$(mb)
Legend E_o(MeV) Curve Table I
10 138 137
11 152 150.5
12 163 162
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
$\sigma(E_{LAB})$, mb/MeV
E_{LAB}, NEUTRON ENERGY, MeV
0
1
2
3
4
5
6
7
8
9
10
4
8
12
16
20
24
28
32
36

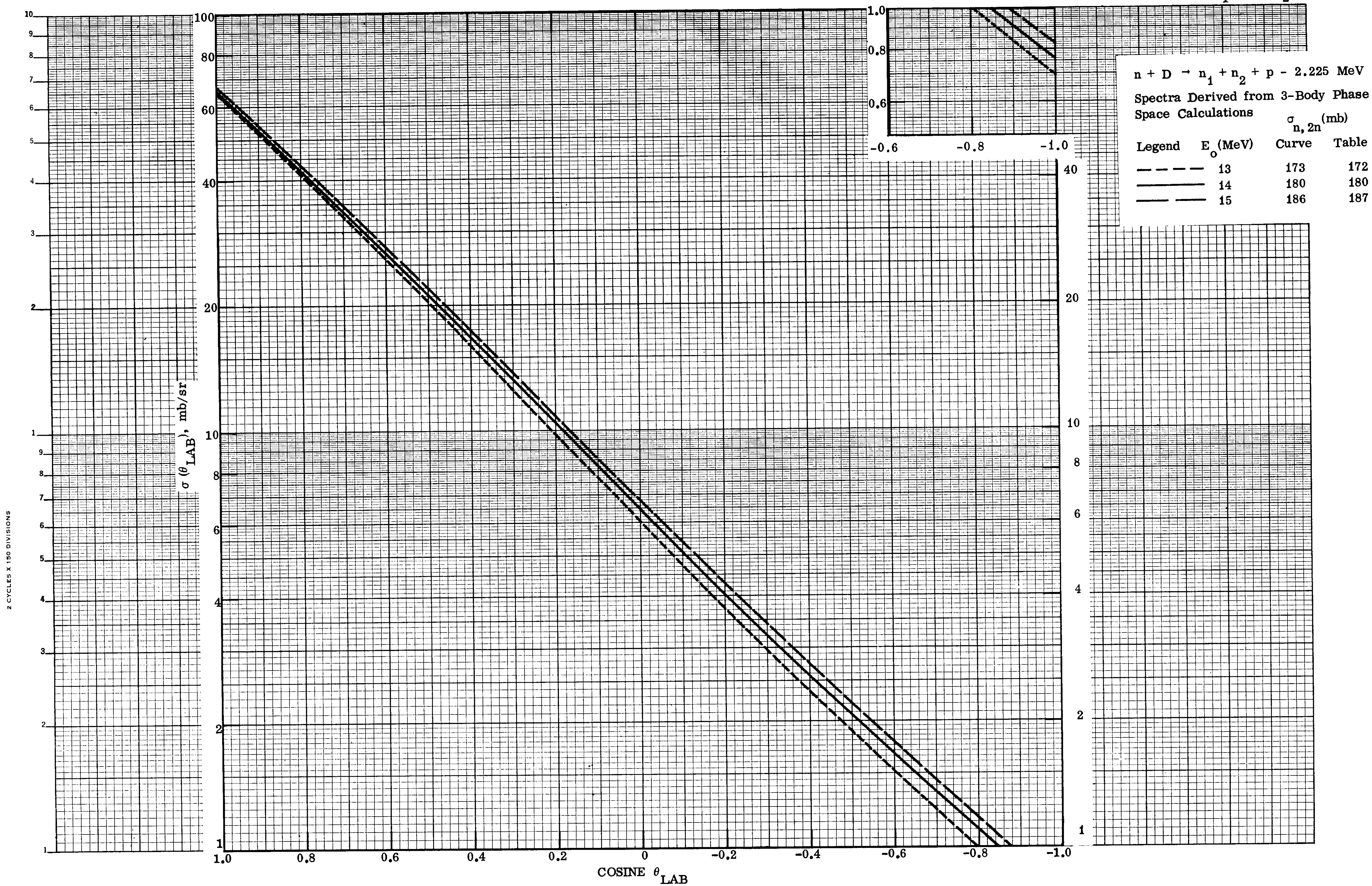

REACTION CROSS SECTION; for Neutron Production, Multiply by Two
n + D → n1 + n2 + p - 2.225 MeV
Spectra Derived from 3-Body Phase Space Calculations
σn, 2n(mb)
Legend | E0(MeV) | Curve | Table I
13 | 173 | 172
14 | 180 | 180
15 | 186 | 187
θLAB = 0°
σ (ELAB, θLAB), MILLIBARNS/(MeV sr)
ELAB, NEUTRON ENERGY, MeV
0
1
2
3
4
5
6
7
8
9
10
11
12
13
2
4
6
8
10
12
10 X 10 PER HALF INCH

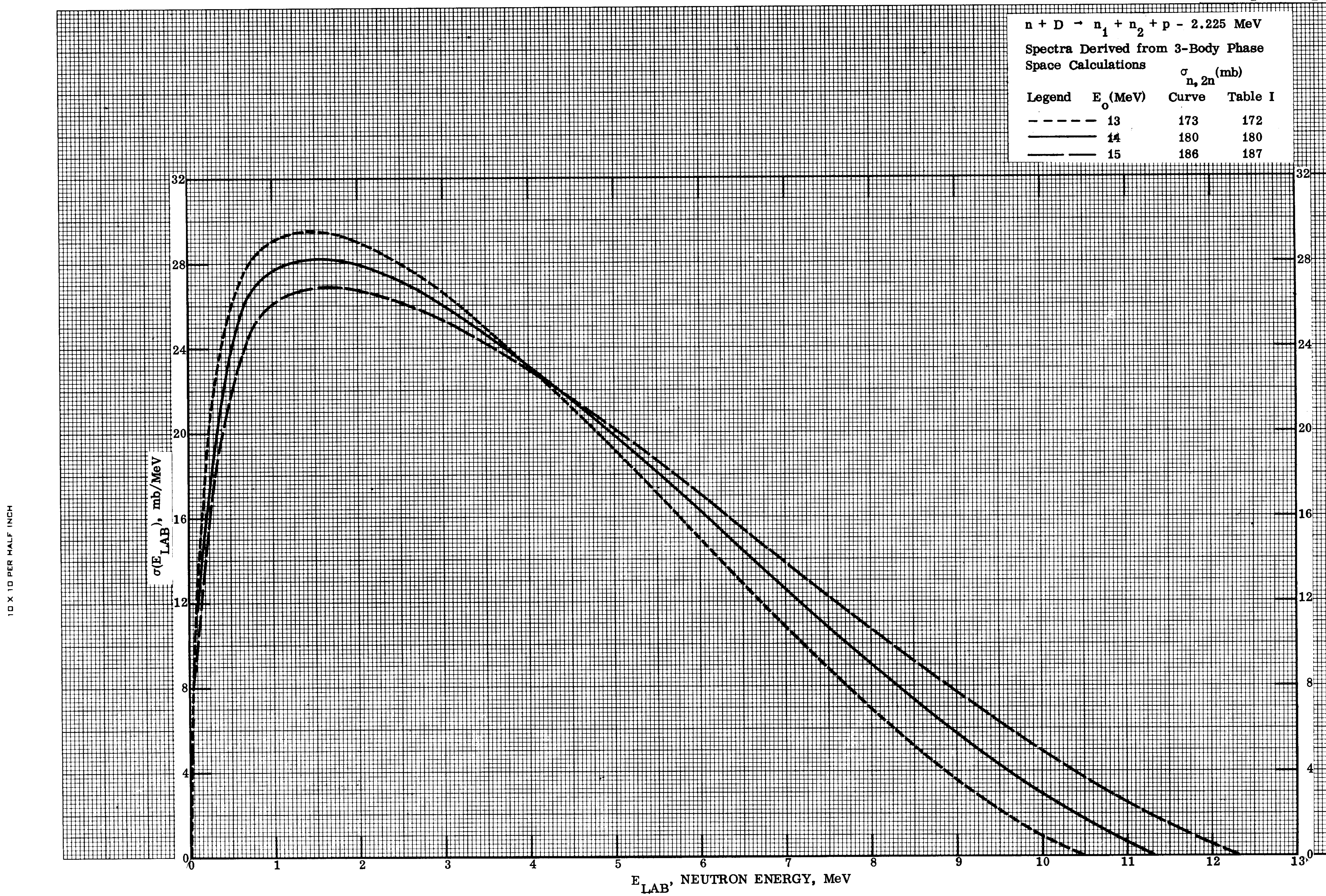

$n + D \rightarrow n_1 + n_2 + p - 2.225$ MeV
Spectra Derived from 3-Body Phase Space Calculations
Legend | E_o (MeV) | $\sigma_{n,2n}$ (mb) Curve | Table I
13 | 173 | 172
14 | 180 | 180
15 | 186 | 187
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
$\theta_{LAB} = 20°$
$\sigma(E_{LAB}, \theta_{LAB})$, MILLIBARNS/(MeV sr)
E_{LAB}, NEUTRON ENERGY, MeV
0
1
2
3
4
5
6
7
8
9
10
11
12
13
0
2
4
6
8
10
12
10 X 10 PER HALF INCH


n + D → n1 + n2 + p - 2.225 MeV
Spectra Derived from 3-Body Phase Space Calculations
Legend | E0 (MeV) | σn, 2n (mb) Curve | Table I
13 | 173 | 172
14 | 180 | 180
15 | 186 | 187
D Z MASS
1 2
REACTION CROSS SECTION; for Neutron Production, Multiply by Two
θLAB = 40°
θLAB = 90°
θLAB = 120°
σ (ELAB, θLAB), MILLIBARNS/(MeV sr)
ELAB, NEUTRON ENERGY, MeV
0 1 2 3 4 5 6 7 8 9 10
0 2 4 6 8

REACTION CROSS SECTION; for Neutron Production, Multiply by Two

D Z 1 MASS 2




$n + D \rightarrow n_1 + n_2 + p - 2.225$ MeV
Spectra Derived from 3-Body Phase Space Calculations
$\sigma_{n,2n}$(mb)
Legend | E_o(MeV) | Curve | Table I
13 | 173 | 172
14 | 180 | 180
15 | 186 | 187
$\sigma(E_{LAB})$, mb/MeV
E_{LAB}, NEUTRON ENERGY, MeV
0 1 2 3 4 5 6 7 8 9 10 11 12 13
0 4 8 12 16 20 24 28 32
10 X 10 PER HALF INCH

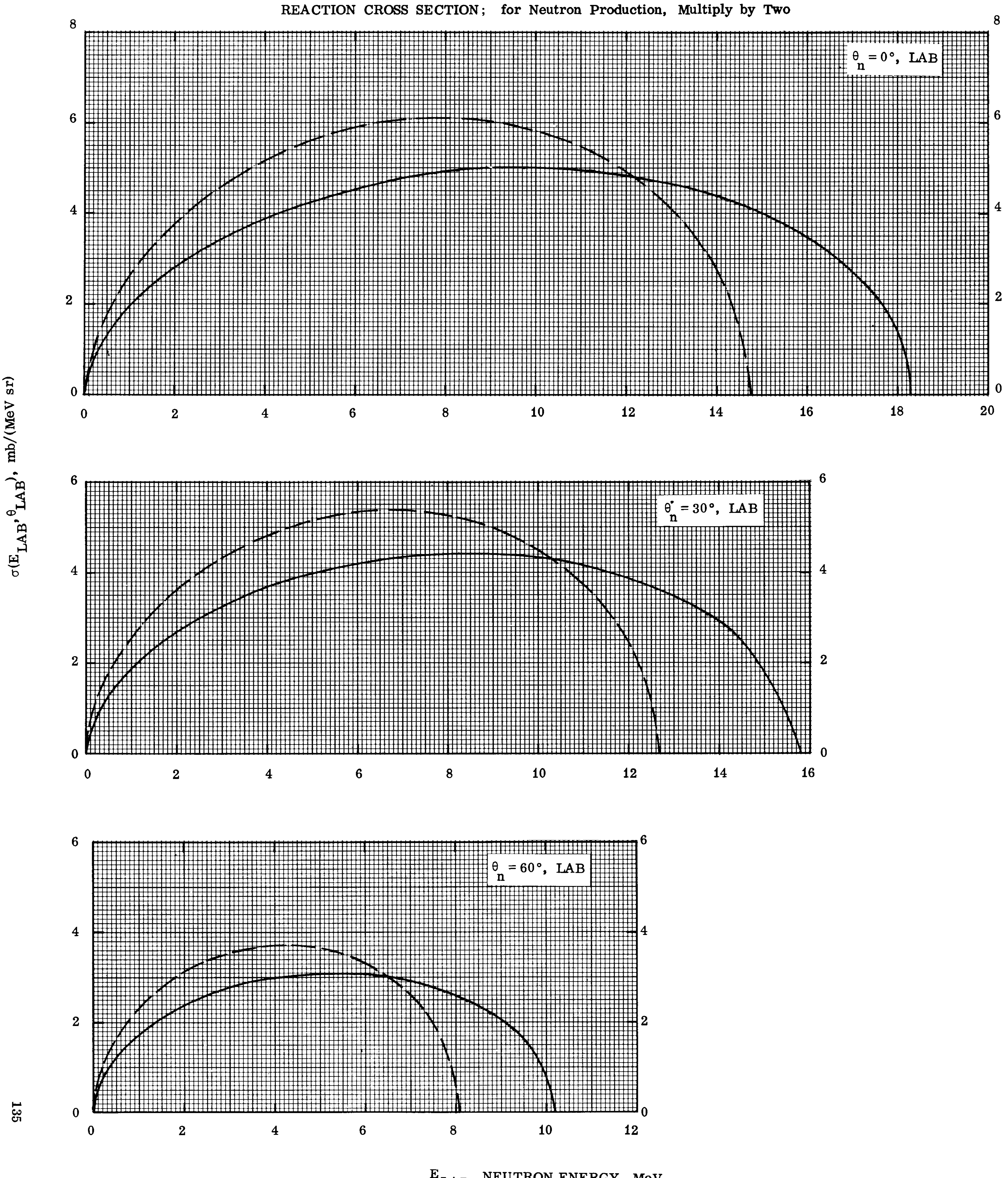
$n + D \rightarrow n_1 + n_2 + p - 2.225$ MeV

D	Z	MASS
	1	2

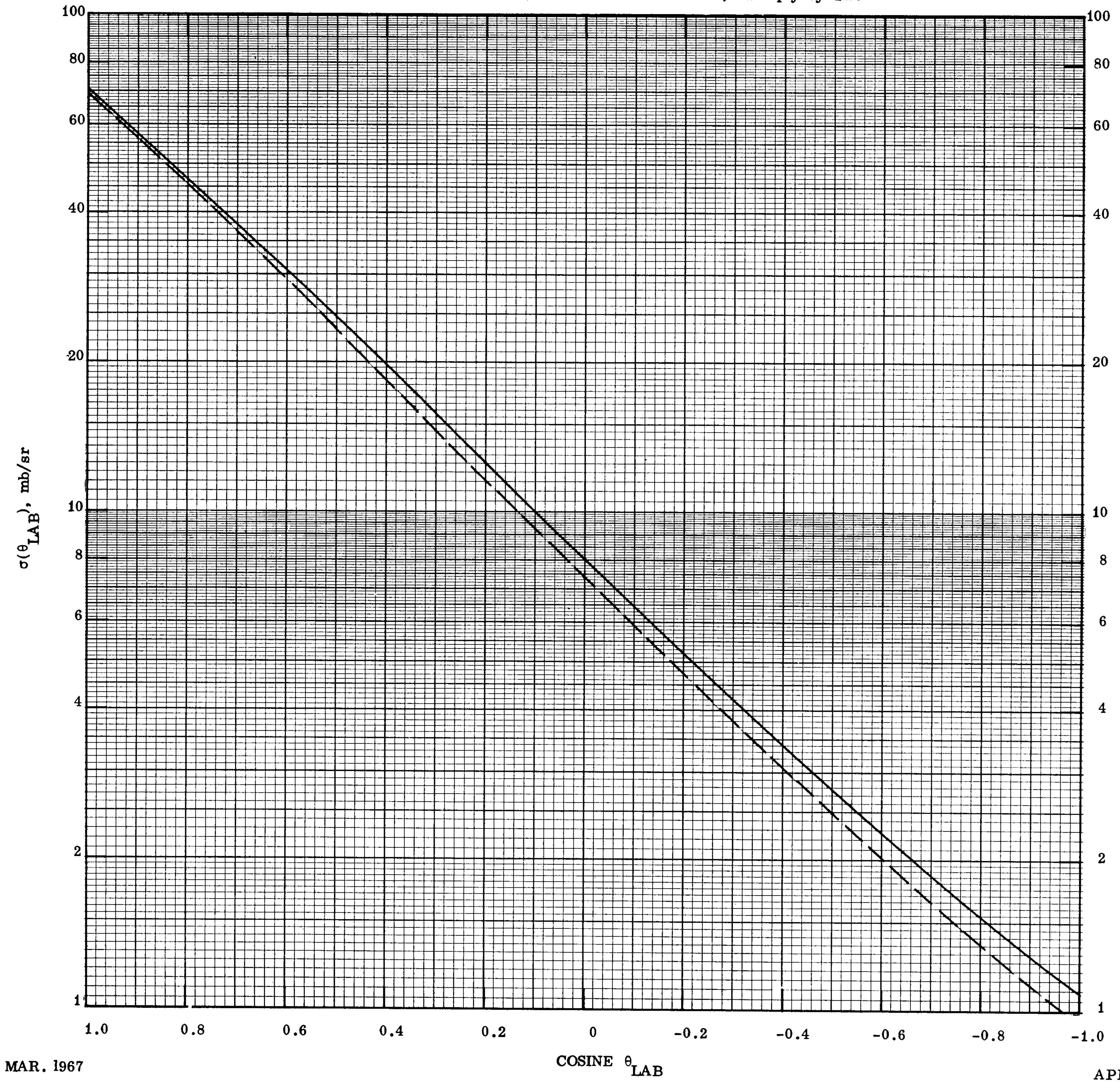
Spectra Derived from 3-Body Phase Space Calculations at 0°, 30°, and 60°

Curve	E_o	$\sigma_{n,2n}$	Table I $\sigma_{n,2n}$
— — —	17.0 MeV	197 mb	197 mb
———	20.57 MeV	206 mb	206 mb

REACTION CROSS SECTION; for Neutron Production, Multiply by Two



REACTION CROSS SECTION; for Neutron Production, Multiply by Two



$n + D \rightarrow n_1 + n_2 + p - 2.225$ MeV

Spectra Derived from 3-Body Phase Space Calculation

Curve	E_o	$\sigma_{n,2n}$	Table I $\sigma_{n,2n}$
— — — (dashed)	17 MeV	197 mb	197 mb
——— (solid)	20.57 MeV	206 mb	206 mb

$n + D \rightarrow n_1 + n_2 + p - 2.225$ MeV

D Z 1 MASS 2

Spectra Derived from 3-Body Phase Space Calculation

Curve	E_0	$\sigma_{n,2n}$	Table I $\sigma_{n,2n}$
— — — —	17 MeV	197 mb	197 mb
————	20.57 MeV	206 mb	206 mb