# Total Cross Section of Deuterium for Neutrons from 0.2 to 22 Mev*

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Transmission measurements of the total neutron cross section of deuterium have been made with an accuracy of about 2 percent at 29 energies between 0.2 and 22 Mev, using deuterium gas in a cell 1 meter long. The cross section decreases monotonically with increasing energy, and its reciprocal appears to be a linear function of neutron energy over the interval from 1.5 to 22 Mev:

$$\sigma = 14.35(E_n + 3.6 \text{ Mev})^{-1} \text{ barn.}$$

## INTRODUCTION

SEVERAL transmission measurements[1–11] of the total neutron cross section for deuterium have been reported; these are indicated in Table I. With the exception of the Brookhaven measurement[9] at 14.1 Mev and the high-energy measurements,[6–8] all these experiments were performed in relatively "poor geometry" with a probable error of about 5 percent, and a comparable (and uncertain) correction for inscattering. Moreover, all these determinations of $\sigma_T(D)$ were obtained by the indirect method from measurements of the cross sections of hydrogenous compounds.

The present experiment was designed to measure the cross section for deuterium gas over the neutron energy range 0.2 to 22 Mev in a uniform manner to an accuracy of two percent using very good geometry.

## PROCEDURE

Neutrons were obtained at the large Los Alamos electrostatic generator by using the $T(p,n)He^3$, $D(d,n)He^3$, and $T(d,n)He^4$ reactions. The target gas was contained in a cell 3.1 cm long having 0.25-mm thick walls and a 1.25-micron Ni entrance foil. Neutrons in the forward direction were used to maximize the yield and minimize background effects. A stilbene scintillator 2 cm in diameter and 2 cm long in a conventional photomultiplier assembly was employed as the neutron detector.

Pulses from the detector were amplified by two independent systems in parallel. The output of one system went to two discriminator-scalers with different bias settings, and the output of the other was counted by a scaler with both upper and lower discriminators. Suitable amplifier gains and discriminator settings were determined for each energy such that only pulses corresponding to neutrons were counted, and the pulse-height distributions were observed on a 10-channel pulse-height analyzer. Bombardments were made by reference to a beam current integrator, and a completely separate scintillator detector observed neutrons at 40° from the axis of the charged-particle beam to serve as a monitor.

Transmission cells 100 cm long were placed symmetrically between the source and detector, which were 154 cm apart. Details of the transmission cells are given in Appendix I. Alignment of the cells and detector with the beam axis was accomplished optically, and could be done to within a few tenths of a millimeter.

The principal sources of background in this experiment were taken into account in the cycle of measurements made at each energy. To obtain the background from neutrons and gamma rays not coming directly from the target, a 24-inch long copper rod was inserted into an open-ended cell to serve as a shadow bar. To evaluate the background originating in the target window, collimators, and control slits, an additional complete cycle of measurements was made with the target cell evacuated. Each run was terminated by a precision beam current integrator, and the length and number of runs with filled and empty cell in position were adjusted so that approximately 20 000 neutrons were counted in each case. A normal cycle was as follows: evacuated cell, gas-filled cell shadow bar, gas-

TABLE I. Previous measurements of the fast neutron total cross section of deuterium.

| Reference | Neutron energy, Mev | Year | Institution |
|---|---|---|---|
| 1 | 2.88 | 1939 | Columbia University |
| 2 | 2.1–2.8 | 1939 | Japan (Aoki) |
| 3 | 0.26–0.66, 2.35, 3.80 | 1942–46 | Cavendish Laboratories |
| 4 | 0.35–6.0 | 1946 | Univ. of Minnesota |
| 5 | 4.1, 12.5, 13.5 | 1947 | Rome (Ageno *et al.*) |
| 6 | 42 | 1950 | Univ. of Calif. (Berkeley) |
| 7 | 90 | 1949 | Univ. of Calif. (Berkeley) |
| 8 | 95 | 1950 | Univ. of Calif. (Berkeley) |
| 9 | 14.1 | 1952 | Brookhaven Natl. Lab. |
| 10 | 0.26–2.96 | 1953 | Univ. of Wisconsin |
| 11 | 14–18 | 1954 | Rice Institute |

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[1] Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939).
[2] H. Aoki, Proc. Phys. Math. Soc. Japan **21**, 232 (1939).
[3] E. Bretscher and E. B. Martin, Helv. Phys. Acta **23**, 15 (1950).
[4] Nuckolls, Bailey, Bennett, Bergstralh, Richards, and Williams, Phys. Rev. **70**, 806 (1946).
[5] Ageno, Amaldi, Bocciarelli, and Trabacchi, Phys. Rev. **71**, 20 (1947).
[6] R. H. Hildebrand and C. E. Leith, Phys. Rev. **80**, 842 (1950).
[7] Cook, McMillan, Peterson, and Sewell, Phys. Rev. **75**, 7 (1949).
[8] J. DeJuren and N. Knable, Phys. Rev. **77**, 611 (1950).
[9] Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).
[10] Adair, Okazaki, and Walt, Phys. Rev. **89**, 1165 (1953).
[11] C. F. Cook and T. W. Bonner, Phys. Rev. **94**, 651 (1954).

filled cell, evacuated cell. The symmetrical order of measurement compensated for linear drifts in neutron intensity and electronic equipment. By observation of drifts and comparison of transmission values obtained from the several channels of the instrumentation good control of the time-dependent variables was secured. The errors due to nonlinear drifts were much smaller than the statistical uncertainties.

It is shown in Appendix III that for the geometry used in this experiment, corrections for inscattering by the gas are less than 0.2 percent, and were not applied. From the transmission $T$ and values $nL$ shown in Table IV (Appendix II), preliminary cross sections were calculated from the usual relation $T=e^{-n\sigma L}$, where $n$ is the atom density of the filling, $L$ the cell length, and $\sigma$ the cross section.

The number of atoms in the cell was calculated from weight data by computing the average atomic weight from the mass spectrometer analysis, and also from $PVT$ data by using the assumption that the impurities had the same equation of state as deuterium. Very good agreement was noted. The impurities in the gas contribute to the observed cross section in proportion to the amount their cross sections differ from $\sigma_D$. It can readily be shown that

$$\frac{\Delta\sigma}{\sigma}=\sum_i f_i\left(\frac{\sigma_i}{\sigma_D}-1\right),$$

where $f_i$ are the atomic fractions of the impurities, and $\sigma_i$ the corresponding cross sections.[12] This correction was applied to the preliminary cross sections and was less than 0.4 percent for all energies except 0.26 Mev where it jumped to 1.08 percent largely because of the rapid rise of $\sigma_H$ at this energy.

TABLE II. Total cross section of deuterium for fast neutrons.

| Source | Energy Mev | Half-spread Mev | Cross section barns | Probable error barns | Departure from approximation (percent) |
|---|---|---|---|---|---|
| | 0.267 | 0.040 | 3.022 | ±0.046 | |
| | 0.640 | 0.028 | 2.944 | 0.040 | |
| | 0.995 | 0.022 | 2.854 | 0.039 | |
| | 1.371 | 0.019 | 2.754 | 0.036 | |
| T($p$,$n$)He$^3$ | 1.750 | 0.016 | 2.690 | 0.030 | +0.29 |
| | 2.124 | 0.015 | 2.492 | 0.038 | −0.59 |
| | 2.504 | 0.013 | 2.395 | 0.036 | +1.91 |
| | 3.262 | 0.011 | 2.140 | 0.035 | +2.34 |
| | 4.002 | 0.010 | 1.851 | 0.042 | −1.90 |
| | 4.390 | 0.062 | 1.805 | 0.027 | +0.55 |
| | 4.766 | 0.047 | 1.678 | 0.023 | −2.15 |
| | 5.261 | 0.047 | 1.664 | 0.028 | +2.77 |
| | 5.815 | 0.038 | 1.548 | 0.028 | +1.57 |
| D($d$,$n$)He$^3$ | 6.264 | 0.025 | 1.436 | 0.026 | −1.23 |
| | 6.773 | 0.022 | 1.368 | 0.026 | −1.01 |
| | 7.288 | 0.020 | 1.297 | 0.020 | −1.51 |
| | 7.790 | 0.018 | 1.269 | 0.019 | +0.71 |
| | 8.126 | 0.017 | 1.237 | 0.030 | +1.14 |
| | 14.85 | 0.20 | 0.767 | 0.014 | −1.31 |
| | 15.50 | 0.20 | 0.753 | 0.012 | +0.26 |
| | 16.26 | 0.20 | 0.734 | 0.011 | +1.66 |
| | 17.33 | 0.11 | 0.689 | 0.014 | +0.73 |
| | 18.29 | 0.08 | 0.661 | 0.014 | +0.76 |
| T($d$,$n$)He$^4$ | 19.01 | 0.06 | 0.632 | 0.014 | −0.32 |
| | 19.67 | 0.06 | 0.620 | 0.015 | +0.49 |
| | 20.32 | 0.05 | 0.591 | 0.014 | −1.50 |
| | 20.94 | 0.04 | 0.567 | 0.015 | −2.93 |
| | 21.55 | 0.04 | 0.571 | 0.015 | +0.17 |
| | 21.85 | 0.03 | 0.564 | 0.010 | +0.17 |

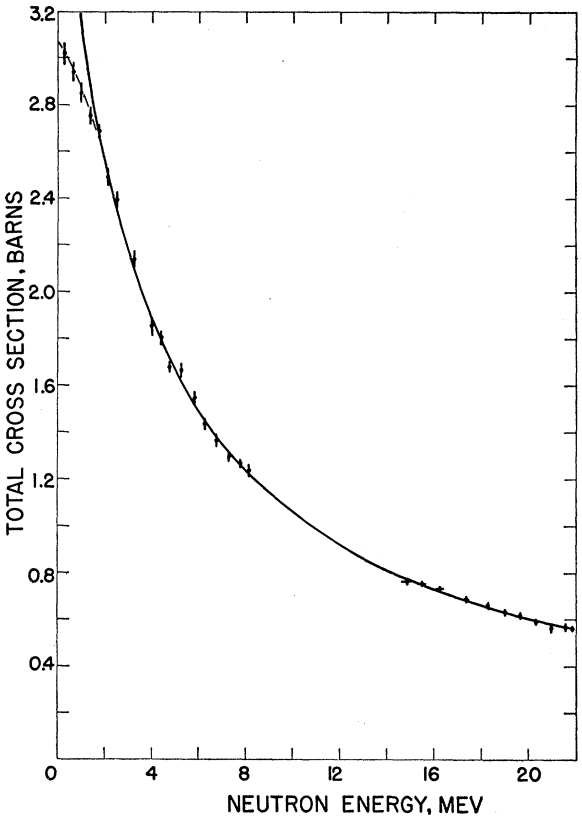


FIG. 1. Total neutron cross section of deuterium. The solid curve is the approximation $\sigma=14.35\ (E_n+3.6\ \text{Mev})^{-1}$ barn.

## RESULTS

The total cross section for deuterium was measured at 29 neutron energies between 0.2 and 22 Mev with an average probable error of 2 percent. The results are tabulated in Table II, and presented graphically in Fig. 1. Disagreement with previous work is appreciable, in view of the quoted uncertainties; there seems to be a systematic discrepancy with reference 11. The present data joins smoothly with the high-energy results.[6–8]

In view of the smooth decrease of cross section with increasing energy, an attempt was made to find a simple mathematical expression by which the results might be approximately represented. The formula

$$\sigma=14.35(E_n+3.6\ \text{Mev})^{-1}\ \text{barn}$$

represents the present results over the energy range 1.5

[12] *Neutron Cross Sections*, Atomic Energy Commission Report AECU-2040 (Technical Information Division, Department of Commerce, Washington, D. C., 1952).

to 22 Mev with an rms fractional deviation of 1.4 percent which is better than the probable error of any of the data points. This function is plotted in Fig. 1, and the percent deviations of the individual points from the curve are included in Table II. The function given above probably represents with comparable precision the neutron energy range 8–14 Mev, where it was not feasible to make measurements.


## ACKNOWLEDGMENTS

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## APPENDIX I

### Transmission Cell

The transmission cell was developed in 1951 by R. L. Mills, F. J. Edeskuty, and A. Sesonsky of this laboratory for use in neutron transmission experiments and has been used previously by J. H. Coon and others at pressures up to 4000 psi.

The cell is nominally 1 meter long inside, with 0.100-in. end plates, 1-in. outside diameter, and $\frac{1}{16}$-in. wall thickness. The tube was made of Type 321 stainless steel, but to avoid distortion of the ends by the process of attachment, the ends were machined in the form of flat-bottomed cups about 1 in. deep from Type 347 stainless steel flat stock, and these were welded to the main tube without distortion of the ends. An inlet nipple of Type 347 stainless steel was threaded and silver-soldered into the side of the tube at its center, and a 4-foot length of stainless steel capillary of 0.027-in. outside diameter and 0.010-in. inside diameter was silver-soldered at one end to the cell nipple. The other end of the capillary was silver-soldered to a jam fitting[13] which was in turn joined to two straight-through 60 000-psi valves.[13] Soldered joints of the capillary were protected by tightly-coiled tapered springs which clamped over shoulders on the nipple and the jam fitting to prevent sharp bending of the capillary at these points. Two complete assemblies were built, so that one could be used to contain the gas sample, and the other evacuated for use in measuring the neutron intensity.

Outside dimensions of the cells were measured with high precision, and the joints were radiographed. The cell selected as the sample cell was within 0.024 in. of straight, and the end windows were perpendicular to the axis of the tube to within 10 minutes of arc. Both cells were filled with helium at 4000 psi and examined for leaks with a helium leak detector with negative results, and left at that pressure for seven days in equilibrium with a sensitive pressure gauge, with no indicated loss of gas.

The volume of the sample cell was determined prior to attaching the capillary tube by determining the weight of freshly-boiled distilled water which would just fill the cell to its nipple, when the cell was immersed in a thirty-gallon constant-temperature bath. The weighings of the cell were performed on a Seederer-Kohlbusch balance modified so that hooks to hold the cell and a dummy weight projected down through the case into a cabinet large enough to enclose the cells. The volume of the sample cell was determined from the mean of 5 independent trials to be 383.487 $\pm$0.037 cm$^3$ at 30.00°C. The inside length of the cell is 0.99972 meters at 30°C. From measurements on the cell as a function of gas pressure, it was found that the length changes by 0.29 mm/1000 psi, and the volume by about 0.165 cm$^3$/1000 psi. (These measured pressure coefficients of length and volume imply the reasonable value 0.29 for Poisson's ratio.) Since all measurements and fillings were made at the same temperature, no temperature corrections were necessary.

[13] Made by Autoclave Engineering Company.

## APPENDIX II

### Deuterium Gas Filling

The atomic density of the contents of the cell was determined in two independent ways, by means of the equation of state for deuterium,[14] and by weighing supplemented by mass-spectrometry of the gas. The cell was filled while immersed in the constant-temperature bath and the equilibrium pressure read on a 16-in. Heise Bourdon gauge which was calibrated with a dead-weight testing apparatus just before using. Since $D_2$ gas was available at only 1500 psi, the actual filling to 2500 psi was achieved by cooling the cell in liquid nitrogen until a sufficient amount of deuterium had been collected from the source tank. The cell was then allowed to warm to room temperature and was finally placed in the water bath. A sample for mass-spectrometry was collected from the gas released in approaching the desired pressure. From the PVT data, the atomic density could be computed from the information given in Table III, computed from the equation of state.[14,15] The pressures in Table III were chosen for convenience in calculation of molar volumes. The atomic densities of the actual fillings were computed by means of the tabulated function $V_{D_2}/V_{Ideal}$ which is also the ratio of the pressure required per unit number of atoms/cm$^3$ to the corresponding value for an ideal gas (3035.5 psi/$10^{22}$ atoms/cm$^3$). A convenient approximation which gives the ratio to within 0.1 percent between 0 and 2500 psi is

$$(V_{D_2}/V_{Ideal})_{30°C}=1+3.605\times10^{-5}P+1.760\times10^{-9}P^2,$$

where $P$ is the pressure in psi (absolute).

TABLE III. The equation of state for deuterium at 30.00°C.

| $P$ psi | $V_{D_2}$ cm$^3$/mole | $V_{D_2}/V_{Ideal}$ | $n$ atoms/cm$^3$ |
|---|---|---|---|
| 395.53 | 938.43 | 1.0147 | $1.2842\times10^{21}$ |
| 930.76 | 407.12 | 1.0359 | 2.9600 |
| 1489.59 | 259.95 | 1.0586 | 4.6358 |
| 1798.79 | 217.86 | 1.0713 | 5.5315 |
| 2240.85 | 177.88 | 1.0897 | 6.7747 |
| 2780.78 | 146.32 | 1.1123 | 8.2360 |

Mass spectrometer analysis of the gas sample withdrawn from the cell after filling gave the following composition in atom percent: 99.13 D, 0.54 H, 0.02 O, and 0.31 N. This analysis leads to an average atomic weight of 2.0495$\pm$0.0060 amu. The result of weighings of the cell before and after filling led to an atom density almost precisely equal to that calculated from the PVT data. The results are tabulated in Table IV. While such extreme agreement is surely fortuitous, it is gratifying to find that an accuracy of better than 0.3 percent can be attained by these methods. The uncertainty in the average molecular weight is due primarily to the uncertainty in the mass-spectrometer determination of the

TABLE IV. Determination of transmission cell contents.

| Pressure psi | Mass grams | $n$(PTV) $10^{21}$ atoms/cm$^3$ | $n$(Mass) | $nL$ atoms/barn | $\sigma$ barns | $E_n$ Mev |
|---|---|---|---|---|---|---|
| 2480.7 | 9.699 | 7.426 | 7.427 | 0.7429 | 0.5–0.8 | 14–22 |
| 1090.5 | ··· | 3.446 | ··· | 0.3446 | 1.2–1.8 | 4–8 |
| 600.5 | 2.5177 | 1.929 | 1.929 | 0.1929 | 1.8–3.0 | 0.2–4 |

[14] Wooley, Scott, and Brickwedde, J. Research Natl. Bur. Standards 41, 379 (1948).

[15] The molar volumes were kindly computed from reference 14 by F. G. Brickwedde.

nitrogen impurity in the gas. In view of the excellent agreement of the calculations from PVT and from weighing data, the pressure was simply dropped after the high-energy run to the intermediate pressure, and no weighing was made until after the pressure had been dropped to the lowest value, where good agreement was again observed.

## APPENDIX III

### Inscattering Correction

It can be shown that the correction for neutrons singly-scattered into the detector by a long scattering sample is given by

$$\frac{\Delta\sigma}{\sigma}=\frac{8a}{S^2}\frac{\sigma(0)}{\sigma_T}\left[\frac{1}{1-(L/S)^2}+\frac{\tanh^{-1}(L/S)}{L/S}\right],$$

where $L$=length of the scattering sample, $S$=source to detector distance, $a$=cross sectional area of the sample ($a\ll S^2$), $\sigma(0)$=differential cross section for forward scattering by the sample, and $\sigma_T$=total cross section. For $L\ll S$, the quantity in brackets in the above equation reduces to 2, and the equation is equivalent to the usual equation quoted elsewhere;[16,17] for the present experiment, the value was 2.92. $\sigma(0)/\sigma_T$ for deuterium increases slowly with energy, and may be calculated[18] with sufficient precision for purposes of correction. In this experiment, the correction was less than 0.2 percent at 14.1 Mev and was not applied. Multiple scattering would produce a much smaller effect due to the elongated shape of the sample employed. In a "poor geometry" experiment at high energies, it would also be necessary to consider the effect of the neutrons from the inelastic $n$-$d$ interaction, which are forward-peaked, and whose energy distribution is peaked at the upper end.[19,20] $\sigma_{in}/\sigma_T$ is nearly $\frac{1}{4}$ at $E_n$=14.1 Mev,[20] and increases rapidly with energy. No such correction was required in the present experiment.

[16] R. B. Day and R. L. Henkel, Phys. Rev. **92**, 358 (1953).
[17] Hafner, Hornyak, Falk, Snow, and Coor, Phys. Rev. **89**, 204 (1953).
[18] R. S. Christian and J. L. Gammel, Phys. Rev. **91**, 100 (1953).
[19] R. M. Frank and J. L. Gammel, Phys. Rev. **93**, 463 (1954).
[20] J. D. Seagrave, Phys. Rev. **97**, 757 (1955).

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# Elastic Scattering Angular Distributions of Fast Neutrons on Light Nuclei

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New measurements of the total cross section of $Be^9$ (resolution 4 kev) give maxima of 7.75±0.20 barns ($\Gamma$=25 kev) and 5.25 ±0.20 barns ($\Gamma$=8 kev) for the 0.62 Mev and 0.81 Mev resonances, consistent with $J=3$ and $J=2$ for the respective compound state spin values. Elastic scattering angular distributions indicate that the 0.62-Mev resonance may be formed by $p$-wave neutrons with the $s$-wave potential scattering ($\delta_0=-54.2°$) spin-dependent and all channel spin 1, or possibly by $d$-wave neutrons with the resonance scattering all channel spin 2. Potential scattering phase shifts for $B^{10}$ are $\delta_0=-53.5°$ at 0.55 Mev; $\delta_0=-60.7°$, $\delta_1=-4.0°$ at 1.00 Mev; and $\delta_0=-66.9°$, $\delta_1=-10.3°$, and $\delta_2=-2.9°$ at 1.50 Mev. The 0.43-Mev resonance in $B^{11}$, agrees with a $J=2, l=1$ assignment, while the 1.28-Mev resonance is best fitted by $J=3$, $l=2$; with a mixing ratio of channel spin 2 equal to 10 times channel spin 1. Potential scattering is nearly all $s$-wave up to 1.50 Mev where $\delta_0=-90°$. $C^{12}$ has pure $s$-wave scattering at 0.55 Mev ($\delta_0=-50.1°$) and 1.00 Mev ($\delta_0=-68.9°$), and at 1.50 Mev a small amount of $p$-wave appears, ($\delta_0=-79.4°$, $\delta_1=-5.7°$). In general the observed $s$-wave phase shifts are larger than those calculated from a hard sphere model, whereas the $p$- and $d$-wave phase shifts are smaller.

## I. INTRODUCTION

GOOD energy resolution measurements of the total elastic scattering cross sections of fast neutrons permit the unambiguous assignment of the spin ($J$) of energy levels observed in the compound nucleus. The width of the level will place limits on the parity to be assigned; but more information is needed, in general, to insure that this value is unique. Angular distributions of the elastically scattered neutrons should determine the parity as well as serve as a check on the $J$-value.

In principle such data can be obtained by bombarding a small sample of the substance to be investigated with a well-defined beam of neutrons, and detecting the scattered wave with a counter subtending a small solid angle. In practice severe limitations are imposed by source strength, multiple scattering in the sample, detector efficiency, and background. Recently Walt and Barschall[1] have succeeded in obtaining differential cross sections for 1-Mev neutrons elastically scattered by 28 elements from titanium through thorium. The present work modifies their method to scattering from light nuclei with good energy resolution.

[1] M. Walt and H. H. Barschall, Phys. Rev. **93**, 1062 (1954).

## II. EXPERIMENTAL METHOD

Figure 1 shows the geometry employed. The $Li^7(p,n)Be^7$ reaction served as a source of 0.2- to 1.5-Mev neutrons. This reaction is not monoergic, but the second group which appears above 0.6 Mev was corrected for by using the observed values for the fraction of the primary group.[2] Targets of varying thickness (dictated by the width of the resonance studied) were prepared by evaporating in place lithium metal onto a rotating 10-mil tantalum backing. Cylindrical scattering samples, 3 inches long and with diameters such as to give a minimum transmission of 70 percent (about one-third of a mean free path),

[2] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 334 (1952).