The Slow Neutron Cross Section of H

W. B. JONES, JR.*
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
(Received April 25, 1948)

The total neutron cross section of water has been measured with a slow neutron velocity spectrometer in the energy interval 0.003 to 100 ev. A treatment of the data for energies above 0.8 ev gave a value of 20.0×10^{-24} cm² for the free neutron-proton cross section. Measurements of the total cross section of cyclohexane in the energy interval 0.8 to 100 ev were also made, and from these data a value of 20.1×10^{-24} cm² was obtained for the free neutron-proton cross section. Measurements of the oxygen and carbon cross sections were made in order that the data on water and cyclohexane could be corrected to obtain the bound proton cross sections. The values obtained for these cross sections for the high energy neutrons are: for oxygen, 3.7×10^{-24} cm², and for carbon, 4.7×10^{-24} cm². The data on water for energies below 0.8 ev yield evidence for the existence of a cross section for inelastic scattering of neutrons by water.

I. INTRODUCTION

REPORTED in this paper are some measurements of the neutron cross section of two hydrogenous materials. The measurements were made with the slow neutron velocity spectrometer at Cornell. The total cross section of water was measured in the energy range 0.003 to 100 ev. In the energy interval 0.8 to 100 ev, the water cross section was measured rather precisely in order to make a determination of the variation of the cross section with energy and to obtain an accurate value for the free neutron-proton scattering cross section. In order to obtain a check on the value of the neutron-proton cross section obtained from the measurements on water in the energy interval 0.8 to 100 ev, an equally precise measurement was made of the total cross section of cyclohexane, a hydrocarbon of well-known structure, in this energy interval. The cross sections of oxygen and carbon were also measured so that the cross sections of these nuclei could be accounted for in making the determinations of the neutron-proton cross section from the data on water and cyclohexane.

The neutron velocity spectrometer and the technique of determining the cross section of a material by measuring the transmission of a sample of the material have been described previously.[1,2] The modulating and timing apparatus used in making the measurements presented here were the same as those described in reference 2. The BF_3 ionization chamber used as the neutron detector was filled to two atmospheres of pressure with B^{10}-enriched BF_3. The geometrical arrangements used were somewhat different from the geometrical arrangements used in making the capture cross-section measurements described in the references.[1,2] The details of the geometry will be given in the discussion of the data obtained in the various energy intervals, because no single geometrical arrangement could be used throughout the energy range covered in the experiment. However, one important geometrical factor, namely, the source-detector distance, was held constant and equal to three meters for all the measurements reported here.

II. MEASUREMENTS IN THE 0.8- TO 100-EV INTERVAL AND THE NEUTRON-PROTON CROSS SECTION

The on-time chosen for the source and detector was 10 μsec. for all the measurements in this energy interval. Since the source-detector distance was 3 m, this on-time corresponds to 3.3 μsec./m. Thus, the half-width of the resolution function for the apparatus was about 3.5 μsec./m. This is rather poor resolution compared with the best resolution practicable with the apparatus used, but since the cross section measured varies so very slowly with neutron time of flight, better resolution is of no advantage. The poorer resolution gives the advantage of higher neutron counting rates than

* Present address: Research Laboratory, General Electric Company, Schenectady, New York.
[1] B. D. McDaniel, Phys. Rev. **70**, 832 (1946).
[2] W. B. Jones, Jr., Phys. Rev. **72**, 362 (1947).

obtained with the best resolution. The standard technique of using a thick Cd filter (0.9 g/cm^2) to remove from the neutron beam the neutrons of energies less than 0.5 ev was employed so that a 2500-cycle/sec. repetition frequency could be used without difficulty with recycled neutrons.

The collimation arrangement used in this energy interval is shown in Fig. 1. Ordinarily, in making transmission measurements with the neutron spectrometer, the sample being studied is placed directly in front of the detector collimator section in the position where the filter is shown in Fig. 1, and the restricting aperture shown in the middle of the main part of the collimator is absent. Such an arrangement is satisfactory in a scattering experiment only if the detector collimator section is composed of a material which has a large ratio of absorption to scattering coefficient. A large ratio of absorption to scattering coefficients for the collimator material makes it unlikely that neutrons scattered by the sample being studied will be scattered by the collimator into the detector. The ratio of the absorption to scattering coefficients for B_2O_3 becomes smaller with increasing energy, and the ordinary arrangement was found to be unsatisfactory for scattering experiments at energies above 5 ev. For this reason, the collimation arrangement shown in Fig. 1 was used. It will be noted that, in this arrangement, for most of the solid angle into which neutrons can be scattered by the scatterer the scattered neutrons either must be scattered two or more times by the collimator or must pass through a large thickness of B_2O_3 in order to arrive at the detector.

Another geometrical effect which must be considered is that a certain fraction of the neutrons scattered through small angles by the scatterer are scattered into and detected by the detector. This "in-scattering" effect is determined by certain characteristics of the geometry, the thickness of the scatterer, and the characteristics of the scattering process.

A quantity characterizing the geometry with regard to the in-scattering effect is $\alpha=\omega_1\omega_2/4\pi\omega_3$, where ω_1 = the effective solid angle subtended at the source by the scatterer, ω_2 = the effective solid angle subtended at the scatterer by the detector, and ω_3 = the effective solid angle subtended at the source by the detector. For the geometry shown in Fig. 1, $\alpha=1.6\times10^{-3}$. If one measures the transmission of a scatterer which scatters neutrons isotropically in the laboratory coordinate system and which is sufficiently thin so that multiple scattering effects are not important, then

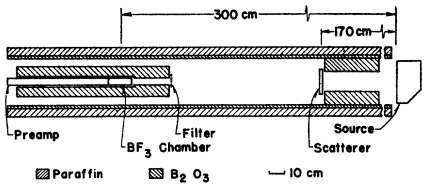

FIG. 1. Collimator arrangement for high energy measurements.

$$T_0=T+(1-T)\alpha,$$

where T_0 = the observed transmission, $T=e^{-n\sigma}$, n = the thickness of the scatterer in particles/cm^2, and σ = the scattering cross section in cm^2/particle. It is assumed that the scattered neutrons which reach the detector have not undergone an energy change upon being scattered. If the scattering is elastic but not isotropic in the laboratory coordinate system, then one may write

$$T_0=T+(1-T)k\alpha,$$

where k is a quantity depending on the angular distribution of scattered neutrons in the laboratory system. Thus, for the scattering of neutrons by free protons, which is isotropic in the center of mass system, $k=4$.

Distilled water was used as one of the scattering materials. The cyclohexane used as the other scattering material was analyzed in the Cornell chemistry department and certified to have a hydrogen to carbon ratio of 2 and to have only traces of impurities besides hydrocarbons. These scattering materials were held in containers made of aluminum alloy 2*S*. The containers constrained the liquid scatterers to be of uniform thickness known to within 0.3 percent. A "blank" was provided with each scatterer holder which was of the same thickness as the two faces of the holder which "blank" was made from the same sheet of aluminum alloy used for the faces of the holder. The transmission of each container and 'blank" was 0.96 for neutrons in the energy interval of interest here.

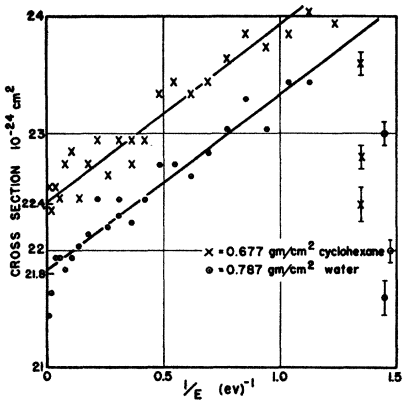

FIG. 2. Observed total cross section per hydrogen atom of cyclohexane and water *versus* reciprocal neutron energy. Curves shown are the best fitting straight lines for the two sets of data. Experimental probable errors for the points are shown at the right.

In Fig. 2 are shown the measured cross sections per hydrogen atom in water and in cyclohexane *versus* the reciprocal of the neutron energy. The ordinate scale is very much expanded in order to show the variation in cross section with the reciprocal energy. The data have been corrected for the in-scattering effect, assuming $k=4$. The correction was 0.25×10^{-24} cm^2 for both sets of data.

In order to determine the cross section which should be attributed to the hydrogen in the water and cyclohexane, it was necessary to measure the oxygen and carbon cross sections in this energy interval. For convenience, a solid compound containing oxygen was chosen for the oxygen cross-section measurement. Aluminum oxide was chosen. A pure aluminum "blank" was used which had the same mass of aluminum per cm^2 as in the aluminum oxide sample. The

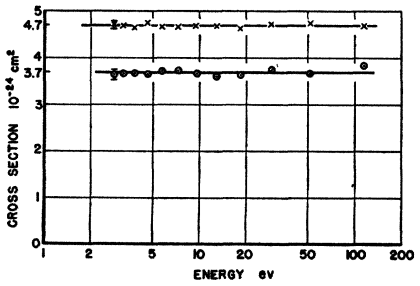

FIG. 3. ⊙ = cross section of oxygen from measurements on 11.6 g/cm^2 Al_2O_3. × = cross section of carbon from measurements on 4.11 g/cm^2 graphite. Probable errors are the same for all points in each set of data and are shown on only one point in each set.

aluminum oxide had the disadvantage that it is an adsorber of water, and some difficulty was experienced in drying the aluminum oxide. The aluminum oxide used in obtaining the data shown in Fig. 3 contained 0.7 percent water, and the data have been corrected for the effect of the water. A slab of very pure graphite machined to uniform thickness was used as the scattering material in the measurement of the carbon cross section. The data obtained for the carbon cross section are also shown in Fig. 3.

From a theory[3] assuming that hydrogen is anisotropically bound (to the oxygen or carbon), it is found that if the free neutron-proton cross section is constant and if the neutron energies are much greater than the maximum of the three energies associated with the hydrogen bond, then the neutron cross section of the bound hydrogen is given by

$$\sigma=\sigma_0(1+h\bar{\nu}/4E), \qquad (1)$$

where σ_0 = the free neutron-proton scattering cross section, h = Planck's constant, $\bar{\nu}$ = the mean of the three frequencies of vibration of the bound hydrogen, and E = the neutron energy.

Since the oxygen cross section and the carbon cross section are constant and the neutron-proton absorption cross section is small in the energy range being considered, one would expect that the relationship between the measured cross sections per H atom in water and cyclohexane and $1/E$ would be linear. Hence, the straight lines with the least square deviations from the points in the two sets of data shown in Fig. 2 were calculated, and these straight lines are shown in Fig. 2.

According to Eq. (1), the free neutron-proton cross section is given by the intercept on the cross-section axis of the curve of the bound hydrogen cross section as a function of reciprocal neutron energy. Since the oxygen and carbon cross sections are measured to be constant in the energy interval being considered, it is convenient to take the cross-section intercepts of the curves shown in Fig. 2 and correct these intercepts for the oxygen and carbon cross sections, for the water and cyclohexane, respectively, in order to obtain the free neutron-proton cross section. Using 3.7×10^{-24} cm^2 as the oxygen cross section,

[3] G. Placzek, private communication

the value obtained from the measurements on the water for the free neutron-proton cross section is 20.0×10^{-24} cm^2. Using 4.7×10^{-24} cm^2 as the carbon cross section, the value obtained from the measurements on cyclohexane for the free neutron-proton cross section is 20.1×10^{-24} cm^2. The *probable* error in these values due to all sources of error is believed to be no greater than $\pm0.3\times10^{-24}$ cm^2. These values for the free neutron-proton cross section agree with the values obtained by several authors[4] within their stated experimental errors. Other values for the free neutron-proton cross section have been obtained[5] which are much lower than the values obtained here, and it is believed that these low values must be considered incorrect.

The slopes of the two curves shown in Fig. 2 are very nearly equal to each other and equal to 1.5×10^{-24} cm^2 ev. This gives the $h\bar{\nu}$ the value of 0.3 ev. This is in fair agreement with a value of about 0.25 ev for $h\bar{\nu}$ obtained from the characteristic bond frequencies for the hydrogen.

III. MEASUREMENTS IN THE 0.05- TO 0.8-EV INTERVAL

The on-time used for the source and detector was 50 μsec. which corresponds to 16.7 μsec./m. No beam filter was used, and a repetition rate for the timing apparatus of 200 cycles/sec. was used without difficulty with recycled neutrons. Exploratory measurements indicated that the collimating system and geometry are not critical in this energy interval. It was convenient to make the final measurements with the same geometrical arrangement that was used for the high energy measurements (Fig. 1). The neutron moderator shown in Fig. 1 was modified for these measurements with a 2-cm slab of paraffin in front of the water moderator, used for high energy measurements, and with a sheet of thick Cd (0.9 g/cm^2) between the paraffin and the water tank. This 2-cm slab of paraffin backed by thick Cd is referred to as the "tray."

[4] See, for example, L. J. Rainwater, W. W. Havens, Jr., J. R. Dunning, and C. S. Wu, Phys. Rev. **73**, 733 (1948); J. Marshall, *ibid.* **70**, 107A (1946); H. B. Hanstein, *ibid.* **59**, 489 (1941); V. W. Cohen, H. H. Goldsmith, and M. Hamermesh, *ibid.* **57**, 352 (1940); V. W. Cohen, H. H. Goldsmith, and J. Schwinger, *ibid.* **55**, 106 (1939).

[5] See, for example, L. Simons, Phys. Rev. **55**, 792 (1939); E. Amaldi, D. Bocciarelli, and G. C. Trabacchi, Ricerca Scient. 11, 121 (1940).

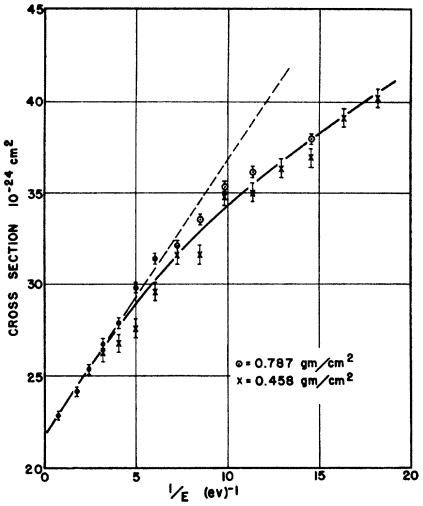

FIG. 4. Total cross section per hydrogen atom of water *versus* reciprocal energy. The dashed curve is the best fitting straight line for the high energy data on water shown in Fig. 2.

The data for this energy region are shown in Fig. 4. The cross section per hydrogen atom of the water is plotted *versus* $1/E$ so that a comparison can be made with the high energy data. The dashed curve is the best fitting straight line for the high energy data on water shown in Fig. 2. The correction of the data for the in-scattering effect was made assuming the scattering to be elastic; and to obtain a value for k, it was assumed that the neutron-hydrogen cross section is proportional to the square of the reduced mass.[6] The correction was less than 0.40×10^{-24} cm^2 for all points, and the correction was negligible for most of the points.

IV. MEASUREMENTS IN THE 0.003- TO 0.05-EV INTERVAL

The on-time used in the measurements in this energy interval for the neutron source and

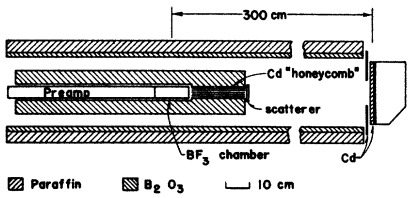

FIG. 5. Collimator arrangement for low energy measurements.

[6] H. A. Bethe, Rev. Mod. Phys. 9, 122 (1937).

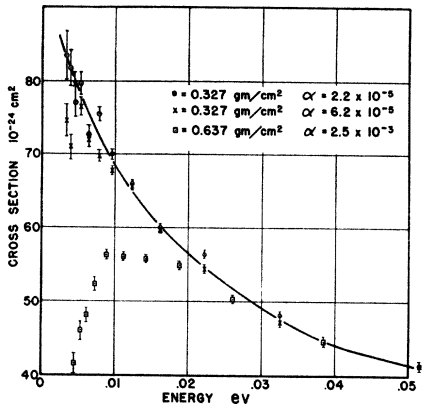

FIG. 6. Measured cross section per hydrogen atom of water for three geometrical arrangements.

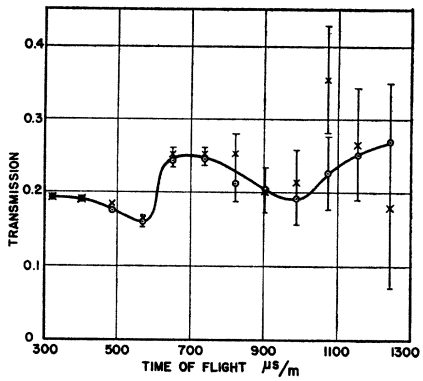

FIG. 8. Graphite test for geometry with $\alpha = 6.2 \times 10^{-5}$. ⊙ = measured transmission of 6.9 g/cm² graphite. × = measured transmission of 6.9 g/cm² graphite with 0.327 g/cm² water "filter" in neutron beam.

detector was 250 μsec. which corresponds to 83 μsec./m. No beam filter was used, and a repetition rate for the timing apparatus of 200 cycles/sec. was used. The tray was used in conjunction with the neutron moderator. The mean life for the low energy neutrons emerging from the tray was 30 μsec.

It was found that for the measurements in this energy range, very good geometry was required in order to obtain consistent results. The collimation arrangement used is shown in Fig. 5. The effective area of the neutron source was determined by a circular hole in a thick sheet of Cd placed between the neutron source and the main section of the collimator. A honeycomb-shaped collimator made of Cd was placed in the region between the scatterer and the BF_3 chamber. By varying the size of the Cd honeycomb-shaped collimator, the geometry factor α could be varied. Data were obtained with three values of α: 2.5×10^{-3}, 6.2×10^{-5}, and 2.2×10^{-5}.

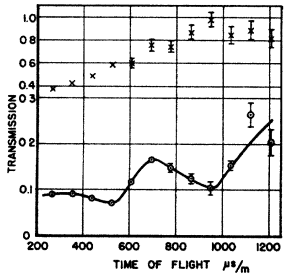

FIG. 7. Graphite test for geometry with $\alpha = 2.5 \times 10^{-3}$. ⊙ = measured transmission of 10 g/cm² graphite. × = measured transmission of 10 g/cm² graphite with 0.327 g/cm² water "filter" in neutron beam.

Shown in Fig. 6 are three sets of data obtained with the three values of α. The measured value of the cross section at low energy increases considerably as the geometry is improved. However, above approximately 0.03 ev, the measured value of the cross section is constant for values of α less than 2.5×10^{-3}.

Anisotropic scattering, predominantly in the forward direction, would give rise to the observed dependence of the measured cross section on α. One effect that would give rise to scattering of neutrons predominantly in the forward direction is inelastic scattering by the water molecule. In order to determine whether or not inelastic scattering was occurring, the following test was carried out. The transmission of a graphite scatterer was measured, and the well-known discontinuities due to interference phenomena were observed in the transmission with the three values of α. A water scatterer was then placed between the graphite scatterer and the neutron source, and with the water in this position, the transmission of the graphite was again measured. If a fraction of the neutrons which pass through the water have their energies changed and are scattered through angles sufficiently small so that they are not excluded from the detector by the collimator, the transmission discontinuities of the graphite will be "smeared." This smearing occurs because changing the energy of a neutron changes its time of flight (per unit distance). Hence, a neutron which loses energy in the water and is detected by the spectrometer to have a

time of flight τ will have had a time of flight less than τ between the neutron source and the water and a time of flight greater than τ between the water and the detector.

Shown in Fig. 7 are the results of this test with $\alpha=2.5\times10^{-3}$, and in Fig. 8 are the results with $\alpha=6.2\times10^{-5}$. The water "filter," when used, was placed between the neutron source and the position for the graphite scatterer and 10 cm from the position for the graphite scatterer. In Fig. 7, it is seen that when the water filter is in place, the transmission discontinuities of the graphite do not appear at all, and the measured transmission of the graphite is very large. Since the cross section of graphite for low energy neutrons is small, it can be concluded from the data in Fig. 7 that for $\alpha=2.5\times10^{-3}$, a fraction of the neutrons which reach the neutron detector after passing through the water have lost energy in the water. One cannot determine the initial energy of the inelastically scattered neutrons from these data. In Fig. 8, it is seen that there is very little smearing of the graphite transmission discontinuities with $\alpha=6.2\times10^{-5}$. It can be concluded that for $\alpha=6.2\times10^{-5}$, few of the neutrons which reach the detector after passing through the water have undergone an energy change in the water. The test was not carried out for $\alpha=2.2\times10^{-5}$, because the neutron intensity was too low to make a conclusive test practicable. However, it is to be expected that with $\alpha=2.2\times10^{-5}$, a smaller fraction of the neutrons which undergo an energy change would reach the detector than with $\alpha=6.2\times10^{-5}$. It is concluded, therefore, that the cross section per hydrogen of water at neutron energies below 0.03 ev is greater than or equal to the cross section measured with $\alpha=2.2\times10^{-5}$.

With $\alpha=2.2\times10^{-5}$, the data (Fig. 6) indicate that the cross section of the protons bound in water exceeds 80×10^{-24} cm^2 at sufficiently low energies. According to the theory given in reference 6, the maximum cross section of bound protons should be four times the free neutron-proton cross section. In this theory, however, the low energy or thermal agitation of the molecule is not taken into account. The Doppler effect arising from the thermal agitation gives rise to an increase in the effective cross section. Also, the capture cross section of the proton is believed to obey the $1/v$ law, and thus the capture cross section will become appreciable at sufficiently low energy.

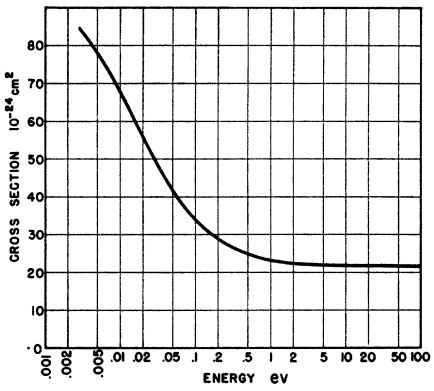

FIG. 9. Total cross section per hydrogen atom of water as a function of energy in the energy range studied. This curve is a composite of the solid curves shown in Figs. 2 (for water), 4, and 6.

Shown in Fig. 9 is the total cross section per hydrogen atom of water for the neutron energy range in which measurements were made. This curve is composed of the solid curves shown in Figs. 2 (for water), 4, and 6.

It is a pleasure to express my thanks to Professor R. F. Bacher, who suggested the problem, and Professor H. A. Bethe for many valuable discussions relative to this investigation. I am especially indebted to Professor B. D. McDaniel for much aid in carrying out and interpreting the measurements. Thanks are also due to Mr. R. R. Meijer who rendered valuable assistance in making many of the measurements.

This work was supported in part by the Office of Naval Research.