Slow Neutron Velocity Spectrometer Studies of H, D, F, Mg, S, Si, and Quartz*

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The neutron proton cross section has been measured using a paraffin sample. The observed free proton cross section is (20.6±1). The cross section-curve below 0.05 ev is well matched by a theoretical curve and approaches 4 times the free proton cross section at very low energies. The thermal cross section of D_2O is well matched by the curve $\sigma_{D_2O}=(10+0.72E^{-\frac{1}{2}})$. The free cross section of D is (3.3±0.2). The thermal cross section of fluorine in a fluorocarbon oil is well matched by the curve $\sigma_F=(3.3+0.11E^{-\frac{1}{2}})$. The cross section of the free fluorine is (3.3±0.5). The cross section of Mg is essentially constant at (3.4±0.1) ev. No resonances are observed in Mg. Microcrystalline interference effects are noticed in the low energy region. The thermal cross section of sulfur is well matched by the curve $\sigma=(1+0.098E^{-\frac{1}{2}})$. No resonances are observed in S. The cross section of Si is essentially constant at (2.25±0.1). No resonances are observed in Si. Microcrystalline interference effects are noticed in the low energy region. The effective neutron cross section of an optical quartz crystal decreases from the additive cross section of (9.2±0.2) at ~10 ev to 1.25 at 0.025 ev which is taken to be the residual incoherent cross section.

1. INTRODUCTION

In several previous papers[1,2] the results of many measurements with the Columbia University slow neutron velocity spectrometer have been described. In order to make available in published form as complete information as possible on slow neutron cross sections we have been urged by several physicists to publish all of the results thus far obtained with the Columbia neutron velocity spectrometer. Therefore, all results acquired over the past few years have been re-examined and the material to be presented divided into three categories.

(a) Materials investigated with the old system[1] which are unlikely to be re-investigated in the near future.

(b) Those materials which have been partially investigated with the new system,[2] and for which the investigation will probably not be completed for some time because of the large number of experiments that are scheduled to be performed with the cyclotron and velocity spectrometer apparatus.

(c) Those materials that were almost completed and should be published in the immediate future as part of the regular series of papers of the Columbia velocity spectrometer group.[2]

The results presented in this paper fall in the first category except for the quartz crystal which has been remeasured for better accuracy. The results presented in this paper are also characterized by the fact that only elements of low atomic weights are involved.

In presenting the results of measurements on H, D, F, Mg, Si, and quartz the conventions previously adopted[2] are used. In particular, the following points should be emphasized: (a) Cross sections are given in units of 10^{-24} cm^2/atom, and energies in electron volts. (b) The total cross section is always measured. (c) The slow neutron flux at the sample position is collimated to $\sim 2\frac{1}{2}$-in. diameter and the detector subtends $<3\times10^{-4}$ of the 4π solid angle viewed from the sample position; therefore, no "geometry" corrections are made. (d) The timing resolution function is nearly triangular in shape with a width at the base between 2 and 3 times the spacing between the adjacent measured points.

2. HYDROGEN IN PARAFFIN

The importance of the data that can be obtained in the study of the neutron transmission of a sample of hydrogenous material as a function of the energy of the incident neutron is essentially twofold. The value of the slow neutron cross section of the free proton can be measured. The effect of the chemical binding of the hydrogen atom in a molecule on the proton cross section can also be studied.

The neutron cross section of the free proton is

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[1] L. J. Rainwater and W. W. Havens, Jr., Phys. Rev. 70, 136, 154 (1946).

[2] Rainwater, Havens, Wu, and Dunning, Phys. Rev. 71, 65 (1947); Havens, Wu, Rainwater, and Meaker, Phys. Rev. 71, 165 (1947); Wu, Rainwater, and Havens, Phys. Rev. 71, 174 (1947).

of particular interest since the magnitude of this value gives information about the excited state of the deuteron and the fundamental nuclear forces.[3] The calculation of the slow neutron, proton cross section on the basis of the known stable triplet state of the deuteron gives much too small a value. Theoretical attempts to explain the large observed value led to the postulation of a virtual singlet level within 70 kev of zero binding energy giving strong evidence for the spin dependence of nuclear forces.

In the region of thermal energies the H cross section in paraffin should increase with decreasing neutron energy because of the chemical binding of the H atom in the lattice.[4] The effective scattering cross section is proportional to the square of the reduced mass of the colliding particles. When there is a collision between a neutron and a free proton the reduced mass is equal to one-half the neutron mass, but when the proton is completely bound, and the energy of the neutron is too small to free the hydrogen or excite the molecule, then the hydrogen has infinite mass effectively and the reduced mass is equal to the neutron mass. Thus the scattering cross section for a completely bound proton should be 4 times that of the free proton. The effective binding of the H atom in the paraffin molecule depends on the ability of the neutron to excite lattice vibrations and will increase as the energy of the neutron decreases. The exact effect of the binding on the cross section is difficult to calculate at any given energy but the proton may be considered free for neutron energies above a few electron volts[4] and completely bound in the limit of zero neutron energy.

In Fig. 1 the results of slow neutron transmission measurements of a sample containing 0.527 g/cm^2 of paraffin in a 0.418 g/cm^2 aluminum container are presented. The composition of the paraffin was assumed to be $C_{22}H_{46}$ with the carbon cross section remaining constant at 4.8.

Between 2.5 and 10 ev the cross section is essentially constant. Since this is in the energy region where the proton can be considered free, the neutron cross section of the free proton can be given as (20.6 ± 1), considering all possible sources of error. Above 10 ev the cross section decreases. This decrease is caused by the resolution width of the apparatus which permits some fast neutrons to be counted in this region, and since the neutron cross section decreases rapidly above 10 kev, the decrease is to be expected.

The value of 20.6 for the free proton is in excellent agreement with all of the measurements which have been made with good experimental techniques. Cohen, Goldsmith, and Schwinger[5] found $\sigma_H=(20\pm2)$ using Rh (1.3 ev),[6]

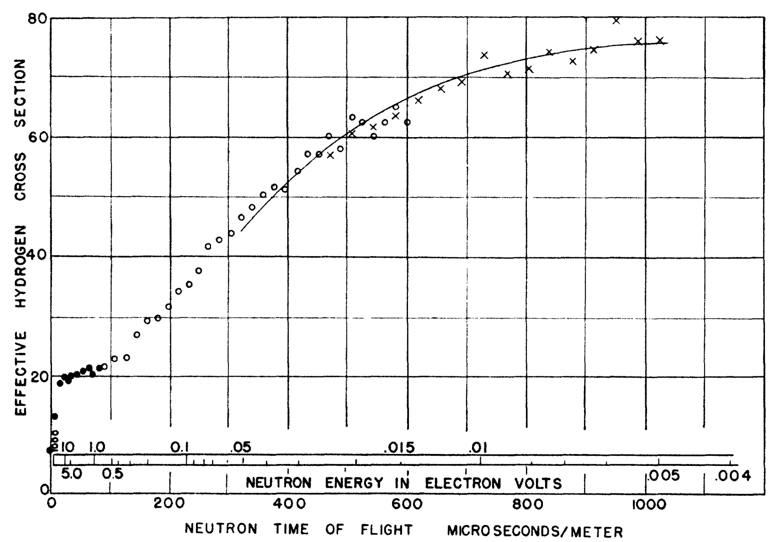

FIG. 1. The slow neutron cross section of hydrogen as a function of the neutron time of flight. The different sets of experimental points were taken with different resolution widths of the apparatus. The solid curve is the calculated theoretical curve.

[3] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 82, 117 (1936).
[4] H. A. Bethe, Rev. Mod. Phys. **9**, 69, 117 (1937).
[5] Cohen, Goldsmith, and Schwinger, Phys. Rev. **55**, 106 (1939).
[6] Borst, Ulrich, Osborne, and Hasbrouck, Phys. Rev. **70**, 557 (1946).

In (1.44 ev),[2,7] and Ag (5.1)[2] resonance detection. Cohen, Goldsmith, and Hornbostel[8] obtained $\sigma_H = 20$ using an I ($\sim$40 ev)[2] detector. Hanstein[9] found $\sigma_H = (21 \pm 1)$ using In (1.44 ev) and $\sigma_H = 20$ using I resonance detectors. Marshall[10] obtained $\sigma_{H_2O} = 44.4$. ($\sigma_H = 20.3$) using an In resonance detector. Frisch[11] measured σ_H at 35, 95, 265 and 490 kev, and obtained results in good agreement with a theoretical curve of Bohm and Richman[12] which had been adjusted to give $\sigma_H = 20.8$ at low energies. These values all lie within the region 20 to 21, in good agreement with the present value but much higher than earlier results[13–15] which were obtained under poorer experimental conditions.

In Fig. 1 the increase in the proton cross section with decreasing neutron energy due to the binding of the proton in the molecule can be seen, At 0.003 ev the proton cross section is 78 which is very near the expected value of about 83 for the completely bound proton. It should be pointed out that at very low energies the carbon nuclei are also effectively bound. This should give a 17 percent increase in the carbon cross section; however, this increase is only 0.8 unit, representing a shift of only 0.4 unit in the measured value of σ_H. This factor of 4 increase in σ_H has also been verified by using the very slow filtered neutron from piles.[16,17] Bethe[4] has calculated the effective cross section of the proton when bound in paraffin for energies well below the vibrational energy perpendicular to the C—H bound ($\sim$0.1 ev). A plot of this calculation below 0.05 ev is the solid curve given in the Fig. 1. The agreement between the theoretical curve and the experimental data is surprisingly good.

Many previous measurements[4,8,18] of σ_H have been made in the thermal region using the entire energy distribution from paraffin sources at room temperature and at lower temperatures, but since the neutron spectrum was only approximately known, direct comparison with the results given here are not possible. However, it is possible to reverse the procedure and obtain the "effective" energy of the thermal neutrons used by comparing the value of the cross section obtained and the results given in Fig. 1. Carroll's[18] value of $\sigma_H = (49.8 \pm 0.2)$ for paraffin is typical of the best measurements and corresponds to a neutron energy of 0.041 ev rather than the assumed temperature of 0.025 ev. This conclusion concerning the effective energy of room temperature neutron distribution agrees with a similar comparison of previously measured values of the boron cross section with values obtained from velocity spectrometer measurements.[1,19,20]

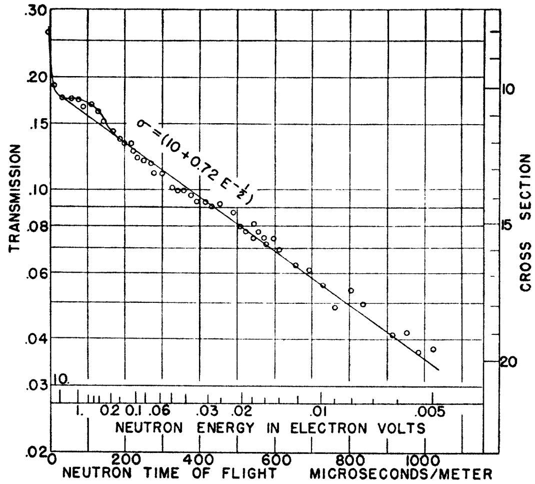

FIG. 2. The slow neutron transmission of a 5.54 g/cm² sample of D_2O. The cross section curve given by $\sigma = (10 + 0.72E^{-\frac{1}{2}})$ is the best line drawn through the experimental data. The $1/v$ term is probably caused by molecular binding effects.

The capture cross section of H is between 0.3 and 0.4 for 0.025 ev neutrons. Schulz and Goldhaber[21] give (1954±24) as the ratio of the boron

[7] B. D. McDaniel, Phys. Rev. **70**, 832 (1946).
[8] Cohen, Goldsmith, and Hornbostel, Phys. Rev. **57**, 352 (1940).
[9] H. B. Hanstein, Phys. Rev. **59**, 489 (1941).
[10] J. Marshall, Phys. Rev. **70**, 107 (A) (1946).
[11] D. H. Frisch, Phys. Rev. **70**, 589 (1946).
[12] D. Bohm and C. Richman, Phys. Rev. **71**, 567 (1947).
[13] E. Amaldi and E. Fermi, Ricerca Scient. **7**, 310 (1936).
[14] L. Simons, Phys. Rev. **55**, 792 (1939).
[15] Amaldi, Bocciarelli, and Trabacchi, Ricerca Scient. **11**, 121 (1940).
[16] Anderson, Fermi, and Marshall, Phys. Rev. **70**, 815 (1946).
[17] E. Fermi and L. Marshall, Phys. Rev. **71**, 666 (1947).
[18] See, for example, Dunning, Pegram, Fink, and Mitchell, Phys. Rev. **48**, 265 (1935); H. Carroll, Phys. Rev. **60**, 702 (1941); Goldhaber and Briggs, Proc. Roy. Soc. **A162**, 127 (1937); G. A. Fink, Phys. Rev. **50**, 738 (1936); Powers, Goldsmith, Beyer, and Dunning, Phys. Rev. **53**, 947 (1938).
[19] Bacher, Baker, and McDaniel, Phys. Rev. **69**, 443 (1946).
[20] Sutton, McDaniel, Anderson, and Lavatelli, Phys. Rev. **71**, 272 (1947).
[21] L. G. Schulz and M. Goldhaber, Phys. Rev. **67**, 202 (1945); Manley, Haworth, and Luebke, Phys. Rev. **61**, 152 (1942).

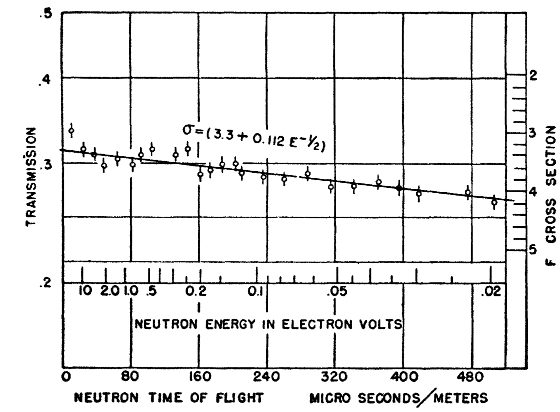

FIG. 3. The slow neutron transmission of 8.84 g/cm^2 of a fluorocarbon oil $(CF_{1.9})_n$. The cross section of carbon has been assumed constant at 4.8 and subtracted from the total cross section of the oil to give the effective fluorine cross section.

to H capture cross sections corresponding to $\sigma_{abs}=0.37$ at 0.025 ev, or to about 0.03 in the region where the free proton cross section was measured.

Further study of hydrogenous material in the energy region where chemical binding is unimportant should give more exact values of the cross sections of the free proton, and velocity spectrometer studies of the neutron cross section of the simpler hydrogenous molecules, such as methane, ethane, propane, etc., should throw more light on the different chemical binding of hydrogen in the molecules which were first systematically investigated by Carroll.[19]

3. DEUTERIUM IN D_2O

The slow neutron transmission of a sample containing 5.54 g/cm^2 of D_2O has been investigated. The D_2O was in an aluminum sample holder and an identical empty container was used for the "sample out" measurements to cancel effects due to the container. The D_2O sample was obtained from the metallurgical laboratory of the University of Chicago and was of the highest purity obtainable. The results of the measurements are shown in Fig. 2.

The rise in transmission near zero time of flight is due to the effect of the very fast neutrons as explained above for hydrogen. In the region near 5 ev, the curve is relatively flat corresponding to a cross section of 10.5. Since the effect of chemical binding should be negligible in this region, the value $\sigma_{D_2O}=(10.5\pm0.3)$ may be taken as the $(2\sigma_D+\sigma_O)$ "free" cross section. At lower energies, binding effects should give an increase in the cross section for a maximum factor of $(3/2)^2$ for the D atoms and $(17/16)^2$ for the O atoms. Using the relative D and O cross sections chosen below, this would give a maximum value of $\sigma_{D_2O}=19.5$, which is very near the maximum measured value. This does not consider the effect of the thermal motion the D_2O molecules which will tend to increase the measured cross section for very slow neutrons. Considering all of the complicating effects, it was rather unexpected that the experimental points could be so closely matched over the entire region by the 1/v type relation $\sigma_{D_2O}=(10+0.72E^{-\frac{1}{2}})$.

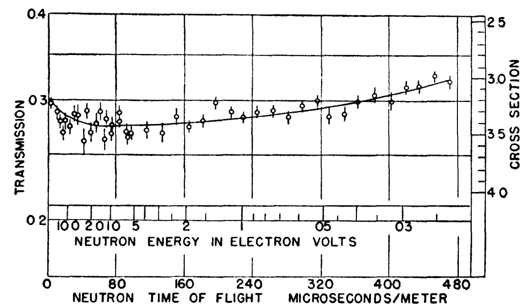

FIG. 4. The slow neutron transmission of 15.3 g/cm^2 of magnesium. The rise in transmission at very long time of flight is caused by the microcrystalline interference effects.

It is well known from the use of D_2O as a pile moderator material that both D and O have unusually small capture cross sections. Frisch, Halban, and Koch[22] gives $\sigma_{abs}<0.03$ for D and <0.01 for O in agreement with the results obtained for O by Muelhause and Goldhaber.[23] The 1/v effect observed is thus *not* due to capture.

The results of Fig. 2 may be compared with previously published values for the thermal region ($\sim$0.042 ev) and the resonance region ($>$1 ev). Hanstein[9] obtained $\sigma_{D_2O}=10.6$ for indium resonance neutrons and 15.4 for thermal neutrons. Carroll[18] found $\sigma_{D_2O}=10.3$ for indium resonance neutrons. Beyer and Whitaker[24] obtained $\sigma_{D_2O}=16$ for thermal neutrons. The values for the resonance region are in good agreement

[22] Frisch, Holban, and Koch, Nature **140**, 895 (1937).
[23] C. O. Muelhause and M. Goldhaber, Phys. Rev. **70**, 85 (1946).
[24] H. G. Beyer and M. D. Whitaker, Phys. Rev. **57**, 976 (1940).

with the value 10.5 from Fig. 2, but the thermal values are consistently higher than the value of ~ 14 for 0.04 ev in Fig. 2.

Previous measurements[24,25] of the oxygen cross section in the thermal region have given $\sigma_0 \sim 4.1$. However, the cross section of O_2 gas has recently been measured in this laboratory to be 3.7 in the resonance region and this value is subtracted from $\sigma_{D_2O} = 10.5$, a value of

$$\sigma_D = (3.3 \pm 0.2)$$

is obtained for the free deuteron cross section. The increased cross section of D_2O at lower energies is mainly due to the deuterium but is partly due to the oxygen. For this reason only the D_2O cross section is given in this region.

4. FLUORINE

The slow neutron transmission of a sample containing 8.84 g/cm² of a fluorocarbon oil has been investigated to determine the cross section of fluorine. A chemical analysis of the oil showed that there were 1.9 atoms of fluorine per carbon atom and that the sample contained negligible

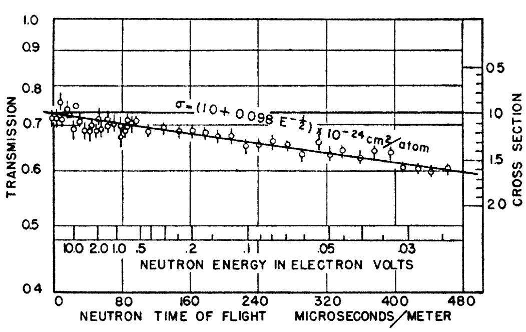

FIG. 5. The slow neutron transmission of 16.4 g/cm² of sulfur. This curve shows the usual 1/v type cross section $\sigma = (1.0 + 0.098E^{-\frac{1}{2}})$.

hydrogen (<0.02 percent by weight). The results of these transmission measurements are presented in Fig. 3.

In determining the cross section of fluorine the formula for the oil was assumed to be $(CF_{1.9})_n$ and the cross section of carbon was assumed to be constant and equal to 4.8.

The transmission of the sample is relatively constant above 0.25 ev and corresponds to a fluorine cross section of (3.3 ± 0.15). This may be taken as the "free" fluorine cross section since binding effects should be negligible in this region. The cross section curve has a small slope and is well matched over the entire energy region studied by the formula $\sigma_f = (3.3 + 0.11E^{-\frac{1}{2}})$. The slope of this curve cannot be attributed to capture for both the capture cross sections of fluorine and carbon are too small. For fluorine Volz[26] found $\sigma_{capt} = 0.05$ from absorption measurements. Muelhause and Goldhaber[23] found $\sigma_{abs} \sim 10^{-2}$ and Manley, Hayworth, and Luebke[27] gave $\sigma_{abs} = 0.01$. For carbon, Anderson *et al.*[28] give $\sigma_{capt} = 0.0049$. This 1/v increase in the cross section might be accounted for by the binding of fluorine in a molecule. If the C and F atoms were completely bound, a value of 14 percent higher than the "free" cross sections would be expected. The maximum measured value of $(\sigma_f + 0.526\sigma_c) = 6.5$ is 12 percent larger than the free value of 5.8 at a neutron energy of about 0.019 ev. Slow neutron capture in the 100 percent abundant F^{19} isotope[29] produces F^{20} which is β-active with a 12 sec. half-life.

The results given in Fig. 3 can be compared with previous measurements of the total and scattering cross sections for fluorine. Dunning *et al.*[18] found $\sigma_{tot} = 2.5$ using thermal neutrons. Goldhaber and Briggs[18] found $\sigma_{scatt} = 4.1$. Marshall[10] gives $\sigma_{tot} = 3.7$ using In resonance neutrons. This last value should be reliable and directly comparable with Fig. 3. The fact that it is slightly larger than the value 3.3 suggests

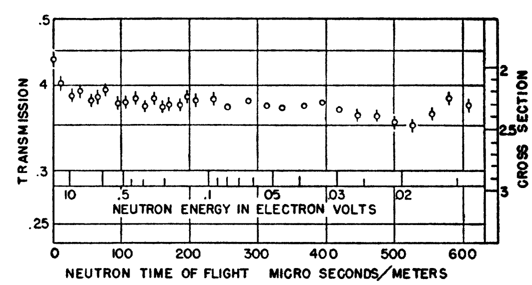

FIG. 6. The slow neutron transmission of 19.43 g/cm² of powdered silicon from 0.015 to 10 ev. The cross section is approximately constant at 2.25.

[25] H. Carroll and J. A. Dunning, Phys. Rev. **54**, 541 (1938).

[26] Volz, Zeits. f. Physik **121**, 201 (1943).

[27] Manley, Hayworth, and Luebke, Phys. Rev. **59**, 109 (1941).

[28] Anderson, Fermi, Wattenberg, Weil, and Zinn, Phys. Rev. **72**, 16 (1947).

[29] G. T. Seaborg, Rev. Mod. Phys. **16**, 1 (1944).

that the C_7F_{16} sample used may not have been completely hydrogen free. It is also interesting to note that Fields, Russell, Sachs, and Wattenburg[30] obtain total cross sections of 3.5, 5.7, 6.9, 4.6, and 4.1 at 24 kev, 130 kev, 220 kev, 620 kev, and 830 kev, respectively. This suggests that there is a broad resonance between 130 and 220 kev. Goloborodko and Leipunski[31] also find $\sigma_{tot}=6.4\pm1.3$ at 210 kev.

5. MAGNESIUM

The slow neutron transmission of magnesium has been investigated in a metallic sample containing 15.3 g/cm². The sample was cast from C.P. magnesium in an inert atmosphere to remove traces of hydrogen. The results of the transmission measurements are shown in Fig. 4.

There are no pronounced dips in transmission in the high energy region even though much better resolution was used *in this region.* This indicates that there are no strong neutron resonances in the region studied. Since Mg has such a low atomic weight, it should have broad, strong, widely spaced levels, and thus it is not surprising that none were found in the region of a few volts energy. The curve in Fig. 4 gives an essentially constant value of $\sigma=(3.4\pm0.1)$ in the region above 0.25 ev which may be taken as the "free" magnesium cross section. The rise in transmission near zero time of flight is due to the overlap of some very fast neutrons for which the Mg cross section is lower. The rise in transmission for larger timings is due to the interference effects associated with the microcrystalline structure of the sample.

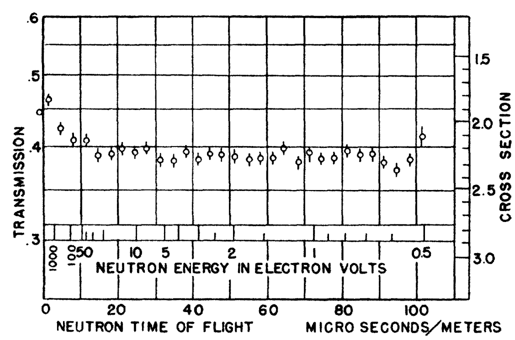

FIG. 7. The slow neutron transmission of 19.43 g/cm² of powdered silicon from 0.5 to ~100 ev with better resolution. The cross section still remains approximately constant at 2.25.

Normal magnesium consists of 77.4 percent Mg^{24}, 11.5 percent Mg^{25}, and 11.1 percent Mg^{26}. Slow neutron capture produces stable isotopes[26] in the first two cases, and β-active Mg^{27} of 10.2 min. half-life in the case of Mg^{26}. Sinma and Yamasaki[32] obtained 0.028 for the thermal neutron capture cross section of Mg for the production of Mg^{27}. Goldhaber and O'Neal[33] find 0.03 as the capture cross section of Mg (thermal neutrons) for the production of Mg^{27} or 0.3 for the Mg^{26} isotopic cross section. Volz[26] gives 0.31 for the total Mg thermal absorption cross section and Ramm[34] obtained 0.22 for the same quantity. The value of $\sigma=3.4$ at higher energies in Fig. 4 is due only to scattering, since the $1/v$ dependence of the capture cross section causes it to be negligible in that region. The results given in Fig. 4 can be compared with previous measurements of the Mg total and scattering cross sections. Dunning *et al.* obtained $\sigma_{tot}=3.5$ in the thermal region. Mitchell, Murphy, and Whitaker[35] obtained $\sigma_{scatt}=4.2$ at thermal energies. A measurement at 210 kev by Goloborodko and Leipunski[31] gives $\sigma_{scatt}=4.4$, 4.9, 5.7, 8.7, 4.2, and 3.4 at 24, 130, 140, 220, 620, and 830-kev neutron energies. This indicates the presence of a broad level near 220 kev. McPhail[36] has shown that Mg^{24} has a scattering level at $E_0=2.54$ Mev with $\Gamma_0=0.15$ Mev.

6. SULFUR

The slow neutron transmission of sulfur has been investigated using 16.40 g/cm² of sulfur in a container with thin aluminum ends. The sample was made of C.P. powdered sulfur which was dried at 120°C and pressed into the container. An empty container was used in the sample position during the "out" runs to eliminate the effect of the container walls. The results of the transmission measurements are shown in Fig. 5.

There are no pronounced dips in the high

[30] Fields, Russell, Sachs, and Wattenberg, Phys. Rev. **71**, 508 (1947).
[31] T. Goloborodko and A. Leipunski, Phys. Rev. **56**, 891 (1939).
[32] K. Sinma and F. Yamasaki, Phys. Rev. **59**, 402 (1941).
[33] M. Goldhaber and R. D. O'Neal, Phys. Rev. **59**, 109 (1941).
[34] Ramm, Naturwiss. **30**, 755 (1942).
[35] Mitchell, Murphy, and Whitaker, Phys. Rev. **50**, 133 (1936).
[36] M. R. MacPhail, Phys. Rev. **57**, 669 (1940).

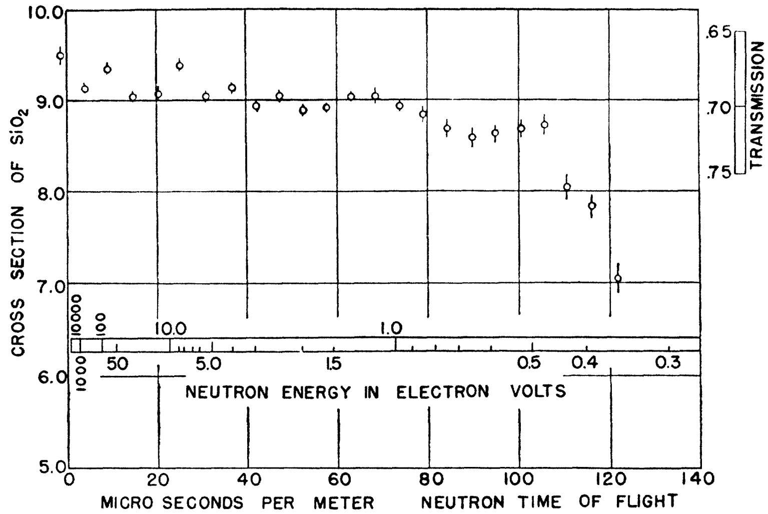

FIG. 8. The slow neutron cross section of quartz measured with a 4.57 g/cm² sample. The cross section is approximately constant at 9.2 in this higher energy region and begins to decrease at 0.45 ev due to the neutron interference.

energy region even though better resolution was used in this region. The curve is well matched by the 1/v relation

$$\sigma=[(1.0\pm0.1)+(0.098\pm0.01)E^{-\frac{1}{2}}].$$

The first term may probably be considered to represent the scattering cross section, and the second term the 1/v capture cross section. This represents the smallest slow neutron cross section known and is of interest for this reason.

Normal sulfur consists[29] of 95.1 percent S^{32}, 0.74 percent S^{33}, 4.2 percent S^{34}, and 0.016 percent S^{36}. Neglecting the S^{36}, the capture of slow neutrons leads to a radioactive product only in the case of the 4.2 percent S^{34} which gives β-active S^{35} of 87.1-day half-life. Since S contains mainly the S^{32} isotope, the small scattering cross section must be explained on the basis of a partial cancellation of the cross section due to the destructive interference of the potential and resonance scattering amplitudes. On the basis of the theory of Feshbach, Peaslee, and Weisskopf,[37] this would indicate that there is a resonance level "near" zero neutron energy. This means "near" relative to the level spacing which is probably quite large since sulfur is of such low atomic weight.

The results shown in Fig. 5 may be compared with previously published values for thermal neutrons. Dunning *et al.*[18] obtained $\sigma_{tot}=1.4$. Volz[26] obtained $\sigma_{abs}=0.62$. Coltman[38] obtained $\sigma_{abs}=(0.44\pm0.03)$. Whitaker and Bright[39] obtained $\sigma_{tot}=9.0$ and $\sigma_{scatt}=8.5$ for CS_2. Subtracting 4.8 for S, leaves $\sigma_{tot}=2.2$ and $\sigma_{scatt}=1.8$ for S. Mitchell, Murphy, and Whitaker[35] obtained $\sigma_{scatt}=0.9$. Kimura[40] found $\sigma_{scatt}=1.1$ for thermal neutrons and 1.05 for In resonance neutrons. Goldhaber and Briggs[18] obtained $\sigma_{scatt}=1.1$ Whitaker and Beyer[24, 41] found $\sigma_{tot}=2.0$. The results shown in Fig. 5 give $\sigma_{tot}=1.5$, $\sigma_{scatt}=1.0$, and $\sigma_{abs}=0.5$ at 0.042 ev.

The results of Fields, Russell, Sachs, and Wattenberg,[30] using photo-neutrons, are in good agreement with Fig. 5 at their lowest energy and show that the position of what is probably the nearest resonance is near 150 kev. They obtain $\sigma_{tot}=1.0$, 4.2, 4.5, 2.9, and 2.2 for 24, 130, 140, 222, and 830-kev neutron energies. Zinn, Seely, Cohen[42] obtain $\sigma_{tot}=3.12\pm0.10$ for 2.88-Mev fast neutrons.

7. SILICON

The slow neutron transmission of silicon has been investigated using a 19.43 g/cm² sample of powdered silicon packed in an aluminum container of 0.418 g/cm² wall thickness. The results

[37] Feshbach, Peaslee, and Weisskopf, Phys. Rev. **71**, 145 (1947).

[38] J. W. Coltman, Phys. Rev. **59**, 917 (1941).

[39] M. D. Whitaker and W. C. Bright, Phys. Rev. **60**, 155 (1941).

[40] Kimura, Phys. and Math. Soc. Japan Proc. **22**, 391 (1940).

[41] M. D. Whitaker and H. G. Beyer, Phys. Rev. **55**, 1124 (1939).

[42] Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939).

of these transmission measurements are presented in Figs. 6 and 7.

There are no pronounced dips in transmission in the high energy region even though the measurements at the higher energies used much better timing resolution. This indicates that there are no strong neutron resonances in the energy region investigated. Small irregularities in the transmission in the thermal energy region are probably due to interference effects. The value of the cross section above thermal energies is (2.25 ± 0.1), from Fig. 7. This represents the free silicon cross section since binding and interference effect should be negligible. A completely bound Si atom would have a 7 percent larger cross section than a free Si atom.

Normal silicon consists[29] of 89.6 percent Si^{28}, 6.2 percent Si^{29}, and 4.2 percent Si^{30}. Capture of a neutron produces a radioactive product only in the case of 4.2 percent Si^{30} to give β-active Si^{31} of 170-min. half-life. Volz[26] gives $\sigma_{abs}<0.06$ for Si using thermal neutrons. Sinma and Yamasaki[32] obtained $\sigma_{abs}=0.063$ for the production of the Si^{31} activity by thermal neutrons. Goldhaber and O'Neal[33] similarly obtained $\sigma_{abs}<0.03$ for the production of Si^{31}. Although Fig. 6 shows a small increase in cross section in the thermal region, the absorption is too low to be reliably indicated by utilizing the 1/v slope of the transmission curve since binding and interference effects can easily be of equal importance.

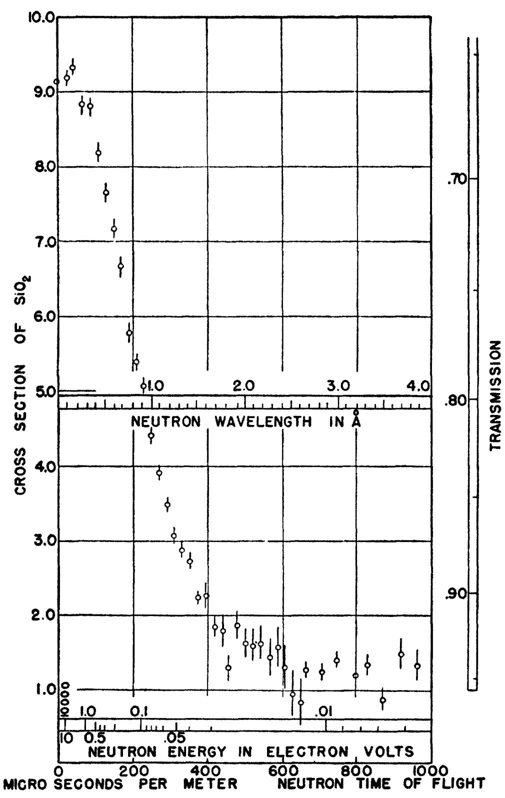

FIG. 9. The slow neutron cross section of quartz as measured with a 4.57 g/cm² sample. The cross section decreases from the free value of 9.2 to about 1.25 at 0.025 ev and then remains approximately constant.

The results of Fig. 6 may be compared with previously published values of σ_{tot} and σ_{scatt} for Si for thermal neutrons. Dunning *et al.*[18] obtained $\sigma_{tot}=2.5$ Goldhaber and Briggs[18] found $\sigma_{scatt}=1.7$.

Because of its low atomic weight, silicon would be expected to have resonance levels for neutron absorption that are strong and widely spaced.[4, 37] This is in agreement with the results of Goloborodko and Leipunski,[31] who obtained $\sigma_{tot}=7.2\pm 0.9$ for 210-kev photo-neutrons, and the results of Aoki,[43] who observed a strong neutron scattering resonance level at 2.45 Mev.

8. QUARTZ CRYSTAL

The slow neutron transmission of a quartz crystal of 4.57 g/cm² thickness has been investigated. The sample was an optical quartz crystal 1.725 cm thick and about 9 cm in diameter with optically flat parallel faces cut perpendicular to the optic axis. The purpose of the experiment was to study the energy dependence of the effective neutron cross section of a single crystal. At short neutron wave-lengths the cross section of the sample should be the sum of the separate free cross sections of the component atoms, whereas at long wave-lengths the effective cross section should be very small because of crystal interference effects. It was considered of interest to see how small the effective cross section would become for long wave-lengths and to study the shape of the cross section *vs.* neutron wave-length curve in transition region between additive and small cross sections.

The results of the transmission measurements are shown in Figs. 8 and 9. The results shown were obtained using the new spectrometer system.[2] The sample thickness was much too

[43] H. Aoki, Phys. Rev. 55, 795 (1939).

small for best accuracy in the cross section measurements since the transmission was so near unity. For best results a sample about 5 times as thick should be used.[1] We intend to investigate quartz again when a suitably thick sample is obtained.

The results of the measurements for neutron energies above the thermal region are shown in Fig. 8 where the neutron cross section of SiO_2 is plotted as a function of the neutron time of flight. The neutron wave-length in angstrom units is also indicated. The cross section is essentially constant in this region and equal to (9.2 ± 0.2), which may be taken as the additive SiO_2 cross sections for the free atoms scattering independently. Combining this result with the similar result for Si gives $\sigma=(3.5\pm0.2)$ for the oxygen cross section. This is somewhat lower than the value 3.7 which is indicated from measurements using O_2 gas.

The results of the measurements over the entire energy range are shown in Fig. 9 which also contains a scale of neutron wave-length. From Figs. 8 and 9 one can see that almost the entire transition between high and low cross sections takes place in the range of neutron wave-lengths between $\lambda=0.45$A and 1.7A (0.45 ev to 0.025 ev) with the half-value of the cross section at $\lambda=0.9$A (0.1 ev). For longer wave-lengths the effective cross section seems to level off at $\sigma=1.25$, which represents the residual incoherent cross section. Previous studies indicated that the minimum effective cross section in the thermal region decreased rapidly with increasing sample thickness. This may also apply for monochromatic neutrons, or it may be that the effect is due entirely to the use of the entire thermal spectrum in earlier studies. When the complete thermal spectrum is used, the neutrons of energy greater than 0.025 ev would be preferentially removed by the front portion of the sample and the "hardened" beam of lower energies would be less effected by the remaining thickness. The thermal neutron capture cross section for SiO_2 should be less than 0.1, as discussed under Si and D_2O.

Since the thermal interference effects in quartz have been investigated frequently in the past, it is of interest to compare the earlier results with those of Figs. 7 and 8. Whitaker, Beyer, and Dunning,[44] using thermal neutrons, obtained $\sigma_{SiO_2}=(8.0\pm1)$ for 3.7 g/cm^2 fused quartz, (8.8 ± 1.7) for 1.3 g/cm^2 of sand, (4.5 ± 0.6) for a 3.7 g/cm^2 quartz crystal, and (4.1 ± 0.6) for a 1.3 g/cm^2 quartz crystal. Whitaker, Bright, and Murphy,[45] using a 4.2-cm thick quartz crystal, found $\sigma_{SiO_2}=(7.2\pm1.2)$, using In and Rh resonance neutrons (1.3–1.44 ev), (3.0 ± 0.7) using room temperature thermal neutrons, and (2.3 ± 0.7) using a liquid-air cooled source. Hanstein[9] obtained $\sigma_{SiO_2}=(7.5\pm0.5)$ for In resonance neutrons and (4.3 ± 0.3) for thermal neutrons using a 4.5 g/cm^2 thick quartz crystal, and (8.8 ± 0.8) and (8.8 ± 1.0) for the In resonance and thermal neutrons using 3.3 g/cm^2 of sand.

The results given above for the SiO_2 cross section for thermal neutrons are not in disagreement with the results given in Fig. 9 but the reason for the previously obtained lower values using resonance neutrons is not clear.

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[44] Whitaker, Beyer and Dunning, Phys. Rev. **54**, 771 (1938); M. D. Whitaker and H. G. Beyer, Phys. Rev. **55**, 1101 (1939).

[45] Whitaker, Bright, and Murphy, Phys. Rev. **57**, 551 (1940).