to be preferred. In the two-carbon molecules[3, 4] some hydrogen molecules were formed but not the maximum number possible. However, in propane, propylene and allene the appearance potentials correspond to the formation of the maximum number of molecules in the hydrogen which is removed. It is reasonable to suppose, however, that a molecule of hydrogen is always formed of two atoms which were originally attached to the same carbon. This hypothesis has been verified in the case of ethylene by Delfosse and Hipple.[10] It will also be observed that propylene is much like ethylene except that one hydrogen has been replaced by a CH_3 radical. One might expect, therefore, that CH_4 would be formed in propylene as H_2 is formed in ethylene and the experiments amply verify this hypothesis. Another example of this behavior occurs in propane where CH_4 appears in the formation of $C_2H_4^+$.

The construction of the apparatus was made possible through the work of Dr. J. A. Hipple, Jr., and it is a pleasure to acknowledge this assistance as well as his help with the initial work on propane. We are greatly indebted to the Research Corporation for financial aid which has helped materially in the perfection of our apparatus.

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[10] J. Delfosse and J. A. Hipple, Phys. Rev. **54**, 1060 (1938).

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Collision Cross Sections for D – D Neutrons*

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The nuclear collision cross sections of 22 elements for the neutrons from a deuteron-deuteron source have been measured. The geometrical arrangement of the experiment was such that only small corrections to the measured transmission were necessary. The neutron energy was 2.88±0.04 Mev. The cross sections are found to vary irregularly with the atomic weight. The proton cross section determined for both paraffin and water scatterers is found to be 2.36×10^{-24} cm^2, which is smaller than the value predicted by theory. In addition, the cross sections of a number of elements for neutrons of 2.46 Mev energy have been measured. For some elements the cross section is found to increase with an increase in neutron energy, for others it decreases.

The total collision cross section of the fast neutrons from radon plus beryllium sources for the nuclei of many of the elements of the periodic table have been measured by Dunning.[1] These cross sections when plotted as a function of the atomic weight show a slow and regular increase with atomic weight. Since, however, the neutrons from Rn+Be are highly inhomogeneous in energy, the total cross sections found with them are only averages for a considerable energy interval.

The importance in nuclear theories of neutron-proton scattering and nuclear scattering in general makes it highly desirable to measure cross sections with neutrons of a single known energy. It is well established that the neutrons from the deuteron-deuteron reaction are, in the main, monoenergetic and hence this source has been used in a number of investigations in which such neutrons were required. Scattering cross sections for deuteron-deuteron neutrons have been measured by Booth and Hurst,[2] Ladenburg and Kanner,[3] and recently by Kikuchi and Aoki.[4]

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[1] J. R. Dunning, Phys. Rev. **45**, 586 (1934).

[2] E. T. Booth and C. Hurst, Proc. Roy. Soc. **161**, 248 (1937).

[3] R. Ladenburg and M. H. Kanner, Phys. Rev. **52**, 911 (1937).

[4] Seishi Kikuchi and Hiroo Aoki, Proc. Phys.-Math. Soc. Japan **21**, 75 (1939); Phys. Rev. **55**, 108 (1939).

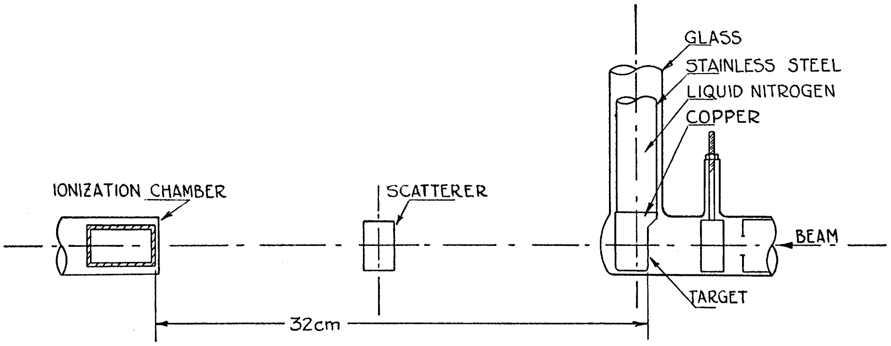

FIG. 1. Arrangement of neutron source, scatterer, and ionization chamber.

In this paper the results of the measurements of the cross sections of 22 elements for neutrons of 2.88 Mev energy are given, as well as the cross sections of some of these elements for neutrons of 2.46 Mev energy. Most of the values given here have been reported as preliminary measurements;[5] in a few instances further investigation has resulted in small changes in the values given previously.

APPARATUS AND TECHNIQUE

The total collision cross section (capture plus scattering) may be determined by measuring the transmission through a sample of material placed in the path of a neutron beam. The ideal arrangement for such an experiment would be to use a point source of neutrons, a point detector, a scatterer of infinitesimal width, and no scattering material in the vicinity of either source or detector. A neutron on suffering either capture or scattering through a finite angle will then fail to be detected. In the present experiment the geometrical arrangement of the source, scatterer and detector is shown schematically in Fig. 1. The scattering samples all had diameters of 3.2 cm and were supported on a thin fiber structure midway between the target and the ionization chamber, the front face of which was 32 cm from the target. The ionization chamber had a diameter of 2.2 cm and a length of 4 cm, and was filled with helium at ten atmospheres pressure. The recoils of the helium nuclei were recorded by a linear amplifier and a scale of two counting circuit. The gain of the amplifier was set so that only the largest recoils, that is, those which had received a considerable portion of the energy of the neutron, were counted. This precaution is necessary since there is some evidence[6] that a deuteron-deuteron source emits neutrons of about 1.0 Mev energy in addition to the main group. Furthermore an anomalous and large value for the helium cross section for 1.0 Mev neutrons has been discovered by Staub and Stephens,[7] from which it follows that the effect of even a small component of low energy neutrons would be unduly large.

The following checks show that the results given here are not influenced by the presence of a group of low energy neutrons. As has been pointed out by Staub and Stephens, the number of recoils recorded when monoenergetic neutrons impinge on a gas-filled ionization chamber should vary linearly with the bias of the pulse selecting Thyratron in the recording circuit. Such a plot produced a straight line for a considerable variation of Thyratron grid voltage on either side of the voltage used in these measurements. Also visual observations of the pulses on a cathode-ray screen established the fact that recoils from 1.0 Mev neutrons could not be counted. As a further check some of the cross sections were measured with a hydrogen-filled chamber and gave values identical, within the limits of error, with those found with the helium-filled chamber.

The neutron generator used in this work has

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[5] W. H. Zinn, S. Seely and V. W. Cohen, Phys. Rev. **53**, 921 (1938). S. Seely, W. H. Zinn and V. W. Cohen, Phys. Rev. **55**, 679 (1939).

[6] T. W. Bonner, Phys. Rev. **53**, 711 (1938).

[7] H. Staub and W. E. Stephens, Phys. Rev. **55**, 131 (1939).

been described[8] and is so designed that the amount of scattering material in the neighborhood of the target is reduced in a minimum. The target was heavy water ice frozen on a thin-walled copper cup cooled by liquid nitrogen. From the thickness of the copper and nitrogen, and a knowledge of the mean free path of neutrons in these substances, it is estimated that a negligibly small number of neutrons were scattered into the beam by the target support. The deuterons were magnetically separated from the molecular ion beam and were focused into a spot approximately 5 mm in diameter. Under these conditions the source of neutrons was a sufficient approximation to a point source.

In measurements of this kind it is desirable to have the background due to neutrons from points other than the target as small as possible. The correction due to room scattering was determined by placing a paraffin cylinder 28 cm long and of the same diameter as the scattering samples between the target and the ionization chamber. The neutron intensity under these conditions was 3 percent of the intensity when the paraffin was removed. This low background intensity is due to the fact that neutrons which have lost energy by scattering are not recorded because the counting circuit was set to discriminate against low energy recoils. The background was also shown to be small by means of an "inverse square" measurement.

TABLE I. *Total collision cross sections. Neutron energy—2.88±0.04 Mev.*

ELEMENT	COMPOUND USED	G/CM^2	CORRECTED TRANSMISSION	$\sigma \times 10^{24}$ CM^{-2}
$_1H$	$C_{22}H_{46}$	1.976	0.571	2.32±0.09
$_1H$	H_2O	3.00	.543	2.40± .09
$_1D$	D_2O	3.32	.574	2.17± .08
$_5B$	B_4C	4.34	.626	1.98± .07
$_6C$		6.14	.547	1.97± .07
$_7N$		7.05	.658	1.38± .06
$_8O$		9.92	.633	1.25± .05
$_{11}Na$		6.31	.676	2.37± .09
$_{12}Mg$		10.88	.545	2.25± .07
$_{13}Al$		9.92	.599	2.34± .07
$_{14}Si$		4.31	.774	2.77± .08
$_{16}S$		8.25	.623	3.12± .15
$_{17}Cl$	CCl_4	4.77	.541	3.42± .16
$_{19}K$		6.22	.741	3.13± .15
$_{25}Mn$		11.76	.611	3.82± .12
$_{26}Fe$		15.68	.588	3.15± .10
$_{29}Cu$		22.86	.549	2.82± .10
$_{30}Zn$		18.24	.576	3.28± .10
$_{34}Se$		12.75	.675	4.05± .16
$_{42}Mo$		12.14	.733	4.06± .14
$_{50}Sn$		22.38	.608	4.39± .16
$_{80}Hg$		33.45	.585	5.34± .20
$_{82}Pb$		33.44	.520	6.74± .24

In order to eliminate any error due to fluctuations of the deuteron current to the target, a current integrator was used. The accelerating voltage was maintained constant to better than one percent by manual manipulation of a resistance in the primary of the transformer of the high tension apparatus. However, errors due to fluctuations in intensity of the neutron beam are possible with constant voltage and a current integrator, because the condition of the target and the composition of the deuteron beam may vary with time. The effect of these was minimized by making observations cyclically, that is, first a count for the direct beam was made, second, a count with the scatterer in place, third, a background count, etc. The time of counting in each case was so adjusted that the total number of neutrons counted with the scatterer in place was the same as the total number without.

The accelerating potential used in these measurements was 121 kv. Bonner's[6] latest Q value of 3.29 Mev for the $_1H^2 + _1H^2$ reaction gives, for the energy of the neutrons which are emitted in the forward direction, a value of 2.88±0.04 Mev. Those emitted at right angles to the deuteron beam have an energy of 2.46 ±0.04 Mev. The width of 80 kv for the neutron energy spectrum results from the use of a thick target and is also due to the finite angle subtended by the ionization chamber at the target.

RESULTS AND DISCUSSION

The results of this investigation for neutrons of 2.88 Mev energy are summarized in Table I. In the first column are given the elements and the atomic numbers; in the second column are listed the compounds which were used in those cases in which the pure elements were not available; the third column gives the mass per cm^2; the fourth column contains the corrected transmissions, the last column gives the scattering cross sections calculated from these transmissions. Two corrections were applied to the measured transmissions. (1) Room scattering: this is a substantially constant term which is

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[8] W. H. Zinn and S. Seely, Phys. Rev. **52**, 919 (1937).

subtracted from the intensities observed with and without the scatterer in place. It decreases the measured transmission in most cases by about 1.2 percent. (2) Scattering of neutrons into the ionization chamber by the scatterer: for isotropic scattering this correction amounts to a decrease of 0.7 percent in the measured transmission. For hydrogen and deuterium where the scattering in the room system is nonisotropic, the corrections are 3 percent and 1.3 percent, respectively. Since all the scatterers were approximately one-half mean free path long the correction for multiple scattering is negligible.

Reasonable care was exercised with regard to the purity of the materials used, compounds, in general, being avoided because of the difficulty of insuring their freedom from moisture contamination. Materials obtainable only in powder or liquid form were placed in thin-walled brass or glass cells. A similar empty cell was used in obtaining the count for the unfiltered beam so that no correction for the effect of the cell was necessary. The liquid oxygen and liquid nitrogen were placed in glass Dewar flasks. The purity of the oxygen was verified by measuring the boiling point with a platinum resistance thermometer.

Neutron-Proton Cross Section

In Table I two values for the neutron-proton cross section are given, one obtained with a paraffin scatterer and the other with water as the scattering material. Repeated measurements, under varying conditions, were made on these substances; for paraffin in particular the dimensions of the samples were varied as well as the source of the paraffin. The chemical composition of the paraffin was estimated by measuring the melting point. The cross sections determined from water and paraffin agree within the limits of error assigned to the measurements and since the cross sections of oxygen and carbon which enter into the proton determination were measured with comparable precision, neither measurement is to be preferred to the other. In view of the great importance of the neutron-proton interaction in nuclear theory it seems quite urgent to make a more precise study of the neutron-proton scattering cross section. The chief limitation in accuracy attainable with the present apparatus is due to slight fluctuations in the emitted neutron intensity associated with changing conditions of the ice target, and with fluctuations in the accelerating voltage. This difficulty may be overcome by using a monitor detector system for checking the neutron emission during readings. Such a system is now under construction in this laboratory.

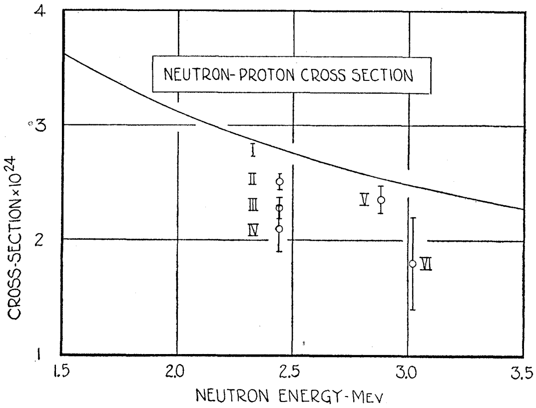

FIG. 2. I. Theoretical curve. II. Aoki. III. Kikuchi and Aoki. IV. Ladenburg and Kanner. V. This paper. VI. Booth and Hurst.

In Fig. 2 the neutron-proton cross sections as measured by various experimenters using deuteron-deuteron neutrons are plotted as a function of the energy of the neutrons. The energy of the neutrons in each case has been computed with $Q=3.29$ Mev. The average of our water and paraffin measurements, namely, $2.36\pm0.12\times10^{-24}$ cm^2, is plotted as representing best the results of this investigation. The solid curve is obtained from the following equation[9] for the scattering cross section.

$$\sigma=\frac{4\pi^2\hbar}{M}\left(\frac{3}{4}\,\frac{1+\alpha_0 r_0}{|E_0|+\frac{1}{2}E}+\frac{1}{4}\,\frac{1+\alpha_1 r_0}{|E_1|+\frac{1}{2}E}\right),$$

where $E_0=2.17$ Mev is the binding energy of the deuteron; $r_0=2.8\times10^{-13}$ cm is the value of the range of the nuclear forces obtained from experiments on proton-proton scattering.[10] $E_1=0.066$ Mev is the energy of the singlet state of the deuteron. This value is chosen so that the slow neutron cross section is in agreement with the

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[9] J. Schwinger and E. Teller, Phys. Rev. **52**, 286 (1937).

[10] G. Breit, H. M. Thaxton and L. Eisenbud, Phys. Rev. **55**, 1018 (1939).

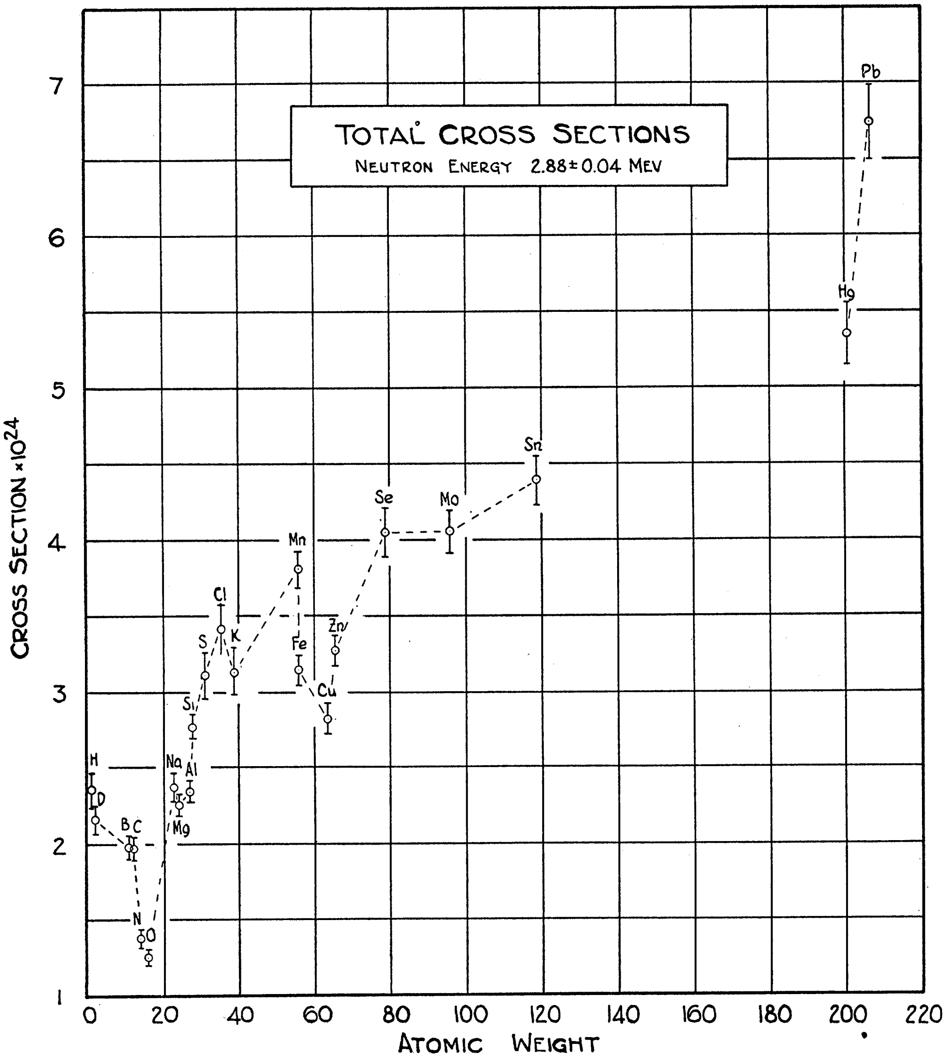

FIG. 3. Cross sections as a function of atomic weight.

value of 20×10^{-24} cm^2 given by Cohen, Goldsmith and Schwinger.[11]

Ladenburg and Kanner[12] first pointed out that a small discrepancy exists between theory and experiment if one assumes a reasonable value for the range of the nuclear forces. An examination of Fig. 2 shows that all measurements made so far definitely lie below the theoretical curve. No reasonable value for the slow neutron cross section will allow a sufficient change in the binding energy of the singlet state of the deuteron to bring the theoretical and experimental values into agreement. Theory gives a cross section in agreement with our value of 2.36×10^{-24} cm^2 if the range is assumed to be 1.88×10^{-23} cm^2. A revision of the theory in order to remove this difficulty, among others, has been proposed by Schwinger.[13] This revised theory does give values for the neutron-proton cross sections which are lower than those calculated from the above formula without requiring a value for the range of the nuclear forces in disagreement with the range found in proton-proton scattering experiments.

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[11] V. W. Cohen, H. H. Goldsmith and J. Schwinger, Phys. Rev. **55**, 106 (1939).

[12] R. Ladenburg and M. H. Kanner, Phys. Rev. **52**, 1255 (1937).

[13] J. Schwinger, Phys. Rev. **55**, 235 (1939).

CROSS SECTIONS AS A FUNCTION OF ATOMIC WEIGHT

In Fig. 3 the cross sections are plotted against the atomic weight. It is clearly evident that there is no smooth and regular increase with atomic weight as found by Dunning[1] with the Rn+Be neutrons or a periodic variation as has been suggested by Kikuchi and Aoki.[4] These results are not directly comparable with those of Ladenburg and Kanner[3] who measured the cross sections for some of the lighter elements or with those of Kikuchi and Aoki because of the different neutron energies used. Staub and Stephens[7] have determined the ratio of the helium cross section to that of hydrogen for these energies from which it follows that the He cross section is 3.3×10^{-24} cm^2. It is to be noted that in going from helium to oxygen the cross section decreases to almost one-third. On the basis of a simplified potential model, Fay[14] has made calculations for the variation of nuclear cross section with atomic number and finds, for certain neutron energies, very sharp resonances. Insufficient elements of higher atomic number have been measured in this work to permit a quantitative comparison. However, in view of the inhomogeneity of the neutron energy, one would expect a smoothing out of extremely sharp resonances into the kind of variation actually observed.

CROSS SECTIONS AS A FUNCTION OF NEUTRON ENERGY

The considerable difference between our value of the oxygen cross section for 2.88-Mev neutrons and that of Ladenburg and Kanner[3] for 2.4-Mev neutrons and the rather large differences between our values and those of Kikuchi and Aoki[4] for such elements as sodium and potassium suggest that the cross sections are quite sensitive to the energy of the neutrons. Accordingly, we have measured the cross section of some elements for two different neutron energies under identical experimental conditions; these are given in Table II.

TABLE II. *Cross sections for different energies.*

ELEMENT	ATOMIC NUMBER	NEUTRON ENERGY	
		2.46 MEV	2.88 MEV
C	6	1.37±0.05	1.97±0.05
N	7	1.40± .06	1.38± .06
O	8	1.05± .03	1.25± .05
Na	11	2.70± .16	2.37± .09
Al	13	2.99± .07	2.34± .06
S	16	2.77± .14	3.12± .15
K	19	3.44± .18	3.13± .15

For each element measured, with the exception of nitrogen, the change in cross section is greater than the error of the measurement. In some cases, notably carbon and aluminum, the percentage change in cross section is considerably greater than the percentage change in neutron energy. It is also to be noted that for about one-half of the elements measured the cross section increases with an increase in neutron energy while for the remainder it decreases. These facts indicate strongly that here we are dealing with a resonance scattering of the neutrons. That this is indeed the case is shown by the recent results of Aoki.[15]

The following should be noted for the elements of Table II: in each case where a real difference exists between our value of a cross section of 2.88 Mev and the measurements of other observers for a lower energy of neutrons, the change in cross section is in such a direction as to bring the values into agreement.

The writers wish to express their indebtedness to the Department of Physics of Columbia University for the laboratory facilities placed at their disposal, to Professor John R. Dunning for the loan of an amplifier and ionization chamber, to Professor S. L. Quimby for measuring the boiling point of the liquid oxygen and to Dr. Julian Schwinger for helpful discussions concerning the neutron-proton cross section.

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[14] C. A. Fay, Phys. Rev. **50**, 560 (1936).

[15] Hiroo Aoki, Phys. Rev. **55**, 795 (1939).