assumption that the differential cross section in the center-of-mass coordinates is a constant. The total cross section $\sigma(E)$ is then only a function of the energy of the proton E in the layer dx of the target.

For convenience in integration, a parameter

$$k=(M_TM_R/M_BM_O)^{\frac{1}{2}}(1-E_0/E)^{\frac{1}{2}}$$

is introduced, where M_T, M_R, M_B, and M_O are the masses of the target, residual, bombarding, and outgoing particles, respectively. E_0 is the threshold energy of the reaction in laboratory coordinates. The total cross section of the reaction is assumed to vary as $(E-E_0)^{\frac{1}{2}}$ near threshold, and since the exact variation above threshold is not known, it is chosen for convenience in integrating to be such that $\sigma dx\sim k^2dk$. The zonal efficiency of the counter $\eta(\theta)$ is also assumed to be a constant.

Using the dynamics of the $H^3(p,n)He^3$ reaction, the value of $d\Omega\phi/d\Omega_\theta$ may be found as a function of k and θ. The integration then may be carried out with the result that

$$Y=(N_0nA/3a)k_1^2 \text{ for } 0<k_1<\sin\theta_0,$$

$$Y=(N_0nA/3a)[k_1^3-\cos\theta_0(k_1^2-\sin^2\theta_0)^{\frac{3}{2}}] \text{ for } \sin\theta_0<k_1<(M_RM_T/M_BM_O)^{\frac{1}{2}} \times[1-E_0/(E_0+at)]^{\frac{1}{2}},$$

$$Y=(N_0nA/3a)[k_1^3-k_2^3-\cos\theta_0(k_1^2-\sin^2\theta_0)^{\frac{3}{2}}] \text{ for } 0<k_2<\sin\theta_0,$$

$$Y=(N_0nA/3a)[k_1^3-k_2^3-\cos\theta_0(k_1^2-\sin^2\theta_0)^{\frac{3}{2}} +\cos\theta_0(k_2^2-\sin^2\theta_0)^{\frac{3}{2}}] \text{ for } k_2>\sin\theta_0, \text{ but } k_1\leqslant 1.$$

In the formulas A is an unknown constant depending on the efficiency of the counter and other constants of the reaction, a is the energy loss per cm for the proton beam in the target, θ_0 is the half-angle subtended by the counter (7.50°), and t is the thickness of the target in cm. k_1 is the value of k at the front edge of the target, and k_2 is the value of k at the back edge of the target, each for an incident proton beam of energy E_B.

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Total Cross Sections of Chlorine, Sodium, Titanium, and Bromine for Fast Neutrons*

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Relatively new liquid scintillation counter methods were adapted to detect fast neutrons with a heretofore unattainable efficiency of about 19 percent. The geometry obtained was the so-called "good" geometry, which was a half-angle at the counter of 2.7°. With the more efficient counter reasonable counting times could be obtained with the detector subtending a half-angle of only 2.7° from the target.

The neutrons were obtained by using a modified Cockcroft-Walton linear accelerator of 100-kev bombarding energy. The neutron energy range was 2.15 to 2.82 Mev.

All the scatterers used were contained in almost identical glass "cells," and the effects of the glass cells were subtracted out by using an empty glass cell of the same type as a reference. The probable error, calculated statistically from the counting rates of the experiment, was 1.3 percent on total cross-section values. Actual reproducibility of each result was about 3 percent or better.

A carbon cross-section curve was obtained as a check on this method, and agreement with previously reported values was excellent. The chlorine and sodium cross sections were found to be about 3×10^{-24} cm², as determined indirectly by using carbon tetrachloride and sodium chloride. The titanium cross section was found to be about 4.1×10^{-24} cm² by using powdered titanium metal. The bromine cross section was found to be about 3.7×10^{-24} cm², by using a sample of liquid bromine. No large resonances were found in the energy region available.

Data were also taken on the angular distribution of the number of neutrons with respect to the forward direction of the incident deuteron beam, and they were found to agree well with theory except in the region where experimentally necessary geometric conditions dictated a deviation.

I. INTRODUCTION

In the past few years there has been much work done with regard to obtaining total cross sections of the elements for fast neutrons. In reviewing many articles, it has been found that there is still work to be done before all the total cross sections have been measured as accurately and with as good an energy resolution as the theoretical physicists would like. Hence, we have taken up a program of augmenting the available data with the apparatus being used here. Several elements were found that have not been reported as yet, and we are planning a systematic study of these elements as well as those elements that have only sparse data for our energy region. Wisconsin,[1,2] Aoki,[3] Argonne,[4] Stafford,[5] Los Alamos,[6,7] Oak Ridge,[8] MacPhail,[9] Ricamo,[10]

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† Part of a dissertation presented to the Faculty of the Graduate School of The University of Texas as partial fulfillment for the degree of Doctor of Philosophy.

[1] R. L. Henkel and H. H. Barschall, Phys. Rev. **80**, 145 (1950).
[2] Miller, Adair, Bockelman, and Darden, Phys. Rev. **88**, 83 (1952).
[3] H. Aoki, Proc. Phys.-Math. Soc. Japan **21**, 232 (1939).
[4] Hughes, Spatz, and Goldstein, Phys. Rev. **75**, 1781 (1949).
[5] G. H. Stafford, Proc. Phys. Soc. (London) **A64**, 388 (1951).
[6] Linenberger, Miskel, and Segrè, U. S. Atomic Energy Commission Report AECD-2458 (unpublished).

and Zinn[11] have studied a total of fifty-one elements either completely or partially in our energy region.

The results of these investigators were used as comparison values to correlate our data whenever possible.

Chlorine, sodium, and titanium are usually classified as lying below the so-called "heavy" nuclei and thus will probably not obey the sort of theory that tends to average over resonances such as the continuum theory of Feshbach, Peaslee, and Weisskopf.[12,13] However, the bromine data may be useful for this purpose.

II. EXPERIMENTAL PROCEDURE

A. Neutron Generator

A very brief description of the neutron generator being used by this group will be included here, since it has not previously been described.

This group is working with a modified Cockcroft-Walton linear accelerator similar to the Rice Institute accelerator.[14] The power supply is a special General Electric full-wave rectifier employing kenotrons, and it was primarily designed for x-ray work. It is capable of furnishing 100 000 volts at 100 milliamperes dc. The ion source power is provided by a transformer insulated for 100 000 volts dc, which is rated at 25 amperes at 20 volts ac. This power supply thus affords a voltage division along the four-element accelerator tube by using resistors instead of corona gaps. The current through the voltage divider is about 40 times larger than the ion beam current, giving very steady potentials on the accelerating electrodes. The available voltage limits the experiments here to the D(d, n) and the T(d, n) reactions.

A magnetic ion source similar to the one described by Kistemaker[15] is presently being used, and it delivers about 550 microamperes of beam about 1.5 centimeters in diameter at the target.

For this experiment a copper target 0.030 inch thick was used, and deuterium was "built up" on the copper[16] after a few hours bombarding which resulted in a neutron flux of about 2×10^6 neutrons per second. Deuterium target build-up has also been observed on aluminum and tungsten at this laboratory.

B. Neutron Counter

This "good" geometry experiment was made possible by the use of a liquid scintillation counter which consisted of a 51-millimeter diameter by 50-millimeter long glass cell filled with 5 grams of terphenyl in one liter of xylene[17] optically coupled with Dow Corning 200-Silicone fluid to an RCA 5819 photomultiplier. The scintillator was covered with a thin foil of highly reflecting aluminum which was crinkled to afford good reflection properties for the light pulses. The entire assembly was then made light tight by wrapping the foil and 5819 tube with black electrical Scotch tape. A mu-metal shield was placed over the assembly to further protect the photomultiplier from the earth's magnetic field and from extraneous magnetic fields, since it was operated in the vicinity of the accelerator. In this particular experiment, no quantitative energy resolution was necessary, since the energy range to be studied was not very great and the neutron energy in any given direction with respect to the incident deuteron beam was essentially monoergic. The scintillation counter was found to be about 19 percent efficient when compared to a long BF_3 counter that had been calibrated with a standard RaD-Be neutron source.

A cathode follower preamplifier was used to match the photomultiplier circuit to the coaxial cable, which in turn fed into an Atomic A-1 amplifier and thence to an Atomic 101M scaler.

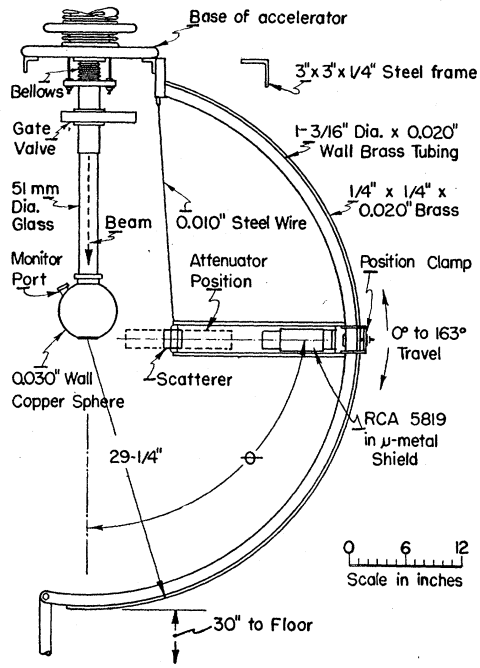

FIG. 1. Scale drawing of experimental apparatus used in measuring total cross section. The scatterer, attenuator, and alignment apparatus are held by a circular 0.020-in. aluminum clamp.

C. Counter Frame, Alignment Apparatus, and Scatterers

Figure 1 shows a scale drawing of the apparatus used to position the counter and scatterers with respect to the target. All the component parts were made of as

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[16] P. Baker, Jr., and A. Waltner, Phys. Rev. **88**, 1913 (1952).
[17] H. Kallman and M. Furst, Phys. Rev. **79**, 857 (1950).

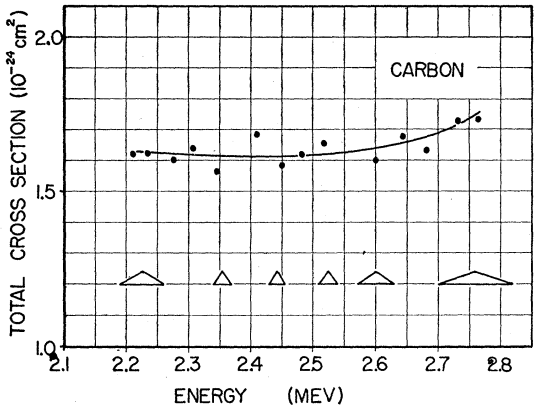

FIG. 2. Total cross section of carbon *vs* neutron energy in Mev. This curve was used as a check on the experimental procedure.

light a material as was believed possible without sacrificing rigidity of support for the 30-centimeter long by 51-millimeter diameter aluminum attenuator. Aluminum was used wherever possible, and no steel was used in the support apparatus proper except for the 0.010-inch diameter piano wire. The alignment apparatus was constructed as follows: A long thin-walled aluminum tube was machined to fit the key socket in the 5819 tube socket at one end, and a thin-walled aluminum cylinder with a diameter equal to the scatterer diameter was placed at the other end. A $\frac{1}{8}$-inch aluminum rod which extended to the target was fitted into the scatterer end of the aluminum tube, and the entire alignment apparatus was centered in a lathe to within 0.1 millimeters. The 5819 tube was removed from its socket key hole and secured at the scatterer clamp end. The crescent and steel wire were adjusted so that the end of the alignment apparatus touched squarely at the middle of the target area on the outside of the sphere. The alignment rig was taken out of the apparatus, the 5819 was plugged back into its socket, and the scatterers were clamped into their place in order. The alignment procedure was again checked after all the scatterers were run at each position to make sure that the relative positions of the mount, scatterer holder and target had not shifted.

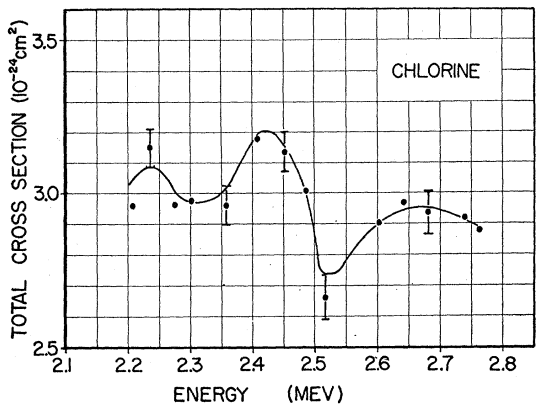

FIG. 3. Total cross section of chlorine *vs* neutron energy.

All the samples except carbon were placed in glass cells that had been made to close tolerances. The inside lengths of the five glass containers were measured to be 1.7755±0.0084 inches, and the glass ends of the containers were all ground to be 0.0575±0.0010 of an inch thick. The cylinders of the glass cells were cut from standard 51-millimeter tubing. An empty glass cell was used to measure the incident intensity of the neutrons at the counter before and after the bottled samples were run. This incident intensity was used for our calculations of the total cross sections. The glass cells were found to produce about 5 percent attenuation of the incident neutron beam compared to the direct neutron beam with no glass cell between the target and counter. It was assumed that this effect of the glass cells was not great enough to affect the results in so far as multiple scattering was concerned.

The carbon sample used was 1.8811±0.0005 inches in diameter and 1.8865±0.0050 inches long. The material was machined from a large electric arc furnace type electrode. The incident neutron intensity used to compute the carbon cross-section data was taken without the empty glass cell.

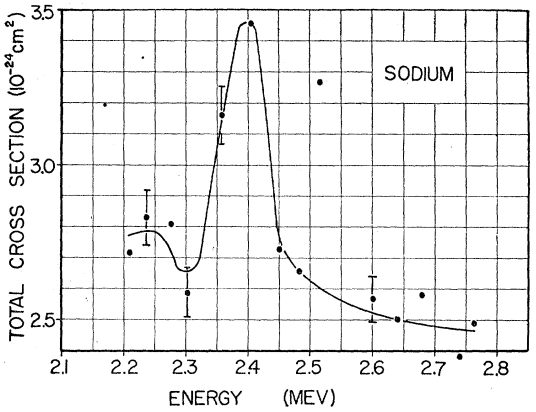

FIG. 4. Total cross section of sodium *vs* neutron energy.

All scatterers used were cylinders rather than properly truncated cones, since Poss *et al.*[18] found that a good geometry experiment was affected very little, if at all, by using the simpler cylindrical form. The scatterers were made slightly larger than absolutely necessary in order that some slight misalignment would not invalidate the results.

The counter was placed with its nearest face 55 centimeters from the target, and the scatterer was placed with its center 27 centimeters from the target. All scatterers were placed in the same position to within plus or minus two millimeters. The half-angle subtended by the active counter volume with respect to the target was 2.7°. The distance between the counter

[18] Poss, Salant, Snow, and Yuan, Phys. Rev. **87**, 11 (1952).

and target was not allowed to vary more than 5 millimeters, and the alignment was visually checked several times during each run to insure against gross errors in misalignment.

The transmission through the attenuator was calculated to be 1.1 percent, and this factor was neglected, since the statistical error for the number of counts that were used was calculated to be ±1.3 percent. The total number of counts accepted for any part of the experiment was at least 10,000 after the background had been subtracted out. With the long aluminum attenuator in position, the background was found to be about 26 percent of the total counts, and with no scatterer between the neutron source and the counter the background was 4.3 percent of the total counts. Each scatterer was run twice in each position, and the average value of the two separate calculations was taken as the best value. A histogram of the error differences was compiled for the entire experiment, and the average experimental error was determined to be ±1.7 percent.

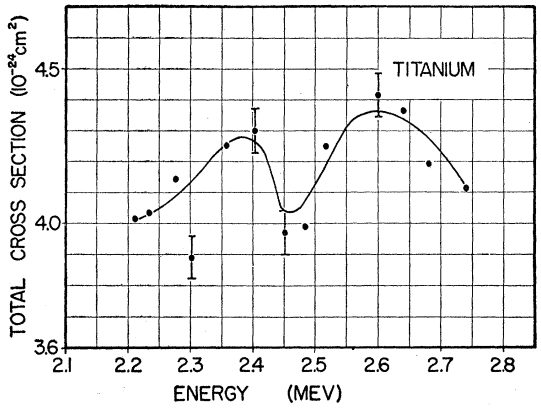

FIG. 5. Total cross section of titanium *vs* neutron energy.

III. RESULTS

A. Carbon

Carbon was used as the final experimental check on the method used in this experiment, and the results as seen in Fig. 2 agreed quite favorably with the results given by the Wisconsin group. The experimental error for the carbon total cross section was found to be ±1.7 percent and the energy resolution obtained in this experiment is shown by the bases of the triangles on Fig. 2 and is the same for the other elements discussed in this paper. Therefore, the experimental errors for the other elements are shown on subsequent figures, but the energy resolution is omitted.

B. Chlorine

The total cross section was measured for CCl_4,[19] and the total cross section for chlorine was obtained by subtracting out the total cross section for carbon. The CCl_4 used met ACS specifications for purity. The data in Fig. 3 indicate that no real resonances lie in this energy region. The experimental error was ±2.4 percent.

[19] Kiehn, Goodman, and Hansen, Bull. Am. Phys. Soc. **28**, 33 (1953).

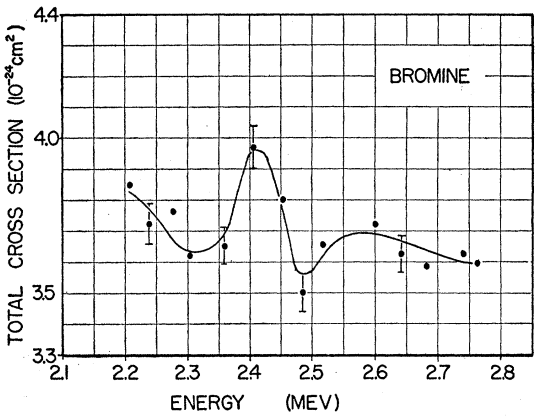

FIG. 6. Total cross section of bromine *vs* neutron energy.

C. Sodium

These data were obtained by using NaCl and subtracting out the total cross section of chlorine as determined from the above paragraph. The NaCl used met ACS specifications and was free of water of crystallization. The glass cell was loaded with the salt in a dry atmosphere. Aoki reported three points for the element sodium in our available energy region as follows: 3 barns at 2.85 Mev, 3.2 barns at 2.50 Mev, and 2.75 barns at 2.85 Mev. Argonne reported one point of 2.35 barns at 2.85 Mev. The data (Fig. 4) agree with Argonne at the high energy end, and we measured one point at 2.515 Mev which agrees with one of Aoki's points. There is a definite maximum at 2.40 Mev as shown by the data. We plan to study this curve using the element sodium in its metallic form more thoroughly in order to determine if there is another peak at about 2.5 Mev. The experimental error was ±2.7 percent.

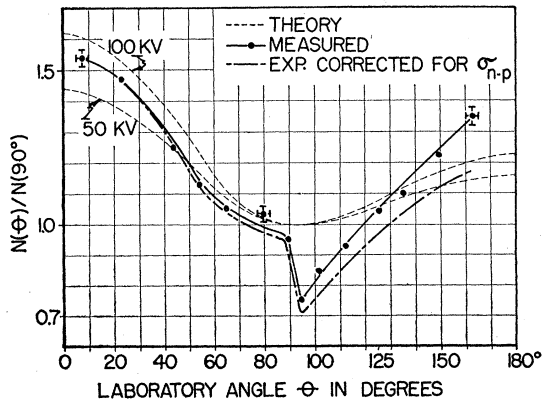

FIG. 7. Angular distribution of numbers of neutrons. Angle measured from forward direction of deuteron beam to direction of neutrons used. A "best fit" was taken in determining the experimental curve.

D. Titanium

The titanium was in the form of a powder and came to us marked 98 to 99 percent pure. No marked resonances were shown to exist in the data (Fig. 5), but it did not correlate Aoki's results. Aoki has reported the following three points: 1.83 barns at 2.23 Mev, 2.15 barns at 2.55 Mev, and 2.05 barns at 2.85 Mev. The experimental accuracy of the final results was ±1.7 percent.

E. Bromine

The element bromine in its liquid form was used, and it met the ACS specifications for purity. An indication of a peak was recorded at about 2.42 Mev. (Fig. 6). The experimental accuracy of the cross-section data was ±1.7 percent.

F. Angular Correlation of Number of Neutrons

The data recorded afforded an experimental check with respect to the angular correlation of number of neutrons in the laboratory system.[20,21] The heavy line in Fig. 7 is the angular distribution of numbers of neutrons with respect to the forward direction of the beam with no corrections. The heavy dotted line is our data corrected for the $n-p$ cross section[3] in the energy region used. This gives an indication that the counter being used at present has an energy sensitivity variation depending principally on the $n-p$ cross section. Plans are being made to do more work to find out more about the properties of this particular counter.

The sudden dip in the curve at 89° was found to be caused by the fact that the neutrons produced at the inside surface of the copper sphere had to pass through a relatively long section of copper to get to the outisde of the sphere. This geometrical consideration was found to exist for our particular apparatus up to about 120° with respect to the forward direction of the beam, and it is seen from the Fig. 7 that the correlation is relatively good on either side of the above-mentioned region. This should not affect the total cross-section data, since it was a constant effect for all readings taken at any given position.

The authors wish to express their gratitude to the following men for assisting them continuously in this work: Mr. N. M. Schaeffer for building the counter; Mr. P. C. Cadenhead for assisting in operation of the accelerator, as well as taking data; Mr. B. P. Leonard, Jr., for assistance in the operation of the accelerator, as well as the calculations; and Mr. G. H. Olewin for assistance in building the apparatus.

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[21] Bretscher, French, and Seidl, Phys. Rev. **73**, 815 (1948).

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Mean Lifetimes of *V*-Particles and Heavy Mesons*

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A maximum-likelihood procedure for determining mean lifetimes of *V*-particles from cloud-chamber data is applied to samples taken from a group of 134 neutral *V*-particle decays. For 74 events which were consistent with a decay into a proton and a negative π-meson, a lifetime of $(2.5\pm0.7)\times10^{-10}$ sec is obtained. Dividing the data into "low Q" and "high Q" groups on the basis of the calculated energy release in the decay, a value of $\tau_L=(2.9\pm0.8)\times10^{-10}$ sec is found for those cases with $0\leqslant Q\leqslant 50$ Mev and a value of $\tau_H=(1.6\pm0.5)\times10^{-10}$ sec is found for those cases with $50<Q\leqslant 150$ Mev. While no significant difference exists between these two values, the difference is greater than for other plausible division schemes which are considered.

A qualitative discussion of lifetimes is given for the case of 23 charged *V*-particle decays. For the charged *V*-particles these data suggest either a lifetime less than that of the neutral *V*-particles, provided the sample is homogeneous, or, more likely, an apparent average lifetime less than that of the neutral *V*-particles, if the sample is a mixture of two or more types of particles. The possibility that κ- and/or χ-mesons make up a part of these decays is considered.

I. INTRODUCTION

SINCE the first report of the discovery of neutral and charged *V*-particles by Rochester and Butler[1] and the subsequent confirmation of the discovery by Seriff *et al.*[2] A number of cloud-chamber experiments[3–8] have been performed to make further studies of these particles. Although the findings have been more complex than one might have expected, and the need for a great deal more work has become apparent, certain definite conclusions have been reached and other possible results have been suggested.[7,8] All of these experiments

* Supported in part by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
† Now at Alabama Polytechnic Institute, Auburn, Alabama.
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