by amounts which increase with neutron energy to a maximum difference of ten percent at 6 Mev. Further studies[7] of $\sigma_s$(H) at higher energies show the necessity of a more complex theory to describe the higher energy results.

A comparison of these results with those of former workers[8] is only possible in the energy range between 2.4 and 2.9 Mev. The agreement is well within the statistical errors given by these authors. Further comparison with E. Bretscher, *et al.*,[9] shows that his work and the present study agree to well within the statistical errors of the two studies. Comparison with the results of D. Frisch[1] show that the present results for energies less than 1 Mev are approximately five percent too small.

It is probably fair to conclude that the values of $\sigma_s$(H) given by the smooth curve of Fig. 2, which is the result of Bohm and Richman's calculation, are correct to within five percent.

With respect to the case of $\sigma_s$(C) there is very little that can be said from a theoretical point of view. A comparison with early observations[8] in the 2.5-Mev energy range shows fair agreement. Again a comparison with Bretscher, *et al.*,[9] gives excellent agreement. Frisch's[1] measurements, represented by the dotted line in Fig. 3, show that the present results for energies less than 1 Mev are approximately five percent too small.

Figure 3 shows that a doublet level of the compound nucleus $C^{13}$ exists with energy levels of 8.25 and 8.90 Mev above the ground state. The width of these levels must be much less than indicated in the figure because the differential thick-target technique provided neutrons of from 100 to 300 kev total energy spread in the energy region between 3 and 5 Mev.

[7] R. Sherr, Phys. Rev. **66**, 240 (1945).

[8] Aoki, Proc. Phys. Math. Soc. Jap. **21**, 232 (1939); Phys. Rev. **55**, 795 (1939). Zinn, Seely, and Cohen, Phys. Rev. **56**, 260 (1939). Booth and Hurst, Proc. Roy. Soc. **A161**, 248 (1937). Ladenburg and Kanner, Phys. Rev. **52**, 911 (1937).

[9] E. Bretscher, *et al.*—unpublished.

PHYSICAL REVIEW VOLUME 70, NUMBERS 9 AND 10 NOVEMBER 1 AND 15, 1946

# The Total Cross Sections of Carbon and Hydrogen for Neutrons of Energies from 35 to 490 kev

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(Received August 8, 1946)

The total cross sections of carbon and hydrogen have been measured at mean neutron energies of 35, 95, 265, and 490 kev.

## EXPERIMENTAL ARRANGEMENT

NEUTRONS were produced by the Li($p$, $n$) reaction. (Figure 1.) Protons accelerated by the smaller Wisconsin electrostatic generator at Los Alamos were collimated to a $\frac{3}{32}''$ diameter beam of from 20 to 30 microamperes. The proton beam fell on a thin lithium film evaporated on an air-cooled copper target backing 0.020″ thick. The stopping power for protons of the lithium film used was measured by observing the energy width of the rise of the neutron yield curve in the forward direction. Targets of 5- to 10-kev stopping power were used.

The nearly monochromatic quality of the neutrons was insured by control of the bombarding proton energy to $\pm 2$ kev. The system of corona control used will be described elsewhere by Dr. J. L. McKibben.

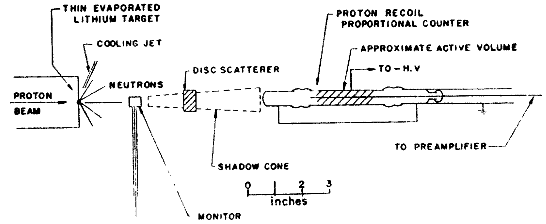


FIG. 1. Arrangement of apparatus.

* Now at the Massachusetts Institute of Technology.

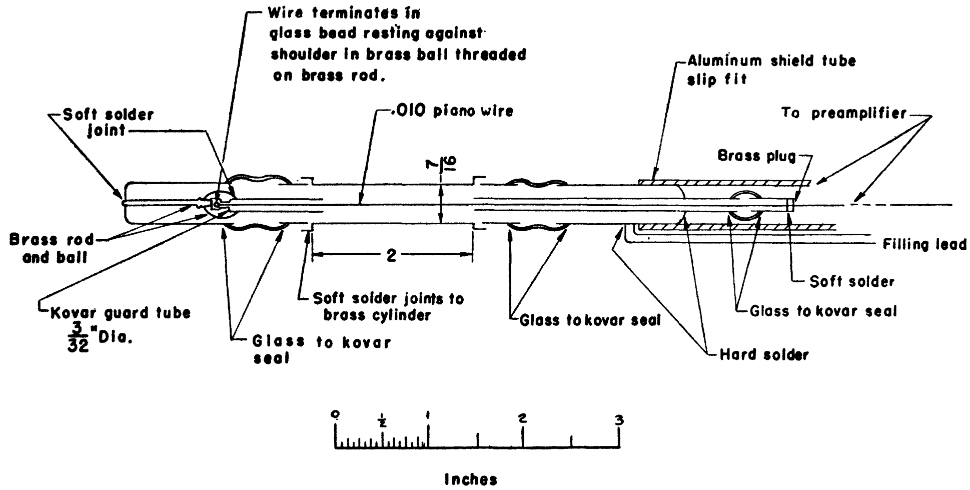


FIG. 2. Construction of neutron detector.

Neutrons for the 35-kev point were made by the "tickling threshold" technique, i.e., setting the proton energy just at the sharp threshold of the neutron-producing reaction. Just at the threshold of this endothermic reaction the neutrons emerge with no velocity in the center of gravity system, and are all carried forward in the room system in a narrow cone with an energy of 29 kev. At a bombarding energy 1 kev above threshold the neutrons get a velocity in the center of gravity system corresponding to only $\frac{7}{8}$ kev, but because of the compounding of velocities those which go forward get an energy of 40 kev in the room system. Those which go backward in the c.g. system are still carried forward in the room and have an energy of 20 kev. Thus in the present case, with a target thick compared to 1 kev, "tickling" at even 1-kev bombarding energy above threshold caused neutrons of all energies from 20 to 40 kev to be present. The mean value of the neutron energy was taken to be $35\pm5$ kev because of the observed change in sensitivity with energy of the neutron detector over this region.

Both scattering disks were $\frac{3}{4}''$ in diameter, and were supported by a single 0.008″ wire passing through a small hole along a chord near the edge. The graphite disk was $0.376\pm0.001''$ thick, and the polythene was $0.1465\pm0.001''$ thick. All parts of the detector and preamplifier lay within the shadow of the scatterers. A polythene shadow cone was inserted to measure room scattering and counter background. The densities of the scatters were computed from their dimensions and agreed with the expected values. The commercial polythene used has been analyzed as pure $CH_2$ to within less than 0.1 percent.

The construction of the neutron detector is shown in detail in Fig. 2. This proton-recoil proportional counter is filled to various pressures of hydrogen (from 50 to 200 cm of mercury) so as to keep the gamma-ray background low compared to the proton recoils in the counter for the various neutron energies used. Details of proportional counter work in this energy region will be published elsewhere.

The intensity of neutrons from the target was monitored by a very small ($\frac{3}{8}''$ diameter and $\frac{5}{16}''$ high) ionization chamber containing uranium (235). This chamber was placed half-way between the target and the scatterer, and thus none of the few neutrons scattered from it could reach the detector without passing through the scatterer. Fissions in the monitor and proton recoils in the detector were amplified by standard amplifiers

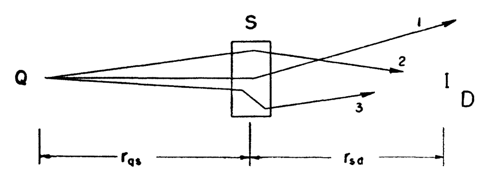


FIG. 3.

designed by M. Sands, and were counted on standard scaling circuits.

### INTERPRETATION OF DATA

Backgrounds taken with the polythene cone were never greater than 3 percent, and, in data taken with higher counter-biases, were about 1 percent. This was primarily from neutrons scattered in the room and by parts of the target not shadowed by the cone.

The geometry of this experiment was such that the maximum angle of scattering into the detector was approximately 10°. The cross sections observed with such geometry must be converted into the total cross sections that would be observed with a point source, point scatterer, and point detector. The only correction applied was for single scattering into the chamber because of the finite sizes of the scatterer and detector. (Figure 3, not to scale.) Since this correction was only about 3 percent for hydrogen and 1 percent for carbon, and since multiple scattering corrections are small compared to this, no higher order corrections were made.

A short discussion of the correction may be of interest. Let the distance from source $Q$ to scatterer $S$ be $r_{qs}$ and from scatterer to detector $D$ be $r_{sd}$. Let $\omega_{sq}$ be the fraction of $4\pi$ solid angle subtended by the scatterer at the source, $\omega_{ds}$ that subtended by the detector at the scatterer, and $\omega_{dq}$ that subtended by the detector at the source. The observed fractional transmission of the scatterer is $T$, its area is $A_s$, and the area of the detector is $A_d$. Neutrons scattered at small angles (path 2 in Fig. 3) have a chance of being counted in the detector because of the finite scatterer and detector sizes. The observed $(1-T)$ must be increased by a factor $(1-\omega_{sq}\omega_{ds}/\omega_{dq})$ to give what would be observed if the neutrons were only scattered out of a point detector by a point scatterer (path 1 in Fig. 3). For isotropic scattering in the room system the fractional correction to the observed $(1-T)$ for small $\omega$'s is an increase of

$$\frac{A_s(r_{qs}+r_{sd})^2}{4\pi r_{qs}^2 r_{sd}^2}.$$

If $r_{qs}=r_{sd}$, the correction is $A_s/\pi r^2$. For the light elements used, $\omega_{ds}$ must be taken in the c.g. system; at small angles the fractional correction is $1.17A_s/\pi r^2$ for carbon and $4A_s/\pi r^2$ for hydrogen.

Transmissions were in the range $0.55\leq T\leq 0.85$. The basis for the assumption of isotropy of scattering by carbon and hydrogen in the c.g. system is discussed in the companion paper by Bailey, Bennett, Bergstralh, Nuckolls, Richards, and Williams. The uncorrected and corrected data are given in Table I. The corrected hydrogen data are plotted in Fig. 4 along with a theoretical curve by Bohm and Richman,[1] and the corrected carbon data are plotted in Fig. 5 along with data from the companion paper by B.B.B.N.R.W., joined by a smooth curve. Extrapolating from the thermal values on a $1/v$ basis, the capture cross sections of carbon and hydrogen are seen to be negligible at these energies. Thus the observed

TABLE I. Uncorrected and corrected values of $\sigma_H$ and $\sigma_C$.

| $E_n$ in kev | $\sigma_H$ Uncorrected | $\sigma_H$ Corrected | $\sigma_C$ Uncorrected | $\sigma_C$ Corrected |
|---|---|---|---|---|
| 35 | 16.15±0.25 | 16.74±0.41 | 4.60±0.14 | 4.63±0.19 |
| 95 | 13.04±0.26 | 13.46±0.39 | 4.62±0.09 | 4.65±0.14 |
| 265 | 8:87±0.15 | 9.12±0.24 | 3.82±0.05 | 3.85±0.09 |
| 490 | 6.19±0.15 | 6.33±0.21 | 3.24±0.07 | 3.26±0.10 |

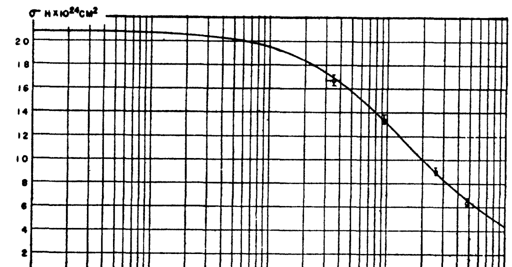


FIG. 4. Neutron-proton cross section. The solid curve is from a theoretical calculation by Bohm and Richman.

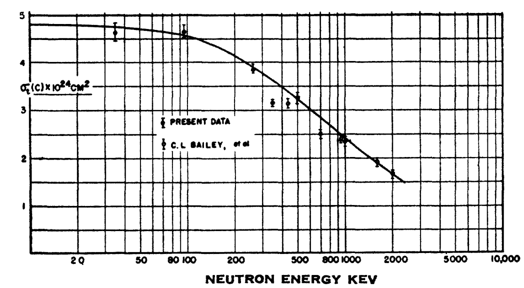


FIG. 5. Corrected data for neutron scattering on carbon.

[1] Bohm and Richman, Phys. Rev., to be published.

total cross sections are effectively the scattering cross sections and are directly applicable to the theory.

The errors given in the "data" column of Table I are the root mean square statistical errors of the total of all data, since there was good consistency between the various runs. The increased error in the "corrected" column includes an estimate of uncertainty in the scattering corrections and in the dimensions and densities of scatterers. The assignment of mean energies (except in the "tickle-threshold" case previously discussed) may be in error by an estimated +5 or −10 kev, the latter error being greater because of possible undetected target thickening.

The author wishes to thank Messrs. C. L. Bailey, D. Greene, R. D. Krohn, R. Perry, and Dr. H. T. Richards for their generous help in taking data and running the electrostatic generator during this experiment.

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# Angular Distribution of 2.5-Mev Neutrons Scattered by Deuterium†

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The angular distribution of the scattering by deuterium of 2.5-Mev neutrons was measured by analyzing the distribution in energy of the recoiling deuterons in an ionization chamber. In the center of mass system the differential cross section exhibits a maximum for backward scattering of the neutron. The value at the maximum is more than twice the value at angles near 90°. Neutron-proton scattering observed under similar conditions showed a departure of not more than 10 percent from isotropic scattering.

## INTRODUCTION

It was pointed out in an earlier paper[1] that the distribution in angle of scattered fast neutrons could be measured by analyzing the distribution in energy of the recoiling nuclei in an ionization chamber filled with the gas the scattering by which one wishes to investigate. If monoenergetic neutrons are used, the distribution in energy of the recoiling particles in the laboratory system gives a direct measure of the angular distribution of the scattered neutrons in the center of mass system, provided that the dimensions of the chamber are large compared to the range of the most energetic recoiling nuclei.

In order to fulfill this condition very high pressures are required for investigations of the scattering properties of hydrogen or deuterium for fast neutrons. In spite of the application of high collecting fields, difficulties were caused in the earlier work by the slow collection of the ions in the gas at high pressure, resulting in a lack of energy resolution. The lack of resolution was caused partly by the fact that the amplification was not entirely frequency independent for the very slow pulses, partly by the relatively small signal to noise ratio for a slow amplifier, and also by the possible superposition of pulses due to recoils and due to gamma-rays. The earlier work[1] did not give any evidence for an anisotropy in the scattering of 2.5-Mev neutrons by hydrogen or deuterium. It was pointed out in the earlier paper that, because of the lack of resolving power both in energy and angle, deviations from isotropy could have been detected only if they were large and varied slowly with angle. The distribution in energy of the recoiling deuterons showed the unexplained feature that its break at high energy occurred at an energy about 10 percent higher than should have been expected from a comparison with Po alpha-particles. This fact, in addition

† This paper is based on work performed under Contract No. W-7405-Eng-36 with the Manhattan Project at the Los Alamos Scientific Laboratory of the University of California.
* Now at the University of Wisconsin.
[1] H. H. Barschall and M. H. Kanner, Phys. Rev. 58, 590 (1940).