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The Neutron-Proton and Neutron-Carbon Scattering Cross Sections for Fast Neutrons

CARL L. BAILEY, WILLIAM E. BENNETT,* THOR BERGSTRALH,** RICHARD G. NUCKOLLS,*** HUGH T. RICHARDS,† AND JOHN H. WILLIAMS
University of Minnesota, Minneapolis, Minnesota

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An experimental investigation of the total scattering cross section of hydrogen and carbon for neutrons of energies 0.35 to 6.0 Mev is reported. Neutrons of discrete energies were produced by particle bombardment of lithium, carbon, and heavy water targets. Transmissions of cyclohexane (C_6H_{12}) and graphite scatterers under conditions of good geometry were measured. Results for σ_s(H) are compared with the theoretical interpretations of Bohm and Richman in a later paper and to the experimental results of D. Frisch at lower energies in a companion paper. It is estimated that σ_s(H) and σ_s(C) are determined to approximately five percent.

INTRODUCTION

An understanding of the interaction between a neutron and proton is fundamental to the basic theory of nuclei. Information on the state of the compound nucleus, the deuteron, exists and serves to determine many of the characteristics of this interaction. On the other hand the scattering of fast neutrons by free protons, where the energy of the system is positive, provides further information necessary to an understanding of the interaction.

A knowledge of the neutron-proton scattering cross sections is also useful as fundamental information in experimental nuclear physics. This may be illustrated by considering the problem of measuring the flux of fast neutrons. If a beam of fast neutrons impinges on a thin foil of hydrogen-containing material, the number of recoil protons observed can be interpreted in terms of the fast neutron flux if the cross section for neutron-proton scattering is known as a function of neutron energy.

The companion paper by D. H. Frisch[1] and a forthcoming report by Bohm and Richman[2] amplify the information given in this report. In the work reported in this paper σ_s(H) and σ_s(C) were measured in the energy range 0.35 to 6.0 Mev. D. H. Frisch[1] has extended the energy range covered down to 0.035 Mev and has made measurements up to 0.50 Mev. In the overlapping region between 0.35 Mev and 0.50 Mev his data are more accurate than those of the present work. Bohm and Richman[2] have used the present data and those of Frisch to interpret the neutron-proton scattering in terms of a potential well of fitted characteristics.

EXPERIMENTAL METHOD

Consider a point source, P, of neutrons of a given energy as illustrated in Fig. 1. Suppose a scatterer, S, in the form of a disk of thickness x and diameter d intercepts a cone of neutrons of angle α. A detector of fast neutrons subtends an angle $\beta \leq \alpha$ at the source P.

If α and β are very small, the observations can be translated into the total cross section by the following expression

$$I/I_0 = e^{-n\sigma x},$$

where I is the intensity of neutrons measured by the detector with the scatterer present, I_0 is the intensity of neutrons measured by the detector when the scatterer is absent, n is the number of

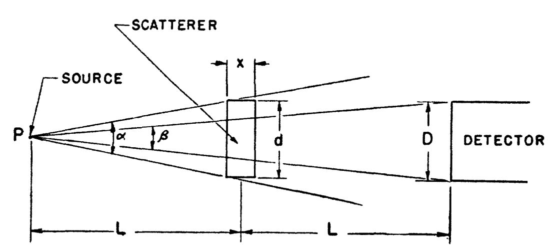

FIG. 1. Geometry of source, scatterer, and detector used in scattering experiment.

* Now at Rice Institute, Houston, Texas.
** U.S.N.R.
*** Now at Naval Research Laboratory, Washington, D. C.
† Now at the University of Wisconsin.
[1] D. H. Frisch, Phys. Rev. **70**, 589 (1946).
[2] Bohm and Richman, Phys. Rev. (forthcoming report).

TABLE I. List of geometrical conditions, transmissions, and cross sections.

E_n	Transmission C_6H_{12}	Transmission C	$2L$ cm	d cm	D cm	x cm	Corrected Transmission C_6H_{12}	Corrected Transmission C	$\sigma_s(C_6H_{12})$ in barns	$\sigma_s(C)$ in barns	$\sigma_s(H)$ Expt in barns	$\sigma_s(H)$[2] Theory in barns
0.35	0.465		36	4.0	2.5	1.5	0.442		104.7 ±2.8	3.15±0.08	7.15±0.24	7.70
		0.450	36	4.0	2.5	3.0		0.444				
0.46	0.490		36	4.0	2.5	1.5	0.469		97.2 ±1.68	3.15±0.10	6.52±0.15	6.70
		0.450	36	4.0	2.5	3.0		0.444				
0.72	0.553		36	4.0	2.5	1.5	0.533		77.76±1.38	2.49±0.06	5.22±0.12	5.21
		0.532	36	4.0	2.5	3.0		0.526				
0.97	0.594		36	4.0	2.5	1.5	0.577		67.80±0.78	2.40±0.03	4.45±0.08	4.43
		0.547	36	4.0	2.5	3.0		0.541				
1.0±0.1	0.444		29	4.0	4.0	2.5	0.408		64.50±1.68	2.38±0.09	4.16±0.15	4.35
		0.410	29	4.0	4.0	4.6		0.399				
1.6	0.516, 0.321		40	4.0	4.0	2.5, 4.0	0.500, 0.299		51.54±0.96	1.90±0.05	3.36±0.08	3.38
		0.484	40	4.0	4.0	4.6		0.479				
2.0	0.402		75	8.0	4.0	4.0	0.364		45.30±0.72	1.63±0.04	2.96±0.07	2.98
		0.535	90	4.0	4.0	4.6		0.534				
2.6	0.433, 0.412		60	4.0	4.0	2.5, 4.0	0.426, 0.403		40.86±0.54	1.60±0.03	2.60±0.05	2.55
		0.540	60	4.0	4.0	4.6		0.538				
2.85		0.607	60	8.0	4.0	4.12		0.600		1.57±0.11		

scattering nuclei per cm^3 in the scatterer, x is the length of the scatterer in cm, and σ is the total cross section in cm^2. In view of the fact that the radiative capture cross section for fast neutrons by H and C is very small, we can assume the scattering cross section is equal to the measured total cross section.

If the conditions are such that α and β are not negligibly small the measured transmission $T = I/I_0$ is greater than that for the ideal "good geometry" condition described above. Neutrons will not be diverted from the detector unless they are deflected by more than an average angle β which is no longer small. Also if α is large, neutrons from the external annular portion of the scatterer which would normally not reach the detector may be scattered into the detector. If it is assumed that the angular distribution of scattering is spherically symmetrical in the center of gravity system of coordinates these two effects can be corrected for. This assumption is justified by experimental observations on light elements[3,4] for neutrons of the energies under discussion. Further justification is evident from the relatively large wave-lengths of the incident neutrons as compared to the nuclear dimensions of the scatterer.

In practice α and β were kept small enough to reduce the corrections outlined in the above paragraph to five percent or less. The geometrical conditions for the scattering measurements are shown in Table I.

It should also be pointed out that the thickness x of the scatterer must be kept small in order that the effects of multiple scattering may be neglected. In practice this means that the transmission T should be as large as convenient since the correction for multiple scattering is proportional to, but much less than, $(1-T)$

[3] Barschall and Kanner, Phys. Rev. **58**, 590 (1940). Coon, Davis, and Barschall, Phys. Rev. **70**, 104 (1946).

[4] Kikuchi, Aoki, and Wakatuki, Proc. Phys. Math. Soc. Jap. **21**, 410 (1939).

TABLE I.—*Continued.*

E_n	Transmission C_6H_{12}	Transmission C	2L cm	d cm	D cm	x cm	Corrected Transmission C_6H_{12}	Corrected Transmission C	$\sigma_s(C_6H_{12})$ in barns	σ_s(C) in barns	σ_s(H) Expt in barns	$\sigma_s(H)^2$ Theory in barns
3.0	0.445		50	4.0	4.0	4.0	0.432		37.56±1.44	1.59±0.08	2.33±0.13	2.34
		0.520, 0.623	40, 60	4.0, 8.0	4.0	4.6, 4.12		0.515, 0.605				
3.25		0.585	64	8.0	4.0	4.12		0.578		1.69±0.13		
3.5	0.448		45	4.0	4.0	4.0	0.434		37.32±1.50	2.39±0.09	2.09±0.09	2.09
		0.401, 0.464	45, 64	4.0, 8.0	4.0	4.6, 4.12		0.396, 0.456				
3.75		0.461	61	8.0	4.0	4.12		0.452		2.43±0.12		
4.0	0.477		85	4.0	4.0		0.474		33.30±0.90	1.85±0.10	1.85±0.09	1.87
		0.501, 0.550	85, 58	4.0, 8.0	4.0	4.6, 4.12		0.500, 0.542				
4.25		0.502	63	8.0	4.0	4.12		0.494		2.16±0.07		
4.5	0.500		60	8.0	4.0	4.0	0.472		33.60±1.08	1.93±0.06	1.83±0.10	1.69
		0.540	60	8.0	4.0	4.12		0.532				
4.75		0.598	95	8.0	4.0	4.12		0.595		1.60±0.15		
5.0	0.561		85	8.0	4.0	4.0	0.549		26.70±0.60	1.18±0.03	1.63±0.05	1.54
		0.685	85	8.0	4.0	4.12		0.682				
5.5	0.588		85	8.0	4.0	4.0	0.577		24.18±0.67	1.07±0.04	1.48±0.06	1.42
		0.673	85	4.0	4.0	4.6		0.672				
6.0	0.608, 0.603		63, 100	4.0, 8.0	2.0, 4.0	4.0	0.605, 0.599		22.56±1.32	1.11±0.10	1.32±0.12	1.31
		0.698	100	8.0	4.0	4.12		0.696				

times the geometrical correction described above. In none of the work reported in this paper has a correction for multiple scattering been made. Experience gained from this work would lead to a selection of scatterers with smaller x and consequently greater T in future work, although the multiple scattering correction for the present conditions is probably negligible compared to the statistical accuracy of these results.

MEASUREMENTS

The measurements described in this report were made during the winter 1942–43 at the University of Minnesota under an O.S.R.D. contract. The Minnesota pressure-insulated Van de Graaff generator[5] provided monoenergetic ions of energies up to 3 Mev as a primary source of fast neutrons.

In order to cover the neutron energy interval from 0.35 to 6.0 Mev we used the following reactions:

$$Li^7+H^1\rightarrow Be^7+n^1, \quad (1)$$

$$C^{12}+D^2\rightarrow N^{13}+n^1, \quad (2)$$

$$D^2+D^2\rightarrow He^3+n^1. \quad (3)$$

To provide neutrons in the energy interval 0.35 to 0.97 Mev an evaporated thin (about 40 Kev) lithium target was bombarded with protons of discrete energies from 2.10 to 2.68 Mev.

Deuteron bombardment of a thick carbon target provided neutrons of energy 1.0±0.1 Mev which served to check the 0.97 Mev results obtained with neutrons from the Li reaction.

[5] Williams, Rumbaugh, and Tate, Rev. Sci. Inst. **13**, 202 (1942).

Although neutrons of all energies from 0 to 1.15 Mev were emitted in the forward direction when this thick target was bombarded with deuterons of 1.45 Mev, the spectrum was detected by a biased detector whose cut-off was at 0.70 Mev. A study of the response of this detector led us to believe that the average neutron energy to be associated with our measured scattering cross sections was 1.0 ± 0.1 Mev. This point is the only uncertain value on our energy scale. Deuteron bombardment of thin carbon (soot) targets provided neutrons of energies 1.6 and 2.0 Mev.

Reaction (3) is sufficiently exoergic to provide neutrons in the interval from 2.0 to 6.3 Mev with the bombarding energies available to us. Although one would prefer to use thin D^2 targets, time did not allow us to develop this technique. Sufficient work was done to show that it is extremely difficult if not impossible to maintain a thin heavy ice target of a thickness constant to a few percent under deuteron currents of two to five microamperes. Later work at Los Alamos has shown it to be quite feasible to employ gas targets of about 100-Kev stopping power separated from the accelerating tube by thin nickel foils. These gas targets provide sufficient neutron intensity and neutron energy definition for many nuclear problems. We were forced by lack of development time to employ a thick heavy ice target so that it was necessary to use a differential method to select a restricted band of neutron energies. The difference in the number of neutrons, per unit charge of bombarding deuterons, at two neighboring deuteron energies was considered to be the number of neutrons of an energy equal to that produced by the deuterons of energy equal to the mean of the two bombarding energies. The following example illustrated the above statement and the general method of taking the scattering data.

$0=45°$ (angle between d and n in lab system)

$E_1(D)$	$=1.83$ Mev	$E_2(D)$	$=2.23$ Mev
N_{01B}	=number of neutrons detected per unit charge of bombarding deuterons with an empty brass container interposed midway between source and detector	N_{02B}	similar to N_{01B} but taken with neutrons produced by deuterons accelerated to an energy $E_2(D)$
N_{1B}	=number of neutrons detected per unit charge of deuterons with a long paraffin candle between source and detector	N_{2B}	similar to N_{1B} but taken with neutrons produced by deuterons accelerated to an energy $E_2(D)$
N_{H1B}	=number of neutrons detected per unit charge of deuterons with an identical brass container filled with C_6H_{12} interposed	N_{H2B}	similar to N_{H1B} but taken with neutrons produced by deuterons accelerated to an energy $E_2(D)$

The data are calculated as follows:

$N_{01B}-N_{1B}=N_{01}$ = number of neutrons coming directly from the source for $E_1(D)$

$N_{H1B}-N_{1B}=N_{H1}$ = number of neutrons from source at $E_1(D)$ which are transmitted by the scatterer

$N_{02B}-N_{2B}=N_{02}$ = number of neutrons coming directly from the source for $E_2(D)$

$N_{H2B}-N_{2B}=N_{H2}$ = number of neutrons from source at $E_2(D)$ which are transmitted by the scatterer

$N_{02}-N_{01}=N_{02-01}$ = number of neutrons of average energy E_n coming from source

$N_{H2}-N_{H1}=N_{H2-H1}$ = number of neutrons of average energy E_n coming from the source which are transmitted by the cyclohexane scatterer

$$\frac{N_{H2-H1}}{N_{02-01}}=\exp\left[-n\sigma(C_6H_{12})x\right]$$

And E_n is taken as that corresponding to $E=\frac{2.23+1.83}{2}=2.03$ Mev. As $\theta=45°$, $E_n=4.5$ Mev for $E(D)=2.03$ Mev.

Similar data were taken simultaneously on C.

It should be emphasized that the method outlined above is more tedious and less accurate than observations with relatively monoenergetic neutrons from a thin target. Even with a thick target it is difficult to maintain the absolute yield and detection efficiency sufficiently constant for the times of observation necessary to obtain statistically significant differences in the numbers obtained at different bombarding energies. This is particularly true if the heavy ice is not continually replenished. This difficulty was overcome by allowing D_2O vapor to flow continuously on to a liquid-air-cooled target at the overly generous rate of about $\frac{1}{4}$ cc of heavy water per hour. A recovery of about 75 percent of the D_2O was possible if the deuteron current was less than five microamperes. In most of this work the neutron intensity was monitored by simultaneously counting unscattered neutrons of the same energy with an identical detector placed at a symmetrical angle and at the same distance from the source.

The neutrons from these sources were detected by counting the individual recoil protons in ionization chambers of various designs. For the energy region up to 1 Mev the recoils were obtained from methane at 60 lb./in.^{2} in a chamber 2.5 cm in diameter and 1.0 cm deep. The ionization pulses from the individual recoils were recorded by a linear amplifier and scalar designed by R. G. Nuckolls. By a suitable choice of bias of the detecting equipment it was found possible to exclude the detection of neutrons of energy 100 kev less than the energy under investigation.

The $C(d, n)$ and $D(d, n)$ neutrons were detected by counting recoil protons from a paraffin radiator inside the front face of an argon filled ionization chamber. These chambers were of 2.0 or 4.0 cm diameter, 10 cm long, and filled with argon to pressures up to 100 lb./in.^{2}. The ionization pulse was collected on a central rod of approximately $\frac{1}{8}$-inch diameter. The pressure was usually adjusted to provide sufficient stopping power for the most energetic recoils. Biases were selected to favor the neutron energy studied.

In most cases the fluctuation of individual observations of cross sections from the mean (usually of ten or more observations at a given energy) was not caused by the statistical fluctuations in the number of neutrons recorded but arose from other instrumental effects such as source fluctuations.

The scatterers used in these experiments were C_6H_{12} and C. The cyclohexane was carefully tested for purity and found to be more than 98 percent C_6H_{12}, the remainder being other compounds of carbon and hydrogen. The carbon was especially selected and tested for purity. The liquid cyclohexane was contained in accurately machined copper cylinders. Duplicate empty copper cylinders were necessary to determine the scattering of these containers. Cyclohexane scatterers of diameters 2.0 and 4.0 cm and lengths 1.5, 2.5, and 4.0 cm in corresponding containers were used for appropriate neutron energies. The carbon scatterers were in the form of machined graphite cylinders of radii 4.0 and 8.0 cm and lengths 3.0, 4.12, and 4.6 cm. The multiplicity of sizes of scatterers was required to obtain an appropriate transmission and to make rough tests on the validity of the assumption of spherical symmetry of scattering used in correcting the observations for imperfect geometry.

These scatterers were supported midway between the neutron source (diameter $\sim\frac{1}{4}$ inch) and the detector by fine wire supports. In order to measure the number of neutrons recorded by the detector which did not come directly from the source to the detector in the cone defined by β in Fig. 1, a long cylinder of paraffin of diameter equal to the scatterer was interposed between source and detector. Principally as a result of the directional sensitivity of the paraffin faced recoil detectors the measured "room background" was less than two percent of the primary neutrons recorded. This directional sensitivity was not great enough to influence the relative detection efficiency for neutrons whose incident direction varied by angles of the order of β.

RESULTS

Table I presents a collection of the measured and corrected transmissions of C_6H_{12} and C scatterers of different sizes for different neutron energies. It may be noted that the maximum correction to the measured transmission is less than five percent and for most cases less than one percent. The total cross sections of C_6H_{12} and C are given with probable errors calculated from the deviations of the individual observations of cross section from the mean of several observations.

The value of $\sigma_s(H)$ is obtained from the above cross sections by taking

$$\sigma_s(H)_{\mathrm{expt}} = \frac{1}{12}\{\sigma_s(C_6H_{12}) - 6\sigma_s(C)\}.$$

The experimental value is compared to the smooth curve values of Bohm and Richman in the last column of Table I. Plots of $\sigma_s(H)$ and $\sigma_s(C)$ as a function of neutron energy are shown in Figs. 2 and 3.

DISCUSSION

An interpretation of the results for $\sigma_s(H)$ will be given in a later paper by Bohm and Richman. These authors have given us permission to make

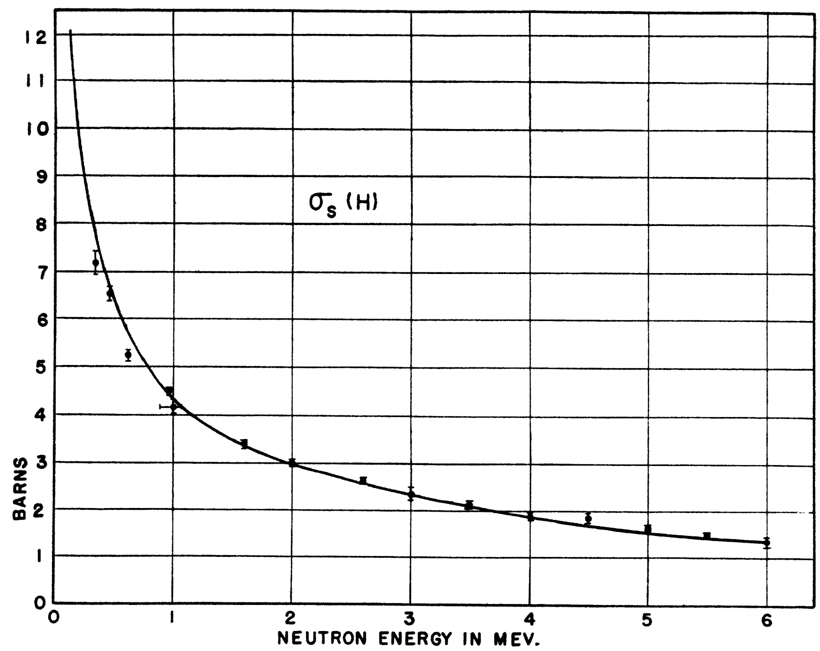

FIG. 2. Scattering cross section of H in barns (10^{-24} cm^2) as a function of neutron energy.

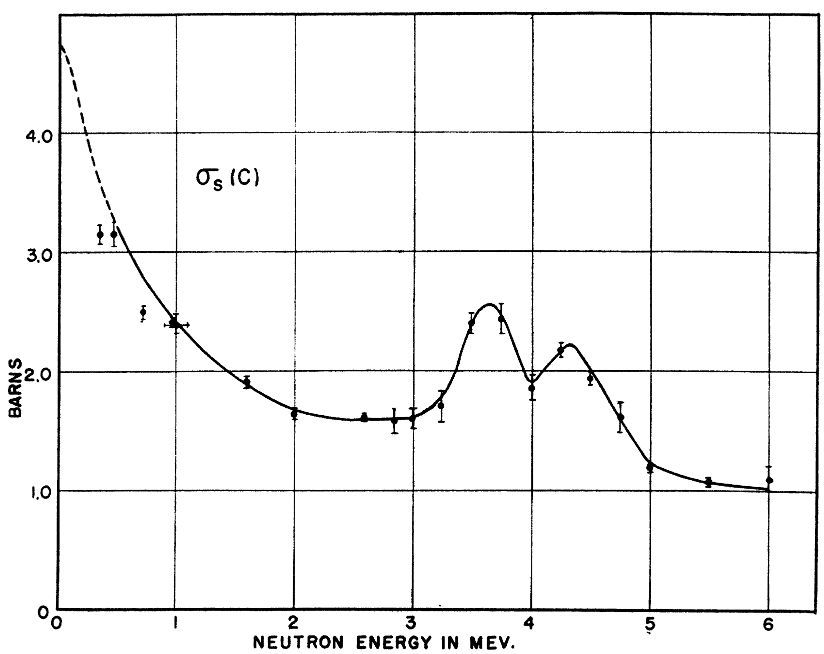

FIG. 3. Scattering cross section of C in barns (10^{-24} cm^2) as a function of neutron energy. The full line is drawn through the experimental results of this paper except below 1 Mev where the more precise work of D. H. Frisch is given preponderant weight.

the following statements about their results. The values of σ_s(H) as a function of neutron energy can be readily understood by assuming a potential function to represent the interaction of neutrons and protons moving with relative velocities covered by the neutron energy range investigated in this report. This potential function is made up of a narrow deep square well and a wide shallow square tail of dimensions necessary to fit the value of the quadrupole moment of the deuteron and the proper values of ^1S scattering. The experimental results fall below the theoretical predictions of Kittel and Breit[6]

[6] Kittel and Breit, Phys. Rev. 56, 744 (1939).

by amounts which increase with neutron energy to a maximum difference of ten percent at 6 Mev. Further studies[7] of σ_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.

[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.

It is probably fair to conclude that the values of σ_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 σ_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.

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

DAVID H. FRISCH*
Los Alamos Laboratory, Los Alamos, New Mexico

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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.

* Now at the Massachusetts Institute of Technology.

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

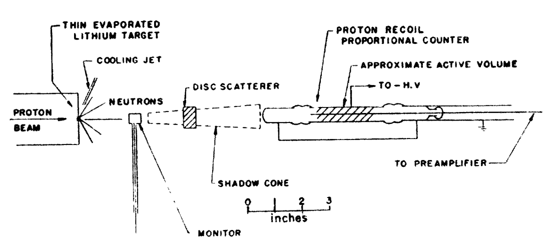

FIG. 1. Arrangement of apparatus.