0

**Total Cross Sections of Carbon and Hydrogen
for High Energy Neutrons***

by

George R. Mott

Gordon L. Guernsey

Bruce K. Nelson

Department of Physics

University of Rochester, Rochester, New York

January 15, 1952

AT(30-1)-875

Submitted to the Physical Review

Individual copies will be supplied upon request as long as the supply lasts.

***This research has been assisted by the joint program of the Atomic Energy Commission and the Office of Naval Research.**

This document is
PUBLICLY RELEASABLE

H. K. Krieger

Authorizing Official

Date: *10/20/09*

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

-1-

Total Cross Sections of Carbon and Hydrogen
for High Energy Neutrons

21817

Abstract

AD-33-1
AD-33-17

Measurements of the total cross sections of carbon and hydrogen have been made at neutron energies of 97 ± 5 , 117 ± 5 , 140 ± 5 , 156 ± 5 , 180 ± 7 , and 220 ± 10 Mev, using a calibrated anthracene crystal as an energy sensitive detector for recoil protons. This proportional crystal was used as the fourth of a quadruple coincidence anthracene scintillation counter telescope which detected recoil protons scattered at 20° from a polyethylene radiator in the collimated neutron beam from the University of Rochester 130" synchrocyclotron. The methods employed permit the simultaneous measurement of total cross sections over a continuous spectrum of neutron energies. The results are in general agreement with previously reported data. (auth)

1. Introduction

The total n-p cross section was measured at 220 Mev to enable normalization of the differential cross section data to an absolute scale. In view of the relative lack of experimental values for the total n-p scattering cross sections in the energy range from 100 to 200 Mev, it was decided to repeat the measurements at lower energies. The unique method of detection of recoil protons used in this experiment has made feasible the measurement of total cross sections over a spectrum of neutron energies simultaneously. The data for neutron energies from 140 to 220 Mev have been obtained from runs using the neutron beam produced by protons of 240 Mev, and the values corresponding to 97 and 117 Mev have been obtained from neutron beams

from targets bombarded by lower energy protons at small cyclotron radii.

All measurements have been made by observing the attenuation of a collimated beam of neutrons in carbon and paraffin, using the source and detector in good geometry.

Previous investigators, in performing similar experiments have used various detectors, including gas-filled counters,^(1,2) carbon activation⁽³⁾, bismuth fission chambers^(4,5,6), and anthracene scintillation counters⁽⁷⁾. In some instances the effective neutron energy has been set for the experiment by means of absorbers, while others have used the energy dependence of the $C^{12}(n-2n)C^{11}$ and bismuth fission reactions. By establishing a pulse height vs proton energy calibration for a 1 cm. anthracene crystal, it has proven feasible to ascertain neutron energies to better than 10% using a counter telescope containing no thick absorbers, thus obviating the necessity for making uncertain corrections. The proton calibration curve obtained for the crystal has as its major uncertainty the present information concerning the range of protons in copper and anthracene.

I. Experimental Method

A. Principle

Basically, the same principle underlies the present experiment as has been used by others in performing the same type of measurement. Namely, one measures the exponential decrease in intensity of a well collimated beam of monoenergetic neutrons, as the thickness of material traversed by the neutrons is increased. Since

only heterogeneous neutron beams are available from high energy proton bombardment, methods must be incorporated into the experiment to insure counting only recoil protons of a given energy interval, and hence set the range of effective neutron energies. One method of accomplishing this has been to use absorbers in conjunction with the recoil proton detector, usually a hydrogenous radiator and counter telescope.

It has been shown that a moderately thick anthracene crystal can be used in a proportional fashion by utilizing the variation with energy of specific ionization by protons⁽⁸⁾. One is thus provided with a method of proton energy determination by measurement of the amplitude of the scintillation pulses, once a suitable calibration has been made. A discussion of the calibration procedure used is given in the preceeding paper, and the resulting curve giving pulse height vs proton energy is shown in Figure 1.

The agreement between the observed widths of the calibrating proton pulse height distributions and the theoretical values for the energy loss widths expected for protons in anthracene as calculated by the method given by K. K. Symon⁽⁹⁾ is indicated in Table 1. $\frac{\Delta E}{E}$ is the % width at half-maximum for a set of observed pulse height distributions, and $\frac{E-E_p}{E_p}$ is the % width at half-maximum, given to the nearest integer for the energy loss distribution function calculated for the corresponding proton energies and the anthracene thickness used. Only the small-thickness calculation has been made, i. e. the special case wherein the energy loss is of the order of, or smaller than one-tenth of the kinetic energy of the incident proton. For this reason, many of the observed widths are not directly comparable to the corresponding theoretical

values. To make these comparisons, the general case of the calculation must be employed. A few of the pulse height spectra obtained during the calibration runs are shown in Figure 2. Smooth curves have been drawn through the experimental points, these curves being very nearly gaussian.

The pulse height analyzer was a 24 channel device⁽¹⁰⁾ which presented a spectrum of pulse heights corresponding to the energy spectrum of the recoil protons, in view of the aforementioned calibration. Calculations for the range-energy relation in anthracene were made using $1 = 11.52 \text{ ev}^{(8,11)}$. This information was used to estimate the energy losses for protons traversing the crystals of the telescope. Figure 3 indicates the relation between the energy of a proton scattered in the radiator and the corresponding energy when incident on the last crystal, as inferred from the range-energy data. This curve was obtained by assuming that the total absorption was due not only to the crystals of the telescope, but also to half the radiator thickness, on the average. It has further been assumed that the stopping power of polyethylene is so nearly equal to that of anthracene, that allowances for this difference would constitute a negligible correction to the energy determination.

The neutron energy E_N appropriate to the observed scattered proton energy E_p and laboratory recoil angle ϕ was calculated using the relativistic formula. This data is shown in Figure 4. To use this information for this particular experiment, E_N vs E_p for $\phi = 20^\circ$ was plotted.

Since numbers proportional to neutron intensity over an entire spectrum of neutron energies are furnished by the pulse height analyzer, one needs only to use in the calculations for the cross

sections the ordinates to the recoil proton pulse height spectra, corresponding to various attenuator thicknesses, at the appropriate pulse height. Backgrounds are determined in the same manner.

To be rigorously correct, one must use proton spectra which correspond only to recoils from hydrogen. This is customarily done by counting proton first from a polyethylene radiator and then from a graphite radiator containing the same number of carbon atoms.

← Subtracting the carbon spectrum from the polyethylene spectrum yields the hydrogen effect provided the runs are properly timed by the monitoring procedure. A preliminary attenuation run was made using copper with thicknesses ranging from zero to about 1.3 mean free paths for 220 Mev neutrons. For each attenuator, runs were made using both the polyethylene and graphite radiators. Pulse height spectra for both polyethylene and poly-carbon differences were plotted for each attenuator, and it was found that the ratio of the polyethylene counts to the hydrogen counts at a given pulse height was constant within the errors over the range of attenuator thicknesses used. The constancy of these ratios was observed to hold over an interval of pulse heights corresponding to neutrons from the peak energy of 220 Mev down to 140 Mev, near the end of the data for the spectra. Evidently the cross sections for elastic and inelastic processes occurring in the carbon content of the polyethylene radiator do not vary sufficiently rapidly with energy to alter the ratios significantly as the neutron spectrum at the radiator was modified by the attenuator. In view of these observations, all subsequent measurements were made using only the polyethylene radiator. This afforded the attainment of reasonable accuracy at a considerable saving in cyclotron operating time.

In treating the data, it has been found convenient to draw a smooth curve through the experimental points for each spectrum and take values for the calculations from it. The uncertainty introduced by this procedure was reduced by repeating each spectrum several times and using the average values in the computations.

Measurements were made for graphite and paraffin attenuators separately, and the value for the hydrogen cross section deduced in the usual way:

$$\sigma_H = \frac{\sigma_P - \sigma_C}{f}$$

where σ_C = total cross section for carbon

σ_H = " " " " hydrogen

$\sigma_P = \sigma_C + f \sigma_H$, and $f = 2.06$ for the paraffin samples used.

B. Arrangement

The experimental arrangement is shown in Figure 5. A $\frac{1}{2}$ " beryllium target at 58 $\frac{1}{2}$ " radius intercepts the 240 Mev proton beam. The resulting neutron spectrum has been shown by B. A. Nelson, (previous paper), to be peaked near 220 Mev with half intensity points at approximately 170 and 220 Mev. This beam emerged thru a thin window in the tank wall and was collimated by a 1"x1" aperture in the three foot copper block which shielded the counter telescope from direct radiation from the cyclotron. The attenuators of either graphite or paraffin blocks were interposed in the neutron beam between the target and the collimator. The line of sight from the polyethylene radiator thru the collimator aperture to the target was carefully established using a transit, and the equipment was so designed that it could be dismantled and reassembled along the same line without

the necessity for making further measurements. The attenuator samples were maintained in alignment with the reference direction by a support consisting of thin dural rails.

C. Counter Telescope

D. Electronics

Since the telescope and electronics, including the monitor, were common to the three present experiments, the reader is referred to the preceeding paper for a complete discussion.

E. The Neutron Attenuators

The attenuators consisted of carefully machined blocks of graphite and paraffin 2" x 2", of assorted lengths to provide a diversity of transmission values for the neutron energies used. Maximum attenuator thicknesses employed were approximately two mean free paths. The analyst's report showed negligible impurities in both the graphite and paraffin samples, and that the average composition of the paraffin was:

III. Experimental Procedure

The method of collecting data for a complete attenuation curve consisted of interspersing a run with the reference attenuator between groups of repeated runs with various attenuators. The procedure was repeated until data for several values of attenuator thickness were taken. The average of all runs made with the reference attenuator was used for the undegraded intensity since this procedure tends to minimize the effect of systematic errors arising from slight changes in

monitoring over periods of six to eight hours which were required to complete an entire attenuation curve.

The background was determined for each run by replacing the attenuator with lead absorbers slightly longer than four mean free paths for the highest neutron energies used. The background rates observed under these conditions amounted to several times the expected value, or approximately 5% of the counting rates with no attenuation in the worst case. The possibility of slight leaks in the collimator or scattering around the collimator from extraneous neutron sources in the cyclotron may be possible contributing factors to this discrepancy. Subtraction of this background, however, gave attenuation curves which were linear within the experimental errors.

Preliminary runs at 220 Mev with the most intense beams available from the cyclotron resulted in attenuation curves displaying excellent linearity among all points except the no attenuator value, which was too high to be compatible with the rest. Possibly the high singles counting rates in the first crystals were contributing to random gate openings and hence the excessive counting rate observed. However, attenuation of the beam with several centimeters of material provided sufficient reduction of intensity to reduce the effect to negligible proportions. This value of attenuator was used as the "reference attenuator" for subsequent runs at 220 Mev. For runs made with lower energy neutrons from targets at smaller radii, the beams available were less intense, and this effect was not observed; all points including the no attenuator values of these attenuation curves being consistent with a linear relation.

IV. Determination of the Neutron Energy

Prior to making the total cross section runs, an electrical calibration of the entire proportional channel was made as described in the preceeding paper. This calibration enabled transforming the counts per channel data furnished by the pulse height analyzer to a counts per unit pulse height spectrum for the proton recoils. In addition, the 200 Mev calibrating proton beam was intercepted by the telescope at 0° and a run was made to locate the peak of the 193 Mev proton pulse height distribution on the pulse height scale previously established. By using this pulse height as a reference, all pulse heights in the recoil spectrum could be expressed as ratios to the reference.

The steps involved in determining the neutron energy associated with any given pulse height in the recoil spectrum are as follows:

1. Determination of proton energy incident on the last crystal. Figure 1 gives proton energy at the last crystal vs pulse height ratio.
2. Determination of proton energy when scattered. Using the value of proton energy at the last crystal from step 1, Figure 3 gives the corresponding energy when scattered in the radiator.
3. Determination of primary neutron energy. Using the energy of the scattered proton from step 2 together with the telescope angle used, Figure 4 gives the corresponding neutron energy.

The errors assigned to the neutron energies have been obtained from the standard deviation in the average pulse heights for both the recoil and the 193 Mev proton peaks, and allowances have been made

for possible inaccuracies in the range-energy relation.

V. Scattering Corrections

Effects arising from elastic and inelastic scattering into the detector have been estimated for the geometry and found to be sufficiently small compared to the stated probable errors that these corrections have not been applied to the experimental values⁽¹²⁾.

VI. Results

Sample pulse height spectra for protons from the polyethylene radiator exposed to the full energy neutron beam are shown in Figure 6, and typical attenuation curves for carbon and paraffin are shown in Figure 7. All experimental results are summarized in Table II, and these points are indicated in Figure 8 together with previously reported values in the energy interval 60 to 280 Mev. It may be remarked that the agreement in energy and cross section values is good in most cases.

The experimental values in the region from 100 to 200 Mev are approximately half the N-P total cross sections predicted by Ashkin and Wu⁽¹³⁾ using tensor force and the symmetrical Karita-Schwinger exchange model in the rigorous scattering theory. The results of this calculation for neutron energies of 100 and 200 Mev are also shown in Figure 8. The values from the Born Approximation calculation are still farther from the measured values.

The cross sections calculated by Christian and Hart⁽¹⁴⁾ using tensor force and a Yukawa potential ($R = 1.35 \times 10^{-13}$ cm.) for $E_N = 90$ and 260 Mev constitute a better fit to experimental data, however. These values are also indicated in Figure 8.

A purely empirical formula has been obtained for the variation of the N-P total cross section with energy. This formula has been found to fit not only the data of the present report, but also all existing total cross section data from neutron energies of 1 Mev to 280 Mev. In nearly every case the empirical fit falls within the stated errors of the experimental value, the average departure from all available data being about 6%.

This formula may prove useful for interpolating between experimental data to estimate the total cross section at some particular energy. It is:

$$\sigma = \frac{2.55 + 0.028E + 10 (e^{-0.0165E} - e^{-0.2E})}{E}$$

where E is the neutron energy in the Laboratory system in Mev and

σ is the total cross section in barns.

Acknowledgments

The author wishes to thank Dr. Arthur Roberts for his guidance of this work, Mr. Hugo Logemann for his helpful discussions and development of the 24 channel pulse height analyzer, and Mr. Fred Palmer and the cyclotron operating crew for their cooperation during the runs. This research has been supported by the Joint Program of the Atomic Energy Commission and Office of Naval Research.

Table I

Widths of Experimental Pulse Height Distributions
for
Protons Incident on 1.09 cm. Anthracene
and
Comparison with "Small-Thickness" Calculation Using Method
of K. K. Symon

Target 4 $E_p = 192$ Mev at proportional crystal

E_p (Mev)	$\frac{\Delta P}{P}$ (%)	$\frac{E - E_D}{E_p}$ (%)	
192	15.7	15	
170	16	13	
152	13.5	12	
125	12.7	11	
112	11.5	10	
94.5	11.7	--	"small- thickness" calculation invalid
81.5	12.1	--	
74.5	11.2	--	
60.5	16	--	
46.5	27	--	

Target 2 $E_p = 77$ Mev at proportional crystal

E_p (Mev)	$\frac{\Delta P}{P}$ (%)
77	9.6
62.5	10
51	16

Table II 13

Summary of Experimental Results

Primary Determinations			Hydrogen Differences	
Attenuator	Neutron Energy (Mev)	total (barns)	Neutron Energy (Mev)	total (barns)
carbon	220 ± 7	$0.297 \pm .004$	220 ± 10	$0.0413 \pm .0035$
paraffin	216 ± 6	$0.383 \pm .006$		
carbon	216 ± 6	$0.296 \pm .005$		
paraffin	216 ± 6	$0.382 \pm .006$	220 ± 10	$0.0413 \pm .0037$
carbon	180 ± 7	$0.311 \pm .009$		
paraffin	180 ± 7	$0.403 \pm .022$	180 ± 7	$0.044 \pm .012$
carbon	156 ± 5	$0.325 \pm .010$		
paraffin	156 ± 5	$0.430 \pm .014$	156 ± 5	$0.0505 \pm .0083$
carbon	140 ± 5	$0.349 \pm .004$		
paraffin	140 ± 5	$0.450 \pm .011$	140 ± 5	$0.0485 \pm .0056$
carbon	121 ± 4	$0.392 \pm .006$		
paraffin	113 ± 3	$0.520 \pm .017$	117 ± 5	$0.0615 \pm .0086$
carbon	96 ± 3	$0.502 \pm .012$		
paraffin	100 ± 3	$0.656 \pm .017$	97 ± 5	$0.074 \pm .010$

References

1. J. Hadley, E. Kelly, C. Leith, E. Segre, C. Wiegand and H. York, Phys. Rev. 75, 351 (1949)
2. R. E. Taylor, T. G. Pickavance, J. M. Cassels and T. C. Randle, Phil. Mag. 42, 20 (1951)
3. L. J. Cook, E. M. McMillan, J. H. Peterson and D. Sewell, Phys. Rev. 75, 7 (1949)
4. J. DeJuren and N. Knable, Phys. Rev. 77, 606 (1950)
5. J. DeJuren and B. J. Moyer, Phys. Rev. 81, 919 (1951)
6. J. DeJuren, Phys. Rev. 80, 27 (1950)
7. H. Fox, C. Leith and L. Wouters, Phys. Rev. 80, 22 (1950)
8. G. L. Guernsey, G. A. Mott, and B. K. Nelson, Rev. Sci. Inst. (to be published)
9. K. A. Symon, Doctor's Dissertation, Harvard University (1949)
It is indeed unfortunate that this work, which we have found to be so pertinent, and which others would no doubt find equally important, does not have the widespread circulation commonly afforded to research of similar importance to experimentalists. The publishing of this thesis would seem to be a worthwhile undertaking.
10. H. Logemann, Rev. Sci. Inst. (to be published)
11. H. A. Bethe, Rev. Mod. Phys. 9, 262 (1937) equations 749, 749a and 750.
12. E. M. McMillan and D. Sewell, U. S. AEC report MDDC-1558 (unpublished)
13. J. Ashkin and Ta-You Wu, Phys. Rev. 73, 972 (1948)
14. K. S. Christian and E. W. Hart, Phys. Rev. 77, 441 (1950)

Figure 1

Pulse Height Distributions for Calibrating Protons

Figure 2

Theoretical Relation Between Energy of
Scattered Proton and Corresponding Energy
at Proportional Crystal

Figure 3

18

Recoil Proton Energy
vs
Laboratory Recoil Angle

Figure 4

19

Experimental Arrangement

Figure 5

Typical Polyethylene Spectra

Figure 6

21

Attenuation of 120 Mev Neutrons in Carbon and Paraffin

X - cm of carbon or paraffin

Figure 7

22

Figure 8