The Total Scattering Cross Section of Neutrons by Hydrogen and Carbon*

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The total cross sections of hydrogen and carbon for neutrons has been determined by measuring the transmission of polythene and graphite scatterers for neutrons with energies 0.798, 1.078, 1.340, 1.578, 4.92, and 4.97 Mev. The correction for the finite geometry of the experiment was made by measuring the cross section as a function of the scatterer area and extrapolating to zero area. The cross sections are considered to be reliable to approximately ±2 percent.

I. INTRODUCTION

THE scattering of neutrons by protons is of prime importance in the study of the interaction between these fundamental particles. The total cross section has been measured by a number of investigators, but the data have not been accurate enough for an evaluation of the constants for the potential functions which describe the nuclear scattering.

The work of Bailey *et al.*[1] as analyzed by Bohm and Richman[2] showed that the interaction between the neutron and proton could not be represented by a square well potential of radius e^2/mc^2 and depth determined by the binding energy of the deuteron for the triplet interaction and the thermal cross section for the singlet interaction.

In terms of Schwinger's shape independent approximation analysis[3,4] the values of the singlet scattering length, triplet scattering length, and triplet effective range have been fairly accurately determined. A determination of the total scattering cross section in the 0.5- to 5-Mev energy range would then give the singlet effective range. An accuracy of ±1 percent in the measurement of the total cross section is necessary in order to obtain an evaluation of the singlet range to $\pm 0.5\times 10^{-13}$ cm without allowance for the error in the triplet effective range. A comparable accuracy is also necessary in the measurement of the neutron energy.

II. EXPERIMENTAL METHOD

The total cross section, σ_t, of a scatterer can be defined in terms of the transmission for neutrons by the expression

$$T=\exp(-nx\sigma_t) \tag{1}$$

where T is the transmission and nx is the number of atoms per sq. cm of the scattering sample. The transmission is given by

$$T=(N_1-N_B)/(N_0-N_B), \tag{2}$$

where N_1 is the number of neutrons transmitted by the scatterer. N_0 is the number of neutrons counted with no scatterer and N_B is the background count determined with a 3 inch by 8 inch paraffin cylinder between the source and detector. Because the radiative capture cross section is small, we assume that the measured cross section is the elastic scattering cross section.

The geometry of the source, scatterer, and detector is shown in Fig. 1. The measured transmission will be greater than the true value since the detector subtends a finite solid angle at the scatterer. Consider the source to be of strength Q per unit solid angle. The number of neutrons with no scatterer is given by

$$Q\omega_{qd}\epsilon_1, \tag{3}$$

where ω_{qd} is the solid angle subtended by the detector at the source, and ϵ_1 is the efficiency of the detector. With a scatterer in position the number of neutrons detected will be

$$T_0Q\omega_{qd}\epsilon_1+\frac{(1-T_0)Q\omega_{qs}\omega_{sd}\epsilon_2}{4\pi}, \tag{4}$$

where T_0 is the true transmission of the scatterer, ϵ_2 is the efficiency of the detector to neutrons which have been scattered through a small angle but still reach the detector, ω_{sd} is the solid angle subtended by the detector at the scatterer measured in the center-of-mass system of coordinates, and ω_{qs} is the solid angle subtended by the scatterer at the source. The measured transmission, T, is then given by

$$T=T_0\left[1+\frac{1-T_0}{T_0}\left(\frac{\omega_{qs}\omega_{sd}\epsilon_2}{4\pi\omega_{qd}\epsilon_1}\right)\right]. \tag{5}$$

The correction term could be evaluated with some assumption of the angular distribution of the scattered neutrons and a determination of the dependence on energy of the sensitivity of the neutron detector. A

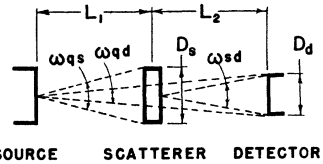

FIG. 1. Geometry of source, scatterer, and detector.

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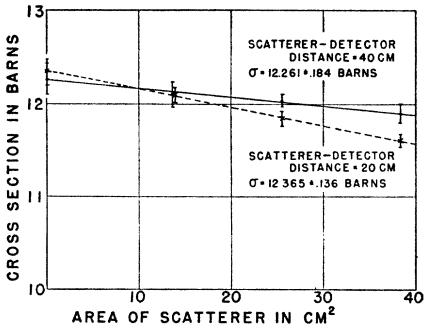

FIG. 2. Cross section of polythene at 0.807 Mev as a function of scatterer area. Dashed curve is for 20 cm and full curve for 40 cm scatterer-detector distance.

simple expression of the measured cross section, σ_t, can be obtained by substituting Eq. (5) into (1). If the correction is considered to be small compared to unity in the expansion of the logarithm, the cross section is given by

$$\sigma_t=\sigma_{t0}-\frac{1}{nx}\left[\left(\frac{1-T_0}{T_0}\right)\frac{\omega_{sd}\epsilon_2 A_s}{4\pi\omega_{qd}\epsilon_1 L_1^2}\right], \tag{6}$$

where A_s is the area of the scatterer, and L_1 is the distance from the scatterer to the source. This equation shows that the measured cross section is a linear function of the area of the scatterer. In order to determine the true cross section for a given E_n, we have measured the cross section for three areas of scatterer and extrapolated a straight line to zero area by least squares.

The scatterers were disks of polythene, C_6H_{12}, and carbon graphite. The polythene was obtained from E. I. duPont deNemours and Company. They reported that the hydrogen-carbon ratio was 2.00 as closely as could be measured and that there were only traces of impurities present. The carbon graphite was obtained from the National Carbon Company.

The number of atoms per cm³ was determined from the density, the atomic weights as given in the Segrè chart of nuclear properties, and the value of Avogadro's number, taken to be 6.0251×10^{23}. The consistency for a large number of scatterers showed that number of atoms per cm³ could be measured to 0.1 percent.

III. MEASUREMENT OF NEUTRON ENERGY

The source of 0.798- to 1.578-Mev neutrons was the reaction

$$Li^7+H^1\rightarrow Be^7+n+Q. \tag{7}$$

The neutron source for 5-Mev determination was the reaction

$$D^2+D^2\rightarrow He^3+n+Q. \tag{8}$$

The University of Minnesota Van de Graaff generator provided monoenergetic protons and deuterons up to 3.6 Mev. The voltage of the generator was measured and controlled by means of an electrostatic analyzer described by Hanson.[5] The threshold of reaction (7) was used as a reference for the calibration of the generator energy scale. We have taken it to be the value, 1.882 Mev, given by Herb *et al.*[6] The linearity of our analyzer was checked by measuring the value of the $Li^7(p,n)Be^7$ threshold for molecular ions. Within the accuracy of our experiments this was twice the value determined for atomic ions.

The lithium was evaporated on a thin tantalum cap of a rotating target. The lithium target thickness was measured by the method described by Taschek and Hemmindinger.[7]

The source for neutrons from the *D-D* reaction was similar to the gas target described by Hanson, Taschek, and Williams[8] with a 0.0001-inch thick nickel foil separating the deuterium gas from the vacuum.

IV. DETECTION OF NEUTRONS

The neutrons were detected by counting recoil protons from a paraffin radiator inside the front face of an argon filled ionization chamber. The chamber was 5 cm in diameter and 9 cm long. It was filled with a 97 percent argon and a 3 percent methane mixture at 1-atmos. pressure. The ionization pulse was collected on a concentric cylinder 2.5 cm in diameter. The amplifiers were similar to the Los Alamos type 100. The pulses were counted with scaling circuits described by Higginbotham, Gallagher, and Sands.[9]

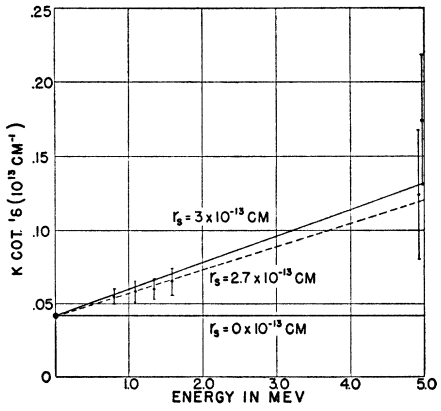

FIG. 3. The function $K\cot^1\delta=-(1/a_s)+\frac{1}{2}r_sK^2$ plotted against incident neutron energy in the laboratory system of coordinates. The singlet scattering contribution to the measured total scattering cross section is calculated on the assumption that the triplet scattering length is 5.39×10^{-13} cm and the triplet effective range is 1.73×10^{-13} cm. The value of a_s, the singlet scattering length, is taken as -23.68×10^{-13} cm. The slopes of the straight lines correspond to values of the effective singlet range of 3×10^{-13}, 2.7×10^{-13} and 0×10^{-13} cm.

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TABLE I. Total cross sections of hydrogen and carbon.

Run	Neutron energy	Carbon cross section	Hydrogen cross section	Average carbon cross section	Average hydrogen cross section
1	0.798±0.008 Mev	2.85±0.04 barns	4.81±0.16 barns		
2	0.807±0.008	2.78±0.13	4.74±0.11		
3	0.807±0.008	2.82±0.07	4.77±0.08		
	0.798±0.008			2.82±0.07 barns	4.79±0.11 barns
4	1.078±0.010	2.56±0.05	4.10±0.06		
5	1.078±0.010		4.06±0.06		
6	1.078±0.010		4.06±0.11		
7	1.078±0.010	2.55±0.06	4.13±0.08		
	1.078±0.010			2.55±0.05	4.09±0.08
8	1.340±0.011	2.24±0.04	3.66±0.06		
9	1.340±0.011	2.27±0.05	3.65±0.06		
	1.340±0.011			2.26±0.04	3.66±0.06
10	1.578±0.013	1.99±0.04	3.38±0.08		
11	1.578±0.013	2.03±0.04	3.35±0.08		
12	1.578±0.013	1.94±0.04	3.23±0.06		
	1.578±0.013			1.99±0.04	3.32±0.07
13	4.92 ±0.14	1.36±0.04	1.64±0.04	1.36±0.04	1.64±0.04
14	4.97 ±0.14	1.34±0.03	1.56±0.04	1.34±0.03	1.56±0.04

V. PROCEDURE

The scatterers were supported on fine wires halfway between the source and the detector. The detector was placed 40 cm from the target at zero degrees to the direction of the proton beam. The neutrons were monitored with a paraffin-covered, boron trifluoride-filled, proportional counter placed about 200 cm from the source.

At the beginning of each day's run all the scatterers were aligned with respect to the detector. The analyzer zero setting was adjusted, and then the analyzer voltage was set to give the desired proton or deuteron energy. The following sequence of runs was taken for a determination of the hydrogen cross section: a background run, a run with no scatterer, a run with each of three polythene scatterers of different diameter, another run with no scatterer, and a run with each of two carbon scatterers of different diameter. From these data a polythene and a carbon cross section was calculated for each size of scatterer. The mean values were extrapolated to zero area of scatterer to obtain the true polythene and carbon cross section. The value $\sigma_{t0}(H)$ was obtained from the above results by taking

$$\sigma_{t0}(H)=\tfrac{1}{2}[\sigma_{t0}(\text{polythene})-\sigma_{t0}(c)]. \quad (9)$$

Since the lithium target collected a carbon deposit during bombardment, the carbon thickness was measured by determining the shift in the threshold voltage for reaction (7) immediately after the target was made and then after completion of the data for one energy. One-half of the average energy loss in the Li target was subtracted from the nominal energy of the incident proton beam.

The geometry correction was checked by increasing the distance from the source to the scatter from 20 cm to 40 cm. The cross section of polythene as a function of scatterer areas at a neutron energy of 0.807 Mev is shown in Fig. 2.

The data taken with the deuterium gas target required a correction for the neutrons emitted by the slit surfaces and other parts of the target assembly that were bombarded by the deuteron beam. In order to evaluate this effect the deuterium target was filled with hydrogen gas to one atmosphere pressure, and runs were taken with the paraffin cylinder, with the 2.25-inch diameter polythene scatterer, with the 2.75-inch carbon scatterer, and with no scatterer. These counts were normalized and subtracted from the counts obtained with deuterium gas in the target. This background was approximately 9 percent of the counts with deuterium as a target.

When several determinations of σ_{t0} were made with the same proton energy, the neutron energies would not, in general, be exactly equal because of different lithium target thickness or different electrostatic analyzer calibration. For purposes of comparison, the values of total cross section were interpolated to one value of neutron energy by assuming that the cross section varied as $E^{-\frac{1}{2}}$. In most cases this correction was $\frac{1}{2}$ percent or less.

Since this work was done, several investigators[10–12] have found a second group of neutrons in reaction (7) arising from an excited state of the Be^7 nucleus 430 kev above the ground state. The intensity of the second group is approximately 10 percent of the main group in our energy range. Our proton recoil ionization chamber detector had a threshold of approximately 0.5 Mev so that the low energy group was biased out at neutron energies of less than 1 Mev. At energies greater than 1 Mev our data have been corrected for the presence of this low energy group. The correction was approximately 1 percent for these higher energies. There is some uncertainty in these corrections because we lacked exact

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knowledge of the energy dependence of the sensitivity of our detector.

VI. RESULTS

Values of σ_{t0}, the total cross section for a neutron energy E_n, are given in Table I. The statistical uncertainty in σ_{t0} was calculated from the extrapolation formula and the reproducibility of the cross section for each scatterer during the run. The probable errors assigned to the cross section include the uncertainty in the background count and the uncertainty in the correction for the low energy group of neutrons.

The data have been analyzed by Schwinger's shape independent method described by Blatt and Jackson[3] and by Bethe.[4] To calculate the triplet scattering cross section, we have used Hughes'[13] value of -3.75×10^{-13} cm as the coherent scattering amplitude, 20.36 barns[14] as the zero energy neutron proton scattering cross section, and 2.23 Mev as the binding energy[15] of the deuteron. In terms of this shape independent approximation the effective range and scattering length are 1.73×10^{-13} cm and 5.39×10^{-13} cm, respectively for the triplet interaction. The value of the singlet scattering length is -23.68×10^{-13} cm. The singlet scattering cross section was obtained by subtracting the triplet contribution from the total cross section. The values of the phase shift function, $K\cot^1\delta$ for the singlet interaction were calculated from the singlet scattering cross section and are shown as a function of neutron energy in Fig. 3. The singlet effective range for the neutron proton interaction appears to be approximately equal to the proton-proton effective range[4] of 2.7×10^{-13} cm. One can then infer, to within the accuracy of the above experiments, the charge independence of nuclear forces in the energy range up to 5 Mev.

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Pressure Measurement in Superflow

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The pressure of flowing liquid HeII has been measured in the capillary link as well as on its ends. Flow under gravitational and thermal potential has been studied in narrow slits and tubes packed with fine powder. On the basis of ordinary pressure measurement the results are not consistent and it is concluded that the definition of "pressure" in superflow requires additional parameters.

I. INTRODUCTION

THE experiments on liquid HeII have disclosed the existence of a peculiar type of flow which has not been observed in any other fluid. The main characteristic of this "superflow" seems to be the disappearance of viscous dissipation of energy. Linked with this is often the phenomenon of pressure independent flow which is completely free of friction. However, the first condition is evidently the more general one since, as the present work shows, there exist cases in which superflow is accompanied by a loss in kinetic energy. The situation is unfortunately complicated by the fact that liquid HeII in bulk seems to exhibit superflow and ordinary viscous flow side by side and that it is usually difficult to separate the two components of the transport mechanism. In first approximation the flow phenomena can be interpreted by means of a semi-empirical "two-fluid model"[1] which treats the liquid as an interpenetrating mixture of a normal and an anomalous component, the relative concentration of which varies with temperature. The question as to whether or not there exists any theoretical justification for such a concept must be left open, but it is already clear that in spite of the general success of the two-fluid model it cannot be applied in this simple form to some of the observed facts. In particular, most of the results on capillary flow near the lambda-point[2,3] cannot be represented as a simple superposition of viscous and frictionless flow.

A simplification of the flow phenomena can be achieved experimentally by decreasing the diameter of the flow channel and thereby suppressing the viscous component. Pure frictionless flow is observed in film transfer[4] and these results are closely approximated by

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