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The Total Cross Section of the He_3 Nucleus for Slow Neutrons*

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Using the slow neutrons available from the thermal column of the enriched uranium pile of this Laboratory, the total cross section of the He_3 nucleus was determined by the transmission method. To the precision of the data, this cross section obeys the $1/v$ law in the range of averaged neutron energies extending from about 0.001 to 0.03 electron volt. The product $(\sigma_{He_3}\times v)$ is found to be $(11.2\pm 0.5)\times 10^6$ barns×meters×sec.$^{-1}$. The possible theoretical implications of these results are briefly discussed in connection with the properties of the compound He_4 nucleus.

I. INTRODUCTION

THE large thermal neutron cross section observed in the reaction $He_3(n,p)H_3$[1] suggested that it might be of interest to study the behavior of the neutron cross section of He_3 nuclei over a wide neutron energy range. These measurements appeared of interest also, in connection with a suggested method[2] of obtaining the distribution of He_3 atoms in the vapor and liquid phases of He_4-He_3 fluid mixtures. This same method might yield good absolute density values of pure He_3 in its vapor and liquid phases since a known small amount of this fluid may be experimented on while fully isolated thermally.

The large thermal neutron cross section of the $He_3(n,p)H_3$ reaction is readily explained in terms of the principle of detail balance[3] applied to the inverse reaction $H_3(p,n)He_3$ studied previously to some extent.[4]

The experiments reported here form the beginning for a more complete exploration of the neutron-proton exchange reaction in the He_3 nucleus. These studies could yield information[3] on some of the possible properties of the compound He_4 nucleus through which this reaction takes place presumably. Total neutron cross-section measurements have been made on He_3, using the low energy neutrons available in the thermal column of the enriched uranium pile of this laboratory. Previous studies at Chicago[5] as well as here[6] have shown that relatively intense neutron beams of low energies can be obtained from a cavity in a thermal column by filtration through graphite. Such neutrons have energies ranging from somewhat greater than thermal energy to about 0.001 electron volt, depending on the cavity and thickness of graphite filter used.

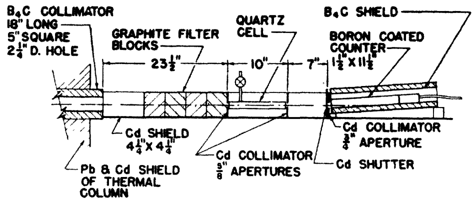

FIG. 1. Experimental arrangement.

On quite general grounds it is to be expected that the variation of the absorption cross section of He_3 nuclei for slow neutrons should obey the $1/v$ law, v being the relative velocity of the neutrons and He_3 nuclei. This should, indeed be so, provided in this low neutron energy region the compound He_4 nucleus does not exhibit some narrow unstable excited energy level. The results described below indicate that such a level does not exist within the precision of our data.

II. EXPERIMENTAL PROCEDURE

The total transmission of a neutron beam through a known amount of He_3 gas has been compared to the transmission of the same beam through a known amount of normal boron trifluoride (BF_3) gas and also to the transmission through an evacuated reference cell. All three quartz absorption chambers were essentially identical. The experiment was performed by obtaining transmission data from a series of rapid exchanges, each of a few minutes duration, of the reference, helium, boron, and reference chambers, respectively. This method should tend to reduce errors caused by faulty alignment of the chambers, drifts in the neutron beam intensity, or neutron detector behavior. The close checks between exchanges indicated that these errors were small.

The detection equipment consisted of a boron coated proportional counter with a battery voltage supply; a scaler with a variable scaling rate of 64

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* This work has been reported on at the New York meeting of the American Physical Society, January 28, 1949.

[1] Coon, Goldblatt, Nobles, and Robinson, Declassified Los Alamos Report, LADC No. 462, December, 1947; Phys. Rev. **75**, 1358 (1949).

[2] L. Goldstein, Declassified Los Alamos Report, LADC No. 546, June 1948.

[3] L. Goldstein, Declassified Los Alamos Report, LADC No. 539, December 1947.

[4] Taschek, Jarvis, Hemmendinger, Everhart, and Gittings, Declassified Los Alamos Report, LADC No. 538, January 1947, and Phys. Rev. **75**, 1361 (1949).

[5] H. L. Anderson, E. Fermi, and L. Marshall, Phys. Rev. **70**, 815 (1946).

[6] L. D. P. King and J. Fox, unpublished.

TABLE I. Experimental results.

Graphite thickness (cm)	Transmission I/I_0*		σ barns						
	He	BF_3	He (total)	B (absorption)**	v(average) meters/sec.	$E=(\frac{1}{2}mv^2)$ volts	$T=E/k$*** degrees K	$(\sigma\times v)$ He 10^6 barns $\times$meters/sec.	Statistical fluctuations in $(\sigma\times v)$ (percent)
0	0.8832	0.8952	4660	625	2471	0.0319	370	11.52	0.25
0	0.8801	0.8917	4792	648	2385	0.0297	345	11.43	0.22
8.89	0.8666	0.8739	5373	764	2021	0.0213	248	10.86	0.26
17.78	0.7461	0.7644	10,990	1554	1004	0.00527	61.2	11.04	0.51
26.67	0.6078	0.6354	18,680	2623	593	0.00183	21.3	11.07	1.8
26.67	0.6158	0.6267	18,190	2702	575	0.00173	20.1	10.46	2.3
35.56	0.5554	0.5948	22,070	3004	517	0.00140	16.2	11.40	3.2

* I and I_0 are the respective counting rates through the helium or boron cells and the blank cell. All corrected for background.

** Obtained from $\sigma(BF_3)$ after correction for elastic cross section of boron and total cross section of F nuclei. This involves the omission of the possible coherent scattering effects caused by F nuclei in the BF_3 molecule.

*** k is Boltzmann's constant.

or 256 depending on the counting rates; together with a model 100 amplifier and preamplifier.[7] An independent neutron counter in the thermal column acted as a neutron intensity monitor.

The experimental arrangement is shown in Fig. 1. The neutron beam originates in a cavity, 4 ft. deep and 12×12 inches in cross section, in the thermal column of the pile. This cavity tapers toward the outer end of the column and terminates in an 18-inch long boron collimator shown in the figure. The average energy in the neutron beam is varied by inserting, in front of the absorption cells 3.5 inch (8.89 cm) long graphite blocks, 4.25″×4.25″ in cross section. The neutrons passing through the quartz absorption cells are collimated by $\frac{5}{8}''$ diameter circular apertures in cadmium shutters placed at both ends of the quartz tube. An additional collimator with a $\frac{3}{4}''$ diameter circular aperture is placed immediately in front of the boron counter. The entire set-up is enclosed in a $\frac{1}{32}''$ thick cadmium box. An additional boron carbide shield is placed around the boron counter. Counter background readings were obtained by placing a cadmium shutter over the $\frac{3}{4}''$ aperture in front of the counter. Background readings varied from 0.5 percent to 10 percent of the counting rate through the absorbers depending on the number of filter blocks used.

The quartz containers had a volume of about 200 cc and an effective length of 25 cm with 0.19-cm flat quartz windows on either end. Two of these chambers contained 50.44 cc NTP of BF_3 gas, with the natural isotopic abundance ratio, and 8.33 cc NTP of He_3, respectively.

The transmission measurement determines the total cross section of the He_3 nucleus and the BF_3 molecule. These are associated with a neutron velocity averaged over the distribution of the velocities in the incident neutron beam, i.e., if all the neutrons had this same average velocity. These average velocities can be determined from the known boron cross section and its $1/v$ behavior in the low energy region. This cross section was determined from the measured absorption of the BF_3 gas by correcting for the known boron scattering and total fluorine cross sections.

III. EXPERIMENTAL RESULTS

The data obtained have been collected in Table I. The first column gives the thickness of the graphite filter blocks in centimeters (1 block = 3.5 inches). The second and third columns give the transmission coefficients of the He_3 and BF_3 gases. The fourth and fifth columns contain the total He_3 and boron absorption cross sections. The latter of these has been obtained by taking the average elastic cross section of boron to be three barns[8] (1 barn $=10^{-24}$ cm^2), and the total fluorine cross section[9] to be 4 barns in the whole energy range investigated in this work. The average velocity, energy and associated temperature of the neutron beam are given in the sixth, seventh, and eighth columns, respectively. The individual determinations of the product $(\sigma_{He_3}\times v)$ are exhibited in the ninth column

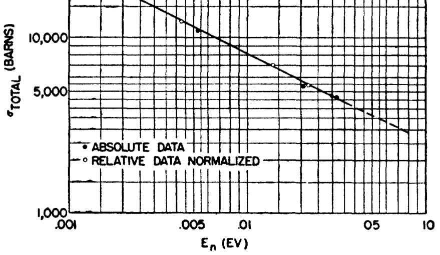

FIG. 2. The total cross section of He_3 as a function of the average neutron energy.

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[7] M. Sands, Declassified Manhattan District Reports, MDDC No. 131 and 303, January and June 1946.

[8] H. Lichtenberger, unpublished.

[9] See H. H. Goldsmith, H. W. Ibser, and B. T. Feld, Rev. Mod. Phys. **19**, 259 (1947).

while the corresponding relative statistical fluctuations are given in the last column.

The statistically weighted average of the product $(\sigma_{\mathrm{He}_3}\times v)$ turns out to be 11.22×10^6 barns×meters/second. A weighting procedure resulting from the squares of the deviations Δ_i, where

$$\Delta_i=(\sigma\times v)_{\mathrm{weighted}}-(\sigma\times v)_i$$

again leads to an average value almost identical to the statistically weighted average.

The constant for the He_3 cross section is given by

$$(\sigma_{\mathrm{He}_3}\times v)=(\sigma_{\mathrm{B}}\times v)\frac{n_{\mathrm{BF}_3}l_{\mathrm{BF}_3}}{n_{\mathrm{He}_3}l_{\mathrm{He}_3}}\frac{\ln I_0/I_{\mathrm{He}_3}}{\ln I_0/I_{\mathrm{BF}_3}}.$$

Here the constant $(\sigma_{\mathrm{B}}\times v)$ has the value 1.545×10^6 barns×meters/second,[10] the n's are the number of the BF_3 molecules and He_3 atoms per cubic centimeter in the absorption cells, the l's are the effective lengths of these two gas columns. I_0's, I_{He_3}, and I_{BF_3} are counting rates, corrected for background, with the evacuated, He_3 and BF_3 filled cells, respectively.

Possible sources of absolute error are those resulting from the measurement of: (1) pressure, temperature, and degree of purity of the filling gases; (2) effective lengths of the gas columns; (3) the differences in the thicknesses of cell windows; (4) the variations in the alignment of the absorbing vessels. These together with the statistical fluctuations lead to a final value

$$\sigma_{\mathrm{He}_3}\times v=(11.2\pm 0.5)\times 10^6\ \text{barns}\times\text{meters/sec.}$$

This excludes any errors inherent in the value of $(\sigma_{\mathrm{B}}\times v)$, the elastic cross section of boron and the total cross section of fluorine used in the evaluation of $(\sigma_{\mathrm{He}_3}\times v)$.[11]

The weighted root mean square deviation of $(\sigma_{\mathrm{He}_3}\times v)$ expressed in percent fraction of the statistically weighted average $(\sigma_{\mathrm{He}_3}\times v)$ is 2.7 percent. This lies well within the limits resulting from the more complete estimate of the different sources of error described above.

The results obtained are shown in Fig. 2. This is a plot of the total He_3 cross section as a function of the average neutron energy. In addition to the above described absolute cross-section measurements, some normalized cross-section values are shown. These were determined previously with the same experimental set-up. Since the composition of He_3 and B_{10} enriched BF_3 samples for these experiments was known with less precision, the results have been used to establish only the validity of the $1/v$ law. The energy range in these experiments extended to energy values as low as 0.001 electron volt (44.46-cm graphite filter).

The usual procedure of reducing the values to a definite temperature associated with a Maxwell distribution, according to a procedure suggested by Bethe,[12] has not been carried out for the following reasons. Although the neutron beam from the cavity of the pile proper is probably Maxwellian,[13] its distribution is distorted by the graphite filter blocks used. This is due to the very nature of the filtration process whereby neutrons with de Broglie wave-lengths larger than twice the lattice spacing of the poly-crystalline material are no longer scattered coherently. Furthermore, in order to obtain as close a comparison as possible between the boron and He absorption cells their gas concentrations were adjusted to give neutron transmissions within a few percent of each other. This was possible from the knowledge of the approximate value of $\sigma_{\mathrm{He}_3}\times v$ at thermal energies.[1]

A Bethe type of correction which is determined by the magnitude of the natural logarithm of the transmission coefficients could be applied for the actual beams used if their distributions were relatively simple and known. Such a correction, however, would not alter the results obtained for $(\sigma_{\mathrm{He}_3}\times v)$, to the precision of the data, as a result of the almost equal value of the natural logarithm of the transmission coefficients of the He_3 and BF_3 samples used.

IV. DISCUSSION AND POSSIBLE IMPLICATIONS OF THE RESULTS

In the interpretation of the results obtained with slow neutrons, whereby the absolute neutron velocities are of the same order of magnitude or smaller than the gas atom velocities, the question arises what actual velocities the observed phenomena correspond to.

It can be shown[14] that for any $1/v$ absorber in which the absorbing light nucleus is bound to a molecule the zero-point velocity of the absorbing nucleus does not alter the apparent relative motion between the nucleus and the neutron. This means that the absorption process is determined by the absolute neutron velocity only. A similar reasoning applies to the He_3 atoms as used in this experiment. This effect may be stated by saying that the cross section for a given neutron beam is independent of the temperature of the He_3 gas.

The precision of these experiments did not allow

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[10] E. Fermi, J. Marshall, and L. Marshall, Phys. Rev. **72**, 193 (1947); see also, Sutton, McDaniel, Anderson, and Lavatelli, Phys. Rev. **71**, 272 (1941); and J. Rainwater and W. W. Havens, Jr., Phys. Rev. **70**, 136 (1946).

[11] An additional error may also result from neglecting the possible coherent scattering of the fluorine nuclei in the BF_3 molecules.

[12] H. A. Bethe, Rev. Mod. Phys. **9**, 135–136 (1937).

[13] Walter H. Zinn, Phys. Rev. **71**, 752 (1947); William J. Sturm, Phys. Rev. **71**, 757 (1947).

[14] See for instance, Willis E. Lamb, Jr., Phys. Rev. **51**, 187 (1937).

for a separation of the He_3 absorption and scattering cross sections for the slow neutrons used here. It is possible to show, on quite general grounds, that the nuclear scattering cross section in the thermal and subthermal energy range should be a constant. In view of this and the precision of the data it is justified to set an upper limit for the elastic cross section of He_3 for slow neutrons to be less than about 200 barns. An estimate of the lower limit can also be obtained as follows: It is to be remembered here that using the quantum mechanical collision cross-section formulas for the (n,p) exchange reaction and the (n,n) elastic scattering process, it is easy to show, that in the $1/v$ region of the former, we may write:

$$\frac{\sigma(n,n)}{\sigma(n,p)}=\frac{|H_{nn}|^2}{|H_{np}|^2}\left(\frac{E_n}{Q}\right)^{\frac{1}{2}},$$

where the $|H|s$ are the matrix element moduli for the processes indicated by the subscripts, E_n is the kinetic energy of relative motion of the $(n-He_3)$ system, while Q is the energy released in the (n,p) exchange reaction (kinetic energy of relative motion of the $p-H_3$ system $=0.75$ Mev). The ratio $|H_{nn}|^2/|H_{np}|^2 \geqslant 1$, so that taking its lower limit, the scattering cross section, $\sigma_{He_3}(n,n)$ turns out to be, for thermal neutrons, $(E_n \sim 0.025$ volt),

$$\sigma_{He_3}(n,n)_{293^\circ K}=5100(0.025/0.75\times10^6)^{\frac{1}{2}}\simeq 1 \text{ barn}.$$

As to the implications of the "$1/v$" law for the He_3 absorption cross section for slow neutrons, which is essentially measured in these experiments one may make a few qualitative statements.[15] One may say that in the slow neutron energy region the compound He_4 nucleus through which, presumably, the reaction takes place, has no unstable level. Furthermore, it is equally unlikely that there be in the α-particle a bound excited level near but below the reaction energy Q, for the process $He_4+Q\rightarrow He_3+n$, which is about 20.5 Mev. It is indeed probable, that if such a bound level existed not too far below 20.5 Mev, that it might have deformed the $1/v$ behavior of the He_3 slow neutron absorption cross section.

A final remark of some interest may be added here concerning the implications on the existence of an unstable energy level in He_4 above 20.5 Mev. Using the formalism of the dispersion theory of nuclear reactions it can be shown that such a level could be expected to exist on the basis of the $1/v$ region of the $He_3(n,p)H_3$ cross section. One finds, in particular, that the ratio (E_r/Γ), of the neutron resonance energy E_r to the total width Γ of the excited He_4 level in question, might be included between, about 0.5 and 2.0. By guessing a value of Γ, which could be done by analyzing similar situations in somewhat heavier nuclei, one is led to the conclusion that the existence of a broad unstable level in He_4, above 20.5-Mev excitation energy, is in the realm of possibilities.[3] This interesting point of the presence or absence of such a level in He_4 around the above mentioned energy could only be settled by experiments with higher energy neutrons or other types of experiments where this level might manifest itself in some way. Such experiments might help in disclosing limitations of the $1/v$ behavior of the $He_3(n,p)H_3$ cross section at higher neutron energies.

We should like to thank finally, Messrs. E. S. Robinson, M. Goldblatt, and R. M. Potter, from the Chemistry Department for their cooperation in preparing the helium and boron samples used in this experiment. Our thanks are also due to Mr. F. L. Bentzen who helped materially in setting up the counting equipment and the taking of the data.

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[15] See, in this connection, reference 3.