Anomalous Scattering of Neutrons by Helium

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(Received November 21, 1938)

The ratio of the cross sections for elastic backward scattering of neutrons in helium and hydrogen has been measured as a function of the neutron energy. This ratio is practically constant between two- and six-Mev neutron energy and has a value of about 1.3. However, at one Mev, the ratio increases to about nine. This anomaly must be caused by resonance scattering occurring from the formation of an unstable compound nucleus He^5. Theoretical considerations show that the level of He^5 involved must be a p level.

INTRODUCTION

THE investigation of the α-particle spectrum of lithium bombarded by deuterons by Williams, Shepherd and Haxby[3] showed that the continuous spectrum caused by the reaction $Li^7+{}_1D^2\rightarrow{}_4Be^8+{}_0n^1\rightarrow 2{}_2He^4+{}_0n^1$ has superimposed on it a homogeneous group of α-particles which was ascribed by these authors to the reaction ${}_3Li^7+{}_1D^2\rightarrow{}_2He^5+{}_2He^4$. From the range of this α-particle group, one concludes that in this case He^5 is left in a state which is unstable against disintegration into an α-particle and a neutron by 0.84 Mev.

We may, therefore, expect that the scattering of neutrons by helium may be strongly anomalous, because of a resonance effect as soon as the energy of the intermediately formed compound nucleus He^5 lies in the neighborhood of this level, which is 0.84 Mev above the level of a separated He^4 and a neutron. The maximum of such an anomalous scattering should occur at a kinetic energy of $(5/4)0.84=1.05$ Mev of the neutron in the laboratory coordinate system.

EXPERIMENTS

The only neutron spectrum having a line at about one Mev arising from the bombardment of light nuclei by deuterons is the one of beryllium, ${}_4Be^9+{}_1D^2\rightarrow{}_0n^1+{}_5B^{10}$. According to the results of Bonner and Brubaker,[4] the neutron spectrum contains (at 0.9 Mev bombarding energy) four lines of about the same intensities at 4.5, 4.0, 2.6 and 1.4 Mev. As these are the maximum energies of the neutrons of each group, the average energy of the neutrons in the group lies appreciably lower. In particular, the line of 1.4 Mev has its maximum intensity around 1.1 Mev. By reducing the bombarding energy to 0.6 Mev, we were able to change the average energy of the neutrons to 1.1 Mev. The high voltage tube used in these experiments has already been described by one of us.[5] The neutrons at right angles to the deuteron beam entered a cloud chamber of 15 cm diameter filled first with ethane and then with helium. By adopting the well-known technique[6] of taking stereoscopic pictures of the cloud chamber, the spectrum of the neutrons was measured once by helium recoils and once by hydrogen recoils. To get the values for the intensities of the lines, one has to correct the number of tracks which are actually observed in the cloud chamber. This correction is due to the fact that the chance of seeing a track with its complete length within the chamber depends on its length and the diameter of the chamber. By dividing the area of the chamber, in which a track of length l, can start and its whole length lie within a chamber of radius r, by the total area of the chamber, we get the correction K,

$$K=(1/\pi)[2 \arcsin (1-l^2/4r^2)^{\frac{1}{2}} -l/r(1-l^2/4r^2)^{\frac{1}{2}}]$$

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[3] J. H. Williams, W. G. Shepherd and R. O. Haxby, Phys. Rev. **52**, 390 (1937). Confirmed by H. Staub and W. E. Stephens, Phys. Rev. **54**, 236 (1938) and Phys. Rev. **54**, 237 (1938).
[4] T. W. Bonner and G. Brubaker, Phys. Rev. **50**, 308 (1936).
[5] W. E. Stephens and C. C. Lauritsen, Rev. Sci. Inst. **9**, 151 (1938).
[6] T. W. Bonner and G. Brubaker, Phys. Rev. **47**, 910 (1935).

and the true intensity $J_0 = J/K$, where J is the actually observed number of tracks.

The ratio of the corrected intensities of two corresponding lines measured with helium and hydrogen recoils, respectively, gives the ratio of the scattering cross sections of helium and hydrogen times an arbitrary constant. As we used in our experiments only the recoils in the forward direction ($\pm 12°$) with respect to the incident neutron beam we obtained only the cross section ratio for the backward scattered neutrons. It can easily be shown that by counting the recoils of helium and hydrogen within the same solid angle in the laboratory system, the corresponding solid angle subtended by the scattered neutrons in the center of gravity system is in both cases the same, as it is independent of the mass of the recoiling particle.

The absolute values of the ratios of the cross sections were determined by measuring this ratio in an ionization chamber for the 2.5-Mev neutrons of the D+D reaction. For this experiment we used a pressure ionization chamber with plane, circular, parallel electrodes connected to a linear amplifier, operating a thyratron and a mechanical counter. If the stopping power of the gas in the ionization chamber is sufficiently high so that the range of a forward recoil atom is much shorter than the depth of the chamber, one gets directly the number of recoils as a function of the energy by counting the number of pulses as a function of their height. This was performed by measuring the number of counts for a given constant number of incident neutrons as a function of the thyratron bias. In this way one gets the integral of the energy distribution curve of the recoils. If the angular distribution of the recoils is isotropic in the center of gravity system the number-energy curve of the recoils is a horizontal straight line dropping to zero at the maximum energy of the recoils. The height of this straight line is a measure of the cross section. For isotropic distribution in the center of gravity system we have in the laboratory system

$$dN_R = 2N_0\sigma nd \sin\theta \cos\theta d\theta$$

and

$$E_R = \frac{4m}{(m+1)^2} E_0 \cos^2\theta,$$

hence

$$dN_R = N_R dE_R = \frac{N_0\sigma nd}{4mE_0/(m+1)^2} dE_R = \text{const } dE_R,$$

where N_R is the number of recoils between E_R and $E_R + dE_R$, N_0 the number of neutrons, n the number of atoms per cc in the ionization chamber, d its depth, E_0 the energy of the neutrons and m the mass of the recoil. By observing the number of recoils N_T as a function of the bias V of the thyratron, we obtain:

$$N_T = \int_V^{V_0} N_R dE_R = -\frac{N_0\sigma nd(V - V_0)}{4mE_0/(m+1)^2},$$

which represents a straight line having its intercept with the abscissa at V_0, the bias corresponding to the maximum energy of the recoils. For protons, the measurements of Dee and Gilbert[7] and Bonner[8] have clearly shown the angular distribution of the recoils to be isotropic. For He, the curve given by Baldinger, Huber and Staub[9] shows that at least for $0 < \theta < \pi/4$, the distribution of the recoils is uniform. Also, our results show that the number of recoils plotted against the thyratron bias can be represented by a straight line. Furthermore, even in the case of nonisotropic distribution, still the slope at $V = V_0$ would give the cross section for the backward scattered neutrons.

A very serious distortion of the distribution curve would arise, if the track length of the recoils were much larger than the depth of the chamber. This can be avoided by using a sufficiently high gas pressure. However, this requires a very high collecting voltage in order to collect the ions in a time which is small compared to the time constant of the amplifier. However, we would expect for He and H nonlinear but similar curves whose slope we could compare if the track length of the recoils in both cases were the same. We therefore adjusted the pressures of the helium and the ethane so that the tracks were shorter than the depth of the chamber and had approximately the same track length. However,

[7] P. I. Dee and C. W. Gilbert, Proc. Roy. Soc. **A163**, 265 (1937).
[8] T. W. Bonner, Phys. Rev. **52**, 685 (1937).
[9] E. Baldinger, P. Huber and H. Staub, Helv. Phys. Acta **11**, 245 (1938).

in the case of ethane this procedure would have required too high a collecting voltage. This is because the mobility in ethane is very low at high pressure because of the fact that room temperature is already below the critical temperature of ethane. We therefore used a mixture of ethane and argon. In this way we were able to obtain satisfactorily high stopping power at a reasonable collecting voltage. The recoils of argon have not enough energy to give pulses of appreciable length. In the final experiments we used the following values:

Bombarding voltage	0.6 Mev
Direction of neutrons	90° to ion beam
Depth of chamber	1.0 cm
(1) Helium: Max. energy of recoil	1.67 Mev
Range in air	0.88 cm
Pressure	6.8 atmos.
Stopping power	1.19
Max. track length	0.74 cm
Collecting voltage	2100 volts
(2) Ethane-argon mixture:	
Max. energy of recoil	2.6 Mev
Range in air	11.0 cm
Pressure of ethane	2.3
Pressure of argon	11.2 atmos.
Stopping power	14.42
Max. track length	0.76 cm
Collecting voltage	5700 volts

The three-stage amplifier was of the Wynn-Williams type, with a W. E. 259-B as a first stage tube. The pulses on the thyratron were visually checked by a cathode-ray oscillograph. The characteristic response of the amplifier was found to be linear up to an output potential of 80 volts. The relation between input charge and output voltage was determined by changing the potential of the collecting voltage plate by a given amount ΔV. As the ionization chamber was of the guard ring type, the capacity c between voltage plate and the collector could easily be computed. From this, the induced charge $\Delta q = c\Delta V$ was determined.

The deuterium target consisted of heavy water frozen on a solid copper block which closed a Dewar vessel of thin-walled German silver tubing containing liquid air. Before every run, the target was renewed by opening a stopcock and allowing fresh heavy water vapor to condense. In order to get, during every run, the same number of primary neutrons falling on the ionization chamber, a Lauritsen electroscope was used as a monitor. The target tube had a window of one cm air equivalent aluminum through which the protons of the reaction ${}_1D^2+{}_1D^2 \rightarrow {}_1H^1+{}_1H^3$ were allowed to enter the electroscope. As this reaction has exactly the same excitation function as the one producing neutrons, the total number of neutrons hitting the ionization chamber was always the same for the same deflection of the electroscope. A checking measurement showed that, by inserting absorption foils between the target and the electroscope, the deflection for an equal number of counts of the amplifier at constant bias was independent of the number of foils until an air equivalent of about 14 cm was reached. At this value of the absorption, which is the range of the protons, the deflection dropped suddenly to about 10 percent of its original value, indicating that the deflection of the electroscope is mainly caused by protons and not by x-rays or electrons.

A similar measurement to the one taken with the ionization chamber for the D+D neutrons was performed with the neutrons of the reaction ${}_6C^{12}+{}_1D^2 \rightarrow {}_0n^1+{}_7N^{13}$. The neutrons were observed at an angle of 30° with respect to the ion beam. The neutrons of this reaction are monochromatic[4] with a Q value of -0.28 Mev. So at 30° and 0.83 Mev bombarding energy, the neutrons have an energy of 0.50 Mev. As the ranges of the recoils of He and H are respectively 0.28 and 0.70 cm of air, one can use very low pressure. Actually, the chamber was first filled with 5.5 atmos. of He, and then with 2.8 atmos. of ethane. The collecting voltage in both cases was 1000 v. Unfortunately, the accuracy of these measurements is very poor, because of the fact that the yield of neutrons of this reaction is very small. Furthermore, an appreciable background of neutrons from the reaction D+D was present, which, at the low stopping power in the ionization chamber, does not show a straight line distribution. However, the curves for He and H are similar, and can be compared after adjustment to the same end point.

Results

Figure 1 shows the spectrum of the Be+D neutrons with bombarding energy of 0.6 Mev obtained with hydrogen and helium recoils,

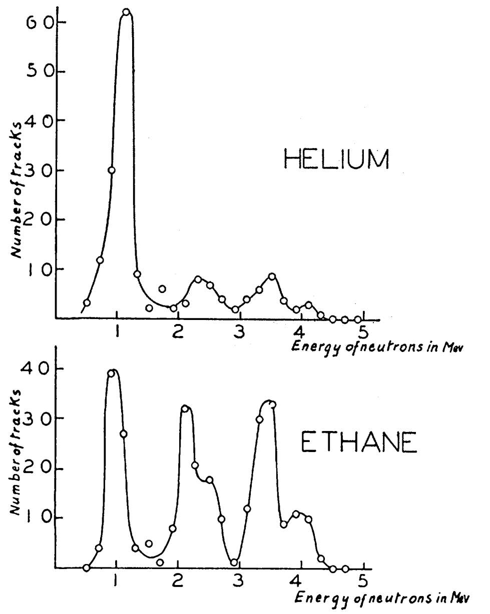

FIG. 1. The spectrum of the neutrons of Be+D at 0.6 Mev bombarding energy measured with helium and hydrogen recoils. The peak on the right side of the line at 2.5 Mev is caused by the neutrons from D+D.

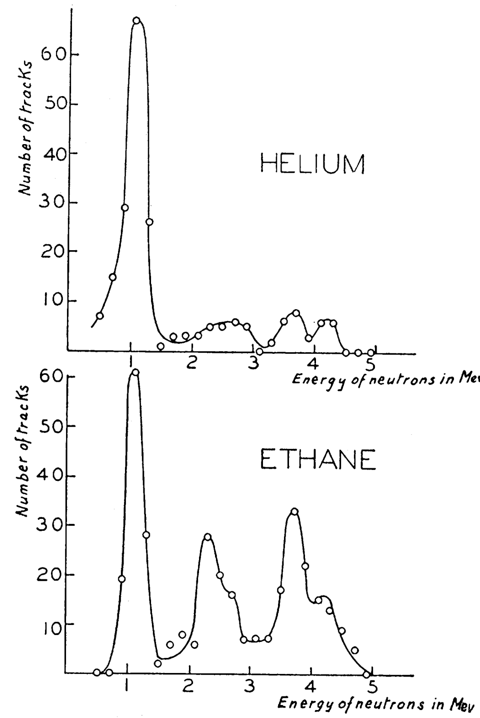

FIG. 2. The spectrum of the neutrons of Be+D at 0.88 Mev bombarding energy measured with helium and hydrogen recoils.

respectively. In the figures, no correction of the intensities for the track length has been applied. In the case of the hydrogen recoils, the chamber was filled with 1.78 atmos. of ethane and water vapor. 1500 pictures gave 278 measurable tracks within $\pm 12°$ to the direction of the incident neutron. From the D−D contamination neutrons, we determined the stopping power of the gas to be 2.96. With this number, the Q values of the four lines are 4.13, 3.54, 2.02 and 0.79 Mev in fairly good agreement with Bonner's[4] values of 4.2, 3.7, 2.2 and 0.9 Mev. It may be pointed out that we did not take any particular precautions to get accurate values of the stopping power. In the case of the helium filled chamber, the pressure was one atmos. helium and water vapor. 7250 pictures yielded 180 tracks. Since, in this case, the D+D contamination did not show up separated from the 2.2-Mev line (because of the small number of tracks in this line) the stopping power was afterward determined by taking a set of pictures with the D+D neutrons. This gives roughly a value of 0.226 for the stopping power using the range energy relation of Blewett and Blewett.[10] The Q values calculated from this number are 4.18, 3.53, 2.29 and 0.80 Mev, in good agreement with the ethane results, except the value 2.29. This seems to be caused by the nonresolved D+D contamination. From the range energy curve of Holloway and Livingston,[11] the stopping power is 0.258 and the Q values are 4.47, 3.69, 2.33 and 0.78 Mev.

A second run was then taken at a bombarding voltage of 0.88 Mev, thus slightly increasing the energy of every neutron group. Fig. 2 shows the results of these measurements. Again for hydrogen recoils the chamber contained 1.93 atmos. ethane with water vapor. Because of the higher bombarding energy, the lines are somewhat wider and the D+D contamination neutrons are not well separated. Therefore, the stopping power was again determined by a run with the D+D neutrons. This gave a stopping power of 3.04. The Q values are: 4.28, 3.74, 2.29 and 0.72 Mev—all being slightly higher than in the previous set.

For the measurements with helium recoils, the chamber was again filled with about one atmos.

[10] A graph of this curve was sent to us by Dr. Bethe.

[11] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 18 (1938).

He and water vapor. The calibration by the D+D neutrons gave a stopping power of 0.230, from the range energy curve of Blewett and Blewett[10] and 0.258, from Holloway and Livingston's[11] data. With the curve of Blewett and Blewett, the Q values are 4.09, 3.54, 2.47 and 0.69 Mev, while with the curve of Livingston they are 4.38, 3.70, 2.54 and 0.66 Mev.

The measured intensities J_H and J_{He} of the different lines are given in columns 2 and 4 of Table I. Columns 6 and 7 give the intensities after being corrected for the track length. The corrections (by which the measured value was divided) are listed in columns 3 and 5. The stopping power we used was chosen so that the corrections for corresponding lines in the two different gases are as equal as possible. In the last column the values of J_{He}/J_H times an arbitrary constant, A, are listed. The value of A is, of course, different for the two sets at 0.6 and 0.88 Mev. Accidentally they are almost equal. The errors given are estimated as the sum of the relative mean statistical errors of two corresponding lines.

The results of the H and He measurements with the counter are shown in Fig. 3 where the number of recoils is plotted against their energy for equal numbers of neutrons of 2.6 Mev entering the ionization chamber. As the curves are practically straight lines, the distribution of the scattered neutrons is in both cases isotropic. Thus the ratio of the total scattering cross section is equal to the ratio of the backward scattering cross sections measured in the cloud-chamber experiments. The transformation of the biasing voltage of the thyratron into energy of the recoil was done in the following way. We extrapolated the straight part of the curve to the intercept with the abscissa at V_0. After having subtracted $V_0'=11$ volts, the voltage at which ignition of the thyratron takes place, V_0-V_0' corresponds to the maximum energy of the recoil (i.e., 2.6 Mev for the hydrogen and (16/25)2.6 $=1.66$ Mev for the helium recoils). Since the characteristic curve of the amplifier is linear, one obtains in this manner the energy corresponding to one volt on the grid of the thyratron for every one of the two measurements. This result may be checked in the following way: By

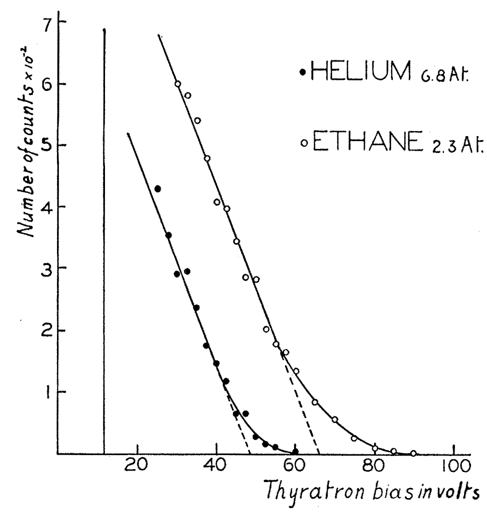

FIG. 3. Number of counts for a given number of incident neutrons as a function of the thyratron bias measured with an ionization chamber filled with ethane and helium, respectively. The vertical line at 11.0 v marks the zero line, i.e., the voltage at which the thyratron breaks down.

inducing a charge of 1.18×10^{-14} coul. on the collecting electrode of the chamber, we obtained a voltage of 56 volts at the output. In the case of helium, the maximum energy of the recoil is 1.67 Mev and the average energy spent per formation of one ion pair is 27.8 ev, so the maximum charge produced by one recoil is

TABLE I. *Measured and corrected intensities J_H and J_{He} of the different lines.*

	Mean Energy	J_H	Track Length Corr. for H	J_{He}	Track Length Corr. for He	J_H Corr.	J_{He} Corr.	$(J_{He}/J_H)A$
0.6 Mev set	1.1	77	0.97	126	0.84	79	149	1.88 ± 0.27
	2.3	93	0.76	24	0.71	122	34	0.28 ± 0.06
	3.6	78	0.51	24	0.56	153	43	0.28 ± 0.06
	4.1	23	0.37	7	0.47	62	15	0.24 ± 0.10
0.88 Mev set	1.3	117	0.93	146	0.89	126	164	1.30 ± 0.16
	2.5	84	0.73	29	0.73	115	40	0.35 ± 0.07
	3.8	92	0.43	19	0.56	214	34	0.16 ± 0.04
	4.3	27	0.27	12	0.47	100	26	0.26 ± 0.09

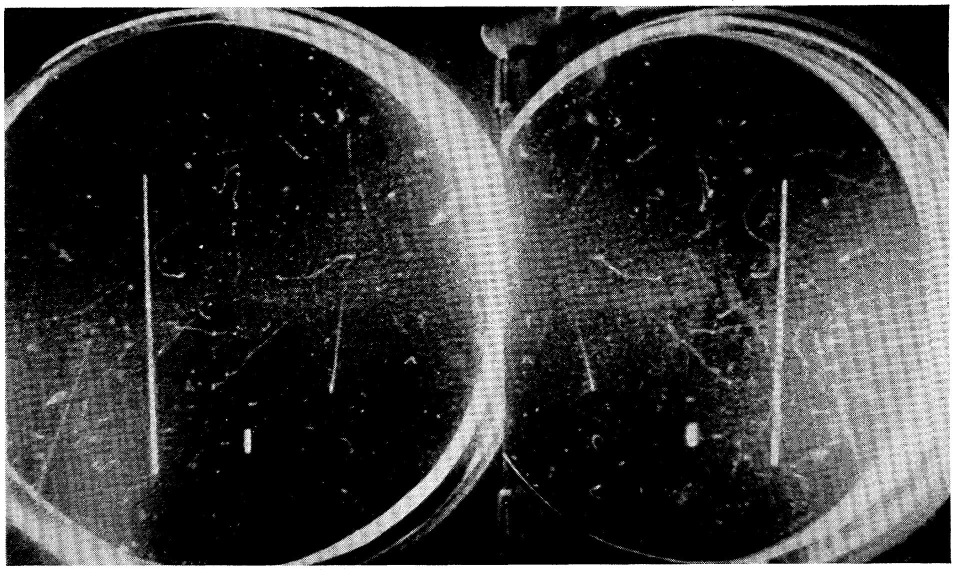

FIG. 4. Two recoils of He and H, respectively, arising from the D+D neutrons in a cloud chamber filled with a mixture of methane and helium.

$(1.67\times10^{6})(1.6\times10^{-19})/27.8=0.96\times10^{-14}$ coul. Of this charge we estimated that, because of the finite collecting time of the ions, about 86 percent reach the collector.[12] From these data we would estimate that the highest pulses should be 38.5 volts. The observed end point lies at $49-11=38$ volts. In the case of the ethane, the sensitivity of the amplifier was unchanged. The maximum charge produced is $(2.6\times10^{6})(1.6\times10^{-19})/25.6 =1.63\times10^{-14}$ coul., 66 percent are estimated to reach the collector, so the maximum voltage is estimated to be 51 volts. The observed value is 55 v. Following the procedure described before, one obtains now the ratio of the scattering cross sections by the following formula:

$$\frac{\sigma_{\mathrm{He}}}{\sigma_{\mathrm{H}}}=\frac{(dN_R/dE_R)_{\mathrm{He}}}{(dN_R/dE_R)_{\mathrm{H}}}\frac{n_{\mathrm{H}}}{n_{\mathrm{He}}}\cdot\frac{4m_{\mathrm{He}}}{(1+m_{\mathrm{He}})^2},$$

using for dN/dE_R the slopes of the two straight lines. As the pressure of the ethane was 2.3 atmos. and that of helium 6.8 atmos., the ratio $n_{\mathrm{H}}/n_{\mathrm{He}}=2.03$. The slopes of the two lines are 6.33 and 9.10, respectively, so

$$\sigma_{\mathrm{He}}/\sigma_{\mathrm{H}}=1.41\pm0.18 \text{ at } 2.5 \text{ Mev}.$$

This result was checked roughly by taking cloud-chamber pictures of the recoils arising from the DD neutrons in a chamber filled with a mixture of methane and helium. One of these pictures containing a helium and a proton recoil both in the forward direction is shown in Fig. 4. The few number of tracks measured on these pictures indicate a ratio of $\sigma_{\mathrm{He}}/\sigma_{\mathrm{H}}$ of about 1.5.

In the case of the carbon neutrons, the ratio of the cross section was determined in the same way, but the accuracy is certainly much smaller. The result we obtained indicates that:

$$\sigma_{\mathrm{He}}/\sigma_{\mathrm{H}}=0.4 \text{ at } 0.5 \text{ Mev}.$$

It cannot be decided whether the angular distribution is isotropic or not, because of the general uncertainty of the observed points.

With the value of 1.41 of the cross-section ratio at 2.5 Mev, we are now able to determine the value of the constant A. Then the ratio of the corrected intensities observed with the cloud

TABLE II. *Values of* $\sigma_{\mathrm{He}}/\sigma_{\mathrm{H}}$.

Neutron Mean Energy Mev	$\sigma_{\mathrm{He}}/\sigma_{\mathrm{H}}$ Backward	Neutron Mean Energy Mev	$\sigma_{\mathrm{He}}/\sigma_{\mathrm{H}}$ Backward
0.5	0.4 ± 0.2	2.5	1.41 ± 0.18
1.0	9.5 ± 1.4	3.6	1.4 ± 0.3
1.2	6.5 ± 0.8	3.8	0.8 ± 0.2
2.2	1.4 ± 0.3	4.1	1.2 ± 0.5
2.4	1.8 ± 0.4	4.3	1.3 ± 0.5

[12] C. E. Wynn-Williams, Proc. Roy. Soc. 131, 391 (1931).

chamber gives directly σ_{He}/σ_H. The result is given in Table II. ($A=1.41/0.28=5.04$.) A further point at $E=0$ is obtained by using the value $\sigma_{He}/\sigma_H=0.05$ for thermal neutrons given recently by Carroll and Dunning.[13] As here again the angular distribution is certainly isotropic, this value holds also for the backward scattering. Some points at higher energies may be obtained from the measurements of Bonner and Brubaker[4] and Staub and Stephens[14] on the neutron spectrum emitted when boron is bombarded by deuterons. These results are shown in Fig. 5. The measurements of Bonner and Brubaker were done with a methane-filled cloud chamber. The four lines have mean energies of 13.0, 8.8, 5.9 and 4.1 Mev. Only the two low energy lines can be used, since the recoils of the higher energy groups

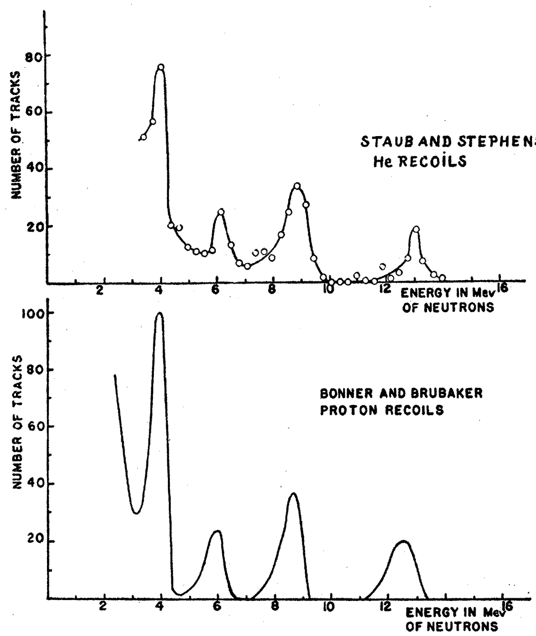

FIG. 5. The neutron spectrum of B+D measured by He and H recoils, respectively.

had to pass through a sheet of mica, thus making the track length correction to be applied very uncertain. The corrected intensities are 1.0 and 3.45 for the 5.9- and 4.1-Mev lines, respectively. In the case of the helium recoils, one obtains from the data of Staub and Stephens the corrected intensities 1.2 and 5.1. If we adjust now the ratio of the intensities at 4.1 Mev to be 1.3, we obtain 1.1 for the ratio of the backward scattering cross section at 5.9 Mev. Fig. 6 shows the results of all the measurements. The shape of the curve between 0.5 and 1 Mev and 1 and 2.4 Mev is, of course, very uncertain because of the lack of measured points.

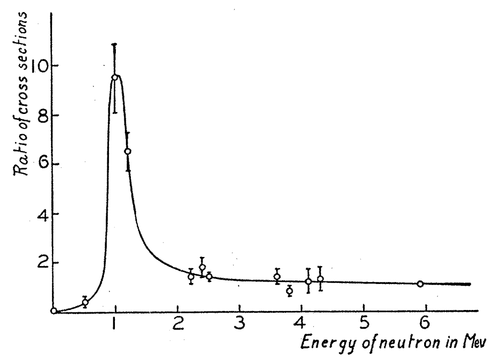

FIG. 6. The ratio of the backward scattering cross section of helium to hydrogen as a function of the energy of the incident neutron. (The energy is measured in the laboratory coordinate system.)

DISCUSSION

The theory of the elastic scattering of neutrons, as influenced by the presence of a resonance level has been given by Bethe and Placzek[15] for heavy nuclei. Although it is doubtful whether as light a nucleus as He^5 can be treated according to this theory, there should remain certain features characteristic for any resonance scattering. Indeed one can assume the cross section for elastic scattering to have the form[15]

$$\sigma=\frac{\pi}{(2s+1)(2i+1)}\sum_J(2J+1)\times\left|2R_Je^{i\delta}+\sum_r\left(\frac{\Gamma_{rJ}\lambda_{rJ}}{E_A+E_P-E_{rJ}+\frac{1}{2}i\gamma_{rJ}}\right)\right|^2.$$

The second part within the bars represents the amplitude of the out-going wave caused by resonance scattering. The first part takes care of an additional scattering which can be thought of arising from an effective potential. The main difference between our formula and the one of Bethe and Placzek lies in the phase factor

[13] H. Carroll and J. R. Dunning, Phys. Rev. **54**, 541 (1938).

[14] H. Staub and W. E. Stephens, Phys. Rev. **53**, 212 (1938).

[15] H. A. Bethe and G. Placzek, Phys. Rev. **51**, 450 (1937), (Formula 54).

$e^{i\delta}$. Indeed, while for heavy nuclei one has to assume the wave function to vanish at the surface of the nucleus and thus the phase δ to be zero, one has for a light nucleus to leave this phase undetermined, unless one wants to trust a particular model. Furthermore, the quantity R_J in the case of Bethe and Placzek can be assumed to be a constant, properly called the nuclear radius. In our case, however, it means a length of a somewhat different significance and must be assumed to depend on the energy of the incident neutron. For p and higher types of scattering, we may well assume the contribution to the cross section arising from the R_J to be negligible. In the case of a neutron incident on He^4, we have the following:

$$s=\tfrac{1}{2},\quad i=0.$$

For s scattering, $J=\frac{1}{2}$. For p scattering, $J_1=\frac{1}{2}$, $J_2=\frac{3}{2}$. If we assume, furthermore, that the spin-orbit interaction is small, we have in the case of p scattering the same resonance energy for both levels and may well assume their width to be the same. Furthermore, as we do not know any other type of disintegration, the partial neutron width is equal to the total width. Thus we get at exact resonance,

$$\sigma_s=4\pi(R^2+\lambda\!\!\!^-{}_r{}^2+2R\lambda\!\!\!^-{}_r\sin\delta)\quad \text{for an } s \text{ resonance level,}$$

$$\sigma_p=4\pi(R^2+3\lambda\!\!\!^-{}_r{}^2)\quad \text{for a } p \text{ resonance level.}$$

One may notice that in the case of a p level, there occurs no phase δ in the expression for σ, as in this case the s potential wave and the p resonance wave do not interfere.

As we observed in our experiments, only the forward scattered recoils within an angle of $\pm 12°$, we have to consider the angular distribution of the recoils. For the s scattering, the distribution in the center of gravity system is isotropic. In the case of p type, it is proportional to $\cos^2\varphi$ per unit solid angle where φ is the angle of the scattered neutron with respect to the direction of incidence. Considering that between the angle θ of the recoil nucleus in the laboratory system and the angle φ there exists the relation $2\theta=-\varphi$, one obtains for the fraction of recoils between θ and $\theta+d\theta$

$$N_s(\theta)d\theta=\sin 2\theta d\theta\quad \text{for } s \text{ scattering,}$$
$$N_p(\theta)d\theta=3\cos^2 2\theta\sin 2\theta d\theta\quad \text{for } p \text{ scattering.}$$

Integrating these between 0° and 12° gives the numerical factors $a_s=0.0432$ and $a_p=0.1187$. Thus we get now for the partial scattering cross section σ' for recoils between 0° and 12° at exact resonance:

$$\sigma_s'=4\pi\times 0.0432(R^2+\lambda\!\!\!^-{}_r{}^2+2R\lambda\!\!\!^-{}_r\sin\delta)$$
$$\sigma_p'=4\pi(0.0432R^2+3\times 0.1187\lambda\!\!\!^-{}_r{}^2).$$

For the numerical evaluation we cannot say anything about the value of δ; thus we are only able to give an upper and lower limit for σ_s'. Furthermore, we have no certain values for R. However, our ratio of cross sections at 2.6 Mev neutron energy, together with the value $\sigma_H=2.1\times 10^{-24}$ cm^2 for the cross section of hydrogen[16] gives the quite reasonable value for R of 4.8×10^{-13} cm (assuming $\sigma_{He}=4\pi R^2$). On the other hand, with Carroll and Dunning's[13] value $\sigma_{He}=1.5\times 10^{-24}$ cm^2 at $E=0$, we get $R=3.4\times 10^{-13}$ cm. As the resonance energy is between these two energies, we may consider the two values for R as upper and lower limit. Thus we get now finally with $\lambda\!\!\!^-{}_r=5.5\times 10^{-13}$ cm:

$$0.003\leq\sigma_s'\leq 0.58\times 10^{-24}\text{ cm}^2,$$
$$1.42\leq\sigma_p'\leq 1.48\times 10^{-24}\text{ cm}^2.$$

The hydrogen cross section at 1.05 Mev can easily be computed from Wigner's[17] formula, since an experimental value at this energy is not available.

With the values $\epsilon_1=0.11$ Mev and $\epsilon_2=2.15$ Mev (which gives σ in excellent agreement with the experimental value at 2.6 Mev) one obtains

$$\sigma_H=3.54\times 10^{-24}\text{ cm}^2.$$

As the neutron-proton scattering at one Mev neutron energy certainly is isotropic, the partial scattering cross section for recoils between 0° and 12° becomes

$$\sigma_H'=0.153\times 10^{-24}\text{ cm}^2.$$

Thus we get, finally, for the ratios of the cross sections:

$$0.02\leq L\leq 3.7\quad \text{for an } s \text{ resonance level,}$$
$$9.1\leq L\leq 9.4\quad \text{for a } p \text{ resonance level.}$$

[16] W. H. Zinn, S. Seeley and V. W. Cohen, Phys. Rev. **53**, 921 (1938).
[17] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 117 (1936).

Our results thus indicate strongly that the anomalous scattering is due to a p resonance level.[18]

The assumption of a weak spin-orbit interaction cannot theoretically be justified. However, figuring out the ratio L under the assumption of strong spin-orbit coupling leads to the result that again L would be much smaller than the observed value (4.8 for $J=\frac{3}{2}$).

It may be pointed out that we would expect that the observed ratio L would be somewhat smaller than the actual because the neutron line has an appreciable width (caused by the penetration in the resonance peak of the cross section). Assuming that the resonance peak has a width of about 0.2 Mev and the neutron line a width of 0.1 Mev (probably less) one estimates that under the most unfavorable conditions the measured ratio L should be about $\frac{2}{3}$ the actual ratio. So we still think our experiment to be in fairly good agreement with the assumption of a p resonance level.

Our result does not say anything, of course, about the existence of a stable He^5 as suggested by Joliot and Zlotowski.[19] As such a stable level would be about 3.6 Mev lower than the one here considered, it would not give an appreciable contribution to the cross section.

It may be of interest to note that the existence of the anomalous n-He scattering cross section described above explains the appearance of a rather strong group of low energy neutrons in the experiments of Baldinger, Huber and Staub[9] on the neutron spectrum of the D+D reaction. While Bonner,[20] using proton recoils, found this group to be about 1/10 of the main peak, Baldinger, Huber and Staub found it to have about the same intensity, using He recoils in an ionization chamber. As the low energy peak occurs at about 1.1 Mev, it is obvious that the anomalous cross section gives too high a value for the number of neutrons. We applied the calculated value of the He cross section to these results and found, considering the angular distribution, that the correct intensity is just 11 percent of the main peak in good agreement with Bonner's result.

In conclusion, we wish to thank Mr. R. Becker, Mr. T. Lauritsen and Mr. J. F. Streib, Jr., for valuable assistance, and Dr. F. Bloch, Dr. L. Schiff and Dr. R. Serber for the discussion of the theoretical aspects of this problem. We gratefully acknowledge the support and advice of Dr. C. C. Lauritsen. One of us (H. Staub) is very much indebted to the "Jubiläumsfond" and the "Stipendienfond der Eidgenössischen Technischen Hochschule," Zürich, Switzerland, for a grant enabling him to carry out this work at Pasadena.

[18] As Dr. Bloch pointed out to us, there is a further support for the conclusion that the resonance scattering is of the p type. The peak in the α-particle curve of Williams, Shepherd and Haxby, reference 3, due to the recoil from He^5 shows an additional width of about 0.15 to 0.25 Mev—this value thus is just the width of the resonance level of He^5 here considered. Indeed if it were an s type scattering, there would be no reason why the width should not be of the order of several Mev. The explanation of Bohr of the occurrence of sharp levels in heavy nuclei cannot be applied here, since we cannot expect the neutron to make many collisions in the compound nucleus before it escapes. The explanation seems to lie in the fact that for a given energy the lifetime of the compound nucleus in a p state is considerably longer than that of an s state. A reasonable measure for their ratio is that of the square of the p and s wave functions of the incident neutron. Since this ratio measures the relative probability of finding the neutron in the compound nucleus, it is given by $(R/3\lambda\!\!\!^{-})^2$ which, in our case, is between 13 and 26 for the two limiting values of R. The very fact that the observed width is of the order of 0.2 Mev indicates that the resonance level is a p state.

[19] F. Joliot and I. Zlotowski, Comptes rendus **206**, 1256 (1938).

[20] T. W. Bonner, Phys. Rev. **53**, 711 (1938).

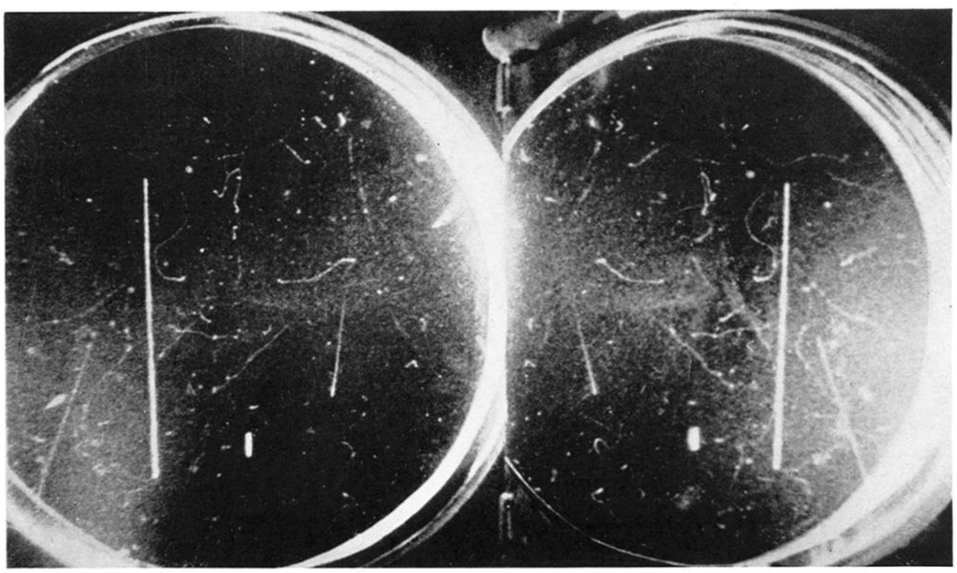

FIG. 4. Two recoils of He and H, respectively, arising from the D+D neutrons in a cloud chamber filled with a mixture of methane and helium.