NOVEMBER 1, 1940 PHYSICAL REVIEW VOLUME 58

Anomalous Scattering of Neutrons by Helium. (II)

H. STAUB AND H. TATEL*
Stanford University, Palo Alto, California

(Received September 3, 1940)

The anomalous scattering of neutrons by helium at neutron energies around 1 Mev has been investigated more closely. The backward scattering cross section shows a peak of 0.4 Mev half-width and indicates a doublet structure with a splitting of about 0.3 Mev. The absolute value of the ratio of the scattering cross sections of helium and hydrogen at 2.5-Mev neutron energy was redetermined and found to be considerably smaller than given in a previous investigation. This lowers the absolute values of the resonance scattering cross section given previously. The new values, however, are still consistent with the assumption that the resonance level is a *P* level. The measurements are found to be in agreement with the dispersion theory. The present experiments do not fix the sign of the splitting, although there is some indication that the doublet is normal.

INTRODUCTION

STAUB and Stephens[1] (hereafter referred to as I) have shown that the backward scattering cross section of He for neutrons of about 1 Mev energy shows a strong anomaly, caused by a virtual level of He^5 which is unstable by 0.8 Mev against disintegration into a neutron and an alpha-particle. The existence of this level was discovered by Williams, Shepherd and Haxby,[2] who investigated the reaction

$${}_3Li^7+{}_1H^2\rightarrow{}_2He^5+{}_2He^4.$$

From the maximum observed ratio of the forward scattering cross section and the fact that the width of the level is some hundred kilovolts, Staub and Stephens[1] concluded that the level of He^5 involved must be a *P* level.

Since He^5 certainly represents a rather simple nuclear configuration it seemed desirable to carry on further investigation to obtain more information about the shape of the anomalous cross section curve, particularly since Staub and Stephens measured only two points close to the maximum. Furthermore, it seemed to be of considerable interest to investigate whether or not a splitting of the two levels, could be observed for values of the total angular momentum $J=\frac{3}{2}$ and $J=\frac{1}{2}$, respectively. Indication of a splitting was given by Gaerttner, Pardue and Streib.[3] Their results, however, were not analyzed according to the theoretical formulas and, therefore, did not present conclusive evidence.

The previous experiment (I) was carried out with almost monochromatic neutrons from the line spectrum of the Be (d, n) reaction. The neutron energy could be slightly changed by varying the bombarding energy of the deuterons. In the present experiment a continuous neutron spectrum was used, thus making it possible to investigate the scattering cross section in detail between 0.5 and 2 Mev. The continuous spectrum was produced by allowing the monochromatic neutrons of 2.5 Mev energy from the $d(d, n)$ reaction to strike a paraffin howitzer of suitable shape, in which they were slowed down by elastic scattering. The howitzer had a cylindrical shape with a coaxial conical opening, the common axis passing through the center of the target of the neutron generator and the center of the cloud chamber (Fig. 1). For a neutron point source the angle of the conical hole determines the maximum energy of the continuous neutron spectrum. This angle was 27°, hence the spectrum extended to about 2 Mev. The outer radius of the howitzer was 5.7 cm, its thickness 4.5 cm. Neutrons which are scattered so as to have about 1 Mev after scattering are produced in an effective layer of paraffin of about 5 cm and have to pass through about 3 cm to emerge. An estimate shows that, for this kind of a howitzer, the number of neutrons per 0.1 Mev energy interval is about 2 percent of the total

---

* Now at Physics Department, University of Michigan, Ann Arbor, Michigan.

[1] H. Staub and W. E. Stephens, Phys. Rev. **55**, 131 (1939).

[2] J. H. Williams, W. G. Shepherd, R. O. Haxby, Phys. Rev. **52**, 390 (1937).

[3] E. R. Gaerttner, L. A. Pardue and J. F. Streib, Phys. Rev. **56**, 856 (1939).

number observed in the undisplaced group at 2.5 Mev. The conical opening of the howitzer is important for two reasons: First, it allows, with or without the howitzer, the same number of neutrons of 2.5 Mev energy to strike the recording instrument. Secondly, it facilitates the emission of the low energy neutrons by reducing the amount of paraffin through which they have to pass. Since the howitzer as a whole represents the neutron source, its dimensions have to be kept small enough to insure a sufficiently small uncertainty in the origin of the observed neutrons. This, in turn, requires that the density of hydrogen in the howitzer material be as great as possible. This was obtained by turning the howitzer from a solid block of bubble-free paraffin.

The neutron source used in this experiment was a *dd* neutron generator operated at 170 kv and similar to a generator previously described by one of us.[4] Since the ion current was turned on only during the short time of sensitivity of the cloud chamber, a heavy ice target cooled with a mixture of dry ice and alcohol proved to be very satisfactory. The arrangement of the howitzer requires a small target spot, the diameter of which was limited by suitable diaphragms to $\frac{3}{4}''$ (19 mm). The maximum obtainable ion current was about 200 μa. Since the ion source was of the high voltage type[5] it is estimated that about 60 percent of the ions were atomic. The total yield of neutrons was equivalent to that from 10 g of Ra+Be. The ion source was easily timed by letting the cloud-chamber mechanism operate a relay which controlled the primary current of the high voltage for the ion source.

An automatic cloud chamber of the diaphragm type was used for recording the neutrons. It had an effective diameter of 13.4 cm and a depth of 2.6 cm. Its center was 50 cm from the target and 108 cm above the floor, in order to reduce the excessive recording of neutrons scattered from there. For the hydrogen experiments the chamber was filled with methane at a pressure of 6 lb. above atmospheric, having a stopping power of about 1.4. For He a pressure of 1 lb. above atmospheric was used, the stopping power being about 0.26.

EXPERIMENTS

To obtain the ratio of the backward scattering cross sections of He and H the neutron spectrum was recorded, once with a helium- and once with a methane-filled cloud chamber, according to the technique developed by Bonner and Brubaker.[6] Stereoscopic pictures of the recoil tracks were taken by simultaneously photographing the direct image and one reflected on a surface aluminized mirror. Only tracks within an angle of ±8° with respect to the direction of the incident neutron were measured. The ratio of the scattering cross section is then simply obtained as the ratio of the numbers of observed helium and hydrogen recoils in each energy interval. This ratio, however, has to be multiplied by a constant depending on the total number of neutrons hitting the chamber in either one of the experiments. The value of this constant is determined by the ratio of the intensities of the group of 2.5-Mev neutrons in either one of the two experiments, provided that the ratio of the cross section of helium and hydrogen is known. The absolute value of the backward scattering cross section finally is obtained from the theoretically known value of the hydrogen cross section.

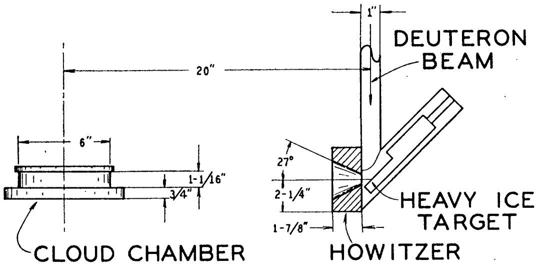

FIG. 1. Arrangement of chamber, target and howitzer.

Preliminary experiments had revealed that without any paraffin in the neighborhood of the target, the neutron spectrum still shows an appreciable low energy tail which consists mainly of neutrons scattered from the surrounding walls and the floor. Since these neutrons have random directions, they produce recoils of various energies in the direction of measurement. This fact makes it necessary to subtract this background from the two spectra taken with the paraffin howitzer in place. The background

---

[4] E. Baldinger, P. Huber and H. Staub, Helv. Phys. Acta **11**, 245 (1938).

[5] F. A. Heiyn, Philips Tech. Rev. **3**, 339 (1938).

[6] T. W. Bonner and W. M. Brubaker, Phys. Rev. **47**, 910 (1935).

measurements were taken with a carbon howitzer in place of the paraffin. This howitzer was geometrically identical with the one of paraffin and contained the same number of carbon atoms. Such an arrangement was chosen because it may well be that the distribution of the background recoils is affected by elastic scattering of the carbon in the paraffin. This can hardly be the case for the hydrogen in the howitzer, however, since every neutron scattered by the hydrogen has to undergo a large deflection in order to be scattered back by the floor, thus losing practically its whole energy. Moreover, the carbon may easily scatter additional neutrons of the monochromatic 2.5-Mev group into the cloud chamber which would affect the monitor intensity of the 2.5-Mev group.

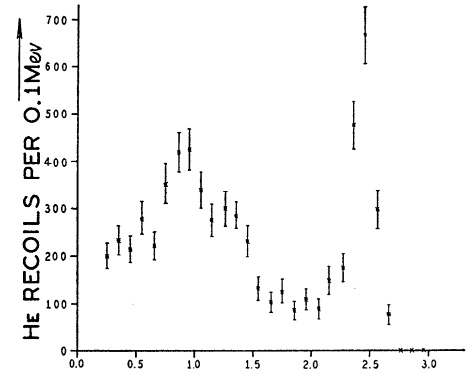

FIG. 2. Corrected number-energy curve of the He recoils in 0.1-Mev intervals as observed with the paraffin howitzer in front of the target.

In this experiment the following cloud-chamber pictures were taken: with He and the paraffin howitzer, 3500 pictures, yielding 635 measured tracks within the correct angle; with the carbon howitzer, 3750 pictures containing 499 tracks; with methane, 3000 pictures, with each of the howitzers yielding 1082 and 1168 tracks, respectively.

Considerable care was taken in measuring the tracks. Since the source of neutrons subtends an angle of 6.5°, the angle with respect to the direction to the target center within which a track has to be located to be measured, was chosen to be ±8°. The uncertainty of the recoil angle is therefore 14.5° and hence the uncertainty of the neutron energy is 6.5 percent. The pictures were always carefully examined so that short tracks were not missed. Since the interesting energy region corresponds to a track length in the interval from about 0.9 to 3.8 cm in case of He, and from 0.5 to 11.4 cm in methane, one has to correct the results for the decreasing chance that a track will have its entire length visible in the chamber as its length increases. In the previous work this correction did not substantially affect the result. In the present case, however, the result depends largely on this correction, requiring, therefore, a more accurate formula. A simple calculation shows that in order to take the finite depth of the chamber and the finite distance from the neutron source into account one has to multiply the expression given in (I) by the two factors

$$(1-4l\sin\vartheta_0/3\pi h)\cdot(1-l/2D),$$

where l is the apparent track length, ϑ_0 the maximum allowed angle of the recoils with respect to the horizontal plane of symmetry of the chamber, h its depth, and D the distance of its center from the target. The first of these two factors arises from the decreasing chance of a track within ±8° to the horizontal to have its entire length within the depth of the chamber. The second factor is due to the fact that the incident neutrons are not parallel because the source (assumed to be point-like) has a finite distance from the chamber. These two factors have to be multiplied with the expression given in (I) which was derived by assuming parallel incidence of the neutrons, large depth of the chamber, and a negligibly small angular spread of the recoils. Thus the expression by which the observed number of tracks of length l has to be divided is

$$K=(1/\pi)[2\sin^{-1}(1-l^2/4r^2)^{\frac{1}{2}}-(l/r)\times(1-l^2/4r^2)^{\frac{1}{2}}]\cdot(1-4l\sin\vartheta_0/3\pi h)\cdot(1-l/2D),$$

where r is the radius of the cloud chamber. It was frequently checked on the cloud-chamber pictures, by measuring nonhorizontal tracks, that the full depth of the chamber was always sensitive. The stopping power of the gas was determined by the extrapolated integral number range curve of the homogeneous group. Bonner's[7] Q value of 3.28 Mev for the *dd* reaction was used with the correction given by Livingston and

---

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

Bethe.[8] By means of the range-energy relation given by Livingston and Bethe and corrected for protons according to Parkinson, Herb, Bellamy and Hudson[9] and for α-particles by Holloway and Livingston,[10] the results were converted into equal energy intervals.

After completion of the resonance experiments the absolute values of the helium backward scattering cross section were determined in the above-mentioned way by using the value 1.4 for the ratio of the cross section of helium and hydrogen at 2.5 Mev as determined in (I). A comparison with the theory, however, revealed that these values were much too large even if one assumed zero splitting and a very low value of the potential scattering. As the experimental value of the hydrogen cross section at this energy is very close to the theoretical one, the discrepancy must have been caused by the value of the ratio at 2.5 Mev. The present results indicate that the influence of the resonance level is still appreciable at 2.5 Mev causing a strong angular anisotropy of the scattering. As discussed later there is indeed a strong increase of low energy recoils at 2.5 Mev. The technique used in (I) is rather insensitive to angular anisotropy. The result obtained in this way is, therefore, probably rather the average ratio of the scattering cross sections of helium and hydrogen than the value for the backward direction. It seemed, therefore, desirable to repeat this measurement with a different technique. For this purpose the cloud chamber was filled with a known mixture of the gases. The observed number of recoils in the forward direction of each kind then gives directly the value of the ratio. This simple procedure involves, however, a serious difficulty because the ranges of protons of 2.5 Mev and α-particles of $(16/25)\times 2.5$ Mev$=1.6$ Mev are enormously different. This can be avoided by measuring first the scattering cross section ratio of helium and deuterium and then of deuterium and hydrogen, since deuterons of $(8/9)\times 2.5$ Mev$=2.22$ Mev have only about half the range of protons of 2.5 Mev. For these experiments the same cloud chamber at the same distance was used and the tracks measured in the same way as before. First the chamber was filled with 1.590 atmos. helium of 96 percent purity (the rest being oxygen and nitrogen) and 0.795 atmos. of deuterium of 99.5 percent purity ($\frac{1}{2}$ percent hydrogen). A small amount of argon was added to increase the stopping power. Water was used as a liquid in order to avoid an excessive number of protons. The mean ranges of the particles are in this case 8.15 and 1.12 cm, respectively. For the second experiment 0.791 atmos. of deuterium were mixed with 0.825 atmos. of ordinary tank hydrogen (purity assumed to be 100 percent) and 0.9 atmos. of argon added. Again, pure water was used as liquid and since, in this experiment, the hydrogen of the water contributes to the recoils, the temperature of the cloud-chamber gas was always carefully measured and the water vapor taken into account. The ranges of the particles were 8.57 and 4.5 cm. The evaluation was made in the same way as before; in particular the same track length corrections were applied. The fact that the density of the tracks is different for the three kinds of particles should not involve any serious errors

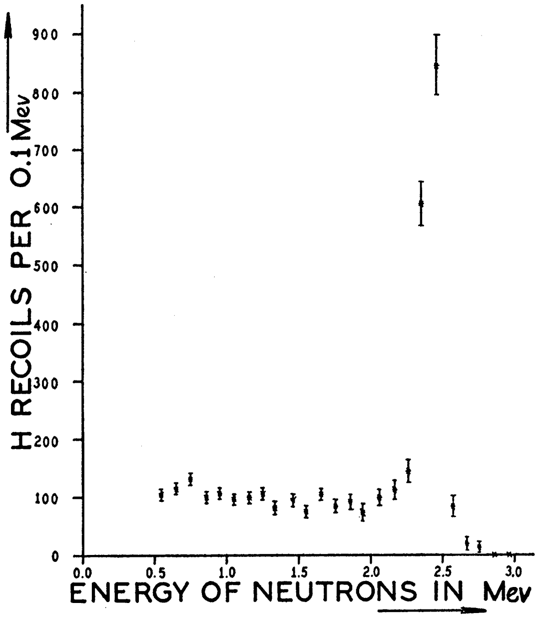

FIG. 3. Corrected number-energy curve of the H recoils in 0.1-Mev intervals as observed with the paraffin howitzer in front of the target.

---

[8] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 245 (1937).

[9] D. B. Parkinson, R. G. Herb, J. C. Bellamy and C. M. Hudson, Phys. Rev. **52**, 75 (1937).

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

by omitting fainter tracks, since in every case the specific ionization is still so high that no individual droplets can be observed and furthermore because recoils only originate during a time which is probably much shorter than the time of sensitivity of the chamber.

RESULTS

Figures 2 and 3 show the results of the measurements of the spectrum with helium and methane, respectively, in the cloud chamber and the paraffin howitzer at the target. The anomalous cross section of He produces a marked and rather wide peak which indicates clearly a doublet structure, whereas the methane spectrum has no irregularities exceeding the statistical error. The scale of the two figures is such as to give the same intensity to the homogeneous group. The width of this line is in very good agreement with the calculated value[8] thus proving that no extraneous instrumental width has been introduced.

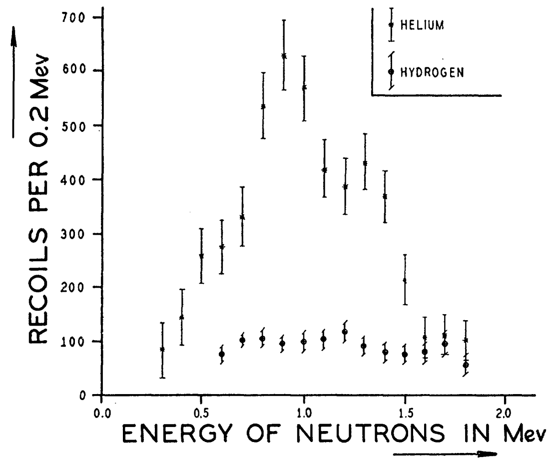

FIG. 4. The difference curves of helium and hydrogen in 0.2-Mev overlapping intervals.

The measurements with the carbon howitzer show the same shape for the homogeneous line. For methane, the measurements indicate that about 50 percent of the observed recoils in the low energy region are due to the presence of the paraffin. The number of neutrons per 0.1-Mev interval is then about 1.7 percent of the total number of neutrons in the homogeneous group, in agreement with the calculation for this howitzer. For He the background is the same at 1.7 Mev but about twice as big at 1 Mev as the methane background. This indicates that part of the neutrons scattered from the surroundings have lost an appreciable fraction of their original energy and therefore show up more in He, because of its increased scattering cross section. No indication of the homogeneous group at 0.9 Mev found by Bonner[7] is present. With both gases the background is rather uniform, increasing slightly towards small energies. It may be pointed out that most of the background neutrons are not scattered on the cloud chamber, for in that case the background would be appreciably changed by substituting the carbon howitzer for the paraffin. Preliminary experiments had definitely shown that the number of slow neutrons emerging from the paraffin increased relative to the background when the chamber was placed closer to the target. This indicates that the scattering on the cloud chamber can only be a fraction of that due to the surroundings. The two difference spectra in helium and in methane are represented in Fig. 4. They were obtained after adjusting the intensity of the homogeneous group to one common value. The probable errors do not contain the contribution due to the uncertainty in the multiplicative constant used for matching to equal intensity because this error affects every point of the difference in the same way.

The cloud-chamber pictures taken with the gas mixtures for the determination of the absolute value of the ratio of the backward scattering cross sections at 2.5 Mev yielded two distribution curves with distinct groups from which only a small background had to be subtracted. Their mean ranges determined according to Livingston and Bethe[8] were in excellent agreement with the calculated ones. 3000 pictures taken with the helium-deuterium mixture yielded 398 α-particles and 330 deuterons in the $\pm 8°$ forward direction. After correcting for track length, the ratio of helium to deuterium backward scattering cross section becomes 0.409 ± 0.03. The second set of 3000 pictures taken with the hydrogen-deuterium mixture contained 413 deuterons and 129 protons. The ratio of the backward scattering cross sections becomes thus 1.307 ± 0.110. Hence the ratio of the backward scattering cross sections of helium and hydrogen is 0.534±0.06. This value is considerably lower than the one found previously (I) which was 1.41. The new value, however, is in agreement with a more recent measurement by Ladenburg[11] who used an ionization chamber and observed a differential number-energy distribution. This value is 0.65±0.13.

With the value of the ratio at 2.5 Mev, the absolute value of the ratios at the lower energies is determined. To compare the present results with the theory, one has to obtain the helium scattering cross section. Experimental data on the hydrogen cross section around 1 Mev neutron energy are not available. Thus one has to rely on the theoretical formula of Wigner and Bethe[12]

$$\sigma_{\mathrm{H}}=\frac{4\pi\hbar^2}{M}\left[\frac{3}{4}\frac{1+\alpha_0 r}{E_0+\frac{1}{2}E}+\frac{1}{4}\frac{1+\alpha_1 r}{E_1+\frac{1}{2}E}\right];$$

$$\alpha_1=\frac{(ME_0)^{\frac{1}{2}}}{\hbar};\quad \alpha_1=\frac{(ME_1)^{\frac{1}{2}}}{\hbar}.$$

In this formula the values given by Zinn, Seely and Cohen,[13] *viz.:* $r=2.8\cdot 10^{-13}$ cm; $E_0=2.17$ Mev; $E_1=0.066$ Mev were used. According to their measurements the experimental value at 2.88 Mev disagrees only by about 5 percent from the theoretical value whose parameters are chosen in agreement with the results of the proton-proton scattering and the scattering cross section of thermal neutrons. Whether the formula is correct at 1 Mev may be questionable, since several measurements[14] give values which are lower than required by the above formula. Such a large deviation would affect the present results. It is furthermore assumed that the neutron-proton scattering is isotropic in the center of gravity system. Because of the finite dimensions of the source, the recoils measured within ±8° extend, on the average, over a region from −12 to +12° in the laboratory system. The hydrogen cross section within this solid angle is given by

$$\sigma_{\mathrm{H}}'=2\int_0^{12^0}\sigma_{\mathrm{H}}\sin\vartheta_r\cos\vartheta_r d\vartheta_r=0.0432\sigma_{\mathrm{H}}.$$

where σ_{H} is the total hydrogen cross section, ϑ_r the angle of the recoil proton and the incident neutron in the laboratory system.

The experimental results obtained in this way for the backward helium scattering cross section (±12°) are represented in Fig. 5 in 0.2-Mev overlapping energy intervals. The points at 1.0 and 1.2 Mev include the previous measurements (I) after readjusting them to the new value at 2.5 Mev, since they were in agreement within the statistical errors with the present values. The resonance peak shows a half-width of about 0.4 Mev and indicates clearly a structure with a separation of about 0.3 Mev. It may be mentioned that the same structure has been obtained in two independent preliminary experiments with entirely different paraffin howitzers. As already mentioned, the present data are consistent with the ones published in (I) provided the new calibrating value at 2.5 Mev is taken into account. The only exception is the point at 0.5 Mev the accuracy of which, as stated in (I), is quite small. The measurements recently published by Hudspeth and Dunlap[15] are also in

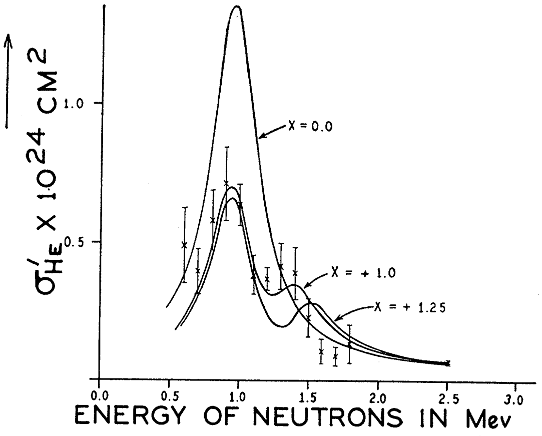

FIG. 5. The backward scattering cross section of helium for a solid angle of ±12° of the recoils in the laboratory system and inverted splitting. Curves calculated according to formula (2) with $\Gamma=0.4$ Mev, $E_{3/2}=0.95$ Mev, $\sigma_0=0.7\times 10^{-24}$ cm², $\delta_0>0$, $x=0.0$; $+1.0$; $+1.25$. Points represent observed values in 0.2-Mev overlapping intervals.

---

[11] We are very much indebted to Professor Ladenburg for communication of his results prior to publication.

[12] See, for example, J. Schwinger and E. Teller, Phys. Rev. **52**, 286 (1937).

[13] W. H. Zinn, S. Seely and V. W. Cohen, Phys. Rev. **56**, 260 (1939).

[14] E. Amaldi, D. Bocciarelli, F. Rasetti and G. C. Trabacchi, Phys. Rev. **56**, 881 (1939). T. Goloborodko and A. Leipunski, Phys. Rev. **56**, 891 (1939); M. Goldhaber, Nature **137**, 824 (1936); W. E. Good and G. Scharf-Goldhaber, Phys. Rev. **58**, 89 (1940).

[15] E. Hudspeth and H. Dunlap, Phys. Rev. **57**, 971 (1940).

agreement with the present results. The fact that their data lack the indication of a structure is obviously due to the smaller number of recoils which they observed. The results of Bonner and Hudspeth[16] cannot be compared, since they refer to the total scattering cross section.

DISCUSSION OF THE RESULTS

It may first be pointed out that although the absolute values of the helium cross section have been considerably lowered by the newly determined smaller value at 2.5 Mev, the height of the resonance peak is still larger than the highest possible value for an S resonance level. If one assumes the potential and resonance scattering to be caused only by an S wave, the scattering cross section for the observed solid angle would be:

$$\sigma_{\mathrm{He}}'\leq 0.0432\cdot 4\pi\bar{\lambda}^2=0.182\cdot 10^{-24}\ \mathrm{cm}^2,$$

which is about one-fourth of the observed value.

The complete expression for the resonance scattering of neutrons in helium, taking potential scattering and a finite splitting of the two P levels into account has been given by Bloch[17] (see following article). It is given by

$$\frac{d\sigma_{\mathrm{He}}}{d\omega}=\bar{\lambda}^2\left\{\left|\sin\delta_0+e^{-i\delta_0}\left(\frac{\Gamma}{E_{3/2}-E-\frac{1}{2}i\Gamma}+\frac{1}{2}\,\frac{\Gamma}{E_{1/2}-E-\frac{1}{2}i\Gamma}\right)\cos\Theta\right|^2\right.$$
$$\left.+\frac{1}{4}\sin^2\Theta\left|\frac{\Gamma}{E_{3/2}-E-\frac{1}{2}i\Gamma}-\frac{\Gamma}{E_{1/2}-E-\frac{1}{2}i\Gamma}\right|^2\right\}. \qquad (1)$$

For comparison, the above expression has to be integrated over a solid angle of the recoil α-particles of ±12° in the laboratory system. The angle of the recoil ϑ_r in the laboratory system is related to the angle Θ of the scattered neutron in the center of gravity system by:

$$\vartheta_r=\tfrac{1}{2}(\pi-\Theta).$$

Thus the backward scattering cross section for the recoil within ±12° becomes:

$$\sigma_{\mathrm{He}}'=\bar{\lambda}^2\left\{0.0432\sin^2\delta_0+1.49\frac{[(\epsilon-x)^2+1]+2[(\epsilon+x)^2+1]-8x^2/3}{[(\epsilon-x)^2+1]\cdot[(\epsilon+x)^2+1]}+\frac{0.132\cdot 4x^2/3}{[(\epsilon-x)^2+1][(\epsilon+x)^2+1]}\right.$$
$$\left.-1.040\sin\delta_0\cos\delta_0\left[\frac{2(\epsilon-x)}{1+(\epsilon-x)^2}+\frac{\epsilon+x}{1+(\epsilon+x)^2}\right]-1.040\sin^2\delta_0\left[\frac{2}{1+(\epsilon-x)^2}+\frac{1}{1+(\epsilon+x)^2}\right]\right\}, \qquad (2)$$

where ϵ and x have the following meaning:

$$\epsilon=\frac{2}{\Gamma}\left(\frac{E_{3/2}+E_{1/2}}{2}-E\right);\quad x=\frac{E_{3/2}-E_{1/2}}{\Gamma}.$$

Therefore, positive values of x mean an inverted doublet, negative values a normal one. $E_{3/2}$, $E_{1/2}$, Γ are the energies of the two P levels and their width, which is assumed to be constant over the resonance region, in either center of gravity or laboratory system; $\bar{\lambda}$ is the wavelength of the neutron in the center of gravity system. The four parameters $E_{3/2}$, δ_0, x and Γ have to be chosen so as to be in agreement with the experimental facts. It is assumed that the pure "potential scattering" $4\pi\bar{\lambda}^2\sin^2\delta_0=\sigma_0$ is constant over the resonance region and has a value which is comparable to that determined by Carroll and Dunning[18] for thermal neutrons, *viz.:*

$$\sigma_0=1.5\times 10^{-24}\ \mathrm{cm}^2.$$

The analysis was carried out for positive and negative values of $\sin\delta$ corresponding to values: 0.0, 0.7, 1.5×10^{-24} cm² for σ_0. The width Γ was

---

[16] T. W. Bonner and E. Hudspeth, Phys. Rev. **57**, 1188 (1940).

[17] F. Bloch, Phys. Rev. **58**, 829 (1940), formula (48).

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

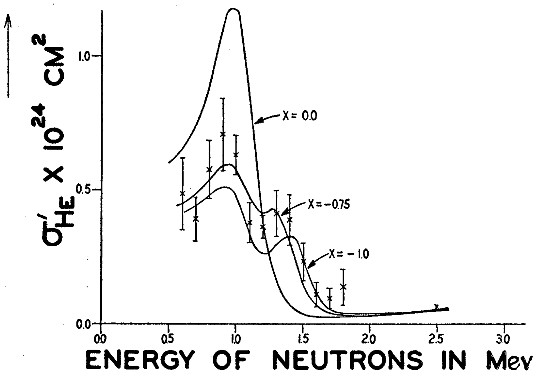

FIG. 6. The backward scattering cross section of helium for a solid angle of ±12° of the recoils in the laboratory system and normal splitting. Curves calculated according to formula (2) with: $\Gamma=0.4$ Mev, $E_{1/2}=1.05$ Mev; $\sigma_0=1.5\times10^{-24}$ cm^2, $\delta_0<0$, $x=0.0$; -0.75; -1.0.

chosen to be 0.4 Mev for the neutrons in the laboratory system and the values of $E_{1/2}$ or $E_{3/2}$ so that the maximum of the curve occurred at 0.95 Mev. This was done for various positive and negative values of the splitting x.

The position of the experimental points would, of course, suggest that the splitting is positive since the more intense peak occurs at lower energies. In fact one finds a well fitting theoretical curve with the following values of the parameters:

$$x=+1.0^{+0.31}_{-0.20};\quad E_{3/2}=0.95\text{ Mev};\quad E_{1/2}=1.35\text{ Mev};$$
$$\Gamma=0.4\text{ Mev};\quad \sigma_0=0.7\times10^{-24}\text{ cm}^2.$$

This curve is represented in Fig. 5 together with two curves corresponding to $x=0.5$ and $x=1.25$, respectively, and the same values of σ_0, $E_{3/2}$ and Γ. It is evident that both structure and height of the resonance peak are distinctly in agreement within their statistical errors for $x=+1.0$. This would, therefore, indicate that if the doublet is inverted the splitting would be $0.4^{+0.12}_{-0.08}$ Mev for the neutrons in the laboratory system.[19] For the two states of He^5 one obtains the corresponding energies by multiplying by $m_{He}/(m_{He}+m_n)$

$$E_{3/2}=0.76\text{ Mev};\quad E_{1/2}=1.08\text{ Mev};$$
$$\Delta E=0.32^{+0.10}_{-0.06}\text{ Mev};\quad \Gamma(He^5)=0.32\text{ Mev}$$

where $E_{3/2}$ and $E_{1/2}$ represent the energies above a separated α-particle and a neutron. The probable errors are estimated from the statistical errors indicated in the figure and the systematic errors arising from matching the four measurements determining the points to the same intensity of the 2.5-Mev line. The theoretical curve was not integrated over 0.2 Mev, since this would not substantially affect its shape.

If one chooses the negative sign of the phase, the curve looks entirely different. In fact, the interference term in formula (2) which is proportional to $\sin\delta_0\cos\delta_0$ and changes its sign with δ, tends, in the case of negative phase, to lower the value of σ_{He}' on the high energy side and to increase it on the low energy side. For positive values of x and negative values of δ the curve shows scarcely any structure.

This influence of one of the interference terms suggests, therefore, that it may be possible that the doublet is normal. If one chooses negative values of the phase and of x, it may happen that for sufficiently large σ_0 the apparent intensities are reversed. This is shown in Fig. 6. A well fitting curve is again obtained with

$$x=-0.75\pm{}^{+0.19}_{-0.25};\quad E_{1/2}=1.05\text{ Mev};$$
$$E_{3/2}=1.35\text{ Mev};\quad \Gamma=0.4\text{ Mev};$$
$$\sigma_0=1.5\times10^{-24}\text{ cm}^2.$$

The corresponding values for He^5 would be

$$E_{1/2}=0.84\text{ Mev};\quad E_{3/2}=1.08\text{ Mev};$$
$$\Gamma(He^5)=0.32\text{ Mev};\quad \Delta E=0.24^{+0.06}_{-0.08}\text{ Mev}.$$

The width $\Gamma(He^5)$ which is found from the present results may be checked against the experiments of William, Shepherd and Haxby[2] on the reaction:

$${}_3Li^7+{}_1H^2\rightarrow{}_2He^5+{}_2He^4.$$

The observed group of α-particles has a width of $\Gamma_\alpha=0.14$ Mev. In order to obtain[20] from Γ_α the width $\Gamma(He^5)$, one has to observe that

$$\Gamma(He^5)=(1+m_\alpha/m(He^5))\Gamma_\alpha=0.25\text{ Mev}$$

which is in good agreement with the present value of 0.32 Mev.

---

[19] Compare previous results given in Phys. Rev. **57**, 936 (1940).

[20] It may be noted that the statement given in (I) that $\Gamma_\alpha=\Gamma(He^5)$ is, of course, erroneous.

The analysis of the experimental data shows that it is not possible within the present accuracy to decide whether the two states of He^5 form a normal or an inverted doublet. However, it is evident that the sign of the splitting is related to the sign of the phase of the S potential scattering. A normal doublet requires a negative phase and vice versa. An investigation of the angular distribution of the helium recoils produced by resonance neutrons would quite easily show the sign of the phase and hence of the splitting. The present cloud-chamber data which are taken with nonmonochromatic neutrons do not allow this procedure. If one assumes that δ does not change its sign between 1 and 2.5 Mev one may obtain its sign according to a suggestion of Ladenburg from measurements of the angular distribution of the recoils at 2.5 Mev. This distribution was found by Ladenburg, Barschall and Kanner[21] to be highly anisotropic, showing a rapid increase of the number of recoils toward small scattering angles of the neutrons. This increase was believed (I) to arise from a small number of slow neutrons in the spectrum of the *dd* reaction. The recent measurements of Ladenburg, Barschall and Kanner show clearly that the anisotropy is not caused by slow neutrons. The steep rise of the recoils with small scattering angles of the neutrons can be explained at least partly by the fact, that at 2.5 Mev there is still a considerable amplitude of the P resonance wave interfering with the S potential wave. One obtains an increase of low energy recoils only if one assumes a negative phase. A positive phase would produce a decrease of the low energy recoils. This would, therefore, indicate that if one assumes that δ does not change its sign between 1 and 2.5 Mev, the He^5 doublet is normal.

Theoretically the doublet structure of He^5 has been investigated by Dancoff.[22] His results show that a doublet caused by the relativistic Thomas force would be inverted but would show a splitting of only some kev. A splitting of several hundred kev as observed can be obtained by calculating the second-order spin-orbit interaction due to the tensor forces. Dancoff showed that in this case the doublet should be normal.

In conclusion, we wish to express our gratitude to Dr. F. Bloch and Dr. N. Bradbury for much helpful discussion and advice during the course of this experiment.

---

[21] We are very much indebted to Professor Ladenburg for the kind communication of his results before publication and the discussion of this point.

[22] S. M. Dancoff, Phys. Rev. **56**, 384 (1939).