cant erratic fluctuations seem to be present in the measurements.

ACKNOWLEDGMENT

The writers thank Dr. Donald H. Andrews for his friendly encouragement of this research, and acknowledge the financial aid of the Research Corporation in the construction of the apparatus used. One of us (R. W. D.) is grateful to the American Can Company for a fellowship, and to the Hynson, Westcott, and Dunning Fund for a grant-in-aid.

JUNE 1, 1940 PHYSICAL REVIEW VOLUME 57

Anomalous Scattering of Neutrons by Helium and the $d-d$ Neutron Spectrum

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(Received March 25, 1940)

An investigation of the variation of the ratio of the scattering cross section of neutrons by helium and hydrogen has been made. Neutrons were obtained from a $d-d$ source partly surrounded by 3 cm of paraffin. The anomalously high cross section in helium at 1.0 Mev was found, and the helium-hydrogen cross-section ratio diminishes to about half this maximum value at 1.4 Mev. No other maxima were observed. The $d-d$ neutron spectrum was also investigated by helium recoils. The spectrum appears to be homogeneous; no evidence was found for a low energy group of neutrons with an intensity as great as 1 percent of the main group. This indicates that He^3 is not formed in an excited state.

IN an investigation of the α-particle spectrum obtained when Li^7 is bombarded by deuterons, Williams, Shepherd and Haxby[1] found that the continuous energy distribution had superposed on it a homogeneous group. The continuous spectrum was supposed to arise from the reaction ${}_3Li^7+{}_1D^2\rightarrow 2{}_2He^4+{}_0n'$, while the homogeneous group was ascribed to the reaction ${}_2Li^7+{}_1D^2\rightarrow{}_2He^4+{}_2He^5$. From the range of this group, the mass of the He^5 formed in the reaction is calculated to be 5.0137, which would make it unstable against disintegration[2] into an α-particle and a neutron by 0.84 Mev.

One may expect the scattering of neutrons by helium to be extremely high when the energy of the neutron is sufficient to produce an intermediate He^5 nucleus in the state formed in the Li^7 reaction; this should occur for a neutron energy of about one Mev, or five-fourths that of the energy of instability of He^5.

Staub and Stephens[3] have made a cloud-chamber investigation of this point by obtaining recoil tracks in helium and in ethane, using neutrons from the reaction ${}_4Be^9+{}_1D^2\rightarrow{}_5B^{10}+{}_0n'$. It is known[4] that this reaction yields four neutron groups, of maximum neutron energies 4.5, 4.0, 2.6, and 1.4 Mev at a bombarding energy of 0.9 Mev. By reducing the bombarding energy to 0.6 Mev, Staub and Stephens reduced the energy of the 1.4-Mev group to about 1.1 Mev at the point of maximum neutron intensity. This is very close to the neutron energy calculated to yield a resonance in the formation of He^5, and hence the ratio of the intensities of helium to proton recoils formed by this group might be expected to be large. This was found to be the case, and the ratio σ_{He}/σ_H of the backward scattering cross section of helium to hydrogen rose to about 9.5 at this point. With the bombarding energy increased to 0.88 Mev, the mean neutron energy of the group becomes 1.3 Mev, and the ratio of the cross sections at this point was observed to be about 6.5. At 2.3 Mev, their next measured point, the ratio dropped to its "normal" value of about 1.4, and remained nearly constant at this value up to about 6 Mev.

[1] 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).

[2] A stable state of He^5 has been reported by F. Joliot and I. Zlotowski, Comptes rendus **206**, 1256 (1938), and J. de phys. et rad. **9**, 393 (1938).

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

[4] T. W. Bonner and G. Brubaker, Phys. Rev. **50**, 308 (1936).

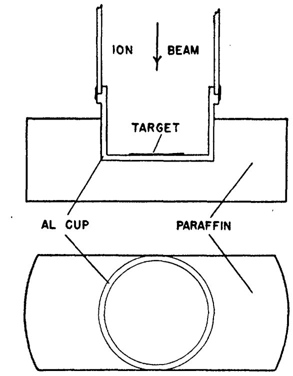

FIG. 1. Top and side views of the neutron source, showing the distribution of paraffin about the target. The cloud chamber was placed about 15 cm to the right.

A neutron group of 0.5 Mev energy from ${}_6C^{12}+{}_1D^2\rightarrow{}_7N^{13}+{}_0n'$ showed a very sharp decline from the maximum at 1.1 Mev, σ_{He}/σ_H having dropped to 0.4. Staub and Stephens point out that the shape of the curve is rather uncertain on either side of the maximum because of the small number of measured points. It was the purpose of the present work to investigate the anomaly further and to obtain more points in the intervals out to 2.5 Mev.

EXPERIMENT

Using apparatus previously described,[5] we have made a cloud-chamber study of recoil protons and recoil helium nuclei produced by neutrons from the $d-d$ reaction. A group of neutrons of mean energy 2.5 Mev results from this reaction, and in order that neutrons of all energies below the maximum might be obtained, the target was surrounded by about 3 cm of paraffin arranged as shown in Fig. 1. This is of sufficient thickness to scatter randomly about one-half the neutrons leaving the target. No paraffin was placed on two sides of the target, since it is desirable to have the source as small as possible.

The target was heavy paraffin, which was bombarded with deuterons of about 140 kev energy. It was necessary to change the targets after about a thousand exposures to the ion beam, since the paraffin became coated with carbon. Three new targets were put in the aluminum cup at one time so that each target change did not require letting air into the system. The ion source was flashed for a fraction of a second at expansion of the cloud chamber, and instantaneous unresolved deuteron currents up to about 400 microamperes were obtained. Approximately 25,000 expansions were photographed in this work. The tabulated track data were corrected for probability of observation in the cloud chamber, since the longer tracks have a smaller probability of having their end-points in the chamber than the shorter ones. The chamber was placed about 15 cm from the neutron source and at 90° to the bombarding beam.

The energy distribution of the helium recoils obtained from twelve thousand stereoscopic pictures is shown in Fig. 2. The chamber was operated with water vapor and helium at about one atmosphere pressure. It is necessary to operate the chamber at a low pressure in order that the energy of the recoils produced may be more accurately resolved into small intervals. The stopping power of the gas was 0.32, calculated from the known range of the neutrons from the $d-d$ reaction and the energy-range relations of Holloway and Livingston.[6] The tracks were tabulated in 2-mm intervals, which corresponds to α-particle energy intervals of about 0.13 Mev, or neutron energy intervals of about 0.2 Mev. Tracks measured were in the forward direction (0–15°) and had a length in the chamber from 8 to 30 mm. The energy-number distribution shown in Fig. 2 was obtained by reducing the 2-mm range intervals of the recoil α-particles to the corresponding neutron energy intervals.

The experiment described above was repeated with no change in conditions except that methane and alcohol were used in the cloud chamber.

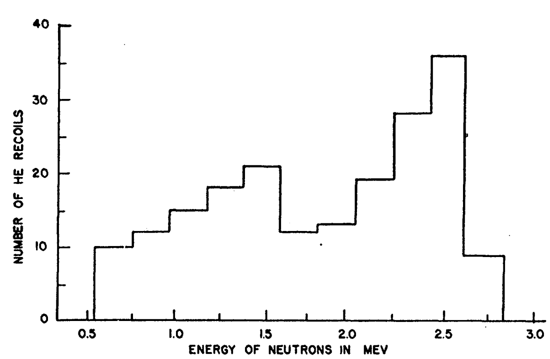

FIG. 2. Number of helium recoils observed as a function of the neutron energy producing the recoils.

[5] T. W. Bonner, Phys. Rev. **52**, 685 (1937).

[6] M. G. Holloway and M. S. Livingston, Phys. Rev. **54**, 31 (1938).

The stopping power of this mixture was found to be 1.03.[7] About 3500 expansions were photographed and 173 recoils in the forward direction were measured. This serves to determine the distribution of the neutrons quite well at energies up to about 2 Mev, but beyond this point the tracks are so long that the correction factor for probability of observation in the 13.5-cm chamber is quite large. In order to determine more accurately the neutron distribution above 2 Mev, photographs were made when the cloud chamber was filled with about 80 percent ethane and 20 percent argon to a total expanded pressure of about 80 cm. Argon was added in order to lower the expansion ratio. The stopping power of the mixture was found to be 1.66, and 273 recoils were measured on 1800 photographs.

The proton recoils obtained in methane and in ethane were tabulated in energy intervals corresponding to the energy intervals of the helium recoils observed previously. The distribution in methane agreed within a few percent with that obtained in ethane above one Mev when the curves were corrected to equal energy intervals. In the lowest energy interval (about 0.6 Mev), only the methane data were used, since the recoils in ethane at this point were only about 6 mm long. In each of the next two intervals about twice as many tracks were observed in methane as in ethane, but this discrepancy might well arise from statistical error, since the number of tracks in this region is small. The two curves were therefore added together, and the results are shown in Fig. 3.

In order to obtain the ratio of cross sections for helium and hydrogen at various energies, the number of recoils shown in a given interval of Fig. 2 were divided by the number of recoils in the corresponding interval in Fig. 3. As a measure of the absolute ratio, the value 1.4 at 2.5 Mev had previously been determined by Staub and Stephens[3] by using an ionization chamber and amplifier, and also by photographing recoils produced in a mixture of methane and helium in a cloud chamber. This value was used in our experiment as the correct ratio of the absolute scattering cross sections at 2.5 Mev, and the results at the other energy intervals are shown in Fig. 4.

[7] The range-energy relation given by M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. **9**, 268 (1938) was used.

Conclusions

It will be observed from Fig. 4 that the maximum at one Mev is in agreement with that obtained by Staub and Stephens.[3] Their result at this point, however, is accurate to a smaller probable error because of the large number of recoils observed. For thermal neutrons, Carroll and Dunning[8] have found σ_{He}/σ_H to be 0.05, but for neutron energies from zero to 0.5 Mev the form of the curve is not established. This region would be extremely difficult to investigate by use of a cloud chamber, since the reduced chamber pressure necessary to obtain tracks of sufficient length to measure accurately would entail a large number of photographs. An electroscope study of carbon neutrons would probably be more satisfactory.

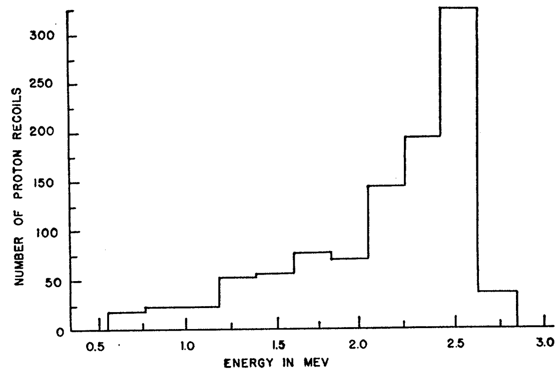

FIG. 3. Number-energy distribution of recoil protons produced in methane and in ethane.

Beyond 1.1 Mev the curve shows no indication of a maximum, falling to half the 1.0 Mev maximum at about 1.4 Mev. The points in the region are accurate to an estimated error of about 25 percent, while the accuracy is somewhat better at higher energies where more recoils were observed.

The absolute cross section for hydrogen at points below 2 Mev is not experimentally well known, but may be calculated from the Wigner formula.[9] According to this relation, the cross section below 2 Mev increases rapidly with

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

[9] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 117 (1936).

decreasing neutron energy, reaching one-half the thermal neutron value at about 100 kev. This relation must of course be known in order to calculate the absolute helium cross sections from Fig. 4

The $d-d$ Neutron Spectrum

Bonner[10] has observed the neutrons from the $d-d$ reaction by using a cloud chamber filled with methane. In addition to the recoils arising in the chamber from the 2.5-Mev neutrons from the reaction, a second group of low energy recoils, of about $\frac{1}{10}$ the intensity of the 2.5-Mev group, was found. It was assumed that these were produced by low energy neutrons coming from the $d-d$ reaction and that the He^3 produced simultaneously was left in an excited state of about 1.89 Mev. Attempts to find the γ-ray of an intensity which might be expected when the He^3 drops to the ground state were not successful.[11]

Baldinger, Huber and Staub[12] have made an ionization chamber analysis of the neutrons from this reaction. The ionization chamber was filled with helium, and recoil α-particles were recorded by an oscillograph operated by a linear amplifier. They also found a group of low energy recoils at an energy of 1.1 Mev, in agreement with the energy of the group observed by Bonner. It appeared to have an intensity about equal to that of the high energy group, but in view of the anomalously high scattering cross section for neutrons of this energy in helium, the ratio of the number of helium recoils in the low energy group with respect to the number of recoils in the high energy group is much larger than the true relative neutron intensities. When the proper corrections for relative scattering cross section were applied,[3] the neutron intensity of the low energy group was found to be 11 percent of the main peak. This result appeared to be in good agreement with the intensity observed by Bonner.[10]

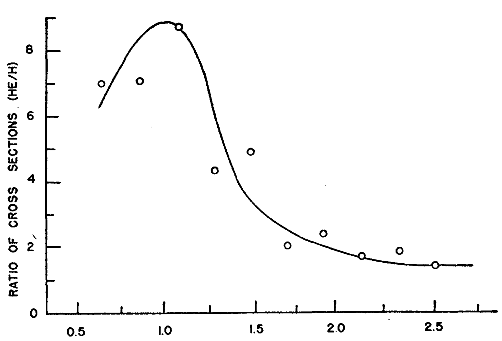

Fig. 4. Ratio of the backward scattering cross section for neutrons by helium and by hydrogen as a function of the neutron energy.

A further study by the authors[13] of this low energy group was made by observing the recoils produced in a chamber filled with hydrogen, where the recoils produced much longer tracks. It was found that the group was well defined, falling to zero on either side of 1.1 Mev, and the intensity agreed with previous work. In further work, Bonner[14] found that two groups were observed in both hydrogen and helium.

Because of the anomalous cross section in helium at the energy of the low intensity group, the effect of a continuous background of inelastically scattered neutrons would be observed as a group at this point. The existence of a low energy group of neutrons from the $d-d$ reaction leads to theoretical difficulties in regard to excited He^3, as Share[15] and Schiff[16] have emphasized. Furthermore, if such an excited state exists in He^3, one might reasonably expect a corresponding level in H^3, but no evidence for this has been found.[17]

In view of these facts, we have made further observations on the neutrons from the $d-d$ reaction. A cloud chamber filled with helium and water vapor was operated at atmospheric pressure. The chamber is the rubber diaphragm type, has glass walls only $\frac{1}{8}$ inch thick, and is of light construction. Velvet placed on a perforated plate above the diaphragm serves as a background for photographs. With the chamber placed at 90° to the 140-kev deuteron beam and 15 cm from the target, 3200 expansions showed 74 α-recoils within 15° of the forward direction.

[10] T. W. Bonner, Phys. Rev. **52**, 685 (1937) and **53**, 711 (1938).
[11] A. J. Ruhlig, Phys. Rev. **54**, 308 (1938); H. Kallmann and E. Kuhn, Naturwiss. **26**, 106 (1938); S. Kikuchi and H. Aoki, Proc. Phys.-Math. Soc. Japan **21**, 20 (1939).
[12] E. Baldinger, P. Huber and H. Staub, Helv. Phys. Acta **11**, 245 (1938).
[13] E. Hudspeth and H. Dunlap, Phys. Rev. **55**, 587 (1939).
[14] T. W. Bonner, Nature **143**, 681 (1939).
[15] S. Share, Phys. Rev. **53**, 875 (1938).
[16] L. I. Schiff, Phys. Rev. **54**, 92 (1938).
[17] F. E. Myers and L. M. Langer, Phys. Rev. **54**, 90 (1938); E. Hudspeth and T. W. Bonner, Phys. Rev. **54**, 308 (1938).

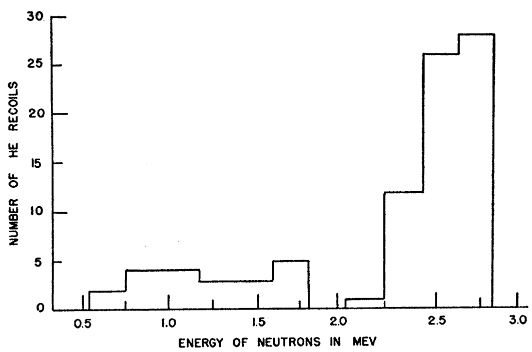

FIG. 5. The d–d neutron spectrum as observed in helium at 90° to the bombarding beam.

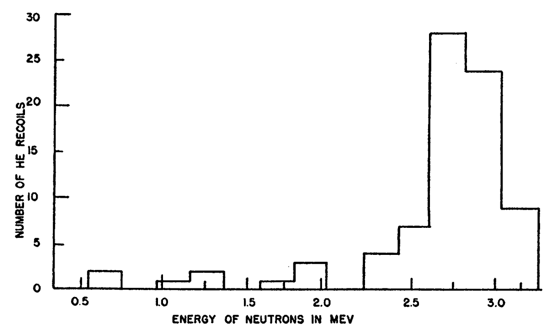

FIG. 6. The d–d neutron spectrum as observed in helium at 51°, under conditions identical with previous work by Baldinger, Huber and Staub.

These were distributed as shown in Fig. 5. Fourteen recoils were below 1.5 Mev energy, which yields a neutron intensity in this region of less than 4 percent of the main group. This is higher than the background which might be expected with this apparatus, but it was found that the bombarding beam was striking the glass tube near the target. The beam intensity is sufficient to melt the paraffin target and make thin depositions on this glass tube, and it is believed that some of the neutrons tabulated in Fig. 5 came from there. This difficulty was overcome by adding a defining slit to the tube.

The experiment of Baldinger, Huber and Staub[12] was then repeated by observing recoils produced in a helium-filled chamber placed at 51° to the bombarding beam and using a bombarding voltage of 130 kv; this duplicates the conditions under which they observed helium recoils by use of an ionization chamber. Four thousand expansions yielded the data shown in Fig. 6. Of a total of eighty recoils observed, only five have energy below 1.5 Mev. After correction for cross-sectional variation with neutron energy, it is found that this represents an intensity of neutrons in this region of less than 2 percent of the intensity of the main group. This can easily be accounted for as due to scattering of the high energy neutrons.

It therefore appears that the low energy group of recoils which have been previously observed in helium must be attributed to the effect of the anomalous cross section on a neutron background produced by inelastic scattering. This assumption, however, would not explain the two groups which have been observed in cloud chambers filled with methane[10] and hydrogen.[13] In this connection it is interesting to note that the low energy recoils are of the range one would expect from a deuteron produced by proton capture of a 2.5-Mev neutron. The cross section for such a capture at this energy is, however, on present theoretical grounds, extremely small, being of the order of 10^{-29} cm^2, or about 10^{-5} the cross section for scattering. Recoils produced by capture would always proceed in the forward direction with respect to the impinging neutron, while only 1/33 of the recoils produced by scattering are in the forward direction (0–10°). Hence the ratio of capture to scattering in the forward direction becomes about 3.3×10^{-4}, a theoretical value still too small to account for the relative intensity of the two recoil groups which have been observed. Such a capture would of course also give rise to a γ-ray, with an energy of approximately 3.5 Mev.

It is now planned to study the neutron recoils from the $d-d$ reaction by use of a cloud chamber filled with deuterium and compare the results with those obtained under identical conditions with a hydrogen-filled chamber. Such results should show whether neutron capture by protons is an appreciable factor with respect to neutron-proton scattering at 2.5 Mev.

Acknowledgments

We wish to express our sincere appreciation to Professor H. A. Wilson for his help and interest in this work, and to Dr. T. W. Bonner for his valued advice and suggestions.

We wish to thank Mr. Franz van der Henst and Mr. Pierson deVries for their assistance as machinists.