Neutron-Proton Scattering and the Disintegration of Deuterium by Deuterons

T. W. BONNER
Rice Institute, Houston, Texas
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The angular distribution of the scattering of neutrons by protons has been observed by the method of recoil protons in a cloud chamber. The source of neutrons was the reaction ${}_1H^2+{}_1H^2\rightarrow{}_2He^3+{}_0n^1+Q_1$ which gave 2.6 Mev neutrons at right angles to the bombarding deuterons. The value of Q_1 was found to be 3.36 ± 0.20 Mev. The recoil proton distribution showed a maximum at 45° as measured in laboratory coordinates. The distribution agreed with the theoretical one which predicts a spherical symmetry with respect to the center of mass of the moving system.

THE angular distribution of the neutrons scattered by protons is of fundamental significance since such a distribution will tell us whether the present ideas of neutron-proton interaction are correct. Numerous experiments[1] have been carried out to determine this angular distribution. Experimentally there are two different methods of attack. The first method is the observation of the scattered neutrons and the second method is the observation of the recoil-protons projected by the neutrons. At present the second method of observing the angular distribution of the recoil protons (usually observed in a cloud chamber) seems capable of greater precision than the first method. Of course the same information would be obtained by either method, since the distribution of the scattered neutrons is uniquely determined by the distribution of recoil protons.[2]

Many experiments on the angular distribution of recoil-protons (from neutrons) have been carried out with highly contradictory results.[1] The interpretation of most of the earlier results has been complicated by two factors. First, neutrons of widely differing energies have usually been employed and, second, much scattering material has been present near the neutron source and cloud chamber. For the latter reason many of the neutrons did not come directly from the source.

In view of the difficulties inherent in the earlier results, the present experiment was undertaken for the purpose of obtaining data under better experimental conditions. The source of neutrons was the nuclear reaction

$$ {}_1H^2+{}_1H^2\rightarrow{}_2He^3+{}_0n^1+Q_1. \qquad (1)$$

This reaction is known to give neutrons which have an energy of about 2.5 Mev.

Experimental Arrangement

The experimental arrangement for the production of neutrons is shown in Fig. 1. The source of potential was a 200 kv kenetron rectifier doubler circuit of the Cockcroft and Walton type. The ion source was a filament controlled low voltage arc. It was similar in design to one described by Crane.[3] The ion source was operated in synchronism with the cloud chamber so that ions only came down the tube at the time of expansion of the chamber. With such an arrangement a total ion current of 200 microamperes reached the deuterium target. The ion spot on the target was less than a cm in diameter.

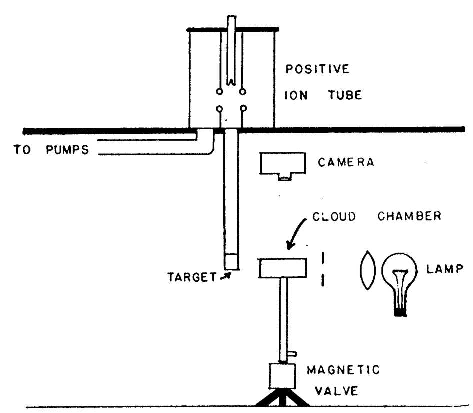

FIG. 1. Diagram of apparatus.

[1] Kurie, Phys. Rev. **44**, 463 (1933); Monod-Hertzen, J. de phys. **5**, 95 (1934); Meitner and Philipp, Zeits. f. Physik **87**, 484 (1934); N. Dobrotin, Comptes rendus de L'Acad. des Sci. U. S. S. R. **4**, 179 (1934); Harkins, Kamen, Newson and Gans, Phys. Rev. **50**, 980 (1936); Kruger, Schoupp and Stallman, Bull. Am. Phys. Soc. April (1937); Lampson, Mueller and Barton, Bull. Am. Phys. Soc. April (1937).

[2] Assuming the conservation of energy and momentum in the collision.

[3] H. R. Crane, Phys. Rev. **52**, 11 (1937).

Since it was only important to get as large a yield of neutrons as possible, no magnetic analysis was made on the ion beam. The deuterium target was made from a mixture of P_2O_5 and heavy water. This target was placed in a thin brass cup at the end of the ion tube. When such a target was bombarded continuously by large ion currents, it lasted only a short time. However, phosphoric acid targets lasted for a much longer period when the current was flashed only during the sensitive time of the chamber.

The cloud chamber, which was used to observe the recoil protons, was of the rubber diaphragm type. All the parts of the chamber were made as light as possible to reduce neutron scattering by such material. The electromagnetic valve, which was opened to produce the expansion, was 80 cm below the cloud chamber. The chamber was 17 cm in diameter and 4.5 cm deep. The distance from the ion spot to the center of the chamber was 18.5 cm. The cloud chamber was filled with a mixture of CH_4 and C_2H_6 at an expanded pressure of 1.1 atmospheres. The stopping power of the gas mixture was determined by using the alpha-particles from polonium as a standard.

Results

One thousand stereoscopic pairs of pictures were taken when the tube was operated at a potential of 100 kv; on these pictures 303 recoil proton tracks were measured. This measurement included the track length and the angle of projection of the recoil proton assuming that the neutron came directly from the ion spot on the deuterium target. The probable errors in the measurements were approximately 1 mm in track length and 5° in the angle of projection.

Calculation of the Energy of the Neutrons

The energy of the neutrons can be determined in two different ways. One method is to calculate the energy of the neutron from the relation $E_H = E_N \cos^2\phi$, where E_H is the proton energy, E_N the neutron energy, and ϕ the angle of projection of the proton. Another and more reliable method is to use only those tracks which are in nearly the forward direction and to make no correction for the $\cos^2\phi$ factor. When ϕ is small the value of $\cos^2\phi$ is nearly unity so the recoil protons have essentially the energy of the primary neutrons. Fig. 2 gives the distribution with energy of the recoil protons in the forward direction $(0-21°)$. This curve indicates a neutron group with an energy of 2.60 ± 0.15 Mev which is approximately the result obtained in the experiments of Bonner and Brubaker.[4] There is also some indication of a weaker group at about 1 Mev. However, further work will have to be done in order to be certain whether these low energy neutrons come from reaction (1) in which the He^3 nucleus is left in an excited level of about 2 Mev.

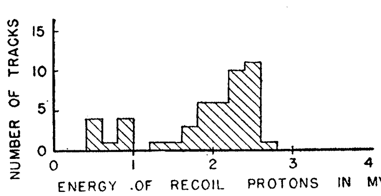

FIG. 2. Energy distribution of the recoil protons in the forward direction (0°–21°).

The energy of disintegration Q_1 can be calculated from the neutron energy of 2.60 ± 0.15 Mev observed at an angle of $90° \pm 10°$ to the direction of the 100 kv deuterons. This value of $Q_1 = 3.36 \pm 0.20$ is a little greater than that given by Bonner and Brubaker. However, it is believed that the new value is more reliable since the stopping power of the gas was determined with polonium alpha-particles.[5]

Figure 3 gives the calculated energy distribution of the neutrons when all the tracks were used and corrected for the $\cos^2\phi$ term. There is a maximum in the curve at 2.5 Mev. There are also neutrons with calculated energies extending far beyond the known end point. This of course is to be expected because of the errors in determination of ϕ[6] and because of a few recoil protons from "scattered neutrons." Although such a method is obviously not reliable for getting neutron energies, it does indicate that there are some low energy neutrons present. This conclusion is inferred from the fact that there are

[4] Bonner and Brubaker, Phys. Rev. **49**, 19 (1936).

[5] A correction of three percent was applied for the difference in stopping power of the gas for particles of 10 cm and 3.8 cm range.

[6] If an error is made in the determination of ϕ for a recoil proton, the calculated neutron energy will have a larger error the greater the value of ϕ. For example, if the angle of projection of a proton recoiling from a 2.6 Mev neutron were measured as 60°, but actually was 50°, the calculated energy of the neutron would be 4.3 Mev.

more calculated neutron energies less than 2.5 Mev than with greater energies.

The disintegration energy of reaction (1) together with reaction

$${}_1H^2+{}_1H^2 \rightarrow {}_1H^3+{}_1H^1+Q_2 \qquad (2)$$

gives an experimental method for getting the difference between the binding energies of He^3 and H^3. This difference is equal to Q_2-Q_1. If neutron-neutron forces are equal to proton-proton forces, then the difference in the binding energies of He^3 and H^3 should alone be due to the Coulomb repulsion between the two protons in He^3. Bethe[7] has shown that the experimental values of Q_1 and Q_2 are consistent with this viewpoint.

The value of Q_2 has been accurately determined by Oliphant, Kempton, and Rutherford,[8] and is 3.97 ± 0.02 Mev. If the new value of Q_1 is used, the difference between Q_2 and Q_1 is 0.61 Mev instead of 0.76 Mev. This is very nearly the expected value of the Coulomb factor as given by recent theoretical calculations.[9]

Angular Distribution of the Recoil Protons

The angular distribution of the recoil-protons is shown in Fig. 4. The data are plotted in two

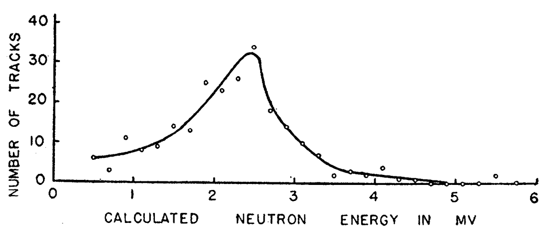

Fig. 3. Distribution of calculated neutron energies.

ways. The open circles represent the distribution with angle of all the measured tracks. Such a distribution should be the correct one if all the neutrons which traversed the chamber came directly from the source and if all recoil protons were observable independent of the angle of projection. With the present experimental arrangement, protons projected by 2.6 Mev

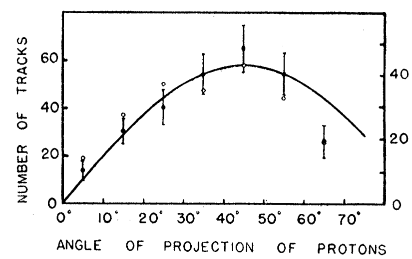

Fig. 4. Angular distribution of the recoil proton tracks. Ordinates on the left side of the graph refer to the open circles; these include all measured tracks. Ordinates on the right refer to the closed circles; these include only those tracks which satisfy the momentum conditions.

neutrons at an angle of 70° would have a track length of 0.5 cm and so would usually be distinguishable. Tracks shorter than this would generally have been missed. Lower energy neutrons, whose presence is indicated, would not have been observable at large angles and so would distort the curve toward the small angles. All the observed tracks were not used because of the low energy neutrons and also because a few neutrons did not come directly from the source (of the order of 5 percent). All tracks were rejected which were not consistent with a 2.6 Mev neutron energy assuming a possible error of as much as 10° in ϕ and one mm in track length.[10] Ninety-six of the observed tracks were rejected for this reason.

The corrected distribution of the recoil protons is given in Fig. 4. The smooth curve of Fig. 4 gives the theoretical distribution of the recoil protons in laboratory coordinates. This corresponds to a spherical symmetry with respect to the center of mass of the moving system. Such a distribution should be expected since the de Broglie wave-length of 2.6 Mev neutrons is large with respect to the currently accepted range of interaction of the neutron-proton forces. The experimental points agree with the theoretical curve within the probable errors. The fact that the experimental point at 65° is too low may be attributed to missing some of the shorter range protons.

In conclusion it may be said that the experiment indicates that there is no large deviation from theory in the scattering of 2.6 Mev neutrons by protons.

[7] Bethe and Bacher, Rev. Mod. Phys. **8**, 82 (1936).

[8] Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **A149**, 406 (1935).

[9] Bethe and Bacher, Rev. Mod. Phys. **8**, 82 (1936); Share, Phys. Rev. **50**, 488 (1936), Rarita and Present, Phys. Rev. **51**, 788 (1937).

[10] Tracks which ended in the walls of the cloud chamber were said to be consistent with this criterion unless they gave neutron energies that were too great.