The Yield Function and Angular Distribution of the D+D Neutrons

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The thin target yield of neutrons from the D+D reaction has been measured for deuteron energies 0.5–1.8 Mev. The neutron yield in the forward direction increases smoothly throughout the interval, but the yield at 80° to the bombarding beam remains almost constant. Values of A in the expression $(1+A\cos^2\theta)$ representing the angular distribution of the neutrons in the c.g. system are calculated from the yield data and plotted as a function of voltage. A is found to increase from 1.8 at 0.5 Mev deuteron energy to 3.4 at 1.8 Mev.

THE yield of neutrons from the D+D reaction has been measured at low voltages in a number of experiments. The yield curve was extended to 300 kev by Roberts[1] and to 1 Mev by Amaldi, Hafstad, and Tuve.[2] Thick targets were used in both experiments. Thin target yields can be calculated from the thick target data, as was done by Reddemann,[3] by differentiating the curve and correcting for variation of the rate of energy loss of the deuterons in the target material. The results are less accurate than thin target data taken directly.

Closely connected with the measurement of the number of neutrons from the D+D reaction is the variation of yield with angle. For example, the results of Roberts were taken in the forward direction, but they could be corrected to give total neutron yields if the variation of angular asymmetry with voltage were known. Kempton, Browne, and Maasdorp[4] have shown that in the center of gravity coordinate system the yield at low voltages in the forward direction is $\frac{3}{2}$ the yield at 90° to the bombarding beam. At higher bombarding voltages this ratio increases. Richards[5] found the yield at 0° to be 2.8 times the yield at 90° for a bombarding voltage of 0.7 Mev.

The production of protons by the D+D reaction is believed to be a very similar process to the production of neutrons.[6] The absolute yields of the two kinds of particles are approximately the same.[7] The variation of yield with voltage is very similar,[1] and the angular asymmetry is the same at corresponding voltages.[4] It has been shown[8,9] that the angular distribution of protons can be represented by the expression $(1+A\cos^2\theta)$, where θ is the angle in the coordinate system in which the center of gravity is at rest and A is a constant which may, however, vary with voltage. A has been found to increase with voltage up to 400 kev.[10] It is highly probable that the angular distribution of neutrons can be represented by the same expression.

Myers[6] has obtained a theoretical value for A which is in reasonable agreement with the experimental values at 100 kev. The agreement confirms the view that the intermediate nucleus formed by the coalesence of two deuterons is in a P state. Feenberg[11] has given reasons to expect an excited P state of the alpha-particle at about the dissociation energy.

The present experiment was undertaken to measure the variation of the yield of neutrons with bombarding voltage when thin targets were used. It was also desired to measure the dependence of the angular asymmetry upon voltage. Such measurements might be expected to give evidence of excited states in the alpha-particle, particularly of the level predicted by Feenberg.[11]

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EXPERIMENTAL ARRANGEMENT

The Rice Institute pressure Van de Graaff electrostatic generator was used to obtain beams of deuterons up to 2.2 Mev in energy. The accelerating voltage was measured by an electrostatic voltmeter, the measurements being reproducible to one-half of one percent. The voltmeter was calibrated against the Wisconsin voltage measurements from the published values[12] of the gamma-ray resonances of fluorine bombarded by protons, particularly the resonance at 1.363 Mev. The atomic beam was deflected through 90° in the magnetic analyzer in such a way that the target and detecting devices were shielded from radiation from the high voltage apparatus by a concrete wall one foot thick. A schematic diagram of this arrangement is shown in Fig. 1 of a previous paper.[13] The deuteron beam on the target was measured by a current integrator of the neon discharge type.[14]

The target was deuterium gas. The gas chamber is illustrated in Fig. 1. It was 2.6 cm deep and was separated from the vacuum system by an aluminum foil. The deuteron beam was reduced in energy by passing through this foil which was 1.40 mg/cm² in thickness. It was supported by microphone screening with a transmission coefficient of 20 percent.

A Wulf bifilar type electroscope was used to detect neutrons by measuring the ionization produced in methane by recoil protons. The electroscope was cylindrical in shape, 3 in. inside diameter and 4 in. long. Its walls were of one-half inch thick iron. The two silvered quartz fibers were 0.01 mm in diameter, and they were repelled by charging them to 360 volts. The electric field was, therefore, not great enough to collect ions very efficiently except in the immediate neighborhood of the fibers. This restriction of the sensitive region meant that neutrons were measured at fairly sharply defined angles since the electroscope fibers were 16.6 cm from the center of the gas target. Wall effects in the neutron detector were eliminated by filling the electroscope with 300 lb. pressure of methane (13 percent ethane). The resultant stopping power limited the range of the highest energy recoil protons to 1.7 cm which range was less than the distance from the wall to the most sensitive region.

There may be some question as to whether the ionization currents as measured in the electroscope were proportional to the actual ionization when the conditions were so far from saturation. The electroscope was checked with two radium sources and the extreme variation from linearity was less than 5 percent over the range used. Should it be worse for ionization by protons, the chief effect would be to make our values for angular asymmetry slightly too small.

RESULTS

Ionization was measured as a function of voltage at 0° and at 80° to the direction of the bombarding beam. In both directions the distance from the middle of the gas chamber to the near wall of the electroscope was 11.57 cm. Measurements were taken at 80° instead of 90° so that the correction to 90° in the center of gravity coordinate system would be small.

The aluminum foil and the carbon deposited on the foil and in the microphone screening gave a considerable yield of neutrons when bombarded by deuterons. To correct for this, a definite procedure was adopted. Deuterium gas was let into the target chamber and its pressure was read on a Bourdon gauge. Several measurements were made of the total ionization during bombardment. The gas was then pumped out, and the background was measured immediately. The net effect was divided by the pressure of deuterium.

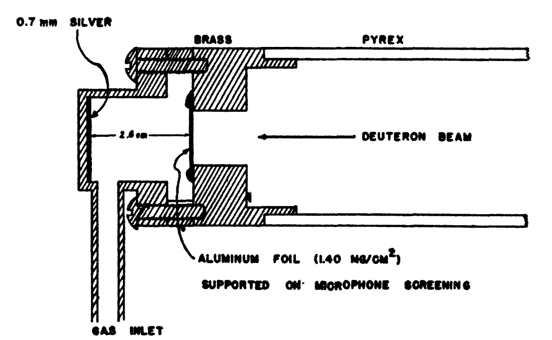

FIG. 1. Diagram of the deuterium gas target. The neutron detector was 16.6 cm from the middle of the gas chamber.

[12] E. J. Bernet, R. G. Herb, and D. B. Parkinson, Phys. Rev. **54**, 398 (1938).
[13] W. E. Bennett, T. W. Bonner, E. Hudspeth, H. T. Richards, and B. E. Watt, Phys. Rev. **59**, 781 (1941).
[14] B. E. Watt, Rev. Sci. Inst. **12**, 362 (1941).

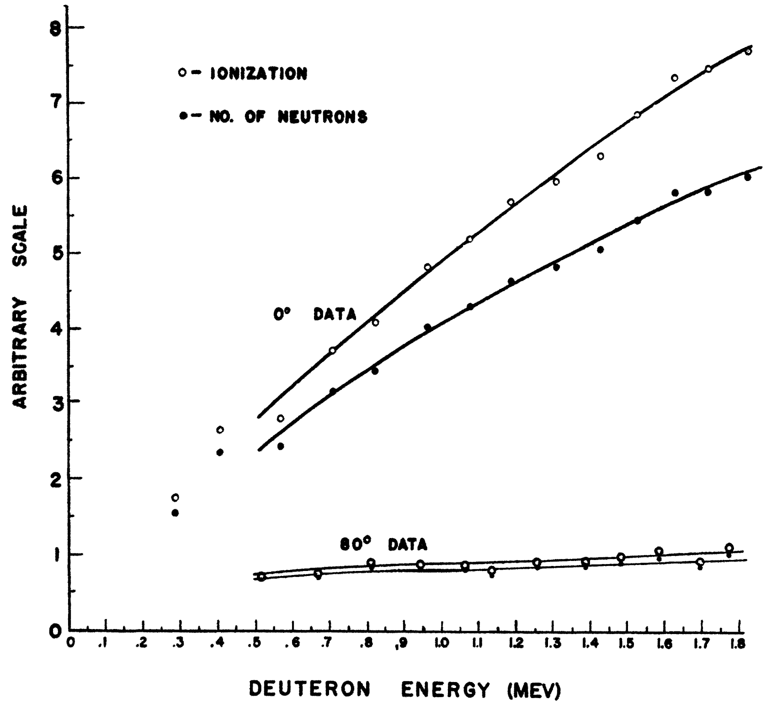

FIG. 2. Experimental yield data. The open circles refer to the ionization produced by recoil protons in a methane filled electroscope. The solid circles represent the number of neutrons per unit solid angle in room coordinates. The number of neutrons was obtained by dividing the ionization effects by the neutron energy and then correcting for the $n-p$ scattering cross section. The deuteron energy is the mean energy of the beam in the gas target.

Pressures of the order of 10 inches of mercury were used in taking the 0° data and the low energy data at 80°. At higher voltages the target thickness was made twice as great to increase the effect from deuterium as compared to the background. The high background was the chief limitation on the accuracy of the results, since at 0° it became equal to the effect from deuterium at the highest voltages, and at 80° it became three times greater. However, the results are believed to be accurate to 2 percent at 0° and to 5 percent at 80°. This mean error was estimated from the reproducibility of several values which were repeated a number of times. All points were checked at least once.

The deuterium gas supplied by the Stuart Oxygen Company was known not to be pure; when it was used in an ion source, the proton beam was of the order of 10 percent of the deuteron beam. Its density was found to be 6 percent higher than expected for pure gas. If the heavy impurity was air, it amounted to 2 percent by volume. A gas analysis showed the presence of oxygen and nitrogen in the proportions of air and amounting to 3 percent by volume. The neutron yield from atmospheric air was 9.5 times the yield from a corresponding pressure of deuterium at 80° and 1.7-Mev bombarding energy. To eliminate this large source of error, the deuterium gas was purified by passing it over hot magnesium on the way to the target chamber. To verify that the air was removed quantitatively, additional air was introduced, and its removal was checked on the electroscope. No magnesium was used when the 0° data were obtained, but measurements were taken at several voltages with air in the target chamber, and the 0° data were corrected on the basis of 2.5 percent air in our deuterium. These corrections amounted to less than 4 percent.

The final results for ionization as a function of voltage are plotted in Fig. 2. The voltage recorded is the mean energy of the deuteron beam as it passed through the deuterium gas of the target. This was obtained from the accelerating voltage by subtracting the loss of energy of the deuterons in the aluminum foil and half the energy loss in the deuterium target. The range-energy relation for protons in aluminum obtained by Parkinson, Herb, Bellamy, and Hudson[15] was used with the usual assumption that a deuteron has twice the range of a proton of half the energy. The stopping

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

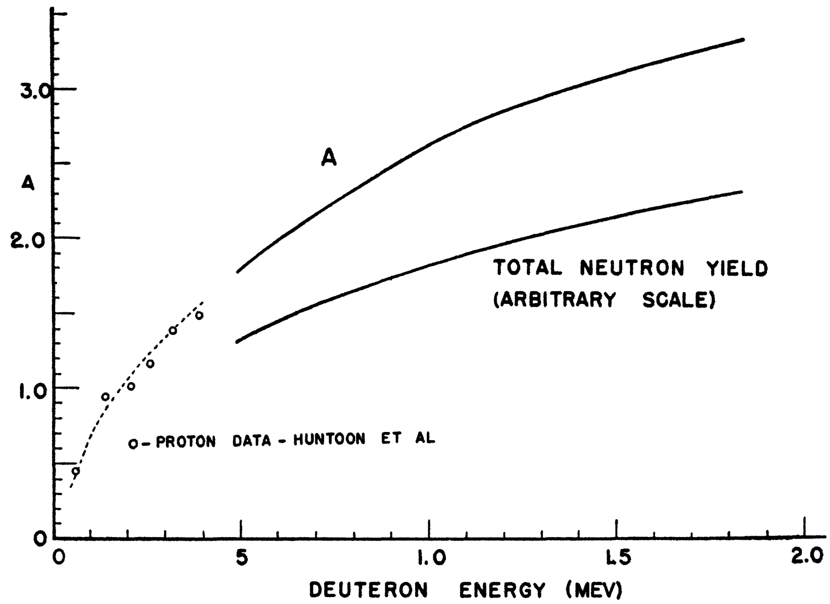

FIG. 3. Variation with voltage of the asymmetry in angular distribution of the neutrons. A is the coefficient of the $\cos^2\theta$ term in the expression for the angular distribution of the neutrons in the c.g. system: $N(\theta)=B(1+A\cos^2\theta)$. The total neutron yield is calculated from the yield at 0° on the assumption that the angular distribution of the neutrons is given by the above expression.

power of deuterium was taken from the data for hydrogen given by Livingston and Bethe.[16]

Figure 2 also shows the yield of neutrons as a function of voltage. To obtain this, the amount of ionization was divided by the energy of a neutron from the D+D reaction at the appropriate voltage and angle, and by the cross section for collision between a neutron of that energy and a hydrogen nucleus. The simplest expression[17] for the cross section (but with $\epsilon'=0.12$ Mev) was considered adequate over the limited range used. The neutron yield given in Fig. 2 will be useful in other experiments where the D+D reaction is used as a thin target source of neutrons.

The yield of neutrons at 80° is so small that an appreciable part of the measured yield might be neutrons produced in the forward and backward direction but scattered toward the electroscope by materials in the room. To check this, the inverse square law was tested in the 80° direction and the result showed that 95 percent of the net effect in the electroscope was produced by radiation from the target itself.

If the angular distribution of neutrons in the center of gravity coordinate system is represented by the expression $B(1+A\cos^2\theta)$, then it is possible to calculate A as a function of voltage from the smoothed curves given in Fig. 2. The neutron yields were first transformed into the center of gravity coordinate system by multiplying by the ratio of the solid angle in the c.g. system to the solid angle in room coordinates,

$$\frac{\sin\theta' d\theta'}{\sin\theta d\theta}=\frac{E_d^{\frac{1}{2}}\cos\theta[6Q+3E_d-E_d\sin^2\theta]^{\frac{1}{2}}+3Q+2E_d-E_d\sin^2\theta}{[\frac{3}{2}(Q+\frac{1}{2}E_d)(6Q+3E_d-E_d\sin^2\theta)]^{\frac{1}{2}}},$$

where θ' and θ refer to the angle in the c.g. system and room coordinates respectively, E_d is the energy of the bombarding deuterons, and $Q=3.31$ Mev.[18] The angle zero is the same in both coordinate systems but the angle 80° in room coordinates becomes an angle in the c.g. system which is a function of bombarding voltage,

$$\cos\theta'=\frac{V_n\cos\theta-\frac{1}{2}E_d^{\frac{1}{2}}}{[\frac{3}{2}(Q+\frac{1}{2}E_d)]^{\frac{1}{2}}},$$

where V_n is the velocity of the neutron in room coordinates. Figure 3 shows the values of A thus calculated from the neutron yield curves of Fig. 2. For comparison the values of A for protons[10] are plotted on the same figure.

[16] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 274 (1937).
[17] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. 8, 117 (1937).
[18] T. W. Bonner, Phys. Rev. 59, 237 (1941).

Figure 3 also shows the total neutron yield on an arbitrary scale as a function of voltage. This was obtained by dividing the neutron yield at 0° in the c.g. system by $(1+A/3)$. The total neutron yield is, of course, the same in either coordinate system.

DISCUSSION

The targets in these experiments were "thin." For the 0° data the loss of energy by the deuteron beam in passing through the target varied from 230 kev at 0.56 Mev deuteron energy to 110 kev at 1.83 Mev deuteron energy. For the 80° data the target thickness varied from 320 kev at 0.52 Mev deuteron energy to 180 kev at 1.83 deuteron energy. The aluminum foil which separated the target from the vacuum system had an average thickness of 260 kev at the highest bombarding energy and was of course thicker at lower energies. These thin foils are known to be rather non-uniform; it was, in fact, difficult to find a square centimeter of it which did not have visible holes. This non-uniformity made the incident beam heterogeneous in energy and added quite appreciably to the effective thickness of the target at low energies. For this reason, points below 0.5 Mev on the 80° data were thrown out because they were apt to be low if the yield at 80° turns sharply down at lower voltages.

Reddemann's calculations[3] of the thin target yields from the thick target data of Amaldi, Hafstad, and Tuve[2] do not agree with our results. He finds that the yield is constant or decreases slightly with increase of voltage between 0.5 and 1.0 Mev while we find a 40 percent increase in total yield. This difference is not in the right direction to be caused by the non-spherically symmetric distribution of thermal neutrons in the water tank used by Amaldi, Hafstad, and Tuve. However, the discrepancy could be caused by rather small experimental errors in the thick target curve, and it is probable that calculations of the type performed by Reddemann are not justified by the accuracy of the data.

The smooth juncture of the values of A for protons and for neutrons, shown on Fig. 3, is further evidence that these two particles are produced in similar processes. The early conclusion[4] that A for neutrons was not a function of voltage led to theoretical difficulties outlined by Schiff[19] which are now clearly removed. We can conclude that the yield curve for the D+D reaction gives evidence concerning a P state of the alpha-particle. The middle of the resonance seems to be at higher bombarding energies than we have attained, but the total yield and the value of A seem to be approaching a maximum. The maximum value of A would be greater than 3.5 and this does not agree with the values 1 and 21/13 calculated by Myers[6] for states $J=1$ and $J=2$ of the compound nucleus. The disagreement could be connected with a breakdown of the Bohr picture for a nucleus containing only four particles. The breadth of the resonance estimated from our curve would not be less than 1.5 Mev in the c.g. system and the half-life of the intermediate nucleus must therefore be less than 4×10^{-22} sec. This is only twice as great as the time required for the emerging neutron to travel across the compound nucleus. If there is much sharing of energy between the particles, it must again be rather quickly concentrated on one particle.

ACKNOWLEDGMENTS

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[19] L. I. Schiff, Phys. Rev. **51**, 783 (1937).