and tube, has been enclosed in an air-tight, copper-lined room. A $\frac{3}{4}$-hp refrigerating unit has been installed which keeps the humidity below 20 percent in the most humid summer weather. With the introduction of freon at a partial pressure[9] of 5 lb./in.^{2} one might expect to obtain a potential of 1000 kv with a corresponding increase in charging current. If, at the same time, the ion current can be maintained, an increase in neutron yield of from 10- to 100-fold may be expected.

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Search for a Short Range Group of Protons in the D−D Reaction

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A thorough search for short range protons arising from the D−D reaction has been made at bombarding energies up to 300 kev, and at angles of 36°, 97°, and 142° to the incident deuteron beam. No evidence for such a group is found. The energy released in the reaction has been rechecked and is found to be in agreement with previous observations.

INTRODUCTION

BONNER'S recent confirmation[1] of previous experiments[2] indicates strongly the presence of a low energy group of neutrons in the reaction $H^2+H^2\rightarrow He^3+n^1$. The tentative explanation of this group is that the He^3 nucleus is left in an excited state about 1.9 Mev above the ground state. Such an excited state cannot readily be accounted for theoretically,[3] and a search for gamma-rays,[4] internal conversion electrons and positrons[5] has led to negative results within an experimental error far below the expected intensities. In spite of these difficulties, the evidence for a low energy neutron group appears strong, and further study of the D−D reaction is desirable.

If one assumes that the only difference between the neutron emitting reaction and the proton emitting reaction is the Coulomb barrier encountered in the latter case, then there should be a corresponding short range group of protons, presumably accompanied by an H^3 nucleus in an excited state. These protons would be expected to have a range of about 5 cm at 90° to an incident beam of 200-kev deuterons. Myers and Langer,[6] and Hudspeth and Bonner[7] found none ejected in a small solid angle approximately at right angles to the beam of incident deuterons.

Since the angular distribution of the protons and neutrons is not spherically symmetrical[8] there must be in some of these nuclear reactions one or more quanta of orbital angular momentum and as has been pointed out to one of us by Ellett[9] there is a possibility that these inter-

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[8] Kempton, Browne and Maasdorp, Proc. Roy. Soc. **157**, 386 (1936). H. Neuert, Physik. Zeits. **38**, 122 (1937). Haxby, Allen and Williams, Phys. Rev. **55**, 140 (1939).

[9] A. Ellett, private communication to R.D.H.

actions might be the ones to give rise to the excited H^3. Further if the reaction responsible for the excited H^3 were of the p type or higher odd order there would be no short range protons ejected at 90° and the negative result for measurements at 90° becomes inconclusive.

From these considerations and because of the fundamental nature of any information about the simplest of the nuclear reactions it seemed advisable to extend the search for short range protons to other angles and to higher bombarding energies.

Apparatus

The search for short range protons has been extended to 200 and 300 kev at angles of 36°, 97°, and 142° with respect to the direction of motion of the incident beam. The essential part of the equipment is shown schematically in Fig. 1. It is practically the same as previously reported[6] except for the addition of a monitor ionization chamber and amplifier to measure accurately a constant fraction of the total number of disintegrations produced in the target during each individual counting period. The differential chamber was equipped with a screw feed of about 15 mm to vary the path in air of the disintegration particles, and provision was made for the insertion of aluminum foils previously calibrated with polonium alpha-particles. The stopping power of the foils was assumed to be the difference in extrapolated range from air to air plus foil as measured with an ionization chamber 1.1 mm deep. The foils were placed close to the source of alpha-particles.

The geometry was such that all disintegrations produced in an area of about four times that of the spot of resolved deuterons would be counted. The spot was always kept at least 1 mm from the edges of the effective target area. A liquid-air-cooled heavy ice target was used in all measurements.

In all the counting the background and pulses were separated by biased rectifiers on the output of the monitor amplifier and the differential chamber amplifier. The maximum pulse height was held constant to within 10 percent and the bias voltage constant to 1 percent. The recorded data in each case were the ratio of the number of counts recorded by the differential chamber to the counts recorded by the monitor, as counted by scale-of-8 counters. With this arrangement extrapolated range measurements agreed to about one millimeter for runs on different days and individual points on single runs checked within statistical error for counting rates of 4000 to 8000 per minute. Each of the experimental points represents 5000 to 10,000 counts on the monitor with the corresponding number on the differential chamber.

In order to make absolute range measurements the thin Celluloid window and differential chamber assembly were calibrated by putting a source of polonium alpha-particles in place of the target and introducing air into the target chamber as a stopping medium. Pulse heights and rectifier biases were set the same as for the proton measurements.

Results

Figure 2 shows a typical curve taken at 36° to the 200-kev deuteron beam. Similar curves were taken at 97° and 142° to a 200-kev beam and 36° and 142° to a 300-kev beam, and 36° to a 100-kev beam (Mass 4 spot, 200 kv). From such curves we estimate a short range proton

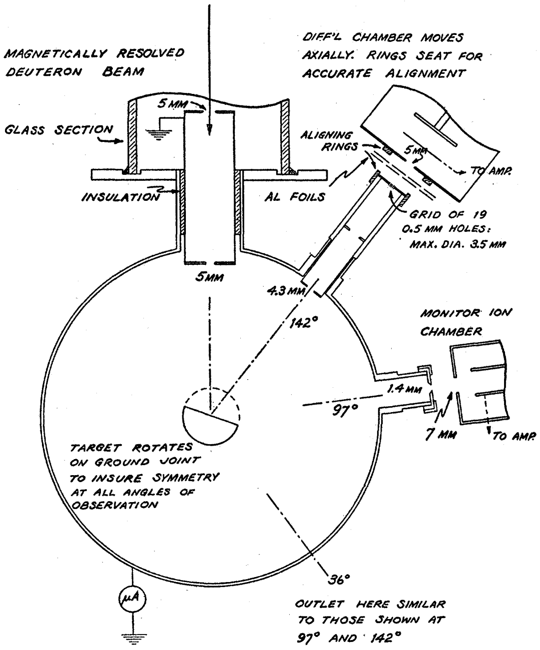

FIG. 1. Schematic diagram of the target chamber and ionization chambers. Scale of cut 1:2.80.

group with an intensity of 2 percent of that of the main group could have been easily detected. This is about $\frac{1}{5}$ the number to be expected upon the basis of Bonner's results and the assumed similarity of the reactions.

The short range peak is evidently the H^3 group. It must be remarked that if the short range protons fall within this group our measurements cannot separate them. Unfortunately our equipment would not measure the complete low range peak.

As a check upon the consistency of our measurements we have calculated the Q of the reaction using the extrapolated ranges in each case with the foil corrections indicated in Livingston and Bethe's paper.[10] In the forward direction and at 97° the full value of the bombarding energy was used in the calculation of Q. In the backward direction it is evident that the longest range protons come from disintegrations produced by deuterons that have been slowed down in the target. This necessitates making estimates of the effective bombarding energy and of the energy lost by the ejected protons in getting out of the target. Accordingly the Gamow disintegration function for deuterons was plotted and the almost linear portion was extrapolated to zero. The bombarding energy of 60 kev thus obtained was used for the calculation of Q. While this approximation is obviously crude, an error of about ±30 kev here does not change the value of Q by more than the indicated experimental error. The observed range of the ejected protons was increased by an amount equal to the range lost by the incident deuterons in slowing down to 60 kev.

TABLE I. *Extrapolated ranges of the protons and calculated values of Q as a function of angle and bombarding energy.*

Energy kev	Angle	Al Foils Air Equiv. 15°C	Air Path 15°C	Corr. Range	Q Mev
200	142	9.81	2.25	12.18	3.96
200	142	9.65	2.28	12.05	3.93
300	142	9.55	2.28	12.10	3.94
200	36	15.35	2.50	17.87	3.90
300	36	16.78	2.50	19.36	3.93
200	36	15.35	2.36	17.73	3.89
100	36	13.92	2.36	16.23	3.88
200	97	11.70	2.48	14.17	4.03*

* This value is slightly less reliable than the others due to minor difficulties with the apparatus while the data were being taken.

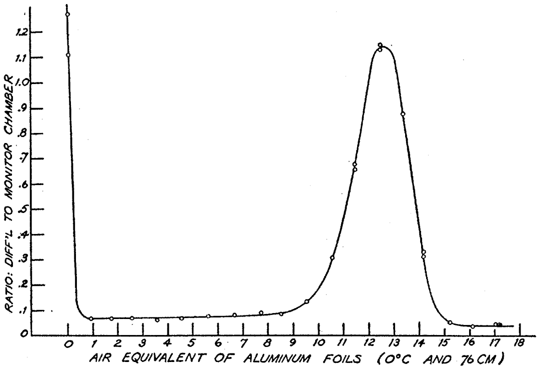

FIG. 2. Differential range curve of the protons ejected at 36° to the 200-kev beam of incident deuterons. The protons pass through 2.37 cm of air (0° and 76 cm) in addition to the aluminum foils indicated in the diagram.

Table I shows the observed extrapolated ranges of the protons as a function of angle and bombarding energy. The last column gives the corresponding calculated values of Q. From these we arrive at $Q = 3.93 \pm 0.10$ Mev.

Rumbaugh, Roberts and Hafstad[11] show that one or more of the four values of Q in the reactions

$$(1)\quad H^2 + H^2 = H^3 + H^1 + Q_1$$

$$(2)\quad H^2 + H^2 = He^3 + n^1 + Q_2$$

$$(3)\quad Li^6 + n^1 = He^4 + H^3 + Q_3$$

$$(4)\quad Li^6 + H^1 = He^4 + He^3 + Q_4$$

must be in error since $Q_1 - Q_2 = Q_3 - Q_4$ whereas experimentally they differ by 0.5 Mev. The Q_1 herein obtained appears to rule out the possibility of a large error in Q_1 previously reported as 3.98.[10]

Our thanks are due to Dr. Lawrence M. Langer for his cooperation in the early part of this work, and to Mr. Henry P. Manning, Jr. for his able technical assistance and help in taking data.

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