Neutrons from the Disintegration of Deuterium by Deuterons

T. W. BONNER* AND W. M. BRUBAKER, *Kellogg Radiation Laboratory, California Institute of Technology*

(Received October 22, 1935)

The excitation functions for the emission of neutrons from the two reactions ${}_1H^2+{}_1H^2\rightarrow{}_2He^3+{}_0n^1$ and ${}_4Be^9+{}_1H^2\rightarrow{}_5B^{10}+{}_0n^1$ have been investigated in the energy range from 0.5 to 0.9 MEV. In this interval the yield of neutrons from a $H_3{}^2PO_4$ target increases nearly linearly with the bombarding energy while the yield from a Be target increases nearly exponentially. At 0.9 MEV three times as many neutrons were observed from the Be target as from the $H_3{}^2PO_4$ target. At the lower voltage of 0.5 MEV only 1/3 as many neutrons came from the Be as from the $H_3{}^2PO_4$. The neutrons from deuterium were found to be nearly homogeneous in energy with a maximum of 2.55 MEV when they are observed at right angles to the direction of the incident 0.5 MEV deuterons. The energy of the disintegration is 3.21 ± 0.13 MEV.

THE emission of neutrons in large numbers from the bombardment of deuterium by deuterons was first reported by Oliphant, Harteck and Rutherford.[1] They attributed the neutrons to the reaction:

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

They reported an equivalent yield of one neutron per 10^6 deuterons incident on a pure deuterium target at 0.1 MEV. This means an actual yield of about 1 in 10^7 from targets such as can be used conveniently ($H_3{}^2PO_4$, $(NH_4{}^2)_2SO_4$, $NH_4{}^2Cl$). This yield from deuterium at 0.1 MEV is comparable to the yield from a Be target at 0.8 MEV as reported by Crane, Lauritsen and Soltan.[2] However previous experiments in this laboratory as well as those at Berkeley[3] indicated that at high voltages the yield of neutrons from the beryllium reaction

$$ {}_4Be^9+{}_1H^2\rightarrow{}_5B^{10}+{}_0n^1 \qquad (2)$$

was considerably greater than that from deuterium. In the present experiment we have compared the yield of neutrons from targets of $H_3{}^2PO_4$ and Be when bombarded by deuterons of energies between 0.5 MEV and 0.9 MEV.

Oliphant, Harteck and Rutherford[1] have used a helium-filled ionization chamber connected to an amplifier and oscillograph to measure the maximum energy of the neutrons from deuterium. From the maximum oscillograph deflection they have estimated that the neutrons have a maximum energy of 2.2 MEV. From the ranges of 30 recoil-helium tracks in a cloud chamber Dee[4] has inferred that the neutrons are homogeneous and have an energy of 1.8 MEV. In the present experiment we have determined the energy distribution of the neutrons more accurately by observing a large number of recoil protons in a cloud chamber.

Excitation Curves

We have compared the excitation functions for the emission of neutrons from Be and $H_3{}^2PO_4$ targets by counting the number of recoil protons photographed in a cloud chamber. We placed the methane-filled cloud chamber close to the target so that a large number of recoil protons could be observed. All observed tracks were counted, regardless of their orientation. When the voltage was increased from 0.5 MEV to 0.9 MEV the average number of tracks per expansion increased from 2.7 to 42 with the Be target, and from 7.1 to 13.4 with the H_3PO_4 target. These data have been reduced to an absolute yield and plotted as shown in Fig. 1. From 1000 to 2000 tracks were counted to determine each point on the curve. The relative yields are much more accurate than the absolute ones; the latter may be in error by as much as a factor of 5 or possibly 10. The curve shows that the yield of neutrons is greater from an $H_3{}^2PO_4$ target for voltages less than 0.68 MEV, but that for higher voltages the yield from Be is greater. Since the hydrogen in the $H_3{}^2PO_4$ molecule is

* National Research Fellow.

[1] Oliphant, Harteck and Rutherford, Proc. Roy. Soc. **A144**, 692 (1934).

[2] Crane, Lauritsen and Soltan, Phys. Rev. **45**, 507 (1935).

[3] McMillan and Livingston, Phys. Rev. **47**, 452 (1935).

[4] P. I. Dee, Proc. Roy. Soc. **A148**, 623 (1935).

responsible for 1/8 of the molecular stopping power, one should multiply the experimental yield by 8 to get the yield from a pure deuterium target.

The Be excitation curve agrees quite well with the one obtained by Crane, Lauritsen and Soltan[2] who used a paraffin-lined ionization chamber to detect the neutrons. The curve is roughly exponential, doubling every 0.1 MEV. The deuterium excitation curve rises only 75 percent in the interval between 0.5 and 0.9 MEV. Since the height of the potential barrier for deuterons on deuterons is only about 0.1 MEV, this increase cannot be due to a greater probability of penetrating the potential barrier but to the increased range of the deuterons in the target. The range of a 0.9 MEV deuteron is approximately 90 percent greater than that of a 0.5 MEV deuteron, so the agreement is fairly good.

The yield from beryllium as compared to that from deuterium at 0.2 MEV can be found by extrapolating the curves down to this energy. This gives the ratio of the number of neutrons from Be to the number from H_3PO_4 as approximately 1/20. Thus it is apparent that, at potentials of the order of 0.2 MEV, deuterium contamination on targets may be responsible for an appreciable portion of the observed neutrons.

Energy Distribution of the Neutrons

In previous papers[5] we described our method of determining neutron energies by measuring the lengths of recoil proton tracks in a high pressure cloud chamber filled with methane. In the present experiment the procedure has been the same except that a pressure of only 2.70 atmospheres was used in the chamber. At this pressure the tracks of the highest energy recoil protons had a length of approximately 4.5 cm. From the stopping power of the gas[6] in the chamber and the range-velocity curve, we have computed the energy of the recoil protons.[7]

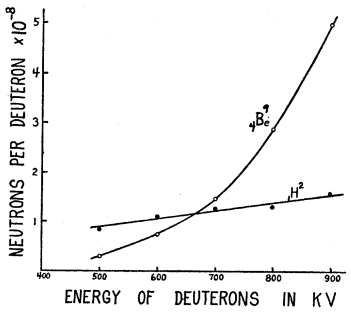

FIG. 1. The yield of neutrons from Be and $H_3{}^2PO_4$ targets when bombarded by deuterons.

Two series of runs were made. In the first we measured only those proton tracks which made angles of less than 8° with the forward direction (for neutrons which came directly from the source). The bombarding potential in this series of runs was 0.5 MEV. Under these conditions we photographed approximately 1200 recoil protons, 110 of which met our requirements for measurement. The energy distribution of these protons is given in the lower curve of Fig. 2. This curve indicates that the neutrons are nearly homogeneous in energy with a maximum of 2.55±0.10 MEV. We do not believe that the long tail on the low energy side of the maximum necessarily means that neutrons of this energy come from the source; it is at least partly due to scattered neutrons which made large angle collisions with protons and projected them in a direction such that they were measured.

The second set of data was obtained from photographs which had been taken in the excita-

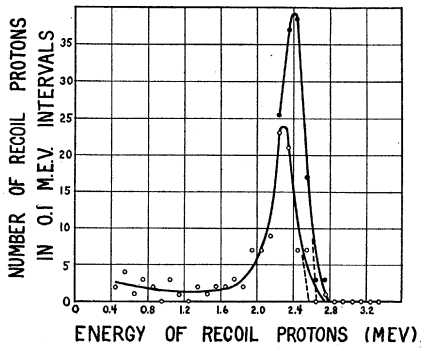

FIG. 2. The energy distribution of the recoil protons projected in the forward direction.

[5] Bonner and Brubaker, Phys. Rev. **47**, 910 (1935); Rev. Sci. Inst. **6**, 143 (1935); Phys. Rev. **48**, 742 (1935).

[6] The gas in the chamber was 85.1 percent CH_4, 13.5 percent C_2H_6, and 1.4 percent N_2. The corresponding stopping powers were 0.86 for methane, 1.52 for ethane, and 0.98 for nitrogen.

[7] G. Mano, J. de phys. et rad. **5**, 628 (1934).

tion curve experiments. In this series of runs the chamber was so close to the target that the direction of the neutrons was not well defined. For this reason we could not investigate the entire energy distribution, but by measuring the long tracks we were able to get an independent value of the maximum energy of the neutrons. The distribution of the high energy protons so measured is given in the upper curve of Fig. 2.

Discussion of Results

When the neutrons are observed at right angles to the direction of the incident deuterons the energy of the neutrons is given by:

$$E_n = \tfrac{3}{4}Q + \tfrac{1}{4}E_d,$$

where E_n is the neutron energy, Q the energy released in the disintegration, and E_d is the energy of the deuteron.

When our bombarding potential was 0.5 MEV, a maximum of 0.125 MEV of this energy appeared in the kinetic energy of the neutrons emitted at right angles. Because we used a thick target and alternating current, disintegrations were effected by deuterons of all energies below the maximum. This gave the neutrons an energy spread of 0.125 MEV, with Q constant. A few neutrons which were emitted in a direction parallel to that of the incident deuteron beam made elastic collisions with little loss of energy in the 3 mm of brass which is directly below the target and so may have been scattered into the chamber. Such neutrons received a maximum of 0.9 MEV more energy than those emitted at right angles and so may have been responsible for a few tracks with energies greater than 2.55 MEV.

The maximum energy of the neutrons as obtained from the first series of runs is 2.55 $\pm$0.10 MEV, and from the second series is 2.62$\pm$0.10 MEV. The corresponding Q's are 3.23$\pm$0.13 and 3.19$\pm$0.13 MEV. Dee and Gilbert[8] have obtained the energy of the short range $_2He^3$ particles which are produced in the same disintegration and from this energy have calculated that Q is 2.8$\pm$0.2 MEV.

From the energy released in this disintegration, one can calculate the mass of $_2He^3$. Using the values $Q=3.2$ MEV, $_1H^2=2.0142$, and $_0n^1=1.0086$, we obtain 3.0164 for the mass of $_2He^3$. This is smaller than the value 3.0172 calculated by Oliphant, Kempton and Rutherford[9] from the disintegration of lithium by protons:

$$_3Li^6 + {}_1H^1 \rightarrow {}_2He^4 + {}_2He^3.$$

It is not clear whether the disagreement is to be attributed to experimental errors or to the fact that the other masses involved in the calculation are not well enough known.

In conclusion, we wish to thank Professor C. C. Lauritsen for valuable suggestions and the Seeley W. Mudd Fund for financial support.

Note added in proof: In view of the discrepancy in the two calculated masses of He^3 and the disagreement in the He^4/H^2 ratio as determined by Bainbridge and by Aston by means of the mass spectrograph, it seems advisable to calculate the mass of the deuteron from disintegration data. The ratio He^4/H^2 can be found by solving the first four of the following equations for the mass of the deuteron

$$_1H^2 + {}_1H^2 = {}_2He^3 + {}_0n^1 + 3.21 \pm 0.13 \text{ MEV.}$$
$$_3Li^6 + {}_1H^1 = {}_2He^4 + {}_2He^3 + 3.6 \pm 0.1 \text{ MEV.}^9$$
$$_3Li^6 + {}_1H^2 = 2{}_2He^4 + 22.06 \pm 0.07 \text{ MEV.}^{10}$$
$$_1H^2 + h\nu = {}_1H^1 + {}_0n^1 - 2.26 \pm 0.08 \text{ MEV.}^{11}$$
$$_3Li^6 + {}_0n^1 = {}_2He^4 + {}_1H^3 + 4.6 \pm 0.2 \text{ MEV.}^{12}$$
$$_1H^2 + {}_1H^2 = {}_1H^3 + {}_1H^1 + 3.97 \pm 0.02 \text{ MEV.}^{10}$$

We get the relation $_1H^2 = \frac{1}{2}(He^4 + 23.93 \pm 0.20$ MEV). This relation toegther with a standard He^4 mass of 4.00336 gives a mass of the deuteron equal to 2.01458$\pm$0.00010; this value is considerably higher than Bainbridge's value 2.01423. A check on this mass of the deuteron is obtained by solving the last four of the equations for the mass of the deuteron. Here we get the relation $_1H^2 = \frac{1}{2}(He^4 + 23.69 \pm 0.23$ MEV) or a mass of 2.01440$\pm$0.00012 which is also higher than 2.01423. From these two results we get a mean disintegration mass of 2.01449$\pm$0.00009 which is nearly the same as Aston's value 2.01443 when referred to the He=4.00336 scale; with such a deuteron mass the discrepancy in the two calculated masses of $_2He^3$ disappears.

If this mass of the deuteron proves to be more nearly correct than the old mass, then the masses of the other elements will be affected by such a change. If we use Bainbridge's mass spectrograph ratio of He^4/H^1 we can calculate the masses of the other elements appearing in the above set of reactions. The best values obtained are:

$_0n^1 = 1.00885 \pm 0.00010$	$_1H^3 = 3.01664 \pm 0.00010$
$_1H^1 = 1.00807 \pm 0.00002$	$_2He^3 = 3.01674 \pm 0.00014$
(mass spectrograph)	$_2He^4 = 4.00336$ (standard)
$_1H^2 = 2.01449 \pm 0.00009$	$_3Li^6 = 6.01593 \pm 0.00011.$

[8] Dee and Gilbert, Proc. Roy. Soc. **A149**, 200 (1935).

[9] Oliphant, Kempton and Rutherford, Proc. Roy. Soc. **A150**, 241 (1935).

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

[11] N. Feather, Nature **136**, 468 (1935).

[12] Chadwick and Goldhaber, Nature **135**, 65 (1935); Taylor and Goldhaber, Nature **135**, 341 (1935).