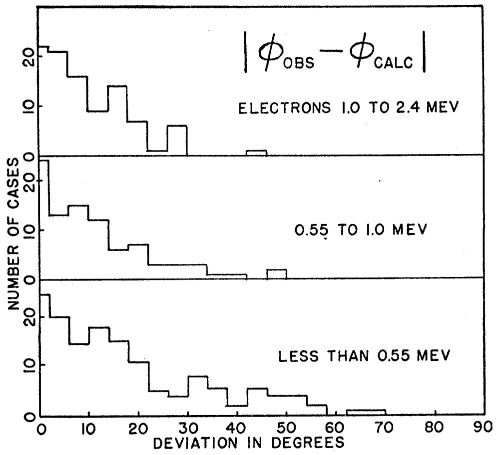

FIG. 9. The data of Fig. 4, plotted in three groups according to the energy of the recoil electrons.

little more satisfying than the other, since a time difference in the process may be imagined to lie anywhere in the large range between the above resolving time and 10^{-20} second or less. There seems at present a great likelihood that with further refinements in both methods of attack, the results of both methods will come into agreement. The desirability of further experiments along these lines can hardly be over-estimated.

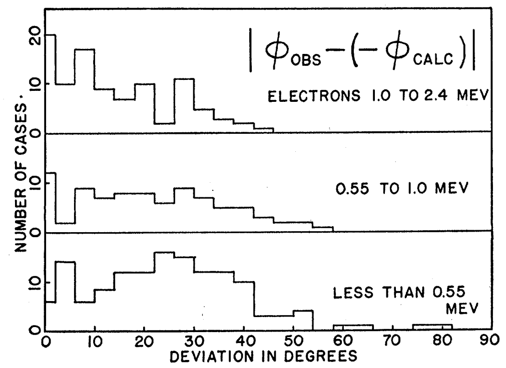

FIG. 10. The data of Fig. 6, plotted in three groups according to the energy of the recoil electrons.

This work was made possible by a grant from the Rackham Fund. The authors wish to express their appreciation for this support.

According to the Klein-Nishina formula most of the recoil electrons due to gamma-rays have nearly the maximum energy. Therefore a division of the data on the basis of electron energy seems permissible. Alternative ways of obtaining the energy of the primary gamma-ray quantum are: (1) Calculation from the energy of the recoil electron and the direction of the scattered photon. This is not satisfactory because the photon is really associated with the electron in only $\frac{1}{2}$ or $\frac{1}{3}$ of the cases. (2) Calculation from the energy and direction of the recoil electron. This is vitiated by scattering of the recoil electron. The result is rather sensitive to this.

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Disintegration of Beryllium, Boron and Carbon by Deuterons

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The energy distribution of the neutrons emitted when beryllium, boron and carbon are bombarded by 0.9 MEV deuterons has been investigated. The neutrons from beryllium are attributed to the reaction

$$_4\mathrm{Be}^9 + {}_1\mathrm{H}^2 \rightarrow {}_5\mathrm{B}^{10} + {}_0n^1 + Q_1. \tag{1}$$

The energy of disintegration Q_1 is 4.25 ± 0.2 MEV. Several lower energy neutron groups attributed to excited B^{10} nuclei were observed with Q's equal to 3.7, 2.1 and 0.8 MEV. The neutrons observed when boron is bombarded by deuterons are attributed to the reactions:

$$_5\mathrm{B}^{11} + {}_1\mathrm{H}^2 \rightarrow {}_6\mathrm{C}^{12} + {}_0n^1 + Q_2, \tag{2}$$

$$_5\mathrm{B}^{11} + {}_1\mathrm{H}^2 \rightarrow 3\,{}_2\mathrm{He}^4 + {}_0n^1 + Q_3, \tag{3}$$

$$_5\mathrm{B}^{10} + {}_1\mathrm{H}^2 \rightarrow {}_6\mathrm{C}^{11} + {}_0n^1 + Q_4. \tag{4}$$

The most probable of these is reaction (3); it gives rise to a group of neutrons with a continuous distribution of energies below 3 MEV. The disintegration energies observed from the other two reactions are:

$$Q_2^0 = 13.5 \pm 0.3 \text{ MEV}, \qquad Q_4^0 = 6.2 \pm 0.2 \text{ MEV},$$
$$Q_2^1 = 9.1 \pm 0.2 \text{ MEV}, \qquad Q_4^1 = 4.0 \pm 0.1 \text{ MEV}.$$

The neutrons observed when carbon is bombarded by deuterons are attributed to the reactions:

$$_6\mathrm{C}^{12} + {}_1\mathrm{H}^2 \rightarrow {}_7\mathrm{N}^{13} + {}_0n^1 + Q_5, \tag{5}$$

$$_6\mathrm{C}^{13} + {}_1\mathrm{H}^2 \rightarrow {}_7\mathrm{N}^{14} + {}_0n^1 + Q_6. \tag{6}$$

It is found that reaction (5) is responsible for approximately 99 percent of the neutrons from carbon and that reaction (6) is responsible for the remainder. The values of the disintegration energies are:

$$Q_5 = -0.37 \pm 0.05 \text{ MEV} \quad \text{and} \quad Q_6 = 5.2 \pm 0.4 \text{ MEV}.$$

The calculated value of the maximum energy of the positrons from N^{13} is 1.16 MEV which is lower than the Konopinski-Uhlenbeck extrapolated value of 1.45 MEV. A complete set of values of the masses of the light elements computed from disintegration data is given.

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* National Research Fellow.

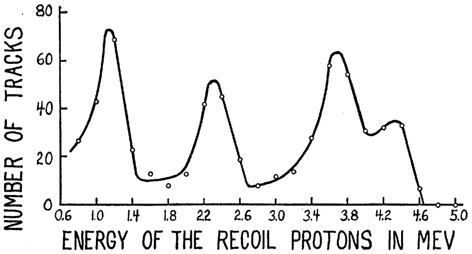

Fig. 1. The energy distribution of the recoil protons observed when beryllium was bombarded by 0.9 MEV deuterons.

In previous papers[1] we have reported on the energy distribution of the neutrons emitted when several of the light elements are bombarded with deuterons. In the present experiments we have extended our observations to boron and carbon. Additional data concerning the neutrons from beryllium are also given. It is the object of these experiments to determine the energies liberated in the nuclear reactions in which the neutrons are produced and to investigate the relative probabilities of the different reactions.

We have continued our method of determining neutron energies by measuring the lengths of recoil proton tracks in a high pressure cloud chamber filled with methane.[1] In the case of the neutrons from boron, we have also observed recoil helium nuclei. As in our previous work, we have measured only the ranges of those recoil nuclei which were projected in nearly the forward direction. Thus recoil protons received essentially the energy of the incident neutrons, while the helium recoils received nearly 16/25 of the neutrons' energy. The cloud chamber was placed 20 cm from the target in a manner such that the neutrons made angles of 83° to 97° with the direction of the incident deuterons.

Results

Beryllium

In our first report[1] on the energy of the neutrons emitted when beryllium is bombarded by deuterons we were principally interested in the maximum energy of the neutrons which are produced in the nuclear reaction:

$$ {}_4Be^9 + {}_1H^2 \rightarrow {}_5B^{10} + {}_0n^1 + Q_1. \qquad (1)$$

However we found that there were several neutron groups with energies lower than the maximum. It is one of the objects of the present experiment to investigate more carefully these lower energy groups which are assumed to result when the B^{10} nuclei are left in excited states.

3500 stereoscopic photographs were taken when a metallic beryllium target was bombarded with 0.9 MEV deuterons. The stopping power of the methane[2] in the cloud chamber was 5.68 in this experiment and the highest energy recoil protons had track lengths of approximately 5 cm. Fig. 1 gives the energy distribution of the 580 protons whose ranges were measured. The curve indicates four neutron groups with energies of 4.52, 4.0, 2.6 and 1.4 MEV.

Since the energy of the 2.6 MEV group is very nearly the same as the energy of the neutrons from the reaction

$$ {}_1H^2 + {}_1H^2 \rightarrow {}_2He^3 + {}_0n^1 + Q_2, \qquad (2)$$

the possibility that this group is due to deuterium contamination has been considered. We find that this 2.6 MEV group is at least ten times as strong as the contamination effects observed on other targets such as Atcheson graphite, brass and $NaNO_2$. The excitation curves for the reactions (1) and (2) are quite different,[3] so a run at 0.6 MEV bombarding potential provided a conclusive means of determining whether a considerable portion of this energy group is due to contamination. At this lower voltage the intensity of the 2.6 MEV group as compared to the intensity of the higher energy groups should be five times as great if it were due entirely to contamination. The experiment showed an increase of only twenty percent, so it is apparent that only a small proportion of the neutrons in the 2.6 MEV group come from the deuteron-deuterium reaction.

The maximum neutron energy corresponds to a disintegration energy Q_1^0 of 4.25±0.20 MEV which is approximately the same as we reported originally. The Q_1's associated with the lower energy groups are:

$$Q_1^1 = 3.7, \qquad Q_1^2 = 2.1 \quad \text{and} \quad Q_1^3 = 0.8 \text{ MEV}.$$

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[1] Bonner and Brubaker, Phys. Rev. **47**, 910 (1935); **48**, 742 (1935); **49**, 19 (1936).

[2] The composition of the gas was 85.1 percent CH_4, 13.5 percent C_2H_6, and 1.4 percent N_2.

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

These Q_1's correspond to the cases when the B^{10} nuclei are left excited to levels of 0.55, 2.15, and 3.45 MEV; one expects gamma-rays of these energies to be emitted. Crane, Delsasso, Fowler and Lauritsen[4] reported intense gamma-rays with an energy of 0.6 MEV and others with energies up to 3.3 MEV when beryllium is bombarded by deuterons. The observed gamma-rays may reasonably be attributed to excited states of B^{10}, but close correlation between the two cannot be made at present.

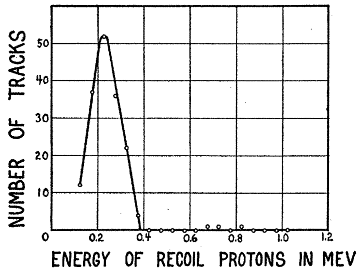

FIG. 2. The energy distribution of the recoil protons observed when carbon was bombarded with 0.88 MEV deuterons.

Carbon

Two nuclear reactions have been shown to take place when carbon is bombarded with deuterons:

$$_6C^{12}+_1H^2\rightarrow _6C^{13}+_1H^1+Q_3, \qquad (3)$$

$$_6C^{12}+_1H^2\rightarrow _7N^{13}+_0n^1+Q_4, \qquad (4)$$

$$_7N^{13}\rightarrow _6C^{13}+e^++Q_5. \qquad (5)$$

Reaction (3) has been carefully studied by Cockcroft and Walton,[5] Livingston and Lawrence,[6] Tuve and Hafstad[7] and by Fowler, Delsasso and Lauritsen.[8] The alternative mode of disintegration, reactions (4) and (5), in which a neutron and N^{13} are the disintegration products was first observed by Crane and Lauritsen,[9] and by Henderson, Livingston and Lawrence.[10] They made observations on the radioactive N^{13}. The neutrons were reported by Tuve and Hafstad[11] and by Newson[6] who made qualitative measurements of their energies.

It is particularly desirable to know the maximum value of Q_4 quite accurately.[12] This value, combined with Q_3 and the mass difference $(_0n^1-_1H^1)$ enables one to predict the maximum energy of the positrons emitted by N^{13}. This predicted maximum positron energy should show one how to choose the end point of the experimentally determined continuous distribution curve. If, on the other hand, the maximum energy of the positrons is in the future accurately determined, then one may compute the rest mass of the neutrino from the maximum positron energy, Q_3, Q_4 and the mass difference $(_0n^1-_1H^1)$. For these reasons we have attempted an accurate determination of the energies of the neutrons from reaction (4). These same questions could be solved by the data of disintegrations of the same type in one of the other light elements such as B^{10}, N^{14}, O^{16}, etc., but as Q_3, Q_4 and Q_5 are all small, the data from the disintegration of carbon are capable of the greatest precision.

Since there are two isotopes of carbon, we should also expect to observe neutrons from the reaction:

$$_6C^{13}+_1H^2\rightarrow _7N^{14}+_0n^1+Q_6. \qquad (6)$$

As C^{13} is only 1/100 as plentiful as C^{12} we should expect the yield of neutrons from reaction (6) to be much smaller than from reaction (4). We have found evidence that some of the observed neutrons are from reaction (6).

Approximately 14,500 sets of stereoscopic photographs were taken when carbon was bombarded by 0.88 MEV deuterons. For 2500 of these the chamber was operated at an expanded pressure of one atmosphere, and for the rest it was operated at 8.5 atmospheres. In the first series of runs we observed 166 tracks of recoil protons which had been projected in nearly the forward direction (0°–10°). The ranges of these protons were computed from the stopping power of the gas and the track lengths. The stopping power of the gas was determined experimentally from the mean length of the tracks of polonium

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[4] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **47**, 782 (1935).

[5] Cockcroft and Walton, Proc. Roy. Soc. **A144**, 704 (1934).

[6] H. W. Newson, Phys. Rev. **48**, 790 (1935).

[7] Tuve and Hafstad, Phys. Rev. **48**, 106 (1935).

[8] Fowler, Delsasso and Lauritsen, Phys. Rev. **49**, 561 (1936).

[9] Crane and Lauritsen, Phys. Rev. **45**, 430 (1934).

[10] Henderson, Livingston and Lawrence, Phys. Rev. **45**, 428 (1934).

[11] Tuve and Hafstad, Phys. Rev. **48**, 106 (1935).

[12] The value of Q_4 which we have found in these experiments was reported at the December (1935) meeting of the Am. Phys. Soc., Phys. Rev. **49**, 203 (1936).

alpha-particles. This value (1.06) was then corrected for the variation of stopping power with velocity;[13] the corrected value was 1.21 for protons with a range of 0.5 cm. The energies of the protons was then found from Blackett's[14] experimentally determined range-velocity curve. The energy distribution of these tracks is given in Fig. 2. The curve indicates a neutron group with a maximum energy of 0.35±0.03 MEV.

As a few tracks were observed which went entirely across the chamber, another series of runs was made when the pressure in the chamber was increased to 8.5 atmospheres. From 12,000 photographs taken when the chamber was operated at this increased pressure, we measured 223 tracks of protons with energies above 1 MEV. The few protons with energies of 2.6 MEV were probably due to neutrons from deuterium contamination, according to reaction (2). There was also an indication of a weak group with an energy of 1.8 MEV. 24 tracks of protons which had energies over 4 MEV were photographed. This group had a maximum energy of 5.6±0.4 MEV. The relative intensities of the 5.6, 1.8 and 0.35 MEV groups were 1, 3 and 300, respectively. The 5.6 and 1.8 MEV groups were probably due to reaction (6), but since their energy was almost the same as that of the neutrons from nitrogen[15] the possibility that they were due to a high contamination of nitrogen on the Atcheson graphite target cannot definitely be excluded. It is possible to explain the 3.5 to 4.0 MEV gamma-rays from carbon bombarded by deuterons by the C^{13} reaction. Approximately the right amount of energy (4.1) MEV and intensity for such gamma-rays is given by the difference between the 5.6 and 1.8 MEV neutron groups. The values of the energies of disintegration of reactions (4) and (6) were calculated to be

$$Q_4=-0.37\pm0.05 \text{ MEV and } Q_6=5.2\pm0.4 \text{ MEV.}$$

Energy of Positrons from N^{13}

By combining Eqs. (3) and (4) we find that the maximum positron energy E_m is given by

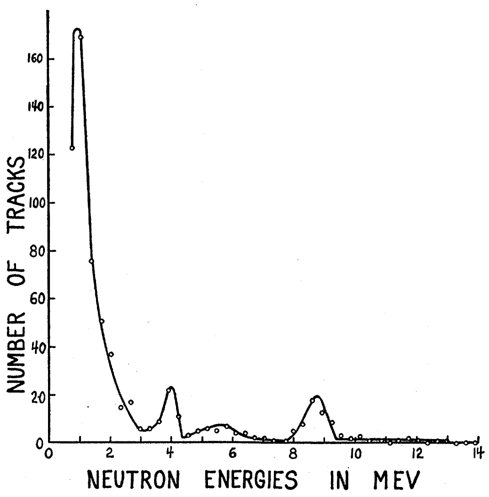

Fig. 3. The energy distribution of the neutrons from $B+H^2$ as inferred from the energy distribution of the recoil helium nuclei.

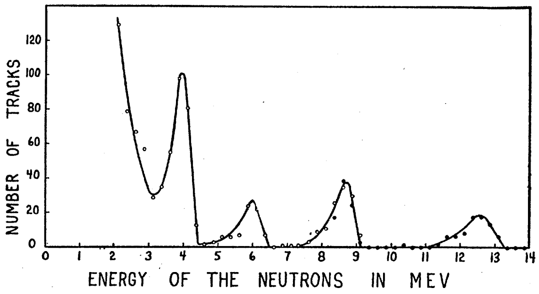

Fig. 4. The energy distribution of the neutrons from $B+H^2$ as inferred from the energies of the recoil protons.

$$E_m=Q_3-Q_4-2m_e-({}_0n^1-{}_1H^1), \qquad (7)$$

where m_e is the rest mass of the electron (0.51 MEV). The value of Q_3 has been obtained by Fowler, Delsasso and Lauritsen[8] in this laboratory under conditions almost identical to those under which we determined Q_4. Since one is interested in the value Q_3-Q_4 any errors in the energy of the bombarding particles is unimportant. The value of the mass difference $({}_0n^1-{}_1H^1)$ is known accurately from the difference between the $H_2{}^{1+}-H^{2+}$ doublet as determined by the mass spectrograph. Bainbridge[16] and Aston[17] now agree that this difference is 0.00152 mass unit. One now only needs to use the binding energy of the deuteron (2.25 MEV),

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[13] Rutherford, Chadwick and Ellis, *Radiations from Radioactive Substances*, p. 96.

[14] P. M. S. Blackett, Proc. Roy. Soc. **A135**, 132 (1932).

[15] As we have found from some incomplete work with nitrogen.

[16] Bainbridge and Jordan, Phys. Rev. **49**, 883A (1936).

[17] F. W. Aston, Nature **137**, 357 (1936).

which has been accurately determined by Feather, to get a $({}_0n^1-{}_1H^1)$ difference of 0.00090 mass unit.

Using the value 0.00090 for the mass difference $({}_0n^1-{}_1H^1)$ and the experimentally determined values of Q_3 and Q_4, we calculate that

$$E_m=1.16 \text{ MEV}.$$

The energy distribution of the positrons from N^{13} has been given by Fowler, Delsasso and Lauritsen[8] and by Kurie, Richardson and Paxton.[19] Our calculated value of E_m seems definitely to favor the inspection end point of the N^{13} positron spectrum (1.25 MEV) rather than the value 1.45 MEV obtained from the Konopinski-Uhlenbeck extrapolation.

Boron

The copious emission of neutrons when boron is bombarded by fast deuterons was first reported by Lauritsen and Crane.[20] Several possible reactions which will account for the neutrons are:

$$ {}_5B^{11}+{}_1H^2\rightarrow{}_6C^{12}+{}_0n^1+Q_8, \tag{8}$$

$$ {}_5B^{11}+{}_1H^2\rightarrow 3{}_2He^4+{}_0n^1+Q_9, \tag{9}$$

$$ {}_5B^{10}+{}_1H^2\rightarrow{}_6C^{11}+{}_0n^1+Q_{10}. \tag{10}$$

A continuous distribution of alpha-particles attributed to reaction (9) has been reported by Cockcroft and Lewis.[21] Radioactive C^{11} produced by bombarding boron with deuterons has been reported by Crane and Lauritsen,[22] Henderson, Livingston and Lawrence,[23] and by others.

We have obtained two sets of data on the energy distribution of the neutrons emitted when an amorphous boron target is bombarded by 0.9 MEV deuterons. From 5400 pairs of stereoscopic photographs taken when the chamber was filled with helium at a pressure of 6 atmospheres, 660 tracks were measured. The stopping power of the gas was determined from the mean length of the tracks of polonium alpha-particles. The neutron energy distribution deduced from these tracks is given in Fig. 3. From this curve we are not able to tell whether there are any neutrons with energies above 9 MEV or not, as the few tracks observed in this region might be attributed to recoil protons. For this reason we obtained another set of data with CH_4 in the chamber instead of He.

We have investigated the energy interval of 2 to 10 MEV with the methane-filled cloud chamber operated at an expanded pressure of 18.8 atmospheres (stopping power = 18.04). For observing the higher energy neutrons we operated the chamber at the same pressure and augmented the stopping power by placing a sheet of mica with a stopping power of 58 cm across the center of the chamber. From 5400 photographs taken with the mica and 6400 taken without the mica we have measured 1100 track lengths. The energy distribution of these recoil protons is given in Fig. 4. The ordinates of the data taken with the mica have been fitted to give the same intensity for the 9 MEV group as was obtained without the mica. The distribution curve shows four neutron groups with energies of 13.2, 9.1, 6.35 and 4.35 MEV. The rise in the distribution curves below 3 MEV indicates the presence of a continuous distribution of neutrons in this energy range. The neutron energy distribution deduced from Fig. 3 is essentially the same as that deduced from Fig. 4, except for the highest energy group; it appears to be very weak in Fig. 3, if not entirely missing. It is not clear whether this is merely a matter of statistics or is of real significance. It may perhaps be that many of the nearly head-on collisions of 13 MEV neutrons with helium nuclei are not elastic, and that a portion of the energy is liberated in the form of a gamma-ray. However, it will be necessary to do further experiments to decide between these two possibilities.

A consideration of the approximate values of the masses of the nuclei involved in Eqs. (8), (9) and (10) enables us to assign these observed neutron energies to the various equations. As reaction (8) is the only one which would give neutrons with energies greater than 7 MEV, we may be reasonably certain that the 13.2 and 9.1 MEV groups result from this reaction. The 6.35 MEV group agrees well with the energy to

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[19] Kurie, Richardson and Paxton, Phys. Rev. **49**, 368 (1936).

[20] Lauritsen and Crane, Phys. Rev. **45**, 493 (1934).

[21] Cockcroft and Lewis, Proc. Roy. Soc. **A154**, 246 (1936).

[22] Crane and Lauritsen, Phys. Rev. **45**, 430 (1934).

[23] Henderson, Livingston, and Lawrence, Phys. Rev. **45**, 428 (1934).

be expected from reaction (10). We think it is likely that the 4.35 MEV group comes from reaction (10) also. The relatively large number of neutrons with energies below 3 MEV appears to have a continuous energy distribution and so is probably due to reaction (9). This disintegration into three alpha-particles and a neutron appears to be more probable than disintegration into C^{12} and a neutron according to reaction (8).

The corresponding values of the Q_8's are: $Q_8{}^0=13.5\pm0.3$ MEV and $Q_8{}^1=9.1\pm0.2$ MEV. The lower value of Q_8 results when the C^{12} nucleus is excited to a 4.4 ± 0.2 MEV level. C^{12} has been excited to this level in two other nuclear reactions. Cockcroft and Lewis[21] found two groups of alpha-particles in the reaction

$$_7N^{14}+{}_1H^2\rightarrow{}_6C^{12}+{}_2He^4+Q_{11} \qquad (11)$$

with an energy difference of 4.2 ± 0.1 MEV. These two excitation values of C^{12} agree within the experimental errors. The first evidence for an excited C^{12} nucleus was that obtained from the study of the reaction

$$_4Be^9+{}_2He^4\rightarrow{}_6C^{12}+{}_0n^1+Q_{12} \qquad (12)$$

by Bothe and Becker,[24] Curie and Joliot,[25] Chadwick[26] and by others. Values ranging from 4 to 5 MEV have been obtained as the energy of the gamma-rays from this reaction and it now appears probable that the C^{12} nucleus in this reaction is excited to the same level as it is in the previous two reactions.

The corresponding values of Q_{10} gives us another means of checking the maximum energy of the continuous beta-ray spectrum in a manner similar to that which has been done in the case of N^{13}. From reactions (10) and (13)

$$_5B^{10}+{}_1H^2\rightarrow{}_5B^{11}+{}_1H^1+Q_{13}{}^{21} \qquad (13)$$

we see that the maximum energy of the C^{11} positrons is

$$E_m=Q_{13}-Q_{10}-1.86 \text{ MEV}$$

(using a mass difference of $_0n^1-{}_1H^1=0.00090$). This gives 1.05 for the value of E_m, which agrees better with the inspection end point (1.15 MEV) than with the Konopinski-Uhlenbeck value (1.3 MEV) as reported by Fowler, Delsasso and Lauritsen.[8] However, the calculated value of E_m agrees with either value within the probable error of 0.3 MEV.

Disintegration Masses of the Light Elements

It is of interest to calculate the disintegration masses of the light elements from the Q's given in this paper and the Q's reported by other investigators. Two mass differences which we shall want to use often are:

$$2{}_1H^2-{}_2He^4=23.82 \text{ MEV}$$

and $\quad {}_1H^1+{}_0n^1-{}_1H^2=2.25$ MEV.

The first of these is the difference which we calculated previously from disintegration data[3] and the second is that found by Feather[27] from the photo-disintegration of deuterium. The first difference is very nearly the same as that recently reported by Aston[17] from new mass spectroscopic data (23.75 MEV). Using these two mass differences we can calculate the O^{16}/He^4 ratio in several different ways from the available disintegration data. For convenience we have done this in two steps. First we computed the B^{11}/He^4 ratio in three different ways and then we found the O^{16}/B^{11} ratio by several methods.

In these calculations we have used the following equations:

(a) $\quad {}_5B^{10}+{}_1H^2={}_5B^{11}+{}_1H^1+9.11,$[21]
(b) $\quad {}_4Be^9+{}_1H^2={}_5B^{10}+{}_0n^1+4.25,$
(c) $\quad {}_4Be^9+{}_1H^2={}_3Li^7+{}_2He^4+7.0,$[28]
(d) $\quad {}_3Li^7+{}_1H^1=2{}_2He^4+17.06,$[29]
(e) $\quad {}_5B^{11}+{}_1H^2={}_4Be^9+{}_2He^4+0.08,$[21]
(f) $\quad {}_5B^{11}+{}_1H^1=3{}_2He^4+8.7,$[30]
(g) $\quad {}_5B^{11}+{}_1H^2={}_6C^{12}+{}_0n^1+13.5,$
(h) $\quad {}_7N^{14}+{}_1H^2={}_6C^{12}+{}_2He^4+13.22,$[21]
(i) $\quad {}_8O^{16}+{}_1H^2={}_7N^{14}+{}_2He^4+2.95,$[21]
(j) $\quad {}_6C^{13}+{}_1H^2={}_5B^{11}+{}_2He^4+5.11,$[21]
(k) $\quad {}_6C^{12}+{}_1H^2={}_6C^{13}+{}_1H^1+2.66,$[21]
(l) $\quad {}_5B^{10}+{}_2He^4={}_6C^{13}+{}_1H^1+3.1,$[31]

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[24] Bothe and Becker, Zeits. f. Physik **76**, 421 (1932).

[25] Curie and Joliot, J. de phys. et rad. **4**, 494 (1933).

[26] J. Chadwick, Proc. Roy. Soc. **A142**, 1 (1933).

[27] N. Feather, Nature **136**, 467 (1935).

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

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

[30] Dee and Gilbert, Proc. Roy. Soc. **A154**, 279 (1936).

[31] Miller, Duncanson and May, Proc. Camb. Phil. Soc. **30**, 549 (1934).

and the mass differences given above.

(a)+(b)−(c)−(d) gives

$${}_5\mathrm{B}^{11}=3{}_2\mathrm{He}^4-{}_1\mathrm{H}^1+8.45\pm0.25\ \mathrm{MEV.}$$

(c)+(d)+(e) gives

$${}_5\mathrm{B}^{11}=3{}_2\mathrm{He}^4-{}_1\mathrm{H}^1+8.32\pm0.22\ \mathrm{MEV.}$$

Another relation is given directly by (f)

$${}_5\mathrm{B}^{11}=3{}_2\mathrm{He}^4-{}_1\mathrm{H}^1+8.7\pm0.3\ \mathrm{MEV.}$$

The weighted mean of these values is

$${}_5\mathrm{B}^{11}=3{}_2\mathrm{He}^4-{}_1\mathrm{H}^1+8.5\pm0.2\ \mathrm{MEV.}$$

The $\mathrm{O}^{16}/\mathrm{B}^{11}$ ratio can be determined from

(g)−(h)−(i) which gives

$${}_8\mathrm{O}^{16}={}_5\mathrm{B}^{11}+2{}_2\mathrm{He}^4-{}_1\mathrm{H}^2-{}_0n^1+2.67\pm0.31\ \mathrm{MEV.}$$

Another way to find this ratio is that used by Cockcroft and Lewis from reactions (h)+(i)+(j)+(k) which yields

$${}_8\mathrm{O}^{16}={}_5\mathrm{B}^{11}+2{}_2\mathrm{He}^4-{}_1\mathrm{H}^2-{}_0n^1+2.38\pm0.21\ \mathrm{MEV.}$$

A third, but less direct way is that originally used by Bethe, (a)+(h)+(i)+(k)−(l) from which

$${}_8\mathrm{O}^{16}={}_5\mathrm{B}^{11}+2{}_2\mathrm{He}^4-{}_1\mathrm{H}^2-{}_0n^1+3.27\pm0.50\ \mathrm{MEV.}$$

The weighted mean of these three values is

$${}_8\mathrm{O}^{16}={}_5\mathrm{B}^{11}+2{}_2\mathrm{He}^4-{}_1\mathrm{H}^2-{}_0n^1+2.7\pm0.3\ \mathrm{MEV.}$$

Combining this with the value of the $\mathrm{B}^{11}/\mathrm{He}^4$ ratio leads to

$${}_8\mathrm{O}^{16}=4{}_2\mathrm{He}^4-14.87\pm0.35\ \mathrm{MEV.}$$

or $${}_2\mathrm{He}^4=4.0040+0.0001.$$

This disintegration mass of He^4 agrees with Aston's[17] new mass spectrograph value (4.0039) within the experimental errors. The mass of ${}_1\mathrm{H}^1$ can be obtained only from mass spectrographic data. Aston gives the value 1.0081, and the value deduced from Bainbridge and Jordan's $(\mathrm{H}_2{}^1-\mathrm{H}^2)$ difference is also 1.0081. Using the values of the masses just determined, we can now compute the masses of the other light elements. A summary of these is given below.

$\mathrm{O}^{16}=16.0000$
$\mathrm{O}^{15}=15.0079$
$\mathrm{N}^{16}=16.0066$
$\mathrm{N}^{15}=15.0049$
$\mathrm{N}^{14}=14.0075$
$\mathrm{N}^{13}=13.0100$
$\mathrm{C}^{14}=14.0078$
$\mathrm{C}^{13}=13.0076$
$\mathrm{C}^{12}=12.0040$
$\mathrm{C}^{11}=11.0150$
$\mathrm{B}^{12}=12.0179$
$\mathrm{B}^{11}=11.0128$
$\mathrm{B}^{10}=10.0160$
$\mathrm{Be}^{10}=10.0163$
$\mathrm{Be}^{9}=9.0149$
$\mathrm{Be}^{8}=8.0080$
$\mathrm{Li}^{8}=8.0195$
$\mathrm{Li}^{7}=7.0182$
$\mathrm{Li}^{6}=6.0170$
$\mathrm{He}^{4}=4.0040$
$\mathrm{He}^{3}=3.0171$
$\mathrm{H}^{3}=3.0170$
$\mathrm{H}^{2}=2.0147$
$\mathrm{H}^{1}=1.0081$
$n^{1}=1.0090$

The probable errors of most of the masses is 0.0001 or 0.0002, but the probable errors of the radioactive atoms Li^8 and B^{12} may be greater. In most cases the mass values agree within 0.0002 mass units with those calculated by Oliphant,[32] from a combination of mass spectrographic and disintegration data.

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[32] M. L. Oliphant, Nature **137**, 396 (1936).