Slow Neutron Disintegration of B^{10} and Li^6

M. STANLEY LIVINGSTON AND J. G. HOFFMAN
Cornell University, Ithaca, New York

(Received December 10, 1937)

The disintegration of B^{10} by slow neutrons is found to result in two groups of alpha-particles, of ranges 0.80 ± 0.03 and 0.66 ± 0.05 cm and with relative intensities 1 : 3, corresponding to disintegration into the ground state of the Li^7 product nucleus and the 0.44 Mev excited state, respectively. The reaction energies obtained from these ranges with the best available range energy relation check well with those computed from atomic masses if a mass of B^{10} is used which is consistent with other nuclear disintegrations. The slow neutron disintegration of Li^6 results in H^3 particles of 5.90 ± 0.06 cm range, indicating a reaction energy of 4.86 Mev. This is in disagreement with the value obtained from atomic masses and suggests errors in the mass values or the proton range energy relation. Techniques for the measurement of very short particle ranges are described, including methods for the determination of the depth of penetration into the recording ionization chamber.

INTRODUCTION

THE strong absorption of slow neutrons by boron and lithium has been of great value to slow neutron experimenters. The reactions assumed to result in these strong absorptions are:

$$B^{10}+n^1\rightarrow Li^7+He^4+Q_a, \qquad \text{(a)}$$

$$Li^6+n^1\rightarrow He^4+H^3+Q_b. \qquad \text{(b)}$$

Neutron absorption coefficients have been measured and used for the determination of neutron resonance energies. The reactions are utilized in instruments for the detection and measurement of slow neutrons, and as slow neutron shields. The probability of the reactions is thought to be inversely proportional to neutron velocity and to have no resonance maxima.

Measurements of particle ranges and reaction energies, necessary for the theoretical interpretation of these high neutron absorptions, have resulted in large discrepancies. Chadwick and Goldhaber[1] first observed the alpha-particles from boron to have ranges of 5 to 10 mm. Taylor and Dabholkar[2] found the over-all Li^7+He^4 range to be 1.14 cm air equivalent using a photographic emulsion technique. Rotblat[3] has reported a range of 0.818 cm for the alphas using a variable pressure method. Haxel[4] interprets his results to indicate two groups of alphas, of 0.64 and 0.94 cm range, and suggests an excitation level in the Li^7 nucleus at about 0.9 Mev. Fünfer[5] has more recently reported the Li^7 and He^4 ranges to be 0.40 and 0.86 cm, respectively, using a proportional counter and a pressure variation method. In the lithium reaction the first observation was by Chadwick and Goldhaber;[1] a singly charged group (H^3 particles) of 5.5 cm range and a doubly charged group (He^4) of 1.5 cm were observed. Rotblat[3] has remeasured these to be 5.36 and 1.08 cm. In a preliminary report of these experiments the present authors[6] found a considerably longer range for the H^3 particles.

A property of reactions among such light elements is that the reaction energy depends sensitively upon the energy of the incident particle. However, the processes to be investigated are exoergic and probably occur with slow neutrons only so there can be no ambiguity with regard to the energy of the incident particle. It was the purpose of this investigation to obtain accurate values of the particle ranges, using appropriate corrections for thickness of the target and for the depth of penetration of the disintegration particles into the recording ionization chamber.

PART I: RANGE MEASUREMENTS

Experimental

The slow neutron source used in these experiments was the usual Rn-Be "bomb," of approximately 500 mC Rn strength, located in a slow neutron "howitzer." The howitzer is found to give from 3 to 5 times the intensity of slow

[1] Chadwick and Goldhaber, Proc. Camb. Phil. Soc. **31**, 612 (1935).
[2] Taylor and Dabholkar, Proc. Phys. Soc. London **48**, 285 (1936).
[3] Rotblat, Nature **138**, 202 (1936).
[4] Haxel, Zeits. f. Physik **104**, 540 (1937).
[5] Fünfer, Ann. d. Physik **29**, 1 (1937).
[6] Livingston and Hoffman, Phys. Rev. **50**, 401 (1936).

neutrons as from a paraffin sphere, depending upon the distance from the source. The targets were placed inside the muzzle of the howitzer to obtain the maximum intensity (see Fig. 1).

The targets were thin layers of B_4C and Li_2CO_3 deposited on aluminum plates of 10.3 cm diameter. They were thin relative to the slow neutron absorption (about 0.01 g/cm^2) but thick relative to the ranges of the particle products. This requires a thick target analysis of the experimental data to obtain the true range.

A shallow ionization chamber (5.1 cm diameter and 0.4 cm deep) was mounted parallel to the plane of the target. A scale and vernier attached to the supporting aluminum tubing was used to record the relative positions of the target and chamber. A linear pulse amplifier, thyratron scale-of-eight counter and electrical impulse counter were used to record the number of particles entering the chamber. A suitable bias voltage impressed on the grid of the first thyratron was used to eliminate the background noise level of the amplifier, and served to determine a limit to the minimum size of pulse in the chamber required to produce a count. The background, with neutron source removed, was of the order of 0.2 counts/minute. The maximum counting rates obtained (1500 counts/minute) were low enough to make corrections for resolving time of the counting circuits unnecessary.

Results

With the experimental arrangement described above motion of the ionization chamber relative to the target resulted in number distance curves showing a gradual increase with decreasing dis-

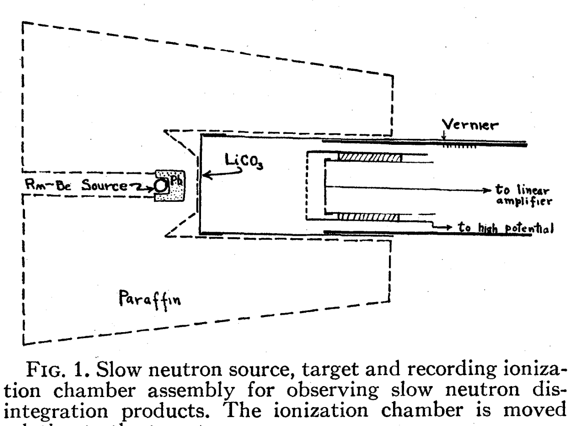

FIG. 1. Slow neutron source, target and recording ionization chamber assembly for observing slow neutron disintegration products. The ionization chamber is moved relative to the target.

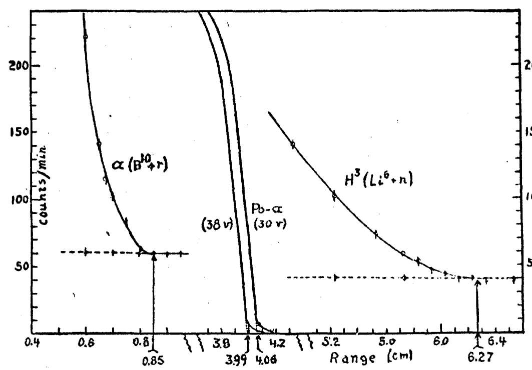

FIG. 2. Number distance curves under operating conditions for the alpha-particles from $B^{10}+n$, Po alphas using two thyratron bias voltages and the H^3 particles from Li^6+n.

tance, starting at about 0.8 cm for boron and 6.1 cm for lithium. The particle groups were superimposed on a background due to nitrogen disintegrations and fast neutron recoils in the air of the chamber. Thin aluminum disks, for which the neutron absorption is small, were placed between the target and chamber to obtain a measure of this background. Counts were taken for 10 minutes or more for each setting of the scale.

In order to obtain a more accurate calibration of the distance between the target and ionization chamber than possible from physical measurements, this distance (including the depth of penetration of alphas into the chamber) was calibrated with Po alpha-particles. A thin layer of Po on a duplicate Al target plate was placed behind a collimating screen formed from a brass disk drilled with many holes of small diameter, so that the maximum angle to the normal was restricted to 8°. This resulted in a well-defined straggling curve from which the extrapolated range of the alphas could be read to ± 0.005 cm. Po alphas have an extrapolated range at 15°C and 760 mm pressure of 3.848 cm,[7] which becomes 4.062 cm under operating conditions of 24°C and 742 mm for example. The readings of the arbitrary scale of the vernier are then shifted to allow the observed extrapolated range of the alphas to intersect the axis at this calculated point.

In Fig. 2 one set of experimental data obtained for the alphas from a boron target, the alpha-particle group from Po, and the H^3 group from a lithium target are plotted on the scale men-

[7] Rutherford, Wynn-Williams, Lewis and Bowden, Proc. Roy. Soc. **139**, 617 (1933).

tioned above to illustrate the results. The H^3 particles have a different specific ionization than the calibrating alphas and hence penetrate further into the chamber. This additional penetration was estimated by varying the bias voltage.

The thyratron tube to which the amplifier output was connected was operated with a grid bias of 30 volts. The "flash-point" of the thyratron was at 22 volts, so that pulses which operated the counter were proportional in size to 8 volts bias of the thyratron. When the bias was increased from 30 to 38 volts the Po alpha-range was decreased by 0.07 cm (Fig. 2), indicating that alphas producing twice the ionization in the chamber penetrated 0.07 cm further. The energy of an alpha-particle of residual range z, sufficient to produce a count through the 30 volt bias, must then be equal to half the energy of a particle of residual range $(z+0.07)$ cm. Using the Cornell range energy curve of 1937[8] (revised according to the recent data of Blewett and Blewett[9]), we find that the residual range z, which is the penetration of the alphas to produce a count, is 0.10_5 cm. This has an energy equivalent of 0.14 Mev. The range of an H^3 particle of this energy is about 0.13_5 cm, or 0.03 cm greater than the alpha range. This correction must be added to the observed range of the H^3 particles under the operating conditions.

The difference in shape of the disintegration particle curves from that of the calibrating alpha-group is due to two features, the thick target and the lack of angular collimation necessitated by the low intensities. This shape can be interpreted in the following way: If the range of the particles is R, the distance between target and chamber is x, and the layer dy from which the particles originate is y equivalent centimeters below the surface, only those particles falling within the solid angle measured by the linear angle θ will be observed, where $\cos\theta=(x+y)/R$. If N_0 is the number emitted per unit solid angle per cm^2 per second in the direction of the normal, the number observed will be:

$$N=2\pi N_0\int_0^{\arccos\,(x+y)/R}\sin\theta\,d\theta$$
$$=2\pi N_0(R-(x+y))/R,$$

[8] Livingston and Bethe, Rev. Mod. Phys. 9, 266 (1937).
[9] Private communication, soon to be published in Proc. Roy. Soc.

and since N_t, the total number emitted from the layer dy in all directions is $2\pi N_0$, we have:

$$N=N_t(R-(x+y))/R.$$

To get the effect of the thick target we must integrate between the limits of $y=0$ and $y=R-x$:

$$N_{ob}=N_t\int_0^{R-x}R-(x+y)/R\,dy=\tfrac{1}{2}N_t(R-x)^2/R.$$

In the range in which the data are taken ($R-x$ small) this equation will be valid, and represents a parabola with an axis at $R=x$. If we plot the square root of the observed intensities (after subtracting the background) as a function of x the curve should be linear and should extrapolate to the true range, $R=x$, for $N^{\frac{1}{2}}=0$.

In Fig. 3 the data of Fig. 2 are plotted in this manner, resulting in an alpha-particle mean range of 0.85 ± 0.04 cm and a H^3 range of 6.27 ±0.10 cm. Adding the penetration correction to the H^3 range and reducing to standard conditions of 15°C and 760 mm from the experimental conditions prevailing during the observations we find: range He^4 from $B^{10}+n=0.81\pm0.04$ cm, and range H^3 from $Li^6+n=5.91\pm0.10$ cm.

In the range of observation the data fall on well-defined straight lines in the square root plot, justifying the analysis and the mean ranges indicated by the intercepts. The probable error of each point is indicated by the extent of a vertical line through the point, obtained from the square root of the total number of counts. The errors for the range intercepts are estimated

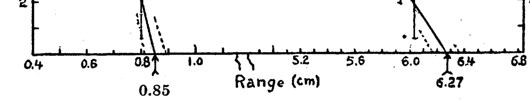

FIG. 3. Plot of $N^{\frac{1}{2}}$ *vs.* distance for the B alphas and the Li H^3 particles to determine the mean range by extrapolation.

TABLE I.

	Range He^4 from $B^{10}+n$	Range H^3 from Li^7+n
I	0.81±0.04 cm	5.91±0.10 cm
II	0.80±0.05	5.79±0.10
III	0.78±0.06	6.01±0.10
	Av. 0.80±0.03 cm	5.90±0.06 cm

TABLE II.

Reaction	Q (calc.)	Q (obs.)	Diff.
B^{10}–d–p	9.30	9.14±0.06	0.16±0.06
B^{10}–d–α	17.90	17.76±0.08	0.14±0.08
B^{10}–d–n	6.34	6.08±0.20	0.26±0.20
(Aston)	(B^{10}=10.0161±.0003)		0.20±0.30
	Weighted average diff.		0.17 Mev

from the limiting straight lines that could be drawn through the points.

Three complete determinations were made for the Li and the B targets, including Po alpha-calibration curves in each case. The geometry was varied by choosing different chamber depths and collimation screens and different thyratron bias settings were used. The result of each determination was computed in the manner described above and a value obtained for the range under standard conditions. These values and the final averages are given in Table I.

Discussion

In attempting to evaluate the energy equivalents of these observed particle ranges we encounter serious difficulties. The alpha-particle range of 0.80 cm falls in the region of the range energy relation in which the experimental determinations are poor and where the capture and loss of charge invalidates the theoretical calculations which seem to be satisfactory for higher energies. The Cornell curves of 1937[8] were based upon the data of Briggs and of Mano (corrected for known errors of calibration) and upon Neuert's measurement of the short He^3 and He^4 ranges in the Li^6–p–α disintegration. This suggests an energy equivalent of 1.51 Mev for the B alphas. Recent data by Blewett and Blewett[9] diverge widely from the Cornell curve in this low energy region. An extrapolation of the curve from their data to somewhat lower energies gives an energy equivalent of 1.75±0.05 Mev for 0.80 cm alphas. The error indicated is just the experimental error and does not include the inaccuracies of the range-energy relation. From momentum considerations we find that 11/7 of the alpha-particle energy represents the reaction energy. The two values above result in reaction energies $Q_a = 2.38$ and 2.75±0.08 Mev. That predicted by the atomic masses[10] is 2.99 Mev, showing discrepancies of 0.61 and 0.24 Mev for the two relations used, and far outside the experimental probable error in either case.

In searching for an explanation of this discrepancy it was found that all nuclear reactions involving B^{10} show similar discrepancies between observed and calculated reaction energies. This suggests strongly that the B^{10} mass used in the calculations is in error. The accepted value,[10] 10.01631, is obtained from the mass-spectroscopic measurements of the $B^{10}H_2-C^{12}$ doublet by Bainbridge and Jordan. If we list the nuclear reactions involving B^{10} which are of sufficient accuracy,[11] and obtain a weighted average of the discrepancies, this proves to be about 0.17 Mev (see Table II). The B^{10}–α–p reaction shows an even larger discrepancy in the same direction (0.85 Mev), but the possibility of constant errors in the measurement of ranges of particles produced in alpha-particle disintegrations makes it impossible to state an error. This reaction should be re-investigated with artificially accelerated alphas. The Be^9–d–n–B^{10} reaction cannot be considered since the Be^9 mass is based upon that of B^{10}, and will also be in error. The result of this summary is to indicate that the B^{10} mass should be reduced by 0.17 Mev (to 10.01613), giving a better check with disintegration results and predicting a reaction energy for the B^{10}–n–α reaction of 2.82 Mev, in much better agreement with the observed value of 2.75±0.08 Mev. This also suggests that the Blewett and Blewett range energy relation for alphas is essentially correct.

The H^3 range of 5.90 cm from the Li^6–n–α reaction may be evaluated from the proton range energy relation. Assuming that the range of particles of the same charge but different mass is proportional to their mass for the same velocity we find: the range of a H^3 particle is three times the range of a proton of $\frac{1}{3}$ the energy

[10] Livingston and Bethe, reference 8, p. 373.

[11] Livingston and Bethe, reference 8, p. 371–372.

of the H^3. This forces us to evaluate the H^3 range from a proton range of 1.96_7 cm. This, again, is in the low energy region which was inaccurately known until recently. The Cornell curves were based on the data of Blackett and Lees at low energy and included an empirical factor of 0.2 cm representing the difference between proton and alpha range due to the difference in capture and loss of charge. Recently Parkinson, Herb, Bellamy and Hudson[12] have reported on the ranges of protons accelerated in their pressure electrostatic generator discharge tube. Their data check the Cornell curves above 2.5 cm range, but show somewhat larger energies in the region between 0 and 2.5 cm. According to these data the protons of 1.97 cm range have an energy equivalent of 0.925 Mev. The H^3 energy is three times this value and the reaction energy 7/4 of the H^3 energy, or $Q_b = 4.86 \pm 0.04$ Mev. The low probable error again includes only the experimental fluctuations. This value is to be compared with that of 4.56 Mev expected from the atomic mass values, a discrepancy of 0.30 Mev.

The discrepancy in the observed and calculated reaction energies for Li^6–n–α is much greater than expected from the possible experimental errors in the range measurements. This statement has more meaning when it is noted that the values obtained for the B target are smaller than those predicted by masses, while from the Li target they are larger. If the 4.56 Mev calculated Q is assumed correct the range of H^3 particles expected would be 5.6 cm under the conditions of Figs. 2 and 3. Exactly similar techniques and calibrations were used for the two targets. Furthermore, the low intensities observed should be expected to lead to ranges shorter than the true range rather than larger.

It seems probable that in the Li case also there are errors much greater than in the range measurements either in the mass values or in the proton range energy relation at these low energies. The Li^6 mass is determined from the mass spectrograph values of Li^7 and He^4 through two disintegration reactions, Li^6–d–p and Li^6–d–α. There are discrepancies in these reactions and in other reactions involving Li^7 which seem to be larger than experimental errors, but they cannot be analyzed to show an error in any single mass value and are probably due to simultaneous errors in the mass values of many of the light atoms.

[12] Parkinson, Herb, Bellamy and Hudson, Phys. Rev. **52**, 75 (1937).

Part II. Evidence for the Excited State of Li^7 from the B^{10}–n–α Reaction

In the analysis of the distance variation data of Part I it was found that there was an excess number of counts due to short range alpha-particles from the boron target. This was indicated by the observation that the counts below 0.6 cm distance rose above the straight line used for extrapolation in the square root plot. This effect was not observed with the Li target. Accordingly a different technique was used to study the short range region.

The distance between the target and the face of the ionization chamber was kept constant (1.00 cm) and the depth of the ionization chamber fixed at 0.40 cm. The region between target and chamber and the chamber itself was sealed so that the pressure could be varied (see Fig. 4). With decreasing pressures the alpha-particle ranges extended into the chamber where they were observed; the number of counts was found to increase with decreasing pressure to a maximum value and then fall off to zero with the decreasing efficiency of the ionization chamber at very low pressures. The background counting rate, observed by inserting a thin aluminum disk between target and chamber, decreased regularly with decreasing pressure.

When a screen faced chamber (no collimation) was used the data plotted in Fig. 5 were observed. This showed the boron counts appearing above the background at about 500 mm, rising very rapidly below 400 mm and reaching a maximum at about 200 mm pressure. The data can be analyzed in a manner entirely similar to

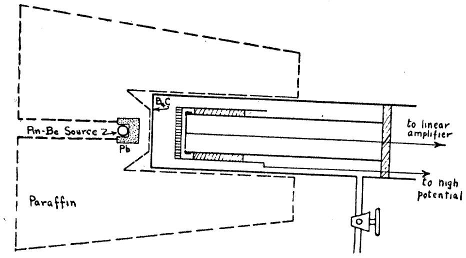

FIG. 4. Pressure variation apparatus for observing the short range alpha-particles from $B^{10}+n$.

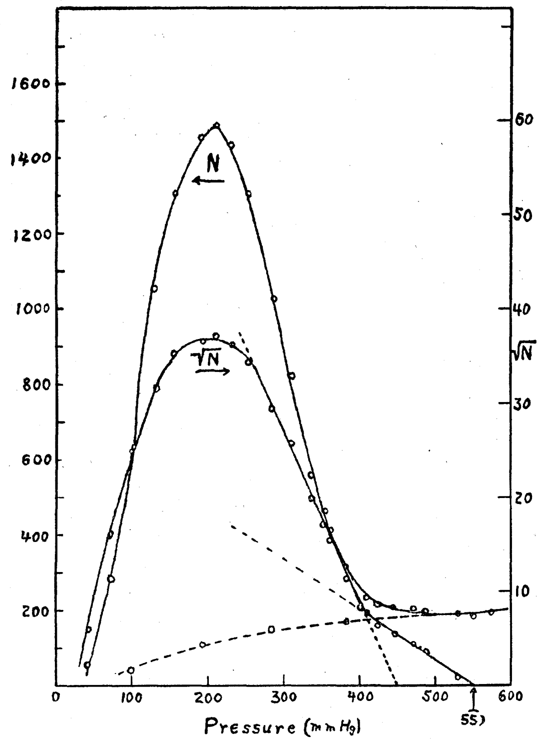

FIG. 5. Number *vs.* pressure curve of alpha-particles from $B^{10}+n$; $N^{\frac{1}{2}}$ *vs.* pressure curve to determine pressure extrapolation.

that used for the distance variation method by plotting the square root of the number of counts (less background) and extrapolating to obtain a pressure representing the range of the alpha-particles. On another scale of Fig. 5 the data are plotted in this manner. It is seen that there are two roughly linear portions of the high pressure side of the curve, one extrapolating to about 550 mm and one to 450 mm. As will be shown later these seem to indicate respectively an alpha-particle group of about 0.81 cm range and another of about 0.66 cm range.

Before range values can be obtained from the pressure intercepts it is necessary to determine the depth of penetration of the particles into the chamber to produce a count, a quantity which is in this case an inverse function of the pressure. This can be determined by an analysis of the shape of the pressure variation curve.

In order to produce a count a particle must release an amount of ionization I (in Mev units) in the chamber. At high pressures a particle stopping in the chamber will result in a count when the residual energy of the particle at the face of the chamber is equal to or greater than I. At low pressures many of the particles will cross the chamber; the limiting condition will be the pressure at which an alpha-particle having the maximum specific ionization (peak of the Bragg curve) will just produce the ionization I in the full chamber depth d. With no angular collimation the high pressure side of the curve will be parabolic, and can be extrapolated by plotting the square root of the number of counts. The low pressure intercept will be significant only if the particles are collimated, so that the depth d represents the length of the particle path in the chamber. From this intercept the ionization I can be determined and so the penetration at the high pressure intercept.

Accordingly, a collimation grid limiting the alphas to within 20° of the normal was substituted for the screen face of the chamber. A pressure variation run with this arrangement resulted in the data plotted in Fig. 6. The boron alpha-counts were much smaller than in the

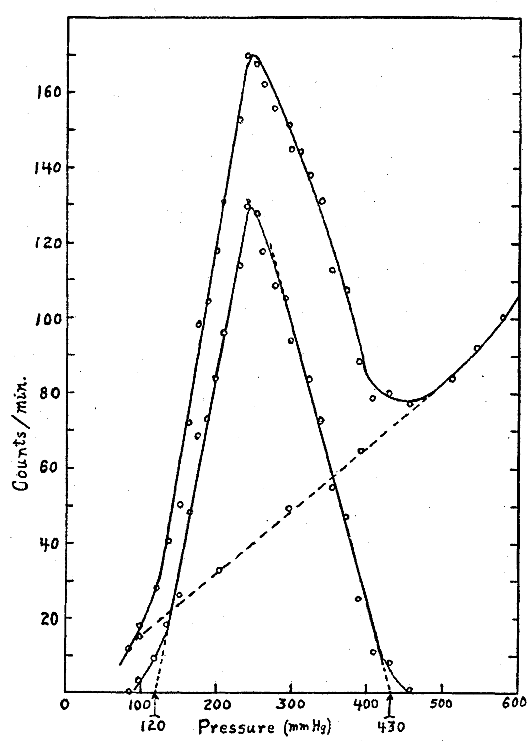

FIG. 6. Number *vs.* pressure curve of alpha-particles from $B^{10}+n$ under 20° collimation, showing pressure intercept for the short range alpha-group.

uncollimated arrangement, but when the background is subtracted they give a sharply peaked curve extrapolating to 120 mm on the low pressure side and 430 mm on the high pressure side. A linear extrapolation of the data is used in this instance (rather than the square root) because with the angular collimation the only disturbing factor is the thickness of the target. It may be noted that the counts due to the longer range alphas (0.81 cm) are now so small that they are not observable above the background, and so the 430 mm extrapolated value should give the range of the short range alpha-group with good accuracy.

The 120 mm low pressure intercept (at 24°C) indicates an air equivalent of the 0.40 cm chamber at standard conditions of 0.061 cm, which when multiplied by the specific ionization at the peak of the Bragg curve (2.36 Mev/cm) gives an energy equivalent of the ionization I of 0.145 Mev. A particle of this energy has a range of $0.10_7 \pm 0.03$ cm, the penetration at standard conditions required to produce a count. This figure is in excellent agreement with that of 0.10_5 cm obtained in Part I for the penetration under essentially standard conditions, and for the same thyratron bias. Since this latter figure was obtained from the revised Cornell range energy curve the check is a confirmation of the correctness of this relation.

The 550 mm intercept of Fig. 5 results in a range to the face of the chamber of 0.702 cm under standard conditions. Adding the 0.107 cm penetration distance we obtain a range for the long range alphas of 0.81 ± 0.05 cm, in good agreement with the value obtained in Part I.

When the straight line extrapolating to 550 mm in Fig. 5 is extended and these values subtracted from the total $N^{\frac{1}{2}}$ curve we find a second extrapolation of 420 mm, indicating a group of shorter range alphas. A better value is obtained from the linear extrapolation of Fig. 6, of 430 mm. This may be used to obtain the range equivalent of the 1.00 cm distance to the face of the chamber of 0.550 ± 0.04 cm. Again adding the penetration distance we find the short range group of alphas to have a range of 0.66 ± 0.05 cm.

Discussion

The interpretation of the experimental results of Part II to indicate two groups of alpha-particles, although experimentally justified, is largely due to the knowledge that the residual Li^7 nucleus has an excited state at about 0.44 Mev above the ground state. This has been observed in the Li^6–d–p reaction as two proton groups,[13] and by the measurement of a 0.4 Mev gamma-ray.[14] In fact, before the evidence discussed in Part I leading to the lower B^{10} mass was analyzed, it seemed probable that the B^{10}–n–α reaction led always to this excited state. We see now that the longer range alphas (0.80 cm) indicate a disintegration into the ground state. Although the range energy relation for alpha-particles is very poorly known in the region about 0.66 cm we can use the best relation available (Cornell—1937—revised according to Blewett and Blewett) to determine a reaction energy for the reaction producing these short range particles. This proves to be 2.27 Mev. The difference between this value and that obtained for the 0.8 cm alphas is 0.48 Mev, in very good agreement with that expected for the 0.44 Mev excitation state of Li^7.

The relative intensities of the two alternate reactions can be obtained from the experimental data of Fig. 5 by extrapolating the two straight line portions of the $N^{\frac{1}{2}}$ curve to zero pressure and comparing the respective ordinates. We find that the excited state transition is 3 times as probable as that leading to the ground state.

The results make it possible to understand the contradictory nature of previous measurements, due to the existence of the two groups of alpha-particles. The good checks with the reaction energies obtained from the new B^{10} mass give a strong confirmation of the essential correctness of the alpha-particle range energy relation used for these low energies. The analysis of the data also shows the necessity of correcting for the distance of penetration of such short range particles into the recording ionization chamber.

The authors wish to express their appreciation for financial assistance in these investigations by the Committee on Radiation of the National Research Council, and to Professor H. A. Bethe and Dr. E. J. Konopinski for valuable suggestions concerning the analysis of the data.

[13] Rumbaugh and Hafstad, Phys. Rev. **50**, 681 (1936).
[14] Shepherd, Haxby and Williams, Phys. Rev. **52**, 247 (1937).