The Energy Spectra of the Neutrons from the Disintegration of Fluorine, Boron and Beryllium by Alpha-Particles

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By using an expansion chamber filled with hydrogen or methane at a pressure of about 15 atmospheres, range-distribution curves have been obtained of the recoil protons from Po-F, Po-B, and Po-Be neutrons. These curves revealed the presence of numerous groups of neutrons in the radiation from the three sources. In the case of Po-F five neutron groups were found. These were fitted into a disintegration scheme, made by assuming that the α-particle enters the nucleus through resonance levels and by using the energies of these levels, which are known from the disintegration of fluorine with proton emission. For Po-B eight groups were detected, but it was not possible to arrange a disintegration scheme. The maximum energy of the neutrons from Po-B was found to be 4.2 M.E.V., a value considerably higher than the previously accepted figure, 3.3 M.E.V. This value decreases the mass of the neutron calculated from the disintegration of B^{11} from 1.0067 to 1.0058. It is suggested that it is possible to explain the high value, 1.0098, obtained by Curie and Joliot from the disintegration of B^{10}, by assuming that both B^{11} and B^{10} emit neutrons. If the maximum energy of the neutrons from B^{10} were about 7.5 M.E.V. it would bring this mass into agreement. Reasons are given for believing that at least 10 times as many neutrons come from B^{11} as from B^{10} so that there may be a few as yet undetected neutrons from B^{10} extending up to this energy. About 22 groups were found in the neutron emission of Po-Be. A possible scheme of disintegration is given.

Introduction

The early work on the energy distribution of the neutrons produced by α-particle bombardment of beryllium and boron was concerned principally with finding the maximum energy for the purpose of obtaining the mass of the neutron. Subsequent work[1, 2, 3, 4] began to reveal more exactly the nature of the energy distribution and indicated the existence of neutron groups analogous to the groups of protons which have been found in the disintegration of light elements with the ejection of a proton. In the case of fluorine previous experiments indicated the existence of neutron emission but no direct energy measurements had been made. The present experiments were undertaken to find the energy distribution of the neutrons from Po-F and to obtain further data on the neutrons from Po-Be and Po-B. Preliminary accounts have been given for fluorine[5] and for boron.[6]

Experimental Method

To obtain the energy of a neutron it is necessary to observe the energy which it gives to an atom in a collision. The energy given to a recoil atom can be found by determining its range by means of ion-counters and absorbing screens, by the Wilson cloud-chamber, or photographically in the manner used by Blau.[3] Ion-counters have the advantage of recording recoil atoms more rapidly than the other methods. As ordinarily used, however, they do not give the actual range of the particle but only the number of particles with ranges greater than a minimum determined by the stopping power of the screens. Accordingly, so-called integral range-distribution curves are ordinarily obtained by this method, and these are not as suitable for detecting groups as the true or "differential" distribution. Ion-counters also suffer from the existence of the residual counting-rate which in the presence of a strong source limits their accuracy when working in regions of low intensity. Another difficulty is that ordinarily the recoil atoms have to be obtained from a thick layer of material (usually protons from paraffin) which results in a further distortion of the energy distribution. On the other hand, with the expansion chamber, if the recoil tracks are formed in the gas, this difficulty is avoided. Also, the actual range is observed, so

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1 I. Curie and F. Joliot, Comptes Rendus **194**, 876 (1932).

2 J. Chadwick, Proc. Roy. Soc. **A142**, 1 (1933).

3 M. Blau, J. d. Physique, **5** 61 (1934).

4 J. R. Dunning, Phys. Rev. **45**, 586 (1934).

5 T. W. Bonner and L. M. Mott-Smith, Phys. Rev. **45**, 552 (1934).

6 L. M. Mott-Smith and T. W. Bonner, Phys. Rev. **45**, 554 (1934).

that the true range distribution can be obtained. In using an expansion chamber various recoil atoms such as H, He, N, O, A may be used. Heavy atoms (O, N, A) are not very satisfactory because their ranges are much too short for accurate measurement with any but the neutrons of highest energy. In addition, to infer the energy distribution of the neutrons from the observed energies of the recoil atoms, it is necessary to take into account that the recoil atom obtains only a portion of the energy of the neutron, and this depends on how direct a collision occurs. It is therefore desirable to use a recoil atom for which as large a fraction as possible of the collisions are nearly head-on. It appears from studies of the angular distribution of recoil protons by Kurie[7] that this condition is probably more satisfactorily met by protons than by heavier atoms. He found a pronounced maximum for protons ejected in the forward direction, and this is confirmed by some results presented below. It is not possible, however, to use recoil protons produced in the gas of an ordinary expansion chamber because their ranges are too great (up to about 150 cm for beryllium), and also because a sufficient number of recoil tracks cannot be obtained without taking an excessively large number of photographs. In order to be able to do this we have employed a special expansion chamber (filled with H_2 or CH_4) in which the pressure of the gas could be raised to about fifteen atmospheres, thereby reducing the range of the protons and also increasing the yield. In this way we could measure recoil protons having ranges up to about 90 cm in air, and increased the yield by roughly a factor of fifteen.

The expansion chamber was of a simple type using a stretched thin rubber diaphragm as the piston, such as the one recently described by Wilson,[8] and operated pneumatically. It consisted of a heavy brass casting, the inside dimensions, or working volume, being 10 cm in diameter by 3.5 cm deep. The top was closed by a thick fused quartz plate (chosen for its superior strength and transparency) through which the interior was photographed. The tracks were formed by condensation of alcohol vapor instead of water vapor. It was found to be more convenient because it requires a smaller expansion-ratio and has less tendency to fog the windows.[9]

The neutrons were produced by bombarding thick targets of Be, B, or CaF_2 with α-particles from polonium. The polonium was deposited on a small silver button and had an average activity of about 10 millicuries during the course of the experiment. The source was placed at the side of the chamber in a recess where the thickness of the side-wall was approximately 0.7 cm (see Fig. 1).

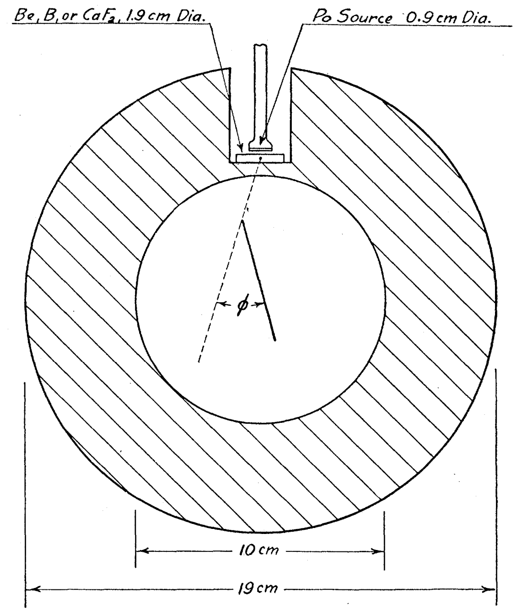

FIG. 1. Diagram of the expansion-chamber and the source of neutrons, as seen from the position of the camera.

The tracks were photographed on 35 mm motion-picture film with a camera taking stereoscopic pairs of photographs at an angle of 16°. Measurement of the lengths of the tracks was carried out by projecting the photographs with the camera lens system in the usual way. A card carrying a scale was adjusted until the two images of the track coincided and lay along the scale. The length could be read to 0.1 mm but due to possible errors in adjusting for coincidence of the images the track lengths might be in error by as much as 0.2 mm. In making the reconstruction it was necessary to take into account the displacement of the images produced by the

[7] F. N. D. Kurie, Phys. Rev. **44**, 463 (1933).
[8] C. T. R. Wilson, Proc. Roy. Soc. **A142**, 88 (1933).
[9] The details of design and operation will be submitted for publication in Rev. Sci. Inst.

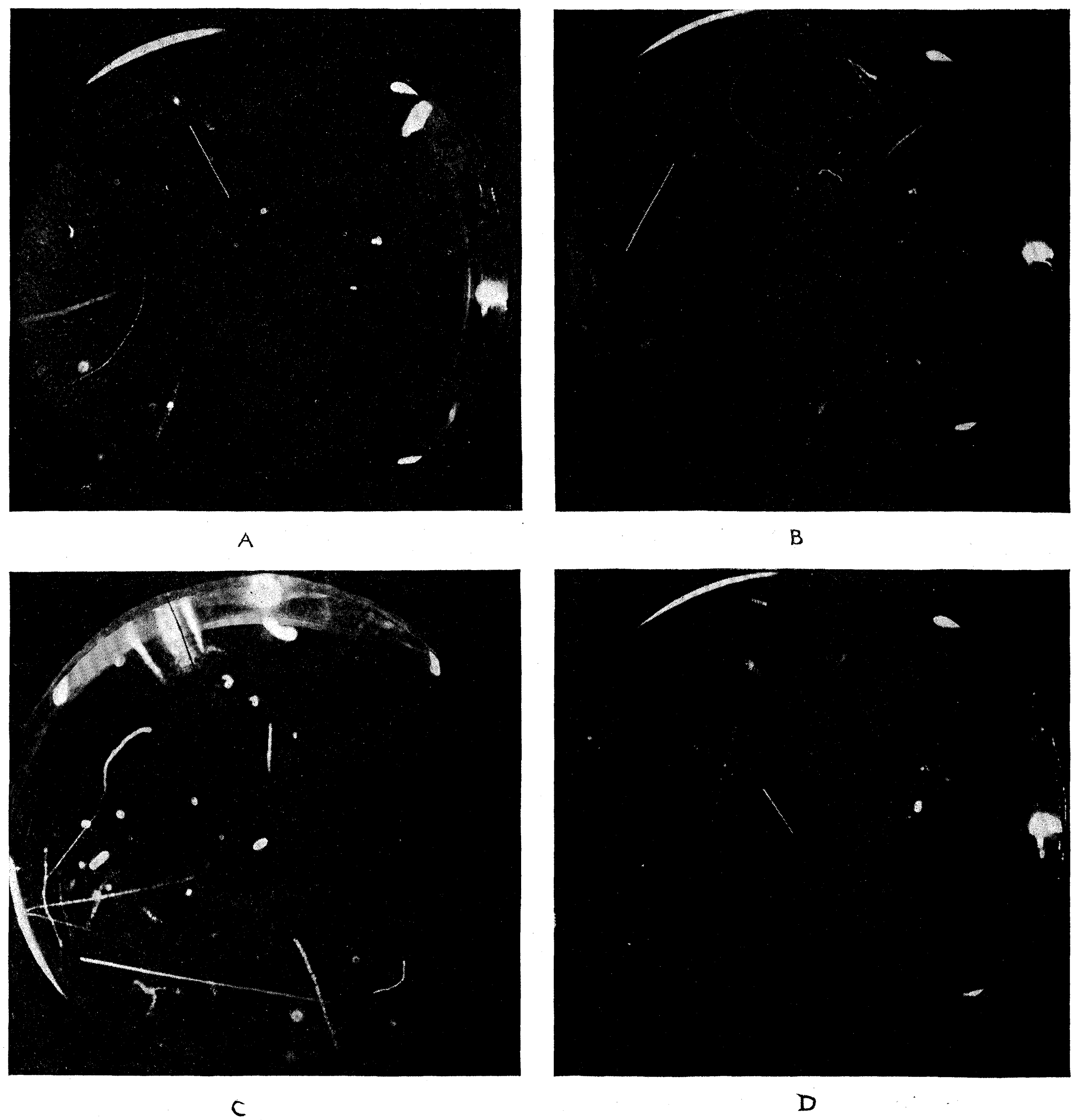

FIG. 2. Tracks of recoil-protons observed with the gas of the expansion-chamber at 12.9 atmospheres pressure. The source of neutrons is behind the center of the illuminated area in the upper left-hand portion of the photographs. (A) A recoil-proton from a fluorine neutron, produced in hydrogen. The actual length of the track was 1.65 cm, corresponding to a range of 5.28 cm in air at 76 cm and 15°C. (B) A recoil-proton from a boron neutron, produced in methane. The actual length was 2.10 cm, corresponding to a range of 22.5 cm in standard air. (C) A long recoil-proton from a beryllium neutron, in methane. The actual length was 5.33 cm, corresponding to a range of 57.0 cm in standard air. (D) A short recoil-proton from beryllium, in hydrogen. The actual length was 1.08 cm, corresponding to a range of 3.68 cm in standard air. This track is nearly in the direction of the source so that (neglecting the possibility that it was produced by a scattered neutron) the proton obtained practically the entire energy of the neutron. *Note:* (C) is incorrectly placed. It should be turned 90° in a clockwise direction.

thick quartz plate. This was done by projecting through a piece of plate glass which gave the same displacement as the quartz plate.

On the photographs were found numerous straight dense tracks which began and ended in the chamber and thus could definitely be identified as recoil protons. Examples of such tracks are shown in Fig. 2. With methane in the chamber many recoil carbon atoms must have been produced, but the length of the longest carbon track was much shorter than the shortest proton track which was measured in methane. Thus there is no possibility that carbon atoms were mistaken for protons. Only sharp narrow tracks were included. Many were found which were rather broad because the proton was projected before completion of the expansion. These were rejected because in this case the stopping power of the gas at the time the ion-track was formed could not be determined.

Hydrogen with a pressure after expansion of about 13 atmospheres was useful for investigating neutrons having energies corresponding to recoil protons up to a range of about 18 cm in air. Methane at the same pressure allowed measurement of protons up to about 90 cm equivalent air range, but could not be used below about 7 cm because the tracks were too short (<0.6 cm) to measure with sufficient accuracy. The hydrogen was obtained from commercial cylinders. The only impurity of consequence was about one percent air which was allowed for in calculating the stopping power. The methane was also obtained from a cylinder; there were no impurities which could appreciably alter the stopping power.

RESULTS

Fluorine

About 9000 pairs of photographs were taken with hydrogen in the chamber. On the photographs 163 protons were found which were suitable for measurement of the range. In addition, since a knowledge of the angular distribution of the recoil protons was of importance in deciding how to treat the observed data on the proton ranges, the angle of projection was measured for 101 of these protons. Only a portion of the total number was used because some of the tracks start at points in the gas too near the source to allow measurement of the angle. The results on the angular distribution are presented in the curve of Fig. 3, where the number of protons in 15° intervals is plotted against the angle (ϕ of Fig. 1) between the direction of the neutron and that of the recoil proton. Since the

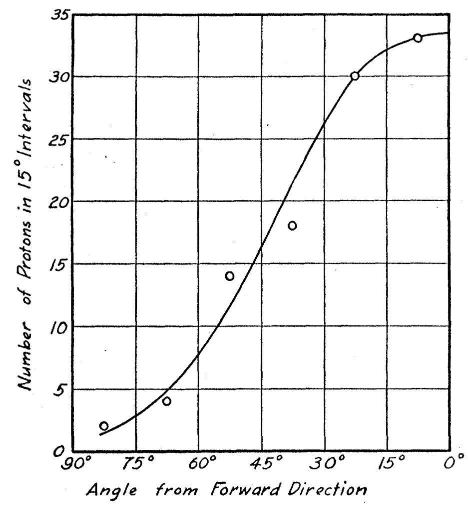

FIG. 3. The angular distribution of the recoil protons from Po-F neutrons.

lengths of the tracks used in constructing this curve were small in comparison to the dimensions of the chamber, the longest being 2.3 cm in actual length, the observed distribution should approximate the true distribution without the necessity of making geometrical corrections. It is noted that a large majority of the protons are projected in nearly the forward direction. This result agrees with Kurie[7] but not with the results of Monod-Herzen[10] or Meitner and Philipp.[11] This lack of agreement is probably due to differing geometrical conditions. It is clear, however, that with our arrangement the majority of the protons which were used for determining the neutron energies were mainly in the forward direction and thus in the majority of cases obtained nearly the entire energy of the neutron. Accordingly, in inferring the energy distribution of the neutrons from the range distribution of the recoil protons it seemed unnecessary to take the angle of projection into account. In fact if it is attempted to do this, by computing the energy of the neutron from the range of the proton and the angle, serious error may be made because of the presence of scattered neutrons. For instance, if a fast neutron were scattered into the chamber at 90° and produced a fairly long proton at nearly right angles to the direction from the source, and

[10] G. Monod-Herzen, J. d. Physique **5**, 95 (1934).
[11] L. Meitner and K. Philipp, Zeits. f. Physik **87**, 484 (1934).

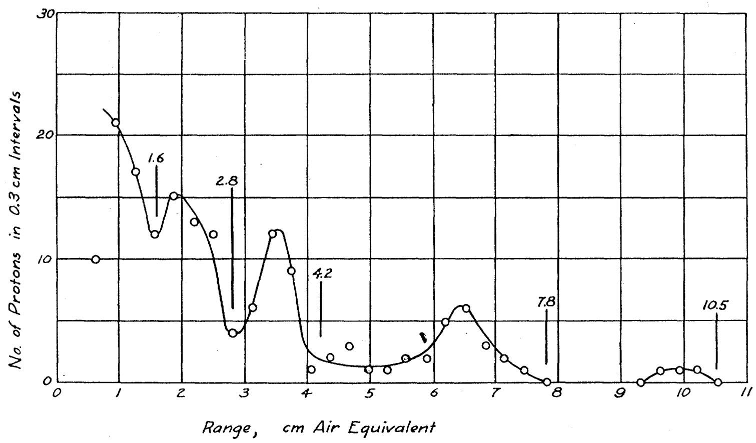

FIG. 4. The range distribution of the recoil protons from Po-F neutrons. The observed ranges in hydrogen at 12.9 atmospheres and 25°C have been converted to the equivalent ranges in air at 76 cm and 15°C.

if this were classed as a proton produced by a neutron coming directly from the source, the computation would lead to an excessively high energy for the neutron. If the angular correction is not made the presence of neutrons scattered from the brass walls of the chamber introduces no serious error because the maximum energy that a neutron can lose in a single elastic collision with a copper or zinc nucleus is only about six percent of its original energy.

The data on the range-distribution are presented in Fig. 4, where the number of protons in 0.3 cm intervals of range is plotted against the air-equivalent range (76 cm, 15°C). These experiments were carried out with hydrogen in the chamber whose pressure after expansion was 12.9 atmospheres at the temperature of the chamber, 25°C. The actual ranges extended from about one mm, the shortest track which could be identified as a proton, to 3.2 cm, the longest observed. These ranges were converted to air under standard conditions by using the differential stopping power data given by Gurney.[12] From these data a curve was obtained relating the stopping power to the range. This curve was extended beyond the ranges investigated by Gurney by assuming that his values of the differential stopping power at long ranges, 0.206, represents the limiting value which should apply to all longer ranges. It will suffice here to give the values of the stopping power from this curve at 2 cm proton-range and at 10 cm. These stopping powers are 0.237 and 0.218, respectively. In making this conversion it was necessary also to take into account the stopping power of the alcohol vapor in the chamber. The stopping power was computed from data given by Philipp.[13]

It will be noted that the range-distribution curve (Fig. 4) shows distinct maxima and minima.[14] Since the number of protons is not very large, an appreciable amount of statistical fluctuation is expected, but it is believed that the points lie too consistently on a smooth curve, particularly in the regions where the larger counts were obtained, to be able to attribute the peaks entirely to this cause. Additional evidence that the peaks represent a real property of the neutron emission was obtained by plotting separately the first and second halves of the data. It was found that substantially the same maxima and minima were present in both curves. The presence of peaks in the range distribution of the recoil protons evidently means that a large fraction of the neutrons are emitted in groups and not with a continuous distribution of energy. From curves of this type it is not possible to obtain the exact energy distribution of the neutrons of a group nor the relative intensities of the groups,[15] but it is possible to find their

[12] R. W. Gurney, Proc. Roy. Soc. **A107**, 340 (1925).

[13] K. Philipp, Zeits. f. Physik **17**, 23 (1923).

[14] This curve differs somewhat from the one previously published (reference 5). The change was caused by a more careful measurement of the proton ranges.

[15] The range distribution curves do not directly give the intensity distribution of the neutrons because the target

maximum energy, which is the maximum energy of the corresponding group of recoil protons. The curve shows five groups of protons, whose maximum energies were chosen as indicated in the figure.

To explain the presence of neutron groups it may first be noted that since the α-particles were allowed to strike a thick piece of CaF_2 they had a continuous distribution of velocity in the material. Accordingly, if groups of neutrons are observed, it must mean that α-particles having certain particular values of the velocity, or narrow ranges of velocity, are more effective in the production of neutrons than others. In the disintegration of light elements by means of an α-particle which results in the emission of a proton, similar results have been obtained and have been shown to be due to the entrance of the α-particle into the nucleus through resonance levels. The resonance levels for the entrance of an α-particle into the fluorine nucleus have been found by the studies of this type of disintegration. Chadwick and Constable[16] found three resonance levels and further that two groups of protons were produced by α-particles entering through each level. For each resonance level the group of protons having the shorter range is produced when the resulting nucleus (Ne^{22} in this case) is left in an excited state. This nucleus then returns to the normal state with the emission of a γ-ray.

It is found that a satisfactory explanation of the neutron groups can be obtained by assuming the same type of process for the disintegration with emission of a neutron. The proposed disintegration scheme is shown by the energy diagram of Fig. 5 and in Table I. The energy of the recoil protons is obtained from the range-velocity data given by Blackett.[17] This scheme was obtained in the following manner. The resonance levels were taken to be the same as

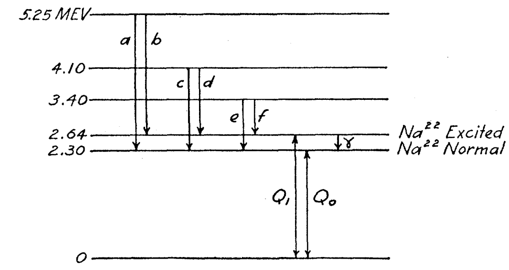

FIG. 5. Energy diagram for the fluorine disintegration scheme.

TABLE I. *Fluorine disintegration scheme.* (Energies in M.E.V.)

$E\alpha$	En_0 (Calc.)	En_1 (Calc.)	En_0 (Obs.)	En_1 (Obs.)	*Energy of disintegration*
5.25	(a) 2.54	(b) 2.18	(a) 2.54	(b) 2.12	$Q_0=-2.30$, $Q_1=-2.68$
4.1	(c) 1.43	(d) 1.06	(c) 1.45	(d) 1.09	$Q_0=-2.28$, $Q_1=-2.60$
3.4	(e) 0.72	(f) 0.37	(e) 0.68	(f) ——	$Q_0=-2.34$, $Q_1=$ ——
					Av. $Q_0=-2.30$ Av. $Q_1=-2.64$ Av. $E\gamma=$ 0.34

$E\alpha$ = energy of resonance level for α-particle.
En_0, En_1 = maximum energies of neutron groups.
Q_0, Q_1 = energies of disintegration.
$E\gamma$ = energy of γ-ray.

those for the proton disintegration (because in both cases the α-particle enters the same nucleus). The observed neutron group of highest energy (group (a)) was attributed to the highest resonance level; and when the neutron obtains this energy it is supposed that the resulting nucleus is left in the normal state. The energies of groups (c) and (e) were then calculated by using the α-particle energies given by the energies of the resonance levels and the energy of disintegration (Q_0), obtained from group (a) and the energy of the first resonance level. Groups (b), (d) and (f) were obtained by assuming a value for (b) and calculating (d) and (f) as before. The value of (b) was chosen to give the best agreement with the experimental data. It was found that better agreement was obtained if the energy of the second resonance level was taken to be 4.1 M.E.V. instead of the value 4.0 M.E.V. given by Chadwick and Constable. An analysis of their data indicated that the value 4.1 M.E.V. is not inconsistent with it. The calculated values of the neutron groups agree reasonably well with the observed values. The group of lowest energy has

area for a collision between the neutron and the hydrogen nucleus increases rapidly with decreasing energy of the neutron, and also because a greater fraction of the longer tracks have to be rejected because they strike the walls of the chamber. The second reason is not as important for fluorine-neutrons as it is for beryllium-neutrons where many of the tracks are considerably longer.

[16] J. Chadwick and J. E. R. Constable, Proc. Roy. Soc. **A135**, 48 (1932).

[17] P. M. S. Blackett, Proc. Roy. Soc. **A135**, 132 (1932), and Blackett and Lees, Proc. Roy. Soc. **A134**, 665 (1932).

not been observed because the very short recoil tracks (2 mm in actual length) which it produces could not be measured with sufficient accuracy to detect a group in this region. Another test of consistency of the scheme of disintegration is obtained by calculating the energy of disintegration from each of the observed neutron groups. There are two sets of values, one (Q_0) when the nucleus is left unexcited and the other (Q_1) when it remains excited. The three values in each set should of course agree with each other. Reasonably good agreement was found, as shown in Table I. The energy of the γ-rays is given by the energy difference Q_0-Q_1. By using the average values of Q_0 and Q_1, this comes out 0.34 M.E.V. This predicted γ-radiation presents no difficulty since it is known that soft γ-rays are produced when fluorine is bombarded by α-particles. The γ-rays predicted by the neutron disintegration have about half the energy of those predicted by the proton disintegration, so that it is expected that a careful analysis of the γ-rays from the disintegration of fluorine by α-particles should reveal these two lines. The scheme of disintegration which is presented above was found to be the only one which is able to account for the observed groups using the three given resonance levels.[18]

The maximum energy of the neutrons from Po-F is found from the curve to be 2.5 M.E.V. This is considerably lower than the value 4.2 M.E.V. which we find for boron, and confirms Bonner's previous work[19] which indicated that the neutrons from fluorine have less energy than those from boron.

Boron

4000 pairs of photographs were taken, about half of these with hydrogen and the rest with methane, both gases being at the same pressure as before. The observed ranges were converted to air-equivalent length as before. The conversion for the hydrogen data was made in the same manner as for fluorine. For the observations in methane a range-stopping-power curve was drawn in the same way using data from Van der Merwe.[20] In order to be able to convert long-range protons it was necessary to make a rather large extrapolation from his data, but since the stopping power of methane changes only slowly with the range at long ranges it is believed that the extrapolated values cannot be in error by more than a few percent. The values adopted for methane at 76 cm and 15°C relative to air were 0.85 at 10 cm range and 0.83 at 70 cm, the intermediate values lying linearly between these. The results are presented in the curves of Fig. 6.

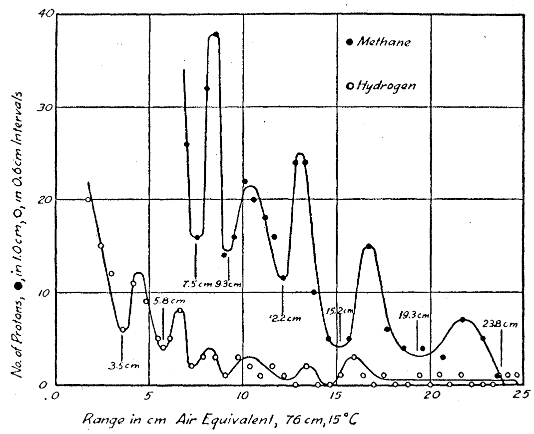

FIG. 6. The range distribution of the recoil protons from Po-B neutrons. Upper curve: recoil protons in methane. Lower curve: recoil protons in hydrogen. The observed ranges have been converted to the equivalent ranges in air.

It is seen that six groups are indicated by the methane curve, while two additional groups are shown by the hydrogen data below the 7.0 cm range where the tracks in methane become too short to measure accurately. Where the two curves overlap the hydrogen curve also gives indication of the presence of peaks which correspond approximately to those of the methane curve. As in the case of fluorine separate plots of the first and second halves of the data again gave consistent results, so that as before we believe that the maxima and minima represent the effect of neutron groups. The values of the maximum range corresponding to each group are indicated in the figure; these values and their corresponding energies are given in Table II.

TABLE II. *Boron neutron groups.*

Maximum range of recoil proton group (cm)	23.8	19.3	15.2	12.2	9.3	7.5	5.8	3.5
Energy of neutron group (M.E.V.)	4.16	3.65	3.17	2.75	2.35	2.05	1.77	1.29

[18] This scheme is substantially the same as one of two schemes kindly suggested to us by Dr. Wu in a private communication.

[19] T. W. Bonner, Phys. Rev. **45**, 601 (1934).

[20] C. W. Van der Merwe, Phil. Mag. **45**, 379 (1923).

In the case of boron it is not possible to fit the eight observed neutron groups into a disintegration scheme because of lack of knowledge of the resonance levels. It seems that four resonance levels would be needed. From neutron excitation curves (number of neutrons as a function of the α-particle energy) Curie and Joliot[21] have found only one level. From the present results it seems probable that others exist. For boron it is not possible to use the resonance levels found from the disintegration with emission of a proton, as was done for fluorine, because of complications caused by the existence of the two isotopes. The proton disintegration has been satisfactorily explained by the reaction $B_5^{10}+\alpha\rightarrow C_6^{13}+p$ involving the isotope B^{10}. For the neutron disintegration two reactions have been proposed. Chadwick[2] assumed $B_5^{11}+\alpha\rightarrow N_7^{14}+n$, while Curie and Joliot[22] suggest $B_5^{10}+\alpha\rightarrow N_7^{13}+n$, followed by $N_7^{13}\rightarrow C_6^{13}+e^+$. It seems possible that both the above reactions occur. B^{11} would be expected to give the greater neutron intensity. The number of α-particles captured by B^{11} should be about five times as great as the number for B^{10} since it is about five times more abundant in the isotopic mixture. In addition B^{10} may disintegrate either with emission of a proton or with a neutron so that the relative number of neutrons from B^{10} is still further reduced, perhaps by a factor of two.

An estimate of the relative numbers of neutrons from B^{10} and B^{11} can be obtained in another way. It is evident that in the neutron disintegration of B^{10} a positron must accompany each neutron, while only neutrons are given by B^{11}. Thus by comparing the relative numbers of neutrons and positrons an estimate of the relative numbers of neutrons from the two reactions can be obtained. It is possible to do this by comparing the emission of neutrons and positrons by boron with that by aluminum.

Using an ionization chamber filled with hydrogen at 20 atmospheres and using a 2 cm lead filter to absorb the γ-rays, it was found that the ratio of the ionization currents produced by boron and aluminum neutrons was 25/1. Correcting for the fact that the maximum energy of the boron neutrons is about double[23] that of the aluminum neutrons, it appears that boron gives from 10 to 20 times as many neutrons as aluminum. On the other hand Curie and Joliot[24] found that positrons are produced in roughly equal numbers by boron and aluminum. From this it appears that the large excess in the number of neutrons from boron must be due to B^{11}. Both arguments indicate an approximate factor of 10 or more between the neutron emission of B^{11} and B^{10}.

The maximum energy of the neutrons from boron as obtained from the curve of Fig. 6 is higher than that found by Chadwick[2] and by others.[21] We find the value 4.2 M.E.V. while the earlier value was 3.3 M.E.V. This difference is not surprising since the tendency has been toward detecting neutrons of higher energy as more data are accumulated. It may be pointed out that we observe a rapid decrease in the number of protons at about 3.2 M.E.V. which might have been taken as the maximum by previous observers. If both isotopes give neutrons, the neutrons having a maximum energy of 4.2 M.E.V. may be due to either B^{10} or B^{11} but since the intensity of this group seems fairly high, it is probable that they come from B^{11}. Assuming that they come from B^{11}, this higher value of the maximum energy reduces the mass of the neutron, as calculated by Chadwick from the disintegration of B^{11}, from 1.0067 ± 0.0010 to 1.0058 ± 0.0010. The new value agrees somewhat more satisfactorily with the value of the upper limit, 1.0063 ± 0.0008, which has been calculated by Bainbridge[25] from the disintegration of lithium by α-particles. For the disintegration of B^{10} the mass as calculated by Curie and Joliot[21] is considerably higher using either the old value of the neutron energy or the new. A possible explanation of this discrepancy is that there is a relatively small number of neutrons from B^{10} with a maximum energy of about 7.5 M.E.V. Since according to the argument given above the number of neutrons from B^{10} is only about 1/10 or

[21] I. Curie and F. Joliot, J. d. Physique **4**, 278 (1933).
[22] I. Curie and F. Joliot, Nature **133**, 721 (1934).

[23] The maximum energy of the neutrons from aluminum is given by Curie-Joliot as 2 M.E.V., those from boron as 3.3 M.E.V. Using our value for boron (4.2 M.E.V.) we obtain a somewhat higher ratio.
[24] I. Curie and F. Joliot, J. d. Physique **5**, 153 (1934).
[25] K. T. Bainbridge, Phys. Rev. **43**, 367 (1933).

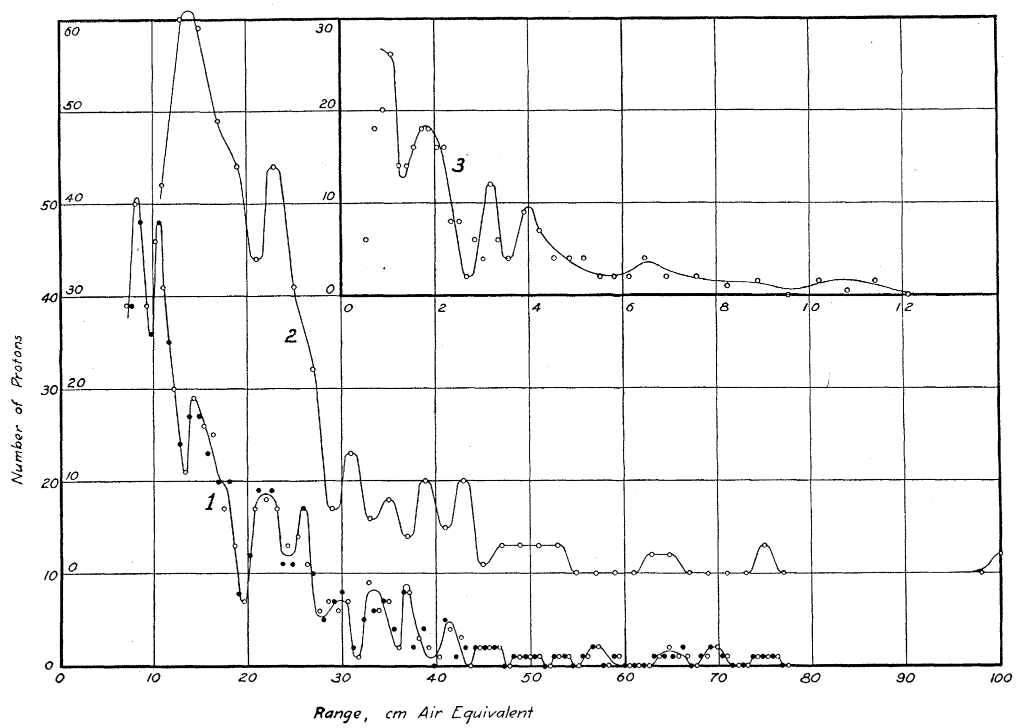

FIG. 7. The range distribution of recoil protons from Po-Be. The points on curve 1 (two sets of overlapping intervals are used) show the distribution of recoil protons in methane; curve 3 gives the data for recoil protons in hydrogen; curve 2 (shifted upward 10 divisions) is a reproduction of Blau's curve.

less of the number from B^{11}, they might have escaped detection.

Beryllium

A total of about 8000 photographs were taken, 3000 with hydrogen and 5000 with methane, the pressure being the same as before. 180 recoil protons were measured in hydrogen, 575 in methane. The observed ranges were converted to air-equivalent range in the manner described above. The results for methane are given in curve 1 of Fig. 7, those for hydrogen in curve 3 of this figure. The longest proton track which was measured corresponds to a length of 76 cm in air, though two tracks which collided with the wall of the chamber had lengths greater than 85 cm. This is approximately the maximum length of track which could be measured with our arrangement, and thus does not mean that these protons are the protons from Po-Be with the maximium energy. The maximium energy for Po-Be is probably at present best obtained by calculation from Dunning's work[4] with radon-Be. It is found to be approximately 11.7 M.E.V. corresponding roughly to a proton-range of 150 cm.

Again it is noted that the curves show maxima and minima and that for Be these seem to be very numerous. Apparently then it seems that beryllium disintegrates with the emission of a large number of neutron groups. Table III gives a list of the maximum ranges of all the groups which are indicated by the curves. Many of

TABLE III. *Beryllium neutron groups.*

Rp (cm)	*En* (M.E.V.)	*Rp* (cm)	*En* (M.E.V.)
1.3	0.58	31.8	4.87
2.7	1.07	36.0 (?)	5.26 (?)
3.5	1.31	39.7	5.57
5.4 (?)	1.68 (?)	43.5 (?)	5.85 (?)
7.5 (??)	2.06 (??)	47.3 (??)	6.13 (??)
9.75	2.42	51.5 (??)	6.42 (??)
13.5	2.94	54.5 (??)	6.64 (??)
16.5 (??)	3.32 (??)	60.0 (?)	7.06 (?)
19.5	3.65	67.3 (??)	7.49 (??)
24.3	4.20	71.5 (??)	7.76 (??)
28.0 (?)	4.56 (?)	77.5 (??)	8.10 (??)

Rp = maximum range of recoil-proton groups.
En = maximum energy of neutron groups.

these, however, are questionable, and some, particularly at the higher energies, where we were unable to obtain large counts, must be considered very questionable. These are indicated by question marks. Apparently the only other "differential" distribution curve for the neutrons from Po-Be is one recently given by Blau.[3] It has been reproduced in Fig. 7 (displaced upward ten divisions). It is seen that this curve also indicates numerous groups. For ranges between 15 and 45 cm the same groups are indicated at approximately the same maximum ranges. Between 10 and 15 cm agreement cannot be expected because the range intervals on Blau's curve are too large. Above 45 cm both curves are not reliable on account of the small number of protons but it may be noted that even in this region the three groups indicated by her curve are also indicated by ours. Blau's curve also indicates a group at 100 cm which is outside of the region we were able to investigate.

In order to account for the observed large number of groups it is evident that a large number of resonance levels are needed. In fact, Kirsch and Slonek[26] apparently have found five resonance levels in the relatively narrow range of energy which they investigated, between 3.7 and 5.3 M.E.V. The work of Rasetti,[27] Curie-Joliot,[21] Chadwick,[2] and others indicates two further resonance levels at about 2.6 and 1.5 M.E.V. However, to account for all the neutron groups we find it necessary to assume four additional levels lying between 3.7 and 1.4 M.E.V. and forming, along with Kirsch and Slonek's levels and the ones at 2.6 and 1.5 M.E.V., a series of roughly equally spaced levels. In this way, and by assuming that the resulting nucleus (C_6^{12}) can be left in two possible excited states, it has been possible to explain fairly satisfactorily the observed neutron groups as well as the γ-rays produced by this disintegration. It was necessary to assume two excited states instead of the single excited state which was adequate for fluorine in order to explain both the group at about 12 M.E.V. and the groups of very low energy extending down to about 0.6 M.E.V. This disintegration scheme is given in Table IV. The first column gives the resonance levels. The first five

TABLE IV. *Beryllium disintegration scheme.*

$E\alpha$ (M.E.V.)	En_0 (M.E.V.) calc.	En_0 obs.	En_1 (M.E.V.) calc.	En_1 obs.	En_2 (M.E.V.) calc.	En_2 obs.
5.3	11.3	11.7*	7.1	7.06	4.2	4.20
4.8	10.8	—	6.6	6.64	3.7	3.65
4.4	10.4	—	6.2	6.13	3.3	3.32
4.1	10.1	—	5.9	5.85	3.0	2.94
3.7	9.8	—	5.5	5.57	2.7	—
3.4 (?)	9.5	9.5**	5.2	5.26	2.4	2.42
3.0 (?)	9.1	—	4.9	4.87	2.1	2.06
2.6	8.7	—	4.5	4.56	1.7	1.68
2.2 (?)	8.3	8.10	4.1	4.20	1.3	1.31
1.8 (?)	7.9	7.76	3.7	3.65	1.0	1.07
1.4	7.5	7.49	3.3	3.32	0.6	0.58

$Q_0=6.2$ M.E.V. $E\gamma_1=4.1$ M.E.V.
$Q_1=2.1$ M.E.V. $E\gamma_2=6.8$ M.E.V.
$Q_2=-0.6$ M.E.V.

* This maximum energy for the neutrons from Po-Be was calculated from Dunning's data.
** The 100 cm group found by Blau.

are those given by Kirsch and Slonek. The lowest one was taken at 1.4 instead of the rough value of 1.5 given by Chadwick because it fitted better into the scheme. The second, third and fourth columns give the values of the calculated and observed energies of the neutron groups for the cases when the resulting nucleus is left unexcited or excited to either the first or second energy-level, respectively. The scheme predicts several groups which have not been observed, but all but one of these is at long ranges which are beyond the region investigated. On the other hand, it gives fairly well all but one of the observed groups, and this group is one which is very doubtful. Two γ-ray lines are predicted, one having an energy of 4.1 M.E.V., the second, 6.8 M.E.V. The experimental data on the energy of the γ-rays from Po-Be, does in fact indicate the presence of a line at about 4.5 M.E.V. and possibly a small amount of radiation at around 7 M.E.V.[2, 28, 29] The disintegration scheme which has been given is of course rather arbitrary because of lack of exact knowledge of the resonance levels and also of the energy of the γ-rays. A confirmation of this scheme or the development of a more satisfactory one must await further experimental data.

In closing we wish to thank Dr. J. Cramer Hudson whose gift of spent radon tubes materially aided this work.

[26] G. Kirsch and W. Slonek, Naturwiss. **21**, 62 (1933).
[27] F. Rasetti, Zeits. f. Physik **78**, 165 (1932).
[28] I. Curie and F. Joliot, J. d. Physique **4**, 494 (1933).
[29] J. Chadwick, P. M. S. Blackett and G. P. S. Ochialini, Proc. Roy. Soc. **A144**, 235 (1934).

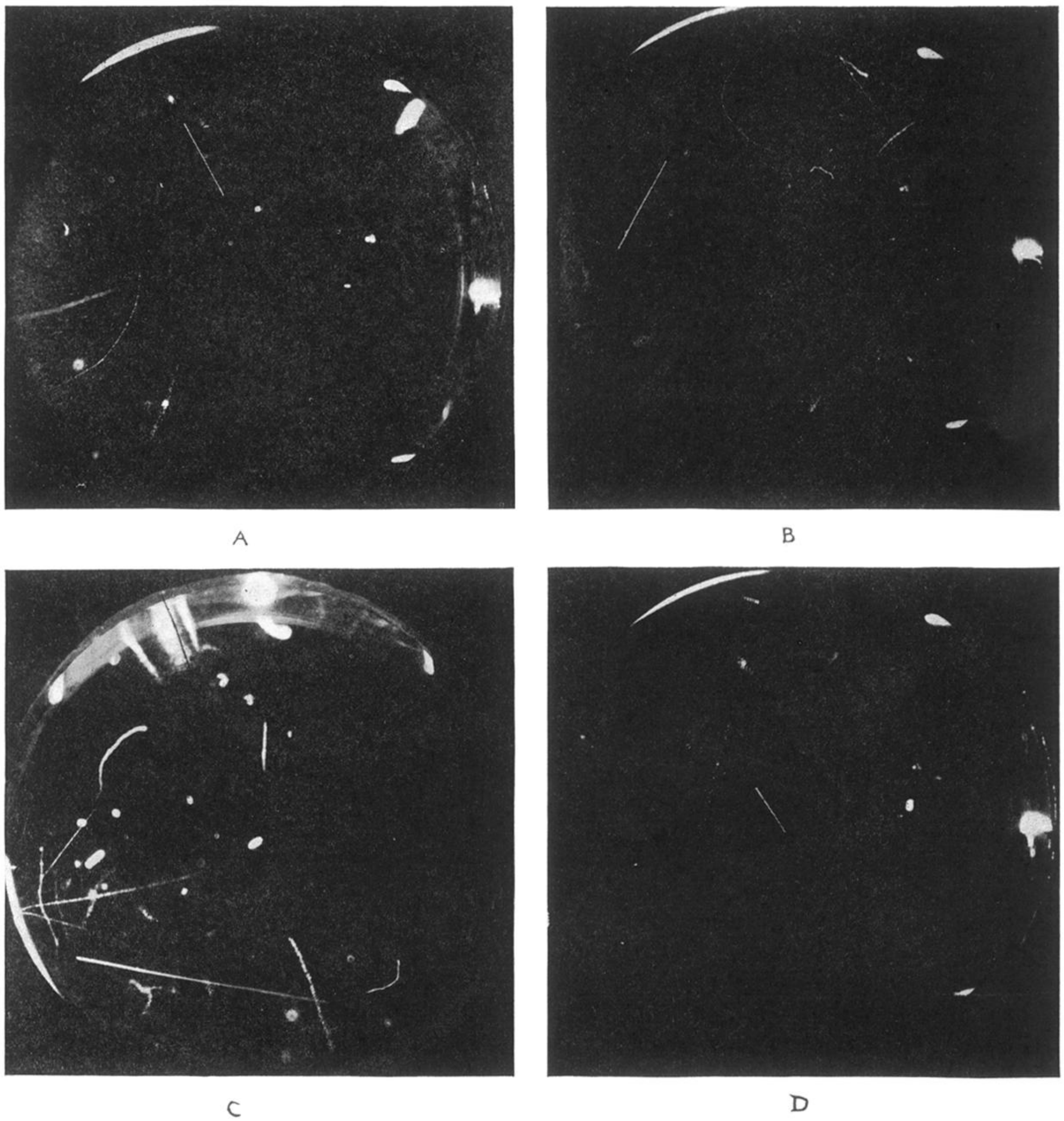

FIG. 2. Tracks of recoil-protons observed with the gas of the expansion-chamber at 12.9 atmospheres pressure. The source of neutrons is behind the center of the illuminated area in the upper left-hand portion of the photographs. (A) A recoil-proton from a fluorine neutron, produced in hydrogen. The actual length of the track was 1.65 cm, corresponding to a range of 5.28 cm in air at 76 cm and 15°C. (B) A recoil-proton from a boron neutron, produced in methane. The actual length was 2.10 cm, corresponding to a range of 22.5 cm in standard air. (C) A long recoil-proton from a beryllium neutron, in methane. The actual length was 5.33 cm, corresponding to a range of 57.0 cm in standard air. (D) A short recoil-proton from beryllium, in hydrogen. The actual length was 1.08 cm, corresponding to a range of 3.68 cm in standard air. This track is nearly in the direction of the source so that (neglecting the possibility that it was produced by a scattered neutron) the proton obtained practically the entire energy of the neutron. *Note:* (C) is incorrectly placed. It should be turned 90° in a clockwise direction.