doubt quite similar as regards the energies of the emitted neutrons, it seems reasonable to assume that no serious difficulty exists in this respect.

It will be observed from Fig. 5 that the experimental points agree best with the theoretical values for C assumed zero. However, on the basis of the picture underlying these calculations $C\sim 0$ is hardly reasonable because of the stability of Li^6. In the final analysis, the disagreement between the present results and the work of Massey and Mohr is not to be regarded as serious, since it is now well known that calculations based on a simple potential well are not to be trusted.

In conclusion, it is a pleasure to thank Professor A. F. Kovarik for much helpful discussion and advice throughout the course of this work. The writer also wishes to express his appreciation to Dr. E. C. Pollard for discussion and technical assistance.

APRIL 15, 1938 PHYSICAL REVIEW VOLUME 53

The Gamma-Radiation from Boron Bombarded by Protons

W. A. FOWLER, E. R. GAERTTNER* AND C. C. LAURITSEN
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received January 28, 1938)

Employing a Wilson cloud chamber we have determined the distribution in energy of pairs and recoil electrons ejected from lead and carbon laminae by the gamma-radiation from boron bombarded by protons. Both the pair and electron distributions indicate three prominent gamma-ray components at 4.3 ± 0.3 Mev, 11.8 ± 0.5 Mev, and 16.6 ± 0.6 Mev with relative intensities of 1 : 1 : 1/7, respectively. The radiation is believed to result from proton capture by B^{11} to form an excited state of C^{12} which radiates in a single transition to the ground state or in a double transition through the well-known intermediate state at 4.3 Mev. Resonance in the yield has been found only in the region $150\rightarrow200$ kv and the total yield of quanta per incident proton above resonance on a thick boron target is estimated to be $\gtrsim 5\times10^{-10}$.

TWO previous communications from this laboratory[1] have described in some detail improvements in the method of determining the energy of gamma-rays from cloud chamber studies of the secondaries produced by these radiations. These improvements essentially involved the elimination as far as possible of secondaries of uncertain origin by proper collimation of the gamma-ray beam and by the use of stereoscopic photographs. Only those secondaries originating in a thin lamina placed within the cloud chamber were employed to determine the gamma-ray energies.[2] This improved method was first used in studies of the radiation from Li^7+H^1 and $F^{19}+H^1$. We have recently extended the observations to the radiation from boron bombarded by protons. The original results concerning the radiation[3] had indicated a complex distribution of electrons extending up to 13 Mev with greatest intensity below 4 Mev and groups of electron-positron pairs near 10 and 14.5 Mev. It will be seen that these results are not in contradiction with those reported here if due allowance is made for the lower resolving power in the original experiments.

Because of the low intensity of the radiation from $B+H^1$ some slight modifications were made in the experimental arrangement described in the first reference. In order to have the target as close as possible to the secondary emitters the length of the lead collimator was reduced from 18 to 10 cm and the target tube was located adjacent to the Helmholtz coils surrounding the

* National Research Fellow.
[1] Delsasso, Fowler and Lauritsen, Phys. Rev. **51**, 391, 527 (1937).
[2] See also Richardson and Kurie, Phys. Rev. **50**, 999 (1936); Gaerttner and Crane, Phys. Rev. **51**, 49 (1937); **52**, 583 (1937); Kruger and Green, Phys. Rev. **52**, 773 (1937).
[3] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **48**, 102 (1935).

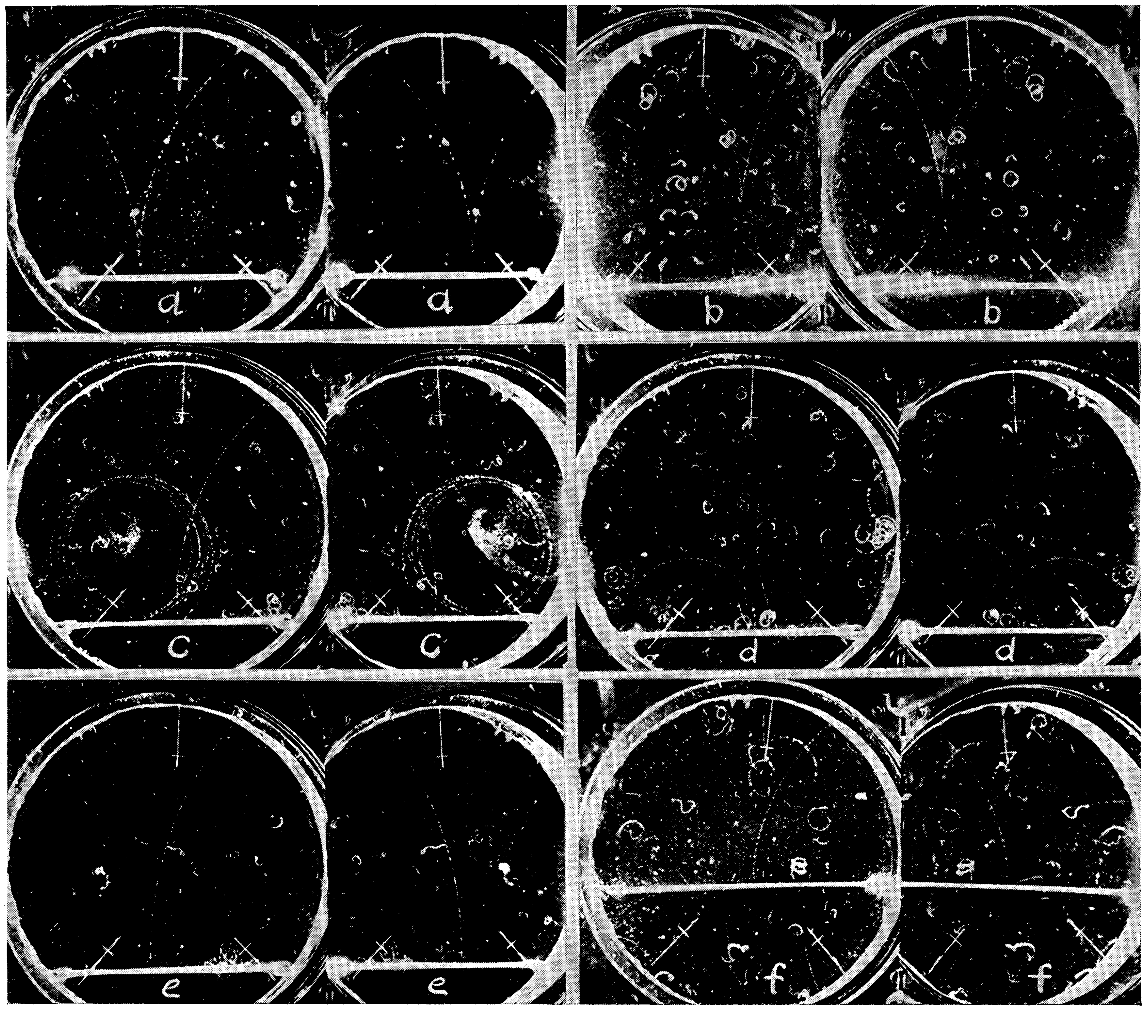

FIG. 1. Stereoscopic views. *a*, A 15.6 Mev pair ejected from a 1.00 mm lead foil by the gamma-radiation from $B+H^1$ (500 kv). The negative pair member bending toward the intersection of the two views has 7.0 Mev kinetic energy while the positive member has 7.6 Mev kinetic energy. Magnetic field = 2000 gauss. *b*, A 16.1 Mev pair (negative has 9.5 Mev, positive has 5.6 Mev) originating in the air-alcohol vapor within the cloud chamber. $B+H^1$ (900 kv). 2500 gauss. *c*, A 10.8 Mev pair (negative has 7.9 Mev, positive has 1.9 Mev) ejected from a 0.33 mm lead foil by the radiation from $B+H^1$ (900 kv). 2500 gauss. *d*, A 4.2 Mev pair (negative has 1.4 Mev, positive has 1.8 Mev) ejected from a 0.33 mm lead foil by the radiation from $B+H^1$ (900 kv). 2500 gauss. *e*, An 11.7 Mev electron ejected from a 0.33 lead foil by the radiation from $B+H^1$ (900 kv). 1500 gauss. *f*, A 4.0 Mev electron ejected from a 1.2 mm carbon lamina by the radiation from $B+H^1$ (900 kv). 1500 gauss.

chamber. The secondary emitters were a 0.33 mm lamina of lead (18,000 photographs) and a 1.2 mm lamina of carbon (4000 photographs). The theoretical average energy loss by collision for electrons of energy between 2 and 20 Mev is approximately 0.4 Mev for the lead and 0.5 Mev for the carbon lamina.

The accelerating tube was operated at 850 to 900 kilovolts peak voltage while the total current was about 20 microamperes during the chamber expansion. The ion beam was not magnetically analyzed and therefore some of the low energy radiation might be attributed to boron bombarded by deuterons. However, deuterium gas had not been used in the tube for several months previous to these observations and it is thus certain that the deuterium contamination did not exceed one part in several

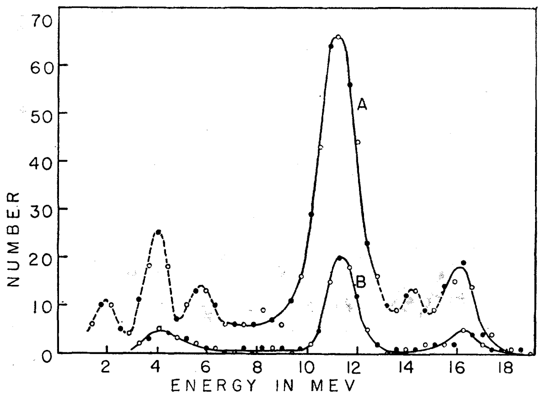

FIG. 2. Curve A, the distribution in energy (kinetic plus $2\,mc^2$) of 347 pairs ejected from a 0.33 lead foil by the radiation from $B+H^1$ (900 kv). The points have been connected by broken curves in regions where the nature of the curve is somewhat doubtful because of low resolving power and large statistical fluctuations. Curve B, the distribution in energy of the 68 most distinct and most accurately measured pairs from curve A. In both curves energy intervals of 0.77 Mev overlapping by one-half their width have been used.

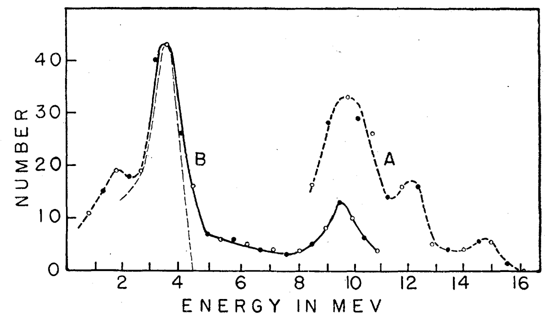

FIG. 3. Curve A, the distribution in kinetic energy of recoil electrons ("single" negative electron distribution minus "single" positive electron distribution) ejected from a 0.33 mm lead foil plotted in overlapping 1 Mev intervals. Curve B, the distribution in kinetic energy of 177 single electrons ejected from a 1.22 mm carbon lamina plotted in overlapping 0.9 Mev intervals. The superimposed dotted curve indicates the theoretical shape of the distribution in energy of electrons produced in a 1.2 mm carbon lamina by a gamma-ray of 4.3 Mev energy (same energy interval).

thousand. As the radiation is about one-fiftieth to one-tenth as intense as that from $B+H^2$, less than five percent of the observed tracks can be due to this source. Thick targets of pure amorphous boron (Eimer and Amend) were employed and were frequently replaced. Such targets have not been found to emit disintegration particles characteristic of transmutations involving lithium or fluorine, the only elements showing a greater yield of gamma-radiation under proton bombardment. We feel that practically all the radiation observed must be attributed to boron bombarded by protons.

The measurement of tracks on the cloud chamber photographs was carried out independently by two observers and the results presented represent the average of their separate data. In all cases the data have been plotted as the number of secondaries observed in equal energy intervals separated by one-half the interval width. The two sets of points so secured are indicated by open and full circles in the accompanying figures. The points have been connected by broken curves in regions where the nature of the curve is somewhat doubtful because of low resolving power and large statistical fluctuations. Examples of the cloud chamber photographs are shown in Fig. 1.

Energy of the Gamma-Radiation

Curve A of Fig. 2 shows the distribution in energy (kinetic plus $2\ mc^2$) of 347 pairs ejected from the 0.33 mm lead foil. Of these pairs 234 were secured with the foil located 2 cm from the center of the chamber and with a magnetic field of 1700 gauss while the remaining 113 were secured with the foil located 5 cm from the center of the chamber and with a field of 2580 gauss. Of the pairs secured under the latter conditions, 68 were selected for particular distinctness and as representing those most accurately measured, and have been plotted as curve B in Fig. 2. In both curves the energy interval is 0.77 Mev.

Curve A of Fig. 3 shows the distribution in kinetic energy of recoil electrons ejected from the 0.33 mm lead foil plotted in 1.0 Mev intervals. The magnetic field was 1700 gauss, and as the foil was located only 2 cm from the center of the 15 cm chamber, tracks originating in the scatterer could be distinguished from traversals originating in the chamber wall. The large angle subtended by the target at the foil made it possible to eliminate only those tracks making an angle greater than 30° with the incident radiation. This failure, however, seriously reduces the resolving power of the method only for radiation below 3 Mev energy.

To secure the distribution in energy of the recoil electrons the number of single positrons observed in any interval has been subtracted from the number of observed single electrons. This procedure is based on the assumption that none of the "observed" positrons are electrons originating in the glass walls of the chamber and terminating in the lead lamina and that all are members of pairs, the negative member of which was stopped or greatly scattered in the lead lamina. It is further assumed that an equal number of single electrons is observed because of the stopping or scattering of positive members of some pairs. In the high energy region this is a feasible procedure as the number of single positrons is approximately 10 percent the number of single electrons and it is entirely reasonable that the low energy electrons associated in pairs with that number of positrons should have been completely absorbed in the lead foil. Even so, curve A of Fig. 3 is subject to the large statistical fluctuations in the number of single positrons and hence is represented by a broken line connecting the observed points. In the low energy region the number of single positrons was almost one-half the number of single electrons, and the difference curve was not considered to be at all trustworthy. It is well to point out in this connection that the number of single positrons observed seems to exceed somewhat the number for which the associated negative pair member should be completely absorbed in the lead foil or scattered at a very large angle, and that the origin of these low energy unassociated positrons is not entirely clear. When collimation is employed and stereoscopic photographs are taken few such single positrons appear to originate in carbon or aluminum laminae of equivalent stopping power and hence not all of those observed with lead laminae can be electrons terminating in the lead. It remains however for more definite experiments to clear up this difficulty. In order to investigate the low energy end of the spectrum more carefully we used the 1.2 mm carbon lamina and found 177 measurable tracks which are plotted as curve B of Fig. 3 in 0.90 Mev intervals.

From these curves the radiation can be seen to consist of at least three components at 16.6 ± 0.6, 11.8 ± 0.5, and 4.3 ± 0.3 Mev as tabulated in Table I. The energies of the two high energy components are determined most accurately from the pair distributions. The maxima in this distribution correspond to pairs originating in the center of the lead foil and as each member of the pair loses energy before emerging from the foil, the gamma-ray energy is given by adding the equivalent foil thickness in energy units, namely 0.4 Mev, to the energies at which the maxima occur. Only the ionization energy loss is added as the radiative loss will merely introduce a small increase in the lower energy side of a given group of pairs. The positions of the maxima were taken as an average of the positions given by curves A and B, Fig. 2. The component at 11.8 Mev has a width at half-maximum of 1.8 Mev all of which can be attributed quite reasonably to the sources of error inherent in this method.[1] From theoretical considerations the natural width of nuclear gamma-rays is very small and our results give no evidence that this is not true for the radiation discussed in this paper.

The existence of a component at 4.3 ± 0.3 Mev is most clearly demonstrated by Fig. 3, curve B, where the superimposed dotted curve indicates the theoretical shape[2] of the distribution in energy of electrons produced in a 1.2 mm carbon sheet by a gamma-ray of 4.3 Mev energy. The higher energy recoil electron distribution is as consistent with the pair curves as can be expected in view of the large radii of curvature of the tracks measured (20 to 30 cm).

It is apparent that neither the pair nor the

TABLE I. *Relative intensities of the three main components of the gamma-radiation from* B+H[1]. (π = *pair formation cross section;* σ = *Klein-Nishina cross section*).

Gamma-Ray Energy	Relative Pair Intensities	Relative π	Corrected Values For π	Corrected Values Final	Relative Recoil Intensities	Relative σ	Corrected Values For σ	Corrected Values Final
16.6 ± 0.6	0.2	1.3	0.16	<0.16	0.1	0.85	0.12	>0.12
11.8 ± 0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
4.3 ± 0.3	0.25	0.35	0.7	>0.7	3.5	2.25	1.5	<1.5

recoil electron curves are completely accounted for by the theoretical expectations based on the three components in Table I. To account completely for the curves with the calculated distributions it is necessary to assume the existence of weak components at roughly 2.5, 6.0 and 14.5 Mev. Much more extended observations will be necessary to establish definitely the existence and energy of these components. Indications of a 6.0 Mev component were not obtained consistently so that the pairs near this energy in curve A, Fig. 7, may be due to some contamination, possibly fluorine.

The Relative Intensities of the Gamma-Ray Components

Estimates of the relative intensities of the gamma-ray components made from both the pair and recoil electron curves are given in Table I. In estimates from the pair curve, the relative number of pairs thought to be due to the three main components has been computed and corrected for the variation in pair formation cross section with energy.[4] The relative intensity of the 4.3 Mev component must be greater than the value secured by making this simple correction because of the relatively greater loss of low energy members of pairs produced by this line by absorption and scattering in the lead lamina. A not unreasonable increase of 40 percent will make the intensity of this component equal to that of the 11.8 Mev component. In the case of recoil electrons a correction for the Klein-Nishina cross section[4] has been applied. As most of the recoils lie within a cone about the direction of the incident radiation which is smaller than the angle subtended at the secondary emitter by the target, the total cross section for the production of recoils has been employed. The relative loss of recoil electrons from 4.3 and 11.8 Mev radiation is not nearly as marked as the relative loss of pairs from such radiations. To make even fairly accurate measurements of the high energy recoils at 1500 gauss required very distinct and sharp tracks traversing the full length of the chamber. For this reason the relative intensity of the 4.3 Mev component must be somewhat lower than the result given by the simple Klein-Nishina correction. It is thus seen that the recoil electron and pair data agree to within a factor less than 2. The 16.6 Mev component is roughly 15 percent as intense as the 11.8 Mev component, while the 4.3 Mev component, neglecting the secondaries near 2.5 and 6.0 Mev, is approximately equal in intensity to this component.

The Origin of the Radiation

The only transmutation involving either of the two isotopes of boron under proton bombardment which on the basis of the conservation of energy can result in the production of the two high energy components of the observed radiation is

$$B^{11}+H^1\rightarrow(C^{12})\rightarrow C^{12}+h\nu. \qquad (1)$$

The difference between the doublet $B^{11}H^1-C^{12}$ is given by Bainbridge and Jordan[5] as 17.14 ± 0.10 thousandths of a mass unit corresponding to a difference on the energy scale of 16.0 ± 0.1 Mev.

Reasons will be advanced in a later section of this paper for believing that the excited state of C^{12} from which the observed radiation originates corresponds to the resonance at 180 kv observed in the excitation function for the gamma-rays from $B^{11}+H^1$ by Bothe and Gentner.[6] This excited state of C^{12} thus differs from the ground state by 16.2 ± 0.1 Mev.

The energy of the most energetic component of the observed radiation (16.6 ± 0.6 Mev) is in agreement with this difference and thus substantiates the existence of the capture process implied in reaction (1). The 11.8 ± 0.5 Mev component must result from at least a double radiative transition to the ground state of C^{12} and as the 4.3 ± 0.3 Mev component is of equal intensity within the experimental errors, it seems reasonable to associate the two lines in such a double transition yielding 16.1 ± 0.6 Mev as the total transition energy, again in agreement with the energy difference calculated from the masses. The position of the intermediate excited state of C^{12} is not uniquely determined but it is most reasonable to place the level at 4.3 Mev as the

[4] See *Quantum Theory of Radiation* by Heitler, pp. 158, 200.

[5] Bainbridge and Jordan, Phys. Rev. **51**, 385 (1937).

[6] Bothe and Gentner, Zeits. f. Physik **104**, 684 (1937).

existence of such a level has been established in the reactions

$$N^{14}+H^{2}\rightarrow C^{12}+He^{4}, \qquad (2)$$

where alpha-particle groups differing by 4.3 Mev have been observed[7] and in

$$B^{11}+H^{2}\rightarrow C^{12}+n^{1}, \qquad (3)$$

$$Be^{9}+He^{4}\rightarrow C^{12}+n^{1}, \qquad (4)$$

where neutron groups differing by 4.4 Mev have been observed.[8] Gamma-radiation with energy from 4.3 to 4.4 Mev has been found to accompany these reactions.[9]

A reaction similar to (1) involving B^{10}

$$B^{10}+H^{1}\rightarrow(C^{11})\rightarrow C^{11}+h\nu \qquad (5)$$
$$\downarrow$$
$$B^{11}+e^{+}$$

has been suggested by Crane and Lauritsen[10] to account for the production of positron active C^{11} (20 min.) when boron is bombarded with protons. The mass difference of the doublet $B^{10}H^{1}-B^{11}$ is given by Bainbridge and Jordan[5] as 11.60 ± 0.10 thousandths of a mass unit corresponding to 10.8 Mev and the positrons have been found[10] to have an observed maximum energy of 1.1 ± 0.1 Mev. The energy available for radiation is thus 8.7 Mev. The yield found by Crane and Lauritsen[10] at 900 kv peak corresponds to 10^{-11} to 10^{-10} positrons per incident proton while Allison[11] was unable to find any effect at 500 kv and set an upper limit for the yield at 10^{-12} positrons per proton on pure B^{10}. The resonance voltage for reaction (5) must thus be above 500 kv.

The absolute yield of the observed radiation will be shown in a later section to be at least 5×10^{-10} quanta per incident proton above resonance. Since the yield per proton at 900 kv for reaction (5) is less than this and since the resonance occurs above 500 kv as compared to 180 kv for the observed radiation it is not surprising that with alternating voltage and a beam containing molecular as well as atomic ions we do not obtain any definite indication of radiation near 8.7 Mev. Part of the observed radiation below 8.7 Mev may be attributed to (5) and it will remain for experiments with targets of the separated isotopes to solve this particular problem.

The Excitation Function

It is of primary importance in arriving at some understanding of capture reactions similar to (1) to determine the energy of the excited nuclear states from which the various components of the radiation arise. In the majority of cases the energy breadth of these states is small compared to the range of the bombarding voltages available and thus an excellent measure of the energy of the states is secured by the determination of the voltages at which resonance occurs in the excitation function for the radiation. To complete the observational details, the measurement of the resonance voltage and breadth must be supplemented by an analysis of the structure and absolute intensity of the radiation due to the resonance in question. In this way complete information concerning the energy values of the excited states of various nuclei and their transition probability for radiation to lower states will be secured. There can be little doubt that such information is necessary in reaching an understanding of nuclear structure.

In the case of the radiation from boron bombarded by protons the existence of two resonances in the excitation function has already been established. Using accelerating voltages up to 500 kv Bothe and Gentner[6] found a resonance effect at 180 kv and no effect of comparable magnitude at any other voltage except 360 kv where the molecular ions produced by their ion source became effective for the 180 kv resonance. The existence of resonance at 820 kv has been found by Herb, Kerst and McKibben.[12] The intensity of the radiation which they observed at voltages below 820 kv was so small that lower resonances would probably have escaped detection.

[7] Lawrence, McMillan and Henderson, Phys. Rev. **47**, 273 (1935); Cockcroft and Lewis, Proc. Roy. Soc. **154**, 261 (1936).
[8] Bonner and Brubaker, Phys. Rev. **50**, 308 (1936); Bernardini and Bocciarelli, Accad. Lincei, Atti. **24**, 132 (1936).
[9] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **48**, 484 (1935); **46**, 1109 (1934); Bothe, Zeits. f. Physik **100**, 273 (1936).
[10] Crane and Lauritsen, Phys. Rev. **45**, 497 (1934); **48**, 103 (1935); Fowler, Delsasso, and Lauritsen, Phys. Rev. **49**, 561 (1936).
[11] Allison, Proc. Camb. Phil. Soc. **32**, 179 (1936).
[12] Herb, Kerst and McKibben, Phys. Rev. **51**, 691 (1937).

No completely satisfactory answer can be given to the question of which resonances contributed to the radiation discussed in this paper. The difficulties inherent in the interpretation of yield curves secured with alternating voltage tubes, with ion sources giving both atomic and molecular ions, and with thick targets are well known. Observations with the cloud chamber are further complicated by the fact that the ions are quite appreciably deflected by the external magnetic field of the Helmholtz coils. In the experiments described above in which the energy and relative intensity of the radiation was determined the ion tube was operated at its maximum steady peak voltage of from 850 to 900 kv (spark gap determinations) simply to get a large percentage of ions to the target through the magnetic field and to insure a reasonable yield of gamma-rays.

We have made additional observations to compare the variation of yield of the $B^{11}+H^1$ gamma-rays with excitation curves for Li^7+H^1 and for $F^{19}+H^1$ which are known to exhibit resonance effects at 440 and 330 kv, respectively. The radiation from metallic lithium previously exposed to air and calcium fluoride targets bombarded with protons was found to be intense enough to permit the use of a sensitive electroscope in determining the excitation curves. The electroscope was surrounded by 5 cm of lead except on the side toward the target where the thickness of lead was reduced to 1 cm. Readings of 50 to 100 times the background (background $=0.2$ divisions per minute) were secured at the maximum tube voltage available and with currents of 25 microamperes to the target. The yield curve for $F^{19}+H^1$ was found to rise linearly from about 370 to 750 kv peak. A second linear rise of increased slope was found between 750 and 850 kv peak. The excitation curve for Li^7+H^1 rose linearly from about 485 to 850 kv peak. The observed rise for atomic and molecular ions was thus found to occur at peak voltages approximately ten percent higher than the known resonance voltages. A similar yield curve for the Li^7+H^1 radiation was secured by counting the number of high energy secondaries observed per cloud chamber expansion. The radiation from $B^{11}+H^1$ was so weak in intensity that it was not practical to determine its yield curve with the electroscope but data secured from 1500 cloud chamber photographs taken with a magnetic field of 400 gauss revealed no other resonance effects than the expected ones at peak voltages near 200 and 400 kv. Above 700 kv peak the yield was found to increase only slightly, indicating that the resonance effect at 820 kv was not reached at the maximum peak voltage used.

Even before the experiments described above dealing with the yield curves were carried out, it was realized that some information concerning the resonances entering into the production of the radiation from $B^{11}+H^1$ could be gained by determining the energy distribution of the radiation at a lower bombarding voltage than 900 kv peak. Since Bothe and Gentner's investigations extended to 500 kv it was deemed sufficient to repeat the original experiments with voltages of 500 kv and 700 kv peak. On 1500 photographs taken at 500 kv peak and 500 photographs at 700 kv peak, pairs corresponding to all three of the main components in practically the same relative proportions as given in Table I were found. The results of Bothe and Gentner are consistent with these results as they found the recoil electrons produced when their tube was operated at 410 kv to have a "range" corresponding to an energy of 14 Mev in good agreement with intense radiation at 11.8 Mev and weaker radiation at 16.6 Mev.

From the evidence yielded by the excitation curves and from the fact that the energy distribution of the radiation is independent of the voltage it is reasonable to conclude that only the resonance at 180 kv or possibly a weak but so far undetected resonance between 180–500 kv enters into the production of any of the three main components of the observed radiation.

The Absolute Intensity of the Radiation

The importance of determining the absolute intensity of the radiation from capture reactions has been indicated in the beginning of the previous section. One attempt in this direction has been made by Hafstad, Heydenburg and Tuve[13] who concluded from their electroscope determinations that the cross section for the

[13] Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936); Bethe, Rev. Mod. Phys. **9**, 207 (1937); Hafstad and Tuve, Phys. Rev. **48**, 306 (1935).

resonance capture of protons by Li^7 at 440 kv was roughly 10^{-27} cm^2 corresponding to a yield of 7×10^{-10} quanta per incident proton on LiOH (Bethe). The measurements of Bothe and Gentner[6] on the relative yields of the radiation from $B^{11}+H^1$ and Li^7+H^1 then make it possible to determine the absolute yield of that from $B^{11}+H^1$. However, we have felt that a more direct estimate would make it possible to determine the absolute yield somewhat more closely.

On the basis that the only resonance is at a voltage low compared to the peak voltage used in our observations, a fairly reliable estimate of the yield can be made from the number of secondaries observed per cloud chamber expansion for a given target current. Assuming for simplicity that the radiation is emitted isotropically in all directions the number of secondaries (N) is related to the yield of quanta by the relation

$$N = IY_cTC\Omega/4\pi,$$

where I = current to the target, Y_c = yield of quanta per unit current, T = sensitive time of chamber, Ω = solid angle subtended at the target by the secondary emitter, and C = number of secondaries produced per quantum falling on the secondary emitter.

The yield per incident ion in the beam is thus

$$Y_i = 2N/ITC\Omega\times10^{-12}$$

if I is measured in microamperes. The integrated yield above resonance per incident proton (Y_p) then can be determined if the atomic and molecular constitution of the beam is known and if the fractions of atomic and molecular ions above their respective resonance voltages are known.

Magnetic analysis of the ion beam revealed that it is composed chiefly of approximately equal numbers of ions corresponding to m/e ratios of $+1$ and $+2$. These components of the beam have been identified as being responsible for the yield increases at 370 and 750 kv peak in the excitation curve for $F^{19}+H^1$. Weak components corresponding to m/e ratios of -1 and $+3$ have also been found. The mass 1 component of negative charge is due to the acceleration during one-half of the alternating voltage cycle of hydrogen atoms which have captured an additional electron. The bands found on the photographic plates secured in the magnetic analysis indicated that the components corresponding to various m/e ratios were composed of ions of all energies with a definite concentration near the maximum voltages (at least 80 percent above one-half the maximum voltage). On the basis that the beam is composed equally of atomic and diatomic ions all of which are above the resonance voltage, a minimum value for Y_p can be secured which is given by $Y_p \geq 2/3\,Y_i$. In the case of the $B^{11}+H^1$ radiation this minimum value will not be far wrong if the only resonance is at 180 kv as the measurements were made at 900 kv peak. If resonances above 500 kv enter in, contrary to our present belief, then only atomic ions will be effective and the above expression will yield too low an estimate of the yield for all resonances involved.

With a total current of 20 microamperes to the target we have found 0.04 pairs per photograph in the region near 11.8 Mev on the best twenty-five percent of the films taken at 900 kv peak. Although this figure is larger than the average number of pairs found on all films, it probably approaches very closely the actual yield when both the ion tube and cloud chamber were simultaneously operating in the most satisfactory manner. The effective solid angle subtended by the secondary emitter at the target was $\Omega = 0.013$ steradians. The number of pairs produced by an 11.8 Mev quantum in passing through the secondary emitter of 0.33 mm of lead is $C = 0.015$. The sensitive time of the chamber was found by varying the time of bombardment with respect to the time of chamber expansion. The time from the first appearance of sharp tracks until no tracks appeared was found to be $T = 0.06$ seconds. From these data we find $Y_i = 3.4\times10^{-10}$ quanta per ion and thus $Y_p \geq 2.3\times10^{-10}$ quanta (11.8 Mev) per proton. The yield for the 4.3 Mev component is also at least 2.3×10^{-10} quanta per proton and that for the 16.6 Mev component at least 0.4×10^{-10} quanta per proton. The total yield of the three main components is thus $Y_p \geq 5.0\times10^{-10}$ quanta per proton.

It is interesting to compare the yields of gamma-rays from $B+H^1$ with the yields of those from Li^7+H^1 and $F^{19}+H^1$. Using a Geiger counter surrounded by 1.5 cm of lead Bothe and Gentner[5] secured 600, 100 and 20 counts per minute from $LiOH+H^1$, CaF_2+H^1, and $B+H^1$, respectively. These results were secured under different experimental conditions for each target and indicate only the order of magnitude of the relative yields. Using an electroscope surrounded by 1 inch of lead, Hafstad and Tuve[13] found a ratio of ionizations of 0.13 for CaF_2+H^1 and $LiOH+H^1$. Observations made in this laboratory indicate a higher yield from CaF_2+H^1 relative to $B+H^1$ than the ratio of five to one indicated roughly by Bothe and Gentner's results. The yields found for $Li+H^1$ in this laboratory are not trustworthy as the composition of the surface of the target employed was uncertain. In all cases the observed yields must be corrected for the relative response of a counter or electroscope to incident quanta of different energies. In case the secondaries are produced in lead it can be shown that the response is roughly proportional to the energy of the quantum. The theoretical cross sections for pair formation and recoil electron production must be taken into account as well as the range of the pair and recoil secondaries. On this basis the yields from $LiOH+H^1$ and CaF_2+H^1 must be corrected by factors of ~ 2 and ~ 0.5 relative to that from $B+H^1$. The corrected yields are, respectively, 7×10^{-9} and 5×10^{-9} quanta per incident proton.

The yield for $LiOH+H^1$ is much larger than that given by the results of Hafstad, Heydenburg and Tuve, and the source of the discrepancy is not entirely clear. More direct evidence is obviously needed. Our results indicate a gamma-ray breadth of 40 volts for the 440 kv resonance for Li^7+H^1.

In conclusion it is well to point out that the radiative capture of protons by B^{11} is intimately connected with the alpha-particle transmutations occurring when boron is bombarded by protons. The $B^{11}+H^1$ reactions have been discussed by Kalckar, Oppenheimer and Serber,[14] but it is difficult to reconcile their conclusions simultaneously with the energy distribution of the gamma-radiation, with the large yield which we find and with other recent experimental results on these reactions. Further discussion of these difficulties will be found in this issue in an article by Professor Oppenheimer and Dr. Serber.

[14] Kalckar, Oppenheimer and Serber, Phys. Rev. **52**, 279 (1937).

APRIL 15, 1938 PHYSICAL REVIEW VOLUME 53

Note on Boron Plus Proton Reactions

J. R. Oppenheimer and R. Serber
University of California, Berkeley, California

(Received February 1, 1938)

A discussion of the experimental evidence on the $B^{11}+H^1$ reactions and of the selection rules available for their interpretations shows that it is not possible to obtain a satisfactory description on the assumption that the same resonance level of C^{12} is responsible, both for the 16 Mev γ-ray observed by Fowler, Gaerttner and Lauritsen, and the long range alpha-particles whose angular distribution was determined by Neuert.

The disintegrations induced when B^{11} is bombarded with protons exhibit certain striking peculiarities. We wish to return to their interpretation in the light of new experimental evidence[1] on the yield and spectrum of the γ-rays observed in these reactions.

The essential findings may be briefly summarized. The most probable reaction involves[2] the emission of short range α-particles, leaving the Be^8 in an excited unstable state (probably ^1D). This reaction shows no resonance,[3] and is accompanied by no observable γ-rays or long range α's. Both the long range α's and the

[1] Fowler, Gaerttner and Lauritsen, Phys. Rev. **53**, 628 (1938).

[2] Dee and Gilbert, Proc. Roy. Soc. **154**, 279 (1936).

[3] Williams, Wells, Tate and Hill, Phys. Rev. **51**, 434 (1937).

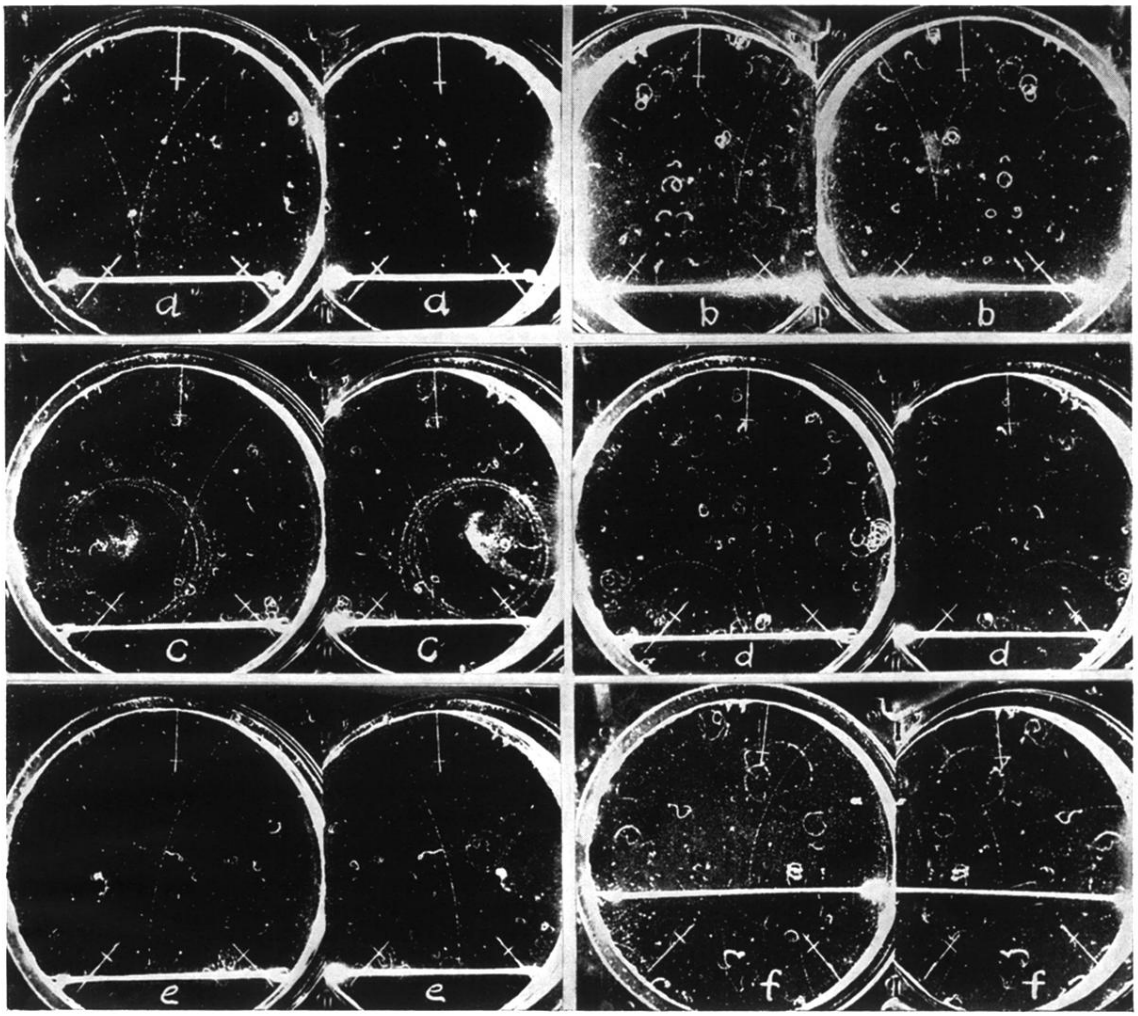

FIG. 1. Stereoscopic views. *a*, A 15.6 Mev pair ejected from a 1.00 mm lead foil by the gamma-radiation from $B+H^1$ (500 kv). The negative pair member bending toward the intersection of the two views has 7.0 Mev kinetic energy while the positive member has 7.6 Mev kinetic energy. Magnetic field = 2000 gauss. *b*, A 16.1 Mev pair (negative has 9.5 Mev, positive has 5.6 Mev) originating in the air-alcohol vapor within the cloud chamber. $B+H^1$ (900 kv). 2500 gauss. *c*, A 10.8 Mev pair (negative has 7.9 Mev, positive has 1.9 Mev) ejected from a 0.33 mm lead foil by the radiation from $B+H^1$ (900 kv). 2500 gauss. *d*, A 4.2 Mev pair (negative has 1.4 Mev, positive has 1.8 Mev) ejected from a 0.33 mm lead foil by the radiation from $B+H^1$ (900 kv). 2500 gauss. *e*, An 11.7 Mev electron ejected from a 0.33 lead foil by the radiation from $B+H^1$ (900 kv). 1500 gauss. *f*, A 4.0 Mev electron ejected from a 1.2 mm carbon lamina by the radiation from $B+H^1$ (900 kv). 1500 gauss.