Disintegration of the Deuteron by Alpha-Particles*

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The noncapture disintegration of the deuteron by fast alpha-particles has been observed. Neutrons emitted in the transmutation were detected with the aid of a BF_3 filled ionization chamber surrounded by paraffin and connected to a high gain amplifier thyratron recording system. Both Ra C′ and Th C′ alpha-particles were used to bombard a gaseous target of heavy hydrogen. Essentially "thin layer" technique was employed in obtaining cross sections for the disintegration process by comparing the neutron yields from D_2 and N_2 under identical conditions. Mean cross sections of 0.12×10^{-26} cm² and 0.30×10^{-26} cm² were obtained for the range intervals 5.7 to 6.9 cm and 7.4 to 8.6 cm, respectively. These experimental values are lower than theoretical estimates obtained from computations made by Massey and Mohr who used an approximation method.

I. INTRODUCTION

PREVIOUS to the present work several attempts had been made to observe the noncapture disintegration of the deuteron according to

$$ {}_1H^2 + {}_2He^4 \rightarrow {}_1H^1 + {}_0n^1 + ({}_2He^4). $$

Rutherford and Kempton[1] using a H_2 filled ionization chamber amplifier arrangement found no detectable yield of neutrons when D_2O was bombarded by polonium alpha-particles. Dunning[2] performed the same experiment with radon instead of polonium, and with the aid of a similar but improved detection apparatus obtained indications of a small neutron yield of doubtful origin. Recently, McCarthy[3] of this laboratory has made with a Wilson cloud chamber and Th C+C′ alpha-particles a study of the range-velocity relation for recoil deuterons. The analysis of a large number of photographs failed to reveal a deuteron disintegration.

The method of distorted wave functions has been applied by Massey and Mohr[4] in calculating cross sections for the process in question at several alpha-particle energies. These calculations indicate an order of magnitude for the disintegration yield sufficient to permit experimental detection, at least for Th C′ particles. Energetically, the reaction is possible for alpha-particle energies greater than three times the binding energy of ${}_1H^2$.

Since data on the interactions of light nuclei are fundamental in nuclear theory, it was considered desirable to search for the neutrons emitted from deuterium under fast alpha-particle bombardment (especially by Th C′ particles). The search was made with a more sensitive method of detection, in particular for lower energy neutrons, than employed by the previous investigators. As recently pointed out by Bethe,[5] the method of calculation adopted by Massey and Mohr is probably not applicable to nuclear problems. Thus, an experimental determination of cross section for several incident energies will be valuable in connection with any more rigorous theoretical treatment that may be made in the future.

Positive results have been obtained with the aid of a highly sensitive BF_3 filled ionization chamber paraffin arrangement for detecting neutrons. The use of a target of D_2 gas (1.2 cm air equivalent absorption) made it possible to compare directly the relative neutron yields from deuterium and nitrogen from which comparison cross sections for D_2 were obtained. The data of Fahlenbrach[6] on the absolute neutron yields

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1 Lord Rutherford and A. E. Kempton, Proc. Roy. Soc. **A143**, 724 (1933).

2 J. R. Dunning and G. B. Pegram, Phys. Rev. **45**, 275 (1934).

3 J. T. McCarthy, Dissertation, Yale University (1937).

4 H. S. W. Massey and C. B. O. Mohr, Proc. Roy. Soc. **A148**, 206 (1935).

5 H. A. Bethe, Rev. Mod. Phys. **9**, 69 (1937).

6 H. Fahlenbrach, Zeits. f. Physik **94**, 607 (1935).

from nitrogen under alpha-particle bombardment have been applied. The final results with both Ra C′ alpha-particles and Th C′ alpha-particles consist of two mean cross sections which are 0.12×10^{-26} cm² for the range interval 5.7–6.9 cm, 0.30×10^{-26} cm² for the range interval 7.4–8.6 cm.

II. Experimental Technique

A. Detection equipment

An experimental study of the reaction

$$_1H^2+{}_2He^4\rightarrow{}_1H^1+{}_0n^1+({}_2He^4)$$

must be concerned with the detection of at least one of the two final products, neutron or proton. Any attempt to count the small number of disintegration protons must involve considerable difficulty due to the presence of projected deuterons and "natural" protons emitted from radioactive sources. In addition, strong β- and γ-radiation from the sources may cause trouble. Modifications in geometry undertaken to improve the situation in all of these respects will lead to a serious reduction in numbers counted. Hence, the only alternative is to count the neutrons also emitted. Unfortunately, this causes the determination of cross sections to be much less direct.

Of the several methods of neutron detection available for investigation of the reaction in question, the one chosen must satisfy the requirements of (1) high sensitivity especially for neutrons of energies below the fast region, and (2) suitability for obtaining absolute yields.

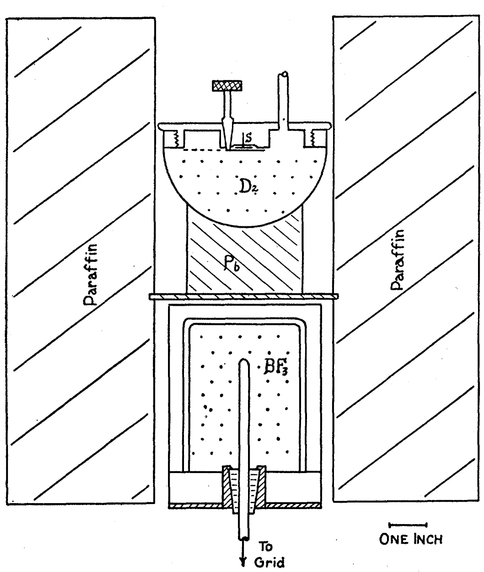

Fig. 1. Source and detector arrangement.

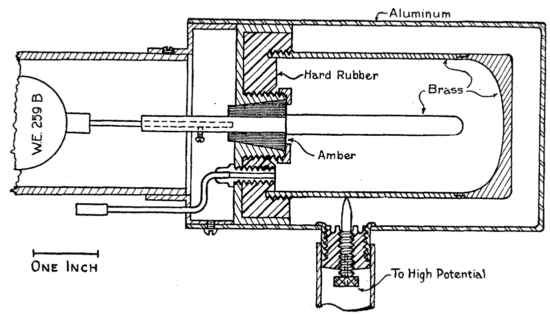

Fig. 2. Ionization chamber.

Chadwick and Goldhaber,[7] Dunning and his co-workers,[8] Fink[9] and others have emphasized the large detection efficiencies of B and Li lined ionization chambers for slow neutrons. Goldhaber[10] and Tuve and Hafstad[11] have in particular applied this method to the detection of fast neutrons by slowing them down in paraffin. The BF_3 filled chamber is not only more sensitive than a similar B or Li lined chamber, but also surpasses the usual artificial radioactive detector. It thus appeared that a BF_3 filled ionization chamber surrounded by paraffin and connected to the conventional high gain amplifier offered the best possibilities for the detection of neutron yields from deuterium. The advantages of this method may be summarized as follows:

(1) High sensitivity as a result of (a) large effective solid angles for counting due to the paraffin surroundings, and (b) high disintegration probability for B by slow neutrons.

(2) Ultimate detection of heavy particles (alpha-particles from the disintegration of B by neutrons), thus giving high ionization currents and less difficulty in recording.

(3) Continuity of detection efficiency with neutron energy, i.e., absence of resonance phenomena.

The location of the ionization chamber in relation to the cylindrical paraffin block used and neutron source is shown in Fig. 1. Details of

[7] J. Chadwick and M. Goldhaber, Proc. Camb. Phil. Soc. **31**, 612 (1935).

[8] J. R. Dunning, G. B. Pegram, G. A. Fink and D. P. Mitchell, Phys. Rev. **48**, 265 (1935).

[9] G. A. Fink, Phys. Rev. **50**, 738 (1936).

[10] M. Goldhaber, Nature **137**, 824 (1936).

[11] M. A. Tuve and L. R. Hafstad, Phys. Rev. **50**, 490 (1936).

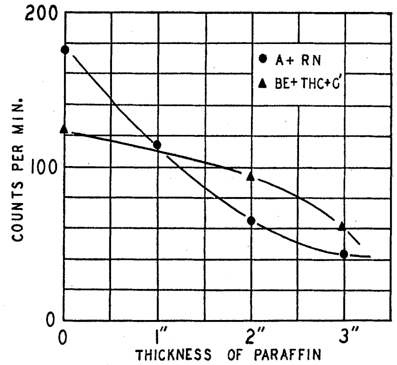

FIG. 3. Variation of detection efficiency with thickness of paraffin between neutron source and BF_3 chamber.

construction of the ionization chamber are given in Fig. 2. This type of design provided for large effective counting volume. The large depth obtainable with this arrangement appeared desirable in view of neutron scattering from all sections along the inner paraffin wall. This chamber was filled to 1 atmosphere with BF_3. At this pressure a collecting potential of 1400 volts gave good uniformity in the size of pulses observed on a cathode-ray oscillograph.

The lead (or copper) block, placed between the neutron source and ionization chamber as indicated in Fig. 1 served to reduce disturbance caused by γ-radiation from the sources employed, and to scatter some of the fast neutrons originally directed toward the chamber into the paraffin. Replacement of the lead block by layers of paraffin of various thicknesses gave a marked diminution in the number of neutrons counted. This decrease in sensitivity was found to be more rapid for sources of neutrons of lower energies. Fig. 3 depicts the variation in counting efficiency with thickness of paraffin interposed between the source and ionization chamber for two different neutron sources. These were Be+Th(C+C′) and A+Rn, the latter reaction having been recently observed in this laboratory and known to represent a source of neutrons of considerably lower energy than that of the Be+Th(C+C′) combination. It was also noted that without any paraffin between the source and chamber, the variation of detection sensitivity with position of the neutron source was not appreciable over the distance of separation implied in the above experiments. Thus the cylindrical paraffin block acts to concentrate the neutrons emitted from the source into a beam of slow ones, hence emphasizing the role of back scattering and accounting in part for the high detection sensitivity noted with this arrangement. These observations are in accord with those of Hopwood and Chalmers[12] and of Fink[9] in connection with the neutron "howitzer."

Frequent checks on the detection sensitivity of the entire arrangement (i.e., amplifier and recording circuit included) were made with radioactive sources of known activity by counting neutrons emitted from a standard Be target. This factor remained constant during the course of the present work. Some idea of the large sensitivity obtainable with this type of apparatus may be gained from the fact that, using air (N_2) as a target in the hemispherical container to be described later, on the average at least one neutron out of every 1000 emitted in the reaction

$$_7N^{14}+{}_2He^4\rightarrow{}_9F^{17*}+{}_0n^1$$

could be recorded.

The amplifier and recording circuit were of conventional design after Wynn-Williams and Ward[13] and Dunning.[14] Since the counting rates dealt with did not exceed 50 per minute, a simple self-extinguishing thyratron circuit with a "Cenco" high impedance counter gave satisfactory results in recording disintegrations.

In view of the small yields from D_2, considerable effort was spent in reducing the ionization chamber background. The final figure attained was 1.4 counts per minute, and this reading was found to be duplicated day after day.

B. Radioactive sources

Two types of sources, namely the active deposits of thorium and of radium were employed. These were collected on 9 mm silver buttons by the recoil method.

Determination of the alpha-ray activities of these sources was effected by directly counting with a small proportional counter the number of alpha-particles emitted in a small solid angle per

[12] F. L. Hopwood and T. A. Chalmers, Nature **135**, 341 (1935).

[13] C. E. Wynn-Williams and F. A. B. Ward, Proc. Roy. Soc. **A131**, 391 (1931).

[14] J. R. Dunning, Rev. Sci. Inst. **5**, 387 (1934).

unit time. The method of employing a γ-ray electroscope and standard radium source was open to the criticism that considerable radioactive material might be deposited on the back side of the button, this portion not being useful for transmutation purposes in the target arrangement adopted.

Although source strengths are given in millicuries, it is to be noted that the final cross sections are free from any error caused by inaccuracy in expressing activities in this unit.

The sources of radium active deposit were usually of from 10 to 15 millicuries initial strength, while sources of Th C′ particles generally did not exceed one millicurie. The subsequent data imply that strengths of the latter type sources are given in terms of the 8.6 cm particles, since Th C (4.8 cm) alpha-particles also present contribute very little or not at all to neutron yields from nitrogen and deuterium, respectively.

All the sources were found to exhibit what appeared to be a weak neutron emission. With the detection system already described, a source placed in an evacuated copper or silver container resulted in a noticeable increase in the chamber background. With air in the ionization chamber, this effect was not noted, and, hence, it is unreasonable to attribute it to instantaneous accumulations of ionization caused by secondary β-rays. In any case, with the lead block between the source and ionization chamber, the γ-radiation produced negligible disturbance. This spurious activity appeared to be greater (per millicurie of alpha-activity) for sources of Th C′ particles than for radium active deposits, and in each case depended somewhat on the surface conditions of the buttons employed for collection. For thorium active deposit on silver, the effect amounted to about one count per minute per millicurie. Considerations in regard to the stability of nuclei indicate that the spontaneous emission of neutrons is unfavorable. This and further experiments led to the conclusion that the background activity must be attributed to such factors as contamination of the surface of the source button by light elements, thus giving rise to neutron emission under the alpha-particle bombardment.

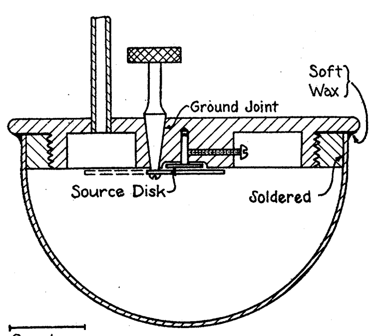

FIG. 4. Deuterium container.

C. Target arrangements

Preliminary experiments with targets of $Ca(OD)_2$ and D_2O indicated the small magnitude of the neutron yield from deuterium by alpha-particles, and emphasized the need of using deuterium in as pure a form as possible in order to be certain of results. The use of the gaseous form also had the advantage that a more direct comparison between the yields from deuterium and nitrogen was possible.

The final arrangement for bombardment is shown in Fig. 4. The source of alpha-particles was located at the center of curvature of the 5.5 cm radius copper container. With D_2 at 76 cm pressure, the total absorption for the alpha-particles was 1.2 cm air equivalent. This factor is not in general correct for all angles since a point source was not employed. Errors introduced in this respect are unimportant in view of the small absorption of the target. This arrangement allowed approximately a solid angle of 2π for bombardment. It seemed that 1.2 cm absorption was a reasonable compromise between the magnitude of the yield convenient for detection and spread in alpha-particle energy. Furthermore, with this absorption the nuclear photo-effect should result in a negligible contribution to the neutron yield.

In order to avoid the difficulty introduced by the stray neutron background associated with the radioactive sources, the arrangement was fitted with a ground joint such that, from the exterior, a thin copper plate could be turned over the source. The thickness of this plate was sufficient to stop all alpha-particles. Thus, this device enabled background counts to be conveniently recorded without removing the D_2 each time such a count was desired.[15]

[15] W. J. Henderson and L. N. Ridenour (Phys. Rev. **52**, 40 (1937)) have recently observed the emission of neutrons

D. Experimental procedure

With a given source, counting was done over periods with the source button alternately exposed to D_2 and covered by the copper absorber. The same procedure was adopted in obtaining yields from nitrogen by bombarding air at 17 cm pressure. At this pressure air gives approximately the same absorption as D_2 at atmospheric pressure.

The time intervals referred to above in which counting was done, were chosen of such length (depending upon the kind of source used) that over each such interval the decay curve of the source could be closely approximated by a straight line. Thus, with this procedure, correction for course decay was easily carried out by using strengths appropriate to the midpoints of these counting periods.

III. Results

The data obtained are summarized in Table I, and the total numbers of counts actually recorded are given in Table II. In the latter table R_α denotes the maximum air range of the alpha-particle in the target substance, i.e. $R_\alpha=0$ for example refers to background recordings. Thus,

TABLE I. *Net yields from D_2 and from air in number of counts per minute per millicurie.*

Source	Target D_2 (76 cm)	Target air (17 cm)
Ra C′	0.32	1.75
Th C′	0.77	2.46

TABLE II. *Total counts.*

Source	R_α	Target D_2 (76 cm)	Target air (17 cm)
Ra C′	0	1928	609
	6.9	2436	1343
Th C′	0	3115	806
	8.6	3937	1251

from Cu under bombardment of 7–8 Mev alpha-particles from a cyclotron. The use of Cu in the target arrangement just described, however, introduced no difficulty in the present case, since control experiments showed that the yield from this element was not detectable above the natural chamber background.

taking into account the amount of nitrogen present in air, the observed yields from a N_2 target of 1.2 cm absorption would have been 2.18 and 3.08 counts per minute per millicurie for Ra C′ and Th C′ particles, respectively. These data in all represent about 70 hours of recording.

In obtaining cross sections for deuterium, the data of Fahlenbrach[6] on the absolute neutron yields from nitrogen under alpha-particle bombardment have been applied. Fahlenbrach has investigated the reaction

$$_7N^{14}+{}_2He^4\rightarrow{}_9F^{17*}+{}_0n^1$$

by observing the positron emission from radioactive $_9F^{17*}$. Using his excitation curve, one finds the mean cross section $\bar{\sigma}$ for N^{14} in the range interval 5.7 to 6.9 cm is 3.8×10^{-26} cm², which corresponds to a range of alpha-particle of 6.3 cm.

Now the effective cross section for transmutation may be defined by

$$\sigma(E)=(dp(E)/dx)(1/N), \tag{1}$$

where $dp(E)$ is the probability of a transmutation occurring as a result of bombardment by a particle of kinetic energy E when this particle traverses a layer of thickness dx of the substance bombarded. N is the number of atoms per unit volume of the target material. If it is desirable to employ range interval rather than actual thickness, then

$$\begin{aligned}\sigma(E)&=(dp(E)/dR_s)(1/N)\\&=(b/N)(dp(E)/dR_b)\end{aligned} \tag{2}$$

where R_b and R_s are the ranges of particles in the target and in standard air, respectively. The quantity b is defined by $R_s=bR_b$ and N has the same significance as in the preceding relation. Under the conditions of the present experiment where essentially a "thin" target has been employed, it is sufficiently accurate to use $\Delta p(E)/\Delta R_s$ instead of the differential expression above. In this case, the value of σ obtained will be the mean effective cross section appropriate to the midpoint of the interval ΔR_s (1.2 cm).

Thus, from an experimental determination of X, the ratio of the neutron yield from D_2 to that from N_2 under identical conditions, and from a knowledge of $\bar{\sigma}_N$, the mean cross section for nitrogen, $\bar{\sigma}_D$ for deuterium may be obtained

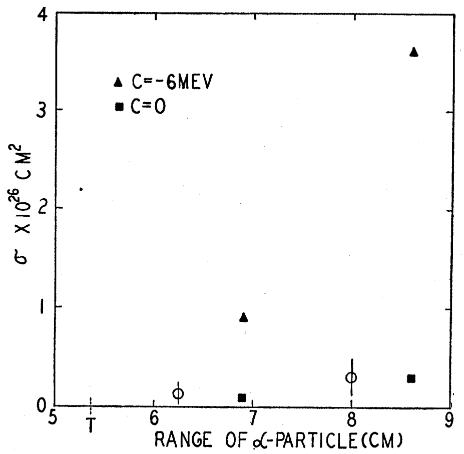

FIG. 5. Comparison between experimental and theoretical (after Massey and Mohr) cross sections. Circles denote experimental values. The theoretical points are for two values of C (the average alpha-particle deuteron interaction).

by application of the relation

$$\bar{\sigma}_D = \bar{\sigma}_N \cdot X \cdot (p_{N_2}/p_{D_2}), \quad (3)$$

an immediate consequence of Eq. (1) or (2). p_{N_2} and p_{D_2} are the pressures of N_2 and D_2, respectively, as used in the hemispherical target arrangement. Therefore, for the alpha-particle range interval 5.7 to 6.9 cm, $\bar{\sigma}_D$ is 0.12×10^{-26} cm^2 corresponding to a range of 6.3 cm.

Rather than rely entirely upon Fahlenbrach's results for higher energies, the method that was adopted in obtaining $\bar{\sigma}_N$ for the range interval 7.4 to 8.6 cm is as follows:

The ratio of the neutron yield from N_2 in the range interval 7.4 to 8.6 cm and the yield in the interval 5.7 to 6.9 cm was multiplied by $\bar{\sigma}_N$ corresponding to 6.3 cm range of alpha-particle. This procedure gives a good approximation to $\bar{\sigma}_N$ at the alpha-particle range 8.0 cm, this value being 5.4×10^{-26} cm^2. (This is in agreement with the value obtained by extrapolating Fahlenbrach's curve to 8.6 cm range.) Finally $\bar{\sigma}_D$ appropriate to 8.0 cm range may be calculated in the same manner as that used in obtaining $\bar{\sigma}_D$ at 6.3 cm with the result $\bar{\sigma}_D = 0.30 \times 10^{-26}$ cm^2 at 8.0 cm.

Haxel[16] has also given cross sections for the emission of neutrons from nitrogen under alpha-particle bombardment. These values are somewhat smaller than the corresponding ones employed in making the above calculations for deuterium. However, these data do not appear to be as complete as those published by Fahlenbrach; moreover, some preliminary experiments on nitrogen with the present apparatus give a form of excitation function more in agreement with that of the latter worker. Thus, it seemed desirable to apply the results of Fahlenbrach in obtaining the cross sections for deuterium. However, the results so calculated probably represent upper limits, particularly if both sets of data on nitrogen are considered.

[16] O. Haxel, Zeits. f. Physik **93**, 400 (1934–35).

Theoretical cross sections of σ_D as given by the treatment of Massey and Mohr are plotted in Fig. 5. Each point implies the value 2.2 Mev as the binding energy of the deuteron. The two sets of points indicated are for two assumed values of C (the average alpha-particle deuteron interaction). Circles are used to represent the experimental values of σ_D on the same diagram, and estimated experimental errors in these values are given by vertical lines through these points. T denotes the threshold range for the reaction.

IV. DISCUSSION

The data obtained definitely establish a neutron yield when deuterium is bombarded by the fast alpha-particles of Ra C′ or of Th C′. An explanation of the emission of neutrons from deuterium in terms of a reaction involving the capture of the alpha-particle is probably excluded in view of existing information concerning mass defects in the lighter nuclei.

Obviously, the number of experimental points obtained is much too small to permit any very definite conclusions about the excitation function for the process in question. Nevertheless, these points taken in conjunction with the threshold range value corresponding to an alpha-particle energy of 6.6 Mev, necessary for the reaction to begin, lie on a smooth curve, and thus suggest a reasonable excitation function.

The validity of the comparison method employed in obtaining cross sections may be questioned in view of possible variation of detection sensitivity with neutron energy. However, since the two reactions involved are no 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.

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The Gamma-Radiation from Boron Bombarded by Protons

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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→200 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

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[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).