aries, the effect would be too small to be detected at lower altitudes. Thus the effect observed by Schein and Wilson[13] with 2.2 cm of lead at 25,000 feet altitude is different from the effect observed with ten times greater thickness in the experiments, such as the present ones, made at lower altitudes.

On the basis of the results of Maass,[6] Heitler[15] postulates the existence of a neutretto (a neutral particle having mass and other properties similar to the barytron) which could be transformed into a negative barytron by colliding with a neutron or into a positive barytron by colliding with a proton. Because of the great thickness of lead absorber used in this experiment, the probability of registering soft secondary and scattered rays was less than in the work of Hsiung[4] and Maass.[6] Thus the results presented in this paper offer more definite evidence for the existence of a penetrating neutral ray than do the results of previous experiments.

[15] N. Arley and W. Heitler, Nature **142**, 158 (1938).

ACKNOWLEDGMENT

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The Gamma-Radiation from Boron Bombarded by Deuterons

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By a method already described, the gamma-ray spectrum from B+D has been obtained by observing the positron-electron pairs ejected from a thin lead lamina (0.033 cm) and the recoil electrons from a carbon lamina (0.12 cm). Gamma-ray components with quantum energies 1.5 ± 0.2, 2.2 ± 0.3, 4.4 ± 0.3, 6.9 ± 0.4 and 9.1 ± 0.4 Mev are indicated with relative intensities $>2.5 : 2.5 : 1.0 : 0.3 : 0.1$. An attempt is made to correlate the energies and relative intensities of the observed gamma-ray components with those of the proton and neutron groups.

INTRODUCTION

THE recoil electrons ejected from the thick glass wall of a cloud chamber by the gamma-radiation from boron bombarded with deuterons were studied by Crane, Delsasso, Fowler and Lauritsen,[1] and indicated two lines at about 2.4 and 4.2 Mev and a number of weak components of higher energy. An improved method for determining gamma-ray energies from the secondary electrons and pairs ejected from thin laminae has already been described in detail in earlier publications.[2,3] This method has been extended to the study of this radiation, and if due allowance is made for the lower resolving power of the earlier experiments, the original results are not in contradiction with those reported here.

Except for a few minor changes the experimental procedure employed was essentially the same as that described in reference 2. In order to select those recoil electrons which were ejected nearly in the forward direction by the gamma-rays the distance from the target to the scatterer

* Horace H. Rackham Post-Doctoral Fellow. This work was completed during the tenure of his National Research Fellowship.

[1] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **46**, 1109 (1934).

[2] Delsasso, Fowler and Lauritsen, Phys. Rev. **51**, 391 (1937).

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

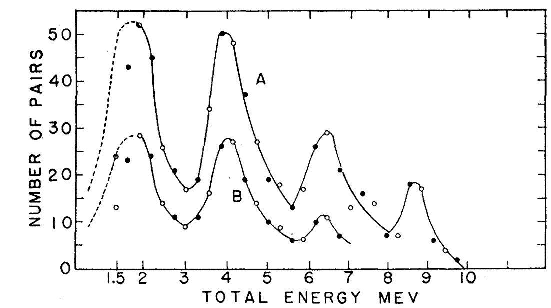

FIG. 1. Curve A, the distribution in total energy of 300 positron-electron pairs ejected from 0.033 cm lead foil by the radiation from B+D measured in fields of 1700 and 1000 gauss, and plotted in overlapping intervals of 0.57 Mev. Curve B contains that portion of the pairs measured in the 1000 gauss field. The dotted portions indicate by how much the low energy component has been broadened to account for those low energy pairs which have been lost in the measuring process.

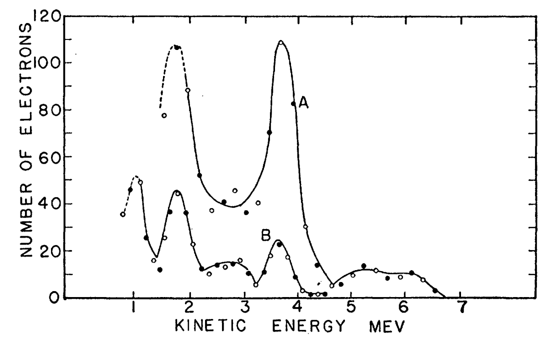

FIG. 2. Curve A, the distribution in kinetic energy of 450 electrons ejected from a carbon lamina 0.12 cm thick within an angle of 20° with the forward direction of the radiation, measured in fields of 1500 and 1000 gauss, and plotted in overlapping intervals of 0.46 Mev. Curve B contains that portion of the electrons measured in the 1000 gauss field. The curves have been broken in the regions of low resolving power.

was increased to 20 cm. This made it possible to select those electrons which made an angle less than 20° with the forward direction of the radiation. Also, in order to have a clear view of both sides of the scatterer so that only those tracks originating in the carbon lamina could be selected, the scatterer was placed two cm from the center of the chamber. In the experiments with pairs where the origin of the tracks was more certain, the lead foil was placed five cm from the center of the chamber to allow more space for measuring the energy of the pair members. The thickness of the carbon scatterer was 1.2 mm (0.5 Mev) and that of the lead 0.033 cm (0.4 Mev).

The accelerating tube was operated at 550 to 850 kilovolts peak voltage while the total ion current was about twenty microamperes during the chamber expansion. The ion beam was not magnetically separated during the cloud chamber observations but previous magnetic analysis indicated that the proton contamination was less than five percent. Light hydrogen, except for one percent in the heavy hydrogen employed, was not introduced into the tube in the period intervening between the magnetic analysis and the cloud chamber observations. That none of the observed radiation can be attributed to boron bombarded by protons is further substantiated by the fact that no evidence was found for a gamma-ray line near 11.8 Mev, the energy of the most intense component of the radiation from B+H.[3] Targets of pure amorphous boron (Eimer and Amend) were used and were frequently replaced, consequently very little of the radiation can be attributed to other reactions involving deuterium.

THE ENERGY OF THE GAMMA-RADIATION

Curve A (Fig. 1) shows the distribution in total energy (kinetic energy $+2\ mc^2$) of 300 positron-electron pairs ejected from the lead lamina, plotted in overlapping 0.57-Mev intervals. These pairs were measured in magnetic fields of 1000 and 1700 gauss. Curve B shows that portion of the pairs (209) measured in the lower field. The relative intensities of the high energy pairs (groups at 4, 6.5 and 8.7 Mev) are best secured from the higher field measurements. On the other hand, those of the lower energy pairs (groups at two and four Mev) are best secured from the lower field measurements because there is a tendency in the measuring process to discriminate against tracks of small radius of curvature. Consequently the relative intensities of the two- and the four-Mev groups given by curve B have been assumed correct and those of curve A have been made to conform with this. Also, because low energy pairs are lost, the apparent width of the two-Mev group is less than that of the four-Mev group. Therefore, in the determination of the energy of the lowest group, the average energy taken from a curve which has been broadened to agree roughly with that of the four-Mev group has been used. The corrected part of the curve is indicated by the dotted line. The quantum energies of the four groups indicated in curve A are determined by adding 0.4 Mev (thickness of the lead) to the average energies of the groups. This procedure gives 2.2 ± 0.3, 4.4 ± 0.3, 6.9 ± 0.4 and 9.1 ± 0.4 Mev for the average energies with their estimated probable errors. The half-widths of the groups can be reasonably attributed entirely to errors inherent in this method of measurement.

Curve A (Fig. 2) shows the distribution in kinetic energy of 450 electrons ejected from a carbon lamina (0.12 cm) within an angle of 20° with the forward direction of the gamma-radiation, and plotted in overlapping intervals of 0.46 Mev. These electrons were measured in magnetic fields of 1000 and 1500 gauss. Curve B shows only those electrons measured in the lower field. Again the relative intensities are best represented by the lower field measurements of curve B, and curve A has been dotted in the region where it is considered untrustworthy. The data of Fig. 2 reveal two prominent groups at approximately two and four Mev in addition to a group of 1.3 Mev which is evident only in the lower field measurements. Adding 0.25 Mev to the extrapolated recoil electron energies gives the most probable quantum energies, with their estimated probable errors, as 1.5 ± 0.2, 2.3 ± 0.3 and 4.3 ± 0.3 Mev. Because of the decrease of Klein-Nishina scattering with energy the data at higher energy are too meager to check those high energy groups indicated by the pair distribution although there is some indication of the group at 6.9 Mev. Because of the low efficiency of pair production just above one Mev, the line at 1.5 Mev was not indicated by the pair data.

The Relative Intensities of the Gamma-Ray Components

Estimates of the relative intensities of the gamma-rays from both the pair and recoil distributions are given in Table I. In estimates from the pair curves the relative intensities have been corrected for the variation in pair formation cross section with energy. In computing the relative pair intensities of the 2.2- and 4.4-Mev components the corrected curve of the low energy pair distribution has been employed. In estimates from the recoil curves the relative intensities have been corrected for the total Klein-Nishina cross section. Since only those electrons enter into the distribution which are scattered within an angle of 20° with the forward direction of the quanta, little error is introduced by using the total cross section for all components except the one at 1.5 Mev. A lower limit of the intensity of this component is given.

Origin of the Radiation

The reactions which have been suggested to account for the emission of protons, neutrons, and β-particles when boron is bombarded with deuterons are as follows:

$$B^{10}+H^{2}\rightarrow C^{11}+n^{1}+6.34\text{ Mev} \quad (1)$$

$$\downarrow$$

$$B^{11}+\beta^{+} \quad (1')$$

$$B^{11}+H^{2}\rightarrow C^{12}+n^{1}+13.68\text{ Mev} \quad (2)$$

$$B^{10}+H^{2}\rightarrow B^{11}+H^{1}+9.30\text{ Mev} \quad (3)$$

$$B^{11}+H^{2}\rightarrow B^{12}+H^{1}+\sim 0\text{ Mev} \quad (4)$$

$$\downarrow$$

$$C^{12}+\beta^{-} \quad (4')$$

The Q values of the above reactions are those

Table I. *Relative intensities of five main components of the gamma-radiation from* $B+H^{2}$.

Gamma-Ray Energy	Relative Pair Intensities	Relative π*	Int. from Pairs	Relative Recoil Intensities	Relative σ**	Int. from Recoils	Weighted Intensities
1.5	—	—	—	>4.0	1.73	>2.5	>2.5
2.2	1.0	0.28	3.5	2.5	1.57	1.6	~2.5
4.4	1.0	1.00	1.0	1.0	1.00	1.0	1.0
6.9	0.5	1.73	0.3	0.2	0.72	0.3	0.3
9.1	0.25	2.26	0.1	—	—	—	0.1

* π = pair-formation cross section.
** σ = Klein-Nishina cross section.

calculated from the atomic masses by Livingston and Bethe.

The neutrons emitted when boron is bombarded with deuterons have been investigated by Bonner and Brubaker[4] who observed four homogeneous groups with Q values 13.4, 9.0, 6.0 and 3.9 Mev and relative intensities 0.36 : 0.38 : 0.07 : 0.19[5] Of these four groups the first two must be attributed to reaction (2) because it alone is exothermic enough to produce them. If the last two groups are also caused by this reaction, then three excited states of C^{12} at 9.5, 7.4 and 4.4 Mev are indicated and the quantum energies of the possible optical transitions are 9.5, 7.4, 5.1, 4.4, 3.0 and 2.1 Mev. The existence of gamma-ray components at 9.1 ± 0.4 and 6.9 ± 0.4 shows that the higher states of C^{12} are produced in the disintegration. That they do not couple readily with the state at 4.4 Mev is the simplest explanation of the nonexistence of components at 5.1 or 3.0 Mev. If the last two neutron groups are also partly caused by reaction (1) then the ground state of C^{11} and an excited state at 2.1 Mev enter.

The protons from B+D have been attributed to reaction (3) by Cockcroft and Lewis[6] who found three homogeneous groups of protons with Q values 9.11, 6.99 and 4.62 Mev and relative intensities 0.40 : 0.13 : 0.47. The over-all intensity was given as one-half that of reaction (1). Excited states of B^{11} at 4.5 and 2.1 are indicated, the quantum energies of the possible optical transitions being 4.5, 2.4 and 2.1 Mev. No proton group of intensity comparable to the yield of β-rays (20 times the 9.11-Mev proton group), reported by Crane, Delsasso, Fowler and Lauritsen[7] was found down to a range of 1 cm. The state of B^{12} is thus at least 13.7 Mev above the ground state of C^{12}, and as the observed β-rays extend only to 12 Mev the β-transition may be to an excited state of C^{12}. Another, but improbable, alternative is that an excited state of B^{12} is always produced in reaction (4).

The reactions producing alpha-particles when boron is bombarded by deuterons do not, in general, result in excited states of the nuclei Be^9 or Be^8 which emit gamma-radiation. The observed gamma-ray components agree well with the majority of the optical transitions among states of C^{12} and B^{11} discussed above. It is comparatively simple to devise a set of linear equations which the intensities of these transitions must obey employing the proton and neutron group intensities given above. Unfortunately, the equations do not give the intensities of each transition uniquely. We find, however, that the observed intensities satisfy the required relationships derived assuming only reactions (1), (2) and (3) as long as the strong component at 1.5 Mev is excluded. It is well to note that the observed intensities of the 9.1 and 6.9 Mev components require that the over-all neutron yield of reaction (2) be at least ten times that of (1). Correction for the abundance ratio of the isotopes of boron reduces this factor to 2.5. We are tempted to ascribe the strong 1.5-Mev component to reaction (4) which is comparable in intensity to (2). If an excited state of C^{12} is involved the gamma-emission should be radioactive and we are now attempting to observe this.

[4] Bonner and Brubaker, Phys. Rev. **50**, 308 (1936).

[5] Dr. W. E. Stephens has kindly computed the relative intensities of the neutron groups by correcting Bonner and Brubaker's data for geometrical factors of cloud chamber observation and for the change of neutron-proton collision cross section with energy (Wigner).

[6] Cockcroft and Lewis, Proc. Roy. Soc. **154**, 246 (1936).

[7] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **47**, 887 (1935).