The Gamma-Ray Spectrum of B^{10}

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(Received June 21, 1937)

The gamma-rays from B^{10}, produced by bombarding beryllium with 1 Mev deuterons, have been investigated by an examination of the momentum distribution of Compton electrons ejected from a thin mica foil in an expansion chamber. This spectrum consists of six gamma-rays of energies 0.51, 1.07, 1.44, 1.96, 2.81 and 3.21 Mev. These gamma-rays result from all possible transitions between three excited levels and the ground state of B^{10}. The energy levels determined are in agreement with those obtained from a study of the neutron spectrum emitted by the same reaction.

WHEN beryllium is bombarded with deuterons a multienergy spectrum of gamma-rays and neutrons is observed. Bonner and Brubaker[1] have examined the energies of the neutron groups and from them have determined a set of energy levels for the B^{10} nucleus. However, they could not correlate their energy levels and the energies of the gamma-rays reported by Crane, Delsasso, Fowler, and Lauritsen.[2] For this reason, the present investigation sought to determine the gamma-ray energies with sufficient accuracy to fix their origin and their relation to the neutron energies.

In this study the deuteron beam produced by a small cyclotron[3] bombarded a metallic beryllium target. The target was placed in a thin walled brass exposure chamber fixed to the end of the beam outlet tube. A bombarding current of 0.2 microampere of 1 Mev deuterons, which was used throughout the experiment, yielded as large a gamma-ray intensity as could be used in an expansion chamber.

To study the gamma-rays, an air-filled expansion chamber containing alcohol and water vapor was operated at about one atmosphere. The chamber is sylphon actuated and is 13 cm in diameter, with a usable depth of 2 cm. A 96 mg per cm^2 mica conversion foil was cemented to the glass lid of the chamber with water glass and the chamber positioned so that the foil was 40 cm from the target and perpendicular to the line from the foil center to the target.

[1] Bonner and Brubaker, Phys. Rev. **50**, 308 (1936).
[2] Crane, Delsasso, Fowler and Lauritsen, Phys. Rev. **47**, 782 (1935).
[3] P. G. Kruger and G. K. Green, Phys. Rev. **51**, 699 (1937).

A magnetic field of the order of 730 oersteds was maintained by a pair of Helmholtz coils whose constant is 18.8 oersteds per ampere. The field strength of these coils was determined with a flux coil and ballistic galvanometer calibrated against a standard solenoid, whose constants are known to 0.2 percent. The same standard ammeter was used to measure the current in the Helmholtz coil during calibration and also during the experiment. The field of the coils varies less than 1.5 percent over the volume in which tracks were measured, and its absolute value is known within 1 percent.

At a current of 40 amperes the Helmholtz coils ran hot even though the current was applied only at the moment of expansion. This required that the expansion chamber be protected from heating with a water-cooled copper shield which was placed between the chamber and Helmholtz coils. A slot in the shield admitted light from a carbon arc. Continuous illumination produced localized heating in the chamber, and consequently poor tracks, so a shutter was arranged to allow the arc to illuminate the chamber only during the time the film was exposed. The tracks were photographed on Super X panchromatic film by a Sept camera (non-stereoscopic) equipped with an $f:3.5$ lens.

Gamma-rays from the target eject Compton electrons from the mica foil. Richardson and Kurie[4] have investigated the characteristics of the momentum distribution of such recoil electrons using the Klein-Nishina formula, and have demonstrated the use of this distribution in determining the energy of the gamma-rays pro-

[4] Richardson and Kurie, Phys. Rev. **50**, 999 (1936).

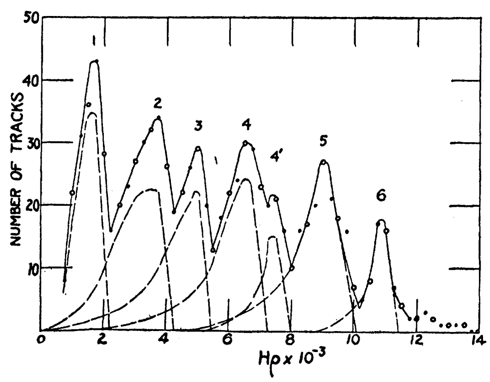

FIG. 1. Momentum distribution of Compton electrons projected by gamma-rays from B^{10}. Solid curve is distribution curve given by experimental data. Dotted curves represent corrected form of each peak.

ducing it. The tracks, reprojected through the same optical systems as was used in the photography, were viewed and measured on a translucent screen.

The tracks selected for measurement satisfied the following criteria. (1) The track must be plainly visible, of uniform curvature and free from any indication of scattering. (2) It must appear to originate in the mica and emerge at an angle of not more than 10° with the direction of the incident gamma-ray. (3) It must be long and of uniform focus so that it does not make an angle of more than 10° with the horizontal. (4) It must not be the negatron of a pair. The curvature of tracks satisfying these criteria was determined by superimposing finely ruled circles on the track image. These circles were ruled on thin celluloid in sets, with successive radii increasing by 2 mm. In practice it is possible to match the track and ruled circle to about ± 2 mm for $\rho < 6$ cm and about ± 4 mm for $\rho > 6$ cm.

Twelve hundred pictures yielded 480 acceptable tracks. During the experiment the magnetic field was not held constant, but varied from 711 to 797 oersteds and was recorded for every expansion. From the values of the magnetic field and ρ, a table of the $H\rho$ products was compiled so that the number of tracks in any $\Delta H\rho$ interval can be found readily. These data can be plotted as a histogram. However, it is preferable to plot the number of tracks occurring in each of a set of $\Delta H\rho$ intervals (i.e., $\Delta H\rho = 500$) as a point at its center and represent the data as a distribution curve drawn through these points. The statistical fluctuations can be smoothed somewhat, and the curve improved, by selecting a second set of $\Delta H\rho$ intervals overlapping the first set by half the interval and plotting the corresponding set of points, which will fall halfway between the first set of points. Distribution curves have been drawn for $\Delta H\rho = 300$, 400, 500, 600, and 700, of which the $\Delta H\rho = 500$ curve is the most satisfactory, since a smaller $\Delta H\rho$ gives rise to larger statistical fluctuations and a larger $\Delta H\rho$ rounds off the peaks too much. The $\Delta H\rho = 500$ curve is shown by the solid line in Fig. 1. The dots represent the number of tracks in one set of intervals, the circles the number of tracks in the overlapping set. The peaks are not completely resolved so that the points of the curve on the high energy sides of all but number 6 include a considerable number of tracks due to the straggling from the peaks of higher energy. For this reason a straight line extrapolated down the high energy side of each peak would give too high a value for the maximum energies of the electrons ejected by the various gamma-rays. In order to correct the curve, the shape of the straggling for peak number 6 was calculated from the data given by White and Millington,[5] and the "tail" of number 6 subtracted from peak 5. This process was continued until all the peaks were corrected. The final form of the peaks is shown by the dotted lines in Fig. 1. The intercepts of the high energy sides of these corrected peaks with the momentum axis are 2250, 4250, 5500, 7250, 8000, 10,100, 11,500 $H\rho$. It will be noted that these intercepts coincide with the abscissae of the points at which the "tail" of each peak cuts the high energy side of the preceding one. After adding the energy of the recoil photon to the electron energies calculated from the above values of $H\rho$, the gamma-ray energies are found to be 0.51, 1.07, 1.44, 1.96, 2.17, 2.81 and 3.21 Mev.

The reality of peak number 4′ might be questioned if the 500 $H\rho$ interval plot of Fig. 1 were considered alone. However, curves similar to those in Fig. 1 but having $\Delta H\rho = 300$, 400 and 600 show peak number 4′ equally prominent and give it the same energy of 2.17 Mev so that it is considered a real peak. Its presence can be

[5] White and Millington, Proc. Roy. Soc. **A120**, 701 (1928).

explained from the fact that the spectrum of gamma-rays from beryllium bombarded by protons has an intense line at 2.2 Mev, but no other strong lines in the region below 3.5 Mev.[2] A small molecular hydrogen contamination of the deuteron beam from the cyclotron will produce protons of 0.5 Mev energy, which is sufficient to excite this 2.2 Mev line. Thus the 2.17 Mev gamma-ray is probably due to proton bombardment of the beryllium target and will not fit in the energy level scheme discussed below. For these reasons it is not included in the data given in Table I, column *C*, which gives the observed gamma-ray energies.

Though it is not shown in Fig. 1, because it would unduly complicate the figure, the effects of probable statistical fluctuations have been studied graphically by replacing each point by a vertical line of length $2\sqrt{N}$, where N is the ordinate of the point. Lines drawn within the envelopes of these vertical lines intersect the momentum axis in a region, the size of which gives an estimate of the effect of statistical fluctuations. The different $\Delta H\rho$ groupings give a spread of intercepts of the same order of magnitude as that produced by the former process. These considerations indicate a probable error of about ± 0.1 Mev.

The conclusions drawn by Oliphant, Kempton and Rutherford[6] from their observation of the charged particles emitted when beryllium is bombarded with deuterons indicate that no gamma-radiation should accompany these particles. Therefore it is logical to associate the gamma-ray and neutron spectra.

In the investigation of the neutron energies

TABLE I. *Comparison of predicted and observed gamma-rays.*

A Line Number	*B* Gamma-Ray Energies Predicted from Neutron Data	*C* Observed Gamma-Ray Energies	*D* Relative Intensity of Gamma-Rays	*E* Observed Half-Width ($H\rho$)	*F* Theoretical Half-Width ($H\rho$)
1	0.55 Mev	0.51 Mev	10.0	1000	790
2	1.30	1.07	10.2	1900	700
3	1.60	1.44	5.8	1400	725
4	2.15	1.96	5.5	1400	800
5	2.90	2.81	5.4	1400	950
6	3.45	3.21	1.7	700	1075

[6] Oliphant, Compton and Rutherford, Proc. Roy. Soc. **A150**, 241 (1935).

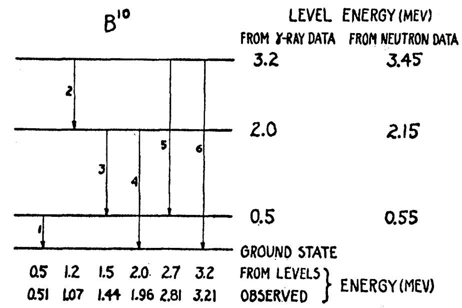

FIG. 2. Energy level diagram for B^{10}. Numbers on the transition arrows correspond to peak numbers in Fig. 1.

Bonner and Brubaker[1] found four groups from whose energies they deduced excited levels of 0.55, 2.15 and 3.45 Mev (± 0.2 Mev) for the B^{10} nucleus. If the gamma-rays originate from transitions between these levels their energies must be the level differences. Crane, Delsasso, Fowler and Lauritsen[2] found gamma-rays of energies 0.8, 1.3, 2.0, 2.5, 2.9, 3.3 and 4.0 Mev, of which the 4.0 Mev line is probably due to proton contamination of the bombarding beam. These energies were obtained by analyzing 206 tracks ejected from the glass wall of an expansion chamber. Inaccuracies introduced by the thick electron source, which flattens the distribution curve, and large relative statistical fluctuations due to the small number of tracks, make impossible a close correlation of these gamma-ray energies with the neutron energy levels.

The energies corresponding to transitions between the levels given by Bonner and Brubaker are entered in Table I, column *B*. Our observed gamma-ray energies (column *C*) agree with these transition energies within the probable errors assigned (± 0.1 and ± 0.2 Mev, respectively), but it will be noted that our values are all lower than those of Bonner and Brubaker, indicating a systematic error entering into one of the determinations.

A set of energy levels which best fits all six gamma-ray lines was determined by trial, and is shown in Fig. 2. The level energies are 0.5, 2.0 and 3.2 Mev and are somewhat lower than Bonner and Brubaker's values. At the bottom of Fig. 2 the observed energies are compared with the energies to be expected from transitions between levels of 0.5, 2.0 and 3.2 Mev and the ground state.

If we assume that the energy levels are associated with B^{10}, the reaction is

$$_4Be^9 + {_1H^2} \rightarrow {_5B^{11}} \rightarrow {_5B^{10*}} + {_0n^1}$$
$$\downarrow$$
$$_5B^{10} + \gamma.$$

The alternative assumption would require the energy levels to be inverted and associated with the composite nucleus, B^{11}. Under such an assumption the highest temporary semistable state would be at 15.6 Mev (as calculated from mass data) and the lowest at 12.3 Mev, since no gamma-rays of energy higher than 3.3 Mev have been detected. In addition all neutron transitions would have to end in the ground state of B^{10}. Moreover, in general, the probability of mechanical decay of the light elements is much greater than that of radiation. All of these considerations indicate that the energy levels are excited states of the B^{10} nucleus. It will be noted that all possible transitions between the four levels occur.

The relative intensities of the gamma-ray lines given in Table I were calculated from the area included under the distribution curve (corrected curves, Fig. 1) between the abscissa corresponding to the half-maximum values of the ordinate. These areas are proportional to the intensities of the gamma-rays but do not represent relative intensities on account of the dependence of electron ejection on the gamma-ray energy. To get relative intensities, the areas must be divided by the appropriate intensity correction factor as given by Richardson and Kurie.[4] It is difficult to estimate the accuracy of these intensities, but it is probably better than thirty percent.

A tentative classification of the energy levels of Fig. 2 can be obtained in the following way. By applying the relation $I \propto P_i(Sw)_f \nu^3$, where I is the intensity of the line, P_i the population of the initial state, $(Sw)_f$ the statistical weight of the final state, and ν the frequency of the line, to two lines originating on the same upper level, but ending on two different lower levels, one obtains $(Sw)_1 = (E_0^3/E_1^3)(I_1/I_0)(Sw)_0$, where E is the energy of the line and the subscripts 0, 1 refer to the ground state and first level, respectively. By using lines 5 and 6 of Table I and considering that the possible values of j for the ground state may be $j_0 = 1; 3; 1, 2; 2, 3;$ or $1, 2, 3$, and $(Sw)_0 = 3$, 7, 8, 12 and 15; one gets

$$(Sw)_1 = 14, 33, 38, 56, \text{ and } 70. \quad (1)$$

Repeating the process for lines 3 and 4 gives

$$(Sw)_1 = 8, 19, 21, 32, \text{ and } 40. \quad (2)$$

Of the values in (1) only

$$(Sw)_1 = 14 \quad (1')$$

and in (2)

$$(S_w)_1 = 8 \quad (2')$$

are allowed. All others give statistical weights which are too large. Thus one must conclude that $j_0 = 1$ and $j_1 = 1$, 2 and 3. These j values agree with the results of the calculations of Feenberg and Wigner[7] which give the ground state as $^3S_1$ and the next higher level as $^3D_{1,2,3}$ (our 0.5 Mev level).

From the mass defect difference between B^{10} and Be^{10} it seems likely that the 2 Mev level is $^1D_2$. However it may also include $^1S_0$. On account of the large relative intensity of line 2 it seems likely that the 3.2 Mev level is $^3D_{1,2,3}$. This is supported by the large difference between the observed line width and the theoretical line width given in Table I. However in view of the limited resolving power of the method used in this experiment and the accompanying inaccuracy of the intensity estimates it must be emphasized that this interpretation of the level system, though in agreement with the calculations of Feenberg and Wigner, is tentative and needs much additional information before it can be considered certain.

The authors wish to thank Professor Wigner for his helpful comments concerning the tentative level classification.

One of us (P. G. K.) wishes to acknowledge a Grant-in-Aid from the National Research Council and generous aid from the Graduate School Research Board of the University of Illinois.

[7] Feenberg and Wigner, Phys. Rev. **51**, 95 (1937).