states considered which will be significantly affected by configuration mixing are gamma decay rates and (p,d) or (d,p) cross sections, in addition, of course, to beta decay. These properties will need to be calculated, and similar analyses made of other nuclei in the vicinity before it can be concluded that the successful calculations reported here indeed represent an adequate description of the nuclear state.

It is a pleasure to acknowledge the many enlightening conversations we had with Professor Keith Brueckner, Dr. Richard Edén, Dr. Norman Francis, and Dr. Leonard Kisslinger.

PHYSICAL REVIEW VOLUME 100, NUMBER 1 OCTOBER 1, 1955

Gamma-Ray and Neutron Yields from the Proton Bombardment of Boron

J. K. BAIR, J. D. KINGTON, AND H. B. WILLARD
Oak Ridge National Laboratory, Oak Ridge, Tennessee

(Received June 21, 1955)

Yield curves of the gamma rays and neutrons resulting from the proton bombardment of boron have been measured for proton energies from approximately 2 to 5 Mev. Both the 0° and 90° yields for the $B^{11}(p,\gamma)C^{12}$ reaction have been measured for the ground state transition and for the transition to the 4.43-Mev state in C^{12}, as has the yield of the 2.14-Mev γ ray resulting from the inelastic scattering of protons on B^{11}. The neutron yield from $B^{11}(p,n)C^{11}$ is given at 0° and for almost 2π solid angle in the forward direction. New levels were observed in the C^{12} compound nucleus at 18.3, 18.39, 18.84, 19.2, 19.41, 19.66, 19.87, 20.25, 20.48, and 20.64 Mev. Preliminary data are given for the $B^{10}(p,n)C^{10}$ and $B^{10}(p,\gamma)C^{11}$ reactions.

I. INTRODUCTION

GAMMA-ray yield curves for B^{11} bombarded by protons have been reported by Huus and Day,[1] by Cochran, Ryan, Given, Kern, and Hahn,[2] and by Gove and Paul,[3] who give references to earlier data. In the present work, the γ-ray yields have been extended from the previous limit of 2.8 Mev to about 5-Mev proton bombardment energy for the reactions

$$B^{11}+p\rightarrow C^{12}+\gamma_0,$$

$$B^{11}+p\rightarrow C^{12*}+\gamma_1\rightarrow C^{12}+\gamma_1+\gamma_2,$$

and

$$B^{11}+p\rightarrow B^{11*}+p'\rightarrow B^{11}+p'+\gamma_3.$$

Measurements were made at both 0° and 90° with respect to the bombarding proton beam.

Richards, Smith, and Browne[4] have found the threshold for the reaction

$$B^{11}+p\rightarrow C^{11}+n$$

to be 3.015±0.003 Mev. Blaser, Boehm, Marmier, and Scherrer[5] have reported observation of the yield of C^{11} by a stacked foil technique. Neutron yield curves are given in the present paper for proton energies from threshold to approximately 5 Mev.

II. EXPERIMENTAL PROCEDURE

Protons from the ORNL 5.5 Mv Van de Graaff were magnetically analyzed by a 90° magnet whose slits were adjusted to about 0.1 percent energy resolution. A proton moment device was used to measure the magnetic field. Energy calibration is believed to be accurate within ±0.2% relative to the $Li^7(p,n)Be^7$ threshold at 1.882 Mev.[6] An electrostatic strong focus lens system was used to focus the beam on targets located 15 to 25 feet from the magnet.

Thin boron targets were prepared by evaporating elemental boron of natural isotopic ratio on tantalum backings. Target thicknesses used for the data given here were about 30 kev at 3 Mev, although thinner targets were at times used. Target thicknesses were determined by measurements on the geometrical peak of the neutron yield from a very thin target, and then comparing the yield of this and the unknown target at a proton energy where the neutron yield was slowly varying. Similar targets of 96% B^{10} were available* and were used to check that the reactions measured were due to B^{11}. Although the B^{10} targets were free from serious impurities, considerable effort was necessary to produce suitable B^{11} targets. In addition to the usual fluorine contamination on the backing material, the first boron used contained an impurity, probably aluminum, which gave rise to a number of narrow resonances yielding high-energy γ rays and a rather intense low-energy γ ray of about 1 Mev. Targets made from natural boron of greater than 99% purity[7] were finally used for the γ-ray work and were quite satisfactory.

[1] Torben Huus and Robert B. Day, Phys. Rev. **91**, 599 (1953).
[2] Cochran, Ryan, Given, Kern, and Hahn, Phys. Rev. **87**, 672 (1952).
[3] H. E. Gove and E. B. Paul, Phys. Rev. **97**, 104 (1955).
[4] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).
[5] Blaser, Boehm, Marmier, and Scherrer, Helv. Phys. Acta **24**, 465 (1951).
[6] Herb, Snowden, and Sala, Phys. Rev. **75**, 246 (1949).
* Elemental B^{10} was obtained from the Stable Isotopes Division of this Laboratory.
[7] Varlocoid Chemical Company, 116 Broad Street, New York City.

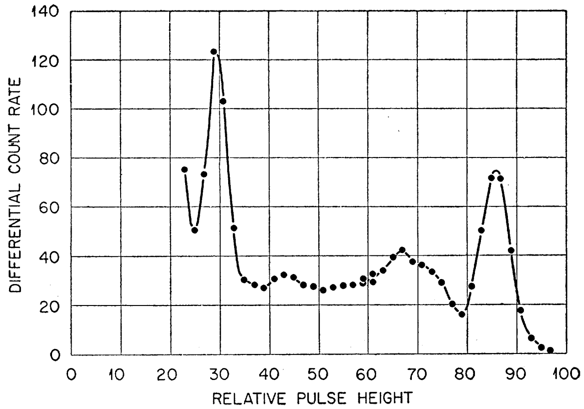

FIG. 1. $B^{10}(p,p')B^{10}$ and $B^{11}(p,p')B^{11}$ γ-ray spectrum as seen by NaI crystal spectrometer. $E_p=2.8$ Mev. The peak at a pulse height of 29 corresponds to the 0.72 Mev γ ray from scattering on B^{10}. The remaining three peaks are the usual single crystal peaks corresponding to the 2.14-Mev γ ray from scattering on B^{11}.

III. GAMMA-RAY MEASUREMENTS

A large 3-in. diameter, 3-in. high sodium iodide crystal in conjunction with a 3-in. photocathode photomultiplier tube, DuMont type K1197, was used as a detector for the proton-capture and inelastic-scattering γ rays. This combination has a resolution of 8% (full width at half maximum) for the Cs^{137} photopeak. Pulses from the photomultiplier were amplified using standard electronic techniques and recorded with a 20 channel pulse-height analyzer.[8] For the yield curves shown, the 20 channel analyzer was adjusted so as to cover only the region of the γ-ray spectrum of immediate interest, the datum plotted for a given proton bombarding energy (uncorrected for target thickness) is the reading in the channel corresponding to the maximum of the full energy peak corrected, if necessary, for the effect of any higher energy γ rays. This technique not only minimizes the effects of small changes in the over-all gain of the system, but simplifies measurements of the capture γ-ray yields since as the γ-ray energy changes due to changes in the bombarding proton energy, the peak in the spectrum merely moves from one channel to the next and can be easily followed.

Figure 1 gives a differential pulse height spectrum for the low-energy γ rays resulting from the bombardment of natural isotopic boron with 2.8-Mev protons. The peak at a pulse height of 29.5 is the 0.72-Mev γ ray from the reaction $B^{10}(p,p')B^{10*}$. The remaining peaks are the usual single crystal spectrometer peaks produced by the 2.14-Mev γ rays from the reaction $B^{11}(p,p')B^{11*}$, although the two-quantum escape peak (at a pulse height of 43) shows some effect of the target impurity previously mentioned. Energies were obtained by calibrating the crystal spectrometer with the known Cs^{137} and ThC″ γ rays, and agree with the previously measured level energies of 0.718 and 2.138 Mev in B^{10} and B^{11}, respectively,[9] and with the gamma-ray energies determined by Huus and Day.[1] It is to be noted that the full energy peak, at a pulse height of 86, is considerably accentuated over that obtained with the usual $1\frac{1}{2}$ in. diameter crystal. The count rate corresponding to this peak (pulse height of 86) was plotted as a function of proton energy to obtain the B^{11} inelastic scattering γ-ray yield curves.

The lower curve (open circles) of Fig. 3 is the yield of the 2.14-Mev γ ray from the reaction $B^{11}(p,p')B^{11*}$ and was measured at 0° with respect to the proton beam and with the detector approximately 100 cm from the target. A similar curve taken at 90° differed in no essential respects and is not shown. Measurements of the 2.66-Mev resonance as well as higher energy resonances show the γ ray to be emitted isotropically. Neutron effects in the crystal could safely be neglected due to the intense yield of the inelastic scattering γ rays. Table I includes in Column 7 the energies of these γ-ray resonances, corrected for target thickness. No attempt was made to determine absolute γ-ray cross sections. However, the proton bombarding energy overlaps that of Huus and Day[1] sufficiently to permit normalization to their values.

Figure 2 shows a differential pulse-height curve of the B^{11} capture gamma rays for a bombarding proton energy (1.4 Mev) well below the threshold for neutron production. The maximum in the region of 17 pulse height units is due to the γ ray from the 4.43-Mev excited state in C^{12} and, when observed with narrower channels in the pulse-height analyzer, the usual three peaks were resolved. Peaks at 50 and 67 pulse-height units correspond to the capture transition to the 4.43-Mev state in C^{12} and to the ground state respectively.

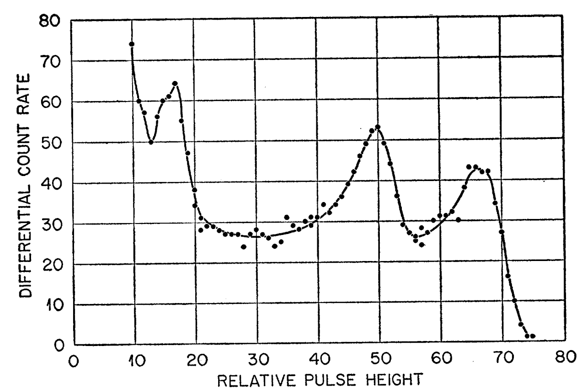

FIG. 2. $B^{11}(p,\gamma)C^{12}$ γ-ray spectrum as seen by 3 in.×3 in. NaI crystal spectrometer. $E_p=1.4$ Mev. The maximum at a pulse height of 17 is due to the γ ray from the 4.43-Mev excited state of C^{12}. The three peaks usually obtained with a single crystal spectrometer are not resolved due to the wide channel width. The maxima at pulse heights of 67 and 50 are due respectively to the ground state transition and the transition to the 4.43-Mev excited state. No structure was observed in these maxima even with considerably narrower channels.

[8] Kelley, Bell, and Goss, Oak Ridge National Laboratory Quarterly Progress Report ORNL–1278, 1951 (unpublished).

[9] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952), and Revs. Modern Phys. **27**, 77 (1955).

TABLE I. Characteristics of the observed levels in the C^{12} compound nucleus. Columns 2 through 7 give the proton energies at which maxima were observed in the yield respectively: of neutrons; γ rays to the 4.43-Mev level, as measured at 0°; the same γ ray as measured at 90°; the γ ray to the ground state, as measured at 0°; the same γ ray as measured at 90°; and the inelastic scattering γ ray. Column 8 gives an estimate of the width of the level at half maximum. Column 9 lists the energy of excitation in the compound nucleus.

1 Level	2 Neutrons Mev	3 $\gamma_{12}0°$ Mev	4 $\gamma_{12}90°$ Mev	5 $\gamma_{16}0°$ Mev	6 $\gamma_{16}90°$ Mev	7 γ_{in} Mev	8 Width Mev	9 Energy Mev
1	···	2.5	2.65	weak	···	···	0.3	18.3
2	···	···	···	···	···	2.66	0.046	18.39
3	3.17	3.12	3.14	weak	···	3.15	0.1	18.84
4	3.65	3.6	3.5	3.6	weak	3.4	0.5	19.2
5	···	···	···	···	···	3.78	0.05	19.41
6	4.05	···	···	···	···	···	0.2	19.66
7	···	weak	···	···	···	4.28	0.1	19.87
8	4.70	···	···	···	···	4.68	0.2	20.25
9	···	4.95	4.93	···	···	···	0.2	20.48
10	···	5.12	5.12	···	···	5.13	0.2	20.64

Measurements on these peaks with narrower channels did not resolve additional structure. Although the peaks are broad for these high-energy γ rays and one is uncertain as to their interpretation, they are in agreement with the energies expected from mass values and the kinetics of the reaction (15.95 Mev$+11/12\ E_p$), and with this energy less that of the 4.43-Mev excited state in the C^{12} residual nucleus.

Due to the low intensity of the capture γ rays, neutron capture effects in the crystal itself are very troublesome above the neutron threshold. These effects can be minimized by neutron shielding between the source and crystal, provided such shielding does not seriously effect the gamma rays. A useful shield can be made by stirring as much finely divided lithium fluoride as possible into melted paraffin and casting the mixture into suitable shapes. For all the capture γ-ray yield curves given here, the crystal was located 3 in. to 5 in. from the target, the intervening space containing the neutron shield. Even with this neutron shielding, the number of neutron produced pulses, corresponding to γ-ray energies below 8 or 9 Mev, was sufficiently high to effectively prevent measurement of γ rays from the 4.43-Mev state in C^{12}. The background for the higher energy capture γ rays was negligibly small.

The yield of the capture γ rays as measured at 0° to the proton beam is given by the top two curves of Fig. 3. Measurements made at 90° are shown in the middle two curves. Open points indicate the transition direct to the ground state of C^{12}, whereas the solid points are essentially for the transition to the 4.43-Mev excited state. The data plotted for the "16" Mev gamma ray is the reading in the channel corresponding to the maximum in the pulse-height distribution. Data for the "12" Mev gamma ray have been corrected for the presence of the "16" Mev gamma ray by a method similar to that used by Gove and Paul.[3] For the large crystal used in this work, the "12" Mev gamma-ray data was corrected by subtracting $\frac{1}{3}$ of the count in the "16" Mev peak. Table I includes in columns 3, 4, 5, and 6 these data. A preliminary run ($E_p=2$ to $E_p=5$ Mev) on the B^{10} capture gamma rays at 90° to the proton beam, made for the purpose of checking any possible effects of the B^{10} content of the natural boron targets, indicated only a single, broad (one-half Mev) level at a proton energy of approximately 4 Mev.

IV. NEUTRON MEASUREMENTS

A conventional long counter was used to measure the neutron yield. Figure 4 shows typical curves of neutron yield as a function of bombarding proton energy, uncorrected for target thickness. The top curve (open points) was taken with the long counter at zero degrees with respect to the proton beam and 5 cm from the target; therefore, it gives the yield into somewhat less

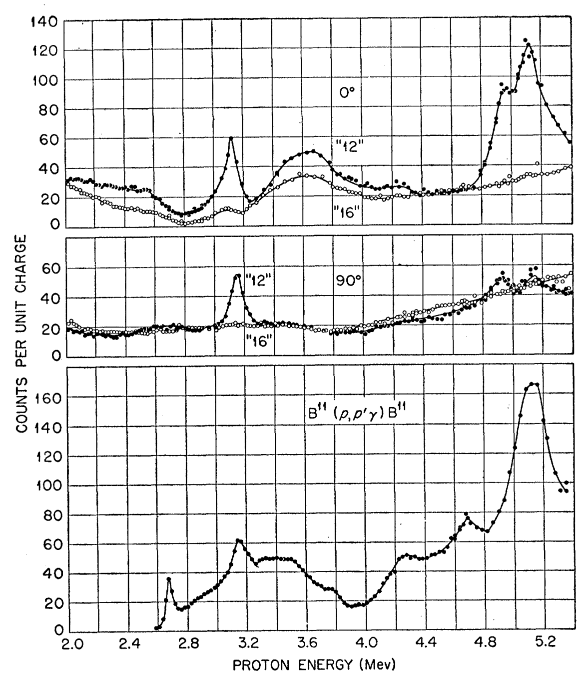

FIG. 3. Top pair of curves give the γ-ray yield from $B^{11}(p,\gamma)C^{12}$ in the forward direction. The middle pair of curves give similar data at 90°. Solid points represent the transition to the 4.43-Mev state in C^{12} and the open circles represent transitions to the ground state. The bottom curve is the 0° yield of 2.1-Mev γ rays resulting from the reaction $B^{11}(p,p')B^{11}$.

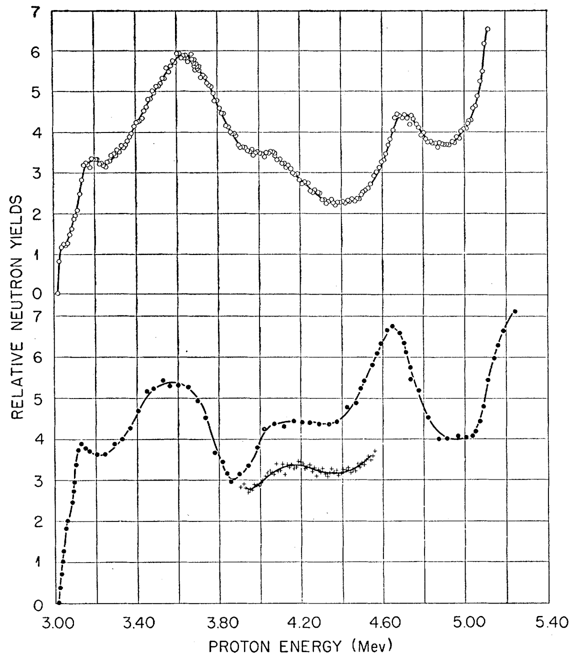

FIG. 4. Yield of neutrons from the $B^{11}(p,n)C^{11}$ reaction. Top curve: long counter at 0° and 5 cm from target. Middle curve: long counter at 0° and approximately 60 cm from target. Bottom curve: long counter at 15° and 40 cm from the target, region between $E_p=3.9$ and $E_p=4.55$ Mev only.

than 2π solid angle in the forward direction. The middle curve (solid points) was taken at zero degrees but with the long counter 60 cm from the target. It was thought that the flat portion of the yield curve between 4.0 and 4.4 Mev might conceal more than one level in the compound nucleus. Early crude angular distribution data also indicated such a possibility, with the most pronounced effect being observed in measurements made at angles near 15°. The bottom curve (crosses) of Fig. 4 was made with the long counter at 15° and 40 cm from the target to further investigate the existence of a second maximum. It is concluded that only one maximum is observed in this region. That the neutrons observed came from B^{11}, and not B^{10}, was verified by measurements made on 96% B^{10} targets. Although beta-decay results,[10] the recent photographic plate work of Ajzenberg and Franzen,[11] and the threshold measurement of Cook, Marion, and Bonner[9] lead to $B^{10}(p,n)C^{10}$ threshold at about 4.8 Mev, preliminary data up to proton energies of 6 Mev showed no B^{10} threshold observed through the $B^{11}(p,n)C^{11}$ background due to the 2% B^{11} content of the B^{10} targets. At 3.55 Mev the absolute 0° cross section for the $B^{11}(p,n)C^{11}$ reaction was measured to be 5.4 ± 0.5 millibarns per steradian. [*Note added in proof.*—The value of this cross section is about one-third that observed by the group at Rice Institute (T. W. Bonner, private communication). It is quite possible that our targets were actually B_2O_3 instead of metallic boron, as suggested by Dr. Bonner. A check on the cross section will be made.]

Table I lists the proton energies of the observed levels, the corresponding excitation energies in the C^{12} compound nucleus, and an estimate of the width of the levels. Resonant energies are taken from the large solid angle yield curve (top of Fig. 4), since such a procedure minimizes any apparent energy shifts due to the angular distribution of the neutrons. Energies are corrected for target thickness.

V. DISCUSSION

In addition to the known resonance at 2.66 Mev, maxima are found in the $B^{11}(p,p'\gamma)B^{11}$ yield at 3.15, 3.4, 3.78, 4.28, 4.68, and 5.13-Mev proton bombarding energies. These levels are observed in both 0° and 90° yield curves with the same intensity. This isotropy, independent of energy and hence of the levels formed in the compound nucleus, could lead to the conclusion that the spin of the first excited state in B^{11} is $\frac{1}{2}$. Due to the curious accidental degeneracy of the Racah coefficient relating an $L=2$ transition between two states of $J=\frac{3}{2}$, there is some ambiguity in this assignment. However, in the case of $\frac{3}{2}\rightarrow\frac{3}{2}$, some admixture of the $L=1$ transition might be expected, which would remove the isotropy.

Capture γ-ray yield curves show resonances at proton energies of 2.6, 3.14, 3.6, 4.94, and 5.12 Mev. This lowest energy resonance was not apparent in the work of Huus and Day[1] since they give 90° yield curves only, and at this angle their maximum proton energy was barely above the maximum yield. There is no disagreement in the data. Gove and Paul[3] discuss a level at about this energy.

Neutron yield curves, Fig. 4, indicate resonances at proton energies of 3.17, 3.65, 4.05, and 4.70 Mev. Blaser[5] *et al.*, using a stacked foil technique and detecting C^{11}, have found maxima at 3.7, 5.18, 5.87, and 6.37 Mev. Their levels at 3.7 and 5.18 Mev evidently correspond to our level at 3.65 Mev and to the rise at the upper energy of our data, respectively. The low resolution of the stacked foil technique undoubtedly explains why our resonances at 3.17, 4.05, and 4.70 Mev are not apparent in their work.

Table I summarizes the data on the resonances in C^{12} as obtained from the present work.

The authors would like to express their thanks to Dr. Normal H. Lazar of this Laboratory for the large NaI crystal used in the γ-ray work.

[10] R. Sherr and J. B. Gerhart, Phys. Rev. **91**, 909 (1953).
[11] F. Ajzenberg and W. Franzen, Phys. Rev. **95**, 1531 (1954).