own right.[11] The measured total cross section at 1.163A was 880b/molecule for the Sm^{152} sample and 396b/molecule for the Sm^{154} sample.

The diffraction peaks in both these samples were extremely weak due to the strong absorption, but rough values for the coherent cross sections were obtained. In Fig. 1 portions of the patterns obtained are illustrated. From a consideration of the relative intensities of the reflections shown, it can be deduced that Sm^{152} has a negative scattering amplitude, and from the absolute intensities approximate cross sections were evaluated. No effort has been made to extract total scattering cross sections from the transmission data.

Er

Erbium has six stable isotopes all of which except Er^{167} (22.9 percent) are even-even nuclei. Bernstein *et al.*[12] have measured the total cross section of Er in Er_2O_3 over the near thermal energy range and they find capture resonances at 0.45 ev and 0.58 ev. The total cross section which was obtained at $\lambda=1.163$A (0.06 ev) for Er was 138b and this compares favorably with 135b taken from the curve of Bernstein and coworkers. Pomerance found the thermal absorption cross section to be 166 ± 17b. The contribution of the magnetic scattering of Er at 0.06 ev to the total scattering cross section is 5b based on the experimentally determined form factor. From the diffuse scattering in the diffraction pattern a value of 15 ± 4b was obtained which is not inconsistent with the less precise value of 26 ± 11b from the transmission data.

The cooperation of Dr. F. H. Spedding of the Ames Laboratory, and of Dr. G. E. Boyd of the Chemistry Division of the Oak Ridge National Laboratory in making these samples available to us is gratefully acknowledged. For the loan of the isotopically enriched samples we are indebted to the Stable Isotopes Division of the Laboratory, and for x-ray analyses of all the samples to Mr. B. S. Borie and Mr. R. M. Steele.

[11] Lapp, Van Horn, and Dempster, Phys. Rev. **71**, 745 (1947).
[12] Bernstein, Borst, Stanford, Stephenson, and Dial, Phys. Rev. **87**, 487 (1952).

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The Gamma Radiation from B^{11} Bombarded by Protons*

Torben Huus† and Robert B. Day‡
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California
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The spectrum of gamma radiation emitted when B^{11} is bombarded by protons has been investigated with a NaI scintillation counter. Capture gamma rays have been found which occur in a direct transition to the ground state of C^{12} and a cascade transition through a level in C^{12} at 4.45 Mev. Yield curves for these gamma rays have been obtained for proton energies up to 2.8 Mev, and the cross sections for emission of the various gamma rays are given. In addition to the well-known resonance at 0.163 Mev, new resonances have been found at 0.675 Mev with $\Gamma=0.33$ Mev and 1.388 Mev with $\Gamma=1.27$ Mev. Spin and parity assignments for these states which are deduced from the results of this and the $B^{11}(p,\alpha)Be^8$ reactions are 2^- (or 3^+) and 1^-, respectively. A 2.13-Mev gamma ray has also been observed, which is produced in an inelastic scattering reaction involving the first excited state of B^{11}. This reaction exhibits a resonance at 2.664 Mev with a width of 48 kev. The cross section at resonance is 3.1×10^{-26} cm^2.

I. INTRODUCTION

In the bombardment of boron by protons a number of gamma rays have been found by various investigators, but the variation of their yield with energy is known only in a rough way or over a limited energy region. The purpose of this investigation was to determine the energies of the gamma rays from proton reactions with B^{11} and their yields for proton bombarding energies up to about 3 Mev.

Previous work on gamma rays from B^{11} reactions has been confined to the reaction

$$\begin{aligned}B^{11}+H^1\rightarrow(C^{12})&\rightarrow C^{12}+\gamma_0\\ &\searrow C^{12*}+\gamma_1\rightarrow C^{12}+\gamma_1+\gamma_2.\end{aligned}$$

The yield curve for this capture radiation in the region up to 500-kev bombarding energy was investigated by Tangen,[1] who found the position of the well-known low-energy resonance to be 162 kev, with a width of 5.3 kev. From measurements of the absorption of secondary electrons he concluded that the radiation is harder off resonance than at 162 kev. Excitation curves at higher energies have been made by Herb, Kerst,

* This work was assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.
† Now at the Institute for Theoretical Physics, Copenhagen, Denmark.
‡ Now at Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

[1] R. Tangen, Kgl. Norske Videnskab. Selskabs, Skrifter No. 1 (1946).

and McKibben[2] and by Curran, Dee, and Petrzilka.[3] The former found a resonance at 820 kev, while the latter reported resonances at 650, 850, and 950 kev. From the position of these resonances and also from work done at this laboratory (see Sec. II), it seems likely that these were actually produced by fluorine contamination in the targets. The rise at higher energies in the curve of Herb *et al.* is probably due to the reaction $B^{10}(p, \alpha\gamma)Be^7$. Recently Cochran *et al.*[4] have reported a broad resonance at 670 kev with a width of 390 kev.

The energies of the gamma rays produced in this reaction have been measured by several investigators. Using a cloud chamber to measure the energy of secondary electrons, Fowler, Gaerttner, and Lauritsen[5] found gamma-ray lines at 4.3, 11.8, and 16.6 Mev, with relative intensities of 7:7:1. The measurements were taken with a peak bombarding voltage of 850–900 kev and a thick boron target. Walker[6] has measured the gamma-ray energies with a magnetic pair spectrometer. Bombarding a thick B_4C target with 1.2 Mev protons he found $E_\gamma = 16.70$, 12.12, and 4.41 Mev. The relative intensity of the 16.7- and 12.12-Mev lines was 1:2.1, while the intensity of the 4.41-Mev line was of the same order of magnitude. At a bombarding energy of 0.52 Mev, gamma-ray lines were found at 16.34 and 11.76 Mev with a relative intensity of 1:4. Carver and Wilkinson[7] have also found a gamma ray of 12.5 Mev at a proton bombarding energy of 0.85 Mev. This measurement was made by determining the spectrum of recoil protons from the photodisintegration of the deutron.

A number of experiments have been conducted on the angular distribution and angular correlation of the gamma rays at low bombarding energies. Although earlier work indicated that the angular distribution was isotropic, more recent work has revealed an anisotropy in both the 12- and 16-Mev gamma rays. There is also a definite angular correlation between the 12- and 4-Mev gamma rays. The recent work on these phases of the reaction is summarized by Ajzenberg and Lauritsen[8] in their review article.

Another reaction for which gamma radiation is energetically possible is

$$B^{11}+H^1 \rightarrow (C^{12}) \rightarrow B^{11*}+H^1$$
$$\searrow B^{11}+\gamma.$$

The low-energy levels of B^{11} have been located quite precisely by Van Patter, Buechner, and Sperduto[9] by a magnetic analysis of the proton groups occurring in the reaction $B^{10}(d, p)B^{11}$. The only level they found with an excitation energy less than 3 Mev was at 2.138 Mev. An inelastically scattered proton group corresponding to this level has also been found at higher bombarding energies by Fulbright and Bush and by Cowie, Heydenburg, and Phillips,[10] although the gamma-ray has not previously been detected.

The only other reaction which might possibly produce gamma rays is

$$B^{11}+H^1 \rightarrow (C^{12}) \rightarrow Be^{8*}+He^4$$
$$\searrow Be^8+\gamma.$$

A gamma-emitting level at 4.9 Mev in Be^8 has been reported[11] in the reaction $Li^7(d, n)Be^{8*}$ but it has not yet been observed in any other reaction. No other low levels in Be^8 have been observed to emit gamma radiation.

We have used a scintillation counter to measure the energy of the gamma radiation produced in these reactions and have also obtained yield curves up to proton bombarding energies of about 2.8 Mev. From these measurements it has been possible to deduce some of the properties of the nuclear energy levels involved in the reactions.

II. EXPERIMENTAL PROCEDURE

The gamma-ray energies were measured by means of a sodium iodide scintillation counter. This counter consisted of a NaI(Tl) crystal $1\frac{1}{2}$ inches long and $1\frac{1}{2}$ inches in diameter mounted in a Lucite container on a selected 5819 photomultiplier. A magnesium oxide reflector surrounding the Lucite container served to improve the optical coupling between the crystal and the photomultiplier. Pulses from the photomultiplier were amplified and then analyzed by a single-channel pulse-height analyzer designed by Professor M. Sands. After a pulse-height distribution had been obtained, the gain of the system was calibrated by introducing artificial pulses, whose height could be measured to an accuracy of a few tenths of a percent, into the input of the preamplifier. This calibration was made in the neighborhood of each peak observed in the pulse-height spectrum and served to eliminate errors due to nonlinearity of the amplifier and analyzer as well as to reduce the effect of any slow drifts in the gain of the equipment.

The calibration of pulse height in terms of energy was performed by analyzing the pulse-height spectrum of some radioactive substance which emits gamma rays of known energy. For this purpose we used a number

[2] Herb, Kerst, and McKibben, Phys. Rev. **51**, 691 (1937).
[3] Curran, Dee, and Petrzilka, Proc. Roy. Soc. (London) **169**, 269 (1939).
[4] Cochran, Ryan, Givin, Kern, and Hahn, Phys. Rev. **87**, 672 (1952).
[5] Fowler, Gaerttner, and Lauritsen, Phys. Rev. **83**, 628 (1938).
[6] R. L. Walker, Phys. Rev. **79**, 172 (1950).
[7] J. H. Carver and D. H. Wilkinson, Proc. Phys. Soc. (London) **64A**, 199 (1951).
[8] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
[9] Van Patter, Buechner, and Sperduto, Phys. Rev. **82**, 248 (1951).
[10] H. W. Fulbright and R. R. Bush, Phys. Rev. **74**, 1323 (1948); Cowie, Heydenburg, and Phillips, Phys. Rev. **87**, 304 (1952).
[11] Bennett, Bonner, Richards, and Watt, Phys. Rev. **71**, 11 (1947).

of elements, including radiothorium (2.615 Mev) and Na^{22} (0.511 Mev and 1.277 Mev). In these calibrations it was assumed that the pulse height was proportional to energy. This relation had already been verified for energies up to 1.3 Mev,[12] and our work showed that it was valid to within one percent for electron energies up to 12 Mev.

The protons were accelerated in the 3-Mev electrostatic accelerator and analyzed in energy by a 90° electrostatic or magnetic analyzer. These were generally adjusted to give a resolution of 0.1 percent or better. The energy calibration of the analyzers was made in terms of the 873.5-kev resonance in $F^{19}(p, \alpha\gamma)O^{16}$ or the 993.3-kev resonance of $Al^{27}(p, \gamma)Si^{28}$. The beam current incident on the target was measured with a current integrator that has been in use for several years and has proved to be reliable to a few percent. For proton energies below 450 kev the mass-3 beam was used. Above this energy the mass-1 beam was used.

Since boron is not readily obtainable in a pure form and is difficult to evaporate without impurities being carried over from the furnace, we decided to use targets prepared by evaporating B_2O_3 on a thin tantalum backing. This material proved quite easy to evaporate in a vacuum furnace in thin layers whose thickness could be controlled fairly easily. Our first results on the gamma-ray yields with these targets showed peaks at 670, 870, and 940 kev, which seemed to corroborate the earlier work of Curran, Dee, and Petrzilka.[3] However, a closer examination showed that the position and relative yield of these peaks was exactly that to be expected from fluorine contamination. By cleaning the tantalum backing more carefully and evaporating most of the B_2O_3 in the furnace to get rid of volatile impurities before finally evaporating onto the target, we were able to prepare targets in which the fluorine contamination was generally negligible.

The relatively low melting point of B_2O_3 prevented us from using target currents of more than one or two microamperes since the targets tended to deteriorate under excessive heating. Accordingly a method was developed for preparing thin layers of pure boron by decomposing diborane (B_2H_6) on a thin sheet of tantalum.[13] This was accomplished by heating the tantalum in vacuum in an induction furnace and then admitting a small amount of diborane, which decomposed in a fairly uniform layer on the tantalum. By controlling the amount of diborane admitted to the furnace it was possible to obtain the desired target thickness. The development of these targets was not completed until most of the results on the capture radiation reaction had been obtained; consequently they were used only in the work on inelastic scattering.

[12] R. Hofstadter and J. A. McIntyre, Phys. Rev. **79**, 389 (1950).
[13] This method was developed and the targets produced by Dr. James Shoolery. The pure diborane was obtained through the courtesy of Professor Anton Burg of the University of Southern California.

III. EXPERIMENTAL RESULTS

1. $B^{11}(p, \gamma)C^{12}$ / $B^{11}(p, \gamma)C^{12*}(\gamma)C^{12}$

Excitation curves for these reactions were obtained by using two scalers in parallel—one biased to count pulses from the scintillation counter larger than 8 Mev and the other set to count pulses larger than 13.5 Mev. Figure 1 shows the results of a run obtained in this manner by bombarding a B_2O_3 target that had a stopping power of 165 kev at an energy of 244 kev. The curves here show two new resonances, at 0.675 Mev and 1.388 Mev, in addition to the previously known resonance at 0.163 Mev.

The gamma radiation at the peak of each resonance was investigated by measuring the pulse-height distribution from the scintillation counter. In Figs. 2–4 are shown the results of spectra obtained at the resonances. Each of these shows the typical pulse-height distribution to be expected of a 4.45-Mev gamma ray as well as those of gamma rays near 12 and 16 Mev. It will be observed that the 16-Mev gamma ray does not show any of the peaks typical of lower-energy gamma rays. In determining the energy of this gamma ray we have arbitrarily assumed that the position of the usual pair peak should correspond to the "knee" of the curve. However, even with this assumption the energies obtained are somewhat low, hence we have placed little confidence in them. Figure 4 also shows peaks at 5.2 and 6.1 Mev which we have attributed to fluorine contamination of the target, since they correspond to two known gamma rays[14] from the reaction $F^{19}(p, \alpha\gamma)O^{16}$.

The averages of a number of energy measurements at each resonance are summarized in Table I, together with the excitation energy E_x of the compound nucleus. These results show that there is a direct gamma-ray transition to the ground state of C^{12} as well as a cascade transition through a level in C^{12} at 4.45 Mev. The fact that the sum of the energies of the two cascade gamma rays is equal to the excitation energy of the compound nucleus is to be interpreted as demonstrating the proportionality of the light output of the NaI crystal for electron energies up to 12 Mev. At higher energies wall effects and energy loss from bremsstrahlung distort the pulse-height spectrum too much for the size of crystal used here to permit accurate energy measurements to be made. A notable characteristic of these pulse-height curves is the flat region below the pair peak of the higher energy gamma rays. This makes it possible to obtain the total number of pulses produced in the crystal by extrapolating horizontally to zero pulse height and then integrating under the curve. The gamma-ray yield can then be obtained in a rather simple way by dividing the number of pulses thus

[14] R. L. Walker and B. D. McDaniel, Phys. Rev. **74**, 315 (1948); Rasmussen, Hornyak, Lauritsen, and Lauritsen, Phys. Rev. **77**, 617 (1950).

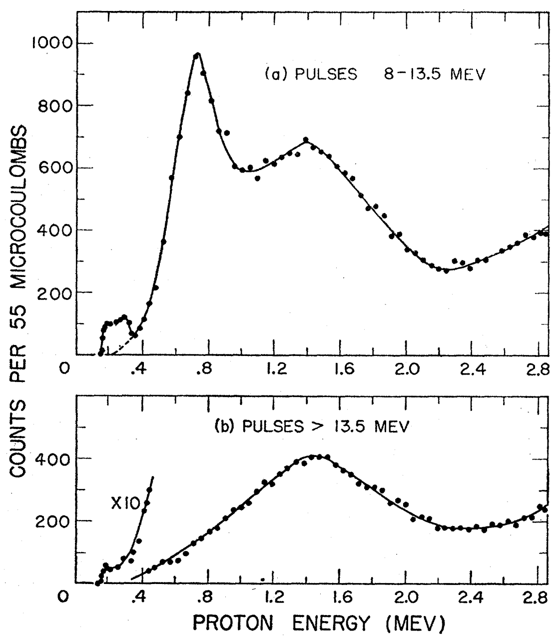

FIG. 1. Variation of yield with bombarding energy. (a) Pulses from the scintillation counter corresponding to secondary electron energies from 8 to 13.5 Mev. (b) Pulses corresponding to energies greater than 13.5 Mev.

obtained by the calculated total absorption of the crystal. This method has been checked with gamma rays of known yield and has given agreement in each case within 10 percent.

The curves shown in Fig. 1 do not represent the true excitation curves for the ground-state and cascade transitions. However, the true curves can be obtained from these in a straightforward manner from a consideration of a typical integral bias curve (Fig. 5). From the properties of the pulse-height distribution mentioned in the last paragraph it is clear that the total yield of pulses from any given gamma ray can be obtained by extrapolating the corresponding straight portion of the integral bias curve linearly to zero bias. In Fig. 5, E_1 and E_2 are the end points for the two

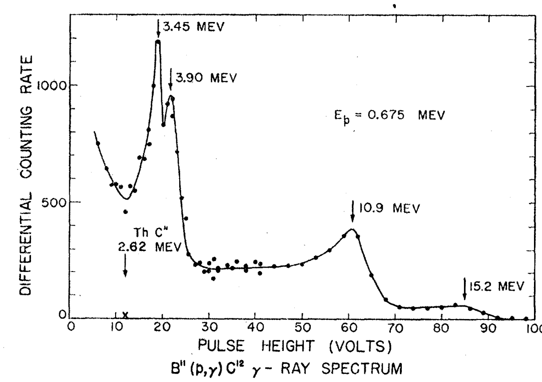

FIG. 3. Pulse-height distribution at the 0.675-Mev resonance.

high-energy gamma rays, B_1 and B_2 the biases at which the scalers were set in obtaining the curves in Fig. 1, Y_1 and Y_2 the total number of pulses from each gamma ray. Knowing B and E, and taking into account the linear variation of E with bombarding energy, which can be calculated from the Q of the reaction and a knowledge of the dynamics involved, one can correct each point of the curves in Fig. 1 to obtain the true yields $Y_{1,2}$. To aid in doing this, integral bias curves were obtained at each of the resonances and at 2 Mev. These gave a check on the positions of the end points $E_{1,2}$ as well as on the yields. The curves finally obtained, which represent the actual excitation curves for the two possible transitions, are given in Fig. 6. The total yield of gamma rays from the target was obtained by dividing the total number of pulses in the crystal by the probability that a gamma ray emitted from the target would be absorbed. Since all measurements were made at an angle of 90° to the beam this procedure actually gave $4\pi \cdot Y(90°)$. When a correction for the target thickness is applied, these curves give for the width at half-maximum and the resonance energy of the two new resonances $\Gamma = 0.33$ Mev at $E_r = 0.675$ Mev and $\Gamma = 1.27$ Mev at $E_r = 1.388$ Mev. The value

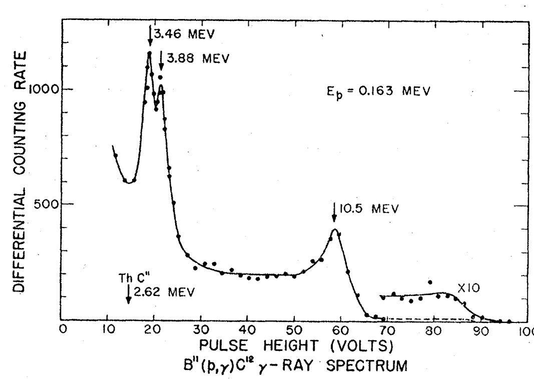

FIG. 2. Typical pulse-height distribution at the 0.163-Mev resonance.

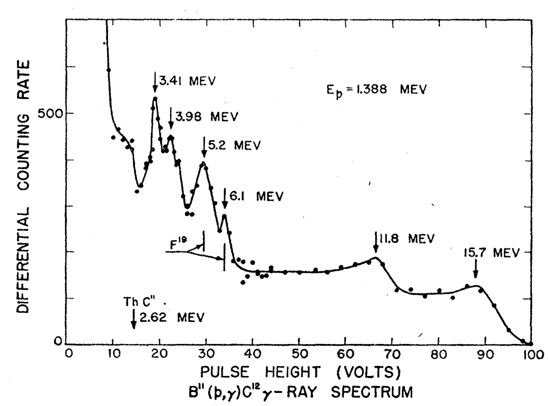

FIG. 4. Pulse-height distribution at the 1.388-Mev resonance. The peaks at 5.2 Mev and 6.1 Mev are probably from the $F^{19}(p, \alpha\gamma)O^{16}$ reaction.

for the width of the lower of these resonances is significantly less than the value of 390 kev reported by Cochran *et al.*[4] This discrepancy probably arises from the fact that they did not measure the excitation curves for the two transitions separately and therefore they were not aware of the existence of the resonance at 1.388 Mev. The distortion of their curve by this resonance would tend to increase the apparent width of the 0.675-Mev level.

The apparent intensity of the 16-Mev gamma ray at the 163-kev resonance was only seven percent of that of the cascade transition. This must be reduced to take into account the case when both the 4.45- and 11.6-Mev gamma rays are emitted in the same direction and absorbed in the crystal simultaneously. To correct for this effect, one must know both the probability of absorption in the crystal and the angular correlation of the two cascade gamma rays. Since the correlation function is not completely known we have assumed it to be isotropic in making the correction. The corrected intensity of the 16-Mev gamma ray is then four percent of the 11.6-Mev gamma ray. If there is a strong correlation for emission of the two gamma rays at 90°, the intensity of the 16-Mev gamma ray may be even lower, although it is not likely that it is zero. Investigations at the Oak Ridge National Laboratory[15] under conditions in which the correction is negligible have showed that the 16-Mev gamma-ray yield is approximately two percent of the 11.6-Mev gamma-ray yield at the resonance.

TABLE I. Gamma-ray energies at the three resonances. E_x is the excitation energy of the compound nucleus.

E_r (Mev)	E_x (Mev)	E_γ (Mev)		
0.163	16.10	4.45	11.6	
0.675	16.58	4.44	12.0	16.4
1.388	17.23	4.45	12.7	16.9

Since it has been suggested[16] that the cascade and ground-state transitions originate in different states of the compound nucleus, a careful examination of the yield curves for the two transitions was made. It showed that both were resonant at 163 kev. If they are indeed resonant at different energies, it would appear that these cannot be more than 2 kev apart. However, this conclusion is rendered somewhat uncertain by the large resonant contribution of the gamma-gamma coincidences.

The target thickness was obtained from the apparent width of the resonance at 163 kev. To obtain the variation of the stopping power with proton energy, a curve of the differential stopping cross section for B_2O_3 was prepared by extrapolation from Bethe's curve[17] for the stopping cross section of air and from the experimental data on beryllium of Warshaw[18] and Madsen and Venkateswarlu.[19] The data for air were extrapolated to oxygen as $Z^{\frac{1}{2}}$ since available stopping powers in this region generally vary in this manner as a function of the atomic number. The data for beryllium were extrapolated as Z since a calculation of the average ionization potential[20] gave the same result for boron as for

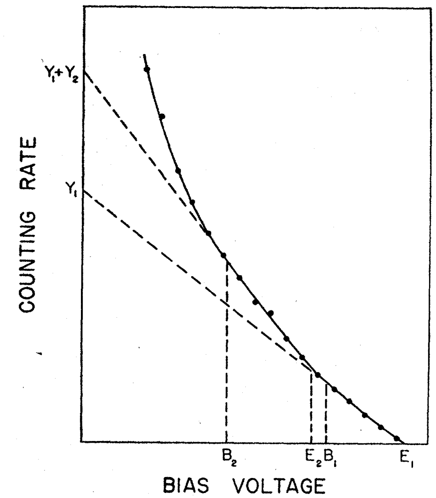

FIG. 5. Typical integral bias curve for $B^{11}(p,\gamma)C^{12}$. E_1 and E_2 are the end points of the two high-energy gamma rays. Y_1 and Y_2, which are the total number of pulses from each gamma ray, are obtained by extrapolating the corresponding straight portion of the curve linearly to zero bias. B_1 and B_2 are the biases used in obtaining the curves in Fig. 1.

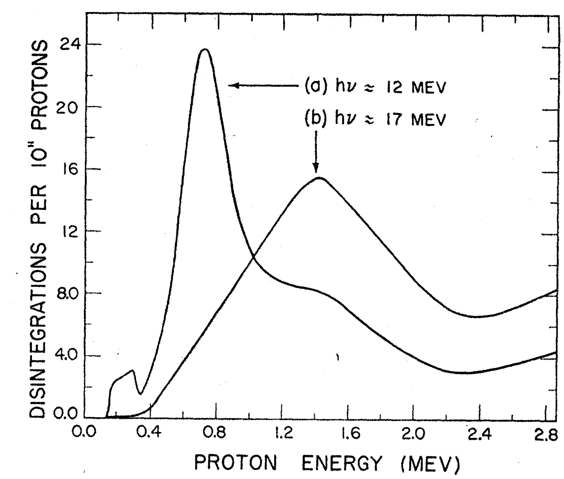

FIG. 6. True yield curve for the capture radiation, obtained from Fig. 1 by applying the corrections described in the text. The target thickness at the three resonances is given in Table II. Except at the lowest-bombarding energies, the distortion of the shape of the curve by the target thickness is small.

[15] C. D. Moak, (private communication).
[16] G. B. Arfken and L. C. Biedenbarn, Phys. Rev. **83**, 238 (1951).
[17] H. A. Bethe, Brookhaven National Laboratory Report BNL-*T*-7, June 1, 1949 (unpublished).
[18] S. D. Warshaw, Phys. Rev. **76**, 1759 (1949).
[19] C. B. Madsen and P. Venkateswarlu, Phys. Rev. **74**, 648 (1948).
[20] This calculation was performed by Dr. R. G. Thomas. We would like to thank Dr. Thomas for making the results of his calculations available to us.

TABLE II. Resonance yields and cross sections for the reactions $B^{11}(p,\gamma)C^{12}$ and $B^{11}(p,\gamma)C^{12*}(\gamma)C^{12}$. The yields (in gamma rays per proton) are given for a B_2O_3 target whose stopping power at the various resonances is given in column 3.

E_r (Mev)	Γ(Mev)	Target thickness (Mev)	$B^{11}(p,\gamma)C^{12}$ Yield (γ/p)	$B^{11}(p,\gamma)C^{12}$ σ(barns)	$B^{11}(p,\gamma)C^{12*}(\gamma)C^{12}$ Yield (γ/p)	$B^{11}(p,\gamma)C^{12*}(\gamma)C^{12}$ σ(barns)
0.163	0.005	0.165	0.098×10^{-11}	5.5×10^{-6}	2.71×10^{-11}	152×10^{-6}
0.675	0.33	0.088	$<1\times10^{-11}$	$<2.3\times10^{-6}$	20.7×10^{-11}	48×10^{-6}
1.388	1.27	0.055	15.5×10^{-11}	35×10^{-6}	8.1×10^{-11}	18×10^{-6}

beryllium. Because of the uncertainties in the method of extrapolation, as well as in the data for beryllium and air, it is expected that the stopping power for B_2O_3 may be in error by possibly 10 percent.

From a knowledge of the gamma-ray yield per proton as well as the target thickness and stopping cross section one can calculate the cross sections for the ground state and cascade transitions. These results are given in Table II. Except for the 11.6-Mev gamma-ray at the 163-kev resonance all the yields and cross sections were calculated for an isotropic angular distribution. For this case, the results of Hubbard, Nelson, and Jacobs[21] that $I(\theta)=1+0.23\cos^2\theta$ were used in correcting the data obtained at 90°. At the 0.675-Mev resonance the values given were obtained after subtracting out the effects of the higher resonance. The upper limit given here for the ground-state transition is our estimate of the maximum contribution to this resonance that would have escaped detection. These cross sections are estimated to have an accuracy of 15 percent.

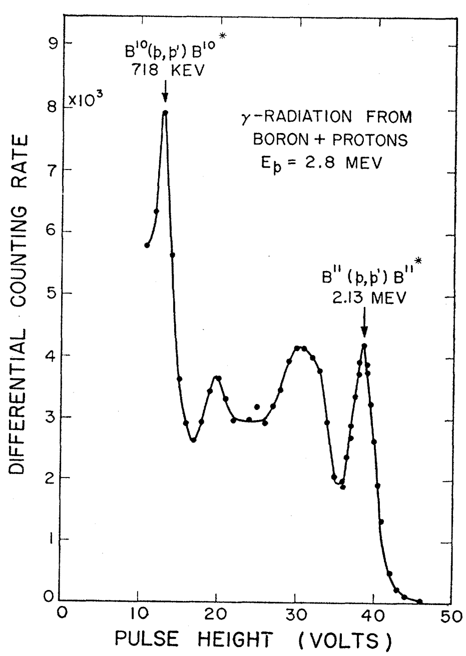

FIG. 7. Pulse-height distribution obtained at a bombarding energy of 2.8 Mev for the gamma radiation resulting from inelastic scattering.

[21] Hubbard, Nelson, and Jacobs, Phys. Rev. **87**, 378 (1952).

The same energy region was also investigated with a B_2O_3 target of a few kilovolts thickness. Several narrow, weak resonances were observed at which gamma-radiation of about 12-Mev energy was emitted. However, a search for these resonances with the improved boron targets developed later failed to reveal them. It seems likely that these originated in some target contamination, possibly sodium.

2. $B^{11}(p,p'\gamma)B^{11}$

At higher energies a new gamma ray was observed which was considerably stronger than the capture radiation. From measurements of the pulse-height distribution the energy of the gamma ray was found to be 2.13 Mev. This agrees very well with the value 2.138 Mev determined by Van Patter, Buechner, and Sperduto[9] for the energy of the first excited state of B^{11}. A typical pulse-height spectrum is shown in Fig. 7. The assignment of this radiation to a B^{11} reaction was checked by bombarding a similar target of enriched B^{10}. The gamma ray was absent then, although the 718-kev gamma ray from inelastic scattering in B^{10} (also evident in Fig. 7) was very strong.

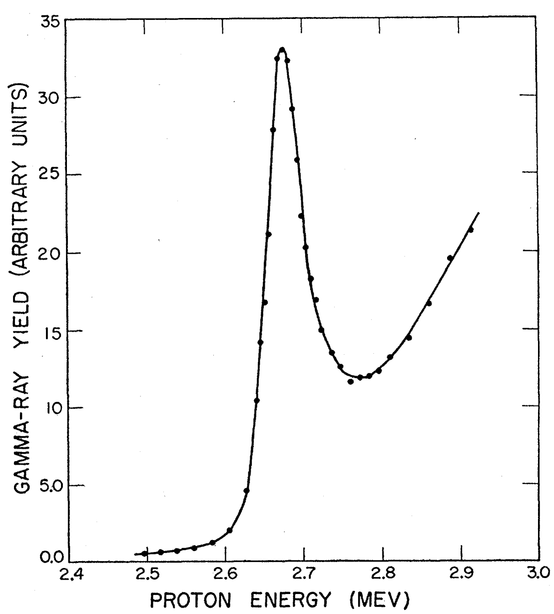

FIG. 8. Excitation curve for the reaction $B^{11}(p,p'\gamma)B^{11}$. $E_\gamma=2.13$ Mev.

The excitation curve for this reaction is shown in Fig. 8. The target used here was a thin film of normal boron whose thickness was measured by comparing the yield of the capture radiation from B^{11} with the yield from the previously calibrated B_2O_3 target. A resonance at 2.664 Mev with a width at half-maximum of $\Gamma = 48$ kev was found superposed on a rapidly rising background. The cross section at resonance for this radiation is 3.1×10^{-26} cm^2 assuming an isotropic angular distribution.

Following the discovery of this resonance the excitation curve for the high-energy gamma rays was investigated closely in this region. However, there was no evidence of a resonance here for the capture radiation. A resonance cross section as large as 2×10^{-30} cm^2 would have been detectable.

3. $B^{11}(p, \alpha)Be^{8*}(\gamma)Be^8$

Although a systematic search was not made, no evidence was found for gamma radiation from the reaction $B^{11}(p, \alpha)Be^{8*}(\gamma)Be^8$.

IV. DISCUSSION

A considerable amount of work has been done on the $B^{11}(p, \alpha)$ and $B^{11}(p, \gamma)$ reactions at the 163-kev resonance.[22] The results of these experiments are all consistent with the assignment to this level of spin two and even parity (2^+), hence the nature of this level is fairly well established.

Analysis of the levels at 0.675 Mev and 1.388 Mev is aided considerably by recent results on the excitation curves for the $B^{11}(p, \alpha)$ reaction.[23] Using the (p, α) cross section one can calculate Γ_p, the width for proton emission, and from this the reduced width γ^2 of a state can be obtained. A value of γ^2 greater than $3\hbar^2/(2MR)$ indicates that the assumed orbital angular momentum can be ruled out, but since in general there are two possible solutions for Γ_p one cannot always use this means of excluding a particular angular momentum. However, given Γ_p one can calculate the radiation width Γ_γ of the level and compare this with the upper limits given by Blatt and Weisskopf.[24] Thus, there are two possibilities for limiting the range of values for the spin and parity of the resonances. In this way one can restrict the possible assignments of the 0.675-Mev resonance to $1^\pm$, $2^\pm$, and 3^+. Of these, only the values 2^- and 3^+ can be used to explain readily the fact that the ground-state gamma-ray transition and the high-energy alpha particles (α_0) going to the ground state of Be^8 are not resonant at this energy. For these two assignments the magnetic quadrupole or electric octopole radiation to the ground state of $C^{12}(0^+)$ would be expected to be very much less intense than the electric or magnetic dipole radiation to the 4.45-Mev level (2^+),[25] while the α_0 group would be forbidden since the ground state of Be^8 is 0^+. The results of a recent investigation[26] show that the gamma-ray angular distribution between 300 and 800 kev has a $\cos\theta$ term, which implies the existence of a p wave state. Whether the 0.675-Mev level is that state or whether it is the broad level indicated by the rise in the gamma-ray yield above 2.2 Mev is open to question. More detailed information on the angular distribution is needed to settle this point.

The fact that the α_0 group is resonant at 1.388 Mev shows that this level has either odd spin and parity or even spin and parity. One can further limit the range of spin and parity to 0^+ or 1^- by arguments based on the upper limits for γ^2 and Γ_γ. Finally, we can rule out the possibility of spin zero since 0–0 radiative transitions are forbidden, hence this resonance is clearly a 1^- level. This assignment is supported by the work of Thomsen *et al.*[27] on the angular distribution of the α_0 group at low bombarding energies, which required the existence of a broad 1^- level at higher energies in order to explain the observed interference terms.

To summarize, the considerations outlined above lead us to the conclusion that the resonances at 0.163 Mev, 0.675 Mev, and 1.388 Mev have spin and parity assignments of 2^+, 2^- (or 3^+), and 1^-, respectively.

From the excitation curve for inelastic scattering one can draw no such conclusions concerning the nature of the level at 2.664 Mev. However, from the work of Thirion[28] on the p-γ angular correlation in the reaction $B^{10}(d, p\gamma)B^{11}$ there is evidence that the first excited state of B^{11} has spin $\frac{1}{2}$. The gamma radiation from this state is therefore isotropic, regardless of the way in which the state is formed; hence the assumption of isotropy made in calculating the cross section for inelastic scattering is justified.

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[22] This work and the conclusions to be drawn from it are summarized by Ajzenberg and Lauritsen, reference 8.

[23] Beckman, Huus, and Zupančič, following paper [Phys. Rev. **91**, 606 (1953)].

[24] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952), p. 627.

[25] The fact that this state of C^{12} is 2^+, as expected from theory, has been quite firmly established by the work of Kraus, French, Fowler, and Lauritsen, Phys. Rev. **89**, 299 (1953).

[26] Jenkins, Cockran, Givin, Ryan, Hahn, and Kern, Bull. Am. Phys. Soc. **28**, No. 2, 12 (1953).

[27] Thomsen, Cohen, French, and Hutchinson, Proc. Phys. Soc. (London) **A65**, 745 (1952).

[28] Thirion, Compt. rend. **232**, 2418 (1951).