Cross Sections for the $B^{11}(\gamma,\pi^-)C^{11}$ and $B^{11}(\gamma,\pi^+)Be^{11}$ Reactions*

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Cross sections for the $B^{11}(\gamma,\pi^-)C^{11}$ and $B^{11}(\gamma,\pi^+)Be^{11}$ reactions were studied by measuring the radioactivities of the product nuclei in boron containing samples that were irradiated with bremsstrahlung of maximum energy varying from 80 to 300 MeV. In both cases activity was observed below the thresholds for the meson production reactions. These below-threshold activities were studied in some detail and are believed to be due mainly to low-energy reactions involving impurities in the target materials. Corrections were made to the yield data to remove the contributions from the low-energy reactions before the cross sections were calculated. The resulting cross sections for the production of C^{11} average about seven times those for the production of Be^{11}. The cross sections for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction agree with those calculated by Laing and Moorhouse for surface production of pions. Although detailed theoretical calculations of the cross sections expected for the $B^{11}(\gamma,\pi^+)Be^{11}$ reaction have not been made, the observed cross sections are qualitatively in agreement with those expected for surface production.

I. INTRODUCTION

THIS paper reports the results of a study of the following pion photoproduction reactions that involve B^{11} as the target nucleus:

$$\gamma+{}_5B^{11}\rightarrow{}_6C^{11}+\pi^- \quad (1)$$

and

$$\gamma+{}_5B^{11}\rightarrow{}_4Be^{11}+\pi^+. \quad (2)$$

These are reactions in which only the pions are emitted. They are just two of many possible charged-pion production reactions in B^{11} because the emission of one or more nucleons can also occur. Our interest in these particular reactions stems from a theoretical paper by Laing and Moorhouse[1] in which predictions were made for the cross sections expected for reaction (1).

Most past experimental studies of pion photoproduction in complex nuclei have involved observation of the emitted mesons rather than observation of the product nuclei.[2] These experiments have shown that the cross sections are considerably smaller than those expected from the corresponding numbers of free nucleons. In addition, the total photoproduction cross sections exhibited an $A^{2/3}$ dependence, where A is the mass number of the target nucleus. These results are generally explained by assuming either that mesons are produced only on the nuclear surface (production in the core is suppressed) or that meson production takes place throughout the entire nuclear volume and those mesons produced in the core are reabsorbed before escaping. The Laing and Moorhouse calculations applied these considerations to pion production reactions in which specific final states were considered.

Previous to our study on photoproduction in B^{11}, Hughes and March[3] reported cross sections for the production of C^{11} from B^{11} by reaction (1) above. They measured the C^{11} radioactivity induced in natural boron powder by irradiation with bremsstrahlung of maximum energies ranging from 70 to 320 MeV. Their reported cross sections for reaction (1) were in good agreement with those predicted by Laing and Moorhouse, using the assumption of surface production only. In their experiments they observed the production of some radioactivity which may have been C^{11} at bremsstrahlung energies below the threshold for reaction (1); the source of this activity was unknown. Since the presence of this unexplained activity may interfere with the interpretation of their experiment, we considered it worthwhile to reinvestigate the production of C^{11} from boron targets. Also, since the completion of the study of Hughes and March, the radioactive nuclide Be^{11} has been discovered and its decay properties studied.[4,5] This has made it possible to now study reaction (2) in which Be^{11} is produced.

II. EXPERIMENTAL

The yields of reactions (1) and (2) were studied by measuring the radioactivities of C^{11} and Be^{11} induced in boron containing samples that were irradiated with bremsstrahlung from the University of Illinois 340-MeV betatron. Because the half-lives and decay properties of the two product nuclei are quite different (C^{11} is a 20.4-min positron emitter and Be^{11} is a 13.6-sec beta-minus emitter),[5,6] the two reactions were studied separately.

The main experimental difficulty expected in this work is that the C^{11} and Be^{11} products can be produced by nuclear reactions other than those of interest. In the case of C^{11} the other reactions expected to be important are the $C^{12}(\gamma,n)C^{11}$ reaction involving carbon impurities in the boron samples and the $B^{11}(p,n)C^{11}$ secondary reaction caused by protons produced by (γ,p) reactions

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[1] E. W. Laing and R. G. Moorhouse, Proc. Phys. Soc. (London) **70**, 629 (1957).
[2] Photomeson production has been recently reviewed by E. H. Bellamy, Progr. in Nuclear Phys. **8**, 237 (1960). References to the original studies can be found in this review article.
[3] I. S. Hughes and P. V. March, Proc. Phys. Soc. (London) **72**, 259 (1958).
[4] M. J. Nurmia and R. W. Fink, Phys. Rev. Letters **1**, 23 (1958).
[5] D. H. Wilkinson and D. E. Alburger, Phys. Rev. **113**, 563 (1959).
[6] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

in the target material. The other product of interest Be^{11} could be produced by secondary $B^{11}(n,p)Be^{11}$ reactions utilizing photoneutrons produced by (γ,n) reactions in the target or surroundings. Although these interfering reactions are low-energy reactions, the nature of the bremsstrahlung used in the irradiations and the general behavior of photonuclear reaction cross sections combine to make their competition with the meson production reactions of interest potentially quite serious. The bremsstrahlung spectrum contains a continuous distribution of photon energies from zero to a maximum energy determined by the betatron operating energy. The shape of the spectrum for a given betatron energy varies roughly as E_γ^{-1}; thus, there are a much larger number of low-energy photons in the spectrum than high-energy photons. The feature of photonuclear reaction cross sections that is important here is that the photon absorption cross section has a broad resonance in the vicinity of 20 MeV (the photonuclear giant resonance) and then tails off to smaller values at higher energies. This means that the photonuclear reactions mentioned as being important in interfering with the experiment have large cross sections (peak cross sections of the order of 10 to 100 mb) compared to those for the meson production reactions of interest (cross sections of the order of 10 μb). Furthermore, as indicated above, the shape of the bremsstrahlung spectrum favors the interfering reactions. Much of the discussion that follows is concerned with determining how important the interference problem is and quantitatively correcting for it.

A. $B^{11}(\gamma,\pi^-)C^{11}$ Studies

In this study it is necessary to use target materials that have very low contents of carbon in order to reduce the interference from C^{11} activity produced by the $C^{12}(\gamma,n)C^{11}$ reaction by the low-energy photons ($\sim$22 MeV) that are present in the bremsstrahlung spectrum. For this reason electrolytically purified boron was first used.[7] Later the solid compound decaborane ($B_{10}H_{14}$) was also used because it is relatively volatile and could be repurified by vacuum distillation.[8] The majority of the results reported here were obtained with decaborane as the target material. The results obtained with the elemental boron were consistent with these, but of lower accuracy because of greater interference from impurities.

Samples of the powdered materials weighing up to 8 g were put in Lucite sample holders and placed in the collimated bremsstrahlung beam from the betatron. The range of betatron energies used in this work was from 80 to 300 MeV with data taken at 5- or 10-MeV intervals. An average of five runs were made at each energy. The irradiation times were generally between 20 and 50 min. The bremsstrahlung beam was monitored with a calibrated thick-walled copper ionization chamber. The ionization current collected in the chamber was measured with a vibrating reed electrometer circuit which contained an appropriate *RC* network to correct for the decay of the product activity during the irradiation and eliminate the effects of beam intensity fluctuations.

The C^{11} activity induced in these irradiations was measured by observing the number of 511-keV annihilation quanta with a 3-in.$\times$3-in. NaI(Tl) scintillation crystal coupled with a 100 channel pulse-height analyzer. The powdered target materials were placed in 50-ml beakers which were placed on top of the crystal housing for counting. The observed spectra had no photopeaks other than that at 511 keV. In several cases the decay of the 511-keV photopeak was followed. The decay curves could be resolved into 2- and 20-min components. The 2-min component presumably is due to O^{15} that is produced by (γ,n) reactions on oxygen impurities. The 20-min component is due to the C^{11}. In those cases in which the decay of the 511-keV photopeak was not followed, the samples were not counted until the contribution of the 2-min activity was negligible. In order to determine the absolute C^{11} yields, the usual corrections for geometry, crystal efficiency, and absorption were made. These were evaluated by taking the peak efficiency (including geometry) for a point source located on the top of the crystal housing[9] and multiplying by an experimentally determined ratio of the peak efficiency for our counting arrangement to that for the point source.

B. $B^{11}(\gamma,\pi^+)Be^{11}$ Study

The irradiation procedures for the Be^{11} experiment were the same as those described above with the following exceptions. Only decaborane was used as target material in these runs; the target sizes ranged up to 15 g; and the betatron energy range covered was from 130 to 290 MeV in 10-MeV steps. An average of six irradiations were made at each energy; each irradiation was long enough to saturate the Be^{11} activity (at least two minutes duration). In addition to these yield curve measurements, irradiations were made at 140 MeV in which the target material was placed behind 1/2-in. or 1-in. lead absorbers or placed outside of the bremsstrahlung beam. The purpose of these experiments was to determine if there was any contribution to the yield curve measurements from reactions caused by secondary neutrons that were produced in the betatron target and donut or in the beam-collimating system.

[7] The electrolytic elemental boron was obtained from Fairmount Chemical Company, Inc., New York, New York. Their reported purity was 99.5%.

[8] The decaborane was obtained from the Callery Chemical Company, Pittsburgh, Pennsylvania. Their reported purity was greater than 96%.

[9] S. H. Vegors, Jr., L. L. Marsden, and R. L. Heath, Phillips Petroleum Company Atomic Energy Division Report, Idaho Falls, Idaho, 1958 (unpublished).

The counting arrangement used involved manually transferring the sample to a well in a 4-in.×4-in. plastic scintillator. The time required to enter the betatron room and transfer the sample from the target holder to the well crystal was generally about 25 sec. The samples were then counted for 45 sec.

Pulses from the scintillator system were split, one part going to the 100-channel pulse-height analyzer to record the beta spectrum, and the other part passing through a discriminator to a scaler and recorder. The discriminator was set for 3.65 MeV in order to eliminate any contribution from C^{10} (19 sec half-life, 3.64 MeV decay energy[6]). The counts above 3.65 MeV were totalled for the several runs at each energy to obtain the yield curve. The purpose of the recorder system was to observe the half-life of the events having energy greater than 3.65 MeV. The data for all of the runs at each energy were combined to obtain the decay curves. All of the decay plots for samples irradiated with bremsstrahlung of energies of 180 MeV and greater showed only a single component having a half-life within 2 sec of the half-life of Be^{11}, 13.6 sec.[5] For betatron energies below 180 MeV for which the counting statistics were not as good, the observed decay curves in each case could be fit by a single component whose half-life ranged between 8 and 18 sec. The beta spectra observed with the 100-channel pulse-height analyzer were used to estimate the end points of the spectra. With the exception of the runs below 180 MeV in which poor statistics prevented an accurate estimate of the end points, the observed end points were within 1.5 MeV of the reported Be^{11} end point of 11.5 MeV.[5] The observed end points of the beta spectra and the observed half-lives are the bases for identifying the Be^{11} product.

In order to determine the absolute yield of Be^{11} from the number of counts above 3.65 MeV in the beta spectrum, the efficiency of the counting arrangement was needed. This was estimated by first calculating the shape of the beta spectrum using the decay branches determined by Wilkinson and Alburger[5] and beta-decay theory.[10] Then, for that part of the spectrum above 3.65 MeV, the energy loss and absorption in the source were estimated to give a modified spectrum of beta particles entering the scintillator.[11–13] Corrections were then made for the scintillator response or line shape.[14] The resulting counting efficiency was 19%. The geometry of the well crystal was calculated to be 85%.

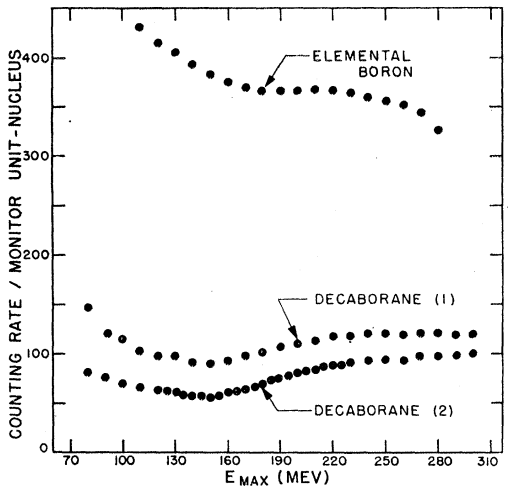

FIG. 1. Yield data for the production of C^{11} in targets of elemental boron, decaborane (1), and repurified decaborane (2). The C^{11} counting rates per unit of monitor response per boron nucleus (in arbitrary units) are plotted against the betatron operating energy.

C. Additional Experiments

In order to account for possible effects in these experiments from photonuclear reactions on impurities in the samples and from secondary nuclear reactions, several additional experimental studies were made. In one of these the yield curve for the $C^{12}(\gamma,n)C^{11}$ reaction was measured for maximum bremsstrahlung energies ranging from 80 to 300 MeV. These measurements were made on powdered graphite targets using the procedures outlined in Sec. A above.

A second experiment involved irradiating the boron containing targets with bremsstrahlung from the University of Illinois 24-MeV betatron. These targets were then counted in the same way as described in Secs. A and B above to determine the presence of C^{11} and Be^{11} resulting from low energy nuclear reactions.

The third auxilliary experiment was the determination of the shape of the yield curve for a secondary nuclear reaction. The reaction studied was the $Al^{27}(n,p)Mg^{27}$ reaction caused by photoneutrons produced in a decaborane target. Aluminum plates (1/16 in. thick) were placed beside a decaborane target but outside of the collimated bremsstrahlung beam. The decaborane target was irradiated with 130-, 150-, 180-, and 250-MeV bremsstrahlung. The Mg^{27} yields at each betatron energy were determined by using the 3-in. NaI(Tl) scintillation spectrometer system to count the number of 840-keV gamma rays.[6]

III. RESULTS

A. $B^{11}(\gamma,\pi^-)C^{11}$ Reaction

Yield curve data for the C^{11} activity produced in several different sets of boron containing targets are shown in Fig. 1. These data are the C^{11} counting rates

[10] E. Konopinski, *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), p. 292.
[11] E. L. Goldwasser, F. E. Mills, and A. O. Hanson, Phys. Rev. **88**, 1137 (1952).
[12] H. E. Hall, A. O. Hanson, and D. Jamnik, Phys. Rev. **115**, 633 (1959).
[13] W. Paul and H. Steinwedel, *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (North-Holland Publishing Company, Amsterdam, 1955), p. 1.
[14] M. S. Freedman, T. B. Novey, F. T. Porter, and F. Wagner, Jr., Rev. Sci. Instr. **27**, 716 (1956).

per unit of response of the bremsstrahlung monitor normalized to the same number of boron nuclei in each target.[15] The figure contains yield data for an electrolytically purified elemental boron sample, a decaborane sample, and the decaborane sample after having been repurified by vacuum distillation. One notes that in all of the samples activity is observed below the threshold for reaction (1) which is 143 MeV.[16] Hughes and March[3] observed a similar effect in their yield curve obtained with elemental boron. (The yield curve obtained by Hughes and March would fall between the elemental boron data and the first decaborane series data in Fig. 1.) From Fig. 1, it is quite evident that the amount of this activity present below threshold varies from one target material to another. One also notes in Fig. 1 that there are changes in the slopes of the yield curves in the region of 143 MeV which indicate a contribution to the observed yields at higher energies from the reaction of interest. This latter effect is much more evident in the decaborane experiments.

In order to obtain the yield as a function of betatron energy for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction from the data shown in Fig. 1, it is necessary to account for the contribution above 143 MeV from the reaction or reactions giving rise to the activity observed below 143 MeV. The most probable sources of this activity are: (1) C^{11} produced by the $C^{12}(\gamma,n)C^{11}$ reaction on carbon impurities in the samples, and (2) C^{11} produced by the $B^{11}(p,n)C^{11}$ reaction caused by secondary protons. Hughes and March were unable to account for this below-threshold activity in their experiments. They reported that the amount of known carbon impurity in their boron samples was not large enough to account for the activity they observed below 143 MeV. Also, they could not explain the activity in terms of secondary (p,n) reactions because the amount of activity produced was linear with target length rather than quadratic. They accounted for the effects of this activity above the threshold by assuming that the energy dependence of the interfering activity was the same as that for the $C^{12}(\gamma,n)C^{11}$ reaction. The main evidence for the applicability of this treatment was that their observed yield curve from boron for bremsstrahlung energies from 70 to 140 MeV had the same shape as the $C^{12}(\gamma,n)C^{11}$ yield curve in that energy region. Our experiments indicate that the activity produced below threshold is mainly due to impurity effects in the elemental boron samples, but a significant contribution from secondary reactions could be present in our decaborane experiments. In addition, we have found that a detailed knowledge of the source of this activity is not needed since both effects can be accounted for by the method used by Hughes and March. The experimental results that lead to these conclusions follow.

First of all, in Fig. 1 we see that there is a dependence of the amount of activity induced below 143 MeV on the nature of the sample used. The amounts are different for elemental boron and for decaborane. In addition, subjecting the decaborane to a vacuum distillation repurification reduces the amount of activity observed at low energies. This variation from sample to sample indicates that impurity effects are a major source of the interfering activity. The irradiations with 24-MeV bremsstrahlung showed that this activity is produced at low energies. This means that the reaction involved here is a relatively simple reaction like a (γ,n) or (γ,p) reaction. The most likely low-energy reaction producing a 20-min positron activity is the $C^{12}(\gamma,n)C^{11}$ reaction. By comparing the amount of activity induced in the boron containing samples below 143 MeV with that produced in the graphite samples, it is possible to determine the percentage of carbon impurities needed to account for the activity in the boron samples. These impurity levels are 4.1% for the elemental boron, 0.9% for the first decaborane sample, and 0.5% for the repurified decaborane. The carbon impurity levels for the decaborane are not unreasonable.[8] The 4.1% carbon impurity required in the elemental boron sample is, however, much higher than the manufacturer's estimate.[7] Hughes and March reported that the carbon impurity required to explain their data (1.5%) was also much higher than the carbon impurities found in their boron by analysis. It may be that the analytical procedures used for determining carbon are just not adequate for carbon in the presence of boron. It is interesting to note that Wilkinson and Alburger[5] reported a similar difficulty with oxygen impurities in boron samples.

The above observations do not rule out the possibility that there is a contribution to the observed activity below threshold from the $B^{11}(p,n)C^{11}$ secondary reaction, particularly for the decaborane runs. The secondary protons needed could arise by (γ,p) reactions on the boron nuclei in the targets. This series of reactions would be possible in the 24-MeV bremsstrahlung irradiations, so they cannot be ruled out on the basis of those experiments. An estimate was made of the possible contribution from secondary reactions here by assuming that the (γ,p) yields from boron were the same as the (γ,n) yields in carbon[17] and using the known $B^{11}(p,n)C^{11}$ cross section data.[18] For the experiments on the repurified decaborane, the estimated contribution ranged from 5 to 50% of the observed activity below threshold depending on the assumptions made about the energy spectrum of the photoprotons. If the contri-

[15] The response of the ion-chamber beam monitor is energy dependent. At 125 MeV, one monitor unit corresponds to 4.70×10^7 ergs of energy in the bremsstrahlung beam. At 280 MeV, one monitor unit equals 6.15×10^7 ergs. The response is approximately linear with bremsstrahlung energy over this energy region.

[16] The mass data needed for the calculation of the thresholds were taken from *American Institute of Physics Handbook*, edited by D. E. Gray (McGraw-Hill Book Company, Inc., New York, 1957), Sec. 8, pp. 6, 67, and 241.

[17] W. C. Barber, W. D. George, and D. D. Reagan, Phys. Rev. **98**, 73 (1955).

[18] N. M. Hintz and N. F. Ramsey, Phys. Rev. **88**, 19 (1952).

bution is as large as 50% and if the energy dependence of the yield from these secondary reactions is not the same as the energy dependence of the $C^{12}(\gamma,n)C^{11}$ yield curve, then using the method of Hughes and March to account for these low-energy effects may introduce significant error in the $B^{11}(\gamma,\pi^-)C^{11}$ cross sections.

The contribution from the secondary (p,n) reaction depends on the yield of photoprotons whose energies are around 10 MeV. Unfortunately, very little is known about the yields of 10-MeV protons from high-energy bremsstrahlung irradiations. A possible method of determining the energy dependence for the secondary reaction would be to place a second boron containing target near the primary target but outside of the bremsstrahlung beam and allow photoprotons produced in the first target to react in the second. Because of the short range of the protons and the necessity of having some type of target holder to contain the powdered boron samples, this method was not practical. However, assuming that there will be little difference in the energy dependences of secondary (p,n) and secondary (n,p) reactions in the light element region, one could use the yield curve for the $Al^{27}(n,p)Mg^{27}$ reaction induced by photoneutrons coming from boron containing targets to account for the effects from the $B^{11}(p,n)C^{11}$ reaction. Since the neutrons are much longer ranged than the protons, this experiment is much easier to do. The experimental results given in Fig. 2 show that the $Al^{27}(n,p)Mg^{27}$ secondary reaction induced by photoneutrons coming from the $B_{10}H_{14}$ target does have essentially the same energy dependence as the $C^{12}(\gamma,n)$-C^{11} reaction over the energy range of interest.

With these data in mind, the method for correcting the higher-energy data to remove the contribution from the lower-energy reactions is to subtract a $C^{12}(\gamma,n)C^{11}$ yield curve that has been normalized to the boron data below 143 MeV. This should account for both the effects of the carbon impurities and for the effects of secondary reactions. [Figure 3 shows a $C^{12}(\gamma,n)C^{11}$ yield curve normalized to the data from the repurified decaborane sample.] This method is approximate to the extent that

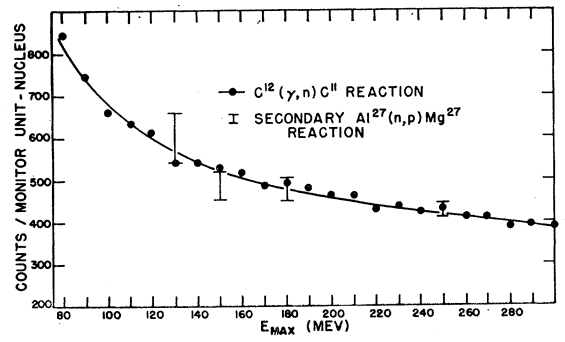

FIG. 2. Yield data (in arbitrary units) for the $C^{12}(\gamma,n)C^{11}$ reaction in graphite targets (solid circles and solid line) and for the $Al^{27}(n,p)Mg^{27}$ reaction induced by secondary neutrons at 130, 150, 180, and 250 MeV. The secondary reaction yield is normalized to the carbon yield at a betatron operating energy of 180 MeV. (Note the suppressed zero on the ordinate scale.)

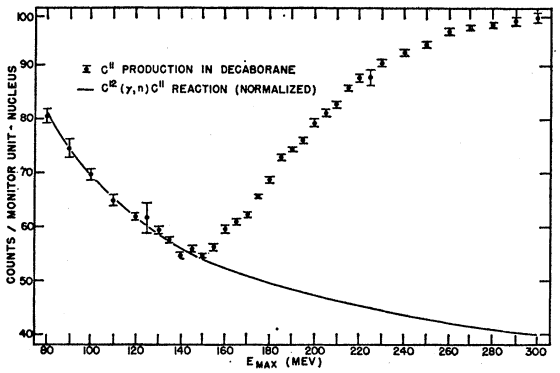

FIG. 3. The C^{11} yield data (in arbitrary units) for the repurified decaborane with a $C^{12}(\gamma,n)C^{11}$ yield curve (solid line) normalized to the decaborane data below 143 MeV. (Note the suppressed zero on the ordinate scale.)

the energy dependence of the actual secondary yield differs from that measured for the $Al^{27}(n,p)Mg^{27}$ reaction. This is the same procedure that Hughes and March used to correct their data.

The resulting yield curve has been analyzed to obtain the integrated cross section and its uncertainty as a function of photon energy by applying the cross section analysis method of Penfold and Leiss.[19] The average cross sections over energy ranges 20 or 30 MeV wide were then determined from the integrated cross sections. The resulting cross sections from the experiments using repurified decaborane are shown in Fig. 5. The uncertainties shown there include a 10% contribution for the uncertainty in the factors involved in converting the yield data in terms of counts per monitor unit to absolute yields. The data from the other two series of experiments (the elemental boron and the original decaborane series) gave cross sections consistent with those shown in Fig. 5, giving additional confidence in the applicability of the method used for correcting for the activity due to low-energy photons. The cross sections obtained by Hughes and March using elemental boron samples are also shown in Fig. 5. They are in satisfactory agreement with our results.

B. $B^{11}(\gamma,\pi^+)Be^{11}$ Reaction

The observed Be^{11} yield data are shown in Fig. 4. There the number of beta counts with energy greater than 3.65 MeV per bremsstrahlung monitor unit per boron nucleus is plotted against the betatron energy. One notes that some activity is observed below the threshold for reaction (2) which is 152 MeV.[16] Irradiations with 24-MeV bremsstrahlung indicate that this activity is also present at low energies. The experiments conducted with the target material behind absorbers or outside of the bremsstrahlung beam showed that the yield of this activity below threshold is not due to secondary $B^{11}(n,p)Be^{11}$ reactions induced by photoneutrons originating in the betatron or beam-collimating

[19] A. S. Penfold and J. E. Leiss, Phys. Rev. 114, 1332 (1599),

system because the yield was always proportional to the bremsstrahlung dose. (The betatron and collimator system are the main sources of photoneutrons incident on the boron nuclei.) We, thus, conclude that this activity is probably due to short-lived nuclei produced by (γ,n) or (γ,p) reactions on impurities present in the decaborane. Because of the poor statistics associated with the decay curves for the samples irradiated below 152 MeV, it is not possible to assign a very accurate half-life to this activity. This makes it difficult to speculate further about the origin of the activity. However, since it is produced by low-energy photons, the energy dependence of the yield of this activity should be very similar to that of the $C^{12}(\gamma,n)C^{11}$ reaction. Thus, we have accounted for the effects of this activity above the threshold for reaction (2) by subtracting a $C^{12}(\gamma,n)C^{11}$ yield curve that has been normalized to the decaborane data below 152 MeV as shown in Fig. 4.

Cross sections were calculated from the resulting yield curve by the method of Penfold and Leiss as described in the previous section. The resulting cross sections are shown in Fig. 5. The uncertainties shown there include a 20% contribution for the uncertainty in the factors involved in converting the yield data in terms of counts per monitor unit to absolute yields.

IV. DISCUSSION

Predictions of the cross sections for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction have been made by Laing and Moorhouse.[1] They consider the photoproduction process as being a single nucleon process in which the struck nucleon undergoes transitions into discrete states of the product nucleus. The nuclear model they used was a simple independent-particle model. They performed calculations for both production throughout the entire volume of the nucleus and for production only on the nuclear surface. The predicted cross sections for volume production are about a factor of 6 greater than those for surface production. Their predicted cross sections for surface production are plotted in Fig. 5 where they

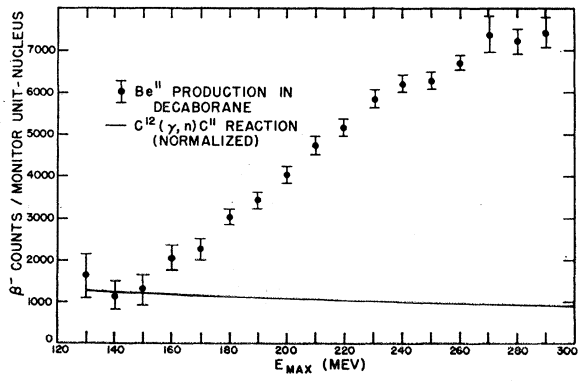

FIG. 4. Yield data (in arbitrary units) for the production of Be^{11} in a decaborane sample. The solid line is a $C^{12}(\gamma,n)C^{11}$ yield curve normalized to the decaborane data below 152 MeV.

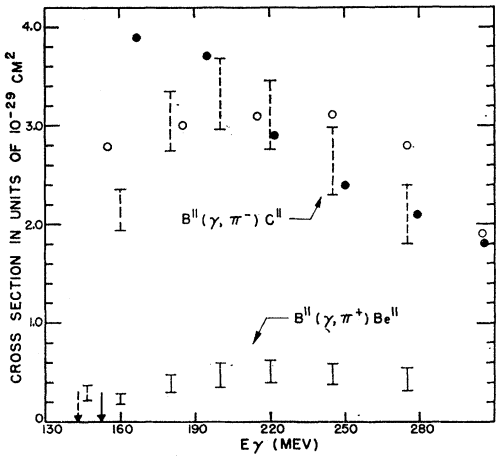

FIG. 5. Cross sections in units of 10^{-29} cm^2 for the $B^{11}(\gamma,\pi^-)C^{11}$ and the $B^{11}(\gamma,\pi^+)Be^{11}$ reactions. The cross sections from this work are shown by the error bars, those with dashed lines giving the $B^{11}(\gamma,\pi^-)C^{11}$ reaction results and those with solid lines giving the $B^{11}(\gamma,\pi^+)Be^{11}$ reaction results. The open circles show the cross sections reported by Hughes and March (reference 3) for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction. Their reported uncertainties are $\pm 20\%$. The solid circles show the cross sections predicted by Laing and Moorhouse (reference 1) for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction for the assumption of surface production of pions. The thresholds for the two reactions are indicated by the arrows, 143 MeV for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction and 152 MeV for the $B^{11}(\gamma,\pi^+)Be^{11}$ reaction.

can be compared with the experimental results. The agreement between the predicted cross sections based on surface production and the experimentally observed cross sections is quite good except at energies near the threshold. Because Laing and Moorhouse neglected the energy difference between the $1p$ and $1d$ shells, the recoil energy of the struck nucleus, and the difference in neutron and proton binding energies, their predictions would be expected to be only approximate in the threshold region.

Experimentally it is observed that the cross sections for the $B^{11}(\gamma,\pi^+)Be^{11}$ reaction range from 1/9 to 1/5 of those for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction. Qualitatively we expect the reaction producing Be^{11} to be less probable because Be^{11} has only one bound state, the ground state,[5,20] compared to the many bound states available in C^{11}. [The results of the Laing and Moorhouse calculations for the $B^{11}(\gamma,\pi^-)C^{11}$ reaction depended more on the total number of states available than on the specific details of the states.] Making an estimate for the production of Be^{11} on the basis of the number of states available, a cross section 1/10 of that for the production of C^{11} is predicted.[21] The fact that the observed cross section is somewhat larger than this may indicate that pion production from the odd proton in B^{11} is enhanced somewhat. Such an enhancement has been discussed previously by Littauer and Walker[22] as a feature of the surface production model.

[20] F. Ajzenberg-Selove and T. Lauritsen, Ann. Rev. Nuclear Sci. **10**, 409 (1960).
[21] E. W. Laing and R. G. Moorhouse (private communication, December, 1959).
[22] R. M. Littauer and D. Walker, Phys. Rev. **86**, 838 (1952).