Investigation of the Gamma Radiation Produced by Irradiating B^{10} with Protons in the Energy Range 0.7 to 3.0 Mev

S. E. HUNT, R. A. POPE, AND W. W. EVANS
Research Laboratory, Associated Electrical Industries Limited, Aldermaston, Berkshire, England
(Received December 5, 1956)

The proton beams from a pressurized Van de Graaff accelerator were used to irradiate targets of separated B^{10} isotopes, and the γ-ray spectra and yield curves from the $B^{10}(p,\alpha\gamma)Be^7$, $B^{10}(p,\gamma)C^{11}$ and $B^{10}(p,p'\gamma)B^{10}$ reactions were measured by using a large crystal spectrometer and pulse-height analyzer.

The 0.43 ± 0.015 Mev γ ray from the $B^{10}(p,\alpha\gamma)Be^7$ reaction was found to have a resonance at 1.540 ± 0.005 Mev, the cross section at resonance being 80 ± 40 millibarns.

The 9.70 ± 0.15 Mev radiation from the $B^{10}(p,\gamma)C^{11}$ reaction exhibited a single resonance at 1.146 ± 0.005 Mev, the cross section at resonance being measured as 5.5 ± 2 μb. γ rays of about one-twentieth of this intensity of energy about 4.2 Mev and 5.5 Mev can also be attributed to this resonance.

The yield of 0.71 ± 0.015 Mev radiation from the $B^{10}(p,p'\gamma)B^{10}$ increased monotonically with energy. The cross section at 2.7 Mev was 11 ± 5 millibarns. For proton energies of greater than 2.4 Mev, weaker γ rays of energy 1.00 ± 0.04 Mev and 2.12 ± 0.06 Mev were also present.

INTRODUCTION

WHEN B^{10} is irradiated with protons, three gamma-emitting reactions can take place. These are radiative capture $B^{10}(p,\gamma)C^{11}$, inelastic scattering $B^{10}(p,p'\gamma)B^{10}$ and α decay to excited states of Be^7, followed by gamma emission $B^{10}(p,\alpha\gamma)Be^7$.

Discrepancies exist in the published work on the first of these reactions. Krone and Seagondollar[1] observed broad resonances for gamma emission at 0.78 Mev and possibly also at 0.95 and 1.33 Mev, while Huus and Day[2] reported a resonance at 1.21 Mev and a doubtful resonance at 2.4 Mev. Hahn, Kern, and Farney[3] found a resonance at 1.18 Mev, and Chadwick, Alexander, and Warren[4] observed one at 1.135 ± 0.015 Mev in the energy range up to 2 Mev. Bair, Kington, and Willard,[5] during their work on $B^{11}+p$, made a preliminary run on B^{10} in the range 2 to 5 Mev, which showed only one broad resonance at about 4 Mev.

The (p,α) reaction has been observed previously by several workers, and the results indicate resonances at about 1.1 Mev and 1.5 Mev for α-particle emission to the ground state of Be^7.[6–8] The yield for shorter range α particles to the 0.43-Mev state in Be^7 also exhibits a resonance at about 1.5 Mev.[6,8] The γ-ray resonance associated with this reaction has been measured at 1.52 Mev by Huus and Day,[2] and at 1.53 Mev by Chadwick *et al.*[4]

One group of gamma rays of energy 0.72 Mev from the inelastic scattering process has been observed previously by Huus and Day.[2] The yield was observed to rise monotonically with proton energy. The 0.72-Mev radiation was also seen by Bair *et al.*[5] and by Chadwick *et al.*[4]

The aim of the present work was to clear up the uncertainty in the reported results on the capture resonances, and also to investigate the gamma-ray spectra and yield arising from all three reactions for proton energies of 0.7 to 3.0 Mev.

EXPERIMENTAL PROCEDURE

Protons were accelerated by a pressurized electrostatic generator[9] and their energies were measured absolutely to an accuracy of better than one part in a thousand by using an electrostatic analyzer.[10] Error signals from the exit slit jaws of the analyzer were used to stabilize the voltage of the generator.[11] A deflecting magnet following the analyzer was used for mass analysis. Target currents of about 5 μa were normally used. The targets consisted of B^{10} of at least 99% purity of thickness 10 $\mu g/cm^2$ and 100 $\mu g/cm^2$, separated by mass spectrographic deposition on copper or tungsten backings by Isotope Division, Atomic Energy Research Establishment, Harwell. These were mounted on a rotatable target holder which also held thin CaF_2 and B^{11} targets and specimens of the backing materials. By rotating the target holder, background measurements could be taken without disturbing the counter geometry and also γ rays of known energy could be produced from the $B^{11}(p,\gamma)C^{12}$ and $F^{19}(p,\alpha\gamma)O^{16}$ reactions for calibration of the γ-ray spectrometer in the high-energy range. A liquid nitrogen trap was placed in front of the target assembly to prevent the deposition of carbon on the target surfaces.

The γ-ray spectrometer consisted of a 4-in. diameter thallium-activated sodium iodide crystal 4 in. long

[1] R. W. Krone and L. W. Seagondollar, Phys. Rev. **92**, 935 (1953).
[2] R. B. Day and T. Huus, Phys. Rev. **95**, 1003 (1954).
[3] Hahn, Kern, and Farney, Phys. Rev. **98**, 1183 (A) (1955).
[4] Chadwick, Alexander, and Warren, Can. J. Phys. **34**, 381 (1956).
[5] Bair, Kington, and Willard, Phys. Rev. **100**, 21 (1955).
[6] Brown, Snyder, Fowler, and Lauritsen, Phys. Rev. **82**, 159 (1951).
[7] Allan, Govindjee, and Sarma, Proc. Phys. Soc. (London) **A69**, 350 (1956).
[8] J. W. Cronin, Phys. Rev. **101**, 298 (1956).
[9] D. R. Chick and D. P. R. Petrie, Proc. Inst. Elec. Engrs. **B103**, 132 (1956).
[10] Hunt, Petrie, Firth, and Trott, Proc. Inst. Elec. Engrs. **B103** 146 (1956).
[11] Millar, Churchill, and Bailey (to be published).

mounted with a $\frac{1}{2}$-in. long Perspex light pipe on to an eleven-stage photomultiplier type E.M.I. 6099 A. The spectrometer was surrounded by a $5\frac{1}{2}$-in. thick cylindrical lead shield, and a lead collimating tube could be inserted in front of the crystal. Pulses from the photomultiplier were fed into a 120-channel pulse-height analyzer of the Hutchinson Scarrott type[12] made by Sunvic Controls Limited. The instrument accepted pulses from 0 to 100 volts and the channel width could be varied between 0.83 and 0.042 volt. In the low-energy range the instrument was calibrated by using the radioactive sources Na^{22}, Cs^{137}, Co^{60}, and Sb^{124}.

The effective dead time of the pulse-height analyzer was 600 μsec and care was taken to restrict the counting rate so that the corrections for counting losses did not become excessive.

Initial exposures were made using the copper-backed targets but the radiation from the copper was found to mask weak 9.7-Mev radiation from the target for high proton energies. The radiation from tungsten was found to be approximately 10 times less intense and did not extend to the higher energies. It was consequently found to be a more satisfactory backing material. Figure 1 shows the relative pulse-height spectra resulting from irradiation of copper and tungsten by 2.6-Mev protons.

For most of the irradiations the spectrometer was placed behind the target, that is, in the forward direction of the beam, but some measurements were also made at 90° to the beam.

The intensity of the γ radiation of a particular energy was estimated by measuring the area under the peak of the γ-ray spectrum curve, after making a correction for the continuous background. These areas were plotted as a function of proton energy in order to produce separate yield curves for each γ ray.

Cross-section measurements were made by comparing the yield of the 9.7-Mev γ ray from the $B^{10}(p,\gamma)C^{11}$ reaction with that of the 6.14-Mev γ ray

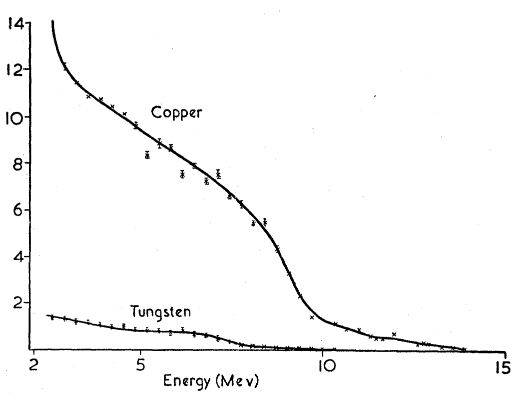

FIG. 1. Pulse-height spectra of gamma rays from copper and tungsten.

[12] G. W. Hutchinson and G. G. Scarrott, Phil. Mag. **42**, 792 (1951).

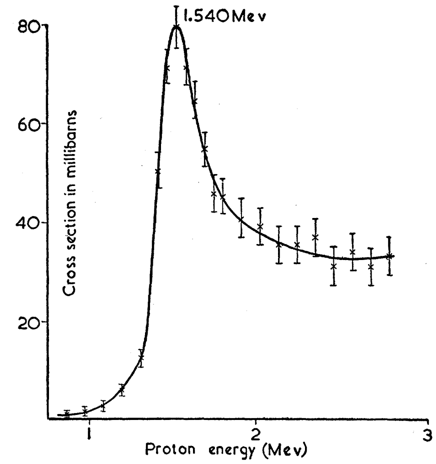

FIG. 2. Yield curve of 0.43-Mev gamma rays from $B^{10}(p,\alpha\gamma)Be^7$ reaction.

from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction at the 1.348-Mev resonance using the same geometry. This was taken as 89 mb from the work of Chao *et al.*[13] The cross sections for the lower energy γ rays were then estimated by comparison with the yield of the 9.7-Mev γ ray, with appropriate allowances being made for changes in the detection geometry and variation in crystal sensitivity. The uncertainty in the result is estimated to be about $\pm 50\%$.

RESULTS

Five gamma-ray peaks were measured at 0.43 ± 0.015 Mev, 0.71 ± 0.015 Mev, 1.00 ± 0.04 Mev, 2.12 ± 0.06 Mev, and 9.7 ± 0.15 Mev. There were also peaks at about 4.2 Mev and 5.5 Mev.

The high-energy spectrum was calibrated with the 6.14-Mev gamma ray resulting from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction, and the 12.8- and 17.2-Mev gamma rays from $B^{11}(p,\gamma)C^{12}$ at a proton energy of 1.35 Mev. The energies of these gamma rays from B^{11} were obtained by consideration of the Q value for the (p,γ) reaction[14] and the bombarding energy in the center-of-mass system, knowing that de-excitation of the C^{12} proceeds both directly to the ground state and via the 4.43-Mev level.[15]

The measurement of the 9.7-Mev capture radiation from $B^{10}+p$ agrees with the value expected by consideration of the Q-value and bombarding energy, as does the measurement of Chadwick *et al.*,[4] although in disagreement with Walker's[16] pair spectrometer result of 9.47 ± 0.12 Mev at a proton energy of 1.2 Mev.

The 0.43-Mev gamma ray was by far the most intense, and is attributed to the $B^{10}(p,\alpha\gamma)Be^7$ reaction,

[13] Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).
[14] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).
[15] T. Huus and R. B. Day, Phys. Rev. **91**, 599 (1953).
[16] R. L. Walker, Phys. Rev. **79**, 172 (1950).

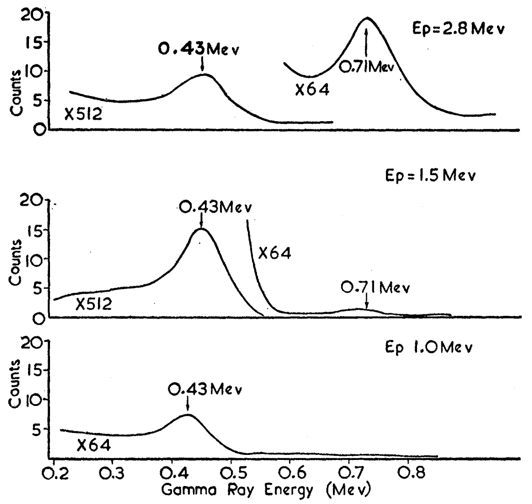

FIG. 3. Low-energy gamma-ray spectra at various energies.

from the results of previous workers. The 9.7-Mev gamma ray is attributed to the $B^{10}(p,\gamma)C^{11}$ reaction and those at 0.71, 1.00, and 2.12 Mev arise from inelastic scattering. The reactions will be discussed separately.

GAMMA RAY FROM THE $B^{10}(p,\alpha\gamma)Be^7$ REACTION

The yield of the 0.43-Mev γ ray exhibited a broad maximum at 1.540 ± 0.005 Mev. This was the mean of several measurements after correction for target thickness. The rather large limits of uncertainty in the resonance measurement are due to the difficulty in determining the peak of such a wide resonance from the experimental curve. The curve is shown in Fig. 2. It was markedly asymmetric, having a pronounced high-energy tail. The experimental curve had a half-width of approximately 400 kev, but if allowance were made for the nonresonant increase in yield with proton energy, this was reduced to 220 kev and the mean resonant energy to 1.533 ± 0.005 Mev.

Since the 0.43-Mev γ ray was by far the most intense, total γ-ray yield curves recorded on a scaler with low

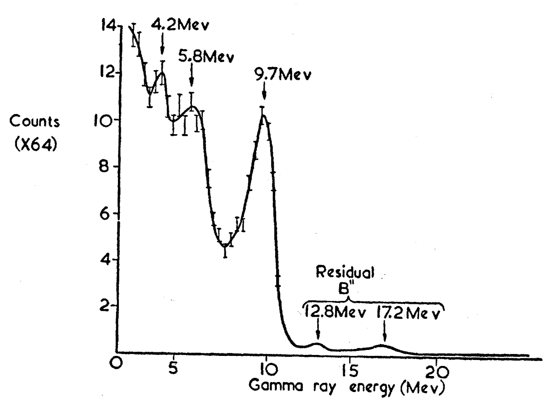

FIG. 4. High-energy gamma spectrum.

bias setting approximated to the 0.43-Mev γ-ray yield curve except at the higher proton energies where the 0.71-Mev γ-ray yield started to become appreciable. This did not affect the measurement of the resonant peak and the half-width and measurements from the total yield curves were in agreement with the values obtained above.

The low-energy γ-ray spectra showing the relative intensities of the 0.43-Mev γ ray and the 0.71-Mev γ ray at various energies is shown in Fig. 3.

The cross section for production of the $B^{10}(p,\alpha\gamma)Be^7$ reaction at resonance was calculated to be 80 millibarns.

The value obtained for the resonant energy in the present work is in agreement with the work of Day and Huus,[2] and Chadwick *et al.*,[4] within the experimental uncertainties. If one takes the Q value for the capture reaction as 8.697 Mev, it indicates a level at 10.097 Mev in C^{11} decaying to the first excited state of Be^7 by α emission.

Our measurement of the γ-ray energy indicates the

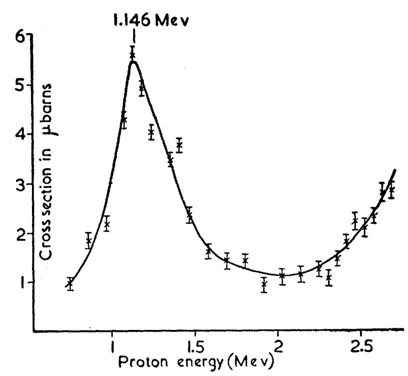

FIG. 5. Yield curve of 9.7-Mev radiation from $B^{10}(p,\gamma)C^{11}$.

energy of the excited state in Be^7 as 0.43 ± 0.015 Mev which is in agreement with the value obtained by Day and Huus.[2]

GAMMA RAYS FROM THE $B^{10}(p,\gamma)C^{11}$ REACTION

The gamma-ray spectrum at resonance is shown in Fig. 4. In addition to the main peak at 9.70 ± 0.15 Mev, a small peak at about 4.2 Mev must also be attributed to this reaction, since it is not energetically possible from either the (p,p') or (p,α) reactions. Its intensity was about one-twentieth of that of the 9.7-Mev gamma ray. The peak at about 5.8 Mev probably consists of 6.14-Mev radiation from fluorine contamination, unresolved from a lower energy gamma ray of about 5.5 Mev. This suggests that decay of the 9.7-Mev level in C^{11}, although proceeding predominantly direct to the ground state, may also decay via the 4.23-Mev level.[9] De-excitation through intermediate states was also observed by Chadwick *et al.*[4]

The 9.7-Mev γ-ray yield curve exhibited a single resonance, the mean value of several determinations being 1.146 ± 0.005 Mev and the half-width 414 ± 20 kev. The yield curve was slightly asymmetric as shown in Fig. 5. Above 2.2 Mev the yield started to increase, but there was no indication of a resonance at 2.4 Mev reported by Huus and Day. Since Huus and Day's measurements were made at 90° while the present ones were made in the forward direction, it was thought that this discrepancy may be due to anisotropy in the γ-ray yields. The present measurements were therefore repeated at 90°. The ratio of the 9.7-Mev γ ray at 2.4 Mev to that at resonance remained unchanged.

Our result, therefore, indicates a level in C^{11} at 9.70 Mev decaying predominantly to the ground state. There is no indication of a level at 10.9 Mev which would correspond to a resonance at 2.4 Mev. A search was also made for resonances at 0.78, 0.95, and 1.33 Mev reported by Krone and Seagondollar, but there was no indication of these.

The cross section for the reaction at resonance was measured as 5.5 μb compared with a value of 7.5 μb obtained by Day and Huus,[2] and one of 3.5 μb by Chadwick *et al.*[4] The agreement is within the limits of experimental uncertainty.

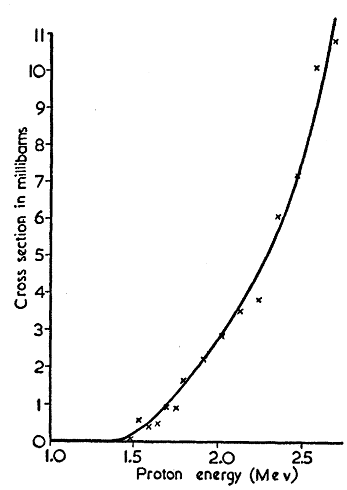

FIG. 6. Yield curve of 0.71-Mev radiation from $B^{10}(p,p'\gamma)B^{10}$.

If our resonance value is to be identified with the one about 1.15 Mev observed by Brown *et al.*,[6] Cronin,[8] and Allan *et al.*[7] for the (p,α) transition to the ground state of Be^7, it indicates that the level at 9.7 Mev in C^{11} may decay either by gamma emission to the ground state of C^{11} or by alpha emission to the ground state of Be^7.

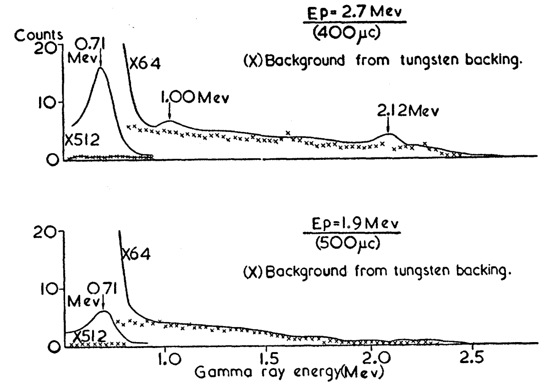

FIG. 7. Medium-energy gamma-ray spectrum.

GAMMA RAYS FROM THE $B^{10}(p,p'\gamma)B^{10}$ REACTION

A gamma ray of energy 0.71 ± 0.015 Mev is interpreted as being the γ ray from the decay of the first excited state of B^{10} to the ground state. Its yield was observed to rise monotonically with energy, as shown in Figs. 3 and 6. The cross section at 2.7 Mev was calculated to be 11 millibarns.

When the proton energy was increased to 2.4 Mev a weak γ ray of energy 1.00 ± 0.04 Mev appeared, and at slightly higher energies a 2.12 ± 0.06-Mev γ ray was present (Fig. 7). Since they were not present at lower energies, it is reasonable to interpret these as arising from transitions from the 1.74-Mev to the 0.72-Mev state in B^{10} and from the 2.15-Mev state to the ground state. These peaks were approximately one hundred times less intense than the 0.71-Mev peak. The absence of radiation from the 1.74-Mev state direct to the ground state is in agreement with spin and parity assignments made by previous authors.[14] There was no definite indication of 1.43-Mev radiation between the 2.15-Mev and 0.72-Mev states.

ACKNOWLEDGMENTS

The authors are pleased to acknowledge the help and advice of D. R. Chick and D. P. R. Petrie in this work, and also to express their thanks to G. Hunt and Miss M. Hunt who assisted in running the generator and recording the experimental results.

Thanks are also due to Dr. T. E. Allibone, F.R.S., for permission to publish this work.