IV. CONCLUSIONS

Of the properties of the three-nucleon bound state those associated with the completely summetrical state S are most well established. Our predictions are in reasonable accord with these. In particular, we have shown that the phenomenological three-body force has the correct dynamical effect on the three-body wave function. Unfortunately, our result for the S'-state probability is rather noncommittal, lying as it does, between the values derived from the conventional analysis of neutron-deuteron capture and from the form-factor data.

Our approach is limited in that it depends on the neglect of the Coulomb repulsion in He^3, the associated $T=\frac{3}{2}$ state, and the small admixtures of P and D states with $T=\frac{1}{2}$. Further uncertainties are introduced by the usual assumption, that the three-nucleon form factors can be expressed as products of the body form factors and the nucleon form factors, and by the fit of the numerical wave function to simple analytic ones. However, a more sophisticated treatment would probably not alter the essential results.

There is scope for further work. Other choices of the two nucleon form factors should be considered. The $T=\frac{3}{2}$ states of H^3 and He^3 can also be calculated by distinguishing between the neutrons and protons and including the long-range Coulomb forces with perturbation theory. It should also be possible to include the P and D states as perturbations. Investigations along these lines are in progress.

ACKNOWLEDGMENTS

I am grateful to Professor R. J. Blin-Stoyle and Dr. L. M. Delves for their interest and encouragement.

PHYSICAL REVIEW VOLUME 145, NUMBER 3 20 MAY 1966

Gamma Rays from $B^{10}+p$; Decay Schemes and Excitation Functions*

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(Received 23 December 1965)

The formation and decay of all the gamma-ray emitting states produced in bombarding B^{10} with protons in the energy range $4 \leqslant E_p \leqslant 12$ MeV has been studied. Re-examination of the gamma-ray decay scheme of B^{10} showed no evidence for the existence of either a 1.74- or a 1.84-MeV transition; the value $\Gamma_\gamma/\Gamma=0.73 \pm 0.15$ was obtained for the alpha-unstable 5.16-MeV level. Gamma rays from the first excited states of Be^7 and C^{10} were also observed; the energy of the latter was determined to be 3.35 ± 0.01 MeV. The formation of the positron-emitting ground state of C^{10} was studied by means of the annihilation radiation. Giant-resonance structures in the region $12 \leqslant E_x(C^{11}) \leqslant 18$ MeV were observed in the yield curves for all reactions that did not leave the final nucleus in a $T=1$ state. A strong correlation between maximum cross sections and reaction energies is noted, but this correlation in itself does not appear to be sufficient to explain the marked suppression of the $T=1$ final states. It is shown that a resonance in the four-particle system $\alpha+\alpha+d+p$ could be responsible for the giant-resonance structures.

INTRODUCTION

THIS paper reports a study of the formation and decay of all the gamma-ray-emitting states that are formed by bombarding B^{10} with protons of energy from 4 to 12 MeV. The energy-level diagram (Fig. 1) shows the states involved in this study. Four of these states (including the positron-emitting ground state of C^{10}) are known to have isotopic spin $T=1$, three have isotopic spin $T=0$, and two have isotopic spin $T=\frac{1}{2}$ [including the ground state of Be^7, previously studied[1] by means of the (p,α_0) reaction]. The (p,He^3) reaction forming the ground state $(T=0)$ of Be^8 has also been reported.[2] The variety of available final states makes it possible to investigate the degree to which various factors (isospin, energy, configuration) influence the

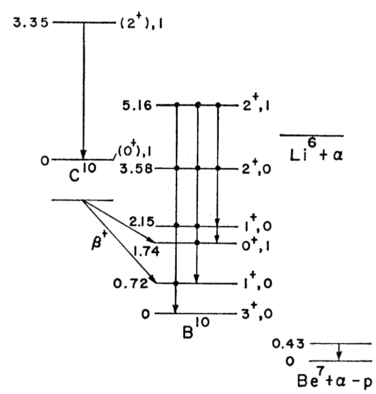

FIG. 1. Energy levels and gamma rays observed in the proton bombardment of B^{10}.

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1 J. G. Jenkin, L. G. Earwaker, and E. W. Titterton, Nucl. Phys. 50, 516 (1964).

2 J. G. Jenkin, L. G. Earwaker, and E. W. Titterton, Phys. Letters 4, 142 (1963).

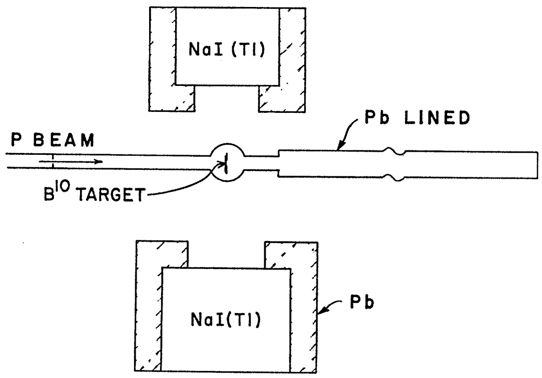

FIG. 2. Schematic diagram of the experimental arrangement.

decay of states at energies corresponding to states in C^{11} at excitations from 12 to 19.5 MeV. In addition, our observation of all the gamma rays emitted by the bound levels of B^{10} permits study of the decay scheme of B^{10}. Of particular interest is the unbound $T=1$ level at 5.16 MeV, which is known to emit gamma rays successfully in competition with alpha particles. Unless otherwise noted, the information about the various states is taken from the compilation of Ajzenberg-Selove and Lauritsen.[3]

EXPERIMENTAL METHOD

Thin metallic boron targets enriched to about 96% B^{10} were prepared on thin carbon backings by the method described by Erskine and Gemmell.[4] A well-focused beam from the ANL tandem Van de Graaff accelerator impinged on the target. To minimize background in the detectors, the last collimator of the beam was about 1 m from the target, $\lesssim 1\%$ of the beam was allowed to strike the collimator, and after passing through the thin target the beam drifted about 6 m before being stopped.

The observations were made with two large NaI(Tl) crystals (25 cm in diam×20 cm thick and 20 cm in diam×15 cm thick) which were operated separately or in coincidence. The experimental arrangement is shown schematically in Fig. 2. The intensities of the gamma rays were extracted from the pulse-height spectra with the aid of an electronic computer. It was assumed that each peak in a spectrum was superimposed on a flat background: the computer was instructed to use selected channels to determine the background and to sum over specified channels to obtain the peak intensity. The calculations of Miller, Reynolds, and Snow[5] were used to convert peak intensities to gamma-ray intensities.

[3] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959).
[4] J. R. Erskine and D. S. Gemmell, Nucl. Instr. Methods **24**, 397 (1963).
[5] W. F. Miller, J. Reynolds, and W. J. Snow, Argonne National Laboratory Report No. ANL-5902 (unpublished).

GAMMA-RAY DECAY SCHEME

Most of the observations on which the decay scheme is based were made at a bombarding energy of 10 MeV. This energy is high enough to populate all of the B^{10} levels known to have significant gamma-ray branches and yet low enough to yield clean gamma-ray spectra. Spectra from the 25×20-cm crystal were recorded in coincidence with various peaks in the spectrum of the 20×15-cm crystal. The spectra were corrected for accidental coincidences (which were usually less than 10%) and for a background that was measured by setting the pulse-height window of the 20×15-cm crystal just above the peak being studied.

The face of the 20×15-cm crystal was about 18 cm from the target, a collimator 12.5 cm in diameter was placed in front of the crystal, and the crystal remained at 90° to the incident beam. The face of the 25×20-cm crystal was 20 cm from the target, its collimator was 15 cm in diameter and observations were made at three angles: 53°, 90°, and 127°. The variations in the coincident yield with angle were not more than about 15%. Figure 3 shows the singles spectrum from the 25×20-cm crystal. Figures 4–7 show spectra in coincidence with four of the prominent gamma rays. The coincidence spectra were actually recorded two at a time by gating two analyzers with pulses from two different peaks in the spectrum of the other counter.

With a well-known[3] level scheme of B^{10}, the interpretation of the gamma-ray spectra is straightforward and unambiguous. The singles spectrum contains the 0.72-, 1.02-, 1.43-, 2.15-, 2.86-, and 3.58-MeV gamma rays from B^{10*}, the 0.43-MeV gamma ray from the $B^{10}(p,\alpha)Be^{7*}$ reaction, the 3.35-MeV gamma ray from $B^{10}(p,n)C^{10*}$, annihilation radiation resulting from C^{10} decay, a 1.78-MeV gamma ray from silicon contamina-

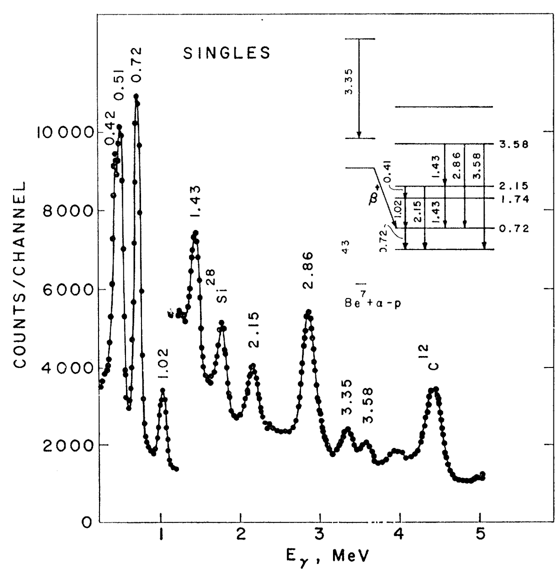

FIG. 3. Pulse-height spectrum of gamma rays observed in the bombardment of B^{10} by 10-MeV protons.

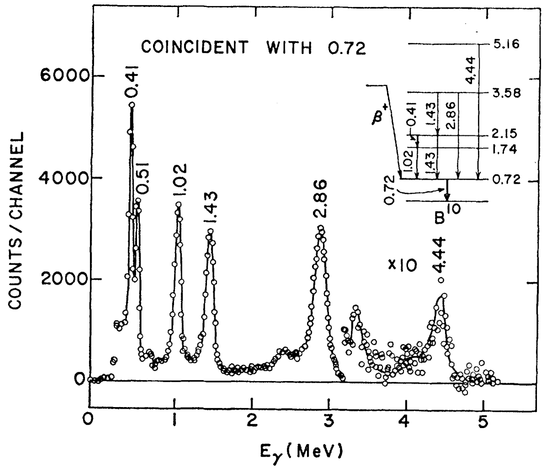

FIG. 4. Pulse-height spectrum of gamma rays observed in coincidence with the 0.72-MeV gamma ray in the bombardment of B^{10} by 10-MeV protons.

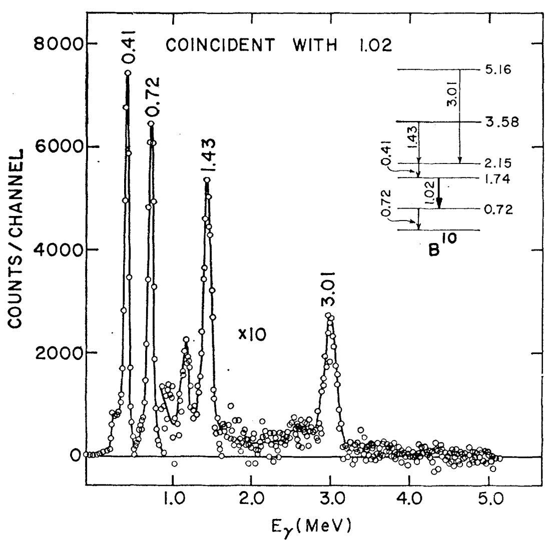

FIG. 5. Pulse-height spectrum of gamma rays observed in coincidence with the 1.02-MeV gamma ray in the bombardment of B^{10} by 10-MeV protons.

tion, and a 4.43-MeV gamma ray from carbon contamination. (The 4.44-MeV gamma ray from B^{10*} is much too weak to account for this last peak in the singles spectrum.) The 0.41-MeV gamma ray from B^{10*} is not resolved from the 0.43-MeV gamma ray from Be^{7*}, while the 3.01-MeV gamma ray from B^{10*} manifests itself as a distortion on the high side of the 2.86-MeV peak. With the exception of the 3.58-MeV gamma ray, which is the ground-state transition from the 3.58-MeV level, all of the B^{10} gamma rays that are present in the singles spectrum also appear in the coincidence measurements. The presence of 1.43-1.43 MeV coincidences assures that this gamma ray appears twice in the decay scheme.[6]

[6] S. M. Shafroth and S. S. Hanna, Phys. Rev. **95**, 86 (1954).

In the decay of the bound levels of B^{10}, there are two possible transitions that do not appear in any of the spectra: the ground-state transition from the 1.74-MeV level, and the 1.84-MeV transition from the 3.58-MeV level to the 1.74-MeV level. Both transitions are expected to be very weak since the 1.74-MeV gamma ray is an $M3$ transition while the 1.84-MeV gamma ray is an $E2$ transition that is not likely to be collectively enhanced because it involves a change in isotopic spin. In order to complete the decay scheme, special efforts were made to find these missing transitions—the interest in this search being heightened by the report[7] that the 1.84-MeV gamma ray is present in considerable strength ($\approx 10\%$ of the decays of the 3.58-MeV level).

The search for the 1.74-MeV gamma ray was carried out at a bombarding energy of 7.0 MeV, since somewhat cleaner spectra are obtained at lower proton energies. In order to reduce the effect of summing of peaks, the 25×20-cm crystal was moved back to a distance of 50 cm from the target and a lead absorber, 1 cm thick, was placed in front of this crystal. The spectrum was gated by pulses (from the 20×15-cm crystal) corresponding to the 0.41-MeV gamma ray that feeds the 1.74-MeV state. Figure 8 shows the coincidence spectrum corrected for accidental coincidences. This spec-

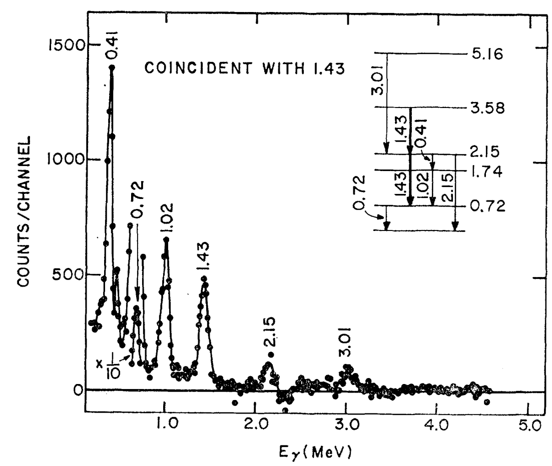

FIG. 6. Pulse-height spectrum of gamma rays observed in coincidence with the 1.43-MeV gamma ray in the bombardment of B^{10} by 10-MeV protons.

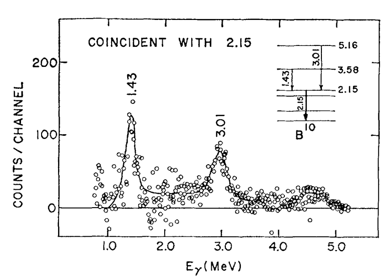

FIG. 7. Pulse-height spectrum of gamma rays observed in coincidence with the 2.15-MeV gamma ray in the bombardment of B^{10} by 10-MeV protons.

[7] W. F. Hornyak, C. A. Ludemann, and M. L. Roush, Nucl. Phys. **50**, 424 (1964).

trum shows the strong 0.72-MeV and 1.02-MeV gamma rays from the cascade decay of the 1.74-MeV level, as well as the 1.43-MeV and 3.01-MeV transitions that feed the 2.15-MeV level from above. A weak peak (<0.6% of the 1.02-MeV gamma ray) is seen at 1.74 MeV. This peak can be accounted for by the 130 counts estimated to be in the 0.72–1.02-MeV sum peak. Taking 200 counts as the maximum that could be in the 1.74-MeV peak and allowing for the summing effect, we find that the 1.74-MeV level decays directly to the ground state less than 0.2% of the time.

The most sensitive search for the 1.84-MeV gamma ray was carried out at a bombarding energy of 5.5 MeV with the 25×20-cm crystal placed at a distance of 50 cm from the target. Pulses (from the 20×15-cm crystal) corresponding to the 1.02-MeV gamma ray were used to gate the spectrum. Coincidence spectra were recorded with the 25×20-cm crystal set at angles of 35°, 90°, and 145°. There was no indication of a 1.84-MeV peak in any of the spectra. The sum of the three spectra from the 25×20-cm crystal is plotted in Fig. 9. In addition to the strong 0.72-MeV peak, there is a peak at 1.43 MeV from the 1.43–0.41—1.02–0.72-MeV chain emanating from the 3.58-MeV state. No accidental or background counts have been subtracted, but the weakness of the 1.02-MeV peak assures that these effects are negligible in the energy region of interest. Aluminum contamination in the target was responsible for the weak peak at 1.72 MeV, which arises from the 1.72–1.01-MeV cascade in Al^{27}. An upper limit of about 45 counts can be placed on any peak at 1.84 MeV in the spectrum of Fig. 9. From the intensity of the 1.43-MeV peak and the fact that the 1.43–0.41—1.02–0.72-MeV cascade represents about 6.5% of the decays of the 3.58-MeV state, we find that the branching ratio of the 1.84-MeV gamma ray from the 3.58-MeV state is less than 0.3%.

Hornyak, Ludemann, and Roush,[7] who populated the 3.58-MeV state with the $Be^9(p,\gamma)B^{10}$ reaction, have

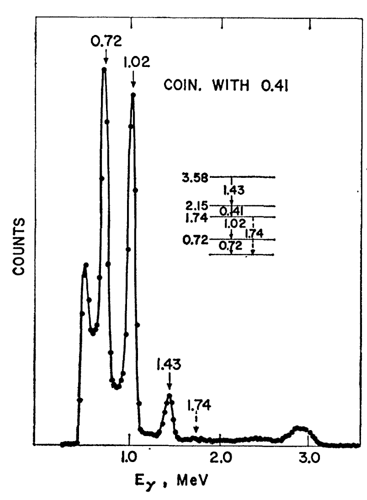

FIG. 8. Pulse-height spectrum of gamma rays observed in coincidence with the 0.41-MeV gamma ray in the bombardment of B^{10} by 7-MeV protons.

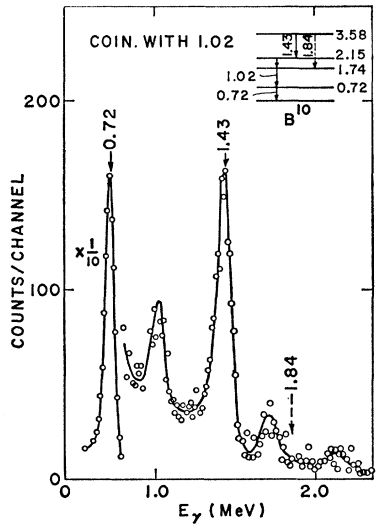

FIG. 9. Pulse-height spectrum of gamma rays observed in coincidence with the 1.02-MeV gamma ray in the bombardment of B^{10} by 5.5-MeV protons.

reported a (10±5)% branching ratio for the 1.84-MeV gamma ray—in direct contradiction to the present null result. This discrepancy was investigated further by examining the same capture reaction. Beryllium foils 100 keV thick were bombarded with 1.05-MeV protons whose energy, after allowing for target thickness, was equivalent to that in the experiment of Hornyak *et al.*[7] The cascades in this capture reaction were observed in much the same manner as in the inelastic proton scattering work described above. The 3.94-MeV gamma ray that feeds the 3.58-MeV state is very weak (<1%) and was only discernible in coincidence spectra. The spectrum in coincidence with 3.94-MeV pulses (Fig. 10) showed the 3.58-, 2.86-, and 1.43-MeV gamma rays, as well as the gamma rays from the 2.15-MeV state (which is fed by the 1.43-MeV gamma ray). Since the window on the 3.94-MeV pulses also accepted events from the

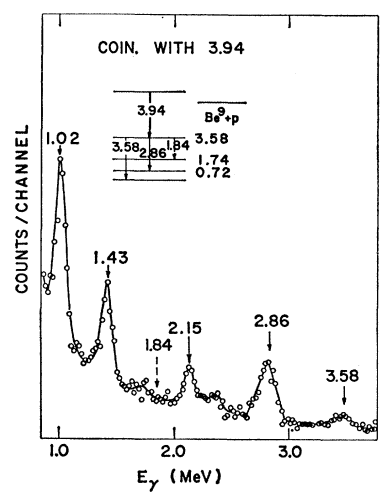

FIG. 10. Pulse-height spectrum of gamma rays observed in coincidence with the 3.94-MeV gamma ray in the bombardment of Be^9 by 1.05-MeV protons.

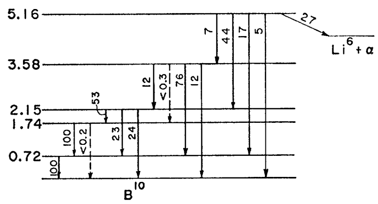

FIG. 11. Decay scheme of B^{10}. The 1.58-MeV branch from the 5.16-MeV level is from Ref. 9 and the ground-state branch from this level is from Ref. 8.

tail of the much stronger ($\approx 5\%$ of the captures) 5.37-MeV gamma ray feeding the 2.15-MeV state, the gamma rays from the 2.15-MeV state are relatively more intense than would be expected from the branching of the 3.58-MeV state. No evidence was found for the 1.84-MeV gamma ray; these measurements placed an upper limit of 3% on the branching ratio. This result agrees with the present results on the gamma rays following inelastic scattering but is in contradiction with the results of Hornyak *et al.*[7]

Figure 11 gives the decay scheme derived from all the measurements in the present experiment. Also shown are two transitions from the 5.16-MeV state that are too weak to have been observed in the present experiment; the gamma ray to the ground state whose branching ratio we take from the work of Meyer-Schützmeister and Hanna[8] and the recently discovered[9] branch to the 3.58-MeV state. Some noteworthy features of the decays of the various levels are as follows.

5.16-MeV level. The ratio of 2.6:1 found here for the intensity of the 3.01-MeV gamma ray relative to that of the 4.44-MeV gamma ray is in satisfactory agreement with the ratio of 2.2:1 reported by Meyer-Schützmeister and Hanna.[8] The alpha branch from this level is discussed below.

3.58-MeV level. In the present work, ratios of 12:76:12 were found for the relative intensities of the 3.58-, 2.86-, and 1.43-MeV gamma rays, respectively. These results are in fair agreement with the ratios of 20:60:20 listed in the compilation[3] and the ratios of 18:64:18 reported by Hornyak *et al.*[7] Theoretically, for the 1.84-MeV transition (which is an $E2$, $\Delta T=1$ transition and therefore not collectively enhanced) one would expect[10] a radiation width $\Gamma_\gamma \approx 0.1\Gamma_{\gamma w} = 2.3\times10^{-6}$ eV, where $\Gamma_{\gamma w}$ is the Weisskopf[11] estimate for a single-particle transition. The competing decay modes are isotopic-spin-inhibited $M1$ transitions whose energies are 3.58, 2.86, and 1.43 MeV for which one expects[10,12] $\Gamma_\gamma \approx 0.01\Gamma_{\gamma w} = 2.7\times10^{-2}$, 6.4×10^{-3}, and 8.0×10^{-4} eV, respectively. {*Note added in proof.* The lifetime of the 3.58-MeV state has recently been measured by Lonergan and Donahue [Bull. Am. Phys. Soc. **11**, 27 (1966)], Warburton, Olness, Jones, Chasman, Ristinen, and Wilkinson (to be published), and Hanna, Fisher, and Paul (private communication). The result of the latter authors, $\tau = (1.32\pm0.20)\times10^{-13}$ sec, gives widths of 7.5×10^{-4}, 3.5×10^{-3}, and 7.5×10^{-4} eV, respectively, for the three transitions. The lifetime of the 2.15-MeV state obtained by Hanna, Fisher, and Paul is $\tau = (4.0\pm1.0)\times10^{-12}$ sec. In a re-analysis of their data, the authors of Ref. 14 obtain a similar value (private communication). This lifetime reduces the radiation widths given in the text by a factor of 3. Thus, the 2.15-MeV transition ($E2$, $\Delta T=0$) is not strongly enhanced and the 0.41-MeV transition ($M1$, $\Delta T=1$) is a relatively weak allowed transition. Hanna, Fisher, and Paul find $\tau < 3\times10^{-14}$ sec for the 1.74-MeV state. This result removes the disagreement with the analog beta transition.} Thus, the failure to observe the 1.84-MeV transition is in accord with theoretical predictions.

2.15-MeV level. Branching ratios of 24:23:53 for the 2.15-, 1.44-, and 0.41-MeV gamma rays, respectively, are found in the present work. These are in good agreement with the 27:26:47 branching ratios reported by Hornyak *et al.*[7] and the 16:29:55 ratios reported by Sprenkel and Daughtry.[13] None of these determinations agrees well with the 30:40:30 ratios shown in the compilation.[3] A lifetime of $1.41\pm0.17\times10^{-12}$ sec has recently been obtained[14] for this level. If we adopt branching ratios of 22:26:52, we find 2:0.002:0.2 for the radiation widths expressed in terms of Weisskopf[11] units. Thus, the 2.15-MeV transition ($E2$, $\Delta T=0$) is collectively enhanced. Its radiation width $|M|^2=2$ may be compared with the width $|M|^2=3$ which has previously been determined[3] for the 0.72-MeV level (also $E2$, $\Delta T=0$). As has been previously pointed out,[15] the inhibition of the 1.43-MeV transition in comparison with the 0.41-MeV transition is an example of the operation of the isotopic-spin selection rule for $M1$ transitions. The values of 0.002 and 0.2 for $|M|^2$ fall within the ranges expected for inhibited ($\Delta T=0$) and allowed ($\Delta T=1$) $M1$ transitions, respectively.

1.74-MeV level. The value of $1.52\pm0.24\times10^{-13}$ sec obtained[14] for the lifetime of this state leads to $|M|^2 = 0.26$ for the 1.02-MeV transition ($M1$, $\Delta T=1$); this width lies in the allowed range. However, we note that a lifetime about a factor of 20 smaller is inferred[16] by the logft of the β decay of the C^{10} ground state (which is the

[8] L. Meyer-Schützmeister and S. S. Hanna, Phys. Rev. **108**, 1506 (1957).
[9] R. E. Segel and R. H. Siemssen, Phys. Letters **20**, 295 (1966).
[10] D. H. Wilkinson, *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, pp. 852–889.
[11] V. F. Weisskopf, Phys. Rev. **88**, 1073 (1951).
[12] E. K. Warburton, in *Proceedings of the Gatlinburg Conference on Electromagnetic Lifetimes and Properties of Nuclear States* (National Academy of Sciences—National Research Council Publication 974, Washington, D. C., 1962), p. 180.
[13] E. L. Sprenkel and J. W. Daughtry, Phys. Rev. **124**, 854 (1961).
[14] J. A. Lonergan and D. J. Donahue, Phys. Rev. **139**, B1149 (1965).
[15] G. Morpurgo, Phys. Rev. **100**, 271 (1958).
[16] D. Kurath (private communication).

analog of the 1.74-MeV state) to the 1.02-MeV state. We would then have $|M|^2 \approx 6$ which is at the high end of the allowed range and a more typical value[12] for a "deuteron transition." The Weisskopf estimate for the $M3$ ground-state transition is about 10^{-9} times the observed width and thus the failure to detect the ground-state transition is in accord with the accepted spin assignments.

ALPHA DECAY OF THE 5.16-MeV STATE

Even though the 2^+, $T=1$ state at 5.16 MeV is about 700 keV above the threshold for alpha emission, the observation of gamma rays emanating from this state indicates that isotopic-spin conservation strongly inhibits alpha emission. A measurement of the alpha branching ratio $\Gamma_\alpha/\Gamma = \Gamma_\alpha/(\Gamma_\alpha+\Gamma_\gamma)$ combined with a determination of the $Li^6(\alpha,\gamma)B^{10}$ yield (which is proportional to $\Gamma_\alpha\Gamma_\gamma/\Gamma$) permits evaluation of the partial widths. The $Li^6(\alpha,\gamma)B^{10}$ yield is known,[8] and in the present work the alpha branching ratio was determined by measuring (at the same incident proton energy) the cross section for inelastic scattering to the state and the cross section for the production of gamma rays that emanate from the state.

The measurements were performed at a proton bombarding energy of 10 MeV. For the measurement of the production of the state by inelastic protons, a thin B^{10} target (50 $\mu g/cm^2$) evaporated onto a thin carbon foil was bombarded with protons from the Aldermaston tandem. The resultant spectra of inelastic protons were analyzed by a magnetic spectrograph. The yields of the groups of interest were obtained at a number of angles between 20° and 175° (Fig. 12). The cross section integrated over angle for each group was determined with a relative error of 2%. The total production of gamma rays from each state was determined from the measurements described above. The decay rates for the higher states (i.e., those mainly populated directly by inelastic scattering) were determined with a relative error of 10%.

Table I compares the measured production of the various states as determined by inelastic protons and

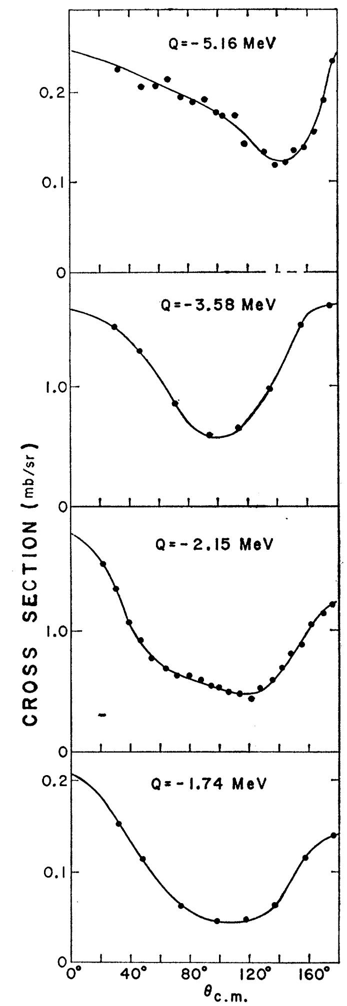

FIG. 12. Yields and angular distributions of four inelastic proton groups from the bombardment of B^{10} with 10-MeV protons.

by gamma rays. The discrepancy between the two measurements for the 5.16-MeV state is considered real and indicates that it decays by gamma rays about 73% of the time; the remainder of the decays must be through the alpha channel. The discrepancy for the 1.74-MeV state probably arises because this state is fed mainly by gamma rays and thus the direct excitation, as computed from the gamma rays, is obtained as the difference between two large numbers. In Table II, the intensities of various gamma-rays predicted from the inelastic proton yields and the gamma-ray branching ratios are compared with the measured intensities. Only the predicted intensities of gamma rays from the 5.16-MeV state are significantly less than the measured values; for the other gamma rays the agreement is satisfactory. The results in Table I give $\Gamma_\gamma/\Gamma = 0.73 \pm 0.15$ for the 5.16-MeV state. This result is in agreement with the value of 0.87 ± 0.04 recently found by Alburger *et al.*[17]

TABLE I. Comparison of the production rates of states in $B^{10}(p,p')B^{10*}$, as determined from the inelastic proton spectra and from the gamma-ray spectra at a bombarding energy of 10 MeV. The two sets of data were normalized by requiring that the sum of the populations of the bound states at 1.74, 2.15, and 3.58 MeV be the same in the two measurements.

Excitation energy (MeV)	Production cross section (mb) From inelastic protons	From gamma rays
5.16	3.36	2.46[a]
3.58	12.0	12.3
2.15	9.12	9.50
1.74	1.46	0.82

[a] Corrected for the two weak branches not observed in the present work.

[17] D. E. Alburger *et al.*, Phys. Rev. 143, 692 (1966).

TABLE II. Cross sections for producing various gamma rays as measured directly and as inferred from the inelastic proton spectra with $\Gamma_\gamma/\Gamma=1$ for the 5.16-MeV state. The two sets of data are normalized on the sum of the intensities of the 1.02-, 1.43-, 2.15-, and 2.86-MeV gamma rays (i.e., those that originate from bound states).

E_γ (MeV)	Cross section (mb) From inelastic protons	Measured directly
4.44	0.79	0.57
3.01	2.04	1.50
2.86	9.12	9.33
2.15	2.89	3.00
1.43	4.26	4.36
1.02	7.89	7.47

Combining the present result for Γ_γ with the known[8] value of $\Gamma_\gamma\Gamma_\alpha/\Gamma$ and taking into account the 1.58-MeV branch[9] to the 3.58-MeV state, we find $\Gamma_\gamma=1.24$ eV and $\Gamma_\alpha=0.34$ eV. This alpha width agrees with the inhibition expected from isotopic-spin conservation, since it is about 0.03% of a single-particle width. The partial widths and their comparison with the single-particle estimate for pure $M1$ radiation for the four gamma rays are: $\Gamma_\gamma(5.16)=0.09$ eV, $|M|^2=0.03$; $\Gamma_\gamma(4.44)=0.33$ eV, $|M|^2=0.16$; $\Gamma_\gamma(3.01)=0.71$ eV, $|M|^2=1.1$; and $\Gamma_\gamma(1.58)=0.11$ eV, $|M|^2=1.2$. These speeds span the range that is expected for $M1$ transitions allowed by isotopic spin. Calculations based on intermediate coupling predict gamma-ray widths that are consistent with these determinations.[16]

THE FIRST EXCITED STATE OF C^{10}

A peak at about 3.35 MeV appears in the singles spectrum of gamma rays at proton bombarding energies greater than about 8 MeV (Fig. 3). The energy and production threshold of this gamma ray identify it as the transition from the first excited state in C^{10}, formed in the reaction $B^{10}(p,n)C^{10*}$. The energy of this state is listed[3] as 3.34 ± 0.2 MeV. In the present work the energy of this transition was determined by calibrating the spectrum with the 0.717- and 2.866-MeV lines from B^{10*}. Determinations from spectra taken at $E_p=9$, 10, 11, and 12 MeV all gave values within 10 keV of 3.35 MeV. As a check, the energy of the strong C^{12} line at about 4.43 MeV (Fig. 13) was always found to be within 10 keV of 4.433 MeV, the listed energy of the first excited state of C^{12}. Hence, we find 3.35 ± 0.01 MeV for the energy of the first excited state in C^{10}. This measurement agrees with the value of 3.38 ± 0.03 MeV which Earwaker, Jenkin, and Titterton[15] obtained from a threshold determination in the $B^{10}(p,n)C^{10}$ reaction. Thus, the energy of C^{10*} agrees very well with the energy of 3.37 MeV for Be^{10*} and with the 3.42-MeV spacing between the first two analog states in B^{10}.

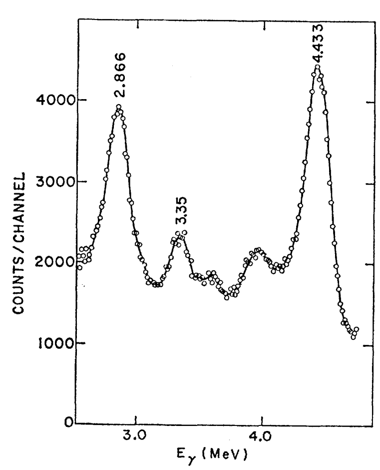

FIG. 13. Pulse-height spectrum of gamma rays observed in the bombardment of B^{10} by 11-MeV protons.

EXCITATION CURVES

Spectra in coincidence with the 0.72-MeV gamma ray were measured at 50-keV intervals for bombarding energies between 4.0 and 10.7 MeV, and in larger steps up to 12 MeV. From these spectra the yield curves for the 0.51-MeV gamma ray (from the β^+ decay of C^{10}), and for the 1.02-, 1.43-, 2.86-, and 4.44-MeV gamma rays from bombardment of B^{10} were obtained as shown in Fig. 14. The two 1.43-MeV gamma rays were not resolved, and a detailed yield curve of the annihilation radiation was measured only up to 10.15 MeV. Accidental coincidences and background (i.e., coincidence events not associated with the 0.72-MeV gamma ray) were usually small; both of these were measured at 1-MeV intervals and the yield curve of each gamma ray was corrected accordingly.

The relative efficiency of the total-energy peak in each crystal was determined as a function of gamma-ray energy by first computing the efficiency for an uncollimated crystal by use of the program described by Miller *et al.*[5] and then, with the aid of radioactive sources, empirically correcting for the effect of the collimator. The absolute efficiency was then determined by normalizing the gamma-ray yields to the inelastic proton yields at $E_p=10$ MeV (see above). This procedure was not valid for the annihilation radiation because these gamma rays did not ordinarily originate at the center of the target since (1) some of the C^{10} recoils could escape the target and (2) the positrons were able to travel some distance before annihilating. Therefore, the absolute cross section for the production of the 0.51-MeV gamma ray was determined by normalizing its yield to the C^{10} yield measured by Earwaker *et al.*[18] The validity of this procedure is demonstrated by the fact that the rise observed just above the threshold in the yield of the 3.35-MeV gamma ray from C^{10*} (as determined by the crystal efficiency since this gamma ray is produced at the

[18] L. G. Earwaker, J. G. Jenkin, and E. W. Titterton, Nucl. Phys. 42, 521 (1963).

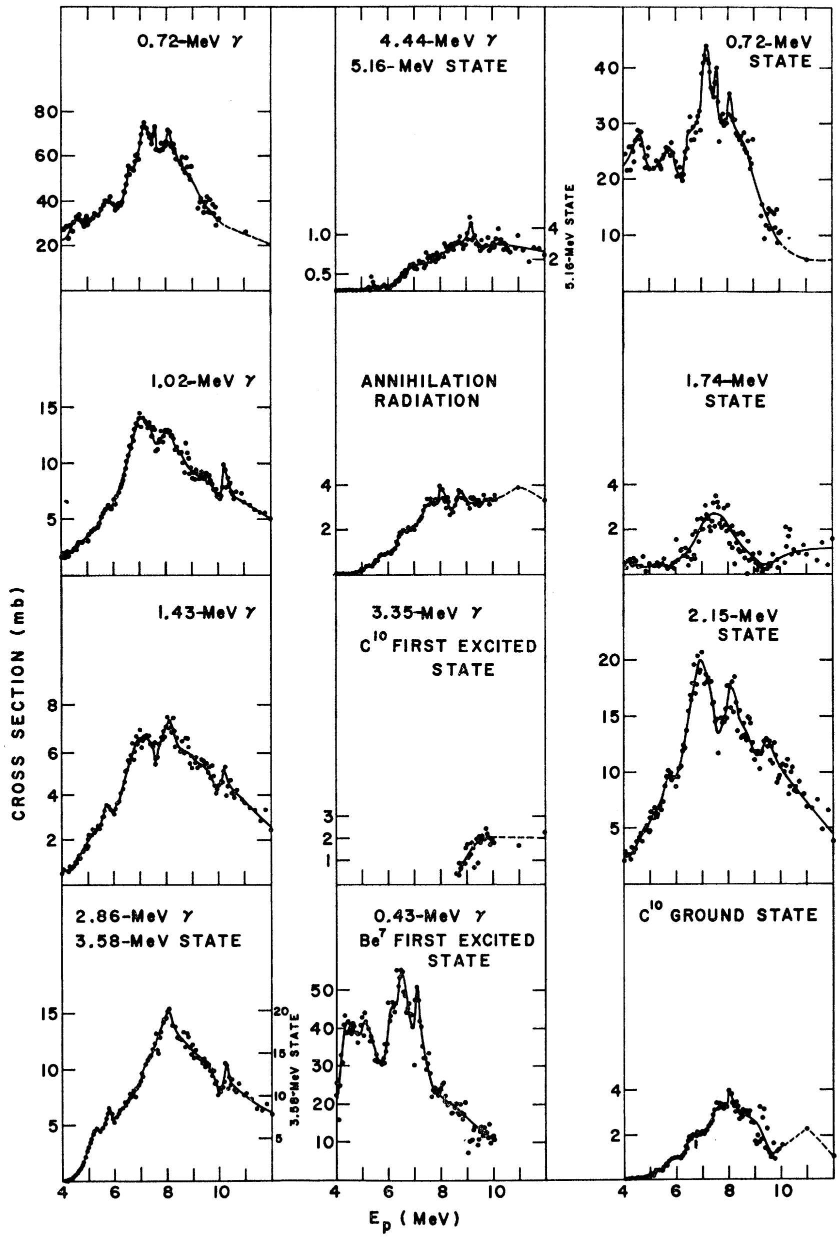

FIG. 14. Yield curves of gamma rays and states produced in the proton bombardment of B^{10}.

center of the target) is equal to the rise in the C^{10} production that Earwaker *et al.*[18] observed in the same energy region.

The intensities of the gamma rays emitted from the first excited states of B^{10}, C^{10}, and Be^7 were extracted from the singles spectra. Because of the large dead-time losses (exceeding 50%) in these spectra, only relative gamma-ray intensities were obtained; therefore, at each energy, the intensity of either the 1.02- or the 2.86-MeV gamma ray was used to normalize the intensities of the singles spectrum to the intensities obtained in the coincidence spectrum. The computed contribution from the 0.41-MeV transition in B^{10} was subtracted from the 0.42-MeV peak to obtain the intensity of the 0.43-MeV gamma ray emitted by the first excited state of Be^7. The singles spectra were recorded at 50-keV intervals between $E_p=4.0$ MeV and 10.15 MeV, and at 11.0 MeV and 12.0 MeV.

The yield curves for the various gamma rays are shown in Fig. 14. The yield of the 0.43-MeV gamma ray from Be^{7*} can be compared with the measurements of Jenkin, Earwaker, and Titterton[2] on the alpha particles in the reaction $B^{10}(p,\alpha_1)Be^{7*}$. The two measurements should be comparable, since the higher excited states in Be^7 do not decay significantly by gamma emission. There is good agreement in the over-all shape of the yield curve; in both experiments the yield is dominated by a broad maximum extending from about

$E_p=4$ MeV to about 7.5 MeV, with secondary maxima centered at about 4.4 MeV and 6.5 MeV. Additional fine structure appears in the present work, and the dip at $E_p=5.7$ MeV between the secondary maxima appears to be deeper than in the work of Jenkin *et al.*[1]; but in view of the various experimental uncertainties, the differences are probably not significant. At the maximum at $E_p=6.5$ MeV, both experiments find a cross section of about 50 mb. However, Jenkin *et al.* obtain a cross section of 75 mb at 4.4 MeV as compared to 40 mb in the present work. In both experiments the yield declines above 7 MeV and at 10 MeV it is only about 20% of the yield in the 4–7-MeV region.

Ophel, Glover, and Titterton[19] have measured the yields of 0.43-MeV and 0.72-MeV gamma rays in the $B^{10}+p$ reactions at proton energies up to 6 and 7 MeV, respectively. The shape of the yield curve for the 0.43-MeV gamma ray agrees with the result of Jenkin *et al.* discussed above; but the measured cross section at the 4.4-MeV resonance is only about 30 mb, in better agreement with the curve in Fig. 14. In the region of overlap, $4<E_p<7$ MeV, the curve of Ophel *et al.* for the 0.72-MeV gamma ray agrees well in shape and cross section with the corresponding curve in Fig. 14.

Some of the gamma-ray yield curves in Fig. 14 give directly the yield curves for the formation of final states in B^{10}, C^{10}, or Be^7. Where this is not so, a separate curve is given for each final state, as derived from the appropriate gamma-ray curves and the established decay scheme. Most of these curves display striking effects. The yields of both the 2.15- and 3.58-MeV states of B^{10} show a broad resonance, about 4 MeV wide and centered at about $E_p=8$ MeV, with some fine structure superimposed. The yield of the 0.72-MeV state displays a resonance about 2.5 MeV wide, centered at about 7.2 MeV, with some indication of fine structure. In the latter case, there is also structure in the $E_p=4$–6-MeV region. Evidence for broad resonances is also seen in the yield curves for the 1.74-MeV state of B^{10} and the ground state of C^{10}, but for these states the absolute yields are an order of magnitude less than for the states discussed above. This is true also of the 5.16-MeV state of B^{10} and the 3.35-MeV state of C^{10}, although in these cases the resonance structure is not as pronounced.

The yield curve for the formation of the first excited state of Be^7 also shows a giant-resonance structure in the region $4<E_p<8$ MeV with a maximum cross section even greater than that for any of the states in B^{10}. In addition, we note that in the work of Jenkin *et al.*[1] the yield curve for forming the ground state of Be^7 exhibits the same general features as does the curve for the first excited state, except that the former yield is usually greater and its maximum (≈ 160 mb) comes at about 4.3 MeV.

[19] T. R. Ophel, R. N. Glover, and E. W. Titterton, Nucl. Phys. 33, 198 (1962).

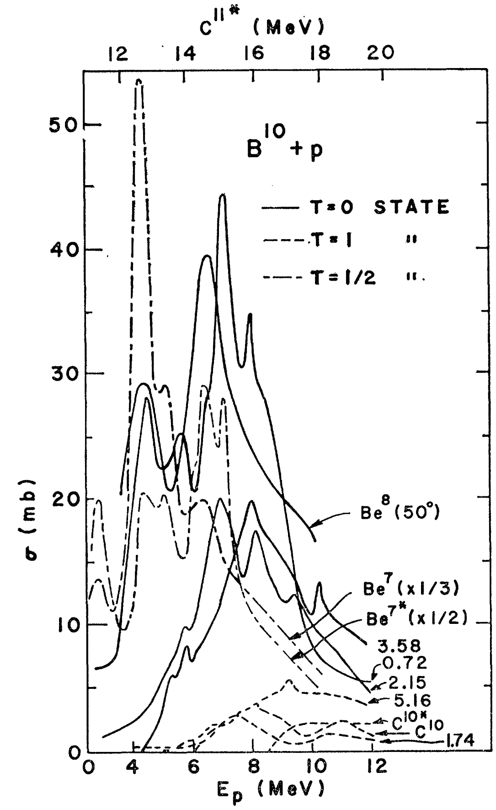

FIG. 15. Comparison of yield curves for the states produced in the proton bombardment of B^{10}. The curves labeled by energies refer to final states in B^{10}. The curves for Be^7 and Be^8 are taken from Refs. 1 and 2, respectively.

To complete the picture, the yield curve which Jenkin, Earwaker and Titterton[2] observed in the reaction $B^{10}(p,He^3)Be^8$ can be compared with the yield curves that are discussed above. Again, a broad complex resonance appears to exist in the region $4<E_p<8$ MeV. In this case the maximum cross section is approximately 35 mb.

In summary, the particles emitted from $B^{10}+p$ appear to fall into at least two distinct classes: (1) those that show strong resonances in the 4–10-MeV region, namely, the alpha and He^3 particles and the inelastic protons forming the 0.72-, 2.15-, and 3.58-MeV states in B^{10}, and (2) those that show a much weaker resonance or none at all in this region, namely, the neutrons and the inelastic protons forming the 1.74- and 5.16-MeV states of B^{10}. For the groups that show the strong resonance, the maximum cross sections vary from 20 mb to 160 mb and tend to increase with increasing Q. For the groups that do not show a strong resonance, the cross sections are all below 5 mb and reach their maxima in the 7–12-MeV region. It is noteworthy that the weak reactions are those for which the residual nucleus is left in a $T=1$ state. For comparison, all the cross section curves are plotted together in Fig. 15.

Schrank, Warburton, and Daehnick[20] have measured the inelastic proton scattering from B^{10} at a bombarding energy of 17 MeV. Table III compares their cross sections for the bound states with those measured at 12 MeV in the present work. In general, the cross sections are smaller—only for the 0.72-MeV state is a possible increase observed—in going from 12 MeV to 17 MeV. Thus, the giant-resonance nature that is observed in some of the yield curves below 12 MeV does not seem to repeat itself at higher energies.

DISCUSSION

Table IV lists the maximum cross sections for the exit channels, together with various quantities that could influence the cross sections. The correlation, noted above, between the cross sections and the reaction energies is quite pronounced and extends over all the channels. On the other hand, the orbital angular momenta of the initial and final particles appear to have little effect on the reactions; a measure of these angular momenta is obtained by listing the smallest possible value of their sum. Table IV also lists the isotopic spins of the final nuclei. As noted above, the formation of states with isotopic spins $(1,\frac{1}{2})$ is characterized by abnormally small cross sections. It would appear that the inhibition of these channels cannot be attributed solely to their Q values; the C^{10} ground state and the 1.74-MeV state in B^{10} both have Q values comparable to those of $T=0$ states having maximum cross sections an order of magnitude larger. The last column of Table IV gives the Clebsch-Gordan coefficients for forming the various isospin final states from the initial $(0,\frac{1}{2})$ state. It can be seen that some, but not all, of the inhibition of the $(1,\frac{1}{2})$ channels can be attributed to the Clebsch-Gordan coefficients.

The suppression of $T=1$ states is explained if the giant-resonance effects observed here are due to a resonance in the four-particle system $\alpha+\alpha+d+p$. In the energy region examined here, such a system could be expected to have rapid modes of decay into $Be^7(=\alpha+d+p)+\alpha$, $Be^8(=\alpha+\alpha)+He^3(=d+p)$, and $B^{10}(=\alpha+\alpha+d)+p$. Only those B^{10} states whose wave functions contain an appreciable amount of $(\alpha+\alpha+d)$ would be coupled strongly to this four-particle system; and such states, consisting of three $T=0$ particles, must of course have $T=0$. The fact that this four-particle giant resonance dominates the $B^{10}+p$ cross sections implies that the ground state of B^{10} contains a significant amount of $(\alpha+\alpha+d)$, while the fact that the channels leading to the other low-lying $T=0$ states in B^{10} also exhibit this resonance implies that they too can consist of these three clusters.

In summary, then, the giant-resonance-type behavior that is observed in $B^{10}+p$ in the $E_p=4$–10-MeV region appears to be explicable as a giant resonance in the $(\alpha+\alpha+d+p)$ system; if this explanation is accepted, the data then require that each of the four lowest lying $T=0$ states in B^{10} can be partially described as two alpha particles plus a deuteron.

We note that a similar explanation has been invoked[21] in order to account for some of the gross structure in the photodisintegration of C^{13} and N^{13}. Here a part of the giant dipole resonance is attributed to configurations consisting of a single nucleon plus a collectively excited, and therefore $T=0$, C^{12} core. Because such configurations can decay rapidly only into $(0,\frac{1}{2})$ states, the picture proposed by Measday, Clegg, and Fisher[21] leads to effects similar to those obseed in the present work.

TABLE III. Comparison of the cross sections of proton groups from the reaction $B^{10}(p,p')B^{10*}$ at bombarding energies of 12 and 17 MeV.

Excitation energy in B^{10} (MeV)	Cross section (mb) At $E_p=12$ MeV[a]	At $E_p=17$ MeV[b]
0.72	6.0±2	8.4±2
1.74	1.5±1	1.0±0.3
2.15	4.6±0.5	2.5±0.6
3.58	8.9+0.9	≈4

[a] Present work.
[b] Reference 17.

TABLE IV. Maximum cross sections observed for the various channels in the $B^{10}+p$ reactions. The reaction energy is given by Q, the orbital angular momenta of initial and final particles by l_i and l_f, and the isotopic spins of the final nuclei by T_{f1} and T_{f2}. The vector-addition coefficient for forming the final isotopic state from the initial state is denoted by CG.

Final state	σ_{max} (mb)	Q (MeV)	$(l_i+l_f)_{min}$	T_{f1}, T_{f2}	CG
$Be^7+\alpha$	160	1.15	1	$\frac{1}{2}$, 0	1
$Be^7{}_{0.43}+\alpha$	55	0.72	3	$\frac{1}{2}$, 0	1
$B^{10}{}_{0.72}+p$	45	−0.72	2	0, $\frac{1}{2}$	1
Be^8+He^3	35	−0.53	2	0, $\frac{1}{2}$	1
$B^{10}{}_{2.15}+p$	20	−2.15	2	0, $\frac{1}{2}$	1
$B^{10}{}_{3.58}+p$	20	−3.58	0	0, $\frac{1}{2}$	1
$B^{10}{}_{5.16}+p$	5	−5.16	0	1, $\frac{1}{2}$	$\frac{1}{3}$
$C^{10}+n$	3	−4.56	2	1, $\frac{1}{2}$	$\frac{2}{3}$
$B^{10}{}_{1.74}+p$	2	−1.74	2	1, $\frac{1}{2}$	$\frac{1}{3}$
$C^{10}{}_{3.35}+n$	2	−7.91	0	1, $\frac{1}{2}$	$\frac{2}{3}$

[20] G. Schrank, E. K. Warburton, and W. W. Daehnick, Phys. Rev. **127**, 2159 (1962).

[21] D. F. Measday, A. B. Clegg, and P. S. Fisher, Nucl. Phys. **61**, 269 (1965).