Gamma-Ray Decay of the Bound Levels of B^{12}†

J. W. Olness and E. K. Warburton
Brookhaven National Laboratory, Upton, New York
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Particle-γ and γ-γ coincidence measurements on the $B^{11}(d,p\gamma)B^{12}$ reaction were performed to determine the decay schemes of the bound excited states of B^{12}. Branching ratios for the decay of the second excited state (1.67 MeV) to the ground state and first excited state (0.953 MeV) were determined to be (96.8 ± 0.5) and $(3.2\pm0.5)\%$, respectively. The 2.62-MeV third excited state was found to decay to the ground state with a branch of $(6\pm1)\%$, and also to the first and second excited states with branches of (80 ± 3) and $(14\pm3)\%$, respectively. The last two values are from a γ-γ-γ coincidence measurement of the $2.62\rightarrow1.67\rightarrow0.95\rightarrow0$ triple cascade. Ge(Li) measurements of the $2.62\rightarrow0.95$ transition energy yield a value of 2620.8 ± 1.2 keV for the excitation energy of the initial state. A lower limit on the ground-state decay of the 2.723-MeV level of $>85\%$ was determined from p-γ coincidence measurements. These results are combined with previously available information on lifetimes, spins, and parities to permit a comparison with the shell-model predictions for the electromagnetic transitions connecting the bound levels of B^{12}.

I. INTRODUCTION

The main purpose of the experimental investigation described in this paper was to resolve the ambiguities connected with the γ-decay scheme of the third excited state of B^{12} at 2.62-MeV excitation energy.

Previous investigations[1] of B^{12} have given excitation energies of 953.14 ± 0.60 keV for the $J^\pi=2^+$ first excited state and 1673.65 ± 0.60 keV for the $J^\pi=2^-$ second excited state, and have further disclosed[2] that the 1674-keV state de-excites to the $J^\pi=1^+$ ground state [$(97.0\pm0.6)\%$] and first excited state [$(3.0\pm0.6)\%$].

A value 2618.5 ± 3.5 keV has been suggested[1] for the B^{12} 1^- third-excited-state excitation energy. Limits of <10 and 16% have been obtained[2] for the $2.62\rightarrow0$ and $2.62\rightarrow1.67$ transitions, indicating the main decay of the 2.62-MeV level is to the 0.95-MeV first excited state. Because of the accidental matching of the γ-ray energies which result for the two possible decay routes, $2.62\rightarrow1.67\rightarrow0$ and $2.62\rightarrow0.95\rightarrow0$, the branching ratios to the first and second excited states are difficult to determine. Evidence for a $2.62\rightarrow0$ ground-state branch of intensity $(9\pm6)\%$ has been reported by Gallmann *et al.*,[3] but is not of itself conclusive. Carlson and Norbeck[4] set a lower limit of $>80\%$ for the ground-state decay of the fourth excited state at 2.72 MeV[5]; no other decay routes have been reported for this level. It is with this information that the present experiment begins.

We have investigated the γ-ray de-excitation of the states of interest via the $B^{11}(d,p\gamma)B^{12}$ reaction ($Q=1.145$ MeV). In Sec. II we report the results of p-γ coincidence measurements in the $B^{11}(d,p\gamma)B^{12}$ reaction designed specifically to determine the relative branching of the $2.62\rightarrow0$ de-excitation. Information on the branching of the 1.67- and 2.72-MeV levels was also obtained. In Sec. III we report the results of γ-γ and γ-γ-γ coincidence measurements designed to unravel the de-excitation of the 2.62-MeV level to the 0.95- and 1.67-MeV levels. The determination of the excitation energy of this third excited state, using Ge(Li) spectroscopy, is reported in Sec. IV. Finally, in Sec. V, these new results are incorporated with previous information—specifically that given in the preceeding paper[2]—to provide the basis for a comparison between the experimentally determined properties of transitions connecting the bound states of B^{12} and various theoretical expectations.

II. PROTON-γ COINCIDENCE MEASUREMENTS

The decay modes of the first four excited states of B^{12} were investigated through proton-γ coincidence studies of the reaction $B^{11}(d,p\gamma)B^{12}$. Deuterons from the BNL 3.5-MV electrostatic accelerator were used to bombard a self-supporting 50 μg/cm^2 foil of enriched B^{11} which was placed at the center of a scattering chamber described previously.[6] Charged reaction products resulting from the bombardment were detected in an annular counter placed at 180° with respect to the incident deuteron beam and at a distance of 4 cm from the target. The angle subtended by the detector relative to the target was $(171\pm1.7)°$. γ rays were detected with a 5×5-in. NaI(Tl) detector placed at $\theta_\gamma=55°$ at a distance of 18.5 cm from the target. Amplified coincidence pulses from the two detectors were analyzed by a TMC 16384-channel two-parameter analyzer, which was gated by an external coincidence circuit operating at a resolving time of ~50 nsec. Data were stored in a $256(\gamma)\times64(p)$-channel array which was then put on magnetic tape for computer analysis, as described in detail previously.[6] The results of a measurement at $E_d=3.33$ MeV are shown in Fig. 1. These data were

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[3] A. Gallmann, F. Hibou, P. Fintz, P. E. Hodgson, and E. K. Warburton, Phys. Rev. **138**, B560 (1965).
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obtained in a run of about 18 h at a beam current of 0.02 μA. The randoms-to-real ratio for this spectrum was 0.21. The separate plots show the γ-ray spectra in coincidence with groups p_1, p_2, and p_3 from the $B^{11}(d,p)B^{12*}$ reaction. The inset shows the proton spectrum measured in coincidence with γ rays of energy $E_\gamma \gtrsim 200$ keV. The positions of the groups corresponding to population of the first 3 levels of C^{13} from the $C^{12}(d,p)C^{13*}$ reaction are indicated. The carbon contamination, due primarily to the presence of carbon introduced in the preparation of the target foils, did not cause any serious difficulty in the data analysis. This latter statement is illustrated by the upper spectrum of Fig. 1, in which only the 0.95-MeV γ ray from de-excitation of the 0.95-MeV state is seen. No evidence is found for annihilation radiation, or for the 3.09-, 3.68-, or 3.85-MeV radiations from C^{13}, which appeared rather strongly in the singles spectrum of γ rays.

The middle spectrum of Fig. 1 shows the de-excitation γ rays from the 1.67-MeV level of B^{12}. In addition to the strong $1.67 \rightarrow 0$ ground-state transition, we see γ rays of energies 0.72 and 0.95 MeV arising from the cascade transition $1.67 \rightarrow 0.95 \rightarrow 0$. The intensities of these latter two γ rays were found to be equal within their individual uncertainties, and hence we take an average of these values in calculating the cascade intensity. The branching ratios for the 1.67-MeV level are thus found to be (3.0 ± 0.6) and $(97.0 \pm 0.6)\%$ for the $1.67 \rightarrow 0.95$ and $1.67 \rightarrow 0$ transitions, respectively.

The lower spectrum of Fig. 1 shows the γ rays in coincidence with protons corresponding to population of the third excited state of B^{12} at 2.62 MeV. Previous γ-γ coincidence measurements[2,7] have determined that the strong peaks at 0.95 and 1.67 MeV arise primarily from the $2.62 \rightarrow 0.95 \rightarrow 0$ cascade transition rather than from the indistinguishable (on the basis of energy) $2.62 \rightarrow 1.67 \rightarrow 0$ cascade ($<16\%$). From the absence of a peak at 0.72 MeV, which would result from the 3% branch in the de-excitation of the 1.67-MeV level, we are able to say that the deexcitation of the 2.62-MeV level proceeds primarily through cascade transitions directly to the 0.95-MeV state, and an upper limit of 40% is placed on de-excitation via the 1.67-MeV level. The peak at 2.62 MeV, after a small correction (17%) for summing of the 1.67–0.95 γ rays, is found to have an intensity of 6.5% relative to the cascade transition intensity. We thus obtain a branching ratio of $(6 \pm 1)\%$ for the ground-state transition relative to the $(94 \pm 1)\%$ branch (or branches) via the cascade route (or routes).

The accuracy of this summing correction was later checked experimentally by placing a Na^{22} source at the target center and measuring the intensity of the 1.79-MeV sum peak relative to the 0.511- and 1.27-MeV peaks. The experimental result was found to agree well with the intensity computed from the peak-

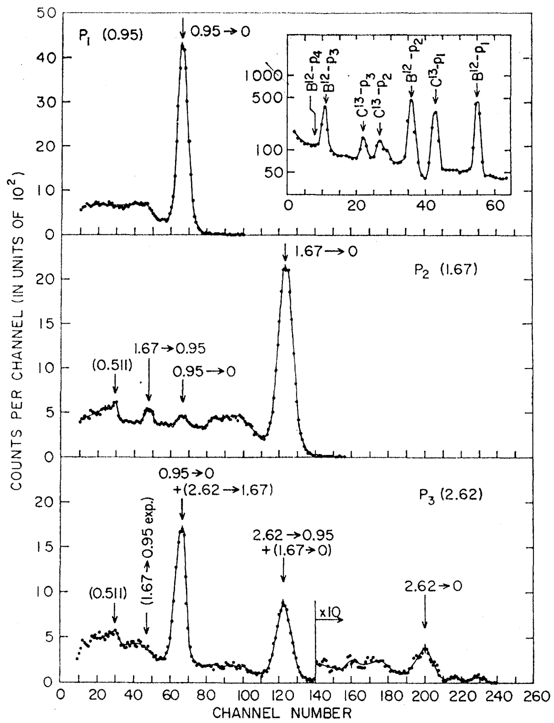

FIG. 1. Partial results of a two-parameter analysis of proton-γ coincidences in the $B^{11}(d,p\gamma)B^{12}$ reaction showing the γ spectra measured in coincidence with the proton groups leading to the first three excited states of B^{12}. These data were acquired in a single run at a bombarding energy $E_d = 3.33$ MeV. For each spectrum, the peaks are labeled according to the energies (in MeV) of the initial and final states of B^{12} between which the transition occurs. The inset shows, on a semilogarithmic scale, the corresponding particle spectrum measured in coincidence with all γ rays of energy $E_\gamma > 200$ keV. The peaks are identified according to the number of the particle group of the final nucleus.

efficiency data previously available[8] for 5×5-in. NaI(Tl) detectors.

By examining the proton spectrum in coincidence with γ rays of 2.72 MeV, it was determined that the B^{12} 2.72-MeV level was populated only very weakly at this bombarding energy and also that the p_4(2.72-MeV level) group was sufficiently well separated from the p_3(2.62-MeV level) group that its presence should have introduced no significant error into the analysis of the latter coincidence spectrum.

A second measurement was then carried out at a bombarding energy, $E_d = 3.775$ MeV, in an attempt to obtain some information on the decay of the 2.72-MeV level of B^{12}. Data were collected for 8 h at a beam current of 0.02 μA, with the proton dispersion increased so that only groups p_4 and p_3 from B^{12} and group p_3 from C^{13} were within the range of the two-parameter analyzer. With this dispersion the two groups from B^{12} were quite well resolved. The random-to-real

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[8] S. H. Vegors, L. L. Marsden, and R. L. Heath, Phillips Petroleum Company Report No. IDO-16370, 1958 (unpublished); F. C. Young, H. T. Heaton, G. W. Phillips, P. D. Forsyth, and J. B. Marion, Nucl. Instr. Methods **44**, 109 (1966).

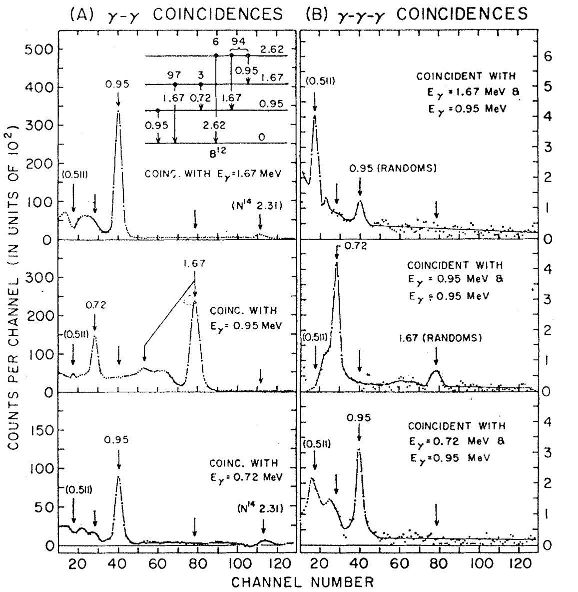

FIG. 2. Pertinent results from a two-parameter analysis of γ-ray coincidences in the $B^{11}(d,p\gamma)B^{12}$ reaction at $E_d=3.2$ MeV. The inset level scheme shows the previously known decay information for the B^{12} levels populated at this bombarding energy. (A) shows the results of a two-detector γ-γ measurement, showing the γ spectra measured by one detector in coincidence with various photopeaks viewed by the other. (B) shows the results of a 3-detector γ-γ-γ coincidence measurements, in which additionally a voltage gate was set on the 0.95-MeV photopeak of the third detector. It is evident from (B) that we have observed in coincidence all three members of the $2.62 \rightarrow 1.67 \rightarrow 0.95 \rightarrow 0$ triple cascade.

ratio for this spectrum was 0.16. Analysis of the spectrum coincident with group p_3 from $B^{11}(d,p)B^{12*}$ yielded the result $(6.1\pm1.0)\%$ for the branching ratio of the ground-state transition of the 2.62-MeV level, in excellent agreement with the results obtained for $E_d=3.3$ MeV. We adopt the value $(6.0\pm1)\%$ for this branching ratio.

The γ spectrum measured in coincidence with the peak corresponding to group p_4 of B^{12} showed the presence of γ rays of energy 2.72 MeV and also 3.85 MeV, indicating the presence of coincidences from the $O^{16}(d,p)O^{17}$ $(3.85 \rightarrow 0)$ reaction, which gives rise to a proton group energetically indistinguishable from the p_4 group of B^{12}. Since the 3.85-MeV level of O^{17} decays 100% by a ground-state transition, all lower energy transitions necessarily arise from B^{12}. The contributions in the net spectrum due to the B^{12} $2.72 \rightarrow 0$ and O^{17} $3.85 \rightarrow 0$ transitions were separated, using for this purpose line shapes generated from data on the 2.62-MeV γ rays from ThC″ and the 3.68- and 3.85-MeV γ rays of C^{13}. From the estimated areas of possible peaks at 1.77 and 0.95 MeV, we set a limit of $<8\%$ for the branching ratio of the $2.72 \rightarrow 0.95$ transition. Similarly, from the maximum possible peak areas corresponding to the 0.95- and 1.67-MeV peaks we set limits of <5 and $<10\%$ for the branching ratios of the $2.72 \rightarrow 1.67$ and $2.72 \rightarrow 2.62$ transitions.

In conclusion then, for the 2.72-MeV level, we can set a limit of $<15\%$ for the sum of all possible cascade transitions and thus for the ground-state transition a lower limit on the branching ratio of $>85\%$ is obtained. This result is in agreement with, but somewhat more restrictive than, the results of previous studies[3,4] of the B^{12} 2.72-MeV level.

III. TWO-PARAMETER STUDIES OF γ-RAY COINCIDENCES

A. Measurements

These studies were undertaken to search for a possible $2.62 \rightarrow 1.67$ branch. Because of accidental energy matching, the primary γ rays from this cascade would be indistinguishable from those γ rays from the stronger $2.62 \rightarrow 0.95$ branch, since either decay gives rise to both 1.67- and 0.95-MeV γ rays. However, the 1.67-MeV level branches ~3% to the 0.95-MeV level, and hence we could expect to see three coincident γ rays resulting from the $2.62 \rightarrow 1.67 \rightarrow 0.95 \rightarrow 0$ cascade, of energies 0.95, 0.72, and 0.95 MeV. Since the primary $2.62 \rightarrow 1.67$ de-excitation is of relative intensity $<16\%$,[2] the resultant intensity of these three cascade γ rays would be $<1\%$, and thus very difficult to see in the γ-singles spectrum, or even in γ-γ coincidence measurements, where the much stronger $1.67 \rightarrow 0.95 \rightarrow 0$ coincidences would predominate. Therefore, we have undertaken a γ-γ-γ coincidence measurement to search for evidence of γ rays from this triple cascade. This automatically removes all γ-ray contributions resulting from direct population of the 0.95- and 1.67-MeV levels, and also from the $2.62 \rightarrow 0.95 \rightarrow 0$ cascade. From the previously described p-γ measurements, it is also known that the 2.72-MeV level is not populated appreciably at energies $E_d<3.3$ MeV.

The measurements were carried out at a deuteron bombarding energy of 3.2 MeV, using the same target as employed for the p-γ measurements of the previous section. In this case, the target was fixed to a 3-mil Ta beam stop and placed at the center of a 1-in.-diam glass target chamber. Three 3×3-in. NaI(Tl) detectors were placed in the horizontal plane at angles and distances of (1) $\theta_1=-105°$, $d_1=2.6$ cm, (2) $\theta_2=+15°$, $d_2=3.1$ cm, and (3) $\theta_3=+105°$, $d_3=3.5$ cm, where for each detector θ is measured relative to the beam direction and d is measured (with an uncertainty of ±1.5 mm) from the target to the front face of the NaI(Tl) crystal. Coincidence pulses from detectors (2) and (3) were analyzed by a TMC 16384-channel analyzer operating in a 128×128-channel mode, with coincidence requirements imposed by an external fast-slow coincidence circuit. Two separate measurements were made: (a) For γ-γ-γ studies the circuit demanded a fast coincidence pulse from detectors (1), (2), and (3), together with a slow-coincidence pulse from a voltage gate set on the 0.95-MeV photopeak of detector No. (1). Thus, the two-parameter data array displayed pairs of γ rays coincident each with the other and, additionally, with 0.95-MeV γ rays. (b) By removing the fast-slow coincidence requirements on detector No. (1), pairs of coincident γ rays were also recorded. Normalization for these measurements was based on the beam charge deposited on target as recorded by a standard current integrator. An RIDL analyzer was used to display the spectrum of detector No. (3) as measured in coincidence with a voltage gate set on the 0.95-MeV photopeak of (alternately) detectors (1) or (2). From the intensity of the 1.67-MeV photopeak thus measured, the absolute population of the 2.62-MeV state during the course of the γ-γ-γ measurements was determined; this information was of course necessary to determine the relative intensity of the $2.62 \rightarrow 1.67$ branch. Partial results of these measurements are shown in Fig. 2.

The γ-γ coincidence data were acquired during a run of 18 h at a beam current of $\sim$2.5 nA for a total integrated charge of 153 μC. At this low beam current, the ratio of reals/randoms was better than 50/1. The plots show the γ spectrum measured by one detector in coincidence with the various photopeaks as viewed by the other. The photopeaks are identified by their energies (in MeV) and are seen to fit well with the B^{12} level scheme shown in the insert.

The γ-γ-γ coincidence data (also shown in Fig. 2) were acquired in a run of 66 h at a beam current of 0.008 μA for a total integrated charge of 1772 μC. In other respects, the conditions were the same as those which were obtained for the γ-γ measurements, save for the additional coincidence requirement that a 0.95-MeV γ ray be detected in detector No. (1). Thus, the spectra of Figs. 2(A) and 2(B) may be compared directly. From Fig. 2(B) we see that there is no third γ ray coincident with both 0.95- and 1.67-MeV γ rays. However, from the lower two plots, it is clear that 0.72- and 0.95-MeV γ rays are coincident with each other and also with a third 0.95-MeV γ ray, as viewed by detector No. (1). Thus we have directly observed in coincidence all three γ rays of the $2.62 \rightarrow 1.67 \rightarrow 0.95 \rightarrow 0$ cascade, determining that the $2.62 \rightarrow 1.67$ branch occurs. The presence in Fig. 2(B) of the peaks marked 0.95 (Randoms) and 1.67 (Randoms) results from random coincidences between pulses from detector No. (1) and the real (strong) 0.95–1.67 coincidence counting rates of detectors (2) and (3).

We now turn to a quantitative evaluation of the results shown in Fig. 2.

B. Measurements

Firstly, the γ-γ coincidence data of Fig. 2(A) were analyzed to provide an independent determination of the $1.67 \rightarrow 0.95$ branching ratio. The absolute photopeak efficiencies were taken from the curves of Heath[9] and from Vegors, Marsden, and Heath[8] for 3×3-in. NaI(Tl) detectors at the distances listed in Sec. III A. From singles measurements it was determined that under the given experimental conditions, the absolute production rate of 1.67-MeV γ rays (due to decay of both the 2.62- and 1.67-MeV levels) was $(3.80 \pm 0.2) \times 10^6$ per μC. From the γ-γ coincidence results of Fig. 2(A) that component due to decay of the 2.62-MeV level was found to be $(0.78 \pm 0.12) \times 10^6$ per μC, indicating the 1.67-MeV state de-excited directly via $1.67 \rightarrow 0$ transitions at a rate of $(3.02 \pm 0.24) \times 10^6$ per μC. Also from Fig. 2(A), the absolute 0.95–0.72 coincidence rate due to $1.67 \rightarrow 0.95 \rightarrow 0$ cascades was found to be 0.13×10^6 per μC. A preliminary value for the $1.67 \rightarrow 0.95$ branching ratio is then $(3.9 \pm 1.0)\%$. In the next subsection it will be shown that the 2.62-MeV level branches $\sim$14% via $2.62 \rightarrow 1.67$ cascade. After correcting for the number of $0.95 \rightarrow 0.72$ coincidences which arise from this source, we arrive at a value of $(3.7 \pm 0.8)\%$ for the $1.67 \rightarrow 0.95$ branching ratio. This is in satisfactory agreement with the value $(3.0 \pm 0.6)\%$ obtained from the p-γ results of Sec. II and we now take the average value $(3.2 \pm 0.5)\%$ for this branching ratio.

The good agreement between the two results for this branching ratio provides a satisfactory check on the accuracy of the absolute calibrations for these γ-γ measurements. In general, the various checks possible in the singles and doubles measurements were found to agree to within 10%, indicating this will not be the principal error in the subsequent γ-γ-γ measurements.

We turn now to a consideration of the γ-γ-γ results of Fig. 2(B). From the singles measurements, and also from the γ-γ results just discussed, we compute that the 2.62-MeV state was formed 15.60×10^8 times during the course of our measurement. (This number necessarily allows for the 6% $2.62 \rightarrow 0$ branch, which does not appear in the coincidence measurements.) From the intensity of 0.72–0.95-0.95 coincidences evident in Fig. 2(B) after a small, obvious correction for randoms, we compute that the 2.62-MeV state decays via $2.62 \rightarrow 1.67$ transitions a total of 2.2×10^8 times. This figure is obtained from the 0.72- and 0.95-MeV peak areas of Fig. 2(B) and is also based on the value $(3.2 \pm 0.5)\%$ for the $1.67 \rightarrow 0.95$ branching ratio. The fact that the $2.62 \rightarrow 1.67 \rightarrow 0.95 \rightarrow 0$ cascade results in *two* 0.95-MeV γ rays was taken account of in obtaining this last number.

We thus finally compute that the $2.62 \rightarrow 1.67$ transition is a $(14 \pm 3)\%$ branch, in competition with the $(6 \pm 1)\%$ $2.62 \rightarrow 0$ and $(80 \pm 3)\%$ $2.62 \rightarrow 0.95$ branches previously observed.

IV. Ge(Li) ENERGY MEASUREMENTS

The NaI(Tl)-Ge(Li) measurements of γ-ray coincidences described here were undertaken for the purpose of determining or setting stricter limits on

[9] R. L. Heath, Phillips Petroleum Company Report No. IDO-16408, 1957 (unpublished).

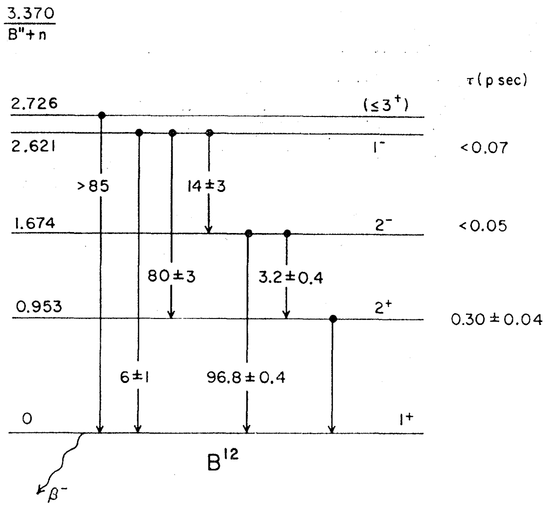

FIG. 3. Level diagram for the bound levels of B^{12}, summarizing the excitation energies and branching ratios determined in this and previous reports, as cited in the text. Values or limits determined for the mean lifetimes of these states are indicated also; the various references are cited in Sec. V of the text.

the relative branching of the 2.62-MeV level to the 1.67- and 0.95-MeV levels. In view of the experimental resolution obtained (a function of both the intrinsic detector line width and the Doppler broadening in the $B^{11}+d$ reaction) it was found that the γ-γ-γ measurements described in the previous section provided the only accurate determination of this branching; hence, the NaI(Tl)-Ge(Li) measurements were used primarily to determine the energy of the predominant $2.62 \rightarrow 0.95$ transition, and thus the excitation energy of the 2.62-MeV state.

The target for the measurement was made from a slurry of B^{11} powder on a 0.5-mil Ta backing. The detectors, a 4-cc Ge(Li) and a 3×3-in. NaI(Tl), were placed opposite each other at 90° relative to the incident deuteron direction and at 4 cm from the target. Each was shielded from the target by 11 gm/cm² of (Lucite+brass) absorber, which was sufficient to stop β's resulting from decay of the B^{12} nuclei.

Pulses from the two detectors were amplified by Ortec Model 220 linear amplifiers; coincidence conditions were imposed by Ortec fast-slow circuitry operating at a resolving time of 22 nsec. Coincidence-gated pulses from the Ge(Li) detector were analyzed and stored in a 1024-channel segment of a TMC 16384-channel analyzer, which was set to analyze the γ-ray pulse-height region 850–1800 keV.

Coincidence measurements (and also singles measurements) were carried out at $E_d=3.45$ MeV, at which energy the 2.62-MeV level is populated fairly strongly. Singles measurements were also made at $E_d=2.1$ MeV, where the only B^{12} γ rays are known[2] to arise from de-excitation of the 1.67- and 0.95-MeV states, and whose energies have been previously determined.[1]

As a check against possible gain shifts in the Ge(Li) detector, a weak Co^{60} source was placed near the target; thus, in all spectra the 1.17- and 1.33-MeV peaks from Co^{60} were evident and provided a convenient energy reference.

Three separate coincidence measurements extending over a 24-h period were made at $E_d=3.45$ MeV at a beam current of 0.4 nA for a total bombardment of 10 μC. The voltage gate on the NaI(Tl) detector was set to cover the region 850–1800 keV; thus, the Ge(Li) coincidence spectrum would display both members of the $2.62 \rightarrow 0.95 \rightarrow 0$ and $2.62 \rightarrow 1.67 \rightarrow 0$ cascades, while coincidences resulting from the $1.67 \rightarrow 0.95 \rightarrow 0$ (3% branch) would not appear. In the coincidence spectrum measured at $E_d=3.45$ MeV prominent peaks were observed at (953±1) and (1668.7±1) keV, having widths (full width at half-maximum≡FWHM) of 10 and 15 keV, respectively, as well as the Co^{60} peaks at 1.17 and 1.33 MeV (FWHM=6 keV). The energies quoted are based on the position of the Co^{60} lines and also on the results of singles measurements at $E_d=3.45$ and 2.1 MeV. The effects of Doppler broadening are evident in the measured widths of the B^{12} lines. However, since the Ge(Li) detector was located at $\theta_\gamma=90°$, the kinematics produce *only* a broadening of the line shape, and *not* a shift in the measured γ energy.

The γ rays resulting from the $1.67 \rightarrow 0$ and $0.95 \rightarrow 0$ transitions are known[1] to be of energy 1673.65±0.60 and 953.14±0.60 keV. The energy of the 0.95-MeV peak observed in the γ-γ measurements agrees with that of the $0.95 \rightarrow 0$ transition; that of the 1.67-MeV peak from the γ-γ measurement is in disagreement with the energy of the $1.67 \rightarrow 0$ transition. Thus, the present results confirm that the major branching of the 2.62-MeV level is via the $2.62 \rightarrow 0.95$ transition and not the $2.62 \rightarrow 1.67$ transition, in agreement with the conclusions of Sec. III. The 1668.7-keV peak is necessarily a doublet, due to the presence of the unresolved $2.62 \rightarrow 1.67 \rightarrow 0$ component. After correcting for this latter 14% branch, we arrive at a value of 1667.9±1.0 keV for the energy of the $2.62 \rightarrow 0.95$ transition. Using the value 953.14±0.60 for the energy of the B^{12} first excited state we conclude $E_{ex}=2621.0$ ±1.2 keV for the third excited state of B^{12}. This result is in good agreement with, and thus confirms, the value 2618.5±3.5 keV suggested by Williams *et al.*,[1] and we adopt the weighted average of 2620.8±1.2 keV for the excitation energy of the B^{12} third excited state.

In view of the excellent agreement between the excitation energies quoted herein for the first three excited states of B^{12} and those given in Ref. 5, we combine these results to arrive at a value of 2726±5 keV for the excitation energy of the B^{12} fourth excited state.

V. DISCUSSION OF RESULTS

The description of the first four levels of B^{12} as based on the results of the present investigation and that previous information cited herein and in Ref. 2 is shown schematically in Fig. 3. The excitation energies quoted for the first and second excited states are from Williams *et al.*,[1] while that for the third is the value obtained in Sec. IV of this paper. The branching ratios quoted are those determined in the present work with one exception: In view of the excellent agreement between the results given in Secs. II and III with those quoted in the preceeding paper,[2] we have adopted the indicated values (96.8±0.4) and (3.2±0.4)% for the branching of the 1.67-MeV level to the ground and first excited states of B^{12}. Also indicated in Fig. 3 are the values or limits adopted (see Secs. VA and VB) for the lifetimes of these B^{12} levels. The spin assignments are those given in the preceeding paper.[2] We note that in the analyses of Ref. 2 the branching-ratio information from the present investigation (Fig. 3) played a crucial part.

With this information in mind, we now proceed to a comparison between the experimental and theoretical descriptions of B^{12}.

A. 0.95-MeV Level

The independent-particle model (IPM) predicts[10] that the B^{12} ground state and first excited state are the two lowest $T=1$ states of the s^4p^8 configuration and have $J^\pi=1^+$ and 2^+, respectively. From Fig. 3 we see that the experimental spin-parity assignments are in agreement with this prediction. The IPM can be further tested by considering the neutron reduced widths of the two states and the electromagnetic transition connecting them.

The IPM calculations of Cohen and Kurath[10] give $B^{11}(d,p)B^{12}$ spectroscopic factors[11] (i.e., ratios of the neutron reduced width to the single-particle value) of 0.83 and 0.56 for the B^{12} 1^+ and 2^+ states, respectively. Spectroscopic factors of 0.78 and 0.54 were obtained for these states, respectively, from distorted-wave Born-approximation (DWBA) analysis of the $E_d=12$ MeV, $B^{11}(d,p)B^{12}$ angular distributions of Schiffer *et al.*[12] These experimental results are also in accord with the conclusions drawn from previous investigations.[3,13] Thus, the IPM predictions appear to be in satisfactory agreement with the $B^{11}(d,p)B^{12}$ stripping results reported to date.

We consider next the B^{12} $0.95\to0$ $M1$, $E2$ transition. Three measurements have been made of the lifetime of this transition. These give mean lifetimes in psec of 0.3±0.1,[14] 0.295±0.04,[15] and 0.29±0.07,[16] with a weighted average

$$\tau_{095}=0.30\pm0.033 \text{ psec}.$$

This mean lifetime corresponds to a radiative width of

$$\Gamma_\gamma(0.95)=(2.2_{-0.22}^{+0.27}) \text{ MeV}.$$

A limit on the magnitude of $x(E2/M1)$, the amplitude ratio of $E2$ to $M1$ radiation in the B^{12} $0.95\to0$ transition, can be inferred from the measured radiative width. We adopt the sum rule[14,17] $Z^2\Gamma_{\gamma W}$ as an upper limit on the radiative width of an $E2$ transition, where $Z^2=25$ for B^{12} and $\Gamma_{\gamma W}$ is the Weisskopf estimate[17] of the $E2$ radiative width evaluated for a radius constant $r_0=1.2$ F. Using this limit we find that $|x(E2/M1)|<0.124$ corresponds to two standard deviations from the measured value of Γ_γ. This we consider as a firm constraint on $x(E2/M1)$ for the $0.95\to0$ transition. Using this constraint, Chase *et al.*[2] found that $x(E2/M1)$ lies in the range $-0.124<x<+0.00$ (0.1% limit) or $-0.124<x<-0.03$ (10% limit). The phase conven-

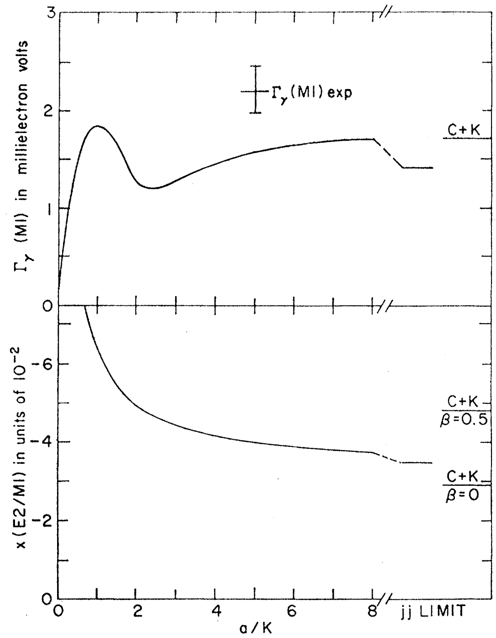

FIG. 4. Theoretical predictions for the M1 radiative width and the $E2/M1$ mixing ratio of the B^{12} $0.95\to0$ transition. The curves are the intermediate-coupling predictions of Soper. a/K is the intermediate-coupling parameter which determines the relative importance of the spin-orbit force ($a/K=0$ corresponds to LS coupling, $a/K=\infty$ corresponds to jj coupling). The predictions labeled C+K are those of Cohen and Kurath (Ref. 10) for their (8–16) POT interaction. For $x(E2/M1)$ the two C+K predictions correspond to no collective enhancement of the $E2$ rate ($\beta=0$) and collective enhancement via the effective-charge approximation with $\beta=0.5$. The predictions of Soper for $x(E2/M1)$ are also for $\beta=0.5$. The experimental measurement of the B^{12} $0.95\to0$ $M1$ radiative width is shown for comparison.

[10] See, e.g., S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965).
[11] S. Cohen and D. Kurath, Nucl. Phys. **A101**, 1 (1967).
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[14] E. K. Warburton and L. F. Chase, Jr., Phys. Rev. **132**, 2273 (1963).
[15] M. J. Throop, Bull. Am. Phys. Soc. **12**, 484 (1962).
[16] G. C. Morrison, J. E. Evans, N. H. Gale, R. W. Ollerhead, and E. K. Warburton (unpublished).
[17] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), Part B, pp. 852–889.

TABLE I. Minimum values of transition strengths and quadrupole mixing ratios from lifetime limits and branching ratios for the B^{12} 1.67- and 2.62-MeV levels.

Transition (MeV)	Minimum Γ_γ[a] (meV)	Minimum transition strength (Weisskopf units)[b] $E1$	$M2$	$E3$	$\lvert x(M2/E1)\rvert_{min}$[c]
$1.67 \rightarrow 0$	12.7	7.8×10^{-3}	1.3×10^{4}	1.1×10^{8}	0.045
$1.67 \rightarrow 0.95$	0.37	2.8×10^{-3}	2.4×10^{4}	1.1×10^{9}	0.032
$2.62 \rightarrow 0$	0.47	7.2×10^{-5}	4.8×10^{1}	1.7×10^{5}	0.72
$2.62 \rightarrow 0.95$	7.2	4.4×10^{-3}	7.3×10^{3}	6.1×10^{7}	0.060
$2.62 \rightarrow 1.67$	1.0	5.5×10^{-2}	9.7×10^{2}	8.0×10^{9}	0.163

[a] These values correspond to one standard deviation in the branching ratios of Fig. 3.

[b] These values are defined as $\Gamma_\gamma(\min)/\Gamma_{\gamma W}$, where $\Gamma_{\gamma W}$ is the Weisskopf estimate of Ref. 17. For the $2.62 \rightarrow 1.67$ transition $|M|^2$ refers to $M1$, $E2$, and $M3$ radiation rather than to $E1$, $M2$, and $E3$ radiation.

[c] Defined by $x^2/(1+x^2) \leq 25\Gamma_{\gamma W}(M2)/\Gamma_\gamma(\min)$. For the $2.62 \rightarrow 1.67$ transition the minimum value of $|x(E2/M1)|$ is given.

tion is that of Rose and Brink,[18] which for $E2/M1$ mixtures is the same as that of Litherland and Ferguson.[19] The upper limit on the percentage $E2$ contribution to the $0.95 \rightarrow 0$ transition corresponding to $|x| < 0.124$ is 1.5%; thus the experimental radiative width for this transition is essentially the $M1$ radiative width. IPM predictions for the $M1$ radiative width and for $x(E2/M1)$ are shown in Fig. 4. The intermediate coupling results, which give $\Gamma_\gamma(M1)$ and $x(E2/M1)$ as a function of a/K, are from calculations of Soper.[20,21] Effective interaction results of Cohen and Kurath[10] are shown on the right. We have taken the radial integral which appears in the expression for the $E2$ matrix element $\langle r^2\rangle_{1p1p}$ to be 7.056 F^2, in conformity with previous calculations.[22] The parameter β appearing in Fig. 4 is the *effective charge* in electronic units, i.e., the neutron is assumed to have a charge βe and the proton a charge $(1+\beta)e$. The intermediate coupling calculations of Soper have $\beta = 0.5$, which appears to give a good description of $1p$-shell $E2$ rates.[22] The results for $x(E2/M1)$ of Cohen and Kurath[10] are shown for both $\beta = 0.5$ and $\beta = 0$.

The phase of the theoretical $x(E2/M1)$ follows the convention of Rose and Brink.[18] Thus it is directly comparable to the experimental value quoted above. This phase was checked in the jj-coupling limit since, in this limit, the transition is a particularly simple one consisting of a transition between the two $T=1$ states which may be formed by coupling a $p_{3/2}$ proton hole to a $p_{1/2}$ neutron.

For B^{12} it is expected that a/K lies somewhere in the range 3–5. It is seen from Fig. 4 that the predictions for $\Gamma_\gamma(M1)$ are somewhat lower than experiment; however, we consider the agreement to be satisfactory.[23] The mixing ratio $x(E2/M1)$ is predicted to be negative and to have a magnitude of the order of ~ 0.05. Thus, both the predicted sign and magnitude of $x(E2/M1)$ are in agreement with the range demanded by the results of Chase *et al.*,[2] but are in disagreement with the sign of $x(E2/M1)$ obtained by Beck.[24]

B. 1.67- and 2.62-MeV Levels

These two states have $J^\pi = 2^-$ and 1^-, respectively, and probably can be roughly described as the two states which can be formed by coupling a $2s_{1/2}$ neutron to the $\frac{3}{2}-$ B^{11} ground state, the center of mass of the excitation energies of these two levels being in good agreement with that expected[25] on this model. However, the $B^{11}(d,p)B^{12}$ spectroscopic factors for these two levels are approximately $\frac{1}{2}$ of that predicted by this model,[3] indicating admixtures of components other than $B_{gs}^{11} \times 2s_{1/2}$.

Upper limits on the mean lifetimes of these two states have been determined as follows: 0.1,[3] 0.05,[15] 0.07[16] psec for the 1.67-MeV level and 0.1[3] and 0.07[16] psec for the 2.62-MeV level. The limits of Refs. 3 and 16 correspond to three standard deviations, while that of Ref. 15 corresponds to two standard deviations. We adopt upper limits of 0.05 and 0.07 psec for the mean lives of the B^{12} 1.67- and 2.62-MeV levels, respectively, which correspond to lower limits on the respective total radiative widths of 13.2 and 9.4 meV. Lower limits on the transition strengths corresponding to these lower limits on the total radiative widths are summarized in Table I. The minimum transition strengths, which are in Weisskopf units, were obtained using branching ratios one standard deviation less than the measured values (Fig. 3); the indicated multipolarity was assumed to be the only one contributing in each case. From this table it is seen that all five transitions are at least partially dipole. The last column of Table I gives, for each transition, upper limits on the magnitude of the quadrupole/dipole mixing ratio. These limits were used in the analysis of the $B^{11}(d,p\gamma\gamma)B^{12}$ angular correlations of Chase *et al.*,[2] which yielded the spins of these levels and limitations on the $E2/M1$ mixing ratio of the $0.95 \rightarrow 0$ transition. The limits were calculated, as outlined in Table I, by taking $Z^2\Gamma_{\gamma W}(=25\Gamma_{\gamma W})$ for the maximum strengths of both $E2$ and $M2$ transitions in B^{12}. The origin of this limit for $E2$ transitions has been discussed (see preceding subsection). The limit imposed for $M2$ transitions has no theoretical justification but is based on the empirical evidence that no $M2$ transitions in light $(A \leq 40)$ nuclei have been observed with strengths greater than ~ 2 Weisskopf units and the average strength of $M2$ transi-

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[19] A. E. Litherland and A. J. Ferguson, Can. J. Phys. **39**, 788 (1961).

[20] J. M. Soper (private communication). See Ref. 21 for details of Soper's intermediate-coupling calculations.

[21] E. K. Warburton, D. E. Alburger, D. H. Wilkinson, and J. M. Soper, Phys. Rev. **129**, 2191 (1963).

[22] A. R. Poletti, E. K. Warburton, and D. Kurath, Phys. Rev. **155**, 1096 (1967).

[23] The $0.95 \rightarrow 0$ $M1$ width is very sensitive to the wave functions of the initial and final states [Dieter Kurath (private communication)]. For instance, the width predicted by the (8–16) 2BME interaction (Ref. 10) is about 30% larger, although the wave functions are very little changed.

[24] F. Beck, Ann. Phys. (Paris) **1**, 503 (1966). The phase convention used by Beck for $E2/M1$ mixtures is opposite to ours.

[25] I. Talmi and I. Unna, Phys. Rev. Letters. **4**, 469 (1960).

tions is of the order of $\frac{1}{10}$ that of $E2$ transitions (both expressed in Weisskopf units).

The simplest model for the B^{12} 1^- and 2^- states at 2.62 and 1.67 MeV is that of a $2s_{1/2}$ neutron coupled to a $p_{3/2}^{-1}$ proton hole. Likewise, the simplest model for the B^{12} 1^+ and 2^+ states at 0 and 0.95 MeV is that of a $p_{1/2}$ neutron coupled to this same $p_{3/2}^{-1}$ proton hole. In spite of the fact that this is not a very realistic model, it is instructive to consider its predictions for the electromagnetic transition rates connecting these four states. These predictions can provide a guide to further experimental and theoretical work and, as already shown (the extreme jj limit results of Fig. 4), these predictions are actually in quite good agreement with the experimental results (and also with more refined calculations) for the $2^+ \rightarrow 1^+$ $0.95 \rightarrow 0$ transition. The predictions of this model are summarized in Table II. The $E1$ radiative widths were calculated with an effective neutron charge of $(-5/12)e$, which results from consideration of the center-of-mass effect. The radial integral $\langle r \rangle_{2s1p}$ which appears in the expression for the $E1$ matrix element, was taken to be -1.68 F.

From Table II we see that a decrease of the $E1$ matrix element for the $1.67 \rightarrow 0.95$ transition by only $\sim 50\%$ (or an $\sim 50\%$ increase in the $E1$ $1.67 \rightarrow 0$ matrix element) would bring the predictions for the branching ratios of the 1.67-MeV level into agreement with experiment. This we consider surprisingly good agreement for the crude model we have used. For the decay of the 2.62-MeV level, however, the agreement between predictions and experiment is markedly worse: our simplified model is obviously in need of refinement.

TABLE II. Comparison of the predictions of extreme jj coupling to experiment for the γ-ray decay of the 1.67- and 2.62-MeV level of B^{12}.

Transition (MeV)	Γ_γ (dipole) (meV)	Branching ratio (%) Extreme jj coupling	Experimental
$1.67 \rightarrow 0$	95.7	92.6	96.8 ± 0.4
$1.67 \rightarrow 0.95$	7.6	7.4	3.2 ± 0.4
Total	103.3	$\tau = 6.4 \times 10^{-15}$ sec	$\tau < 5 \times 10^{-14}$ sec
$2.62 \rightarrow 0$	122.2	26.8	6 ± 1
$2.62 \rightarrow 0.95$	157.2	34.5	80 ± 1
$2.62 \rightarrow 1.67$	175.8	38.6	14 ± 3
Total	455.2	$\tau = 1.4 \times 10^{-15}$ sec	$\tau < 7 \times 10^{-14}$ sec

One striking result of this calculation was the great strength, 9.9 Weisskopf units, predicted for the $M1$ $2.62 \rightarrow 1.67$ transition. The experimental branching ratios indicate a considerably smaller strength; however, these calculations provide a qualitative explanation for the successful competition of this transition with the energy- and parity-favored $E1$ $2.62 \rightarrow 0$ transition.

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