lens spectrometer. The Fermi plot shows groups with end-point energies of 0.801, 0.472, 0.347 Mev, together with the beta-rays from the Pm^{147} daughter with an end point at 0.225 Mev. Lower-energy groups may be hidden under the Pm^{147} beta rays. The energies agree with those originally determined by Kondaiah[18] and fit well into the scheme proposed by Hans *et al.*

The internal-conversion coefficient of the 92-kev gamma ray was measured in two ways. The first method consisted in measuring the intensities of the 92-kev gamma ray and the x-ray with the help of the calibrated scintillation counter described above. In these measurements, corrections were made for the absorption of the gamma ray and x-ray in the housing of the crystal and for the escape peak. The fluorescent yield was also properly taken into account in converting from x-ray intensity to the number of K-conversion electrons. The result of four measurements gave $\alpha_K^{\mathrm{Nd}}=1.53\pm0.08$. This is to be compared with the value obtained by Hans *et al.* of 1.6 ± 0.2.

In the second method, the internal-conversion coefficient was determined by a comparison method using Hg^{203}. The internal-conversion line of Nd^{147} and that of Hg^{203} at 279 kev were both measured in a magnetic lens spectrometer. The gamma-ray intensities of the 92-kev line of Nd^{147} and the 279-kev line of Hg^{203} were determined for the two sources, from which the internal-conversion electrons had been measured, with the help of the calibrated scintillation spectrometer. Using the value of $\alpha_K^{\mathrm{Hg}}=0.159$, as determined by Nordling, Siegbahn, and Sokolowski,[19] the results of the determination gave $\alpha_K^{\mathrm{Nd}}=1.50\pm0.07$. This result together with the one determined from comparison of the x-ray and gamma ray gives $\alpha_K^{\mathrm{Nd}}=1.52\pm0.05$. This value is somewhat lower than the theoretical value, $\alpha_K=1.68$, which one would calculate using 94% $M1$ and 6% $E2$ (from the result of Lindqvist and Karlsson[16]) and the tables of conversion coefficients of Sliv and Band.[9]

ACKNOWLEDGMENTS

The authors are indebted to Professor M. B. Sampson and the Cyclotron group for making the bombardments and to Mr. H. H. Helmick for technical assistance during the early part of the work. They also wish to thank Professor R. G. Wilkinson for allowing them to use his 180° spectrometer.

[18] E. Kondaiah, Phys. Rev. 71, 1056 (1951).

[19] Nordling, Siegbahn, and Sokolowski, Nuclear Phys. 1, 326 (1956).

PHYSICAL REVIEW VOLUME 111, NUMBER 5 SEPTEMBER 1, 1958

Levels of Be^{10} and B^{10}†

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(Received May 12, 1958)

The gamma rays produced in the bombardment of Be^9 (thick target) with 2.8-Mev deuterons were measured with a three-crystal pair spectrometer. The gamma rays are assigned in a consistent manner to decay from known levels of Be^{10} and B^{10}. Using information from stripping reactions it can then be inferred that the spins of the 5.96- and 6.26-Mev levels of Be^{10} are 1^- and 2^-, respectively. Furthermore it is shown that the gamma-ray and stripping information is consistent with spins 2^- and 2^+ for the 5.11- and 5.16-Mev levels of B^{10}, respectively, and that the 5.16-Mev level of B^{10} must have a very small alpha-particle reduced width, in accordance with a proposal of Wilkinson and Jones. Reduced widths of many levels of Be^{10} and B^{10} are summarized and analog levels in the two nuclei are searched for and compared.

I. INTRODUCTION

As part of a survey of gamma rays produced in deuteron-induced reactions,[1] the gamma rays from the Be^9+d reaction at 2.8 Mev were studied. Since recently certain discrepancies have been noted[2] in the spin assignments of the 5.11- and 5.16-Mev levels of B^{10} and in the energy dependence of the gamma-ray excitation in the Be^9+d reaction,[3] we wish to present our results ahead of a more detailed publication[1] in the hope that a certain amount of clarification will result. We also believe that our work, in conjunction with that of others (references given below) will give some clue

† Assisted in part by the Alfred P. Sloan Foundation, Inc., and by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission at Stanford University.

* Alfred P. Sloan Foundation Fellow, 1957–1958. On leave from Stanford University, 1957–1958.

[1] L. F. Chase, Jr., Ph.D. thesis, Stanford University, 1958 (unpublished); L. F. Chase, Jr. (to be published).

[2] L. Meyer-Schützmeister and S. S. Hanna, Phys. Rev. 108, 1506 (1957). We are very grateful to Dr. Hanna for sending us unpublished revisions for some of the level widths in the $Li^6(\alpha,\gamma)$ reaction. These revised widths have been incorporated in our paper (see footnote 27 and Table III).

[3] McCrary, Bonner, and Ranken, Phys. Rev. 108, 392 (1957). We are very grateful to Professor Bonner for sending us some original data of this work.

about the very large isotopic spin mixing which seems to occur[4] in the 6.89-Mev level of B^{10}.

II. EXPERIMENTAL METHOD AND RESULTS

The 2.8-Mev deuterons from the Stanford cyclotron were directed onto a $\frac{1}{16}$-in.-thick piece of Be. Gamma rays produced at 45° with respect to the deuteron beam were collimated by means of a $\frac{3}{8}$-in.-diam×6-in. long hole in a lead shield onto the center crystal of a three-crystal pair spectrometer.[5] The resulting pulse-height spectrum is shown in Fig. 1. (Various parts of the energy spectrum were measured separately with a 20-channel pulse-height analyzer. These were normalized with respect to each other and the curves were compounded to give the curve shown in Fig. 1. In order to show that the compounded curve was consistent with the separate curves, these were analyzed separately also.) The background indicated in Fig. 1 by a dashed line was determined by plugging the gamma-ray collimating hole with lead. Although this eliminates the detection of a possible background due to neutrons passing through the collimating channel, we believe that this introduces a negligible error because of the very small solid angle involved.

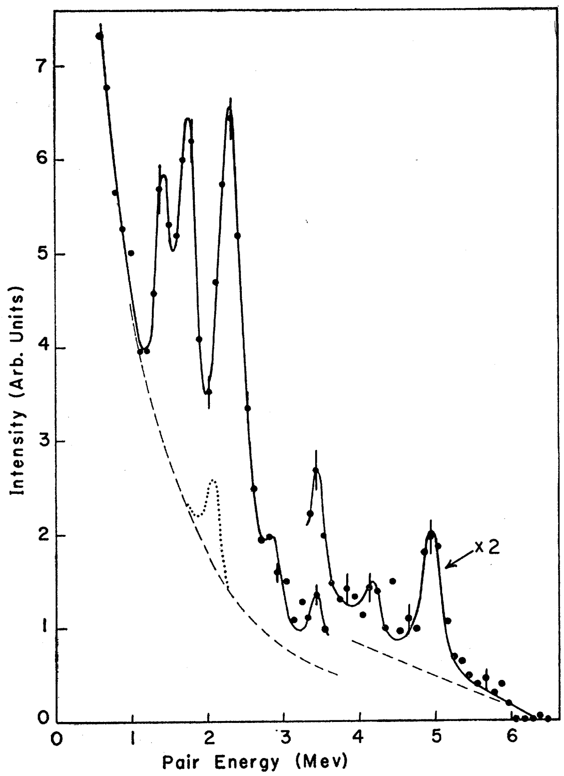

FIG. 1. Scintillation pair spectrometer spectrum of the gamma rays from the Be^9+d reaction (thick target, 2.8-Mev deuteron energy). Note that along the abscissa the pair energy ($E_\gamma-1.02$ Mev) is plotted. The broken line represents the background measured as described in the text (Sec. II). The experimental points were analyzed by means of semiempirical line shapes and the result is given in Table I. The full line is the sum of the background and the semiempirical line shapes as fitted to the experimental points. The line shape for the 3.1-Mev gamma ray is shown in dotted line; the other gamma rays are apparent from the full curve.

[4] D. H. Wilkinson and A. B. Clegg, Phil. Mag. **1**, 291 (1956); A. B. Clegg, Phil. Mag. **1**, 1116 (1956).

[5] The pair spectrometer has been described by H. I. West, Jr. and L. G. Mann, Rev. Sci. Instr. **25**, 129 (1954); the center crystal was replaced by a $\frac{3}{4}$-in.-diam×3-in. long crystal and the photographic pulse-height detection method was replaced by a 20-channel pulse-height analyzer.

TABLE I. Gamma rays from the Be^9+d reaction. All gamma-ray yields are given for thick targets. The gamma-ray energies have not been corrected for Doppler shifts. E_d = deuteron energy.

Gamma-ray energy (Mev) (Chase)[a]	E_d = 2.8 Mev Rel. Int. (Chase)[a]	Rel. Int. (McCrary)[b]	E_d = 2.5 Mev Rel. Int. (Mackin)[c]	Rel. Int. (Bent)[d]	Assignment (energies in Mev)
6.01 ± 0.06	12 ± 3	19	7	7	Be^{10}, 5.96 → 0
5.2 ± 0.2	⩽4	⩽ 7[f]		1	B^{10}, 5.16 → 0
4.46 ± 0.10	11 ± 3	10	5	2	B^{10}, 5.16 → 0.72
3.91 ± 0.08	16 ± 4	⩽14[f]			B^{10}, 4.77 → 0.72
3.64 ± 0.06	16 ± 4	19[f]	26		B^{10}, 3.58 → 0
3.36 ± 0.03	92 ± 6	92	92		Be^{10}, 3.37 → 0
3.11 ± 0.10	15 ± 5				B^{10}, 5.16 → 2.15
2.84 ± 0.04	70 ± 6[e]	62			B^{10}, 3.58 → 0.72
					Be^{10}, 6.26 → 3.37
2.54 ± 0.04	43 ± 6				Be^{10}, 5.96 → 3.37

[a] See reference 1.
[b] See reference 3. The results given there have been interpolated at 2.8-Mev deuteron energy.
[c] See reference 7.
[d] See reference 6.
[e] A relative intensity of 26 ± 4 is assigned to Be^{10}, the rest to B^{10}. See text and Fig. 2.
[f] Taken from the original data of reference 3.

By the use of semiempirical line shapes[1] for monoenergetic gamma rays, the curve shown in Fig. 1 was analyzed. The resulting relative gamma-ray intensities are shown in Table I, where they are compared to the work of McCrary *et al.*[3] (interpolated at 2.8-Mev deuteron energy) and to the work of Bent *et al.*[6] as well as of Mackin[7,8] at 2.5-Mev deuteron energy. Fair agreement of the relative gamma-ray intensities between the various groups of workers may be noted.

III. INTERPRETATION OF EXPERIMENTAL RESULTS

Table I and Fig. 2 show the assignments of the gamma rays to various transitions between known levels[8] of Be^{10} and B^{10}. These assignments follow those of Bent *et al.*[6] and McCrary *et al.*,[3] except that for reasons given below part of the intensity of the 2.84-Mev gamma ray is definitely assigned[9] to the 6.26→3.37-Mev transition in Be^{10} and a (2.54±0.04)-Mev gamma ray, not previously detected, is assigned to the 5.96→3.37-Mev transition in Be^{10}. It should also be noted that the assignments in Table I are consistent with earlier work[8]

[6] Bent, Bonner, McCrary, Ranken, and Sippel, Phys. Rev. **99**, 710 (1955).

[7] R. J. Mackin, Ph.D. thesis, California Institute of Technology, 1953 (unpublished).

[8] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955); T. Lauritsen and F. Ajzenberg-Selove, *American Institute of Physics Handbook*, edited by D. E. Gray (McGraw-Hill Book Company, Inc., New York, 1957), Sec. 8e. We are very grateful to these authors for making available to us unpublished notes for a forthcoming compilation of Energy Levels of Light Nuclei, VI, Revs. Modern Phys. (to be published).

[9] Compare footnote *a* to Table III in reference 3.

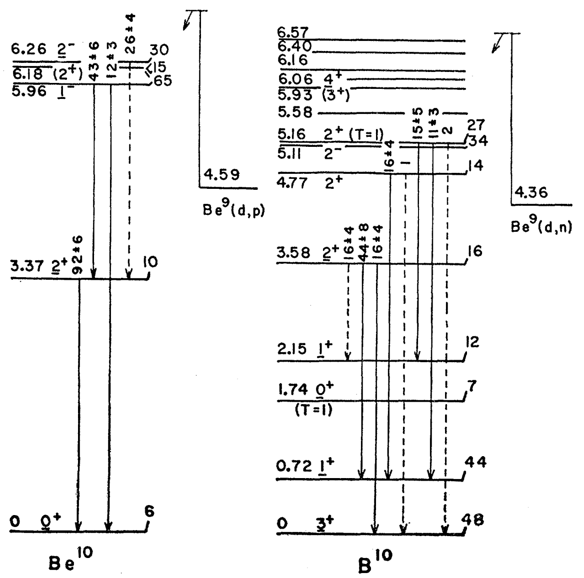

FIG. 2. The gamma rays determined in the present experiment fitted into the known levels of Be[10] and B[10]. Relative thick-target yields (at 2.8-Mev deuteron energy and at 45° to the deuteron beam) of the gamma rays are indicated (see also Table I). Intensities of gamma rays shown in dotted lines were calculated from other data (see text and references 2 and 8). On the right side of each level the thin-target feeding cross sections in the Be^9+d reaction at about 3.5-Mev deuteron energy is given. See text for the significance of a comparison of these feeding cross sections with the relative thick-target gamma-ray yields. Only those levels of Be[10] and B[10] are indicated which could be reached with 2.8-Mev deuteron energy. Spin values which are underlined are believed to be certain, those not so marked are likely, and those in brackets are proposed, as described in the text.

on the Be^9+d reaction, as well as with the gamma decay of B[10] levels reached in the $Li^6(\alpha,\gamma)$ reaction.[2]

An argument, perhaps not previously advanced, for assigning the 6.01-Mev gamma ray (energy not corrected for Doppler shift) to ground state decay from the 5.96-Mev level of Be[10] rather than from the 5.93-Mev level[10] of B[10] can be made on the basis of the excitation functions of the 3.37- and 5.96-Mev gamma rays, shown in Fig. 4 of reference 3. One notices first that the 5.96-Mev gamma-ray excitation rises only very slowly from threshold, contrary to what one would expect on the basis of the $Be^9(d,n)$ excitation[11] of the 5.93-Mev level of B[10]. Second, one notes that the 5.96- and 3.37-Mev excitation curves are rather parallel above 2-Mev deuteron energy, indicating that as the 5.96-Mev level of Be[10] is populated, so is the 3.37-Mev level populated (by the 2.54-Mev gamma ray, mentioned above). As will be discussed immediately, though, some of the 3.37-Mev level feeding occurs via a 2.89-Mev gamma-ray transition from the 6.26-Mev level.[9]

In order to find out whether our gamma-ray assignments are consistent with the neutron and proton branching ratios to the B[10] and Be[10] levels in the Be^9+d reaction at 2.8 Mev, it would have been best to compute the gamma-ray yields from total $Be^9(d,n)$ and $Be^9(d,p)$ cross sections integrated over the appropriate range after taking into account the angular distribution of the gamma rays. Unfortunately not enough absolute cross sections (or even relative cross sections) have been measured to make this possible.[8] Hence we have tried a rather crude approach, which is to compare the thick-target gamma-ray yields at one angle (45°) and at 2.8-Mev deuteron energy with total (d,n) and (d,p) cross sections near 3.5 Mev. These can be calculated from previously published work.[12–15]

(d,n) and (d,p) cross sections for light nuclei seem to have the property that they rise fairly rapidly with energy from threshold and then remain rather constant (to an accuracy sufficient for our purpose). In the case of levels of Be[10] and B[10] reached by exothermic reactions (see Fig. 2), the "plateau" of the cross sections seems to be reached at a deuteron energy below 1 Mev.[16,17] In the case of the other levels of interest to us (see Fig. 2), the cross sections seem to be rising within an energy interval of less than 1 Mev and reach a "plateau" at a deuteron energy close to 3 Mev.[3] This means that at 2.8-Mev deuteron energy the thick-target gamma-ray yield from Be[10] and B[10] levels reached by endothermic reactions (see Fig. 2) will arise mainly from deuterons of energy above 2 Mev and will be roughly proportional to the (d,p) and (d,n) cross sections near 3.5 Mev,[12,13] *at least to within a factor of less than five or so*, which is perfectly sufficient for our later arguments. On the other hand, we may expect that the thick-target yield of gamma rays from a level reached by an exothermic reaction arises from a wide range of deuteron energies and hence a simple comparison with the cross section at 3.5-Mev deuteron energy may underestimate the gamma-ray yield by a large factor.

To make the afore-mentioned comparison, we have first integrated the relative $Be^9(d,n)$ differential cross sections at 3.4-Mev deuteron energy[12] from 0° to 90° (c.m.). The cross sections were not measured beyond 90° (c.m.); neglect of the backward angles should not introduce an error in the relative $Be^9(d,n)$ total cross sections by more than a factor of 2. Second, we have integrated the (absolute) $Be^9(d,p)$ differential cross section at 3.6-Mev deuteron energy[13] to the ground and 3.37-Mev states of Be[10] from 0° to 90° (c.m.). Third, we have calculated the (0° to 90° c.m.) total cross sections to the other excited states of Be[10] at 3.6-Mev deuteron energy by making use of the relative neutron

[10] See remark in reference 8 on this point.
[11] T. W. Bonner and J. W. Butler, Phys. Rev. **83**, 1091 (1951).
[12] F. Ajzenberg, Phys. Rev. **82**, 43 (1951); **88**, 298 (1952).
[13] Fulbright, Brunner, Bromley, and Goldman, Phys. Rev. **88**, 700 (1952).
[14] T. S. Green and R. Middleton, Proc. Phys. Soc. (London) **A69**, 28 (1956).
[15] Calvert, Jaffee, and Maslin, Phys. Rev. **101**, 501 (1957).
[16] A. I. Shpetnyi, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 423 (1957) [translation: Soviet Phys. JETP **5**, 357 (1957)].
[17] N. Jarmie and J. D. Seagrave, Los Alamos Scientific Laboratory, University of California, Report LA-2014, February 1, 1957 (unpublished), available from the Office of Technical Services, U. S. Department of Commerce, Washington 25, D. C.

reduced widths[18] given in reference 14. We have assumed that the relative reduced widths do not change with deuteron energy to any appreciable extent[19] and also that the relative compound-nucleus contribution to the total cross section does not vary appreciably between 3- and 9-Mev deuteron energy. We believe that these assumptions are valid to within a factor of 2.

In order to match the relative total $Be^9(d,n)$ cross sections (at 3.4 Mev) to the relative total $Be^9(d,p)$ cross section (at 3.6 Mev), we have used the fact[15] that the neutron reduced width of the ground state of Be^{10} is about twice as large as the proton reduced width of the 1.74-Mev state of B^{10}, in agreement with theory.[20] Making use of the procedure of reference 18, the match is easily effected. The final results for the "feeding cross sections" of the Be^{10} and B^{10} levels in the Be^9+d reaction at about 3.5 Mev are indicated on Fig. 2. Since the measurements of Fulbright *et al.*[13] were made on an absolute basis, the cross sections (0° to 90° c.m. only) on Fig. 2 happen to be expressed in millibarns, but this is immaterial for our purposes.

Remembering the reservations previously expressed we now proceed to compare our relative gamma-ray yields (see Table I) with the estimated feeding cross sections (see Fig. 2). On the Be^{10} side of Fig. 2 we note that the 6.26- and 5.96-Mev levels are fed in a ratio[21] close to 1:2, but no 6.26-Mev gamma ray has been detected by us or by others.[3,6] From the sum of the measured relative intensities of our 2.54- and 6.01-Mev gamma-rays we calculate the expected relative intensity of the 6.26→3.37-Mev gamma ray in accordance with the feeding cross sections, as shown in Fig. 2. In this way we note that most of the 3.36-Mev gamma-ray intensity is accounted for by gamma-ray transitions from the 6.26- and 5.96-Mev levels. This is in agreement with the small feeding cross section of the 3.37-Mev level. (As mentioned above, though, this feeding cross section underestimates the thick-target proton branching ratio—here apparently by about a factor of 2.)

These gamma-ray assignments agree very roughly with results which can be inferred[22] from the work of McCrary *et al.*[3] Also they explain why the excitation of the 3.37-Mev gamma ray compared to the sum of the 2.84- and 3.11-Mev gamma rays of B^{10} rises more rapidly[3] with increasing deuteron energy than one would expect on the basis of a reasonable energy dependence of the $Be^9(d,p)$ and (d,n) cross sections.[3]

Our Be^{10} assignments are useful for two purposes. First they enable us to normalize our relative gamma-ray yields to the feeding cross sections of the Be^{10} levels; this has indeed been done on Fig. 2 and in Table I. Second, in view of the fact that the 5.96- and 6.26-Mev levels must have spins 1^- or 2^- as shown by the stripping cross section measurements of Green and Middleton,[14] we can make a spin assignment of 1^- to the 5.96-Mev level and 2^- to the 6.26-Mev level of Be^{10}, noting the absence of the 6.26-Mev gamma ray ($2^-\rightarrow 0^+$) and the roughly comparable intensities of the decays from the 5.96-Mev level to the ground state ($1^-\rightarrow 0^+$) and to the 3.37-Mev state ($1^-\rightarrow 2^+$). These spin assignments will be used for further discussions below.

Turning now to the B^{10} side of Fig. 2, we wish to emphasize that since the gamma-ray intensities have been normalized to the feeding cross sections of Be^{10}, and since the feeding cross sections of B^{10} have been matched to those of Be^{10}, no further adjustments are possible. We note first that the feeding cross section to the 3.58-Mev level underestimates the gamma-ray yield from this level by about a factor of 5. This is in agreement with our previous considerations and with the fact that the $Be^9(d,n)$ cross section to the 3.58-Mev level has reached a "plateau" already at 0.5 Mev.[16] It is encouraging that after subtraction of the (estimated) Be^{10} contribution from the 2.84-Mev gamma-ray intensity, the ratio of the intensities of the 2.84- to 3.64-Mev gamma rays is 2.8 ± 0.9 in agreement with the value 3 found elsewhere.[8]

The gamma-ray intensities from the 4.77- and 5.16-Mev levels are reasonable in comparison with the feeding cross sections (even if the latter are multiplied by factors of up to 5 or 10, since these levels have the possibility of decaying by alpha emission[2] to the ground state of Li^6). Within experimental error, no decay from the 5.11-, 5.93-, and 6.06-Mev levels was noted, in agreement with the large alpha-widths[2] of those levels. (The intensity of our 5.2-Mev gamma ray can be assigned to decay from the 5.16-Mev level[2,8] and is

[18] To relate relative neutron reduced widths to (d,p) stripping cross sections we have used the "Numerical Table of Butler-Born Approximation Stripping Cross Sections" by C. R. Lubitz, H. M. Randall Laboratory of Physics, University of Michigan, 1957 (unpublished). The relative neutron reduced width γ_n^2 for a particular level of spin J was related to the experimental maximum differential cross section $\sigma_{\Omega\,\mathrm{max}}{}^{\mathrm{exp}}$ as follows: $\sigma_{\Omega\,\mathrm{max}}{}^{\mathrm{exp}}=\mathrm{const}(2J+1)k_p\sigma_{\Omega\,\mathrm{max}}{}^{\mathrm{tab}}\gamma_n^2$, where k_p is the wave number (c.m.) of the proton leading to the level and $\sigma_{\Omega\,\mathrm{max}}{}^{\mathrm{tab}}$ is the maximum differential cross section tabulated by Lubitz. This procedure is consistent with that used by other workers (see, for example, reference 19). For the sake of definiteness we have used a stripping radius for $Be^9(d,p)$, as well as for $Be^9(d,n)$, equal to 4.53×10^{-13} cm, as in reference 12.

[19] J. B. French and A. Fujii, Phys. Rev. **105**, 652 (1957).

[20] R. K. Adair, Phys. Rev. **87**, 1041 (1952).

[21] In reference 6 a private communication from G. C. Phillips and P. M. Windham is cited, to the effect that at 3.85-Mev deuteron energy the feeding cross sections of the 6.26-Mev and 5.96-Mev levels of Be^{10} are comparable.

[22] We refer to Fig. 4 in reference 3. Noting that the peak differential $Be^9(d,p)$ cross section to the 3.37-Mev state increases from 4.5 mb/sterad at 3.6 Mev (see reference 13) to only ≈5.7 mb/sterad at 14 Mev (see reference 8), we extrapolate the low-energy part of the 3.37-Mev gamma-ray excitation curve parallel to the abscissa to account for the direct feeding of the 3.37-Mev level. After correcting for the detection efficiency of gamma rays (given in reference 3), we calculate for the intensity ratio of the Be^{10} 2.59- and 2.89-Mev gamma rays to the 5.96-Mev gamma ray a value of ≈2 from Fig. 4 of reference 3 (interpolated at 2.8-Mev deuteron energy) and a value of 5.6 ± 1.5 from the assignments made in our Fig. 2. Furthermore, under the same kind of assumption as above, we calculate for the ratio of proton feeding to gamma-ray feeding of the Be^{10} 3.37-Mev level a value of ≈0.3 from Table II of reference 3 (interpolated at 2.8-Mev deuteron energy) and a value of 0.35 ± 0.16 from the gamma-ray assignments in our Fig. 2.

much smaller than the feeding cross section of the 5.11-Mev level, calculated as described below.) The neutron feeding of the 5.58-Mev level is much smaller (by at least a factor of 5 at 3.4-Mev deuteron energy[12]) than that of neighboring levels, so that no appreciable gamma-ray yield is expected in any case. The same expectation holds also for the 6.16-, 6.40-, and 6.57-Mev levels because of insufficient deuteron energy.

In view of the recent work of Meyer-Schützmeister and Hanna[2] on the $Li^6(\alpha,\gamma)$ reaction, the decay of the 5.11- and 5.16-Mev levels must be discussed further, but first we wish to indicate how the feeding cross sections to these levels were estimated. Because of the closeness of these levels, Ajzenberg[12] could not separate the $Be^9(d,n)$ neutron groups from these levels but showed that one of them at least was formed by *s*-wave proton capture and hence must have negative parity (and spin 1 or 2). Ajzenberg[12] also noted that the width of the neutron distribution to these two levels was appreciably smaller at 90° than at 0°. We took this as a possible indication that the distribution at 90° was predominantly due to a *p*-wave proton capture to the 5.16-Mev level and that at 0° mostly due to *s*-wave proton capture to the 5.11-Mev level, as well as some *p*-wave capture to the 5.16-Mev level.[23] This is in agreement with a slight energy shift of the center of the two neutron distributions, after correction for center-of-mass effects.[24] Next we *assumed* that the proton reduced width of the 5.16-Mev level is one-half of that of the 3.37-Mev level of Be^{10}, as would be expected[20] if these levels are analogous.[25] This yields the feeding cross section of the 5.16-Mev level of B^{10} shown in Fig. 2 and very nicely accounts for the relative magnitude of the 90° $Be^9(d,n)$ differential cross section[12] (mostly to the 5.16-Mev state) as compared to the 0° differential cross section[12] (mostly to the 5.11-Mev state), mentioned above.[26]

These considerations, although in accord with earlier work,[25] contradict recent work[2] on the $Li^6(\alpha,\gamma)$ reaction in two respects. First, the total level width of the 5.16-Mev level is given[27] as 0.45 kev (c.m.) and the quantity[28] $\omega\Gamma$ as close to 0.5 ev. Under these conditions gamma rays from the 5.16-Mev level could hardly have been detected in our $Be^9(d,n)$ experiment[1] or that of McCrary *et al.*,[3] if the neutron branching ratio to the 5.16-Mev level is within a *factor of ten or so* of that to the other levels, as indeed it should be considering the estimated feeding cross sections shown in Fig. 2. Hence we believe that the width of the 5.16-Mev level must be appreciably smaller than[27] 0.45 kev (c.m.), in fact in order of magnitude not much larger than the gamma width.[25] Barring the existence of another level very close to 5.16 Mev, one is tempted to assign any possible difference between the experimental width[27] of 1.0 kev (lab) of this level and the Doppler broadening of 0.68 kev (lab) to experimental uncertainties.

The second contradiction of the recent[2] $Li^6(\alpha,\gamma)$ work with other experiments was already discussed by Meyer-Schützmeister and Hanna[2] and concerns the fact that under an assumption of spin 2^- for the 5.11-Mev level, and under the further assumption of a *pure* $E1$ 5.11-Mev transition to the 3^+ ground state of B^{10}, the $Li^6(\alpha,\gamma)$ angular distribution[2] from that level cannot be fitted. We refer to reference 2 for a discussion of the consequent difficulties, but we wish to draw attention to the fact that *if* the spin of the 5.11-Mev state is indeed 2^-, the isotopic-spin selection rule for $E1$ transitions may suppress the $E1$ component of the 5.11-Mev transition sufficiently[25] so that the $M2$ contribution may be significant enough to affect the (α,γ) angular

[23] For the conditions under which the $Be^9(d,n)$ differential distributions were measured (reference 12), the *p*-wave differential cross section to a 5.1-Mev level is practically independent of angle, whereas the *s*-wave differential cross section is strongly peaked forward. Hence even though the *s*-wave assignment to one of the 5.1-Mev levels depends only on a measurement at one angle (0°) in reference 12, this seems to us sufficient to make the *s*-wave assignment certain, unless by chance the compound-nucleus formation of the 5.11-Mev level gives a strong forward maximum at 3.4-Mev deuteron energy. *Note added in proof.*—The work of Neiler, Gibbons, and Good [Bull. Am. Phys. Soc. Ser. II, **2**, 286 (1957)] indicates that the 5.11-Mev level is indeed formed by *s*-wave proton capture (J. H. Neiler, private communication). Furthermore Sample, Dawson, and Neilson [Bull. Am. Phys. Soc. Ser. II, **3**, 323 (1958)] find that the 5.16-Mev level is formed by *p*-wave proton capture. Both these experiments were performed at approximately 2-Mev deuteron energy.

[24] An exact measurement on the curves in reference 12 (1951) shows that the center of the 90° neutron distribution corresponds to about 5.15-Mev and that of the 0° distribution to about 5.10-Mev excitation energy in B^{10}.

[25] D. H. Wilkinson and G. A. Jones, Phys. Rev. **91**, 1575 (1953); G. A. Jones and D. H. Wilkinson, Phil. Mag. **45**, 703 (1954).

[26] The contribution of *p*-wave proton capture to the 5.16-Mev level is approximately equal to 10% of the 0° distribution under the assumptions stated in the text and the experimental conditions of reference 12. *Note added in proof.*—At approximately 2-Mev deuteron energy and at 0° the proton distribution to the 5.11-Mev level has indeed been found to be about 10 times more intense than to the 5.16-Mev level (J. H. Neiler, private communication).

[27] For the 1.085-, 1.175-, and 2.605-Mev alpha resonances in the $Li^6(\alpha,\gamma)$ reaction (see reference 2), Dr. Hanna has very kindly furnished us with the following total widths (lab) (measured between $\frac{1}{4}$ and $\frac{3}{4}$ height of the thick-target step): 2, 1, and <1.5 kev. The Doppler widths (lab) of these levels are 0.65, 0.68 (furnished by Dr. Hanna), and 1.01 kev, respectively. Assuming accurate determinations of the lab widths and no broadening due to experimental effects, one calculates the c.m. widths given in the text and in Tables II and III. In support of the absence of experimental effects Dr. Hanna has kindly informed us of his measurement of a width of 0.4 kev for a resonance in the $Li^7(\alpha,\gamma)$ reaction at 0.82 Mev, which can be mostly explained by Doppler broadening. (For a discussion of the relation between true widths and Doppler widths see, for example, J. Rainwater, *Encyclopedia of Physics* (Springer-Verlag, Berlin, 1957), Vol. 40, pp. 377–8. The Doppler widths given above are equal to twice the quantity Δ in this reference and correspond to an effective target temperature of 430°K.) *Note added in proof.*—Dr. Hanna has informed us recently of new measurements which indicate that the experimental width of the 1.175-Mev alpha resonance in the $Li^6(\alpha,\gamma)$ reaction can be accounted for completely by the Doppler effect. The intrinsic c.m. width of the 5.16-Mev level of B^{10} can be shown only to be *less than* 0.5 kev, in agreement with our assumption.

[28] For a capture reaction with scattering as only competition, one has

$$\omega\Gamma=(2J+1)(2j_t+1)^{-1}(2j_s+1)^{-1}\Gamma_s\Gamma_\gamma(\Gamma_s+\Gamma_\gamma)^{-1},$$

where J, j_t, j_s are the spins of the capturing state, the target nucleus ($j_t=1$ for Li^6), and the captured particle ($j_s=0$ for an alpha particle), respectively, and Γ_s and Γ_γ are the particle and gamma widths of the capturing state.

distribution.[29] Indeed, it can be shown that a reasonable amount of $M2$ admixture gives the experimental[2] α-γ distribution[30] and hence the argument against a spin assignment of 2^- for the 5.11-Mev given in reference 2 should perhaps not be considered as absolutely definitive.

IV. DISCUSSION OF THE LEVELS OF Be[10] AND B[10]

Since our work and our arguments have perhaps contributed to the clarification of some spin assignments and level widths in Be[10] and B[10], we are tempted to use this information for a further discussion of their level structure, especially from the point of view of isotopic spin.

We refer to Fig. 3 which shows the presently known levels of Be[10] and B[10], as well as C[10] added for the sake of completeness. Spins which are believed to be certain are underlined; spins which are likely are given without special marking; spins which are proposed by us are placed in brackets. The latter assignments will be discussed further below. Figure 3 also shows one of the intermediate-coupling predictions of the normal-parity energy levels by Kurath.[31] The agreement between experiment and theory, already previously noted,[31,32] is remarkable. We wish to draw particular attention to the prediction of a $T=1$, 2^+ level near 7.5 Mev in B[10] and near 5.8 Mev in Be[10]. Indications for a 2^+ level in B[10] at 7.47 Mev were found by Mozer[33] but the analog level in Be[10] has not been established. We shall return to this below.

In order to proceed with the discussion of the levels of Be[10] and B[10], we refer to Table II which gives the neutron and proton widths[34] and/or dimensionless

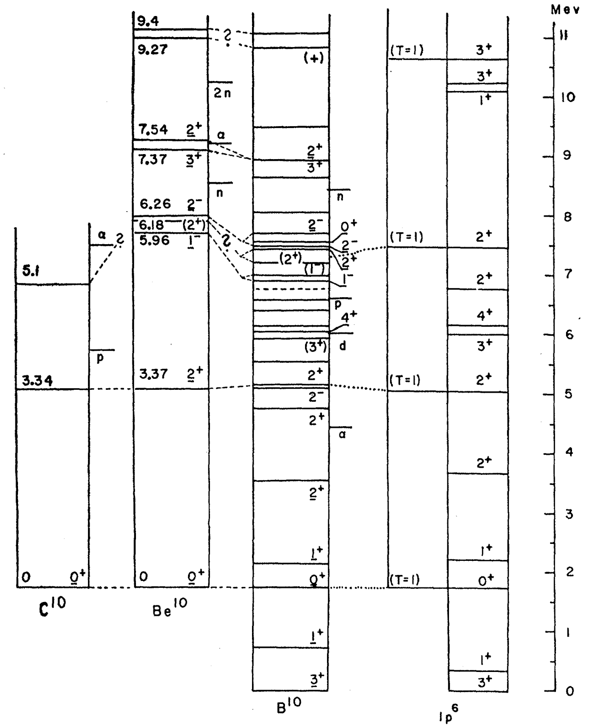

FIG. 3. The energy levels of C[10], Be[10], and B[10] compared among each other and with an intermediate-coupling calculation of Kurath (reference 31; the spectrum shown is for $\xi/K=4.0$, $L/K=5.8$, $K=-1.13$ Mev). Dashed lines connect those levels believed to belong to isotopic-spin triplets (see Sec. IV and references 8 and 37). Dotted lines connect levels of B[10] with the possibly corresponding ones obtained in the intermediate-coupling calculation. Spins which are underlined are believed to be certain, those not so marked are likely, and those in brackets are proposed as described in the text. The energy scale on the right corresponds to the levels of B[10].

reduced widths for these nuclei. In the case of the levels of Be[10], we have normalized the relative reduced widths given by Green and Middleton[14] with those calculated on an absolute basis from deuteron stripping theory by Fujimoto *et al.*[35] We have made the normalization at the 3.37-Mev level since it gives the most consistent reduced width at two different deuteron energies.[19] The dimensionless reduced width for the 7.37-Mev level of Be[10] calculated in this way agrees well with the neutron width of that level.[19,36,37] The neutron widths for the higher levels of Be[10] were taken from reference 37 and are tabulated for comparison.

[29] From the information given in reference 2, one calculates $\Gamma_\gamma \approx 0.06$ ev for the 5.11-Mev gamma ray, assuming $\Gamma_\gamma=\Gamma_\alpha$ and $J=2^-$ for the 5.11-Mev state. This gamma width is roughly 10^{-3} of the Weisskopf estimate for a 5.11-Mev $E1$ gamma ray. On the other hand, from the Weisskopf estimate one can calculate that if the $E1$ component is reduced by a factor 10^{-3}, the $M2$ contribution to the gamma-ray intensity is approximately equal to 2%, assuming it is not reduced.

[30] Using the notation of reference 2 it is not difficult to show that for the α-γ angular distribution $(1+A_2\cos^2\theta+A_4\cos^4\theta)$ discussed in the text, $A_2=-0.27$ if $a_\gamma=0.1$, $\cos\xi_\gamma=-1$, and $a_\alpha=0$. Also $A_2=-0.27$ to -0.30 and $A_4=+0.004$ to -0.004 if $a_\gamma=0.1$, $\cos\xi_\gamma=-1$, $a_\alpha=0.1$, and $\cos\xi_\alpha=+1$ to -1. The experimental values given in reference 2 are $A_2=-0.35\pm0.07$ and $A_4\approx 0$. The value $a_\gamma=0.1$ represents a 1% $M2$ admixture, which is reasonable in view of reference 29. The value $a_\alpha=0.1$ represents a 1% barrier penetrability for f-wave alpha particles compared to p-wave, which is in agreement with calculated penetrabilities (see reference 43). Obviously other reasonable combinations of a_γ, $\cos\xi_\gamma$, a_α, and $\cos\xi_\alpha$ will also give agreement with the experimental results. The above numbers are given only for the purpose of illustration. [The angular distribution calculations were made using the tabulations of L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953) and of Sharp, Kennedy, Sears, and Hoyle, Atomic Energy of Canada, Ltd., Report No. CTR-536, AECL-97, 1954 (unpublished).]

[31] D. Kurath, Phys. Rev. **101**, 216 (1956).

[32] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).

[33] F. S. Mozer, Phys. Rev. **104**, 1386 (1956); Ph.D. thesis, California Institute of Technology, 1956 (unpublished).

[34] We relate the observed particle width Γ_s (c.m.) to the reduced particle width γ_s^2 in the following manner: $\Gamma_s=2k_saP\gamma_s^2$, where k_s is the c.m. wave number of the particle, $a=1.45(A_s^{1/3}+A_t^{1/3})\times10^{-13}$ cm (A_s, A_t are mass numbers of the particle and target, respectively), and P is the penetration factor for the particle corresponding to the correct parity change of the reaction and the minimum orbital angular momentum change of the particle. We relate the reduced particle width to the dimensionless reduced width θ_s^2 in the following manner: $\theta_s^2=\gamma_s^2(2Ma^2/3\hbar^2)$, where $M=A_sA_t/(A_s+A_t)$.

[35] Fujimoto, Kikuchi, and Yoshida, Progr. Theoret. Phys. Japan **11**, 264 (1954).

[36] Adair, Barschall, Bockelman, and Sala, Phys. Rev. **75**, 1124 (1949); Bockelman, Miller, Adair, and Barschall, Phys. Rev. **84**, 69 (1951); Willard, Bair, and Kington, Phys. Rev. **98**, 669 (1955).

[37] J. B. Marion, Phys. Rev. **103**, 713 (1956).

TABLE II. Neutron and proton widths in Be^{10} and B^{10}. J^{π} represents the spin J and parity π of the level. (If the spins are boldfaced they are believed to be certain, if not so marked they are probable, and if given in brackets they are proposed.) Γ, Γ_n, Γ_p are the total, neutron, and proton widths (in the c.m. system), respectively. (The widths are believed to be accurate to about ±25% if not marked, to about a factor 2 if marked ~, and are estimated if given in brackets.) l_n and l_p are the orbital angular momenta of the captured neutron and proton, respectively, which have been used for the calculation of the dimensionless reduced widths θ_n^2 and θ_p^2 (see references 18 and 34). The same markings apply to θ^2 as to Γ. The references given, together with reference 8, give most of the information about the levels.

Level in Be^{10} (Mev)	$J\pi$	Γ (c.m.) (kev)	Γ_n (c.m.) (kev)	l_n	θ_n^2 (%)	Reference
0	**0+**			1	5–9	a, b
3.37	**2+**			1	1	a
5.96	**1−**			0	15	a, b
6.18	(2+)			1	(0.5)	b
6.26	**2−**			0	8	a, b
7.37	3+	22	22	1	1.2^b–1.4	c
7.54	2+	7	7	1	0.34	c

Level in B^{10} (Mev)	$J\pi$	Γ (c.m.) (kev)	Γ_p (c.m.) (kev)	l_p	θ_p^2 (%)	Reference
0	**3+**			1	~1.7	d
0.72	**1+**			1	~3.5	d
1.74	**0+**			1	~2.5	d
3.58	**2+**			1	~0.7	d
4.77	2+	(1.2×10⁻⁴)		1	~0.3	b, d
5.11	2−	1.15		0	~1.3	b, d
5.16	2+	(1.2×10⁻³)		1	(0.5)	b, d
5.93	(3+)	12		1	~0.5	d
6.89	**1−**	130	40	0	30	b, e
7.01	(1−)	(100)	⩽ (5)	0	(0.8)	b
7.20	(2+)	~90	(2)	1	(0.8)	b
7.47	2+	~80	~70	1	~10	f
7.49	2−	79	50	0	2	f
7.56	**0+**	2.7	2.7	1	0.3	f
7.79	2−	~200	~130	0	~4	b, c, f
8.89	3+	76		1	0.9–1.7	c
8.89	2+	32		1	0.16	c

a See reference 14.
b See text.
c See reference 37.
d See references 2, 12, and 27.
e See reference 4.
f See reference 33.

For the bound levels of B^{10} we have used the work of Ajzenberg[12] to calculate relative proton reduced widths[18] and have normalized these by relating the reduced width of the 1.74-Mev state to the ground-state neutron reduced width of Be^{10} using the work of Calvert *et al.*[15]

We wish to emphasize that all our dimensionless reduced widths calculated from stripping theory depend on the value $\theta_n^2=0.05$ for the dimensionless reduced neutron width of the Be^{10} ground state as calculated[35] from the cross sections of Fulbright *et al.*[13] We preferred this to the value $\theta_n^2=0.09$ calculated[19] from the cross sections of McGruer,[38] because the former appear to have been measured somewhat more accurately. If we are mistaken in this, or if reduced widths calculated from stripping theory are energy-dependent,[19] the dimensionless reduced widths for the bound states of Be^{10} and B^{10} given in Table II may have to be multiplied by a factor as large as 2.

For the unbound levels of B^{10} we used recent information[2,4,27,33,37,39,40] in a manner described below to estimate or summarize the dimensionless reduced widths given in Table II. In this we were aided materially by recent compilations[41,42] of particle widths and dimensionless reduced widths and by convenient tabulations.[17,43]

a. Levels of Be^{10}

Referring to Table II, we note that the work of Green and Middleton[14] in connection with our work[1] gives the spins and parities for the 5.96- and 6.26-Mev levels as 1^- and 2^-, respectively, and rather large dimensionless reduced widths. This is just what one would expect[4,14,42] for a configuration which is predominantly $(1s^41p^5)2s$ and for which the ground state of Be^9 forms the main parent. If the 6.18-Mev state is the 2^+ state predicted[31] near that energy, then its dimensionless neutron reduced width can only be[14,44] of the order of $\frac{1}{2}$% according to stripping theory.[18]

As was already done by Wilkinson,[45] it is of interest to compute the slow-neutron scattering cross section of Be^9 on the assumption that it is affected very strongly by the presence of the bound 5.96- and 6.26-Mev states of Be^{10}. Although a detailed comparison with the experimental cross section depends sensitively on the magnitude of the nuclear radius which one uses, the dimensionless neutron reduced widths for the 5.96- and 6.26-Mev states of Be^{10} given in Table II lead to a very favorable comparison. On this basis it does not seem possible that these dimensionless reduced widths could be increased by a factor as large as 2 without destroying this agreement.

One can also compute the slow-neutron capture cross section on the assumption[45] that the neutron is captured into the 5.96- or 6.26-Mev levels. Using our spin assignments for these levels, the 6.80-Mev neutron-capture gamma ray[46] to the ground state of Be^{10} would result from capture into the (1^-) 5.96-Mev level alone, whereas both the 5.96-Mev and (2^-) 6.26-Mev levels would contribute to the 3.43-Mev neutron-capture gamma ray[46] to the 3.37-Mev state of Be^{10}. In this way one finds for the 6.80- and 3.43-Mev neutron-capture gamma rays widths of 4.2 and 1.4 ev, respectively. Both these widths are reasonable for unhindered $E1$ transitions.[45,51] On the other hand, the gamma-ray branching ratio[1] from the 5.96-Mev state of Be^{10} to the ground and 3.37-Mev states is in severe disagreement with the

[38] Quoted in reference 8. See also K. B. Rhodes and J. N. McGruer, Phys. Rev. **92**, 1328 (1953).

[39] Weber, Davis, and Marion, Phys. Rev. **104**, 1307 (1956).
[40] H. Warhanek, Phil. Mag. **2**, 1085 (1957).
[41] E. Vogt, Nuclear Development Associates Report, NDA-14, April, 1955 (unpublished).
[42] A. M. Lane and R. G. Thomas, Revs. Modern Phys. **30**, 257 (1958) and unpublished notes; A. M. Lane, Atomic Energy Establishment, Harwell, Report No. T/R 1289, 1954 (unpublished).
[43] Sharp, Gove, and Paul, Atomic Energy of Canada, Ltd. Report No. TPI-70, AECL-268, 1955 (unpublished).
[44] J. J. Jung and C. K. Bockelman, Phys. Rev. **96**, 1353 (1954).
[45] D. H. Wilkinson, Phil. Mag. **44**, 1019 (1953).

branching ratio[46] of the two afore-mentioned neutron-capture gamma rays, especially if one includes the decay from the 6.26-Mev state (see Fig. 2). Such a disagreement could be explained[47] if the extranuclear contribution[48] to the slow-neutron capture gamma-ray transition probability were comparable to the nuclear contribution. The slow-neutron scattering and capture cross sections seem to indicate that the interaction of a slow neutron with Be^9 is quite similar to that with C^{12}. Thomas[48] showed that for the latter the extranuclear contribution to the $E1$ capture gamma-ray transition probability is important—at least on the independent-particle model. Hence it is possible, although by no means proven, that a similar effect in Be^9 might explain the large difference between the slow-neutron capture gamma-ray branching ratio[46] and the level branching ratio[1,22] in Be^{10}, both of which seem to be well determined experimentally.

About the higher states of Be^{10} we could not make any comments beyond those made elsewhere.[8,19,37,42]

b. Levels of B^{10}

Below 4.45 Mev,[8] the levels of B^{10} are bound. The dimensionless proton reduced widths, estimated from deuteron stripping cross sections[12] as described above, are of reasonable order of magnitude (see Table II).

Above 4.45 Mev,[8] the levels of B^{10} are unstable against alpha-particle emission and, conversely, can be excited by means of the $Li^6+\alpha$ reaction.[8] As far as the dimensionless proton reduced widths are concerned, we wish to point out only that for the 5.11-Mev level the width is not large enough to warrant the assumption[4] that this level has the predominant configuration $(1s^4 1p^5)2s$ with the Be^9 ground state as main parent. Although the stripping angular distribution[12] to this level has $l_p=0$ character,[23,24] the dimensionless proton reduced width is no larger than that of the lower $(l_p=1)$ states. We have no suggestions for a possible configuration[42] of this level.

TABLE III. Deuteron and alpha widths in B^{10}. The symbols and markings used are similar to those described in the caption to Table II. The references given, together with reference 8, give most of the information about the levels.

Level in B^{10} (Mev)	$J\pi$	Γ (c.m.) (kev)	Γ_d (c.m.) (kev)	Γ_α (c.m.) (kev)	l_d	θ_d^2 (%)	l_α	θ_α^2 (%)	Reference
4.77	2^+	$(1.2\times10^{-4})^a$		$(6\times10^{-5})^a$			2	(0.4)	b, c
5.11	2^-	1.15		1.15			1	2.4	b
5.16	2^+	$(1.2\times10^{-3})^a$		$(6\times10^{-4})^a$			2	(0.0064)	b, c
5.93	(3^+)	12		12			2	(11)	b
6.06	4^+	<0.43		<0.43			4	<8	b
6.89	1^-	130	40	50	1	10	1	3	c, d
7.01	(1^-)	(100)	(5)	(90)	1	(0.6)	1	(3)	c
7.20	(2^+)	~90	~45	~45	2	~18	2	~2.5	c
7.47	2^+	~80	$\leqslant10$	$\leqslant10$	2	$\leqslant2$	2	$\leqslant0.5$	d
7.49	2^-	79	~15	~15	1	~0.8	1	~0.4	d
7.79	2^-	~200	$\leqslant70$	$\leqslant70$	1	$\leqslant3$	1	$\leqslant1.6$	d, e
8.89	2^+	32					2	33^f	e

a Assumes $\Gamma_\gamma=\Gamma_\alpha$.
b See references 2 and 27.
c See text.
d See reference 33.
e See reference 37.
f To $T=1$ level of Li^6. See reference 50.

TABLE IV. Gamma widths in B^{10}. E_i and E_f are the initial and final energies of the gamma-ray transition and J_i and J_f the initial and final spins. Γ_γ^{tot} is the total gamma width of the initial level and Γ_γ^{part} the partial gamma width to the final level. $|M|_{E1}^2$ and $|M|_{M1}^2$ are the ratios of the partial gamma widths compared to the Weisskopf estimates for $E1$ and $M2$ transitions, respectively. See caption to Table II for meaning of markings. The references given, together with reference 51, give most of the information about the levels.

E_i (Mev)	J_i	Γ_γ^{tot} (ev)	E_f (Mev)	J_f	Γ_γ^{part} (ev)	$\|M\|_{E1}^2$	$\|M\|_{M1}^2$
4.77	2^+	$(0.06)^{a,b}$	0	3^+	(0.005)		(2×10^{-3})
			0.72	1^+	(0.055)		(4×10^{-2})
5.11	2^-	0.063^c	0	3^+	0.06	9×10^{-4}	
			0.72	1^+	0.003	7×10^{-5}	
			2.15	1^+	$\leqslant0.012$	$\leqslant9\times10^{-4}$	
5.16	2^+	$(0.61)^{b,c}$	0	3^+	(0.04)		(1×10^{-2})
			0.72	1^+	(0.18)		(8×10^{-2})
			2.15	1^+	(0.39)		(0.8)
6.89	1^-	$2.9–3.5^d$	0.72	1^+	0.61–0.76	$(5–6)\times10^{-3}$	
			1.74	0^+	1.5–1.9	$(2–3)\times10^{-2}$	
			2.15	1^+	0.31–0.85	$(5–15)\times10^{-3}$	
			5.11^f	2^-	0.39		$<3^f$
7.01	(1^-)	$\leqslant(3)^b$					
7.47	2^+	$\leqslant7^e$	0	3^+	$\leqslant7$		$\leqslant0.8$
7.49	2^-	16–23	0	3^+	15–21	$(7–10)\times10^{-2}$	
			0.72	1^+	$\leqslant2$	$\leqslant1.3\times10^{-2}$	
7.56	0^+	6	0.72	1^+	4.8		0.72
			2.15	1^+	1.2		0.36
8.89	2^+	8	0.72	1^+	8		0.75

a See references 2 and 40.
b See text.
c See references 2 and 27.
d The first figure refers to reference 4, the second to reference 54, but see text.
e See reference 33.
f *Note added in proof.*—Recent unpublished work by W. E. Meyerhof and N. Tanner shows that the transition indicated takes place, at least predominantly to the 5.16-Mev state and not the 5.11-Mev state, in agreement with reference 55, and in disagreement with reference 4.

In calculating the dimensionless alpha reduced widths (given in Table III) for the 4.77- and 5.16-Mev levels,[27,40] we have assumed $\Gamma_\alpha=\Gamma_\gamma$ for sake of definiteness. Hence the dimensionless alpha reduced widths cannot be smaller than by a factor of 2 from those given, but could be larger by factors of perhaps up to 10 in accordance with our gamma-ray work discussed in Sec. III. The dimensionless alpha reduced width of the 4.77-Mev level is small, but not unreasonably so, and that of the 5.16-Mev level indicates the $T=1$ character of that level, with a reasonable $T=0$ impurity. These arguments are essentially those already given by Wilkinson and Jones.[25] The dimensionless alpha reduced widths of the other B^{10} levels in this energy region were calculated from reference 2, with some corrections.[27] The Thomas correction[49] was not applied to the reduced widths given in Tables II and III, with the exception of the 6.89- and[50] 8.89-Mev levels.

The gamma widths, in absolute value as well as compared to the Weisskopf estimates, are given in

[46] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 49 (1953); Groshev, Adyasevich, and Demidov, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy* (United Nations, New York, 1956), Vol. 2, p. 39. The two groups give for the intensity of the 6.80-Mev neutron capture gamma ray 0.75 and 0.73 photon/capture, respectively, and for the 3.43-Mev gamma ray 0.25 and 0.23 photon/capture.

[47] We are very indebted to Professor R. F. Christy for drawing our attention to this possibility.

[48] R. G. Thomas, Phys. Rev. **88**, 1109 (1952).

[49] R. G. Thomas, Phys. Rev. **81**, 148 (1951).

[50] R. J. Mackin, Jr., Phys. Rev. **94**, 648 (1954).

Table IV. This table is essentially taken from the work of Wilkinson,[51] except for minor modifications and additions due to recent work.[2,27,33,40] For the 4.77- and 5.16-Mev levels we have again assumed $\Gamma_\gamma=\Gamma_\alpha$, and the actual gamma widths could be smaller by factors of up to 2 or larger by factors of up to about 10. The smallness of some of the $M1$ comparative widths ($|M|^2$) from these levels is noteworthy[52]; in fact some of the widths are so small that (collective) $E2$ contributions to the widths may be appreciable.[40] The smallness of $E1$ comparative widths from the 5.11-Mev level are in accord with the isotopic-spin forbiddenness of these transitions.[25,29]

The level structure of B^{10} above 6.58 Mev is complicated but also very interesting because some of these levels must be related to the (1^-) 5.96-, (2^+?) 6.18- and (2^-) 6.26-Mev levels of Be^{10}. The B^{10} levels are unstable against proton, as well as deuteron and alpha, emission and have been extensively studied by means of Be^9+p reactions.[4,8,33,37,39,53–55] We refer to Tables II, III, and IV. As discussed by Wilkinson and Clegg,[4] the (1^-) 6.89-Mev level is predominantly $T=0$ with a large $T=1$ admixture. Our tables contain essentially their data and those of reference 54, except that we chose the peak total cross sections[17,56] of the $Be^9(p,d)$ and (p,α) reactions to calculate $\Gamma_p/\Gamma\sim0.30$ (or 0.70, which can be rejected[4]), in accord with Mozer's result[33] (accurate to within a factor of 2). This changes all the partial widths somewhat, but does not modify any conclusions[4] about the 6.89-Mev level, nor does this alleviate the difficulty caused[4] by the rather large $M1$ matrix element to the 5.11-Mev level (see Table IV).‡

Since on the one hand we have shown that the 5.96-Mev level of Be^{10} is 1^- and since, on the other hand, the (2^-) 7.49-Mev level of B^{10} seems to be[8] the $T=1$ analog of the (2^-) 6.26-Mev level of Be^{10}, it is reasonable to assume that there is another 1^- and predominantly $T=1$ level in B^{10} near 7.2 Mev. Indeed if the Be^{10} levels were predominantly $(1s^41p^5)2s$, one would expect in B^{10} four close-lying levels—$1^-(T=0)$, $1^-(T=1)$, $2^-(T=0)$ and $2^-(T=1)$—due to the same $(1s^41p^5)2s$ configuration (see references 32 and 42). We would like to propose that these four levels in B^{10} are the (1^-) 6.89-, (1^-?) 7.0-, (2^-) 7.49-, and (2^-) 7.79-Mev states.[4,8,33]

We prefer not to identify the 7.20-Mev level[8] in B^{10} with one of the analogs of the (1^-) 5.96-Mev level of Be^{10} for two reasons, both of which are not absolutely convincing, though. First, Mozer[33] stated that in order to fit the low-energy $Be^9(p,p)$ data it appeared necessary to assume a p-wave (positive parity) state near 7.2 Mev. This is consistent with an analysis[56] of the $Be^9(p,d)$ and (p,α) angular distributions in this energy region. Second, the total cross section of the $Be^9(p,d)$ reaction shows a peak[17,56] near 0.46-Mev proton energy (7.0-Mev excitation energy in B^{10}) and the (p,d) angular distribution seems to be isotropic[17,56] at that energy. This indicates a possible s-wave (negative parity) state[57] near 7.0 Mev in B^{10}.

Our proposal therefore is that quite possibly the 6.89- and 7.0-Mev levels[8] are the two 1^- components of the $(1s^41p^5)2s$ configuration, predicted by Inglis[32] and Lane,[42] but due to their proximity very much mixed in their isotopic-spin composition so that the isotopic-spin selection rules break down to a very large extent,[4] explaining the large dimensionless deuteron and alpha reduced widths as well as the anomalously large $E1$ widths to $T=0$ states.[4] It is of interest to note that the sum of the dimensionless proton reduced widths of the two levels ($\sim30\%$) is large, as is the value for the 5.96-Mev level of Be^{10} (15%). If all these levels resulted from a *pure* $(1s^41p^5)2s$ configuration, whose parent is the Be^9 ground state, one would expect the sum of the dimensionless proton reduced widths of the two $B^1{}_0$ levels to be equal to the dimensionless neutron reduced width of the Be^{10} level. Also if the 6.89- and 7.0-Mev levels were isotopically pure, each one should have one-half[20] of the dimensionless reduced width of the Be^{10} level and the fact that this is not so is consistent with a large amount of isotopic-spin mixing of the 6.89- and 7.0-Mev levels of B^{10}. Another argument perhaps in favor of our considerations is that at least in certain cases large isotopic-spin mixing seems to require[58] close proximity of $T=0$ and $T=1$ levels of the same spin and parity.

As indicated already above, we would like to identify the 7.49- and 7.79-Mev levels of B^{10} as the two 2^- components of the $(1s^41p^5)2s$ configuration, again with a fairly high degree of isotopic-spin mixing. Although the predominant ground-state $E1$ decay[8] of the 7.49-Mev level would violate the isotopic spin selection rule

[51] D. H. Wilkinson, Phil. Mag. 1, 127 (1956).
[52] G. Morpurgo, Phys. Rev. 110, 721 (1958).
[53] G. Dearnaly, Phil. Mag. 1, 821 (1956).
[54] R. R. Carlson and E. B. Nelson, Phys. Rev. 98, 1310 (1955).
[55] G. R. Bishop and J. C. Bizot, J. phys. radium 18, 434 (1957).
[56] Neuendorffer, Inglis, and Hanna, Phys. Rev. 82, 75 (1951).
‡ *Note added in proof.*—The transition referred to takes place at least predominantly to the 5.16-Mev level (see footnote f to Table IV) and furthermore may well be nonresonant in the $Be^9(p,\gamma)$ reaction between 0.2- and 1.2-Mev proton energies.

[57] The $Be^9(p,\alpha)$ total cross section (see references 17 and 56) has an anomalously wide peak extending from about 0.3- to 0.5-Mev proton energy. Also the $Be^9(p,\alpha)$ angular distribution is anisotropic down to 0.5-Mev proton energy. We have tried unsuccessfully to fit the $Be^9(p,d)$ and (p,α) total cross sections with a two-level Breit-Wigner formula [E. P. Wigner, Phys. Rev. 70, 606 (1946)] assuming s-wave resonances at 0.31-Mev, and near 0.45-Mev proton energy, taking into account barrier penetration effects and level interference. The (p,d) anomaly near 0.45 Mev seems to be much narrower than the (p,α) anomaly and no choice of level parameters allows a fit to both experimental cross sections. On the other hand, the $Be^9(p,d)$ and (p,γ) cross sections [see reference 4 and Lonsjö, Os, and Tangen, Phys. Rev. 98, 727 (1955)] can be fitted approximately by assuming resonances at 0.31- and near 0.45-Mev proton energy. Estimates for the partial widths of the 0.45-Mev resonance which appear to be reasonable on the basis of our fitting attempts are given in Tables II to IV. *Note added in proof.*—In connection with a search for another possible resonance close to 0.33-Mev proton energy in the $Be^9(p,\gamma)$ reaction, see R. D. Edge and D. S. Gemmell, Proc. Phys. Soc. (London) 71, 925 (1958).
[58] L. A. Radicati, Proc. Phys. Soc. (London) A66, 139 (1953), and A67, 39 (1954); F. C. Barker, Phil. Mag. 2, 286 (1957).

for $E1$ transitions unless the 7.49-Mev level were predominantly $T=1$, the dimensionless deuteron and alpha reduced widths of this level indicate an appreciable amount, perhaps as high as 10%, of $T=0$ admixture. The sum of the dimensionless proton reduced widths[59] of the 7.49- and 7.79-Mev levels of B^{10} ($\approx 6\%$) is again comparable to the dimensionless neutron reduced width of the 6.26-Mev state of Be^{10} (8%), giving an indication favorable to our interpretations. The individual isotopic-spin purity of these B^{10} levels appears to be somewhat greater than that of the 6.89- and 7.0-Mev levels.

The only other levels of B^{10} on which we would like to comment are the 7.2- and[33] (2^+) 7.47-Mev levels. In Sec. IV(a) we mentioned the prediction of Kurath[31] (see Fig. 3) of a 2^+, $T=1$ level we were tempted to identify with the 6.18-Mev level of Be^{10}, whose dimensionless neutron reduced width then turned out to be about $\frac{1}{2}\%$ from deuteron stripping theory. Hence the 7.47-Mev level found by Mozer[33] could not be[20] the B^{10} analog level, since it has a dimensionless reduced width of $\sim 10\%$. We have mentioned above the suspicions[33,56] that a p-wave level in B^{10} near 7.2 Mev should occur and would like to propose that the 7.2-Mev level is the 2^+ analog of the 6.18-Mev level of Be^{10}. We can calculate for the 7.2-Mev level $\Gamma_p/\Gamma \approx 0.02$ or 0.98 assuming reasonable values[17,56] (~ 40 mb) for the $Be^9(p,d)$ and $Be^9(p,\alpha)$ resonance cross sections. The larger value of Γ_p/Γ can be excluded because of the $Be^9(p,p)$ work[33]; the smaller value gives $\sim 0.8\%$ for the dimensionless proton reduced widths of the 7.20-Mev level, roughly in line with what is expected.[20] Here again, though, the accidental close proximity of the (2^+) 7.47-Mev level gives rise to appreciable isotopic-spin mixing as shown by the large dimensionless deuteron and alpha reduced widths. We may also note that since the configurations of the 7.20- and 7.47-Mev levels are presumably not related, the sum of their dimensionless proton reduced widths does not need to be equal to that of the dimensionless neutron reduced width of the 6.18-Mev level of Be^{10}.

We wish to state that we realize that this last section of our article is somewhat speculative, but we hope that it will provide an incentive for further intensive study of the B^{10} levels near 7 Mev.

V. CONCLUSIONS

We have indicated on Fig. 3 by means of dotted lines the levels which we believe to be analogous in Be^{10} and B^{10} and we have related, as far as possible, the level predictions of Kurath[31] to the actual levels. We have tried to make clear in the previous sections to which parts of these relationships our work has contributed. We may note that the analog levels in B^{10} corresponding to the three levels in Be^{10} near 6 Mev lie somewhat lower than a comparison with the lower[8] and higher[37] energy analog levels might lead one to expect. But the close proximity of the B^{10} levels to the proton threshold may well be responsible for this.[4,60] Also in C^{10} the probably analogous levels seem to lie rather low.[4]

ACKNOWLEDGMENTS

One of us (W.E.M.) has profited from stimulating discussions with R. F. Christy and D. H. Wilkinson, as well as with F. Ajzenberg-Selove, A. B. Clegg, and T. Lauritsen. He would like to express his gratitude for the hospitality shown to him during his stay at the California Institute of Technology, especially by Professor R. F. Bacher, Professor J. W. M. DuMond, and Professor C. C. Lauritsen. Also he is very grateful to the Alfred P. Sloan Foundation, Inc., for the grant of a fellowship and for other support.

[59] In view of the work of Marion (see reference 37, footnote 20) we have reduced the total width of the 7.79-Mev level to one-half of that given by Mozer (reference 33).

[60] A similar situation in C^{13} is well known. [R. G. Thomas, reference 48; J. B. Ehrman, Phys. Rev. **81**, 412 (1951).]