Energy Levels of C^{11} and C^{12} from Photographic Plate Observation of Neutron Spectra*

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The energies of neutrons from $B^{10}(d,n)C^{11}$ and $B^{11}(d,n)C^{12}$ reactions have been measured by use of photographic emulsions and enriched B^{10} targets. Neutron groups corresponding to levels in C^{11} at 1.85, 4.23, 4.77, 6.40, 6.77, 7.39, 8.08, 8.39, 8.62, and possibly 8.97 and 9.13 Mev, have been observed. Most of these levels in C^{11} show good correspondence to those previously reported for the mirror nucleus B^{11}. This correspondence supports the assumed equality of n–n and p–p forces. Neutrons from normal boron targets were observed, corresponding to levels in C^{12} at 4.4-, 9.6-, 10.8-, 11.1-, 11.74-, 12.76-, 15.09-, and 16.07-Mev excitation. There were also some indication of additional levels at 13.21-, 13.36-, 14.16-, and 15.52-Mev excitation.

INTRODUCTION

THE hypothesis that the neutron-neutron and proton-proton nuclear forces are equal has been used with considerable success in comparisons of the binding energies of the ground states of pairs of light mirror nuclei.[1] These comparisons show that almost the entire observed energy difference between the ground states can be explained by assuming that the binding energy from nuclear forces is the same in both nuclei and that they differ only in the relatively small Coulomb energies. On the basis of this hypothesis it is also expected that the excited states of mirror nuclei are similar in their excitation energies, and also in their characteristic parameters such as angular momentum and parity. Although differences in excitation energy of some of the mirror levels so far observed are larger than at first expected (particularly in the case of C^{13} and N^{13}),[2] some success has been attained in comparing corresponding excited states of mirror nuclei.[3]

The excited states of the mirror pair, B^{11} and C^{11}, are advantageous to study because of the large range of excitation energy available in these nuclei when produced by (d,p) and (d,n) reactions with B^{10}. In addition, within this excitation range both bound and virtual states occur. It may be expected that the differences in excitation energy of corresponding levels will increase on the average for virtual levels, because of a differential reduction of the Coulomb energy as the wave function spreads out.

Experimental information on B^{11} is quite extensive as to the location of levels below 10 Mev.[4] The energy level spectrum of C^{11} is not so well known. Excited states of C^{11} have been reported at 2.0 Mev by Gibson and at 4.5 and 6.7 Mev by Swann and Hudspeth.[6] The $B^{10}(d,n)C^{11}$ reaction was used in both of these experiments. Excited states at 9.7 and 10.1 Mev have been indicated by resonances in the alpha-particle yield from the $B^{10}(p,\alpha)Be^7$ reaction.[7] Since the above experiments did not cover the region between 7.0 and 9.5 Mev, it was desirable to extend the observations in C^{11} to include this energy region and if possible to increase the energy resolution.

EXPERIMENTAL PROCEDURE

The energy levels of C^{11} were observed by measuring the energies of neutrons produced by deuteron bombardment of B^{10} according to the reaction:

$$B^{10}+D\rightarrow C^{11}+n+6.473 \text{ Mev.}^8 \qquad (1)$$

Monoenergetic deuterons were produced by the Wisconsin electrostatic generator and analyzed by a 90° cylindrical electrostatic analyzer. Thin targets of 96 percent enriched[9] B^{10} were produced by evaporation of elemental B^{10} from a tungsten boat onto tantalum backings. Two separate evaporations of B^{10} were carried out; the thickness of each target, which was determined by weighing before and after evaporation, was about 100 kev for 3.5-Mev deuterons. Energies of the emitted neutrons were obtained by measuring the ranges of recoil hydrogen nuclei produced by the neutrons in 200-micron thick Eastman NTA emulsions mounted 10 centimeters from the target at 0° and 80°

* Work supported by the AEC and the Wisconsin Alumni Research Foundation.

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1 Fowler, Delsasso, and Lauritsen, Phys. Rev. **49**, 561 (1935); E. Feenberg and E. Wigner, Phys. Rev. **51**, 95 (1937); H. A. Bethe, Phys. Rev. **54**, 436 (1938); White, Delsasso, Fox, and Creutz, Phys. Rev. **56**, 512 (1939); H. Brown and D. R. Inglis, Phys. Rev. **55**, 1182 (1939); M. Phillips and E. Feenberg, Phys. Rev. **59**, 400 (1941); D. R. Elliot and L. D. P. King, Phys. Rev. **60**, 489 (1941); E. Feenberg and G. Goertzel, Phys. Rev. **70**, 597 (1946).

2 D. M. Van Patter, Phys. Rev. **76**, 1264 (1949).

3 R. G. Thomas, Phys. Rev. **80**, 136 (1950); R. K. Adair, Phys. Rev. **81**, 310 (1951); E. Feenberg, Phys. Rev. **81**, 644 (1951); J. B. Ehrman, Phys. Rev. **81**, 412 (1951); D. R. Inglis, Phys. Rev. **82**, 181 (1951); S. Bashkin and H. T. Richards, Phys. Rev. **84**, 1124 (1951).

4 Van Patter, Buechner, and Sperduto, Phys. Rev. **82**, 248 (1951).

5 W. M. Gibson, Proc. Phys. Soc. (London) **A62**, 586 (1949).

6 C. P. Swann and E. L. Hudspeth, Phys. Rev. **76**, 168 (1949).

7 Brown, Chao, Fowler, and Lauritsen, Phys. Rev. **78**, 88 (1950).

8 The value of 6.473±0.011 Mev is based on a Q of 9.235±0.011 Mev for the $B^{10}(d,p)B^{11}$ reaction obtained by Strait, Van Patter, Buechner, and Sperduto [Phys. Rev. **81**, 747 (1951)] and a Q of 2.762±0.003 Mev for the $B^{11}(p,n)C^{11}$ reaction as given by Richards, Smith, and Browne [Phys. Rev. **80**, 524 (1950)].

9 Enriched B^{10} was obtained from the AEC Oak Ridge Laboratory.

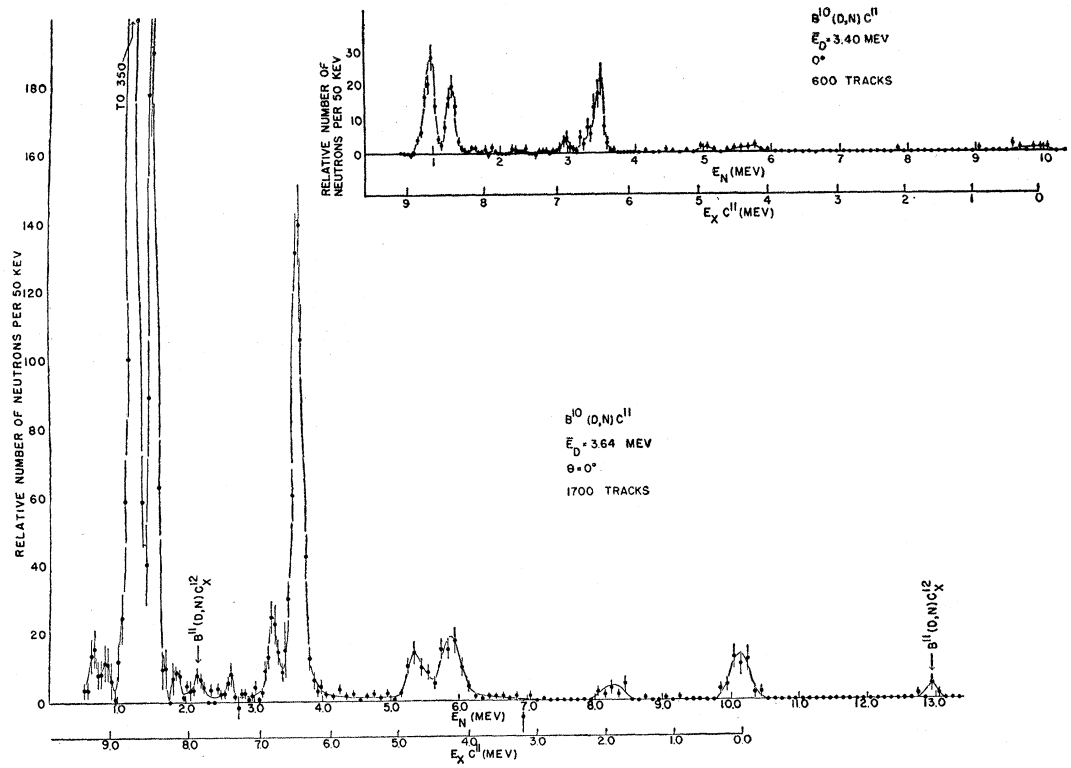

FIG. 1. Neutron spectrum at 0° from deuterons on 96 percent enriched B^{10} target. Upper curve: 3.40-Mev deuterons; lower curve: 3.64-Mev deuterons.

with respect to the incident beam. Conversion from range to energy was accomplished by means of an experimentally determined range-energy curve for the Eastman NTA emulsion. This range-energy curve was the same as that published by Richards *et al.*[10] (The neutron scale shown on the various figures in the present work was based on an earlier range-energy curve which, above 10 Mev, differs appreciably from that of reference 10. The Q values shown in the tables, however, are computed on the most recent data of reference 10.) The method of measurement and the criteria for acceptance of tracks have been described earlier.[11]

In order to eliminate from the resulting neutron spectrum the neutron group arising from the $B^{11}(d,n)C^{12}$ reaction, it was necessary to make an exposure to the neutrons from deuteron bombardment of a normal boron target. A background exposure was also made with the deuteron beam striking a bare tantalum target.

EXPERIMENTAL RESULTS ON C^{11}

One of the B^{10} targets was bombarded with deuterons of mean energy 3.40 Mev. The upper part of Fig. 1 shows the data taken at 0°. Background has been subtracted and a correction has been made for the variation with energy of the $n-p$ cross section[12] and for variation in the probability of the tracks leaving the emulsion.[13] The lower abscissa, labeled "$E_X C^{11}$", gives the excitation energy in C^{11} giving rise to emitted neutrons of the corresponding energy.

Higher energy deuterons, 3.64-Mev mean energy, and the other B^{10} target were used for the second exposure. The 0° data, corrected for background, $n-p$ cross-section variation, and geometry, is given in the lower part of Fig. 1. Because of the much lower intensity of the higher energy neutron groups, most of the measuring time was spent on tracks from neutrons of energies greater than 1.85 Mev; this accounts for the discontinuity in statistical uncertainty at this energy. Before assigning the observed groups to levels in C^{11}, it was necessary to eliminate the possibility that some of the groups might be due to neutrons from deuterons on B^{11} or on the commonly occurring contaminants, oxygen, carbon, and deuterium.

Some neutron groups were assigned to the $B^{11}(d,n)C^{12}$ reaction by comparing the neutron spectrum from the B^{10} targets with that from the normal boron target. The 0° data from the normal boron target is shown in Fig. 2; the mean bombarding deuteron energy was 3.40 Mev.

[10] Richards, Johnson, Ajzenberg, and Laubenstein, Phys. Rev. **83**, 994 (1951).
[11] Johnson, Laubenstein, and Richards, Phys. Rev. **77**, 413 (1950).
[12] R. K. Adair, Revs. Modern Phys. **22**, 249 (1950).
[13] H. T. Richards, Phys. Rev. **59**, 796 (1941).

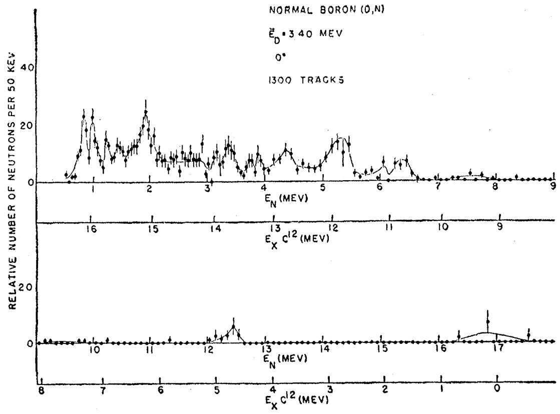

FIG. 2. Neutron spectrum at 0° from 3.40-Mev deuterons on normal boron target.

The peaks which show up in both the enriched B^{10} target data (Fig. 1) and the normal boron target data, are the ones in Fig. 2 which occur at neutron energies of 1.00, 1.25, 1.92, 3.45, and 12.5 Mev. The corresponding groups in the 3.64-Mev data of Fig. 1 are, of course, several hundred kv higher because of the higher E_D. Comparison of the relative intensities from the normal and enriched B^{10} targets shows that of these the 1.92- and 12.5-Mev groups (Fig. 2) result from the $B^{11}(d,n)C^{12}$ reaction, while the other three are from the $B^{10}(d,n)C^{11}$ reaction.

The data at 80° (Fig. 3) is of considerable help in confirming levels and in establishing the absence of contamination neutrons from deuterons on carbon, oxygen, and deuterium in the targets. No neutron groups corresponding to the $d-d$ neutron energies appear in any of the data except the 80° normal boron target data (Fig. 3) at neutron energy of 3.7 Mev. In this case it can be ruled out, since it does not appear at 6.7 Mev in the 0° data for the same target. Secondly, the neutron group at 1.87 Mev in the lower graph of Fig. 1 is at almost the correct energy for $O^{16}(d,n)F^{17}$ neutrons; however, at 80° no group corresponding to neutrons from deuterons on O^{16} appears for the same target, whereas a group does appear which would correspond to a $B^{10}(d,n)C^{11}$ group coming in at 0° at the oxygen neutron energy. Furthermore, there is no evidence on both the 0° and 80° data for neutrons corresponding to F^{17} being left in its 536-kev excited state.[14] Therefore, oxygen is not believed to be a significant contaminant. Large numbers of neutrons from carbon contamination may also be ruled out. In the 3.64-Mev data of Fig. 1 a group of neutrons occurs at 3.28 Mev, which is the energy for the C^{12} neutrons. But at 80° the energy of the neutrons from C^{12} would have shifted with respect to the neutrons from $B^{10}(d,n)C^{11}$ reaction so as to come in on the low energy side of the relatively intense peaks corresponding to formation of a level in C^{11} at 6.40 Mev. The occurrence of neutron groups in both sets of 80° B^{10} target data corresponding to the peak at 3.30-Mev neutron energy at 0° (Fig. 1), is quite good evidence that these groups result from the B^{10} reaction in which C^{11} is left in an excited state at 6.77 Mev.

The presence of some carbon contamination cannot

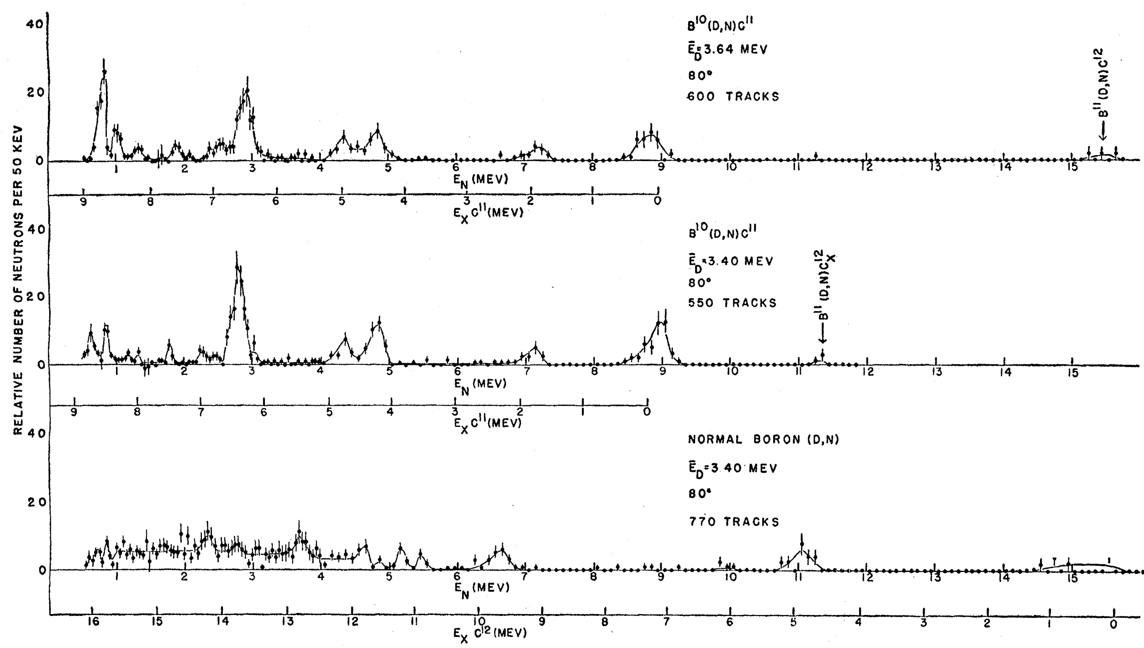

FIG. 3. Neutron spectra at 80° from 3.64-Mev and 3.40-Mev deuterons on 96 percent-enriched B^{10} and 3.40-Mev deuterons on normal boron.

[14] F. Ajzenberg, Phys. Rev. **83**, 693 (1951).

be excluded, however, even though the 6.77-Mev level of C^{11} seems well established. In fact, the weak group in the lower graph of Fig. 1 at 0.85-Mev neutron energy may be due to the $C^{12}(d,n)N^{13*}$ reaction, in which the 2.4-Mev level of N^{13} is formed.[15] Since this group is observed in only one set of data and is poorly resolved there, the level of C^{11} corresponding to it will be listed as uncertain. The low intensity group adjacent to it at 0.65-Mev neutron energy will also be listed as uncertain because it, too, is observed on but one set of data (Fig. 1). It could also possibly result from the $B^{11}(d,n)C^{12}$ reaction. If so, it corresponds to formation of C^{12} in an excited state at 16.7 Mev, a level which has been previously reported.[16]

In summary, all of the neutron groups observed in the B^{10} target data shown in Figs. 1, 2 and 3 are believed to correspond to levels in C^{11} except those marked otherwise. However, the assignment of the two lowest energy groups in the lower graph of Fig. 1 is uncertain.

As mentioned above, the background has been subtracted in all the curves. For comparison purposes the background data is shown in Fig. 4. The amount of background shown results from scanning an area on the 0° plates equivalent (for the total bombardments used) to one-third the area taken for the data of the lower part of Fig. 1 and three-fourths the area for Fig. 2. The background correction did not change the shapes of any of the curves significantly, but it did show up in an increased statistical uncertainty.

The data on C^{11} is summarized in Table I. The uncertainties in Q-values listed are estimated from the fluctuations of different sets of data. Relative intensities are corrected to the center-of-mass system; the ratios of the intensities at 0° to the intensities at 80° lab (ψ in c.m. system) are also from center-of-mass intensities.

COMPARISON OF B^{11} AND C^{11}

A comparison of the levels of B^{11} and C^{11} is shown in Fig. 5. The B^{11} levels shown, with the exception of the

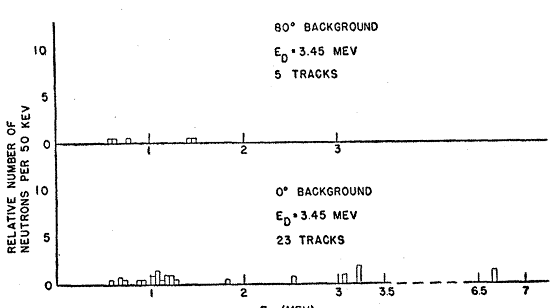

FIG. 4. Neutron background from 3.45-Mev deuteron beam on tantalum target backing.

TABLE I. $B^{10}(d,n)C^{11}$ yield data and the levels of C^{11}.

Excitation energy of C^{11} level (Mev)	Weighted mean Q-value (Mev)	Relative intensity in c.m. system at 0° for data of Fig. 2	Ratio of intensity at 0° to intensity at ϕ° in c.m. system	ϕ° c.m. system
0	(6.473±0.011)[a]	1.1	1.1	84.3°
1.85	4.62±0.06	0.3	0.8	84.8
4.23	2.24±0.06	1.4	1.6	85.8
4.77	1.70±0.06	1.0	1.9	87.1
6.40	0.07±0.04	5.9	3.5	87.4
6.77	−0.30±0.04	1.0	2.1	88.5
7.39	−0.92±0.04	0.2	0.8	89.2
8.08	−1.61±0.02	0.2	1.3	91.1
8.39	−1.92±0.02	5.0	12.2	92.0
8.62	−2.15±0.02	9.2	8.3	94.2
8.97[b]	−2.50±0.02[b]	0.3[b]		
9.13[b]	−2.66±0.02[b]	0.3[b]		

[a] Calculated from $B^{10}(d,p)B^{11}$ and $B^{11}(p,n)C^{11}$ reaction energies, Q_{dp} = 9.235±0.011 Mev (Strait *et al.*, Phys. Rev. **81**, 747 (1951)) and Q_{pn} = −2.762±0.003 Mev (Richards *et al.*, Phys. Rev. **80**, 524 (1950)).
[b] Assignment to C^{11} uncertain.

dotted level at 7.8 Mev, are those found by Van Patter *et al.*,[4] who used the $B^{10}(d,p)B^{11}$ reaction. A similar, though not so complete, spectrum has also been found by other workers.[17,18] The dotted level at 7.8 Mev in B^{11} was reported in the earlier work[17,18] but is apparently excluded by the recent careful work of Van Patter *et al.*[4] (however, see following discussion). Probable mirror levels are indicated in Fig. 5 by connecting lines. The poorer resolution of the photographic plate technique as compared to the method used by Van Patter *et al.*[4] prevented resolution of levels in C^{11} spaced less than 100 kev apart.

The close similarity of the level structure of B^{11} and C^{11} is very apparent in Fig. 5. There is no ambiguity in identifying the corresponding mirror levels until an excitation energy of about 6.5 Mev is reached. Then the question arises as to whether the close-spaced doublet in B^{11} at 6.76–6.81 Mev shifts to an unresolved doublet at 6.40 Mev in C^{11} or whether there is a differential shift of the members of the doublet so that the 6.77-Mev level in C^{11} corresponds to the upper level of the doublet. Only under the latter circumstance could one get a one-to-one correspondence of the higher mirror levels, if a level of B^{11} around 7.8 Mev is excluded. However, there are intensity objections to such an assignment of corresponding levels. Figure 6 shows the relative yields of the various (dp) and (dn) groups normalized to one for the ground-state transitions. The close similarity in intensity of mirror groups corresponding to <6-Mev excitation is marked. Since the higher member of the B^{11} doublet is very weak, it seems unlikely that it corresponds to the 6.77-Mev level in C^{11}. The best correspondence of intensities is obtained if one postulates that the mirror to 7.39 level of C^{11} has

[15] G. Goldhaber and R. M. Williamson, Phys. Rev. **82**, 495 (1951).
[16] Herb, Kerst, and McKibben, Phys. Rev. **51**, 691 (1937); Curran, Lee, and Petrzilka, Proc. Roy. Soc. (London) **A169**, 269 (1938).
[17] H. W. Fullbright and R. R. Bush, Phys. Rev. **74**, 1323 (1948).
[18] W. O. Bateson, Phys. Rev. **78**, 337 (1950); Phys. Rev. **80**, 982 (1950).

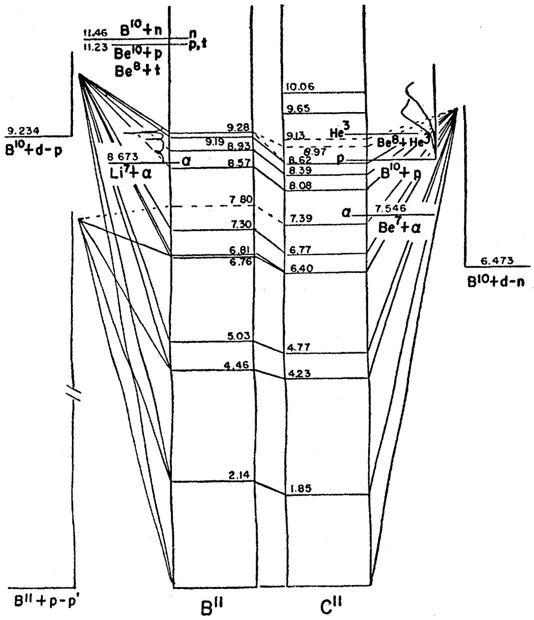

FIG. 5. Comparison of levels of B^{11} and C^{11} (ground state of C^{11} normalized to B^{11} ground state).

escaped observation in B^{11} because of its very low intensity. This hypothesis is reasonable, since the mirror proton group at Van Patter's bombarding voltage might be expected to fall in a momentum interval near the intense group of contamination protons from the $O^{16}(d,p)O^{17*}$ reaction. In fact, in Fig. 2 of reference 4 there is perhaps indication at $H\rho=211$ kilograuss-cm of a weak group on the enriched B^{10} data which is not present on the normal boron data.[19]

Another significant feature of Fig. 6 deserves comment. One notes that experimentally, for both the (d,p) and (d,n) yields, the most intense groups correspond to low energy outgoing neutrons or protons. This result is exactly opposite to that predicted on a compound nucleus picture where one expects the intensity distribution of completely resolved groups to be weighted by the momentum of the outgoing nucleon. The marked forward bunching (by a factor of ten) in the c.m. system of some groups of the outgoing neutrons (see Table I) is also not expected on the compound nucleus picture. However, such angular distributions and intensity distributions are readily understood if the reaction proceeds chiefly by a stripping process (e.g., see Butler[20]). Also, according to Butler, the very strong forward bunching occurs only for $l=0$ deuterons. Therefore, the experimental ratio of intensities (last column, Table I) probably indicates that the 6.4-, 8.39-, and 8.62-Mev levels of C^{11} are even parity and $3/2\leq J\leq 9/2$.

In conclusion, the correspondence of levels of the mirror nuclei B^{11} and C^{11} seems to be reasonably well established, and hence the close equality of neutron-neutron and proton-proton forces is evidenced.

LEVELS OF C^{12}

The data from the normal boron target was taken primarily for the purpose of checking assignments of neutron groups from the enriched B^{10} target. As a result, the normal boron data lack sufficient statistics to resolve clearly some of the weaker neutron groups corresponding to excited states of C^{12}. (For many of the levels, the poor statistics are partially compensated by the occurence of the corresponding neutron groups at both 0° and 80°.) There are strong $B^{10}(d,n)C^{11}$ groups (normal boron is 20 percent B^{10}) which obscure some regions of the $B^{11}(d,n)C^{12}$ spectrum. Therefore, it is emphasized that the present spectrum on C^{12} is certainly not complete. Nevertheless, several new levels in C^{12} are certainly established by the present data which is the first to explore the excitation interval 10–16 Mev and to overlap the proton capture levels observed in the $B^{11}(p,\gamma)C^{12}$ reaction.

The three intense $B^{10}(d,n)C^{11}$ neutron groups (upper part of Fig. 1) appear at the same energies (~1.0, 1.2, and 3.3 Mev) in the normal boron data (Fig. 2) and hence these groups are identified with the C^{11} level system. All the remaining groups apparently result from excited states of C^{12}.

Table II lists our best estimates of the Q-values of these groups. The indicated uncertainty is somewhat subjective, but is believed to be conservative. The present data is in agreement with previous neutron spectra concerning the existence of C^{12} levels at 4.4 and 9.6 Mev.[21] No group was resolved corresponding to

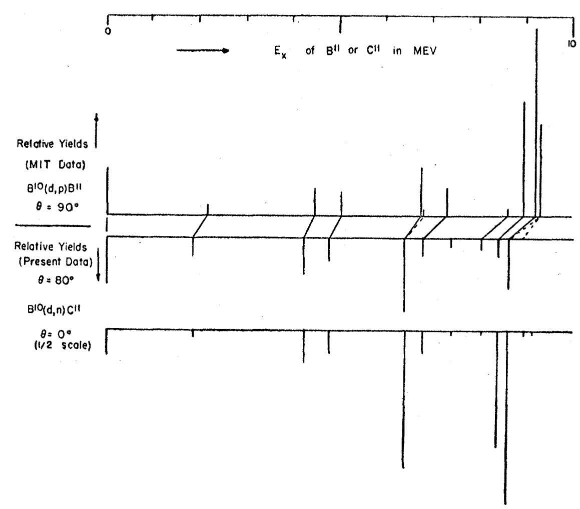

FIG. 6. Relative intensities of neutron and proton groups from $B^{10}(d,p)B^{11}$ and $B^{10}(d,n)C^{11}$.

[19] Recently, Dr. A. B. Lillie of the Rice Institute has found evidence for a B^{11} level at about 8 Mev from an experiment on the $N^{14}(n,\alpha)$ reaction using 14-Mev monoenergetic neutrons. The author is grateful for permission to publish this note.

[20] S. T. Butler, Phys. Rev. **80**, 1095 (1950).

[21] Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 325 (1950); R. Malm and W. W. Buechner, Phys. Rev. **81**, 519 (1951).

the previously reported 7-Mev level, although a few recoil tracks were observed in this region. The 10.8-Mev level here observed has also been inferred from a neutron threshold in the $Be^9(\alpha,n)C^{12}$ reaction and possibly from the B^{12} beta-decay and $C^{12}(p,p')C^{12}$ reaction (see reference 21).

In addition to producing neutron groups of discrete energies, one must consider the possibility that deuterons on B^{11} can produce a continuum of neutron energies by the three- and four-particle break-up of the compound nucleus. For example, the following modes of disintegration are energetically possible: Be^8+He^4+n or 3 He^4+n, or, more likely, by the "cascade" disintegration of C^{13} first into $Be^{9*}+He^4$ or Be^8+He^5 and then into Be^8+He^4+n. The presence of a continuum corresponding to C^{12} excitation energies between 11.5 and 16.3 Mev cannot be ruled out on the basis of the data obtained. However, the occurrence of some unresolved or very broad states of C^{12} would account adequately for the "background" in this energy range.

The author is indebted to Dr. H. T. Richards for invaluable help throughout the course of the work. The author is also grateful to Miss Fay Ajzenberg for development of the plates and for help in exposing the plates and to Dr. G. Goldhaber for assistance in exposing the plates.

TABLE II. Q-values for the $B^{11}(d,n)C^{12}$ reaction and the corresponding energy levels of C^{12}.

Q value (Mev)	Excitation energy C^{12} Mev
$(13.740\pm0.014)^a$	0
$(9.30\pm0.02)^a$	4.44
4.1 ± 0.1	9.6
2.9 ± 0.1	10.8
2.6 ± 0.1	11.1
2.00 ± 0.08	11.74
0.98 ± 0.08	12.76
$\left.\begin{matrix}0.53\pm0.05\\0.38\pm0.05\end{matrix}\right\}$ one level (?)	$\left.\begin{matrix}13.21\\13.36\end{matrix}\right\}$ one level at 13.3 (?)
-0.42 ± 0.05 (?)	14.16 (?)
-1.35 ± 0.03	15.09
-1.78 ± 0.03 (?)	15.52 (?)
-2.33 ± 0.03	16.07

[a] These Q-values are computed from disintegration data (as described in reference 10) not from the present neutron data.