High-Resolution Study of the $B^{10}(He^3,p)C^{12}$ Reaction*

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Proton groups from the $B^{10}(He^3,p)C^{12}$ reaction leading to levels up to 16.2-Mev excitation were analyzed with a broad-range spectrograph. At a bombarding energy of 3.74-Mev spectra were taken at 11 angles from 5 to 139 degrees. Levels were found at excitation energies of 4.43(7), 7.655±0.006, 9.645±0.006, 10.849±0.025, 11.841±0.025, 12.713±0.006, 13.29±0.03, 14.083 ±0.015, 15.108±0.006, and 16.108±0.006 Mev. Widths of the 9.6-, 10.8-, 11.8-, 13.3-, and 14.1-Mev levels are 35±6, 320±30, 245±30, 430±100, and 252±15 kev respectively. Widths of the other levels are less than 15 kev. No levels were found at excitations of 9.0, 11.1, or 15.6 Mev. A level 2 Mev wide at 10.1-Mev excitation would not have been seen above the high background from three-particle breakup. Yields at each angle were measured relative to the yield of the $B^{10}(He^3,d)C^{11}$ reaction. An angular distribution of this reaction was obtained. Absolute differential cross sections were found by comparing the yields with the known yield from the $B^{10}(d,p)B^{11}$ reaction. Cross sections for the $B^{10}(He^3,p)C^{12}$ reaction vary from 0.02 mb/sr to 0.6 mb/sr.

I. INTRODUCTION

The level structure of C^{12}, from the ground state up to the third level at 9.6 Mev, is well known from a large number of experiments on a variety of reactions. Above 16-Mev excitation levels are known from scattering and resonance reactions. In the intermediate region, that is from 9.6 to 16.1 Mev, there is considerable discrepancy in the results of different experiments.

The ground state and first three-excited states have been seen by at least ten different reactions.[1] A level was reported at 9.0 Mev,[2] but this was later shown to be spurious.[3] The level at 15.11 Mev has been the subject of a great deal of experimentation and again some ten reactions have been used to examine it. A level at 12.73 Mev and another level at 16.11 Mev have been seen through five reactions.

Information about other levels between 9.6- and 16.1-Mev excitation comes mainly from the reactions $B^{11}(d,n)C^{12}$, $B^{10}(He^3,p)C^{12}$ and more recently, $B^{11}(He^3,d)C^{12}$. Using the first of these reactions, Johnson[4] reported levels at 10.8, 11.1, and 11.74 Mev with some indication of either a wide level at 13.3 Mev or two narrow levels at 13.2 and 13.36 Mev. He also found an indication of levels at 14.16 and 15.52 Mev in addition to the levels mentioned above with the exception of the 7.6-Mev level. Other results from this reaction confirm the first three excited states[5] and show the level at 12.7 Mev.[6] Two other experiments, one in which slow-neutron thresholds were observed[7] and one in which a gamma-ray threshold was observed[8] give precise values for the excitation energy of the 15.1-Mev state.

The second reaction has been studied at 0.90 Mev by Bigham *et al.*,[9] at 1.25 Mev by Moak *et al.*[10], and at 2.0 Mev by Almqvist *et al.*[11] In each case scintillation detectors were used to analyze the protons. These authors all agree on the existence of levels at 10.8, 11.8, 13.3, and 14.1 Mev and see the well-known levels also. Moak *et al.* also reported a level at 15.62 Mev although from the published data its existence appears a bit uncertain. In each of these three measurements the precision was about 0.1 Mev in the excitation energies. No level at 11.1 Mev was found by any of the authors.

In a recent measurement, using a broad-range spectrograph to analyze the deuterons from the third reaction, Hinds and Middleton[12] found levels at 10.84±0.02, 11.82±0.02, 12.70±0.01, and 13.38±0.02 Mev and reported a new level at 14.71±0.01 Mev. They did not find the level at 14.1 Mev nor a level at 11.1 Mev.

One other level in this range of excitation has been reported. In studies[13] of the beta decay of B^{12} a state was found at about 10.1±0.2 Mev with a width of about 2.5 Mev. Such a level may have been seen with the $C^{12}(n,n)He^4$ reaction,[14] but in this case it was stated to be at 9.7 Mev with a width of 1.6 Mev. There is also a suggestion[15] of such a level from work on the $O^{16}(\gamma,\alpha)C^{12}$ reaction but other authors studying the same reaction interpret the results in terms of the levels at 9.6 and 10.8 Mev[16] or in terms of the $O^{16}(\gamma,\alpha)3\ He^4$ reaction.[17] The existence of such a broad state could probably not

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be confirmed with any of the other reactions mentioned above.

Some data were previously available on level widths[1] and Hinds and Middleton report widths of the levels at 10.8, 11.8, and 13.3 Mev. Differential cross sections for the $B^{10}(He^3,p)C^{12}$ reaction were measured at 2-Mev bombarding energy and 90-degree observation angle for each of the observed levels by Almqvist *et al.*[11]

The present work is a high-resolution study of the $B^{10}(He^3,p)C^{12}$ reaction. The positions and widths of levels in C^{12} up to 16.1-Mev excitation were determined. In addition absolute differential cross sections were obtained for most of the levels at angles from 5 to 140 degrees for a bombarding enegy of 3.74 Mev. As a byproduct the angular distribution of the $B^{10}(He^3,d)C^{11}$ reaction was obtained at this bombarding energy. Comparison of the result with previous work is given.

II. EXPERIMENTAL PROCEDURE

An electrostatic accelerator provided He^3 ions with energies ranging from 2.49 to 3.74 Mev. These ions passed through a magnetic analyzer set for an energy resolution of 0.08%. Reaction products were analyzed with a broad-range spectrograph and recorded on nuclear track plates. The object defining slit was set at 0.5 mm in the energy sensitive direction. Thin targets of enriched B^{10} were prepared by evaporating the elemental material[18] from carbon boats onto thin Formvar backings. For some of the runs a target of 22-μg/cm^2 thickness on a thick aluminum backing was used. This target was made at Harwell and was obtained from D. E. Alburger. For runs made with the thick-backed target it was necessary to prevent the scattered He^3 particles from striking the nuclear track plates by covering the plates with thin aluminum foil. This foil was also used for many of the other runs to slow the high-energy protons somewhat in order to increase the density of the tracks in the emulsion and hence make track counting easier. Details of the apparatus and data-analyzing procedures have been given earlier.[19,20]

Because it was hard to observe the broad groups when thin targets were used and because the thick target was found to have a surface layer, the following procedure was used to measure Q values with the thick target. Five runs were made with fresh, thin targets at various angles and bombarding energies and the results used to calculate the Q value for the prominent group leading to the 12.71-Mev level. The average Q value for this level was then used as a reference value for the runs with the thick targets. That is, this group was used to obtain the input energy at the B^{10} layer for the thick-target runs.

The usual procedure in determining excitation energies is to measure the ground-state Q value with the same condition of bombarding energy and target setting used to measure the Q value for the excited state in question. Uncertainties in input energy and surface layers on targets tend to cancel out. In the present measurement this procedure was unreliable because of the very high (19.7 Mev) ground-state Q value. Protons from the ground-state reaction have such a high momentum that to record them the spectrograph must be run at a field beyond the range in which the calibration is known to be independent of field. The ground-state Q value was measured in several runs and it was gratifying to find that the results agreed with the value calculated from the mass differences given by Everling *et al.*[21] More reliance, however, was placed in the value calculated from the masses and in the fact that use of this value gave excitation energies for the 7.65- and 15.11-Mev levels which agreed with previous precise determinations. A separate project is underway to make a more reliable measurement of the ground-state Q value.

Because of the low yield of this reaction it was impractical to make a series of sufficiently long exposures at the various angles with a given target setting. Angular distributions of the different proton groups were gotten by finding the ratio of the proton yield to the deuteron yield from the $B^{10}(He^3,d)C^{11}$ reaction. The angular distribution of this latter, more prolific, reaction was then taken in a series of short exposures. The thick-backed target was used for angles from 70 to 139 degrees and thin-backed targets were used for the forward angles.

The absolute differential cross section for the $B^{10}(He^3,d)C^{11}$ reaction, and hence the absolute cross sections for the $B^{10}(He^3,p)C^{12}$ reaction, was found by comparing the yield to the yield from the $B^{10}(d,p)B^{11}$ reaction. The results of Marion and Weber[22] were used for the cross section at 90 degrees observation angle and 1-Mev bombarding energy. This reaction was run under these conditions and then, with the target fixed, the $B^{10}(He^3,d)C^{11}$ reaction was run at the bombarding energy used in measuring the angular distribution. A repeat run was made in different sequence to check a possible contamination of the He^{3+} beam with an HD^+ beam. No significant contamination was found.

With thin targets great difficulty was experienced in distinguishing proton groups leading to the wide levels from the background of protons from three-particle breakup. These broad groups were much enhanced by using a thicker targer (50 to 100 kev thick to 3.74-Mev He^{3+}) and by averaging the number of proton tracks for ten $\frac{1}{2}$-mm counting strips. This effectively reduces the resolution of the spectrograph and reduces statistical fluctuations. It was possible to fit the resulting data with the Breit-Wigner single-level formula and hence get a more accurate value for the width and total number of tracks for each group.

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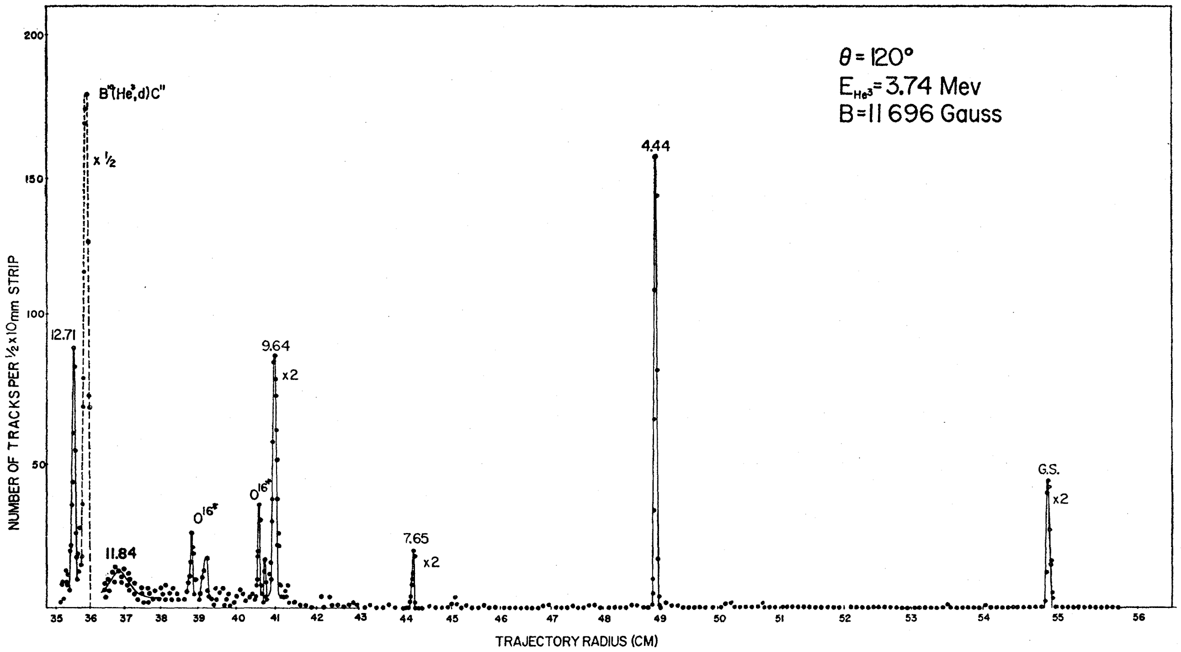

FIG. 1. Spectrum of particles from a B^{10} target observed at 120 degrees with a He^3 bombarding energy of 3.74 Mev. Groups from the $B^{10}(He^3,p)C^{12}$ reaction are labeled with the excitation energy of the residual C^{12} state. Other proton groups from the $N^{14}(He^3,p)O^{16}$ reaction are labeled with the symbol of the residual nucleus. The dashed line represents a deuteron group from the $B^{10}(He^3,d)C^{11}$ reaction.

III. RESULTS

Level Positions

Figure 1 shows a spectrum taken at 3.74-Mev bombarding energy at an observation angle of 120 degrees using a thin target. Excitation energies from the ground state up to 12.8 Mev were covered in this run. Groups leading to the ground state and levels at 4.437, 7.655, 9.645, and 12.713 Mev are seen in the figure and there is an indication of a wide level at 11.84 Mev. The additional proton groups appearing on the plot come from the $N^{14}(He^3,p)O^{16}$ reaction on the nitrogen contaminant present on this target. Finally, a deuteron group from the $B^{10}(He^3,d)C^{11}$ reaction is indicated by dashed lines. All the groups from the $B^{10}(He^3,p)C^{12}$ reaction are labeled with the excitation energy of the C^{12} level to which they lead. The three-particle reaction $B^{10}(He^3,p\alpha)Be^8$ is undoubtedly responsible for the background of protons which rises toward the low-energy end of the plot. This reaction has a threshold corresponding to an excitation of 7.37 Mev in C^{12}. The four-particle reaction giving a proton and three alpha particles may also contribute to the background.

Excitation energies from 7.6 to 16.2 Mev are covered in the plots shown in Fig. 2. The upper plot in this figure shows data from a thin target whereas the lower plot is from a thicker target. The enhancement of the wide groups obtained with thicker targets is thus illustrated. The two runs were made at different observation angles but the spectrograph field was adjusted to put corresponding groups at the same place on the plate. As in Fig. 1 the groups leading to levels in C^{12} are labeled with the excitation energy of the level. Groups from the $C^{12}(He^3,p)N^{14}$ and $C^{13}(He^3,p)N^{15}$ reactions are labeled with the symbol of the residual nucleus. The deuteron group from the $B^{10}(He^3,d)C^{11}$ reaction is shown in the upper plot but was omitted from the lower plot for clarity. In addition to the groups shown in Fig. 1, narrow groups from levels at 15.11 and 16.11 Mev are seen. Broad groups appear in the thick-target run corresponding to levels at 10.849, 11.841, 13.29, and 14.083 Mev. Above an excitation of 15.96 Mev the $B^{10}(He^3,pn)C^{11}$ reaction is expected to contribute to the continuous background of protons.

The large width and low intensity of the group ascribed to a level at 13.29 Mev make identification of this level doubtful. Evidence from the present study for the existence of this level is shown in Fig. 3. Here the number of tracks, above background, per counting strip, averaged over 10 counting strips is plotted against plate distance. Three different observation angles are represented in the figure. The group seen in each case is consistent, within the uncertainty of locating its center, with a level at 13.29 Mev. The arrows on the plots show the positions for the centers of groups, corresponding to a level at 13.290 Mev. The actual excitation calculated for each group is shown on the figure. The average of these numbers gives 13.29±0.03 Mev for the excitation energy of this level.

The Q values from all runs used in the determination of other level positions are given in Table I. The five runs used to calculate the Q value for the 12.713-Mev

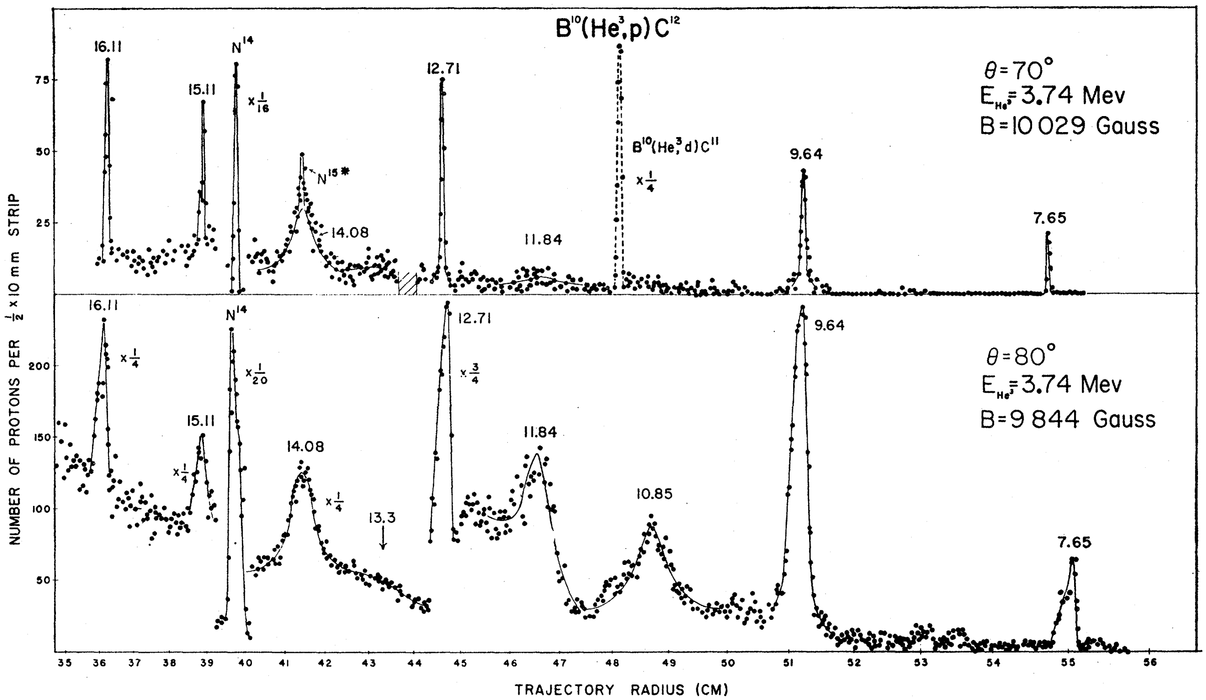

FIG. 2. Spectra showing proton groups leading to C^{12} levels with excitation energies from 7.6 to 16.1 Mev. The upper plot is from a thin target. The lower plot is from a thicker target and shows enhancement of the groups leading to the wide levels. Labeling of groups is similar to that in Fig. 1.

level are listed first. The position of this group was then used as a reference for calculating Q values corresponding to the groups observed in the last four runs made with the thicker target.

To obtain excitation energies it is, of course necessary to know the ground-state Q values. The number used to give the excitation energies listed in the last line of Table I is 19.693 Mev. This is the average of values found in three runs, but as stated above, this result is subject to considerable uncertainty because of the very high proton energies involved. Use of this number gives 15.108 Mev for the energy of the eighth excited state compared to 15.116±0.006 reported by Kavanaugh and Barnes[8] and 15.100±0.006 reported by Marion *et al.*[7] The excitation of the second-excited state is found to be 7.655 Mev compared to 7.653±0.008 Mev reported by Cook *et al.*[23] and 7.663±0.013 Mev obtained by using the average of the Q values found by Pauli[24] (5.910±0.015 Mev) and by Ahnlund[25] (5.912±0.013 Mev) for the $N^{14}(d,\alpha)C^{12}$ reaction to this state. In the latter comparison the ground-state Q value for the $N^{14}(d,\alpha)C^{12}$ reaction was calculated from the $N^{14}-C^{12}$ mass difference obtained to exceptional precision by Bardin *et al.*[26] using the $C^{12}(He^3,p)N^{14}$ reaction. This value is identical with that found from the latest mass tables.[21] Using this same mass difference and the Q value given by Douglas *et al.*[27] for the $N^{14}(d,\alpha)C^{12}$ reac-

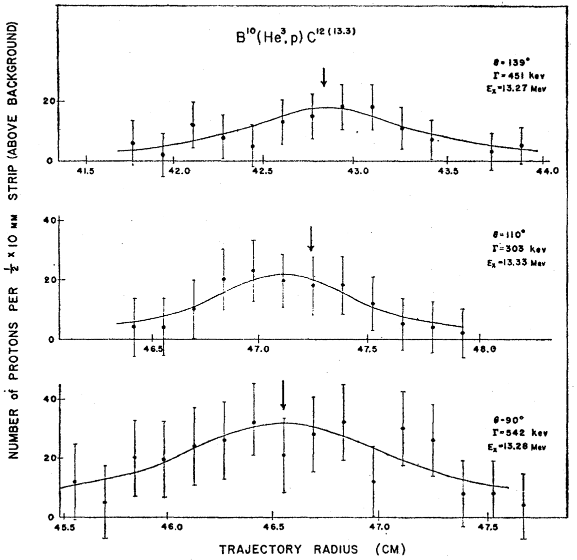

FIG. 3. Evidence for a level at 13.29 Mev in C^{12}. Proton groups seen at three angles with a He^3 bombarding energy of 3.74 Mev. The average number of tracks per counting strip for 10 strips is plotted versus trajectory radius. The arrows show the calculated position of a group leading to a level at 13.290 Mev in C^{12}.

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TABLE I. Summary of Q-value determinations for the $B^{10}(He^3,p)C^{12}$ reaction. The Q values (in Mev) are listed for the levels designated by excitation energies in the column headings. The 4.43- and 13.29-Mev levels are not listed but are discussed in the text.

Run	Observation angle (degrees)	Bombarding energy (Mev)	Q value (Mev)							
			7.65 level	9.64 level	10.85 level	11.84 level	12.71 level	14.08 level	15.11 level	16.11 level
1	70	3.743	12.042	10.048		7.888	6.983	5.612	4.584	3.585
2	90	3.743		10.053			6.977		4.583	3.585
3	60	3.743	12.040	10.042		7.888	6.989	5.611	4.583	
4	90	3.739		10.046			6.976			
5	90	3.743		10.050			6.979		4.588	3.584
6	90	3.743							4.586	3.588
7	80	3.723	12.039	10.056	8.845	7.842	a	5.621		3.584
8	139	3.736	12.034	10.057	8.826	7.832	a	5.606	4.579	3.582
9	110	3.705			8.825	7.833	a	5.586		
10	90	3.721			8.881	7.852	a	5.611		
Weighted mean			12.038[b]	10.048[b]	8.844[c]	7.852[c]	6.980[b]	5.610[d]	4.585[b]	3.585[b]
Excitation energy[e]			7.655	9.645	10.849	11.841	12.713	14.083	15.108	16.108

[a] This group used as a reference for other groups in this run.
[b] These values are ±0.006 Mev.
[c] These values are ±0.025 Mev.
[d] This value is ±0.015 Mev.
[e] Excitation energies are based on a ground-state Q value of 19.693 Mev (see text).

tion to the third-excited state, a third comparison with present results may be made. Douglas' number gives 9.641±0.014 Mev compared to the present result of 9.645±0.006 Mev. The excellent agreement of the excitation energies of the 7.655-, 9.645-, and 15.108-Mev levels with other work and the exact agreement with the latest table of masses[21] lends strong support to the ground-state Q value used.

The 4.43-Mev level appeared on the plates, with one exception, only in runs taken to measure the ground-state Q value and hence the excitation energy is subject to the same uncertainty resulting from the high magnetic field. No accurate measurement of the excitation energy of this state was attempted here because precise determinations have already been made.[28,29] Hence this level does not appear in Table I. The rather large uncertainty in the Q values for the 10.849- and 11.841-Mev levels arises from difficulty in determining the midpoint of the wide, weak groups. The 14.083-Mev level, while wide, yields a more intense group so the uncertainty is less.

All energies given in this paper are based on a value

TABLE II. Comparison of level positions of C^{12} determined by various investigators. See text for comparison with previous precise determinations of excitation energies of the 7.64-, 9.64-, and 15.11-Mev levels.

Johnson[a] $B^{11}(d,n)C^{12}$	Bigham *et al.*[b] $B^{10}(He^3,p)C^{12}$	Moak *et al.*[c] $B^{10}(He^3,p)C^{12}$	Almqvist *et al.*[d] $B^{10}(He^3,p)C^{12}$	Hinds and Middleton[e] $B^{11}(He^3,d)C^{12}$	Present work $B^{10}(He^3,p)C^{12}$
4.44	4.43±0.1	4.43[f]	4.43±0.10		g
	7.77±0.1	7.65[f]	7.65±0.10		7.655±0.006[h]
9.6 ±0.1	9.61±0.1	9.61[f]	9.60±0.10	9.63[i]	9.645±0.006
10.8 ±0.1	10.75±0.1	10.90±0.10	10.76±0.10	10.84±0.02	10.849±0.025
11.1 ±0.1					
11.74±0.08	11.83±0.1	11.84±0.06	11.82±0.10	11.82±0.02	11.841±0.025
12.76±0.08	12.76±0.1	12.69±0.06	12.78±0.10	12.70±0.01	12.713±0.006
13.21±0.05[j]					
13.36±0.05	13.31±0.1	13.30±0.06	13.37±0.10	13.38±0.02	13.29±0.03
14.16±0.05	13.97±0.1	14.05±0.06	14.03±0.10	k	14.083±0.015
				14.71±0.01	
15.09±0.03	15.10±0.1	14.97±0.06	15.10±0.10		15.108±0.006
15.52±0.03		15.62±0.06			
16.07±0.03	16.04±0.1	16.10[f]	16.10±0.10		16.108±0.006
	16.57±0.1	16.57±0.06	16.64±0.10		

[a] See reference 4.
[b] See reference 9.
[c] See reference 10.
[d] See reference 11.
[e] See reference 12.
[f] These levels used for calibration.
[g] Level observed but excitation energy not accurately measured. See text for precise value.
[h] Errors in this column do not include uncertainty in ground-state Q value or in the Po^{210} alpha-particle energy.
[i] All energies in this column based on this value.
[j] This level and the 13.36-Mev level reported as either two narrow levels or one broad level at 13.3 Mev.
[k] Possibly obscured by high background.

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[28] C. P. Browne and J. R. Lamarsh, Phys. Rev. **104**, 1099 (1956)
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of 5.3056 Mev[30] for the energy of the alpha particles from Po^{210}. It is to be noted that if the old, lower value for this energy was used the agreement with the mass differences and previously determined excitation energies would be destroyed.

A comparison of the present results with some of the previous work giving the levels of C^{12} is made in Table II. The level reported[13] at 10.1 Mev with a width of about 2 Mev would not be distinguished from the background arising from the three-particle reaction $B^{10}(He^3,p\alpha)Be^8$. A level near 11.1 Mev would have been seen if the yield was 8% of that of the 12.71-Mev level. A second narrow level at 13.2 Mev near the broad level at 13.30 Mev would have been seen if the yield was 8% of that of the 12.71-Mev level and a level at 15.6 Mev would have been seen with a yield of 7% of the yield of the 16.11-Mev level if it were less than 30 kev wide and 20% of the yield of the 14.08-Mev level if it had a width of about 250 kev. The possibility stated by Johnson[4] that the two groups ascribed by him to levels at 13.21 and 13.36 Mev actually represented a single broad level at 13.3 Mev seems to be the case.

The level structure of C^{12} up to 16.11 Mev as presently determined is shown in Fig. 4. The levels observed in this work are shown by solid lines. Excitation energies shown are those presently determined with two exceptions. The excitation of the 4.43-Mev level is taken from previously reported determinations of 4.431±0.005 Mev[28] and 4.431±0.008 Mev[29] corrected for the higher value of the Po^{210} alpha-particle energy presently adopted, and the excitation of the 10.1-Mev state is taken from Cook *et al.*[13]

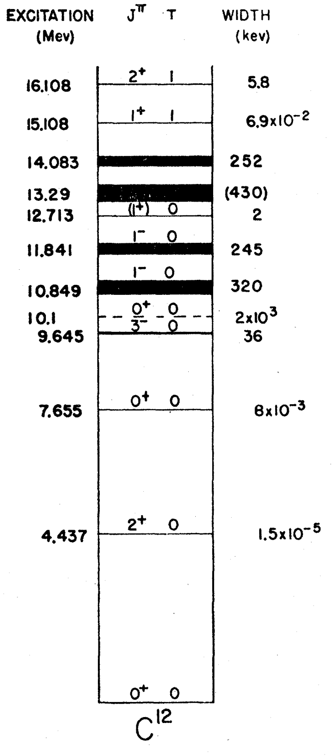

FIG. 4. Energy level diagram for C^{12}. Widths of the broad levels were measured in this work. Spins and parities are taken from other work. The very broad level at 10.1 Mev could not be seen in this work.

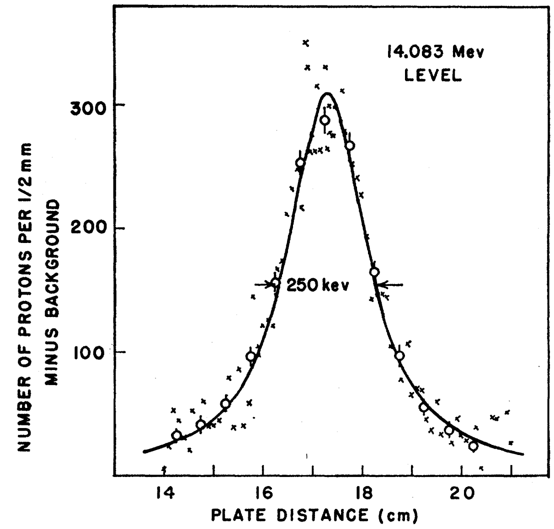

FIG. 5. Large-scale plot of a proton group leading to the 14.083-Mev level. The X marks give the number of tracks per counting strip. The circles are the averages for ten counting strips. The curve was calculated from the Breit-Wigner single-level formula.

Level Widths

To illustrate the method and results for width determinations a large-scale plot of a group leading to the 14.083-Mev level is shown in Fig. 5. A background, rising slightly with decreasing plate distance, has been subtracted from the total number of tracks per counting strip. The result is shown by the X marks in the figure. The average of these numbers for ten counting strips is also shown by the circles in the figure. The solid curve through the points is calculated from the Breit-Wigner single-level formula. The half-width of the group in plate distance is read off the plot and converted to energy spread by using the known dispersion of the spectrograph. This energy spread is then used to find the spread in Q value, i.e., the level width. Only in the case of the 9.64-Mev level was the instrumental width of the group an appreciable fraction of the observed width. In this case the instrumental width was removed by taking the square root of the difference of the squares.

The data on level widths are summarized in Table III and are also included in Fig. 4. All the other levels observed here but not included in the table were found to have widths <15 kev. Previous data on level widths measured here are also listed in Table III. It is seen that the width found for the 9.64-Mev level is in excellent agreement with the value given by Douglas *et al.*[27] The value for the 10.85-Mev level is in excellent agreement, and that for the 11.84-Mev level in fair agreement,

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[30] C. P. Browne, J. A. Galey, J. R. Erskine, and K. L. Warsh, *Proceedings of the International Conference on Nuclidic Masses* (University of Toronto Press, Toronto, 1960).

TABLE III. Widths of C^{12} levels determined in this work and comparison with previous work.

Excitation energy (Mev)	Level width (kev) Previous work	Present work
9.645	30± 8[a]	36± 6
10.849	320± 30[b]	320± 30
11.841	300± 30[b]	245± 30
13.29	700±100[b]	430±100
14.083		252± 15

[a] See reference 27.
[b] See reference 12.

with the values found by Hinds and Middleton.[12] The width of the 13.29-Mev level does not agree with that found in the last work but in both measurements the level is barely discernable above background and width measurements are questionable. The 14.08-Mev level width has not previously been reported.

Widths of the other C^{12} levels are known from other work[31] and are included in Fig. 4. It is seen that in each case the actual value is <15 kev in agreement with the present measurements.

Spin and Parities

The spin and parity is now known for most of the C^{12} levels. The values, which are given in Fig. 4, are taken from the latest compilation[31] with the exceptions of those for the 9.64-, 10.85-, and 11.84-Mev levels which come from the $B^{11}(He^3,d)C^{12}$ work.[12] A recent study[32] of gamma-ray transitions confirms the assignment for the 9.64-Mev level.

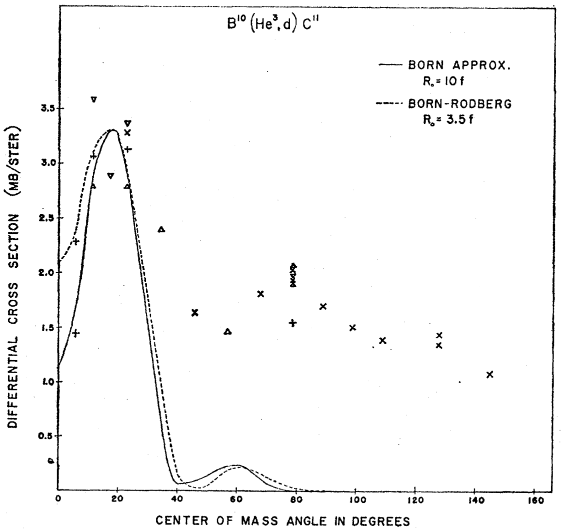

FIG. 6. Angular distribution from the $B^{10}(He^3,d)C^{11}$ reaction at 3.74 Mev. Different symbols represent different runs. The curves are theoretical.

Angular Distributions

The angular distribution of the ground-state group from the $B^{10}(He^3,d)C^{11}$ reaction taken at a bombarding energy of 3.743 Mev is shown in Fig. 6. This group was used as a reference for all the proton groups from the $B^{10}(He^3,p)C^{12}$ reaction. Data points are shown by various symbols representing different runs. For runs at laboratory angles of 70 degrees and above, the thicker target on a thick backing was used. A repeat run was taken at 120 degrees after the other angles were run. The reproducibility in this run is seen to be good. For angles from 70 degrees forward, thin backed targets were used and target stability became a problem. Three runs were taken which were normalized at 70 degrees and one run (indicated by plus signs in the figure) normalized at 20 degrees. The reproducibility of the first three runs is shown by the scatter of the points at 79 degrees (c.m.) in the figure. In the last run there was very bad target stability but the data definitely show the drop in the cross section between ten degrees and five degrees.

Although it is not required for the present work an attempt was made to fit the data with theoretical expressions for stripping reactions. The solid curve shown in Fig. 6 was calculated following Newns[33] and the dashed curve following Rodberg.[34] In each case an angular momentum transfer characterized by $l=1$ was assumed. A calculation was also made following Macfarlane and French.[35] When a radius of 8 fermis was used the result was essentially the same as that shown in the figure for the simpler theory. An $l=1$ assignment is consistent with the results for the same reaction obtained at 9.84-Mev bombarding energy.[12] At the higher energy the forward peak was more pronounced and the cross section at back angles was lower than in the present case. A radius of 5.3 fermis gave a fit at the higher energy.

To convert the relative differential cross sections to absolute cross sections a value of 0.8 mb/sr[22] was used for the cross section of the $B^{10}(d,p)B^{11}$ reaction at 90 degrees and 1 Mev. Two runs were made in which the proton group was observed three times and the deuteron group from $B^{10}(He^3,d)C^{12}$ was observed twice. The repeat runs agreed within 10% and the averages of the two series was 1.4 mb/sr (c.m.) for the differential cross section of $B^{10}(He^3,d)C^{12}$ at 3.743 Mev and 90 degrees. This result was used to construct the ordinate scale in Fig. 6.

Once the angular distribution of the $B^{10}(He^3,d)C^{11}$ reaction was known, the angular distributions of each of the proton groups observed from the $B^{10}(He^3,p)C^{12}$ reaction could be found by taking the ratio of the intensity of the proton group in question to the intensity of the deuteron group which appeared on the same nuclear track plate. As the two groups were recorded

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[31] For summary see F. Ajzenberg-Selove and T. Lauritsen, Technical Report, California Institute of Technology, Pasadena, 1960 (unpublished).
[32] R. R. Carlson (to be published).
[33] H. C. Newns, Proc. Phys. Soc. (London) **A65**, 916 (1952).
[34] L. S. Rodberg, Nuclear Phys. **21**, 270 (1960).
[35] M. H. Macfarlane and J. B. French, Revs. Modern Phys. **32**, 567 (1960).

TABLE IV. Ratio of the $B^{10}(He^3,p)C^{12}$ differential cross section to the $B^{10}(He^3,d)C^{11}$ differential cross section at various angles. Bombarding energy 3.74 Mev.

C^{12} Level (Mev)	5°	20°	40°	60°	70°	80°	90°	110°	120°	139°
7.65	0.011		0.016	0.022	0.021	0.028			0.019	0.039
9.64	0.055	0.054	0.10	0.14	0.11	0.12	0.16	0.15	0.16	0.21
10.85						0.11	0.38	0.068		0.11
11.84	0.14	0.018	0.12	0.081	0.067	0.12	0.039	0.087		0.057
12.71	0.10	0.087	0.13	0.12	0.10	0.077	0.10		0.16	0.21
14.08	0.17	0.084	0.28	0.24	0.28	0.29	0.20	0.16		0.11
15.11	0.20	0.071	0.10	0.090	0.059	0.048	0.13			0.034
16.11	0.088	0.068	0.14		0.074	0.40	0.14			0.13

simultaneously there were no problems of target stability or current integration. The only correction applied was that for the variation of solid angle of the spectrograph with position along the plate.

Ratios of the (He^3,p) to (He^3,d) cross sections at the various angles are given in Table IV. The angular distributions from the $B^{10}(He^3,p)C^{12}$ reaction for the different C^{12} levels are shown in Fig. 7. Here the absolute differential cross section in laboratory coordinates is plotted against laboratory angle for each group for which a sufficient number of points was obtained. The bombarding energy was 3.743 Mev. The ground-state group was observed only at 120 degrees. Here the differential cross section was 0.11±0.01 mb/sr. The 4.43 level was observed at 40 and 120 degrees. The differential cross sections obtained were 1.6±0.2 mb/sr and 0.68±0.07 mb/sr, respectively. As the 10.8-Mev group could only be seen when using the thicker target on a thick backing no points forward of 80 deg were obtained for this group. The 13.30-Mev group was too weak and ill-defined to give a value for the yield.

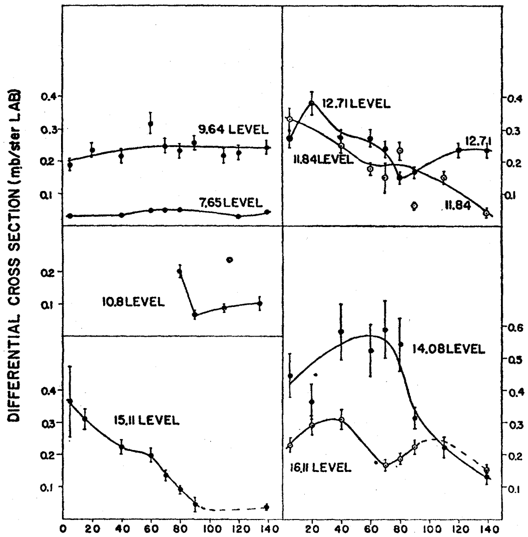

FIG. 7. Angular distributions of proton groups from the $B^{10}(He^3,p)C^{12}$ reaction leading to various levels in C^{12}. The curves are labeled with the excitation energies of the levels to which they correspond.

The error bars in Fig. 7 indicate the estimated error in yield compared to the yield of the $B^{10}(He^3,d)C^{11}$ reaction. The error in the absolute cross section for the $B^{10}(d,p)B^{11}$ reaction used as a reference is not included in this estimate.

IV. SUMMARY

The energy level scheme of C^{12} up to at least 16.1 Mev is established. Above this point many levels are known from scattering data. The widths of all levels up to 16.1 Mev are known and with two exceptions the spins and parities. Almqvist *et al.*[11] give the same level scheme shown in this work and a very complete investigation of the γ-ray transitions that occur between the states. They compare the level structure to that calculated by Kurath[36] using the intermediate-coupling shell model and find fair agreement. Some spins and parities are added or revised in the present summary.

Angular distributions for many of the groups from the $B^{10}(He^3,p)C^{12}$ reaction have been measured and absolute cross sections found.

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[36] D. Kurath, Phys. Rev. **101**, 216 (1956); **106**, 975 (1957).