Compound Nucleus Effects in Deuteron Reactions: $B^{10}(d,p)B^{11}$ and $B^{10}(d,\alpha)Be^8$†

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Angular distributions and excitation curves have been measured in the energy range $E_d=0.9$ to 3.0 Mev for the four highest energy proton groups from the $B^{10}(d,p)B^{11}$ reaction and for the ground state α-particle group from the $B^{10}(d,\alpha)Be^8$ reaction. Several broad resonances were observed in the excitation curves, but the shapes of the curves obtained for the various particle groups differ considerably. Resonance effects are most pronounced for the ground state proton group, whereas the group leading to the third excited state of B^{11} shows no resonance behavior. The (d,p) angular distributions suggest that compound nucleus formation plays an important role at these low bombarding energies. In particular, the stripping peak in the angular distribution of the ground state proton group (p_0) does not begin to take shape until $E_d \gtrsim 2$ Mev, while the p_1 distributions do not indicate a stripping peak at any energy. It is suggested that a shell-model effect is responsible for the lack of stripping in the case of the p_1 group. At $E_d=2.0$ Mev, the p_2 angular distribution is almost symmetric about $\theta(\text{cm})=90°$ while the p_3 distribution shows a fairly well developed $l_n=1$ stripping peak. The α-particle excitation curves indicate that forward-backward asymmetries in the the angular distributions are averaged out when the energy interval $E_d=1$ to 2.5 Mev is considered, in accordance with the statistical model prediction.

INTRODUCTION

A PROGRAM designed to investigate the effects of compound nucleus formation in deuteron-induced reactions at low energies in the light nuclei was begun with studies of the $C^{13}+d$ reactions.[1,2] These experiments indicated a very complicated resonance structure in the excitation curves of the (d,α), (d,t), and (d,p) reactions. The excitation curves for the various reactions showed little similarity; some of the pronounced resonances observed in one of the reactions were not found in the others. The variation with energy of the (d,p) angular distributions suggested that compound nucleus formation dominated the stripping process in the energy range studied, $0.6 \leqslant E_d \leqslant 3.0$ Mev. In fact, the expected $l_n=1$ stripping peak was not observed for $E_d \lesssim 1.7$ Mev and even at 3 Mev the contribution to the total cross section by compound nucleus formation appeared to be at least 50%. The (d,α) excitation curves showed a consistent forward peaking from $E_d=1$ to 3 Mev in apparent contradiction of both the compound nucleus[3] and statistical[4] assumptions of nuclear reactions. Also, the cross section for the emission of α particles from these N^{15} states was found to be about a factor of ten higher than for proton emission.

When C^{13} is bombarded with 2-Mev deuterons, the intermediate nucleus N^{15} is excited to about 18 Mev. In order to determine if the effects observed in the $C^{13}+d$ reactions could also be found in a region of higher excitation energy, the $B^{10}+d$ reactions were investigated. In this case, the intermediate nucleus C^{12} is excited to about 27 Mev for $E_d=2$ Mev. Measurements have been made in the energy range 0.9 Mev $\leqslant E_d \leqslant 3.0$ Mev of the excitation curves and angular distributions of the four highest energy groups of protons from the $B^{10}(d,p)B^{11}$ reaction and of the ground state α particles from the $B^{10}(d,\alpha)Be^8$ reaction.

The reactions investigated were:

$B^{10}(d,p_0)B^{11}$, $Q_0=9.234$ Mev, $E_0^*=0$ Mev,

$B^{10}(d,p_1)B^{11*}$, $Q_1=7.09$ Mev, $E_1^*=2.14$ Mev,

$B^{10}(d,p_2)B^{11*}$, $Q_2=4.77$ Mev, $E_2^*=4.46$ Mev,

$B^{10}(d,p_3)B^{11*}$, $Q_3=4.20$ Mev, $E_3^*=5.03$ Mev,

$B^{10}(d,\alpha_0)Be^8$, $Q_0=17.809$ Mev, $E_0^*=0$ Mev.

EXPERIMENTAL PROCEDURE

The apparatus used in these experiments was the same as that employed in the investigation of the $C^{13}(d,p)C^{14}$ reaction.[2] The angular distribution chamber, 8 inches in diameter, had observation ports located at 5° intervals from 5° to 165° with respect to the beam axis. The particle detector was a polished CsI crystal. The details of the angular distribution chamber and of the method of preparing the crystal have been given previously.[2]

The targets used in the measurement of the excitation curves and angular distributions were prepared by evaporating boron metal (enriched to 96% B^{10}) onto 2-mil tantalum foils. These targets were about 10 kev thick to 2-Mev deuterons. The amount of tantalum used was sufficient to stop the bombarding deuterons but allowed the high energy protons to pass through. The straggling of the protons was small enough to permit the separation with pulse-height analysis of the

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1 J. B. Marion and G. Weber, Phys. Rev. 102, 1355 (1956).
2 J. B. Marion and G. Weber, Phys. Rev. 103, 167 (1956).
3 N. Bohr, Nature 137, 344 (1936); P. L. Kapur and R. Peierls, Proc. Roy. Soc. (London) A166, 277 (1938); E. P. Wigner and L. Eisenbud, Phys. Rev. 86, 431 (1952).
4 L. Wolfenstein, Phys. Rev. 82, 690 (1951).

four highest energy groups without difficulty. Since the α particles were also stopped in the tantalum target-backing, the measurements on the $B^{10}(d,\alpha)Be^8$ reaction were limited to those angles at which it was possible to observe the particles emitted from the target side of the tantalum. By orienting the target at 22.5° with respect to the beam axis, it was possible to observe the α particles as far forward as 40°.

A pulse-height spectrum taken at $E_d=1.96$ Mev, $\theta=90°$ is shown in Fig. 1. By inserting 1.5 mils of aluminum between the detector and the Mylar foil which covers the observation ports,[2] it was possible to move the ground state α-particle peak into a valley between two proton peaks. In order to completely remove the α particles, a 3-mil aluminum foil was used, and under these conditions the four proton groups were well separated and could be studied individually. The resolution (full width at half-maximum) of the peak due to the ground state proton group (p_0) is 3.2%. It is also interesting to note that the α-particle group leaving Be^8 in the broad, first excited state (α_1) appears to be about a factor of 5 more intense than the ground state group (α_0) at this bombarding energy and angle of observation. Since this broad α-particle group is difficult to separate from the various proton peaks, no further measurements were made on this group.

The absolute cross sections were determined by measuring the cross section for the proton group leaving B^{11} in the first excited state (p_1) at $E_d=1.00$ Mev and $\theta=90°$. This was accomplished by observing the thick target step corresponding to this group with a double-focusing 180° magnetic spectrometer.[5] Three targets were used: a thick B_2O_3 target prepared from natural boron, a pressed boron metal target (96% B^{10}), and a thick, isotopically pure B^{10} target, electromagnetically separated at Harwell.[6] The cross-section values obtained with these three targets agreed to within 15%; the mean value was 0.21 ± 0.02 mb/sterad. The cross sections for the other particle groups were obtained by normalizing to this value and are accurate to about 15%. The cross sections measured in this manner are about a factor of 2 smaller than the values estimated by Van Patter, Buechner, and Sperduto,[7] but are a

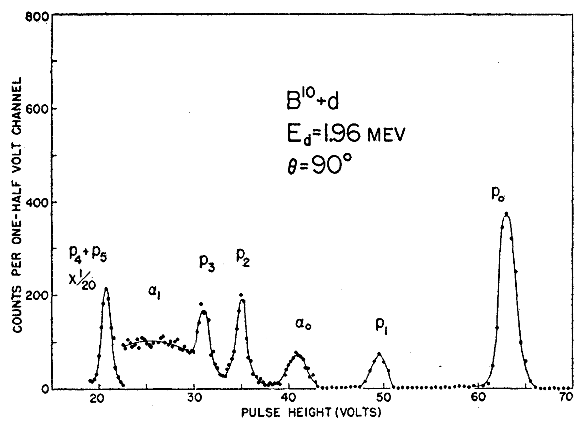

FIG. 1. Pulse-height distribution of reaction products from the deuteron bombardment of B^{10} at $E_d=1.96$ Mev, $\theta=90°$. 1.5 mils of aluminum was inserted between the detector and the 0.9 mg/cm² Mylar foil covering the observation port. The resolution (full width at half-maximum) is 3.2% for the ground state proton group (p_0). The subscript numbers refer to the excited states of the residual nuclei to which the particle groups correspond.

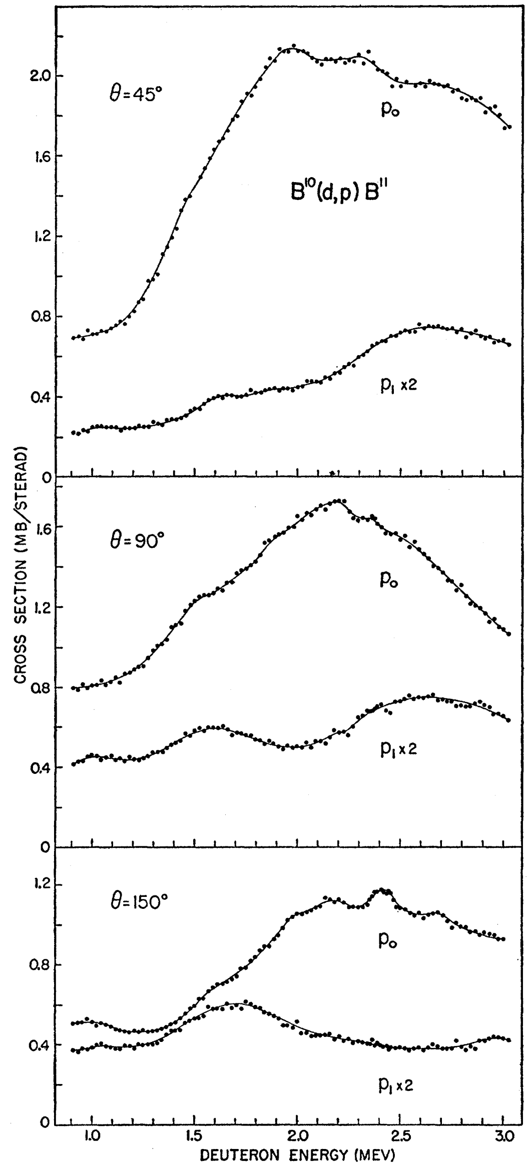

FIG. 2. Excitation curves for the protons leaving B^{11} in the ground state (p_0) and first excited state (p_1) in the $B^{10}(d,p)B^{11}$ reaction at $\theta=45°$, 90°, and 150°.

[5] Snyder, Lauritsen, Fowler, and Rubin, Phys. Rev. 74, 1564 (1948).

[6] We are indebted to Dr. M. L. Smith of the Atomic Energy Research Establishment, Harwell, for his help in procuring this separated target.

[7] Van Patter, Buechner, and Sperduto, Phys. Rev. 82 248 (1951).

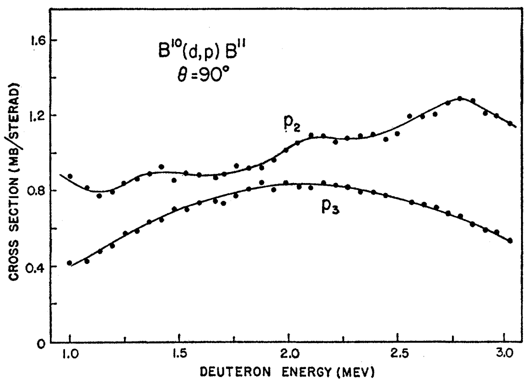

FIG. 3. Excitation curves for the protons leaving B^{11} in the second and third excited states (p_2 and p_3, respectively) in the $B^{10}(d,p)B^{11}$ reaction at $\theta=90°$.

factor of 30 smaller than those obtained by Burke, Risser, and Phillips.[8] Paris, Valckx, and Endt[9] have also found these latter values to be too high.

RESULTS AND DISCUSSION

A. $B^{10}(d,p)B^{11}$

Excitation curves for the groups p_0 and p_1 were measured at angles of 45°, 90°, and 150° from $E_d=0.9$ to 3.0 Mev. These data are shown in Fig. 2. Curves for the p_0 group have previously been obtained by Burke, Risser, and Phillips[8] at angles of 0°, 90°, and 135° from $E_d=0.6$ to 2.0 Mev. The two 90° curves are in good agreement (except for the absolute cross sections as previously mentioned) and the curves for the forward and backward angles are quite similar. The p_0 curves show a number of weak, broad resonances at 1.0, 1.5, 2.0, 2.2, 2.4, and 2.7 Mev. The first two maxima have been reported previously.[8] The peaks in the p_1 curves do not appear to occur at precisely these energies and those that are observed appear rather broad. The p_1 maxima occur at 1.0, 1.6, and 2.7 Mev. The trend of the p_1 curves seems to be to increase with bombarding energy, while the p_0 curves reach a maximum near 2.2 Mev and thereafter decrease. This decrease apparently continues to at least 5 Mev.[10]

Figure 3 shows the p_2 and p_3 excitation curves at $\theta=90°$ from $E_d=1.0$ to 3.0 Mev. The p_2 curve shows maxima near 1.4, 2.2, and 2.8 Mev; these energies correspond approximately to energies at which p_0 resonances were observed. The p_3 curve, however, shows none of these peaks; there is only a broad maximum near 2 Mev.

The fact that the various excitation curves appear quite different in the $B^{10}+d$ reactions (excitation energy near 27 Mev) as well as in the $C^{13}+d$ reactions (excitation energy near 18 Mev) suggests that this phenomenon is not dependent to any marked degree on either the particular nucleus or the excitation energy. This conclusion is supported by recent work on the excitation curves of various particle groups from the deuteron bombardment[11,12] of C^{12} and O^{16} (excitation energies near 12 Mev and 9 Mev, respectively).

The angular distributions of the p_0 group measured at $E_d=1.00$, 1.50, 2.00, 2.50, and 3.00 Mev are shown in Fig. 4. The expected $l_n=1$ stripping peak for the p_0 group does not begin to take shape until $E_d\cong 2$ Mev. Below this energy, there is a broad maximum near $\theta(\mathrm{cm})=45°$ at 1.50 Mev and a peak in the backward hemisphere at 1.00 Mev. For bombarding energies above 2 Mev, a maximum near $\theta(\mathrm{cm})=25°$ is observed and it becomes more pronounced as the bombarding energy is increased. This behavior almost certainly indicates that stripping is of increasing importance for $E_d\gtrsim 2$ Mev, while at lower energies, compound nucleus formation probably is the more important process. These angular distributions are generally in good agreement with those obtained by Burke, Risser, and Phillips,[8] by Pratt,[13] and by Redman.[14] The latter curves, however, do not indicate a decrease in the differential cross section for angles smaller than about

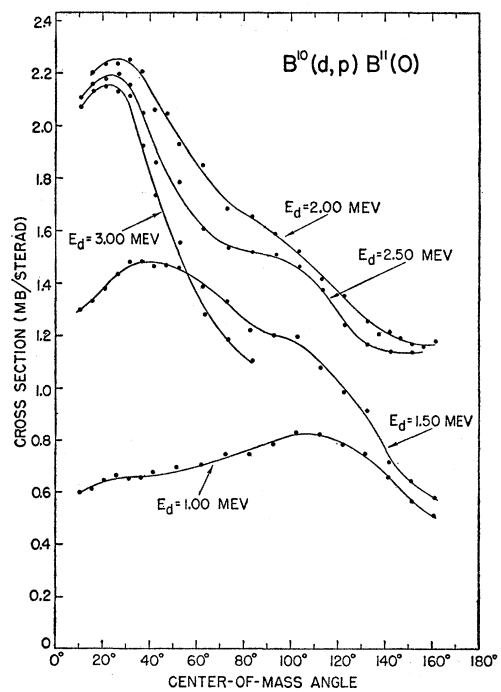

FIG. 4. Angular distributions of the ground state protons from the $B^{10}(d,p)B^{11}$ reaction for $E_d=1.00$, 1.50, 2.00, 2.50, and 3.00 Mev.

[8] Burke, Risser, and Phillips, Phys. Rev. **93**, 188 (1954).
[9] Paris, Valckx, and Endt, Physica **20**, 585 (1954).
[10] A. A. Kraus and J. B. Marion (1955, unpublished).
[11] Bonner, Eisinger, Kraus, and Marion, Phys. Rev. **101**, 209 (1956); Bennett, Bonner, Hudspeth, Richards, and Watt, Phys. Rev. **59**, 781 (1941).
[12] N. P. Heydenburg and D. R. Inglis, Phys. Rev. **73**, 230 (1948); Stratton, Blair, Famularo, and Stuart, Phys. Rev. **98**, 629 (1955); J. C. Grosskreutz, Phys. Rev. **101**, 706 (1956).
[13] W. W. Pratt, Phys. Rev. **93**, 816 (1954).
[14] W. C. Redman, Phys. Rev. **79**, 6 (1950).

25° at bombarding energies above 2 Mev as is shown in Fig. 4.

The angular distributions of the p_1 group measured at $E_d=1.00$, 1.50, 2.00, 2.50, and 3.00 Mev are shown in Fig. 5. In contrast to the p_0 angular distributions, those obtained for the p_1 group do not suggest that stripping is effective even at the highest bombarding energies investigated. It has been noted previously by Evans and Parkinson[15] that even for $E_d=6$ to 8 Mev, in the region in which the stripping theory is usually valid, there is considerable disagreement between the observed angular distributions for this group and those predicted by the stripping theory.

It has been pointed out by Bethe and Butler[16] that in some stripping reactions shell-model effects will suppress certain l values which would be allowed by the conservation of angular momentum in favor of higher values $(l+2, l+4)$ due to the capture of the nucleon into a specified l orbital. It appears possible that the lack of stripping in the case of the p_1 group from the $B^{10}(d,p)B^{11}$ reaction is due to an even more restrictive shell-model effect. Recent experiments on the B^{11}-$(p,p'\gamma)B^{11}$ reaction by Bair, Kington, and Willard[17] and on the $B^{10}(d,p\gamma)B^{11}$ correlation by Thirion[18] support an assignment of $J=\frac{1}{2}^-$ for the first excited state of B^{11} at 2.14 Mev. Since the ground state of B^{10} has $J=3^+$, conservation of spin and parity in the $B^{10}(d,p)B^{11}$ stripping to the 2.14-Mev state require that $l_n=3$. Intermediate-coupling calculations have been made by Inglis[19] and Kurath[20] which give a good description of the low-lying levels in B^{11} by considering only excitations within the p shell; the first excited state was found to have $J=\frac{1}{2}^-$. Therefore, this state cannot be represented by B^{10} in its ground state plus one neutron in a p orbital, but requires the rearrangement of several nucleons. Since the stripping process is one in which a nucleon is captured into a definite orbital, any reaction which requires the rearrangement of several nucleons must have a very small probability of proceeding by a stripping mechanism. In the $B^{10}(d,p)B^{11*}$ (2.14 Mev) reaction, $l_n=3$ stripping could occur only if there were an appreciable f-state impurity in the residual level. Since the first f states must lie above the first $1d$ and $2s$ levels, the f state coupling to low-lying levels should be weak.

Evans and Parkinson[15] found that at $E_d=6$ to 8 Mev, all of the proton groups studied except p_1 could be fitted with $l_n=1$ stripping curves, which are allowed by both the shell model and the conservation of angular momentum. The measurements were not extended beyond $\theta(\mathrm{cm})=74°$, however, and therefore symmetry

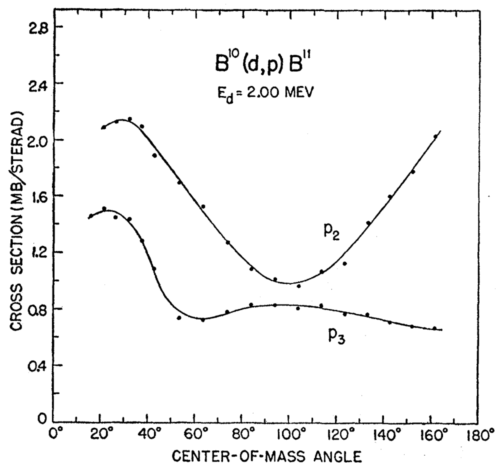

FIG. 6. Angular distributions of the protons leaving B^{11} in the second and third excited states (p_2 and p_3, respectively) in the $B^{10}(d,p)B^{11}$ reaction for $E_d=2.00$ Mev.

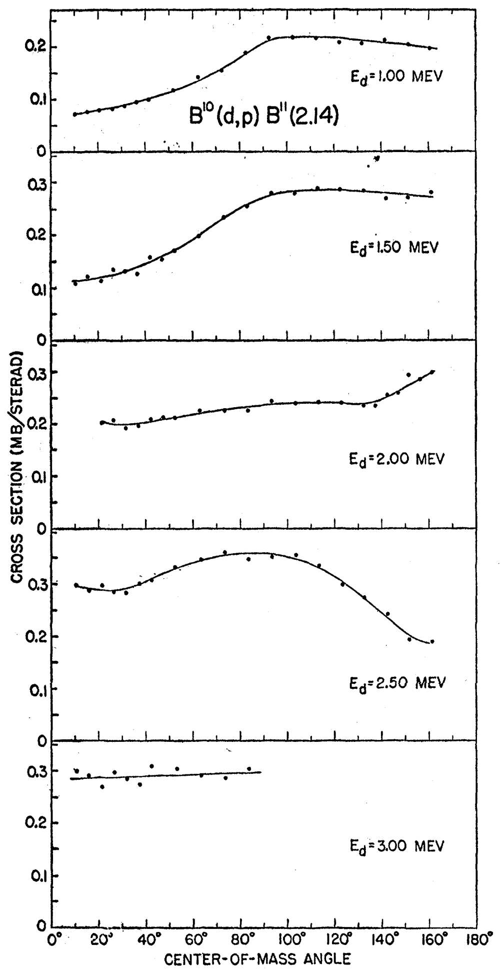

FIG. 5. Angular distributions of the protons from the $B^{10}(d,p)B^{11}$ reaction leaving B^{11} in the first excited state for $E_d=1.00$, 1.50, 2.00, 2.50, and 3.00 Mev.

[15] N. T. S. Evans and W. C. Parkinson, Proc. Phys. Soc. (London) **A67**, 684 (1954).
[16] H. A. Bethe and S. T. Butler, Phys. Rev. **85**, 1045 (1952).
[17] Bair, Kington, and Willard, Phys. Rev. **100**, 21 (1955).
[18] J. Thirion, Ann. phys. **8**, 489 (1953).
[19] D. R. Inglis, Revs. Modern Phys. **25**, 390 (1953).
[20] D. Kurath, Phys. Rev. **101**, 216 (1956).

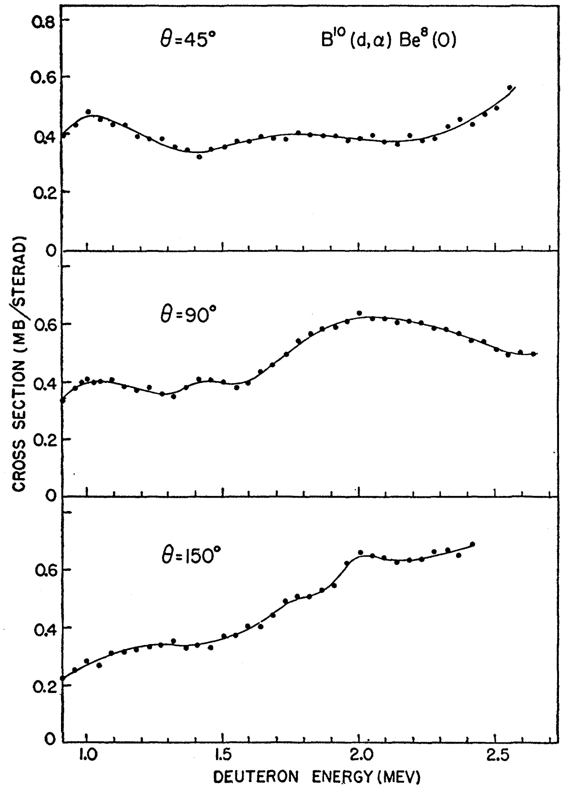

FIG. 7. Excitation curves for the ground state α particles from the $B^{10}(d,\alpha)Be^8$ reaction at $\theta=45°$, 90°, and 150°.

about 90° for the p_1 group (which would be expected from pure compound nucleus formation and the statistical model assumption[4]) cannot be excluded.[21]

At $E_d=2.00$ Mev, the angular distributions of the groups p_2 and p_3 were measured; these data are shown in Fig. 6. The p_2 distribution is almost symmetric about 90° while the p_3 distribution shows a fairly well developed stripping peak. The large cross section for the p_3 group for $\theta>90°$ suggests, however, that perhaps only one-third of the yield is due to stripping at this energy. The excitation curves for these groups (Fig. 3) also indicate that p_2 is more strongly influenced by the compound nucleus states than is p_3. It is interesting to note that at $E_d=8$ Mev, the p_2 angular distribution is more closely fit by a stripping curve than is the p_3 distribution.[15] The reason for the apparent reversal in the character of these two angular distributions between $E_d=2$ and 8 Mev is not yet clear.

B. $B^{10}(d,\alpha)Be^8$

Excitation curves for the ground state α particles from the $B^{10}(d,\alpha)Be^8$ reaction were measured from $E_d=0.9$ to 2.6 Mev at laboratory angles of 45°, 90°, and 150°. These results are presented in Fig. 7. Maxima occur at 1.0, 2.0, and possibly at 1.4 Mev. A peak at 1.0 Mev was also found by Whitehead.[22] The absolute cross sections are comparable with those for the proton groups; even though the α_1 group probably has a somewhat larger cross section in this energy range (see Fig. 1 and reference 22), the total (d,α) yield is much smaller than the total (d,p) yield in contrast to the $C^{13}+d$ reactions where the reverse is true.

Since the α particles could not penetrate the tantalum backing of the targets, the angles of observation were limited to $\theta\geqslant 40°$ in the investigation of the $B^{10}(d,\alpha)Be^9$ reaction (see Experimental Procedure). At a particular angle it was relatively easy to adjust the aluminum foils between the observation port and the detector to keep the α_0 group between two proton groups as the bombarding energy was changed. It was much more difficult, however, to obtain an angular distribution since the α-particle energy is a stronger function of the angle than are the proton energies and different absorbing foils were required for each angle. Consequently, only one α_0 angular distribution was measured ($E_d=0.91$ Mev and

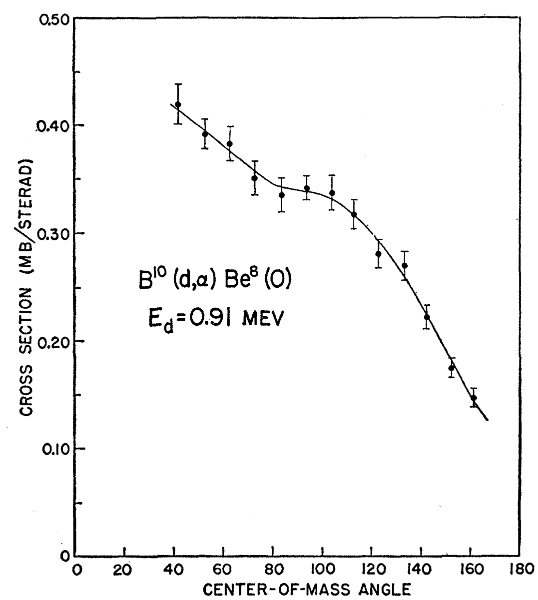

FIG. 8. Angular distribution of the ground state α particles from the $B^{10}(d,\alpha)Be^8$ reaction at $E_d=0.91$ Mev.

[21] In order to test the above hypothesis that there should be very little stripping to this state, it would be of considerable interest to examine the angular distribution at high deuteron energies to determine if it is indeed symmetric about 90°. Since the level density even at such high excitation energies may not be sufficient for the statistical assumption to be valid, it is very likely that an average over a few Mev will be necessary to produce an angular distribution that can be compared with the prediction. A measurement of the magnitude of any $l_n=3$ stripping that does occur in this reaction would permit an estimate of the amount of f-state impurity in this level. If it is found that stripping is not appreciable in this reaction, then an investigation of the angular distribution at even higher deuteron energies ($E_d\gtrsim 15$ Mev) may show the effects of a direct interaction (i.e., proton exchange) process, which differs from the stripping process in that the emergent proton is different from that in the bombarding deuteron. There would be no shell-model restrictions on such a reaction. All of the above considerations should also apply to the $B^{10}(d,n)C^{11}$ reaction leading to the first excited state of C^{11}.

[22] W. D. Whitehead, Phys. Rev. 82, 553 (1951).

$40° \leqslant \theta \leqslant 160°$). This curve is presented in Fig. 8 and shows a peaking in the forward direction. The excitation curves of Fig. 7, however, indicate that the maximum shifts from forward to backward as the bombarding energy is increased, such that an average over the energy range $E_d=1$ to 2.5 Mev would produce an approximately isotropic angular distribution. The statistical model assumption for nuclear reactions,[4] which assumes many overlapping states with arbitrary phases, predicts angular distributions which are symmetric about $\theta(\mathrm{cm})=90°$. The fact that the α_0 group is in general not symmetrically distributed indicates that the compound nucleus states are not sufficiently dense for the statistical assumption to be valid and that the distributions are rendered asymmetric through the interference of levels with opposite parity. (The p_1 angular distributions also support this conclusion.) On the other hand, since an average over the energy range studied produces approximately symmetry (in fact, isotropy), it appears that the statistical model has some validity in this reaction if appropriate averages are taken.

CONCLUSIONS

The fact that the resonance structure in the excitation curves for the $C^{13}+d$ reactions[1,2] is much more pronounced than for the $B^{10}+d$ reactions is probably due to the much higher excitation energy in C^{12} ($\cong$27 Mev) compared with that in N^{15} ($\cong$18 Mev). The increase in level density in the compound nuclei between N^{15} at 18 Mev and C^{12} at 27 Mev probably accounts for the approximate agreement with the statistical model for the (d,α) reaction in the latter case whereas there is marked disagreement in the former case.

All of the maxima observed in the various excitation curves are broad and overlapping. To speak of such effects as "resonances," in the sense that they are due to energy states in the compound nucleus, is open to question. The situation is further confused in deuteron-induced reactions by the competition and interference between compound nucleus formation and stripping, about which very little is known or can be predicted at present. In view of the complex nature of these processes, it is not surprising that the excitation curves measured for the various particle groups bear little similarity to each other. The measurement of excitation curves for a number of particle groups from a given reaction will almost certainly make easier the eventual theoretical analysis of the processes involved. As far as deuteron reactions are concerned, however, this is a point that has received little previous attention. The present results on the $B^{10}+d$ reactions are the only ones at present available which give information concerning as many as five particle groups arising from a given deuteron-induced reaction as a function of both energy and angle.