Isospin Selection Rule in the $C^{12}(d,\alpha)B^{10}$ Reaction*

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The violation of the isospin selection rule has been studied in the reaction $C^{12}(d,\alpha)B^{10}$ with deuteron energies between 9 and 12.5 MeV. The differential and total cross sections of the isospin-forbidden transition to the first $T=1$ state in B^{10} (the $J^\pi=0^+$ state at 1.74-MeV excitation) have been compared with the cross sections of the isospin-allowed transitions to the ground state ($J^\pi=3^+$, $T=0$), the first excited state ($J^\pi=1^+$, $T=0$ at 0.72 MeV), and the third excited state ($J^\pi=1^+$, $T=0$ at 2.14 MeV). Mostly the intensity of the $T=1$ alpha group is less than 1% of the yield of the α groups leading to the neighboring $T=0$ states. This reduction is due not only to isospin forbiddenness but also to angular-momentum and parity selection rules which apply in this particular (d,α) reaction for which both the initial and the final state have $J^\pi=0^+$. These weighting factors have been calculated by use of the statistical theory of nuclear reactions. After these factors have been applied, the $T=1$ alpha group has an intensity of about 10% relative to the other three $T=0$ transitions at a deuteron energy of 9 MeV and 1–2% at an energy of 11 MeV. The small yield is ascribed to the isospin selection rules that to some extent govern this $T=1$ transition. In the energy range from 9 to 11 MeV, the angular distribution of the $T=1$ state stays fairly constant and is nearly symmetric around 90°. The yield decreases steadily. At deuteron energies higher than 11.5 MeV, the angular distribution changes drastically and becomes strongly forward peaked and asymmetric around 90°, and the total yield increases slightly. We assume that this behavior indicates a direct-interaction mechanism in which the process of mixing the isospins takes place at the surface of the nucleus. Coulomb excitation during the process of d capture or α emission might be responsible for the isospin violation at these higher deuteron energies.

INTRODUCTION

THE $C^{12}(d,\alpha)B^{10}$ reaction was chosen as one of the few possibilities in which the isospin impurity in a nucleus, in this case N^{14}, could conveniently be studied as a function of the excitation energy. Since we can assume that the initial system and the α particle have isospin $T=0$ and that for the lower states in B^{10} the isospin is a good quantum number, we expect that the population of the $T=1$ states in B^{10} is inhibited by the isospin selection rules and occurs only by isospin impurity in the highly excited N^{14} nucleus. In general it is assumed that the isospin is a good quantum number at low and very high excitation energy and it is estimated[1] that this region of high excitation energy starts between 14 and 18 MeV in N^{14}. Unfortunately, only a limited portion of this region of excitation energy is accessible to investigation with this reaction. The lower limit is given by the difficulty of detecting low-energy α particles; the upper limit is set by our tandem generator. If we study the reaction leading to the first $T=1$ state in B^{10} at an excitation of 1.74 MeV, these limits allow an investigation of the N^{14} nucleus excited to energies in the range from about 17 to 21 MeV. If we study the population of the second $T=1$ state in B^{10}, this range of excitation energy is further reduced by the fact that this state has an excitation energy of 5.16 MeV and the lower energy limit will be pushed closer to the upper limit. This state also appears to be unsuitable because its inhibited α yield will be perturbed by the allowed α yield of a close-by and overlapping $T=0$ state at 5.18 MeV.

Hence we have studied the yield of the first $T=1$ state in the reaction $C^{12}(d,\alpha)$ as a function of the deuteron energy. This investigation of the highly excited N^{14} nucleus in a region in which the isospin should again become a good quantum number appeared to be interesting because the yield of the α group leading to the $T=1$ state should vanish. One then might be able to find some direct-reaction mechanisms with small cross sections which produce isospin mixture.

Unfortunately the first $T=1$ state in B^{10} has the spin assignment 0^+ so that the (d,α) reaction to this state is also restricted by angular-momentum and parity selection rules, as will be discussed later. We have estimated these reduction factors by use of the Hauser-Feshbach approximations, although we are interested not only in the absolute reduction in the formation of the $T=1$ state but also in the relative yield as a function of the excitation energy in N^{14}. Preliminary results have been published previously.[2,3]

EXPERIMENTAL PROCEDURE

The reaction $C^{12}(d,\alpha)B^{10}$ was studied with self-supporting natural carbon targets with different thicknesses varying from 10–40 $\mu g/cm^2$. It was induced by a deuteron beam supplied by the tandem Van de Graaff of the Argonne Physics Division. For most of the measurements, the target together with four solid-state detectors were mounted in an 18-in. scattering chamber. The four counters were arranged on a disk which could be rotated inside the chamber so that in two different runs the angular distribution of the emitted α particles could be measured at eight angles

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[1] D. H. Wilkinson, Phil. Mag. 1, 379 (1956).
[2] R. G. Allas, J. R. Erskine, L. Meyer-Schützmeister, and D. von Ehrenstein, Bull. Am. Phys. Soc. 8, 538 (1963).
[3] D. von Ehrenstein, L. Meyer-Schützmeister, and R. G. Allas, Bull. Am. Phys. Soc. 10, 440 (1965).

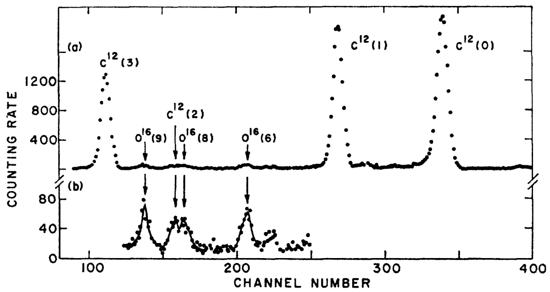

FIG. 1. The α-particle spectrum of the reaction $C^{12}(d,\alpha)B^{10}$ measured with solid-state detectors at a deuteron energy of 9.4 MeV and at an angle $\theta_{lab}=20°$. The α group leading to the nth excited state in B^{10} is indicated by $C^{12}(n)$. Oxygen contaminants in the target give rise to perturbing α groups (similarly indicated) from the reaction $O^{16}(d,\alpha)$. The complete α spectrum [curve (a)] is drawn on an expanded scale [curve (b)] in the neighborhood of the isospin-forbidden α group $C^{12}(2)$.

at 20° intervals. Such an angular distribution was measured, mostly in steps of 100 keV, between the deuteron energies 9 and 11 MeV.

Curve (a) in Fig. 1 is an α-particle spectrum which shows the pronounced peaks of the ground state and the first and the third excited states in B^{10}, indicated by $C^{12}(0)$, $C^{12}(1)$, and $C^{12}(3)$, respectively. It was taken at a deuteron energy of 9.4 MeV and at an angle of 20° to the incident beam. In most cases, proton or deuteron groups with energies interfering with the α-particle groups of interest could be separated by a suitable voltage applied to the solid-state detector so that they appeared as low-energy background.

Since the isospin selection rule forbids the population of the $T=1$ states in B^{10}, the α group $C^{12}(2)$ leading to the second excited state should be absent; but instead, this α group is observed—although often with a very small intensity. Its presence indicates that the isospin selection rule is at least partially violated. Because of the small yield of this α group, impurities in the targets become of great importance. For a better view of the counting rate, the part of the α-particle spectrum [curve (a)] showing the groups between the first and third excited state in B^{10} is enlarged [curve (b)].

Here not only the α group $C^{12}(2)$ is to be seen but also three other α-particle groups produced by the reaction $O^{16}(d,\alpha)N^{14}$ in the oxygen contamination of the C^{12} target. These α particles populate the sixth, eighth, and ninth excited states[4] in N^{14} as indicated by the numbers in parentheses. It is clearly seen that the α groups of the $O^{16}(d,\alpha)N^{14}$ reaction are not only of about the same intensity as the $T=1$ group in B^{10} but also (in this example) one group overlaps partially with the α group under study. Of course this overlap depends on the energy spread which usually is introduced by the detector system when solid-state counters are used. This spread, of the order of 70 keV, often is large enough to produce severe overlap with α groups from target contaminants.

It is therefore of great advantage to use a magnetic spectrograph for detecting the α particles. With this system the energy width of the α groups was ordinarily determined by the target thickness and was normally kept to about 20 keV. Most α groups which overlapped when measured by solid-state detectors could then be separated, as shown in the α spectrum (Fig. 2) measured with the spectrograph.[5] The deuteron energy and angle, 9.4 MeV and 20°, for these measurements were the same as for the data shown in Fig. 1. The integrated charge of deuterons bombarding the target was 2200 μC. Again the spectrum in the region of interest is plotted on an enlarged scale [curve (b)]. In order to make our results independent of perturbing α groups, we studied the contaminant α groups rather thoroughly. A set of such measurements is plotted in Fig. 3, which shows the α spectra for different angles to the incident deuteron beam. For all the measurements, the deuteron energy was 9.4 MeV and the integrated deuteron charge was 2200 μC. At 20°, the most forward angle shown the α groups show narrower peaks than at backward angles. This is in part due to the fact that the alphas emitted at higher angles have smaller energies and suffer a greater energy loss in the target; but in addition the spectrograph shows for an α group of a certain energy width (at any given plate distance) a broader peak for the lower energy alphas than for the ones with higher energy. In fact the half-width of the $C^{12}(2)$ α group shown in Fig. 3 is about 16 keV at 20° and about 25 keV at 120°.

Of the perturbing α groups, the only ones that we detected in all our measurements came from the reaction $O^{16}(d,\alpha)N^{14}$. These groups are indicated in Fig. 3 insofar as they fall in the energy region shown. Note also that none of our measurements showed α groups at

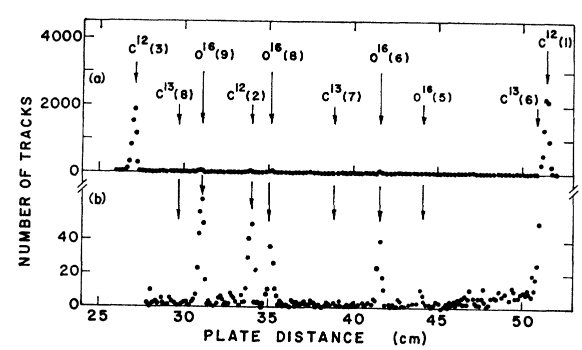

FIG. 2. The α-particle spectrum of the reaction $C^{12}(d,\alpha)B^{10}$ measured with the broad-range magnetic spectrograph at a deuteron energy of 9.4 MeV, at an angle of $\theta_{lab}=20°$, and with an integrated deuteron charge of 2200 μC. Curve (b) shows the α spectrum in more detail in the neighborhood of the $C^{12}(2)$ group.

[4] T. Lauritsen and F. Ajzenberg-Selove, in *Nuclear Data Sheets*, compiled by K. Way *et al.* (National Academy of Sciences—National Research Council, Washington, D. C., 1962), NRC 61-5, 6-3.

[5] J. R. Erskine, Phys. Rev. 135, B110 (1964).

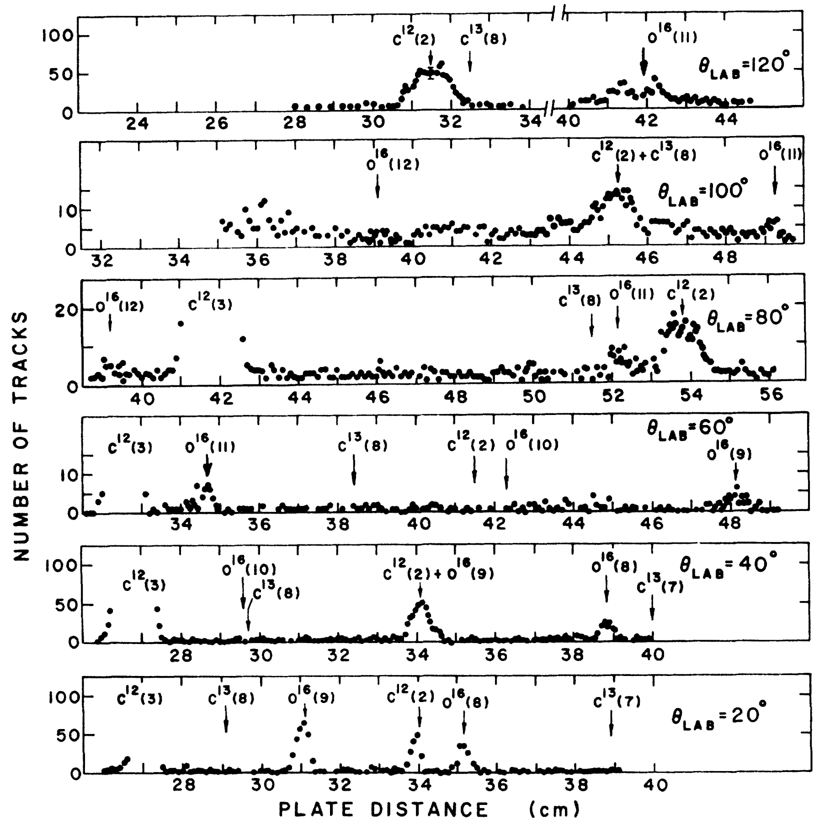

FIG. 3. The α-particle spectrum of the reaction $C^{12}(d,\alpha)B^{10}$ measured with the magnetic spectrograph at different angles to the incident beam. The deuteron energy was 9.4 MeV and the integrated charge was 2200 μC. The different α groups from the C^{12}-(d,α) reaction are indicated together with other α groups which might arise by (d,α) reactions in O^{16} or C^{13} contaminants in the target.

also that none of our measurements showed α groups at the positions of $O^{16}(10)$, $O^{16}(12)$, and $O^{16}(13)$ where they would be found if the 10th, 12th, and 13th excited states of the final nucleus N^{14} were populated in the $O^{16}(d,\alpha)$ reaction. This is in agreement with the report of Lauritsen and Ajzenberg-Selove[4] that the existence of these N^{14} states at excitation energies of 6.70, 7.40, and 7.60 MeV is doubtful. It is also perhaps interesting to note in our spectra that no alpha group belonging to the $C^{13}(d,\alpha)B^{11}$ reaction has an intensity significantly above background. (The positions of such possible peaks from C^{13} in the target are indicated in Fig. 3.)

Although few α groups perturb the $C^{12}(2)$ group, severe overlapping can occur. From Fig. 4 we obtain the conditions for such overlapping. Here the α energy differences ΔE_α of the $C^{12}(2)$ group and the different perturbing α groups $O^{16}(n)$ are plotted for several angles θ_{lab} as a function of the deuteron energy. For the calculations, we have used the energies of the B^{10} and N^{14} levels as they are given in the Nuclear Data Sheets[4]; it is expected that our measurements would deviate slightly from these calculated values. Since the magnetic spectrograph can readily separate two groups whenever their ΔE_α is larger than 20 keV, severe overlapping between the $C^{12}(2)$ group and perturbing α groups is expected only at $\theta_{lab}=40°$ and 80° in our investigated region of deuteron energies. As mentioned above, the $O^{16}(10)$, $O^{16}(12)$, and $O^{16}(13)$ groups are not observed. The situation is unfortunate at $\theta_{lab}=40°$ where overlap with the $O^{16}(9)$ group was observed in the neighborhood of $E_d=9$ MeV. In fact, even with the spectrograph there is no indication of a separation of these two α groups at 9.4 MeV. In such a case we obtained the yield of the $C^{12}(2)$ group from the combined yield of the $C^{12}(2)+O^{16}(n)$ group by subtracting the yield of the $O^{16}(n-1)$ group at the next-lower excitation energy. In general this method might introduce a large error, but a subsidiary check with a WO_3 target confirmed that at $E_d=9.4$ MeV and $\theta_{lab}=40°$ the interfering $O^{16}(9)$ group and the next-lower $O^{16}(8)$ group have equal yields. We conclude, therefore, that it is unlikely that the present results obtained with the magnetic spectrograph suffer from interfering α groups.

The errors in the measurements with the magnetic spectrograph arise from four sources: (1) Statistical error is appreciable, as can be seen from the scatter of points in Fig. 3. (2) The use of different targets was necessary because of the extended time required for the experiment. The yields from these different targets, each of which was used for a series of measurements, were related to each other by normalizing the alpha yield of one of the allowed transitions, mostly only at one angle and at one deuteron energy. (3) To get reasonable statistics for the inhibited alpha groups, the plate exposures were so long that the much more intense

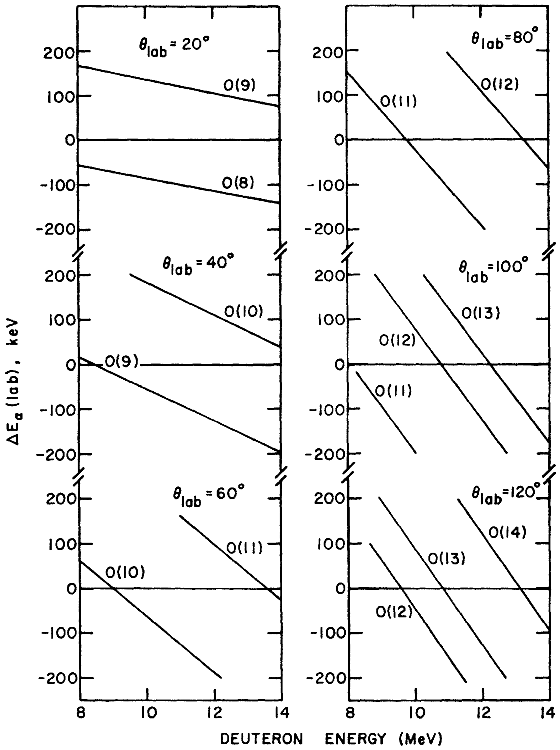

FIG. 4. The α-energy differences ΔE_α of the $C^{12}(2)$ group and the perturbing $O^{16}(n)$ groups, plotted as a function of the incident-deuteron energy. The α groups that are close to the $C^{12}(2)$ group are shown. The positive sign of ΔE_α indicates that the energy of the $C^{12}(2)$ group is larger than the energy of the $O^{16}(n)$ group under consideration.

allowed groups sometimes gave an excessive intensity of α-particle tracks. This led to difficulties and errors in the counting procedure. (4) The alphas in some of the groups are of quite low energy. Alphas of about 2 MeV produce only short tracks in the emulsion, so that counting errors are easily introduced. In addition, they usually exhibit broader peaks in which the background plays a more important role.

It is obvious that measuring with the spectrograph is much more cumbersome than with the solid-state detectors. We therefore used the magnetic spectrograph only (1) to study the perturbing α group in more detail, (2) to confirm the data of the solid-state detectors for which the deuteron energy ranged from 9–11 MeV, and (3) to measure the cross section of the $C^{12}(2)$ group at some other selected deuteron energies, namely 11, 11.3, 11.6, 12.1, 12.5, and 13 MeV.

The absolute cross section of the $C^{12}(d,\alpha)B^{10}$ reaction was obtained by measuring the thickness of one of our C^{12} targets. Here we relied on the results of Nagahara[6] who measured the differential cross section for elastic proton scattering by C^{12} over a wide range of angles and incident proton energies. By choosing his values for the two conditions E_p=9.27 MeV, $\theta_{c.m.}$=94.8° and E_p=8.15 MeV, $\theta_{c.m.}$=84.7°, we measured the elastic proton scattering by our carbon target and obtained two values for its thickness which differed by about 15%. We therefore assume that the absolute differential cross section derived from the knowledge of the target thickness had an error of about 20%. We also can compare our absolute values with those of Baldeweg *et al.*[7] who recently had studied the allowed transition $C^{12}(0)$, $C^{12}(1)$, and $C^{12}(3)$ in the $C^{12}(d,\alpha)B^{10}$ reaction. Although it is difficult to take the accurate values from their graphs, the magnitudes of the absolute differential cross sections agree well with each other.

RESULTS

The absolute differential cross sections of the studied α groups from the $C^{12}(d,\alpha)B^{10}$ reaction were plotted for different angles as functions of the deuteron energies. Figure 5 displays the α group leading to the first $T=1$ state and Figs. 6–8 show the groups populating the ground state and the first and the third excited states, respectively, in B^{10}. The measurements with the magnetic spectrograph are indicated by crosses, the estimated errors are shown as bars, and open circles represent the results obtained by the solid-state detectors. In most cases, two measurements of the isospin-forbidden α group obtained with the solid-state detectors

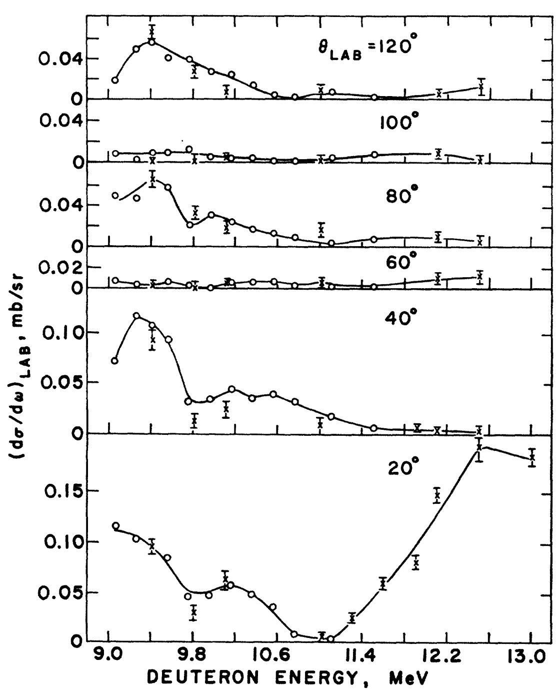

FIG. 5. The differential cross section for the isospin-forbidden $C^{12}(2)$ group, shown as a function of the deuteron energy for different angles to the incident beam. Crosses indicate measurements with the magnetic spectrograph, open circles represent data taken with the solid-state detectors.

[6] Y. Nagahara, J. Phys. Soc. Japan 16, 133 (1961).

[7] F. Baldeweg, V. Bredel, H. Guratzsch, R. Klabes, B. Kühn, and G. Stiller, Nucl. Phys. 64, 55 (1965).

were averaged in order to reduce the large statistical error. For the averaging, the two runs taken together often were measured with deuteron energies 100 keV apart since it appeared that the differences between two such runs were small.

The allowed α groups (Figs. 6–8) are not perturbed by contaminants. Their yield curves measured by the two instruments should therefore agree, as they indeed do. The discrepancies are large in only a few cases, for example, in Fig. 6 at $E_d=9.8$ MeV and $\theta=20°$. For the intense α group produced in such a case, we believe that the data obtained with the magnetic spectrograph are less reliable than those taken with the solid-state detector. Here where the cross section is high, the tracks in the emulsion are too numerous to be counted without appreciable error.

As seen in Fig. 5, the agreement between the results obtained with the magnetic spectrograph and those from the solid-state detector is not as good for the inhibited alpha group $C^{12}(2)$ as it is for the allowed α transitions. As discussed above, the measurements of the $C^{12}(2)$ group with the solid-state detectors suffer from their limited energy resolution. Especially at $\theta_{lab}=40°$, the $C^{12}(2)$ and $O^{16}(9)$ groups are very close together (as seen in Fig. 4) and the data taken with the solid-state detectors give mostly no suggestion that at 9.4-MeV this group is a doublet. As already mentioned above, we corrected for the presence of the $O^{16}(9)$ group by subtracting the yield of the $O^{16}(8)$ from the combined yield of $O^{16}(9)+C^{12}(2)$. The data obtained with the spectrograph indicated some displacement of the two groups at $E_d=9.8$ and 10.1 MeV; this was taken into account in the corrections for the $O^{16}(9)$ group. In short, we assume that the discrepancies between the measured cross sections for these two deuteron energies at $\theta_{lab}=40°$ are due to systematic errors and that the results of the spectrograph are more reliable. But in general we see that the measured points of the two instruments agree quite well with each other.

The yield curves of the $C^{12}(2)$ group as shown in Fig. 5 seem to fall in two parts, one extending from the lowest studied energies up to about 11.4 MeV, the other one reaching from 11.4 MeV to the highest obtained energy (about 13 MeV). The first part shows a nearly symmetric angular distribution about 90°, as can be seen in Fig. 9. Here the angular distributions are presented for different deuteron energies but in contrast to Figs. 5–8, the differential cross sections and the angles are given in the center-of-mass system. As mentioned above, the values of the cross sections which are obtained with the solid-state detectors and which are seen in Fig. 9, are averaged values derived from two different measurements. In cases in which these two different measurements were taken with different deuteron energies, both energies are indicated in Fig. 9. The second part of the excitation curve shows a strongly forward-peaked yield. This distribution is also seen at 11.9, 12.3, and 13 MeV (not included in Fig. 9), although at these energies the yields were measured only at angles up to $\theta_{lab}=80°$ or 100°. The two different parts of the excitation function of the forbidden α group $C^{12}(2)$ can also be visualized with the aid of the top curve in Fig. 10 in which the integrated cross section is plotted as a function of the deuteron energy. At the

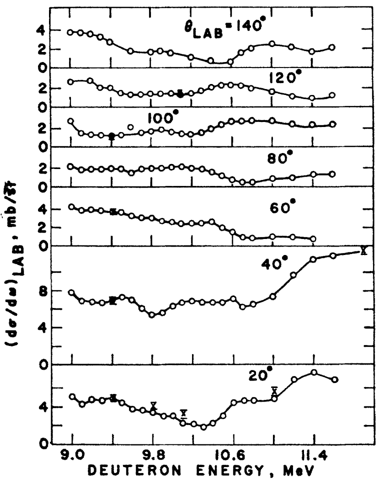

FIG. 7. The differential cross section for the transition $C^{12}(1)$ to the first excited state in B^{10}, shown as a function of the deuteron energy for different angles to the incoming deuteron beam. Crosses indicate measurements with the magnetic spectrograph, open circles represent data taken with the solid-state detectors.

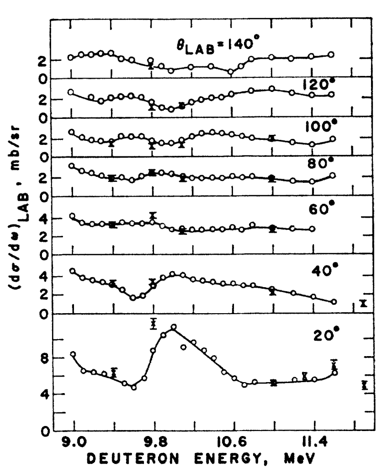

FIG. 6. The differential cross section for the transition to the ground state $C^{12}(0)$, presented as a function of the deuteron energy for different angles to the incident beam. Crosses indicate measurements with the magnetic spectrograph, open circles represent data taken with the solid-state detectors.

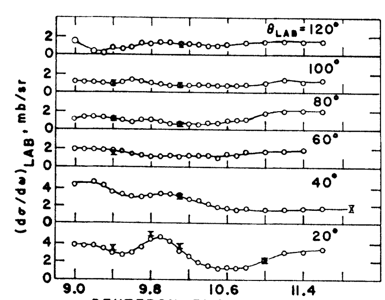

FIG. 8. The differential cross section for the transition $C^{12}(3)$ to the third excited state in B^{10}, shown as a function of the deuteron energy for different angles to the incoming beam. Crosses indicate measurements with the magnetic spectrograph, open circles represent data taken with the solid-state detectors.

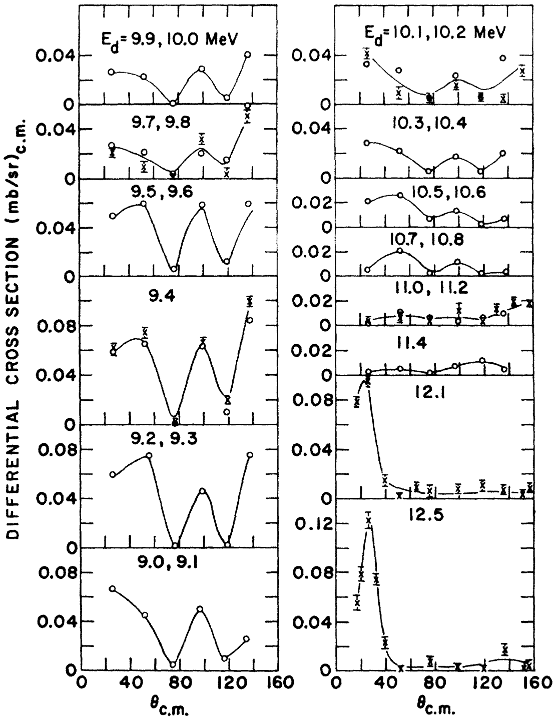

FIG. 9. Angular distributions for the isospin-forbidden α group $C^{12}(2)$ obtained at a number of deuteron energies. Both the differential cross section and the angles are given in the center-of-mass system. Crosses indicate measurements with the magnetic spectrograph, open circles represent data taken with the solid-state detectors. The lines are given as guides for the eye. When the angular distribution was averaged over two runs of different deuteron energies, both energies are indicated.

lower deuteron energies, the cross section decreases rather steadily to a value which is barely significantly above background at about $E_d = 11$ MeV. At higher deuteron energies the yield increases. It is strongly forward-peaked so that the integrated cross section increases only slightly although the yield at $\theta_{lab} = 20°$ becomes 20 times as large at $E_d = 12.5$ MeV as it is at $E_d = 11$ MeV.

Figure 10 also shows the allowed α groups $C^{12}(0)$, $C^{12}(1)$, and $C^{12}(3)$ which were studied to some extent for comparison with the inhibited α group. Since our angular range is rather limited, the derived integrated cross section might have a relatively large error.

DISCUSSION

General Remarks on the Isospin Selection Rule in Light Nuclei

The isospin selection rule has been studied for many years with (d,d'), (α,α'), and (d,α) reactions on light nuclei. In all (d,d') and (α,α') reactions, only small violations of this selection rule were found but large violations have been reported in some of the (d,α) reactions. Many (d,α) processes have been studied in order to investigate the cause for such large violations.

According to Wilkson[1] and Lane and Thomas,[8] one can expect that the isospin of a state is a good quantum number if

$$\langle H_c \rangle \ll D^J, \qquad (1)$$

where $\langle H_c \rangle$ is the average matrix element of the Coulomb forces which are responsible for the mixing of the isospins of two neighboring states having the same spin and parity but different isospin, and D^J is the average spacing of two such states. Usually, according to Wilkinson,[1] $\langle H_c \rangle \lesssim 100$ keV. In most light nuclei, we have $D^J \gg 100$ keV at low excitation energy and therefore condition (1) applies and only states with small isospin mixture are expected.

At very high excitation energies at which the nucleus has overlapping broad resonances with average width $\langle \Gamma \rangle$, the isospin again appears to be pure.[1,8,9] The condition in this case is

$$\langle H_c \rangle \ll \langle \Gamma \rangle. \qquad (2)$$

This condition describes a reaction which takes place in a time $\tau \approx \hbar / \langle \Gamma \rangle$ that is short in comparison with the time $\tau_c \approx \hbar / \langle H_c \rangle$ associated with the isospin-mixing process. Again taking $\langle H_c \rangle \lesssim 100$ keV, we expect that the isospin appears to be a good quantum number at excitation energies at which the nucleus exhibits resonances with width $\langle \Gamma \rangle \gg 100$ keV.

There might then exist a region of medium excitation energies in which the isospin is not a good quantum number. This would imply in particular that in the already mentioned (α,α'), (d,d'), and (d,α) reactions, in which self-conjugate nuclei are used as target material, isospin-forbidden $T=1$ states may be populated in the final nucleus to some extent, provided that the reaction goes via compound nuclear states located in this region of medium excitation energy. Wilkinson[1] has estimated that this region of medium excitation energy for light $(4n+2)$ nuclei starts at 6–10 MeV and ends between 14 and 18 MeV. We expect therefore that

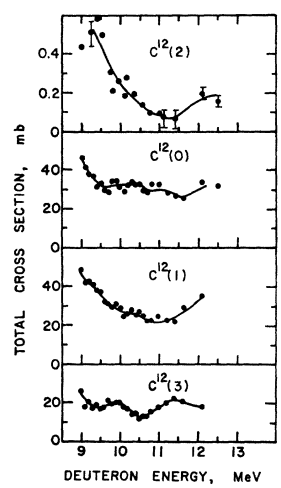

FIG. 10. Total cross sections for the $C^{12}(d,\alpha)B^{10}$ reaction to the lowest four levels in B^{10}. The curves represent the forbidden α group $C^{12}(2)$ and the allowed groups $C^{12}(0)$, $C^{12}(1)$, and $C^{12}(3)$, respectively, as functions of the deuteron energy.

[8] A. M. Lane and R. G. Thomas, Rev. Mod. Phys. **30**, 257 (1958).
[9] H. Morinaga, Phys. Rev. **97**, 444 (1955).

the isospin-forbidden $C^{12}(2)$ group, the group under study, is less inhibited when it is formed via the N^{14} compound nucleus at this particular region of excitation energy. The degree of the violation of the selection rule (i.e., the amount of isospin impurity) usually is obtained by comparing the yield of the $T=1$ state with the yield to a neighboring fully allowed $T=0$ state. Because we study a reaction going from one 0^+ state with $T=0$ to another with $T=1$, population of the final state is further inhibited by the selection rules for angular momentum and parity. This additional reduction can be estimated and is discussed later. On the assumption that the initial and final systems are in states of pure isospin, the comparison will provide an estimate of the isospin impurity in the compound nucleus if both the reaction populating the $T=1$ state and that populating the $T=0$ state in the final nucleus proceed via compound-nucleus formation. If fast reaction mechanisms are involved, they can be responsible only for the formation of the $T=0$ states because their reaction times are too fast for isospin-mixing processes, as one can see from condition (2). In addition, the formation of a $J^\pi=0^+$ state is forbidden by angular-momentum and parity selection rules in a simple stripping reaction[10] in which the incoming deuteron picks up a deuteron from the target nucleus C^{12}. In comparing the probability of forming the $T=1$ state with that of the $T=0$ state, therefore, the part going via the direct interactions must be subtracted from the total yield producing the $T=0$ state. Unfortunately, the proportions of compound-nucleus formation and direct interaction cannot be estimated easily and therefore the isospin impurity can be determined only very crudely. This inability to take account of the possible direct interaction in the isospin-allowed transitions may result in an underestimate of the isospin impurity. But this difficulty can be avoided by studying the relative changes of the isospin impurity with excitation energy, since the cross section of the direct process changes only slowly with energy.

We would like to point out that a violation of the isospin selection rule might not show up as well in the inelastic scattering of deuterons and alphas as it does in the (d,α) reactions. Most probably the isospin-allowed transitions proceed much more strongly via direct interactions in the case of inelastic scattering than in the (d,α) reactions. Thus if the isospin impurity is taken simply as the ratio of the forbidden to the allowed transitions, the value for the inelastic scattering will appear spuriously low. So far no appreciable isospin impurity has been measured in the inelastic scattering of deuterons or alphas.

Earlier Investigations of the Isospin Impurity in the First $T=1$ State in B^{10}

The formation of the $T=1$ states in B^{10} by (d,d') or (d,α) reactions has been studied to some extent. Bockelman *et al.*[11] and Armitage and Meads,[12] who used the magnetic spectrograph as particle detector, made measurements at some few different incident energies and at several angles of particle emission. Neither the first $T=1$ state at 1.74 MeV nor the second $T=1$ state at 5.16 MeV was detected. The (d,α) reaction was investigated with two deuteron energies $E_d=9.86$ MeV, $\theta_{lab}=90°$ and $E_d=10.58$ MeV, $\theta_{lab}=45°$. As one can see from our Figs. 5–8, the yield of the first $T=1$ state under these conditions should indeed be very small (of the order of a hundredth of the ones leading to the neighboring $T=0$ states). It is therefore not surprising that only an upper limit on the formation of the $T=1$ state was given. These measurements of Armitage and Meads[12] also indicate the difficulty connected with a study of the second $T=1$ state at 5.16 MeV. The broad nearby $T=0$ state at 5.18 MeV increases the background considerably at the position of the α group associated with the $T=1$ state and hence the small intensity of the $T=1$ state will usually be obtained only with poor accuracy.

Yanabu[13] studied the $C^{12}(d,\alpha)B^{10}$ reaction with a deuteron energy of 14.7 MeV, and Yanabu *et al.*[14] used seven different deuteron energies between 15 and 20 MeV. The authors showed α spectra whose energy resolution width is about 200 keV. Therefore, it might very well be that the results which they obtained for the isospin-forbidden α group are disturbed by contaminants in the target. They report that in the angle range $\theta_{lab}=40°$–$90°$ the yield of the isospin-forbidden α group is 2–3% of the yield of the $C^{12}(0)$ group. The differential cross section of this particular α group $C^{12}(0)$ changes widely with angle, but (as taken from their graphs) the average value for the angles between 40° and 90° is about 3.5 mb/sr. The differential cross section of the $C^{12}(2)$ group therefore has the value of 70–105 μb/sr. At the higher deuteron energies, the differential cross section of the $C^{12}(2)$ group was measured at three angles: $\theta_{lab}=130°$, 140°, and 165°. Here the values lie between 10 and 50 μb/sr. Although Yanabu[13] and Yanabu *et al.*[14] give no estimate of the errors in their values, they indicate that these might be large.

The Isospin Impurity in N^{14} in the Range of 18–21 MeV Excitation Energy

In spite of all the recent experiments on the $C^{12}(d,\alpha)B^{10}$ reaction leading to the first $T=1$ state in B^{10}, the results still are inadequate for a study of the energy dependence of the isospin impurity in the compound nucleus N^{14}. In particular, the expected vanishing of the isospin impurity in the region of 14–18 MeV excitation

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TABLE I. Comparison of the measured and calculated cross sections of the isospin-forbidden alpha group relative to the cross sections of the different isospin-allowed alpha groups. $R_c(0)$, $R_c(1)$, and $R_c(3)$ represent the ratios of the calculated cross section of the $C^{12}(2)$ group to the calculated cross sections of the $C^{12}(0)$, $C^{12}(1)$, and $C^{12}(3)$ groups, respectively. $R_m(0)$, $R_m(1)$, and $R_m(3)$ represent the same cross-section ratios but they are derived from the measured total cross sections shown in Fig. 10. $R_m(0)/R_c(0)$, $R_m(1)/R_c(1)$, and $R_m(3)/R_c(3)$ indicate the isospin impurity in the N^{14} nucleus at excitation energies E_x when the isospin-forbidden α group is compared with the isospin-allowed transitions to the ground state and to the first and third excited states, respectively.

E_d	$R(0)=\sigma(2)/\sigma(0)$			$R(1)=\sigma(2)/\sigma(1)$			$R(3)=\sigma(2)/\sigma(3)$			E_x
(MeV)	$R_c(0)$	$R_m(0)$	$R_m(0)/R_c(0)$	$R_c(1)$	$R_m(1)$	$R_m(1)/R_c(1)$	$R_c(3)$	$R_m(3)$	$R_m(3)/R_c(3)$	(MeV)
9.0	0.083	0.011	0.13	0.154	0.011	0.07	0.227	0.023	0.10	17.99
11.0	0.094	0.002	0.02	0.175	0.003	0.02	0.222	0.003	0.01	19.70

energy cannot be investigated without additional data. Our own measurements indicate that the isospin impurity disappears in the region $E_d=9$–11 MeV, corresponding to excitation energies of 18–19.7 MeV in N^{14}. From Fig. 10, in which the total cross section is plotted for the four lowest states in B^{10}, we see that the cross section of the isospin-forbidden group $C^{12}(2)$ drops by a factor of about 6 in the range $E_d=9$–11 MeV. This drop could, in fact, be even larger because the cross section at 11 MeV is very uncertain and could be almost zero. The large error is due to the fact that the yield of the $C^{12}(2)$ group is here very small and hardly to be seen above the background.

For a rough estimate of the isospin impurity of the N^{14} nucleus at about 20-MeV excitation energy (corresponding to a deuteron energy of about 11 MeV, where we observe the smallest yield to the first $T=1$ state), we compare the yield of the isospin-forbidden $C^{12}(2)$ group with the yield of the fully allowed neighboring α groups. As we have mentioned earlier, several assumptions and corrections have to be made for this comparison:

(1) We assume that both in the initial and in the final systems in the reaction $C^{12}(d,\alpha)B^{10}$ the isospin is a good quantum number and that the $T=1$ state in B^{10} can be produced only through isospin impurity in the N^{14} compound nucleus.

(2) In a reaction such as $C^{12}(d,\alpha)B^{10}$, for which both the initial and the final state have the spin assignment $J^\pi=0^+$, specific angular-momentum and parity restrictions come into play which do not show up for other final states $J\neq 0$. This reduction or statistical weighting factor can be calculated by assuming that the reaction goes entirely via compound-nucleus formation and that it can be described by the statistical theory of the nucleus. We then use the Hauser-Feshbach[15] calculation as Hashimoto and Alford[16] have done already in another (d,α) reaction. With these calculations, the ratio of the cross sections for the reactions leading to different final states in B^{10} can be obtained if the transmission coefficients T_l for all possible orbital angular momenta l of the captured deuteron and emitted alpha are known. The values of T_l were determined by the ABACUS code,[17] which employs the optical model for the capture process as well as for the emission process. Different optical-model potential wells were used but no spin-orbit term was assumed in any case. Alteration of the different potential parameters caused quite marked variations in the values of T_l for the highest orbital angular momenta required, but the ratio of two cross sections leading to neighboring states in B^{10} changed less than 10%.

Table I lists the calculated ratios R_c and the measured ratios R_m by which the total cross section for the reaction leading to the $T=1$ second excited state is compared with the cross sections associated with the ground state and with the neighboring first and third excited states in B^{10}. As expected, the yield of the $T=1$ state is reduced because its spin is 0^+, and this reduction is expressed in the calculated reduction factors R_c. The factor $R_c(0)$ which gives the calculated comparison with the ground state ($J^\pi=3^+$), is equal to 0.083 and 0.094 at deuteron energies of 9 and 11 MeV, respectively. For the two neighboring $T=0$ states with $J^\pi=1^+$, the factor $R_c(1)$ is 0.154 and 0.175 when the first excited state is taken as comparison, and $R_c(3)$ is 0.227 and 0.222 when the third excited state is considered. We notice that the measured values R_m are much smaller than R_c, and attribute this inhibition to the isospin-forbiddenness of the transition to the $T=1$ state. In fact, the ratio R_m/R_c indicates the violation of the isospin selection rule and represents the isospin impurity in the N^{14} compound nucleus. It is about 10% at the excitation energy $E_d=18$ MeV and 1–2% at $E_d=19.7$ MeV. These values have to be corrected because the $C^{12}(d,\alpha)$ reaction does not go predominantly via compound-nucleus formation as we have assumed; direct-interaction mechanisms have also to be considered. This will be discussed in the next paragraph. As we will see, this correction introduces large uncertainties into the values of the isospin impurities. Any errors that might arise from using the statistical theory to calculate R_c can be assumed to be small in comparison.

(3) This assumption that direct-reaction mechanisms are not participating in the reaction turns the values of 1–2% and 10% (Table I) into the lower limits of the isospin impurity.

An accurate estimate of the contribution of the direct interaction cannot be given, but surely the contribution of the compound nucleus is important. This can be seen

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in the yield curves of all three allowed α groups (Figs. 6–8) which exhibit fluctuations with bumps or valleys that extend over several hundred keV. This indicates that this reaction proceeds at least in part through the formation of the compound nucleus with resonances having widths of the order of several hundred keV. The importance of the compound nucleus formation is confirmed by the results of Baldeweg *et al.*[7] who studied the allowed α group in the $C^{12}(d,\alpha)B^{10}$ reaction in greater detail. In agreement with our results, they observed the strongest fluctuations in the yield curves at the smallest and largest angles to the incident beam. This behavior might suggest that we are dealing with Ericson fluctuations, for which the strongest fluctuations ordinarily are expected at the most forward and backward angles.

For an estimate of the isospin impurity, we assume that 50% of the $C^{12}(d,\alpha)$ reaction leading to the first three $T=0$ states in B^{10} occur through compound-nucleus formation. The isospin impurity then is about 20% at $E_x=18$ MeV and drops to about 3% at $E_x=19.7$ MeV. If the small isospin impurity of 3% is connected with fast reaction times, condition (2), $\langle H_c\rangle \ll \langle\Gamma\rangle$, would lead us to expect that the fluctuations in the cross sections mentioned earlier should have widths larger than 100 keV. The fact that the bumps in the measured cross section indeed have widths of several hundred keV indicates that resonances with widths of these magnitudes are present in the compound nucleus at these excitation energies. Of course, one then would expect that at lower deuteron energies at which the isospin impurity is much larger (about 20%), the average resonance would have a smaller width. Such conclusions cannot be drawn from the measurements made so far.

From our measurements of the total cross sections, we conclude that the (d,α) reaction in general can very well be used to study the isospin impurity in a nucleus as a function of its excitation energy. As expected, a medium-energy region is indicated in which the isospin impurity is quite noticeable but becomes very much smaller with increasing energies.

Comparison with Results Obtained by Other (d,α) Reactions

A result similar to ours was obtained by Jobst[18] who studied the reaction $O^{16}(d,\alpha)N^{14}$ populating the first $T=1$ state in N^{14} over a wide range of deuteron energies. At the lower deuteron energies between 5 and 9 MeV, the reaction exhibits a number of resonances which indicate an appreciable amount of isospin impurity in the compound nucleus F^{18}. In a later abstract,[19] Jobst mentions that at the higher deuteron energies the yield of the $T=1$ state nearly vanishes. This agrees well with our result. But so far the yield at the very forward angles has not been studied in this reaction; it is not yet known if the same strongly forward-peaked reaction we observe at the higher deuteron energies can also be seen in other (d,α) processes.

In another experiment by Browne *et al.*[20] the production of the $T=1$ state at 15.11 MeV was studied in the $N^{14}(d,\alpha)C^{12}$ reaction over the wide range of deuteron energies from 3 to 12 MeV. Although the formation of the $T=1$ state was detected only by a γ-ray counter set at 90° to the incident beam, the measured yield is taken as a measure of the total cross section. They observed a number of resonances. With increasing deuteron energies the cross section decreases and the structure of the yield curve disappears. At a few energies the alphas from reactions leading to different $T=0$ states in C^{12} were measured and the isospin impurity was found to be of the order of a few percent.

From all these investigations it seems reasonable to assume that whenever a large isospin impurity is found, it will disappear when the measurements are extended to higher deuteron energies—but, of course, only in case the compound nucleus and not the initial or final system is responsible for the isospin impurity. We would like to mention here the interesting case of the $B^{10}(d,\alpha)Be^8$ reaction in which Erskine and Browne[21] studied the transitions leading to the two states in Be^8 at 16.62- and 16.92-MeV excitation energy. Both showed the same yield although one state was assumed to be a $T=0$ and the other a $T=1$ state. For many years this result was very puzzling, not only because of the complete breakdown of the isospin selection rule but also because the reaction which was studied with deuteron energies around 4 MeV should go via the compound nucleus at excitation energies around 28 MeV. At such high excitation energies, broad overlapping resonances in the compound system C^{12} are already expected[1] to decrease the isospin impurity. The problem was solved by recent studies of the Be^8 nucleus, in which it was discovered that these two states at 16.62- and 16.92-MeV excitation energy are states with strong admixtures[22] of different values of T and that the $B^{10}(d,\alpha)Be^8$ reaction therefore will populate both levels equally well.

Indication of Direct-Interaction Processes That Produce Isospin Impurities

So far we have assumed that direct interaction does not produce the first $T=1$ state in B^{10} for two reasons as mentioned earlier: (1) direct-interaction mechansims are connected with reaction times too fast for isospin mixing processes, and (2) the formation of a $J^\pi=0^+$ state is forbidden in a simple (d,α) stripping reaction on C^{12}.

In fact, the measured angular distributions of the

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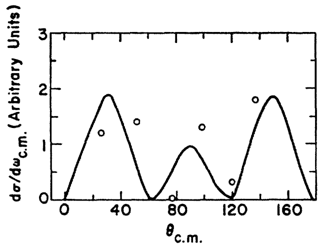

FIG. 11. Comparison between the angular distribution of the isospin-forbidden α group $C^{12}(2)$ measured at a deuteron energy of 9.4 MeV (open circles) and a calculated distribution (curve) that assumes a transition through a 3^- state in the compound nucleus N^{14}. Both the incoming deuteron and the outgoing alpha then necessarily have an orbital angular momentum of 3.

isospin-forbidden alpha group in the range of 9–11-MeV deuteron energies confirm the assumption of compound-nucleus formation. As can be seen in Fig. 9, in which the differential cross section $(d\sigma/d\Omega)_{c.m.}$ is plotted as a function of the angle $\theta_{c.m.}$ for different deuteron energies, the angular distributions are nearly symmetric around 90°. Although the total cross section (Fig. 10) in this energy region decreases strongly with increasing deuteron energy, the shape of the angular distribution remains nearly constant with two pronounced minima at about $\theta_{c.m.}=70°$ and 120°. For comparison Fig. 11 shows the angular distribution calculated on the assumption that the reaction goes via 3^- states in the compound nucleus. The distribution is unique because the incoming deuteron, like the outgoing alpha, carries only the orbital angular momentum $l=3$. This calculated angular distribution closely resembles the measured one which is indicated by circles. The slight deviation from the calculated 3^- distribution together with the slight deviation from symmetry around 90° may well be due to interference with states of positive parity.

At deuteron energies larger than $E_d=11.3$ MeV, there are strong indications of a drastic change in the reaction mechanism by which the $T=1$ state is formed. (1) The angular distribution changes abruptly and becomes very asymmetric for all investigated deuteron energies larger than 11.5 MeV. It does not appear to be caused by interference effects. (2) The angular distribution is strongly forward peaked, its differential cross section at $\theta_{lab}=20°$ increases about 20-fold in a steady rise from $E_d=11.3$ MeV to $E_d=12.5$ MeV and then seems to level off. The total cross section increases only by a factor of about 2.5 and stays well below the value measured at $E_d=9$ MeV.

From these facts, we tentatively conclude that at the higher deuteron energies the reaction leading to the first $T=1$ state in B^{10} no longer proceeds through the compound nucleus in which the isospin impurity is produced by the mixing of different isospin states. We think instead that the shape of the angular distribution suggests a surface reaction that includes the production of the observed isospin impurity. Of course, as mentioned above a simple stripping reaction can be excluded, and a more complicated reaction has to be considered.

(1) For example, Hashimoto and Alford[16] have mentioned a (d,a) reaction in which, according to a suggestion of French, the incoming deuteron is polarized in the Coulomb field of the target nucleus. This procedure mixes other $T=1$ states into the ground state of the deuteron and a more complicated direct reaction could occur in which the angular-momentum and parity selection rules of a simple stripping reaction are no longer applicable. Hashimoto and Alford,[16] who studied the reaction $Ca^{40}(d,\alpha)K^{38}$ with deuterons incident at energies between 3.2 and 4.1 MeV, have estimated that the relative intensity of the $T=1$ states in the deuteron polarized in the Coulomb field of the target nucleus could become at most 0.1, not large enough to explain their measured value of about 0.5. In our case at the higher deuteron energies, the isospin impurity is $\leqslant 0.1$—small enough that it might be produced by the polarization of the deuteron.

(2) Another possibility, not yet considered and calculated, is the production of the $T=1$ state by Coulomb excitation during the emission process. In this procedure, one of the neighboring states that have the spin assignment $T=0$, $J^\pi=1^+$ would be formed in a direct (d,α) reaction; but during the emission process the outgoing α particle produces the $T=1$, $J^\pi=0^+$ state by Coulomb excitation.

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